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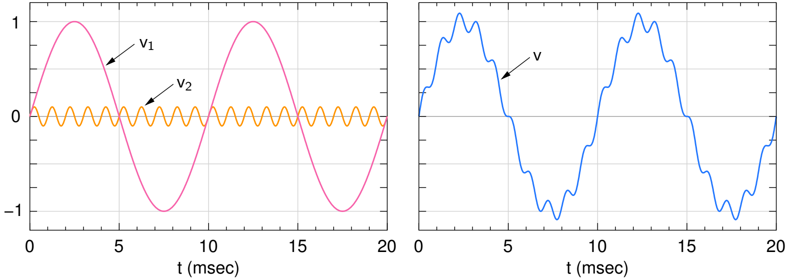

Introduction to filters

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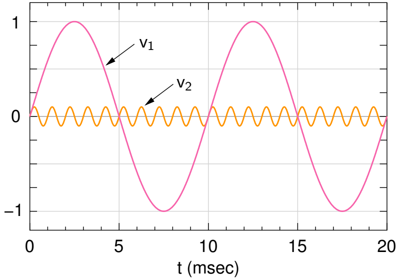

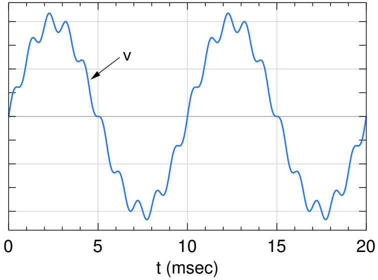

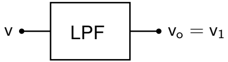

A low-pass filter with a cut-off frequency $\omega_1 < \omega_c < \omega_2$ will pass the low-frequency component $v_1(t)$ and remove the high-frequency component $v_2(t)$.

Introduction to filters

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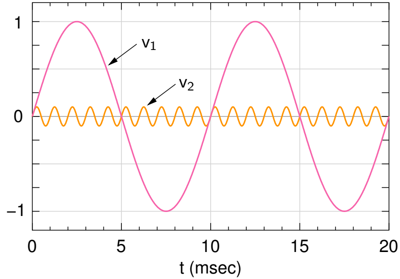

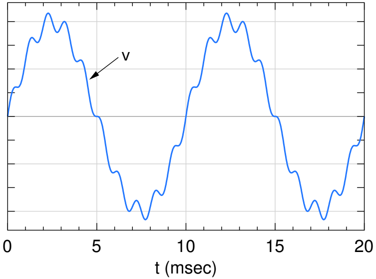

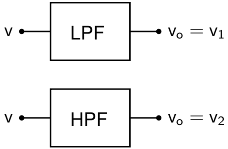

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Introduction to filters

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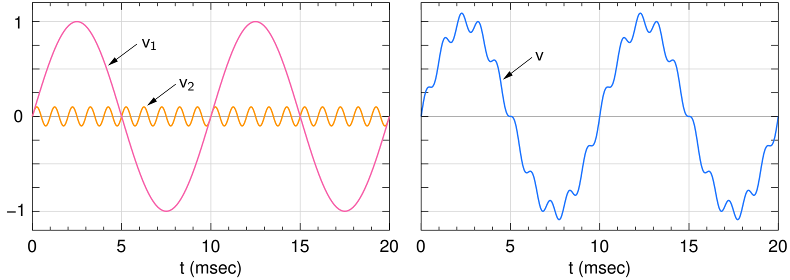

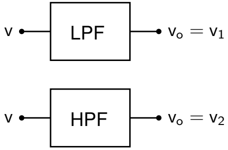

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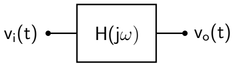
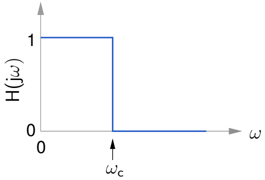
A high-pass filter with a cut-off frequency $\omega_1 < \omega_c < \omega_2$ will pass the high-frequency component $v_2(t)$ and remove the low-frequency component $v_1(t)$.

There are some other types of filters, as we will see.

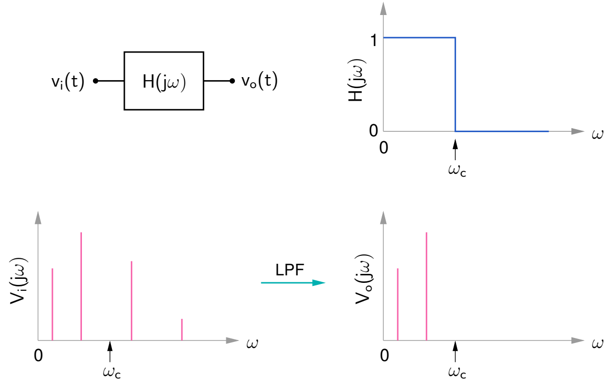
Ideal low-pass filter





$$V_o(j\omega) = H(j\omega)\, V_i(j\omega)\,.$$

Ideal low-pass filter



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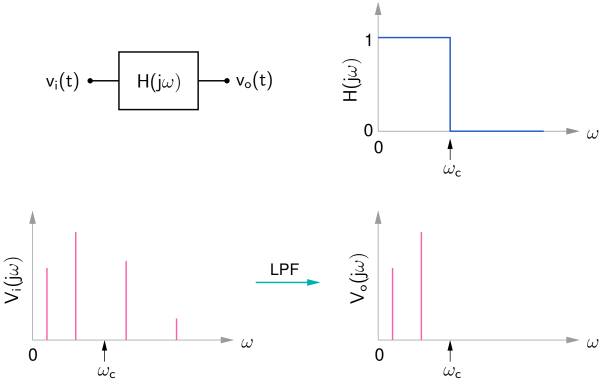


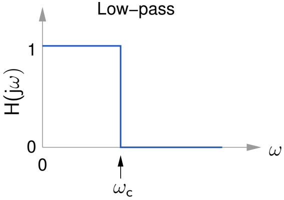
$V_o(j\omega) = H(j\omega)\, V_i(j\omega)$.

All components with $\omega < \omega_c$ appear at the output without attenuation.

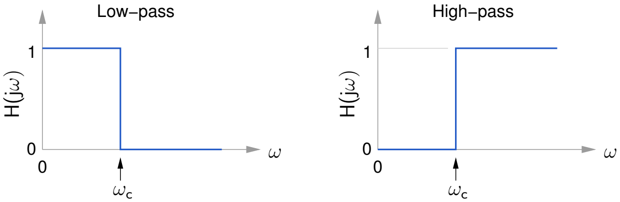
All components with $\omega > \omega_c$ get eliminated.

(Note that the ideal low-pass filter has $\angle H(j\omega) = 1$, i.e., $H(j\omega) = 1 + j0$.)

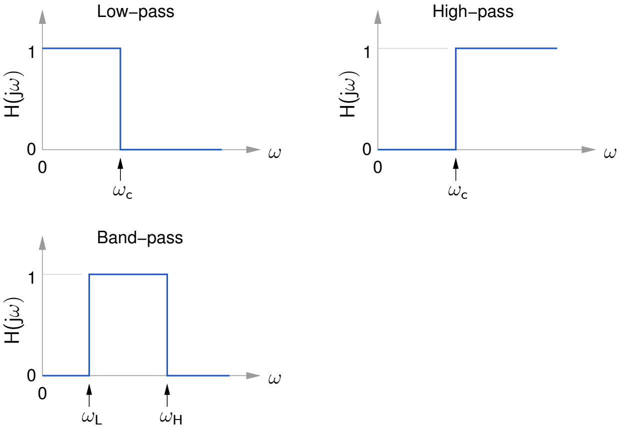
Ideal filters

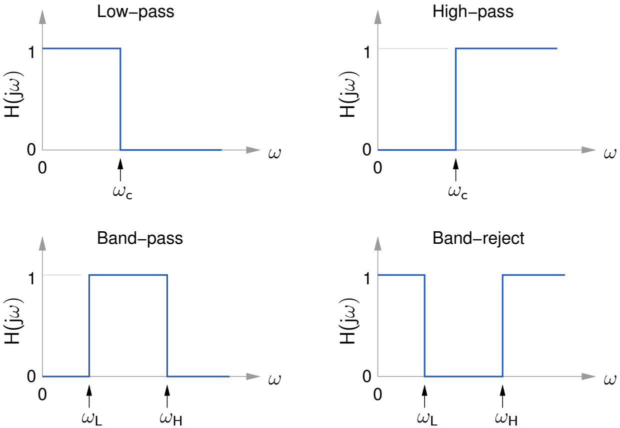


Ideal filters

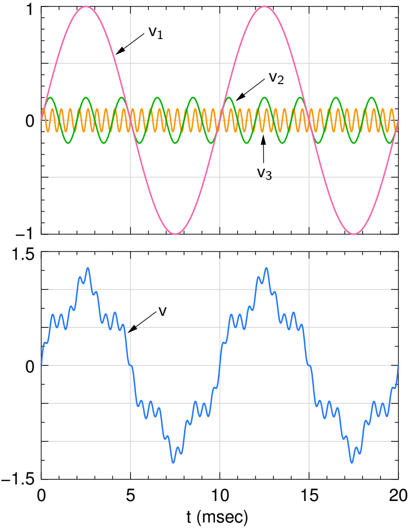


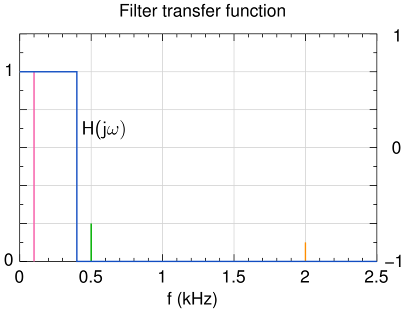
Ideal filters

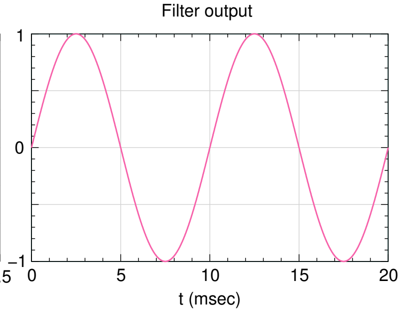



Low−pass
H(jω)
1
0
0
ω
ω_c
High−pass
H(jω)
1
0
0
ω
ω_c
Band−pass
H(jω)
1
0
0
ω
ω_L
ω_H
Band−reject
H(jω)
1
0
0
ω
ω_L
ω_H

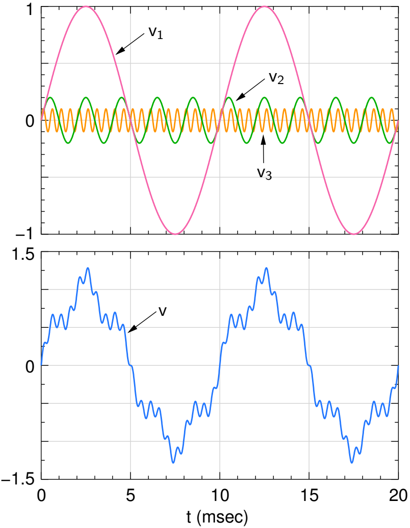
Ideal low-pass filter: example

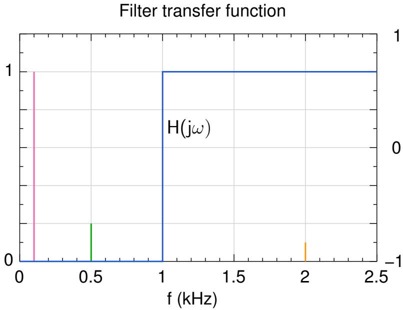


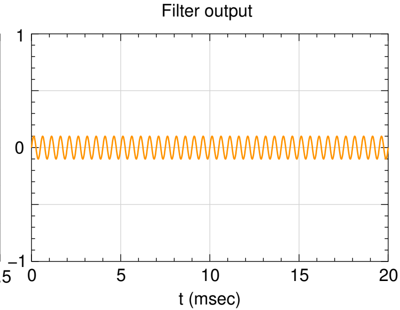




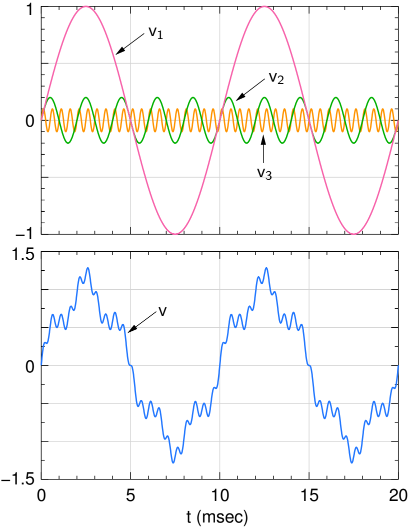
Ideal high-pass filter: example

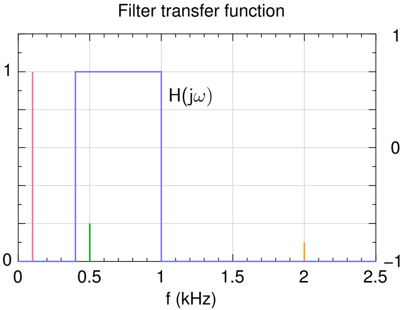


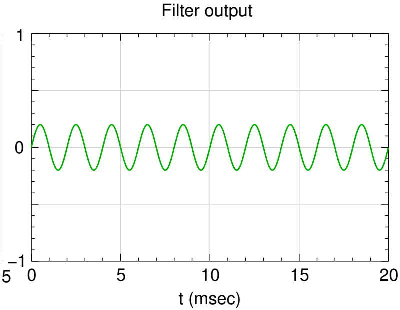




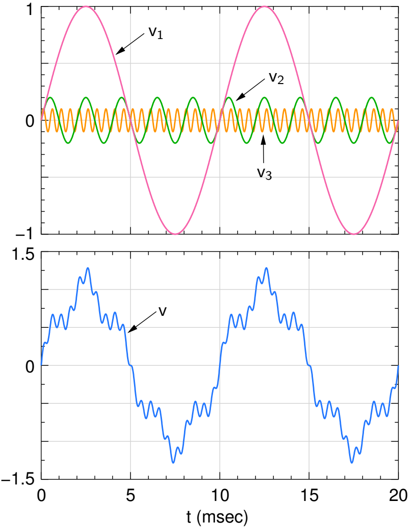
Ideal band-pass filter: example



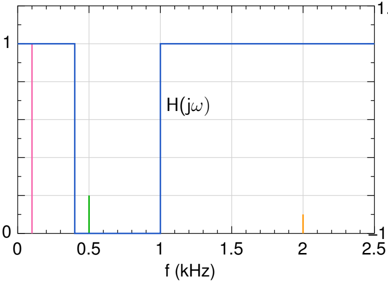




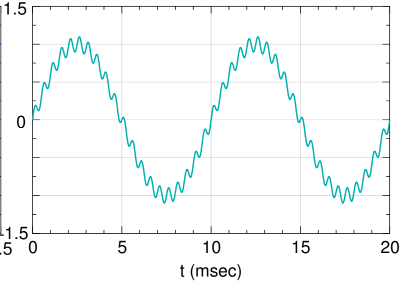
Ideal band-reject filter: example



Filter transfer function



Filter output



* In practical filter circuits, the ideal filter response is approximated with a suitable $H(j\omega)$ that can be obtained with circuit elements. For example,

$$H(s) = \frac{1}{a_5 s^5 + a_4 s^4 + a_3 s^3 + a_2 s^2 + a_1 s + a_0}$$

represents a 5^{th}-order low-pass filter.

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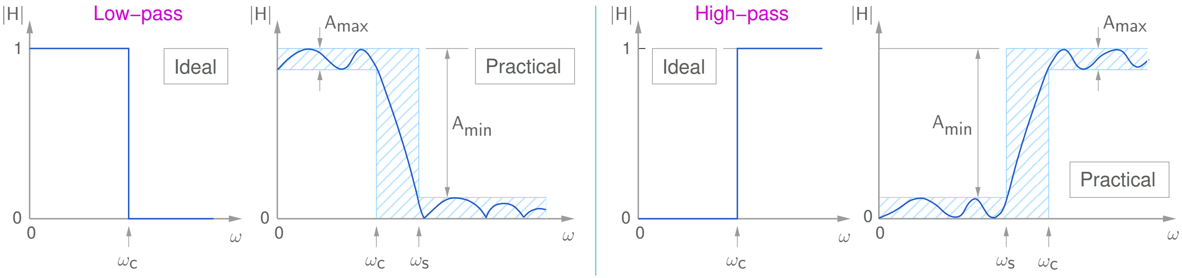
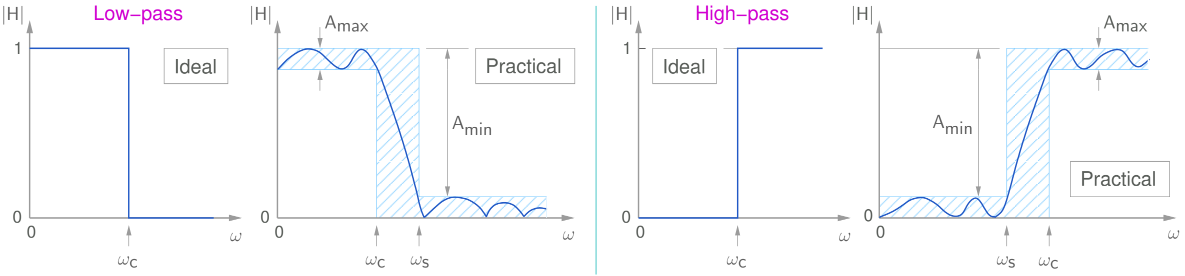
* Coefficients for these filters are listed in filter handbooks. Also, programs for filter design are available on the internet.

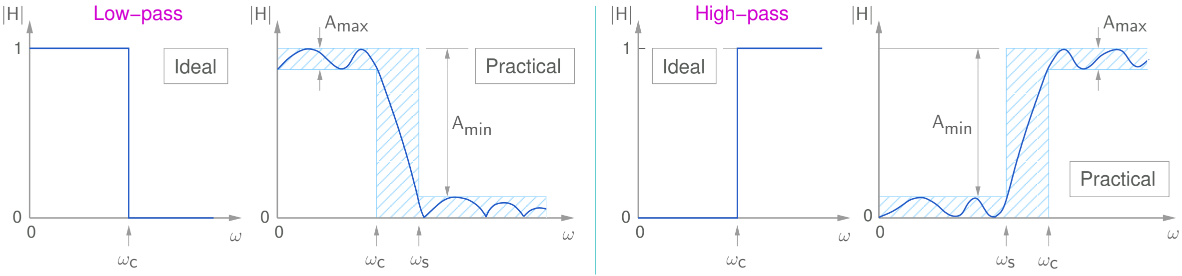
Practical filters



Practical filters



* A practical filter may exhibit a ripple. A_{max} is called the maximum passband ripple, e.g., $A_{\text{max}} = 1$ dB.



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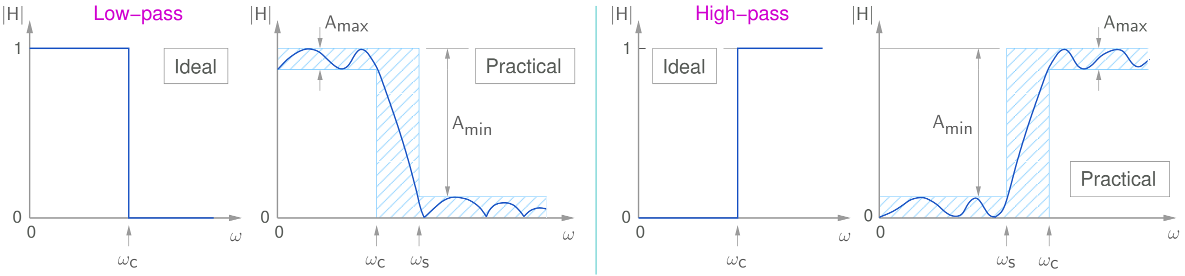

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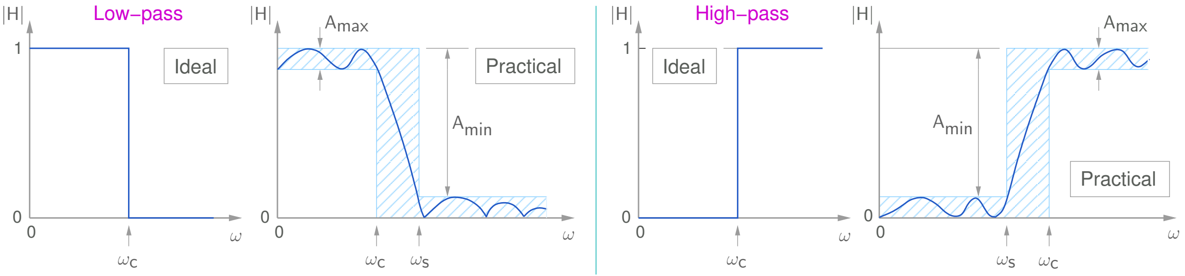

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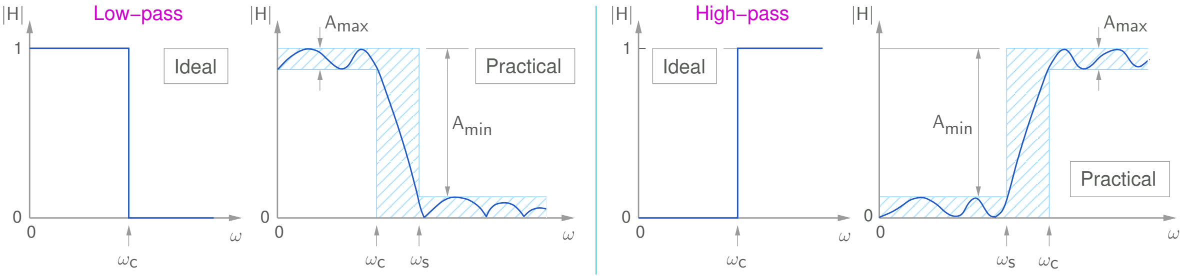
Practical filters



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* ω_s: edge of the stop band.
* ω_s/ω_c (for a low-pass filter): selectivity factor, a measure of the sharpness of the filter.
* $\omega_c < \omega < \omega_s$: transition band.

For a low-pass filter, $H(s) = \dfrac{1}{\displaystyle\sum_{i=0}^{n} a_i (s/\omega_c)^i}$.

Coefficients (a_i) for various types of filters are tabulated in handbooks. We now look at $|H(j\omega)|$ for two commonly used filters.

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Chebyshev filters:

$$|H(j\omega)| = \frac{1}{\sqrt{1+\epsilon^2 C_n^2(\omega/\omega_c)}} \quad \text{where}$$

$$C_n(x) = \cos\left[n\cos^{-1}(x)\right] \quad \text{for } x \leq 1,$$

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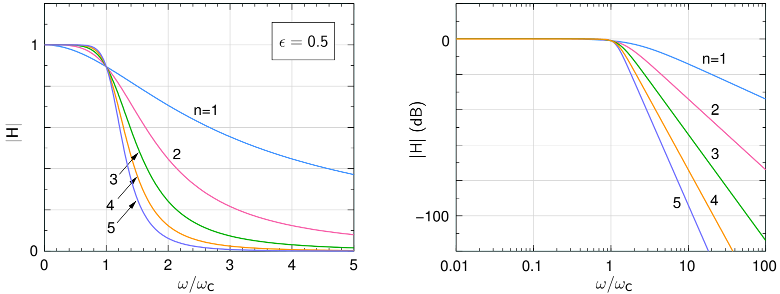
$H(s)$ for a high-pass filter can be obtained from $H(s)$ of the corresponding low-pass filter by $(s/\omega_c) \rightarrow (\omega_c/s)$.

Butterworth filters:



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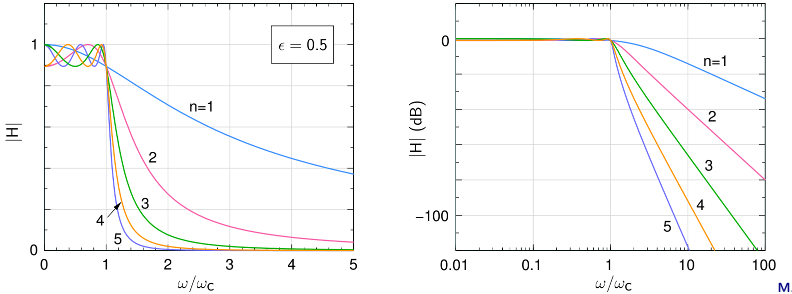
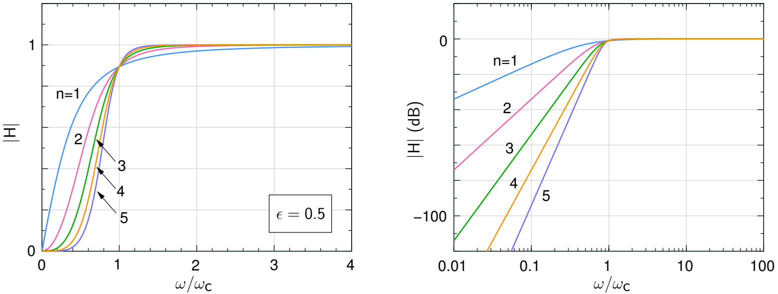


Practical filters (high-pass)

Butterworth filters:



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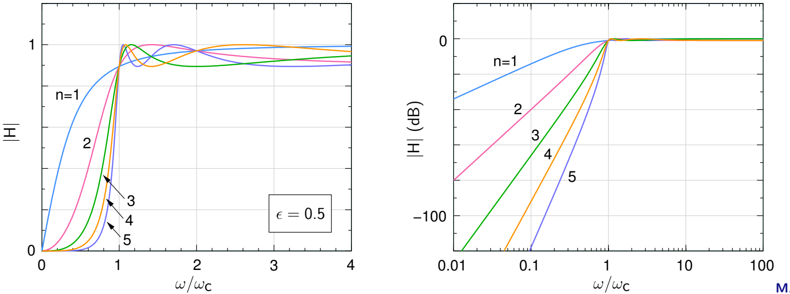
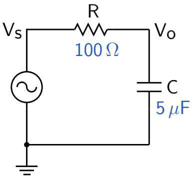


Passive filter example



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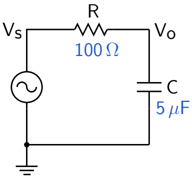
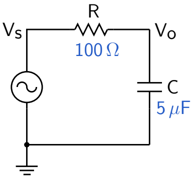


$$H(s) = \frac{(1/sC)}{R + (1/sC)} = \frac{1}{1 + (s/\omega_0)}\,,$$

with $\omega_0 = 1/RC \rightarrow f_0 = \omega_0/2\pi = 318\,\mathrm{Hz}$

(Low–pass filter)

Passive filter example



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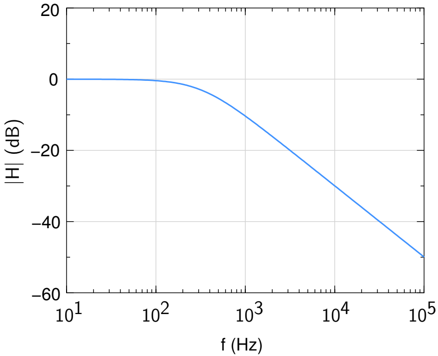
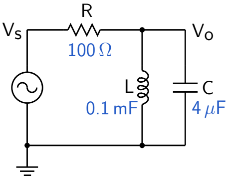
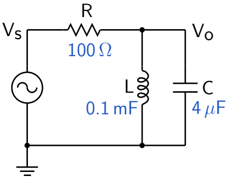


(SEQUEL file: `ee101_rc_ac_2.sqproj`)

Passive filter example



Passive filter example

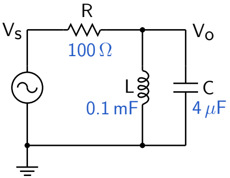


$$H(s) = \frac{(sL) \parallel (1/sC)}{R + (sL) \parallel (1/sC)} = \frac{s(L/R)}{1 + s(L/R) + s^2LC}$$

with $\omega_0 = 1/\sqrt{LC} \rightarrow f_0 = \omega_0/2\pi = 7.96\,\text{kHz}$

(Band–pass filter)

Passive filter example



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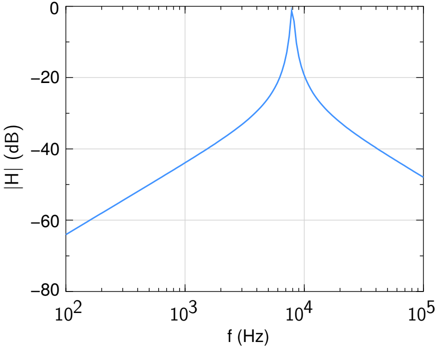
(Band–pass filter)



(SEQUEL file: `ee101_rlc_3.sqproj`)

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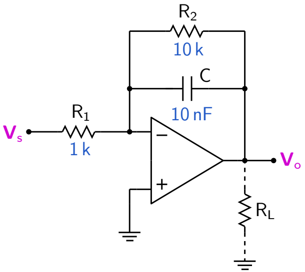
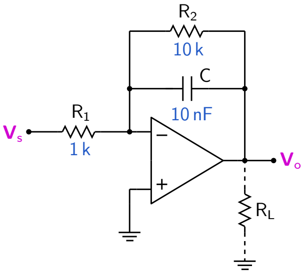
* Op-amp filters can be easily incorporated in an integrated circuit.
* However, there are situations in which passive filters are still used.
  - high frequencies at which op-amps do not have sufficient gain
  - high power which op-amps cannot handle

Op-amp filters: example



Op-amp filters: example

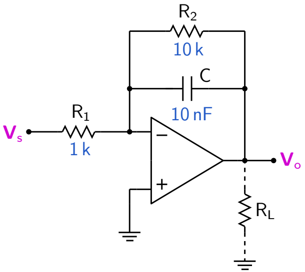


Op-amp filters are designed for op-amp operation in the linear region
→ Our analysis of the inverting amplifier applies, and we get,

$\mathbf{V_o} = -\dfrac{R_2 \parallel (1/sC)}{R_1}\,\mathbf{V_s}$ ($\mathbf{V_s}$ and $\mathbf{V_o}$ are phasors)

$$H(s) = -\frac{R_2}{R_1}\,\frac{1}{1 + sR_2C}$$

Op-amp filters: example

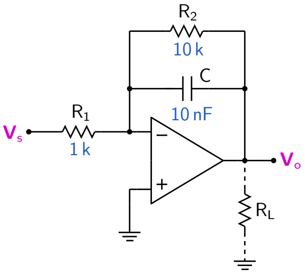


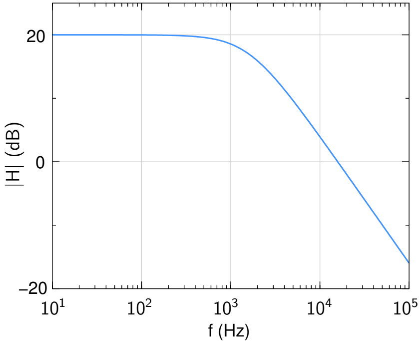
Op-amp filters are designed for op-amp operation in the linear region
$\rightarrow$ Our analysis of the inverting amplifier applies, and we get,

$$\mathbf{V_o} = -\frac{R_2 \parallel (1/sC)}{R_1}\,\mathbf{V_s} \quad (\mathbf{V_s} \text{ and } \mathbf{V_o} \text{ are phasors})$$

$$H(s) = -\frac{R_2}{R_1}\,\frac{1}{1 + sR_2C}$$

This is a low-pass filter, with $\omega_0 = 1/R_2C$ (i.e., $f_0 = \omega_0/2\pi = 1.59\,\text{kHz}$).





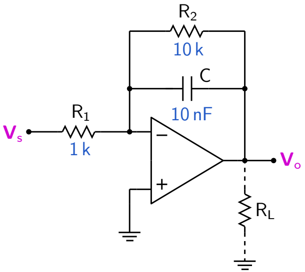
Op-amp filters are designed for op-amp operation in the linear region
$\rightarrow$ Our analysis of the inverting amplifier applies, and we get,

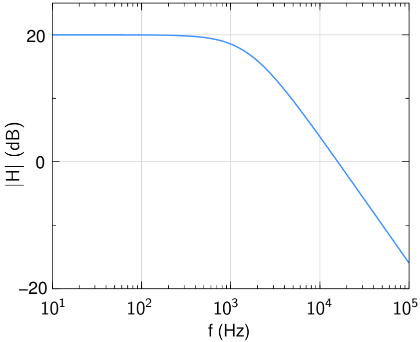
$$\mathbf{V_o} = -\frac{R_2 \parallel (1/sC)}{R_1}\,\mathbf{V_s} \quad (\mathbf{V_s} \text{ and } \mathbf{V_o} \text{ are phasors})$$

$$H(s) = -\frac{R_2}{R_1}\,\frac{1}{1+sR_2C}$$

This is a low-pass filter, with $\omega_0 = 1/R_2C$ (i.e., $f_0 = \omega_0/2\pi = 1.59\,\text{kHz}$).

Op-amp filters: example





Op-amp filters are designed for op-amp operation in the linear region
$\rightarrow$ Our analysis of the inverting amplifier applies, and we get,

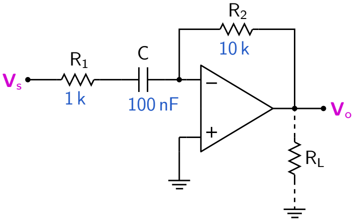
$$\mathbf{V_o} = -\frac{R_2 \parallel (1/sC)}{R_1}\,\mathbf{V_s} \quad (\mathbf{V_s} \text{ and } \mathbf{V_o} \text{ are phasors})$$

$$H(s) = -\frac{R_2}{R_1}\,\frac{1}{1+sR_2C}$$

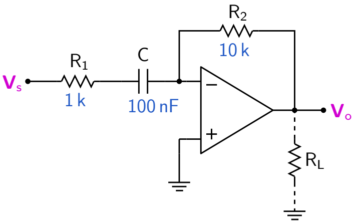
This is a low-pass filter, with $\omega_0 = 1/R_2C$ (i.e., $f_0 = \omega_0/2\pi = 1.59\,\text{kHz}$).

(SEQUEL file: `ee101_op_filter_1.sqproj`)

Op-amp filters: example

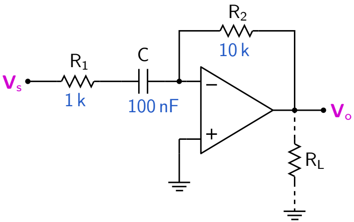


Op-amp filters: example



$$H(s) = -\frac{R_2}{R_1 + (1/sC)} = -\frac{sR_2 C}{1 + sR_1 C}\,.$$

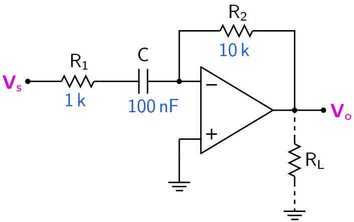
Op-amp filters: example

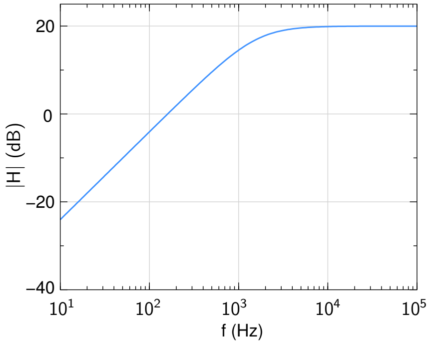


$$H(s) = -\frac{R_2}{R_1 + (1/sC)} = -\frac{sR_2C}{1 + sR_1C}\,.$$

This is a high-pass filter, with $\omega_0 = 1/R_1C$ (i.e., $f_0 = \omega_0/2\pi = 1.59\,\mathrm{kHz}$).

Op-amp filters: example

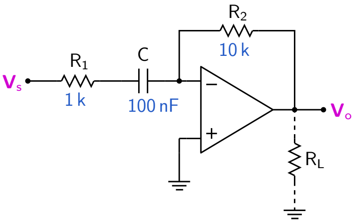


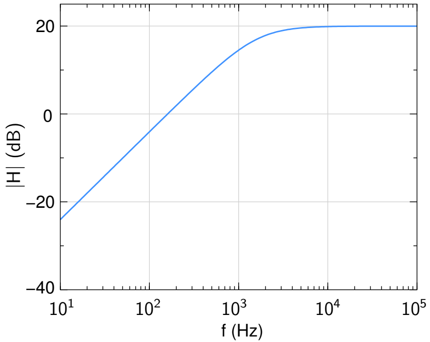


$$H(s) = -\frac{R_2}{R_1 + (1/sC)} = -\frac{sR_2C}{1 + sR_1C}\,.$$

This is a high-pass filter, with $\omega_0 = 1/R_1C$ (i.e., $f_0 = \omega_0/2\pi = 1.59\,\mathrm{kHz}$).

Op-amp filters: example



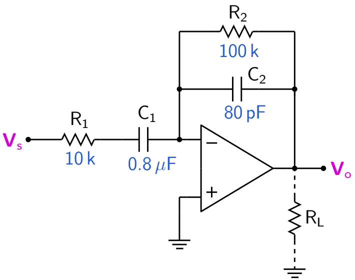


$$H(s) = -\frac{R_2}{R_1 + (1/sC)} = -\frac{sR_2C}{1 + sR_1C}\,.$$

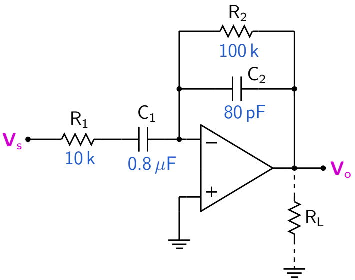
This is a high-pass filter, with $\omega_0 = 1/R_1C$ (i.e., $f_0 = \omega_0/2\pi = 1.59\,\text{kHz}$).

(SEQUEL file: `ee101_op_filter_2.sqproj`)

Op-amp filters: example

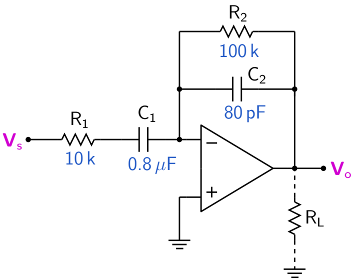


Op-amp filters: example



$$H(s) = -\frac{R_2 \parallel (1/sC_2)}{R_1 + (1/sC_1)} = -\frac{R_2}{R_1}\,\frac{sR_1C_1}{(1+sR_1C_1)(1+sR_2C_2)}\,.$$

Op-amp filters: example

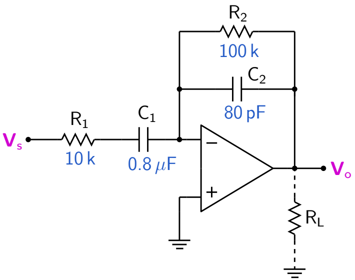


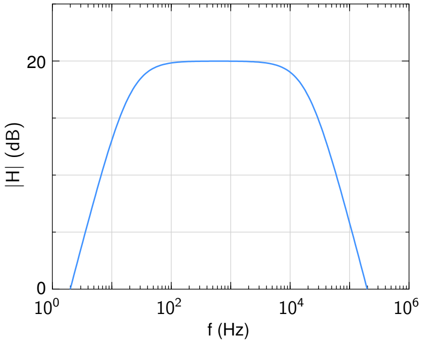
$$H(s) = -\frac{R_2 \parallel (1/sC_2)}{R_1 + (1/sC_1)} = -\frac{R_2}{R_1}\,\frac{sR_1C_1}{(1+sR_1C_1)(1+sR_2C_2)}\,.$$

This is a band-pass filter, with $\omega_L = 1/R_1C_1$ and $\omega_H = 1/R_2C_2$.

$\rightarrow f_L = 20\,\text{Hz},\ f_H = 20\,\text{kHz}.$

Op-amp filters: example



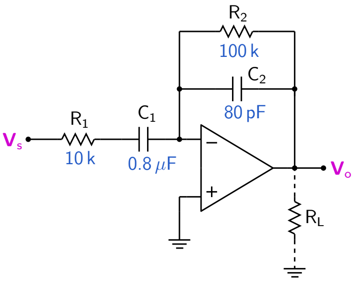


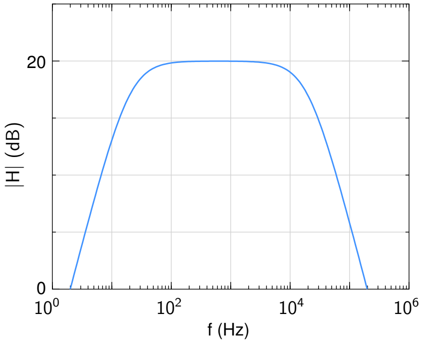
$$H(s) = -\frac{R_2 \parallel (1/sC_2)}{R_1 + (1/sC_1)} = -\frac{R_2}{R_1}\,\frac{sR_1C_1}{(1+sR_1C_1)(1+sR_2C_2)}\,.$$

This is a band-pass filter, with $\omega_L = 1/R_1C_1$ and $\omega_H = 1/R_2C_2$.

$\rightarrow f_L = 20\,\text{Hz},\ f_H = 20\,\text{kHz}.$

Op-amp filters: example



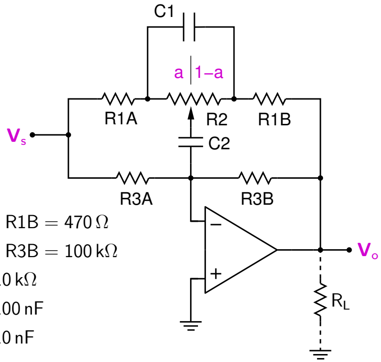


$$H(s) = -\frac{R_2 \parallel (1/sC_2)}{R_1 + (1/sC_1)} = -\frac{R_2}{R_1}\,\frac{sR_1C_1}{(1+sR_1C_1)(1+sR_2C_2)}\,.$$

This is a band-pass filter, with $\omega_L = 1/R_1C_1$ and $\omega_H = 1/R_2C_2$.

$\rightarrow f_L = 20\,\text{Hz},\ f_H = 20\,\text{kHz}.$

(SEQUEL file: `ee101_op_filter_3.sqproj`)



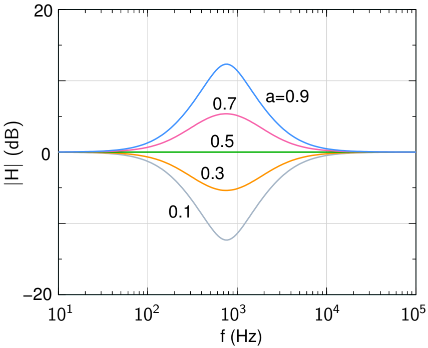
R1A = R1B = 470 Ω

R3A = R3B = 100 kΩ

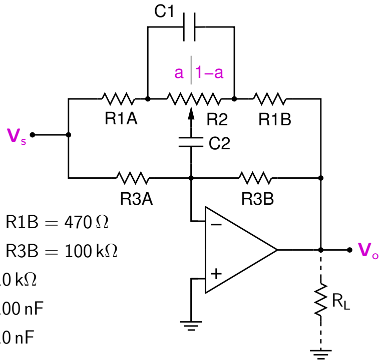
R2 = 10 kΩ

C1 = 100 nF

C2 = 10 nF



(Ref.: S. Franco, "Design with Op Amps and analog ICs")



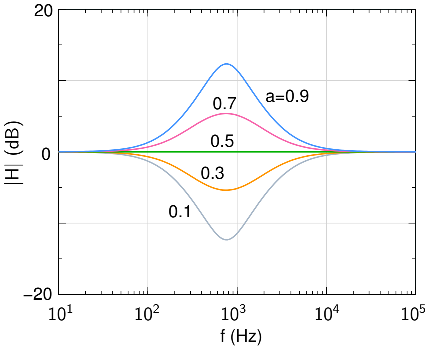
$R1A = R1B = 470\,\Omega$

$R3A = R3B = 100\,k\Omega$

$R2 = 10\,k\Omega$

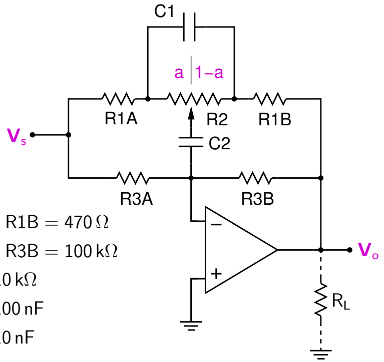
$C1 = 100\,nF$

$C2 = 10\,nF$



(Ref.: S. Franco, "Design with Op Amps and analog ICs")

* Equalizers are implemented as arrays of narrow-band filters, each with an adjustable gain (attenuation) around a centre frequency.



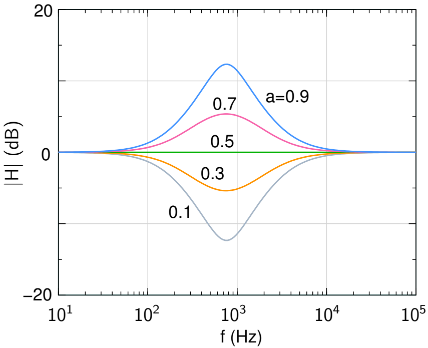
R1A = R1B = 470 Ω

R3A = R3B = 100 kΩ

R2 = 10 kΩ

C1 = 100 nF

C2 = 10 nF

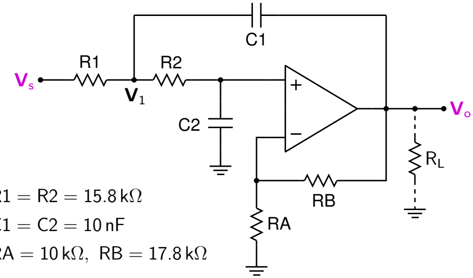


(Ref.: S. Franco, "Design with Op Amps and analog ICs")

* Equalizers are implemented as arrays of narrow-band filters, each with an adjustable gain (attenuation) around a centre frequency.
* The circuit shown above represents one of the equalizer sections.
  (SEQUEL file: `ee101_op_filter_4.sqproj`)


EQ-20 GRAPHIC EQUALIZER
ADVANCED EQ
NUMBER
+15
0
-15
(dB)
WRITE
LIGHT
SELECT
MEMORY
30
60
120
200
400
800
1.6 k
3.2 k
6.4 k
12.8 k
(Hz)
LEVEL
+15
0
-15
(dB)
MANUAL
PEAK
POWER
EQ-20
EFFECT
ON / OFF
MANUAL /
MEMORY
BOSS

Sallen-Key filter example (2nd order, low-pass)

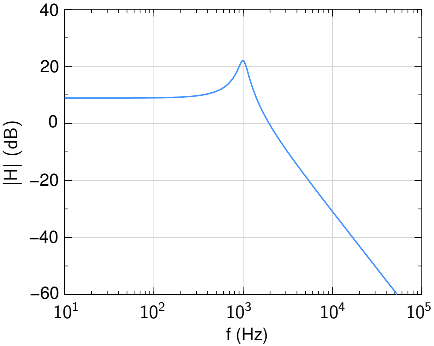


$R1 = R2 = 15.8\,\text{k}\Omega$

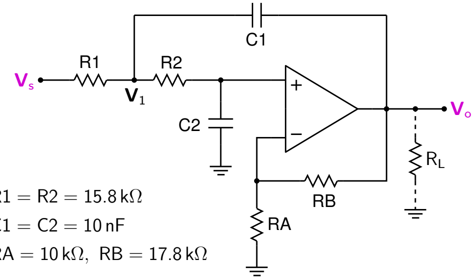
$C1 = C2 = 10\,\text{nF}$

$RA = 10\,\text{k}\Omega,\;\; RB = 17.8\,\text{k}\Omega$

(Ref.: S. Franco, "Design with Op Amps and analog ICs")



Sallen-Key filter example (2^{nd} order, low-pass)

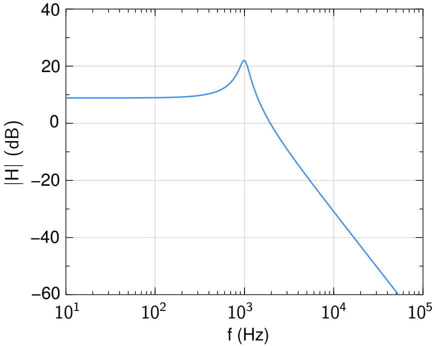


R1 = R2 = 15.8 kΩ

C1 = C2 = 10 nF

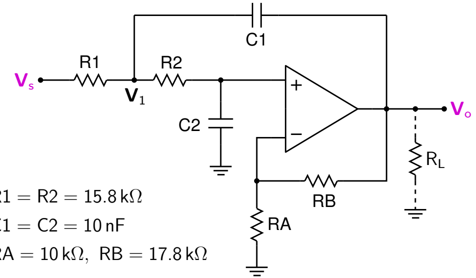
RA = 10 kΩ, RB = 17.8 kΩ

(Ref.: S. Franco, "Design with Op Amps and analog ICs")



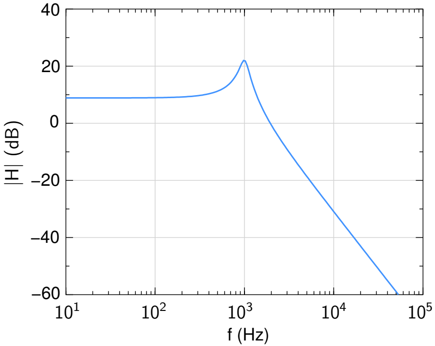
$$\mathbf{V}_+ = \mathbf{V}_- = \mathbf{V}_o \frac{R_A}{R_A + R_B} \equiv \mathbf{V}_o/K\,.$$

Sallen-Key filter example (2nd order, low-pass)



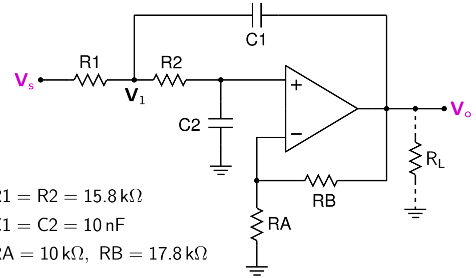
R1 = R2 = 15.8 kΩ
C1 = C2 = 10 nF
RA = 10 kΩ, RB = 17.8 kΩ

(Ref.: S. Franco, "Design with Op Amps and analog ICs")



$$\mathbf{V}_+ = \mathbf{V}_- = \mathbf{V}_o \frac{R_A}{R_A + R_B} \equiv \mathbf{V}_o / K\,.$$

Also, $\mathbf{V}_+ = \dfrac{(1/sC_2)}{R_2 + (1/sC_2)} \mathbf{V}_1 = \dfrac{1}{1 + sR_2C_2} \mathbf{V}_1\,.$

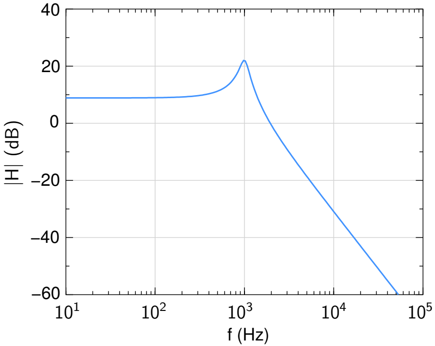


R1 = R2 = 15.8 kΩ

C1 = C2 = 10 nF

RA = 10 kΩ, RB = 17.8 kΩ

(Ref.: S. Franco, "Design with Op Amps and analog ICs")

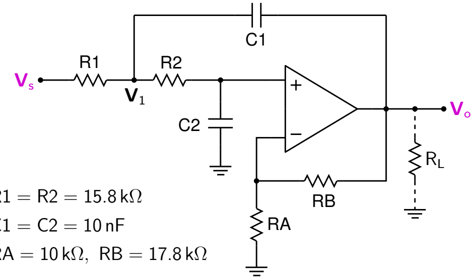


$$\mathbf{V}_+ = \mathbf{V}_- = \mathbf{V}_o \frac{R_A}{R_A + R_B} \equiv \mathbf{V}_o / K\,.$$

Also, $\mathbf{V}_+ = \dfrac{(1/sC_2)}{R_2 + (1/sC_2)}\,\mathbf{V}_1 = \dfrac{1}{1 + sR_2C_2}\,\mathbf{V}_1\,.$

KCL at $\mathbf{V}_1 \rightarrow \dfrac{1}{R_1}(\mathbf{V}_s - \mathbf{V}_1) + sC_1(\mathbf{V}_o - \mathbf{V}_1) + \dfrac{1}{R_2}(\mathbf{V}_+ - \mathbf{V}_1) = 0\,.$

Sallen-Key filter example (2nd order, low-pass)

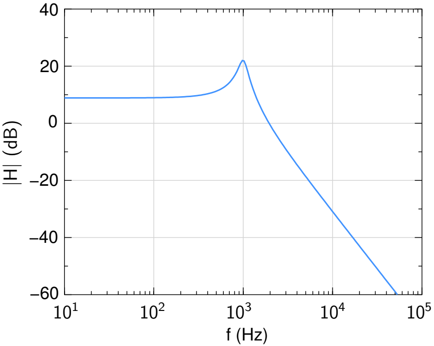


$R1 = R2 = 15.8\,\mathrm{k}\Omega$

$C1 = C2 = 10\,\mathrm{nF}$

$RA = 10\,\mathrm{k}\Omega,\;\; RB = 17.8\,\mathrm{k}\Omega$

(Ref.: S. Franco, "Design with Op Amps and analog ICs")



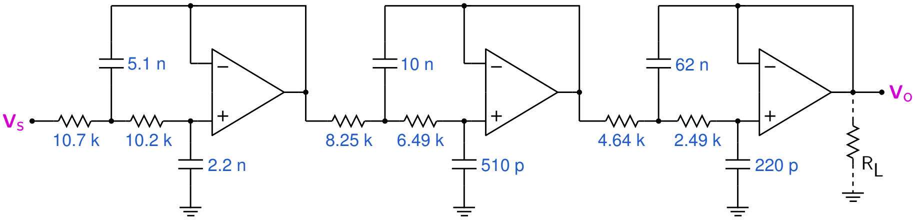
$$\mathbf{V}_+ = \mathbf{V}_- = \mathbf{V}_o \frac{R_A}{R_A + R_B} \equiv \mathbf{V}_o/K\,.$$

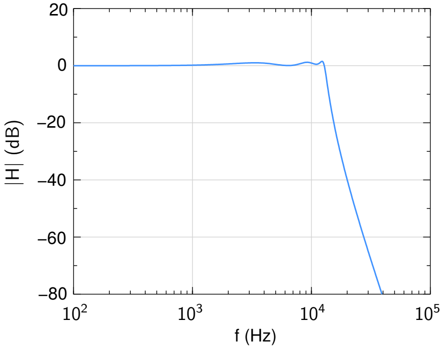
Also, $\mathbf{V}_+ = \dfrac{(1/sC_2)}{R_2 + (1/sC_2)}\,\mathbf{V}_1 = \dfrac{1}{1 + sR_2C_2}\,\mathbf{V}_1\,.$

KCL at $\mathbf{V}_1 \rightarrow \dfrac{1}{R_1}(\mathbf{V}_s - \mathbf{V}_1) + sC_1(\mathbf{V}_o - \mathbf{V}_1) + \dfrac{1}{R_2}(\mathbf{V}_+ - \mathbf{V}_1) = 0\,.$

Combining the above equations, $H(s) = \dfrac{K}{1 + s\left[(R_1 + R_2)C_2 + (1-K)R_1C_1\right] + s^2R_1C_1R_2C_2}\,.$

(SEQUEL file: `ee101_op_filter_5.sqproj`)

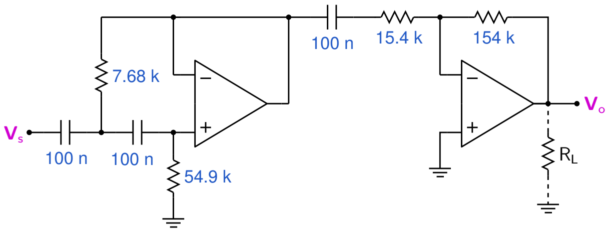




(Ref.: S. Franco, "Design with Op Amps and analog ICs")

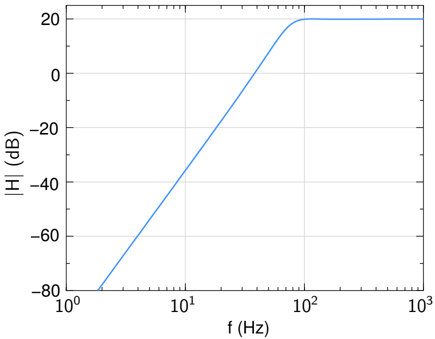
SEQUEL file: ee101_op_filter_6.sqproj

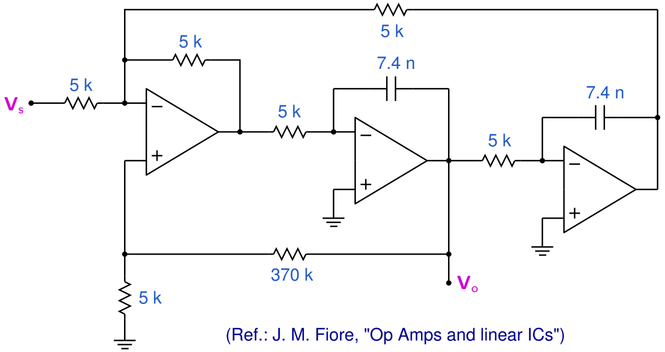
Third-order Chebyshev high-pass filter

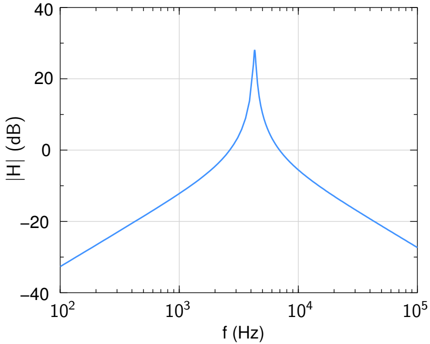


(Ref.: S. Franco, "Design with Op Amps and analog ICs")

SEQUEL file: ee101_op_filter_7.sqproj



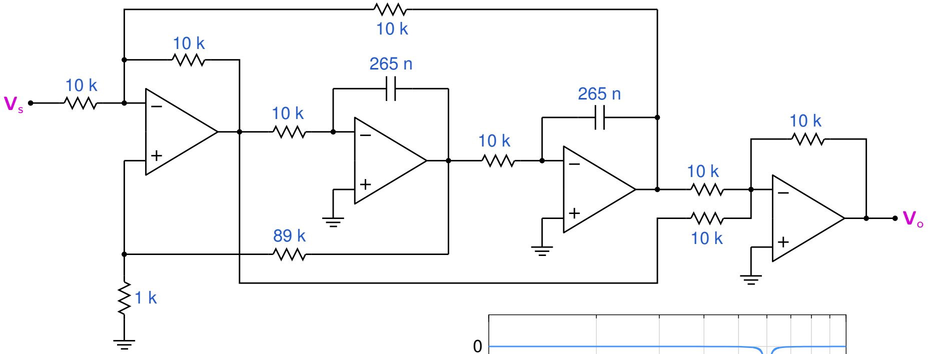


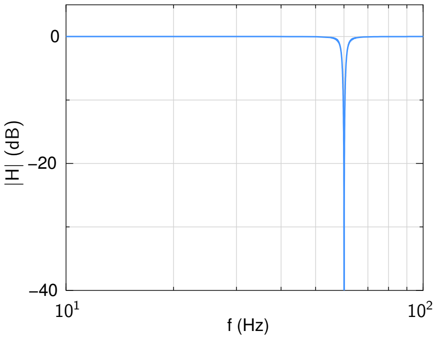


(Ref.: J. M. Fiore, "Op Amps and linear ICs")

SEQUEL file: ee101_op_filter_8.sqproj

Notch filter example

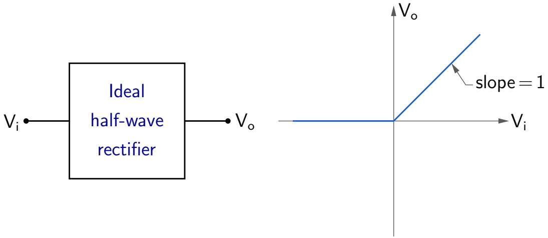




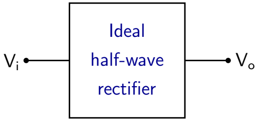
(Ref.: J. M. Fiore, "Op Amps and linear ICs")

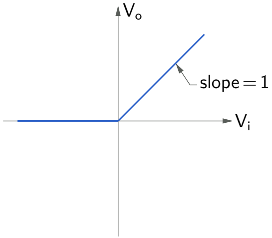
SEQUEL file: ee101_op_filter_9.sqproj

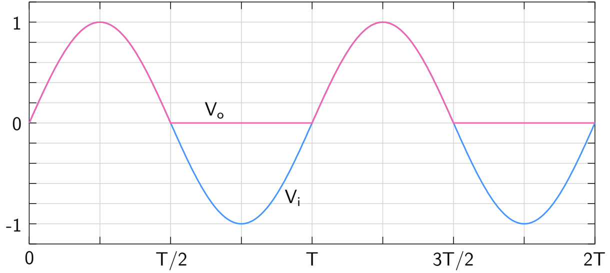
Half-wave rectifier



Half-wave rectifier







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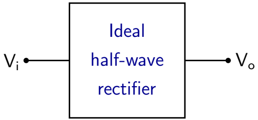
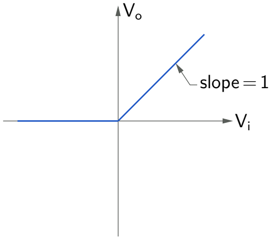
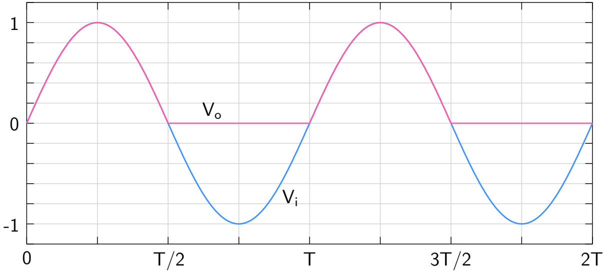
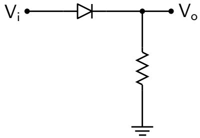
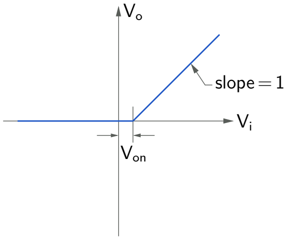


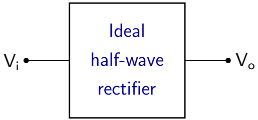


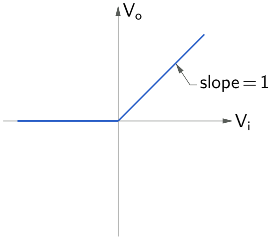


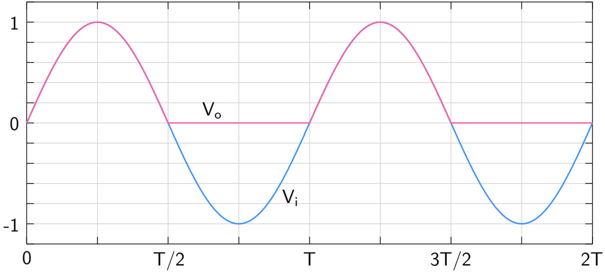


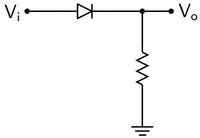


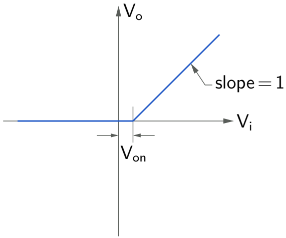
Half-wave rectifier

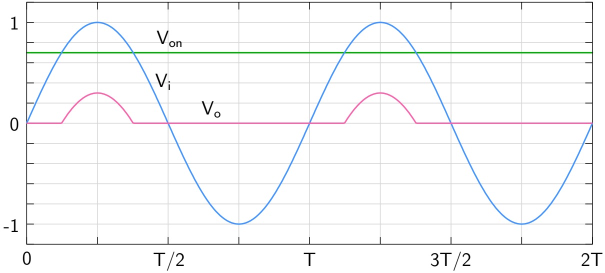












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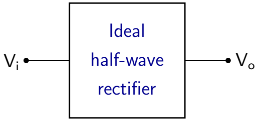
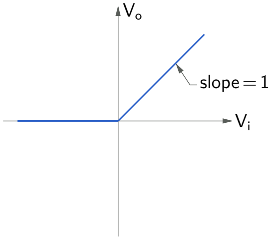
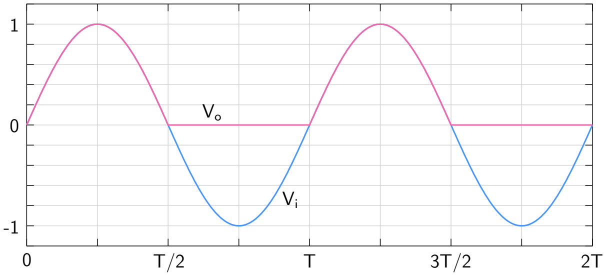
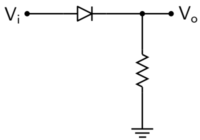
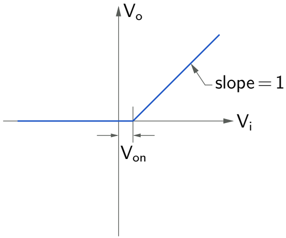
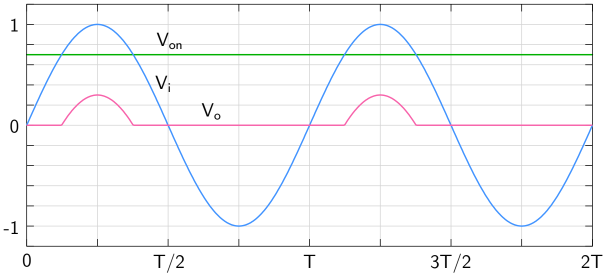






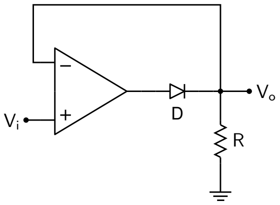




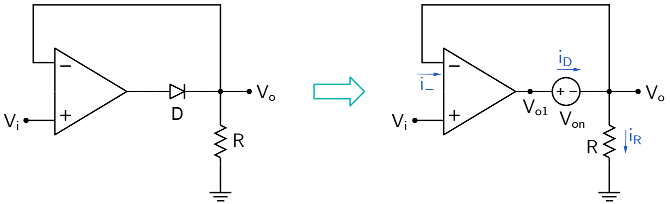


→ need an improved circuit

Half-wave precision rectifier



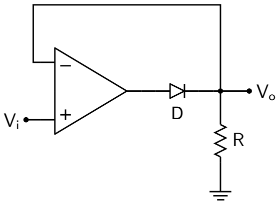
Half-wave precision rectifier

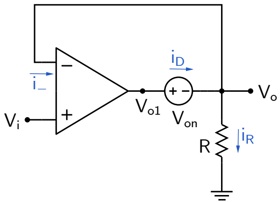


Consider two cases:

(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.

Half-wave precision rectifier





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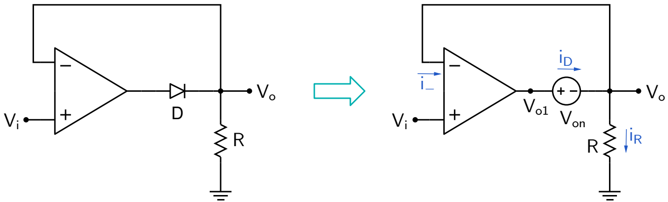
(i) D is conducting: The feedback loop is closed, and the circuit looks like (except for the diode drop) the buffer we have seen earlier.

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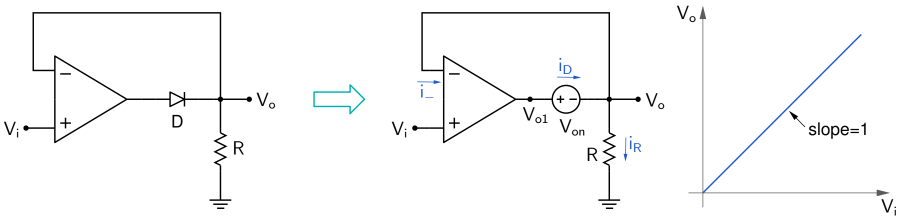
This situation arises only if $i_D > 0$ (since the diode can only conduct in the forward direction), i.e., $i_R > 0 \rightarrow V_o = i_R R > 0$, and therefore $V_i = V_o > 0\ V$.



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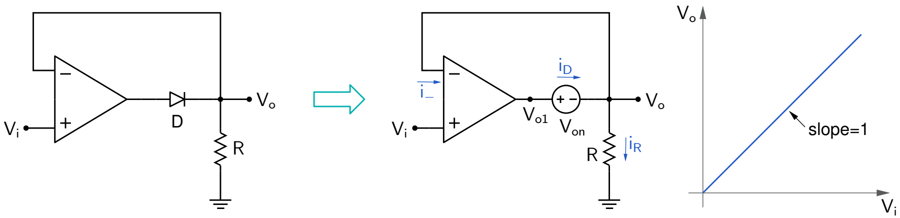

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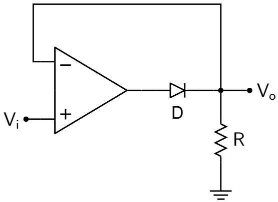
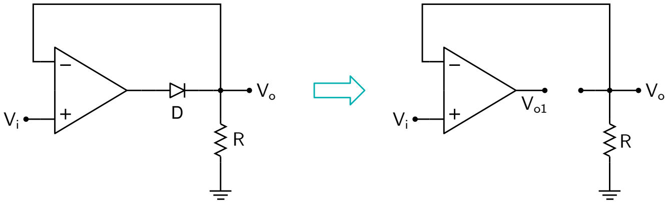
Note: V_{on} does not appear in the graph.

Half-wave precision rectifier





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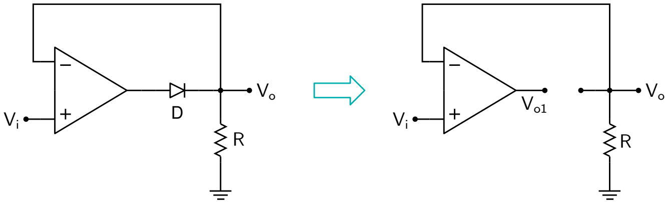
Half-wave precision rectifier



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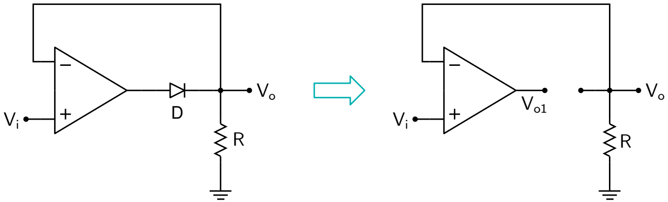
What about V_{o1}?

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

Half-wave precision rectifier



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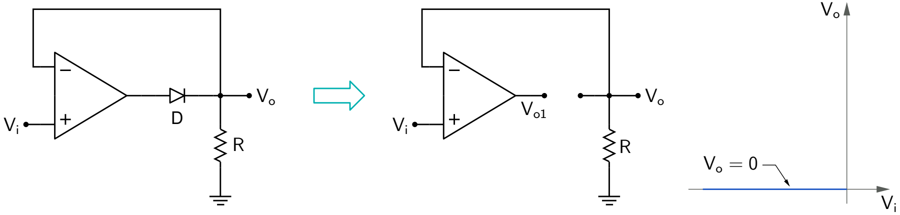
Half-wave precision rectifier



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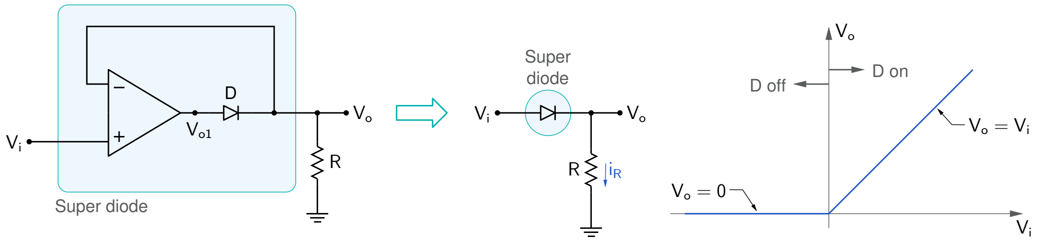
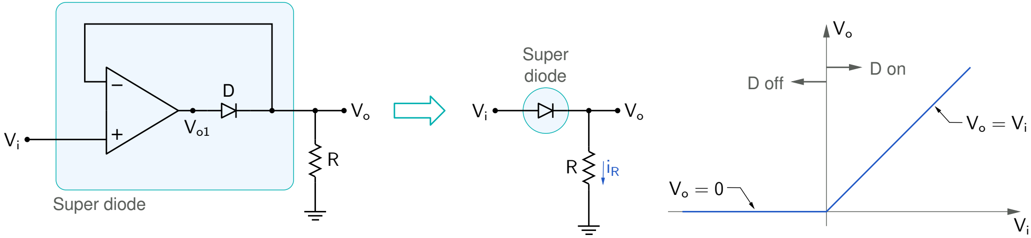
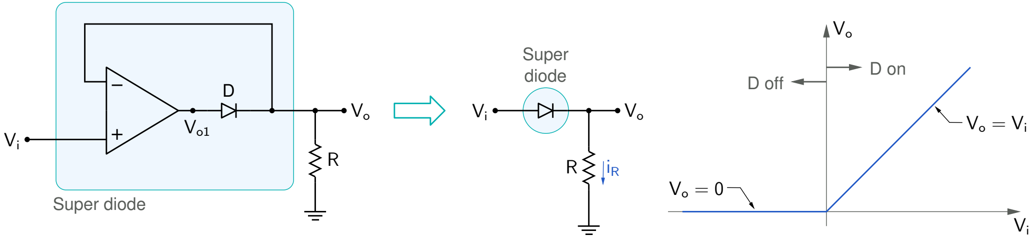

D
V_o
V_i
V_{o1}
R
Super diode
Super
diode
V_i
V_o
R
i_R
V_o
D on
D off
$V_o = V_i$
$V_o = 0$
V_i



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

Half-wave precision rectifier



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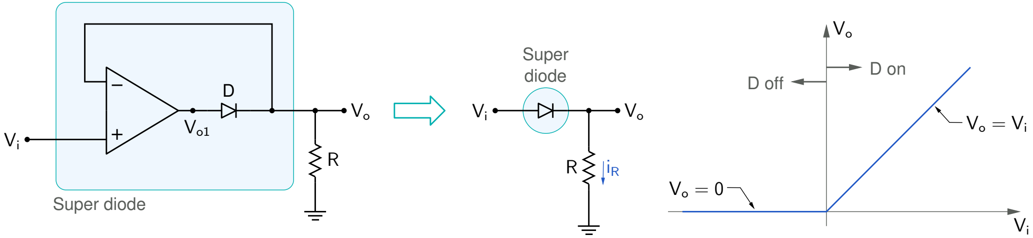

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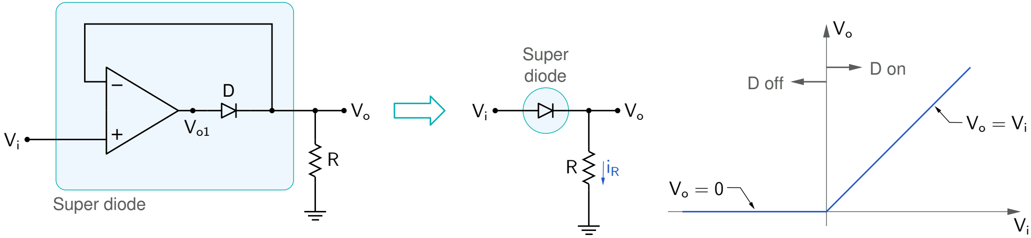
Half-wave precision rectifier



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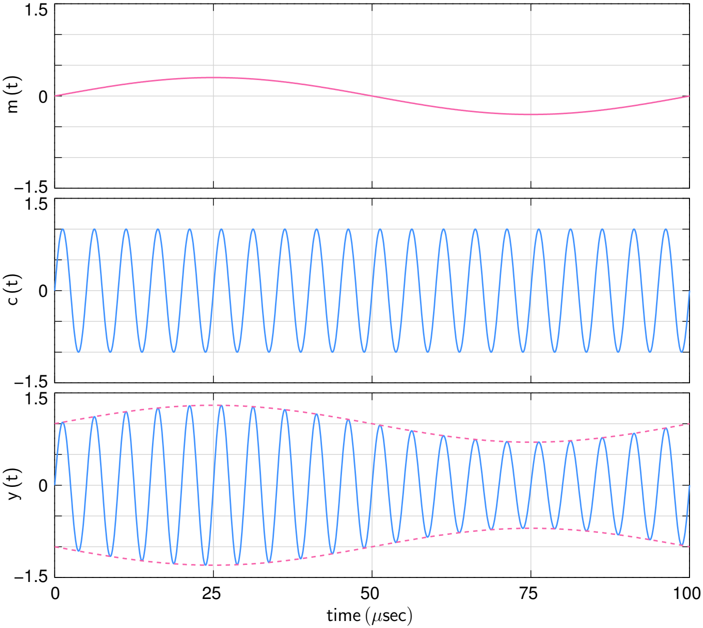
* Where does i_R come from?

$A = 1$
$M = 0.3$
$f_c = 200\,\text{kHz}$
$f_m = 10\,\text{kHz}$

Application: AM demodulation



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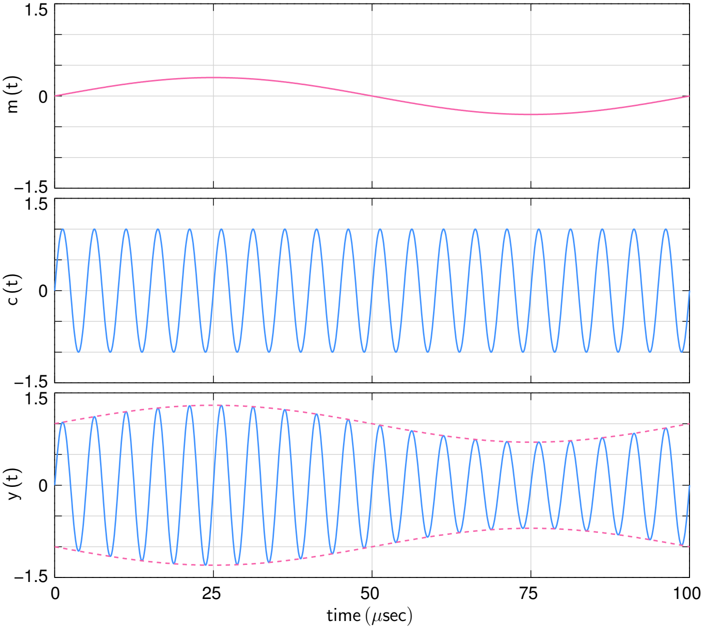
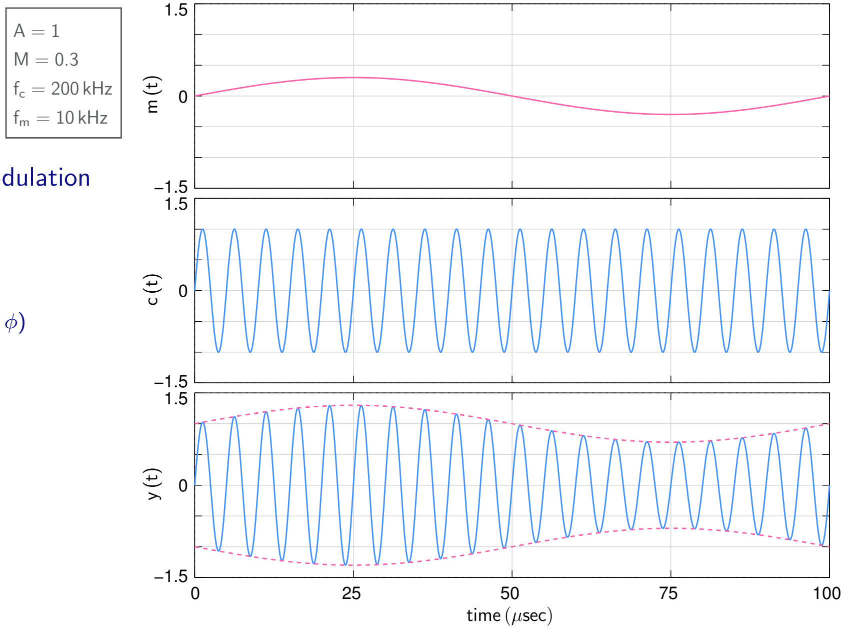
Application: AM demodulation

Carrier wave:

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





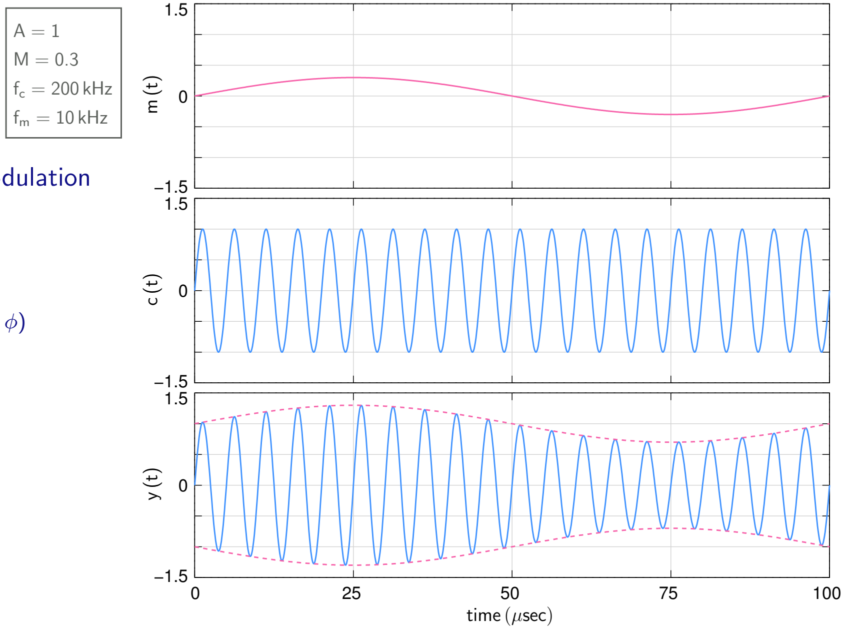
Application: AM demodulation

Carrier wave:

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

Signal (e.g., audio):

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



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AM wave:

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

(Assume $M < 1$)

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AM wave:

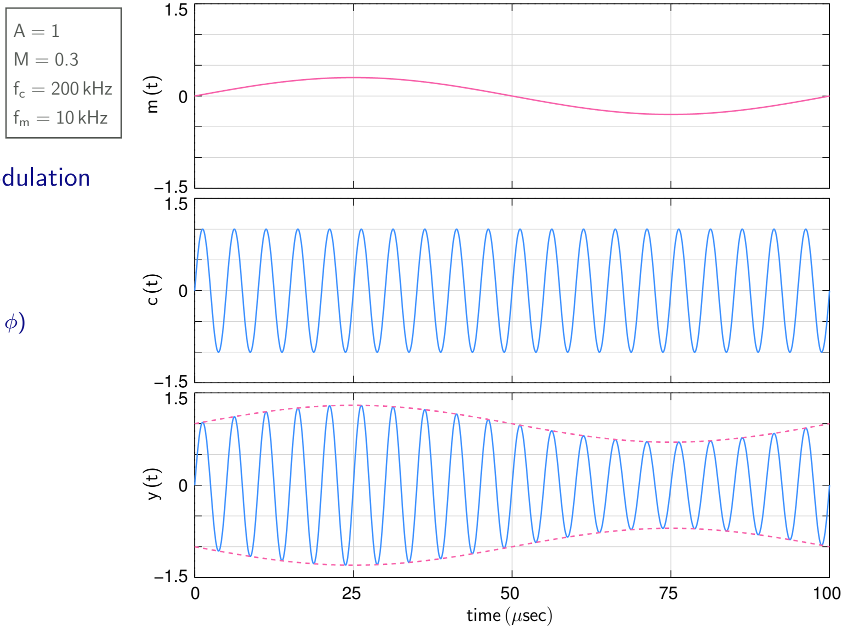
$$y(t) = [1 + m(t)]\ c(t)$$

(Assume $M < 1$)

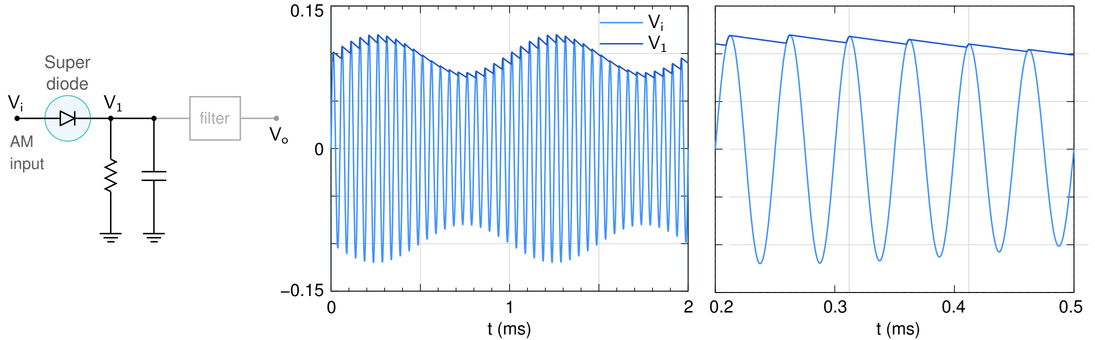
e.g., Vividh Bharati:

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

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



AM demodulation using a peak detector



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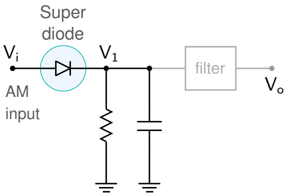
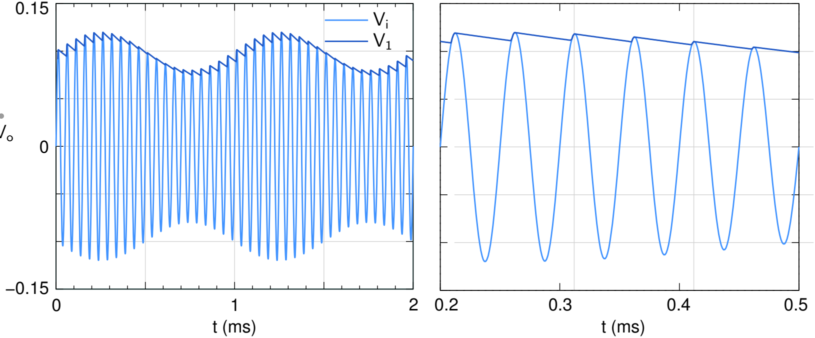
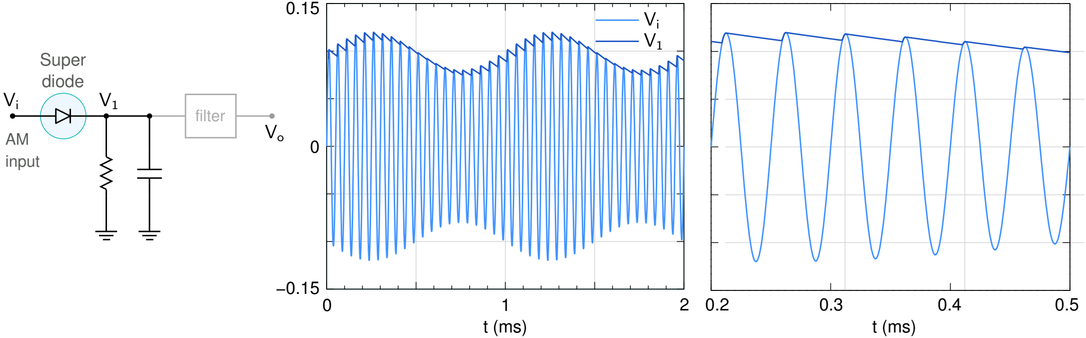




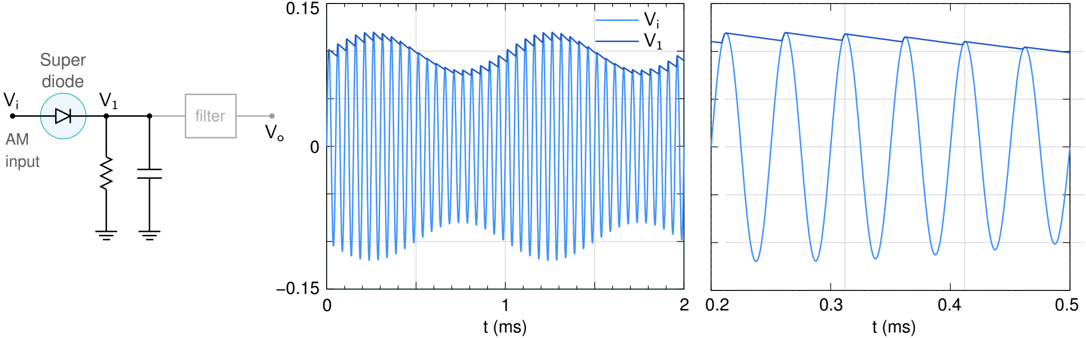
* charging through super diode, discharging through resistor

AM demodulation using a peak detector



* 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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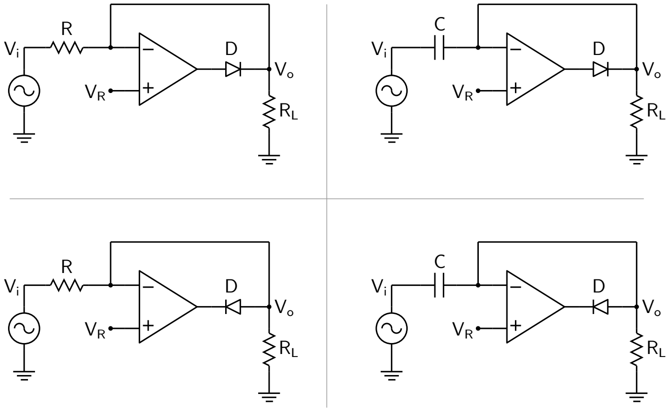
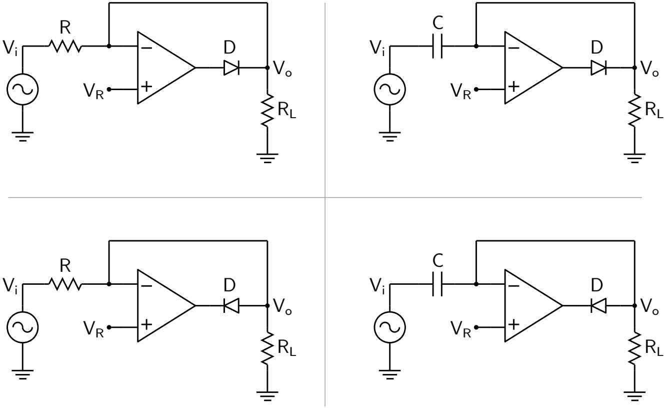
  SEQUEL file: `super_diode.sqproj`

Clipping and clamping

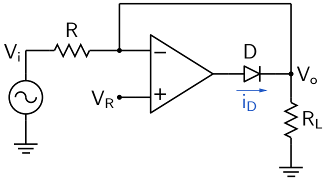


∗ What is the function provided by each circuit?

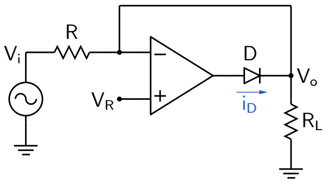
Clipping and clamping



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



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



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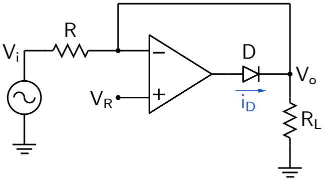
KCL: $i_D = \dfrac{V_R}{R_L} + \dfrac{V_R - V_i}{R}$.



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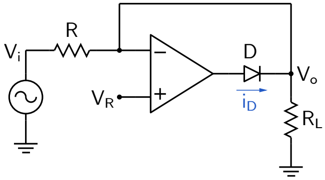
KCL: $i_D = \dfrac{V_R}{R_L} + \dfrac{V_R - V_i}{R}$.

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



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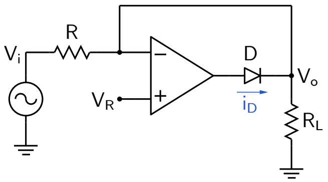
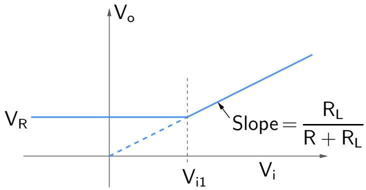
Since $i_D > 0$, $\;V_R\left(\dfrac{1}{R_L} + \dfrac{1}{R}\right) > \dfrac{V_i}{R} \;\rightarrow\; V_i < V_R\left(\dfrac{R + R_L}{R_L}\right) \equiv V_{i1}$.

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





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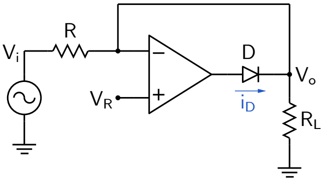

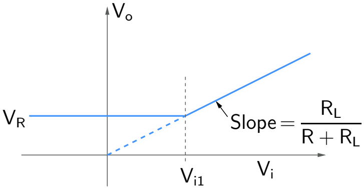

When D conducts, feedback path is closed $\rightarrow$ $V_- \approx V_+ = V_R$ $\rightarrow$ $V_o = V_R$.

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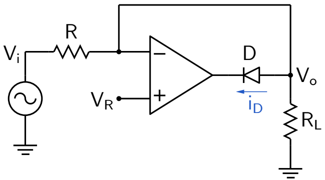
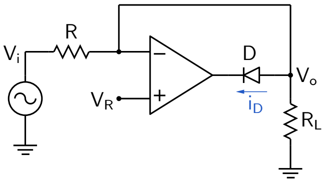


When D conducts, feedback path is closed $\rightarrow V_{-} \approx V_{+} = V_R \ \rightarrow \ V_o = V_R$.



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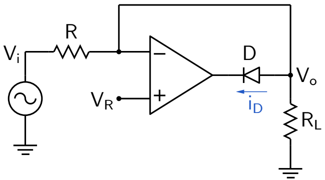

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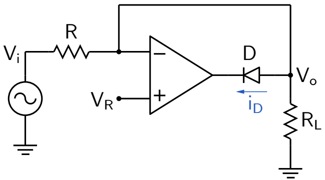

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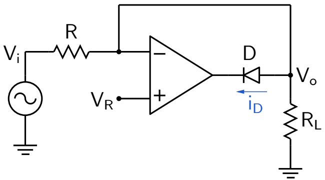
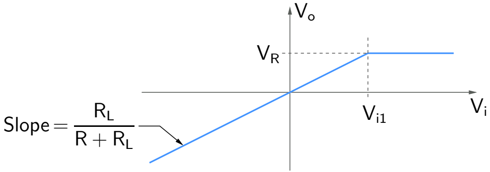
For $V_i < V_{i1}$, D does not conduct $\ \rightarrow\ V_o = \dfrac{R_L}{R+R_L}\,V_i$.





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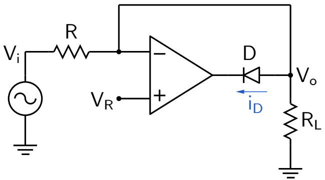

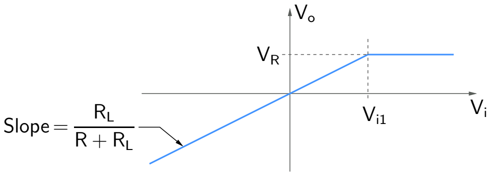

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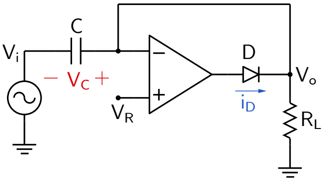
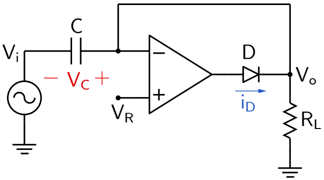


Time constant for the discharging process is $R_L C$.

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



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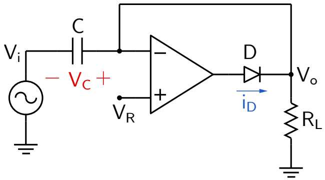
$\rightarrow \ V_C^{\text{max}} = V_R - (-V_m) = V_R + V_m$.



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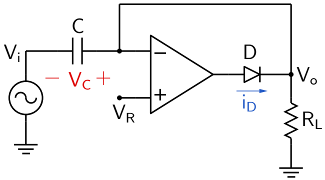

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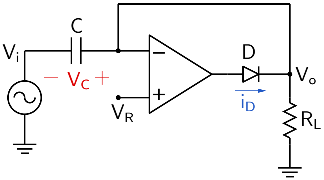
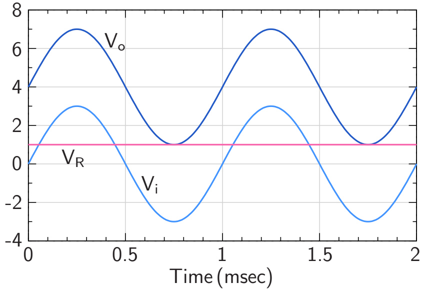
Note: V_{on} of the diode does not appear in the expression for $V_o(t)$.





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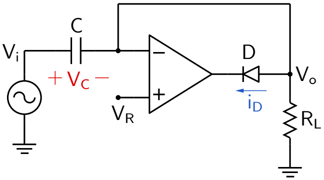

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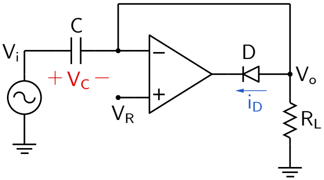

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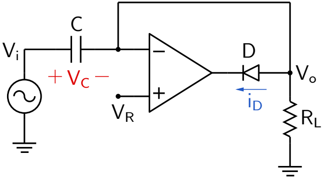

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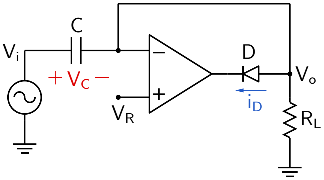

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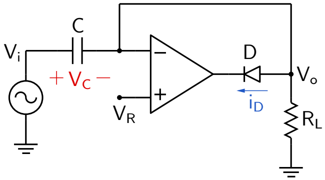

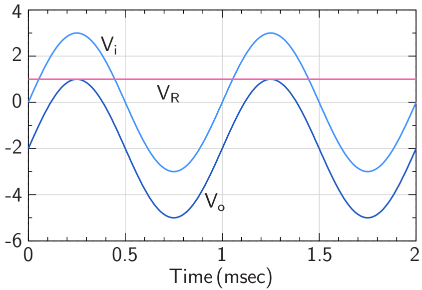

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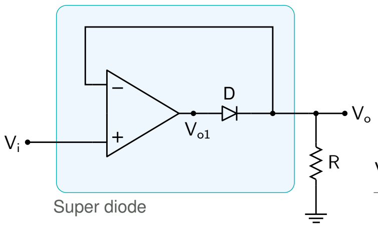
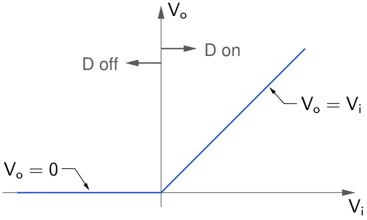
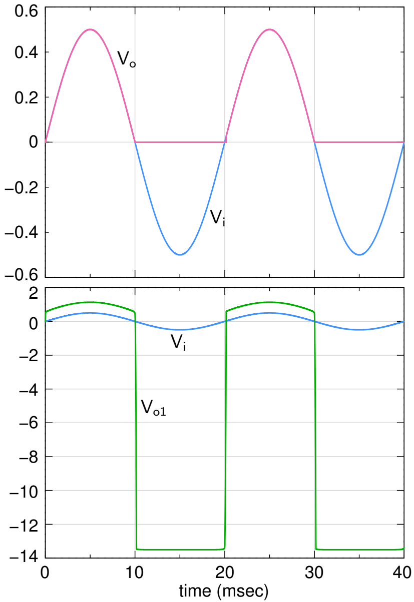
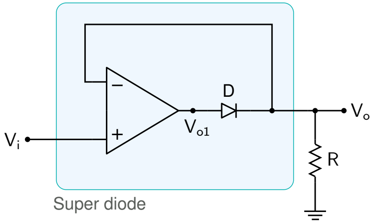
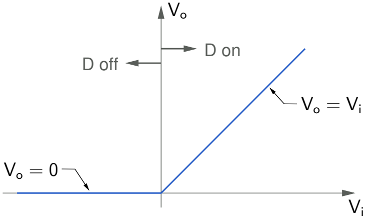
Half-wave precision rectifier

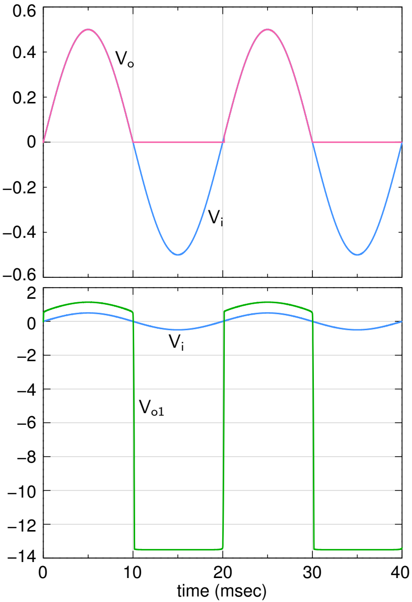






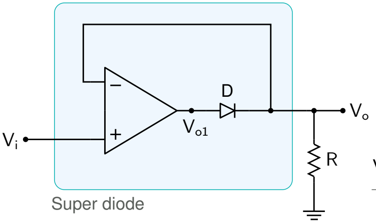


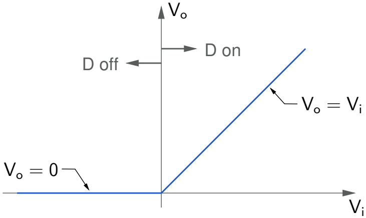


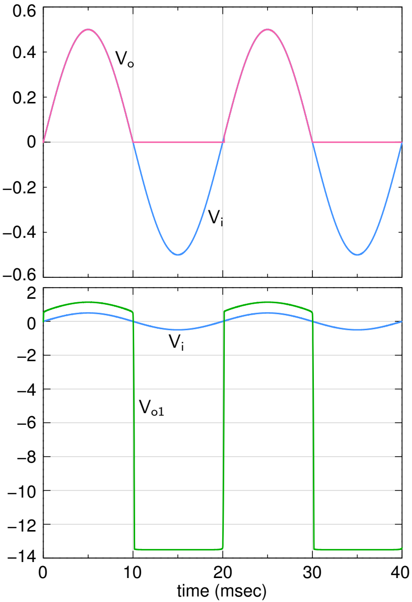


* When $V_i > 0$, the op-amp operates in the linear region, and $V_{o1} = V_o + V_{on}$.

Half-wave precision rectifier

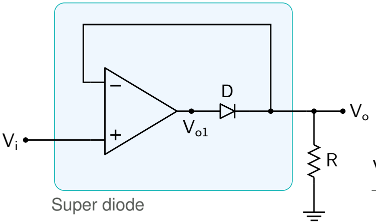


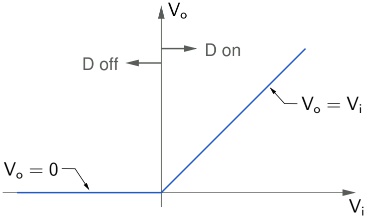


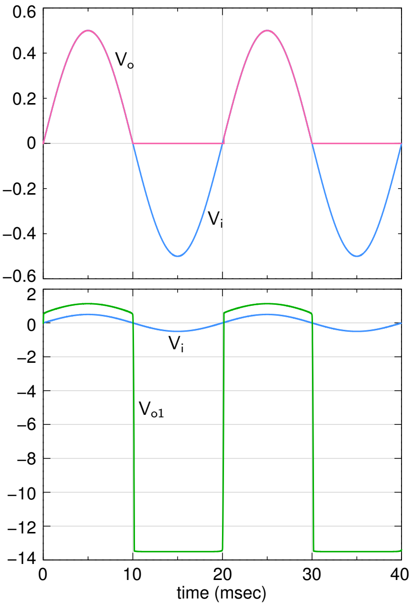


* When $V_i > 0$, the op-amp operates in the linear region, and $V_{o1} = V_o + V_{\text{on}}$.
* When $V_i < 0$, the op-amp operates in the open-loop configuration, leading to saturation, and $V_{o1} = -V_{\text{sat}}$.

Half-wave precision rectifier







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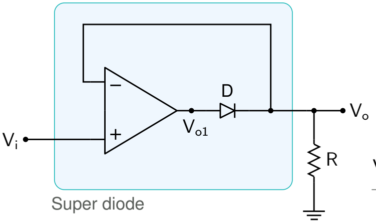
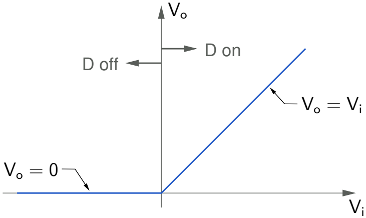
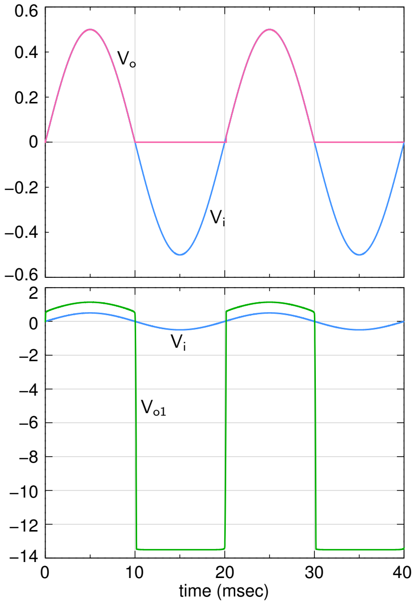
* The $V_i < 0$ to $V_i > 0$ transition requires the op-amp to come out of saturation. This is a relatively slow process and is limited by the op-amp slew rate.







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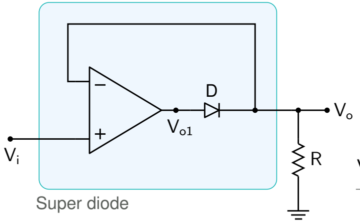
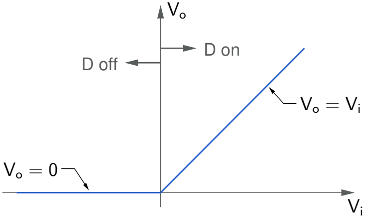
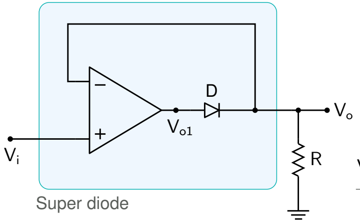
SEQUEL file: `ee101_super_diode_1.sqproj`

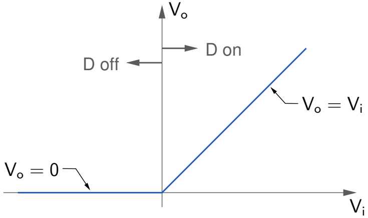
Half-wave precision rectifier

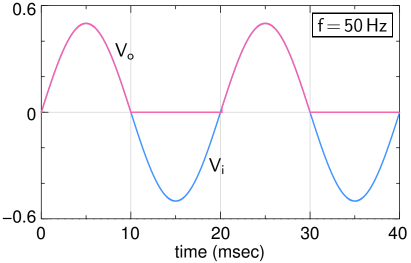




* The time taken by the op-amp to come out of saturation can be neglected at low signal frequencies.

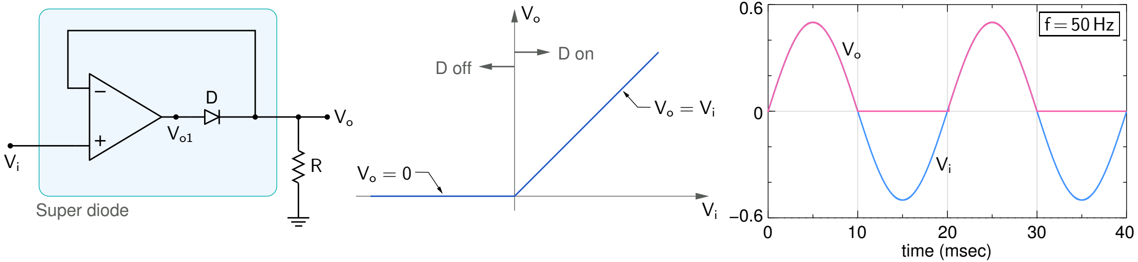






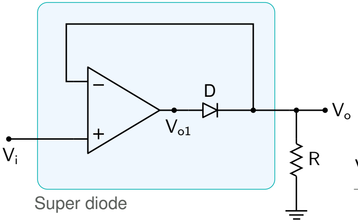
* The time taken by the op-amp to come out of saturation can be neglected at low signal frequencies.

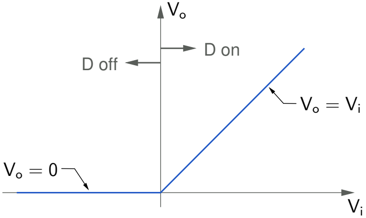
Half-wave precision rectifier

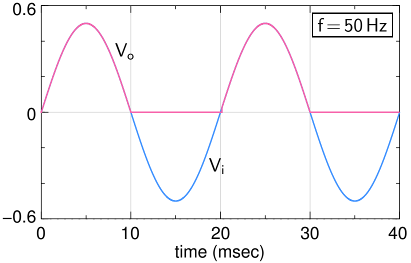


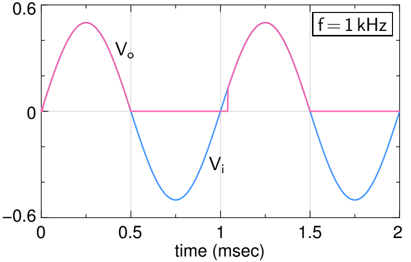
* The time taken by the op-amp to come out of saturation can be neglected at low signal frequencies.
* At high signal frequencies, it leads to distortion in the output waveform.

Half-wave precision rectifier

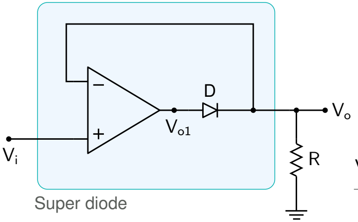


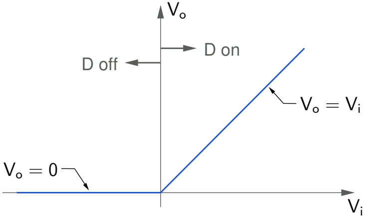


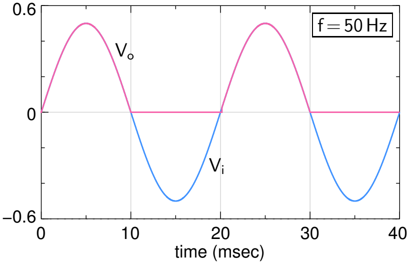


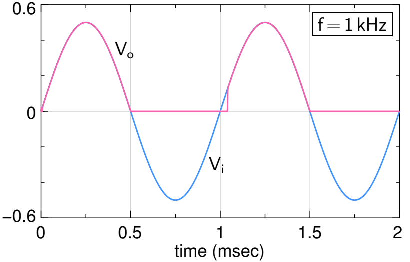


* The time taken by the op-amp to come out of saturation can be neglected at low signal frequencies.
* At high signal frequencies, it leads to distortion in the output waveform.



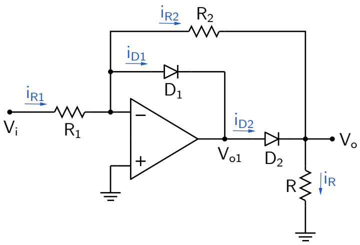




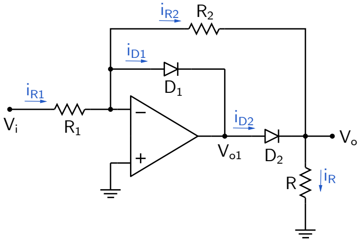


* The time taken by the op-amp to come out of saturation can be neglected at low signal frequencies.
* At high signal frequencies, it leads to distortion in the output waveform.
* Hook up the circuit in the lab, and check it out!

Improved half-wave precision rectifier

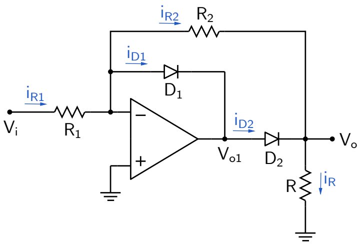


Improved half-wave precision rectifier



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

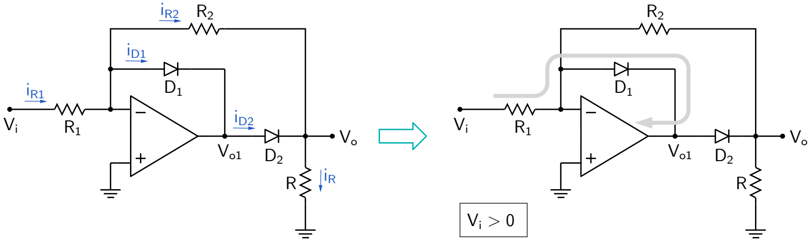
Improved half-wave precision rectifier



(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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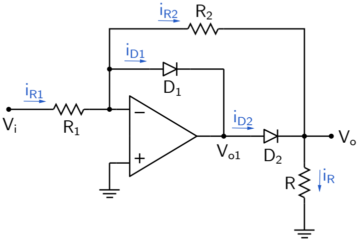
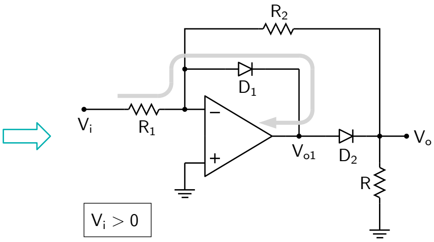
Improved half-wave precision rectifier





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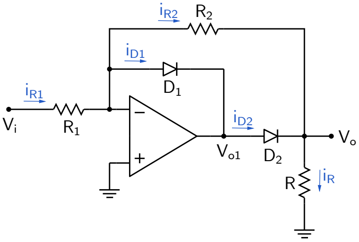
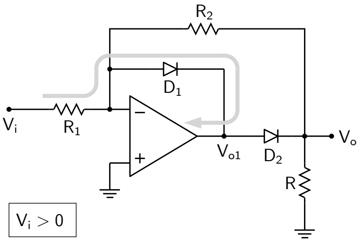
D_2 cannot conduct (show that, if it did, KCL is not satisfied at V_o).
$\rightarrow i_{R2} = 0$, $V_o = V_- = 0\,V$.

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

Improved half-wave precision rectifier





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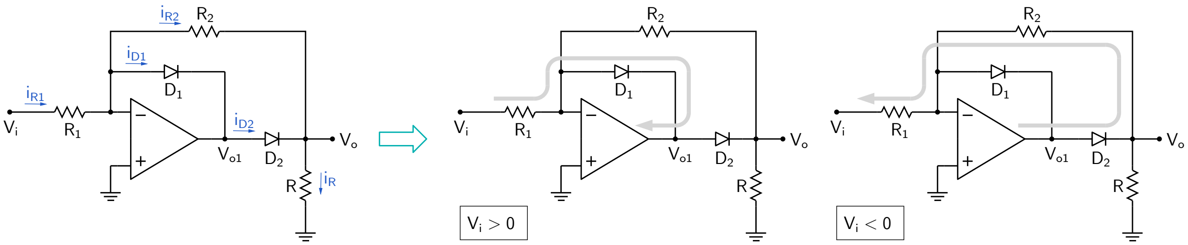
D_2 cannot conduct (show that, if it did, KCL is not satisfied at V_o).
$\rightarrow i_{R2} = 0,\ V_o = V_- = 0\,V$.

$i_{R1} = i_{D1}$ 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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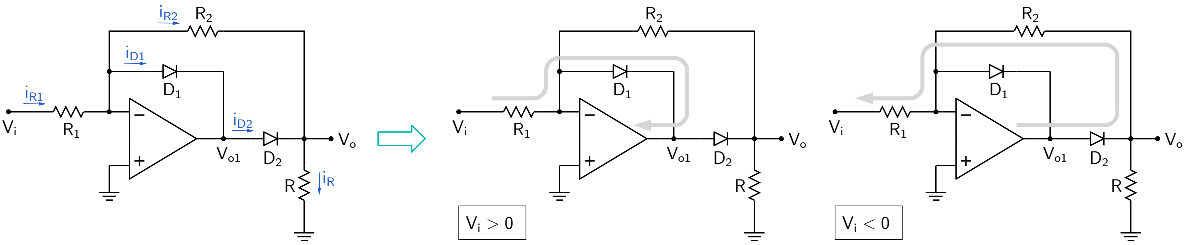
In this case, D_2 conducts and closes the feedback loop through R_2.



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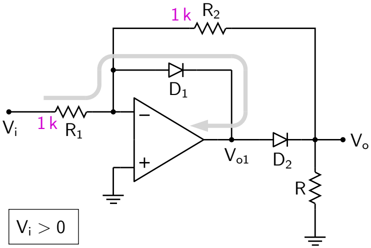
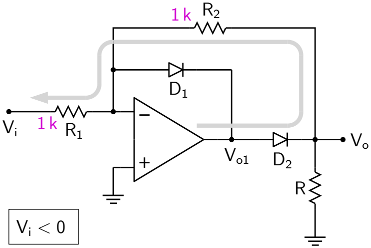
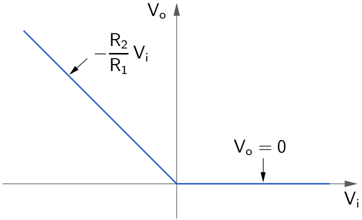
In this case, D_2 conducts and closes the feedback loop through R_2.

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

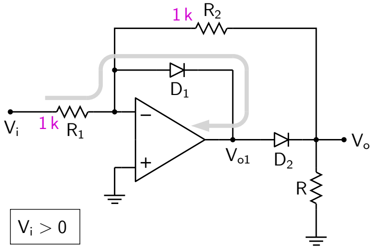
Improved half-wave precision rectifier

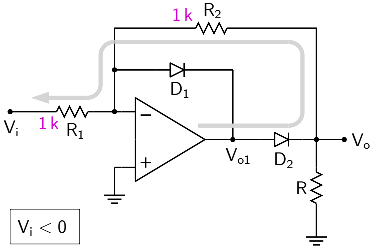


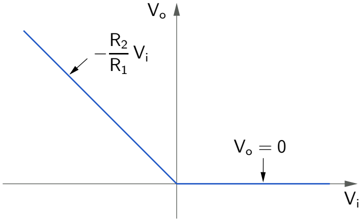


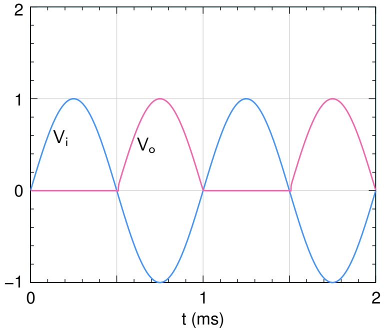


Improved half-wave precision rectifier

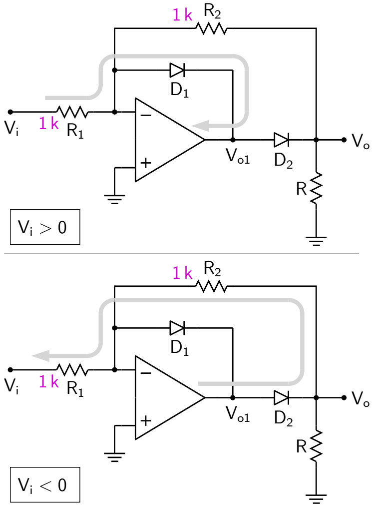


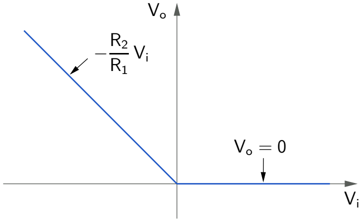


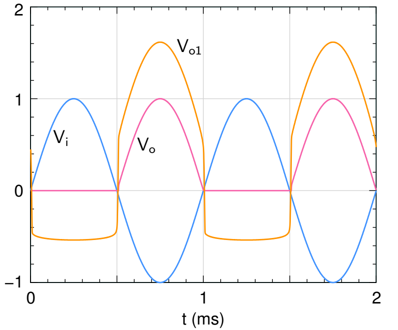




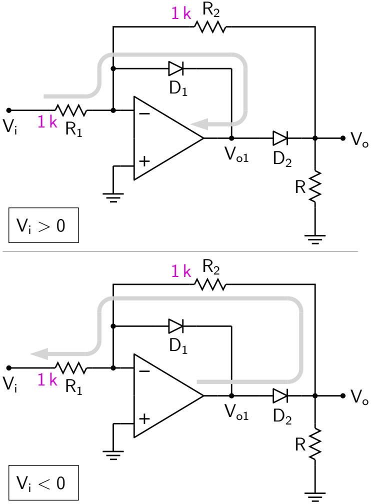
Improved half-wave precision rectifier

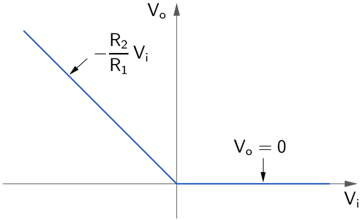


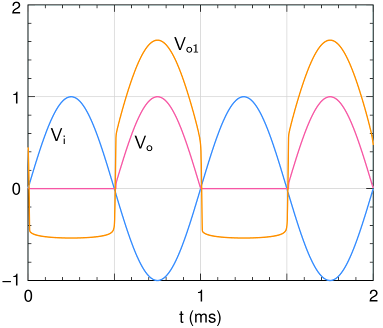




Improved half-wave precision rectifier

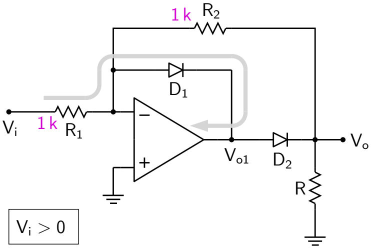


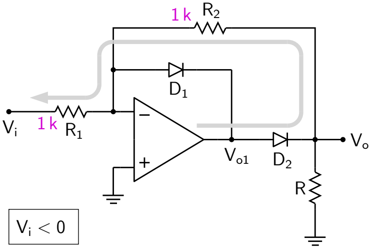


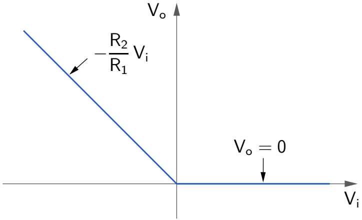


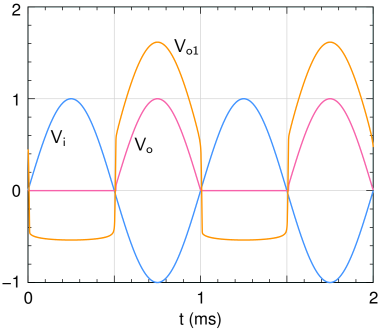
* Note that the op-amp does not enter saturation since a feedback path is available for $V_i > 0\,V$ and $V_i < 0\,V$.

Improved half-wave precision rectifier





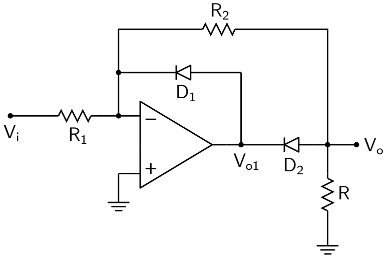


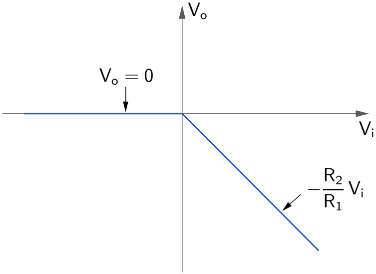


* Note that the op-amp does not enter saturation since a feedback path is available for $V_i > 0\ V$ and $V_i < 0\ V$.

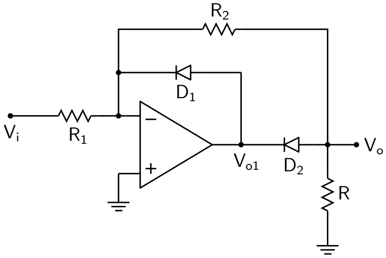
SEQUEL file: `precision_half_wave.sqproj`

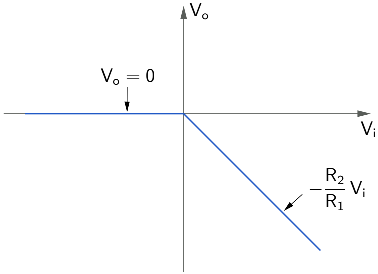
Improved half-wave precision rectifier





The diodes are now reversed.

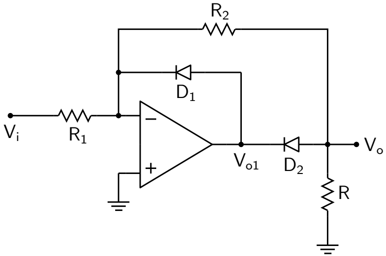


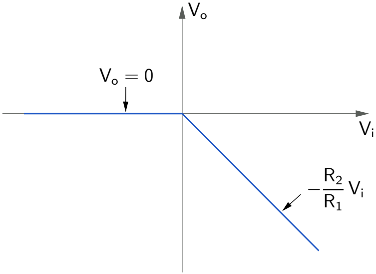


The diodes are now reversed.

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



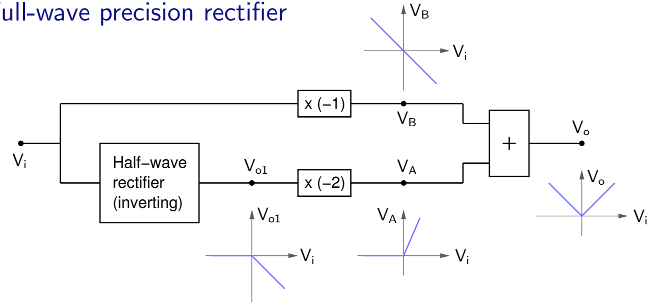


The diodes are now reversed.

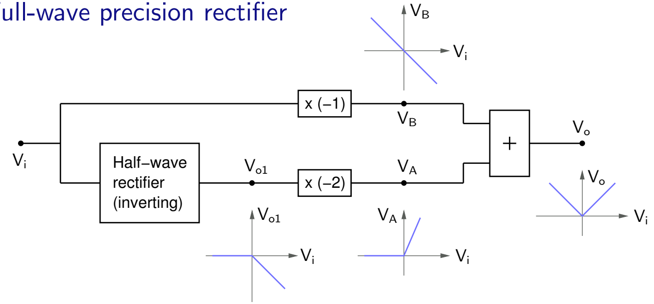
By considering two cases: (i) D_1 on, (ii) D_1 off, the V_o versus V_i relationship shown in the figure is obtained (show this).

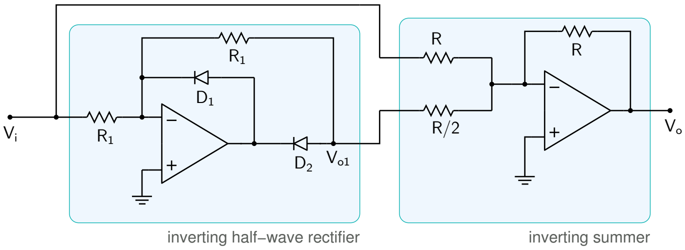
SEQUEL file: `precision_half_wave_2.sqproj`

Full-wave precision rectifier



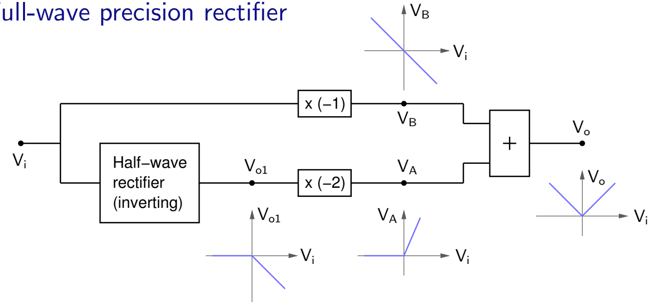
Full-wave precision rectifier

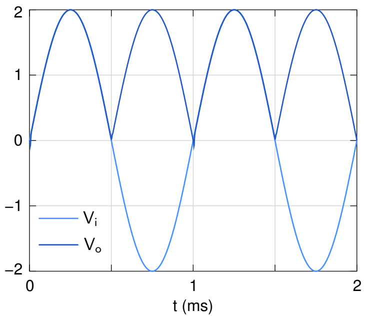


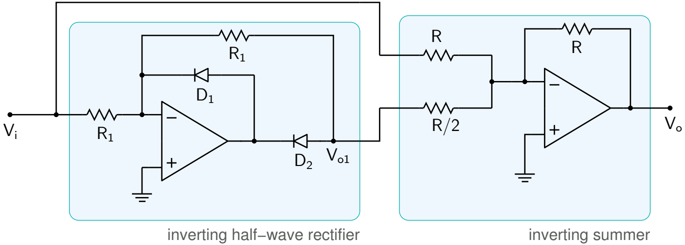


(SEQUEL file: `precision_full_wave.sqproj`)

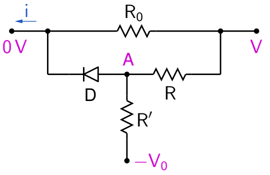
Full-wave precision rectifier





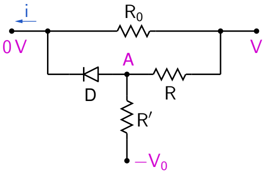


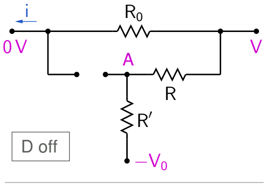
(SEQUEL file: `precision_full_wave.sqproj`)



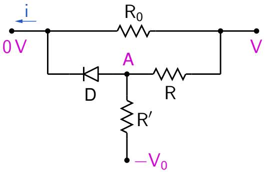
i
R_0
0 V
V
A
D
R
R'
$-V_0$

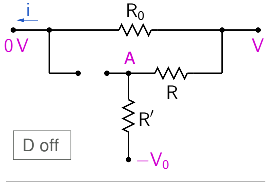
Wave shaping with diodes





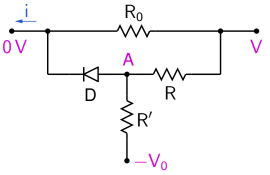
Wave shaping with diodes

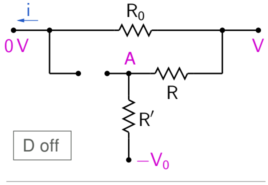




When D is off, $i = \dfrac{V}{R_0}$, and V_A is (by superposition), $V_A = V\dfrac{R'}{R+R'} - V_0\dfrac{R}{R+R'}$.

Wave shaping with diodes

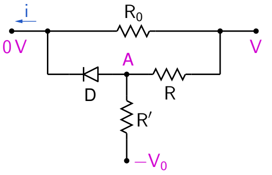


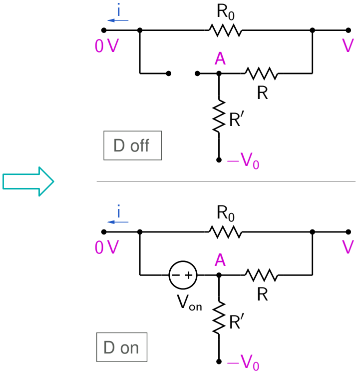


When D is off, $i = \dfrac{V}{R_0}$, and V_A is (by superposition), $V_A = V\dfrac{R'}{R+R'} - V_0\dfrac{R}{R+R'}$.

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

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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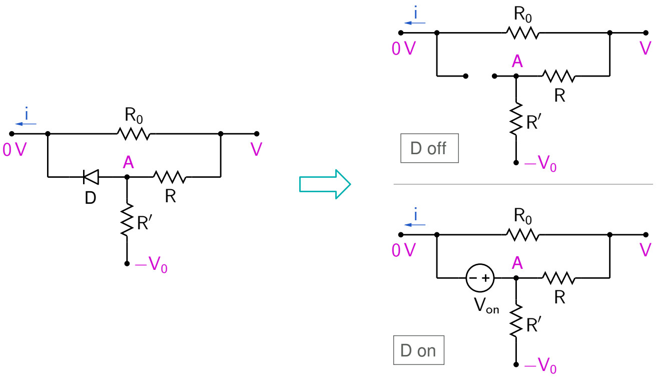
Wave shaping with diodes

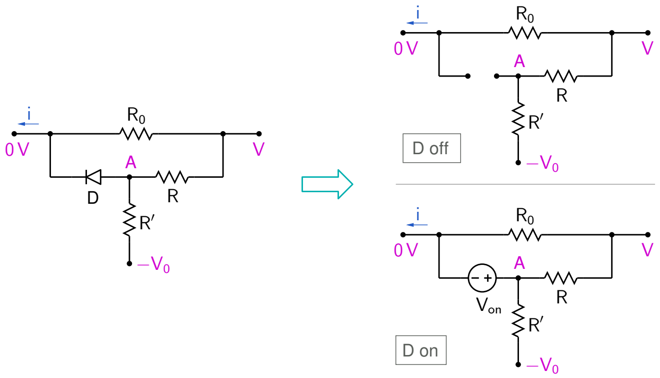


When D is off, $i = \dfrac{V}{R_0}$, and V_A is (by superposition), $V_A = V\,\dfrac{R'}{R+R'} - V_0\,\dfrac{R}{R+R'}$.

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

Wave shaping with diodes

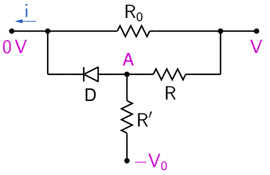


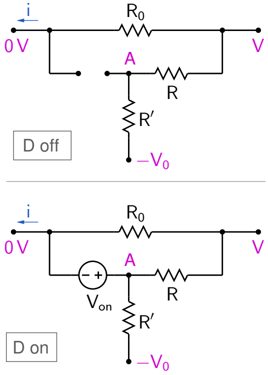
When D is off, $i = \dfrac{V}{R_0}$, and V_A is (by superposition), $V_A = V\dfrac{R'}{R+R'} - V_0\dfrac{R}{R+R'}$.

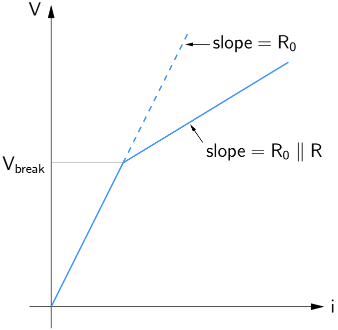
For D to turn on, $V_A = V_{on} \approx 0.7\ V \rightarrow V \equiv V_{break} = \dfrac{R}{R'}(V_0 + V_{on}) + V_{on}$.

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

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







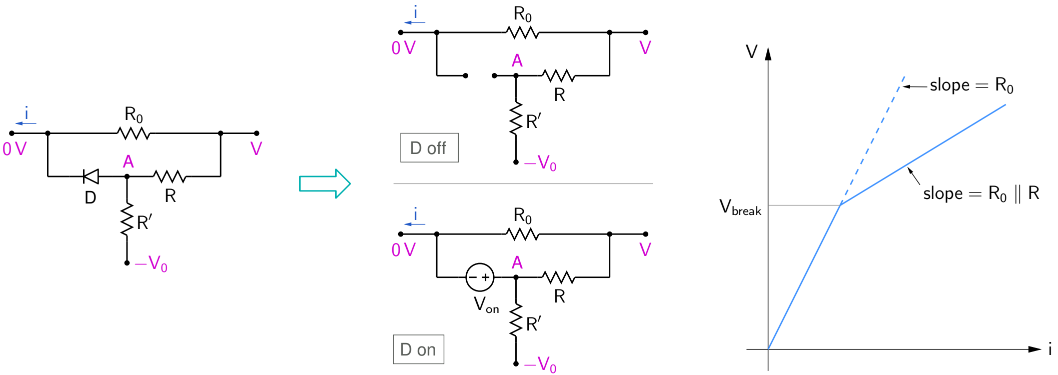
When D is off, $i = \dfrac{V}{R_0}$, and V_A is (by superposition), $V_A = V\,\dfrac{R'}{R+R'} - V_0\,\dfrac{R}{R+R'}$.

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

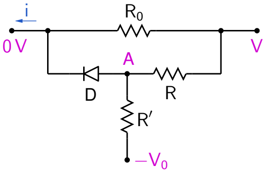
i.e., $V = (R_0 \parallel R)\,i + \text{(constant)}$.

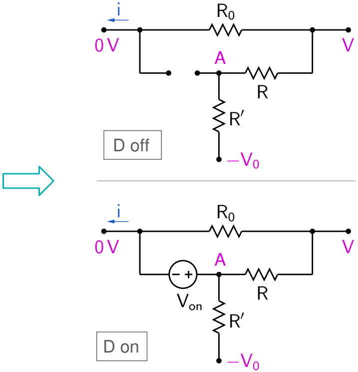
Wave shaping with diodes

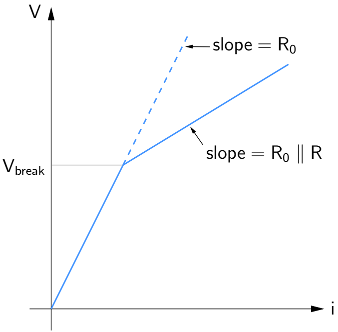


(a) $V_{\mathrm{break}} = \dfrac{R}{R'}\,(V_0 + V_{\mathrm{on}}) + V_{\mathrm{on}}$. (b) When D is on, $V = (R_0 \parallel R)\, i + (\text{constant})$.

Wave shaping with diodes



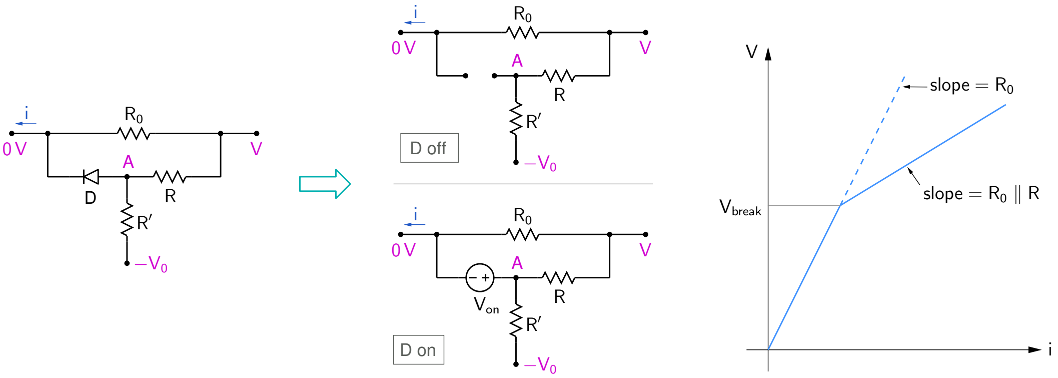




(a) $V_{break} = \dfrac{R}{R'}(V_0 + V_{on}) + V_{on}$. (b) When D is on, $V = (R_0 \parallel R)\, i + (\text{constant})$.

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

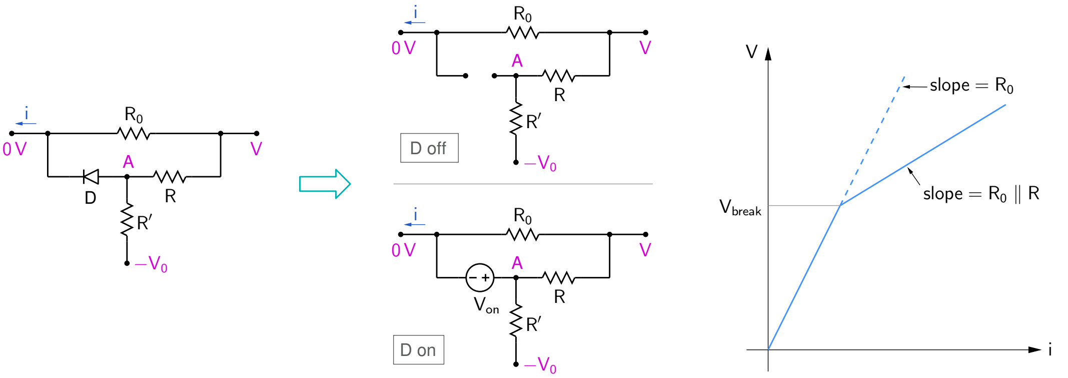
Wave shaping with diodes



(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.

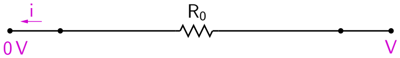
Wave shaping with diodes



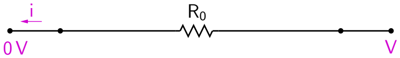
(a) $V_{\text{break}} = \dfrac{R}{R'}\,(V_0 + V_{\text{on}}) + V_{\text{on}}$. (b) When D is on, $V = (R_0 \parallel R)\, i + (\text{constant})$.

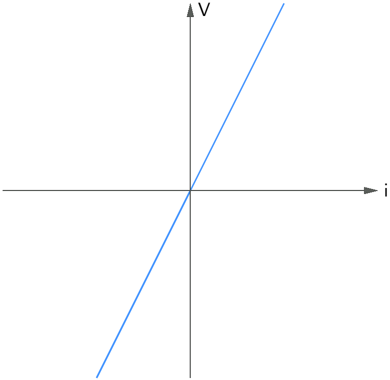
- V_{break} depends on the ratio R/R'.
- The slope $R_0 \parallel R$ depends on the resistance values.
- Given the break point and the two slopes, the resistance values can be easily determined.

Wave shaping with diodes

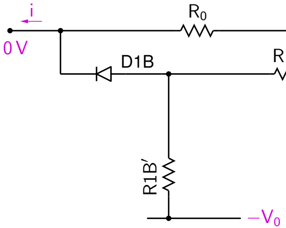


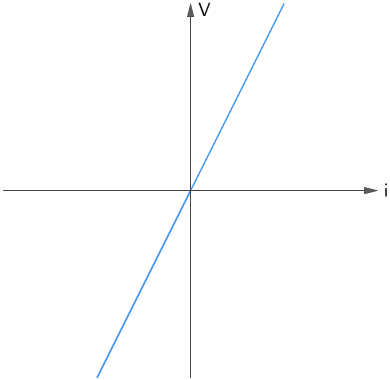
Wave shaping with diodes



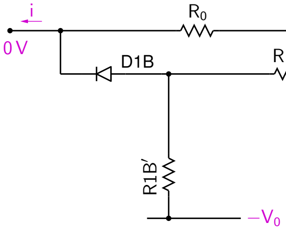


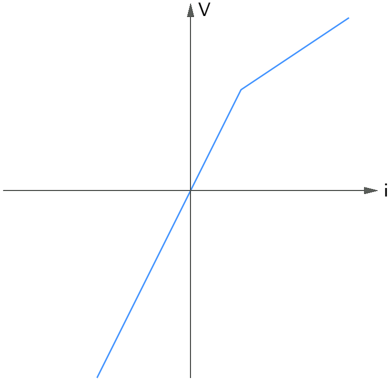
Wave shaping with diodes



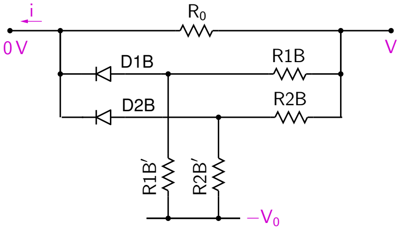


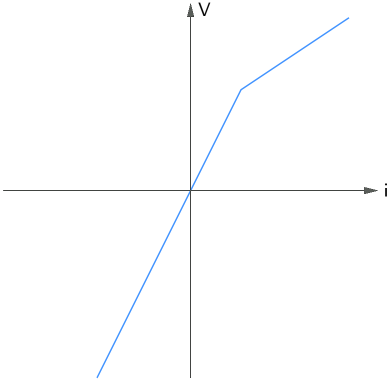
Wave shaping with diodes

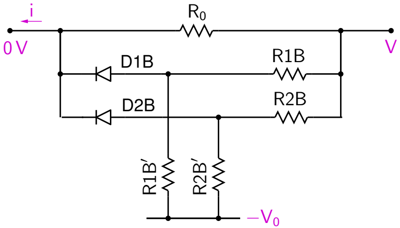


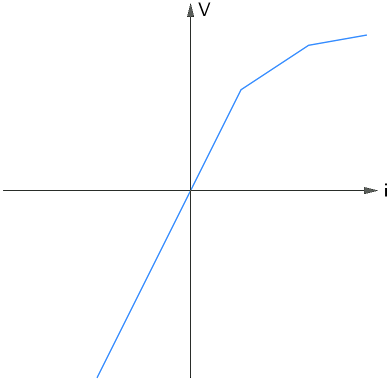


Wave shaping with diodes

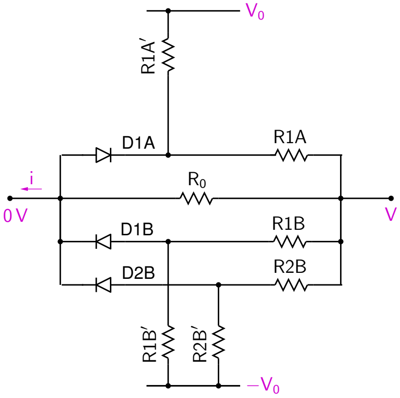


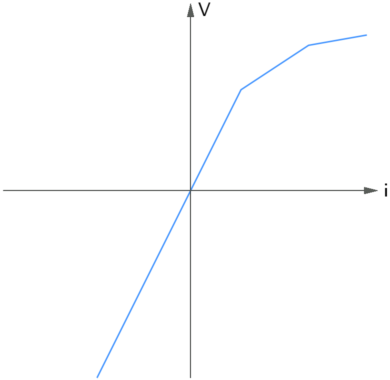



i
R0
0 V
V
D1B
R1B
D2B
R2B
R1B′
R2B′
−V0

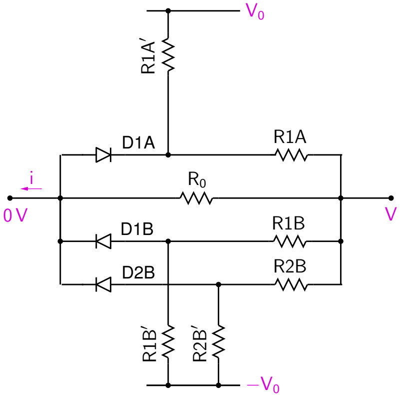

V
i

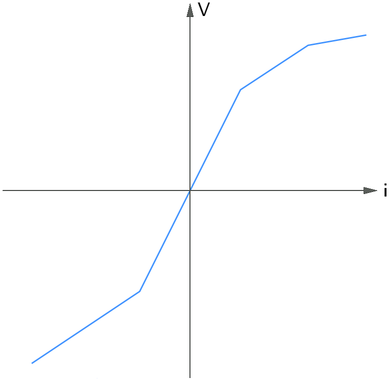
Wave shaping with diodes



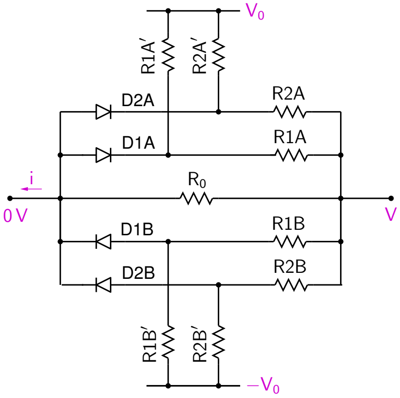


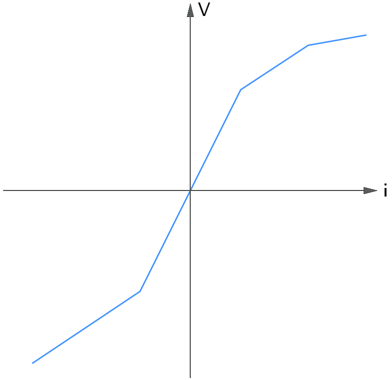
Wave shaping with diodes

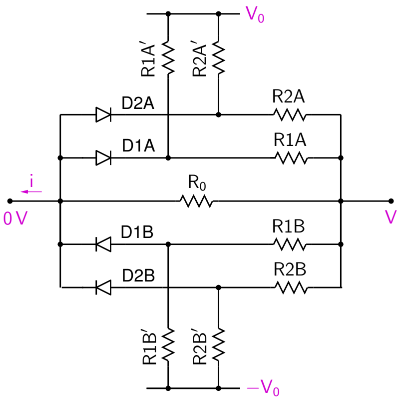


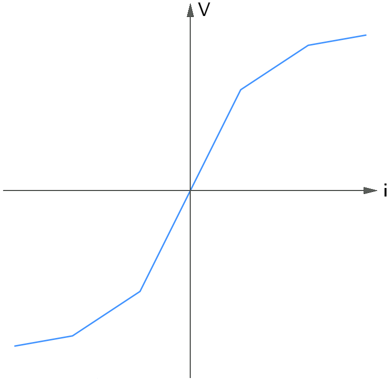


Wave shaping with diodes



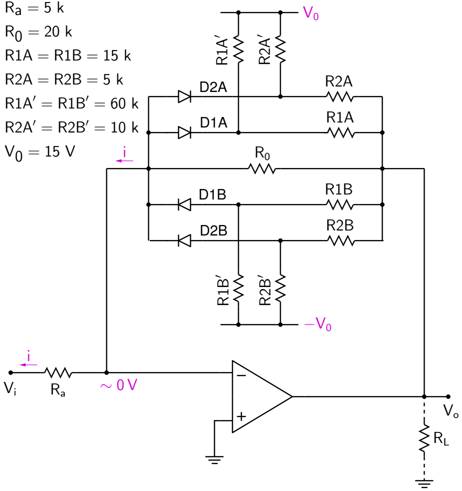


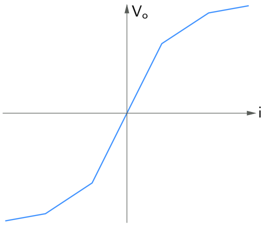

V0
R1A′
R2A′
D2A
R2A
D1A
R1A
i
R0
0 V
V
D1B
R1B
D2B
R2B
R1B′
R2B′
−V0


V
i

Wave shaping with diodes

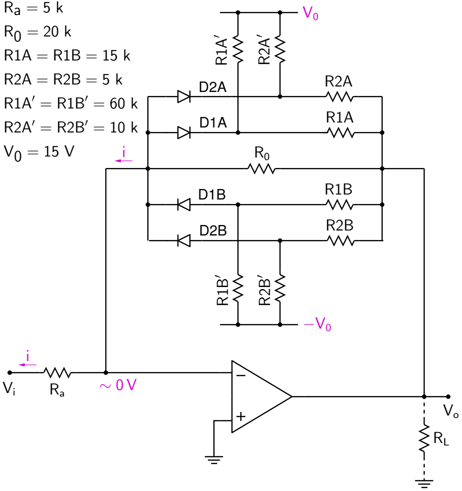
$R_a = 5$ k
$R_0 = 20$ k
$R1A = R1B = 15$ k
$R2A = R2B = 5$ k
$R1A' = R1B' = 60$ k
$R2A' = R2B' = 10$ k
$V_0 = 15$ V

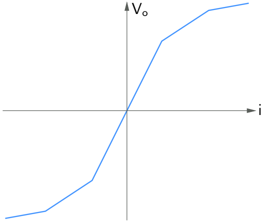




Wave shaping with diodes

$R_a = 5$ 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

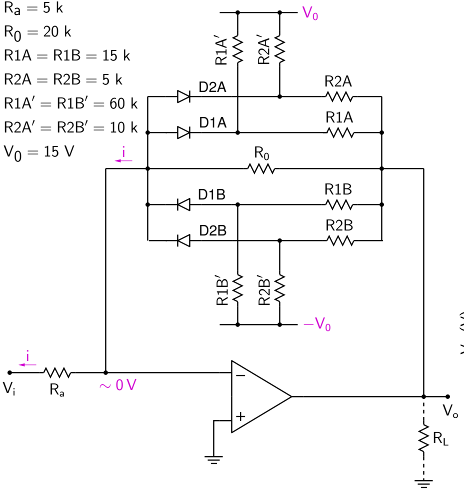


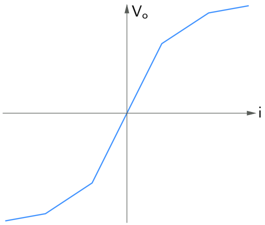


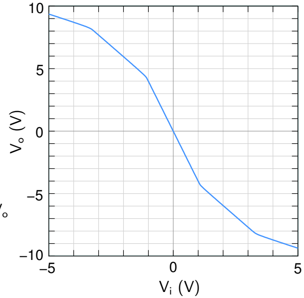
Since $V_i = -R_a i$, the V_o versus V_i plot is similar to the V versus i plot, except for the $(-R_a)$ factor.

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

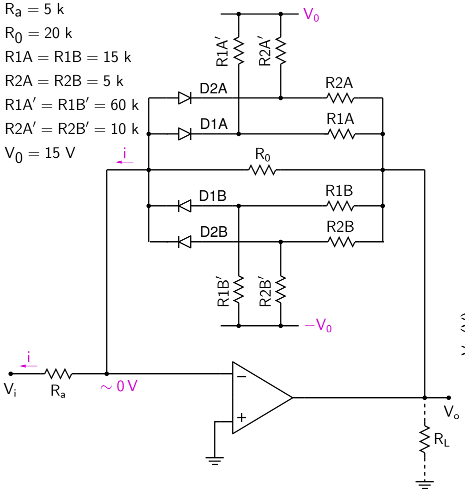


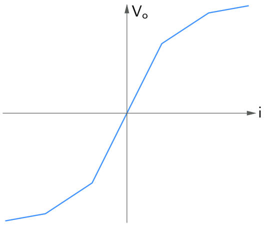


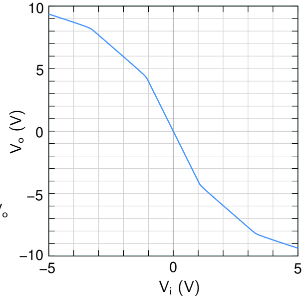


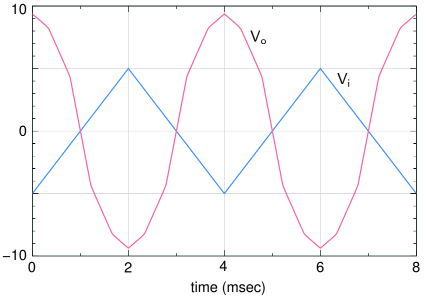
Since $V_i = -R_a i$, the V_o versus V_i plot is similar to the V versus i plot, except for the $(-R_a)$ factor.

Wave shaping with diodes





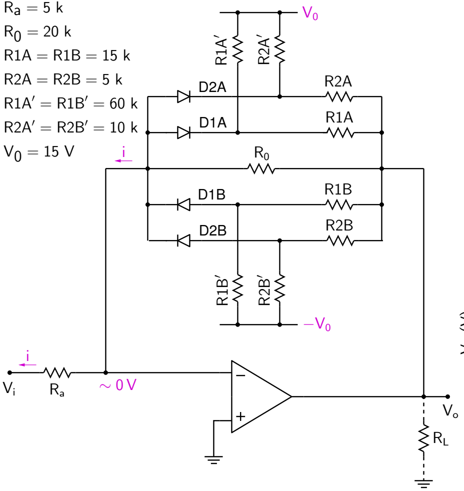


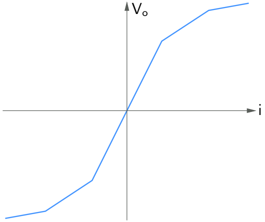


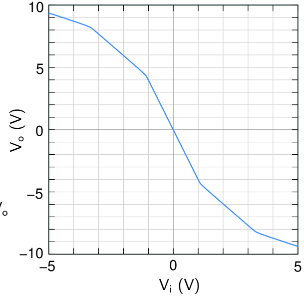
Since $V_i = -R_a i$, the V_o versus V_i plot is similar to the V versus i plot, except for the $(-R_a)$ factor.

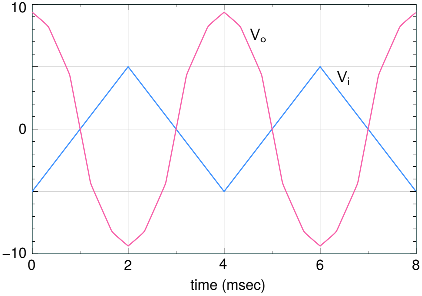
Wave shaping with diodes

$R_a = 5$ 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





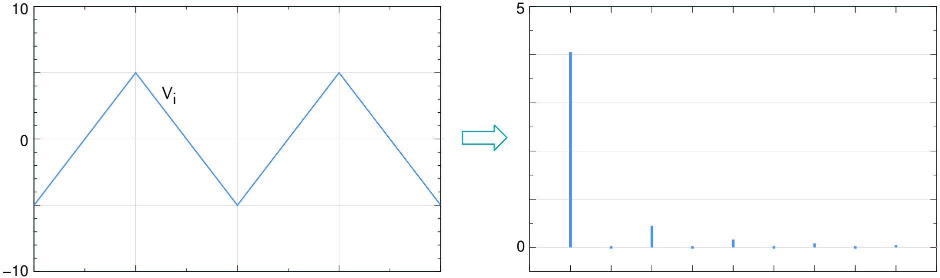




Since $V_i = -R_a i$, the V_o versus V_i plot is similar to the V versus i plot, except for the $(-R_a)$ factor.

SEQUEL file: `ee101_wave_shaper.sqproj`

Wave shaping with diodes: spectrum



Wave shaping with diodes: spectrum