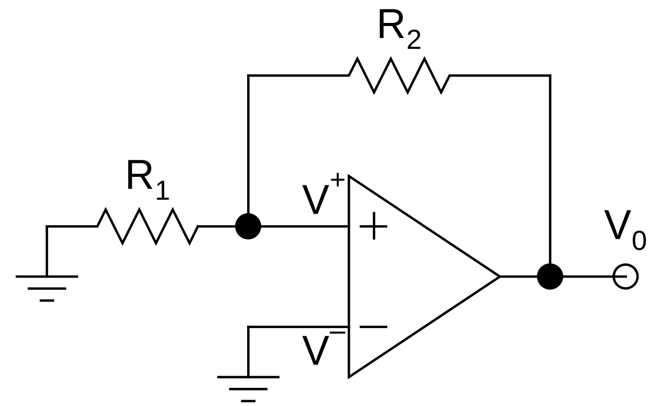
- **Closed-Loop**: ***Positive Feedback***:
  - Connection between output and **non-inverting** terminal of the OA
  - Analysis technique for such circuits needs special care and attention:
    - **Concept of Virtual Ground and Summing Point Constraint can't be applied anymore**
  - **Applications**:
    - ***Schmitt Trigger***
    - ***Waveform Generation*** (***Square-*** and ***Triangular-Wave***)
    - ***Oscillators*** (***Wein-Bridge*** and ***Phase-Shift***)

***Concept of Positive Feedback*: Metastability:**



* Circuit looks remarkably similar to an inverting amplifier, but it's not, since the output is fed back to the ***non-inverting*** terminal
* Also, the **circuit doesn't have any input signal source**
* The output V_0 should be ***zero***, if the OA were assumed to be ***ideal*** (i.e., ***without any offset voltage***)
* Now, suppose that the output V_0 picks up some ***positive noise signal***

* This would be fed back to the ***non-inverting*** terminal of the OA through the voltage divider action of R_1 and R_2
* With the ***inverting terminal grounded***, this would ***increase the differential input voltage*** of the OA, which would result in a ***greater output***
* This would cause ***more fraction*** of the output fed back to the input, causing an ***even greater output***
* This process ***repeats***, and the output ***grows*** to be eventually ***limited*** by the ***saturation voltage*** V_{SAT^+}

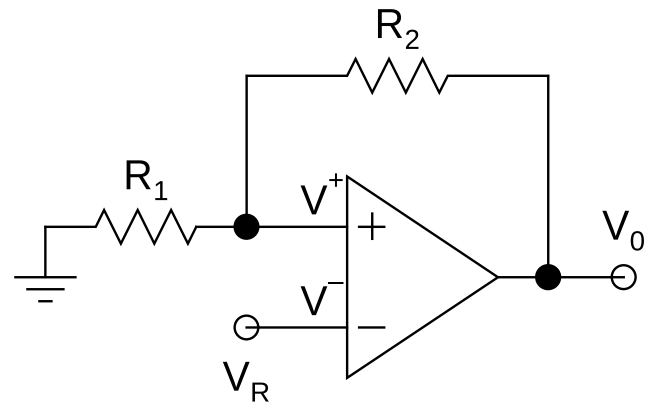
* The process described is called ***signal regeneration***
* Similarly, if V_0 picked up a ***negative noise signal***, then the output would eventually ***saturate*** to V_{SAT^-}
* Once this happens, it is ***impossible*** to bring the system out of it, i.e., $\boldsymbol{V_0}$ ***would get stuck at*** $\boldsymbol{\pm V_{SAT}}$, **unless the power supply to the OA is turned off**!
* Thus, the ***presumption*** that the output of the circuit would be ***zero*** is **wrong**, since the chance of the output ***picking up noise signals***, and thus the output eventually ***saturating*** to $\pm V_{SAT}$ is almost a cinch

* Hence, such a state (i.e., $\boldsymbol{V_0 = 0}$) is known as a ***metastable state*** for the circuit
* ***Metastable***: A state of precarious stability
* The circuit is known as a **bistable** circuit, since the output can stay at either of $\pm V_{SAT}$ for an indefinite time, until and unless it's ***forced*** to switch state
* This ***forced transition*** is known as ***external triggering***
* The circuit shown has ***no such provision***
* A circuit, known as **Schmitt Trigger**, has this ***triggering mechanism*** built-in

Schmitt Trigger:

* Named after the inventor ***Otto H. Schmitt*** (in 1934)

* Note the signal V_R applied at the ***inverting*** input and the ***positive feedback*** (output fed back to the ***non-inverting*** terminal)



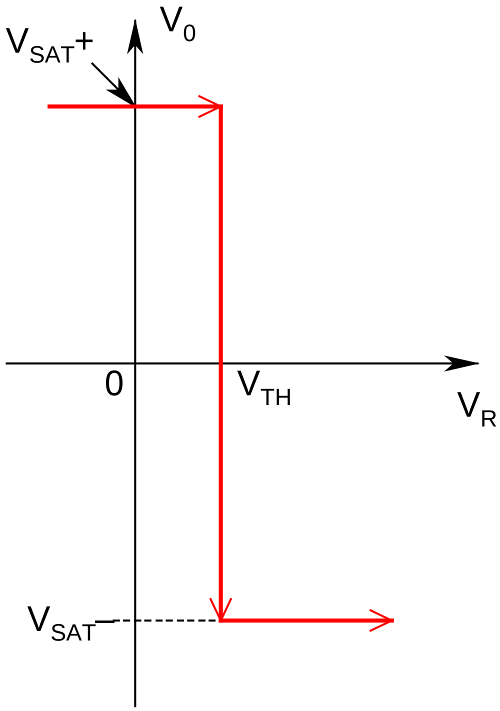
$\Rightarrow$ V_R is the ***trigger signal*** that creates change of state

* Assume ***negative*** $\boldsymbol{V_R}$ $\Rightarrow$ V_0 would ***saturate*** to V_{SAT^+}

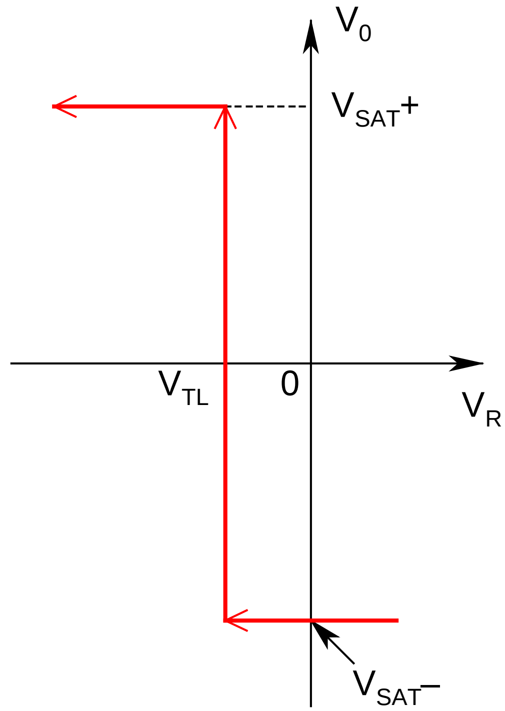
$$\Rightarrow V^+ = f'V_{SAT^+}, \text{ where } f' = \textbf{\textit{feedback factor}} = \frac{R_1}{R_1 + R_2}$$

* Now, if V_R is ***increased***, i.e., it's made ***less negative***, then ***zero***, and then ***positive***, output can't change state till V^- becomes ***greater*** than V^+, which is at $f V_{SAT^+}$
* Once this happens, the output will immediately ***toggle*** to V_{SAT^-}, and remain there till V_R is reduced ***below*** $f V_{SAT^-}$ (note that $V^+ = f V_{SAT^-}$ under this condition)
* Thus, the circuit has ***two stable states*** at $\pm V_{SAT}$, and is hence known as a **bistable circuit**
* For a ***change of state*** at the output, ***appropriate trigger signal*** (V_R) needs to be applied at the input

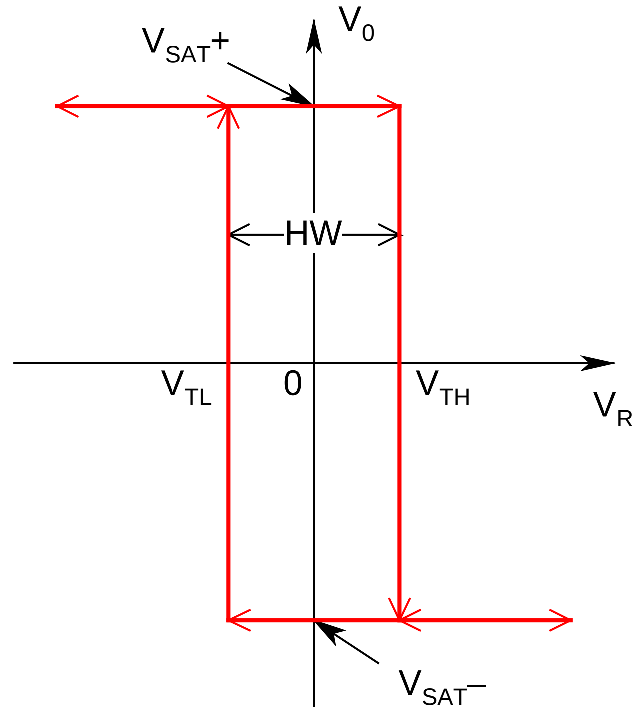
* The value of V_R at which this change of state takes place is known as the ***threshold voltage*** of the **Schmitt Trigger**
* The ***upper*** one is known as **threshold high** (V_{TH}) and is given by $f V_{SAT^+}$, while the ***lower*** one is known as **threshold low** (V_{TL}) and is given by $f V_{SAT^-}$
* Note that for values of V_R ***in between*** V_{TL} and V_{TH}, the output is ***indeterminate*** ($\because$ it can be ***either*** of $\pm V_{SAT}$), and depends on ***direction of change*** of V_R
* $\left(V_{TH} - V_{TL}\right)$ is known as the **Hysteresis Width** (HW)



V_R Increasing



V_R Decreasing



Overall VTC

* The region bound by HW is known as the **dead zone** or **forbidden zone**

* Note for $V_R > V_{TH}$, the output remains at V_{SAT^-}, while for $V_R < V_{TL}$, the output remains at V_{SAT^+}

  $\Rightarrow$ Circuit known as **Inverting Schmitt Trigger**

* Note that the ***hysteresis characteristic*** is absolutely ***symmetric around zero***, i.e., $|V_{TL}| = V_{TH}$, since $|V_{SAT^-}| = V_{SAT^+}$, and f' is a constant

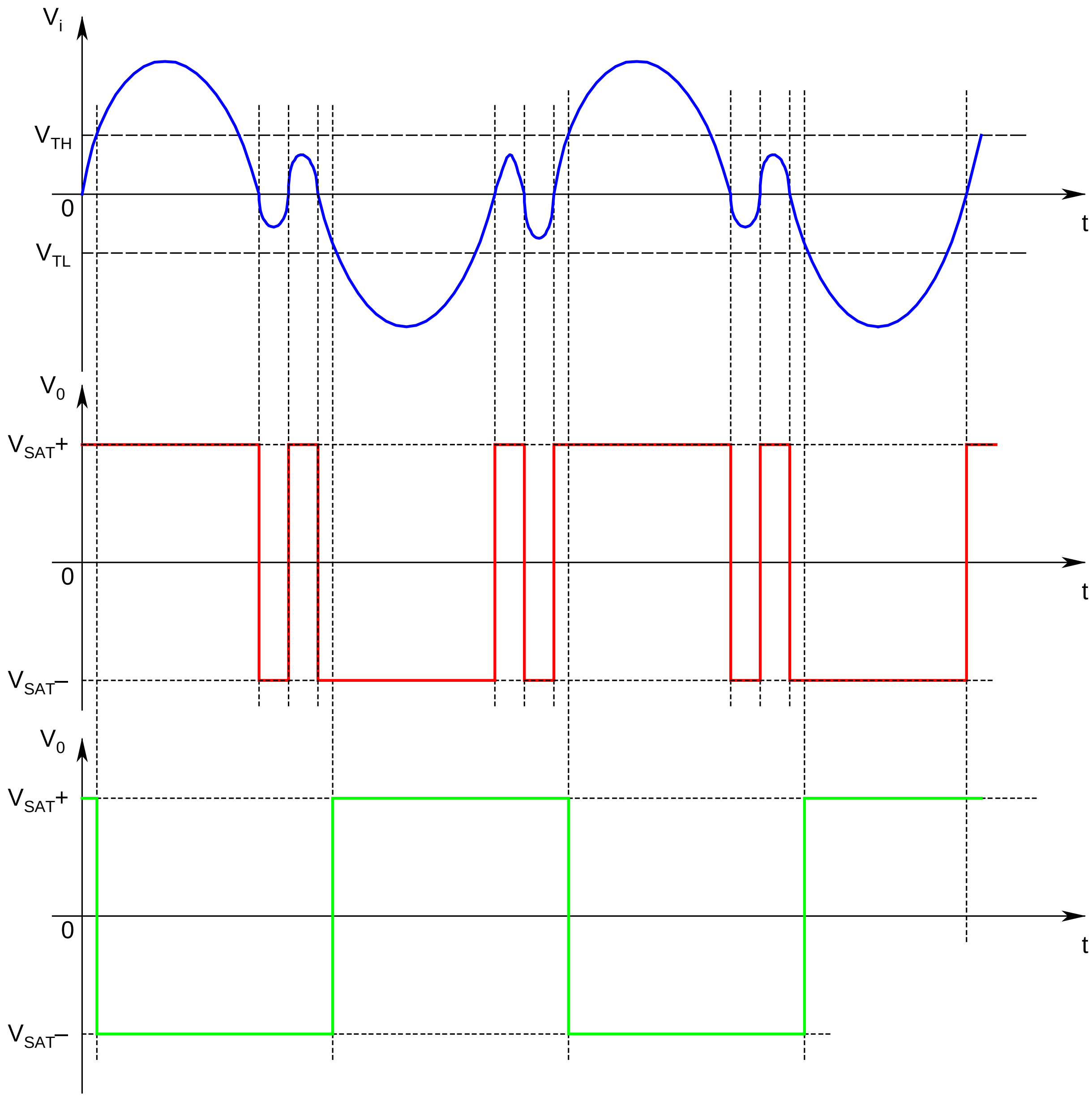
* However, it is **not necessary** for a Schmitt Trigger to be always symmetric: there are ways to make it ***asymmetric***

* Since the ***direction of change*** of V_R has a profound impact on the outcome of the circuit, hence, this type of circuits is also known as ***directional circuit***
* Note that once the circuit has reached one of the ***stable states***, V_R can be safely ***grounded***, since it has ***no impact*** on the circuit any more
* ***For example***, if V_R becomes greater than V_{TH}, thus causing a change of state at the output from V_{SAT^+} to V_{SAT^-}, then the only way the output can be switched back to V_{SAT^+} is by reducing V_R below V_{TL}

* Thus, ***grounding*** V_R would have absolutely ***no effect*** on the circuit once a ***transition*** has been achieved
* Therefore, these circuits are considered to have a ***memory effect***, i.e., by observing the ***output*** at any given instant of time, the ***last input*** applied to the circuit can be easily assessed
* Also, for values of V_R ***between*** V_{TL} and V_{TH}, the output could ***either*** be V_{SAT^+} or V_{SAT^-}, which would depend on the ***last input signal*** V_R that caused the ***transition*** – again it is a ***memory action***

Schmitt Trigger as an Effective Noise Suppressor:

* ***Recall***: A ***comparator*** with $V_R = 0$ acts as a ***zero-crossing detector***
  - ⇒ As soon as the input ***crosses zero***, the output ***changes state***
  - ⇒ Thus, if there is ***noise*** present during the ***zero crossings*** of the input, then an absolutely ***unusable*** output results
* Now, if the same signal is applied in place of V_R to a ***Schmitt Trigger***, then the output will ***change state*** only when the signal ***crosses*** V_{TH} or V_{TL}



Input signal with noisy zero crossings

Output obtained from a non-inverting comparator with $V_R = 0$: Totally unusable with lots of undesirable spikes

Output obtained from an inverting Schmitt Trigger: Absolutely clean

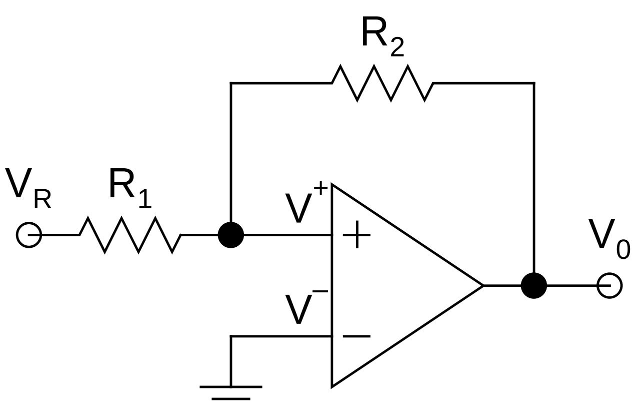
Non-Inverting Schmitt Trigger:

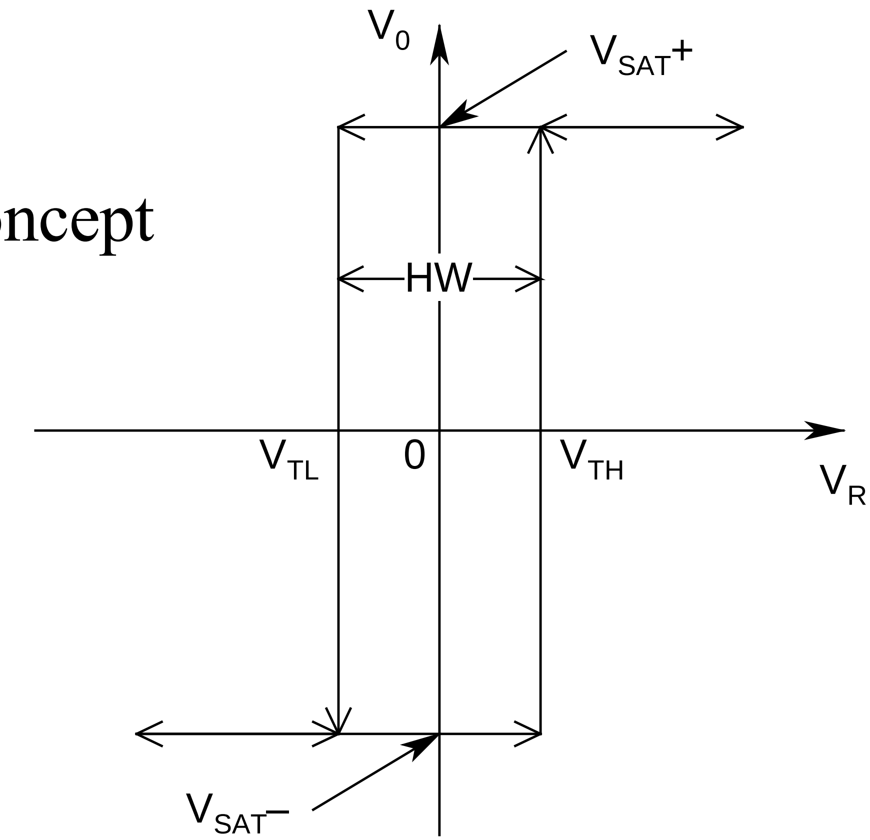
* Using ***superposition***:

$$V^+ = \frac{R_2}{R_1 + R_2} V_R + \frac{R_1}{R_1 + R_2} V_0 \quad (1)$$

* Note that $V^- = 0$ (ground)

* ***Caution***: ***Virtual Ground*** concept cannot be used





* Due to ***positive feedback***, the output V_0 will be at V_{SAT^+} for $V^+ > V^-$, and at V_{SAT^-} for $V^- > V^+$

* Now, with $V^- = 0$, if V_0 is at V_{SAT^+}, then ***no positive value*** of V_R can change the state of the output

$\Rightarrow$ To switch V_0 to V_{SAT^-}, V^+ must be ***pulled below ground*** (which is the potential V^-), and from (1), it would be possible only if V_R goes below $-\left(R_1 / R_2\right)V_{SAT^+}$

$\Rightarrow$ This corresponds to the ***threshold low*** (V_{TL}) of the circuit

* Similarly, when V_0 is at V_{SAT^-}, ***no negative value*** of V_R can change the state of the output

$\Rightarrow$ To cause a change in the state of the output under this condition, V_R must be ***more positive*** than $-\left(R_1 / R_2\right)V_{SAT^-}$ (***Note***: V_{SAT^-} is ***negative***)

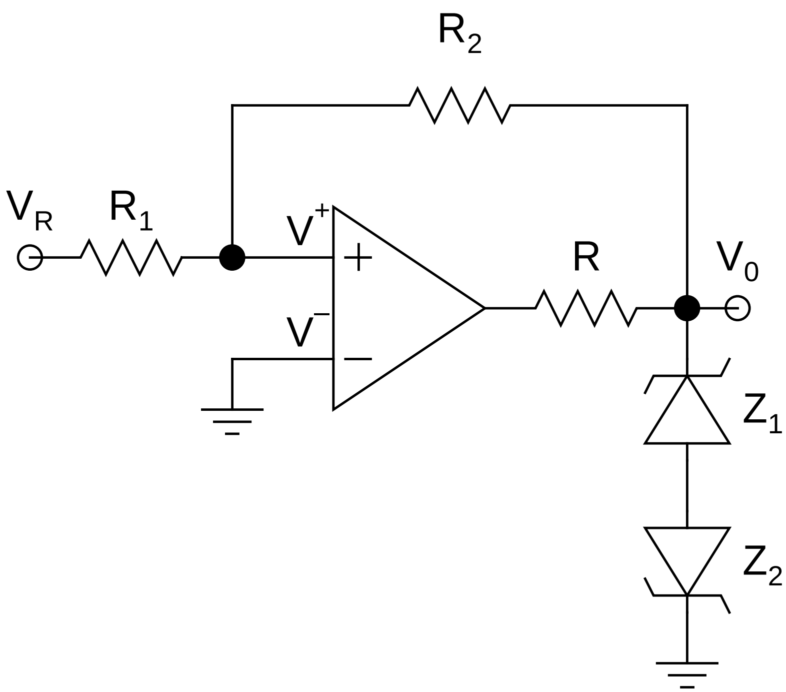
$\Rightarrow$ This corresponds to the ***threshold high*** (V_{TH}) of the circuit

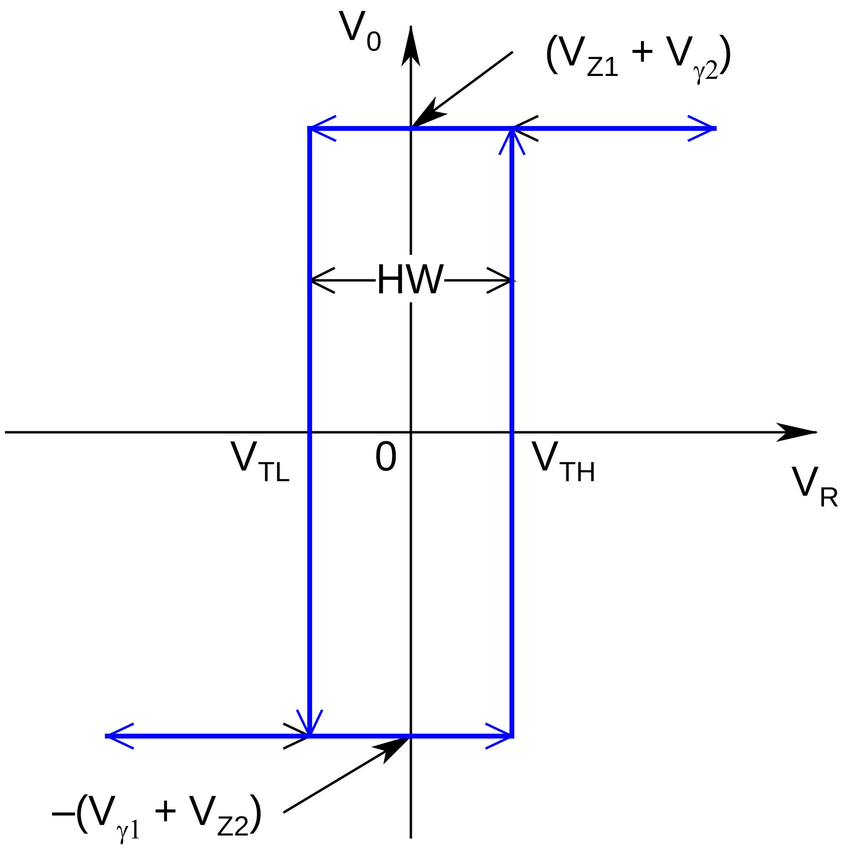
* Thus, $V_{TH} = -f'V_{SAT^-}$, $V_{TL} = -f'V_{SAT^+}$, $f' = R_1/R_2$, and $HW = V_{TH} - V_{TL}$

* From the VTC, the ***non-inverting*** behavior is obvious
* Also, the hysteresis characteristic is ***symmetric*** around zero, however, as mentioned before, **it need not be**
* Simplest way to make the hyesteresis characteristic ***asymmetric*** is to attach a ***reference voltage*** V_I to the inverting terminal of the OA

  $\Rightarrow$ By properly choosing the ***sign*** and ***magnitude*** of V_I, the entire hystersis characteristic can be ***shifted*** either to ***first and fourth*** or to ***second and third*** quadrants

***Non-Inverting Schmitt Trigger With Output Clamp*:**





* By putting a ***Zener diode clamp*** (identify Z_1-Z_2 as a ***double-anode Zener***) at the output, V_0 can be made to swing between extremes ***other than the saturation voltages***

* $V_{0,max} = V_{Z1} + V_{\gamma 2}$ (Z_1 under ***breakdown***, Z_2 under ***forward bias***)

* $V_{0,min} = -\left(V_{Z2} + V_{\gamma 1}\right)$ (Z_2 under ***breakdown***, Z_1 under ***forward bias***)

* Quite useful circuit, with the output ***adjustable*** by a proper choice of the ***Zener breakdown voltages*** (it can even be made ***asymmetric***)

Waveform Generation:

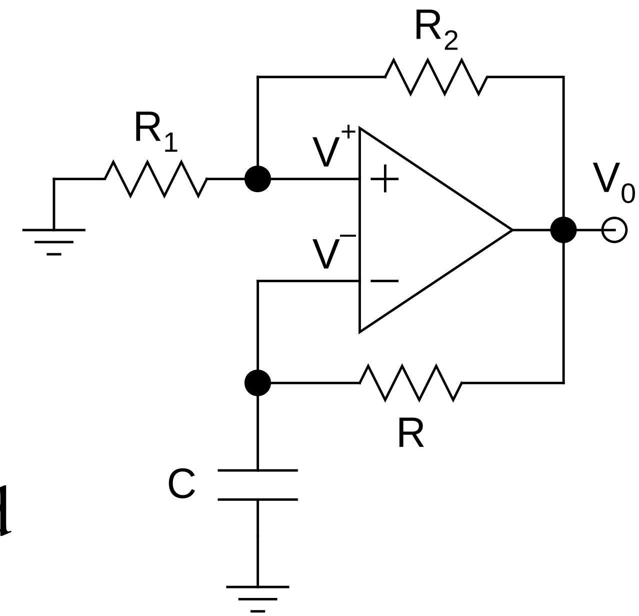
* A very important instrument in the lab is the ***Function Generator***
* Capable of producing ***sinuoidal***, ***triangular***, and ***square*** waveforms
* ***Sinusoidal waveforms*** are generated by ***Sinusoidal Oscillators***
* ***Triangular*** and ***Square waves*** can be generated effectively using ***Schmitt Triggers***

Square-Wave Generation:

* ***Recall***: A ***Schmitt trigger*** circuit is essentially ***bistable***, with both output states (V_{SAT^+} and V_{SAT^-}) being ***stable states***, and a ***triggering mechanism*** is needed for the ***change of state*** to take place
* Now, if somehow this ***triggering mechanism*** can be made ***automatic***, then the output waveform would keep on ***switching*** between its two extremes ***periodically***, without any further intervention

* Thus, under such a condition, none of the output states are ***stable states***, since they keep on ***changing*** with respect to time
* Such circuits are known as ***astable circuits***, since they do have ***two output states***, however, **none of them are stable states**
* An extremely popular ***square-wave generator*** circuit uses only three resistors and a capacitor, along with an OA

* ***Note***: The circuit has ***both*** positive and negative feedback



* Due to the ***positive feedback*** present in the circuit, irrespective of the ***negative feedback***, V_0 would be ***saturated*** at either V_{SAT^+} or V_{SAT^-}, depending on whether V^+ is greater than or less than V^-, respectively

* Assume that at time t = 0, the capacitor is completely discharged, i.e., $V^- = 0$

* Thus, for the result to be ***consistent***, V_0 must be at $V_{SAT^+} \Rightarrow V^+ = f'V_{SAT^+}$ (> 0), with $f' = R_1 / (R_1 + R_2)$
* Now, for $t > 0$, C would start to ***charge*** through R, V^- would ***rise***, attempting to reach its ***final*** maximum value of V_{SAT^+}
* However, ***this won't happen***, $\because$ as soon as V^- ***rises*** above V^+, which is at a constant potential of $f'V_{SAT^+}$, the output would ***change state*** to V_{SAT^-}
* ***Note***: $f'V_{SAT^+}$ is the ***threshold high*** (V_{TH}) of this circuit
* Thus, V^+ would now become equal to $f'V_{SAT^-}$

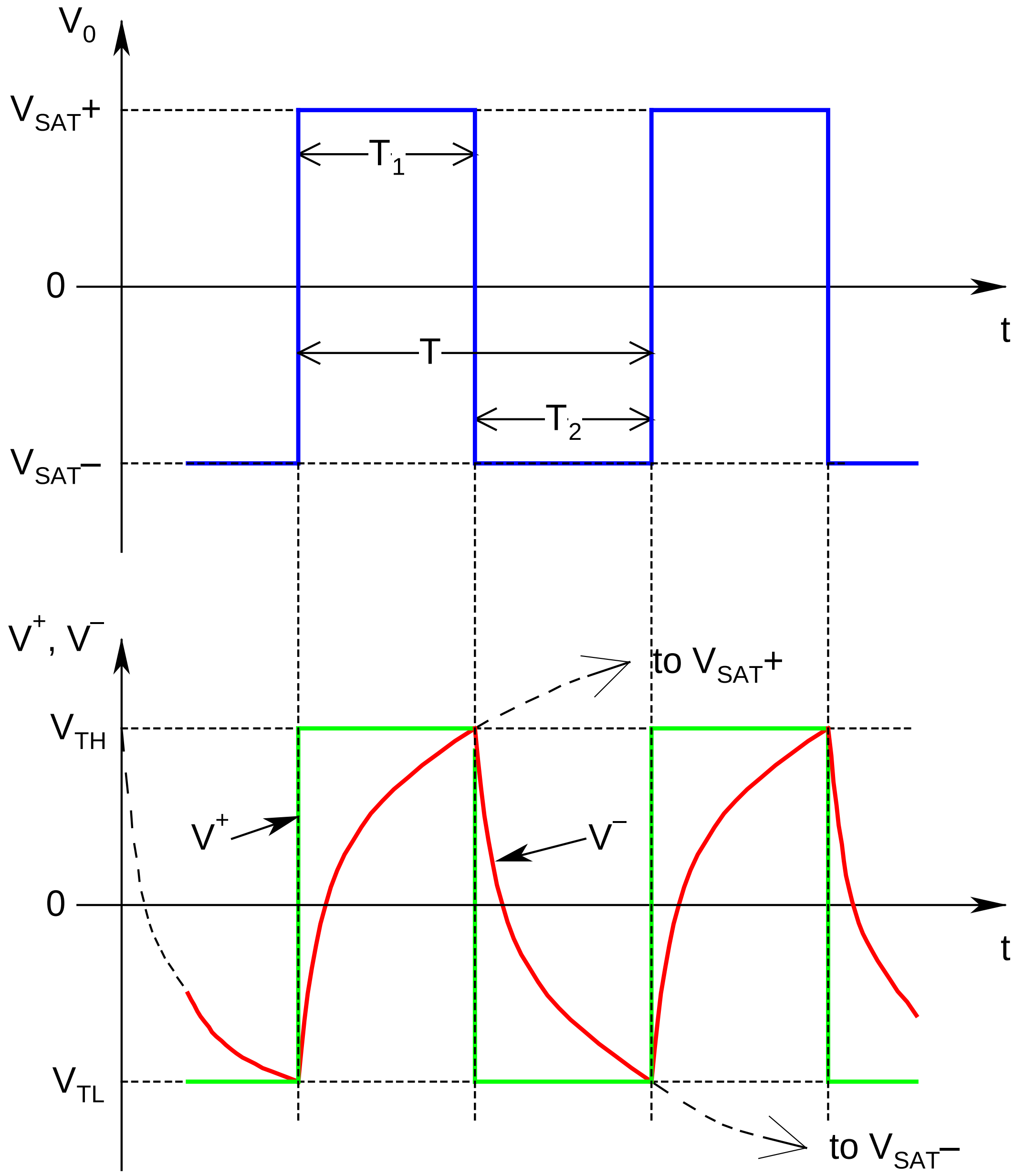
* The capacitor also would now start to ***discharge*** towards V_{SAT^-}

* Similar to the previous situation, it won't be able to ***discharge*** all the way down to V_{SAT^-}, since as soon as V^- would ***fall*** below $f'V_{SAT^-}$, the output would again ***toggle*** to V_{SAT^+}

* ***Note***: $f'V_{SAT^-}$ is the ***threshold low*** (V_{TL}) of the circuit

* These two processes of capacitor ***charging*** and ***discharging*** would continue ***ad infinitum*** and a ***square wave*** will be produced at the output, ranging between $\pm V_{SAT}$

* Note that the circuit does not need ***any source***: as soon as the ***power supply*** to the circuit is turned on, the ***oscillations*** would start, and a ***square wave*** will appear at the output
* Refer to the figure on the next page:
    - T_1: ***On*** (or ***High***) ***Time***
    - T_2: ***Off*** (or ***Low***) ***Time***
    - T ($= T_1 + T_2$): ***Time Period***
    - f ($= 1/T$): ***Frequency***
    - δ ($= T_1/T$): ***Duty Cycle***



V_0
$V_{SAT}+$
T_1
0
t
T
T_2
$V_{SAT}-$
V^+, V^-
to $V_{SAT}+$
V_{TH}
V^+
V^-
0
t
V_{TL}
to $V_{SAT}-$

Evaluation of T_1 and T_2:

* Use the familiar expression for ***capacitor charging***/ ***discharging***:

$$v_c(t) = v_c(\infty) + \left[v_c(0) - v_c(\infty)\right]\exp(-t/\tau)$$

* Note that the ***time constant*** $\tau = RC$

* ***For T_1***: $v_c(0) = V_{TL}$, $v_c(\infty) = V_{SAT^+}$, and $v_c(T_1) = V_{TH}$

$$\Rightarrow\ T_1 = \tau \ln\left[\frac{1 - f' V_{SAT^-}/V_{SAT^+}}{1 - f'}\right] = \tau \ln\left[\frac{1 + f'}{1 - f'}\right]$$

where we have assumed that $V_{SAT^+} = -V_{SAT^-}$

* ***For T₂***: $v_c(0) = V_{TH}$, $v_c(\infty) = V_{SAT^-}$, and $v_c(T_2) = V_{TL}$

$$\Rightarrow\ T_2 = \tau \ln\left[\frac{1 - f' V_{SAT^+} / V_{SAT^-}}{1 - f'}\right] = \tau \ln\left[\frac{1+f'}{1-f'}\right]$$

where again we have assumed that $V_{SAT^+} = -V_{SAT^-}$

* Note that for ***symmetric*** saturation voltages, the on and off times are same, resulting in a ***50%*** duty cycle square wave

* ***Frequency***:

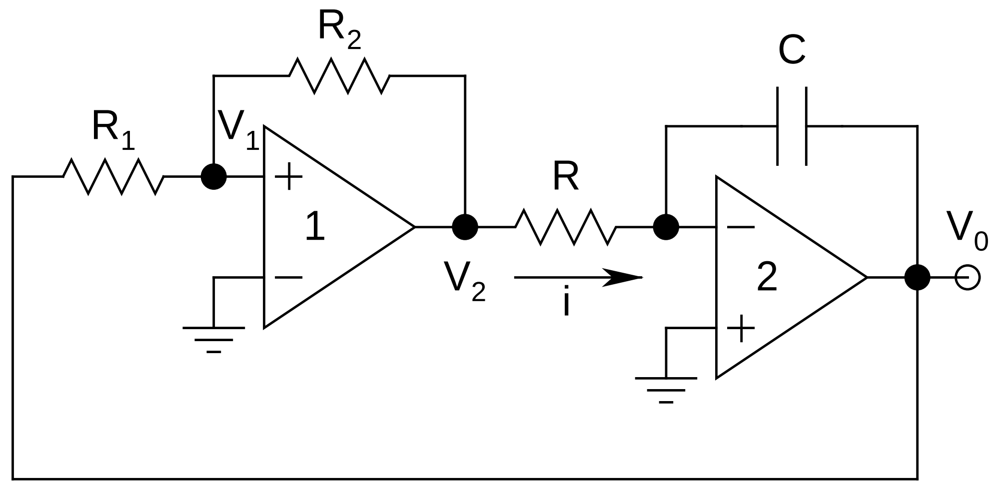
$$f = \frac{1}{T} = \frac{1}{T_1 + T_2} = \frac{1}{2T_1} = \left(2\tau \ln\left[\frac{1+f'}{1-f'}\right]\right)^{-1}$$

* Note that the output swings between $\pm V_{SAT}$
* In order to obtain other swings, a ***double-anode Zener*** can be connected at the output
* Also, the ***breakdown voltages*** of the Zeners can be chosen to be ***unequal***, which would produce different values of ***positive and negative amplitudes***, as well as ***duty cycle*** other than 50%

  $\Rightarrow$ Significant ***waveshaping***
* ***Exercise***: Assume that the positive and negative saturation voltages are V_1 and $-V_2$, find T_1 and T_2

Triangular-Wave Generation:

* Note that with regard to the ***square-wave*** generator circuit, if τ is made ***very large***, and/or f' is made ***very small***, then the voltage waveform across the capacitor will be approximately ***linear***, since it will traverse only a ***very small part*** of the exponential characteristic $\Rightarrow$ ***Triangular-Wave Generation***
* However, there is a much simpler way to generate triangular waves, which is basically a ***non-inverting Schmitt Trigger*** (with ***symmetric*** values of V_{TL} and V_{TH}) followed by an ***integrator***



* Identify OA1 as a ***non-inverting Schmitt Trigger*** with symmetric threshold, and OA2 as an ***integrator***
* Due to ***positive feedback*** present in OA1, V_2 will always be either at V_{SAT^+} or V_{SAT^-}, depending on whether V_1 is greater than or less than zero, respectively

* Note also that OA2 is under ***negative feedback***

$\Rightarrow$ Concept of ***virtual ground*** can be applied, and the ***inverting terminal*** of OA2 is effectively ***ground***

* Assume that at some arbitrary time, the capacitor was completely discharged (i.e., $V_0 = 0$), and V_2 is at V_{SAT^+}
* This would push a ***constant current*** $i = V_{SAT^+}/R$ through R, which would flow through the capacitor as well
* Note that it is a case of ***constant current charging*** of a capacitor, which will lead to a ***linear*** change in voltage across it

* Thus, $dV_0/dt = -i/C = -V_{SAT^+}/(RC)$

$\Rightarrow$ V_0 ***decreases linearly*** with time, producing a ***ramp waveform***, with a slope of $-V_{SAT^+}/(RC)$

* Note that V_0 is fed back to the ***Schmitt trigger*** as its input, which has a ***threshold low*** $V_{TL} = -f'V_{SAT^+}$, with $f' = R_1/R_2$

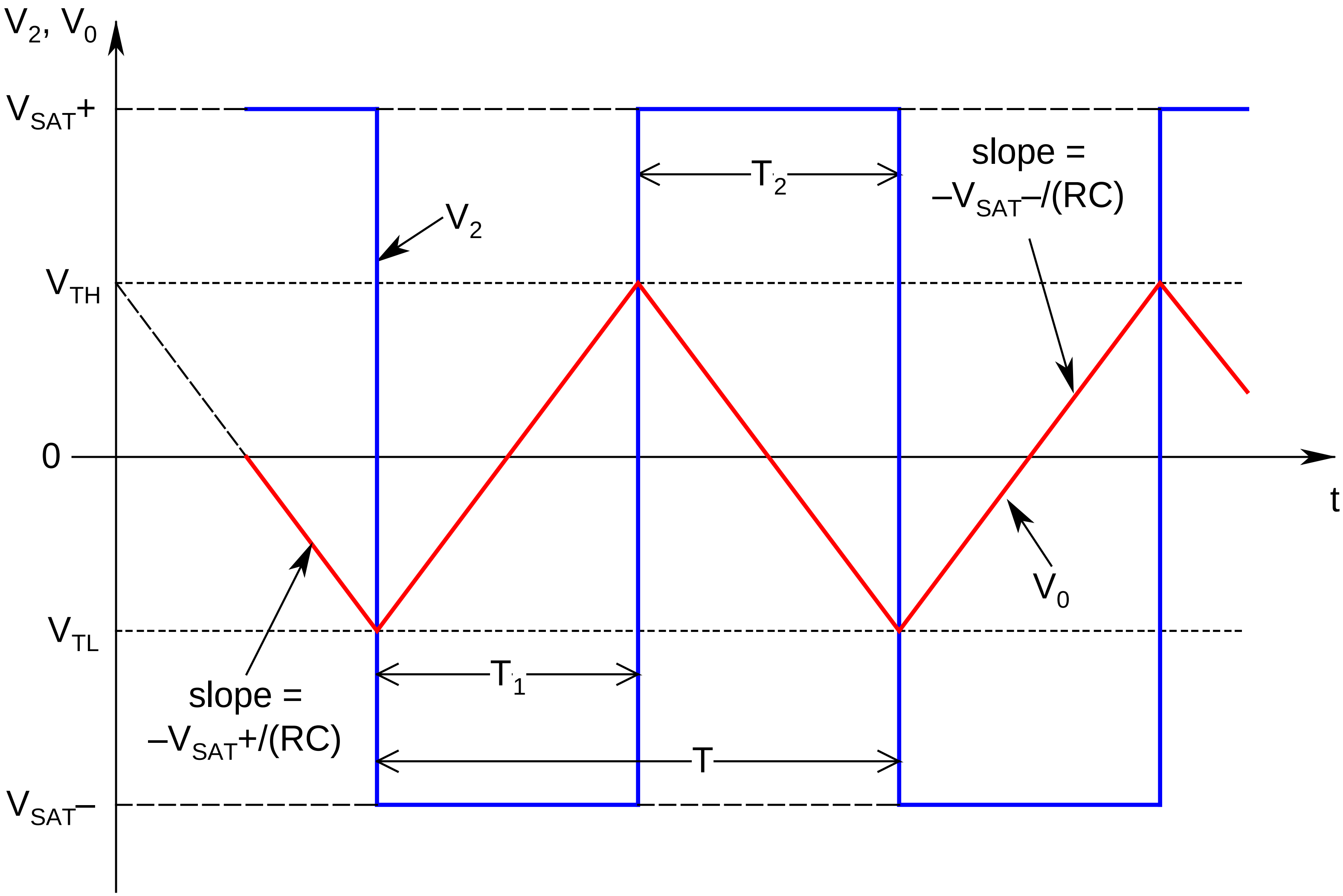
* $\therefore$ As soon as V_0 falls below V_{TL}, the ***Schmitt Trigger*** would get ***triggered***, and V_2 would ***toggle*** to V_{SAT^-}

* This would immediately ***change the sign*** of the current i, however, if the saturation voltages are ***symmetric***, then its ***magnitude*** would remain the ***same***

* Now, C would start to ***discharge*** with this constant current, and V_0 would increase ***linearly*** with time, with a slope of $-V_{SAT^-}/(RC)$

* It would rise all the way to the ***threshold high*** V_{TH} $(= -f V_{SAT^-})$, and again a ***change of state*** would take place, with V_2 ***swinging back*** to V_{SAT^+}

* This sequence of events would keep on ***repeating*** itself, and at the output, we would get a clear ***triangular*** waveform, swinging between V_{TL} and V_{TH}



V2, V0
VSAT+
VTH
0
VTL
VSAT–
t
V2
T2
slope =
–VSAT–/(RC)
V0
T1
slope =
–VSAT+/(RC)
T

* ***Note***: When $V_2 = V_{SAT^+}$, V_0 ***decreases linearly*** from V_{TH} to V_{TL} with a slope of $-V_{SAT^+}/(RC)$

* On the other hand, when $V_2 = V_{SAT^-}$, V_0 ***increases linearly*** from V_{TL} to V_{TH} with a slope of $-V_{SAT^-}/(RC)$

* Thus, ***positive ramp time duration***:

$$\frac{V_{TH} - V_{TL}}{T_1} = -\frac{V_{SAT^-}}{RC} \quad \Rightarrow \quad T_1 = RC \times \left(\frac{V_{TH} - V_{TL}}{-V_{SAT^-}} \right)$$

* Similarly, ***negative ramp time duration***:

$$\frac{V_{TL} - V_{TH}}{T_2} = -\frac{V_{SAT^+}}{RC} \quad \Rightarrow \quad T_2 = RC \times \left(\frac{V_{TH} - V_{TL}}{V_{SAT^+}} \right)$$

* ***Note***: For symmetric saturation voltages, a ***50%*** duty cycle triangular waveform results
* ***Time Period*** $T = T_1 + T_2$
* ***Oscillation Frequency*** $f = 1/T$
* Note that this circuit also ***does not need any source***
  - As soon as the ***power supply*** is turned on, the ***oscillations*** would start, and would continue ***ad infinitum*** till the ***power supply*** is turned off

Sinusoidal Oscillators:

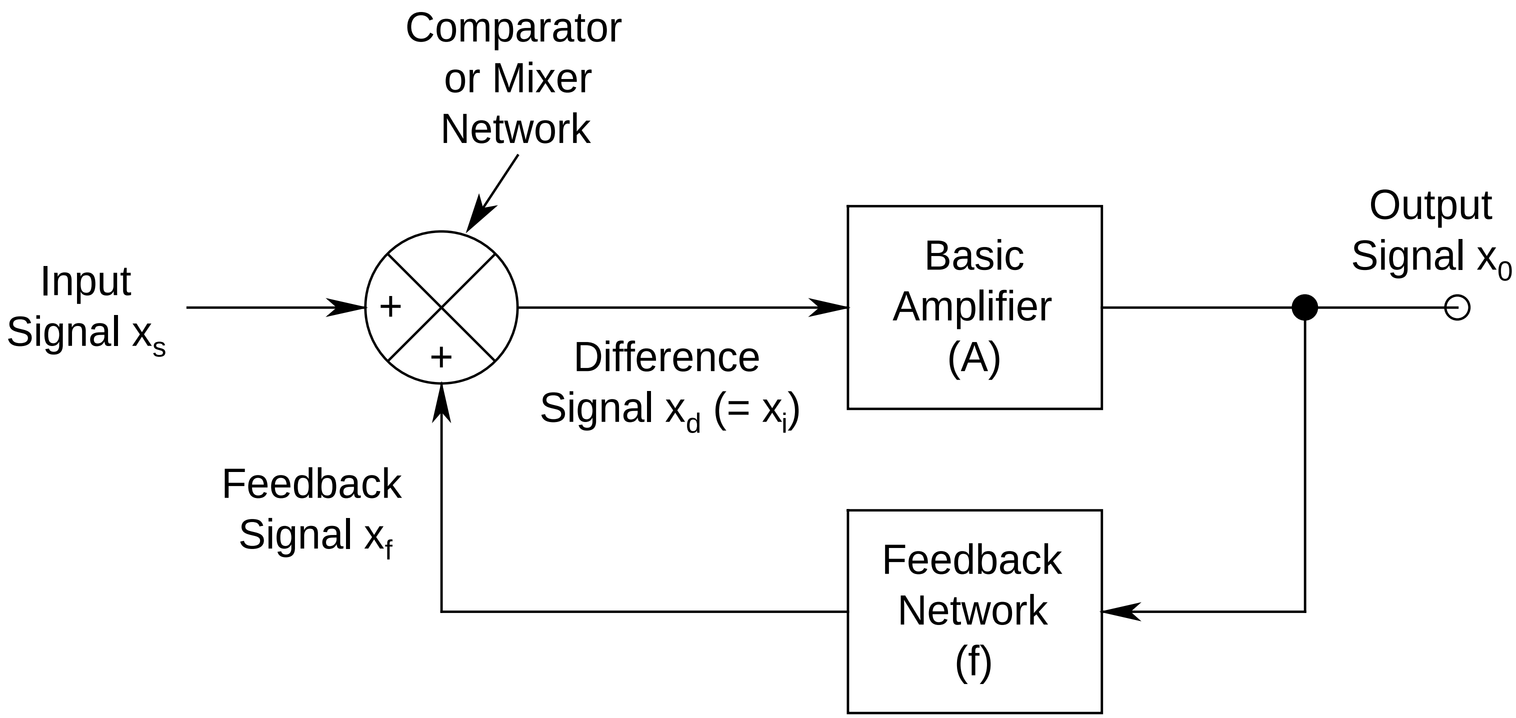
* ***Note***: The ***square- and triangular-wave generator circuits*** discussed earlier ***do not need any source***

- As soon as the ***power supply*** to the circuit is turned on, the ***oscillations*** start, and continue till the ***power supply*** is turned off
- These circuits are also known as ***oscillators***

* However, generating ***sinusoidal oscillations*** is a totally different ball game

* ***Sinusoidal Oscillators*** achieve this task

Concept of Oscillation : Positive Feedback:



A: Gain of the Basic Amplifier

f: Feedback Factor of the Feedback Network

$x_0 = Ax_i$, $x_f = fx_0$, $x_i = x_d = x_s + x_f$

* ***Gain with feedback***:

$$A_f = \frac{x_0}{x_s} = \frac{x_0}{x_i}\frac{x_i}{x_s} = A\frac{x_s + x_f}{x_s} = A\left(1 + \frac{x_f}{x_s}\right)$$

$$= A\left(1 + \frac{x_f}{x_0}\frac{x_0}{x_s}\right) = A\left(1 + fA_f\right)$$

$$\Rightarrow A_f = \frac{A}{1 - fA}$$

* An extremely interesting relation: **If $\mathbf{fA \rightarrow 1}$,**

$\mathbf{A_f \rightarrow \infty}$, and output appears without any input!

* This is what ***oscillators*** are all about: Make ***fA*** [known as the ***Loop Gain*** (L)] approach ***unity***!

Conditions for Oscillation : Barkhausen's Criteria:

* Note that both f and A are ***functions of frequency*** (ω)

* Therefore, there may be a ***certain frequency*** (ω_0), at which: $\mathbf{L(j\omega_0) = f(j\omega_0)A(j\omega_0) = 1}$

* Note that at this frequency (ω_0), the ***gain*** of the system would be ***infinite***, and the signal will ***self-regenerate***, without the need for any external input

* Thus, ω_0 becomes the ***oscillation frequency***

* **Also, since this oscillation happens only for a particular frequency (ω_0), hence, a pure sinusoidal waveform results**

* German physicist ***Heinrich Georg Barkhausen*** summarized this condition into two criteria, which came to be known as **Barkhausen's Criteria**:

- $\left|L\left(j\omega_0\right)\right| = 1$ and $\angle L\left(j\omega_0\right) = 0°$

* Barkhausen's Crietria in words:

- **For a positive feedback system to oscillate, the magnitude of the loop gain must at least be unity, and the total phase shift around the loop should be 0° (or 360°)**

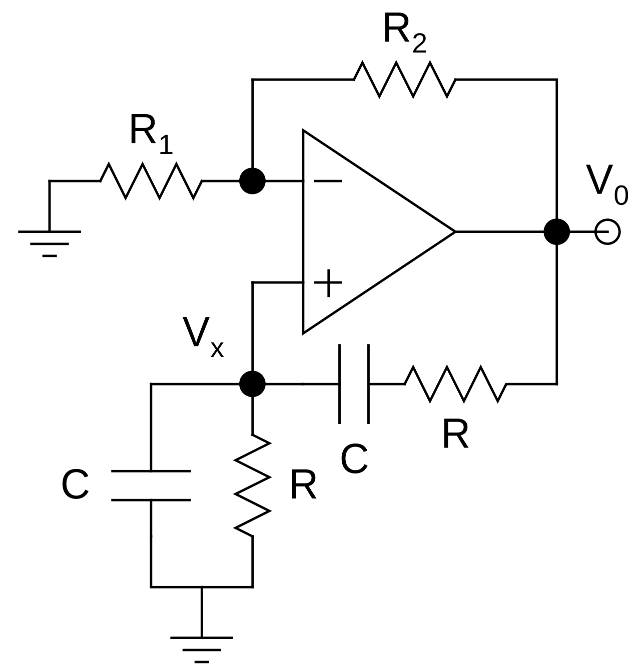
* Note that once the oscillations start, it cannot be stopped without turning the power supply off
* At ω_0, if $|\boldsymbol{L}| < \boldsymbol{1}$, then with each pass around the loop, the ***amplitude*** of the output signal would keep on ***decreasing***, and eventually, it will ***die down*** on its own $\Rightarrow$ **Under this condition, sustained sinusoidal oscillation is impossible to achieve**
* On the other hand, at ω_0, if $|\boldsymbol{L}| > \boldsymbol{1}$, then with each pass around the loop, the output signal would keep on ***increasing***, and will eventually get ***limited*** by the power supply voltages $\Rightarrow$ **Creates distorted output**

* $|L|$ ***exactly equal to unity is a risky proposition, since component values drift with age and temperature***

* Practical oscillator circuits operate with $|L|$ ***slightly greater than unity***, which lets the oscillations ***build up***, and then control it using ***automatic gain control*** (AGC) circuit

* Two very popular OA-based ***sinusoidal oscillators***:
   - **Wien-Bridge Oscillator**
   - **Phase-Shift Oscillator**

Wien-Brige Oscillator:



* Identify that the circuit has ***both positive and negative feedback***

* Identify that the ***non-inverting terminal*** with a potential of V_x is the ***positive feedback node***

* In the absence of the positive feedback, the circuit is simply a ***non-inverting amplifier***, with the gain (A) given by:

$$A = \frac{V_0}{V_x} = 1 + \frac{R_2}{R_1}$$

* ***Impedance*** of series RC circuit:

$$Z_1 = R + 1/(j\omega C)$$

* ***Impedance*** of parallel RC circuit:

$$Z_2 = R \,||\left(\frac{1}{j\omega C}\right) = \frac{R}{1 + j\omega RC}$$

* Thus, the ***feedback factor***:

$$f = \frac{V_x}{V_0} = \frac{Z_2}{Z_1 + Z_2} = \frac{1}{3 + j\left[\omega RC - 1/(\omega RC)\right]}$$

* Hence, the ***loop gain***:

$$L = fA = \frac{1 + R_2/R_1}{3 + j\left[\omega RC - 1/(\omega RC)\right]}$$

* ***For sustained sinusoidal oscillations, Barkhausen's criteria must be satisfied***

  $\Rightarrow$ **L must be a real number with zero phase angle**

  $\Rightarrow$ **The imaginary part of L must vanish**

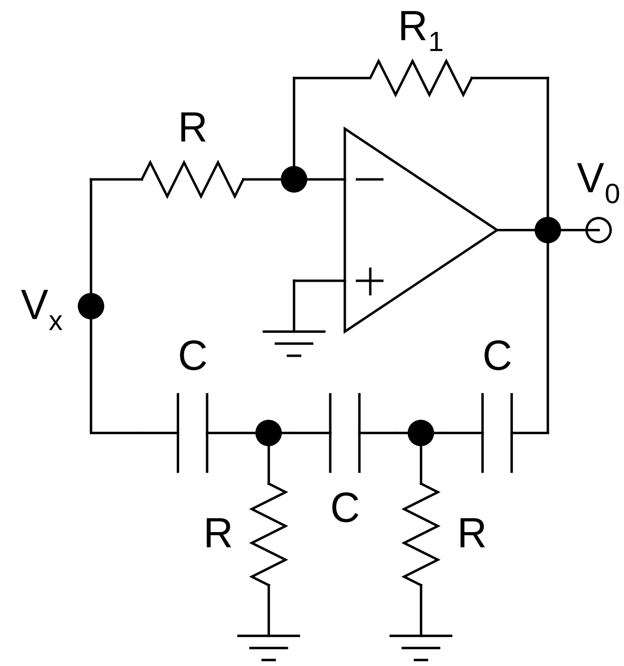
  $\Rightarrow$ Gives the ***oscillation frequency*** $\omega_0 = 1/(RC)$

* Also, $|\mathbf{L}|$ **must equal unity**

  $\Rightarrow R_2/R_1 = 2$

* Actually, R_2/R_1 is made ***slightly larger than 2*** to take care of the drift of component values with temperature and age $\Rightarrow$ ***Amplitude builds up and eventually gets controlled by the AGC circuit***

Phase-Shift Oscillator:



* Interesting to note that the circuit uses ***negative feedback*** with the non-inverting terminal grounded
* Thus, the circuit is simply an ***inverting amplifier***, with the gain (A) of the ***basic amplifier*** given by:

$$A = \frac{V_0}{V_x} = -\frac{R_1}{R}$$

* **Note the negative sign in front, which implies 180° phase shift between V_x and V_0**

* ***Note also that the feedback path consists of three RC-sections***

* **If each of these sections contribute a phase shift of 60°, then the total phase shift of the feedback path will be 180°, which would result in 0° phase shift for the loop gain (L)**

* The ***feedback factor*** (f):

$$f = \frac{V_x}{V_0} = \frac{(\omega RC)^3}{\omega RC\left[(\omega RC)^2 - 5\right] + j\left[1 - 6(\omega RC)^2\right]}$$

* **Now, for L to be real, the imaginary part of f must vanish at the oscillation frequency $\boldsymbol{\omega_0}$**

$$\Rightarrow \ \omega_0 = \frac{1}{RC\sqrt{6}}$$

* At ω_0, $f = -1/29$

* **This negative sign, implying a phase shift of 180°, coupled with the phase shift of 180° of A, makes the total phase of L to be 0°**

$\Rightarrow$ ***One part of Barkhausen's criteria satisfied***

* L at ω_0:

$$L = fA = \left(-\frac{1}{29}\right)\times\left(-\frac{R_1}{R}\right) = \frac{R_1}{29R}$$

which should be slightly larger than unity

* Thus, **R_1 should be made slightly larger than 29R**
* This would ***initiate the oscillations***, which will ***tend to blow up***

  $\Rightarrow$ **Amplitude needs to be controlled by AGC circuit**
* Typical ***oscillation frequency*** for both these oscillators ~ ***tens of Hz to hundreds of kHz***