Op-Amp Circuits: Part 4

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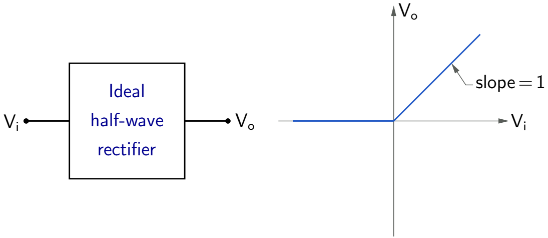
Half-wave rectifier



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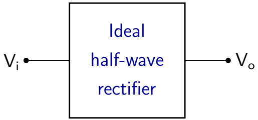

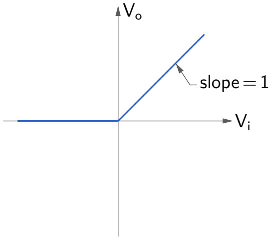

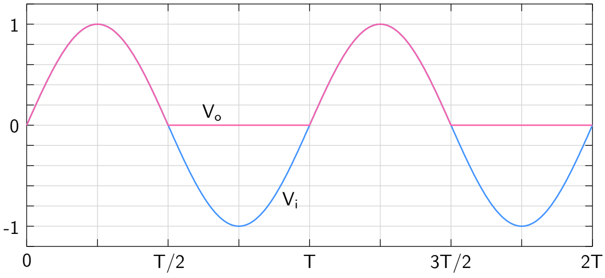

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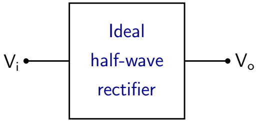

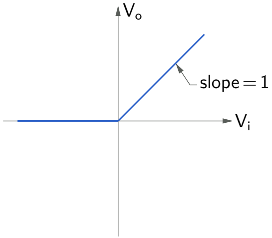

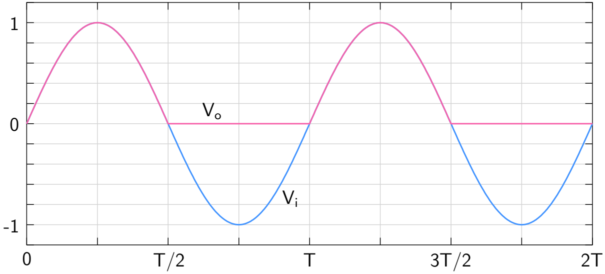

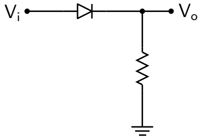

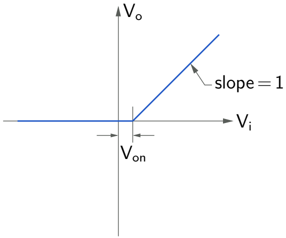

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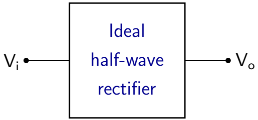

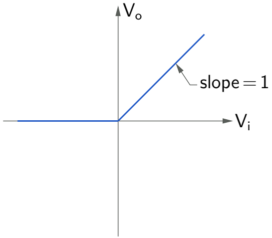

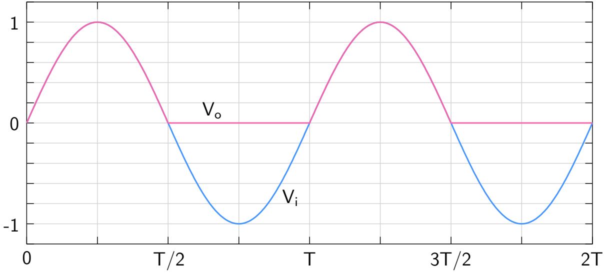

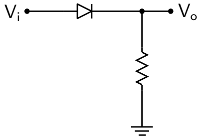

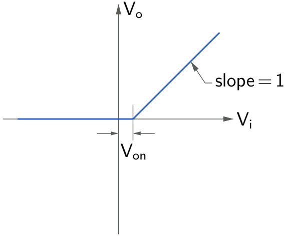

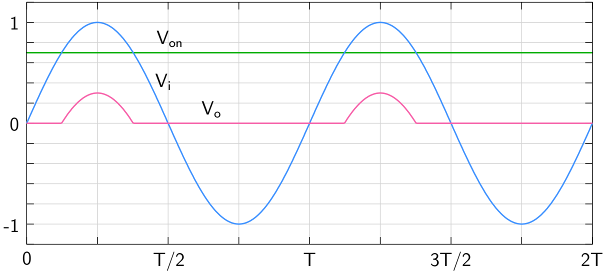

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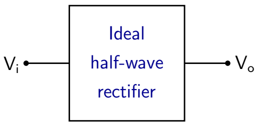
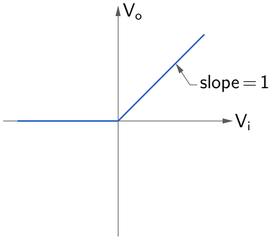
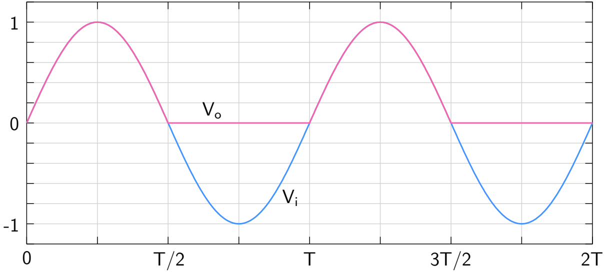
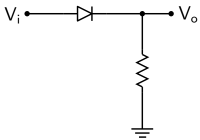
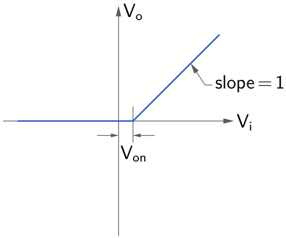
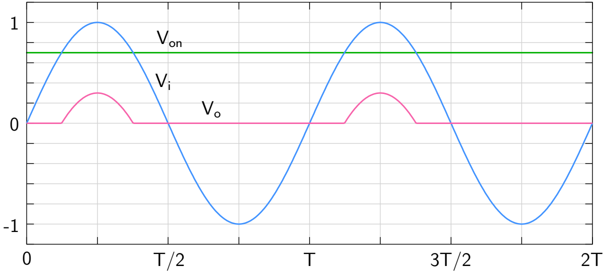






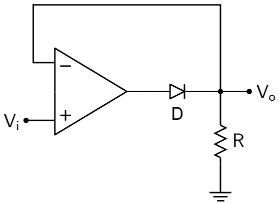






→ $\boxed{\text{need an improved circuit}}$

Half-wave precision rectifier



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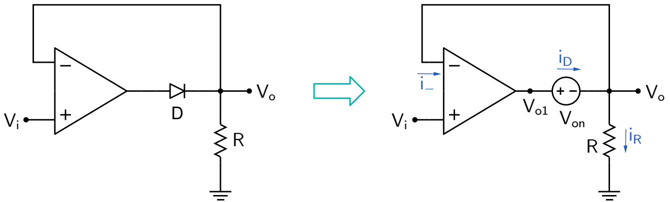
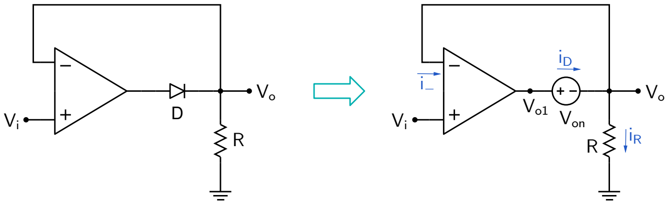


Consider two cases:

(i) D is conducting: The feedback loop is closed, and the circuit looks like (except for the diode drop) the buffer we have seen earlier.



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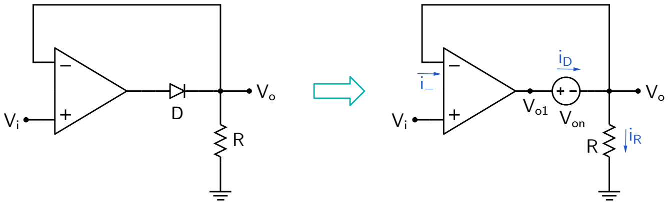
Since the input current $i_- \approx 0$, $i_R = i_D$.

$$V_+ - V_- = \frac{V_{o1}}{A_V} = \frac{V_o + 0.7\ V}{A_V} \approx 0\ V \rightarrow V_o = V_- \approx V_+ = V_i.$$



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This situation arises only if $i_D > 0$ (since the diode can only conduct in the forward direction), i.e., $i_R > 0 \rightarrow V_o = i_R R > 0$, and therefore $V_i = V_o > 0\,V$.

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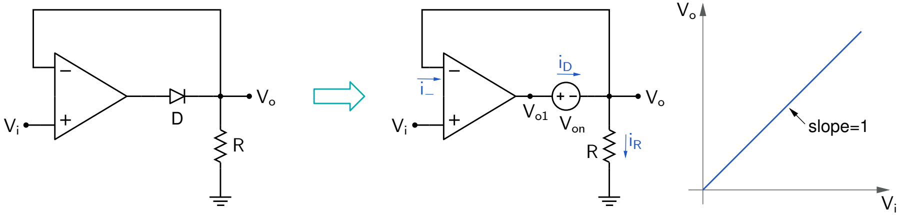

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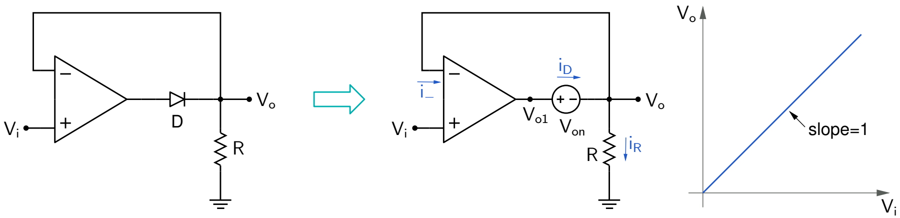

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Note: V_{on} does not appear in the graph.

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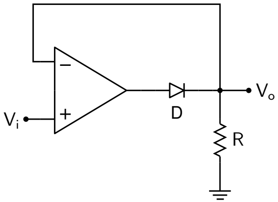

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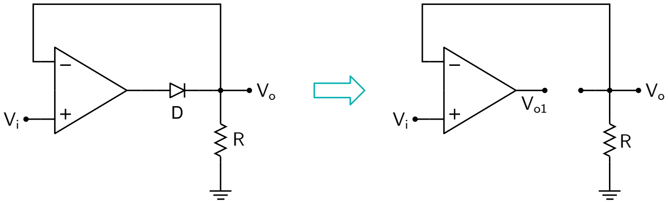

(ii) D is not conducting $\rightarrow V_o = 0\,V$.

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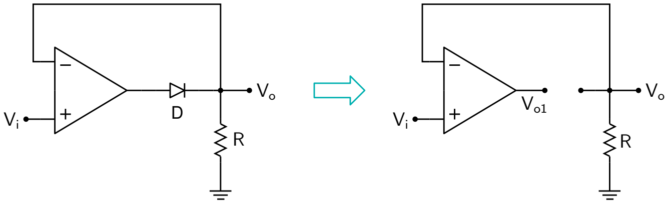

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Since the op-amp is now in the open-loop configuration, a very small V_i is enough to drive it to saturation.

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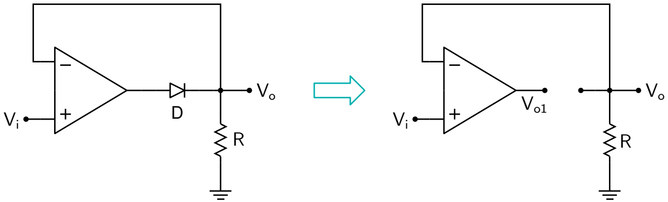

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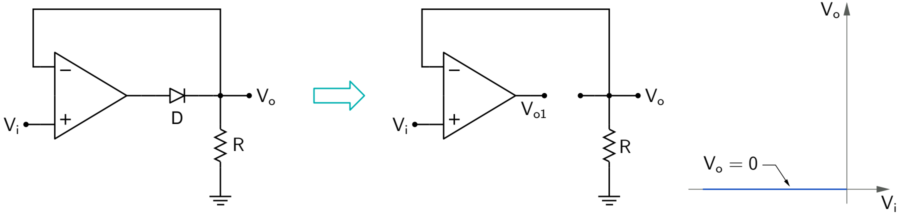
Note that Case (ii) occurs when $V_i < 0\,V$ (we have already looked at $V_i > 0$). Since $V_+ - V_- = V_i - 0 = V_i$ is negative, V_{o1} is driven to $-V_{\text{sat}}$.



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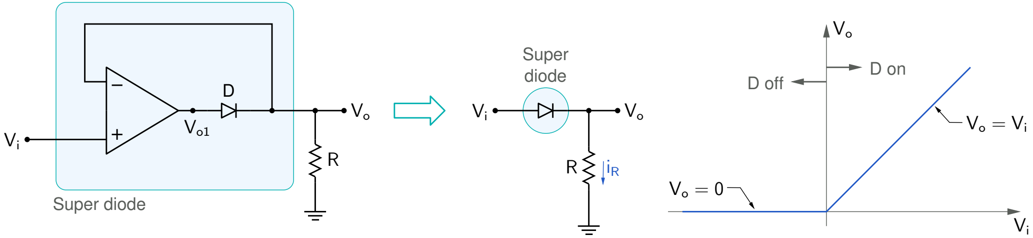
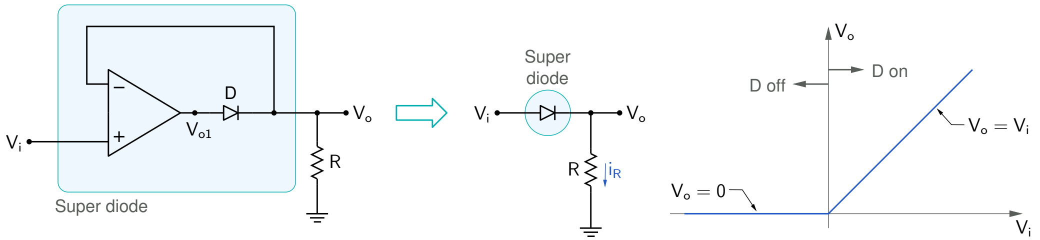
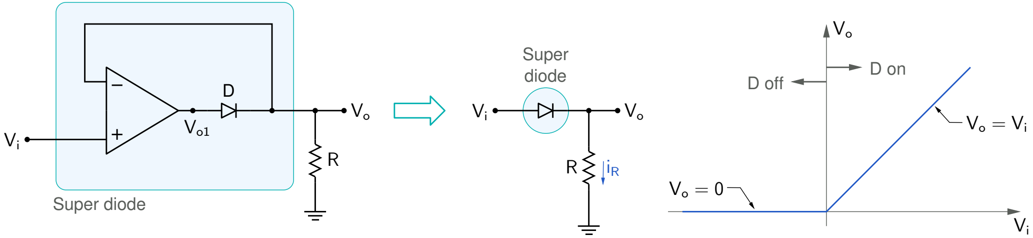

D
V_o
V_{o1}
V_i
R
Super diode
Super
diode
V_i
V_o
R
i_R
V_o
D on
D off
$V_o = V_i$
$V_o = 0$
V_i



* The circuit is called "super diode" (an ideal diode with $V_{on} = 0\,\text{V}$).



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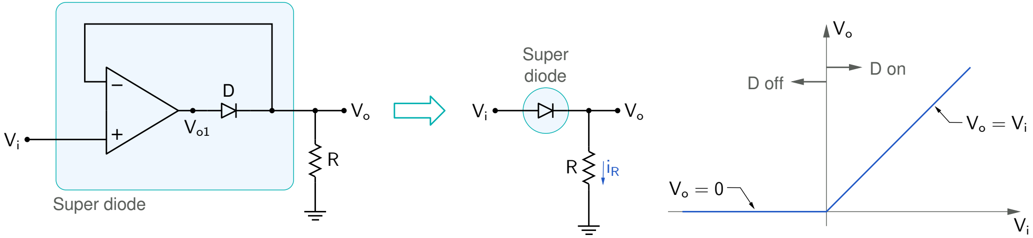

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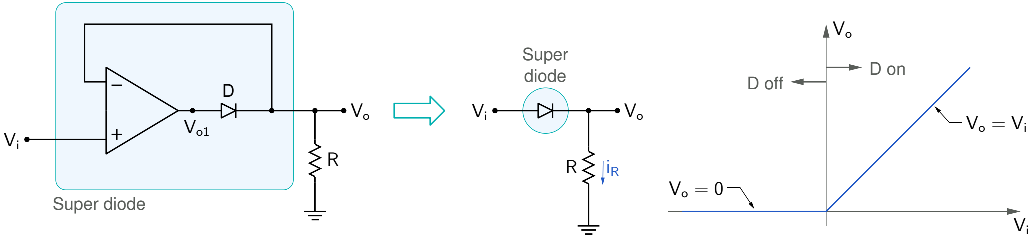

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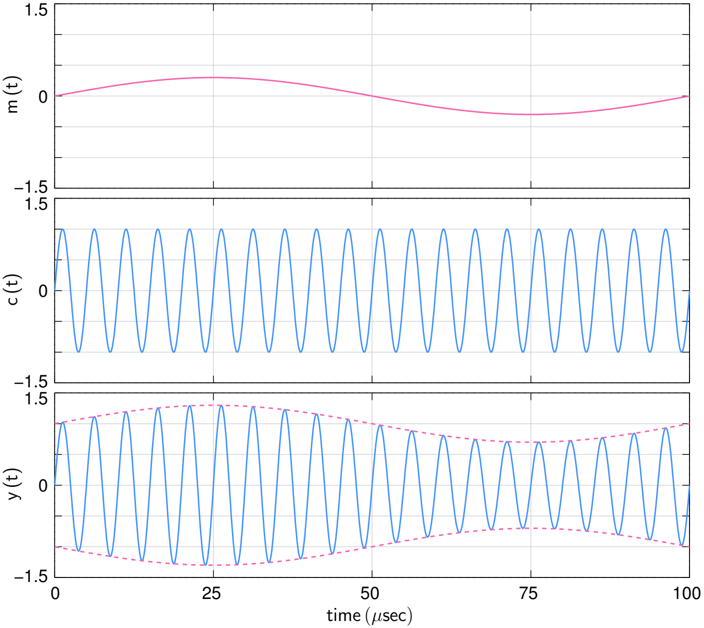
* Where does i_R come from?

A = 1
M = 0.3
f_c = 200 kHz
f_m = 10 kHz

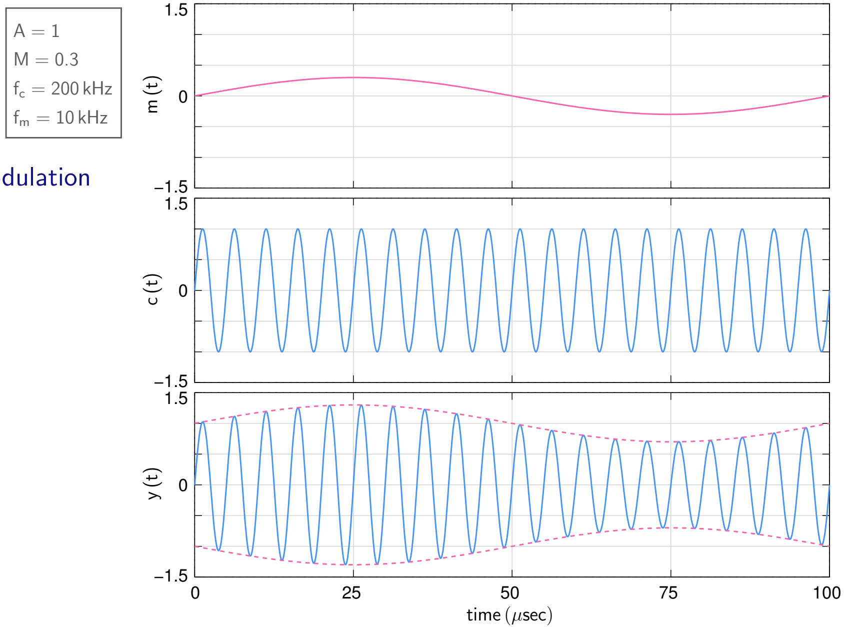
Application: AM demodulation



Application: AM demodulation

Carrier wave:

$$c(t) = A\sin(2\pi f_c t)$$



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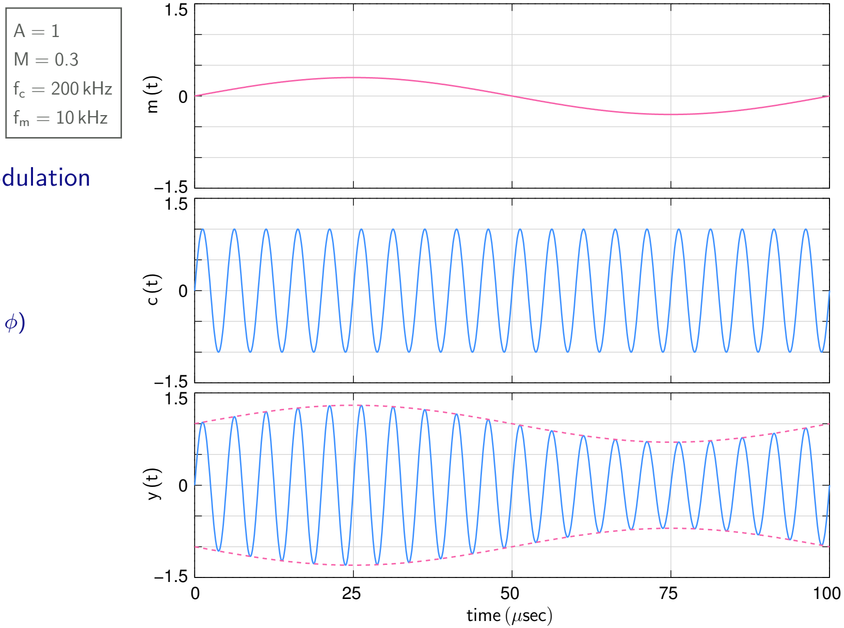
Carrier wave:

$$c(t) = A\sin(2\pi f_c t)$$

Signal (e.g., audio):

$$m(t) = M\sin(2\pi f_m t + \phi)$$



$A = 1$
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$f_c = 200\,\text{kHz}$
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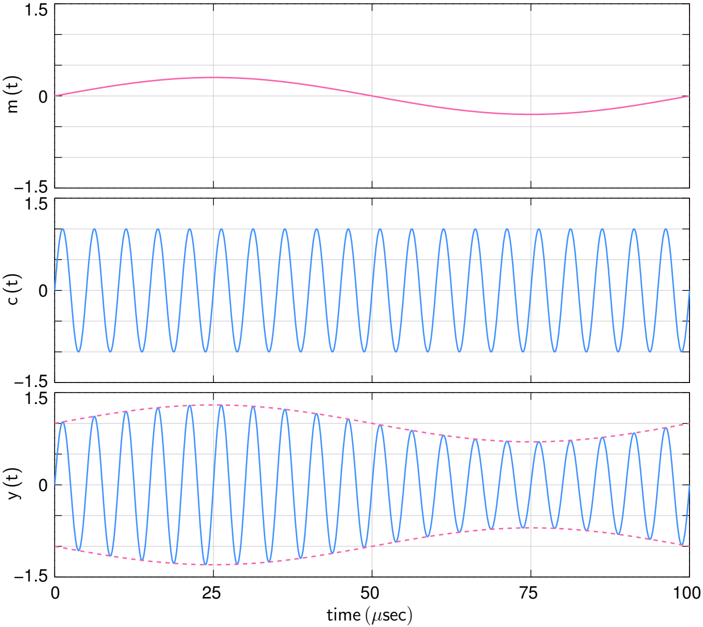
AM wave:

$$y(t) = [1 + m(t)]\; c(t)$$

(Assume $M < 1$)



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AM wave:

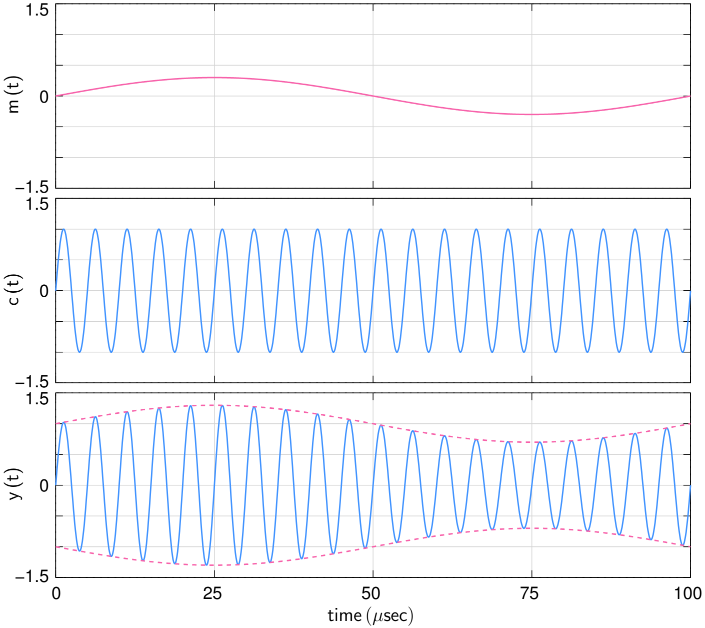
$y(t) = [1 + m(t)]\; c(t)$

(Assume $M < 1$)

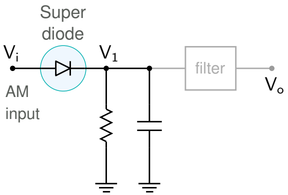
e.g., Vividh Bharati:

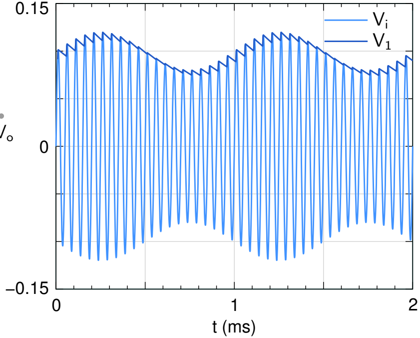
$f_c = 1188\,\text{kHz}$,

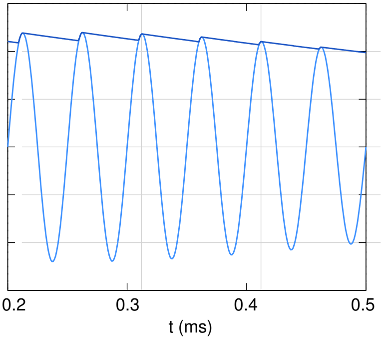
$f_m \simeq 10\,\text{kHz}$ (audio).



AM demodulation using a peak detector







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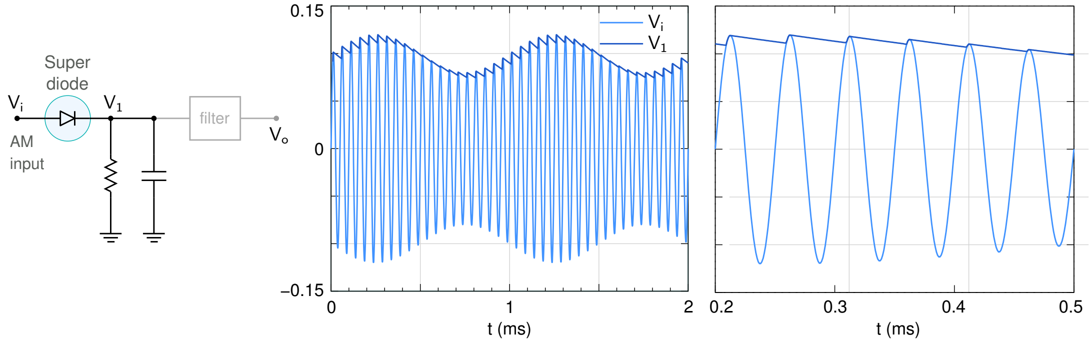
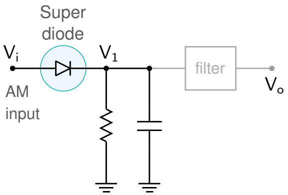
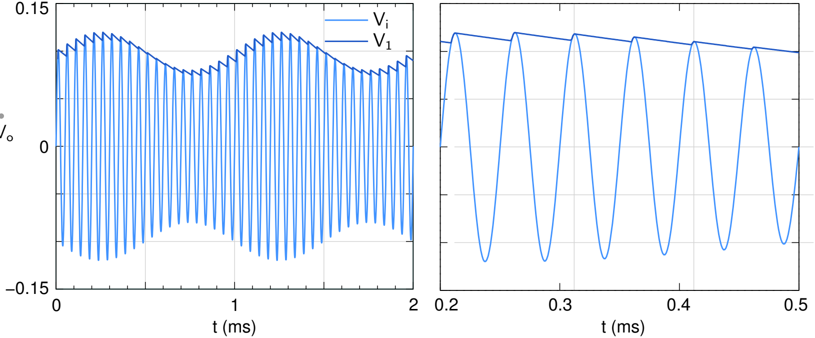


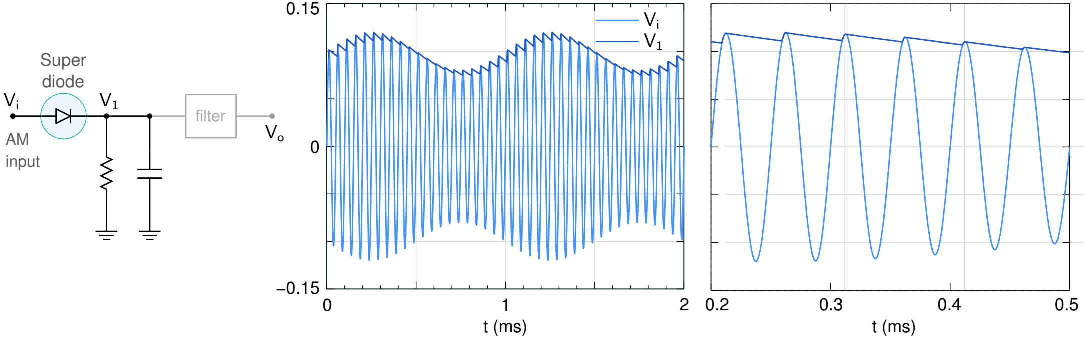
* charging through super diode, discharging through resistor





* charging through super diode, discharging through resistor
* The time constant (RC) needs to be carefully selected.

AM demodulation using a peak detector



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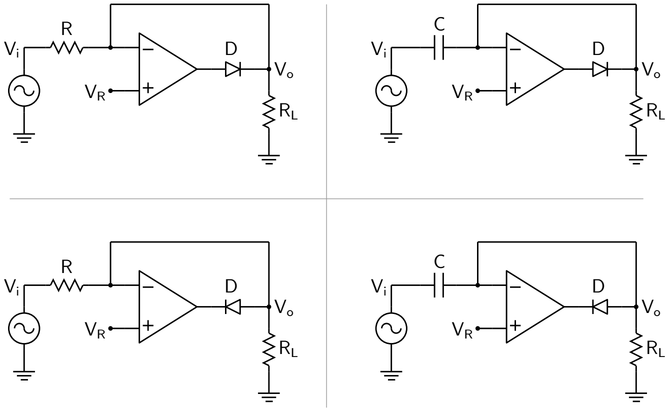
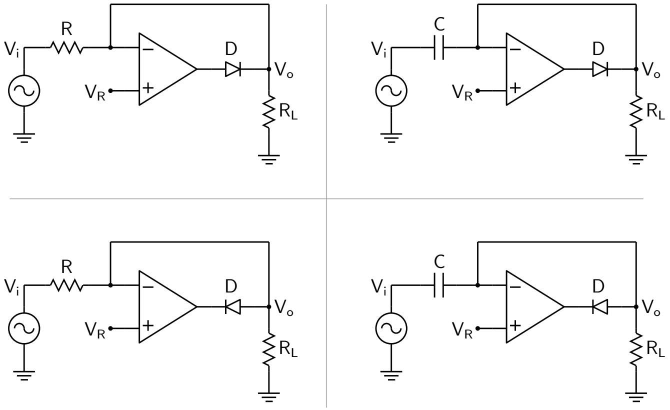
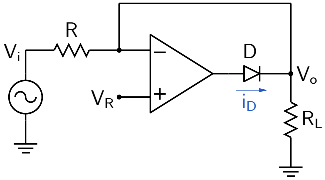
  SEQUEL file: `super_diode.sqproj`



∗ What is the function provided by each circuit?



* What is the function provided by each circuit?
* Verify with simulation (and in the lab).



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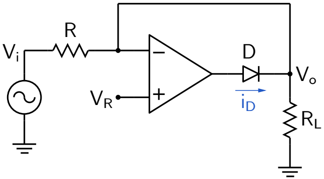

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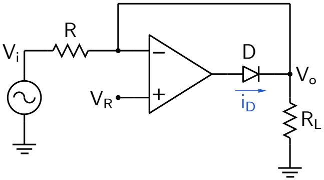
KCL: $i_D = \dfrac{V_R}{R_L} + \dfrac{V_R - V_i}{R}$.



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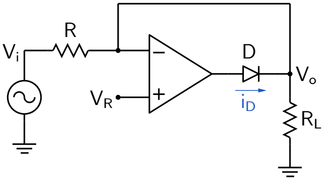
KCL: $i_D = \dfrac{V_R}{R_L} + \dfrac{V_R - V_i}{R}$.

Since $i_D > 0$, $\;V_R\left(\dfrac{1}{R_L} + \dfrac{1}{R}\right) > \dfrac{V_i}{R} \;\rightarrow\; V_i < V_R\left(\dfrac{R + R_L}{R_L}\right) \equiv V_{i1}$.

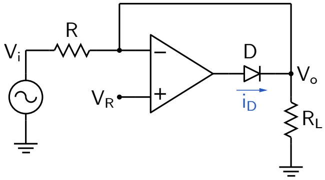


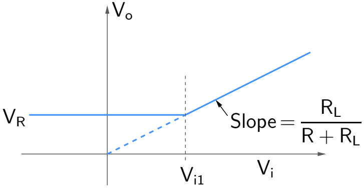
When D conducts, feedback path is closed $\rightarrow V_- \approx V_+ = V_R \;\rightarrow\; V_o = V_R$.

KCL: $i_D = \dfrac{V_R}{R_L} + \dfrac{V_R - V_i}{R}$.

Since $i_D > 0$, $\;V_R\left(\dfrac{1}{R_L} + \dfrac{1}{R}\right) > \dfrac{V_i}{R} \;\rightarrow\; V_i < V_R\left(\dfrac{R+R_L}{R_L}\right) \equiv V_{i1}$.

For $V_i > V_{i1}$, D does not conduct $\;\rightarrow\; V_o = \dfrac{R_L}{R+R_L}\,V_i$.





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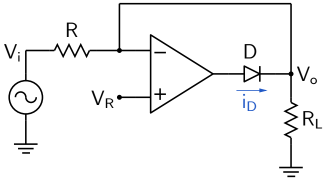

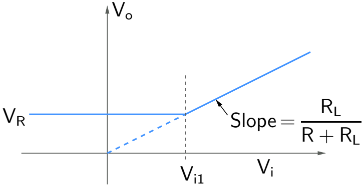

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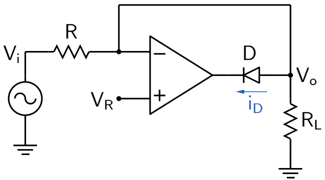
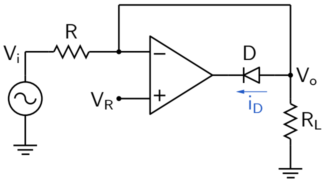
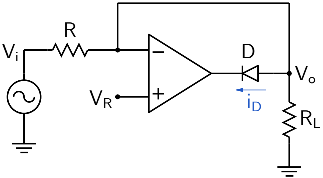


When D conducts, feedback path is closed $\rightarrow V_{-} \approx V_{+} = V_R \ \rightarrow \ V_o = V_R$.



When D conducts, feedback path is closed $\rightarrow V_- \approx V_+ = V_R \ \rightarrow \ V_o = V_R$.

KCL: $i_D + \dfrac{V_R}{R_L} + \dfrac{V_R - V_i}{R} = 0$.



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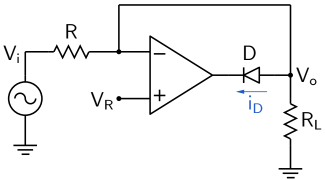

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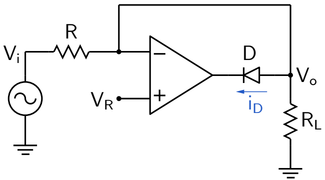
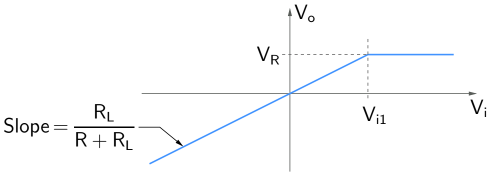
For $V_i < V_{i1}$, D does not conduct $\;\rightarrow\; V_o = \dfrac{R_L}{R + R_L}\, V_i$.





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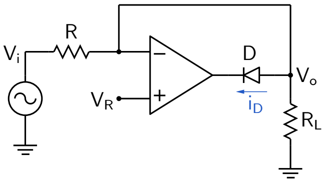

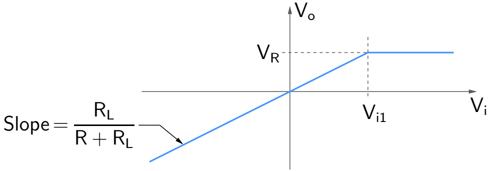

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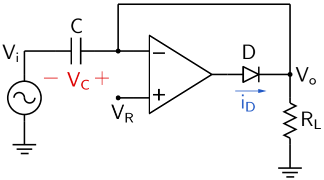
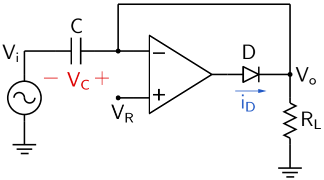


Time constant for the discharging process is $R_L C$.

Assume $R_L C \gg T \ \rightarrow V_C$ can only increase (in one cycle).



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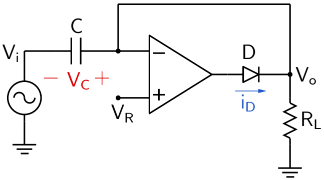
Assume $R_L C \gg T \;\rightarrow V_C$ can only increase (in one cycle).

When D conducts, $V_- \approx V_R$, and $V_C(t) = V_R - V_m \sin \omega t$.

$\rightarrow \; V_C^{\text{max}} = V_R - (-V_m) = V_R + V_m$.



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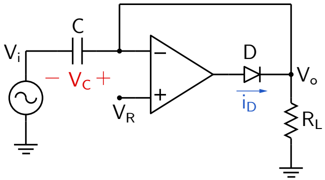
In steady state, V_C remains equal to $V_C^{\max} \;\rightarrow\; V_o(t) = V_i(t) + V_C^{\max} = V_m \sin\omega t + V_R + V_m$.



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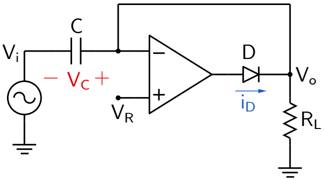
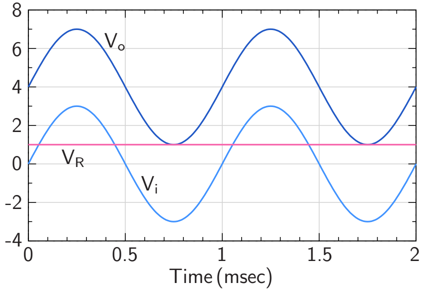
Note: V_{on} of the diode does not appear in the expression for $V_o(t)$.





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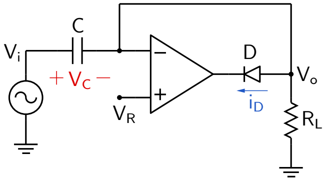

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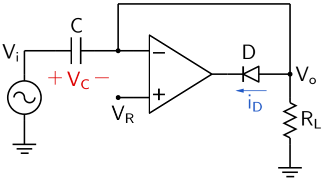

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When D conducts, $V_- \approx V_R$, and $V_C(t) = V_m \sin \omega t - V_R$.

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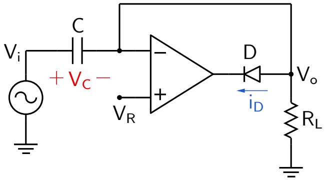

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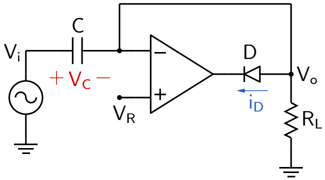

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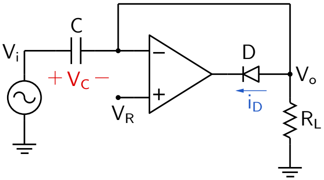

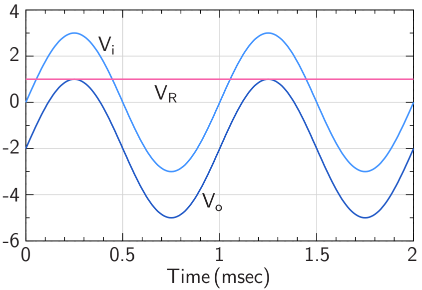

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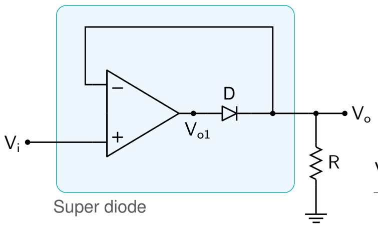
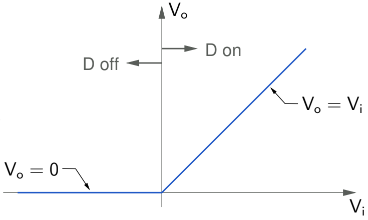
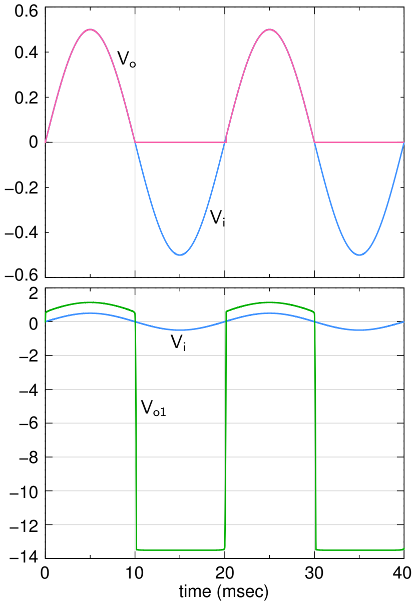
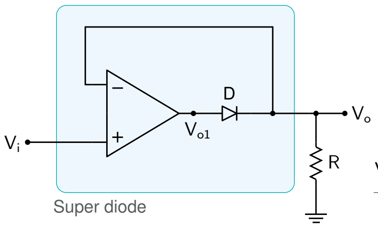
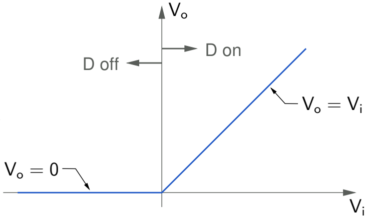
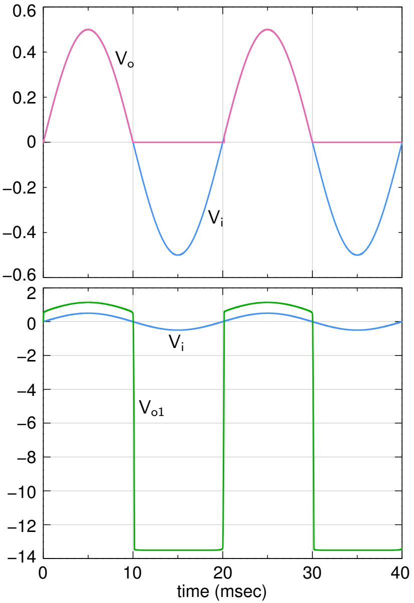

D
V_o
V_{o1}
V_i
R
Super diode


V_o
D off
D on
$V_o = V_i$
$V_o = 0$
V_i

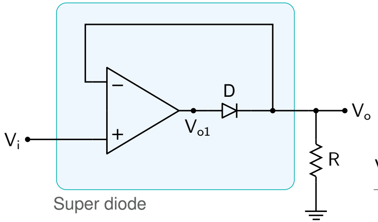

0.6
0.4
0.2
0
−0.2
−0.4
−0.6
V_o
V_i
2
0
−2
−4
−6
−8
−10
−12
−14
V_i
V_{o1}
0
10
20
30
40
time (msec)

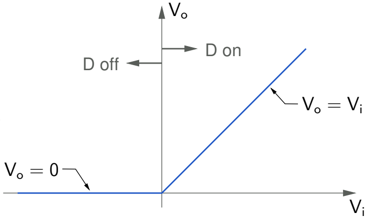


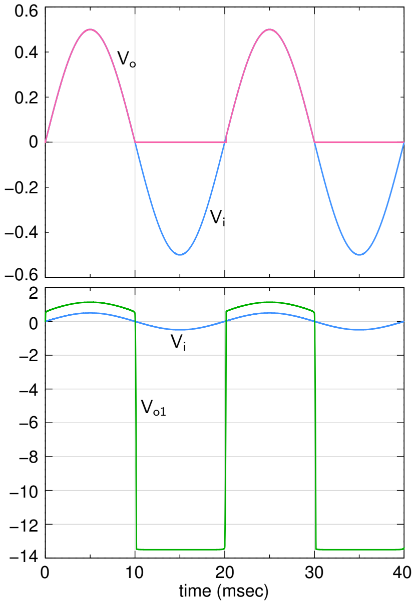




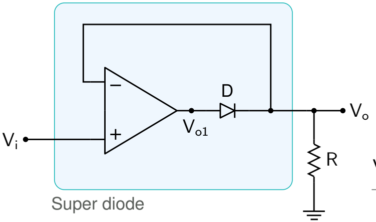
* When $V_i > 0$, the op-amp operates in the linear region, and $V_{o1} = V_o + V_{on}$.

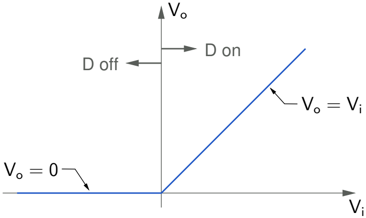


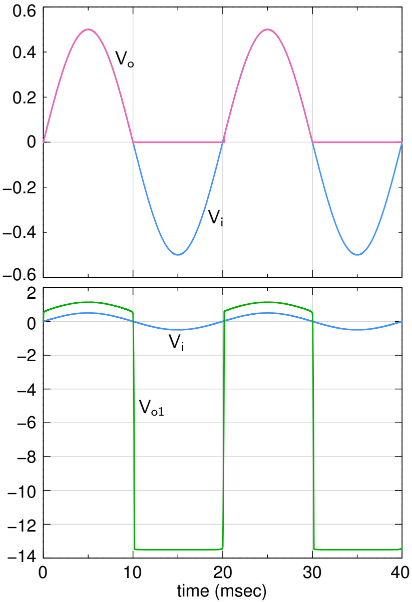




* When $V_i > 0$, the op-amp operates in the linear region, and $V_{o1} = V_o + V_{\text{on}}$.
* When $V_i < 0$, the op-amp operates in the open-loop configuration, leading to saturation, and $V_{o1} = -V_{\text{sat}}$.







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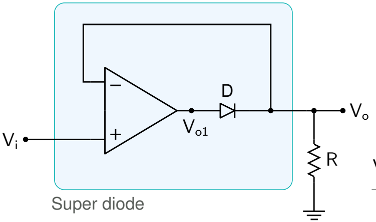
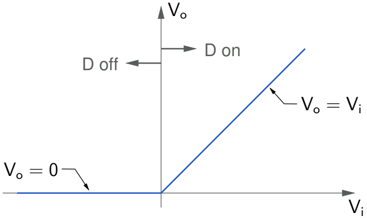
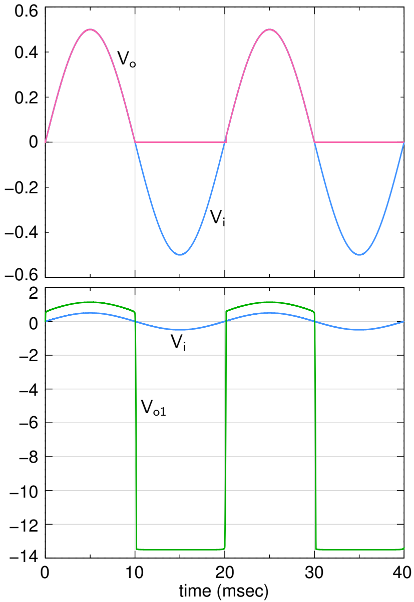
* The $V_i < 0$ to $V_i > 0$ transition requires the op-amp to come out of saturation. This is a relatively slow process and is limited by the op-amp slew rate.







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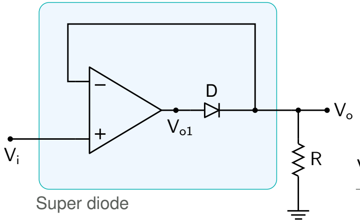
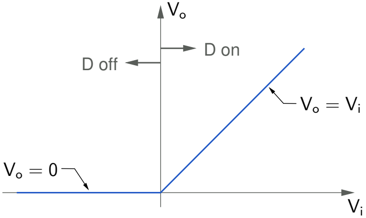
SEQUEL file: `ee101_super_diode_1.sqproj`

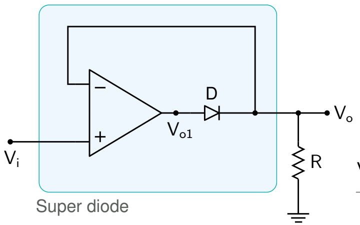
Half-wave precision rectifier

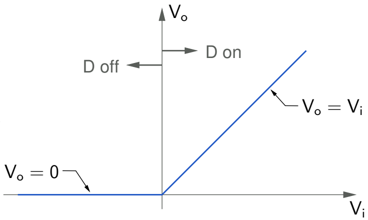


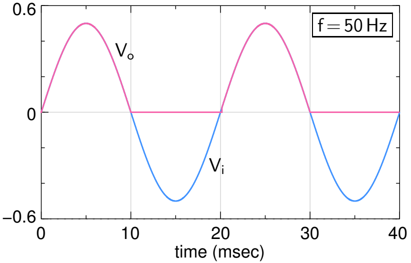


* The time taken by the op-amp to come out of saturation can be neglected at low signal frequencies.

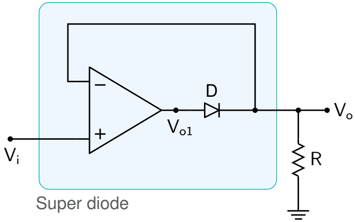
Half-wave precision rectifier

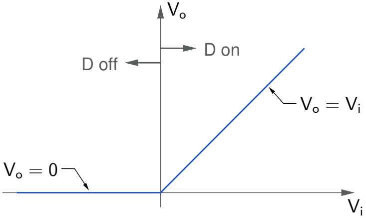


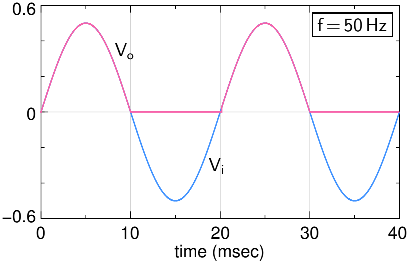




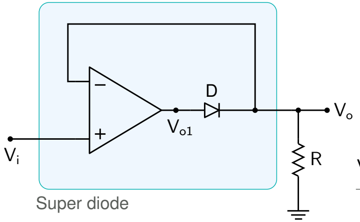
* The time taken by the op-amp to come out of saturation can be neglected at low signal frequencies.

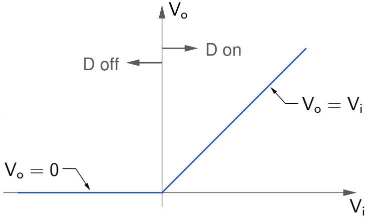


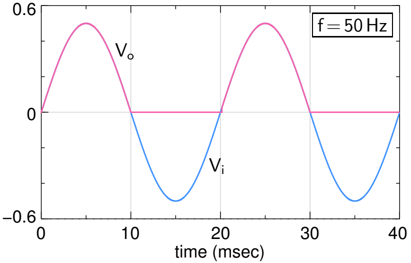


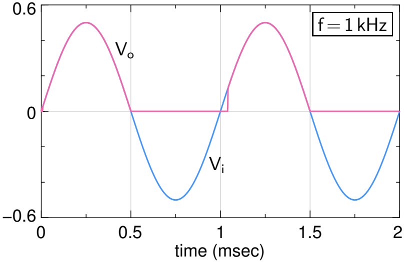


* The time taken by the op-amp to come out of saturation can be neglected at low signal frequencies.
* At high signal frequencies, it leads to distortion in the output waveform.









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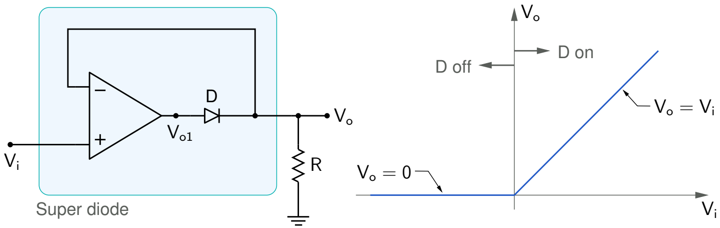
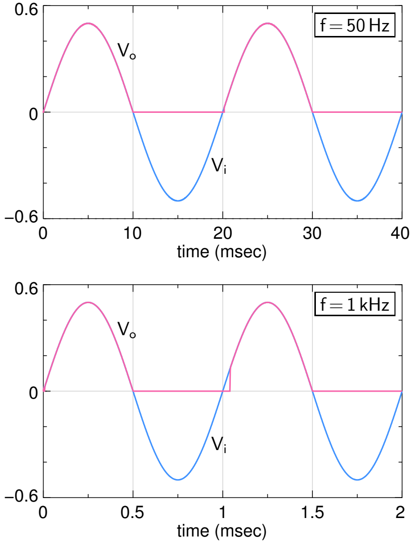
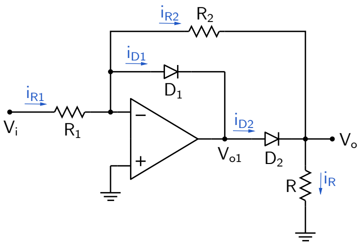


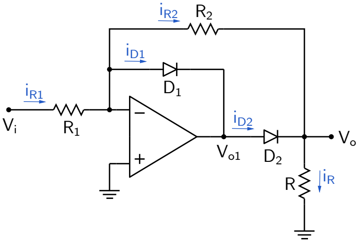


* The time taken by the op-amp to come out of saturation can be neglected at low signal frequencies.
* At high signal frequencies, it leads to distortion in the output waveform.
* Hook up the circuit in the lab, and check it out!

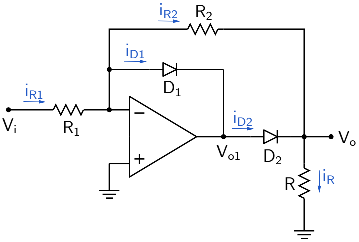
Improved half-wave precision rectifier



Improved half-wave precision rectifier



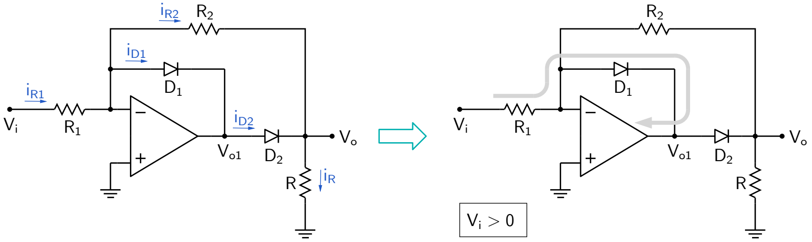
(i) D_1 conducts: $V_- = V_+ = 0\,V$, $V_{o1} = -V_{D1} \approx -0.7\,V$.



(i) D_1 conducts: $V_- = V_+ = 0\,V$, $V_{o1} = -V_{D1} \approx -0.7\,V$.

D_2 cannot conduct (show that, if it did, KCL is not satisfied at V_o).
$\rightarrow i_{R2} = 0$, $V_o = V_- = 0\,V$.

Improved half-wave precision rectifier



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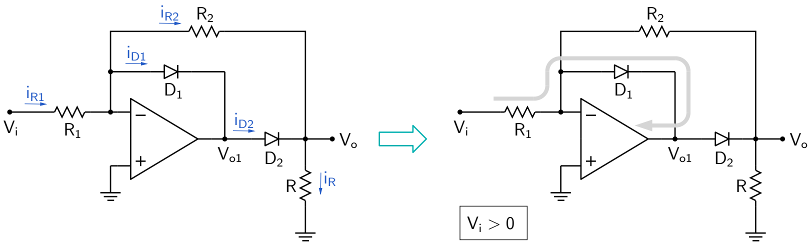
Improved half-wave precision rectifier



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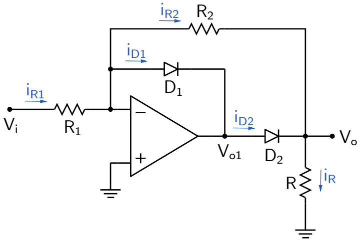
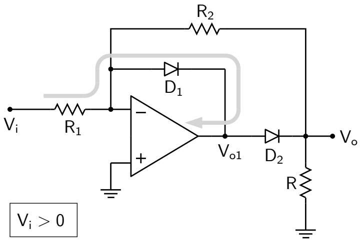
$\rightarrow i_{R2} = 0$, $V_o = V_- = 0\,V$.

$i_{R1} = i_{D1}$ which can only be positive $\Rightarrow V_i > 0\,V$.





$V_i > 0$

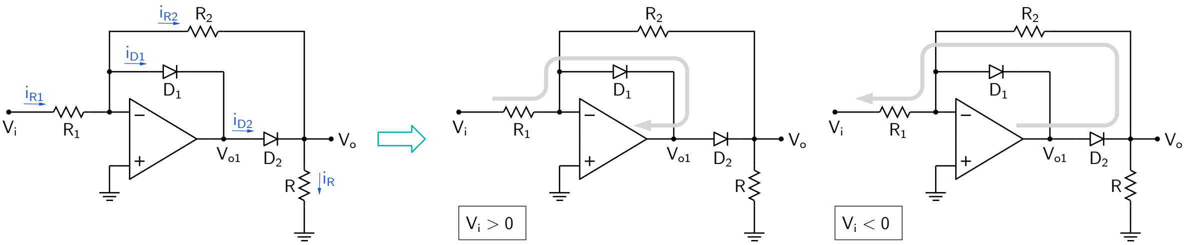
(i) D_1 conducts: $V_- = V_+ = 0\,V$, $V_{o1} = -V_{D1} \approx -0.7\,V$.

D_2 cannot conduct (show that, if it did, KCL is not satisfied at V_o).
$\rightarrow i_{R2} = 0$, $V_o = V_- = 0\,V$.

$i_{R1} = i_{D1}$ which can only be positive $\Rightarrow V_i > 0\,V$.

(ii) D_1 is off; this will happen when $V_i < 0\,V$.

Improved half-wave precision rectifier



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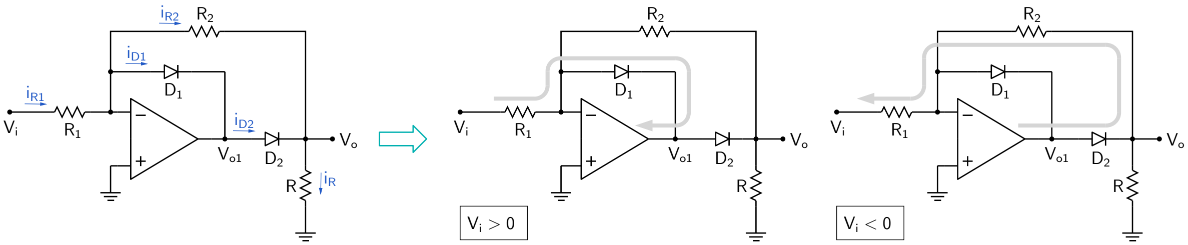
In this case, D_2 conducts and closes the feedback loop through R_2.

Improved half-wave precision rectifier



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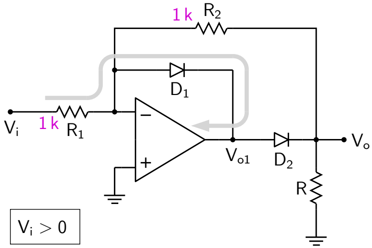
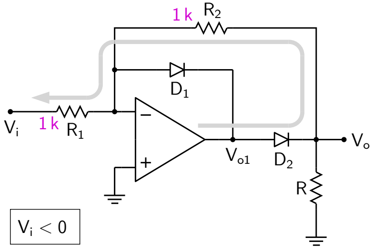
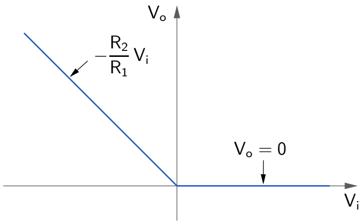
In this case, D_2 conducts and closes the feedback loop through R_2.

$$V_o = V_- + i_{R2}R_2 = 0 + \left(\frac{0 - V_i}{R_1}\right) R_2 = -\frac{R_2}{R_1} V_i \,.$$

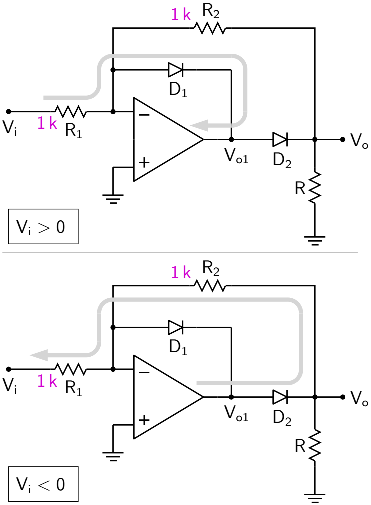
Improved half-wave precision rectifier

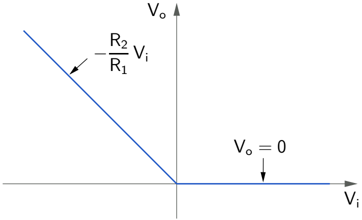


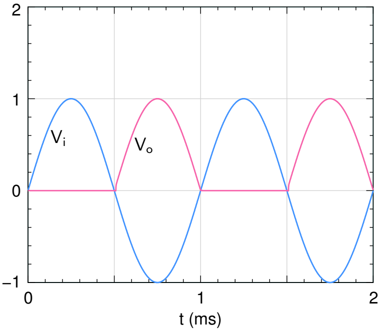




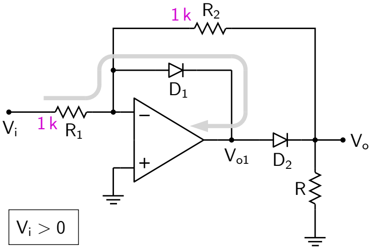
Improved half-wave precision rectifier

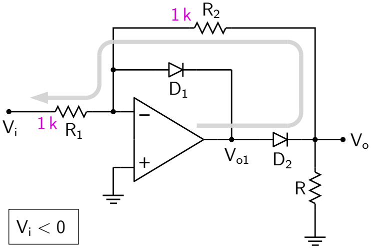


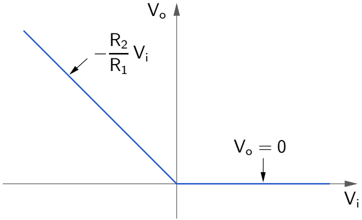


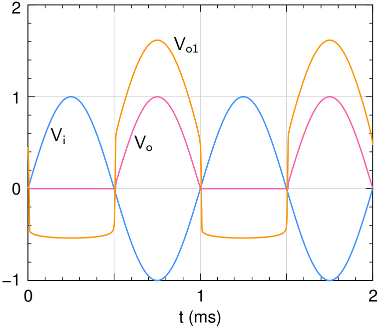


Improved half-wave precision rectifier

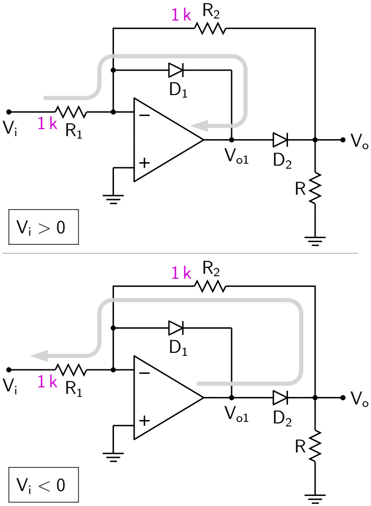


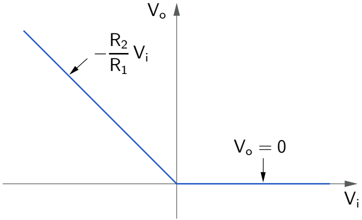


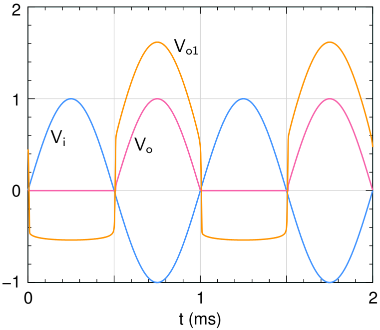




Improved half-wave precision rectifier

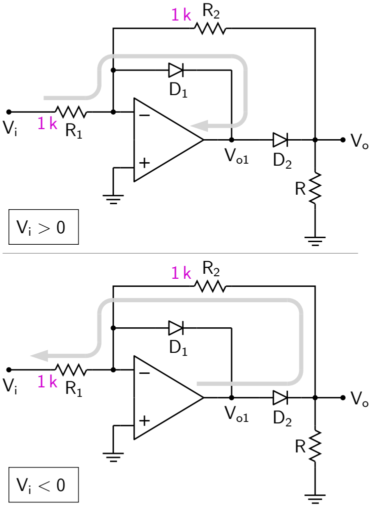


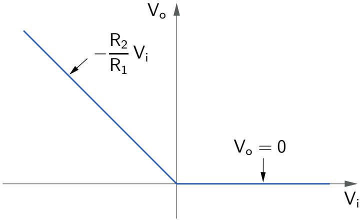


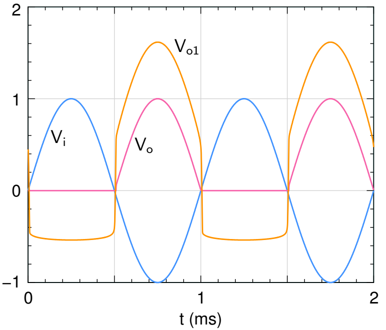


* Note that the op-amp does not enter saturation since a feedback path is available for $V_i > 0\,V$ and $V_i < 0\,V$.

Improved half-wave precision rectifier



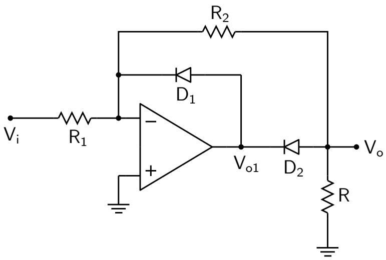


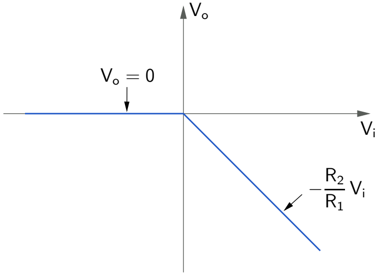


* Note that the op-amp does not enter saturation since a feedback path is available for $V_i > 0\ V$ and $V_i < 0\ V$.

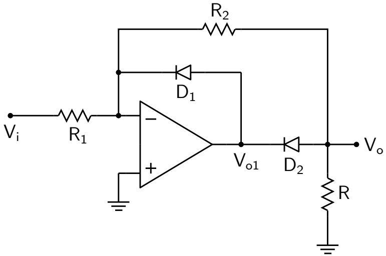
SEQUEL file: `precision_half_wave.sqproj`

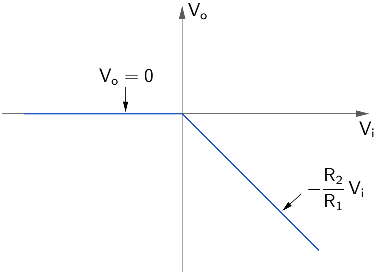
Improved half-wave precision rectifier





The diodes are now reversed.

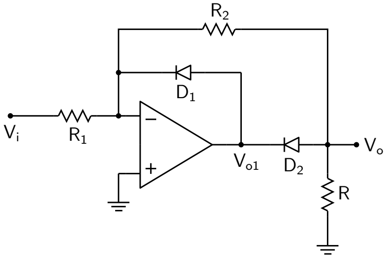


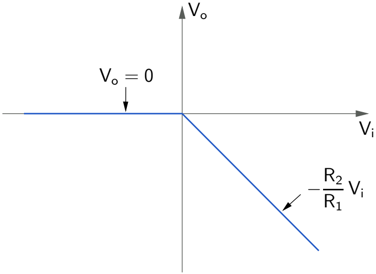


The diodes are now reversed.

By considering two cases: (i) D_1 on, (ii) D_1 off, the V_o versus V_i relationship shown in the figure is obtained (show this).

Improved half-wave precision rectifier



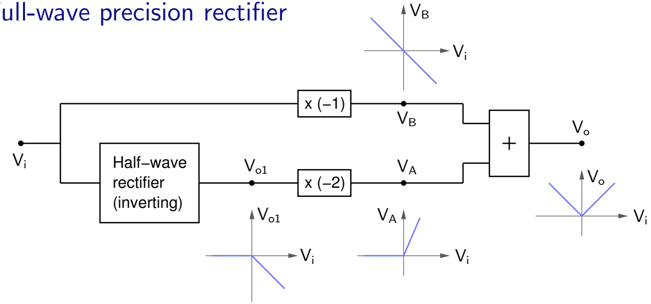


The diodes are now reversed.

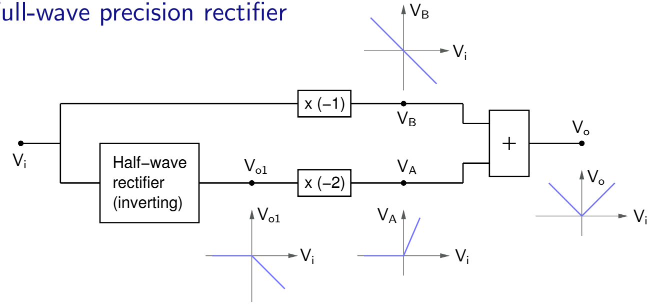
By considering two cases: (i) D_1 on, (ii) D_1 off, the V_o versus V_i relationship shown in the figure is obtained (show this).

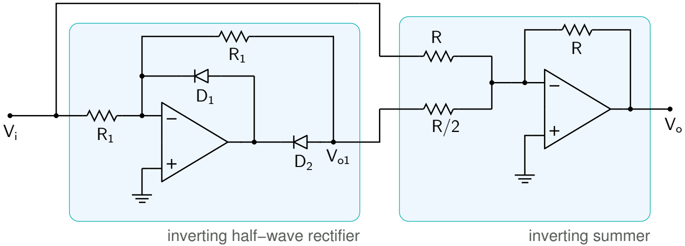
SEQUEL file: `precision_half_wave_2.sqproj`

Full-wave precision rectifier



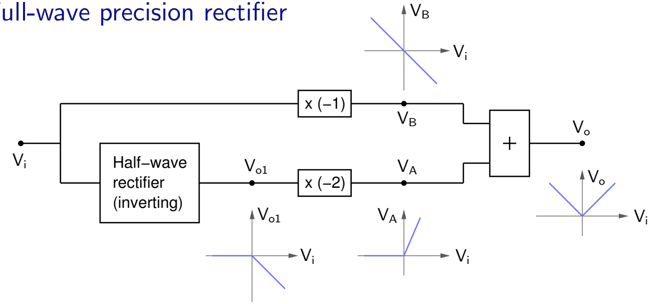
Full-wave precision rectifier

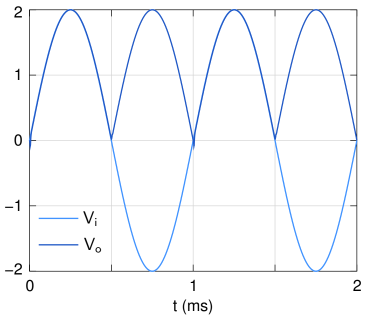


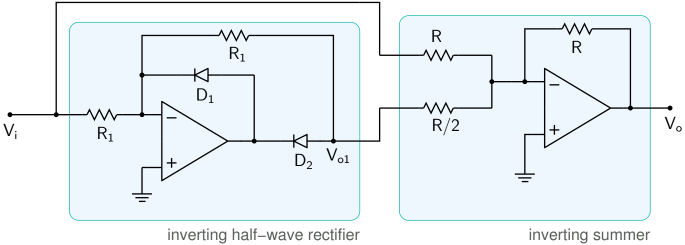


(SEQUEL file: `precision_full_wave.sqproj`)

Full-wave precision rectifier

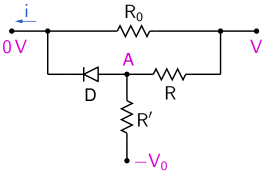




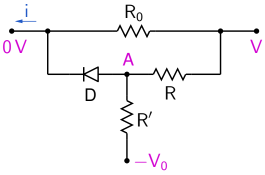


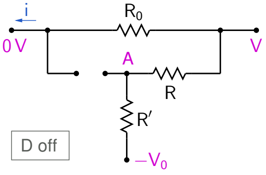
(SEQUEL file: `precision_full_wave.sqproj`)

Wave shaping with diodes

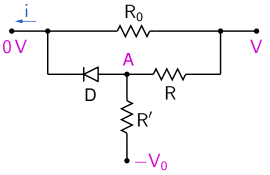


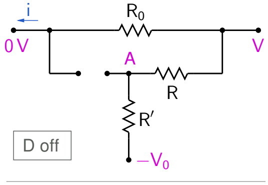
Wave shaping with diodes



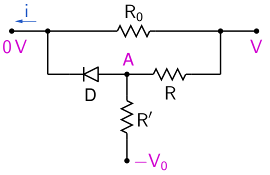


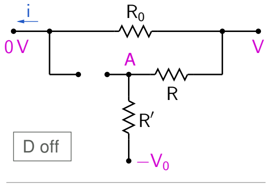
Wave shaping with diodes





When D is off, $i = \dfrac{V}{R_0}$, and V_A is (by superposition), $V_A = V\,\dfrac{R'}{R+R'} - V_0\,\dfrac{R}{R+R'}$.

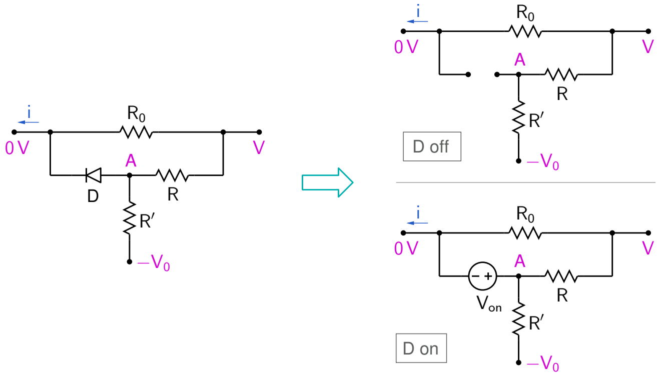




When D is off, $i = \dfrac{V}{R_0}$, and V_A is (by superposition), $V_A = V\,\dfrac{R'}{R+R'} - V_0\,\dfrac{R}{R+R'}$.

For D to turn on, $V_A = V_{\text{on}} \approx 0.7\,V \rightarrow V \equiv V_{\text{break}} = \dfrac{R}{R'}\,(V_0 + V_{\text{on}}) + V_{\text{on}}$.

Wave shaping with diodes



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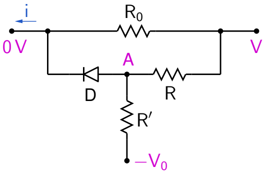
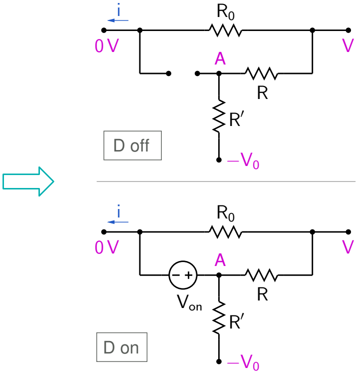


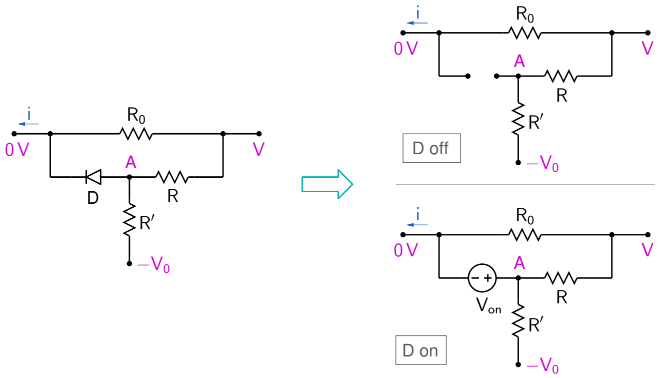


When D is off, $i = \dfrac{V}{R_0}$, and V_A is (by superposition), $V_A = V\dfrac{R'}{R+R'} - V_0\dfrac{R}{R+R'}$.

For D to turn on, $V_A = V_{on} \approx 0.7\,V \rightarrow V \equiv V_{break} = \dfrac{R}{R'}(V_0 + V_{on}) + V_{on}$.

When D is on, $i = \dfrac{V}{R_0} + \dfrac{V - V_{on}}{R} + \dfrac{-V_0 - V_{on}}{R'} = V\left[\dfrac{1}{R_0} + \dfrac{1}{R}\right] + (\text{constant})$

Wave shaping with diodes



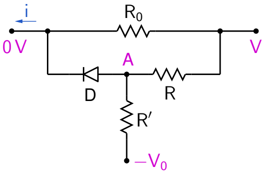
When D is off, $i = \dfrac{V}{R_0}$, and V_A is (by superposition), $V_A = V\,\dfrac{R'}{R+R'} - V_0\,\dfrac{R}{R+R'}$.

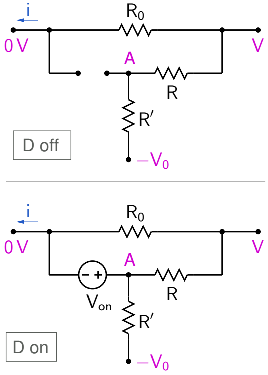
For D to turn on, $V_A = V_{\text{on}} \approx 0.7\,V \rightarrow V \equiv V_{\text{break}} = \dfrac{R}{R'}\,(V_0 + V_{\text{on}}) + V_{\text{on}}$.

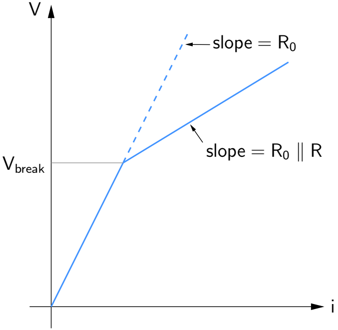
When D is on, $i = \dfrac{V}{R_0} + \dfrac{V - V_{\text{on}}}{R} + \dfrac{-V_0 - V_{\text{on}}}{R'} = V\left[\dfrac{1}{R_0} + \dfrac{1}{R}\right] + (\text{constant})$

i.e., $V = (R_0 \parallel R)\,i + (\text{constant})$.

Wave shaping with diodes







When D is off, $i = \dfrac{V}{R_0}$, and V_A is (by superposition), $V_A = V\,\dfrac{R'}{R+R'} - V_0\,\dfrac{R}{R+R'}$.

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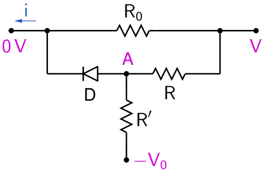
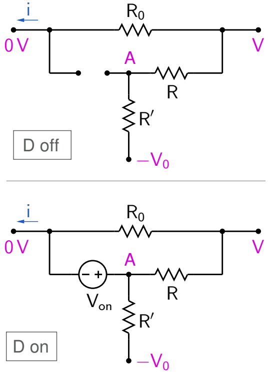
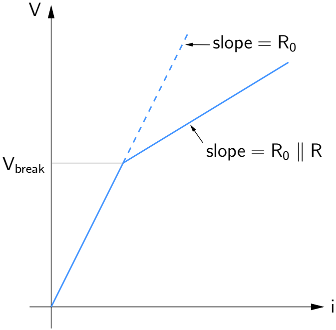
i.e., $V = (R_0 \parallel R)\, i + (\text{constant})$.

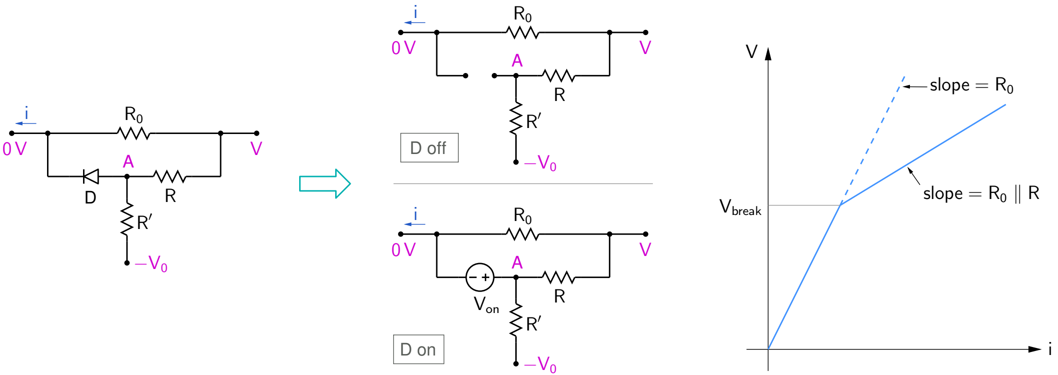
Wave shaping with diodes





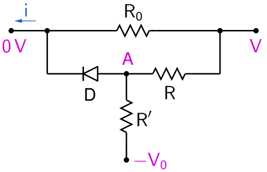


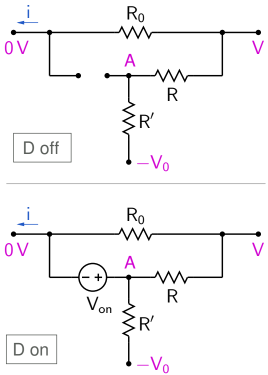
(a) $V_{break} = \dfrac{R}{R'}\,(V_0 + V_{on}) + V_{on}$. (b) When D is on, $V = (R_0 \parallel R)\, i + \text{(constant)}$.

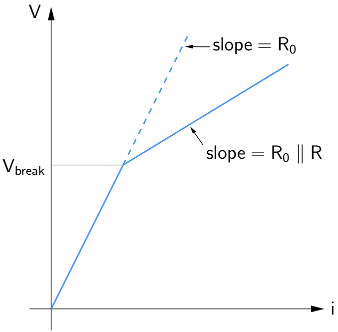


(a) $V_{\text{break}} = \dfrac{R}{R'}\,(V_0 + V_{\text{on}}) + V_{\text{on}}$. (b) When D is on, $V = (R_0 \parallel R)\, i + (\text{constant})$.

* V_{break} depends on the ratio R/R'.



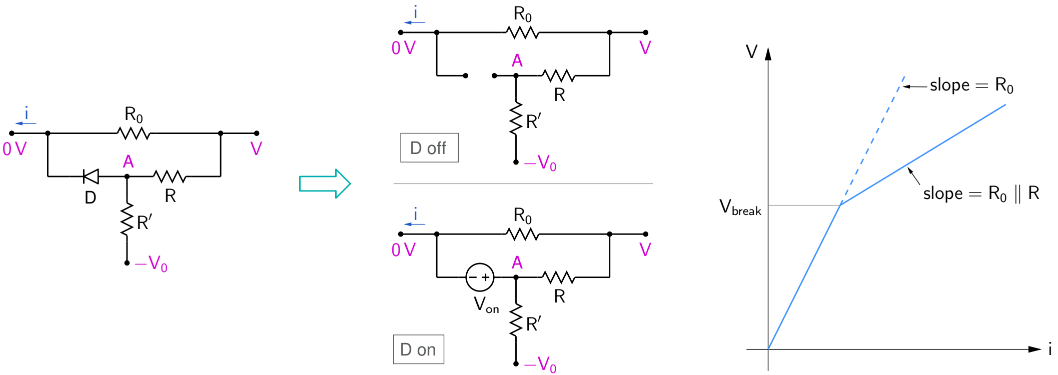




(a) $V_{\text{break}} = \dfrac{R}{R'}\,(V_0 + V_{\text{on}}) + V_{\text{on}}$. (b) When D is on, $V = (R_0 \parallel R)\, i + (\text{constant})$.

* V_{break} depends on the ratio R/R'.
* The slope $R_0 \parallel R$ depends on the resistance values.

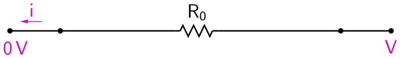
Wave shaping with diodes



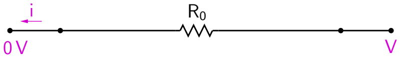
(a) $V_{break} = \dfrac{R}{R'}\,(V_0 + V_{on}) + V_{on}$. (b) When D is on, $V = (R_0 \parallel R)\, i + (\text{constant})$.

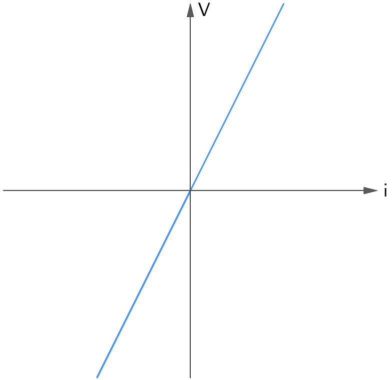
- V_{break} depends on the ratio R/R'.
- The slope $R_0 \parallel R$ depends on the resistance values.
- Given the break point and the two slopes, the resistance values can be easily determined.

Wave shaping with diodes

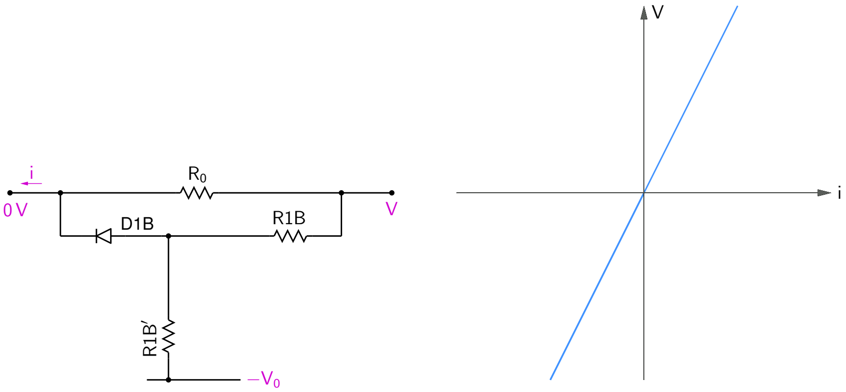


Wave shaping with diodes

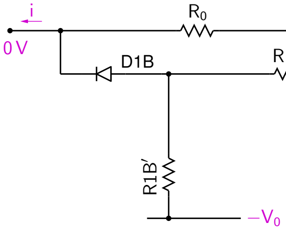


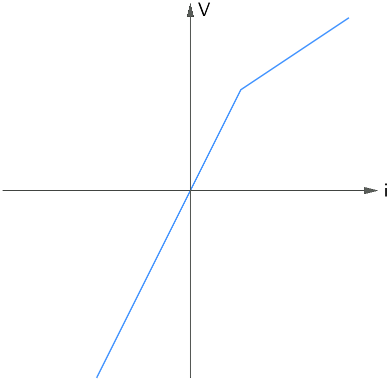


Wave shaping with diodes

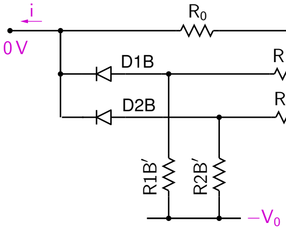


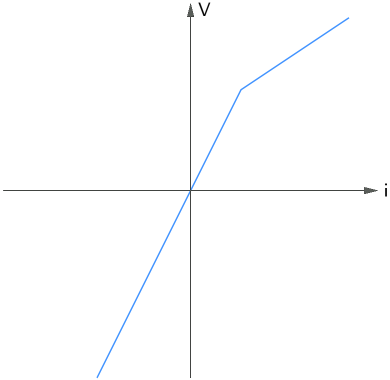
Wave shaping with diodes



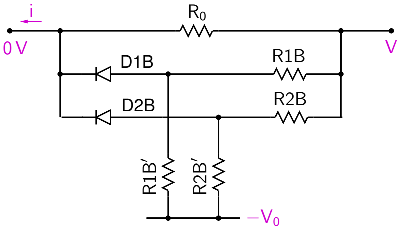


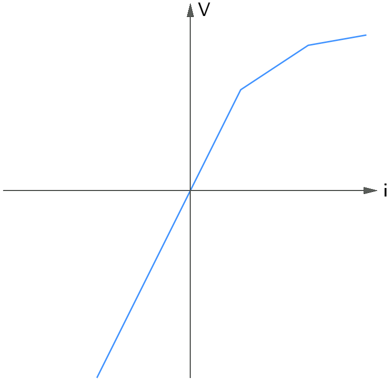
Wave shaping with diodes



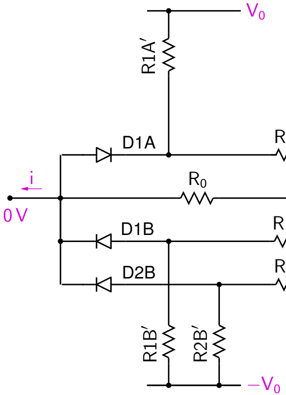


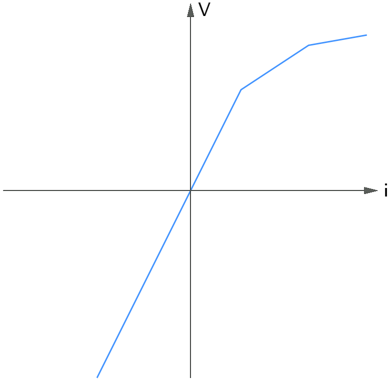
Wave shaping with diodes



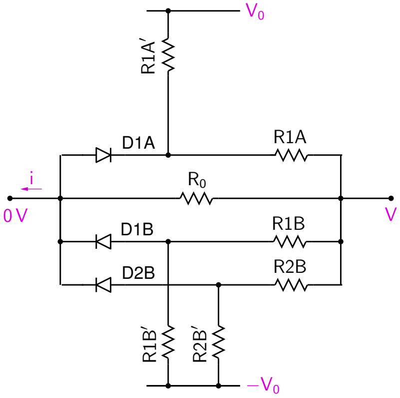


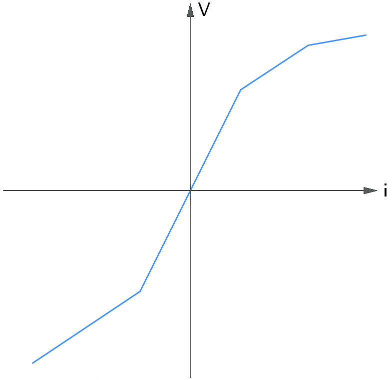
Wave shaping with diodes



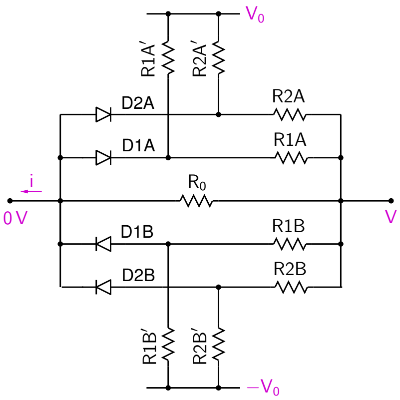


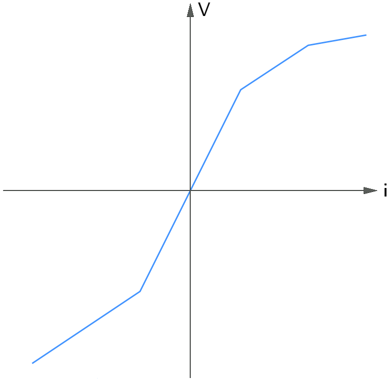
Wave shaping with diodes

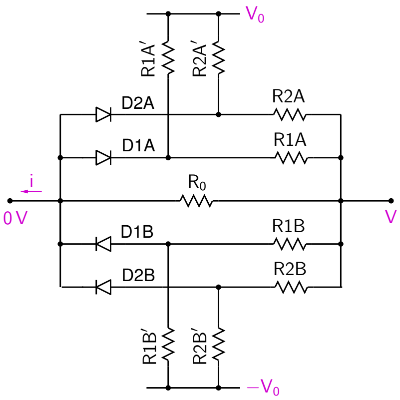




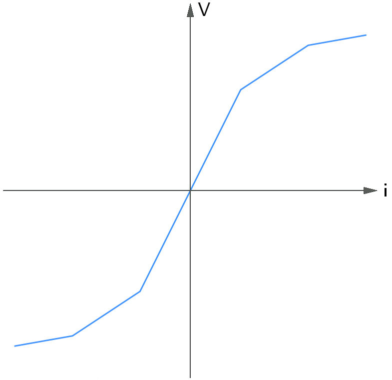
Wave shaping with diodes







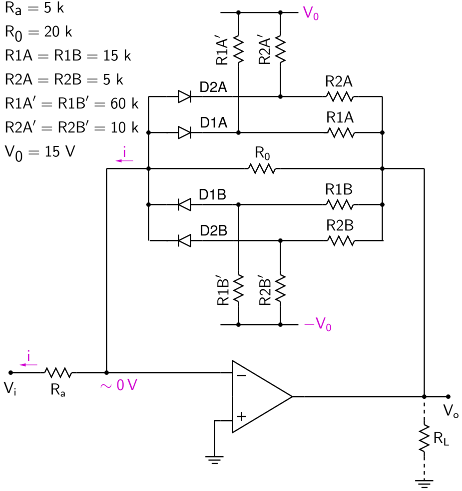
V_0
R1A′
R2A′
D2A
R2A
D1A
R1A
i
R_0
0 V
V
D1B
R1B
D2B
R2B
R1B′
R2B′
$-V_0$

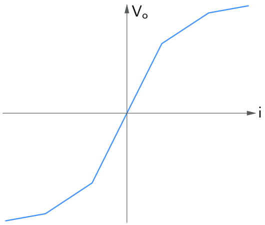


V
i

Wave shaping with diodes

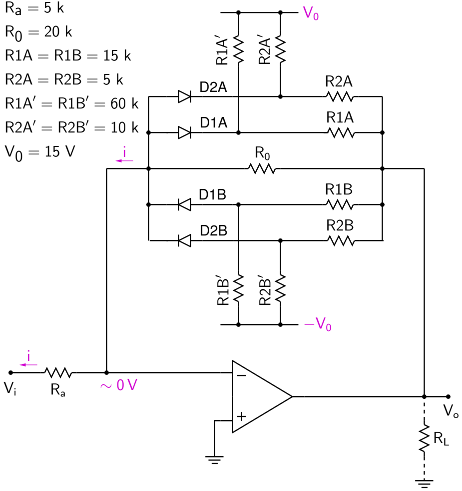
$R_a = 5$ k
$R_0 = 20$ k
$R1A = R1B = 15$ k
$R2A = R2B = 5$ k
$R1A' = R1B' = 60$ k
$R2A' = R2B' = 10$ k
$V_0 = 15$ V

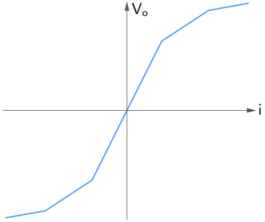




Wave shaping with diodes

$R_a = 5$ k
$R_0 = 20$ k
$R1A = R1B = 15$ k
$R2A = R2B = 5$ k
$R1A' = R1B' = 60$ k
$R2A' = R2B' = 10$ k
$V_0 = 15$ V

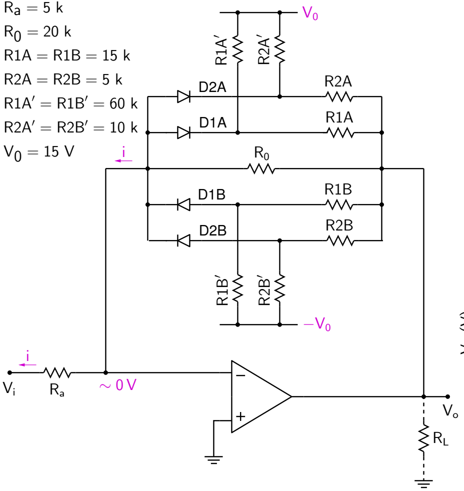


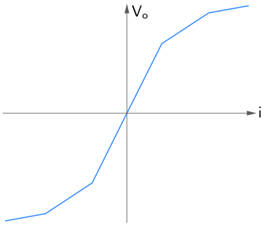


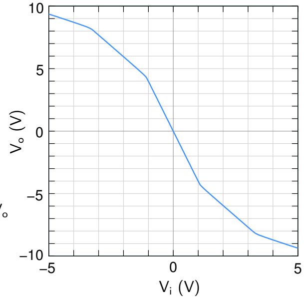
Since $V_i = -R_a i$, the V_o versus V_i plot is similar to the V versus i plot, except for the $(-R_a)$ factor.

Wave shaping with diodes

$R_a = 5$ k
$R_0 = 20$ k
$R1A = R1B = 15$ k
$R2A = R2B = 5$ k
$R1A' = R1B' = 60$ k
$R2A' = R2B' = 10$ k
$V_0 = 15$ V







Since $V_i = -R_a i$, the V_o versus V_i plot is similar to the V versus i plot, except for the $(-R_a)$ factor.

Wave shaping with diodes

$R_a = 5$ k

$R_0 = 20$ k

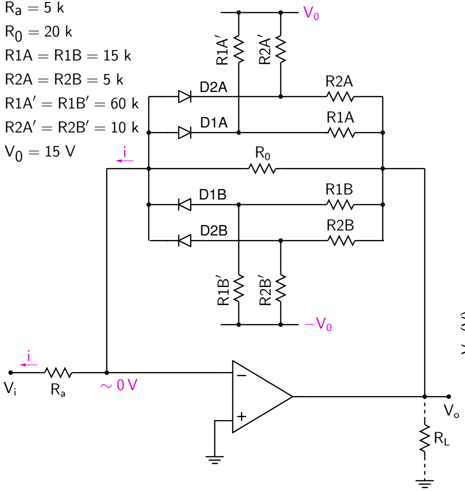
$R1A = R1B = 15$ k

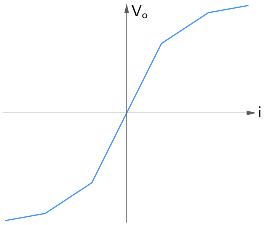
$R2A = R2B = 5$ k

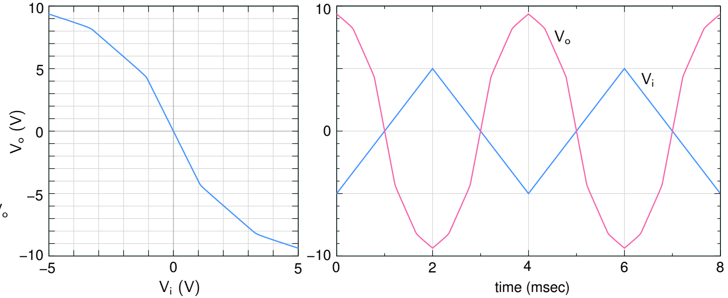
$R1A' = R1B' = 60$ k

$R2A' = R2B' = 10$ k

$V_0 = 15$ V

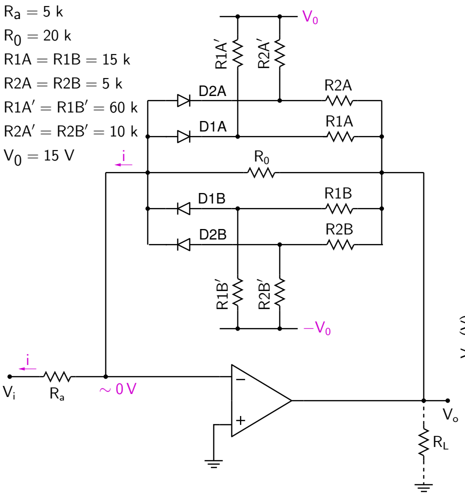


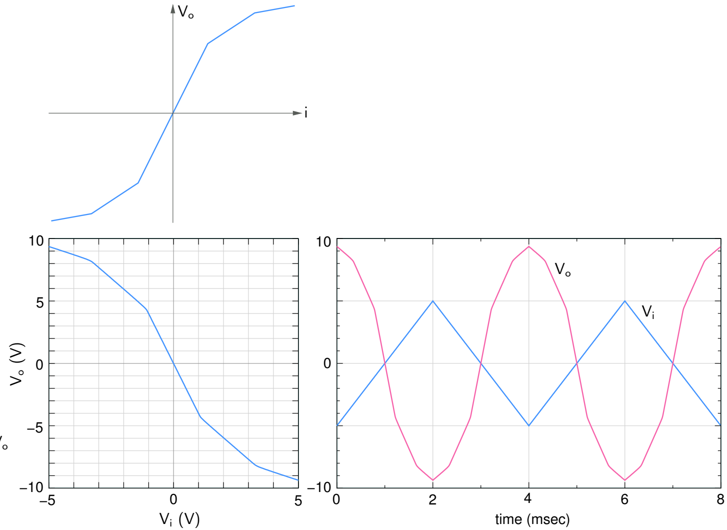




Since $V_i = -R_a i$, the V_o versus V_i plot is similar to the V versus i plot, except for the $(-R_a)$ factor.

Wave shaping with diodes

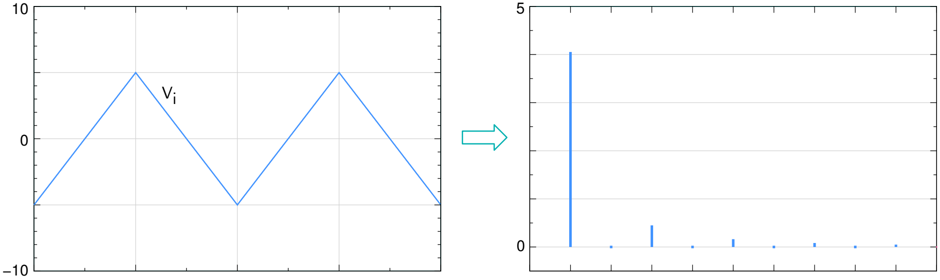




Since $V_i = -R_a i$, the V_o versus V_i plot is similar to the V versus i plot, except for the $(-R_a)$ factor.

SEQUEL file: `ee101_wave_shaper.sqproj`

Wave shaping with diodes: spectrum



Wave shaping with diodes: spectrum