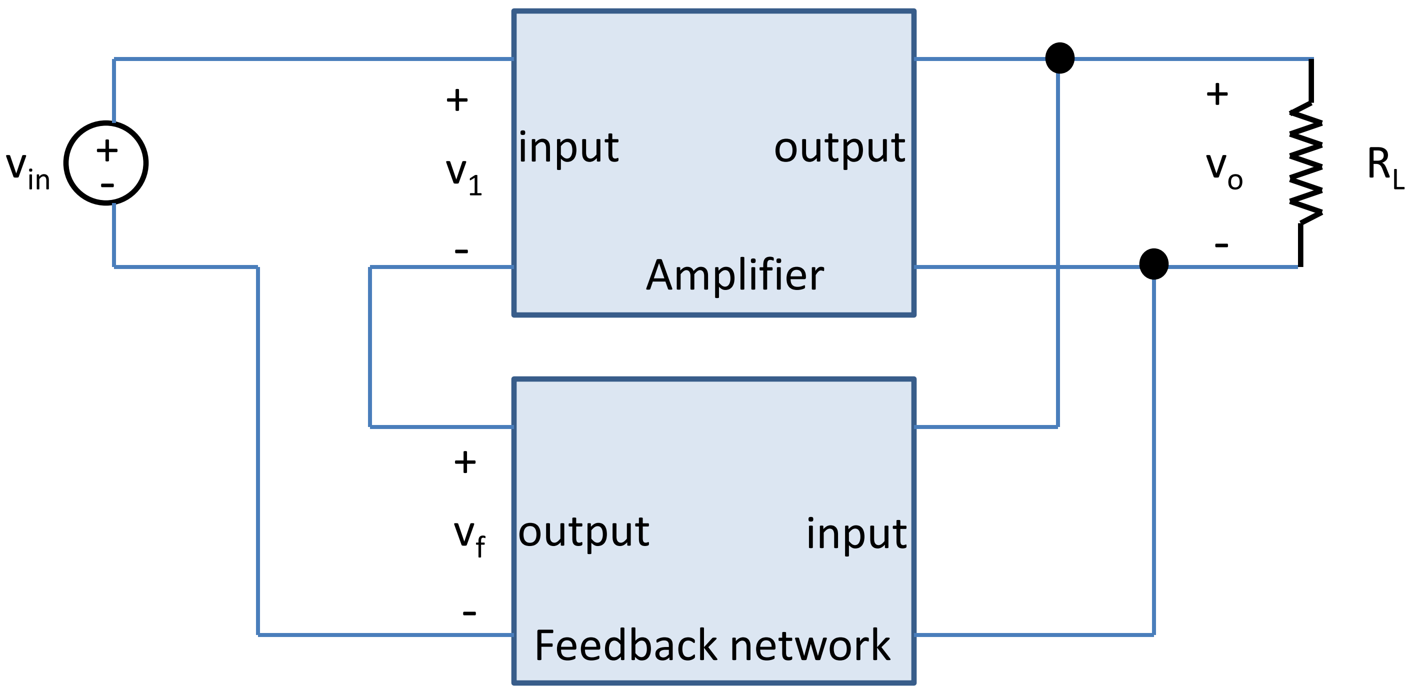
Op-Amp Circuits: Feedback

S. Lodha

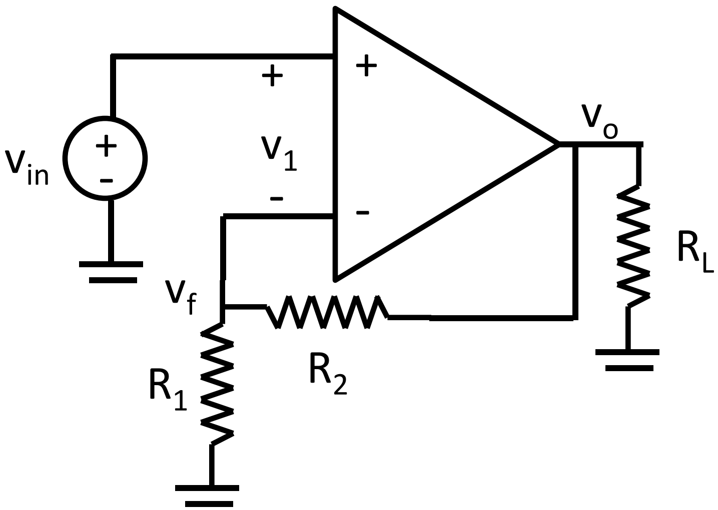
References: L. Bobrow’s book and Prof. M. B. Patil’s slides

What is feedback?



- Output of circuit/system returned back to input
- Four possible connections
  - Above is an example of ***series-parallel*** feedback
  - Output of feedback in ***series*** with input of amp, input of feedback in ***parallel*** with output of amp
  - Most beneficial for voltage amplification applications

Example of series-parallel feedback



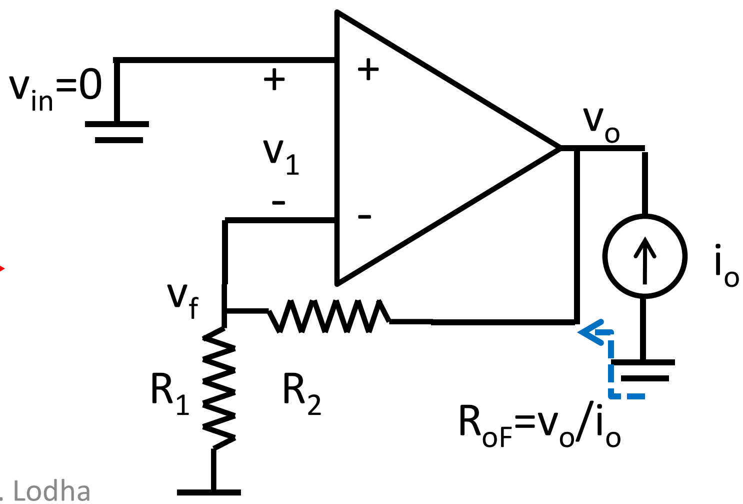
Negative feedback

$$v_1 = v_{in} - v_f$$

$$A_F = \frac{v_o}{v_{in}} = 1 + \frac{R_2}{R_1}$$

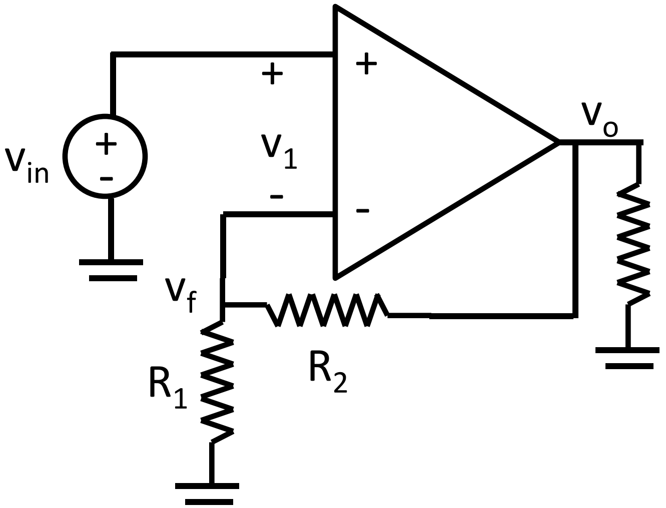
$$B = \frac{v_f}{v_o} = \frac{R_1}{R_1 + R_2} = \frac{1}{A_F}$$

For Ideal Op-Amp
-Infinite gain
-Infinite Input Resistance
-Zero Output Resistance



Feedback with non-ideal Op Amp

Assume A is finite, but $R_{in}=\infty$ and $R_o=0$



$$v_f = Bv_o$$

$$v_o = A(v_{in} - v_f) = Av_{in} - ABv_o$$

$$\boxed{A_F = \frac{v_o}{v_{in}} = \frac{A}{1+AB}}$$

$$A_F = \frac{A}{1+AB} \approx \frac{A}{AB} = \frac{1}{B} = 1 + \frac{R_2}{R_1}$$

For large A

Trade-off gain with increase in stability!

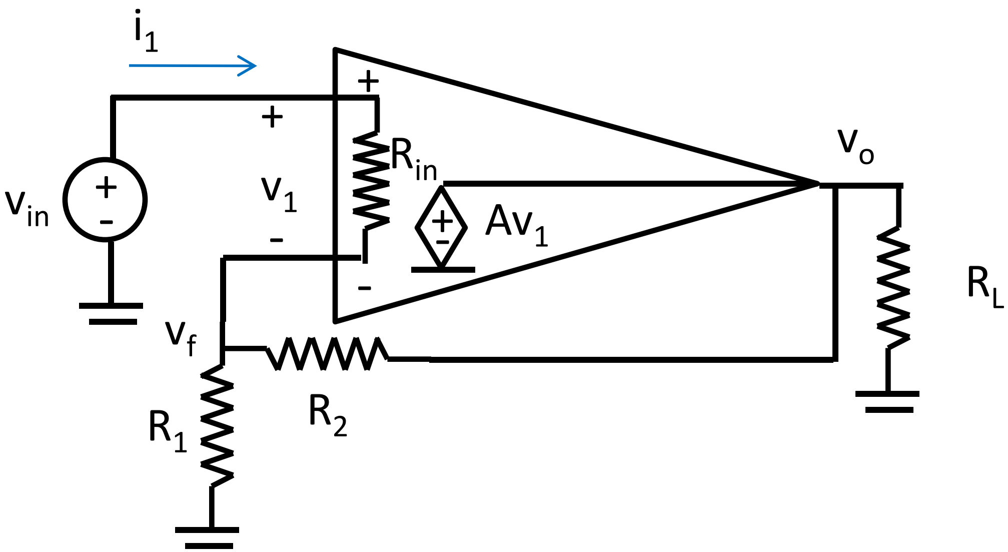
A=200000, R_1=1 kΩ, R_2=100 kΩ → A_F=100.959

Suppose A changes by 10% to 220,000 → A_F=100.964

Only 0.005% change!

Feedback effect on input R

Assume A and R_{in} are both finite, but R_o=0



$$R_{iF} = \frac{v_{in}}{i_1} = \frac{v_{in}}{v_1} R_{in} = \frac{v_{in}}{v_o} AR_{in}$$

$$R_{in} >> R_1$$

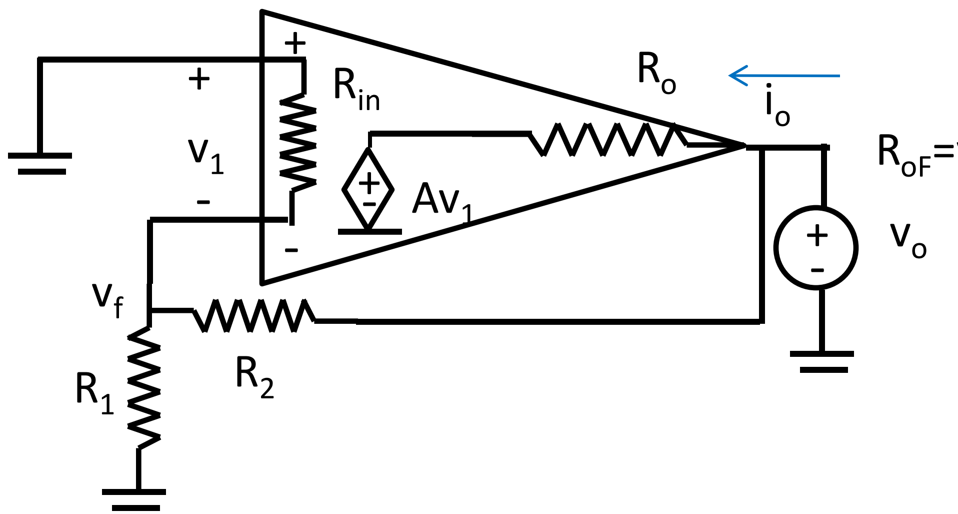
$$\frac{v_o}{v_{in}} = \frac{A}{1+AB}$$

$$\boxed{R_{iF} = (1+AB)R_{in}}$$

Negative feedback can be used to increase the input resistance of an amplifier.

Feedback effect on output R

Assume A, R_{in} and R_o are all finite



$$R_{in} >> R_1$$

$$i_o = \frac{1+AB}{R_o} v_o + \frac{1}{R_1+R_2} v_o$$

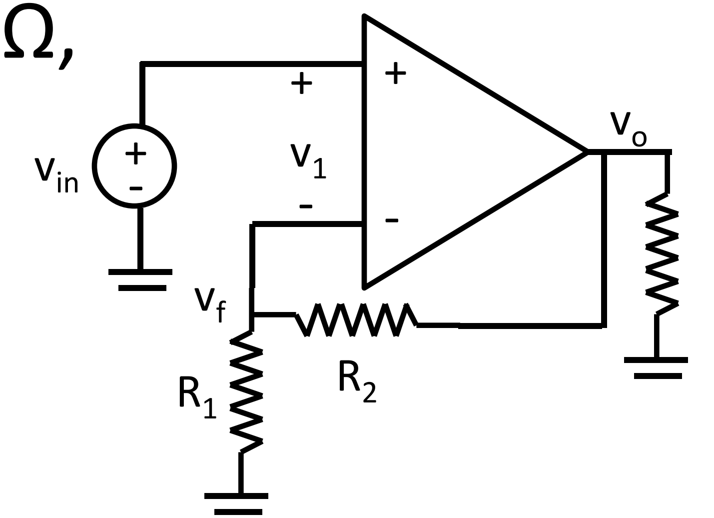
$$\Rightarrow \frac{1}{R_{oF}} = \frac{i_o}{v_o} = \frac{1+AB}{R_o} + \frac{1}{R_1+R_2}$$

$$\Rightarrow \boxed{R_{oF} = \frac{R_o}{1+AB} \parallel (R_1+R_2) \approx \frac{R_o}{1+AB}}$$

Negative feedback can be used to decrease the output resistance of an amplifier.

Example

- $A=200000$, $R_{in}=2\ M\Omega$, $R_o=75\ \Omega$, $R_1= 1\ k\Omega$, $R_2= 100\ k\Omega$
  - $B=R_1/R_1+R_2=0.0099$
  - $R_{iF}=(1+AB)R_{in}=3960\ M\Omega$
  - $R_{oF}=R_o/1+AB=0.038\ \Omega$



Frequency Response

$$\mathbf{A} = \frac{A}{1 + j\omega/\omega_H}$$

A is called the "open-loop" gain (frequency dependent), A is the dc gain

$$\mathbf{A_F} = \frac{\mathbf{A}}{1+\mathbf{A}B} = \frac{\left[\dfrac{A}{1+j\omega/\omega_H}\right]}{1+\left[\dfrac{A}{1+j\omega/\omega_H}\right]B}$$

For the example, A_F=A/1+AB

$$\mathbf{A_F} = \frac{A}{1+AB}\,\frac{1}{1+j\left[\dfrac{\omega}{(1+AB)\omega_H}\right]} = \frac{A_F}{1+j\omega/\omega_{HF}}$$

$$\omega_{HF} = (1+AB)\omega_H$$

Upper cut-off frequency

- Lower cut-off frequency is 0
- Internal transistor capacitances determine upper cut-off frequency
  - Acts like a low-pass filter
- With feedback, upper-cut off frequency multiplied by (1+AB)
  - Large increase in bandwidth

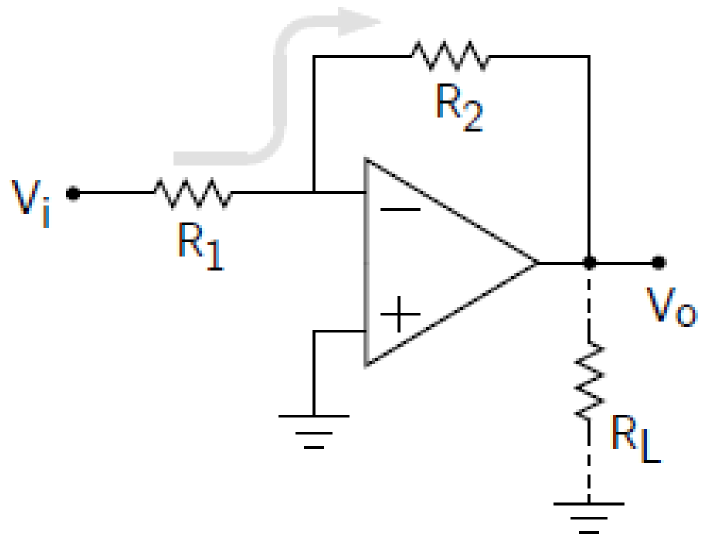
Gain-Bandwidth Product

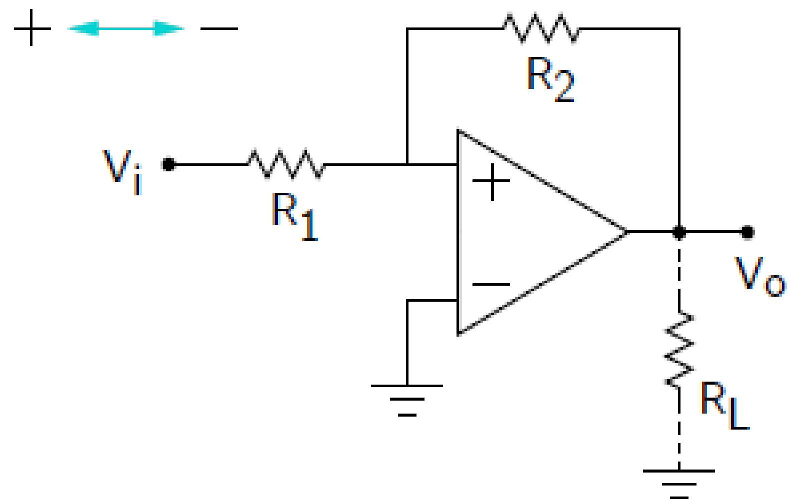
$f_T = Af_H$ Product of dc gain with upper cut-off frequency in Hz

$$f_{HF} = A_F\, f_{HF} = \frac{A}{1+AB}(1+AB)\, f_H = Af_H = f_T$$

- Addition of feedback does not change the gain-bandwidth product
  - Feedback amplifier and op-amp have the same product
  - What you lose in gain is made up in bandwidth

Feedback: Inverting Amplifier





$$V_o = A_V (V_+ - V_-) \qquad \text{Eq. 1}$$

$$V_- = V_i \frac{R_2}{R_1 + R_2} + V_o \frac{R_1}{R_1 + R_2} \qquad \text{Eq. 2}$$

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

Eq. 2 Eq. 1 Eq. 2

Stable equilibrium is reached

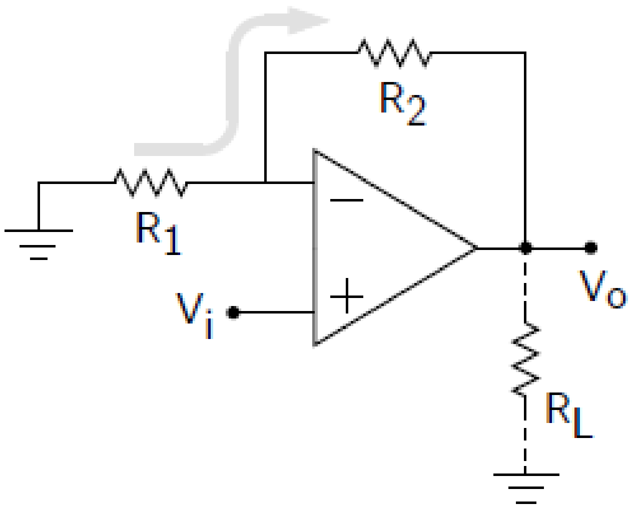
$$V_+ = V_i \frac{R_2}{R_1 + R_2} + V_o \frac{R_1}{R_1 + R_2} \qquad \text{Eq. 3}$$

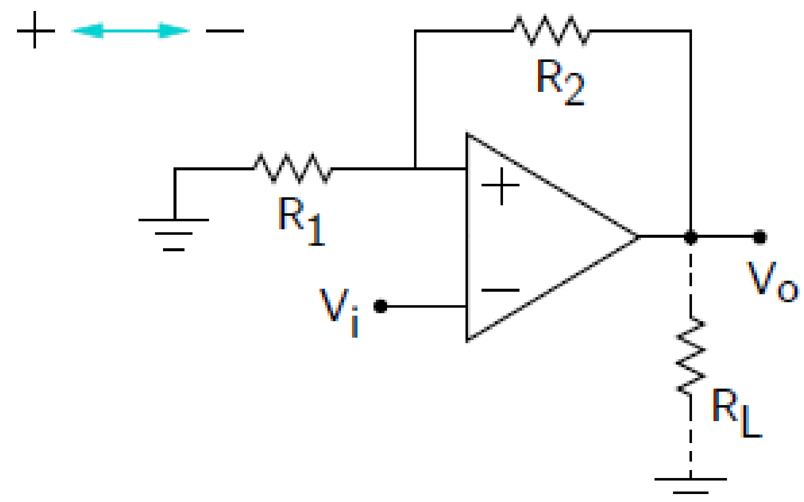
$$V_i \uparrow \rightarrow \boxed{V_+ \uparrow} \rightarrow V_o \uparrow \rightarrow \boxed{V_+ \uparrow}$$

Eq. 3 Eq. 1 Eq. 3

V_o rises (or falls) indefinitely till saturation→ positive feedback

Feedback: Non-Inverting Amplifier





$$V_o = A_V (V_+ - V_-)$$ Eq. 1

$$V_- = V_o \frac{R_1}{R_1 + R_2}$$ Eq. 2

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

Eq. 1 Eq. 2 Eq. 1

Stable equilibrium is reached

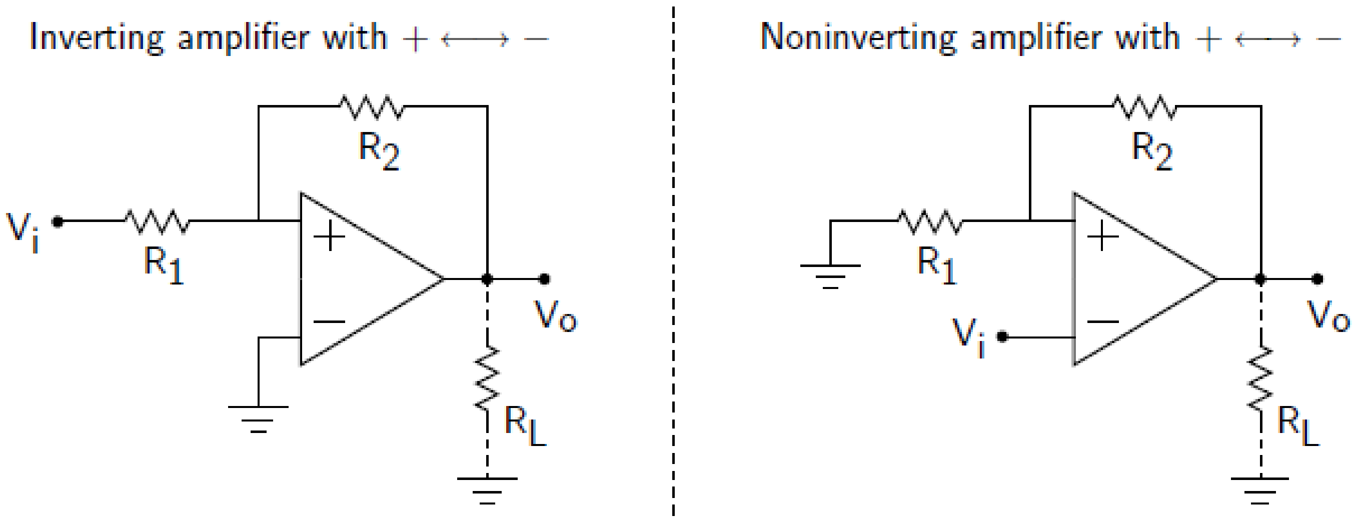
$$V_+ = V_o \frac{R_1}{R_1 + R_2}$$ Eq. 3

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

Eq. 1 Eq. 3 Eq. 1

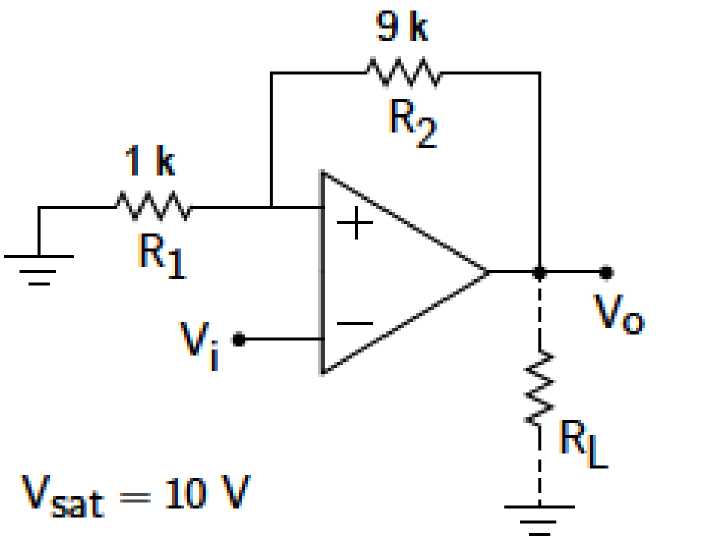
V_o rises (or falls) indefinitely till saturation→ positive feedback

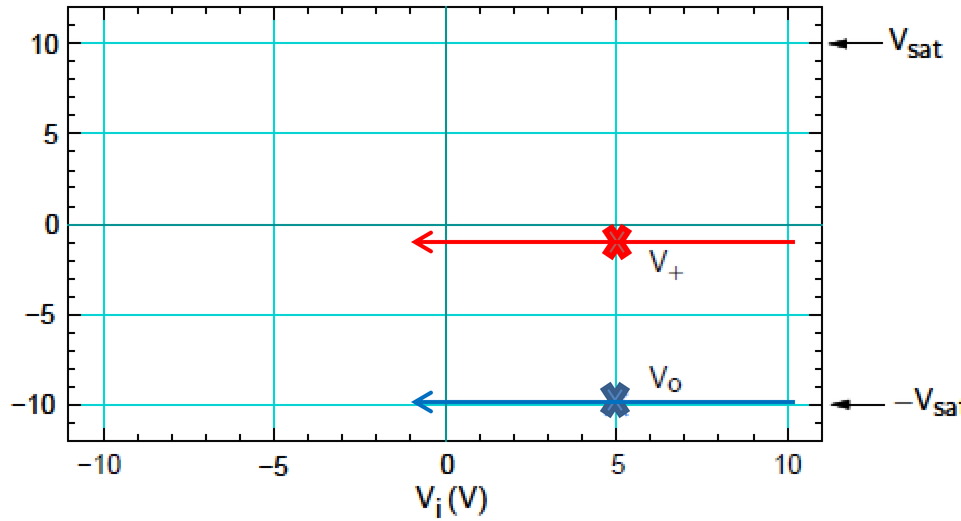
Feedback



- Both circuits exhibit positive feedback
- Output is limited by saturation, i.e. $V_o = \pm V_{sat}$

Inverting Schmitt Trigger





V_o is either +10V ($V_+>V_-$) or -10V ($V_+<V_-$) because of positive feedback

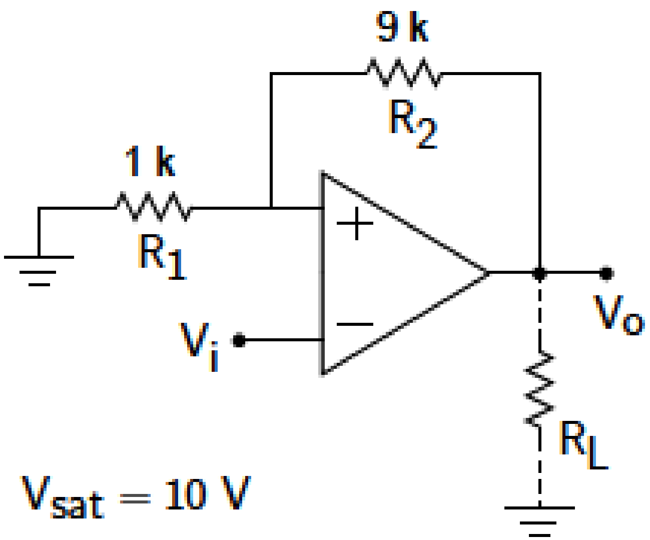
Case 1

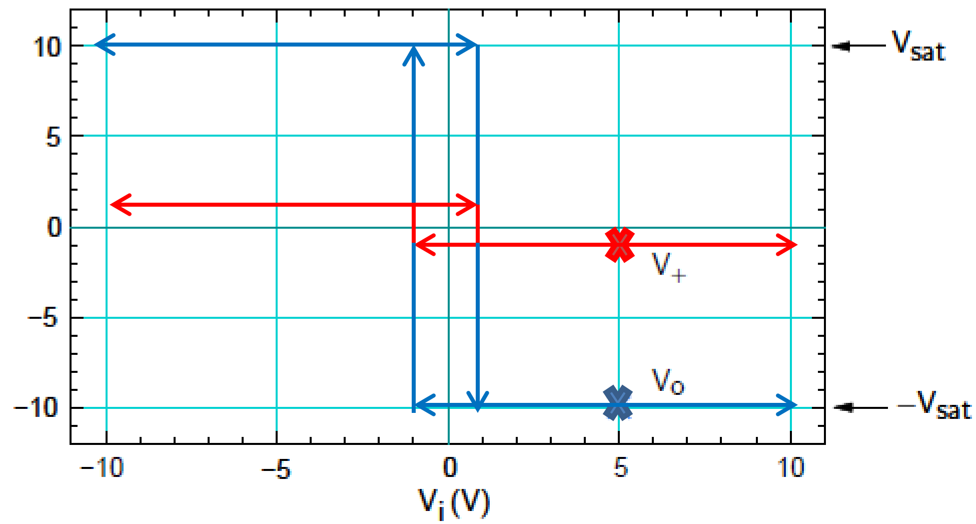
V_i=5V, Assume V_o=10V, V_+=1V → V_+-V_-=1-5=-4 V → V_o=-10V Inconsistent!

Case 2

V_i=5V, Assume V_o=-10V, V_+=-1V → V_+-V_-=-1-5=-6 V → V_o=-10V consistent!

Inverting Schmitt Trigger





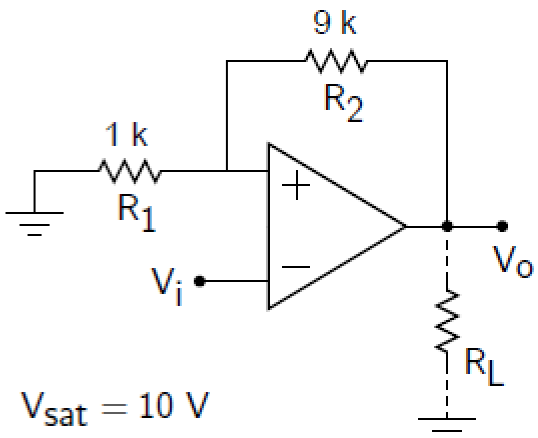
For decreasing values of V_i, V_o=-10V and V_+=-1V till V_i goes below -1V

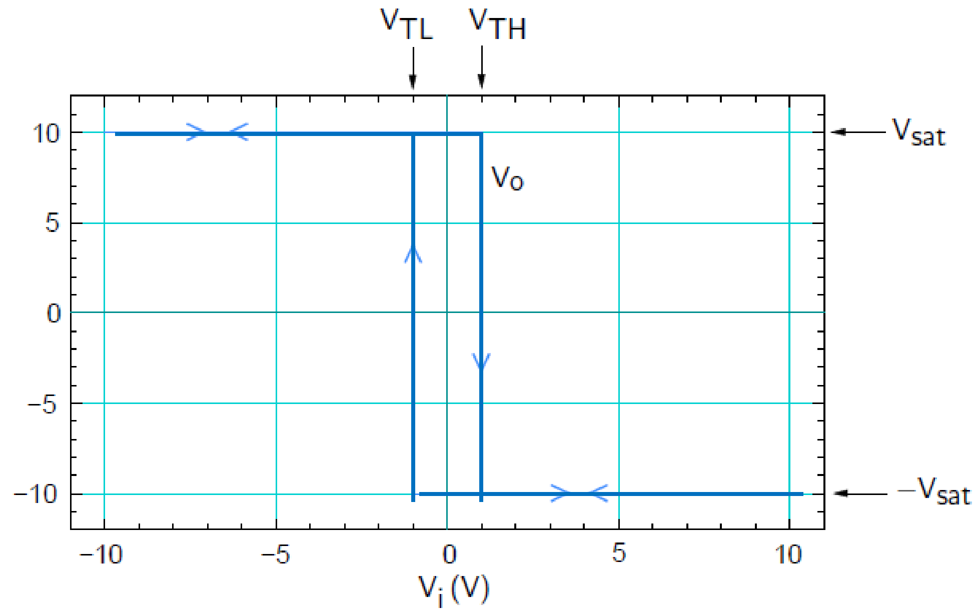
When V_i=V_-<V_+=-1V V_o=+V_{sat}=10V V_+ becomes +1V

Decreasing V_i further does not change V_o, since V_+-V_-=1-V_i>0

Coming back (increasing V_i) threshold voltage for flipping is +1V.

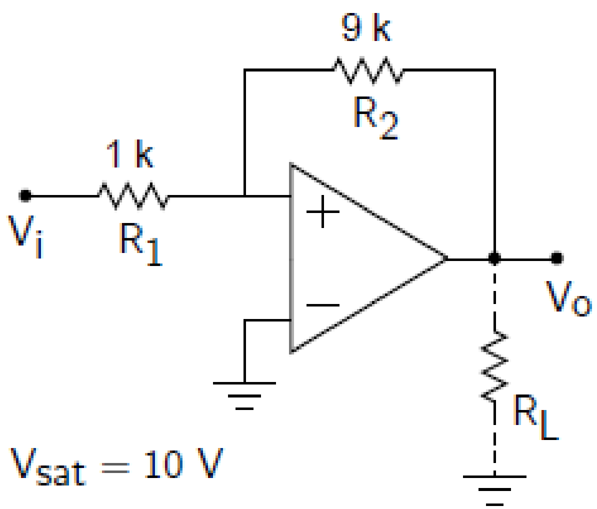
Inverting Schmitt trigger

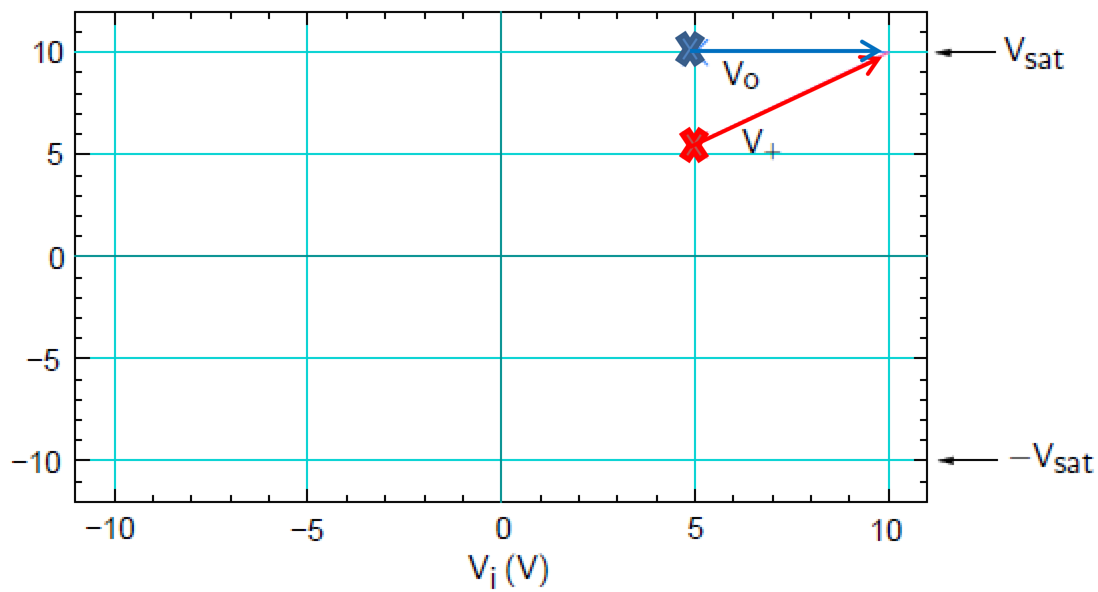




- The threshold (tripping) voltages V_{TL} and V_{TH} are $\pm\left(\dfrac{R_1}{R_1+R_2}\right)V_{sat}$
- Tripping point depends on position on V_o axis → MEMORY!
- $\Delta V_T = V_{TH} - V_{TL}$ is called hysteresis width

Non-inverting Schmitt Trigger





V_o is either +10V ($V_+ > V_-$) or -10V ($V_+ < V_-$) because of positive feedback

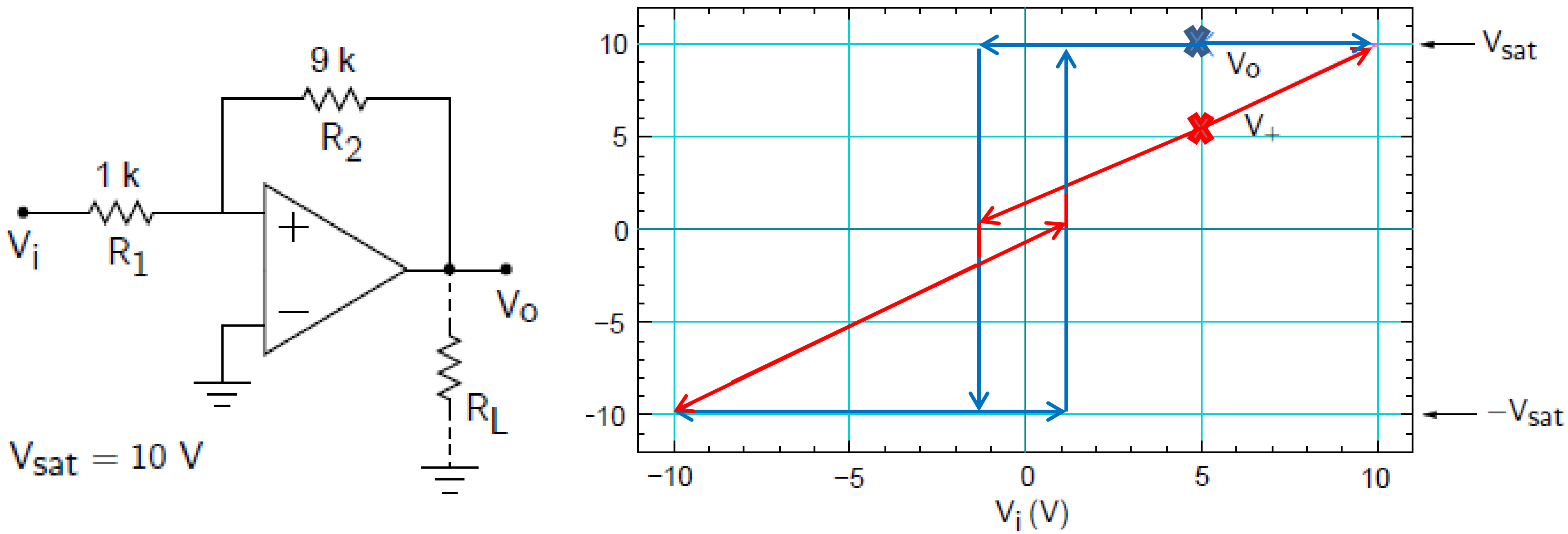
Case 1

V_i=5V, Assume V_o=-10V, $V_+=(R_2/R_1+R_2)V_i+V_o(R_1/R_1+R_2)$=3.5V → V_+-V_-=3.5-0=3.5 V → V_o=-10V Inconsistent!

Case 2

V_i=5V, Assume V_o=+10V, V_+=5.5V → V_+-V_-=5.5-0=5.5 V → V_o=+10V consistent!

Non-inverting Schmitt Trigger



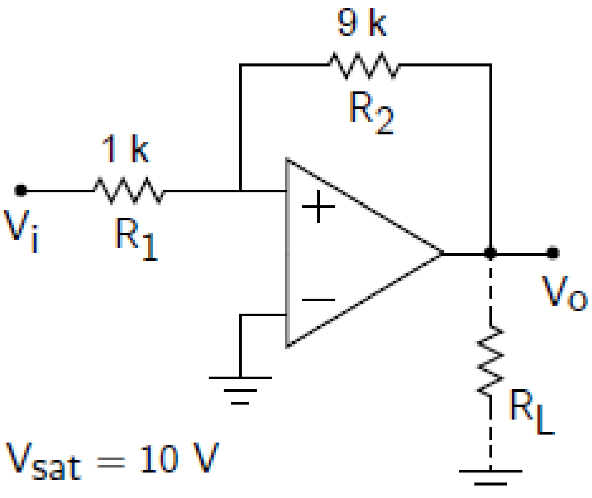
$$V_+ = \frac{R_2}{R_1+R_2}V_i + \frac{R_1}{R_1+R_2}V_o = \frac{9}{10}V_i + \frac{1}{10}V_{sat}$$

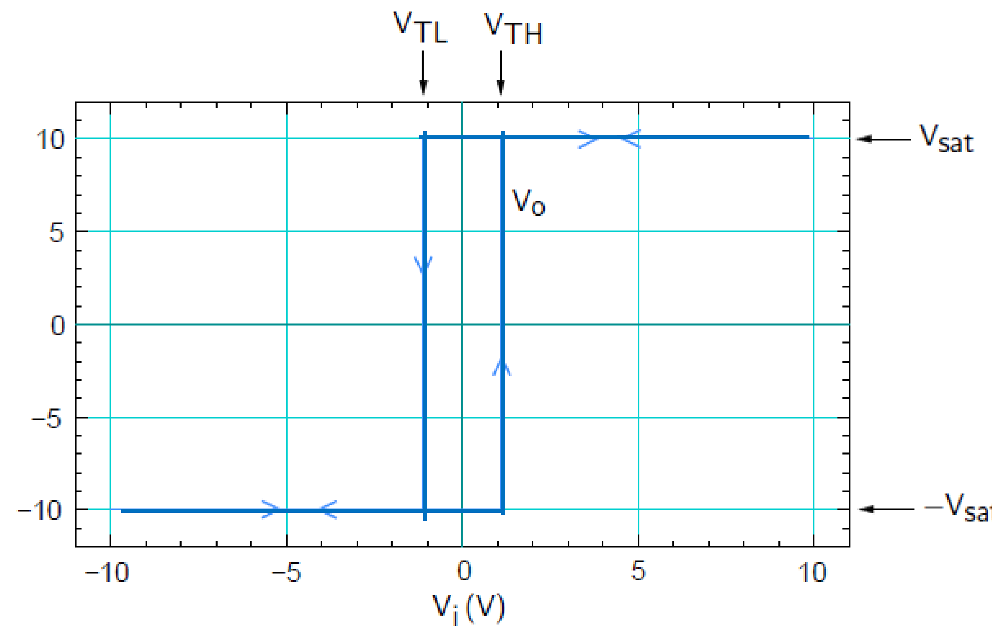
As V_i decreases and till $V_+>0$ $V_o=V_{sat}$
For $V_+=0V$, $V_i=-(R_1/R_2)V_{sat}=-1.11$ V, $V_o=-V_{sat}$

$$V_+ = \frac{R_2}{R_1+R_2}V_i + \frac{R_1}{R_1+R_2}V_o = \frac{9}{10}V_i - \frac{1}{10}V_{sat}$$

Further reduction of V_i does not change $V_o=-V_{sat}$, since $V_+<0$
V_o again flips to $+V_{sat}$ when $V_+=0V$, when $V_i=1.11V$

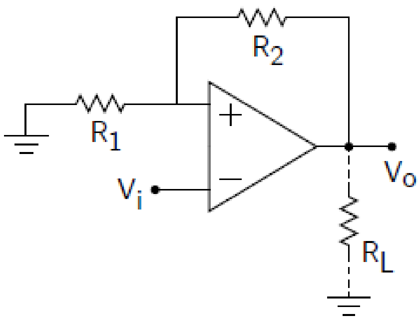
Non-inverting Schmitt Trigger

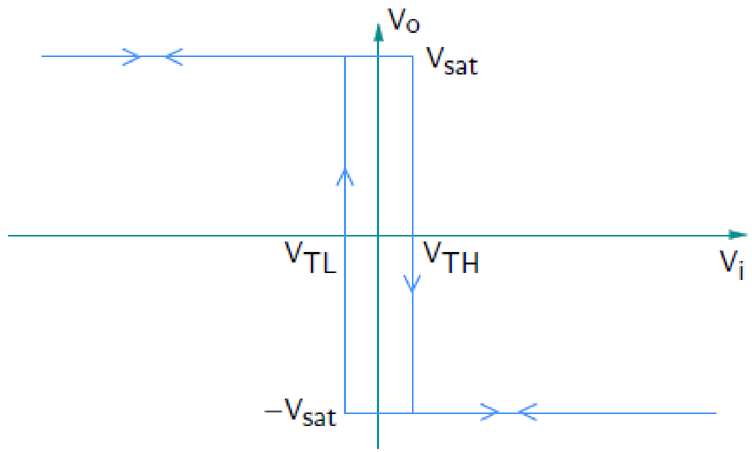


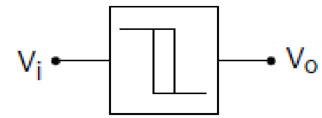


- The threshold (tripping) voltages V_{TL} and V_{TH} are $\pm\left(\frac{R_1}{R_2}\right)V_{sat}$
- Tripping point depends on position on V_o axis → MEMORY!
- $\Delta V_T = V_{TH} - V_{TL}$ is called hysteresis width

Schmitt Triggers

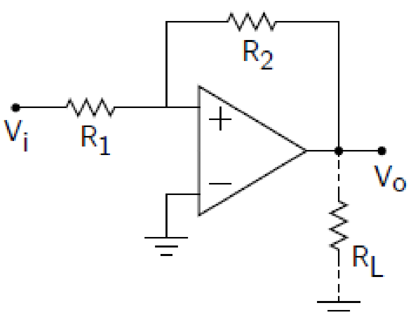


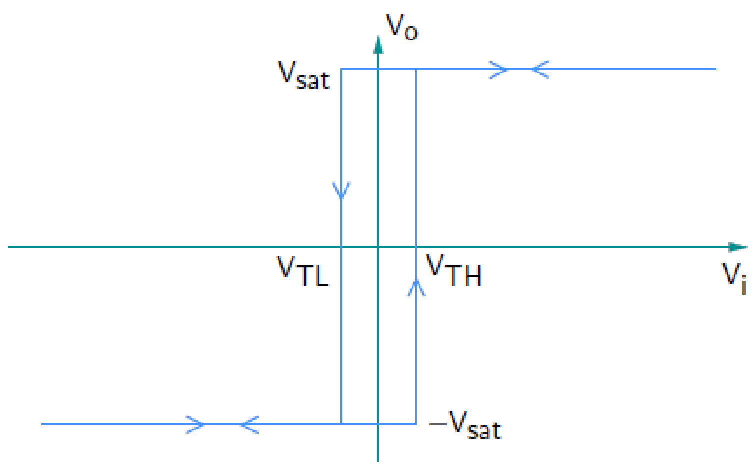


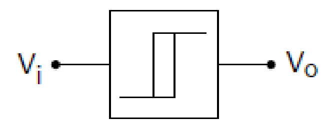


Inverting

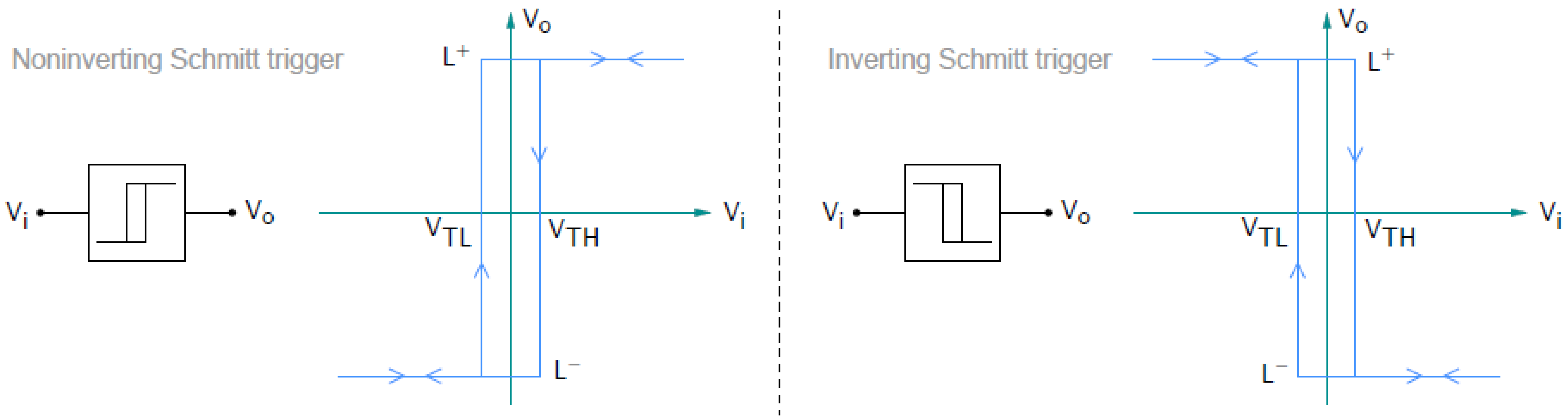
Noninverting





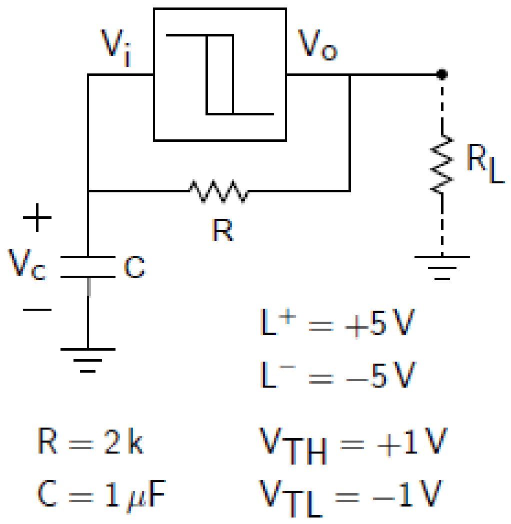


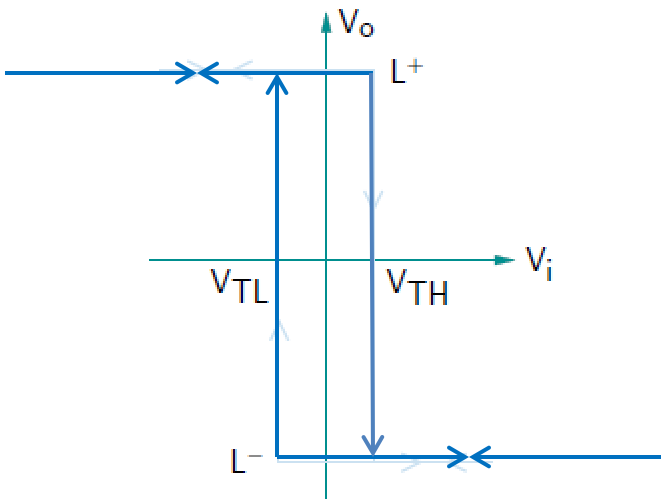
Schmitt Trigger: Application→ Astable multivibrator



- With a suitable RC circuit, Schmitt trigger can be made to freely oscillate between L^+ and L^-
  - Called an "astable multivibrator" (oscillator, wave-form generator)
- Produces oscillations where the frequency is controlled by component values (f_{max}~10 kHz)
- Other vibrator circuits
  - Monoshot (Timer)
  - Bistable (Flip-flop)

Astable MV





At t=0, V_o=L^+ and V_c=0

Capacitor starts charging towards L^+
As V_c (=V_i) crosses V_{TH}, V_o flips to L^-

Capacitor starts discharging towards L^-
As V_c(=V_i) crosses V_{TL}, V_o flips to L^+

Circuit oscillates on its own.

Also called a "relaxation oscillator".