Op-Amp Circuits: Part 5

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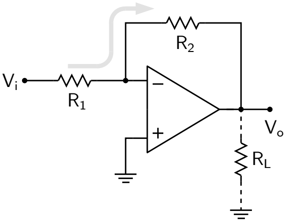
Feedback: inverting amplifier



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

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

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

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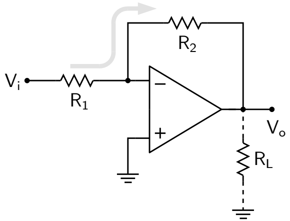

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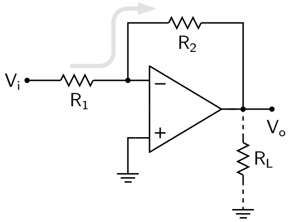

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The circuit reaches a stable equilibrium.

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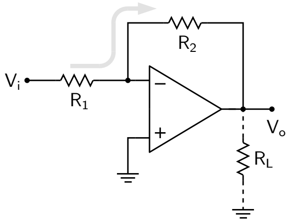

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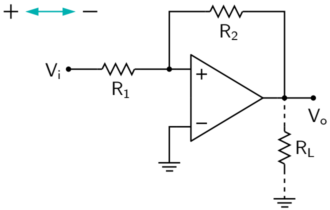

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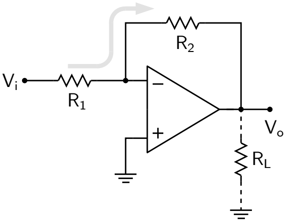

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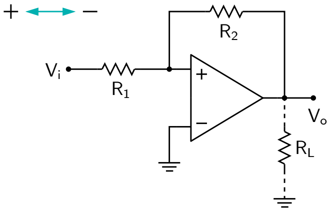

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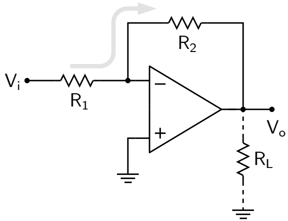

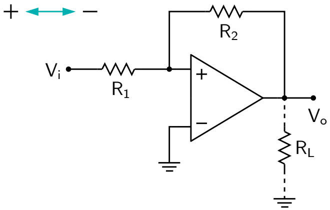

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The circuit reaches a stable equilibrium.

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

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

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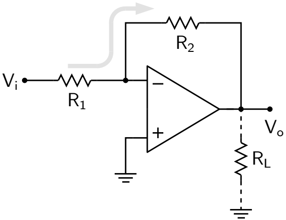

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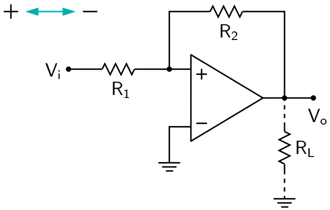

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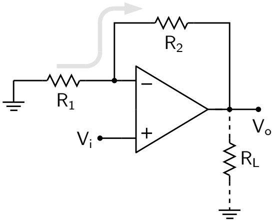

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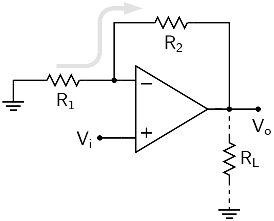

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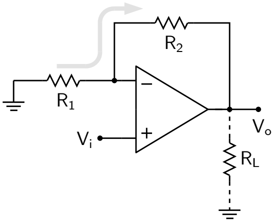

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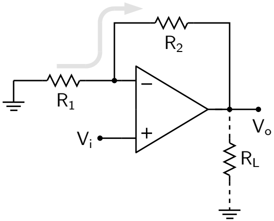

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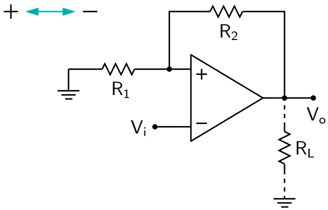

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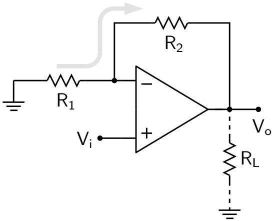

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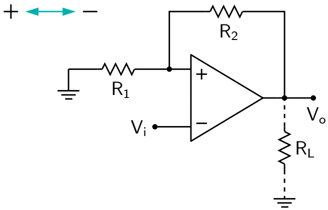

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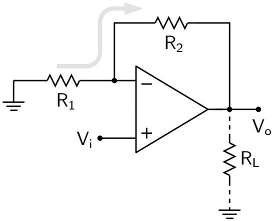

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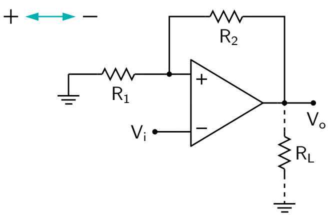

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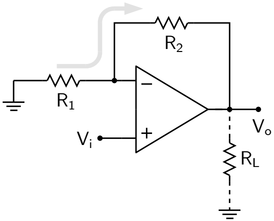

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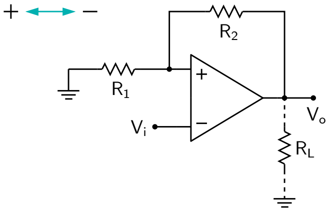

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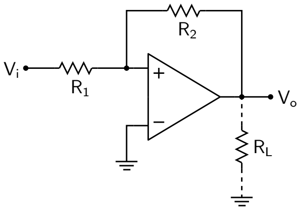
Inverting amplifier with $+ \longleftrightarrow -$



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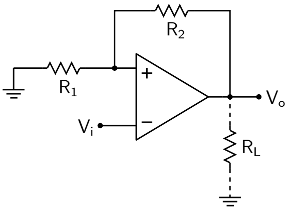

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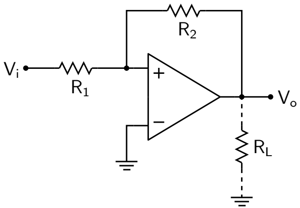

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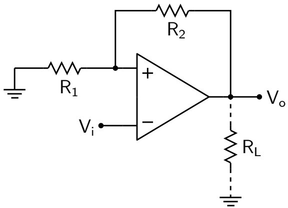

* Because of positive feedback, both of these circuits are unstable.

Feedback

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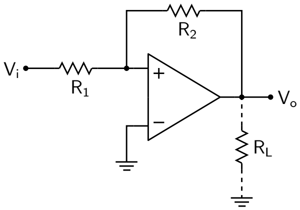

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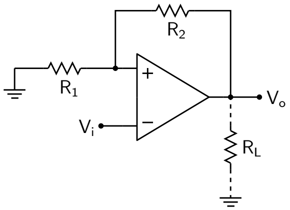

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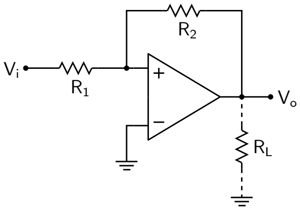

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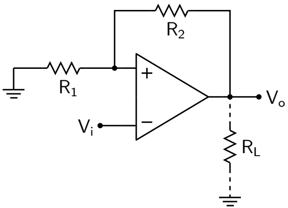
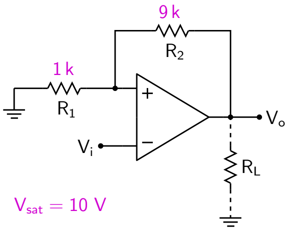


* Because of positive feedback, both of these circuits are unstable.
* The output at any time is only limited by saturation of the op-amp, i.e., $V_o = \pm V_{\mathrm{sat}}$.
* Of what use is a circuit that is stuck at $V_o = \pm V_{\mathrm{sat}}$? It turns out that these circuits are actually useful!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

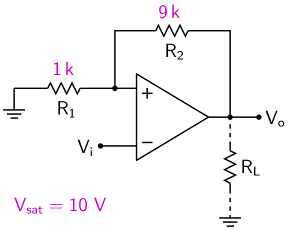
Inverting Schmitt trigger



$V_{sat} = 10$ V

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

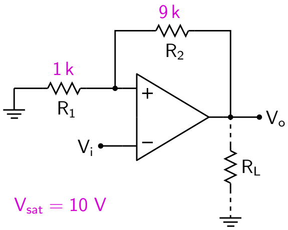
Inverting Schmitt trigger



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

Consider $V_i = 5\ V$.

Inverting Schmitt trigger



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Consider $V_i = 5\,V$.

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

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

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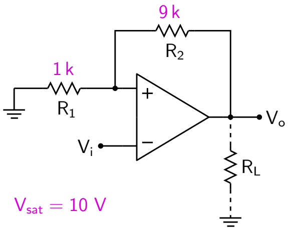

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$(V_+ - V_-) = (1 - 5) = -4\,\text{V} \rightarrow V_o = -V_{\text{sat}}$.

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

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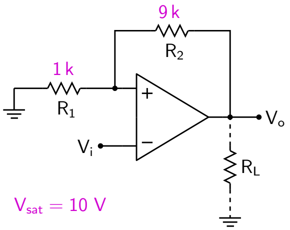

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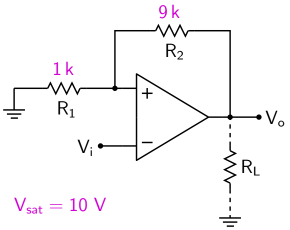
$(V_+ - V_-) = (1 - 5) = -4\,\text{V} \rightarrow V_o = -V_{\text{sat}}\,.$

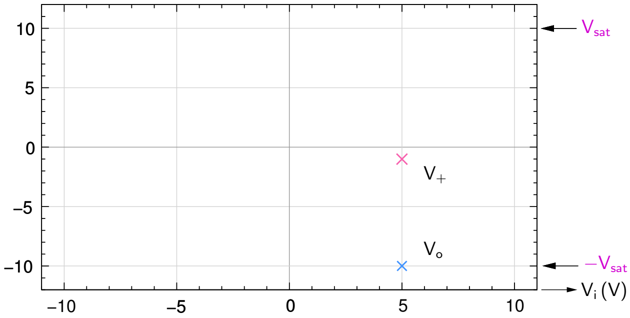
This is inconsistent with our assumption ($V_o = +V_{\text{sat}}$).

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





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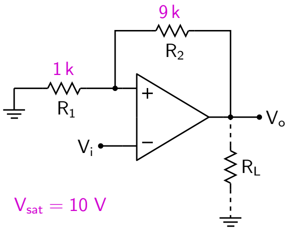
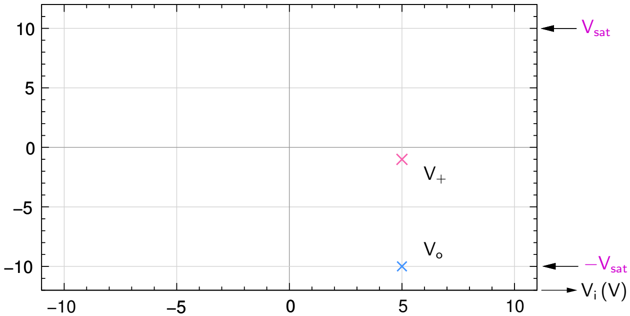
$(V_+ - V_-) = (-1 - 5) = -6\,\text{V} \rightarrow V_o = -V_{\text{sat}}$ (consistent)

Inverting Schmitt trigger



$V_{sat} = 10\ V$



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

Consider $V_i = 5\ V$.

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

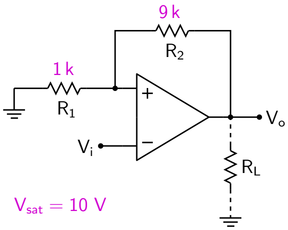
$(V_+ - V_-) = (1 - 5) = -4\,\text{V} \rightarrow V_o = -V_{sat}\,.$

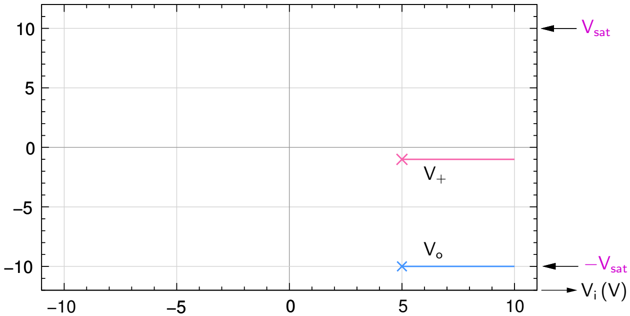
This is inconsistent with our assumption ($V_o = +V_{sat}$).

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

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

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





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

Consider $V_i = 5\,V$.

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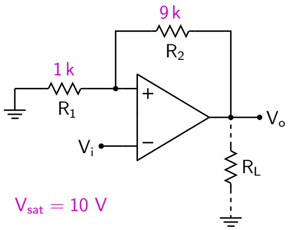
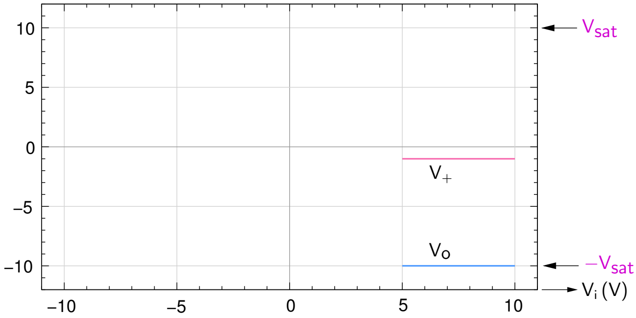
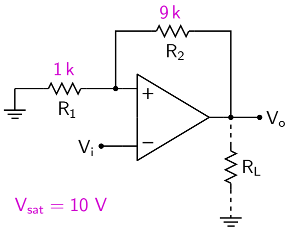
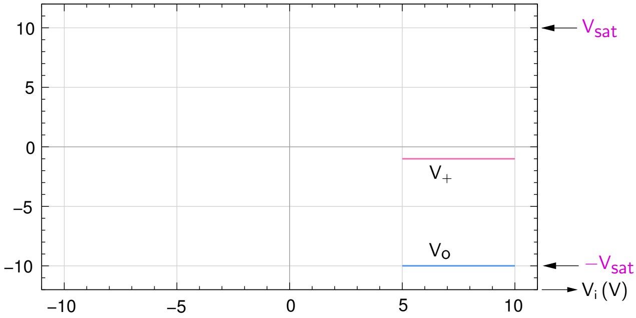
Inverting Schmitt trigger



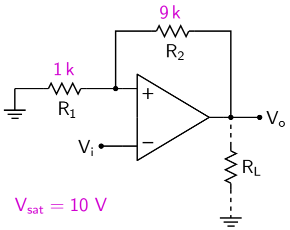




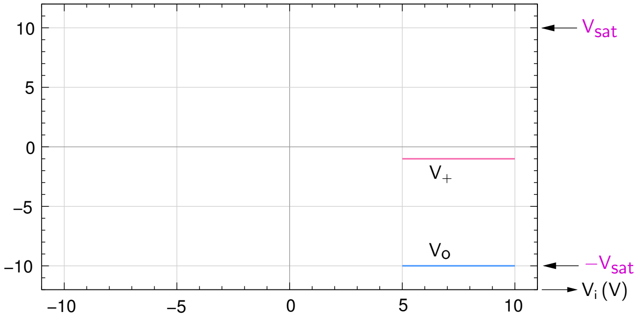


Consider decreasing values of V_i.

Inverting Schmitt trigger



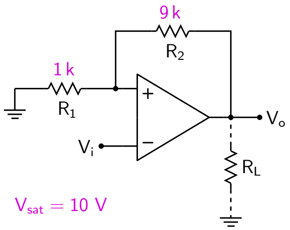
$V_{sat} = 10$ V

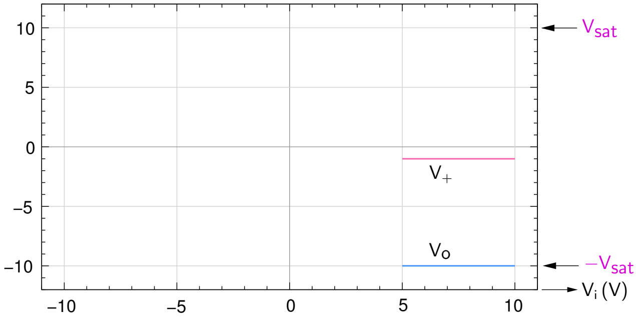


Consider decreasing values of V_i.

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

Inverting Schmitt trigger





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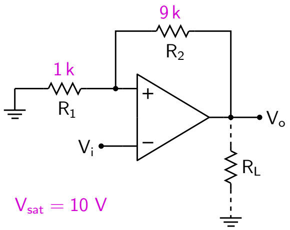
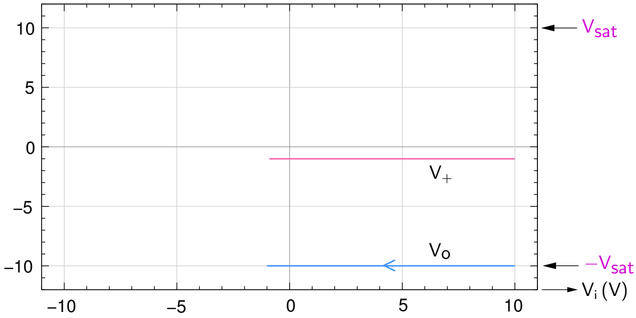
As long as $V_i = V_- > V_+ = -1\ V$, V_o remains at $-V_{\mathrm{sat}}$.

Inverting Schmitt trigger





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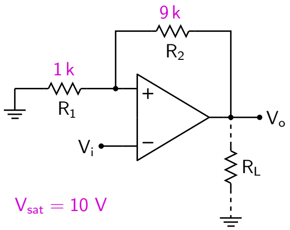

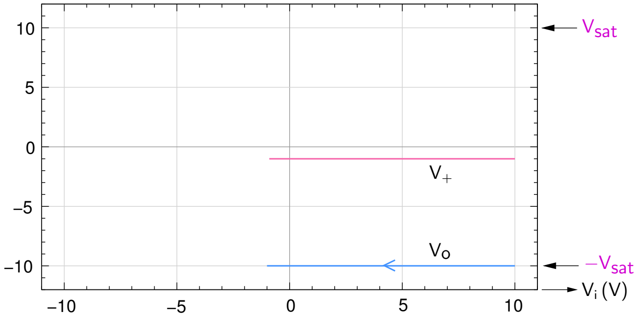

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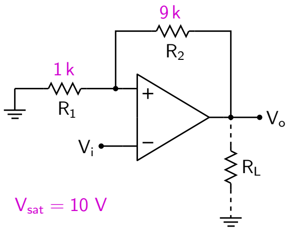
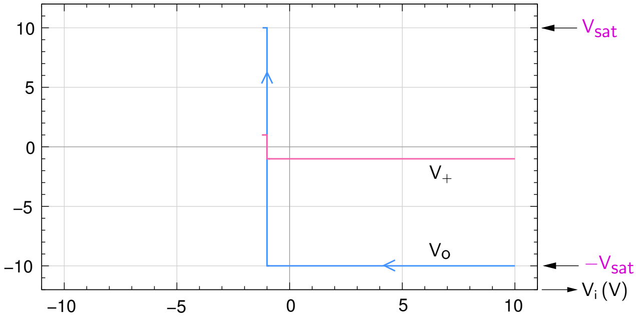
When $V_i < V_+ = -1\ V$, V_o changes sign, i.e., $V_o = +V_{\text{sat}}$.

Inverting Schmitt trigger





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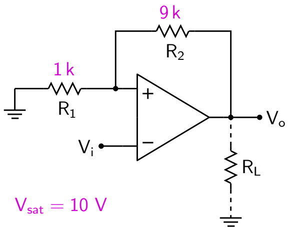

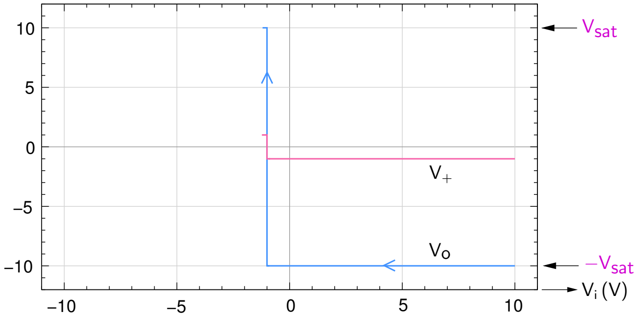

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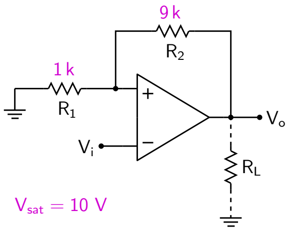
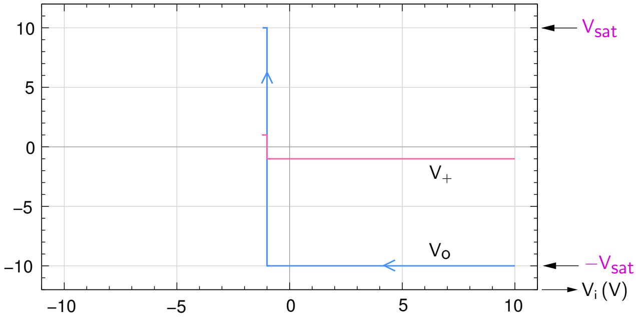
V_+ now becomes $\dfrac{R_1}{R_1 + R_2}(+V_{\text{sat}}) = +1\ V\,.$

Inverting Schmitt trigger





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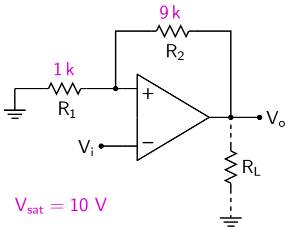
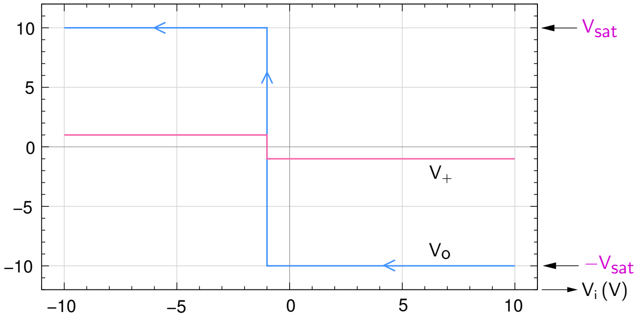
Decreasing V_i further makes no difference to V_o (since $V_i = V_- < V_+ = +1\ V$ holds).

Inverting Schmitt trigger





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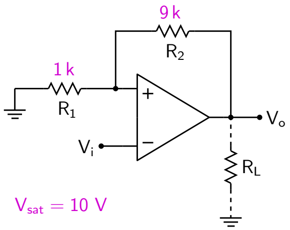

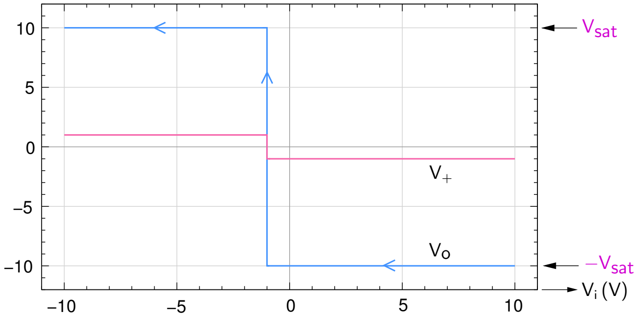

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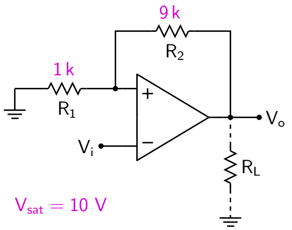
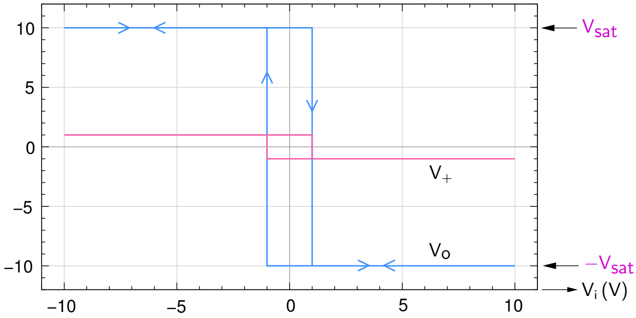
Decreasing V_i further makes no difference to V_o (since $V_i = V_- < V_+ = +1\ V$ holds).

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

Inverting Schmitt trigger





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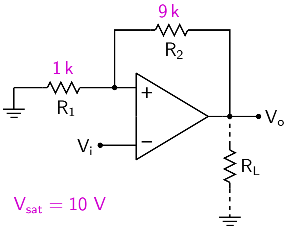
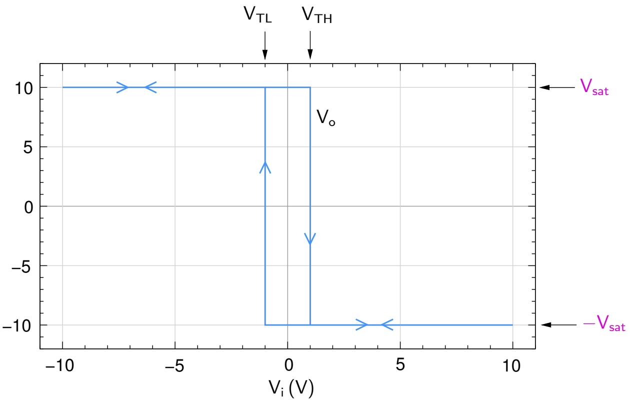
Inverting Schmitt trigger





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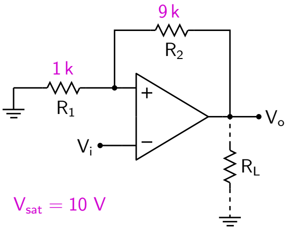
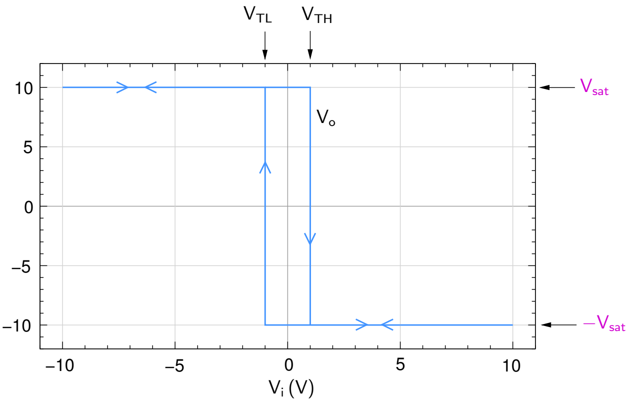
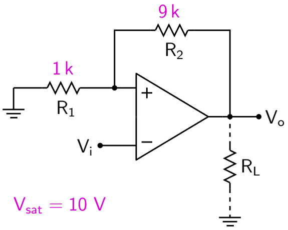
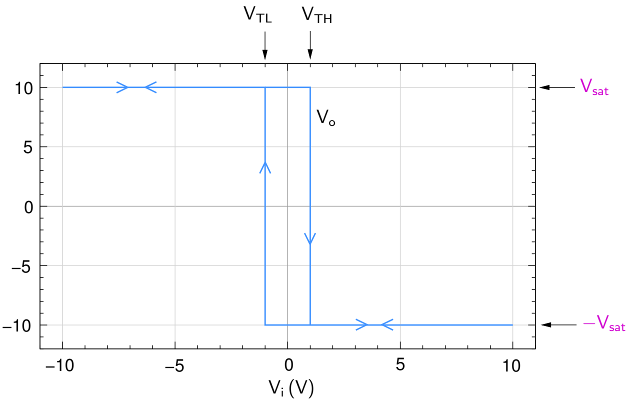


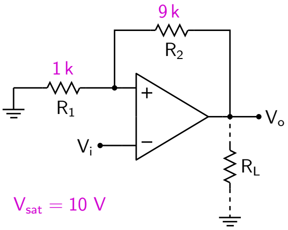


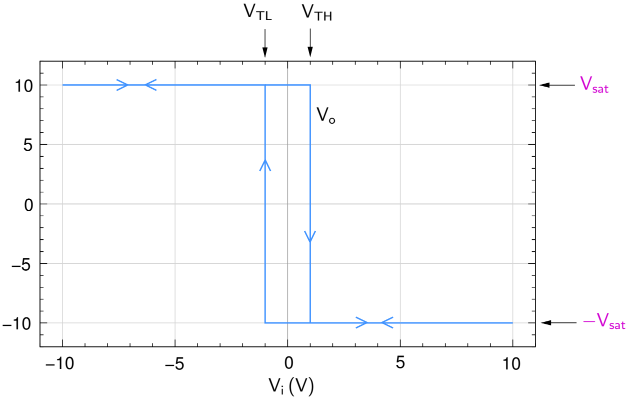
* The threshold values (or "tripping points"), V_{TH} and V_{TL}, are given by $\pm \left(\dfrac{R_1}{R_1 + R_2} \right) V_{\mathrm{sat}}$.





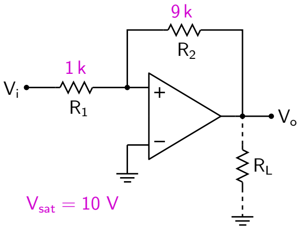
- $*$ The threshold values (or "tripping points"), V_{TH} and V_{TL}, are given by $\pm \left(\dfrac{R_1}{R_1 + R_2} \right) V_{sat}$.
- $*$ The tripping point (whether V_{TH} or V_{TL}) depends on where we are on the V_o axis. In that sense, the circuit has a memory.





- The threshold values (or "tripping points"), V_{TH} and V_{TL}, are given by $\pm\left(\dfrac{R_1}{R_1+R_2}\right)V_{\text{sat}}$.
- 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.
- $\Delta V_T = V_{\text{TH}} - V_{\text{TL}}$ is called the "hysteresis width."

Non-inverting Schmitt trigger



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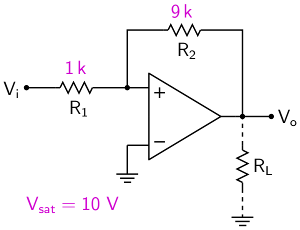
Non-inverting Schmitt trigger



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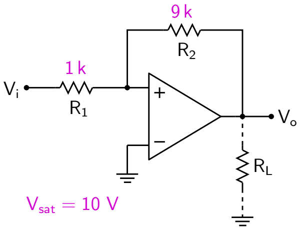
Consider $V_i = 5\ V$.

Non-inverting Schmitt trigger



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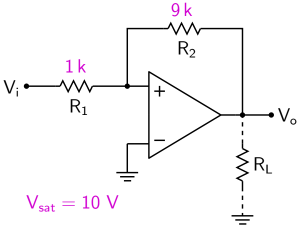
Consider $V_i = 5\ V$.

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



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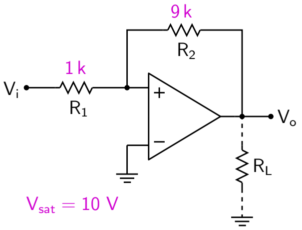
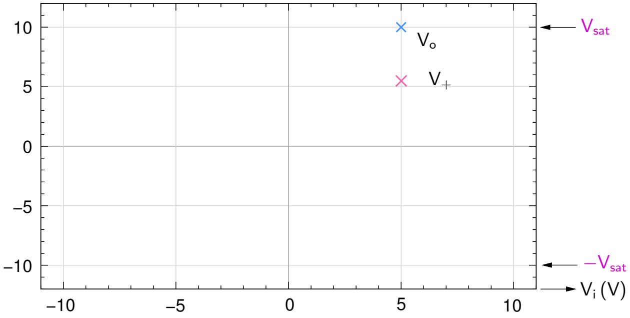
$(V_+ - V_-) = (3.5 - 0) = 3.5\ V \rightarrow V_o = +V_{\text{sat}}$.

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

Non-inverting Schmitt trigger





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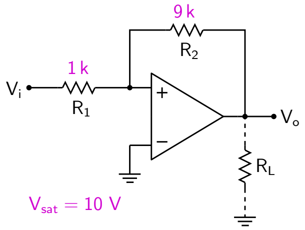
$(V_+ - V_-) = (3.5 - 0) = 3.5\ V \rightarrow V_o = +V_{\text{sat}}$.

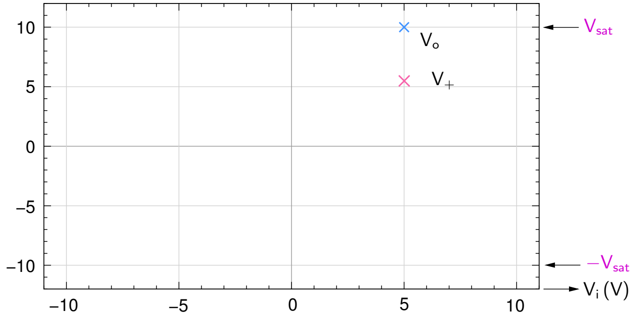
This is inconsistent with our assumption ($V_o = -V_{\text{sat}}$).

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

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

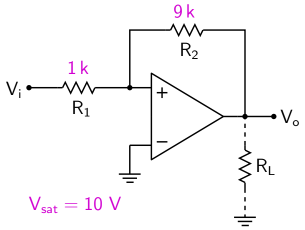
$(V_+ - V_-) = (3.5 - 0) = 3.5\ V \rightarrow V_o = +V_{\rm sat}\,.$

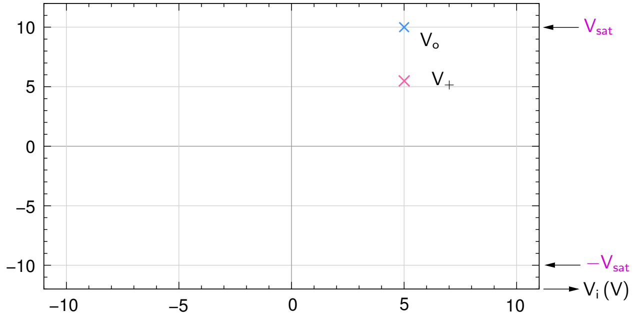
This is inconsistent with our assumption ($V_o = -V_{\rm sat}$).

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





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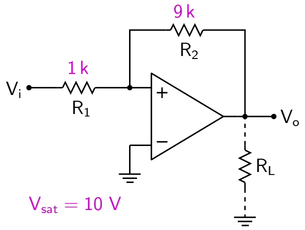
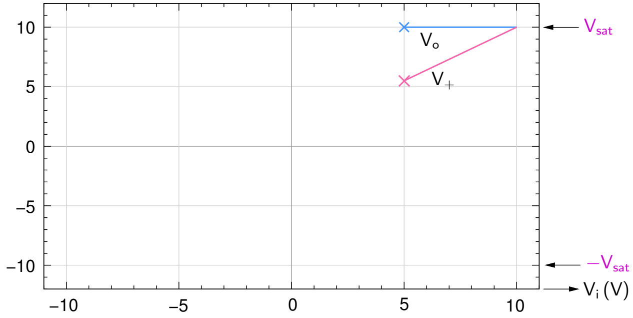
Case (ii): $V_o = +V_{\text{sat}} = +10\ V \rightarrow V_+ = \dfrac{9\text{ k}}{10\text{ k}}\times 5 + \dfrac{1\text{ k}}{10\text{ k}}\times 10 = 4.5 + 1 = 5.5\ V$.

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





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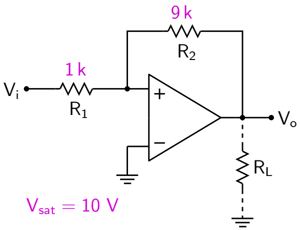

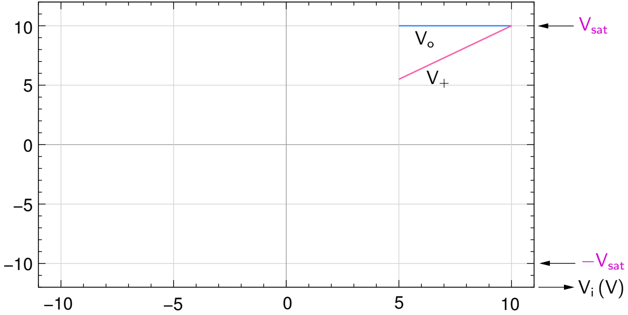

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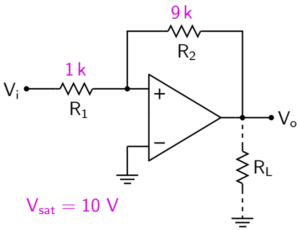
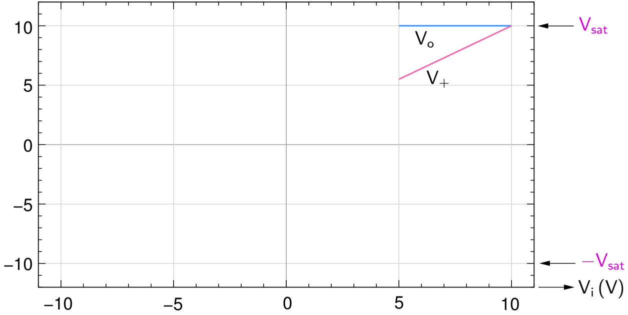
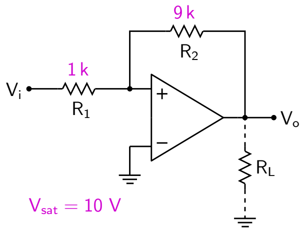
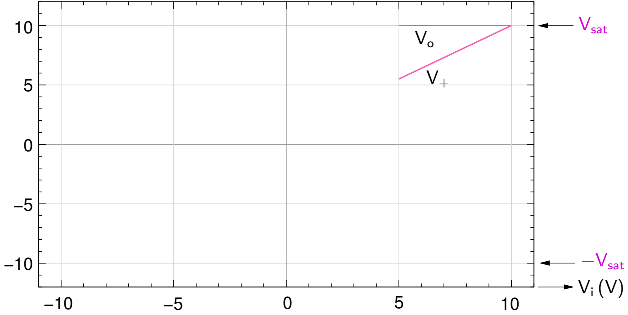




Consider decreasing values of V_i.

Non-inverting Schmitt trigger





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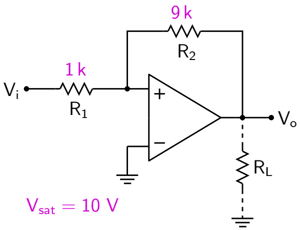

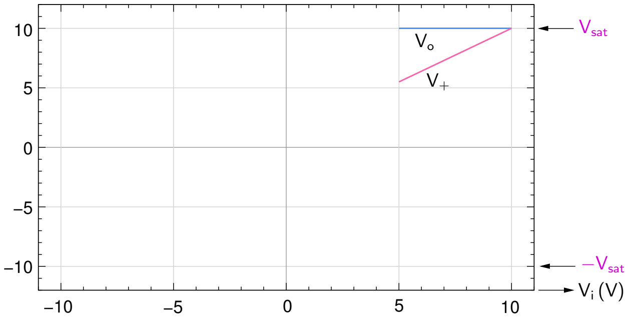

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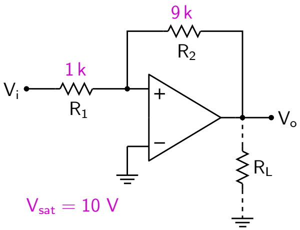

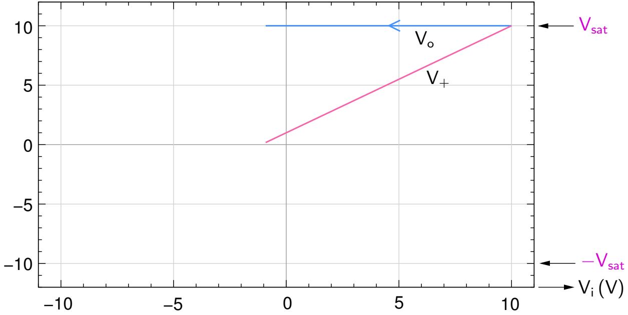

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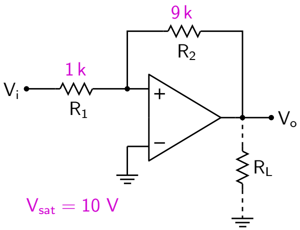

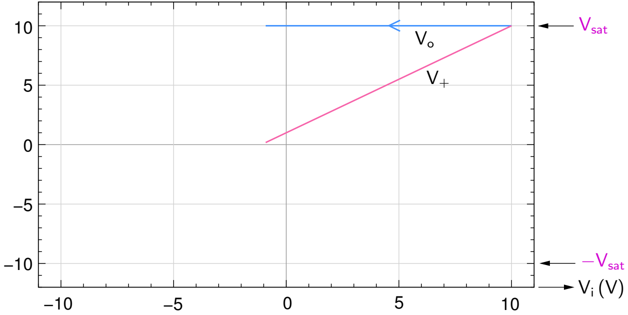

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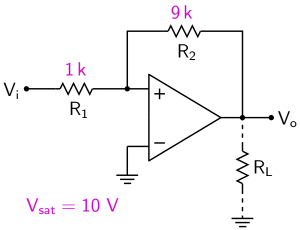

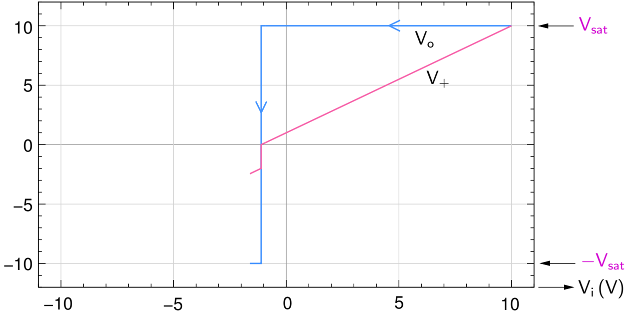

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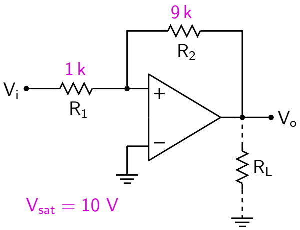

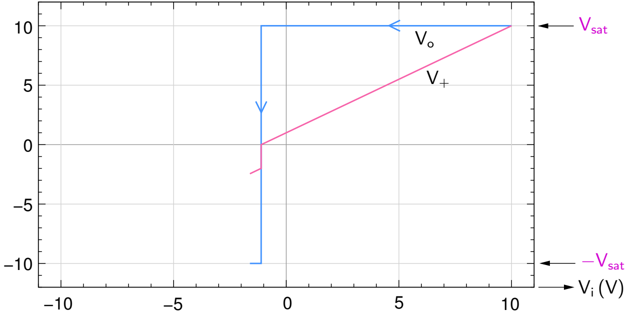

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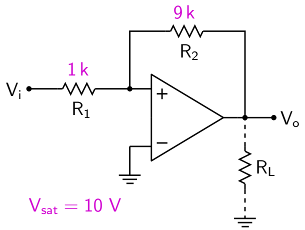

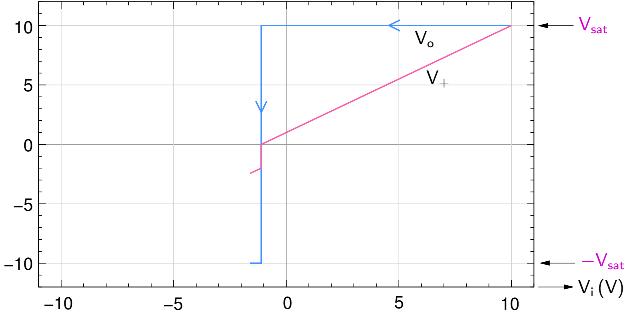

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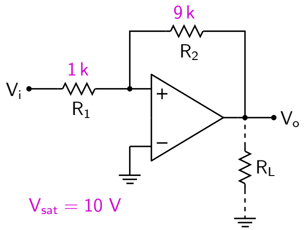
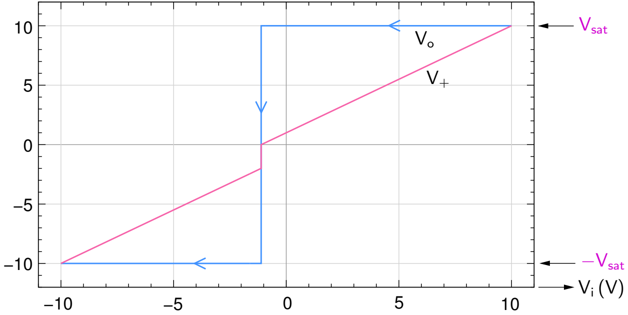
Decreasing V_i further makes no difference to V_o (since V_+ remains negative).

Non-inverting Schmitt trigger





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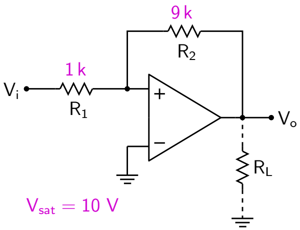

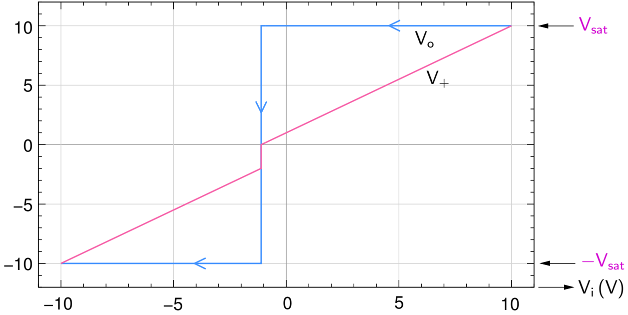

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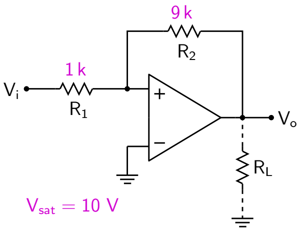
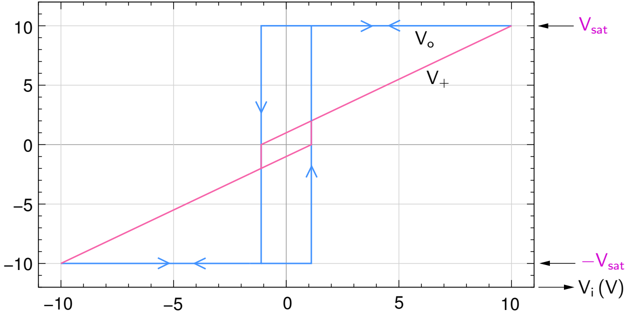
Now, the threshold at which V_o flips is $V_+ = 0$, i.e., $V_i = +\dfrac{R_1}{R_2} V_{\mathrm{sat}} = +1.11\ V$.

Non-inverting Schmitt trigger





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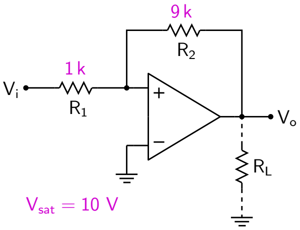

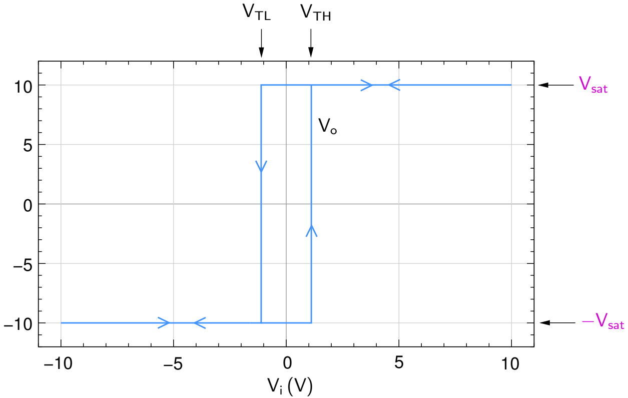

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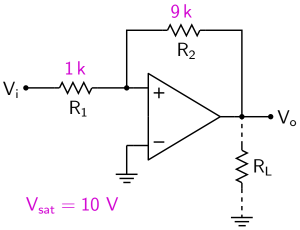
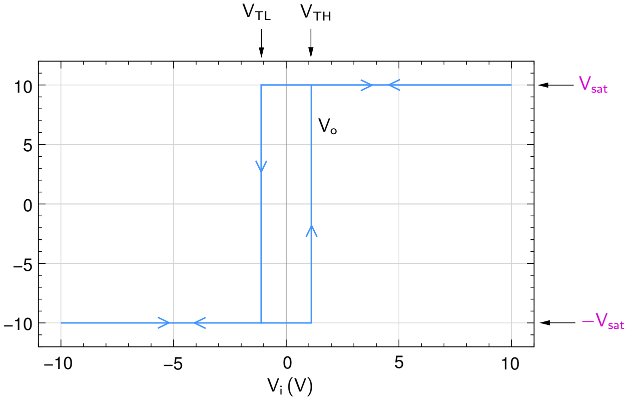
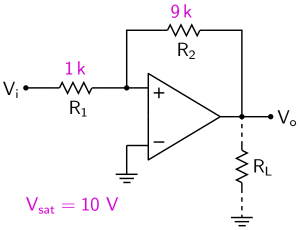
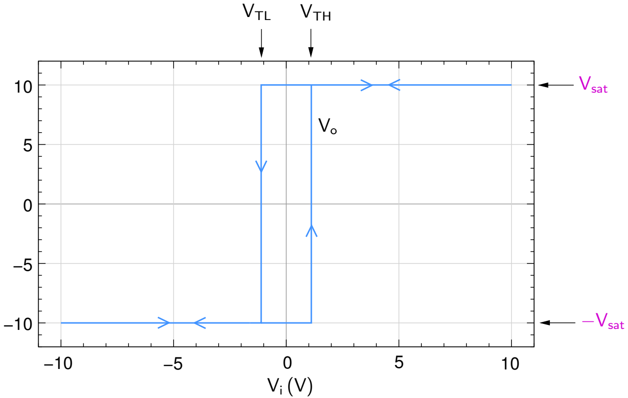




* The threshold values V_{TH} and V_{TL} are given by $\pm\left(\dfrac{R_1}{R_2}\right) V_{sat}$.

Non-inverting Schmitt trigger





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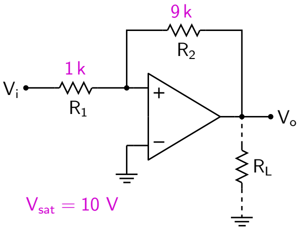

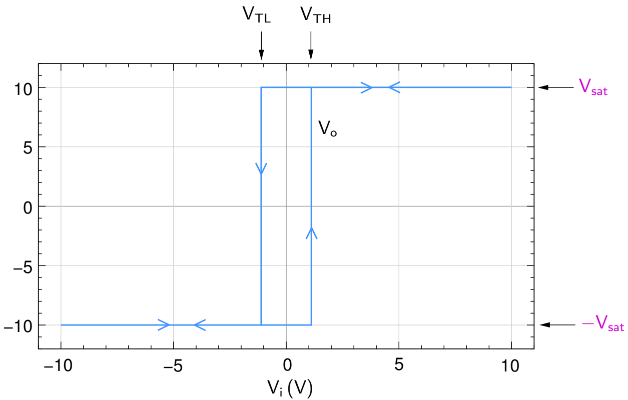

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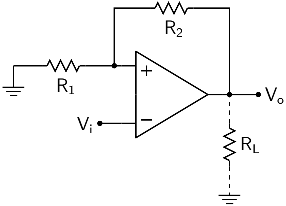
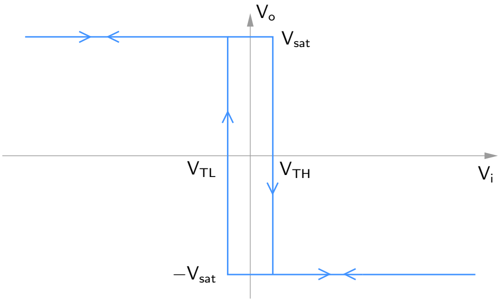
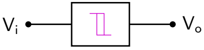
* $\Delta V_T = V_{\text{TH}} - V_{\text{TL}}$ is called the "hysteresis width."

Schmitt triggers

Inverting

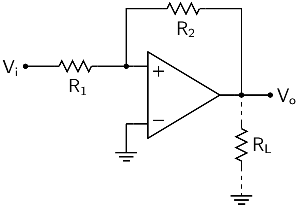


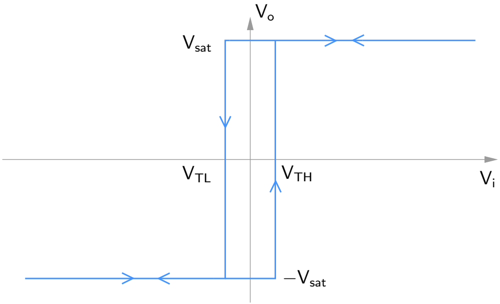


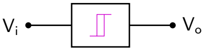


$$V_{TH},\, V_{TL} = \pm \frac{R_1}{R_1+R_2}\, V_{sat}$$

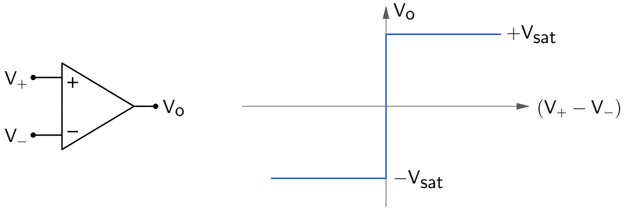
Non–inverting

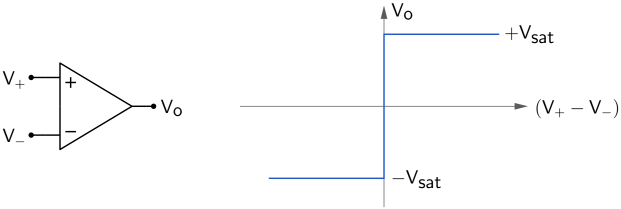




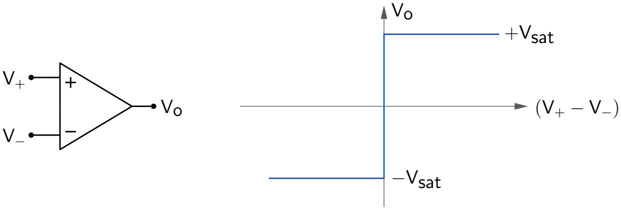


$$V_{TH},\, V_{TL} = \pm \frac{R_1}{R_2}\, V_{sat}$$


V+
V−
+
−
Vo
Vo
+Vsat
(V+ − V−)
−Vsat

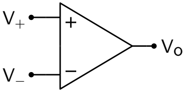


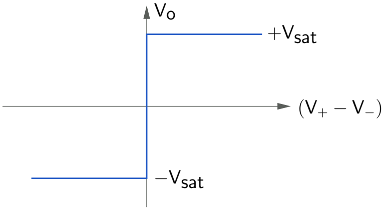
An op-amp in the open-loop configuration serves as a comparator because of its high gain ($\sim 10^5$) in the linear region.



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.



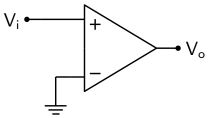


An op-amp in the open-loop configuration serves as a comparator because of its high gain ($\sim 10^5$) in the linear region.

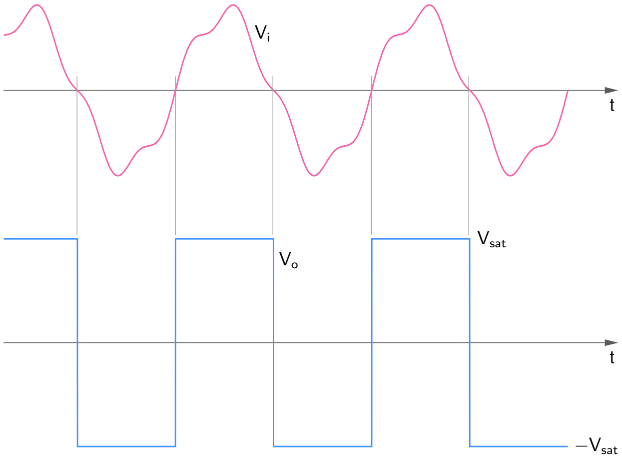
As seen earlier, the width of the linear region, $[V_{\text{sat}} - (-V_{\text{sat}})]/A_V$, is small ($\sim 0.1\,\text{m}V$), and could be treated as 0.

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

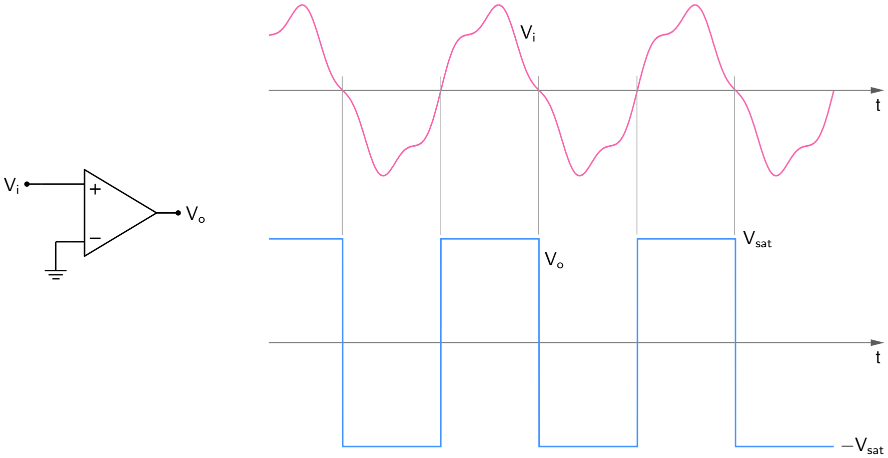
if $V_+ < V_-$, $V_o = -V_{\text{sat}}$.



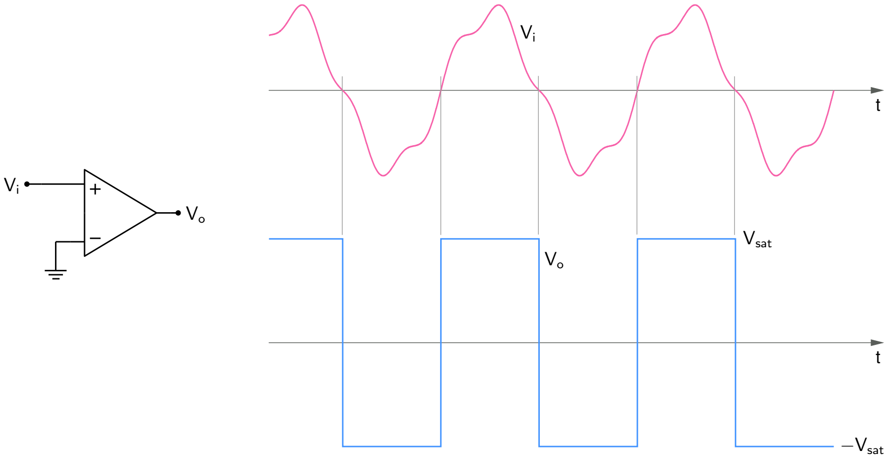
V_i
+
−
V_o



V_i
t
V_sat
V_o
t
−V_sat



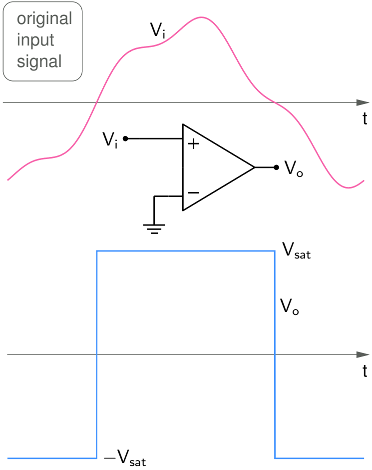
A comparator can be used to convert an analog signal into a digital (high/low) signal for further processing with digital circuits.



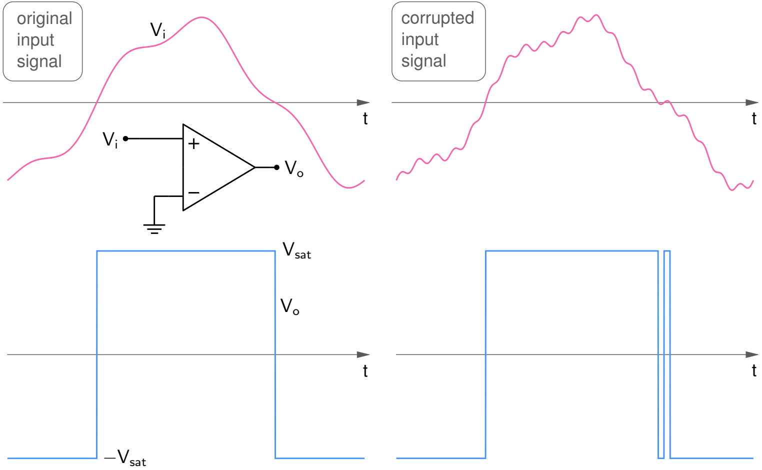
A comparator can be used to convert an analog signal into a digital (high/low) signal for further processing with digital circuits.

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.

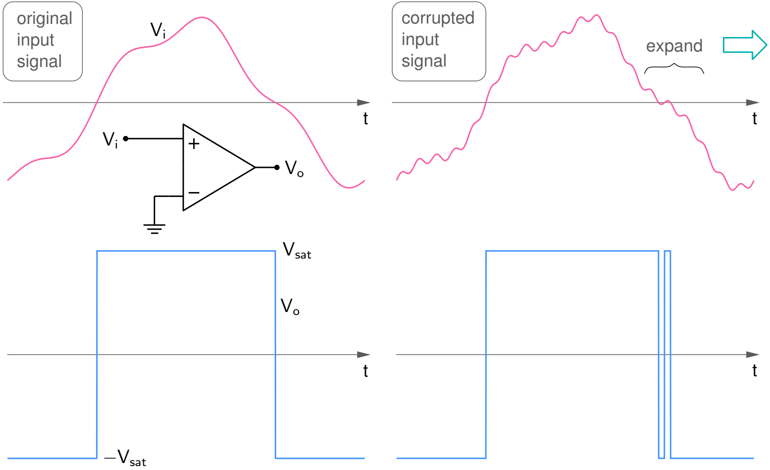
Comparators



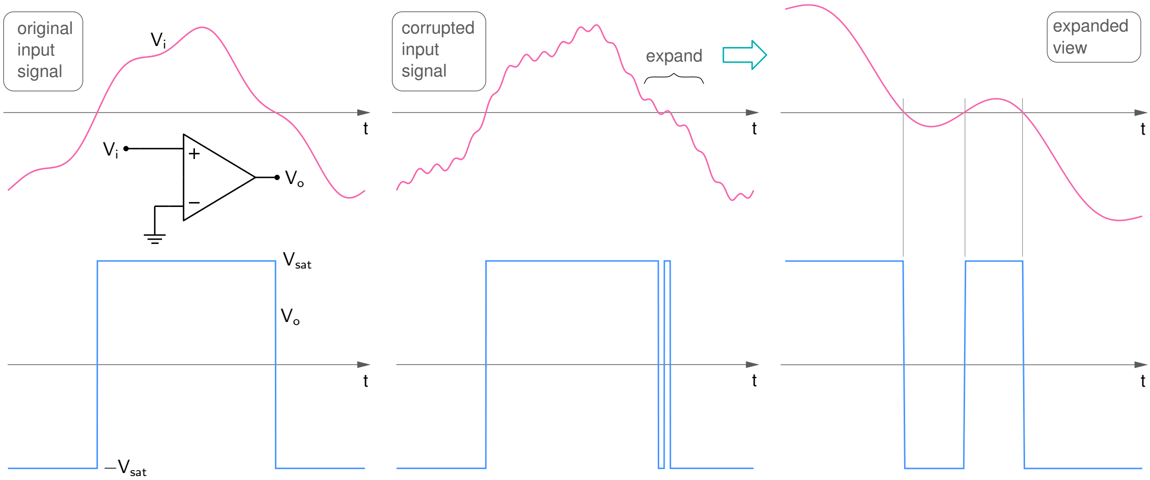
Comparators



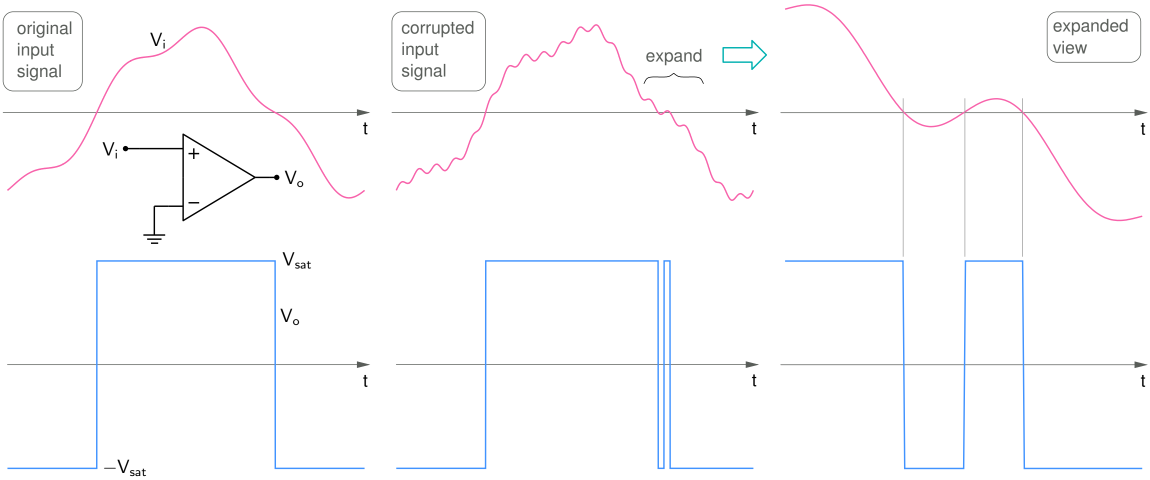
Comparators



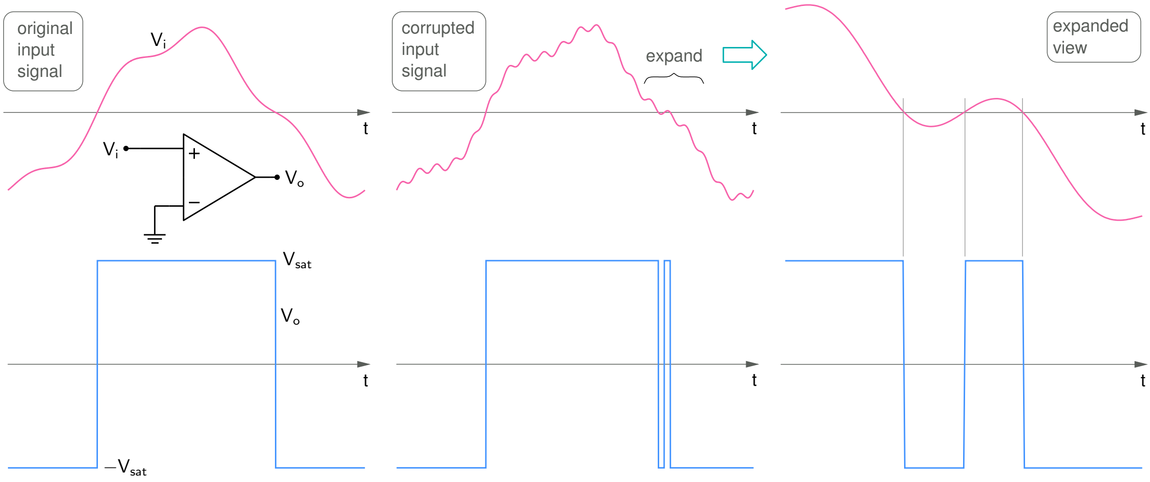
Comparators



Comparators

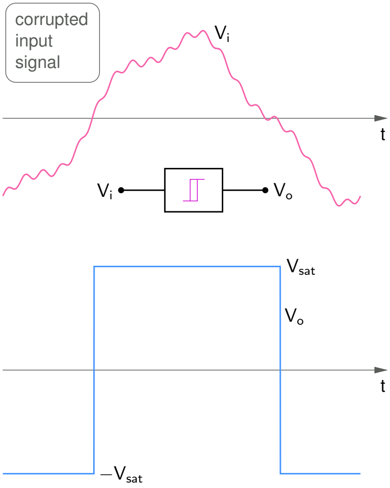


The comparator has produced multiple (spurious) transitions or “bounces,” referred to as “comparator chatter.”

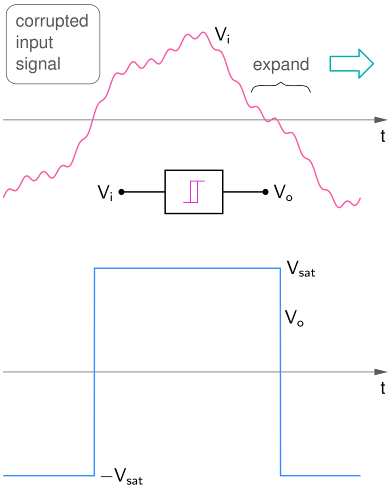


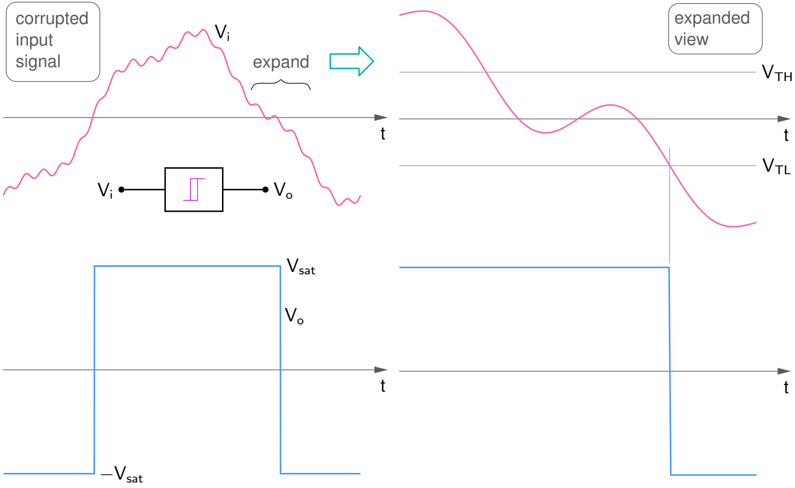
The comparator has produced multiple (spurious) transitions or "bounces," referred to as "comparator chatter."

A Schmitt trigger can be used to eliminate the chatter.

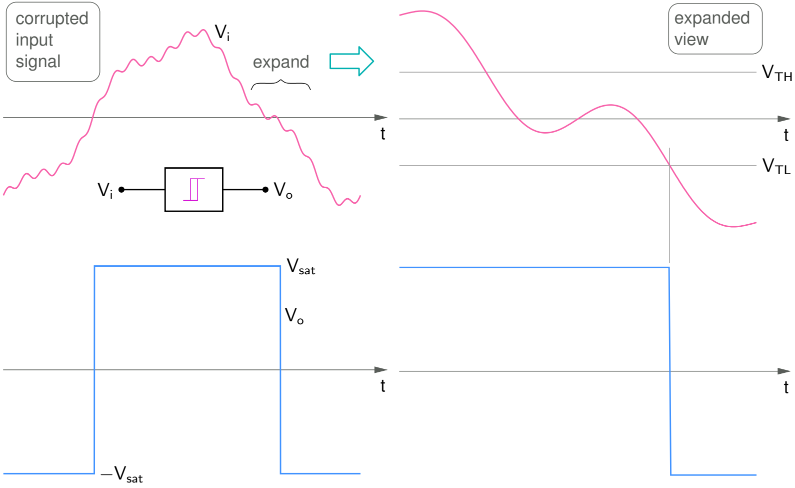


corrupted
input
signal
Vi
t
Vi
Vo
Vsat
Vo
t
—Vsat

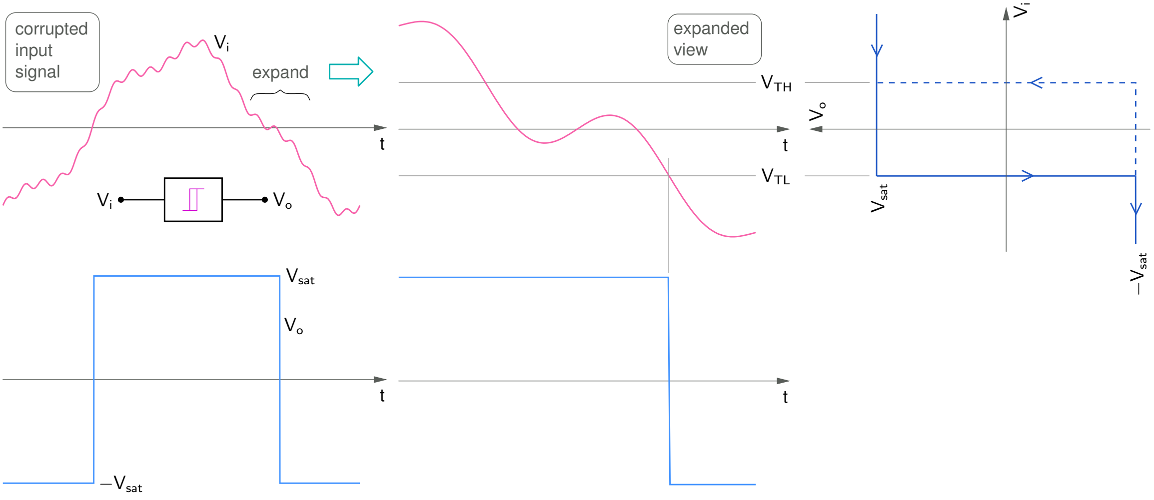

corrupted input signal
V_i
expand
t
V_i
V_o
V_{sat}
V_o
t
$-V_{sat}$



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



* 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.



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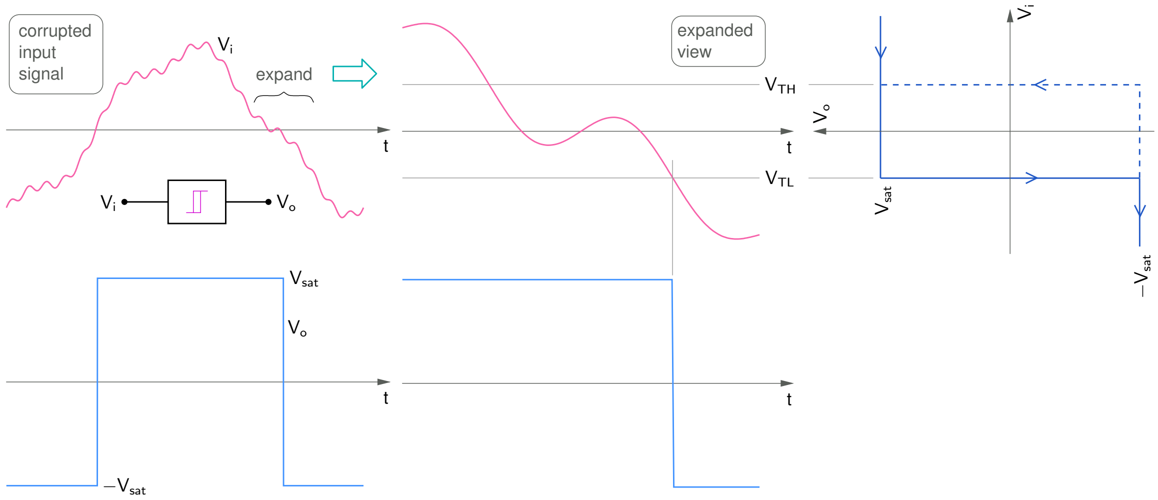
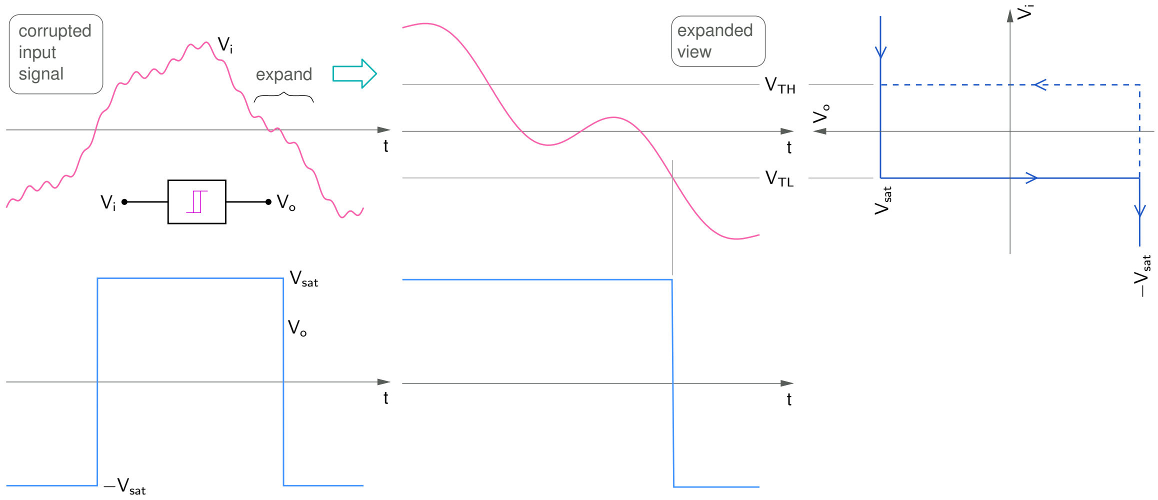
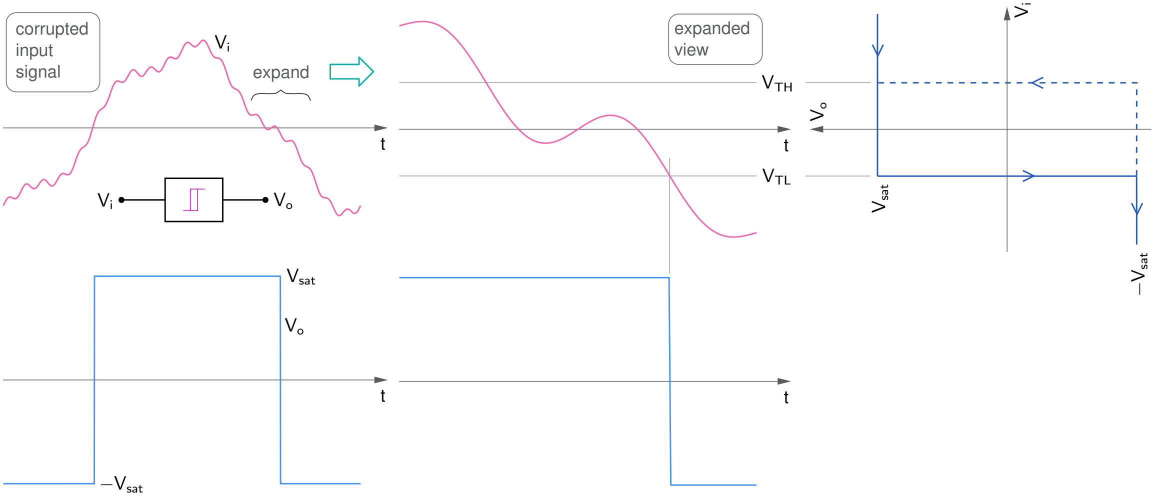


* While going from positive to negative values, V_i needs to cross V_{TL} (and not $0\ V$) to cause a change in V_o.
* In the reverse direction (negative to positive), V_i needs to cross V_{TH}.



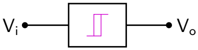
* While going from positive to negative values, V_i needs to cross V_{TL} (and not $0\ V$) to cause a change in V_o.
* In the reverse direction (negative to positive), V_i needs to cross V_{TH}.
* The circuit gets rid of spurious transitions, a major advantage over the simple comparator.

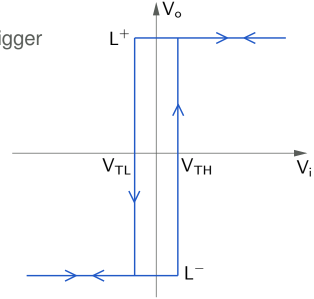


* While going from positive to negative values, V_i needs to cross V_{TL} (and not $0\ V$) to cause a change in V_o.
* In the reverse direction (negative to positive), V_i needs to cross V_{TH}.
* The circuit gets rid of spurious transitions, a major advantage over the simple comparator.
* The hysteresis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

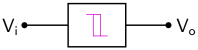
Waveform generation using Schmitt triggers

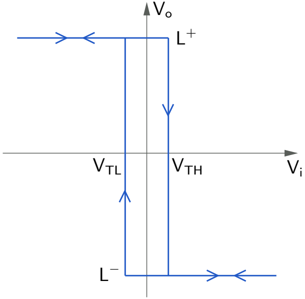
Non–inverting Schmitt trigger

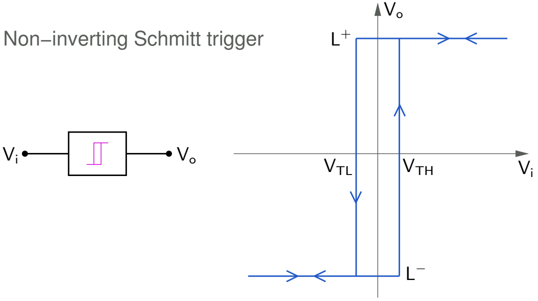


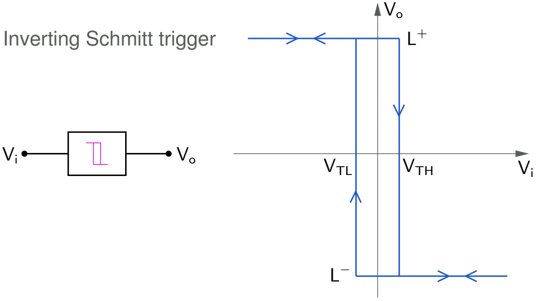


Inverting Schmitt trigger





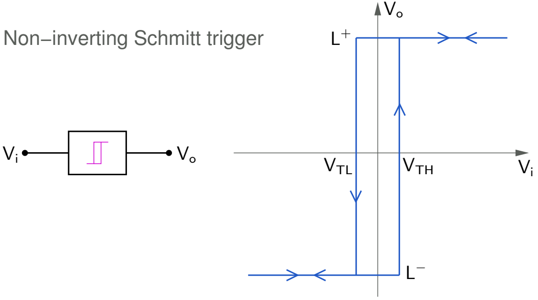




* A Schmitt trigger has two states, $V_o = L^+$ and $V_o = L^-$.

Waveform generation using Schmitt triggers

Non–inverting Schmitt trigger



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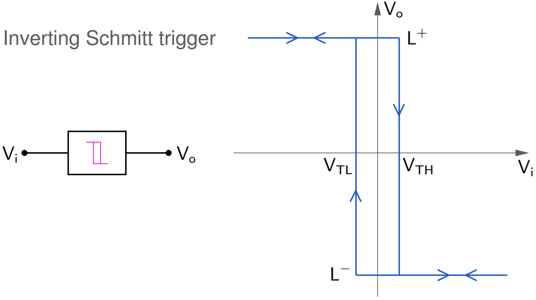
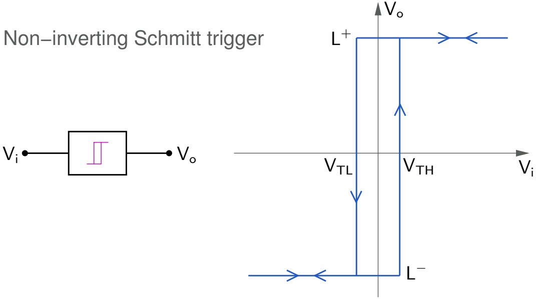
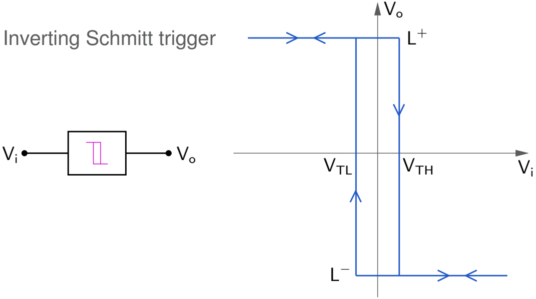


* A Schmitt trigger has two states, $V_o = L^+$ and $V_o = L^-$.
* With a suitable RC network, it can be made to freely oscillate between L^+ and L^-. Such a circuit is called an “astable multivibrator” or a “free-running multivibrator.”

Waveform generation using Schmitt triggers





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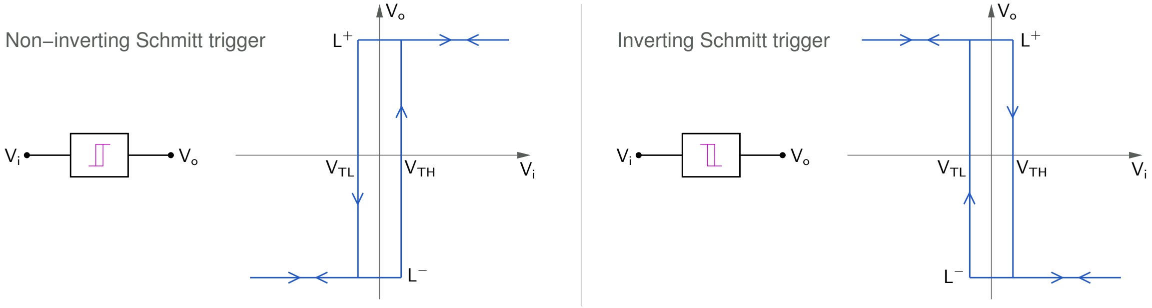
* An astable multivibrator produces oscillations *without* an input signal, the frequency being controlled by the component values.

Waveform generation using Schmitt triggers



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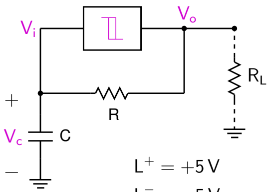
* With a suitable *RC* network, it can be made to freely oscillate between L^+ and L^-. Such a circuit is called an "astable multivibrator" or a "free-running multivibrator."
* An astable multivibrator produces oscillations *without* an input signal, the frequency being controlled by the component values.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

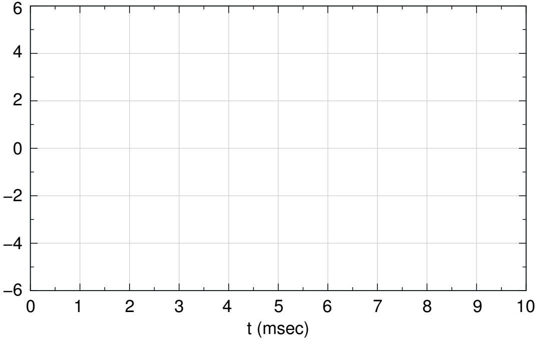


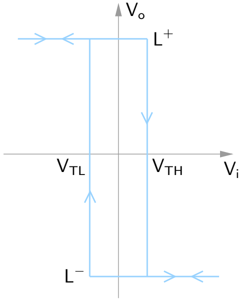
$L^+ = +5\,V$

$L^- = -5\,V$

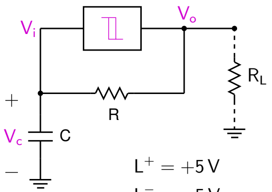
$R = 2\,k$ $\quad$ $V_{TH} = +1\,V$

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





Waveform generation using a Schmitt trigger



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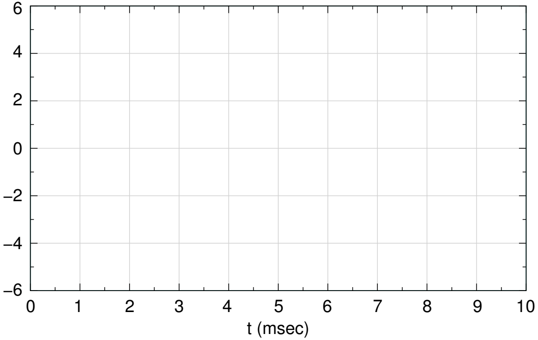
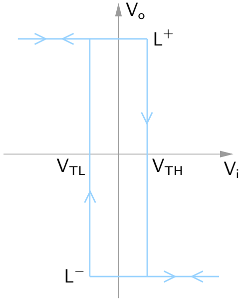
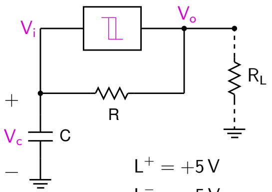




At $t = 0$, let $V_o = L^+$, and $V_c = 0\ V$.

Waveform generation using a Schmitt trigger



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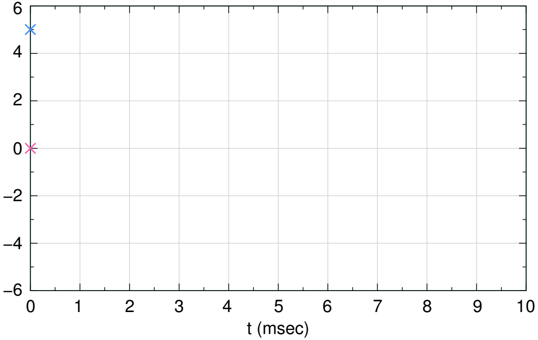

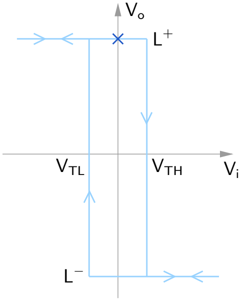

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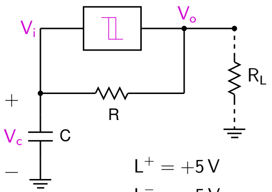
Waveform generation using a Schmitt trigger



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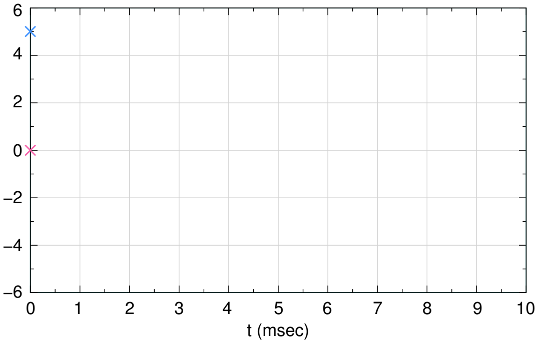
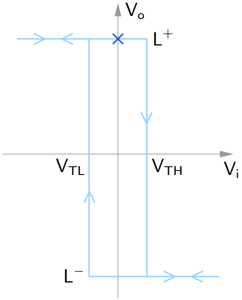
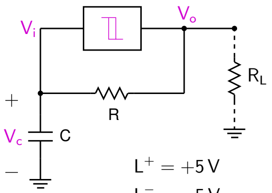




At $t = 0$, let $V_o = L^+$, and $V_c = 0\ V$.

The capacitor starts charging toward L^+.

Waveform generation using a Schmitt trigger



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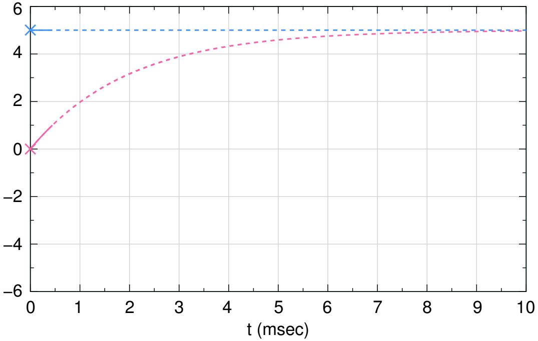
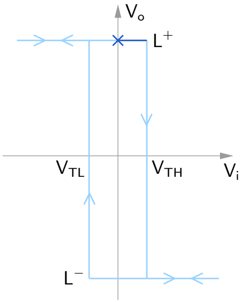
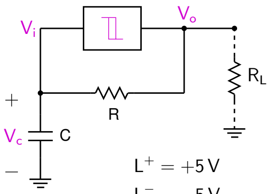




At $t = 0$, let $V_o = L^+$, and $V_c = 0\ V$.

The capacitor starts charging toward L^+.

Waveform generation using a Schmitt trigger



$L^+ = +5\,V$

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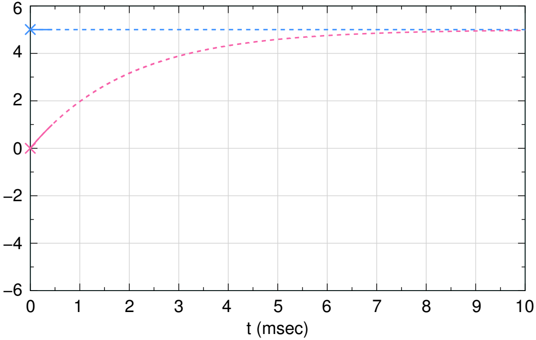
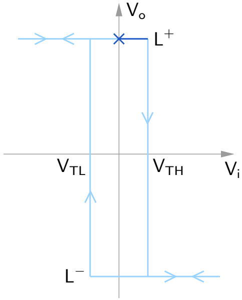


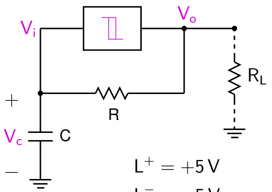


At $t = 0$, let $V_o = L^+$, and $V_c = 0\ V$.

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

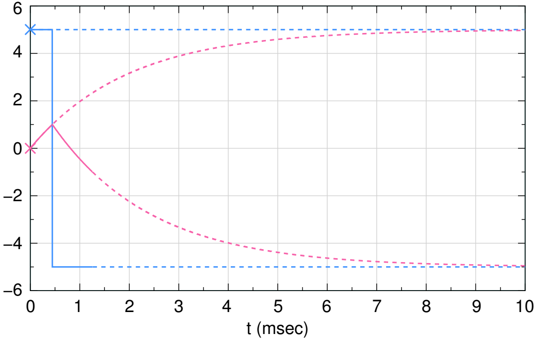


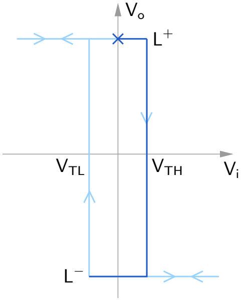
$L^+ = +5\,V$

$L^- = -5\,V$

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

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



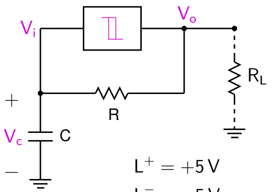


At $t = 0$, let $V_o = L^+$, and $V_c = 0\ V$.

The capacitor starts charging toward L^+.

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

Waveform generation using a Schmitt trigger



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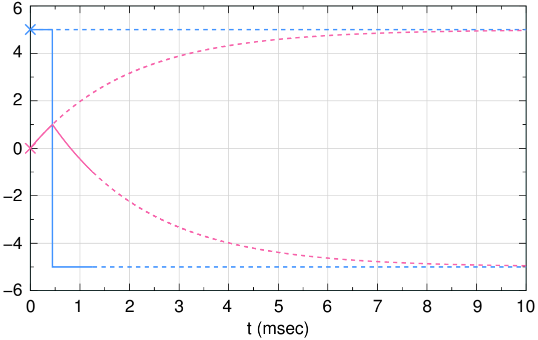
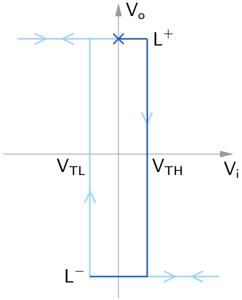




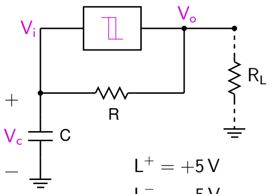
At $t = 0$, let $V_o = L^+$, and $V_c = 0\ V$.

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



$L^+ = +5\,V$

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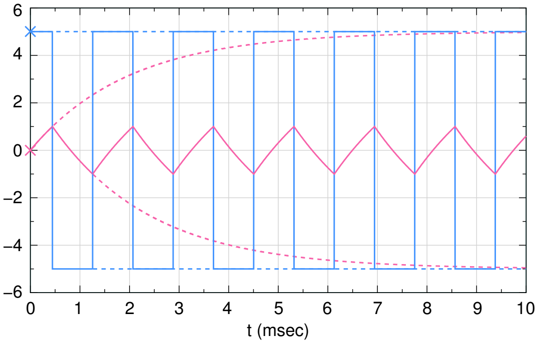
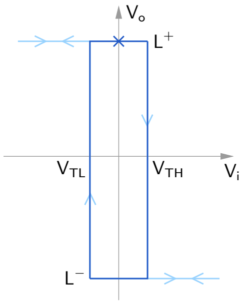
$R = 2\,k$ $\quad V_{TH} = +1\,V$

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





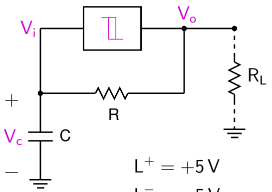
At $t = 0$, let $V_o = L^+$, and $V_c = 0\ V$.

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



$L^+ = +5\,V$

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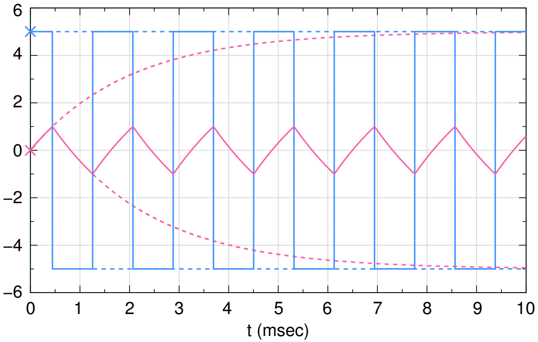
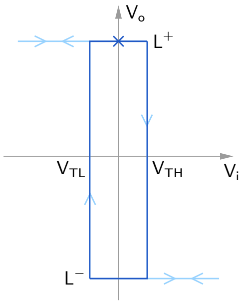
$R = 2\,k$ $\qquad V_{TH} = +1\,V$

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





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

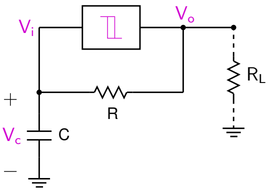
The capacitor starts charging toward L^+.

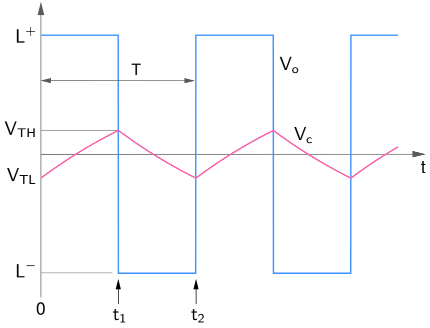
When V_c crosses V_{TH}, the output flips. Now, the capacitor starts discharging toward L^-.

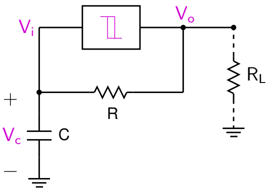
When V_c crosses V_{TL}, the output flips again $\rightarrow$ oscillations.

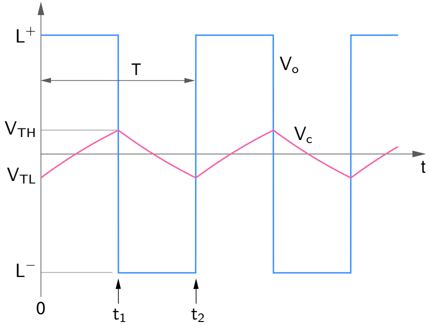
Note that the circuit oscillates *on its own*, i.e., without any input.

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
V_{TL}
t
L^-
0
t_1
t_2



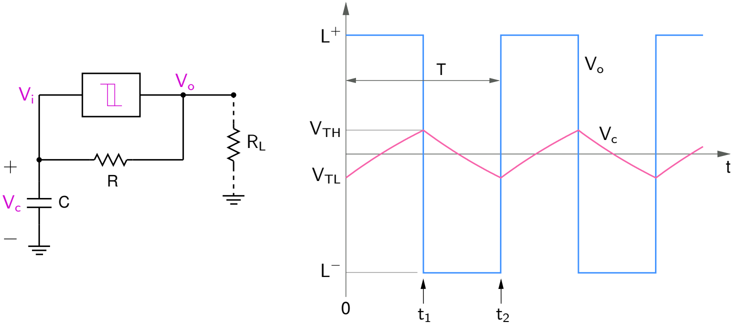


Charging: Let $V_c(t) = A_1 \exp(-t/\tau) + B_1$, with $\tau = RC$.

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.

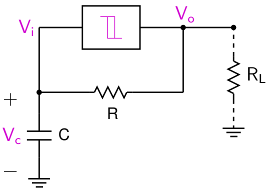
At $t = t_1$, $V_c = V_{TH} \rightarrow V_{TH} = A_1 \exp(-t_1/\tau) + B_1 \rightarrow$ find t_1.

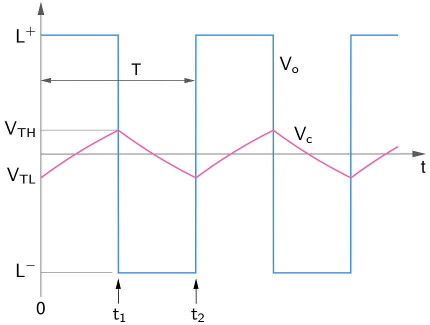
Discharging: Let $V_c(t) = A_2 \exp(-(t - t_1)/\tau) + B_2$.

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 $(t_2 - t_1) \rightarrow t_2 \rightarrow T = t_2$.

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.

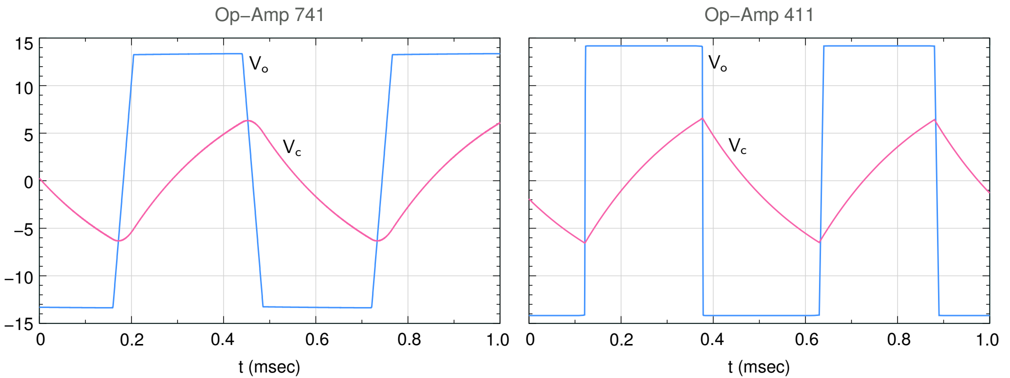
Discharging: Let $V_c(t) = A_2\ \exp(-(t - t_1)/\tau) + B_2$.

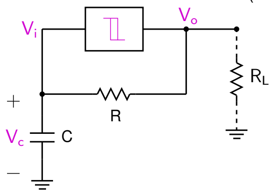
Using $V_c(t_1) = V_{TH},\ \ V_c(\infty) = L^-$, find A_2 and B_2.

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

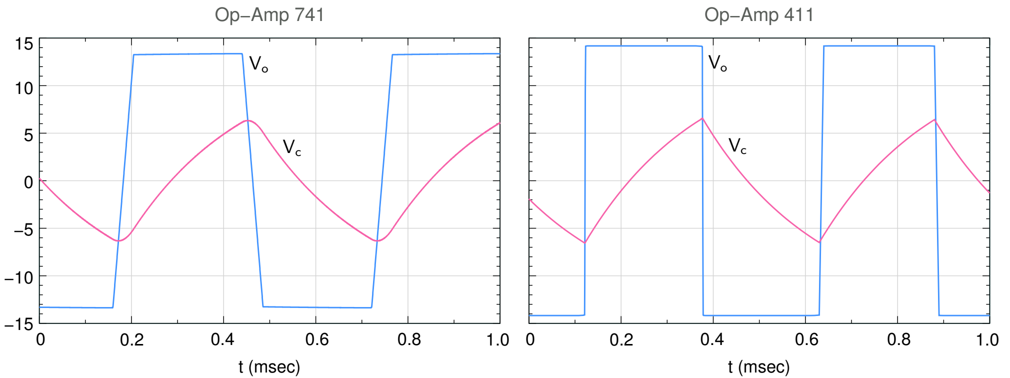
If $L^+ = L,\ L^- = -L,\ V_{TH} = V_T,\ V_{TL} = -V_T$, show that $T = 2\,RC\ln\left(\dfrac{L + V_T}{L - V_T}\right)$.

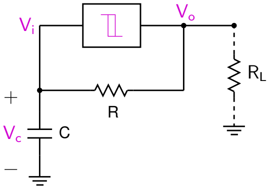
Waveform generation using a Schmitt trigger





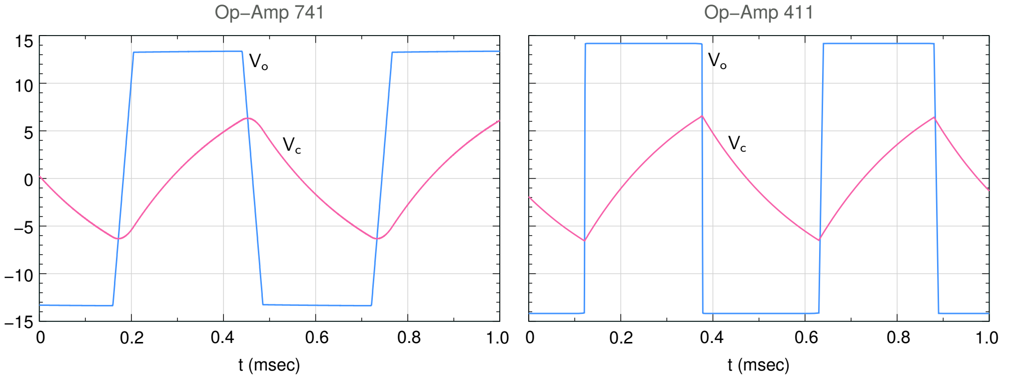
Waveform generation using a Schmitt trigger

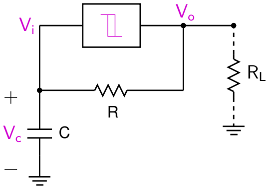




Note that Op-Amp 411 (slew rate: 10 $V/\mu s$) gives sharper waveforms as compared to Op-Amp 741 (slew rate: 0.5 $V/\mu s$).

Waveform generation using a Schmitt trigger



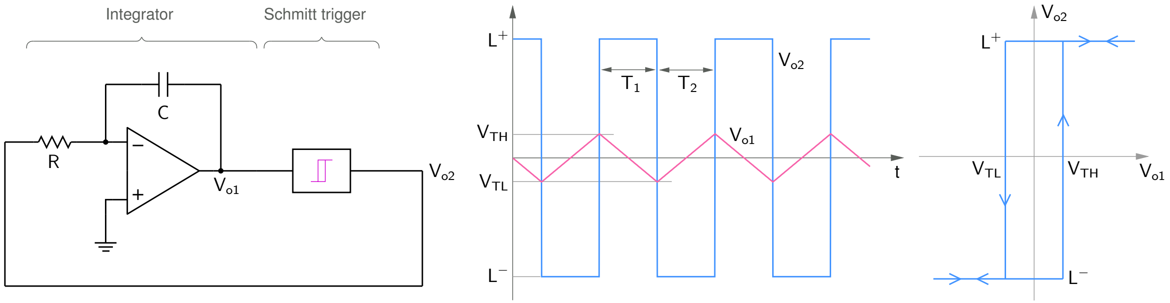


Note that Op-Amp 411 (slew rate: 10 $V/\mu s$) gives sharper waveforms as compared to Op-Amp 741 (slew rate: 0.5 $V/\mu s$).

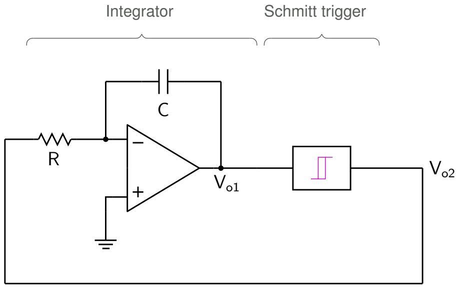
SEQUEL files: `schmitt_osc_741.sqproj`, `schmitt_osc_411.sqproj`

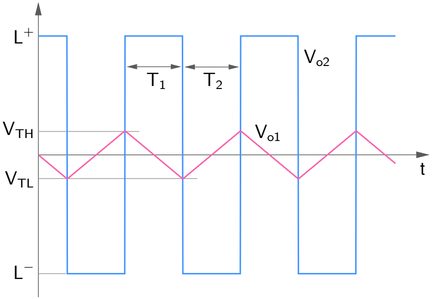
(Ref: J. M. Fiore, “Op-Amps and linear ICs”)

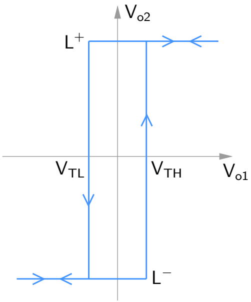
Waveform generation using a Schmitt trigger



Waveform generation using a Schmitt trigger

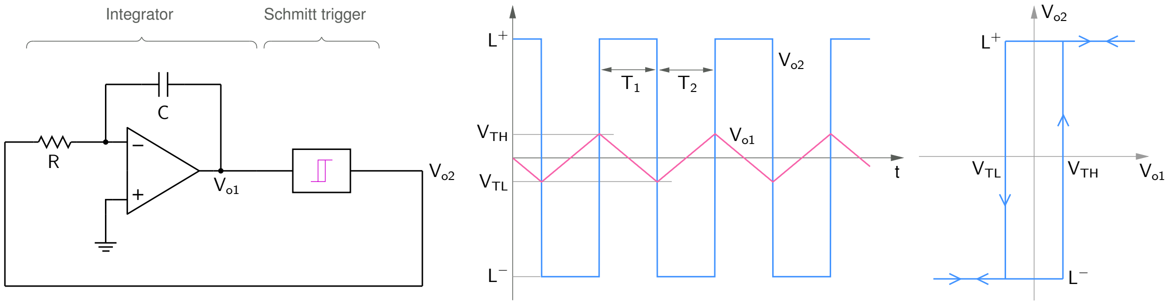






For the integrator, $V_{o1} = -\frac{1}{RC}\int V_{o2}\,dt \equiv -\frac{1}{\tau}\int V_{o2}\,dt$

Waveform generation using a Schmitt trigger



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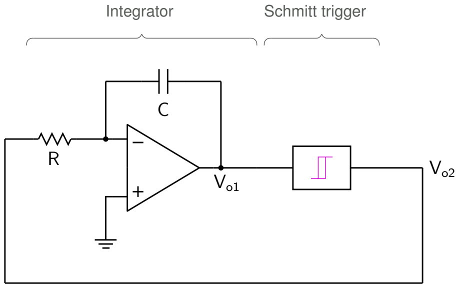
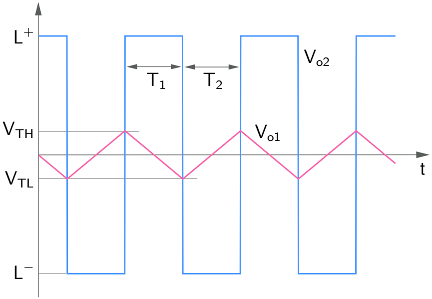
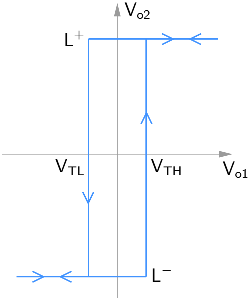
$V_{o2} = L^+ \rightarrow V_{o2}$ decreases linearly, $V_{o2} = L^- \rightarrow V_{o2}$ increases linearly.

Waveform generation using a Schmitt trigger







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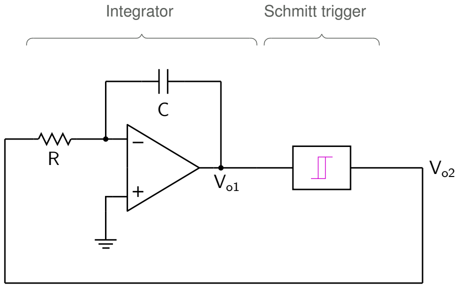
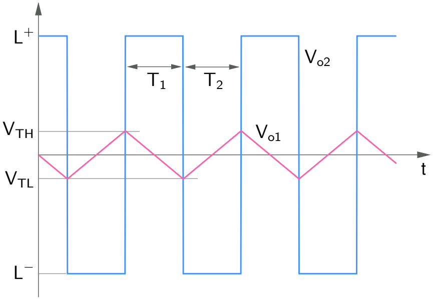
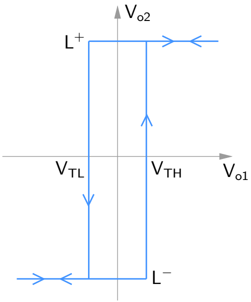
$V_{o2} = L^{+} \rightarrow V_{o2}$ decreases linearly, $\;V_{o2} = L^{-} \rightarrow V_{o2}$ increases linearly.

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

Waveform generation using a Schmitt trigger







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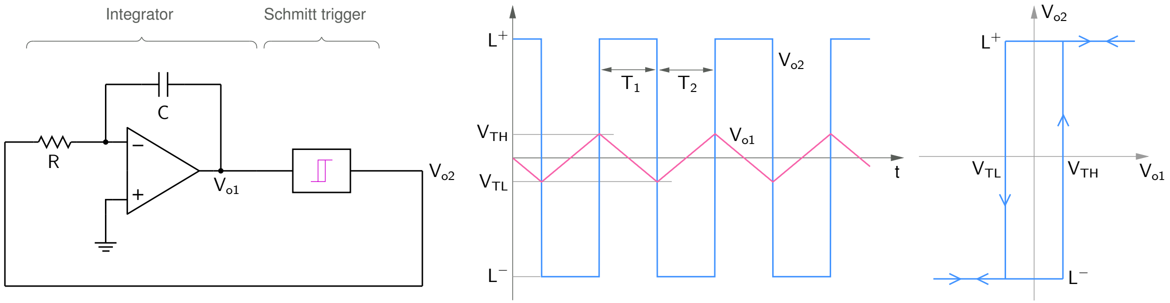
$T_1 = \tau\,\dfrac{V_{TH} - V_{TL}}{L^+}$.

Waveform generation using a Schmitt trigger



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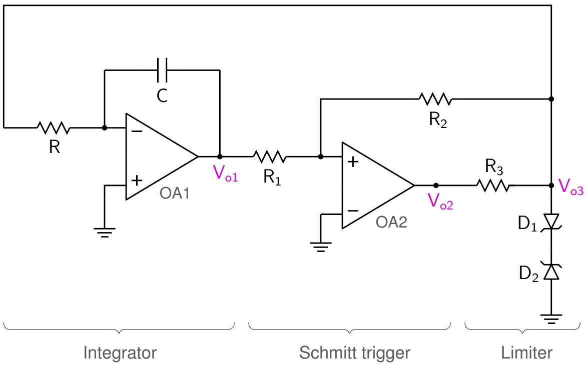
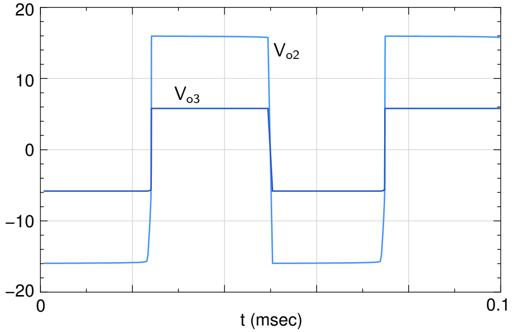
$$T_1 = \tau\,\frac{V_{TH} - V_{TL}}{L^+}\,.$$

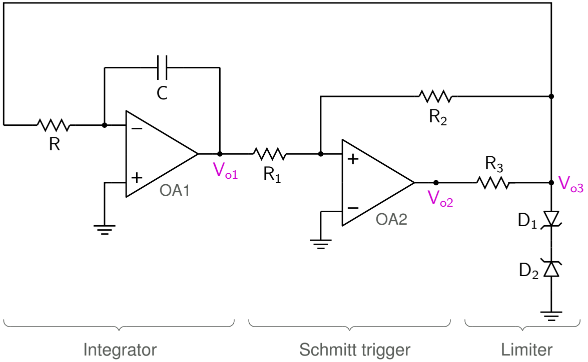
$$T_2 = \tau\,\frac{V_{TH} - V_{TL}}{-L^-}\,.$$

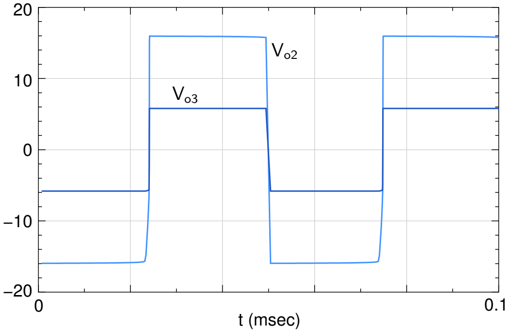
M. B. Patil, IIT Bombay

Limiting the output voltage

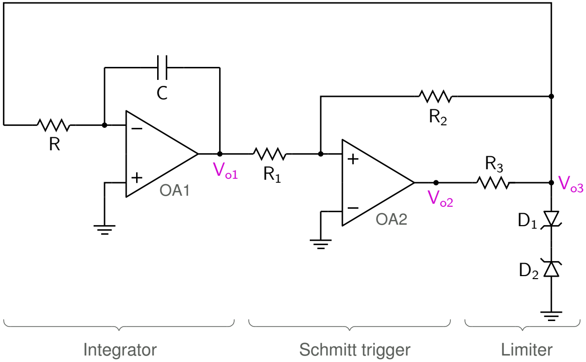


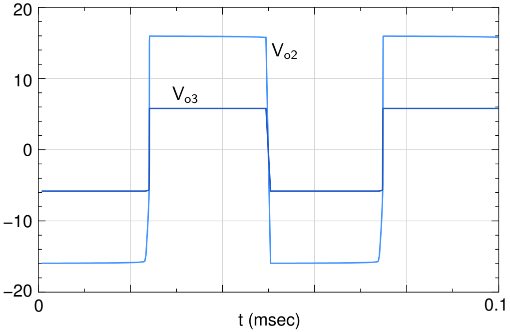




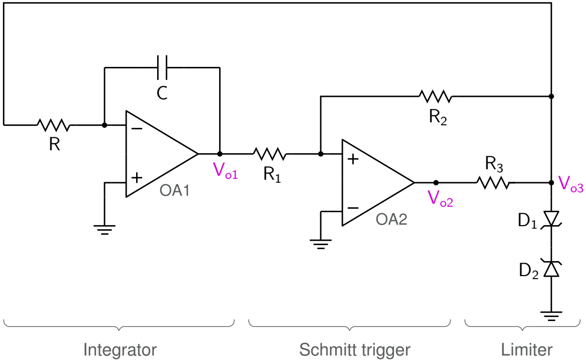


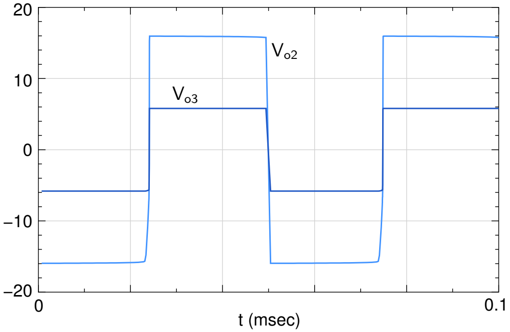
* When $V_{o2} = +V_{\rm sat}$, D_1 is forward-biased (with a voltage drop of $V_{\rm on}$), and D_2 is reverse-biased. The Zener breakdown voltage (V_Z) is chosen so that D_2 operates under breakdown condition.
  $\rightarrow V_{o3} = V_{\rm on} + V_Z$.



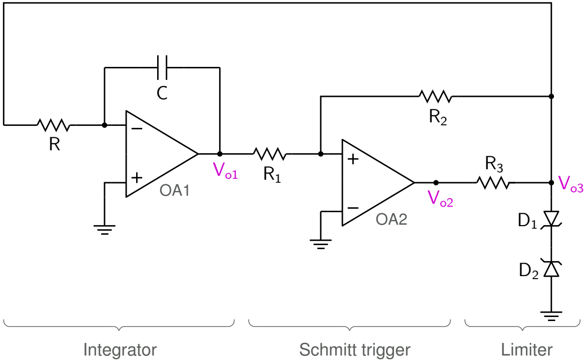


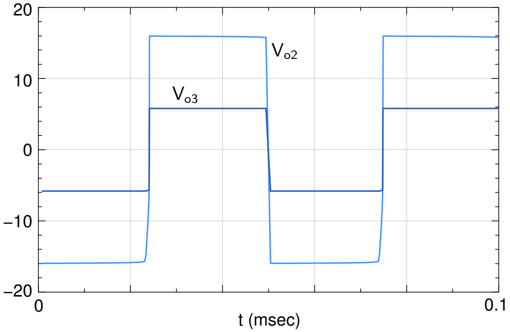
* When $V_{o2} = +V_{sat}$, D_1 is forward-biased (with a voltage drop of V_{on}), and D_2 is reverse-biased. The Zener breakdown voltage (V_Z) is chosen so that D_2 operates under breakdown condition.
  $\rightarrow V_{o3} = V_{on} + V_Z$.
* When $V_{o2} = -V_{sat}$, D_2 is forward-biased (with a voltage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





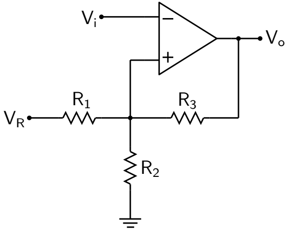
* When $V_{o2} = +V_{sat}$, D_1 is forward-biased (with a voltage drop of V_{on}), and D_2 is reverse-biased. The Zener breakdown voltage (V_Z) is chosen so that D_2 operates under breakdown condition.
  $\rightarrow V_{o3} = V_{on} + V_Z$.
* When $V_{o2} = -V_{sat}$, D_2 is forward-biased (with a voltage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

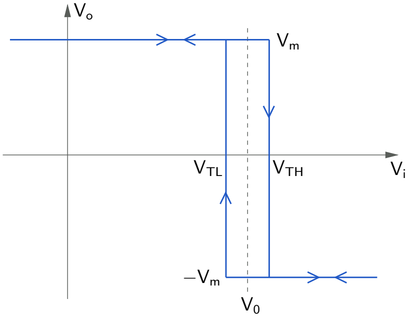




* When $V_{o2} = +V_{\text{sat}}$, D_1 is forward-biased (with a voltage drop of V_{on}), and D_2 is reverse-biased. The Zener breakdown voltage (V_Z) is chosen so that D_2 operates under breakdown condition.
  $\rightarrow$ $V_{o3} = V_{\text{on}} + V_Z$.
* When $V_{o2} = -V_{\text{sat}}$, D_2 is forward-biased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

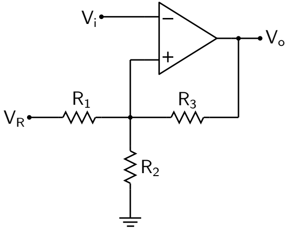
SEQUEL file: `opamp_osc_1.sqproj`

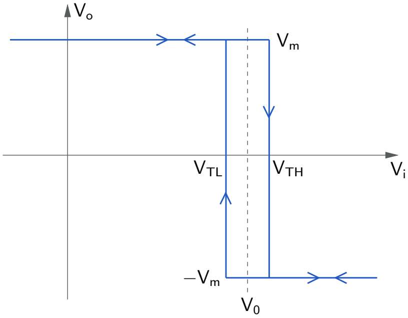




A Schmitt trigger circuit is shown in the figure along with its V_o-V_i relationship. Assume that $V_{\text{sat}} \approx 14\,\text{V}$ for the op-amp. The reference voltage V_R can be adjusted using a pot (not shown in the figure).

Schmitt trigger





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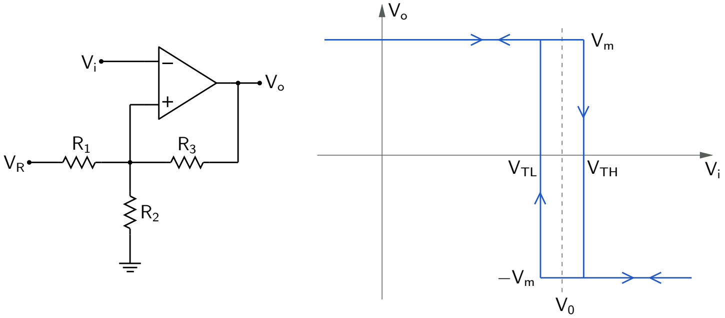
* Design the circuit to obtain $V_0 = 2.5\,\mathrm{V}$ and $\Delta V_T = V_{TH} - V_{TL} = 0.4\,\mathrm{V}$.



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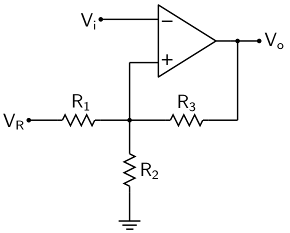
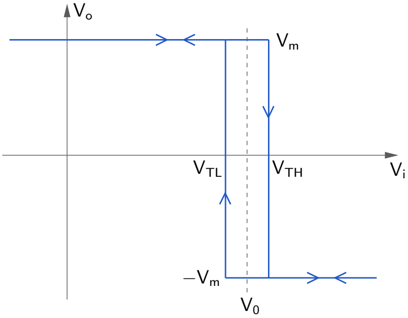
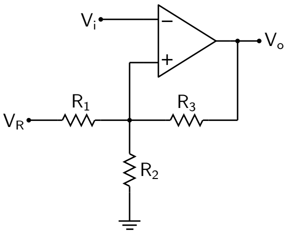
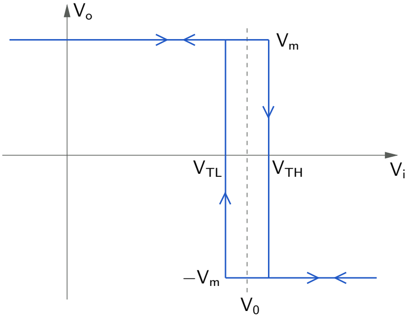
* Design the circuit to obtain $V_0 = 2.5\,\mathrm{V}$ and $\Delta V_T = V_{TH} - V_{TL} = 0.4\,\mathrm{V}$.
* Verify your design with simulation (and in the lab).





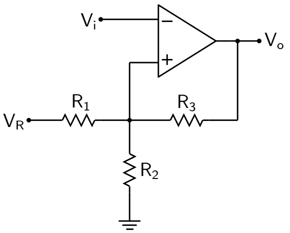
$$V_+ = V_R \frac{(R_2 \parallel R_3)}{(R_2 \parallel R_3) + R_1} \pm V_m \frac{(R_1 \parallel R_2)}{(R_1 \parallel R_2) + R_3}.$$

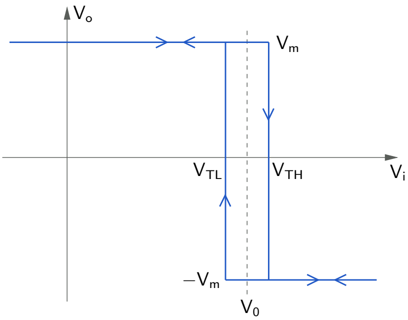




$$V_+ = V_R \frac{(R_2 \parallel R_3)}{(R_2 \parallel R_3) + R_1} \pm V_m \frac{(R_1 \parallel R_2)}{(R_1 \parallel R_2) + R_3}.$$

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





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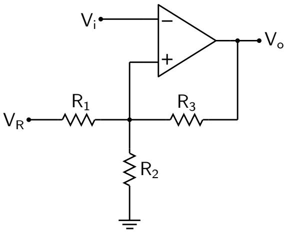
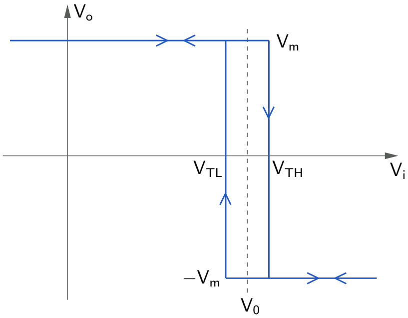
$$\Delta V_T = 0.4\,\text{V} \;\rightarrow\; 2V_m \frac{(R_1 \parallel R_2)}{(R_1 \parallel R_2) + R_3} = 0.4\,\text{V}.$$

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

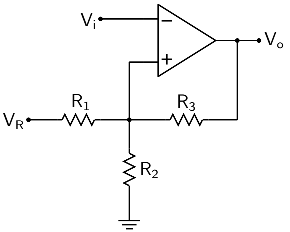
Schmitt trigger

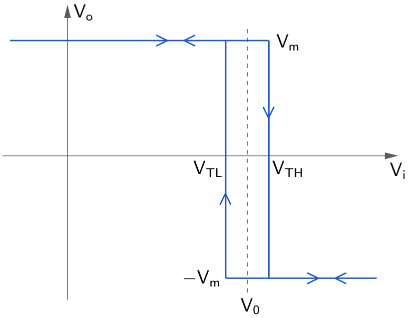




$$\Delta V_T = 0.4\,\mathrm{V} \;\rightarrow\; 2V_m \frac{(R_1 \parallel R_2)}{(R_1 \parallel R_2) + R_3} = 0.4\,\mathrm{V}.$$

Schmitt trigger

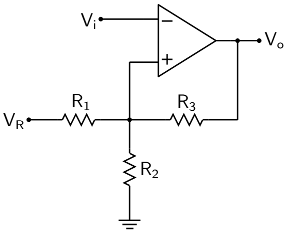


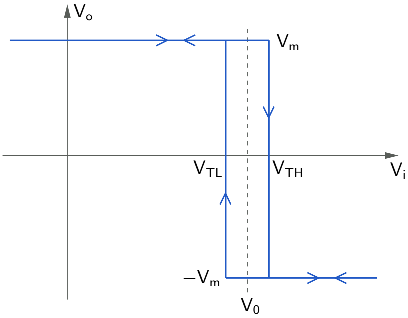


$$\Delta V_T = 0.4\,\text{V} \;\rightarrow\; 2V_m \frac{(R_1 \parallel R_2)}{(R_1 \parallel R_2) + R_3} = 0.4\,\text{V}.$$

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

Schmitt trigger



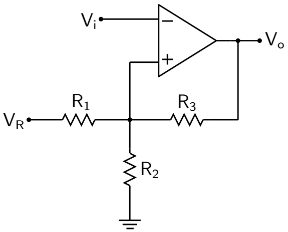


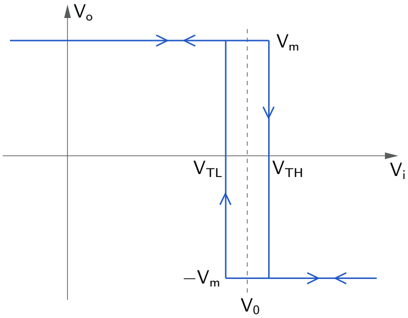
$$\Delta V_T = 0.4\,\text{V} \;\rightarrow\; 2V_m \frac{(R_1 \parallel R_2)}{(R_1 \parallel R_2) + R_3} = 0.4\,\text{V}.$$

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

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

Schmitt trigger





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

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

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

(SEQUEL file: `schmitt_1.sqproj`)