

EE101: Op Amp circuits (Part 5)



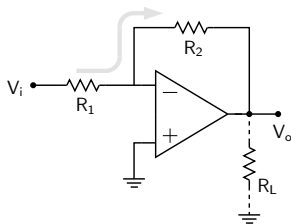
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Indian Institute of Technology Bombay

Feedback: inverting amplifier

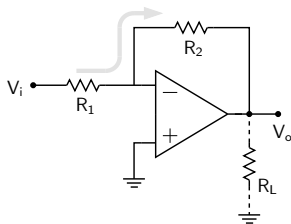


$$V_o = A_V(V_+ - V_-) \quad (1)$$

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

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

Feedback: inverting amplifier



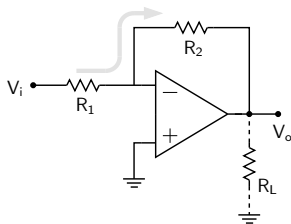
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$$\begin{array}{ccccccc} V_i \uparrow & \rightarrow & V_- \uparrow & \rightarrow & V_o \downarrow & \rightarrow & V_- \downarrow \\ \text{Eq. 2} & & \text{Eq. 1} & & \text{Eq. 2} & & \end{array}$$

Feedback: inverting amplifier



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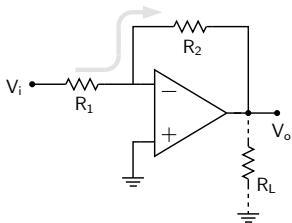
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$$V_i \uparrow \rightarrow \boxed{V_- \uparrow} \rightarrow V_o \downarrow \rightarrow \boxed{V_- \downarrow}$$

Eq. 2 Eq. 1 Eq. 2

The circuit reaches a stable equilibrium.

Feedback: inverting amplifier



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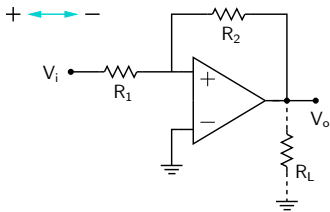
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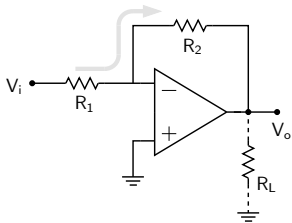
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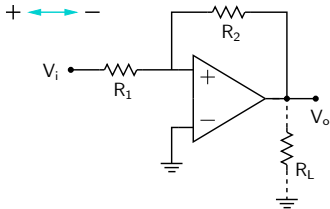
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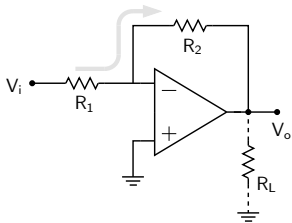
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$$V_+ = V_i \frac{R_2}{R_1 + R_2} + V_o \frac{R_1}{R_1 + R_2} \quad (3)$$

Feedback: inverting amplifier



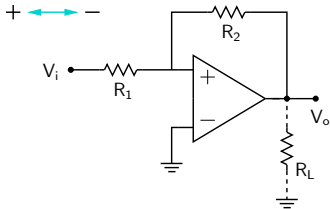
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$$V_i \uparrow \xrightarrow{\text{Eq. 2}} V_- \uparrow \xrightarrow{\text{Eq. 1}} V_o \downarrow \xrightarrow{\text{Eq. 2}} V_- \downarrow$$

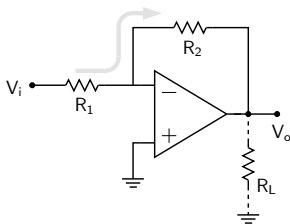
The circuit reaches a stable equilibrium.



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

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

Feedback: inverting amplifier



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

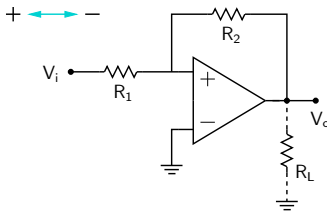
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Eq. 2 Eq. 1 Eq. 2

The circuit reaches a stable equilibrium.



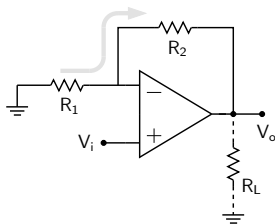
$$V_+ = V_i \frac{R_2}{R_1 + R_2} + V_o \frac{R_1}{R_1 + R_2} \quad (3)$$

$$V_i \uparrow \rightarrow V_+ \uparrow \rightarrow V_o \uparrow \rightarrow V_+ \uparrow$$

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.

Feedback: noninverting amplifier

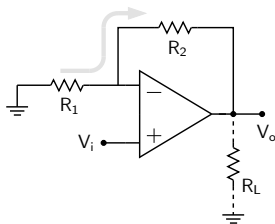


$$V_o = A_V(V_+ - V_-) \quad (1)$$

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

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Feedback: noninverting amplifier



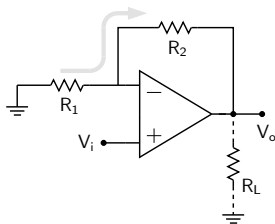
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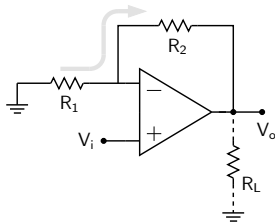
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Eq. 1 Eq. 2 Eq. 1

The circuit reaches a stable equilibrium.

Feedback: noninverting amplifier



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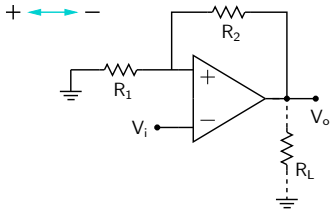
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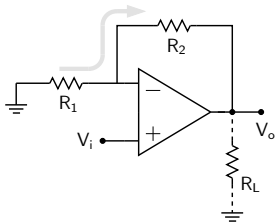
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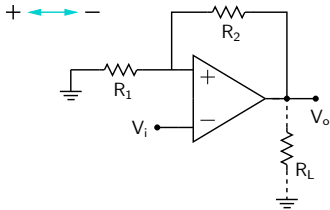
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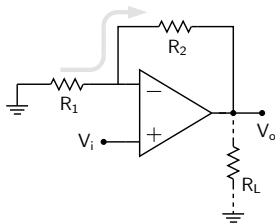
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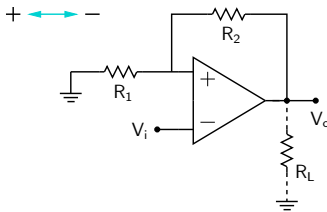
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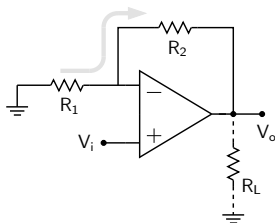


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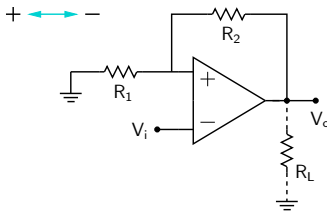
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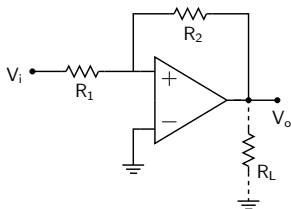
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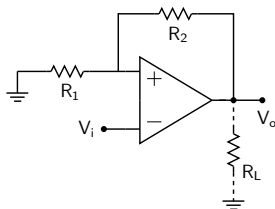
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Inverting amplifier with $+$ \longleftrightarrow $-$

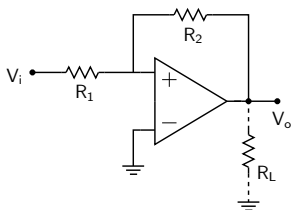


Noninverting amplifier with $+$ \longleftrightarrow $-$

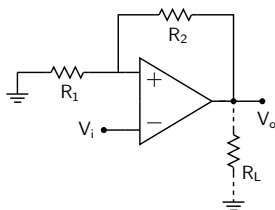


Feedback

Inverting amplifier with $+$ \longleftrightarrow $-$



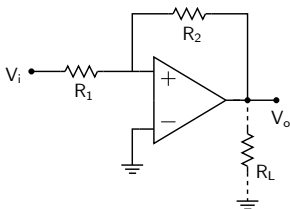
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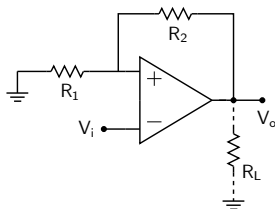
- * Because of positive feedback, both these circuits are unstable.

Feedback

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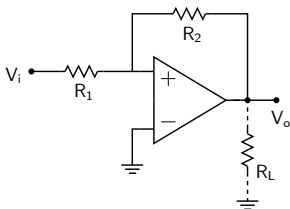
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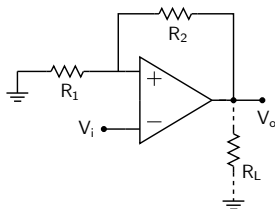
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Feedback

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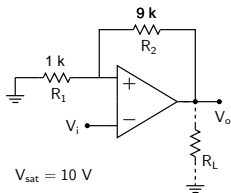


Noninverting amplifier with $+$ \longleftrightarrow $-$



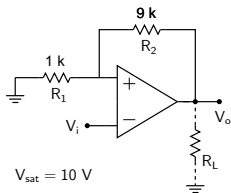
- * Because of positive feedback, both these circuits are unstable.
- * The output at any time is only limited by saturation of the Op Amp, i.e., $V_o = \pm V_{sat}$.
- * Of what use is a circuit that is stuck at $V_o = \pm V_{sat}$? It turns out that these circuits are actually useful! Let us see how.

Inverting Schmitt trigger



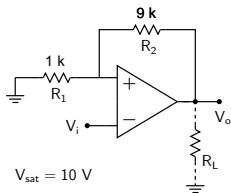
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Inverting Schmitt trigger



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Consider $V_i = 5\text{ V}$.

Inverting Schmitt trigger



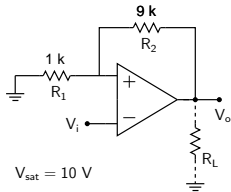
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$$\text{Case (i): } V_o = +V_{\text{sat}} = +10 \text{ V} \rightarrow V_+ = \frac{R_1}{R_1 + R_2} V_o = 1 \text{ V}.$$

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

Inverting Schmitt trigger



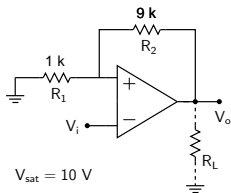
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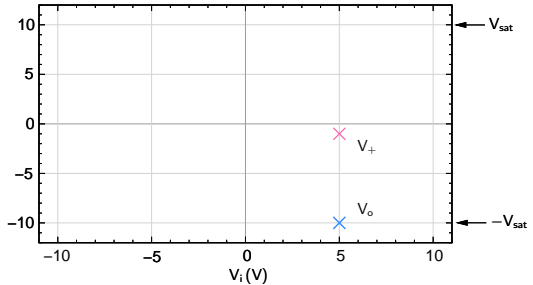
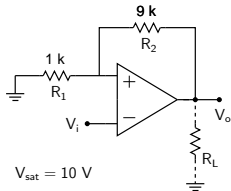
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This is inconsistent with our assumption ($V_o = +V_{\text{sat}}$).

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

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

Inverting Schmitt trigger



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

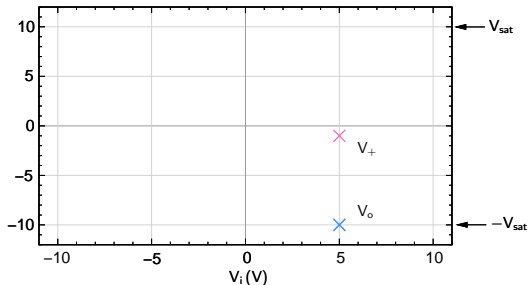
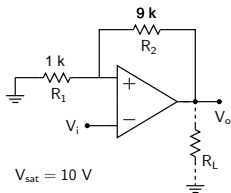
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Inverting Schmitt trigger



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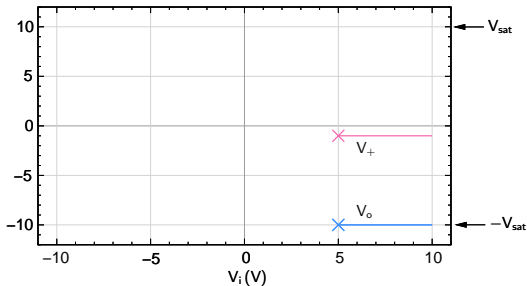
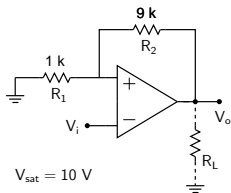
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If we move to the right (increasing V_i), the same situation applies, i.e., $V_o = -V_{\text{sat}}$.

Inverting Schmitt trigger



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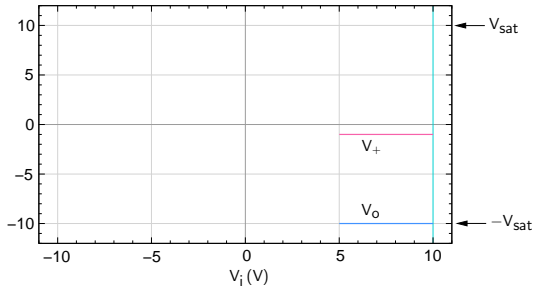
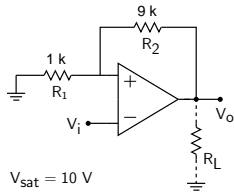
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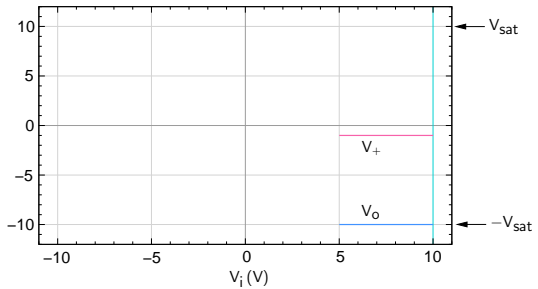
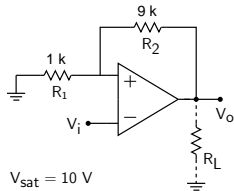
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Inverting Schmitt trigger

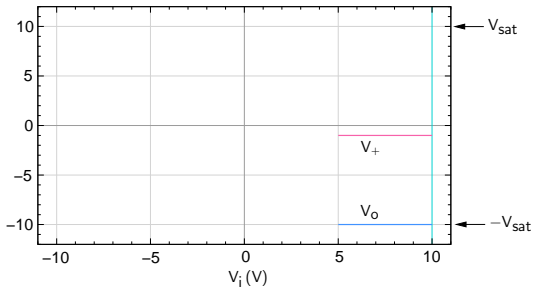
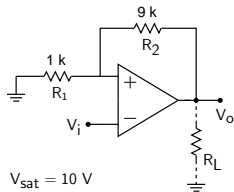


Inverting Schmitt trigger



Consider decreasing values of V_i .

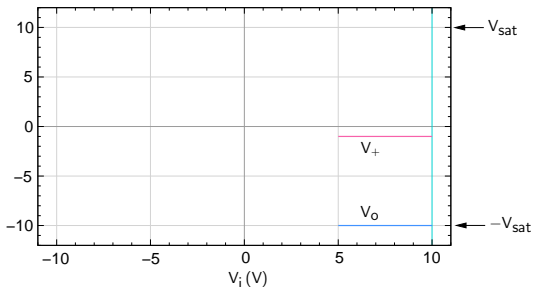
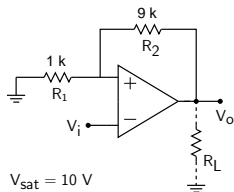
Inverting Schmitt trigger



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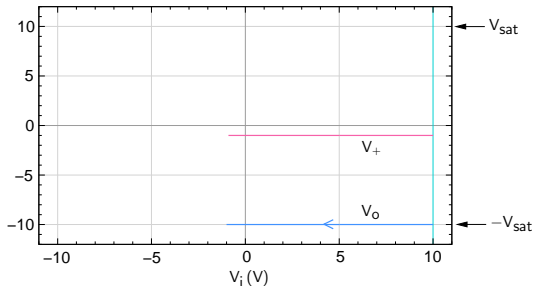
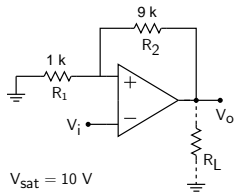


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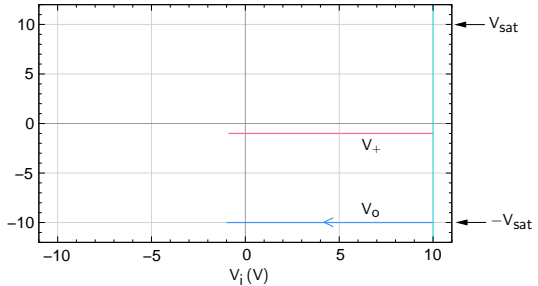
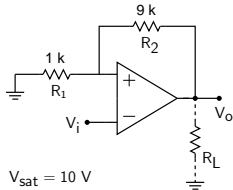


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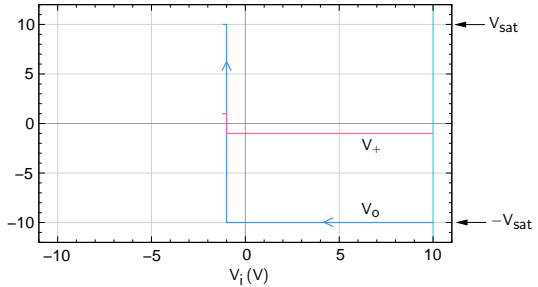
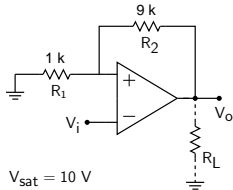
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Inverting Schmitt trigger



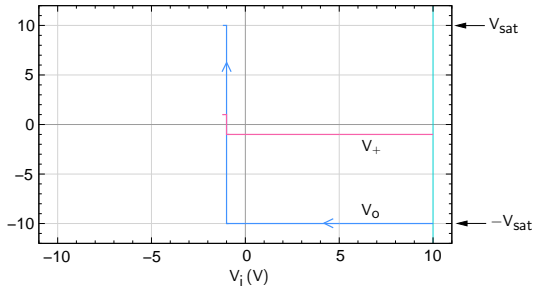
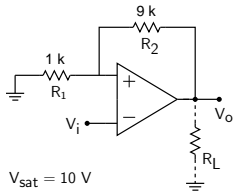
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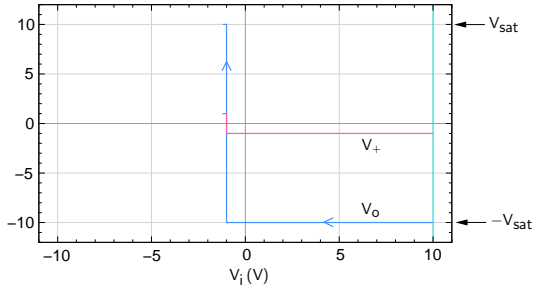
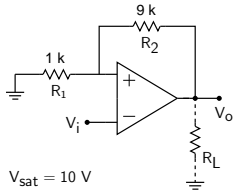
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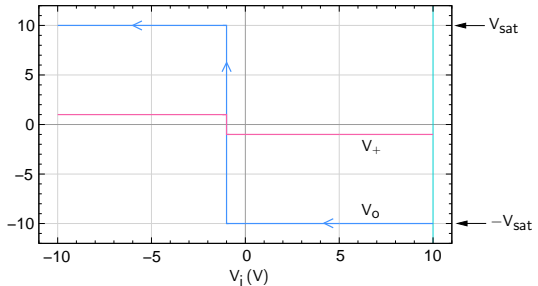
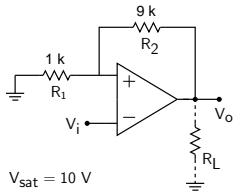
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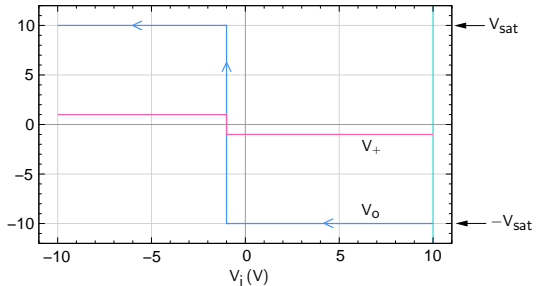
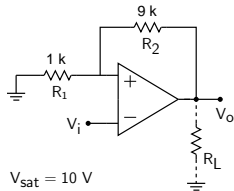
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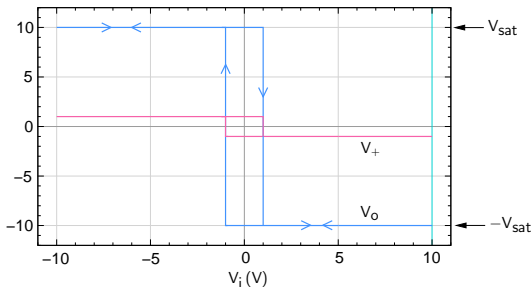
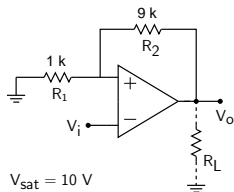
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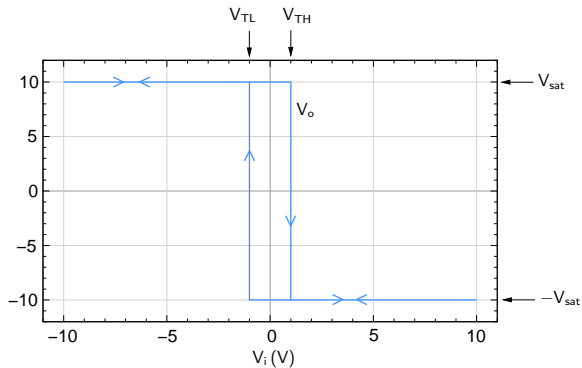
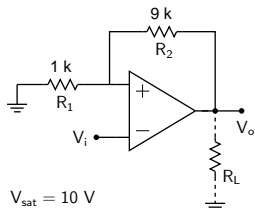
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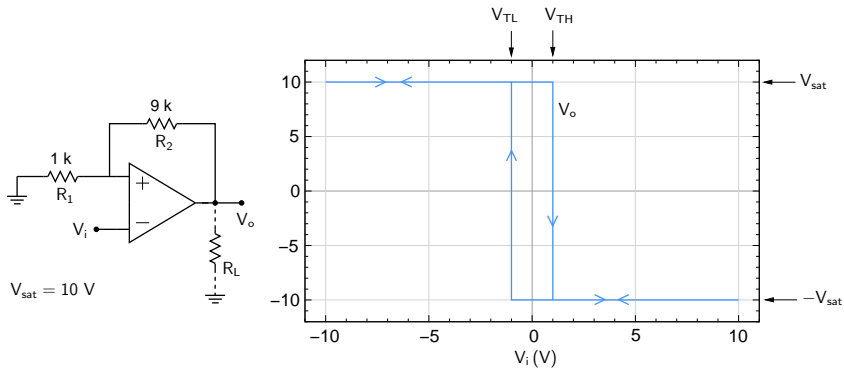
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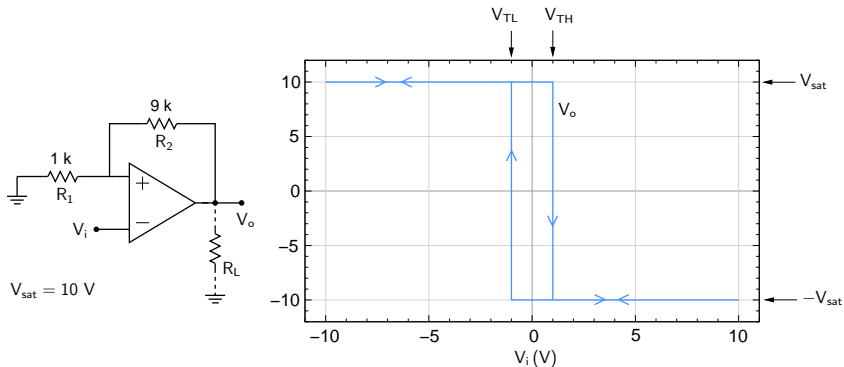
Inverting Schmitt trigger



* The threshold values (or “tripping points”), V_{TH} and V_{TL} , are given by

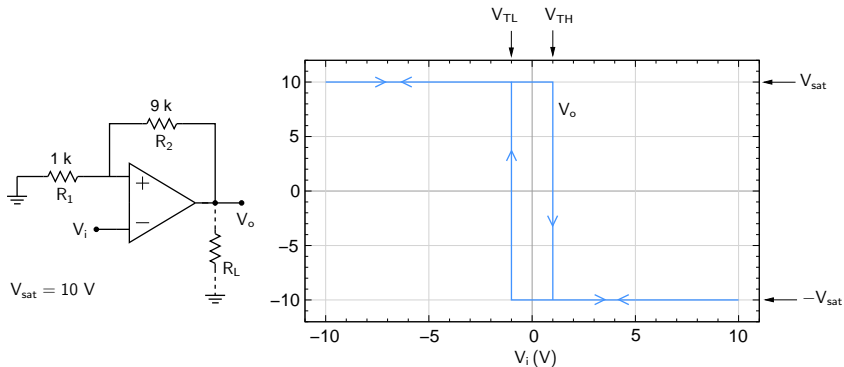
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Inverting Schmitt trigger



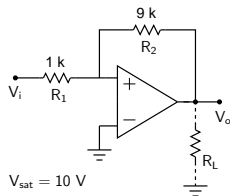
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Inverting Schmitt trigger



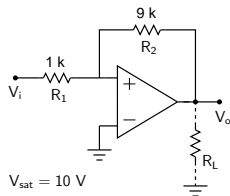
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- * $\Delta V_T = V_{\text{TH}} - V_{\text{TL}}$ is called the “hysteresis width.”

Noninverting Schmitt trigger



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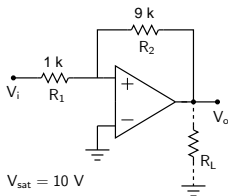
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Noninverting Schmitt trigger



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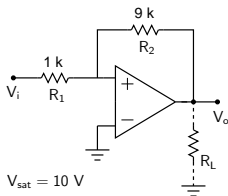
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Case (i): $V_o = -V_{\text{sat}} = -10 \text{ V}$

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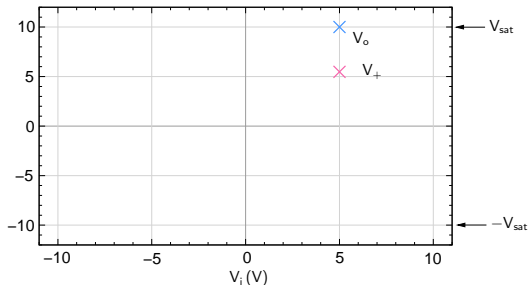
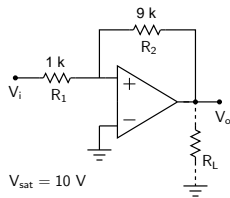
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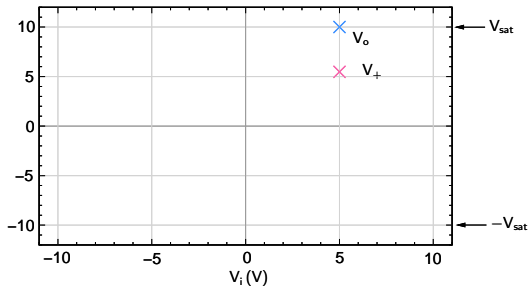
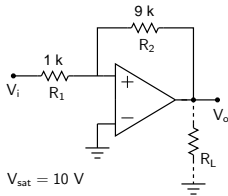
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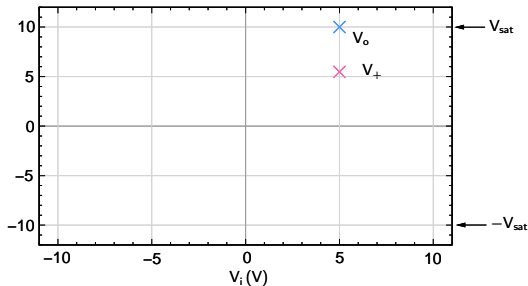
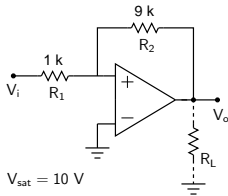
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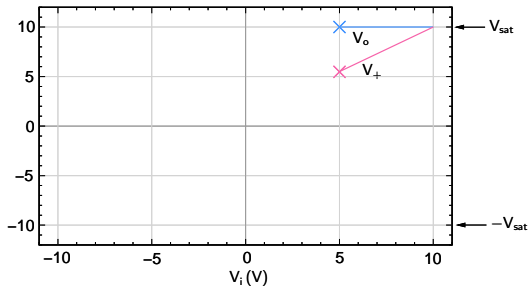
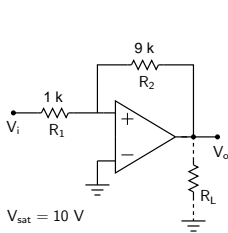
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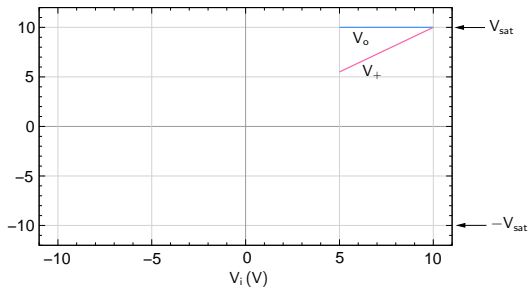
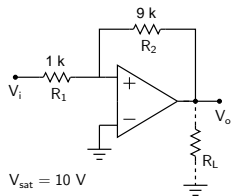
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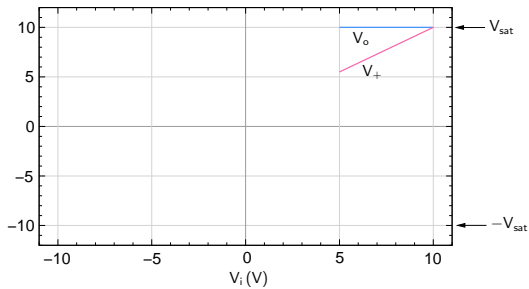
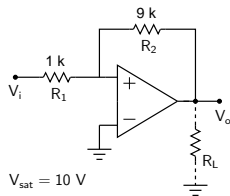
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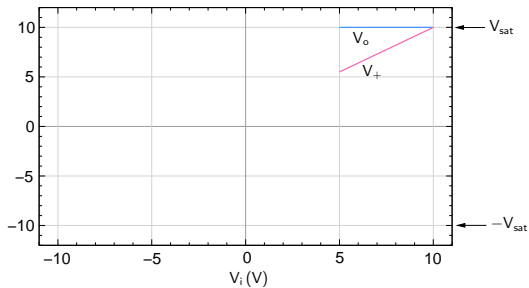
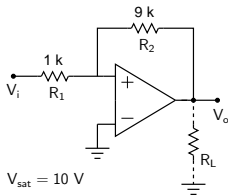


Noninverting Schmitt trigger



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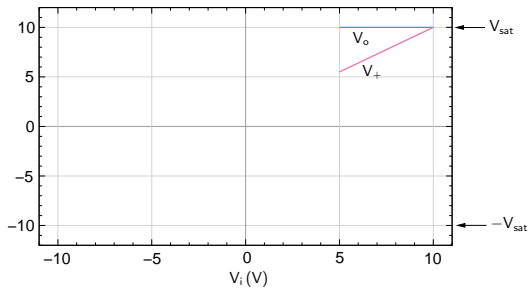
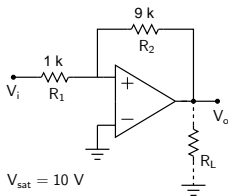
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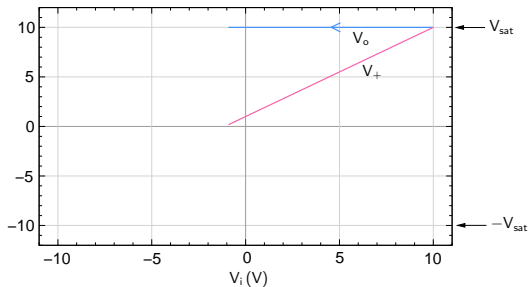
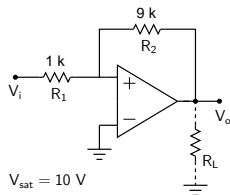


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As long as $V_+ > 0\text{ V}$, V_o remains at $+V_{\text{sat}}$.

Noninverting Schmitt trigger

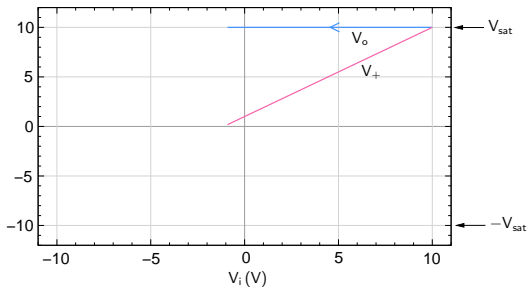
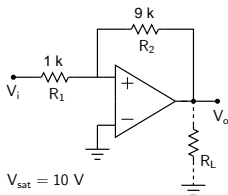


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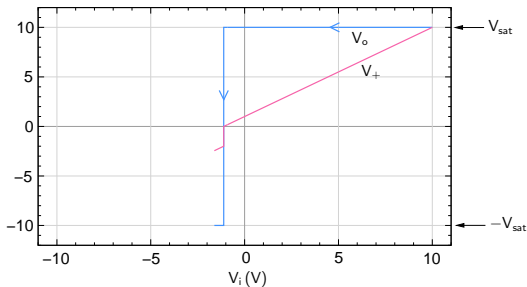
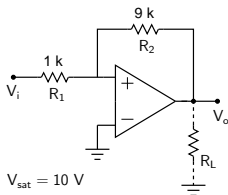
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Noninverting Schmitt trigger



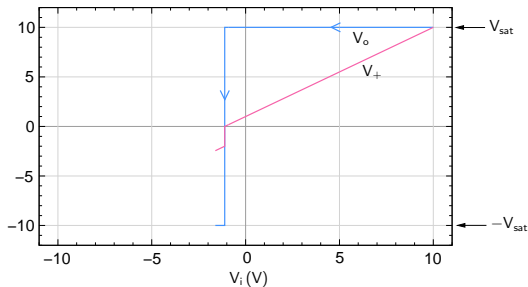
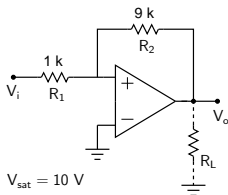
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Noninverting Schmitt trigger



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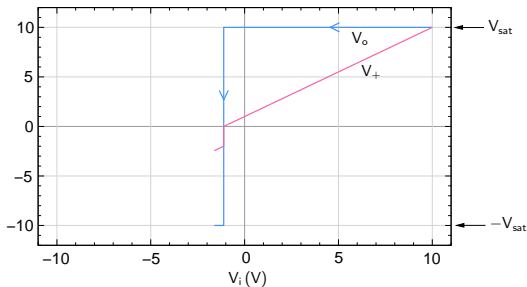
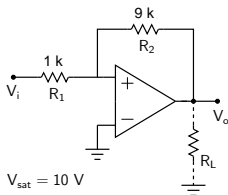
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Noninverting Schmitt trigger



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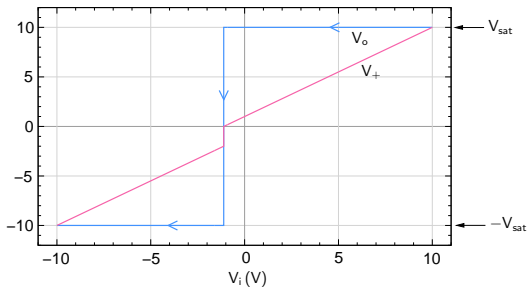
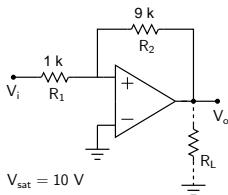
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Noninverting Schmitt trigger



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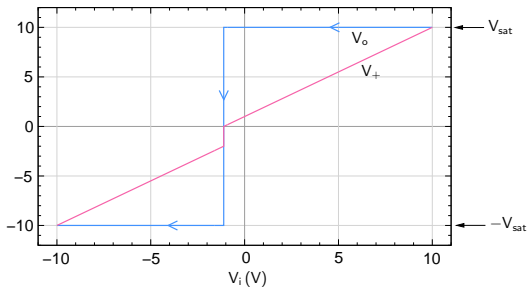
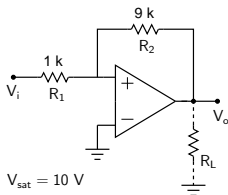
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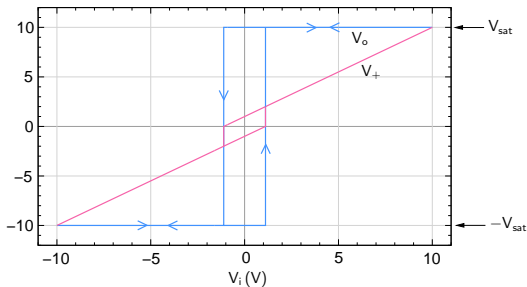
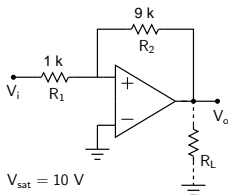
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Now, the threshold at which V_o flips is $V_+ = 0$, i.e., $V_i = +\frac{R_1}{R_2} V_{\text{sat}} = +1.11 \text{ V}$

Noninverting Schmitt trigger



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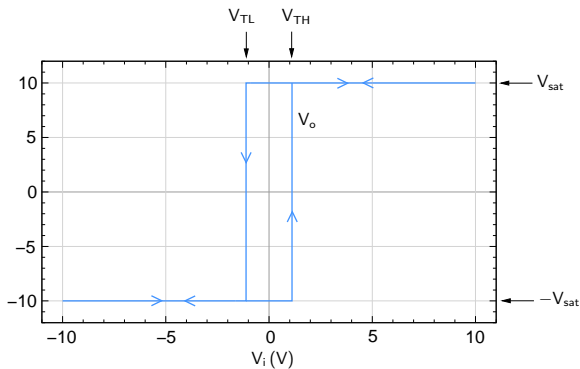
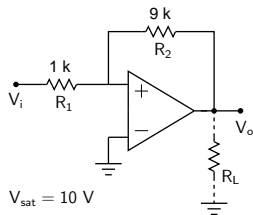
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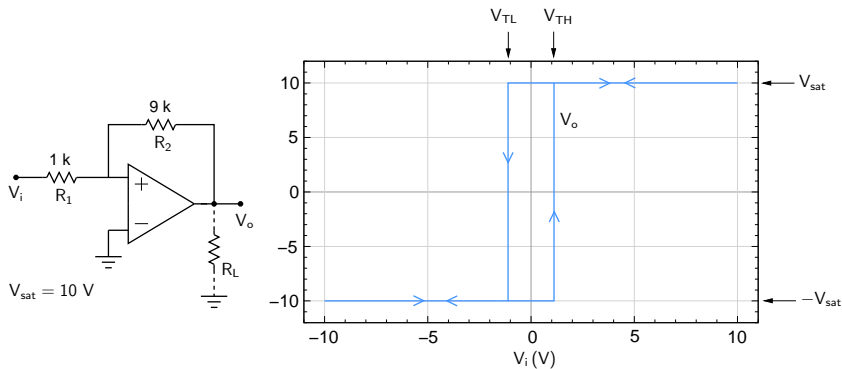
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Noninverting Schmitt trigger

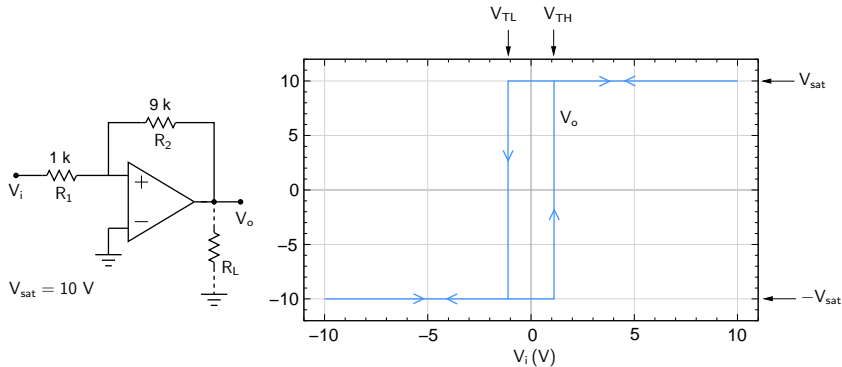


Noninverting Schmitt trigger



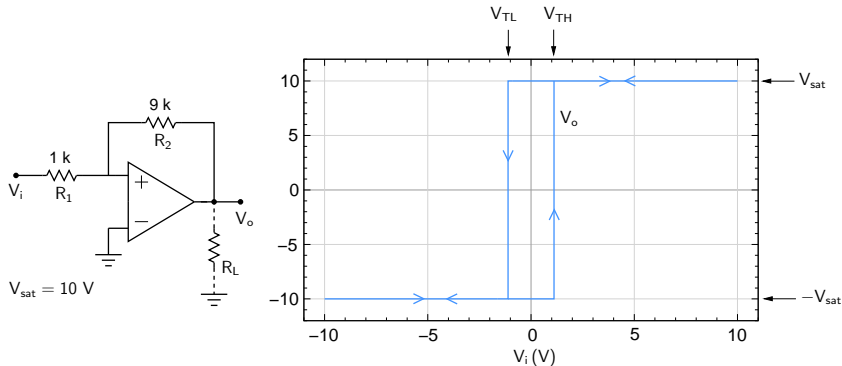
* The threshold values V_{TH} and V_{TL} are given by $\pm \left(\frac{R_1}{R_2} \right) V_{\text{sat}}$.

Noninverting Schmitt trigger



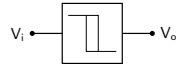
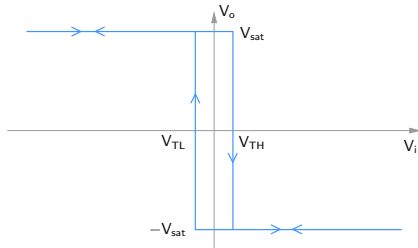
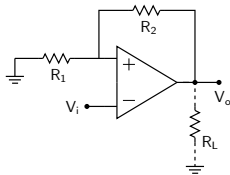
- * The threshold values V_{TH} and V_{TL} are given by $\pm \left(\frac{R_1}{R_2} \right) V_{sat}$.
- * As in the inverting Schmitt trigger, this circuit has a memory, i.e., the tripping point (whether V_{TH} or V_{TL}) depends on where we are on the V_o axis.

Noninverting Schmitt trigger

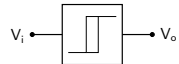
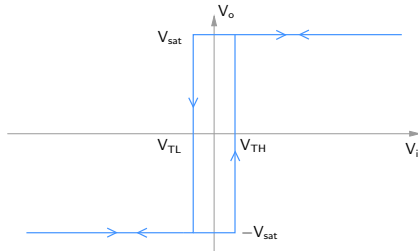
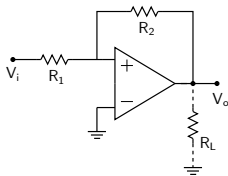


- * The threshold values V_{TH} and V_{TL} are given by $\pm \left(\frac{R_1}{R_2} \right) V_{sat}$.
- * As in the inverting Schmitt trigger, this circuit has a memory, i.e., the tripping point (whether V_{TH} or V_{TL}) depends on where we are on the V_o axis.
- * $\Delta V_T = V_{TH} - V_{TL}$ is called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

Schmitt triggers

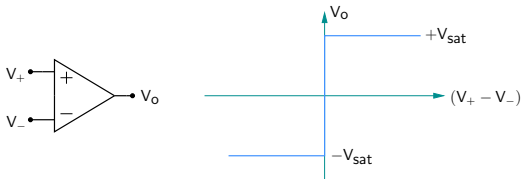


Inverting

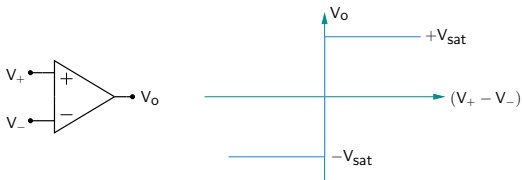


Noninverting

Comparators

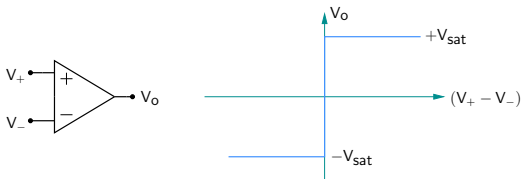


Comparators



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

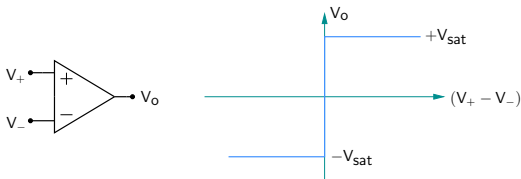
Comparators



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

Comparators

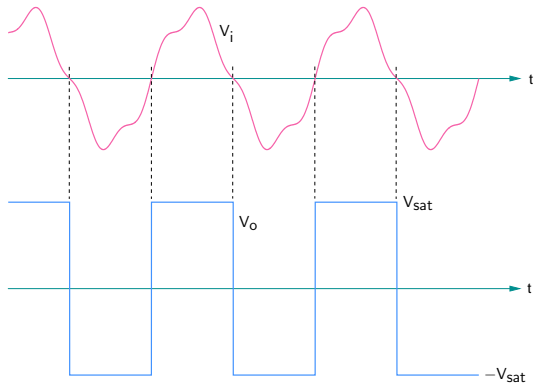
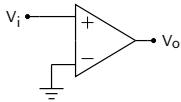


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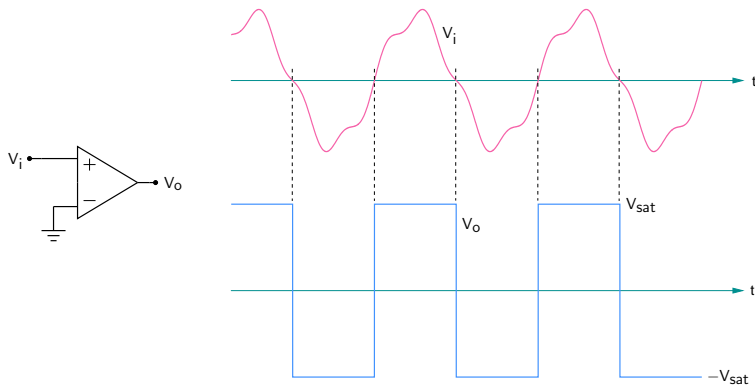
As seen earlier, the width of the linear region, $[V_{sat} - (-V_{sat})]/A_V$, is small ($\sim 0.1 \text{ mV}$), and could be treated as 0.

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

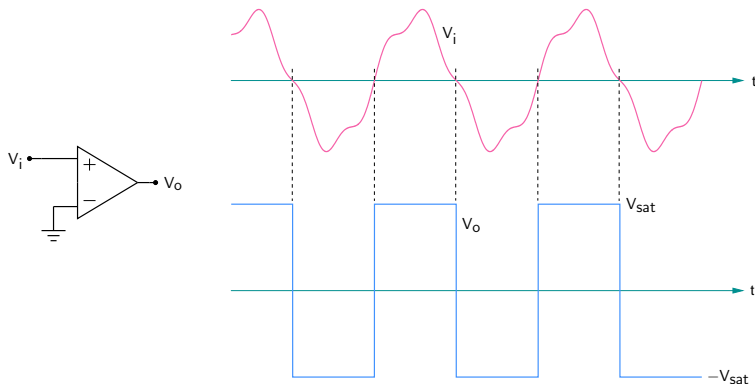


Comparators



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

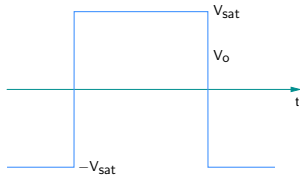
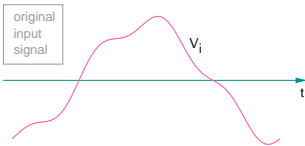
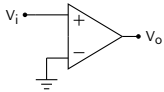
Comparators



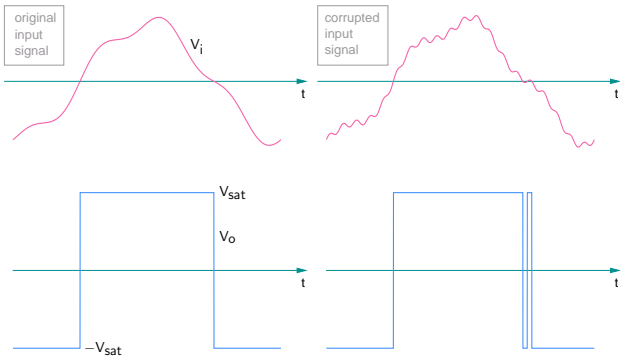
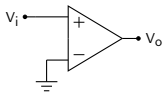
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In practice, the input (analog) signal can have noise or electromagnetic pick-up superimposed on it. As a result, erroneous operation of the circuit may result
→ next slide.

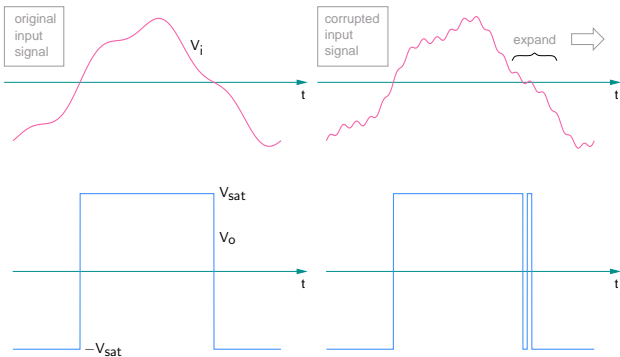
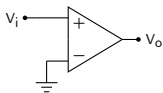
Comparators



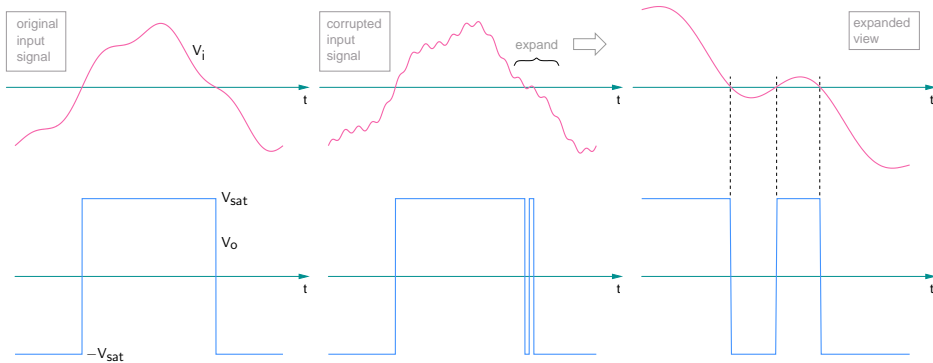
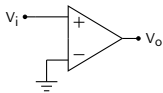
Comparators



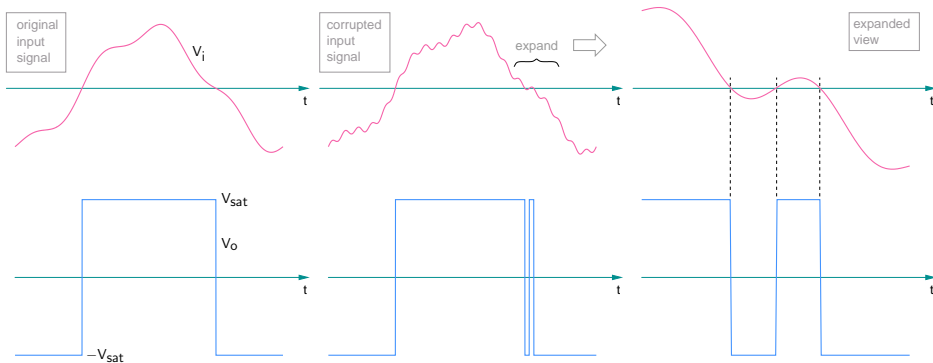
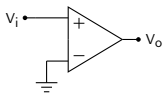
Comparators



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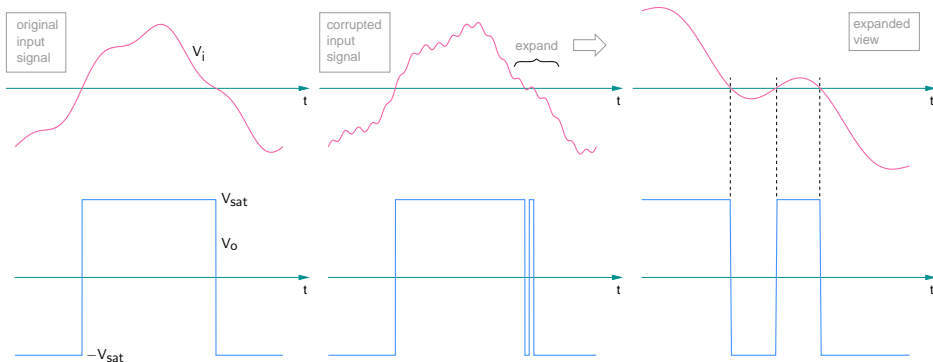
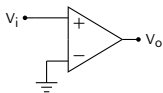


Comparators



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

Comparators

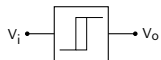


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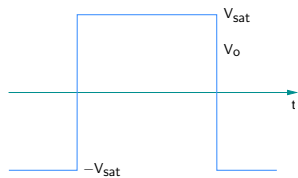
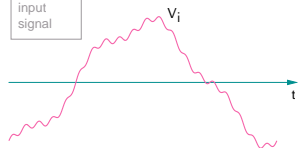
A Schmitt trigger can be used to eliminate the chatter

→ next slide.

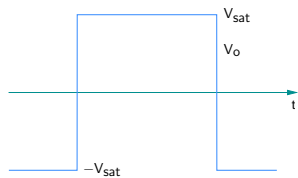
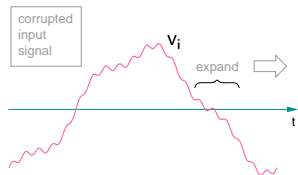
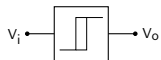
Comparators



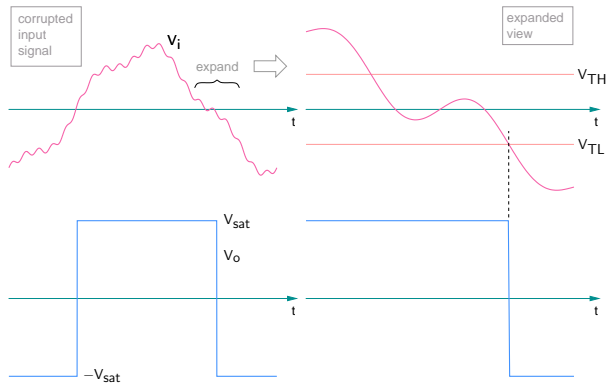
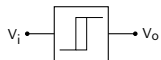
corrupted
input
signal



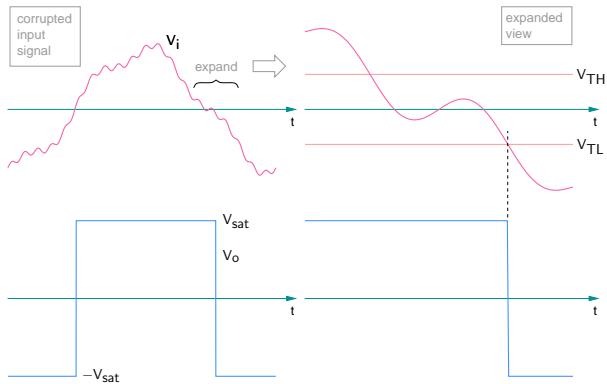
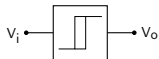
Comparators



Comparators

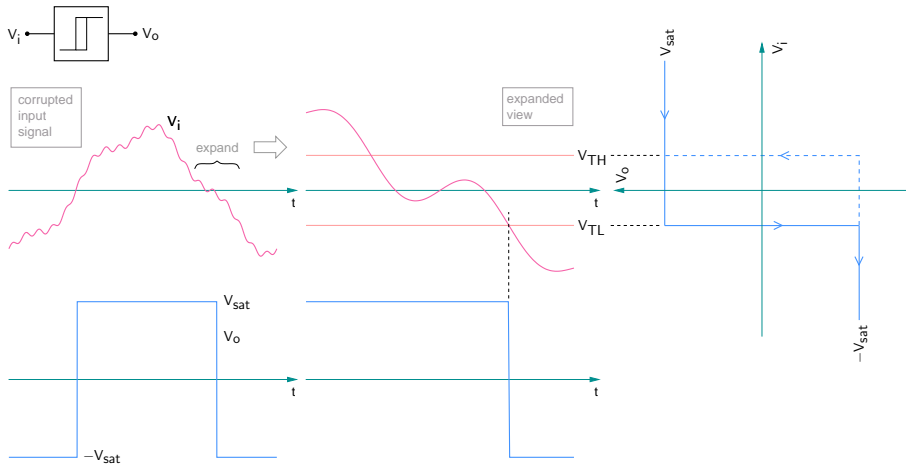


Comparators



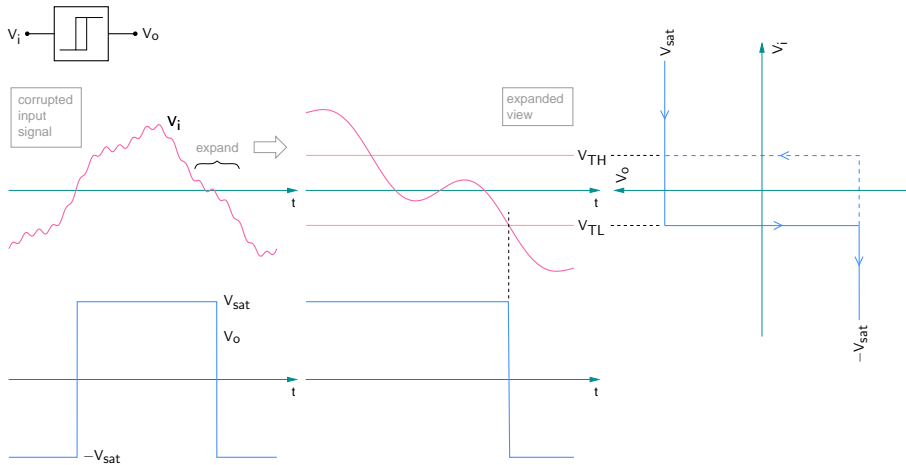
- * While going from positive to negative values, V_i needs to cross V_{TL} (and not 0 V) to cause a change in V_o .

Comparators



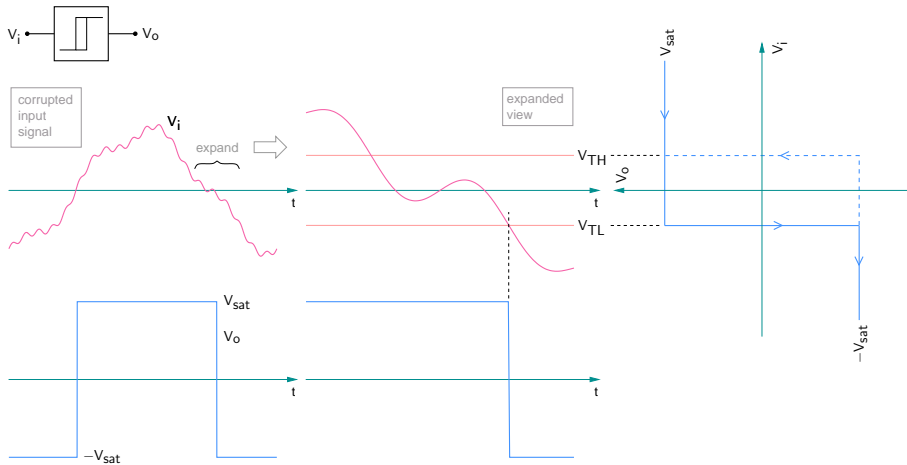
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Comparators



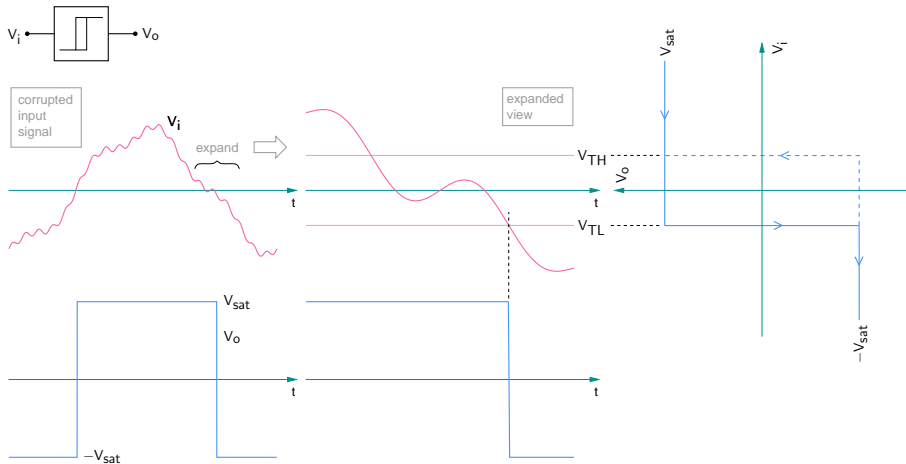
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- * In the reverse direction (negative to positive), V_i needs to cross V_{TH} .

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 .
- * 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.

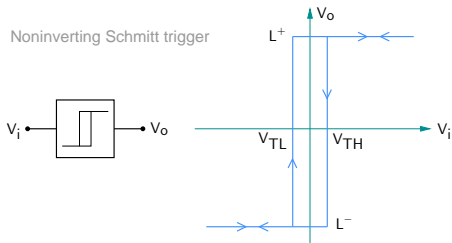
Comparators



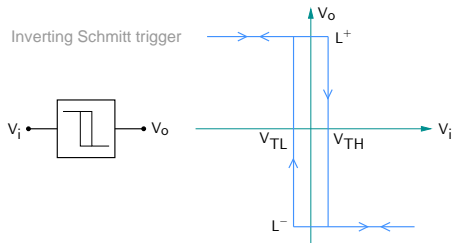
- * While going from positive to negative values, V_i needs to cross V_{TL} (and not 0 V) to cause a change in V_o .
- * In the reverse direction (negative to positive), V_i needs to cross V_{TH} .
- * The circuit gets rid of spurious transitions, a major advantage over the simple comparator.
- * The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

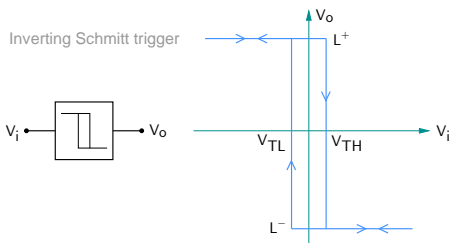
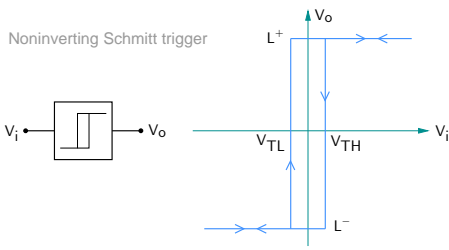
Noninverting Schmitt trigger



Inverting Schmitt trigger

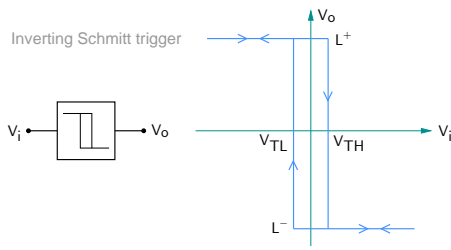
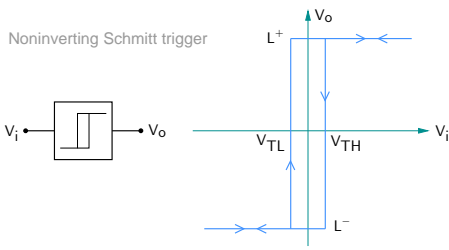


Waveform generation using Schmitt triggers



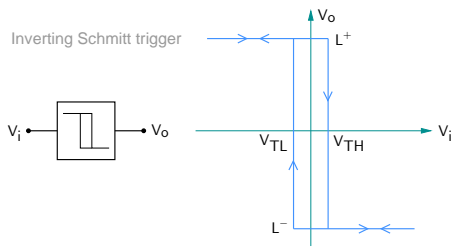
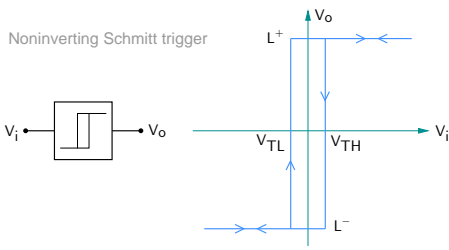
* A Schmitt trigger has two states, $V_o = L^+$ and $V_o = L^-$.

Waveform generation using Schmitt triggers



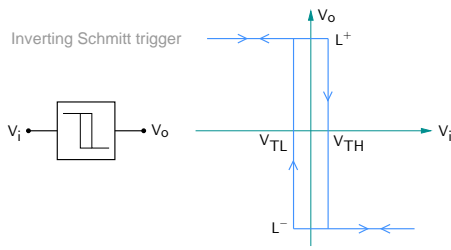
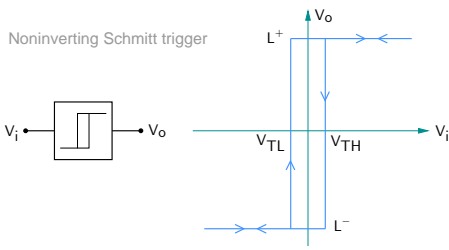
- * A Schmitt trigger has two states, $V_o = L^+$ and $V_o = L^-$.
- * With a suitable RC network, it can be made to freely oscillate between L^+ and L^- . Such a circuit is called an “astable multivibrator” or a “free-running multivibrator.”

Waveform generation using Schmitt triggers



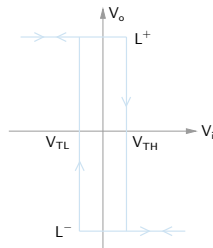
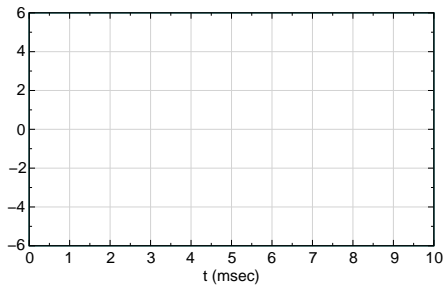
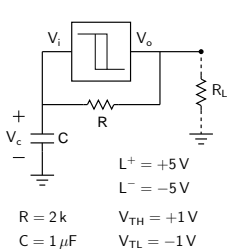
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- * An astable multivibrator produces oscillations *without* an input signal, the frequency being controlled by the component values.

Waveform generation using Schmitt triggers

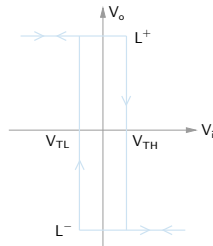
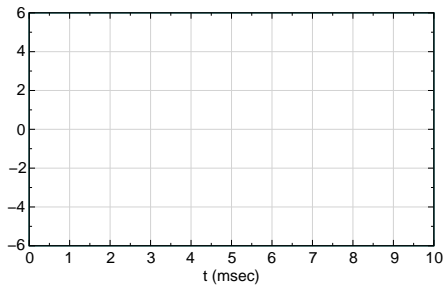
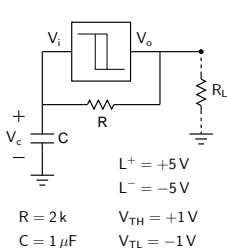


- * A Schmitt trigger has two states, $V_o = L^+$ and $V_o = L^-$.
- * With a suitable RC network, it can be made to freely oscillate between L^+ and L^- . Such a circuit is called an “astable multivibrator” or a “free-running multivibrator.”
- * An astable multivibrator produces oscillations *without*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

Waveform generation using a Schmitt trigger

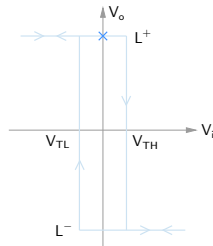
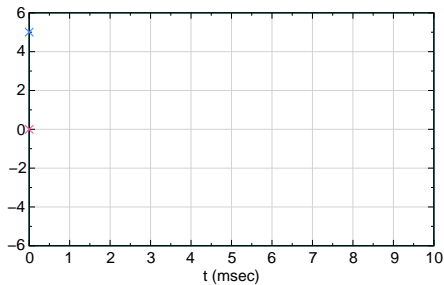
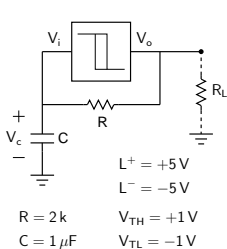


Waveform generation using a Schmitt trigger



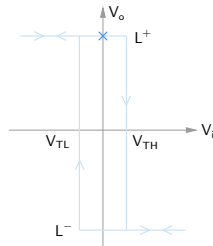
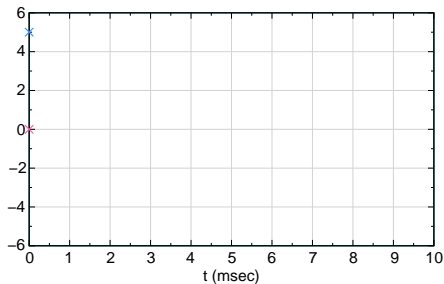
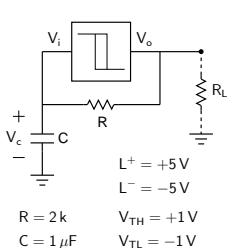
At $t = 0$, let $V_o = L^+$, and $V_c = 0$ V.

Waveform generation using a Schmitt trigger



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

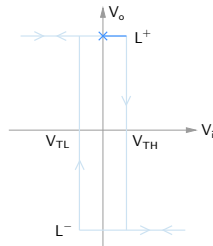
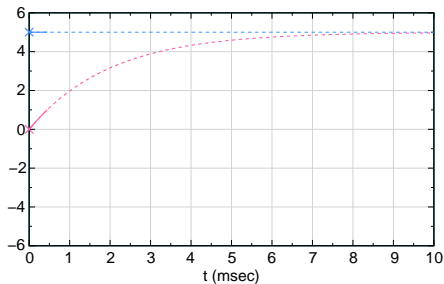
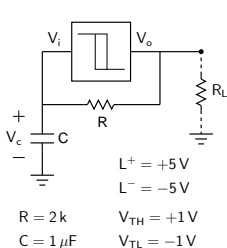
Waveform generation using a Schmitt trigger



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

The capacitor starts charging toward L^+ .

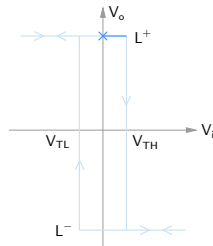
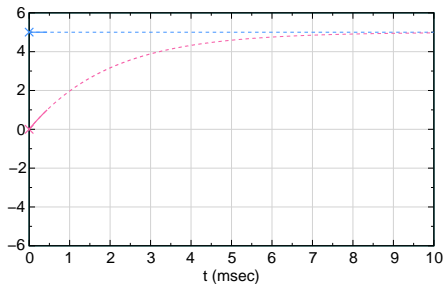
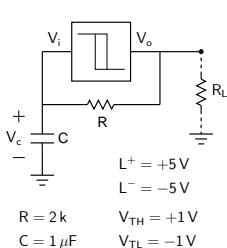
Waveform generation using a Schmitt trigger



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

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Waveform generation using a Schmitt trigger

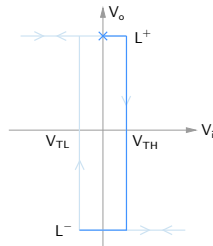
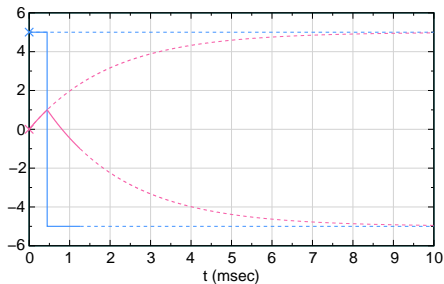
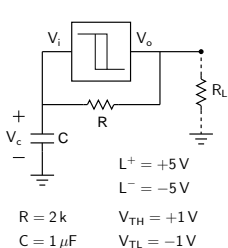


At $t = 0$, let $V_o = L^+$, and $V_c = 0\text{ V}$.

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

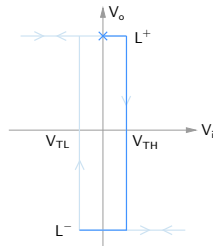
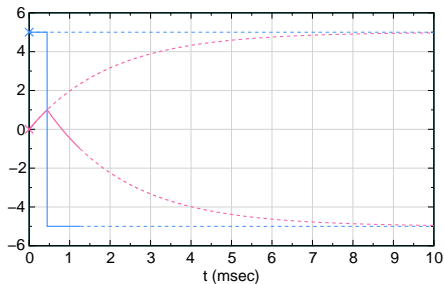
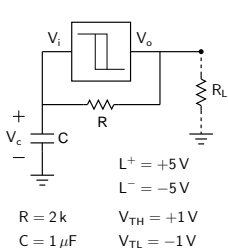


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Waveform generation using a Schmitt trigger



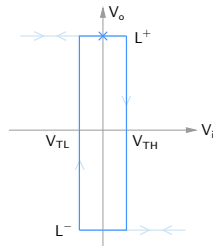
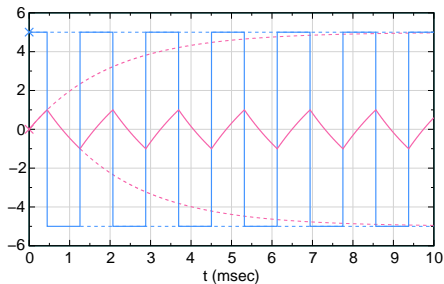
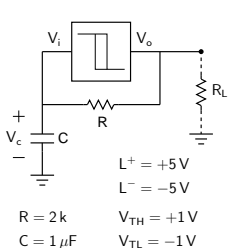
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When V_c crosses V_{TL} , the output flips again \rightarrow oscillations.

Waveform generation using a Schmitt trigger



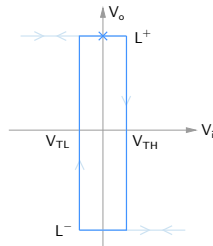
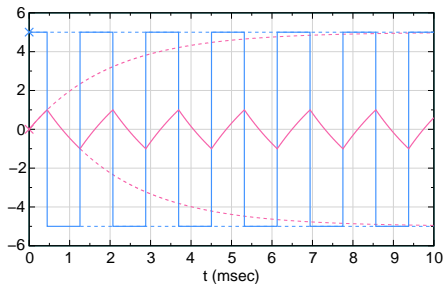
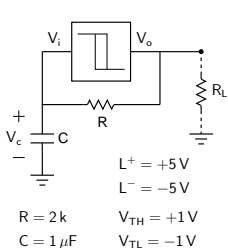
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Waveform generation using a Schmitt trigger



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

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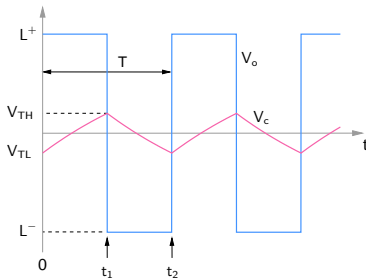
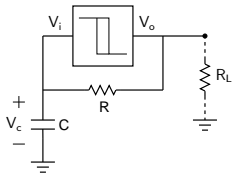
When V_c crosses V_{TH} , the output flips. Now, the capacitor starts discharging toward L^- .

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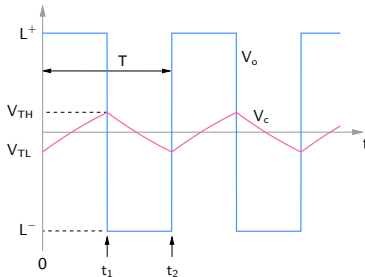
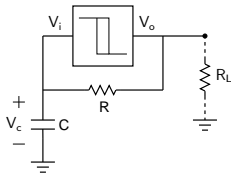
Note that the circuit oscillates *on its own*, i.e., without any input.

Q: Where is the energy coming from?

Waveform generation using a Schmitt trigger



Waveform generation using a Schmitt trigger

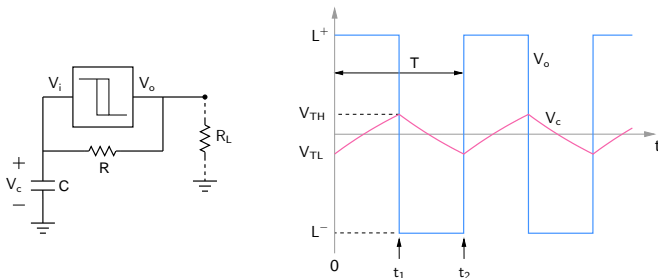


Charging: Let $V_c(t) = A_1 \exp(-t/\tau) + B_1$, with $\tau = RC$.

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 $\tau = RC$.

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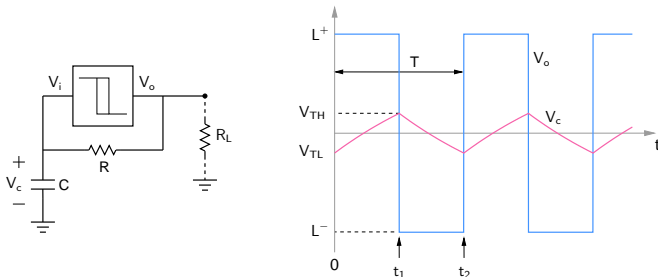
At $t = t_1$, $V_c = V_{TH} \rightarrow V_{TH} = A_1 \exp(-t_1/\tau) + B_1 \rightarrow$ find t_1 .

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 $(t_2 - t_1)$.

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 .

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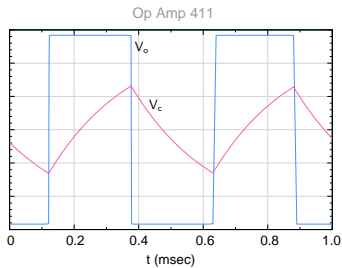
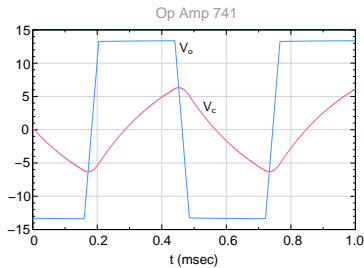
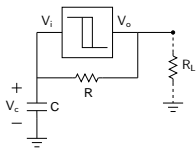
Using $V_c(t_1) = V_{TH}$, $V_c(\infty) = L^-$, find A_2 and B_2 .

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

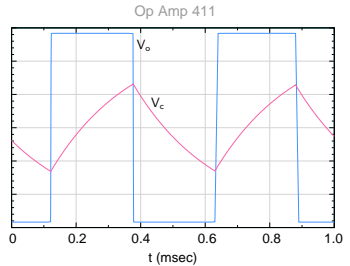
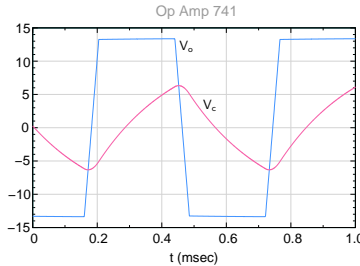
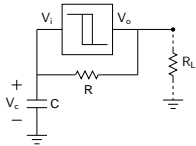
If $L^+ = L$, $L^- = -L$, $V_{TH} = V_T$, $V_{TL} = -V_T$, show that

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

Waveform generation using a Schmitt trigger

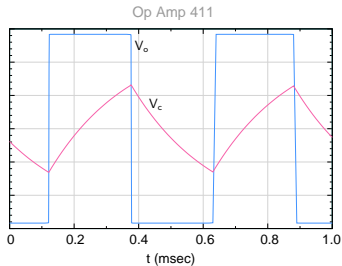
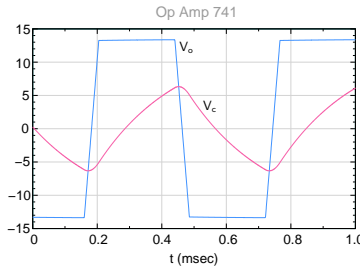
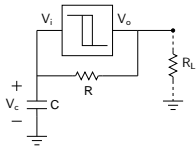


Waveform generation using a Schmitt trigger



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

Waveform generation using a Schmitt trigger

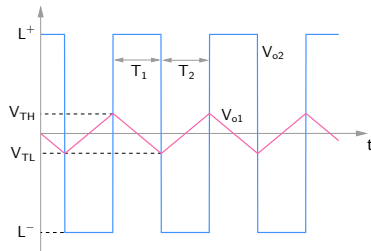
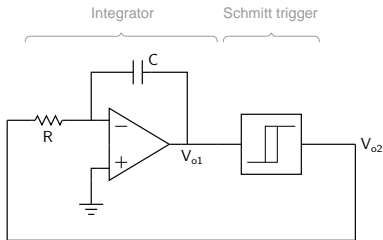


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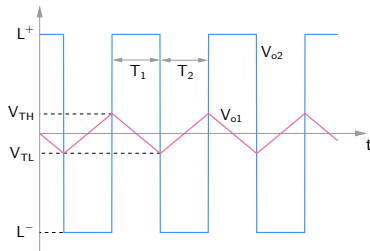
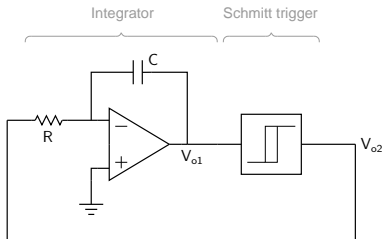
SEQUEL files: `schmitt_osc_741.sqproj`, `schmitt_osc_411.sqproj`

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

Waveform generation using a Schmitt trigger

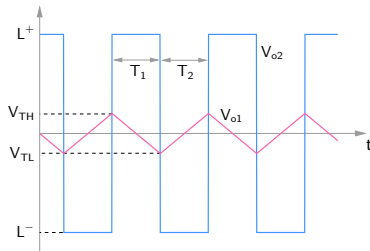
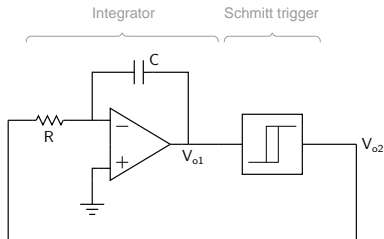


Waveform generation using a Schmitt trigger



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

Waveform generation using a Schmitt trigger

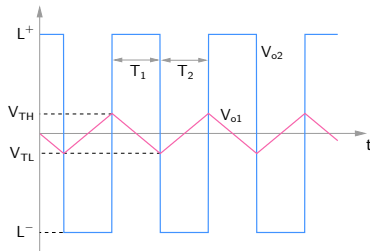
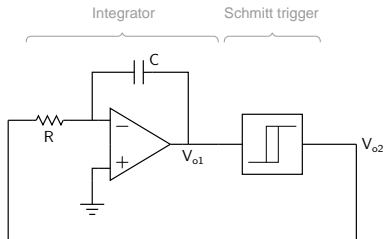


For the integrator, $V_{o1} = -\frac{1}{RC} \int V_{o2} dt$,

$V_{o2} = L^+ \rightarrow V_{o1}$ decreases linearly.

$V_{o2} = L^- \rightarrow V_{o1}$ increases linearly.

Waveform generation using a Schmitt trigger



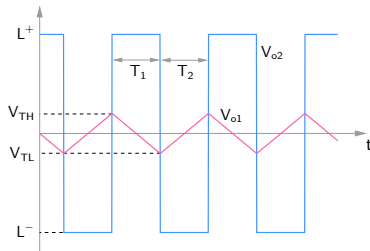
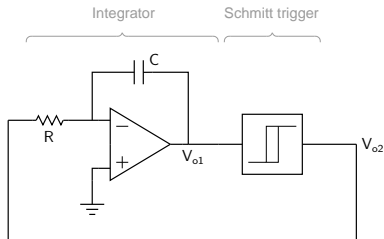
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$$T_1 = \frac{V_{TH} - V_{TL}}{L^+ / RC} = RC \frac{V_{TH} - V_{TL}}{L^+}.$$

Waveform generation using a Schmitt trigger



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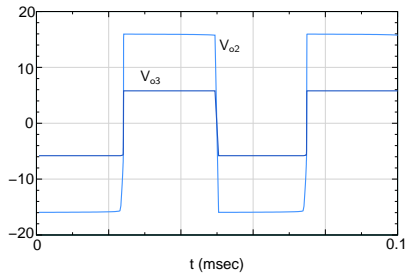
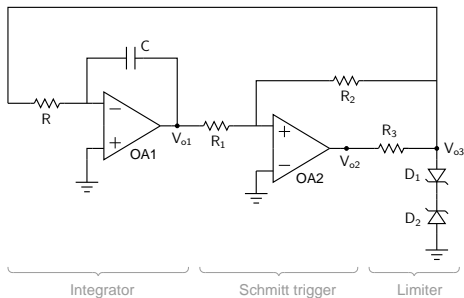
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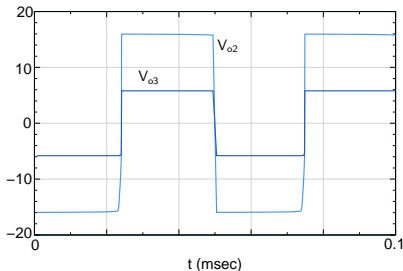
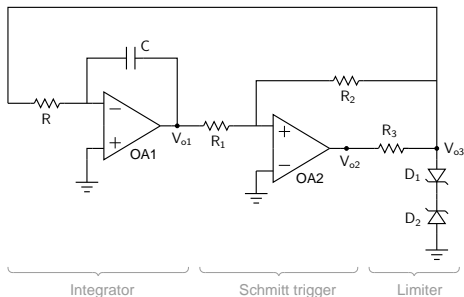
$$T_1 = \frac{V_{TH} - V_{TL}}{L^+ / RC} = RC \frac{V_{TH} - V_{TL}}{L^+}.$$

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

Limiting the output voltage



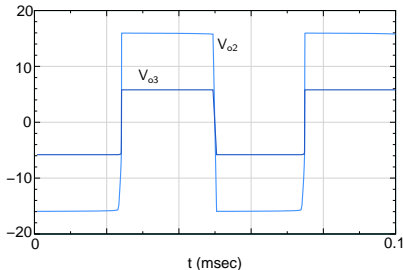
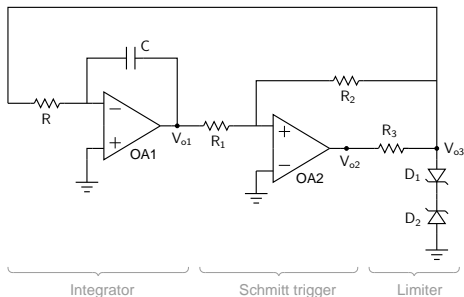
Limiting the output voltage



- * When $V_{o2} = +V_{sat}$, 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.

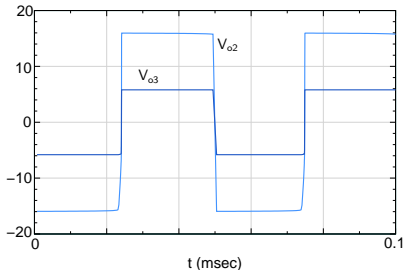
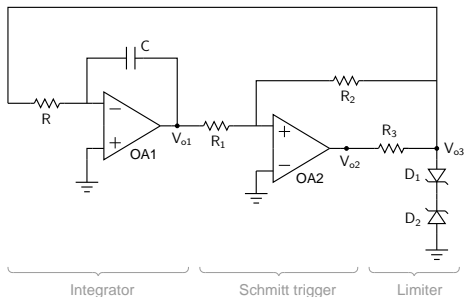
$$\rightarrow V_{o3} = V_{on} + V_Z.$$

Limiting the output voltage



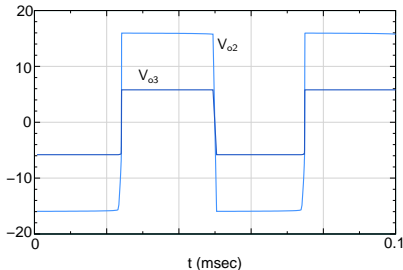
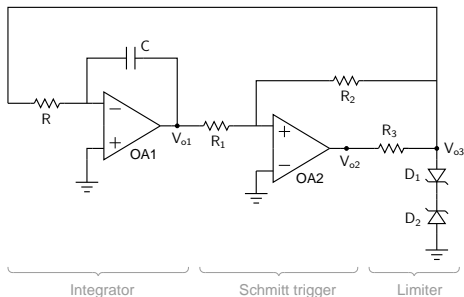
- When $V_{o2} = +V_{sat}$, D_1 is forward-biased (with a voltage drop of V_{on}), and D_2 is reverse-biased. The Zener breakdown voltage (V_Z) is chosen so that D_2 operates under breakdown condition.
 $\rightarrow V_{o3} = V_{on} + V_Z$.
- When $V_{o2} = -V_{sat}$, D_2 is forward-biased (with a voltage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

Limiting the output voltage



- * 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.

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.sproj