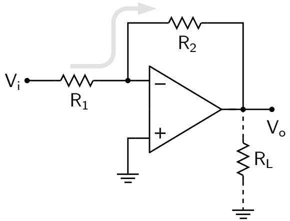
Feedback: inverting amplifier

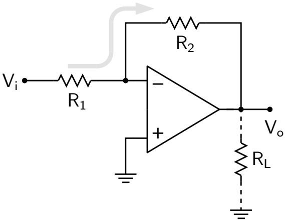


$$V_o = A_V(V_+ - V_-) \quad (1)$$

Since the Op Amp has a high input resistance,
$i_{R1} = i_{R2}$, and we get,

$$V_- = V_i \frac{R_2}{R_1 + R_2} + V_o \frac{R_1}{R_1 + R_2} \quad (2)$$

Feedback: inverting amplifier



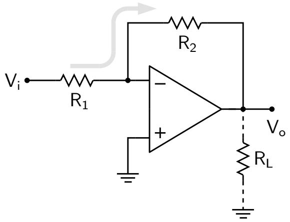
$$V_o = A_V(V_+ - V_-) \quad (1)$$

Since the Op Amp has a high input resistance,
$i_{R1} = i_{R2}$, and we get,

$$V_- = V_i \frac{R_2}{R_1 + R_2} + V_o \frac{R_1}{R_1 + R_2} \quad (2)$$

$$V_i \uparrow \xrightarrow[\text{Eq. 2}]{} V_- \uparrow \xrightarrow[\text{Eq. 1}]{} V_o \downarrow \xrightarrow[\text{Eq. 2}]{} V_- \downarrow$$

Feedback: inverting amplifier



$$V_o = A_V(V_+ - V_-) \quad (1)$$

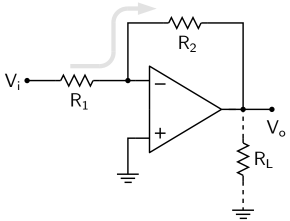
Since the Op Amp has a high input resistance,
$i_{R1} = i_{R2}$, and we get,

$$V_- = V_i \frac{R_2}{R_1 + R_2} + V_o \frac{R_1}{R_1 + R_2} \quad (2)$$

$$V_i \uparrow \xrightarrow[\text{Eq. 2}]{} \boxed{V_- \uparrow} \xrightarrow[\text{Eq. 1}]{} V_o \downarrow \xrightarrow[\text{Eq. 2}]{} \boxed{V_- \downarrow}$$

The circuit reaches a stable equilibrium.

Feedback: inverting amplifier



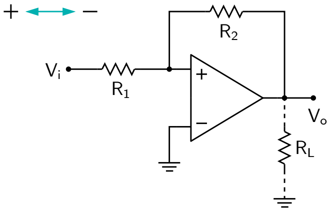
$$V_o = A_V(V_+ - V_-) \quad (1)$$

Since the Op Amp has a high input resistance, $i_{R1} = i_{R2}$, and we get,

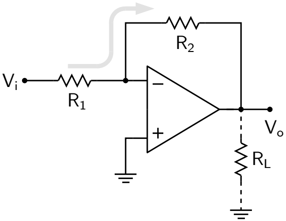
$$V_- = V_i \frac{R_2}{R_1 + R_2} + V_o \frac{R_1}{R_1 + R_2} \quad (2)$$

$$V_i \uparrow \underset{\text{Eq. 2}}{\rightarrow} \boxed{V_- \uparrow} \underset{\text{Eq. 1}}{\rightarrow} V_o \downarrow \underset{\text{Eq. 2}}{\rightarrow} \boxed{V_- \downarrow}$$

The circuit reaches a stable equilibrium.



Feedback: inverting amplifier



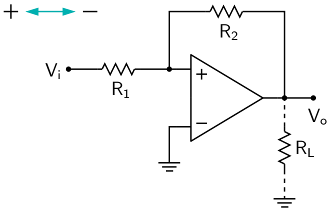
$$V_o = A_V(V_+ - V_-) \quad (1)$$

Since the Op Amp has a high input resistance, $i_{R1} = i_{R2}$, and we get,

$$V_- = V_i \frac{R_2}{R_1 + R_2} + V_o \frac{R_1}{R_1 + R_2} \quad (2)$$

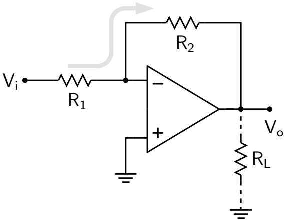
$$V_i \uparrow \underset{\text{Eq. 2}}{\rightarrow} \boxed{V_- \uparrow} \underset{\text{Eq. 1}}{\rightarrow} V_o \downarrow \underset{\text{Eq. 2}}{\rightarrow} \boxed{V_- \downarrow}$$

The circuit reaches a stable equilibrium.



$$V_+ = V_i \frac{R_2}{R_1 + R_2} + V_o \frac{R_1}{R_1 + R_2} \quad (3)$$

Feedback: inverting amplifier



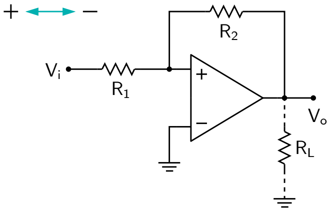
$$V_o = A_V(V_+ - V_-) \qquad (1)$$

Since the Op Amp has a high input resistance, $i_{R1} = i_{R2}$, and we get,

$$V_- = V_i \frac{R_2}{R_1 + R_2} + V_o \frac{R_1}{R_1 + R_2} \qquad (2)$$

$$V_i \uparrow \; \underset{\text{Eq. 2}}{\rightarrow} \; \boxed{V_- \uparrow} \; \underset{\text{Eq. 1}}{\rightarrow} \; V_o \downarrow \; \underset{\text{Eq. 2}}{\rightarrow} \; \boxed{V_- \downarrow}$$

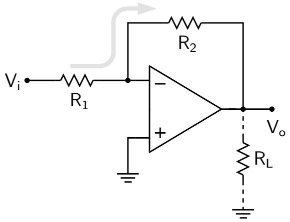
The circuit reaches a stable equilibrium.



$$V_+ = V_i \frac{R_2}{R_1 + R_2} + V_o \frac{R_1}{R_1 + R_2} \qquad (3)$$

$$V_i \uparrow \; \underset{\text{Eq. 3}}{\rightarrow} \; V_+ \uparrow \; \underset{\text{Eq. 1}}{\rightarrow} \; V_o \uparrow \; \underset{\text{Eq. 3}}{\rightarrow} \; V_+ \uparrow$$

Feedback: inverting amplifier



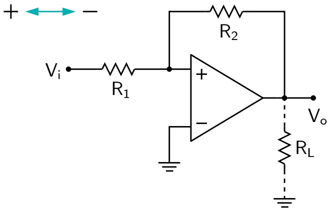
$$V_o = A_V (V_+ - V_-) \quad (1)$$

Since the Op Amp has a high input resistance, $i_{R1} = i_{R2}$, and we get,

$$V_- = V_i \frac{R_2}{R_1 + R_2} + V_o \frac{R_1}{R_1 + R_2} \quad (2)$$

$$V_i \uparrow \xrightarrow[\text{Eq. 2}]{} \boxed{V_- \uparrow} \xrightarrow[\text{Eq. 1}]{} V_o \downarrow \xrightarrow[\text{Eq. 2}]{} \boxed{V_- \downarrow}$$

The circuit reaches a stable equilibrium.

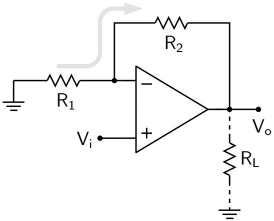


$$V_+ = V_i \frac{R_2}{R_1 + R_2} + V_o \frac{R_1}{R_1 + R_2} \quad (3)$$

$$V_i \uparrow \xrightarrow[\text{Eq. 3}]{} \boxed{V_+ \uparrow} \xrightarrow[\text{Eq. 1}]{} V_o \uparrow \xrightarrow[\text{Eq. 3}]{} \boxed{V_+ \uparrow}$$

We now have a positive feedback situation. As a result, V_o rises (or falls) indefinitely, limited finally by saturation.

Feedback: non-inverting amplifier

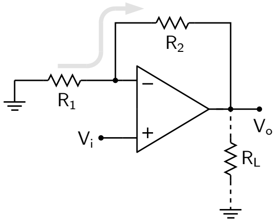


$$V_o = A_V(V_+ - V_-) \quad (1)$$

Since the Op Amp has a high input resistance,
$i_{R1} = i_{R2}$, and we get,

$$V_- = V_o \frac{R_1}{R_1 + R_2} \quad (2)$$

Feedback: non-inverting amplifier



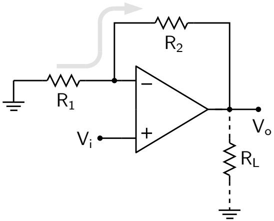
$$V_o = A_V(V_+ - V_-) \quad (1)$$

Since the Op Amp has a high input resistance,
$i_{R1} = i_{R2}$, and we get,

$$V_- = V_o \frac{R_1}{R_1 + R_2} \quad (2)$$

$$V_i \uparrow \ \underset{\text{Eq. 1}}{\rightarrow} \ V_o \uparrow \ \underset{\text{Eq. 2}}{\rightarrow} \ V_- \uparrow \ \underset{\text{Eq. 1}}{\rightarrow} \ V_o \downarrow$$

Feedback: non-inverting amplifier



$$V_o = A_V(V_+ - V_-) \quad (1)$$

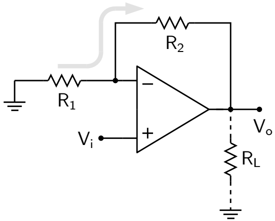
Since the Op Amp has a high input resistance,
$i_{R1} = i_{R2}$, and we get,

$$V_- = V_o \frac{R_1}{R_1 + R_2} \quad (2)$$

$$V_i \uparrow \underset{\text{Eq. 1}}{\rightarrow} \boxed{V_o \uparrow} \underset{\text{Eq. 2}}{\rightarrow} V_- \uparrow \underset{\text{Eq. 1}}{\rightarrow} \boxed{V_o \downarrow}$$

The circuit reaches a stable equilibrium.

Feedback: non-inverting amplifier



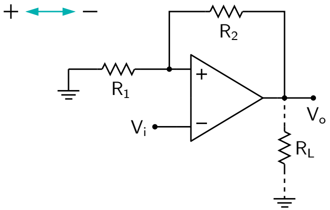
$$V_o = A_V(V_+ - V_-) \quad (1)$$

Since the Op Amp has a high input resistance, $i_{R1} = i_{R2}$, and we get,

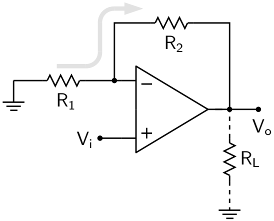
$$V_- = V_o \frac{R_1}{R_1 + R_2} \quad (2)$$

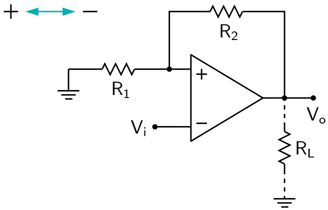
$$V_i \uparrow \underset{\text{Eq. 1}}{\rightarrow} \boxed{V_o \uparrow} \underset{\text{Eq. 2}}{\rightarrow} V_- \uparrow \underset{\text{Eq. 1}}{\rightarrow} \boxed{V_o \downarrow}$$

The circuit reaches a stable equilibrium.



Feedback: non-inverting amplifier





$$V_o = A_V(V_+ - V_-) \qquad (1)$$

Since the Op Amp has a high input resistance, $i_{R1} = i_{R2}$, and we get,

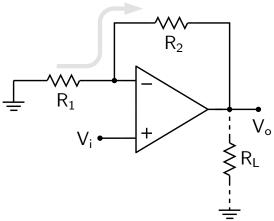
$$V_- = V_o \frac{R_1}{R_1 + R_2} \qquad (2)$$

$$V_i \uparrow \underset{\text{Eq. 1}}{\rightarrow} \boxed{V_o \uparrow} \underset{\text{Eq. 2}}{\rightarrow} V_- \uparrow \underset{\text{Eq. 1}}{\rightarrow} \boxed{V_o \downarrow}$$

The circuit reaches a stable equilibrium.

$$V_+ = V_o \frac{R_1}{R_1 + R_2} \qquad (3)$$

Feedback: non-inverting amplifier



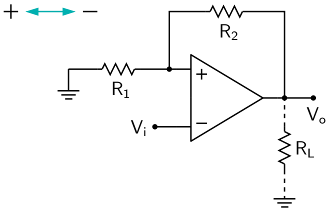
$$V_o = A_V(V_+ - V_-) \quad (1)$$

Since the Op Amp has a high input resistance, $i_{R1} = i_{R2}$, and we get,

$$V_- = V_o \frac{R_1}{R_1 + R_2} \quad (2)$$

$$V_i \uparrow \underset{\text{Eq. 1}}{\rightarrow} \boxed{V_o \uparrow} \underset{\text{Eq. 2}}{\rightarrow} V_- \uparrow \underset{\text{Eq. 1}}{\rightarrow} \boxed{V_o \downarrow}$$

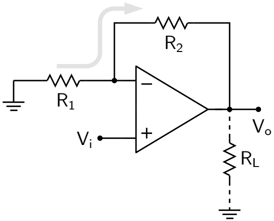
The circuit reaches a stable equilibrium.



$$V_+ = V_o \frac{R_1}{R_1 + R_2} \quad (3)$$

$$V_i \uparrow \underset{\text{Eq. 1}}{\rightarrow} V_o \downarrow \underset{\text{Eq. 3}}{\rightarrow} V_+ \downarrow \underset{\text{Eq. 1}}{\rightarrow} V_o \downarrow$$

Feedback: non-inverting amplifier



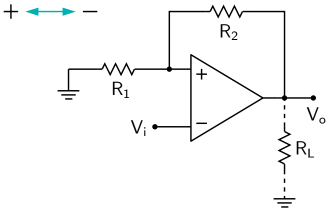
$$V_o = A_V(V_+ - V_-) \qquad (1)$$

Since the Op Amp has a high input resistance, $i_{R1} = i_{R2}$, and we get,

$$V_- = V_o \frac{R_1}{R_1 + R_2} \qquad (2)$$

$$V_i \uparrow \xrightarrow[\text{Eq. 1}]{} \boxed{V_o \uparrow} \xrightarrow[\text{Eq. 2}]{} V_- \uparrow \xrightarrow[\text{Eq. 1}]{} \boxed{V_o \downarrow}$$

The circuit reaches a stable equilibrium.

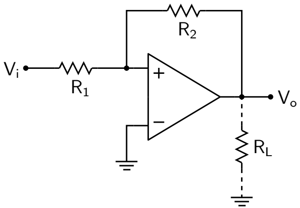


$$V_+ = V_o \frac{R_1}{R_1 + R_2} \qquad (3)$$

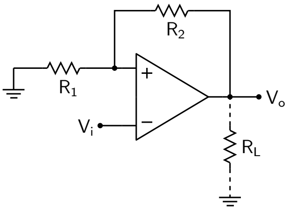
$$V_i \uparrow \xrightarrow[\text{Eq. 1}]{} \boxed{V_o \downarrow} \xrightarrow[\text{Eq. 3}]{} V_+ \downarrow \xrightarrow[\text{Eq. 1}]{} \boxed{V_o \downarrow}$$

We now have a positive feedback situation. As a result, V_o rises (or falls) indefinitely, limited finally by saturation.

Inverting amplifier with $+ \longleftrightarrow -$

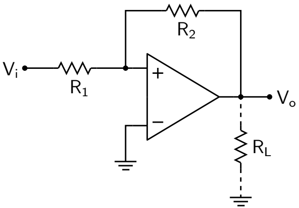


Non-inverting amplifier with $+ \longleftrightarrow -$

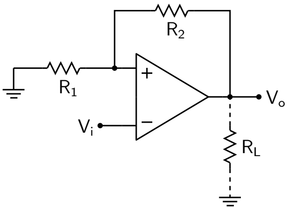


Feedback

Inverting amplifier with $+ \longleftrightarrow -$



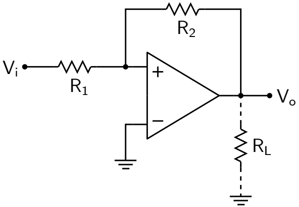
Non-inverting amplifier with $+ \longleftrightarrow -$



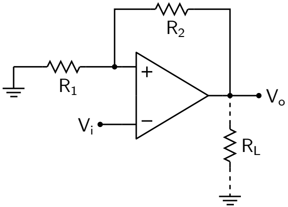
∗ Because of positive feedback, both of these circuits are unstable.

Feedback

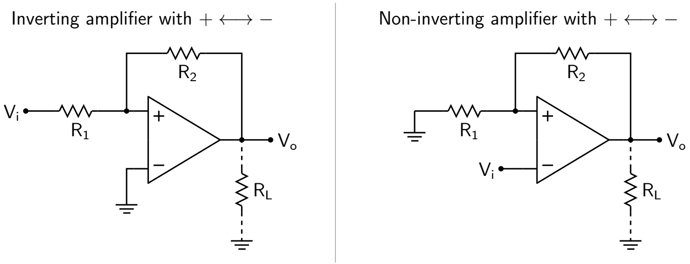
Inverting amplifier with $+ \longleftrightarrow -$



Non-inverting amplifier with $+ \longleftrightarrow -$

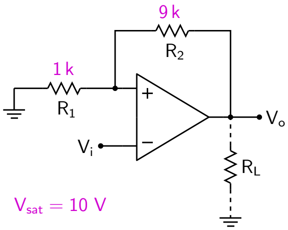


* Because of positive feedback, both of these circuits are unstable.
* The output at any time is only limited by saturation of the op-amp, i.e., $V_o = \pm V_{\mathrm{sat}}$.



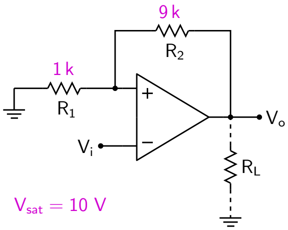
* Because of positive feedback, both of these circuits are unstable.
* The output at any time is only limited by saturation of the op-amp, i.e., $V_o = \pm V_{\text{sat}}$.
* Of what use is a circuit that is stuck at $V_o = \pm V_{\text{sat}}$? It turns out that these circuits are actually useful! Let us see how.

Inverting Schmitt trigger



$V_{sat} = 10$ V

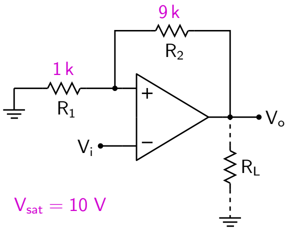
Because of positive feedback, V_o can only be $+V_{\text{sat}}$ (if $V_+ > V_-$) or $-V_{\text{sat}}$ (if $V_+ < V_-$).



Because of positive feedback, V_o can only be $+V_{\text{sat}}$ (if $V_+ > V_-$) or $-V_{\text{sat}}$ (if $V_+ < V_-$).

Consider $V_i = 5\ V$.

Inverting Schmitt trigger



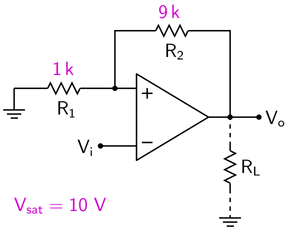
Because of positive feedback, V_o can only be $+V_{\text{sat}}$ (if $V_+ > V_-$) or $-V_{\text{sat}}$ (if $V_+ < V_-$).

Consider $V_i = 5\ V$.

Case (i): $V_o = +V_{\text{sat}} = +10\,\text{V} \rightarrow V_+ = \dfrac{R_1}{R_1 + R_2} V_o = \dfrac{1\,\text{k}}{1\,\text{k} + 9\,\text{k}}\, 10\,\text{V} = 1\,\text{V}$.

$$(V_+ - V_-) = (1 - 5) = -4\,\text{V} \rightarrow V_o = -V_{\text{sat}}\,.$$

Inverting Schmitt trigger



Because of positive feedback, V_o can only be $+V_{\text{sat}}$ (if $V_+ > V_-$) or $-V_{\text{sat}}$ (if $V_+ < V_-$).

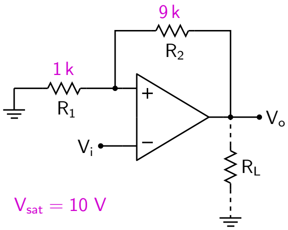
Consider $V_i = 5\,V$.

Case (i): $V_o = +V_{\text{sat}} = +10\,\text{V} \rightarrow V_+ = \dfrac{R_1}{R_1 + R_2} V_o = \dfrac{1\,\text{k}}{1\,\text{k} + 9\,\text{k}}\, 10\,\text{V} = 1\,\text{V}$.

$(V_+ - V_-) = (1 - 5) = -4\,\text{V} \rightarrow V_o = -V_{\text{sat}}$.

This is inconsistent with our assumption ($V_o = +V_{\text{sat}}$).

Inverting Schmitt trigger



Because of positive feedback, V_o can only be $+V_{\text{sat}}$ (if $V_+ > V_-$) or $-V_{\text{sat}}$ (if $V_+ < V_-$).

Consider $V_i = 5\ V$.

Case (i): $V_o = +V_{\text{sat}} = +10\,\text{V} \rightarrow V_+ = \dfrac{R_1}{R_1 + R_2} V_o = \dfrac{1\,\text{k}}{1\,\text{k} + 9\,\text{k}}\, 10\,\text{V} = 1\,\text{V}\,.$

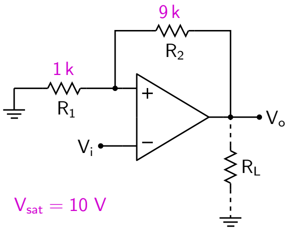
$(V_+ - V_-) = (1 - 5) = -4\,\text{V} \rightarrow V_o = -V_{\text{sat}}\,.$

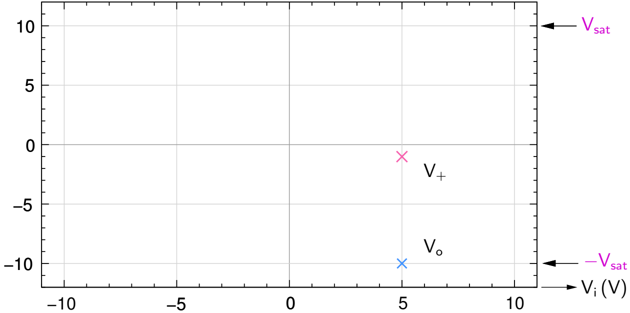
This is inconsistent with our assumption ($V_o = +V_{\text{sat}}$).

Case (ii): $V_o = -V_{\text{sat}} = -10\,\text{V} \rightarrow V_+ = \dfrac{R_1}{R_1 + R_2} V_o = \dfrac{1\,\text{k}}{1\,\text{k} + 9\,\text{k}} \times (-10\,\text{V}) = -1\,\text{V}\,.$

$(V_+ - V_-) = (-1 - 5) = -6\,\text{V} \rightarrow V_o = -V_{\text{sat}}$ (consistent)

Inverting Schmitt trigger





Because of positive feedback, V_o can only be $+V_{\mathrm{sat}}$ (if $V_+ > V_-$) or $-V_{\mathrm{sat}}$ (if $V_+ < V_-$).

Consider $V_i = 5\,V$.

Case (i): $V_o = +V_{\mathrm{sat}} = +10\,\mathrm{V} \rightarrow V_+ = \dfrac{R_1}{R_1 + R_2} V_o = \dfrac{1\,\mathrm{k}}{1\,\mathrm{k} + 9\,\mathrm{k}}\, 10\,\mathrm{V} = 1\,\mathrm{V}\,.$

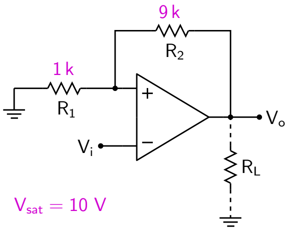
$(V_+ - V_-) = (1 - 5) = -4\,\mathrm{V} \rightarrow V_o = -V_{\mathrm{sat}}\,.$

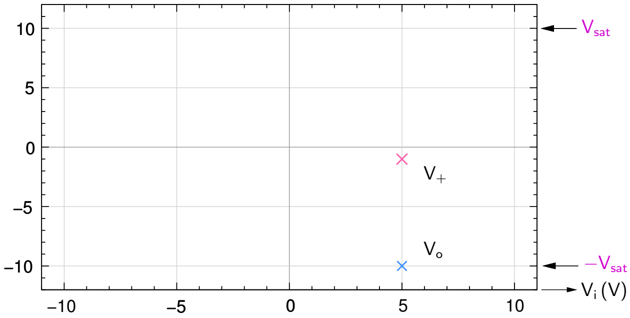
This is inconsistent with our assumption ($V_o = +V_{\mathrm{sat}}$).

Case (ii): $V_o = -V_{\mathrm{sat}} = -10\,\mathrm{V} \rightarrow V_+ = \dfrac{R_1}{R_1 + R_2} V_o = \dfrac{1\,\mathrm{k}}{1\,\mathrm{k} + 9\,\mathrm{k}} \times (-10\,\mathrm{V}) = -1\,\mathrm{V}\,.$

$(V_+ - V_-) = (-1 - 5) = -6\,\mathrm{V} \rightarrow V_o = -V_{\mathrm{sat}}$ (consistent)

Inverting Schmitt trigger





Because of positive feedback, V_o can only be $+V_{\text{sat}}$ (if $V_+ > V_-$) or $-V_{\text{sat}}$ (if $V_+ < V_-$).

Consider $V_i = 5\ V$.

Case (i): $V_o = +V_{\text{sat}} = +10\,\text{V} \rightarrow V_+ = \dfrac{R_1}{R_1 + R_2} V_o = \dfrac{1\,\text{k}}{1\,\text{k} + 9\,\text{k}}\, 10\,\text{V} = 1\,\text{V}$.

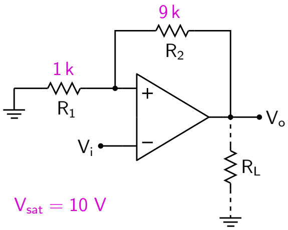
$(V_+ - V_-) = (1 - 5) = -4\,\text{V} \rightarrow V_o = -V_{\text{sat}}$.

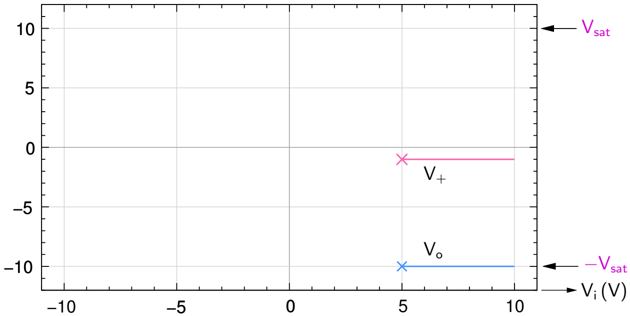
This is inconsistent with our assumption ($V_o = +V_{\text{sat}}$).

Case (ii): $V_o = -V_{\text{sat}} = -10\,\text{V} \rightarrow V_+ = \dfrac{R_1}{R_1 + R_2} V_o = \dfrac{1\,\text{k}}{1\,\text{k} + 9\,\text{k}} \times (-10\,\text{V}) = -1\,\text{V}$.

$(V_+ - V_-) = (-1 - 5) = -6\,\text{V} \rightarrow V_o = -V_{\text{sat}}$ (consistent)

If we move to the right (increasing V_i), the same situation applies, i.e., $V_o = -V_{\text{sat}}$.





Because of positive feedback, V_o can only be $+V_{\rm sat}$ (if $V_+ > V_-$) or $-V_{\rm sat}$ (if $V_+ < V_-$).

Consider $V_i = 5\ V$.

Case (i): $V_o = +V_{\rm sat} = +10\,{\rm V} \rightarrow V_+ = \dfrac{R_1}{R_1 + R_2}V_o = \dfrac{1\,{\rm k}}{1\,{\rm k} + 9\,{\rm k}}\,10\,{\rm V} = 1\,{\rm V}$.

$(V_+ - V_-) = (1 - 5) = -4\,{\rm V} \rightarrow V_o = -V_{\rm sat}$.

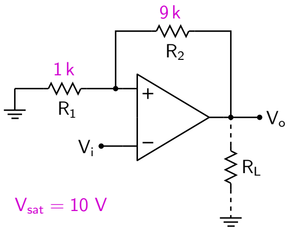
This is inconsistent with our assumption ($V_o = +V_{\rm sat}$).

Case (ii): $V_o = -V_{\rm sat} = -10\,{\rm V} \rightarrow V_+ = \dfrac{R_1}{R_1 + R_2}V_o = \dfrac{1\,{\rm k}}{1\,{\rm k} + 9\,{\rm k}} \times (-10\,{\rm V}) = -1\,{\rm V}$.

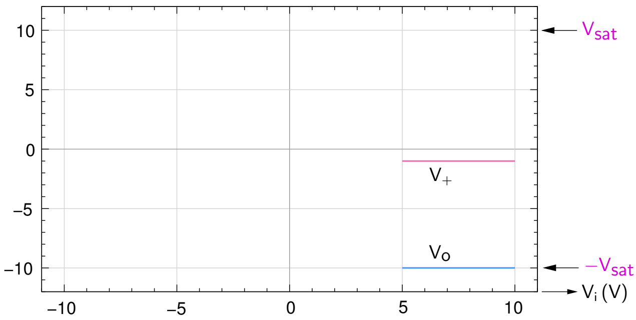
$(V_+ - V_-) = (-1 - 5) = -6\,{\rm V} \rightarrow V_o = -V_{\rm sat}$ (consistent)

If we move to the right (increasing V_i), the same situation applies, i.e., $V_o = -V_{\rm sat}$.

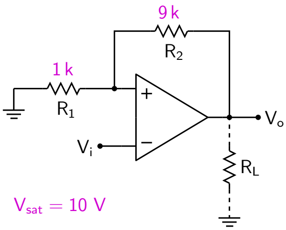
Inverting Schmitt trigger



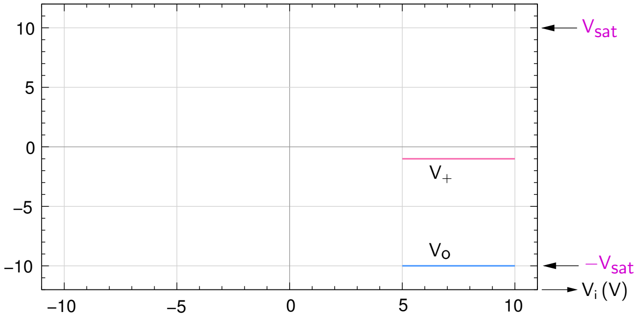
$V_{sat} = 10$ V



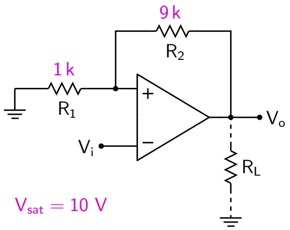
Inverting Schmitt trigger

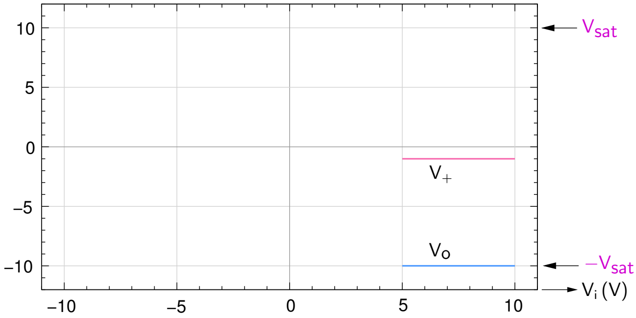


$V_{sat} = 10$ V



Consider decreasing values of V_i.

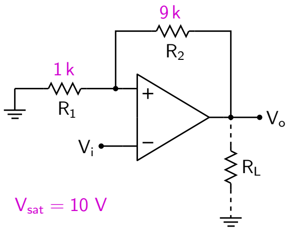


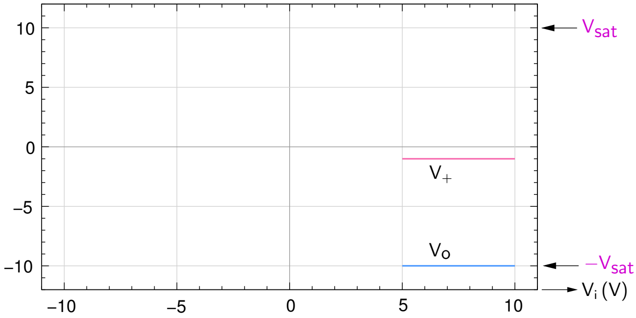


Consider decreasing values of V_i.

$$V_+ = \frac{R_1}{R_1 + R_2} V_o = \frac{1\,\mathrm{k}}{10\,\mathrm{k}} (-V_{\mathrm{sat}}) = -1\ V\ .$$

Inverting Schmitt trigger



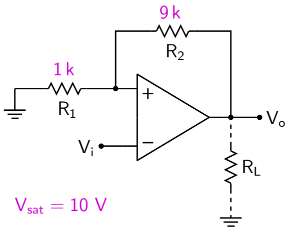


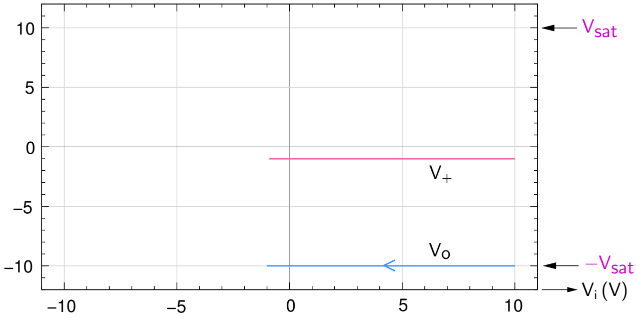
Consider decreasing values of V_i.

$$V_+ = \frac{R_1}{R_1 + R_2} V_o = \frac{1\,\text{k}}{10\,\text{k}}(-V_{\text{sat}}) = -1\,V\,.$$

As long as $V_i = V_- > V_+ = -1\,V$, V_o remains at $-V_{\text{sat}}$.

Inverting Schmitt trigger



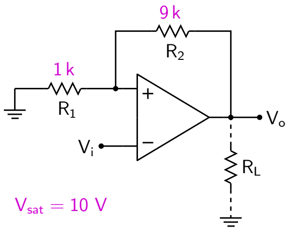


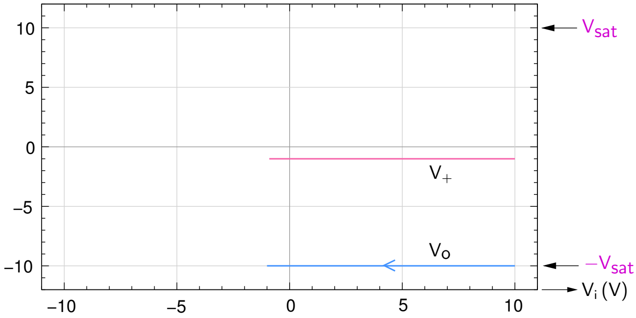
Consider decreasing values of V_i.

$$V_+ = \frac{R_1}{R_1 + R_2} V_o = \frac{1\,\text{k}}{10\,\text{k}} (-V_{\text{sat}}) = -1\ V\ .$$

As long as $V_i = V_- > V_+ = -1\ V$, V_o remains at $-V_{\text{sat}}$.

Inverting Schmitt trigger





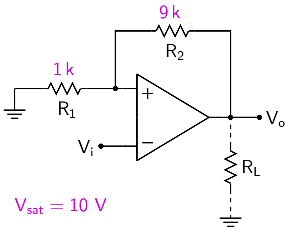
Consider decreasing values of V_i.

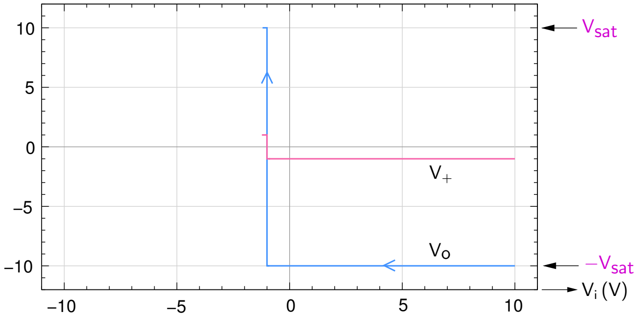
$$V_+ = \frac{R_1}{R_1 + R_2} V_o = \frac{1\text{ k}}{10\text{ k}}(-V_{\text{sat}}) = -1\ V\ .$$

As long as $V_i = V_- > V_+ = -1\ V$, V_o remains at $-V_{\text{sat}}$.

When $V_i < V_+ = -1\ V$, V_o changes sign, i.e., $V_o = +V_{\text{sat}}$.

Inverting Schmitt trigger



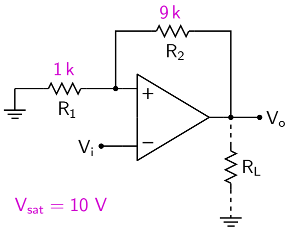


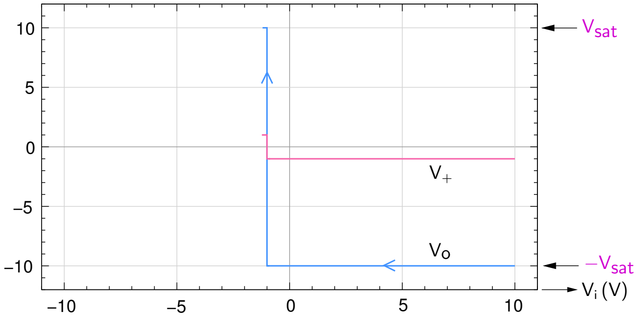
Consider decreasing values of V_i.

$$V_+ = \frac{R_1}{R_1 + R_2} V_o = \frac{1\text{ k}}{10\text{ k}}(-V_{\text{sat}}) = -1\ V\ .$$

As long as $V_i = V_- > V_+ = -1\ V$, V_o remains at $-V_{\text{sat}}$.

When $V_i < V_+ = -1\ V$, V_o changes sign, i.e., $V_o = +V_{\text{sat}}$.





Consider decreasing values of V_i.

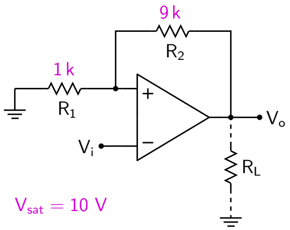
$$V_+ = \frac{R_1}{R_1 + R_2} V_o = \frac{1\ \mathrm{k}}{10\ \mathrm{k}} (-V_{\mathrm{sat}}) = -1\ V\ .$$

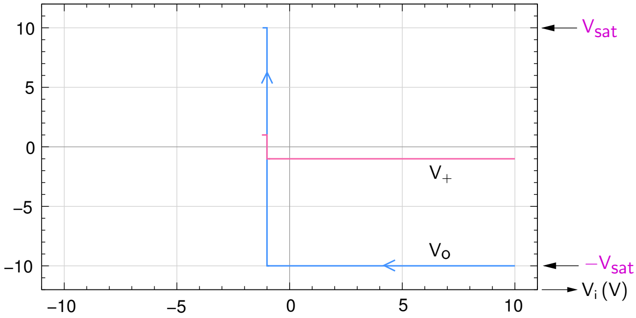
As long as $V_i = V_- > V_+ = -1\ V$, V_o remains at $-V_{\mathrm{sat}}$.

When $V_i < V_+ = -1\ V$, V_o changes sign, i.e., $V_o = +V_{\mathrm{sat}}$.

V_+ now becomes $\dfrac{R_1}{R_1 + R_2}(+V_{\mathrm{sat}}) = +1\ V$.

Inverting Schmitt trigger





Consider decreasing values of V_i.

$$V_+ = \frac{R_1}{R_1 + R_2} V_o = \frac{1\text{ k}}{10\text{ k}}(-V_{\text{sat}}) = -1\ V\ .$$

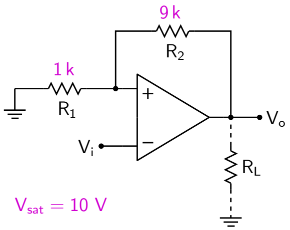
As long as $V_i = V_- > V_+ = -1\ V$, V_o remains at $-V_{\text{sat}}$.

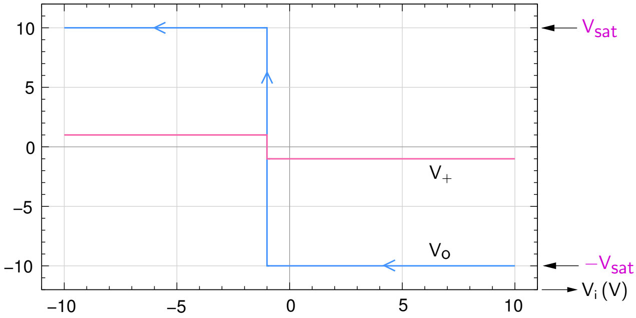
When $V_i < V_+ = -1\ V$, V_o changes sign, i.e., $V_o = +V_{\text{sat}}$.

V_+ now becomes $\dfrac{R_1}{R_1 + R_2}(+V_{\text{sat}}) = +1\ V\ .$

Decreasing V_i further makes no difference to V_o (since $V_i = V_- < V_+ = +1\ V$ holds).

Inverting Schmitt trigger





Consider decreasing values of V_i.

$$V_+ = \frac{R_1}{R_1 + R_2} V_o = \frac{1\,\mathrm{k}}{10\,\mathrm{k}}(-V_{\mathrm{sat}}) = -1\ V\ .$$

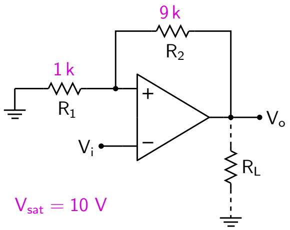
As long as $V_i = V_- > V_+ = -1\ V$, V_o remains at $-V_{\mathrm{sat}}$.

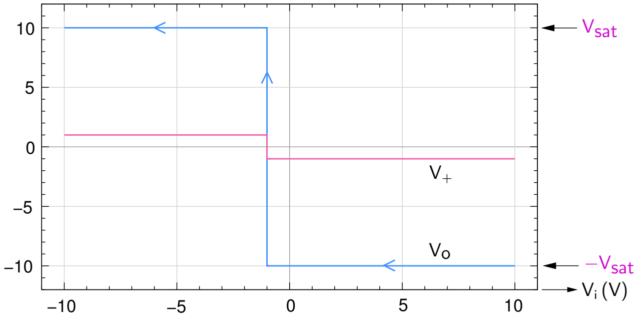
When $V_i < V_+ = -1\ V$, V_o changes sign, i.e., $V_o = +V_{\mathrm{sat}}$.

V_+ now becomes $\dfrac{R_1}{R_1 + R_2}(+V_{\mathrm{sat}}) = +1\ V\ .$

Decreasing V_i further makes no difference to V_o (since $V_i = V_- < V_+ = +1\ V$ holds).

Inverting Schmitt trigger





Consider decreasing values of V_i.

$$V_+ = \frac{R_1}{R_1 + R_2} V_o = \frac{1\text{ k}}{10\text{ k}} (-V_{\text{sat}}) = -1\ V\ .$$

As long as $V_i = V_- > V_+ = -1\ V$, V_o remains at $-V_{\text{sat}}$.

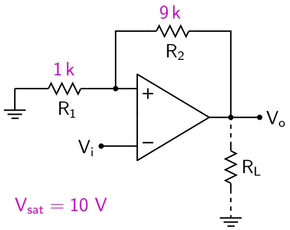
When $V_i < V_+ = -1\ V$, V_o changes sign, i.e., $V_o = +V_{\text{sat}}$.

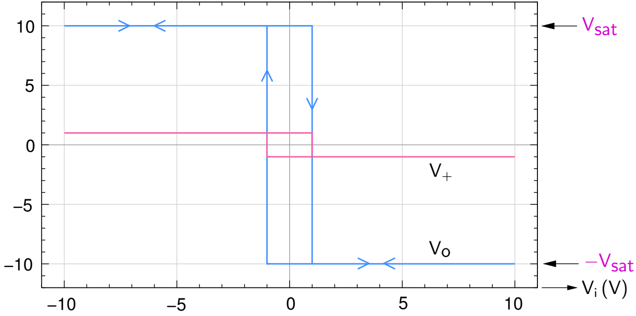
V_+ now becomes $\dfrac{R_1}{R_1 + R_2} (+V_{\text{sat}}) = +1\ V\ .$

Decreasing V_i further makes no difference to V_o (since $V_i = V_- < V_+ = +1\ V$ holds).

Now, the threshold at which V_o flips is $V_i = +1\ V$.

Inverting Schmitt trigger





Consider decreasing values of V_i.

$$V_+ = \frac{R_1}{R_1 + R_2} V_o = \frac{1\text{ k}}{10\text{ k}}(-V_{\text{sat}}) = -1\ V\,.$$

As long as $V_i = V_- > V_+ = -1\ V$, V_o remains at $-V_{\text{sat}}$.

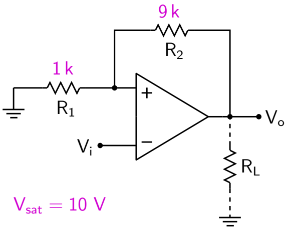
When $V_i < V_+ = -1\ V$, V_o changes sign, i.e., $V_o = +V_{\text{sat}}$.

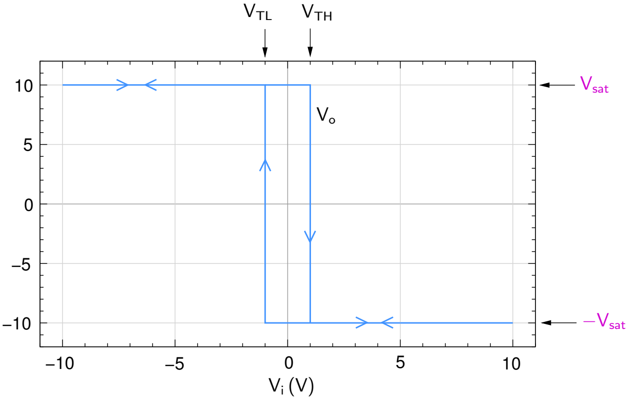
V_+ now becomes $\dfrac{R_1}{R_1 + R_2}(+V_{\text{sat}}) = +1\ V\,.$

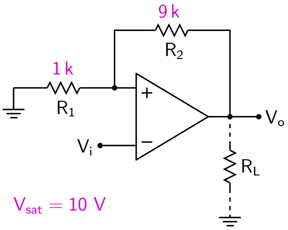
Decreasing V_i further makes no difference to V_o (since $V_i = V_- < V_+ = +1\ V$ holds).

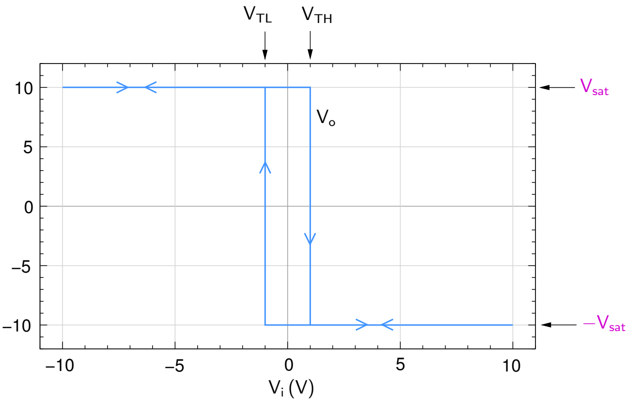
Now, the threshold at which V_o flips is $V_i = +1\ V$.

Inverting Schmitt trigger



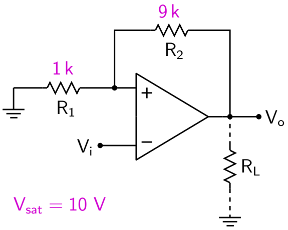


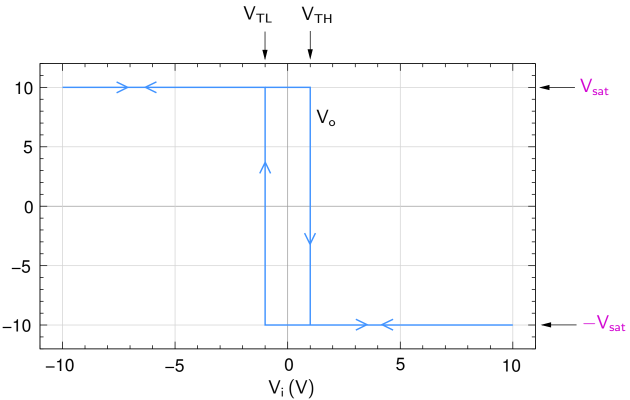




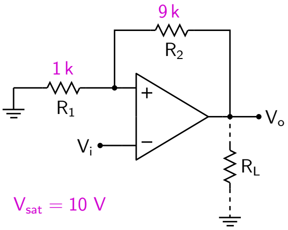
* The threshold values (or "tripping points"), V_{TH} and V_{TL}, are given by $\pm \left(\dfrac{R_1}{R_1 + R_2} \right) V_{sat}$.

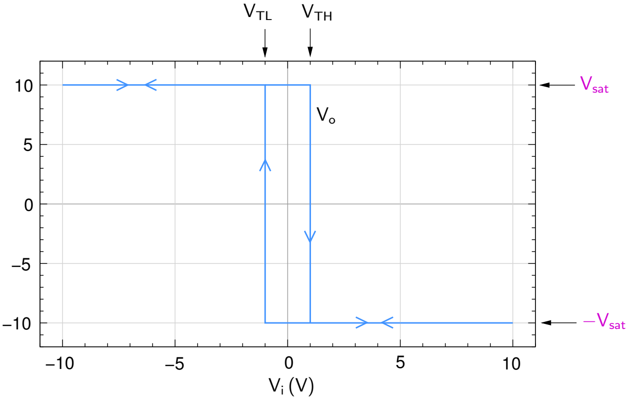
Inverting Schmitt trigger





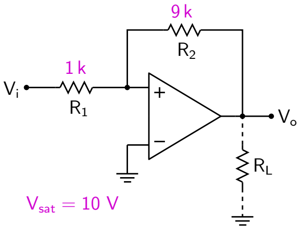
* The threshold values (or "tripping points"), V_{TH} and V_{TL}, are given by $\pm\left(\dfrac{R_1}{R_1+R_2}\right)V_{sat}$.
* The tripping point (whether V_{TH} or V_{TL}) depends on where we are on the V_o axis. In that sense, the circuit has a memory.





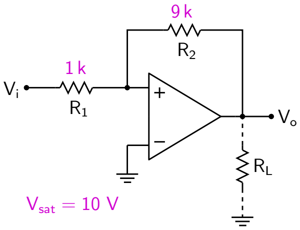
* The threshold values (or "tripping points"), V_{TH} and V_{TL}, are given by $\pm\left(\dfrac{R_1}{R_1+R_2}\right)V_{\mathrm{sat}}$.
* The tripping point (whether V_{TH} or V_{TL}) depends on where we are on the V_o axis. In that sense, the circuit has a memory.
* $\Delta V_T = V_{\mathrm{TH}} - V_{\mathrm{TL}}$ is called the "hysteresis width."

Non-inverting Schmitt trigger



Because of positive feedback, V_o can only be $+V_{\text{sat}}$ (for $V_+ > V_-$) or $-V_{\text{sat}}$ (for $V_+ < V_-$).

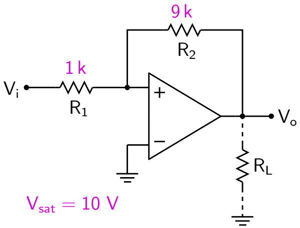
Non-inverting Schmitt trigger



Because of positive feedback, V_o can only be $+V_{\text{sat}}$ (for $V_+ > V_-$) or $-V_{\text{sat}}$ (for $V_+ < V_-$).

Consider $V_i = 5\ V$.

Non-inverting Schmitt trigger



Because of positive feedback, V_o can only be $+V_{\text{sat}}$ (for $V_+ > V_-$) or $-V_{\text{sat}}$ (for $V_+ < V_-$).

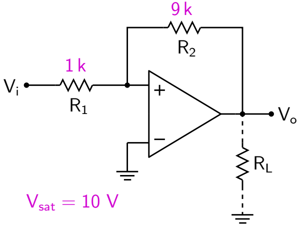
Consider $V_i = 5\ V$.

Case (i): $V_o = -V_{\text{sat}} = -10\ V$

$$\rightarrow V_+ = \frac{R_2}{R_1 + R_2} V_i + \frac{R_1}{R_1 + R_2} V_o = \frac{9\ \text{k}}{10\ \text{k}} \times 5 + \frac{1\ \text{k}}{10\ \text{k}} \times (-10) = 4.5 - 1 = 3.5\ V\,.$$

$$(V_+ - V_-) = (3.5 - 0) = 3.5\ V \rightarrow V_o = +V_{\text{sat}}\,.$$

Non-inverting Schmitt trigger



Because of positive feedback, V_o can only be $+V_{\text{sat}}$ (for $V_+ > V_-$) or $-V_{\text{sat}}$ (for $V_+ < V_-$).

Consider $V_i = 5\ V$.

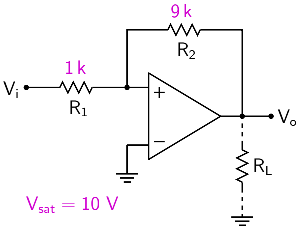
Case (i): $V_o = -V_{\text{sat}} = -10\ V$

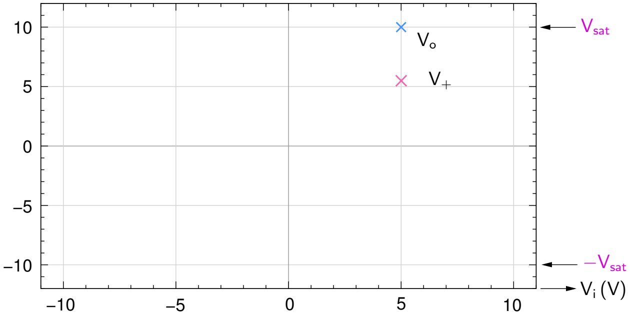
$$\rightarrow V_+ = \frac{R_2}{R_1 + R_2} V_i + \frac{R_1}{R_1 + R_2} V_o = \frac{9\ \text{k}}{10\ \text{k}} \times 5 + \frac{1\ \text{k}}{10\ \text{k}} \times (-10) = 4.5 - 1 = 3.5\ V\,.$$

$(V_+ - V_-) = (3.5 - 0) = 3.5\ V \rightarrow V_o = +V_{\text{sat}}\,.$

This is inconsistent with our assumption ($V_o = -V_{\text{sat}}$).

Non-inverting Schmitt trigger





Because of positive feedback, V_o can only be $+V_{\text{sat}}$ (for $V_+ > V_-$) or $-V_{\text{sat}}$ (for $V_+ < V_-$).

Consider $V_i = 5\ V$.

Case (i): $V_o = -V_{\text{sat}} = -10\ V$

$$\rightarrow V_+ = \frac{R_2}{R_1 + R_2} V_i + \frac{R_1}{R_1 + R_2} V_o = \frac{9\ \text{k}}{10\ \text{k}} \times 5 + \frac{1\ \text{k}}{10\ \text{k}} \times (-10) = 4.5 - 1 = 3.5\ V\,.$$

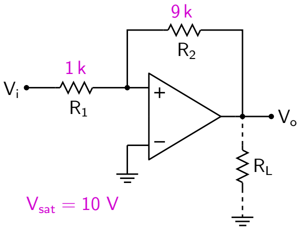
$(V_+ - V_-) = (3.5 - 0) = 3.5\ V \rightarrow V_o = +V_{\text{sat}}\,.$

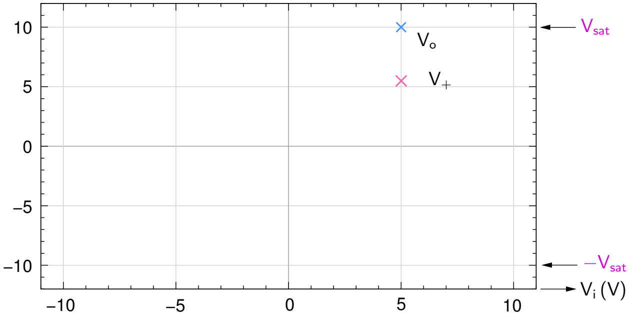
This is inconsistent with our assumption ($V_o = -V_{\text{sat}}$).

Case (ii): $V_o = +V_{\text{sat}} = +10\ V \rightarrow V_+ = \dfrac{9\ \text{k}}{10\ \text{k}} \times 5 + \dfrac{1\ \text{k}}{10\ \text{k}} \times 10 = 4.5 + 1 = 5.5\ V\,.$

$(V_+ - V_-) = (5.5 - 0) = 5.5\ V \rightarrow V_o = +V_{\text{sat}}$ (consistent)

Non-inverting Schmitt trigger





Because of positive feedback, V_o can only be $+V_{\rm sat}$ (for $V_+ > V_-$) or $-V_{\rm sat}$ (for $V_+ < V_-$).

Consider $V_i = 5\ V$.

Case (i): $V_o = -V_{\rm sat} = -10\ V$

$$\rightarrow V_+ = \frac{R_2}{R_1 + R_2} V_i + \frac{R_1}{R_1 + R_2} V_o = \frac{9\ \text{k}}{10\ \text{k}} \times 5 + \frac{1\ \text{k}}{10\ \text{k}} \times (-10) = 4.5 - 1 = 3.5\ V\,.$$

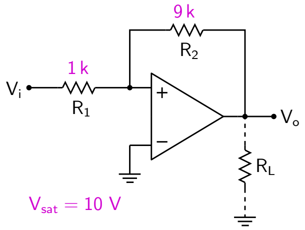
$(V_+ - V_-) = (3.5 - 0) = 3.5\ V \rightarrow V_o = +V_{\rm sat}$.

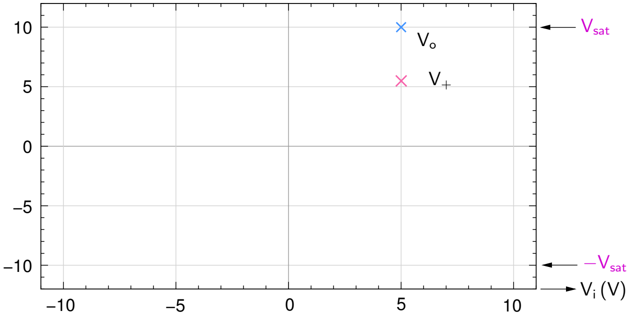
This is inconsistent with our assumption ($V_o = -V_{\rm sat}$).

Case (ii): $V_o = +V_{\rm sat} = +10\ V \rightarrow V_+ = \dfrac{9\ \text{k}}{10\ \text{k}} \times 5 + \dfrac{1\ \text{k}}{10\ \text{k}} \times 10 = 4.5 + 1 = 5.5\ V$.

$(V_+ - V_-) = (5.5 - 0) = 5.5\ V \rightarrow V_o = +V_{\rm sat}$ (consistent)

Non-inverting Schmitt trigger





Because of positive feedback, V_o can only be $+V_{\text{sat}}$ (for $V_+ > V_-$) or $-V_{\text{sat}}$ (for $V_+ < V_-$).

Consider $V_i = 5\ V$.

Case (i): $V_o = -V_{\text{sat}} = -10\ V$

$$\rightarrow V_+ = \frac{R_2}{R_1 + R_2} V_i + \frac{R_1}{R_1 + R_2} V_o = \frac{9\ \text{k}}{10\ \text{k}} \times 5 + \frac{1\ \text{k}}{10\ \text{k}} \times (-10) = 4.5 - 1 = 3.5\ V\,.$$

$(V_+ - V_-) = (3.5 - 0) = 3.5\ V \rightarrow V_o = +V_{\text{sat}}\,.$

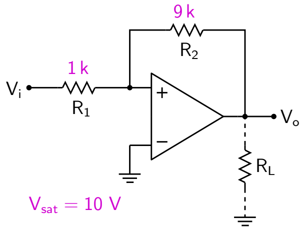
This is inconsistent with our assumption ($V_o = -V_{\text{sat}}$).

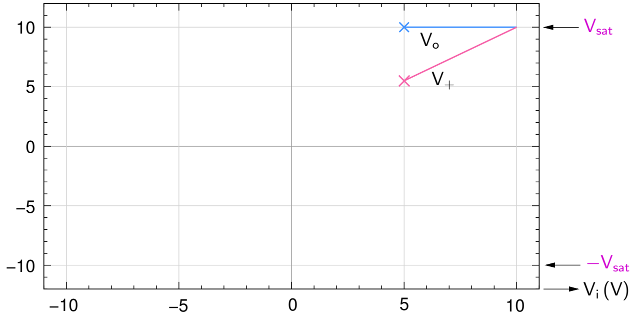
Case (ii): $V_o = +V_{\text{sat}} = +10\ V \rightarrow V_+ = \dfrac{9\ \text{k}}{10\ \text{k}} \times 5 + \dfrac{1\ \text{k}}{10\ \text{k}} \times 10 = 4.5 + 1 = 5.5\ V\,.$

$(V_+ - V_-) = (5.5 - 0) = 5.5\ V \rightarrow V_o = +V_{\text{sat}}$ (consistent)

If we move to the right (increasing V_i), the same situation applies, i.e., $V_o = +V_{\text{sat}}$.

Non-inverting Schmitt trigger





Because of positive feedback, V_o can only be $+V_{\text{sat}}$ (for $V_+ > V_-$) or $-V_{\text{sat}}$ (for $V_+ < V_-$).

Consider $V_i = 5\ V$.

Case (i): $V_o = -V_{\text{sat}} = -10\ V$

$$\rightarrow V_+ = \frac{R_2}{R_1+R_2}V_i + \frac{R_1}{R_1+R_2}V_o = \frac{9\text{ k}}{10\text{ k}}\times 5 + \frac{1\text{ k}}{10\text{ k}}\times(-10) = 4.5 - 1 = 3.5\ V\,.$$

$(V_+ - V_-) = (3.5 - 0) = 3.5\ V \rightarrow V_o = +V_{\text{sat}}$.

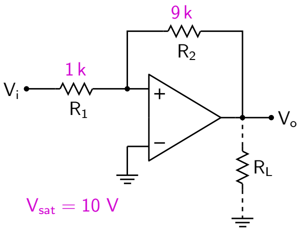
This is inconsistent with our assumption ($V_o = -V_{\text{sat}}$).

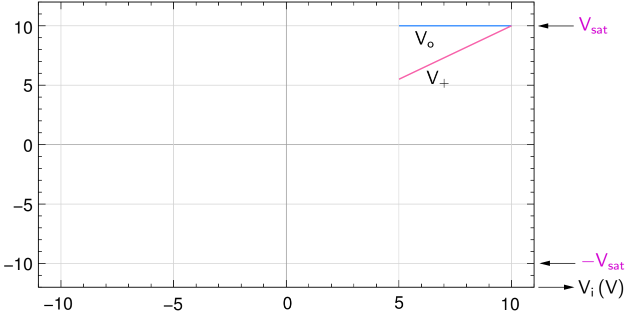
Case (ii): $V_o = +V_{\text{sat}} = +10\ V \rightarrow V_+ = \dfrac{9\text{ k}}{10\text{ k}}\times 5 + \dfrac{1\text{ k}}{10\text{ k}}\times 10 = 4.5 + 1 = 5.5\ V$.

$(V_+ - V_-) = (5.5 - 0) = 5.5\ V \rightarrow V_o = +V_{\text{sat}}$ (consistent)

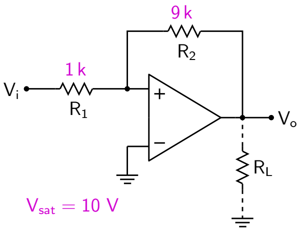
If we move to the right (increasing V_i), the same situation applies, i.e., $V_o = +V_{\text{sat}}$.

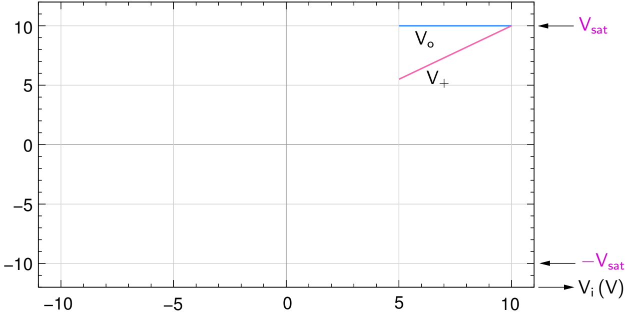
Non-inverting Schmitt trigger





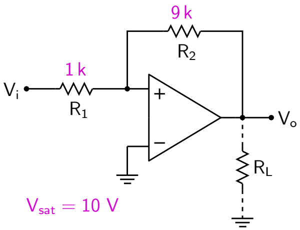
Non-inverting Schmitt trigger

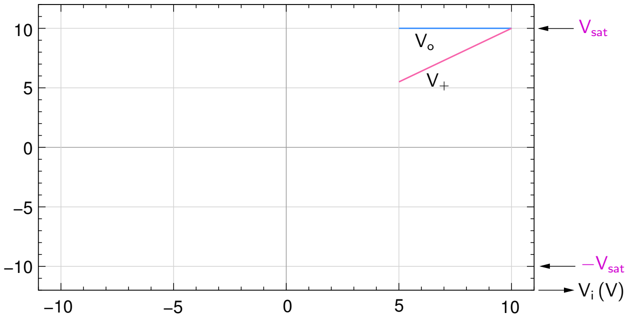




Consider decreasing values of V_i.

Non-inverting Schmitt trigger

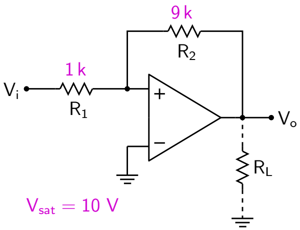


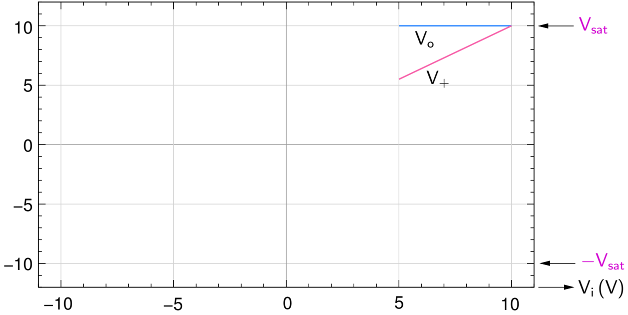


Consider decreasing values of V_i.

$$V_+ = \frac{R_2}{R_1 + R_2} V_i + \frac{R_1}{R_1 + R_2} V_o = \frac{9\,\text{k}}{10\,\text{k}} V_i + \frac{1\,\text{k}}{10\,\text{k}} V_o \,.$$

Non-inverting Schmitt trigger



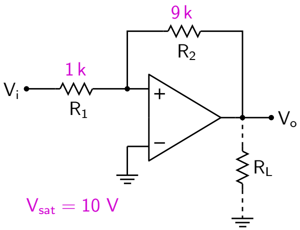


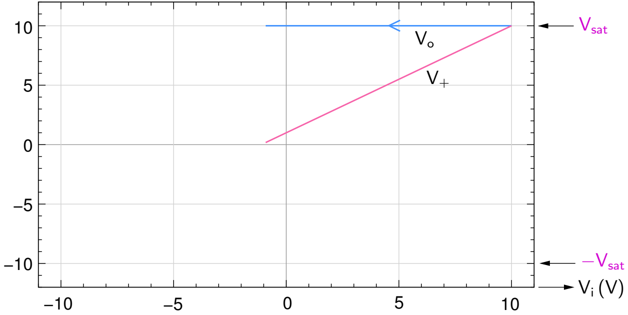
Consider decreasing values of V_i.

$$V_+ = \frac{R_2}{R_1 + R_2} V_i + \frac{R_1}{R_1 + R_2} V_o = \frac{9\,\text{k}}{10\,\text{k}} V_i + \frac{1\,\text{k}}{10\,\text{k}} V_o\,.$$

As long as $V_+ > 0\ V$, V_o remains at $+V_{\text{sat}}$.

Non-inverting Schmitt trigger



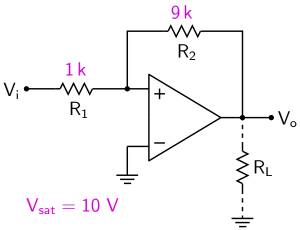


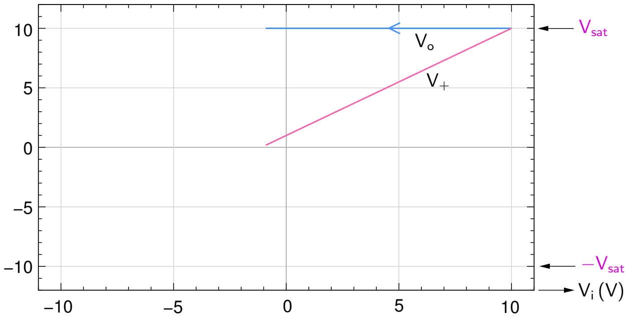
Consider decreasing values of V_i.

$$V_+ = \frac{R_2}{R_1 + R_2} V_i + \frac{R_1}{R_1 + R_2} V_o = \frac{9\,\text{k}}{10\,\text{k}} V_i + \frac{1\,\text{k}}{10\,\text{k}} V_o \,.$$

As long as $V_+ > 0\ V$, V_o remains at $+V_{\text{sat}}$.

Non-inverting Schmitt trigger





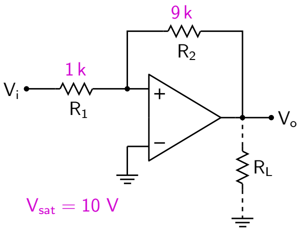
Consider decreasing values of V_i.

$$V_+ = \frac{R_2}{R_1 + R_2} V_i + \frac{R_1}{R_1 + R_2} V_o = \frac{9\,\text{k}}{10\,\text{k}} V_i + \frac{1\,\text{k}}{10\,\text{k}} V_o\,.$$

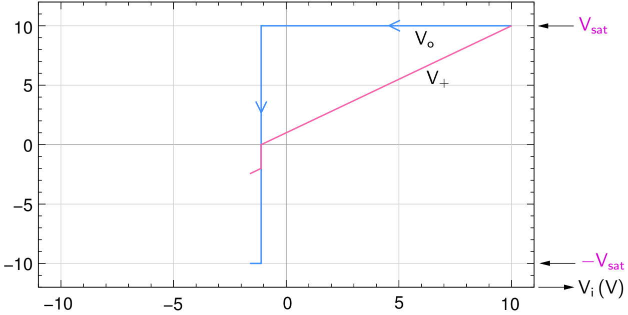
As long as $V_+ > 0\ V$, V_o remains at $+V_{\text{sat}}$.

When $V_+ = 0\ V$, i.e., $V_i = -\dfrac{R_1}{R_2} V_{\text{sat}} = -\dfrac{1\,\text{k}}{9\,\text{k}}\,10\,\text{V} = -1.11\ V$, V_o changes sign, i.e., V_o becomes $-V_{\text{sat}}$.

Non-inverting Schmitt trigger



$V_{sat} = 10$ V



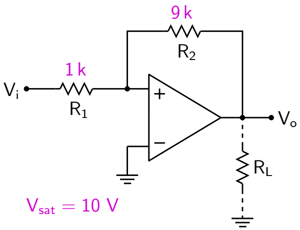
Consider decreasing values of V_i.

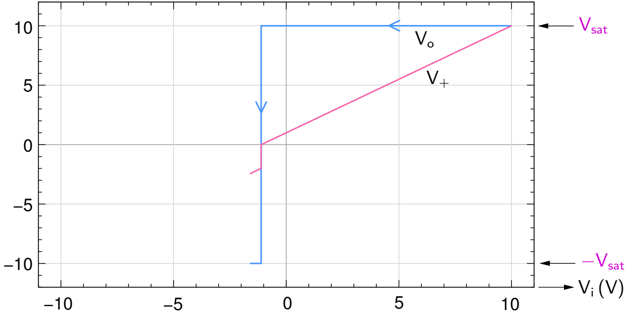
$$V_+ = \frac{R_2}{R_1 + R_2} V_i + \frac{R_1}{R_1 + R_2} V_o = \frac{9\,\text{k}}{10\,\text{k}} V_i + \frac{1\,\text{k}}{10\,\text{k}} V_o \,.$$

As long as $V_+ > 0\ V$, V_o remains at $+V_{\text{sat}}$.

When $V_+ = 0\ V$, i.e., $V_i = -\dfrac{R_1}{R_2} V_{\text{sat}} = -\dfrac{1\,\text{k}}{9\,\text{k}}\, 10\,\text{V} = -1.11\ V$, V_o changes sign, i.e., V_o becomes $-V_{\text{sat}}$.

Non-inverting Schmitt trigger





Consider decreasing values of V_i.

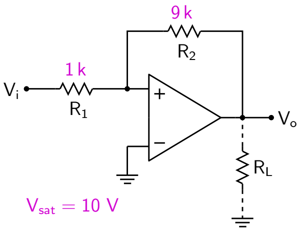
$$V_+ = \frac{R_2}{R_1 + R_2} V_i + \frac{R_1}{R_1 + R_2} V_o = \frac{9\,\text{k}}{10\,\text{k}} V_i + \frac{1\,\text{k}}{10\,\text{k}} V_o\,.$$

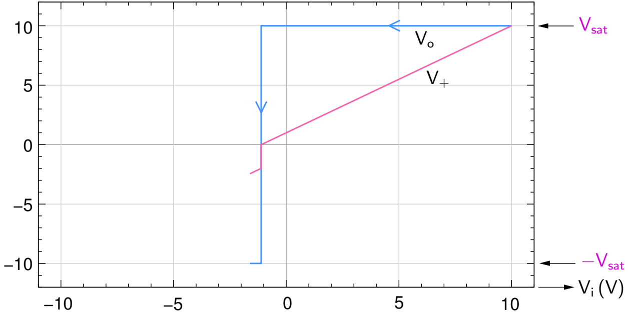
As long as $V_+ > 0\ V$, V_o remains at $+V_{\text{sat}}$.

When $V_+ = 0\ V$, i.e., $V_i = -\dfrac{R_1}{R_2} V_{\text{sat}} = -\dfrac{1\,\text{k}}{9\,\text{k}}\, 10\,\text{V} = -1.11\ V$, V_o changes sign, i.e., V_o becomes $-V_{\text{sat}}$.

V_+ now follows the equation, $V_+ = \dfrac{R_2}{R_1 + R_2} V_i + \dfrac{R_1}{R_1 + R_2} V_o = \dfrac{9\,\text{k}}{10\,\text{k}} V_i - \dfrac{1\,\text{k}}{10\,\text{k}} V_{\text{sat}}\,.$

Non-inverting Schmitt trigger





Consider decreasing values of V_i.

$$V_+ = \frac{R_2}{R_1+R_2}V_i + \frac{R_1}{R_1+R_2}V_o = \frac{9\,\text{k}}{10\,\text{k}}V_i + \frac{1\,\text{k}}{10\,\text{k}}V_o\,.$$

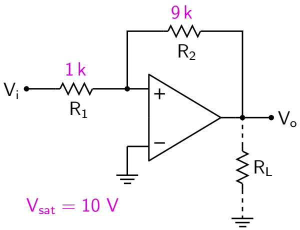
As long as $V_+ > 0\ V$, V_o remains at $+V_{\text{sat}}$.

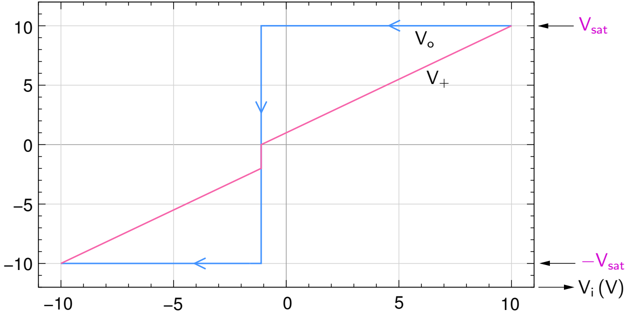
When $V_+ = 0\ V$, i.e., $V_i = -\dfrac{R_1}{R_2}V_{\text{sat}} = -\dfrac{1\,\text{k}}{9\,\text{k}}\,10\,\text{V} = -1.11\ V$, V_o changes sign, i.e., V_o becomes $-V_{\text{sat}}$.

V_+ now follows the equation, $V_+ = \dfrac{R_2}{R_1+R_2}V_i + \dfrac{R_1}{R_1+R_2}V_o = \dfrac{9\,\text{k}}{10\,\text{k}}V_i - \dfrac{1\,\text{k}}{10\,\text{k}}V_{\text{sat}}\,.$

Decreasing V_i further makes no difference to V_o (since V_+ remains negative).

Non-inverting Schmitt trigger





Consider decreasing values of V_i.

$$V_+ = \frac{R_2}{R_1 + R_2} V_i + \frac{R_1}{R_1 + R_2} V_o = \frac{9\,\text{k}}{10\,\text{k}} V_i + \frac{1\,\text{k}}{10\,\text{k}} V_o\,.$$

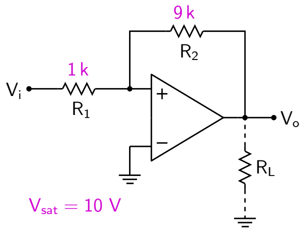
As long as $V_+ > 0\ V$, V_o remains at $+V_{\text{sat}}$.

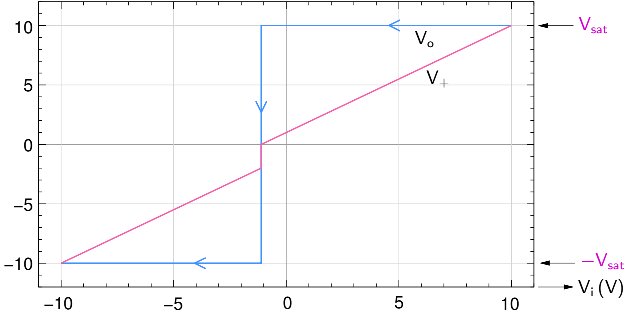
When $V_+ = 0\ V$, i.e., $V_i = -\dfrac{R_1}{R_2} V_{\text{sat}} = -\dfrac{1\,\text{k}}{9\,\text{k}}\, 10\,\text{V} = -1.11\ V$, V_o changes sign, i.e., V_o becomes $-V_{\text{sat}}$.

V_+ now follows the equation, $V_+ = \dfrac{R_2}{R_1 + R_2} V_i + \dfrac{R_1}{R_1 + R_2} V_o = \dfrac{9\,\text{k}}{10\,\text{k}} V_i - \dfrac{1\,\text{k}}{10\,\text{k}} V_{\text{sat}}\,.$

Decreasing V_i further makes no difference to V_o (since V_+ remains negative).

Non-inverting Schmitt trigger





Consider decreasing values of V_i.

$$V_+ = \frac{R_2}{R_1 + R_2} V_i + \frac{R_1}{R_1 + R_2} V_o = \frac{9\,\text{k}}{10\,\text{k}} V_i + \frac{1\,\text{k}}{10\,\text{k}} V_o\,.$$

As long as $V_+ > 0\,V$, V_o remains at $+V_{\text{sat}}$.

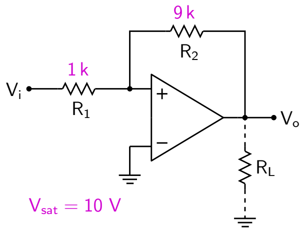
When $V_+ = 0\,V$, i.e., $V_i = -\dfrac{R_1}{R_2} V_{\text{sat}} = -\dfrac{1\,\text{k}}{9\,\text{k}}\,10\,\text{V} = -1.11\,V$, V_o changes sign, i.e., V_o becomes $-V_{\text{sat}}$.

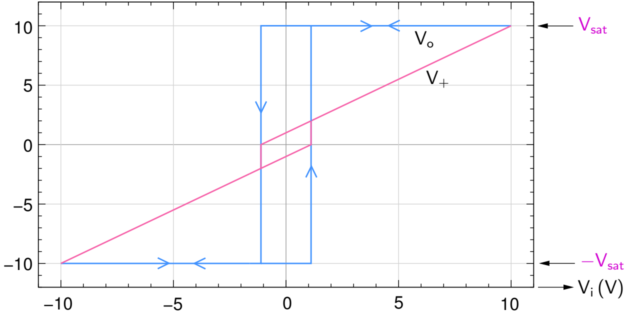
V_+ now follows the equation, $V_+ = \dfrac{R_2}{R_1 + R_2} V_i + \dfrac{R_1}{R_1 + R_2} V_o = \dfrac{9\,\text{k}}{10\,\text{k}} V_i - \dfrac{1\,\text{k}}{10\,\text{k}} V_{\text{sat}}\,.$

Decreasing V_i further makes no difference to V_o (since V_+ remains negative).

Now, the threshold at which V_o flips is $V_+ = 0$, i.e., $V_i = +\dfrac{R_1}{R_2} V_{\text{sat}} = +1.11\,V$.

Non-inverting Schmitt trigger





Consider decreasing values of V_i.

$$V_+ = \frac{R_2}{R_1 + R_2} V_i + \frac{R_1}{R_1 + R_2} V_o = \frac{9\,\mathrm{k}}{10\,\mathrm{k}} V_i + \frac{1\,\mathrm{k}}{10\,\mathrm{k}} V_o\,.$$

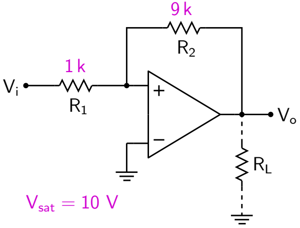
As long as $V_+ > 0\;V$, V_o remains at $+V_{\mathrm{sat}}$.

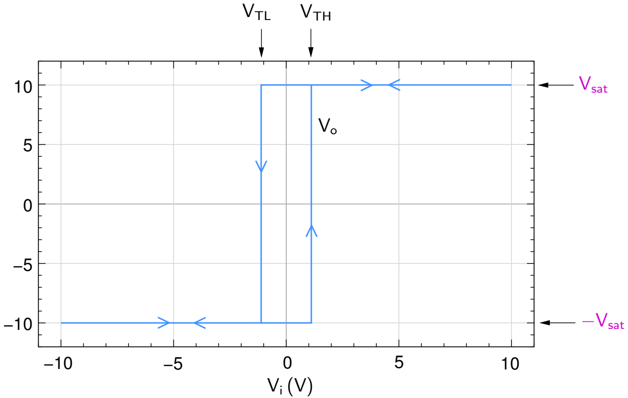
When $V_+ = 0\;V$, i.e., $V_i = -\dfrac{R_1}{R_2} V_{\mathrm{sat}} = -\dfrac{1\,\mathrm{k}}{9\,\mathrm{k}}\,10\,\mathrm{V} = -1.11\;V$, V_o changes sign, i.e., V_o becomes $-V_{\mathrm{sat}}$.

V_+ now follows the equation, $V_+ = \dfrac{R_2}{R_1 + R_2} V_i + \dfrac{R_1}{R_1 + R_2} V_o = \dfrac{9\,\mathrm{k}}{10\,\mathrm{k}} V_i - \dfrac{1\,\mathrm{k}}{10\,\mathrm{k}} V_{\mathrm{sat}}\,.$

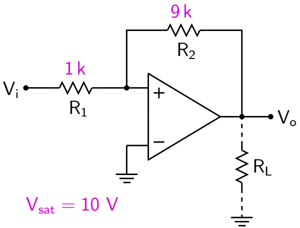
Decreasing V_i further makes no difference to V_o (since V_+ remains negative).

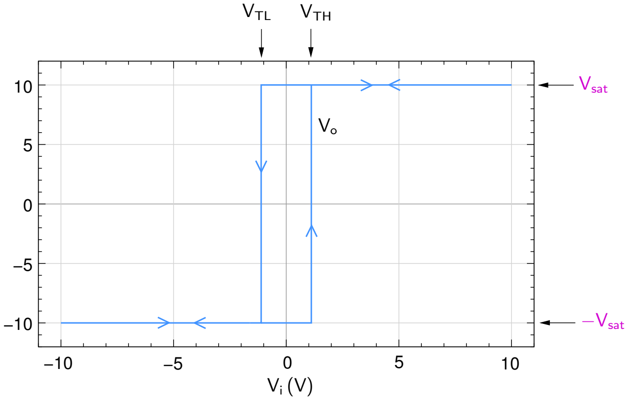
Now, the threshold at which V_o flips is $V_+ = 0$, i.e., $V_i = +\dfrac{R_1}{R_2} V_{\mathrm{sat}} = +1.11\;V$.


9 k
R2
1 k
Vi
R1
+
−
Vo
RL
Vsat = 10 V


VTL
VTH
10
5
0
−5
−10
Vo
Vsat
−Vsat
−10
−5
0
5
10
Vi (V)

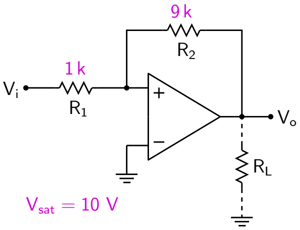
Non-inverting Schmitt trigger

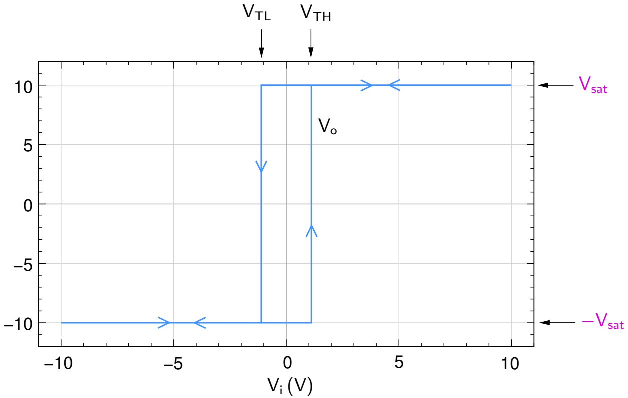




* The threshold values V_{TH} and V_{TL} are given by $\pm\left(\dfrac{R_1}{R_2}\right) V_{sat}$.

Non-inverting Schmitt trigger

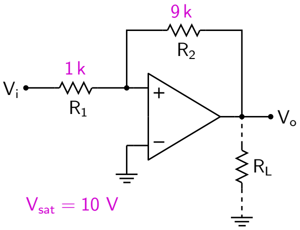


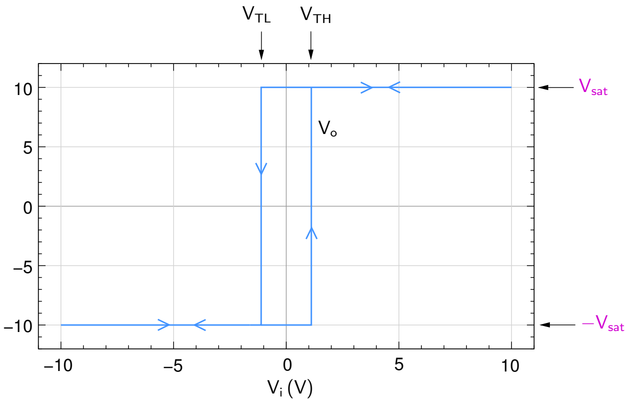


* The threshold values V_{TH} and V_{TL} are given by $\pm\left(\dfrac{R_1}{R_2}\right)V_{sat}$.

* As in the inverting Schmitt trigger, this circuit has a memory, i.e., the tripping point (whether V_{TH} or V_{TL}) depends on where we are on the V_o axis.

Non-inverting Schmitt trigger

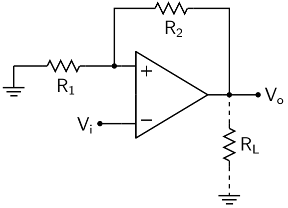


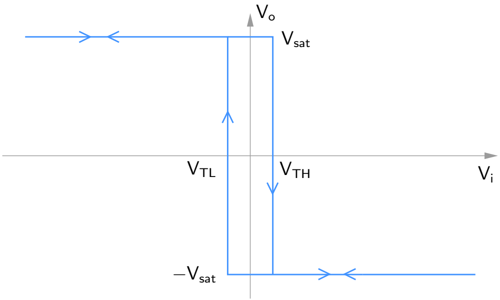


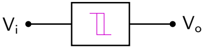
* The threshold values V_{TH} and V_{TL} are given by $\pm\left(\dfrac{R_1}{R_2}\right)V_{\mathrm{sat}}$.
* As in the inverting Schmitt trigger, this circuit has a memory, i.e., the tripping point (whether V_{TH} or V_{TL}) depends on where we are on the V_o axis.
* $\Delta V_T = V_{\mathrm{TH}} - V_{\mathrm{TL}}$ is called the "hysteresis width."

Schmitt triggers

Inverting

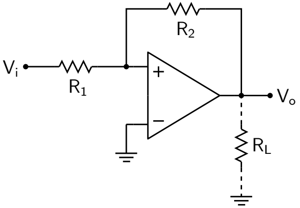


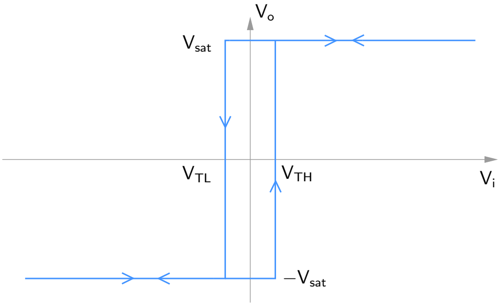


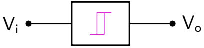


$$V_{TH},\, V_{TL} = \pm \frac{R_1}{R_1 + R_2} V_{sat}$$

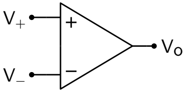
Non–inverting

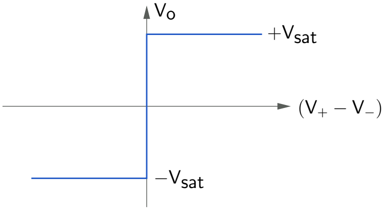




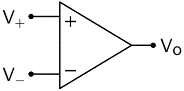


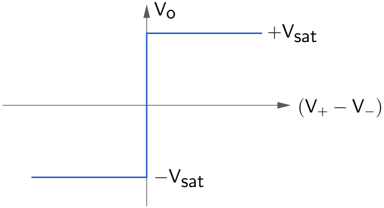
$$V_{TH},\, V_{TL} = \pm \frac{R_1}{R_2} V_{sat}$$


V_+
V_-
+
−
V_o

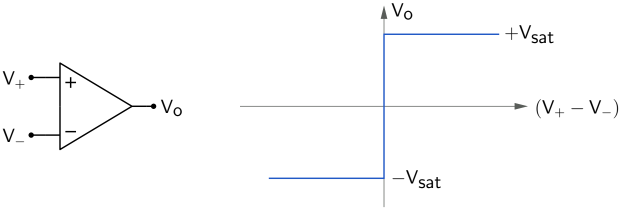

V_o
$+V_{sat}$
$(V_+ - V_-)$
$-V_{sat}$

Comparators





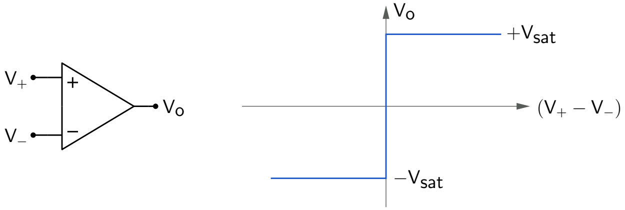
An op-amp in the open-loop configuration serves as a comparator because of its high gain ($\sim 10^5$) in the linear region.



An op-amp in the open-loop configuration serves as a comparator because of its high gain ($\sim 10^5$) in the linear region.

As seen earlier, the width of the linear region, $[V_{\mathrm{sat}} - (-V_{\mathrm{sat}})]/A_V$, is small ($\sim 0.1\,\mathrm{m}V$), and could be treated as 0.

Comparators

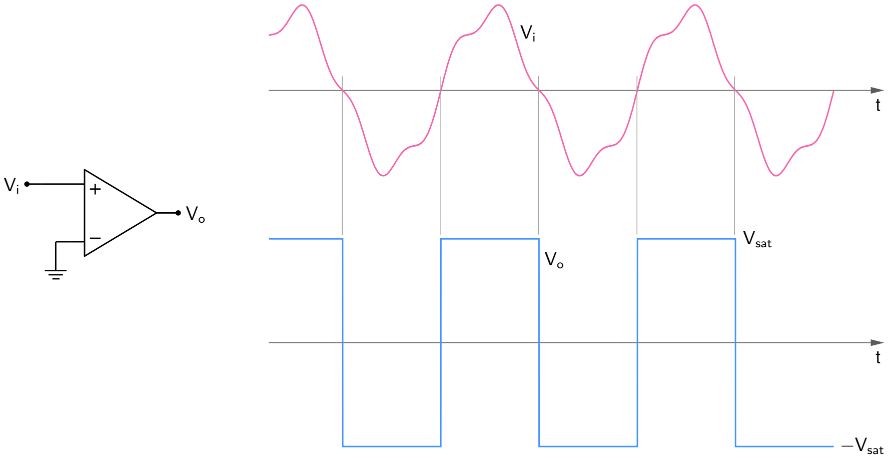


An op-amp in the open-loop configuration serves as a comparator because of its high gain ($\sim 10^5$) in the linear region.

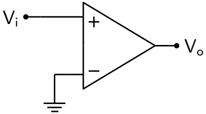
As seen earlier, the width of the linear region, $[V_{\rm sat} - (-V_{\rm sat})]/A_V$, is small ($\sim 0.1\,{\rm m}V$), and could be treated as 0.

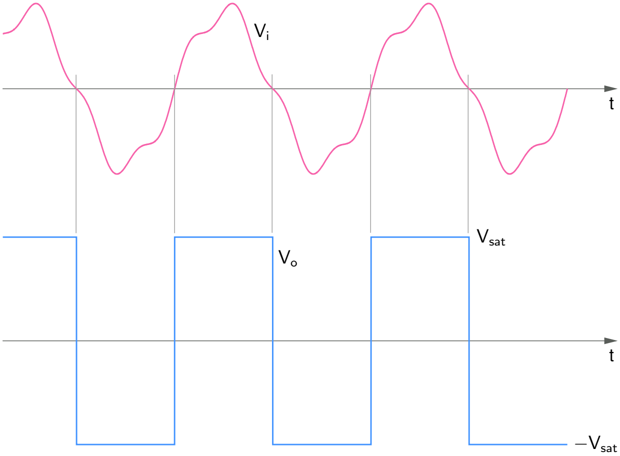
i.e., if $V_+ > V_-$, $V_o = +V_{\rm sat}$,

if $V_+ < V_-$, $V_o = -V_{\rm sat}$.

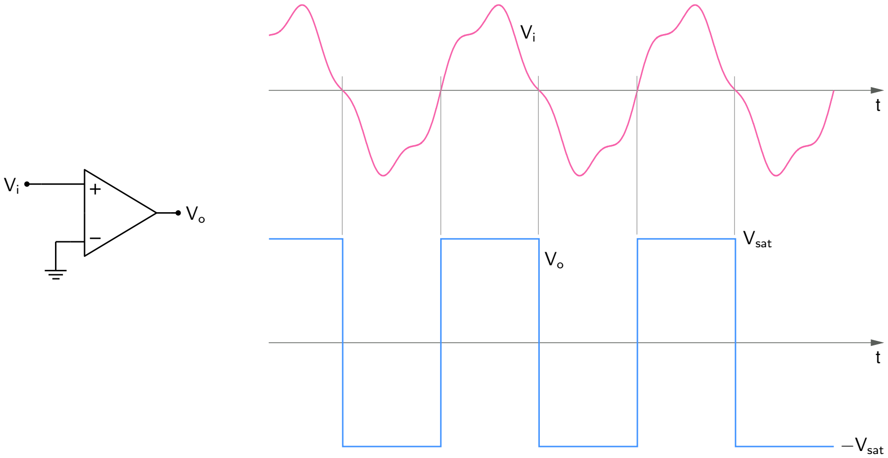


Vi
Vo
+
−
Vi
t
Vsat
Vo
t
−Vsat





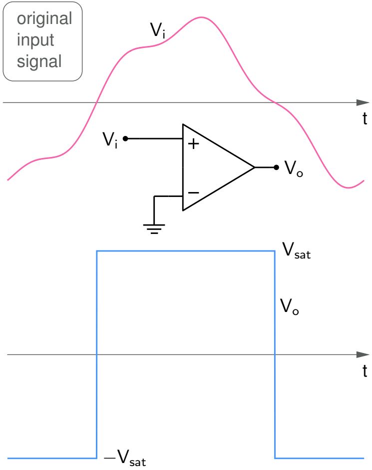
A comparator can be used to convert an analog signal into a digital (high/low) signal for further processing with digital circuits.

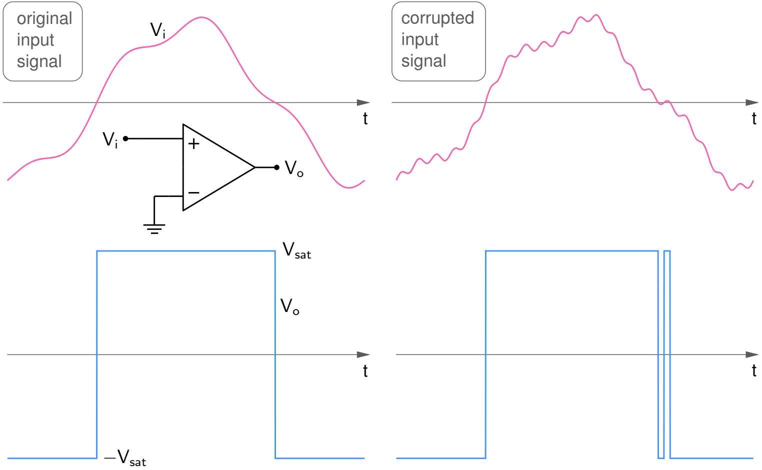


A comparator can be used to convert an analog signal into a digital (high/low) signal for further processing with digital circuits.

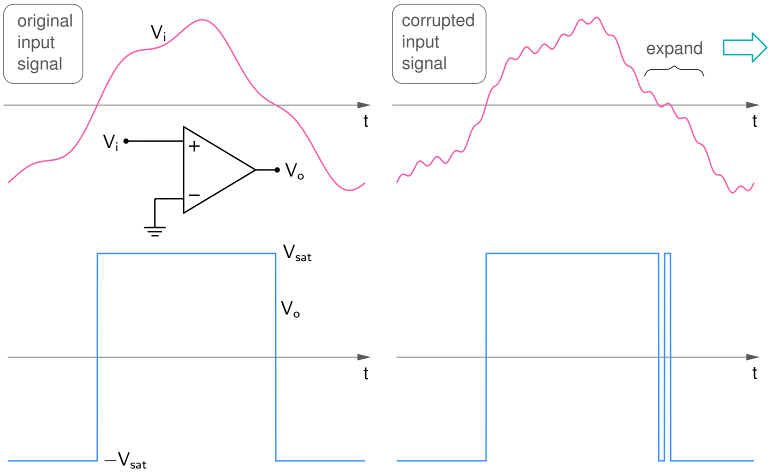
In practice, the input (analog) signal can have noise or electromagnetic pick-up superimposed on it. As a result, erroneous operation of the circuit may result.

Comparators

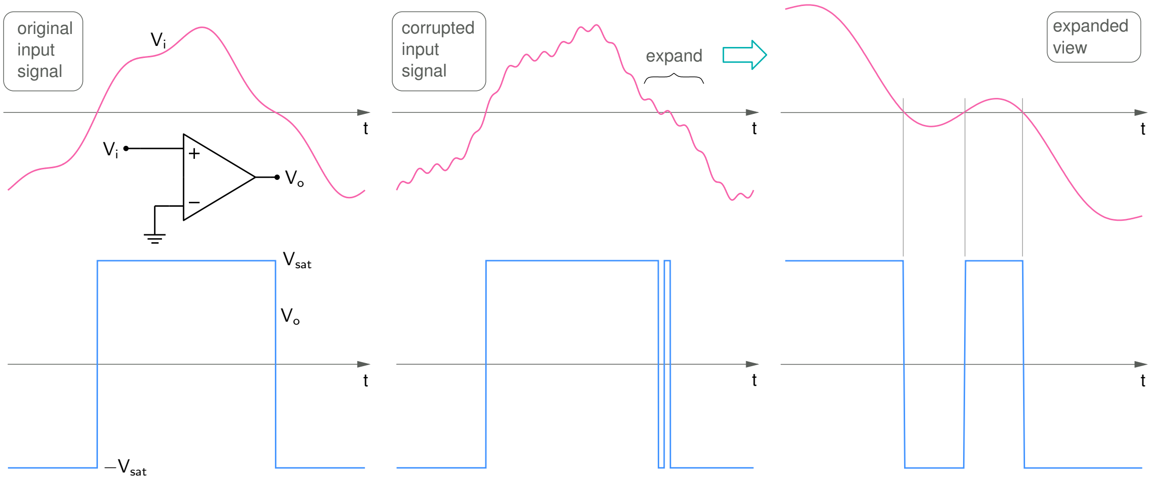


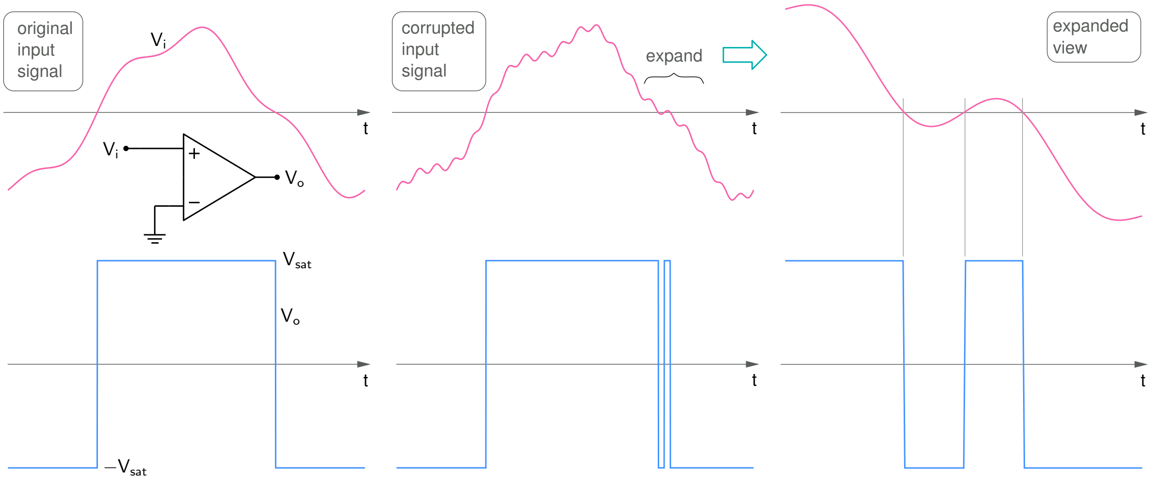

original
input
signal
V_i
V_i
+
−
V_o
t
corrupted
input
signal
t
V_{sat}
V_o
$-V_{sat}$
t
t

Comparators



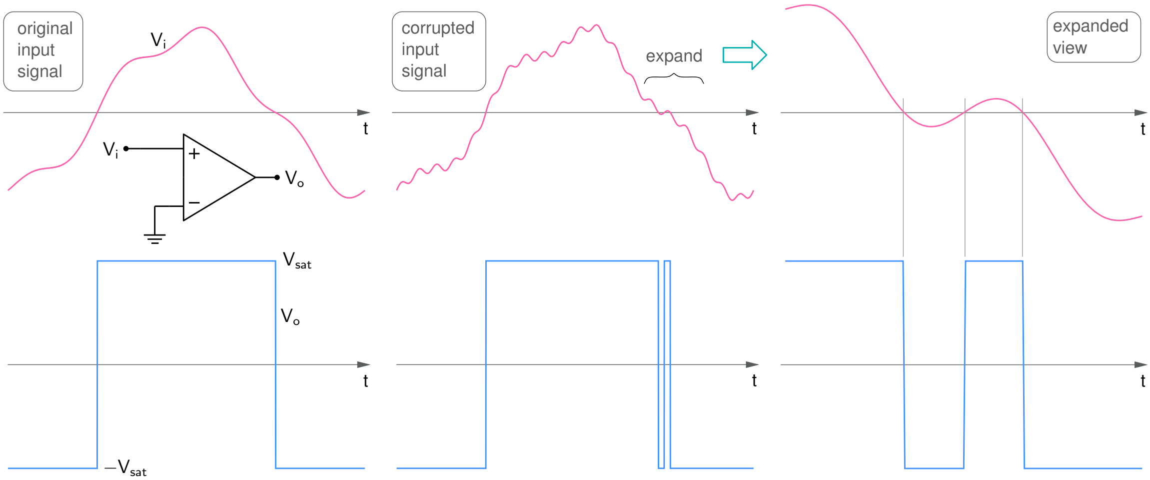
Comparators





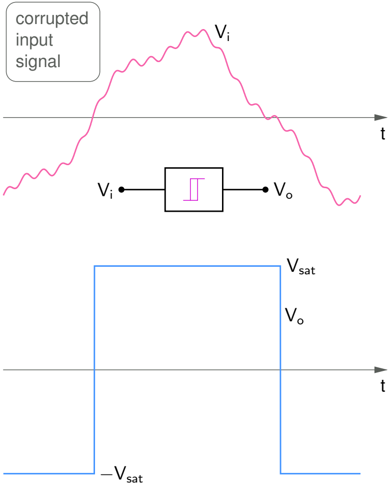
The comparator has produced multiple (spurious) transitions or “bounces,” referred to as “comparator chatter.”

Comparators

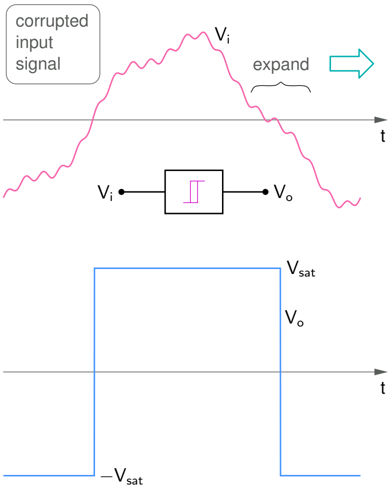


The comparator has produced multiple (spurious) transitions or "bounces," referred to as "comparator chatter."

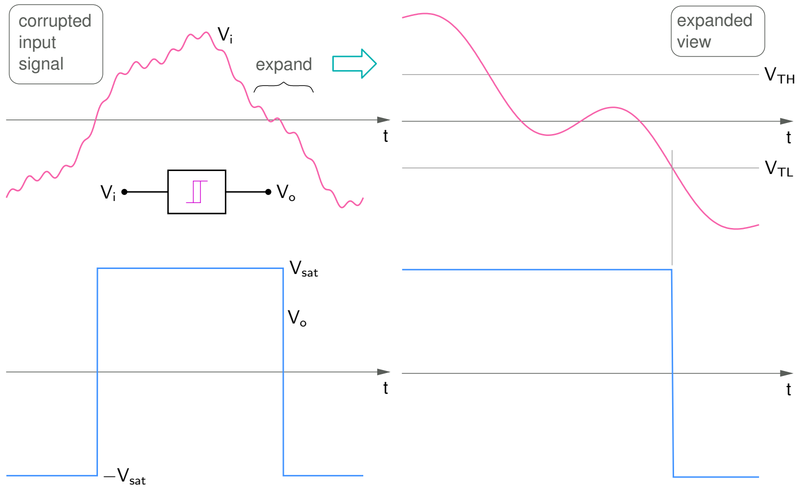
A Schmitt trigger can be used to eliminate the chatter.



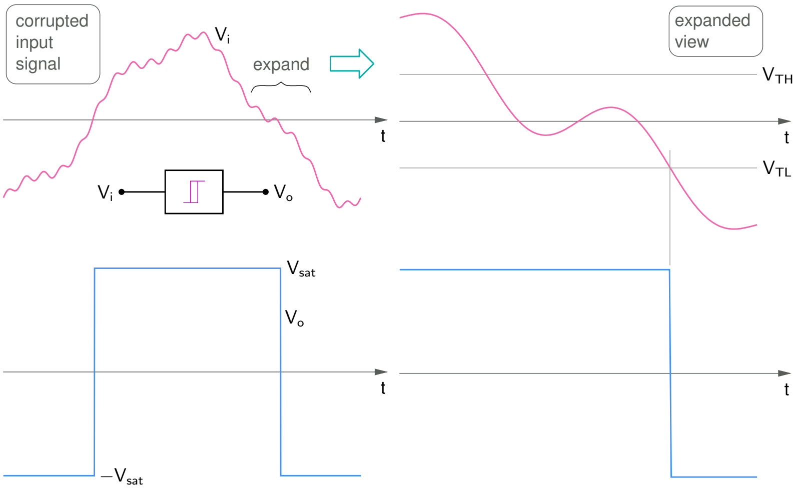
corrupted input signal
V_i
t
V_i
V_o
V_{sat}
V_o
t
$-V_{sat}$



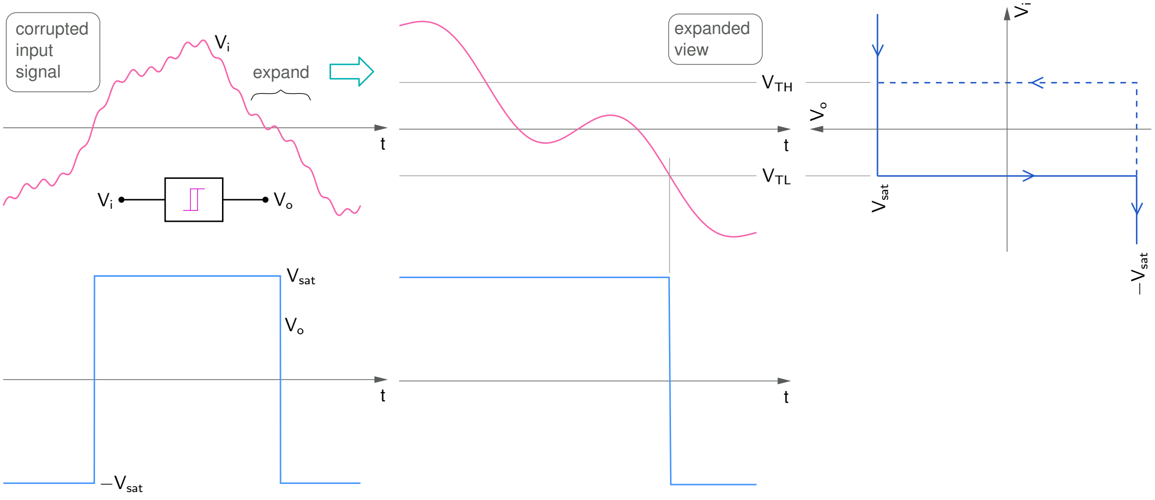
corrupted
input
signal
V_i
expand
t
V_i
V_o
V_sat
V_o
t
−V_sat



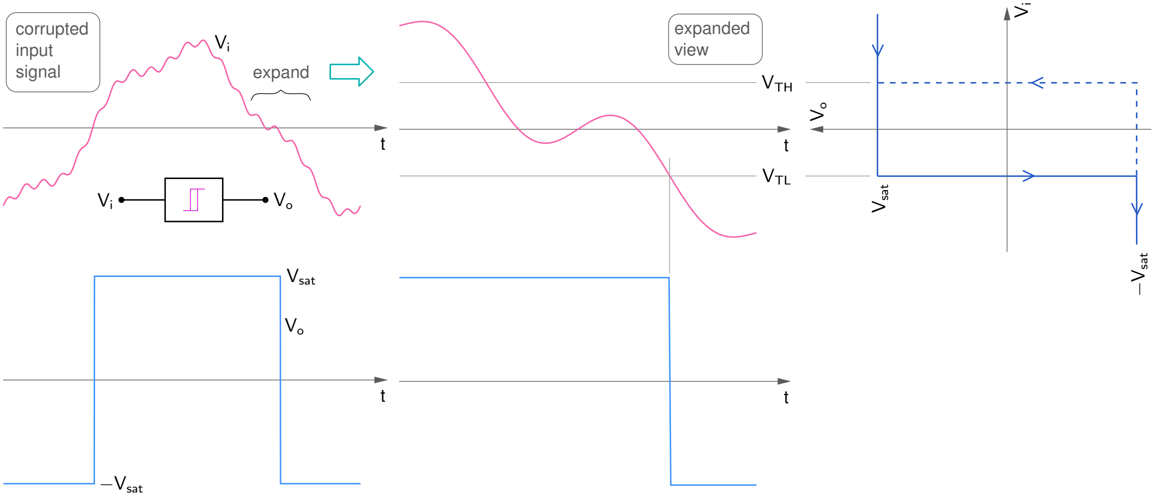
corrupted input signal
V_i
expand
expanded view
V_{TH}
V_{TL}
t
t
V_i
V_o
V_{sat}
V_o
$-V_{sat}$
t
t



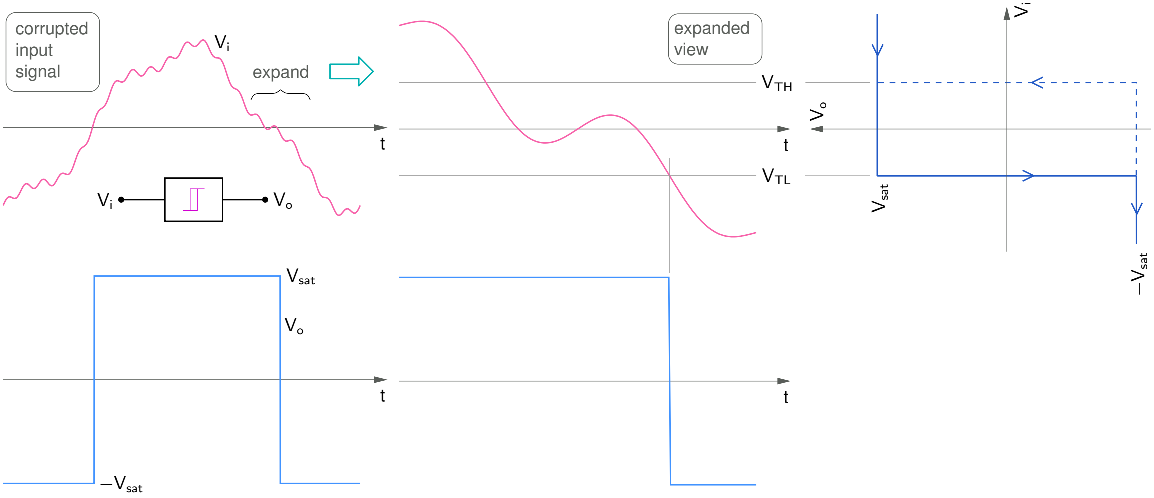
* While going from positive to negative values, V_i needs to cross V_{TL} (and not $0\ V$) to cause a change in V_o.



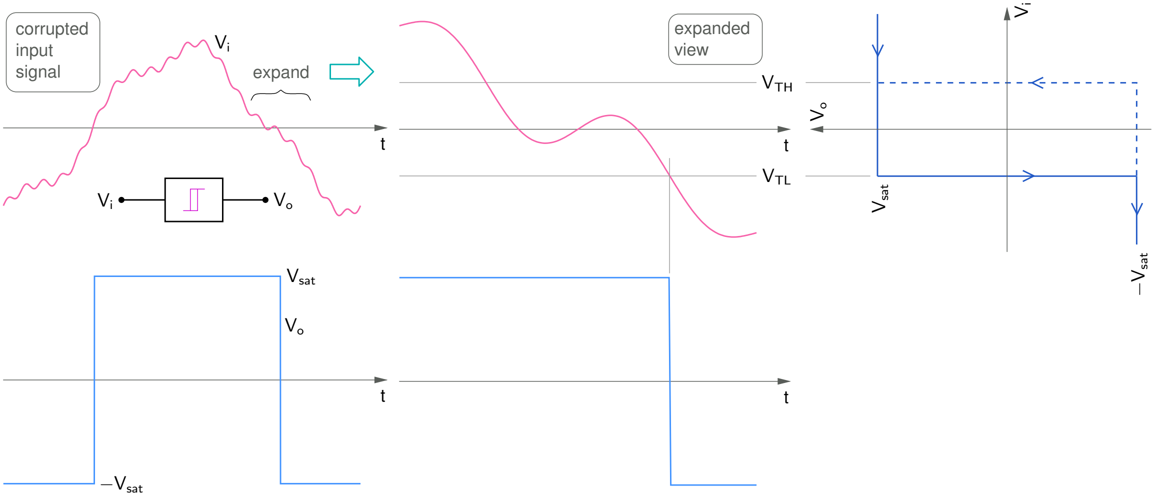
* While going from positive to negative values, V_i needs to cross V_{TL} (and not $0\ V$) to cause a change in V_o.



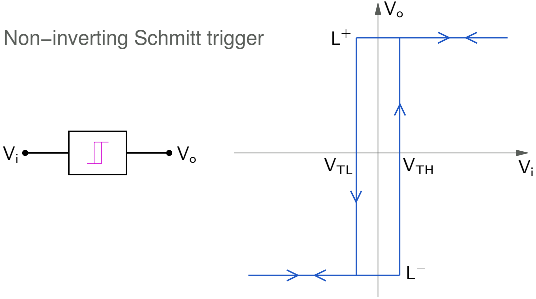
* While going from positive to negative values, V_i needs to cross V_{TL} (and not 0 V) to cause a change in V_o.
* In the reverse direction (negative to positive), V_i needs to cross V_{TH}.

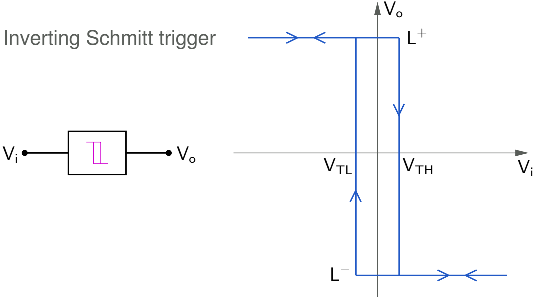


* While going from positive to negative values, V_i needs to cross V_{TL} (and not $0\,V$) to cause a change in V_o.
* In the reverse direction (negative to positive), V_i needs to cross V_{TH}.
* The circuit gets rid of spurious transitions, a major advantage over the simple comparator.

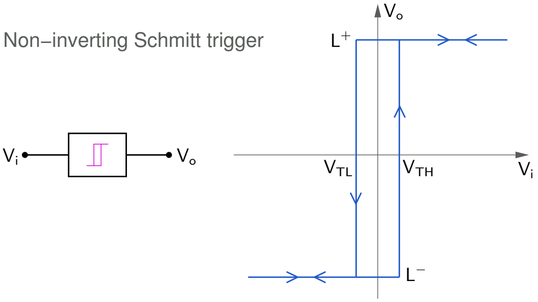


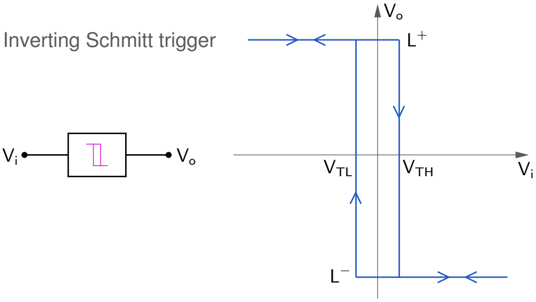
* While going from positive to negative values, V_i needs to cross V_{TL} (and not $0\,V$) to cause a change in V_o.
* In the reverse direction (negative to positive), V_i needs to cross V_{TH}.
* The circuit gets rid of spurious transitions, a major advantage over the simple comparator.
* The hysteresis width $(V_{TH} - V_{TL})$ should be designed to be larger than the spurious excursions riding on V_i.


Non−inverting Schmitt trigger
Vi
Vo
Vo
L+
VTL
VTH
Vi
L−


Inverting Schmitt trigger
Vi
Vo
Vo
L+
VTL
VTH
Vi
L−

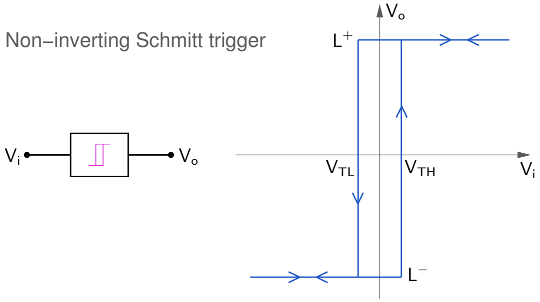
Waveform generation using Schmitt triggers

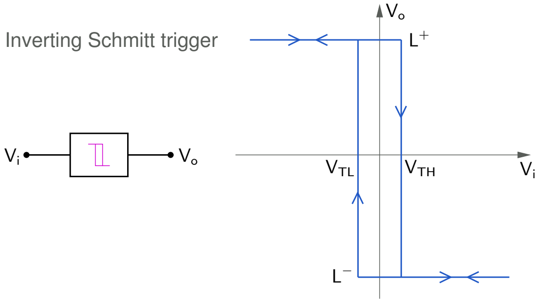




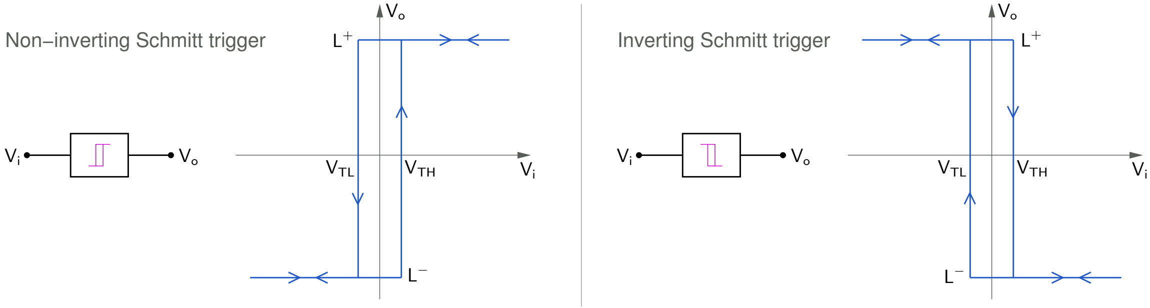
* A Schmitt trigger has two states, $V_o = L^+$ and $V_o = L^-$.

Waveform generation using Schmitt triggers



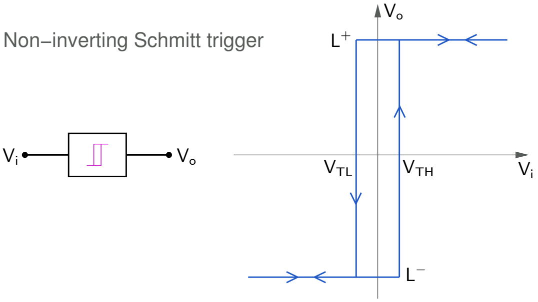


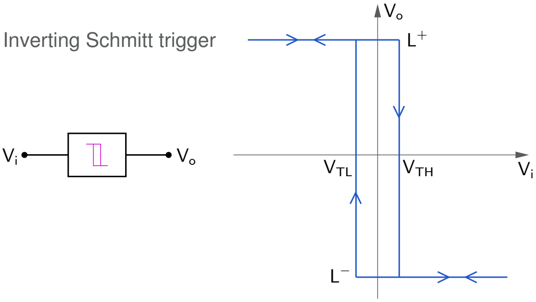
* A Schmitt trigger has two states, $V_o = L^+$ and $V_o = L^-$.
* With a suitable RC network, it can be made to freely oscillate between L^+ and L^-. Such a circuit is called an "astable multivibrator" or a "free-running multivibrator."



* A Schmitt trigger has two states, $V_o = L^+$ and $V_o = L^-$.
* With a suitable *RC* network, it can be made to freely oscillate between L^+ and L^-. Such a circuit is called an "astable multivibrator" or a "free-running multivibrator."
* An astable multivibrator produces oscillations *without* an input signal, the frequency being controlled by the component values.

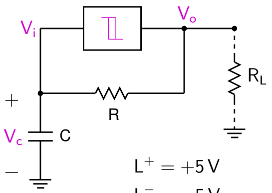
Waveform generation using Schmitt triggers





* A Schmitt trigger has two states, $V_o = L^+$ and $V_o = L^-$.
* With a suitable RC network, it can be made to freely oscillate between L^+ and L^-. Such a circuit is called an "astable multivibrator" or a "free-running multivibrator."
* An astable multivibrator produces oscillations *without* an input signal, the frequency being controlled by the component values.
* The maximum operating frequency of these oscillators is typically $\sim 10\,\text{kHz}$, due to op-amp speed limitations.

Waveform generation using a Schmitt trigger

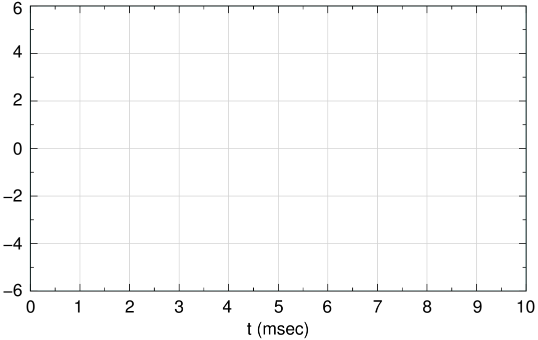


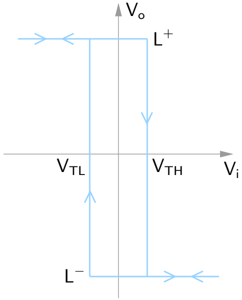
$L^+ = +5\,V$

$L^- = -5\,V$

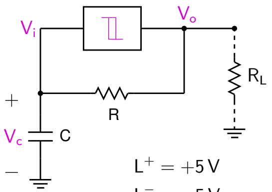
$R = 2\,k$ $\quad V_{TH} = +1\,V$

$C = 1\,\mu F$ $\quad V_{TL} = -1\,V$





Waveform generation using a Schmitt trigger



$L^+ = +5\,V$

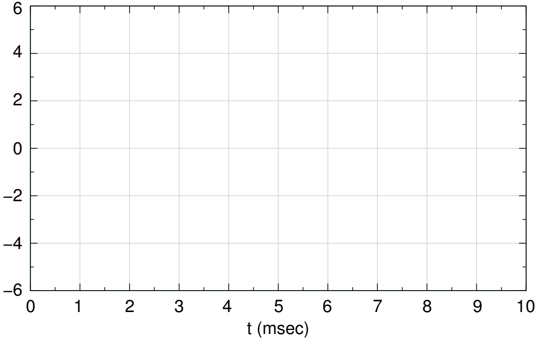
$L^- = -5\,V$

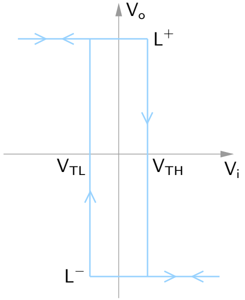
$R = 2\,k$

$V_{TH} = +1\,V$

$C = 1\,\mu F$

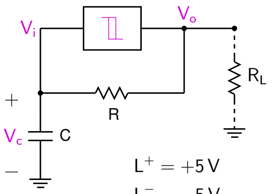
$V_{TL} = -1\,V$





At $t = 0$, let $V_o = L^+$, and $V_c = 0\ V$.

Waveform generation using a Schmitt trigger

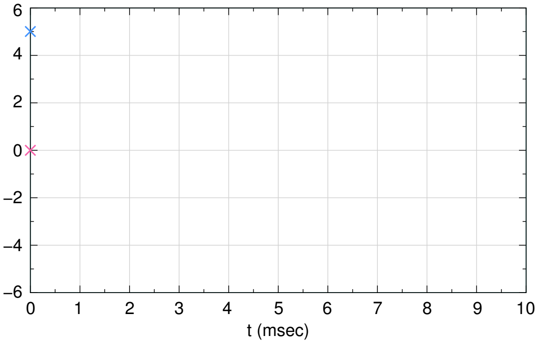


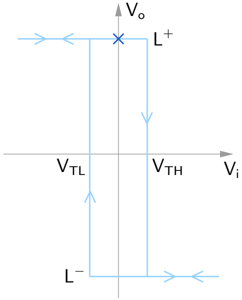
$L^+ = +5\,V$

$L^- = -5\,V$

$R = 2\,k$ $\quad V_{TH} = +1\,V$

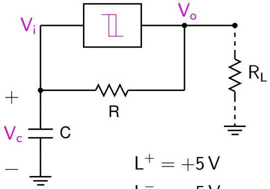
$C = 1\,\mu F$ $\quad V_{TL} = -1\,V$





At $t = 0$, let $V_o = L^+$, and $V_c = 0\ V$.

Waveform generation using a Schmitt trigger

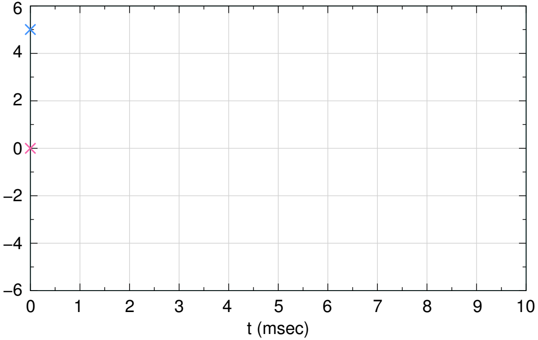


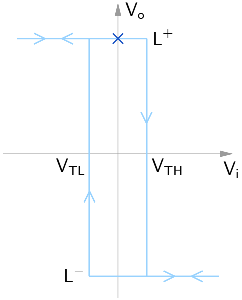
$L^+ = +5\,\mathrm{V}$

$L^- = -5\,\mathrm{V}$

$R = 2\,\mathrm{k}$ $\quad V_{TH} = +1\,\mathrm{V}$

$C = 1\,\mu\mathrm{F}$ $\quad V_{TL} = -1\,\mathrm{V}$

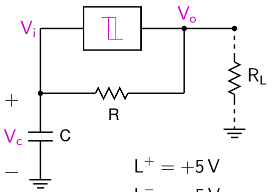




At $t = 0$, let $V_o = L^+$, and $V_c = 0\ V$.

The capacitor starts charging toward L^+.

Waveform generation using a Schmitt trigger

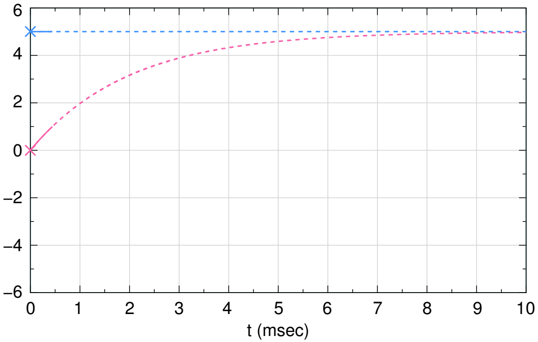


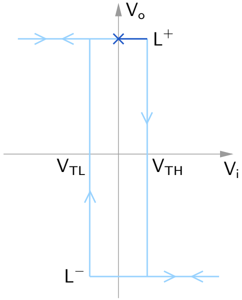
$L^+ = +5\,V$

$L^- = -5\,V$

$R = 2\,k$ $\quad V_{TH} = +1\,V$

$C = 1\,\mu F$ $\quad V_{TL} = -1\,V$

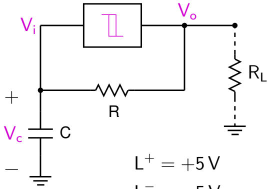




At $t = 0$, let $V_o = L^+$, and $V_c = 0\ V$.

The capacitor starts charging toward L^+.

Waveform generation using a Schmitt trigger

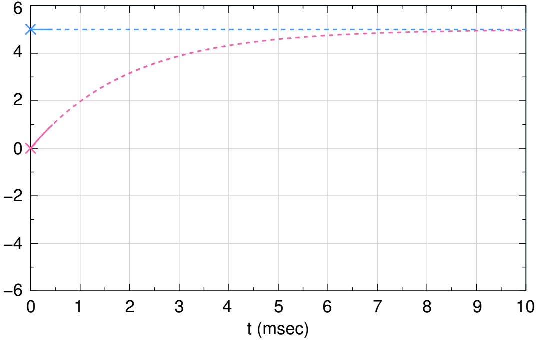


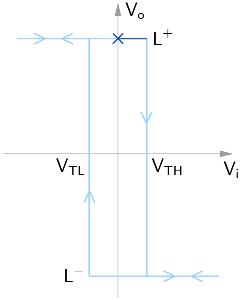
$L^+ = +5\,V$

$L^- = -5\,V$

$R = 2\,k$ $\quad$ $V_{TH} = +1\,V$

$C = 1\,\mu F$ $\quad$ $V_{TL} = -1\,V$



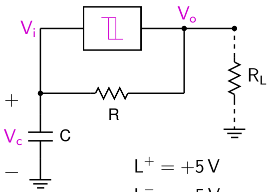


At $t = 0$, let $V_o = L^+$, and $V_c = 0\ V$.

The capacitor starts charging toward L^+.

When V_c crosses V_{TH}, the output flips. Now, the capacitor starts discharging toward L^-.

Waveform generation using a Schmitt trigger

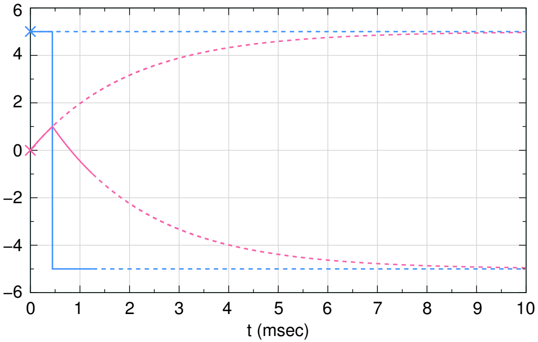


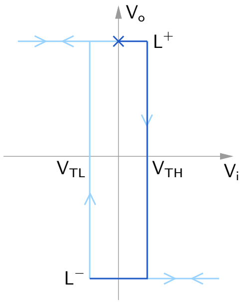
$L^+ = +5\,\text{V}$

$L^- = -5\,\text{V}$

$R = 2\,\text{k}$ $\quad V_{TH} = +1\,\text{V}$

$C = 1\,\mu\text{F}$ $\quad V_{TL} = -1\,\text{V}$



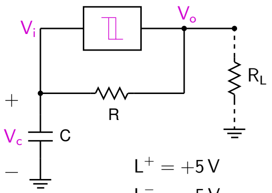


At $t = 0$, let $V_o = L^+$, and $V_c = 0\ V$.

The capacitor starts charging toward L^+.

When V_c crosses V_{TH}, the output flips. Now, the capacitor starts discharging toward L^-.

Waveform generation using a Schmitt trigger

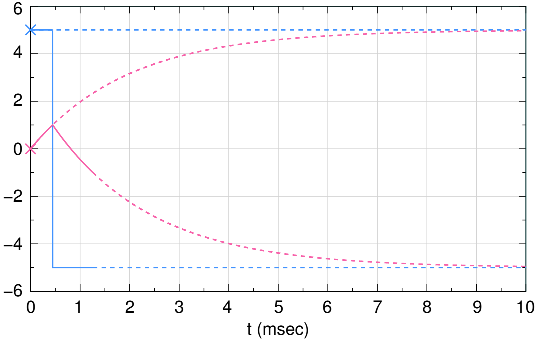


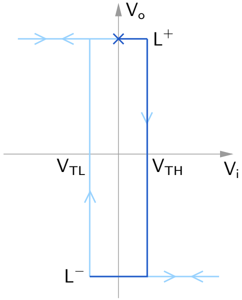
$L^{+} = +5\,V$

$L^{-} = -5\,V$

$R = 2\,k$ $\quad V_{TH} = +1\,V$

$C = 1\,\mu F$ $\quad V_{TL} = -1\,V$





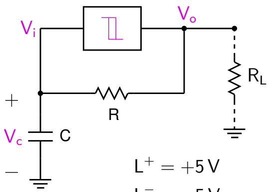
At $t = 0$, let $V_o = L^{+}$, and $V_c = 0\ V$.

The capacitor starts charging toward L^{+}.

When V_c crosses V_{TH}, the output flips. Now, the capacitor starts discharging toward L^{-}.

When V_c crosses V_{TL}, the output flips again $\rightarrow$ oscillations.

Waveform generation using a Schmitt trigger

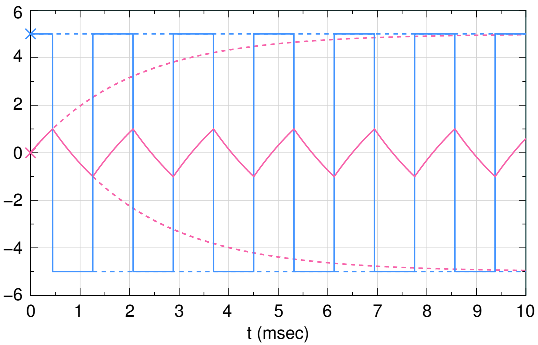


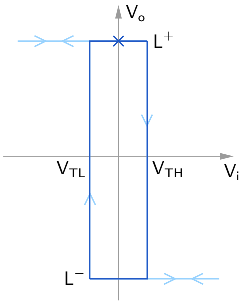
$L^+ = +5\,V$

$L^- = -5\,V$

$R = 2\,k$ $\quad$ $V_{TH} = +1\,V$

$C = 1\,\mu F$ $\quad$ $V_{TL} = -1\,V$





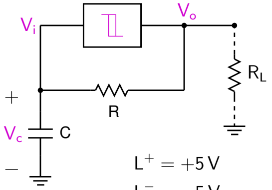
At $t = 0$, let $V_o = L^+$, and $V_c = 0\ V$.

The capacitor starts charging toward L^+.

When V_c crosses V_{TH}, the output flips. Now, the capacitor starts discharging toward L^-.

When V_c crosses V_{TL}, the output flips again $\rightarrow$ oscillations.

Waveform generation using a Schmitt trigger

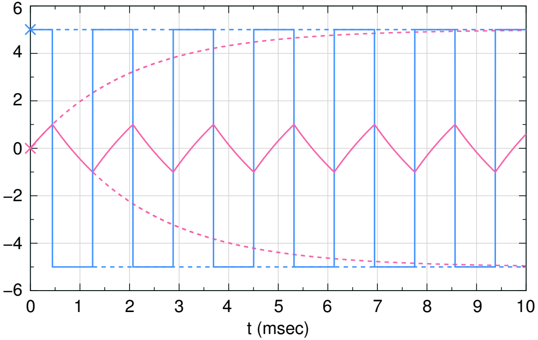


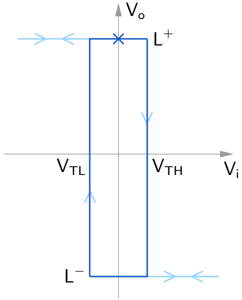
$L^+ = +5\,V$

$L^- = -5\,V$

$R = 2\,k$ $\quad V_{TH} = +1\,V$

$C = 1\,\mu F$ $\quad V_{TL} = -1\,V$





At $t = 0$, let $V_o = L^+$, and $V_c = 0\;V$.

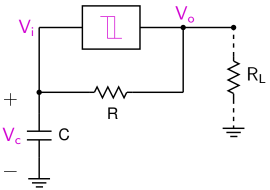
The capacitor starts charging toward L^+.

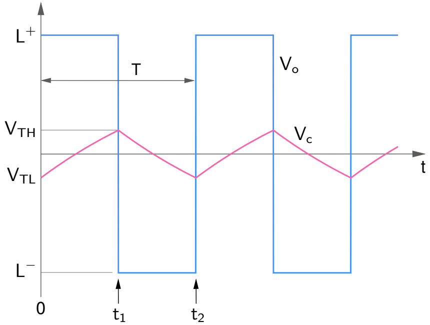
When V_c crosses V_{TH}, the output flips. Now, the capacitor starts discharging toward L^-.

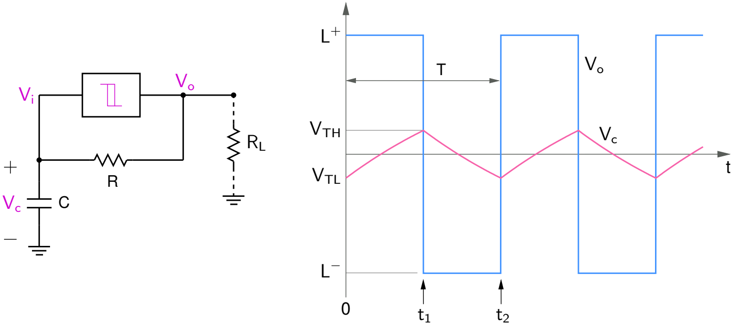
When V_c crosses V_{TL}, the output flips again $\rightarrow$ oscillations.

Note that the circuit oscillates *on its own*, i.e., without any input.

Q: Where is the energy coming from?


V_i
V_o
R_L
+
R
V_c
C
−


L^+
T
V_o
V_{TH}
V_c
t
V_{TL}
L^-
0
t_1
t_2

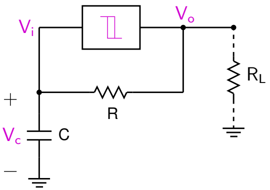


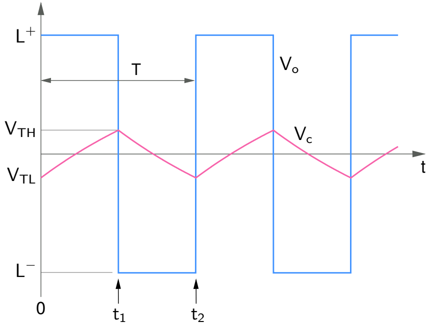
Charging: Let $V_c(t) = A_1 \, \exp(-t/\tau) + B_1$, with $\tau = RC$.

Using $V_c(0) = V_{TL}$, $V_c(\infty) = L^+$, find A_1 and B_1.

At $t = t_1$, $V_c = V_{TH} \rightarrow V_{TH} = A_1 \, \exp(-t_1/\tau) + B_1 \rightarrow$ find t_1.

Waveform generation using a Schmitt trigger





Charging: Let $V_c(t) = A_1 \exp(-t/\tau) + B_1$, with $\tau = RC$.

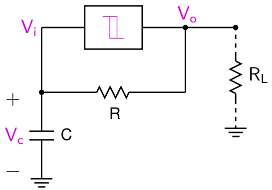
Using $V_c(0) = V_{TL}$, $V_c(\infty) = L^+$, find A_1 and B_1.

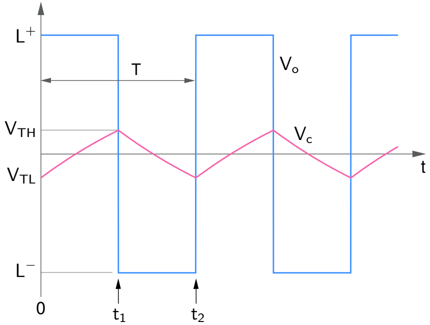
At $t = t_1$, $V_c = V_{TH} \rightarrow V_{TH} = A_1 \exp(-t_1/\tau) + B_1 \rightarrow$ find t_1.

Discharging: Let $V_c(t) = A_2 \exp(-(t - t_1)/\tau) + B_2$.

Using $V_c(t_1) = V_{TH}$, $V_c(\infty) = L^-$, find A_2 and B_2.

At $t = t_2$, $V_c = V_{TL} \rightarrow V_{TL} = A_2 \exp(-(t_2 - t_1)/\tau) + B_2 \rightarrow$ find $(t_2 - t_1) \rightarrow t_2 \rightarrow T = t_2$.





Charging: Let $V_c(t) = A_1\,\exp(-t/\tau) + B_1$, with $\tau = RC$.

Using $V_c(0) = V_{TL}$, $V_c(\infty) = L^+$, find A_1 and B_1.

At $t = t_1$, $V_c = V_{TH} \rightarrow V_{TH} = A_1\,\exp(-t_1/\tau) + B_1 \rightarrow$ find t_1.

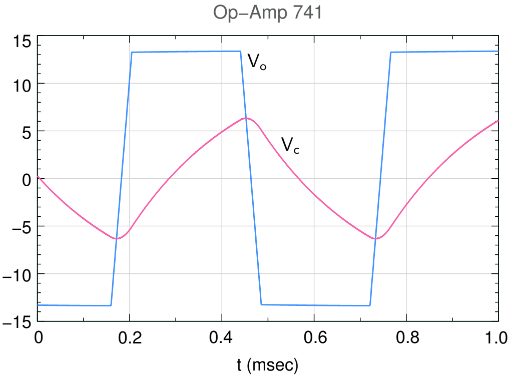
Discharging: Let $V_c(t) = A_2\,\exp(-(t-t_1)/\tau) + B_2$.

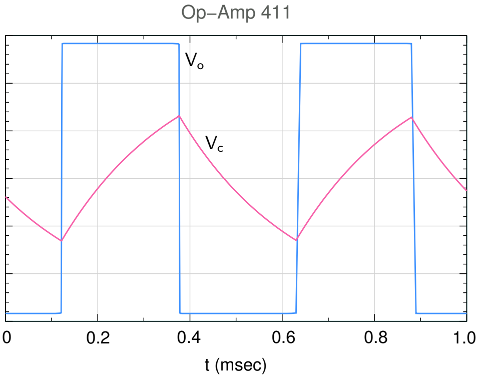
Using $V_c(t_1) = V_{TH}$, $V_c(\infty) = L^-$, find A_2 and B_2.

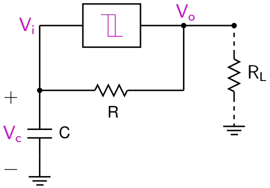
At $t = t_2$, $V_c = V_{TL} \rightarrow V_{TL} = A_2\,\exp(-(t_2-t_1)/\tau) + B_2 \rightarrow$ find $(t_2 - t_1) \rightarrow t_2 \rightarrow T = t_2$.

If $L^+ = L$, $L^- = -L$, $V_{TH} = V_T$, $V_{TL} = -V_T$, show that $T = 2\,RC\ln\left(\dfrac{L+V_T}{L-V_T}\right)$.

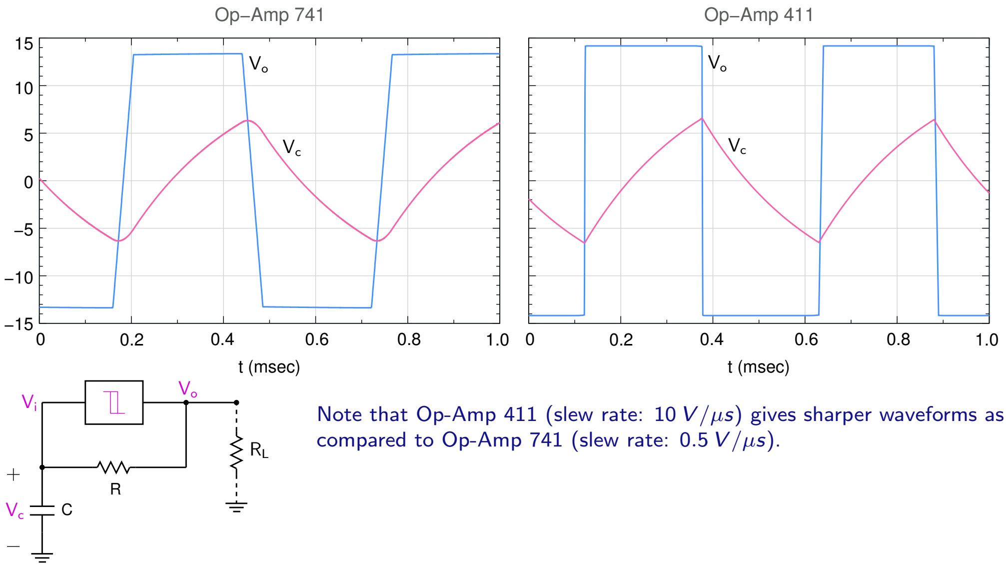
Waveform generation using a Schmitt trigger





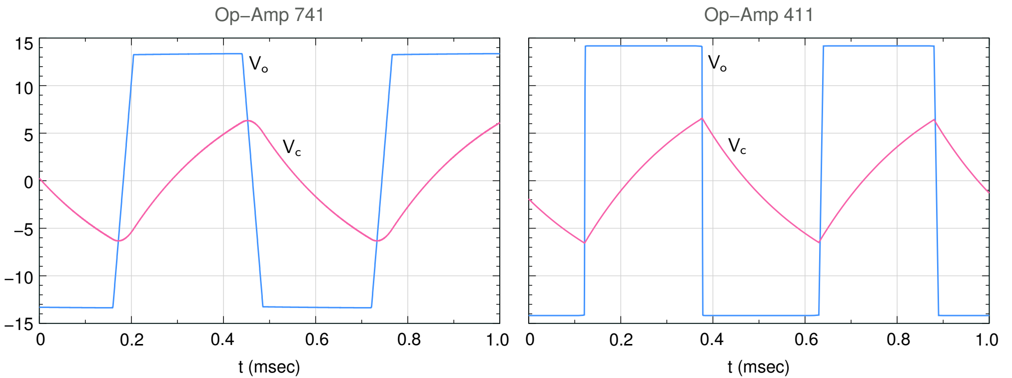


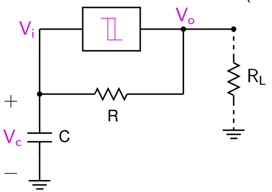
Waveform generation using a Schmitt trigger



Note that Op-Amp 411 (slew rate: 10 $V/\mu s$) gives sharper waveforms as compared to Op-Amp 741 (slew rate: 0.5 $V/\mu s$).

Waveform generation using a Schmitt trigger



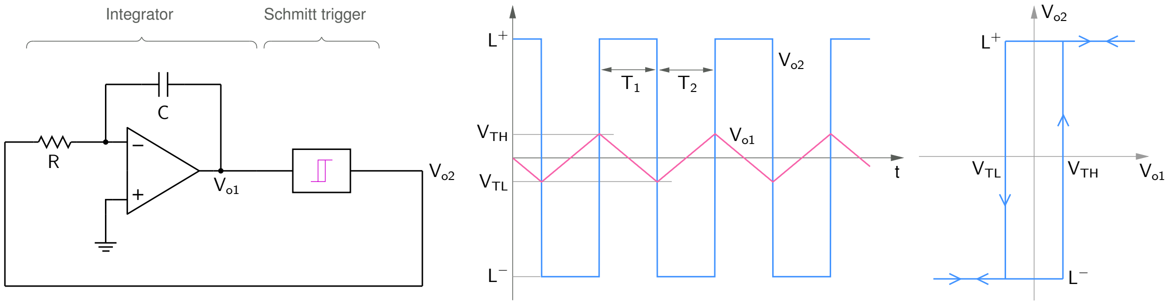


Note that Op-Amp 411 (slew rate: 10 $V/\mu s$) gives sharper waveforms as compared to Op-Amp 741 (slew rate: 0.5 $V/\mu s$).

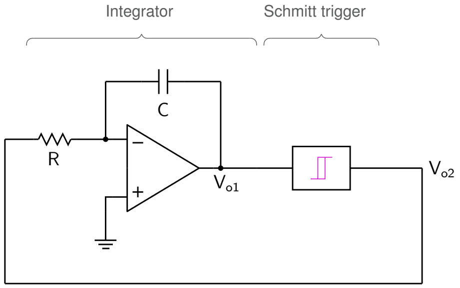
SEQUEL files: `schmitt_osc_741.sqproj`, `schmitt_osc_411.sqproj`

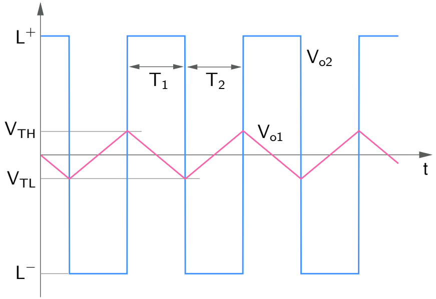
(Ref: J. M. Fiore, "Op-Amps and linear ICs")

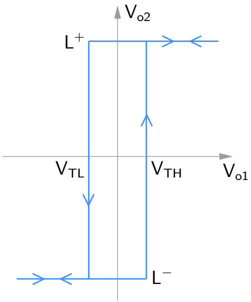
Waveform generation using a Schmitt trigger



Waveform generation using a Schmitt trigger

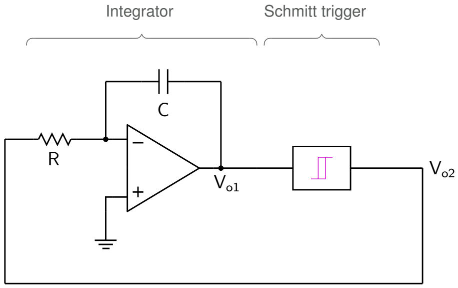


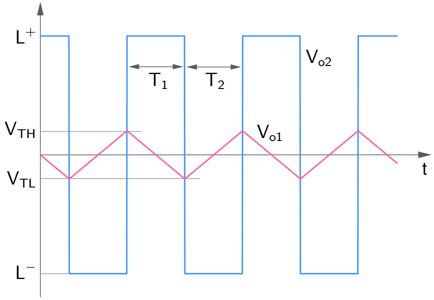


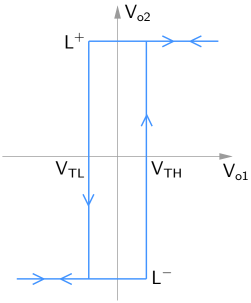


For the integrator, $V_{o1} = -\dfrac{1}{RC}\displaystyle\int V_{o2}\,dt \equiv -\dfrac{1}{\tau}\displaystyle\int V_{o2}\,dt$

Waveform generation using a Schmitt trigger



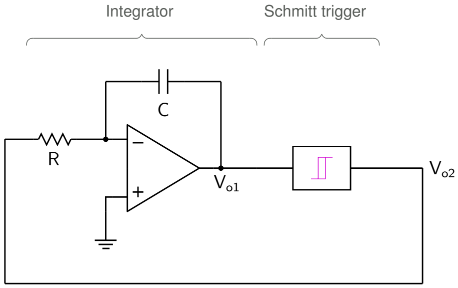


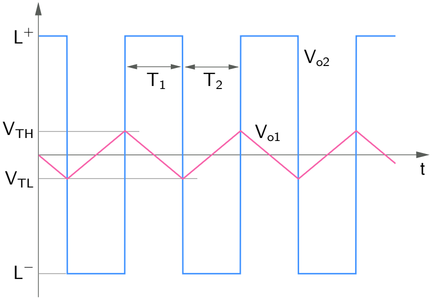


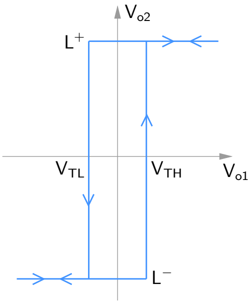
For the integrator, $V_{o1} = -\frac{1}{RC}\int V_{o2}\,dt \equiv -\frac{1}{\tau}\int V_{o2}\,dt$

$V_{o2} = L^+ \rightarrow V_{o2}$ decreases linearly, $V_{o2} = L^- \rightarrow V_{o2}$ increases linearly.

Waveform generation using a Schmitt trigger



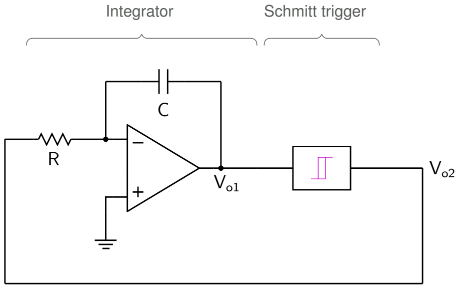


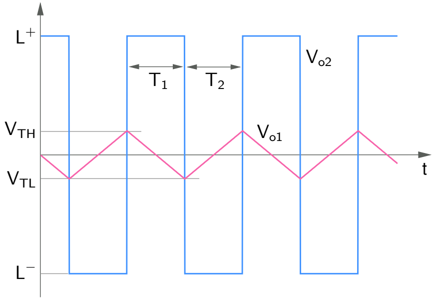


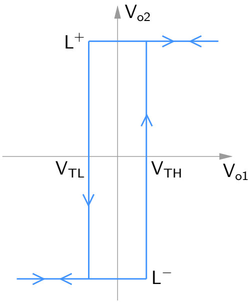
For the integrator, $V_{o1} = -\dfrac{1}{RC}\displaystyle\int V_{o2}\,dt \equiv -\dfrac{1}{\tau}\displaystyle\int V_{o2}\,dt$

$V_{o2} = L^+ \rightarrow V_{o2}$ decreases linearly, $V_{o2} = L^- \rightarrow V_{o2}$ increases linearly.

$\dfrac{dV_{o1}}{dt} = -\dfrac{V_{o2}}{\tau}$. If V_{o2} is constant, $\left|\dfrac{\Delta V_{o1}}{\Delta t}\right| = \dfrac{|V_{o2}|}{\tau} \rightarrow \Delta t = \tau\left|\dfrac{\Delta V_{o1}}{V_{o2}}\right|$







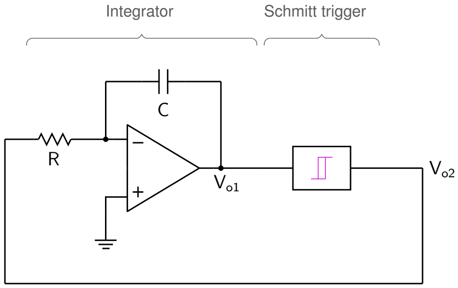
For the integrator, $V_{o1} = -\dfrac{1}{RC}\displaystyle\int V_{o2}\,dt \equiv -\dfrac{1}{\tau}\displaystyle\int V_{o2}\,dt$

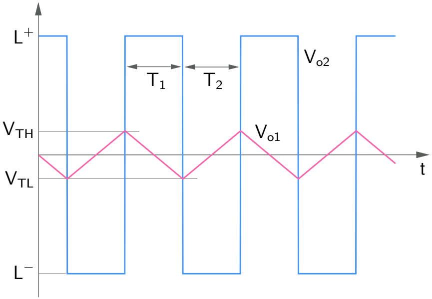
$V_{o2} = L^+ \rightarrow V_{o2}$ decreases linearly, $V_{o2} = L^- \rightarrow V_{o2}$ increases linearly.

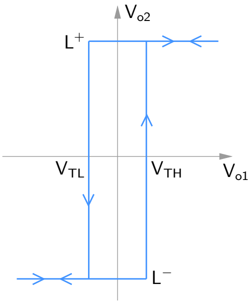
$\dfrac{dV_{o1}}{dt} = -\dfrac{V_{o2}}{\tau}$. If V_{o2} is constant, $\left|\dfrac{\Delta V_{o1}}{\Delta t}\right| = \dfrac{|V_{o2}|}{\tau} \rightarrow \Delta t = \tau\left|\dfrac{\Delta V_{o1}}{V_{o2}}\right|$

$T_1 = \tau\,\dfrac{V_{TH} - V_{TL}}{L^+}$.

Waveform generation using a Schmitt trigger







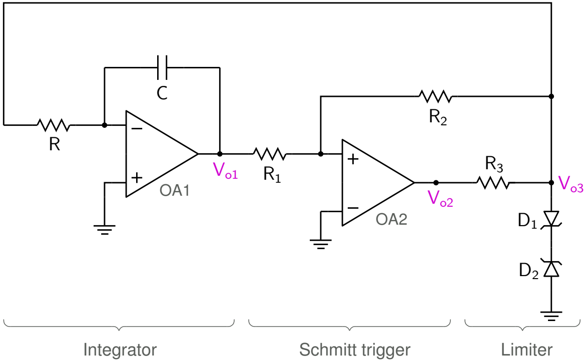
For the integrator, $V_{o1} = -\dfrac{1}{RC}\displaystyle\int V_{o2}\,dt \equiv -\dfrac{1}{\tau}\displaystyle\int V_{o2}\,dt$

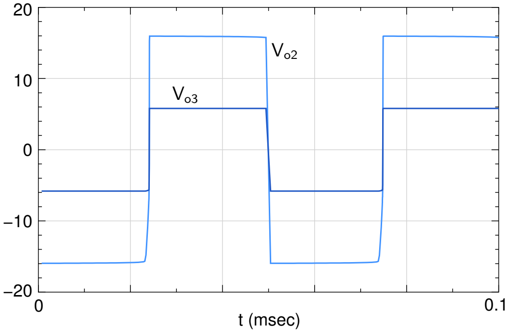
$V_{o2} = L^+ \rightarrow V_{o2}$ decreases linearly, $V_{o2} = L^- \rightarrow V_{o2}$ increases linearly.

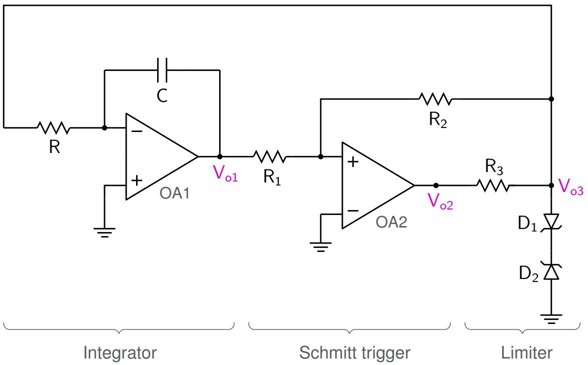
$\dfrac{dV_{o1}}{dt} = -\dfrac{V_{o2}}{\tau}$. If V_{o2} is constant, $\left|\dfrac{\Delta V_{o1}}{\Delta t}\right| = \dfrac{|V_{o2}|}{\tau} \rightarrow \Delta t = \tau \left|\dfrac{\Delta V_{o1}}{V_{o2}}\right|$

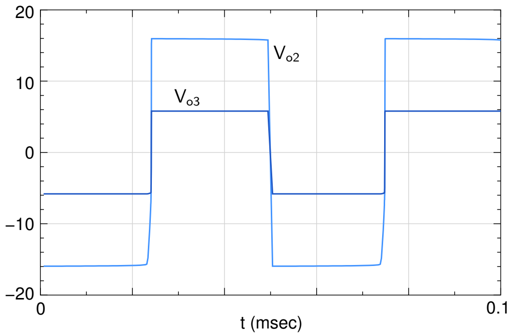
$$T_1 = \tau\,\frac{V_{TH} - V_{TL}}{L^+}\,.$$

$$T_2 = \tau\,\frac{V_{TH} - V_{TL}}{-L^-}\,.$$

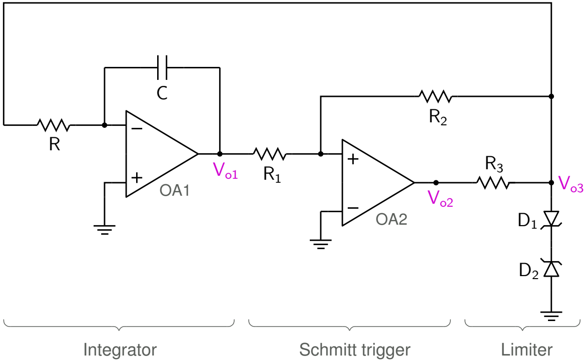

C
R
R2
R1
R3
OA1
OA2
Vo1
Vo2
Vo3
D1
D2
Integrator
Schmitt trigger
Limiter

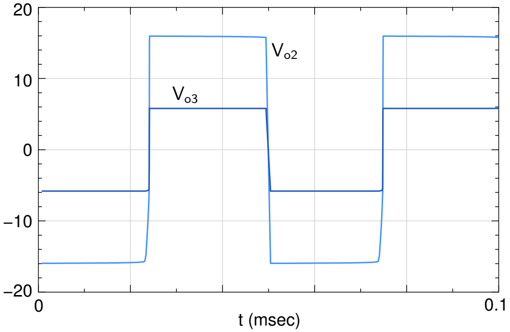

20
10
0
−10
−20
0
0.1
t (msec)
Vo2
Vo3



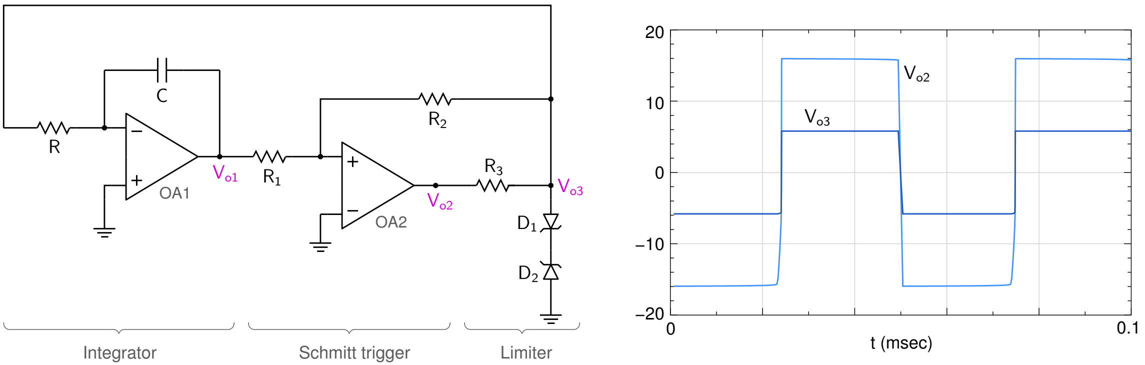


* When $V_{o2} = +V_{\rm sat}$, D_1 is forward-biased (with a voltage drop of $V_{\rm on}$), and D_2 is reverse-biased. The Zener breakdown voltage (V_Z) is chosen so that D_2 operates under breakdown condition.
  $\rightarrow V_{o3} = V_{\rm on} + V_Z$.



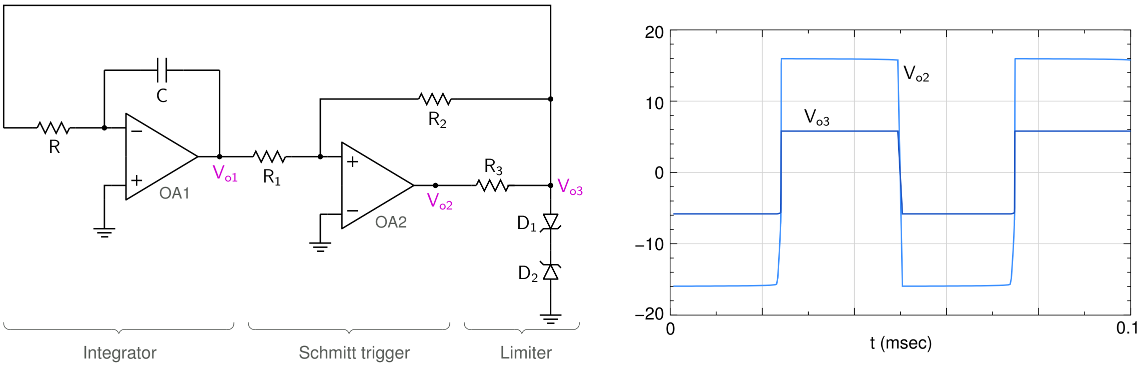


* When $V_{o2} = +V_{\text{sat}}$, D_1 is forward-biased (with a voltage drop of V_{on}), and D_2 is reverse-biased. The Zener breakdown voltage (V_Z) is chosen so that D_2 operates under breakdown condition.
  $\rightarrow V_{o3} = V_{\text{on}} + V_Z$.
* When $V_{o2} = -V_{\text{sat}}$, D_2 is forward-biased (with a voltage drop of V_{on}), and D_1 is reverse-biased.
  $\rightarrow V_{o3} = -V_{\text{on}} - V_Z$.



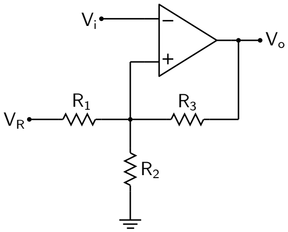
* When $V_{o2} = +V_{\rm sat}$, D_1 is forward-biased (with a voltage drop of $V_{\rm on}$), and D_2 is reverse-biased. The Zener breakdown voltage (V_Z) is chosen so that D_2 operates under breakdown condition.
  $\rightarrow$ $V_{o3} = V_{\rm on} + V_Z$.
* When $V_{o2} = -V_{\rm sat}$, D_2 is forward-biased (with a voltage drop of $V_{\rm on}$), and D_1 is reverse-biased.
  $\rightarrow$ $V_{o3} = -V_{\rm on} - V_Z$.
* R_3 serves to limit the output current for OA2.

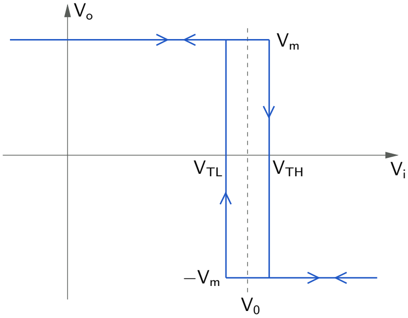
Limiting the output voltage



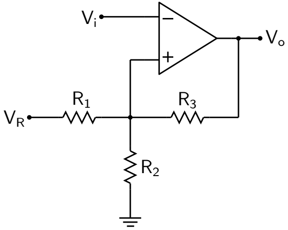
* When $V_{o2} = +V_{\rm sat}$, D_1 is forward-biased (with a voltage drop of $V_{\rm on}$), and D_2 is reverse-biased. The Zener breakdown voltage (V_Z) is chosen so that D_2 operates under breakdown condition.
  $\rightarrow V_{o3} = V_{\rm on} + V_Z$.
* When $V_{o2} = -V_{\rm sat}$, D_2 is forward-biased (with a voltage drop of $V_{\rm on}$), and D_1 is reverse-biased.
  $\rightarrow V_{o3} = -V_{\rm on} - V_Z$.
* R_3 serves to limit the output current for OA2.

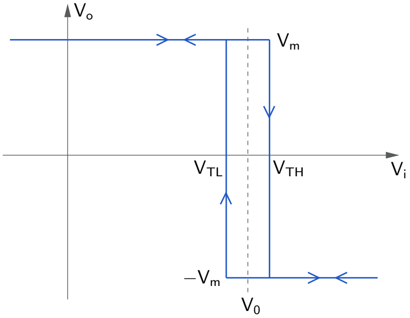
SEQUEL file: `opamp_osc_1.sqproj`





A Schmitt trigger circuit is shown in the figure along with its V_o-V_i relationship. Assume that $V_{\text{sat}} \approx 14\,\text{V}$ for the op-amp. The reference voltage V_R can be adjusted using a pot (not shown in the figure).

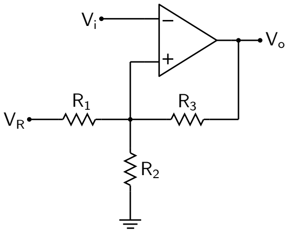


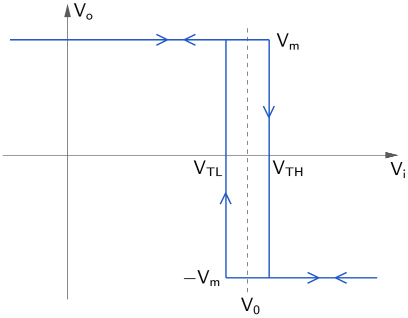


A Schmitt trigger circuit is shown in the figure along with its V_o-V_i relationship. Assume that $V_{\mathrm{sat}} \approx 14\,\mathrm{V}$ for the op-amp. The reference voltage V_R can be adjusted using a pot (not shown in the figure).

* Design the circuit to obtain $V_0 = 2.5\,\mathrm{V}$ and $\Delta V_T = V_{TH} - V_{TL} = 0.4\,\mathrm{V}$.

Schmitt trigger

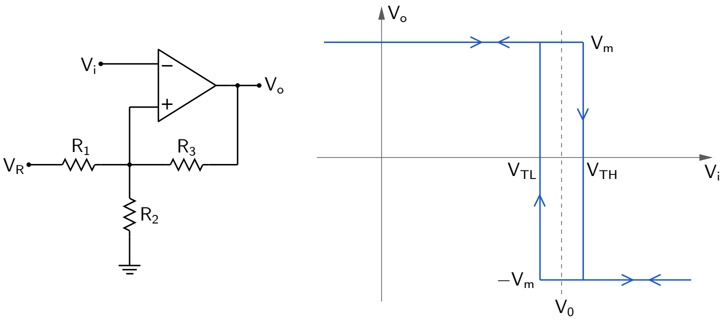




A Schmitt trigger circuit is shown in the figure along with its V_o-V_i relationship. Assume that $V_{\text{sat}} \approx 14\,\text{V}$ for the op-amp. The reference voltage V_R can be adjusted using a pot (not shown in the figure).

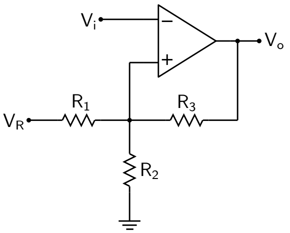
* Design the circuit to obtain $V_0 = 2.5\,\text{V}$ and $\Delta V_T = V_{TH} - V_{TL} = 0.4\,\text{V}$.
* Verify your design with simulation (and in the lab).

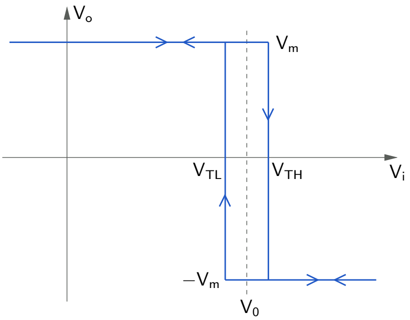
Schmitt trigger



$$V_+ = V_R \frac{(R_2 \parallel R_3)}{(R_2 \parallel R_3) + R_1} \pm V_m \frac{(R_1 \parallel R_2)}{(R_1 \parallel R_2) + R_3} .$$

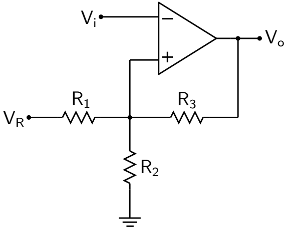
Schmitt trigger

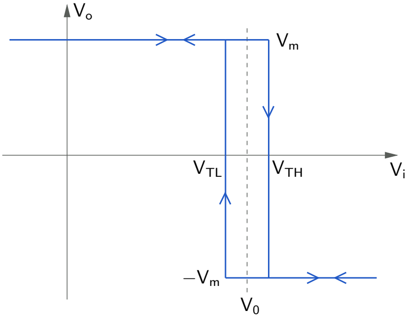




$$V_+ = V_R \frac{(R_2 \parallel R_3)}{(R_2 \parallel R_3) + R_1} \pm V_m \frac{(R_1 \parallel R_2)}{(R_1 \parallel R_2) + R_3}.$$

$$\Delta V_T = 0.4\,\text{V} \;\rightarrow\; 2V_m \frac{(R_1 \parallel R_2)}{(R_1 \parallel R_2) + R_3} = 0.4\,\text{V}.$$



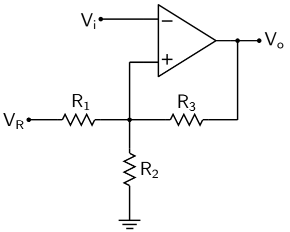


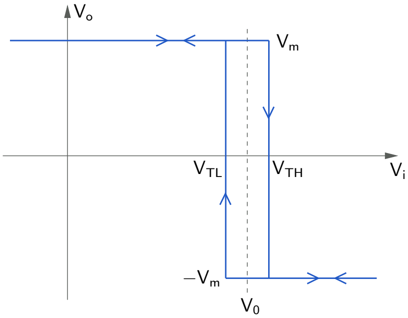
$$V_+ = V_R \frac{(R_2 \parallel R_3)}{(R_2 \parallel R_3) + R_1} \pm V_m \frac{(R_1 \parallel R_2)}{(R_1 \parallel R_2) + R_3}.$$

$$\Delta V_T = 0.4\,\text{V} \;\rightarrow\; 2V_m \frac{(R_1 \parallel R_2)}{(R_1 \parallel R_2) + R_3} = 0.4\,\text{V}.$$

$$V_0 = 2.5\,\text{V} \;\rightarrow\; V_R \frac{(R_2 \parallel R_3)}{(R_2 \parallel R_3) + R_1} = 2.5\,\text{V}.$$

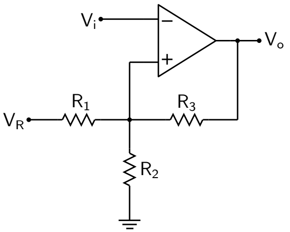
Schmitt trigger

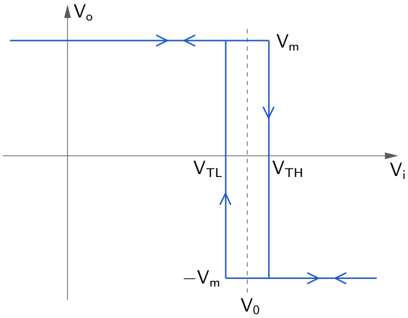




$$\Delta V_T = 0.4\,\text{V} \;\rightarrow\; 2V_m \frac{(R_1 \parallel R_2)}{(R_1 \parallel R_2) + R_3} = 0.4\,\text{V}.$$

Schmitt trigger

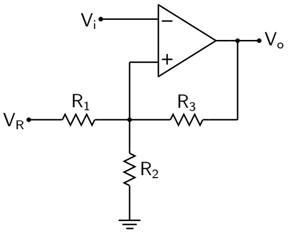


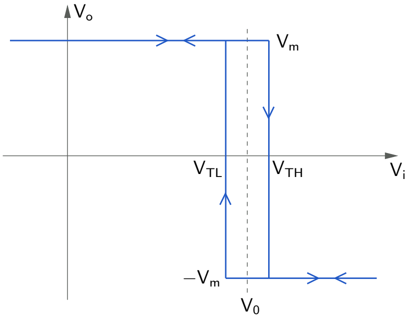


$$\Delta V_T = 0.4\,\text{V} \;\rightarrow\; 2V_m \frac{(R_1 \parallel R_2)}{(R_1 \parallel R_2) + R_3} = 0.4\,\text{V}.$$

$$\text{Let } R_1 = R_2 = 5\,\text{k} \;\rightarrow\; 2V_{sat} \frac{(R/2)}{(R/2) + R_3} = 0.4\,\text{V} \;\rightarrow\; R_3 = 172.5\,\text{k}.$$

Schmitt trigger



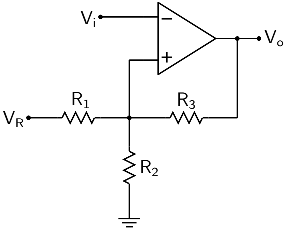


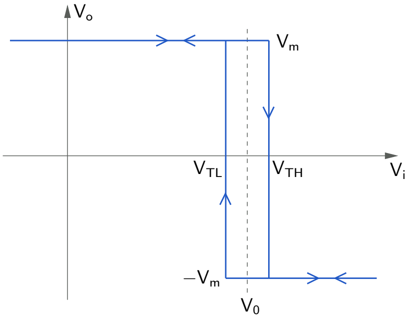
$$\Delta V_T = 0.4\,\text{V} \;\rightarrow\; 2V_m \frac{(R_1 \parallel R_2)}{(R_1 \parallel R_2) + R_3} = 0.4\,\text{V}.$$

$$\text{Let } R_1 = R_2 = 5\,\text{k} \;\rightarrow\; 2V_{\text{sat}} \frac{(R/2)}{(R/2) + R_3} = 0.4\,\text{V} \;\rightarrow\; R_3 = 172.5\,\text{k}.$$

$$V_0 = 2.5\,\text{V} \;\rightarrow\; V_R \frac{(R_2 \parallel R_3)}{(R_2 \parallel R_3) + R_1} = 2.5\,\text{V} \;\rightarrow\; V_R = 5.07\,\text{V}.$$

Schmitt trigger



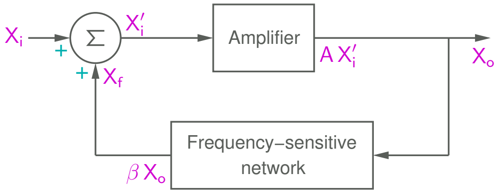


$$\Delta V_T = 0.4\,\mathrm{V} \;\rightarrow\; 2V_m \frac{(R_1 \parallel R_2)}{(R_1 \parallel R_2) + R_3} = 0.4\,\mathrm{V}.$$

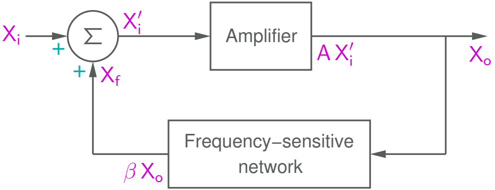
Let $R_1 = R_2 = 5\,\mathrm{k} \;\rightarrow\; 2V_{\mathrm{sat}} \dfrac{(R/2)}{(R/2) + R_3} = 0.4\,\mathrm{V} \;\rightarrow\; R_3 = 172.5\,\mathrm{k}.$

$$V_0 = 2.5\,\mathrm{V} \;\rightarrow\; V_R \frac{(R_2 \parallel R_3)}{(R_2 \parallel R_3) + R_1} = 2.5\,\mathrm{V} \;\rightarrow\; V_R = 5.07\,\mathrm{V}.$$

(SEQUEL file: `schmitt_1.sqproj`)

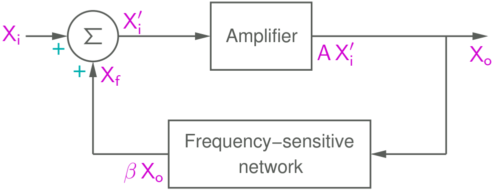


Consider an amplifier with feedback.



Consider an amplifier with feedback.

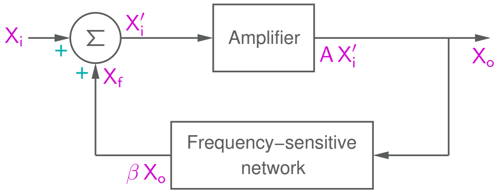
$X_o = A\,X_i' = A\,(X_i + X_f) = A\,(X_i + \beta X_o) = A\,X_i + A\,\beta\,X_o$



Consider an amplifier with feedback.

$X_o = A\,X_i' = A\,(X_i + X_f) = A\,(X_i + \beta X_o) = A\,X_i + A\,\beta\,X_o$

$\rightarrow A_f \equiv \dfrac{X_o}{X_i} = \dfrac{A}{1 - A\beta}$.



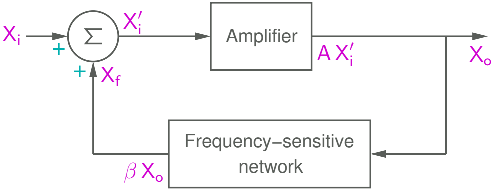
Consider an amplifier with feedback.

$X_o = A\,X_i' = A\,(X_i + X_f) = A\,(X_i + \beta X_o) = A\,X_i + A\,\beta\,X_o$

$\rightarrow A_f \equiv \dfrac{X_o}{X_i} = \dfrac{A}{1 - A\beta}$.

Since A and β will generally vary with ω, we re-write A_f as

$$A_f(j\omega) = \frac{A\,(j\omega)}{1 - A\,(j\omega)\,\beta\,(j\omega)}.$$



Consider an amplifier with feedback.

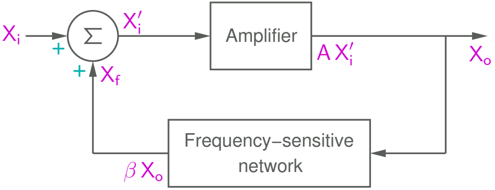
$X_o = A\,X_i' = A\,(X_i + X_f) = A\,(X_i + \beta X_o) = A\,X_i + A\,\beta\,X_o$

$$\rightarrow A_f \equiv \frac{X_o}{X_i} = \frac{A}{1 - A\beta}.$$

Since A and β will generally vary with ω, we re-write A_f as

$$A_f(j\omega) = \frac{A\,(j\omega)}{1 - A\,(j\omega)\,\beta\,(j\omega)}.$$

As $A\,(j\omega)\,\beta\,(j\omega) \rightarrow 1$, $A_f(j\omega) \rightarrow \infty$, and we get a finite $X_o\,(= A_f\,X_i)$ even if $X_i = 0$.



Consider an amplifier with feedback.

$X_o = A\,X_i' = A\,(X_i + X_f) = A\,(X_i + \beta X_o) = A\,X_i + A\,\beta\,X_o$

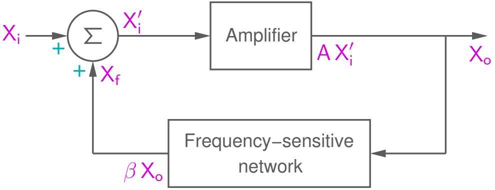
$\rightarrow A_f \equiv \dfrac{X_o}{X_i} = \dfrac{A}{1 - A\beta}.$

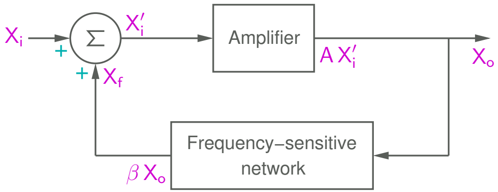
Since A and β will generally vary with ω, we re-write A_f as

$A_f(j\omega) = \dfrac{A\,(j\omega)}{1 - A\,(j\omega)\,\beta\,(j\omega)}.$

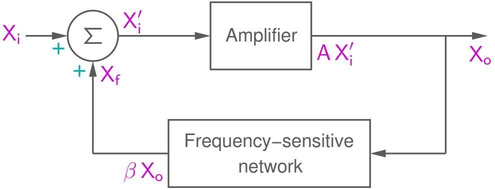
As $A\,(j\omega)\,\beta\,(j\omega) \rightarrow 1$, $A_f(j\omega) \rightarrow \infty$, and we get a finite $X_o\,(= A_f\,X_i)$ even if $X_i = 0$.

In other words, we can remove X_i and still get a non-zero X_o. This is the basic principle behind sinusoidal oscillators.

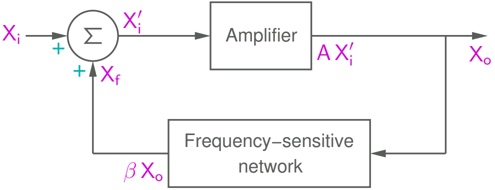

X_i
+
Σ
X_i'
Amplifier
$A\,X_i'$
X_o
+
X_f
Frequency−sensitive
network
$\beta\,X_o$



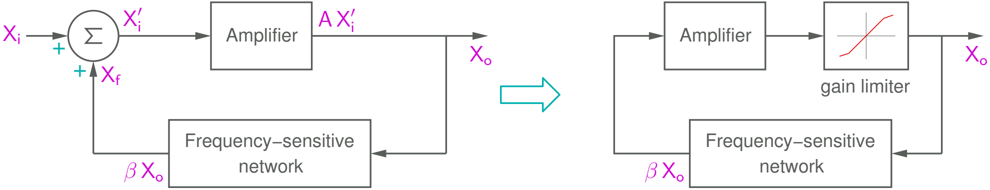
* The condition, $A\,(j\omega)\,\beta\,(j\omega) = 1$, for a circuit to oscillate spontaneously (i.e., without any input), is known as the Barkhausen criterion.

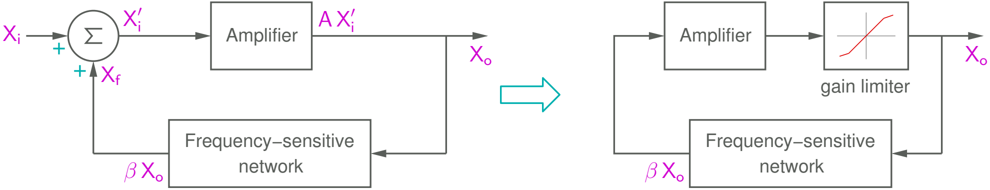


* The condition, $A\,(j\omega)\,\beta\,(j\omega) = 1$, for a circuit to oscillate spontaneously (i.e., without any input), is known as the Barkhausen criterion.
* For the circuit to oscillate at $\omega = \omega_0$, the β network is designed such that the Barkhausen criterion is satisfied only for ω_0, i.e., all components except ω_0 get attenuated to zero.

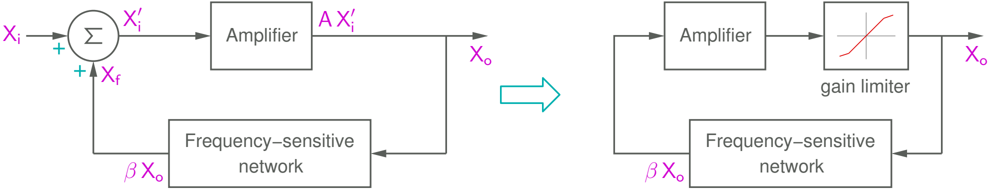


* The condition, $A\,(j\omega)\,\beta\,(j\omega) = 1$, for a circuit to oscillate spontaneously (i.e., without any input), is known as the Barkhausen criterion.
* For the circuit to oscillate at $\omega = \omega_0$, the β network is designed such that the Barkhausen criterion is satisfied only for ω_0, i.e., all components except ω_0 get attenuated to zero.
* The output X_o will therefore have a frequency ω_0 ($\omega_0/2\pi$ in Hz), but what about the amplitude?

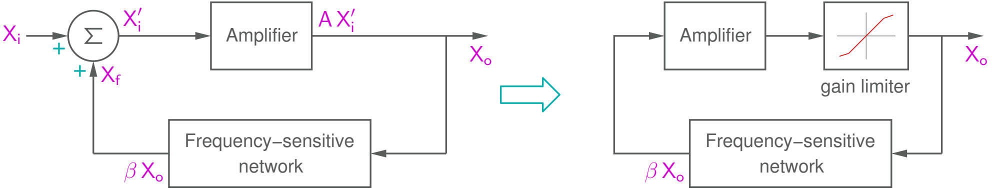

X_i
+
+
Σ
X_i'
X_f
Amplifier
$A\,X_i'$
X_o
Frequency−sensitive network
$\beta\,X_o$
Amplifier
gain limiter
X_o
Frequency−sensitive network
$\beta\,X_o$



* A gain limiting mechanism is required to limit the amplitude of the oscillations.

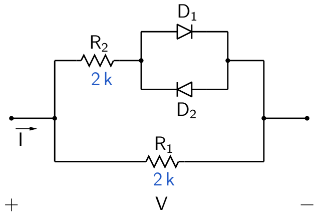


* A gain limiting mechanism is required to limit the amplitude of the oscillations.
* Amplifier clipping can provide a gain limiter mechanism. For example, in an op-amp, the output voltage is limited to $\pm V_{\mathrm{sat}}$, and this serves to limit the gain as the magnitude of the output voltage increases.



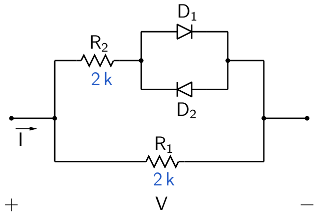
* A gain limiting mechanism is required to limit the amplitude of the oscillations.
* Amplifier clipping can provide a gain limiter mechanism. For example, in an op-amp, the output voltage is limited to $\pm V_{sat}$, and this serves to limit the gain as the magnitude of the output voltage increases.
* For a more controlled output with low distortion, diode-resistor networks are used for gain limiting.

Gain limiting network: example

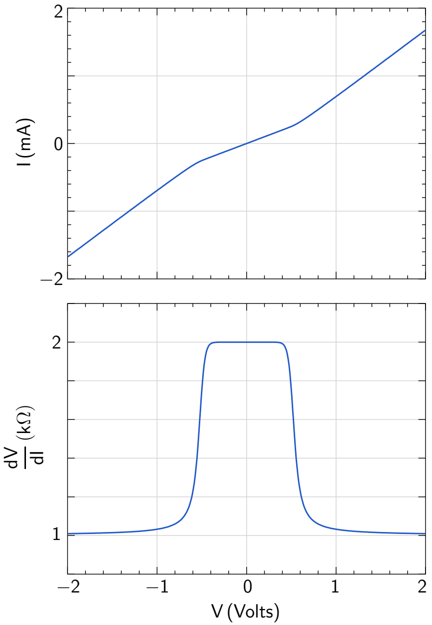


SEQUEL file: ee101_diode_circuit_14.sqproj

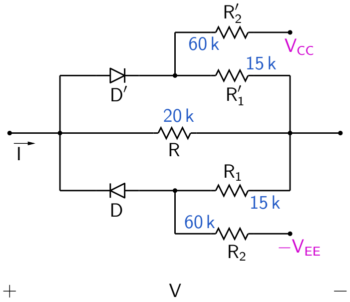
Gain limiting network: example



SEQUEL file: ee101_diode_circuit_14.sqproj

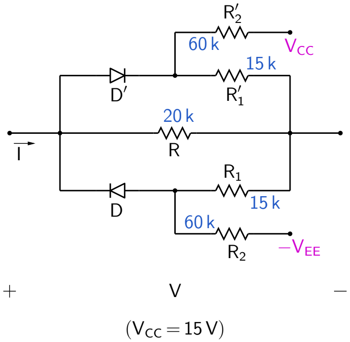


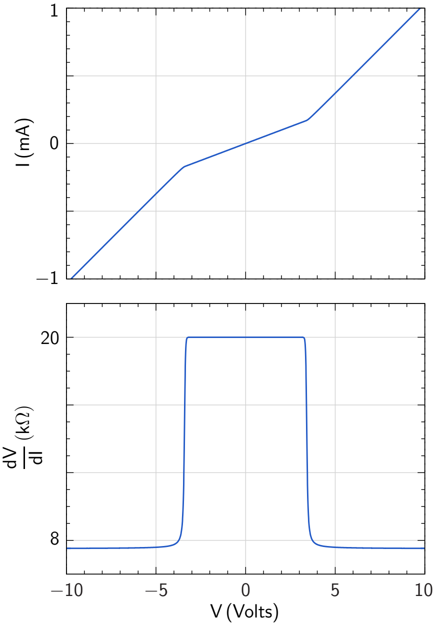
Gain limiting network: example

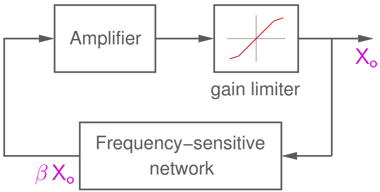


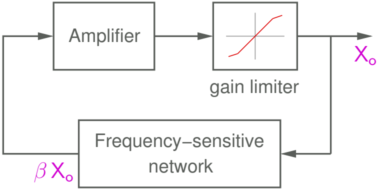
$(V_{CC} = 15\,\text{V})$

Gain limiting network: example

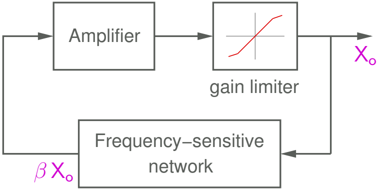




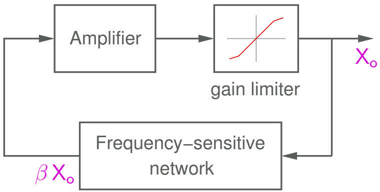

Amplifier
gain limiter
X_o
Frequency−sensitive network
$\beta\, X_o$



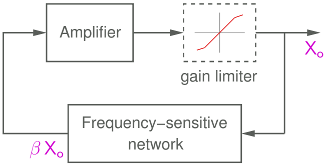
* Up to about 100 kHz, an op-amp based amplifier and a β network of resistors and capacitors can be used.

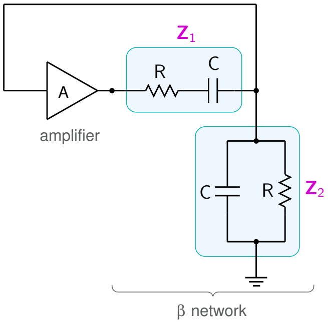


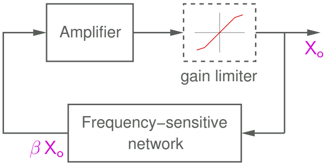
* Up to about 100 kHz, an op-amp based amplifier and a β network of resistors and capacitors can be used.
* At higher frequencies, an op-amp based amplifier is not suitable because of frequency response and slew rate limitations of op-amps.

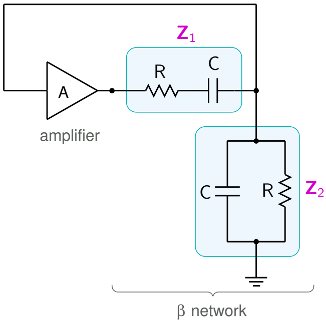


* Up to about 100 kHz, an op-amp based amplifier and a β network of resistors and capacitors can be used.
* At higher frequencies, an op-amp based amplifier is not suitable because of frequency response and slew rate limitations of op-amps.
* For high frequencies, transistor amplifiers are used, and LC tuned circuits or piezoelectric crystals are used in the β network.


Amplifier
gain limiter
X_o
Frequency−sensitive network
βX_o

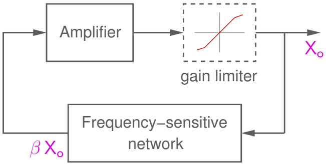

Z_1
R
C
A
amplifier
C
R
Z_2
β network

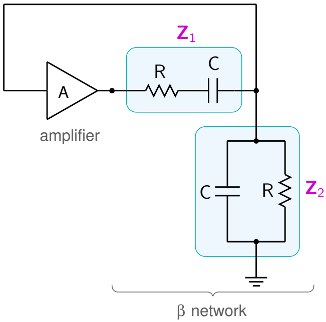




Assuming $R_{\text{in}} \rightarrow \infty$ for the amplifier, we get

$$A(s)\,\beta(s) = A\,\frac{Z_2}{Z_1 + Z_2} = A\,\frac{R \parallel (1/sC)}{R + (1/sC) + R \parallel (1/sC)} = A\,\frac{sRC}{(sRC)^2 + 3sRC + 1}\,.$$



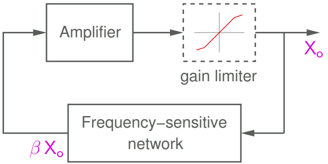


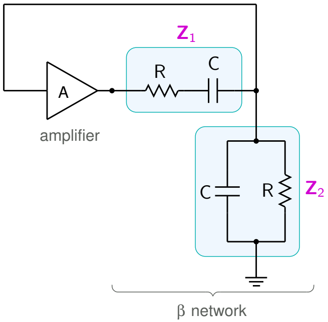
Assuming $R_{\text{in}} \rightarrow \infty$ for the amplifier, we get

$$A(s)\,\beta(s) = A\,\frac{Z_2}{Z_1+Z_2} = A\,\frac{R \parallel (1/sC)}{R+(1/sC)+R \parallel (1/sC)} = A\,\frac{sRC}{(sRC)^2+3sRC+1}.$$

For $A\,\beta = 1$ (and with A equal to a real positive number),

$\dfrac{j\omega RC}{-\omega^2(RC)^2+3j\omega RC+1}$ must be real and equal to $1/A$.





Assuming $R_{\text{in}} \rightarrow \infty$ for the amplifier, we get

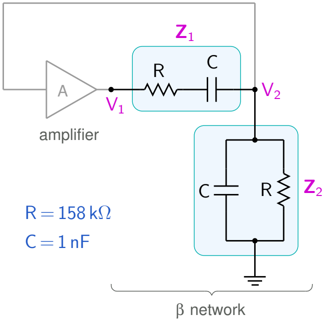
$$A(s)\,\beta(s) = A\,\frac{Z_2}{Z_1 + Z_2} = A\,\frac{R \parallel (1/sC)}{R + (1/sC) + R \parallel (1/sC)} = A\,\frac{sRC}{(sRC)^2 + 3sRC + 1}.$$

For $A\,\beta = 1$ (and with A equal to a real positive number),

$\dfrac{j\omega RC}{-\omega^2 (RC)^2 + 3j\omega RC + 1}$ must be real and equal to $1/A$.

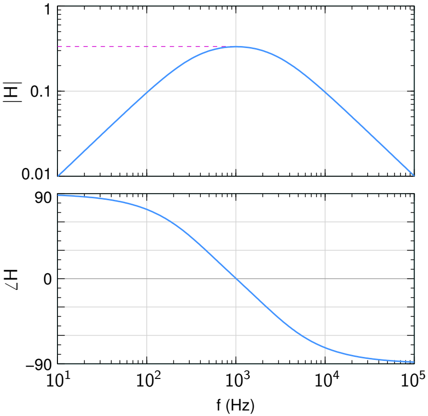
$$\rightarrow \boxed{\omega = \frac{1}{RC},\ A = 3}$$

Wien bridge oscillator



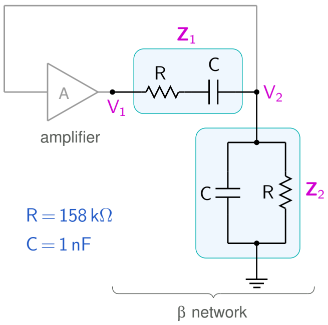
$R = 158\,\text{k}\Omega$

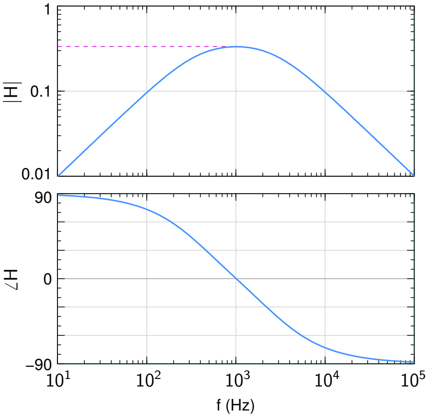
$C = 1\,\text{nF}$



$$H(j\omega) = \frac{V_2(j\omega)}{V_1(j\omega)} = \frac{j\omega RC}{-\omega^2(RC)^2 + 3j\omega RC + 1}.$$

Wien bridge oscillator



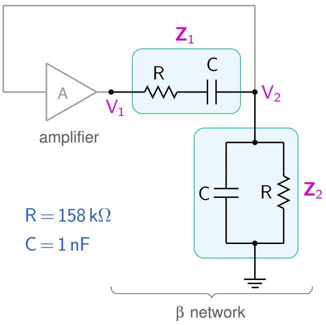


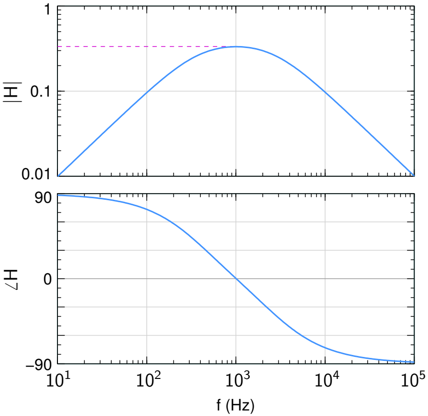
$$H(j\omega) = \frac{V_2(j\omega)}{V_1(j\omega)} = \frac{j\omega RC}{-\omega^2(RC)^2 + 3j\omega RC + 1}.$$

Note that the condition $\angle H = 0$ is satisfied only at one frequency, $\omega_0 = 1/RC$, i.e., $f_0 = 1\,\text{kHz}$.

At this frequency, $|H| = 0.33$, i.e., $\beta(j\omega) = 1/3$.

Wien bridge oscillator



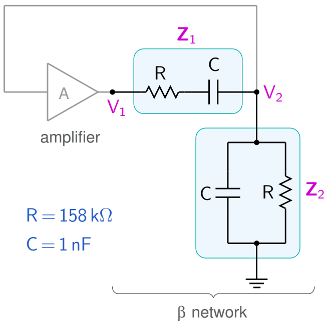


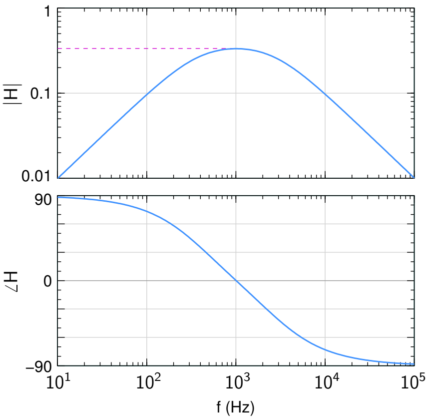
$$H(j\omega) = \frac{V_2(j\omega)}{V_1(j\omega)} = \frac{j\omega RC}{-\omega^2(RC)^2 + 3j\omega RC + 1}.$$

Note that the condition $\angle H = 0$ is satisfied only at one frequency, $\omega_0 = 1/RC$, i.e., $f_0 = 1\,\text{kHz}$.

At this frequency, $|H| = 0.33$, i.e., $\beta(j\omega) = 1/3$.

For $A\,\beta = 1 \rightarrow A = 3$, as derived analytically.





$$H(j\omega) = \frac{V_2(j\omega)}{V_1(j\omega)} = \frac{j\omega RC}{-\omega^2(RC)^2 + 3j\omega RC + 1}.$$

Note that the condition $\angle H = 0$ is satisfied only at one frequency, $\omega_0 = 1/RC$, i.e., $f_0 = 1\,\text{kHz}$.

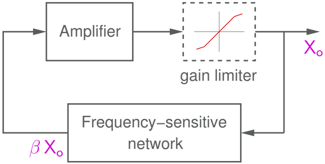
At this frequency, $|H| = 0.33$, i.e., $\beta(j\omega) = 1/3$.

For $A\,\beta = 1 \rightarrow A = 3$, as derived analytically.

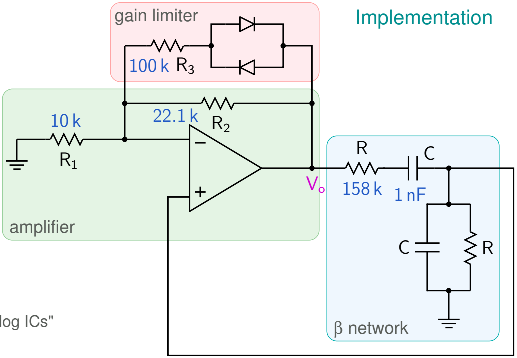
SEQUEL file: `ee101_osc_1.sqproj`

Wien bridge oscillator

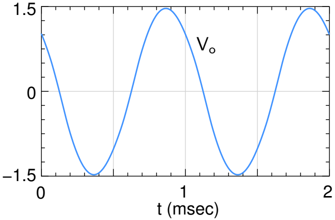
Block diagram



Implementation



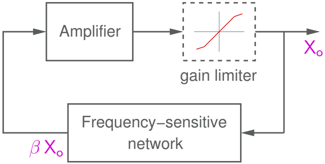
Output voltage



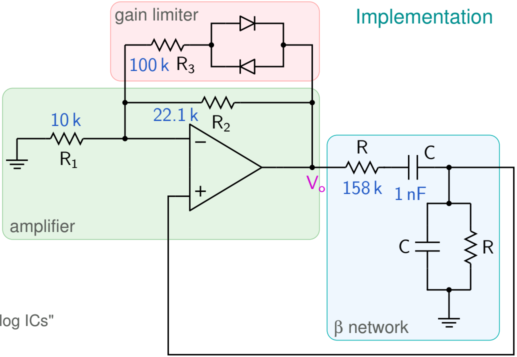
Ref.: S. Franco, "Design with Op Amps and analog ICs"

SEQUEL file: wien_osc_1.sqproj

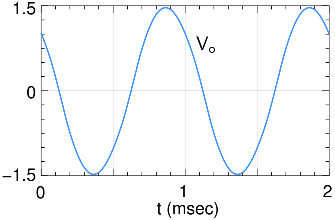
Block diagram



Implementation



Output voltage

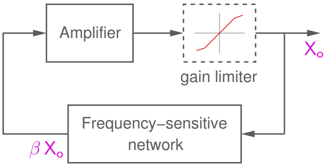


Ref.: S. Franco, "Design with Op Amps and analog ICs"

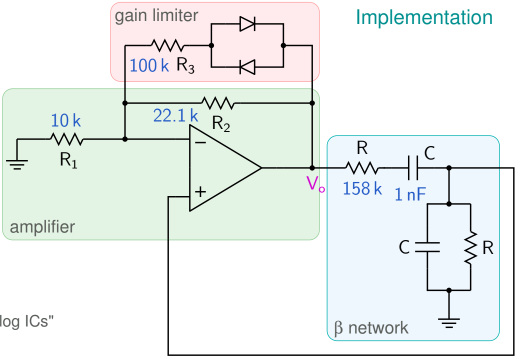
SEQUEL file: wien_osc_1.sqproj

* $\omega_0 = \dfrac{1}{RC} = \dfrac{1}{(158\,\text{k}) \times (1\,\text{nF})} \rightarrow f_0 = 1\,\text{kHz}.$

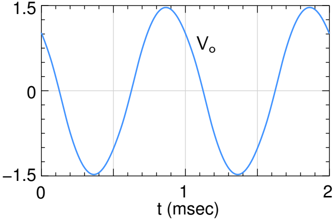
Block diagram



Implementation



Output voltage



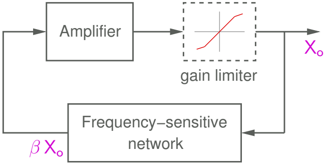
Ref.: S. Franco, "Design with Op Amps and analog ICs"

SEQUEL file: wien_osc_1.sqproj

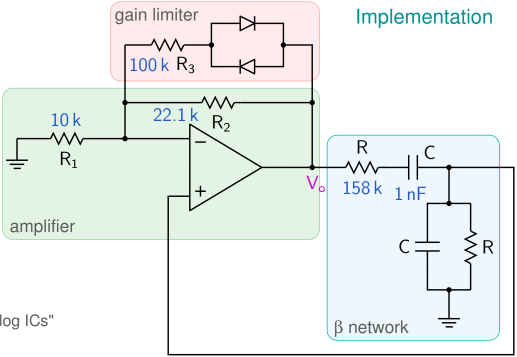
* $\omega_0 = \dfrac{1}{RC} = \dfrac{1}{(158\,\text{k}) \times (1\,\text{nF})} \rightarrow f_0 = 1\,\text{kHz}.$
* Since the amplifier gain is required to be $A = 3$, we must have $1 + \dfrac{R_2}{R_1} = 3 \rightarrow R_2 = 2\,R_1$.

Wien bridge oscillator

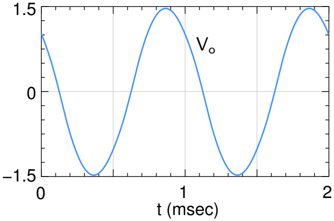
Block diagram



Implementation



Output voltage

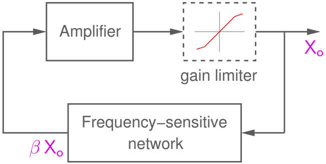


Ref.: S. Franco, "Design with Op Amps and analog ICs"

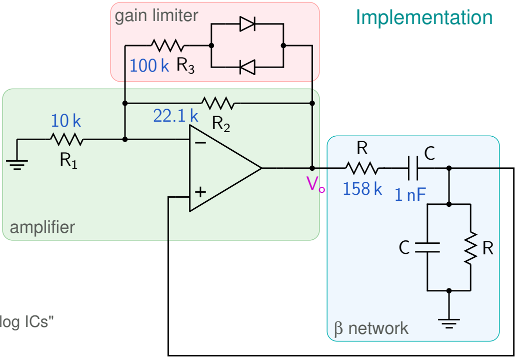
SEQUEL file: wien_osc_1.sqproj

* $\omega_0 = \dfrac{1}{RC} = \dfrac{1}{(158\,\text{k}) \times (1\,\text{nF})} \rightarrow f_0 = 1\,\text{kHz}.$
* Since the amplifier gain is required to be $A = 3$, we must have $1 + \dfrac{R_2}{R_1} = 3 \rightarrow R_2 = 2\,R_1$.
* For gain limiting, diodes have been used. With one of the two diodes conducting, $R_2 \rightarrow R_2 \parallel R_3$, and the gain reduces.

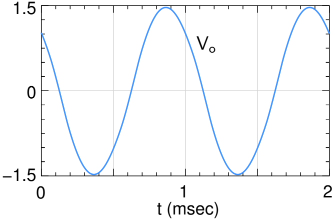
Block diagram



Implementation



Output voltage

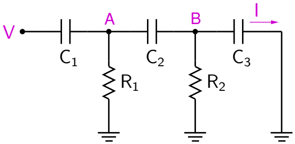


Ref.: S. Franco, "Design with Op Amps and analog ICs"

SEQUEL file: wien_osc_1.sqproj

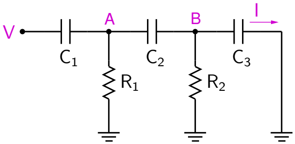
* $\omega_0 = \dfrac{1}{RC} = \dfrac{1}{(158\,\text{k}) \times (1\,\text{nF})} \rightarrow f_0 = 1\,\text{kHz}.$
* Since the amplifier gain is required to be $A = 3$, we must have $1 + \dfrac{R_2}{R_1} = 3 \rightarrow R_2 = 2\,R_1$.
* For gain limiting, diodes have been used. With one of the two diodes conducting, $R_2 \rightarrow R_2 \parallel R_3$, and the gain reduces.
* Note that there was no need to consider loading of the β network by the amplifier because of the large input resistance of the op-amp. That is why β could be computed independently.

Phase-shift oscillator



SEQUEL file: ee101_osc_4.sqproj

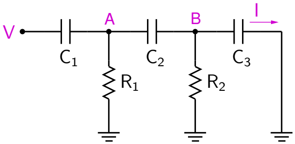
Phase-shift oscillator



SEQUEL file: ee101_osc_4.sqproj

Let $R_1 = R_2 = R = 10\,\mathrm{k}$, $G = 1/R$, and $C_1 = C_2 = C_3 = C = 16\,\mathrm{n}F$.

Phase-shift oscillator



SEQUEL file: ee101_osc_4.sqproj

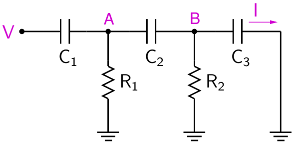
Let $R_1 = R_2 = R = 10\,\text{k}$, $G = 1/R$, and $C_1 = C_2 = C_3 = C = 16\,\text{n}F$.

Using nodal analysis,

$$sC(V_A - V) + GV_A + sC(V_A - V_B) = 0 \qquad (1)$$

$$sC(V_B - V_A) + GV_B + sCV_B = 0 \qquad (2)$$

Phase-shift oscillator



SEQUEL file: ee101_osc_4.sqproj

Let $R_1 = R_2 = R = 10\,\text{k}$, $G = 1/R$, and $C_1 = C_2 = C_3 = C = 16\,\text{n}F$.

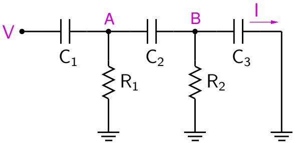
Using nodal analysis,

$$sC(V_A - V) + GV_A + sC(V_A - V_B) = 0 \qquad (1)$$

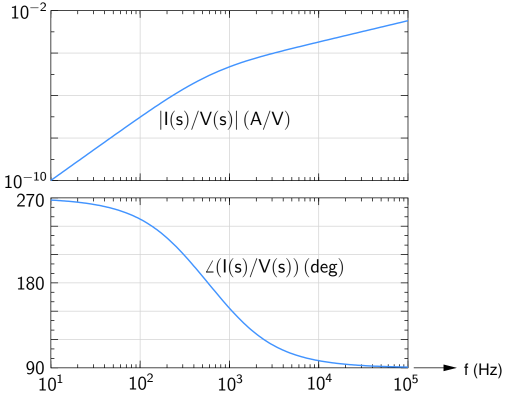
$$sC(V_B - V_A) + GV_B + sCV_B = 0 \qquad (2)$$

Solving (1) and (2), we get $I = \dfrac{1}{R} \dfrac{(sRC)^3}{3\,(sRC)^2 + 4\,sRC + 1}\,V$.

Phase-shift oscillator



SEQUEL file: ee101_osc_4.sqproj



Let $R_1 = R_2 = R = 10\,\text{k}$, $G = 1/R$, and $C_1 = C_2 = C_3 = C = 16\,nF$.

Using nodal analysis,

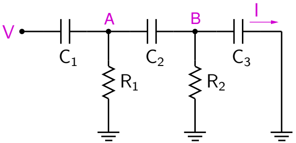
$$sC(V_A - V) + GV_A + sC(V_A - V_B) = 0 \qquad (1)$$

$$sC(V_B - V_A) + GV_B + sCV_B = 0 \qquad (2)$$

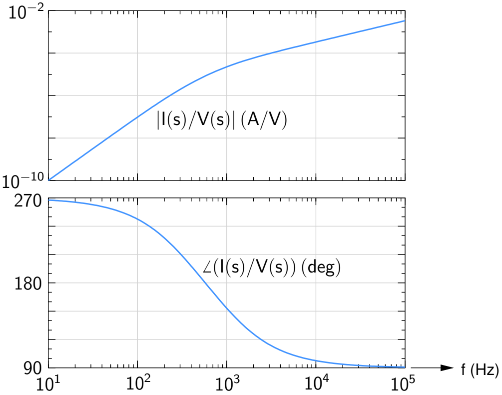
Solving (1) and (2), we get $I = \dfrac{1}{R}\,\dfrac{(sRC)^3}{3\,(sRC)^2 + 4\,sRC + 1}\,V$.

M. B. Patil, IIT Bombay

Phase-shift oscillator



SEQUEL file: ee101_osc_4.sqproj



Let $R_1 = R_2 = R = 10\,\text{k}$, $G = 1/R$, and $C_1 = C_2 = C_3 = C = 16\,\text{n}F$.

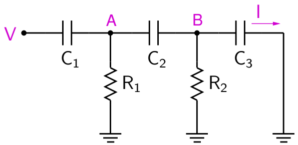
Using nodal analysis,

$$sC(V_A - V) + GV_A + sC(V_A - V_B) = 0 \qquad (1)$$

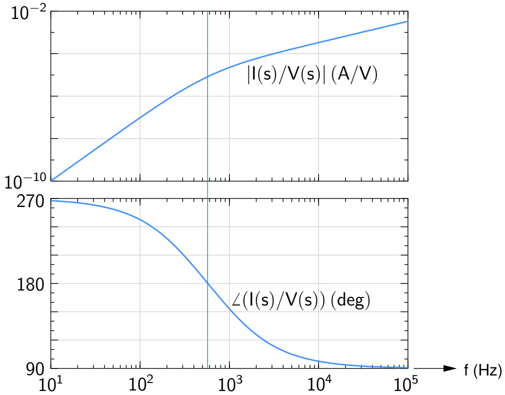
$$sC(V_B - V_A) + GV_B + sCV_B = 0 \qquad (2)$$

Solving (1) and (2), we get $I = \dfrac{1}{R}\,\dfrac{(sRC)^3}{3\,(sRC)^2 + 4\,sRC + 1}\,V$.

Phase-shift oscillator

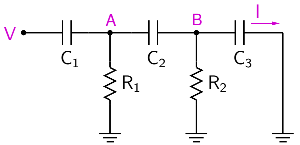


SEQUEL file: ee101_osc_4.sqproj

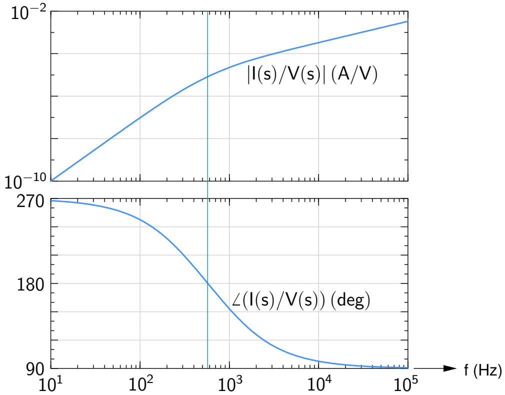


($R_1 = R_2 = R = 10\,\text{k}$, and $C_1 = C_2 = C_3 = C = 16\,\text{n}F$.)

$$\beta(j\omega) = \frac{I(j\omega)}{V(j\omega)} = \frac{1}{R}\,\frac{(j\omega RC)^3}{3(j\omega RC)^2 + 4\,j\omega RC + 1}.$$



SEQUEL file: ee101_osc_4.sqproj

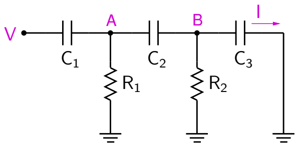


$(R_1 = R_2 = R = 10\,\text{k}$, and $C_1 = C_2 = C_3 = C = 16\,\text{n}F$.)

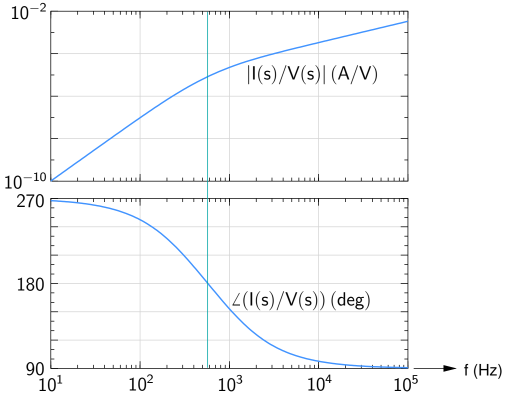
$$\beta(j\omega) = \frac{I(j\omega)}{V(j\omega)} = \frac{1}{R}\,\frac{(j\omega RC)^3}{3(j\omega RC)^2 + 4\,j\omega RC + 1}.$$

For $\beta(j\omega)$ to be a real number, the denominator must be purely imaginary.

$$\rightarrow -3(\omega RC)^2 + 1 = 0, \text{ i.e., } 3(\omega RC)^2 = 1 \rightarrow \omega \equiv \omega_0 = \frac{1}{\sqrt{3}}\,\frac{1}{RC} \rightarrow f_0 = 574\,\text{Hz}\,.$$



SEQUEL file: ee101_osc_4.sqproj



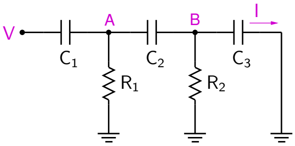
$(R_1 = R_2 = R = 10\,\text{k}$, and $C_1 = C_2 = C_3 = C = 16\,\text{n}F.)$

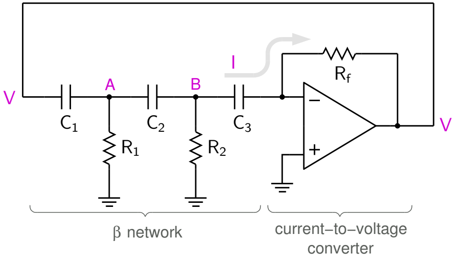
$$\beta(j\omega) = \frac{I(j\omega)}{V(j\omega)} = \frac{1}{R}\,\frac{(j\omega RC)^3}{3(j\omega RC)^2 + 4\,j\omega RC + 1}.$$

For $\beta(j\omega)$ to be a real number, the denominator must be purely imaginary.

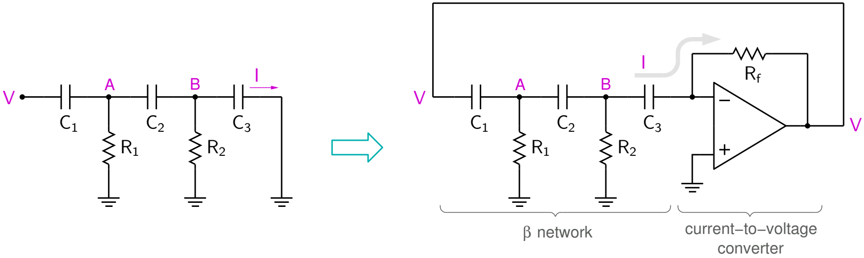
$$\rightarrow -3(\omega RC)^2 + 1 = 0, \text{ i.e., } 3(\omega RC)^2 = 1 \rightarrow \omega \equiv \omega_0 = \frac{1}{\sqrt{3}}\,\frac{1}{RC} \rightarrow f_0 = 574\,\text{Hz}\,.$$

Note that, at $\omega = \omega_0$, $\beta(j\omega_0) = \dfrac{1}{R}\,\dfrac{(j/\sqrt{3})^3}{4\,j/\sqrt{3}} = -\dfrac{1}{12\,R} = -8.33 \times 10^{-6}$.



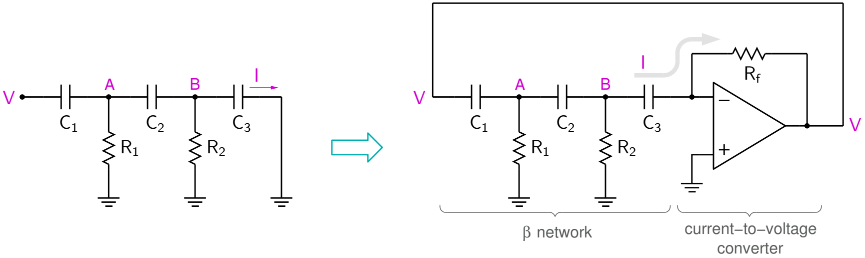


Note that the functioning of the β network as a stand-alone circuit (left figure) and as a feedback block (right figure) is the same, thanks to the virtual ground provided by the op-amp.



Note that the functioning of the β network as a stand-alone circuit (left figure) and as a feedback block (right figure) is the same, thanks to the virtual ground provided by the op-amp.

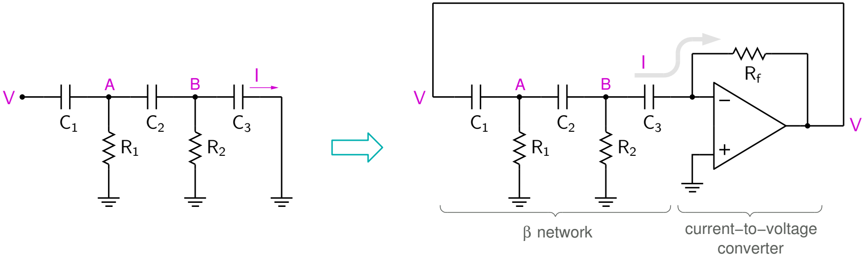
The amplifier gain is $A(j\omega) \equiv \dfrac{V(j\omega)}{I(j\omega)} = \dfrac{0 - R_f I(j\omega)}{I(j\omega)} = -R_f$.



Note that the functioning of the β network as a stand-alone circuit (left figure) and as a feedback block (right figure) is the same, thanks to the virtual ground provided by the op-amp.

The amplifier gain is $A(j\omega) \equiv \dfrac{V(j\omega)}{I(j\omega)} = \dfrac{0 - R_f I(j\omega)}{I(j\omega)} = -R_f$.

$$\rightarrow A(j\omega)\beta(j\omega) = -R_f \, \frac{1}{R} \, \frac{(j\omega RC)^3}{3(j\omega RC)^2 + 4\, j\omega RC + 1}.$$

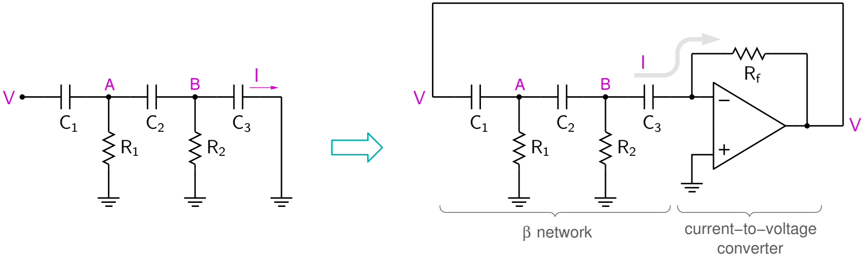


Note that the functioning of the β network as a stand-alone circuit (left figure) and as a feedback block (right figure) is the same, thanks to the virtual ground provided by the op-amp.

The amplifier gain is $A(j\omega) \equiv \dfrac{V(j\omega)}{I(j\omega)} = \dfrac{0 - R_f\, I(j\omega)}{I(j\omega)} = -R_f$.

$$\rightarrow A(j\omega)\beta(j\omega) = -R_f\, \frac{1}{R}\, \frac{(j\omega RC)^3}{3(j\omega RC)^2 + 4\, j\omega RC + 1}.$$

As seen before, at $\rightarrow \omega = \omega_0 = \dfrac{1}{\sqrt{3}}\dfrac{1}{RC}$, we have $\dfrac{I(j\omega)}{V(j\omega)} = -\dfrac{1}{12\, R}$.



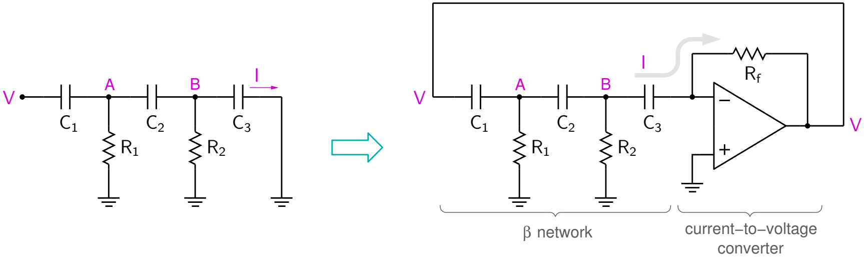
Note that the functioning of the β network as a stand-alone circuit (left figure) and as a feedback block (right figure) is the same, thanks to the virtual ground provided by the op-amp.

The amplifier gain is $A(j\omega) \equiv \dfrac{V(j\omega)}{I(j\omega)} = \dfrac{0 - R_f I(j\omega)}{I(j\omega)} = -R_f$.

$$\rightarrow A(j\omega)\beta(j\omega) = -R_f \, \frac{1}{R} \, \frac{(j\omega RC)^3}{3(j\omega RC)^2 + 4\,j\omega RC + 1}.$$

As seen before, at $\rightarrow \omega = \omega_0 = \dfrac{1}{\sqrt{3}}\dfrac{1}{RC}$, we have $\dfrac{I(j\omega)}{V(j\omega)} = -\dfrac{1}{12\,R}$.

For the circuit to oscillate, we need $A\beta = 1 \rightarrow -R_f\left(-\dfrac{1}{12\,R}\right) = 1$, i.e., $\boxed{R_f = 12\,R}$



Note that the functioning of the β network as a stand-alone circuit (left figure) and as a feedback block (right figure) is the same, thanks to the virtual ground provided by the op-amp.

The amplifier gain is $A(j\omega) \equiv \dfrac{V(j\omega)}{I(j\omega)} = \dfrac{0 - R_f\, I(j\omega)}{I(j\omega)} = -R_f$.

$$\rightarrow A(j\omega)\beta(j\omega) = -R_f\, \frac{1}{R}\, \frac{(j\omega RC)^3}{3(j\omega RC)^2 + 4\, j\omega RC + 1}.$$

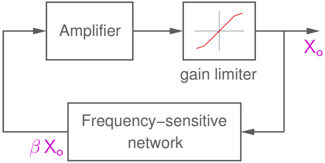
As seen before, at $\rightarrow \omega = \omega_0 = \dfrac{1}{\sqrt{3}}\, \dfrac{1}{RC}$, we have $\dfrac{I(j\omega)}{V(j\omega)} = -\dfrac{1}{12\, R}$.

For the circuit to oscillate, we need $A\beta = 1 \rightarrow -R_f \left(-\dfrac{1}{12\, R}\right) = 1$, i.e., $\boxed{R_f = 12\, R}$

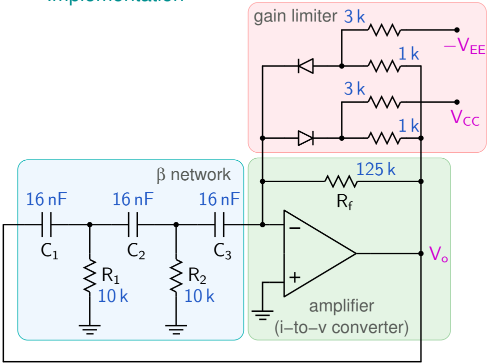
In addition, we employ a gain limiter circuit to complete the oscillator design.

Phase-shift oscillator

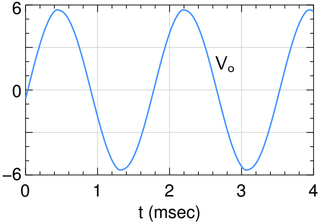
Block diagram



Implementation



Output voltage

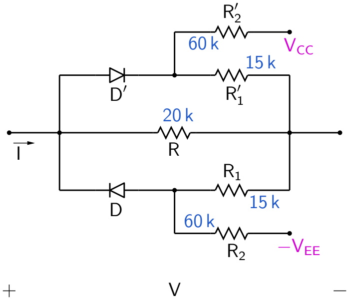


Ref.: Sedra and Smith, "Microelectronic circuits"

SEQUEL file: `ee101_osc_3.sqproj`

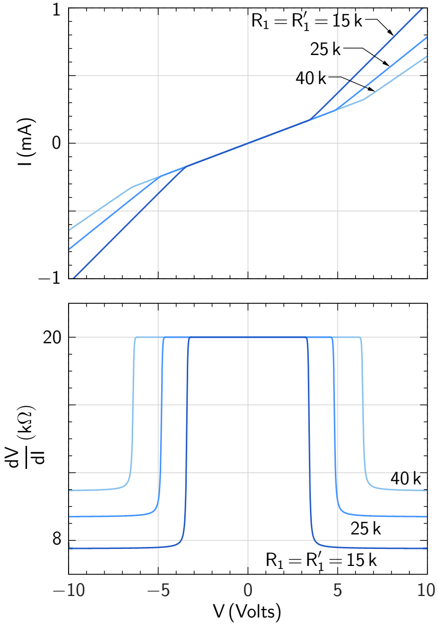
$$\omega_0 = \frac{1}{\sqrt{3}} \frac{1}{RC} \rightarrow f_0 = 574\,\text{Hz}, \quad T = 1.74\,\text{ms}\,.$$

Amplitude control using gain limiting network

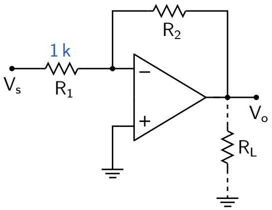


$(V_{CC} = 15\,\mathrm{V})$

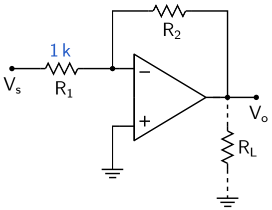
SEQUEL file: ee101_diode_circuit_15.sqproj



Inverting amplifier, revisited

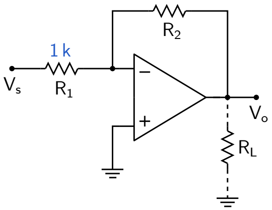


Inverting amplifier, revisited



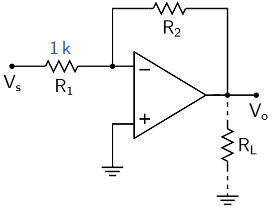
* As seen earlier, $A_V = -R_2/R_1 \rightarrow |A_V|$ should be independent of the signal frequency.

Inverting amplifier, revisited

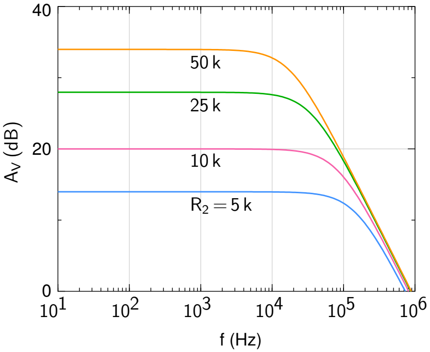


* As seen earlier, $A_V = -R_2/R_1 \rightarrow |A_V|$ should be independent of the signal frequency.
* However, a measurement with a real op-amp will show that $|A_V|$ starts reducing at higher frequencies.

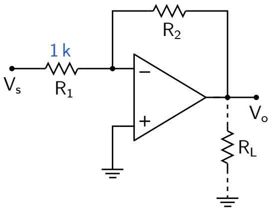
Inverting amplifier, revisited



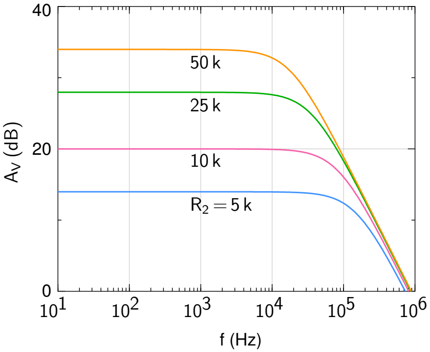
SEQUEL file: `ee101_inv_amp_3.sqproj`



* As seen earlier, $A_V = -R_2/R_1 \rightarrow |A_V|$ should be independent of the signal frequency.
* However, a measurement with a real op-amp will show that $|A_V|$ starts reducing at higher frequencies.

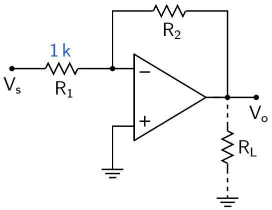


SEQUEL file: `ee101_inv_amp_3.sqproj`

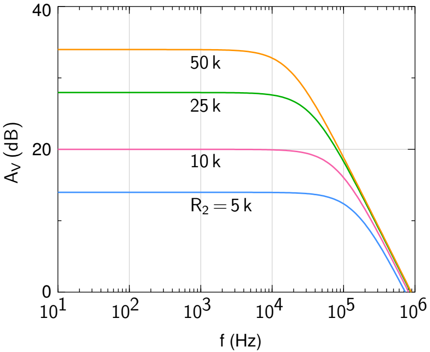


* As seen earlier, $A_V = -R_2/R_1 \rightarrow |A_V|$ should be independent of the signal frequency.
* However, a measurement with a real op-amp will show that $|A_V|$ starts reducing at higher frequencies.
* If $|A_V|$ is increased, the gain "roll-off" starts at lower frequencies.

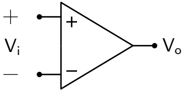
Inverting amplifier, revisited

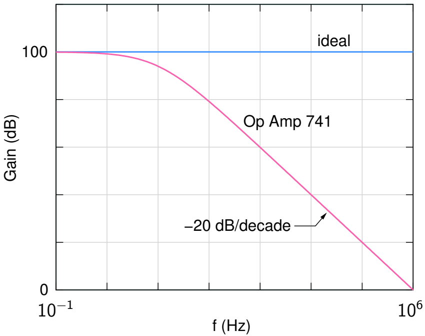


SEQUEL file: `ee101_inv_amp_3.sqproj`

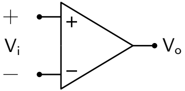


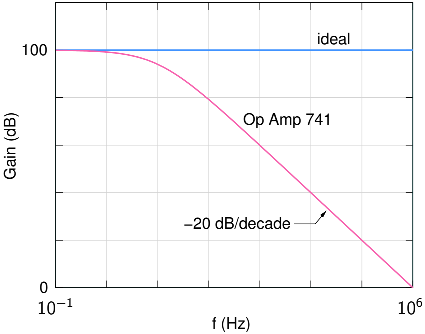
* As seen earlier, $A_V = -R_2/R_1 \rightarrow |A_V|$ should be independent of the signal frequency.
* However, a measurement with a real op-amp will show that $|A_V|$ starts reducing at higher frequencies.
* If $|A_V|$ is increased, the gain "roll-off" starts at lower frequencies.
* This behaviour has to do with the frequency response of the op-amp which we have not considered so far.





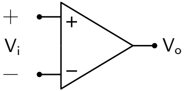
The gain of the 741 op-amp starts falling at rather low frequencies, with $f_c \simeq 10\,\text{Hz}$!

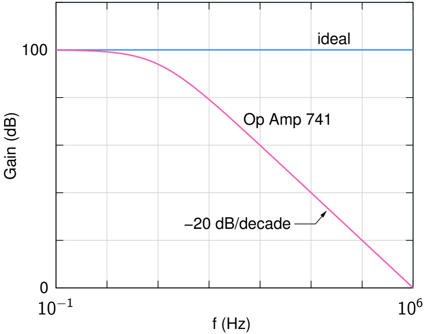




The gain of the 741 op-amp starts falling at rather low frequencies, with $f_c \simeq 10\,\mathrm{Hz}$!

The 741 op-amp (and many others) are *designed* with this feature to ensure that, in typical amplifier applications, the overall circuit is stable (and not oscillatory).



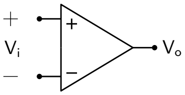


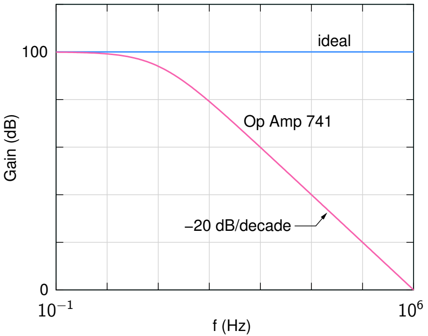
The gain of the 741 op-amp starts falling at rather low frequencies, with $f_c \simeq 10\,\text{Hz}$!

The 741 op-amp (and many others) are *designed* with this feature to ensure that, in typical amplifier applications, the overall circuit is stable (and not oscillatory).

In other words, the op-amp has been *internally compensated* for stability.

Frequency response of Op-Amp 741





The gain of the 741 op-amp starts falling at rather low frequencies, with $f_c \simeq 10\,\text{Hz}$!

The 741 op-amp (and many others) are *designed* with this feature to ensure that, in typical amplifier applications, the overall circuit is stable (and not oscillatory).

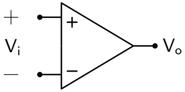
In other words, the op-amp has been *internally compensated* for stability.

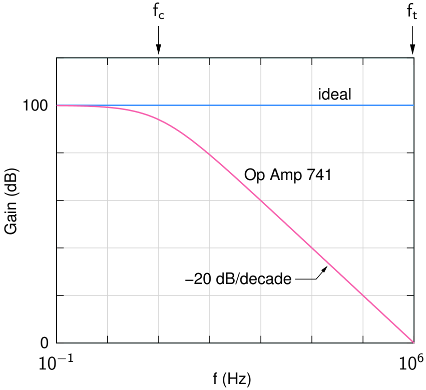
The gain of the 741 op-amp can be represented by,

$$A(s) = \frac{A_0}{1 + s/\omega_c},$$

with $A_0 \approx 10^5$ (i.e., 100 dB), $\omega_c \approx 2\pi \times 10\,\text{rad/s}$.

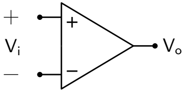
Frequency response of Op-Amp 741

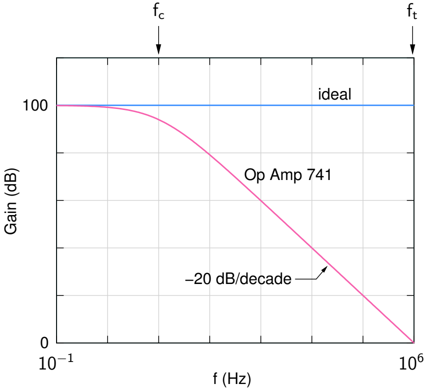




$A(j\omega) = \dfrac{A_0}{1 + j\omega/\omega_c}$, $\omega_c \approx 2\pi \times 10\,\text{rad/s}$.

For $\omega \gg \omega_c$, we have $A(j\omega) \approx \dfrac{A_0}{j\omega/\omega_c}$.



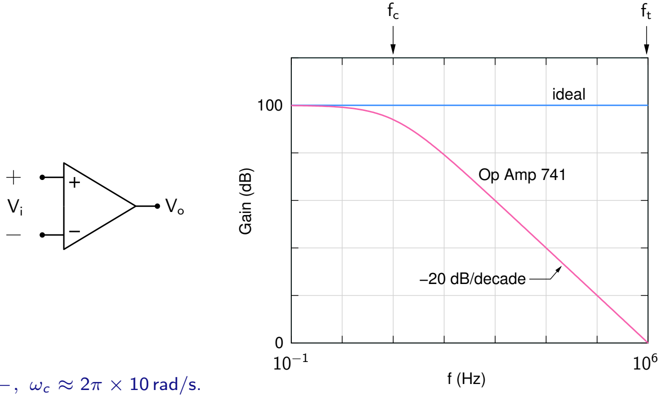


$A(j\omega) = \dfrac{A_0}{1 + j\omega/\omega_c}$, $\omega_c \approx 2\pi \times 10\,\text{rad/s}$.

For $\omega \gg \omega_c$, we have $A(j\omega) \approx \dfrac{A_0}{j\omega/\omega_c}$.

$|A(j\omega)|$ becomes 1 when $A_0 = \omega/\omega_c$, i.e., $\omega = A_0\omega_c$.

Frequency response of Op-Amp 741



$A(j\omega) = \dfrac{A_0}{1 + j\omega/\omega_c}$, $\omega_c \approx 2\pi \times 10\,\text{rad/s}$.

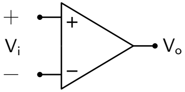
For $\omega \gg \omega_c$, we have $A(j\omega) \approx \dfrac{A_0}{j\omega/\omega_c}$.

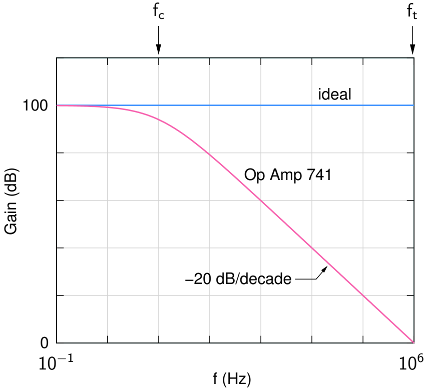
$|A(j\omega)|$ becomes 1 when $A_0 = \omega/\omega_c$, i.e., $\omega = A_0\omega_c$.

This frequency, $\omega_t = A_0\omega_c$, is called the unity-gain frequency.

For the 741 op-amp, $f_t = A_0 f_c \approx 10^5 \times 10 = 10^6$ Hz.

Frequency response of Op-Amp 741





$A(j\omega) = \dfrac{A_0}{1 + j\omega/\omega_c}$, $\omega_c \approx 2\pi \times 10\,\text{rad/s}$.

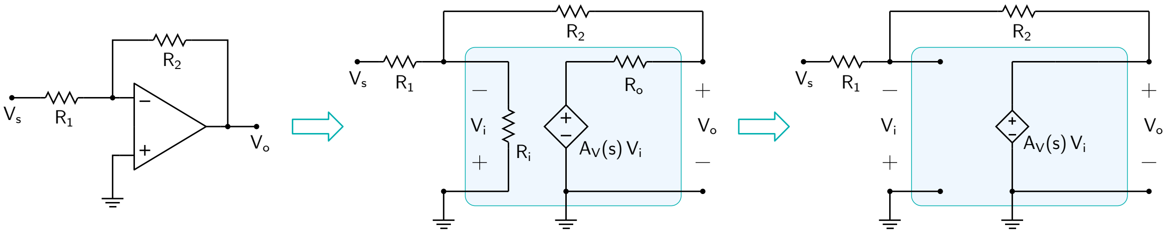
For $\omega \gg \omega_c$, we have $A(j\omega) \approx \dfrac{A_0}{j\omega/\omega_c}$.

$|A(j\omega)|$ becomes 1 when $A_0 = \omega/\omega_c$, i.e., $\omega = A_0\omega_c$.

This frequency, $\omega_t = A_0\omega_c$, is called the unity-gain frequency.

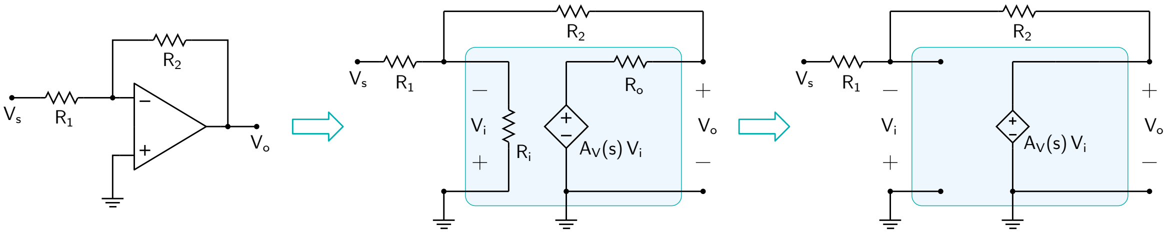
For the 741 op-amp, $f_t = A_0 f_c \approx 10^5 \times 10 = 10^6$ Hz.

Let us see how the frequency response of the 741 op-amp affects the gain of an inverting amplifier.



R2
Vs
R1
Vo
R2
Vs
R1
Ro
Vi
Ri
Av(s) Vi
Vo
R2
Vs
R1
Vi
Av(s) Vi
Vo

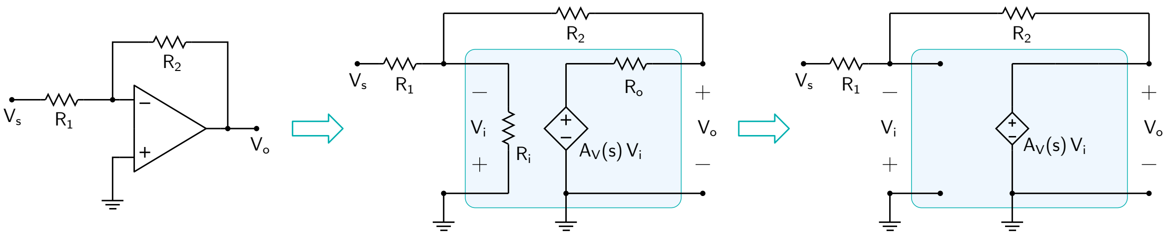
Inverting amplifier, revisited



Assuming R_i to be large and R_o to be small, we get

$$-V_i(s) = V_s(s)\,\frac{R_2}{R_1+R_2} + V_o(s)\,\frac{R_1}{R_1+R_2}\,.$$

Inverting amplifier, revisited

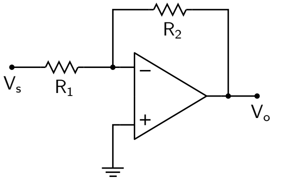


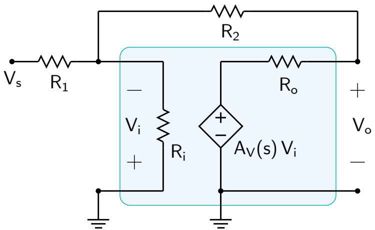
Assuming R_i to be large and R_o to be small, we get

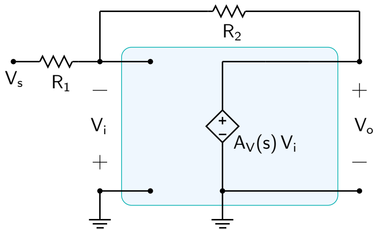
$$-V_i(s) = V_s(s)\,\frac{R_2}{R_1+R_2} + V_o(s)\,\frac{R_1}{R_1+R_2}.$$

Using $V_o(s) = A_V(s)\,V_i(s)$ and $A_V(s) = \dfrac{A_0}{1+s/\omega_c}$, we get

$$\frac{V_o(s)}{V_s(s)} = -\frac{R_2}{R_1}\,\frac{1}{\left[1+\left(\dfrac{R_1+R_2}{R_1}\right)\dfrac{1}{A_0}\right]+\left(\dfrac{R_1+R_2}{R_1A_0}\right)\dfrac{s}{\omega_c}}$$







Assuming R_i to be large and R_o to be small, we get

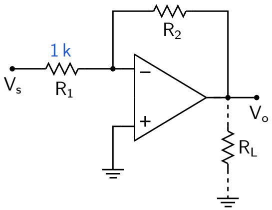
$$-V_i(s) = V_s(s)\,\frac{R_2}{R_1+R_2} + V_o(s)\,\frac{R_1}{R_1+R_2}.$$

Using $V_o(s) = A_V(s)\,V_i(s)$ and $A_V(s) = \dfrac{A_0}{1+s/\omega_c}$, we get

$$\frac{V_o(s)}{V_s(s)} = -\frac{R_2}{R_1}\,\frac{1}{\left[1+\left(\dfrac{R_1+R_2}{R_1}\right)\dfrac{1}{A_0}\right]+\left(\dfrac{R_1+R_2}{R_1A_0}\right)\dfrac{s}{\omega_c}}$$

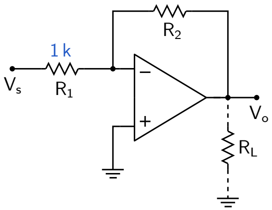
$$\approx -\frac{R_2}{R_1}\,\frac{1}{1+s/\omega_c'},\quad \text{with } \omega_c' = \frac{\omega_c A_0}{1+R_2/R_1} = \frac{\omega_t}{1+R_2/R_1}.$$

Inverting amplifier, revisited



SEQUEL file: `ee101_inv_amp_3.sqproj`

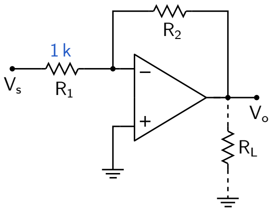
Inverting amplifier, revisited



SEQUEL file: `ee101_inv_amp_3.sqproj`

$$\frac{V_o(s)}{V_s(s)} = -\frac{R_2}{R_1}\,\frac{1}{1+s/\omega_c'} \quad \omega_c' = \frac{\omega_t}{1+R_2/R_1}, \quad (f_t = 1\,\mathrm{MHz}).$$

Inverting amplifier, revisited

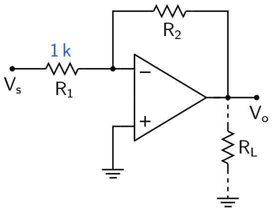


R_2	gain (dB)	f_c' (kHz)
5 k	14	167

SEQUEL file: `ee101_inv_amp_3.sqproj`

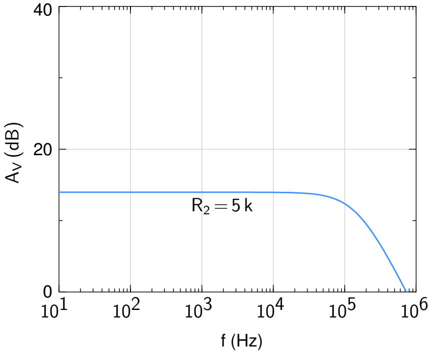
$$\frac{V_o(s)}{V_s(s)} = -\frac{R_2}{R_1}\,\frac{1}{1+s/\omega_c'} \quad \omega_c' = \frac{\omega_t}{1+R_2/R_1}, \quad (f_t = 1\,\text{MHz}).$$

Inverting amplifier, revisited



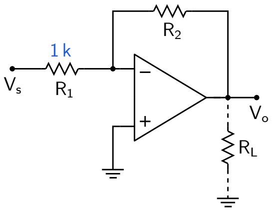
SEQUEL file: `ee101_inv_amp_3.sqproj`

R_2	gain (dB)	f_c' (kHz)
5 k	14	167

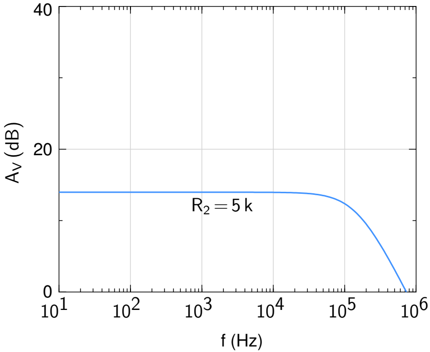


$$\frac{V_o(s)}{V_s(s)} = -\frac{R_2}{R_1}\,\frac{1}{1+s/\omega_c'} \quad \omega_c' = \frac{\omega_t}{1+R_2/R_1}, \quad (f_t = 1\,\text{MHz}).$$

Inverting amplifier, revisited



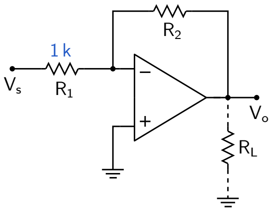
R_2	gain (dB)	f_c' (kHz)
5 k	14	167
10 k	20	91



SEQUEL file: `ee101_inv_amp_3.sqproj`

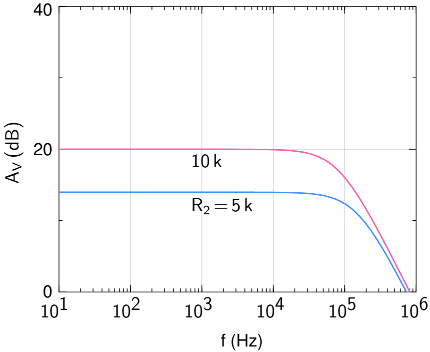
$$\frac{V_o(s)}{V_s(s)} = -\frac{R_2}{R_1}\,\frac{1}{1+s/\omega_c'} \quad \omega_c' = \frac{\omega_t}{1+R_2/R_1}, \quad (f_t = 1\,\text{MHz}).$$

Inverting amplifier, revisited



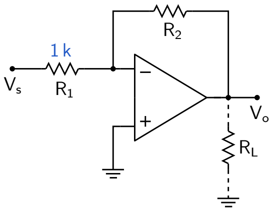
R_2	gain (dB)	f_c' (kHz)
5 k	14	167
10 k	20	91

SEQUEL file: `ee101_inv_amp_3.sqproj`

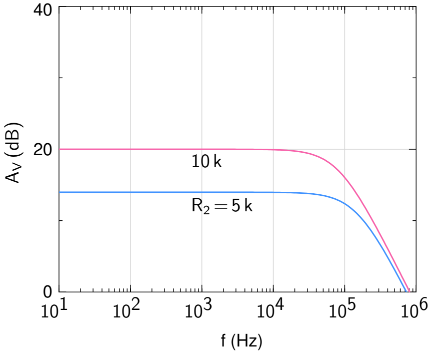


$$\frac{V_o(s)}{V_s(s)} = -\frac{R_2}{R_1}\,\frac{1}{1+s/\omega_c'} \quad \omega_c' = \frac{\omega_t}{1+R_2/R_1}, \quad (f_t = 1\,\text{MHz}).$$

Inverting amplifier, revisited

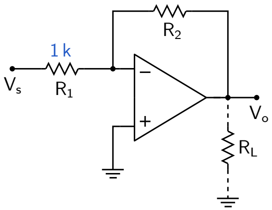


R_2	gain (dB)	f_c' (kHz)
5 k	14	167
10 k	20	91
25 k	28	38



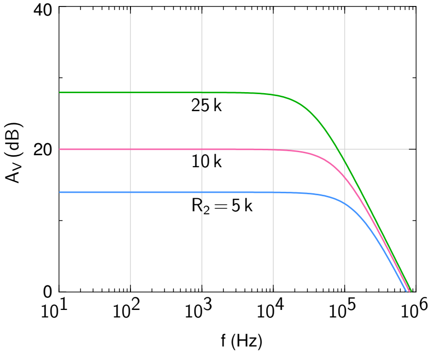
SEQUEL file: `ee101_inv_amp_3.sqproj`

$$\frac{V_o(s)}{V_s(s)} = -\frac{R_2}{R_1}\,\frac{1}{1+s/\omega_c'} \quad \omega_c' = \frac{\omega_t}{1+R_2/R_1}, \quad (f_t = 1\,\text{MHz}).$$



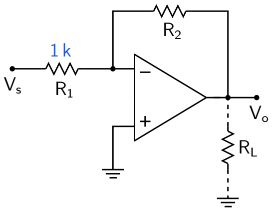
SEQUEL file: `ee101_inv_amp_3.sqproj`

R_2	gain (dB)	f_c' (kHz)
5 k	14	167
10 k	20	91
25 k	28	38



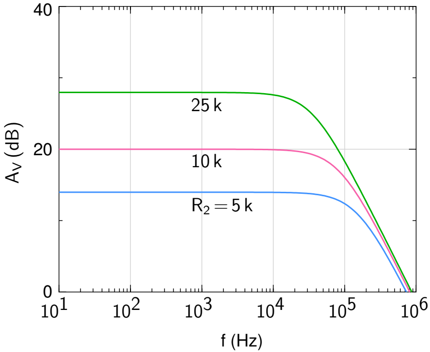
$$\frac{V_o(s)}{V_s(s)} = -\frac{R_2}{R_1}\,\frac{1}{1+s/\omega_c'}\quad \omega_c' = \frac{\omega_t}{1+R_2/R_1},\quad (f_t = 1\,\text{MHz}).$$

Inverting amplifier, revisited



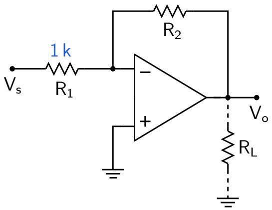
SEQUEL file: `ee101_inv_amp_3.sqproj`

R_2	gain (dB)	f_c' (kHz)
5 k	14	167
10 k	20	91
25 k	28	38
50 k	34	19.6



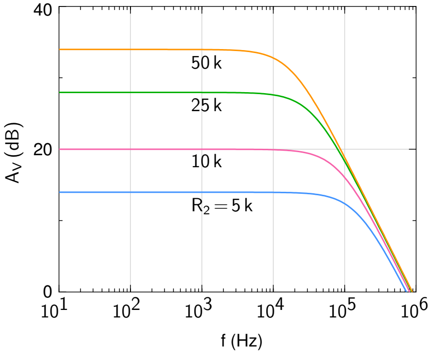
$$\frac{V_o(s)}{V_s(s)} = -\frac{R_2}{R_1}\,\frac{1}{1+s/\omega_c'} \quad \omega_c' = \frac{\omega_t}{1+R_2/R_1}, \quad (f_t = 1\,\text{MHz}).$$

Inverting amplifier, revisited



SEQUEL file: `ee101_inv_amp_3.sqproj`

R_2	gain (dB)	f_c' (kHz)
5 k	14	167
10 k	20	91
25 k	28	38
50 k	34	19.6



$$\frac{V_o(s)}{V_s(s)} = -\frac{R_2}{R_1}\,\frac{1}{1+s/\omega_c'} \quad \omega_c' = \frac{\omega_t}{1+R_2/R_1}, \quad (f_t = 1\,\text{MHz}).$$