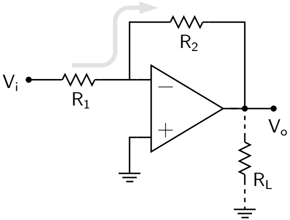
EE101: Op Amp circuits (Part 5)

M. B. Patil
mbpatil@ee.iitb.ac.in
www.ee.iitb.ac.in/~sequel

Department of Electrical Engineering
Indian Institute of Technology Bombay

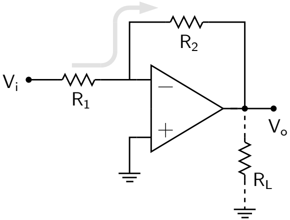


$$V_o = A_V(V_+ - V_-) \quad (1)$$

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



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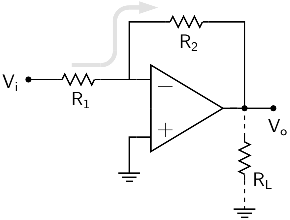
$$\begin{array}{ccccccc} V_i \uparrow & \rightarrow & V_- \uparrow & \rightarrow & V_o \downarrow & \rightarrow & V_- \downarrow \\ & \text{Eq. 2} & & \text{Eq. 1} & & \text{Eq. 2} & \end{array}$$

Feedback: inverting amplifier



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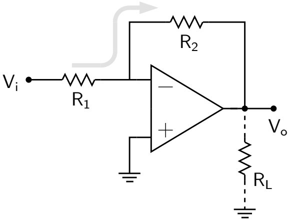
$V_i \uparrow \xrightarrow{\text{Eq. 2}} \boxed{V_- \uparrow} \xrightarrow{\text{Eq. 1}} V_o \downarrow \xrightarrow{\text{Eq. 2}} \boxed{V_- \downarrow}$

The circuit reaches a stable equilibrium.



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Eq. 2 Eq. 1 Eq. 2

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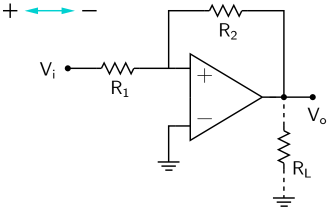
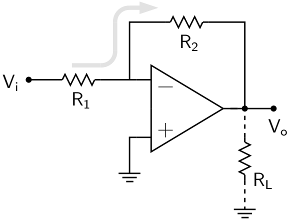


Feedback: inverting amplifier



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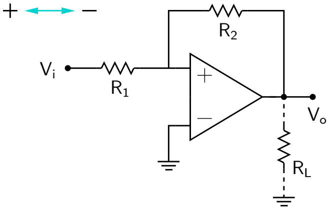
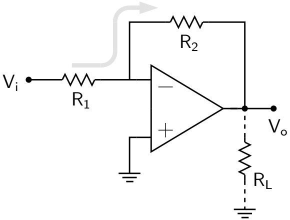


$$V_+ = V_i \frac{R_2}{R_1 + R_2} + V_o \frac{R_1}{R_1 + R_2} \qquad (3)$$



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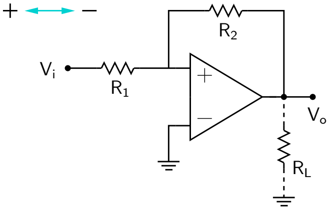
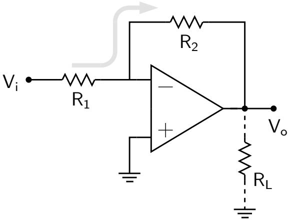
The circuit reaches a stable equilibrium.



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

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

Feedback: inverting amplifier



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Eq. 2 Eq. 1 Eq. 2

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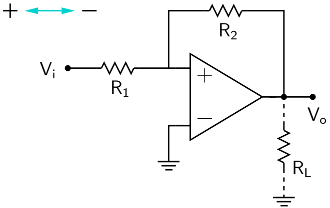

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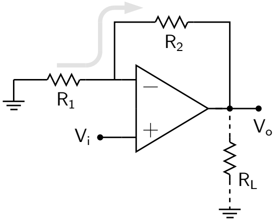
Eq. 3 Eq. 1 Eq. 3

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



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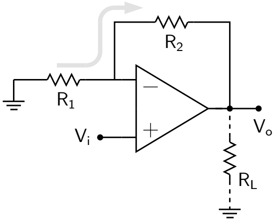

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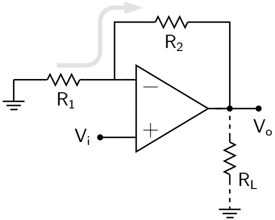

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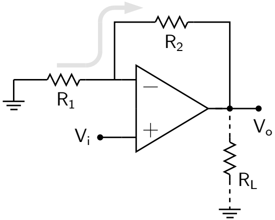
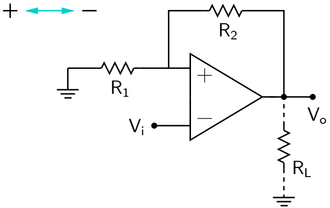
The circuit reaches a stable equilibrium.

Feedback: noninverting amplifier





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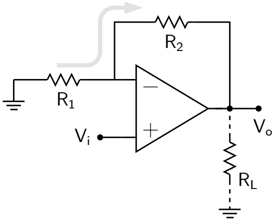

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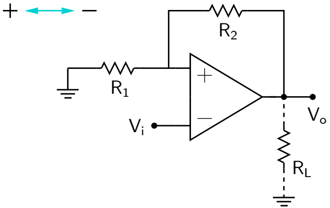

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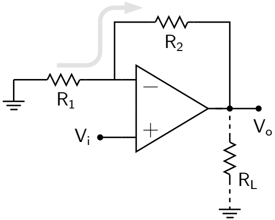

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$V_i \uparrow \rightarrow V_o \uparrow \rightarrow V_- \uparrow \rightarrow V_o \downarrow$

Eq. 1 Eq. 2 Eq. 1

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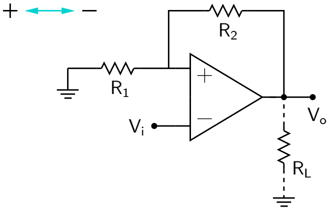

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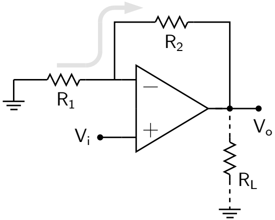

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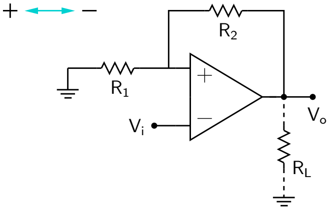

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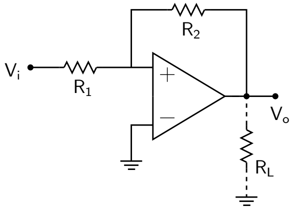
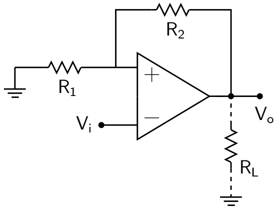
We now have a positive feedback situation. As a result, V_o rises (or falls) indefinitely, limited finally by saturation.

Feedback

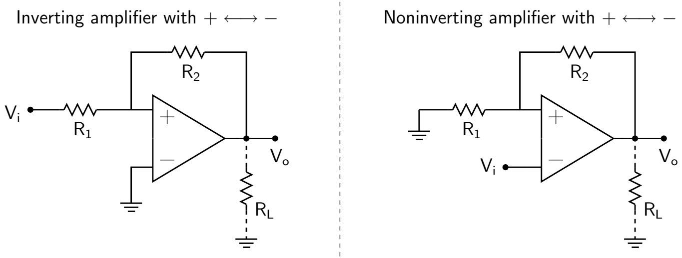
Inverting amplifier with $+ \longleftrightarrow -$



Noninverting amplifier with $+ \longleftrightarrow -$



Feedback



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

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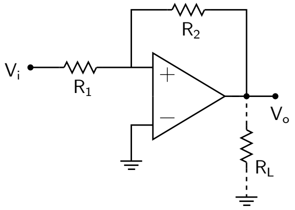

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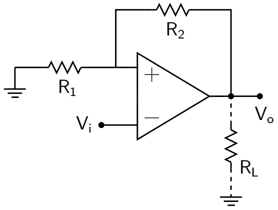
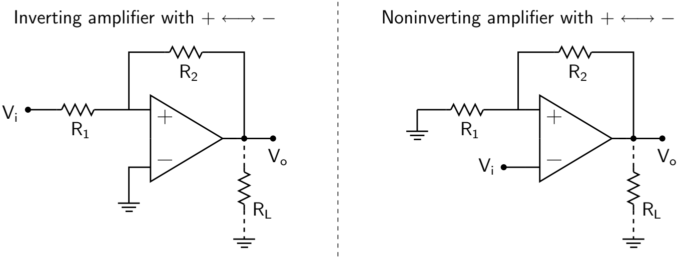
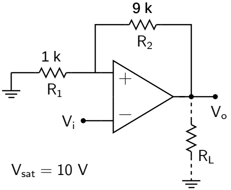


* Because of positive feedback, both these circuits are unstable.
* The output at any time is only limited by saturation of the Op Amp, i.e., $V_o = \pm V_{\text{sat}}$.



* Because of positive feedback, both 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



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

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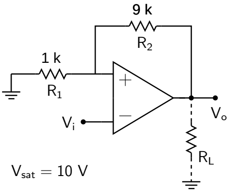

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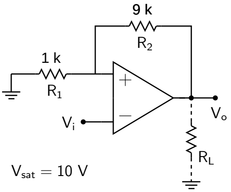
Consider $V_i = 5\ V$.

Inverting Schmitt trigger



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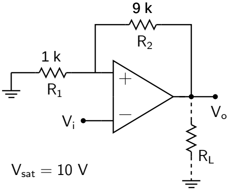
Consider $V_i = 5\ V$.

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

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

Inverting Schmitt trigger



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

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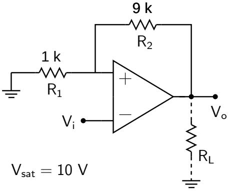

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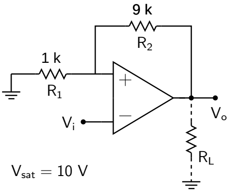
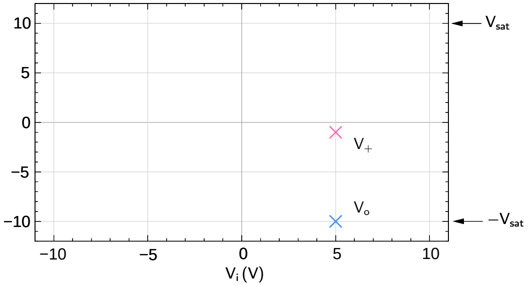
This is inconsistent with our assumption ($V_o = +V_{\text{sat}}$).

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

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





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

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

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

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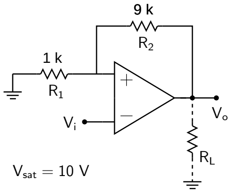

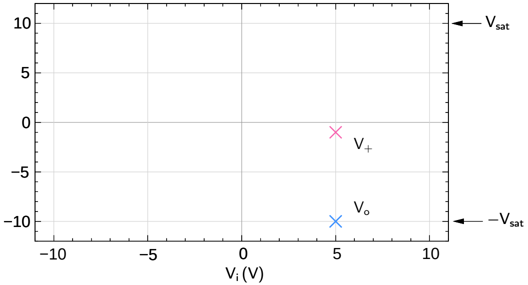

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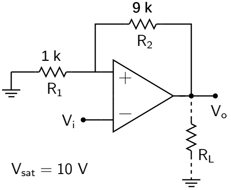
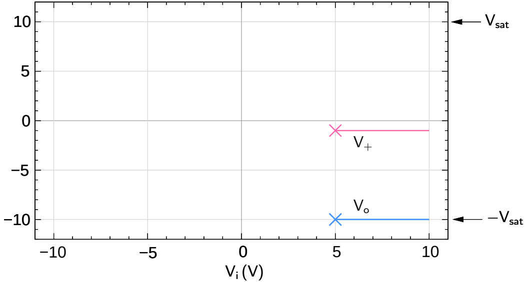
$(V_+ - V_-) = (-1 - 5) = -6\ V \rightarrow V_o = -V_{\text{sat}}$ (consistent)

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

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): $V_o = +V_{\text{sat}} = +10\ V \rightarrow V_+ = \dfrac{R_1}{R_1 + R_2} V_o = 1\ V$.

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

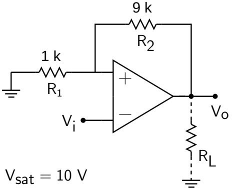
This is inconsistent with our assumption ($V_o = +V_{\text{sat}}$).

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

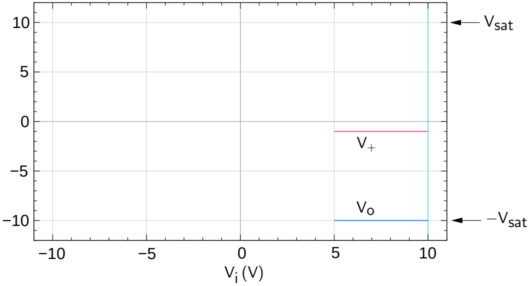
$(V_+ - V_-) = (-1 - 5) = -6\ V \rightarrow V_o = -V_{\text{sat}}$ (consistent)

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

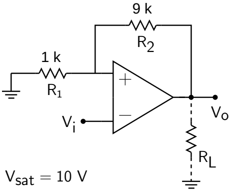
Inverting Schmitt trigger

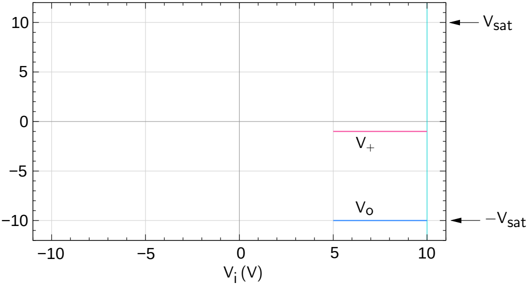


$V_{sat} = 10$ V



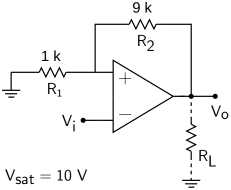
Inverting Schmitt trigger

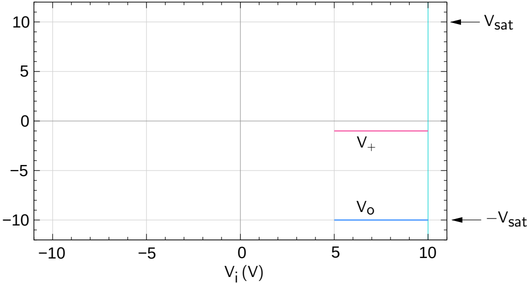




Consider decreasing values of V_i.

Inverting Schmitt trigger

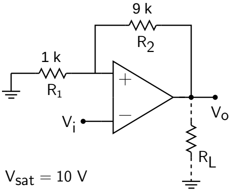


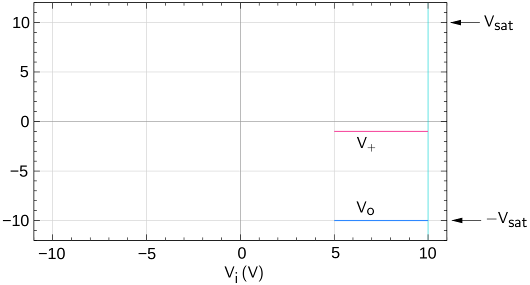


Consider decreasing values of V_i.

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

Inverting Schmitt trigger



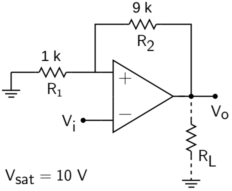


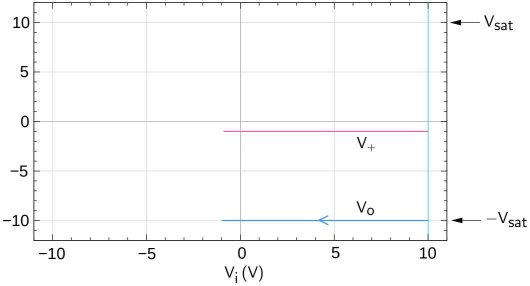
Consider decreasing values of V_i.

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

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

Inverting Schmitt trigger





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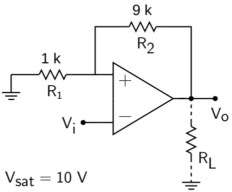
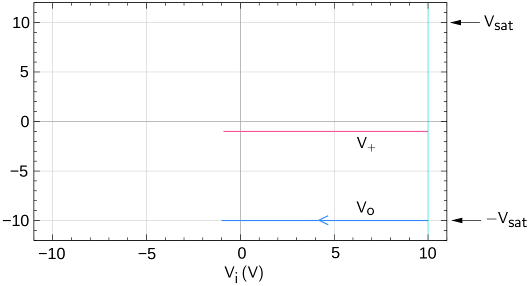
Inverting Schmitt trigger





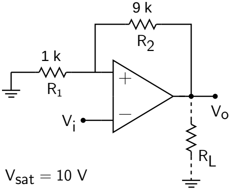
Consider decreasing values of V_i.

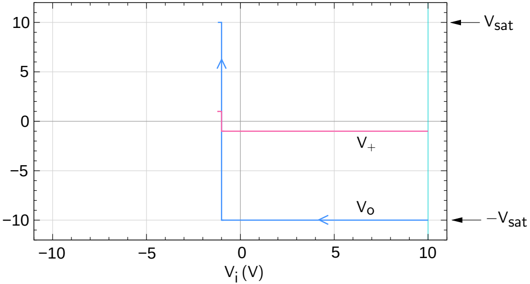
$$V_+ = \frac{R_1}{R_1 + R_2} V_o = \frac{1\text{ k}}{10\text{ k}} (-V_{\text{sat}}) = -1\ V\ .$$

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





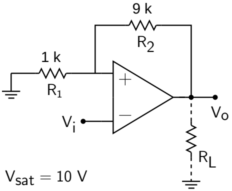
Consider decreasing values of V_i.

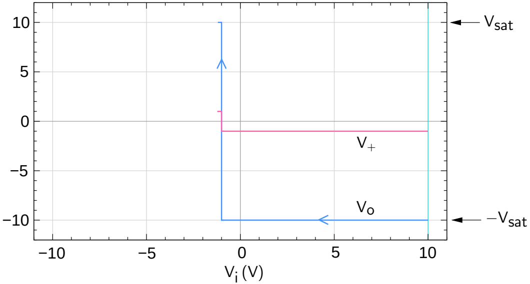
$$V_+ = \frac{R_1}{R_1 + R_2} V_o = \frac{1\text{ k}}{10\text{ k}} (-V_{\text{sat}}) = -1\ V\ .$$

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

Inverting Schmitt trigger





Consider decreasing values of V_i.

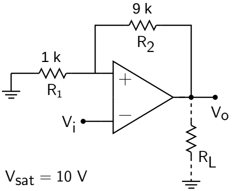
$$V_+ = \frac{R_1}{R_1 + R_2} V_o = \frac{1\text{ k}}{10\text{ k}}(-V_{\text{sat}}) = -1\ V\,.$$

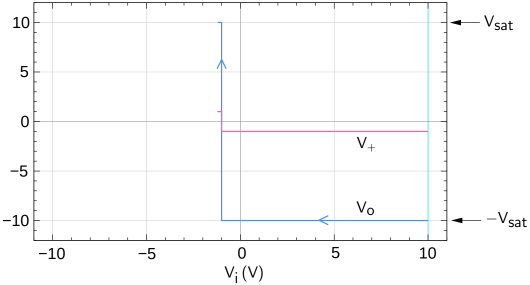
As long as $V_i = V_- > V_+ = -1\ V$, V_o remains at $-V_{\text{sat}}$.

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

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

Inverting Schmitt trigger





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

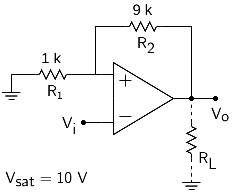
As long as $V_i = V_- > V_+ = -1\ V$, V_o remains at $-V_{\text{sat}}$.

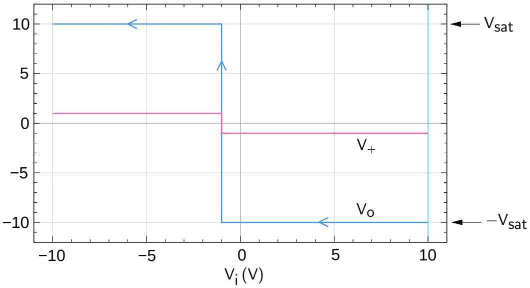
When $V_i < V_+ = -1\ V$, V_o changes sign, i.e., $V_o = +V_{\text{sat}}$.

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





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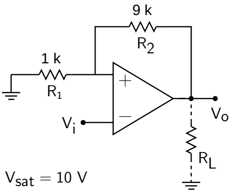
$$V_+ = \frac{R_1}{R_1 + R_2} V_o = \frac{1\ \text{k}}{10\ \text{k}} (-V_{\text{sat}}) = -1\ V\,.$$

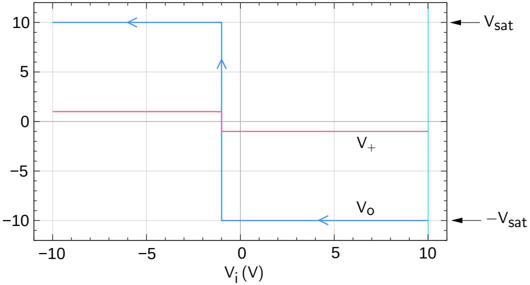
As long as $V_i = V_- > V_+ = -1\ V$, V_o remains at $-V_{\text{sat}}$.

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).





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

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

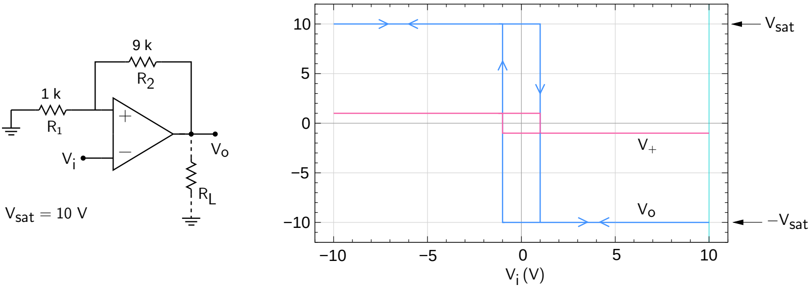
When $V_i < V_+ = -1\ V$, V_o changes sign, i.e., $V_o = +V_{\text{sat}}$.

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.

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

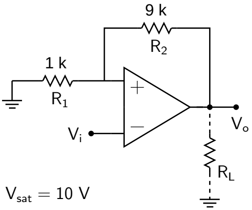
As long as $V_i = V_- > V_+ = -1\ V$, V_o remains at $-V_{sat}$.

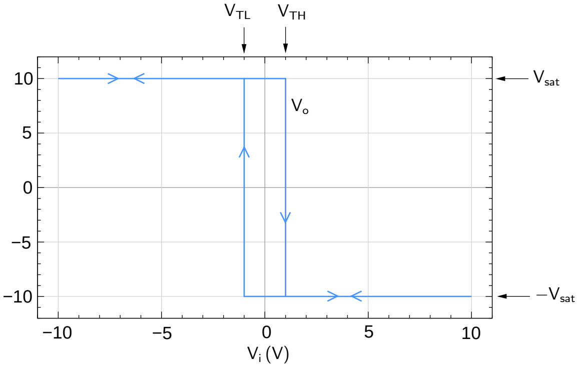
When $V_i < V_+ = -1\ V$, V_o changes sign, i.e., $V_o = +V_{sat}$.

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

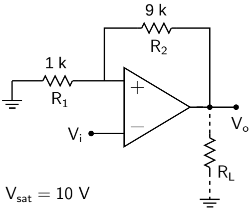
Decreasing V_i further makes no difference to V_o (since $V_i = V_- < V_+ = +1\ V$ holds).

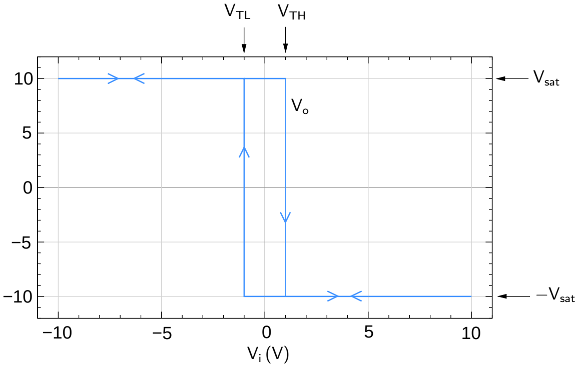
Now, the threshold at which V_o flips is $V_i = +1\ V$.


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

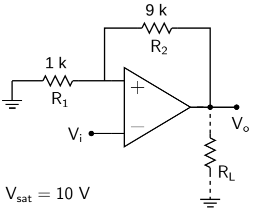

VTL
VTH
10
5
0
−5
−10
Vsat
−Vsat
Vo
−10
−5
0
5
10
Vi (V)

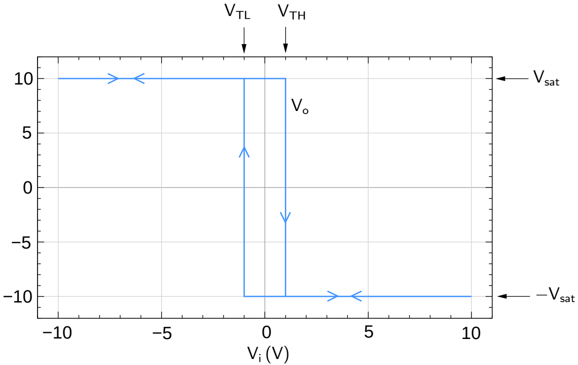
Inverting Schmitt trigger





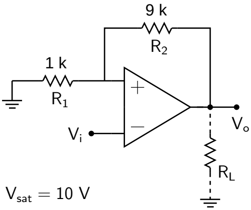
* The threshold values (or "tripping points"), V_{TH} and V_{TL}, are given by $\pm\left(\dfrac{R_1}{R_1+R_2}\right)V_{sat}$.

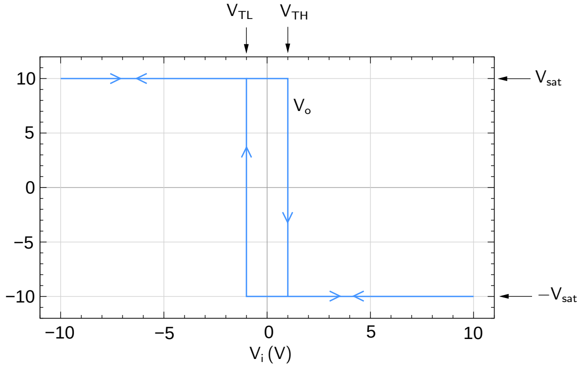




* The threshold values (or "tripping points"), V_{TH} and V_{TL}, are given by $\pm\left(\frac{R_1}{R_1+R_2}\right)V_{sat}$.
* The tripping point (whether V_{TH} or V_{TL}) depends on where we are on the V_o axis. In that sense, the circuit has a memory.

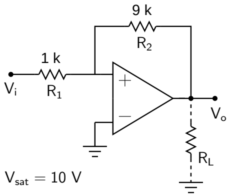
Inverting Schmitt trigger





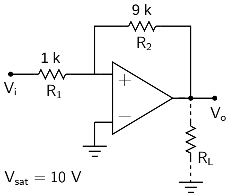
* The threshold values (or "tripping points"), $V_{\rm TH}$ and $V_{\rm TL}$, are given by $\pm\left(\dfrac{R_1}{R_1+R_2}\right)V_{\rm sat}$.
* The tripping point (whether $V_{\rm TH}$ or $V_{\rm TL}$) depends on where we are on the V_o axis. In that sense, the circuit has a memory.
* $\Delta V_T = V_{\rm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

Noninverting Schmitt trigger

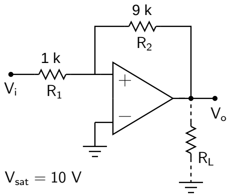


Because of positive feedback, V_o can only be $+V_{sat}$ (for $V_+ > V_-$) or $-V_{sat}$ (for $V_+ < V_-$).

Noninverting 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 $V_i = 5\ V$.



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

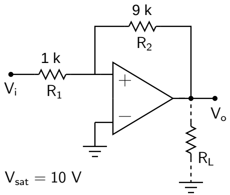
Consider $V_i = 5\ V$.

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

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

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

Noninverting 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 $V_i = 5\ V$.

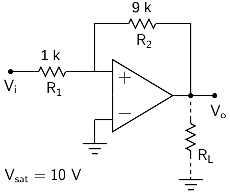
Case (i): $V_o = -V_{\text{sat}} = -10\ V$

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

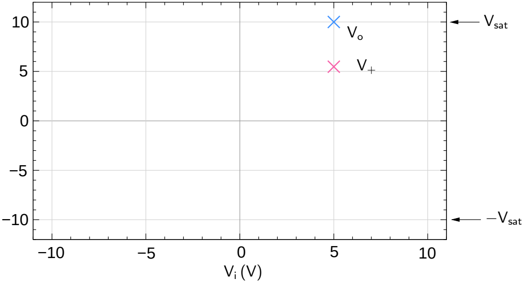
$(V_+ - V_-) = (3.5 - 0) = 3.5\ V \rightarrow V_o = +V_{\text{sat}}$.

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

Noninverting Schmitt trigger



$V_{sat} = 10$ V



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

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

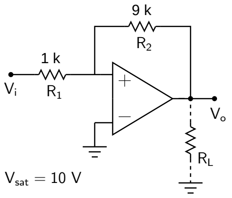
$(V_+ - V_-) = (3.5 - 0) = 3.5\ V \rightarrow V_o = +V_{\text{sat}}$.

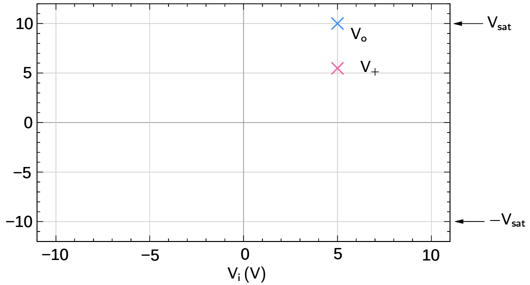
This is inconsistent with our assumption ($V_o = -V_{\text{sat}}$).

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

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

Noninverting Schmitt trigger





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

Consider $V_i = 5\ V$.

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

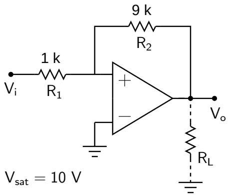
$$\rightarrow V_+ = \frac{R_2}{R_1 + R_2} V_i + \frac{R_1}{R_1 + R_2} V_o = \frac{9\text{ k}}{10\text{ k}} \times 5 + \frac{1\text{ k}}{10\text{ k}} \times (-10) = 3.5\ V\,.$$

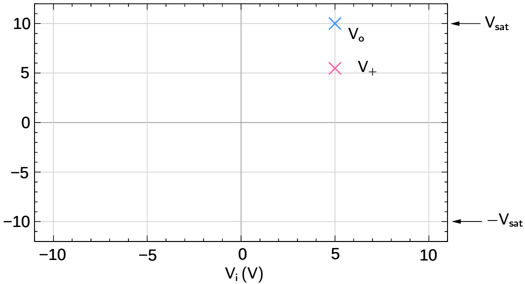
$(V_+ - V_-) = (3.5 - 0) = 3.5\ V \rightarrow V_o = +V_{\mathrm{sat}}$.

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

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

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





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

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

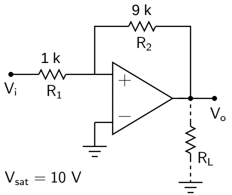
$(V_+ - V_-) = (3.5 - 0) = 3.5\ V \rightarrow V_o = +V_{\text{sat}}$.

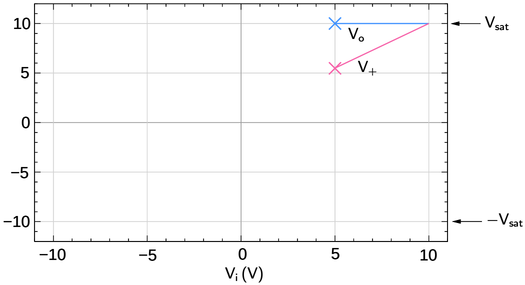
This is inconsistent with our assumption ($V_o = -V_{\text{sat}}$).

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

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

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





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

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

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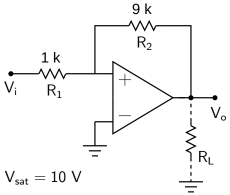
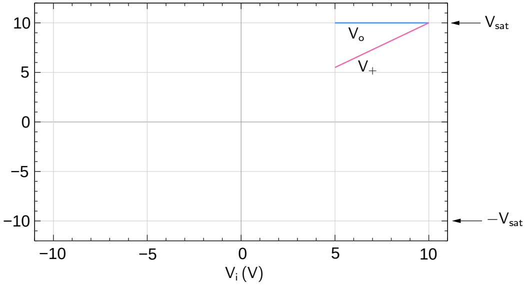
Noninverting Schmitt trigger



$V_{sat} = 10$ V



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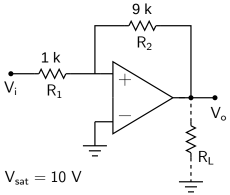
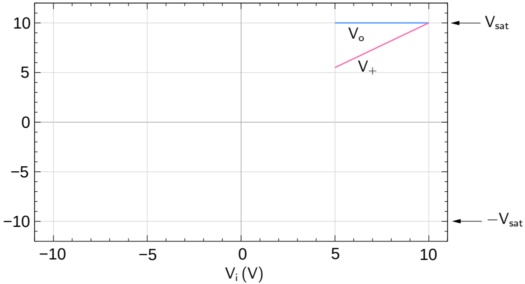
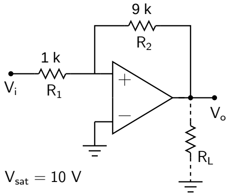
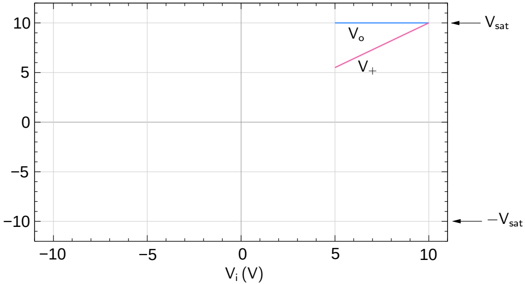




Consider decreasing values of V_i.

Noninverting Schmitt trigger





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

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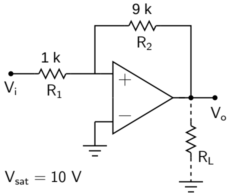

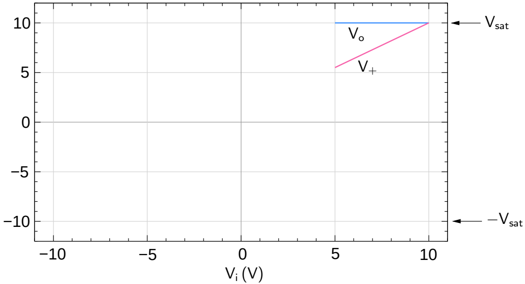

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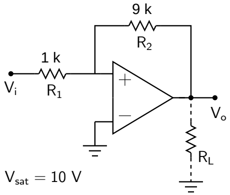
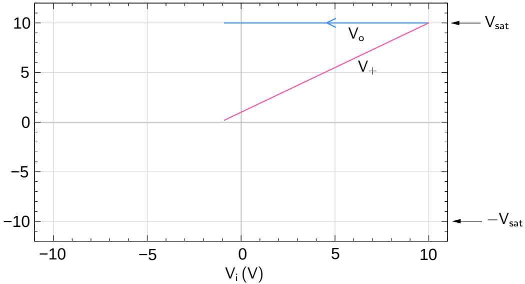
Noninverting Schmitt trigger





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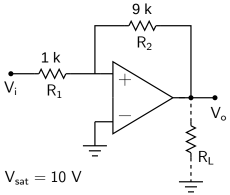

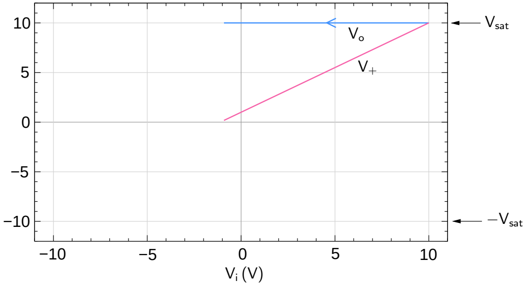

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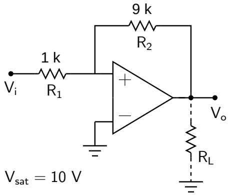

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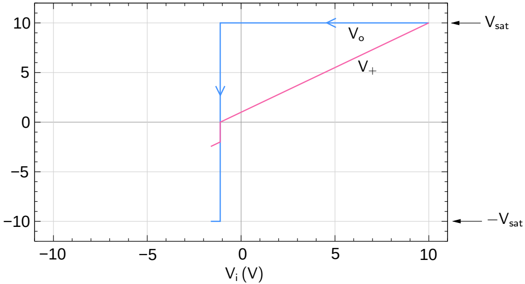

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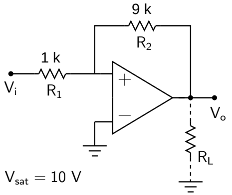

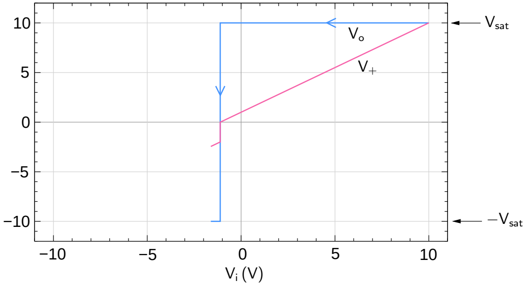

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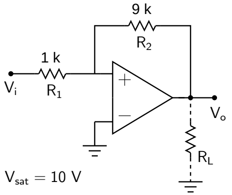
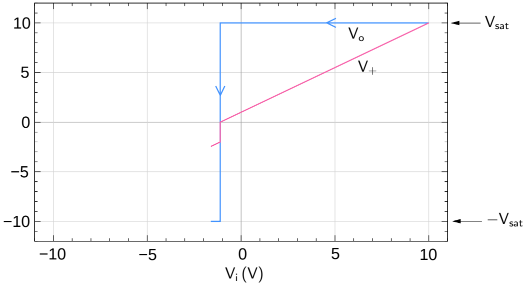
Noninverting Schmitt trigger





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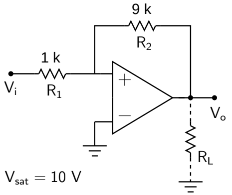
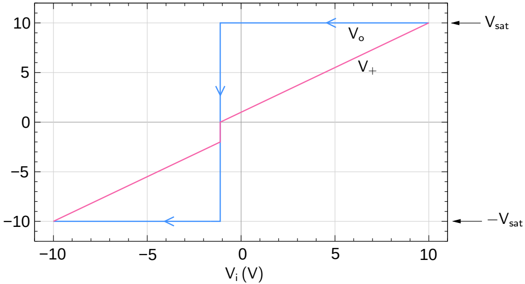
Decreasing V_i further makes no difference to V_o (since V_+ remains negative).

Noninverting Schmitt trigger





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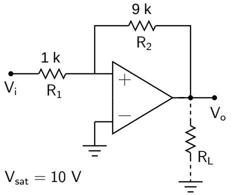

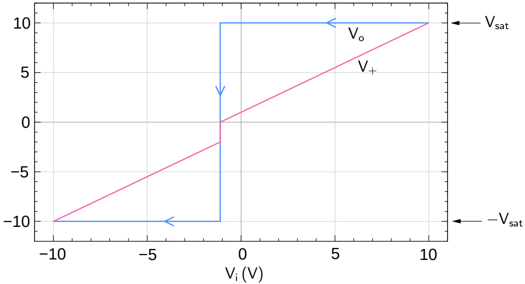

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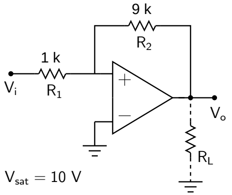
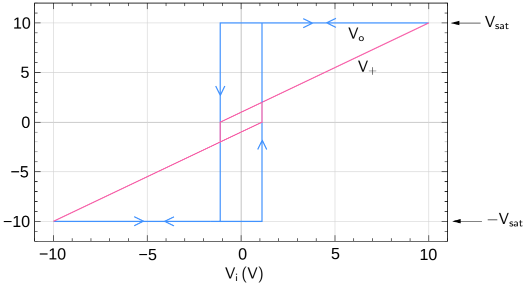
Decreasing V_i further makes no difference to V_o (since V_+ remains negative).

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





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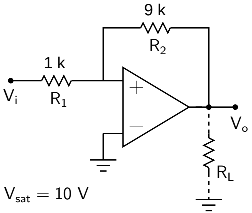
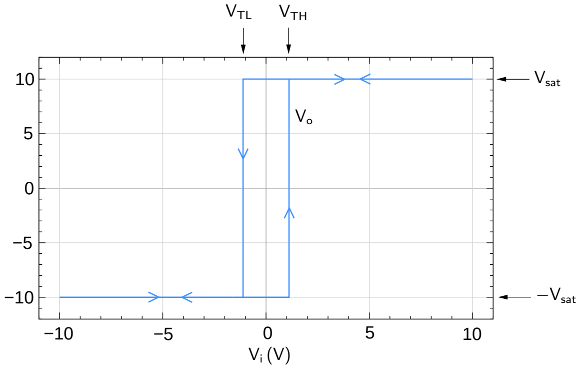
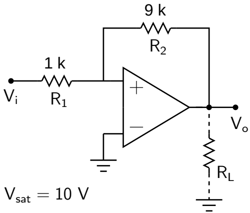
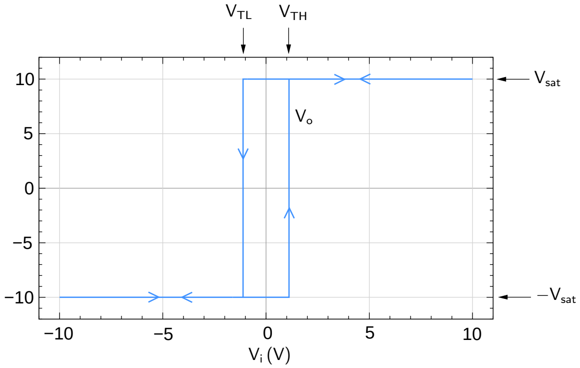

9 k
R2
1 k
Vi
R1
Vo
RL
Vsat = 10 V


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

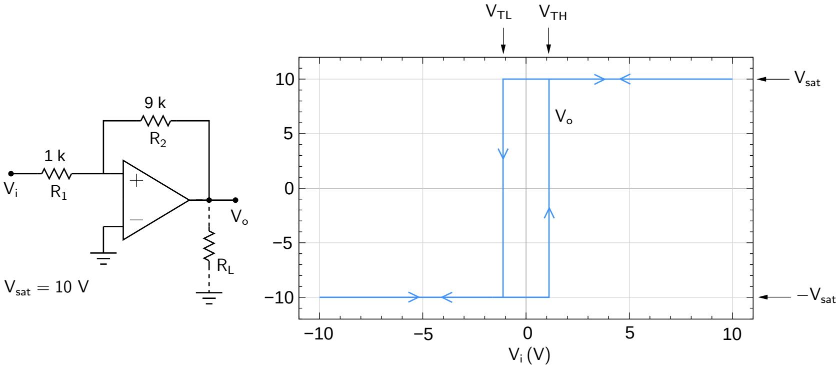
Noninverting Schmitt trigger





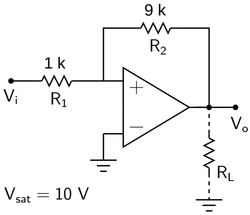
* The threshold values V_{TH} and V_{TL} are given by $\pm\left(\dfrac{R_1}{R_2}\right) V_{sat}$.

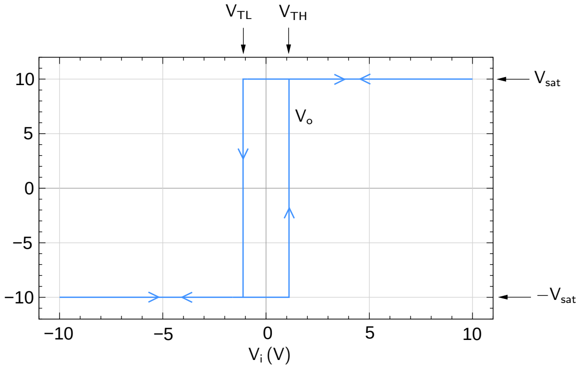
Noninverting Schmitt trigger



- 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.

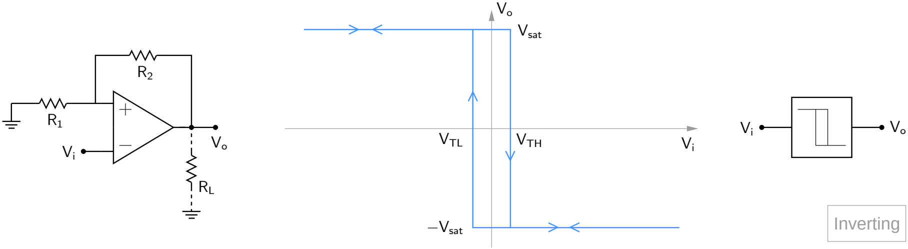
Noninverting Schmitt trigger

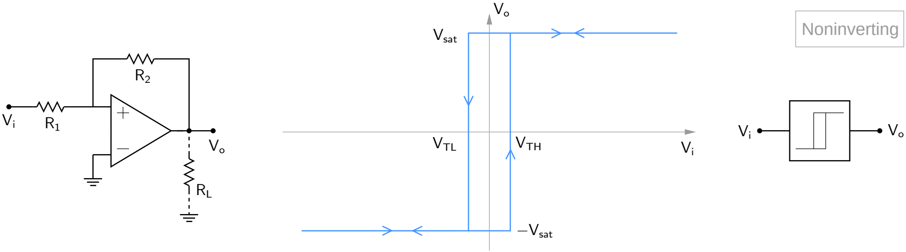


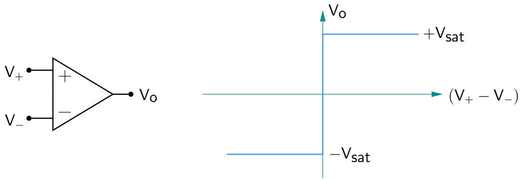


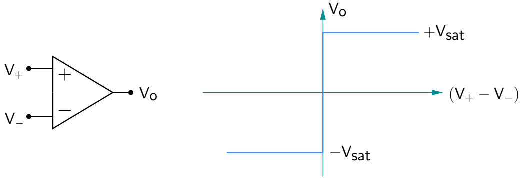
* The threshold values V_{TH} and V_{TL} are given by $\pm\left(\dfrac{R_1}{R_2}\right) V_{\mathrm{sat}}$.
* As in the inverting Schmitt trigger, this circuit has a memory, i.e., the tripping point (whether V_{TH} or V_{TL}) depends on where we are on the V_o axis.
* $\Delta V_T = V_{\mathrm{TH}} - V_{\mathrm{TL}}$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

Schmitt triggers



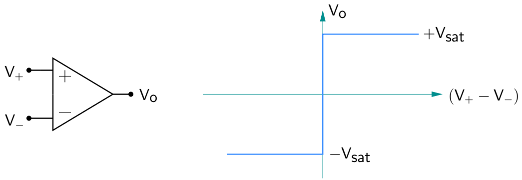



V+
V−
Vo
Vo
+Vsat
(V+ − V−)
−Vsat



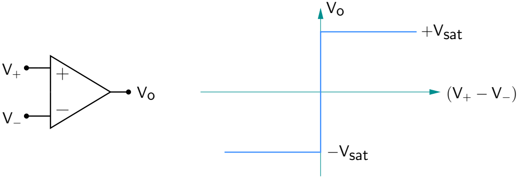
An Op Amp in the open-loop configuration serves as a comparator because of its high gain ($\sim 10^5$) in the linear region.

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.



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

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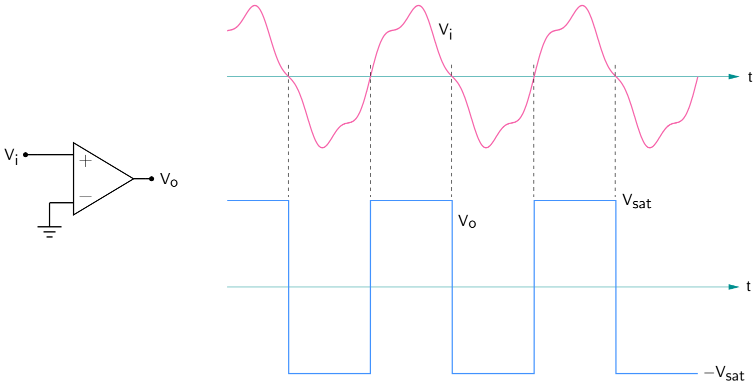
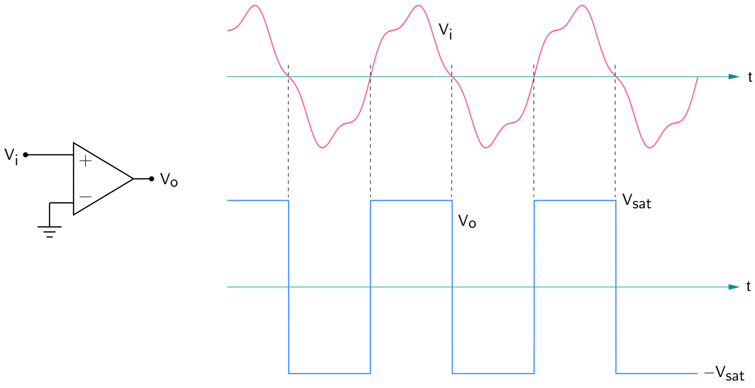
Comparators





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

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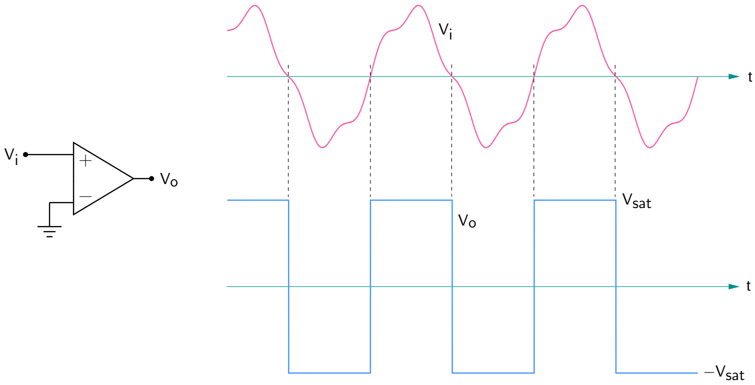

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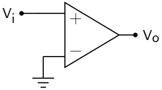
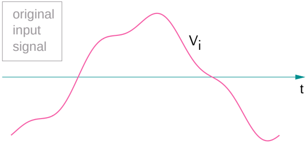
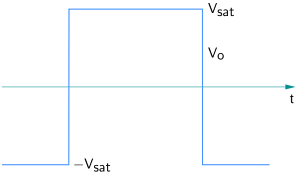
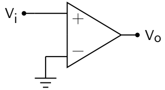
In practice, the input (analog) signal can have noise or electromagnetic pick-up superimposed on it. As a result, erroneous operation of the circuit may result
$\rightarrow$ next slide.

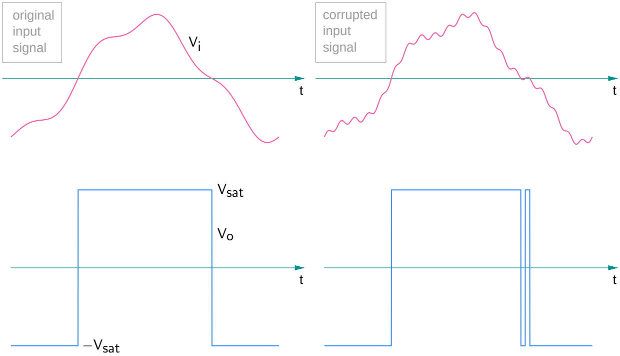
Comparators



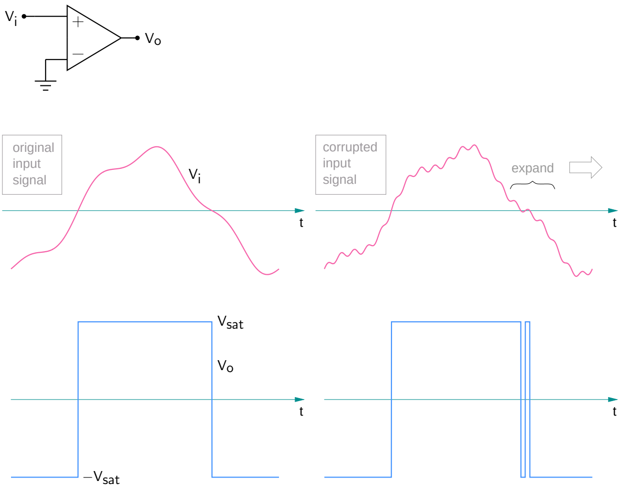




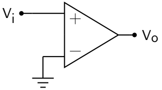

V_i
+
−
V_o

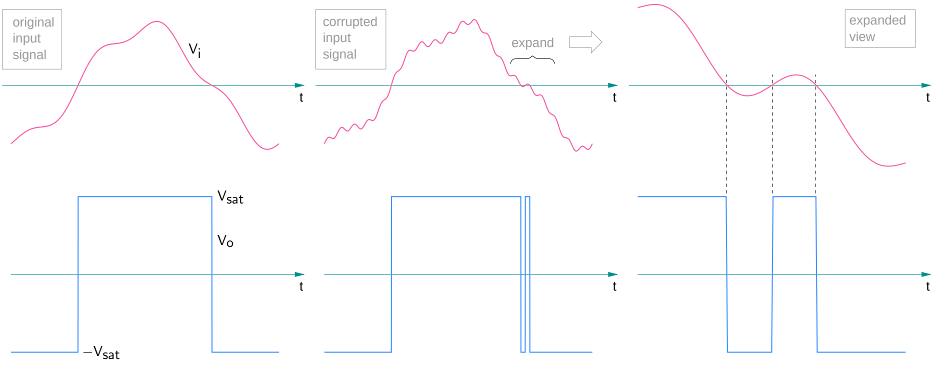

original input signal
V_i
t
corrupted input signal
t
V_sat
V_o
t
−V_sat
t

Comparators

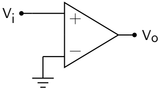


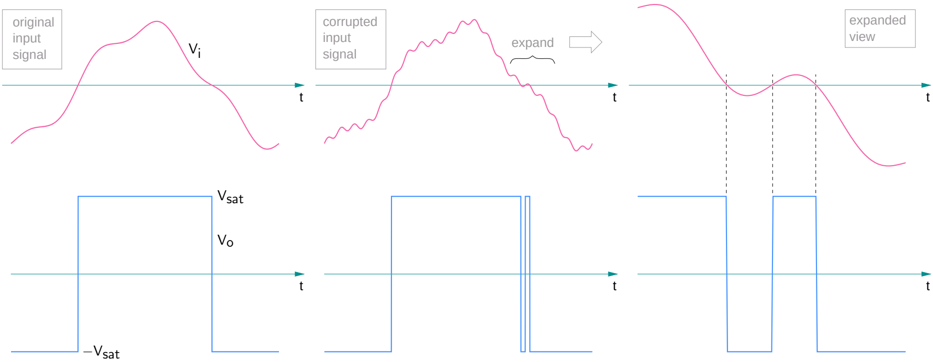
Comparators



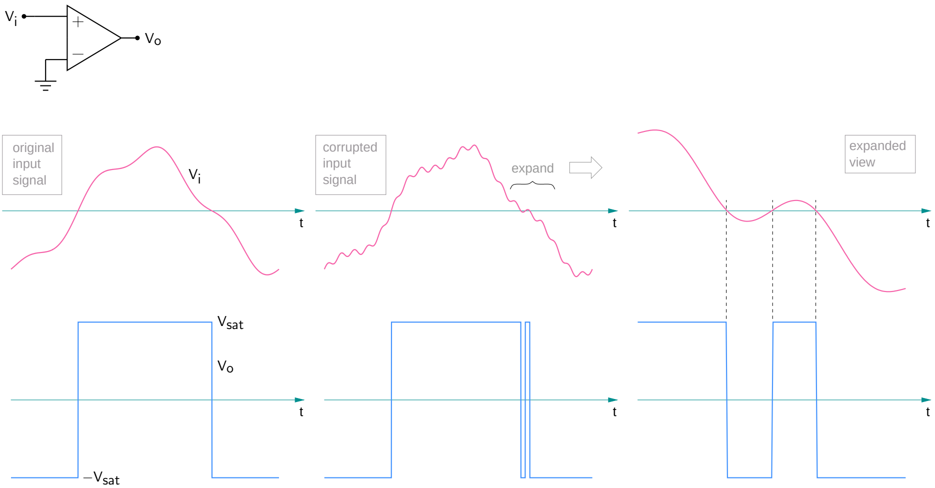


Comparators





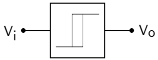
The comparator has produced multiple (spurious) transitions or "bounces," referred to as "comparator chatter."

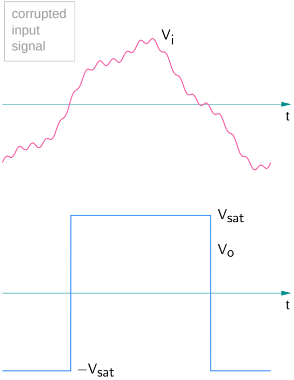


The comparator has produced multiple (spurious) transitions or "bounces," referred to as "comparator chatter."

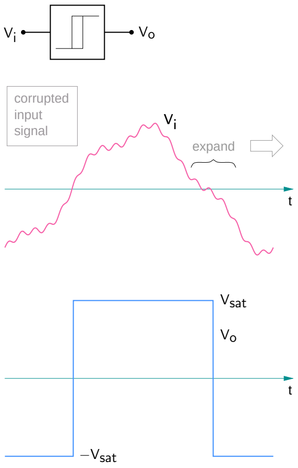
A Schmitt trigger can be used to eliminate the chatter
→ next slide.

Comparators

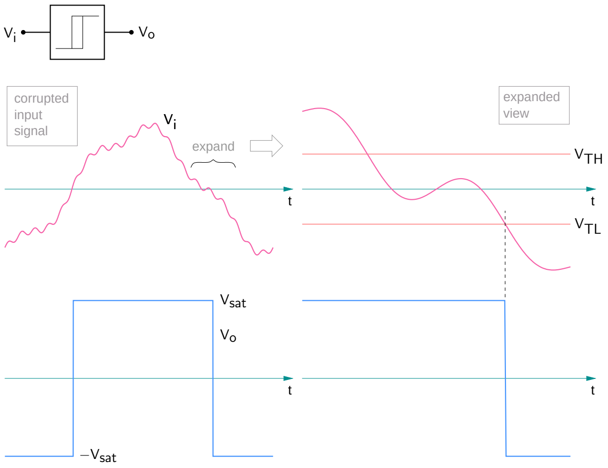




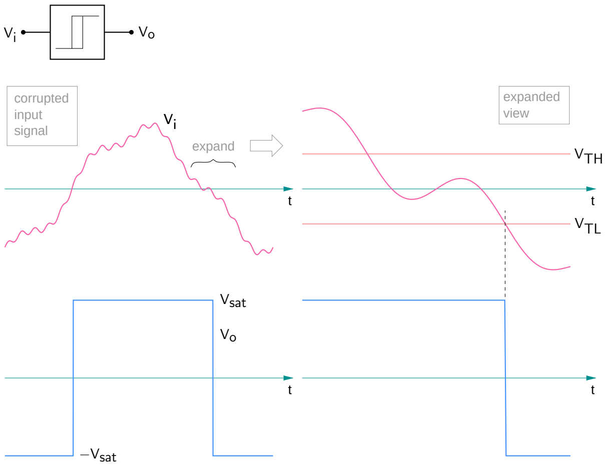
Comparators



Comparators

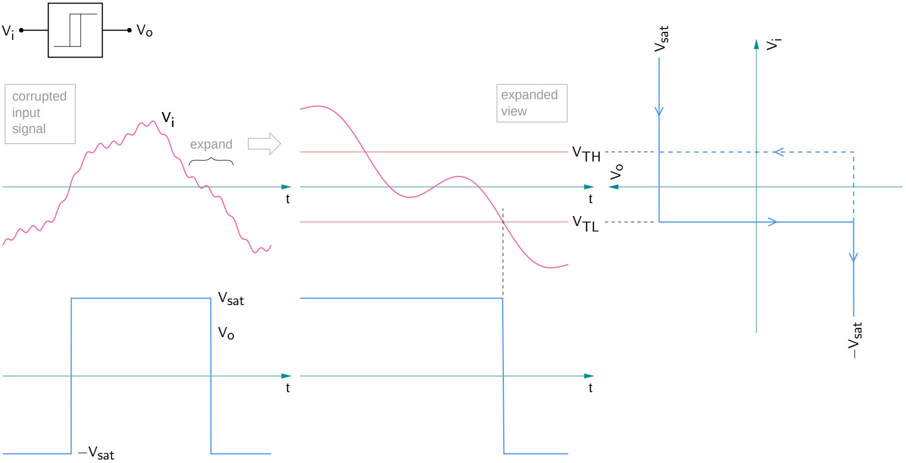


Comparators



* 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.

Comparators



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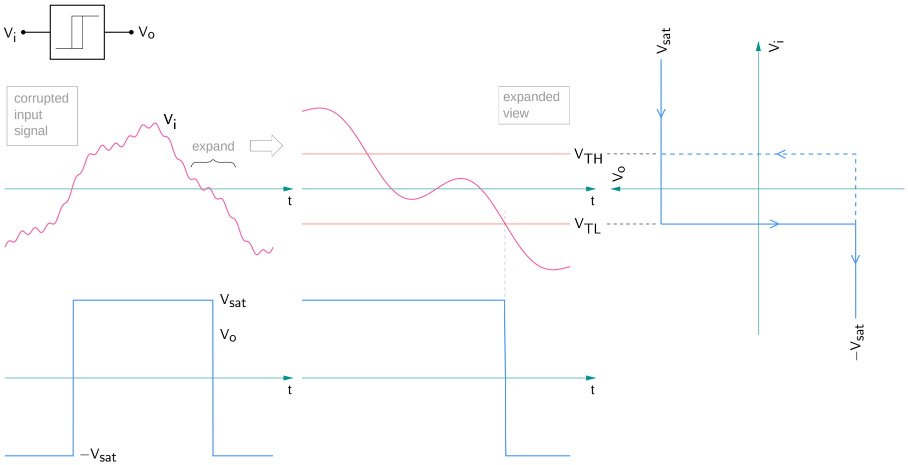
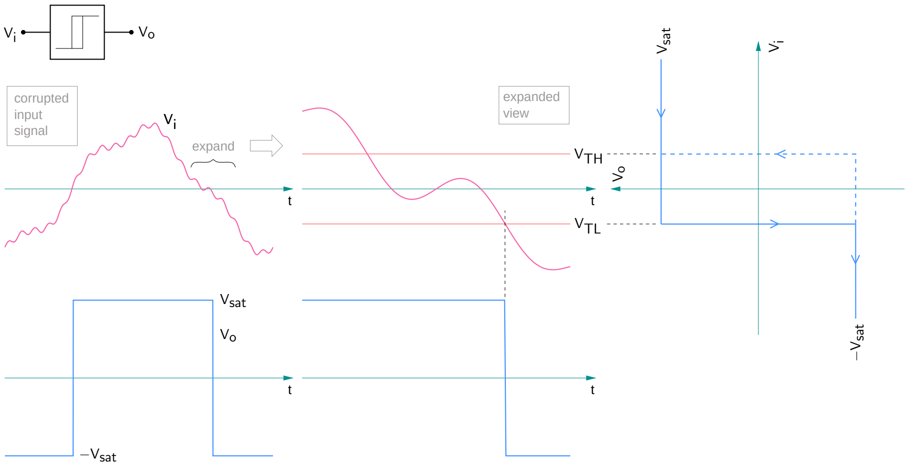
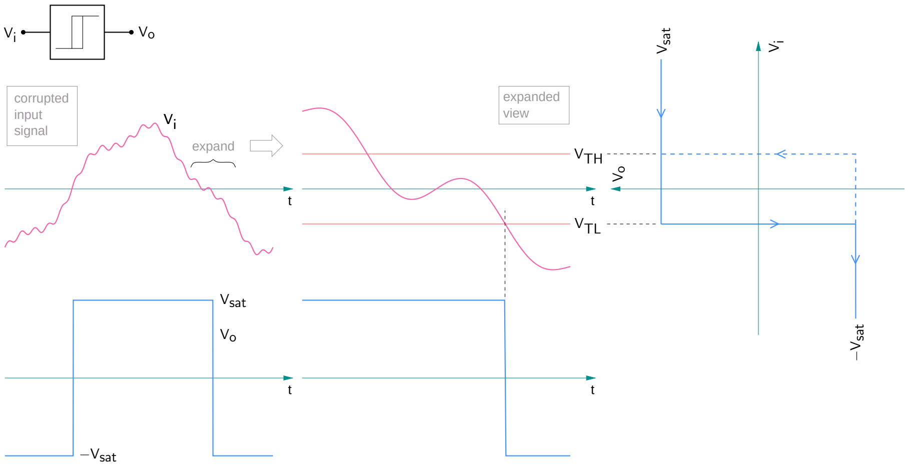


* While going from positive to negative values, V_i needs to cross V_{TL} (and not $0\ V$) to cause a change in V_o.
* In the reverse direction (negative to positive), V_i needs to cross V_{TH}.

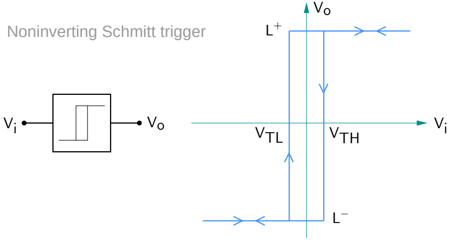


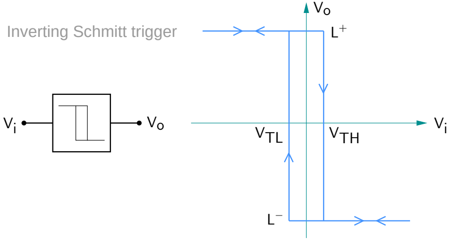
* While going from positive to negative values, V_i needs to cross V_{TL} (and not $0\ V$) to cause a change in V_o.
* In the reverse direction (negative to positive), V_i needs to cross V_{TH}.
* The circuit gets rid of spurious transitions, a major advantage over the simple comparator.

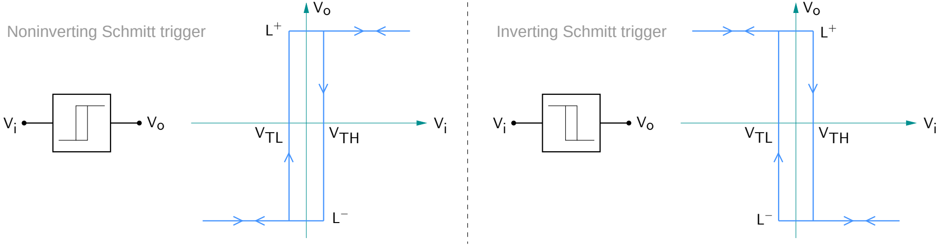


* While going from positive to negative values, V_i needs to cross V_{TL} (and not $0\ V$) to cause a change in V_o.
* In the reverse direction (negative to positive), V_i needs to cross V_{TH}.
* The circuit gets rid of spurious transitions, a major advantage over the simple comparator.
* The hysterisis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

Waveform generation using Schmitt triggers

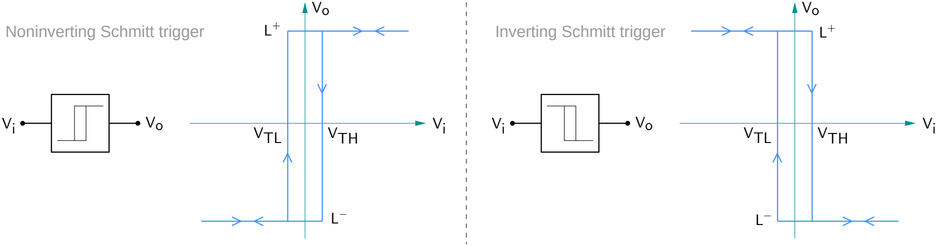






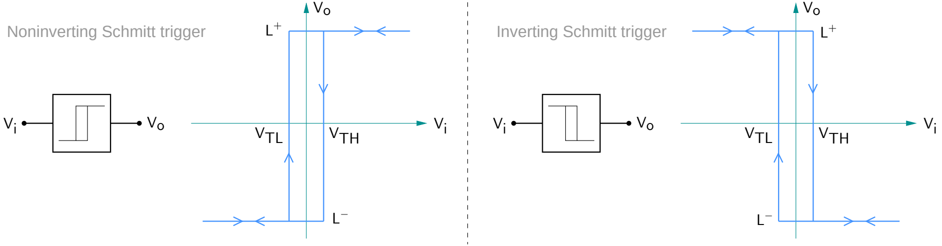
* A Schmitt trigger has two states, $V_o = L^+$ and $V_o = L^-$.

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."

Waveform generation using Schmitt triggers



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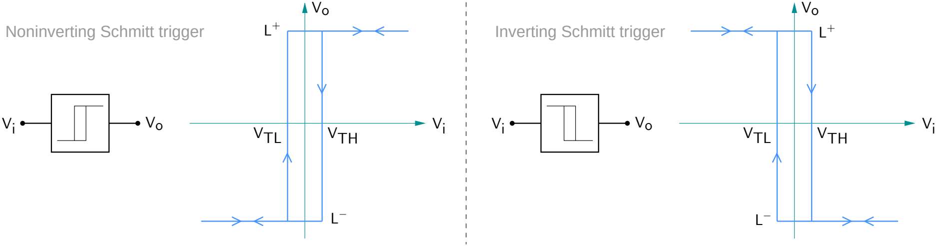
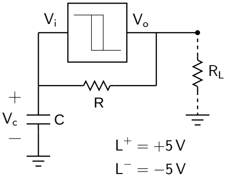
* An astable multivibrator produces oscillations *without* an input signal, the frequency being controlled by the component values.

Waveform generation using Schmitt triggers



* 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

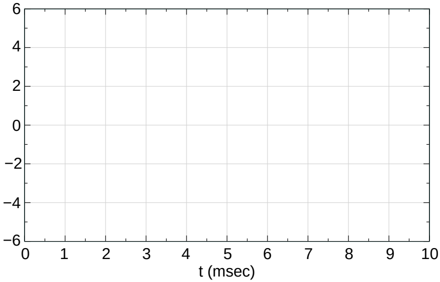


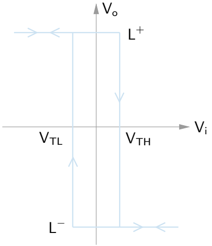
$L^+ = +5\,V$

$L^- = -5\,V$

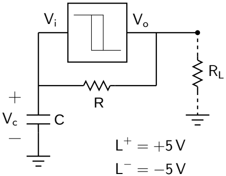
$R = 2\,k$ $\quad V_{TH} = +1\,V$

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





Waveform generation using a Schmitt trigger



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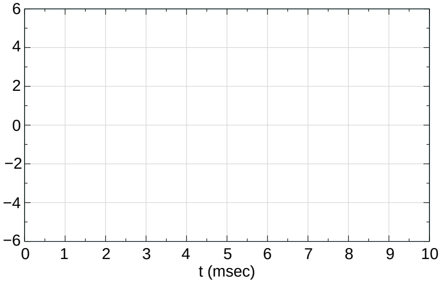
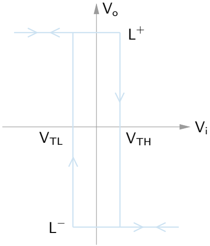
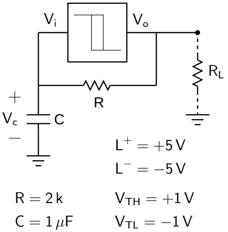
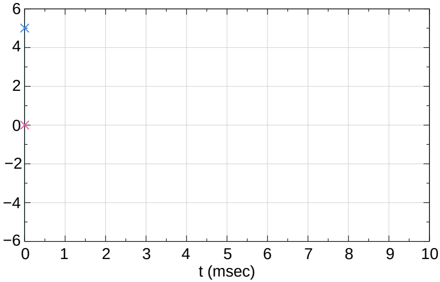


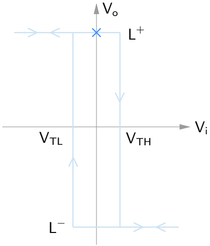


At $t = 0$, let $V_o = L^+$, and $V_c = 0\,V$.

Waveform generation using a Schmitt trigger







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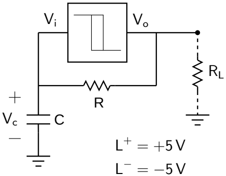

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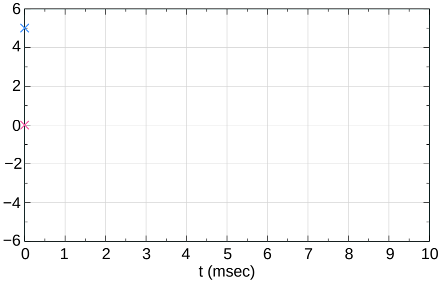
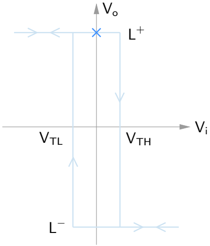
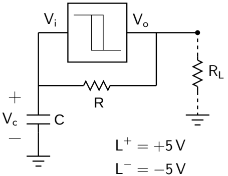




At $t = 0$, let $V_o = L^+$, and $V_c = 0\ V$.

The capacitor starts charging toward L^+.

Waveform generation using a Schmitt trigger



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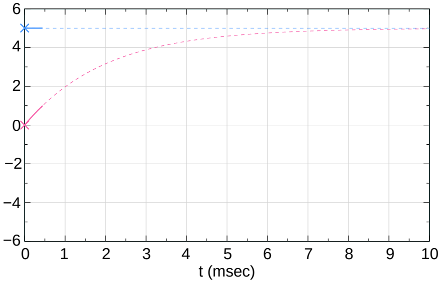
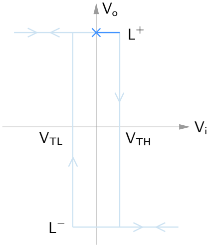
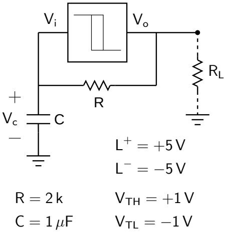


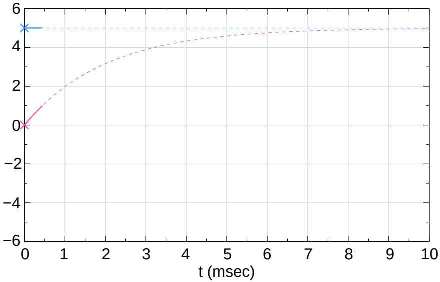


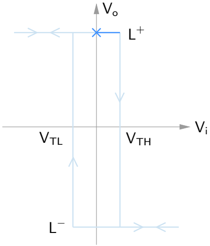
At $t = 0$, let $V_o = L^+$, and $V_c = 0\ V$.

The capacitor starts charging toward L^+.

Waveform generation using a Schmitt trigger





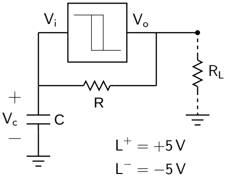


At $t = 0$, let $V_o = L^+$, and $V_c = 0\ V$.

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



$L^+ = +5\,V$

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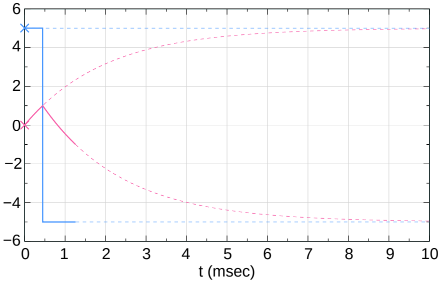
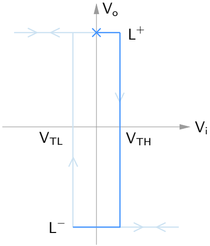


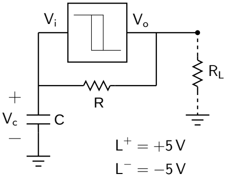


At $t = 0$, let $V_o = L^+$, and $V_c = 0\ V$.

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



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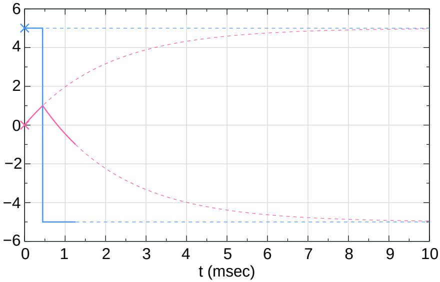
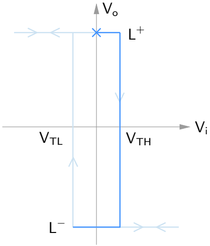




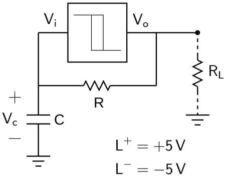
At $t = 0$, let $V_o = L^+$, and $V_c = 0\;V$.

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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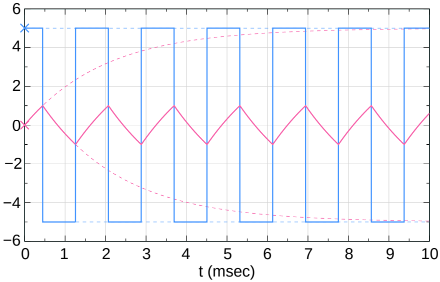
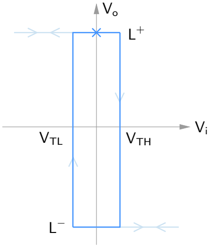




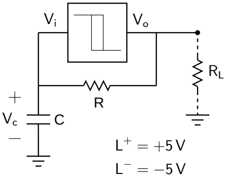
At $t = 0$, let $V_o = L^+$, and $V_c = 0\ V$.

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



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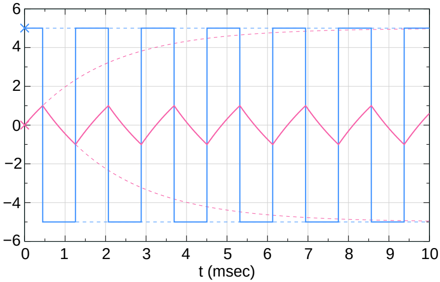
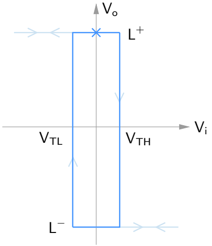




At $t = 0$, let $V_o = L^+$, and $V_c = 0\ V$.

The capacitor starts charging toward L^+.

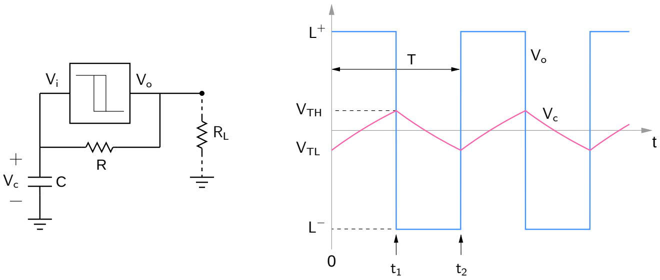
When V_c crosses V_{TH}, the output flips. Now, the capacitor starts discharging toward L^-.

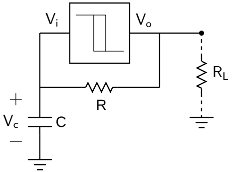
When V_c crosses V_{TL}, the output flips again $\longrightarrow$ oscillations.

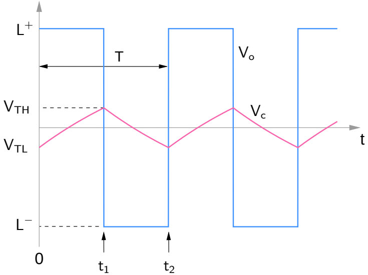
Note that the circuit oscillates *on its own*, i.e., without any input.

Q: Where is the energy coming from?

Waveform generation using a Schmitt trigger





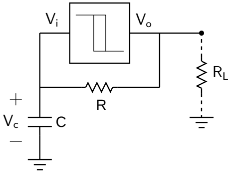


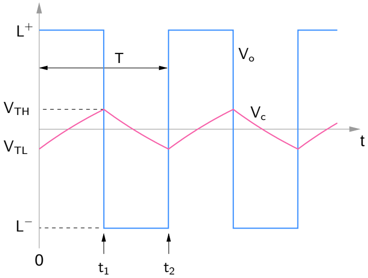
Charging: Let $V_c(t) = A_1 \exp(-t/\tau) + B_1$, with $\tau = RC$.

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.

Waveform generation using a Schmitt trigger





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

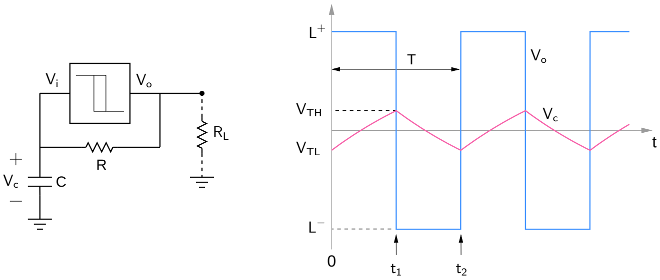
Using $V_c(0) = V_{TL},\ V_c(\infty) = L^+$, find A_1 and B_1.

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 $(t_2 - t_1)$.



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

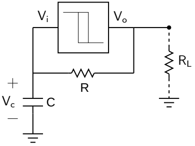
Using $V_c(t_1) = V_{TH}$, $V_c(\infty) = L^-$, find A_2 and B_2.

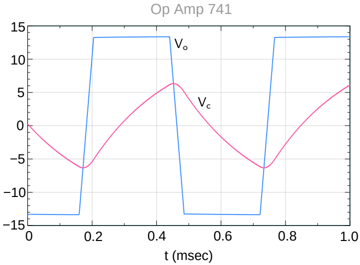
At $t = t_2$, $V_c = V_{TL} \rightarrow V_{TL} = A_2\ \exp(-(t_2 - t_1)/\tau) + B_2 \rightarrow$ find $(t_2 - t_1)$.

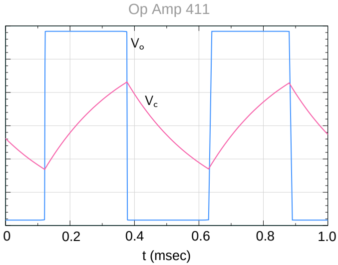
If $L^+ = L$, $L^- = -L$, $V_{TH} = V_T$, $V_{TL} = -V_T$, show that

$$T = 2\,RC\,\ln\left(\frac{L + V_T}{L - V_T}\right).$$

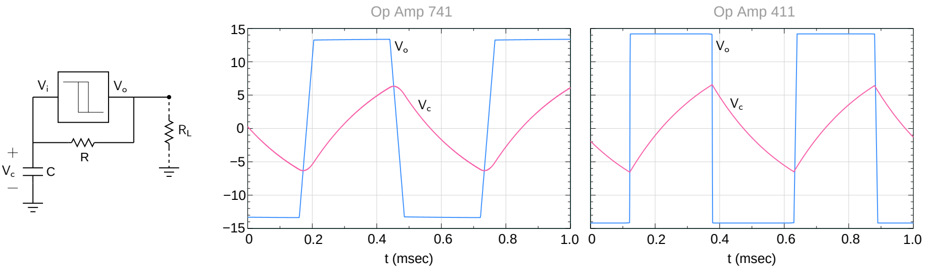
Waveform generation using a Schmitt trigger





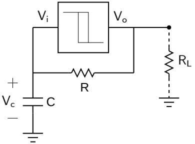


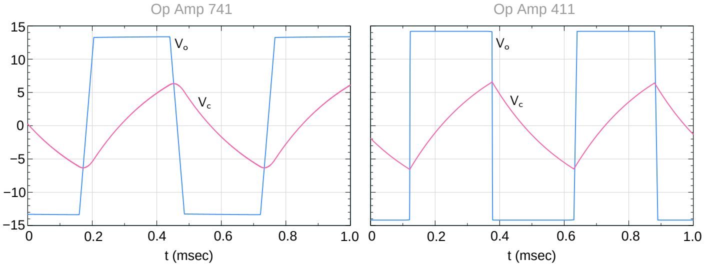
Waveform generation using a Schmitt trigger



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

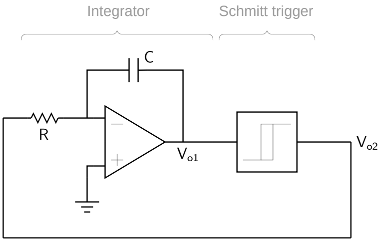


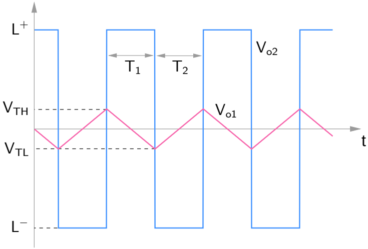


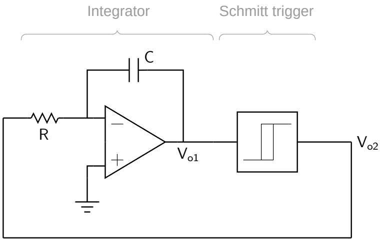
Note that Op Amp 411 (slew rate: 10 $V/\mu s$) gives sharper waveforms as compared to Op Amp 741 (slew rate: 0.5 $V/\mu s$).

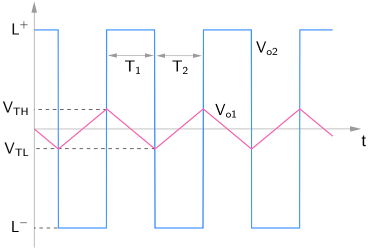
SEQUEL files: `schmitt_osc_741.sqproj`, `schmitt_osc_411.sqproj`

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


Integrator
Schmitt trigger
C
R
Vo1
Vo2

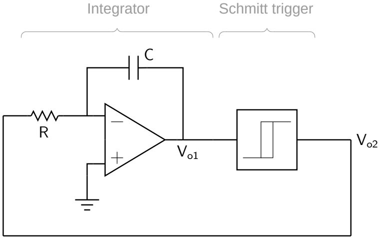

L+
Vo2
T1
T2
VTH
Vo1
VTL
t
L−

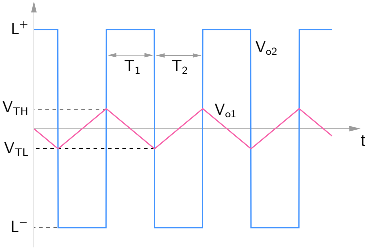




For the integrator, $V_{o1} = -\frac{1}{RC} \int V_{o2} dt$,

Waveform generation using a Schmitt trigger



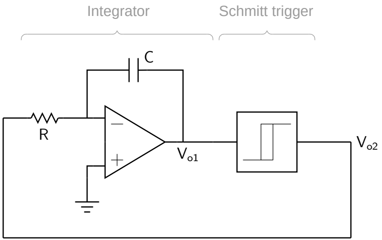


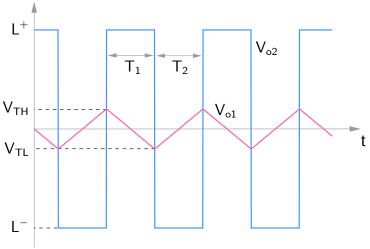
For the integrator, $V_{o1} = -\dfrac{1}{RC}\displaystyle\int V_{o2}\,dt$,

$V_{o2} = L^+ \longrightarrow V_{o2}$ decreases linearly.

$V_{o2} = L^- \longrightarrow V_{o2}$ increases linearly.

Waveform generation using a Schmitt trigger





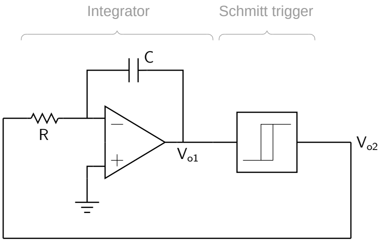
For the integrator, $V_{o1} = -\dfrac{1}{RC}\displaystyle\int V_{o2}\,dt$,

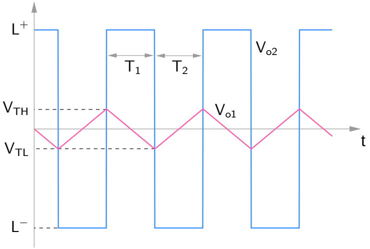
$V_{o2} = L^{+} \longrightarrow V_{o2}$ decreases linearly.

$V_{o2} = L^{-} \longrightarrow V_{o2}$ increases linearly.

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

Waveform generation using a Schmitt trigger





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

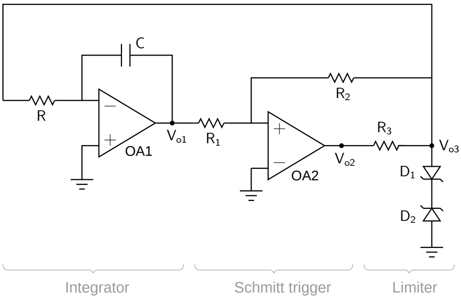
$V_{o2} = L^+ \rightarrow V_{o2}$ decreases linearly.

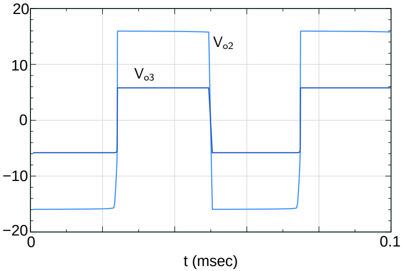
$V_{o2} = L^- \rightarrow V_{o2}$ increases linearly.

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

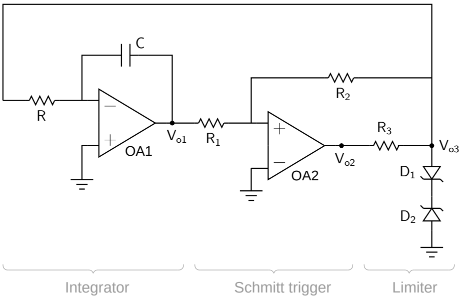
$$T_2 = \frac{V_{TH} - V_{TL}}{-L^-/RC} = RC\,\frac{V_{TH} - V_{TL}}{-L^-} .$$

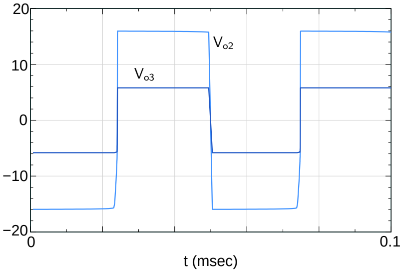
Limiting the output voltage





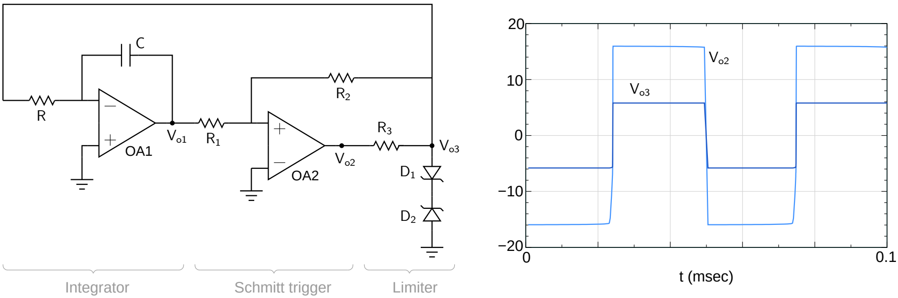
Limiting the output voltage





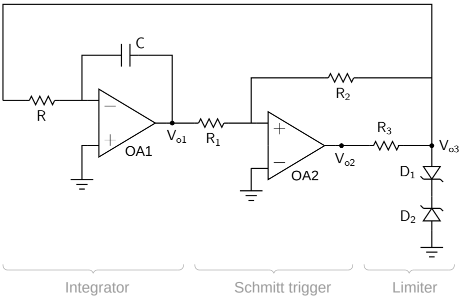
* When $V_{o2} = +V_{\text{sat}}$, D_1 is forward-biased (with a voltage drop of V_{on}), and D_2 is reverse-biased. The Zener breakdown voltage (V_Z) is chosen so that D_2 operates under breakdown condition.
  $\rightarrow$ $V_{o3} = V_{\text{on}} + V_Z$.

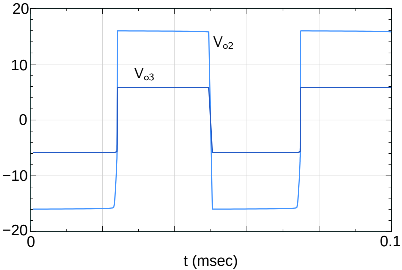
Limiting the output voltage



* 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.
  $\rightarrow V_{o3} = -V_{\text{on}} - V_Z$.

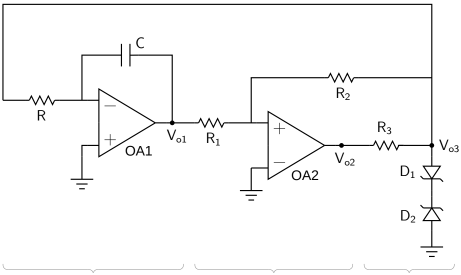
Limiting the output voltage

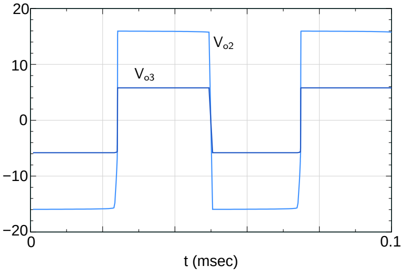




* When $V_{o2} = +V_{\text{sat}}$, D_1 is forward-biased (with a voltage drop of V_{on}), and D_2 is reverse-biased. The Zener breakdown voltage (V_Z) is chosen so that D_2 operates under breakdown condition.
  $\rightarrow V_{o3} = V_{\text{on}} + V_Z$.
* When $V_{o2} = -V_{\text{sat}}$, D_2 is forward-biased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

Limiting the output voltage





- 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`