# Signal generators

# Source of these slides

The following texts have also been used to prepare this lecture:


- A. S. Sedra, and K. C. Smith, Microelectronic Circuits. Oxford, 2011
- R.C. Jaeger, T.N. Blalock, Microelettronica. McGraw-Hill
- Thomas L. Floyd, Electronic Devices. --: Pearson Prentice Hall, 2005
- P. Horowitz and W. Hill, The art of electronics. --: Cambrdige University Press, 2015
- Neil Storey, Electronics, A system approach. --: Pearson Prentice Hall, 2006
- V. K. Mehta, Principles of Electronics

# Signal generators

**Goal:** to learn the operating principles of various circuits for signal generation based on op-amps and BJTs

**Motivation:** It is often necessary to design circuits for generating signals (square waves, triangular waves, sine waves).

Here we will analyze some examples. We will describe some basic circuits (based on op-amps and BJTs) for signal generation

**Lab experiment** → Wavefunction generator based on op-amps and BJTs

# Motivation

In the design of electronic systems, signals having prescribed standard waveforms are frequently needed (sine, rectangular, triangular, pulse, …)

Such signals are required

- **In computer and control systems** as clocks (for timing)
- **In communication systems**, to carry information
- **In test and measurement systems**, for testing and characterizing electronic devices and circuits

There are different approaches to generate sinusoids:

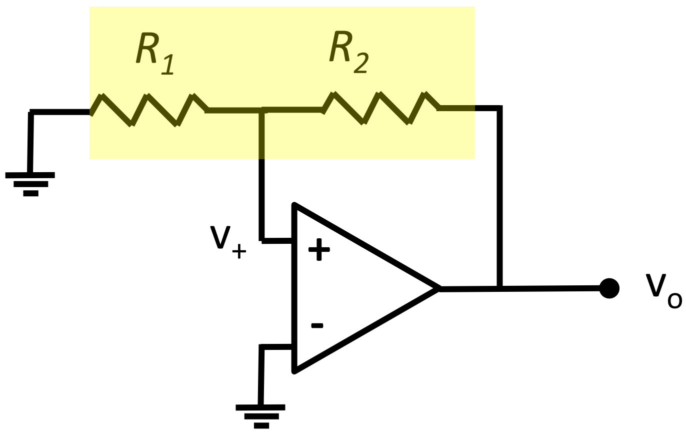
- **The use of positive-feedback loops**, consisting of an amplifier and a RC or LC network, based on the resonance phenomenon. These are often called **linear oscillators**.

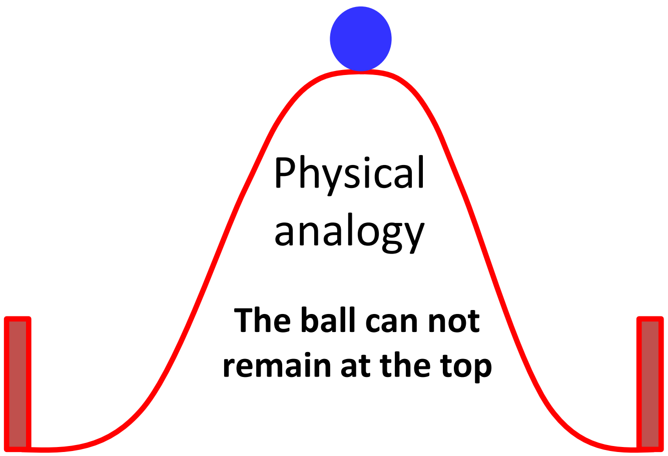
- The use of **circuits that generate sinusoids by shaping triangular waves** (**non-linear oscillators**) → Circuits that generate square, triangular, pulse waveforms employing circuit blocks known as multivibrators (bistable, astable, monostable)

Here we will discuss some basic circuits based on the latter approach

# The bistable circuit

The bistable circuit has two stable states. The circuit can remain in either stable state indefinetely, and moves to the other state only when appropriately triggered

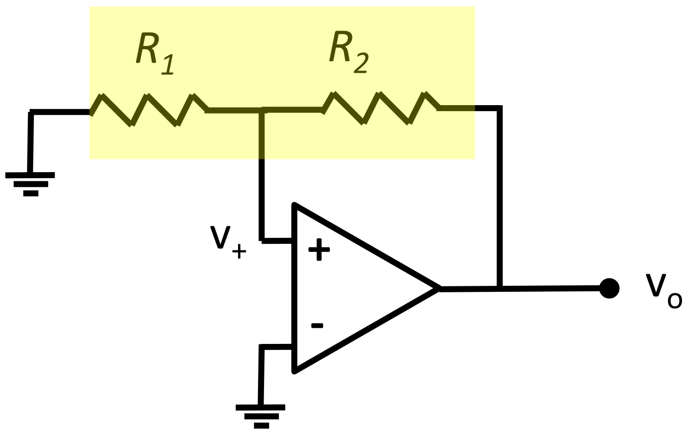


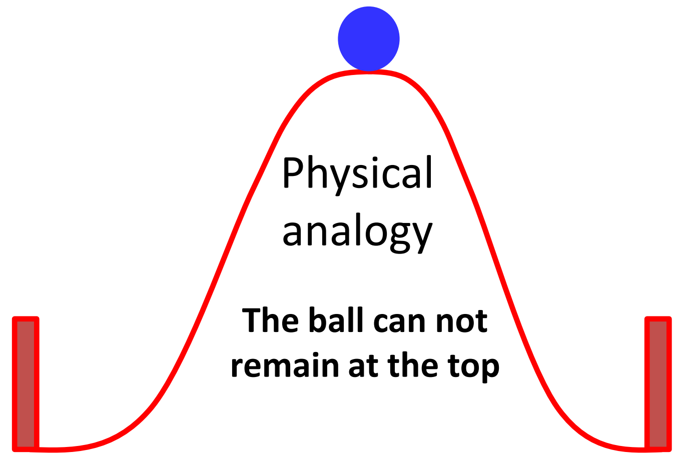




- Consider that the positive terminal $v_+$ is close to zero. Imagine that the electrical noise causes a small positive increment of voltage $v_+$. This small signal will be amplified by the (large) gain of the op-amp, and a much greater signal will appear on the output $v_o$
- The voltage divider ($R_1$, $R_2$) will feed a fraction $\beta=R_1/(R_1+R_2)$ of the output signal on $v_+$
- This process will continue until the op-amp reaches saturation at the positive maximum output ($L_+$)
- When this happens, the voltage at the positive input terminal $v_+$ becomes $L_+R_1/(R_1+R_2)$ → The output stays in this state **for ever**! → this is one of the stable states of the bistable

# The bistable circuit

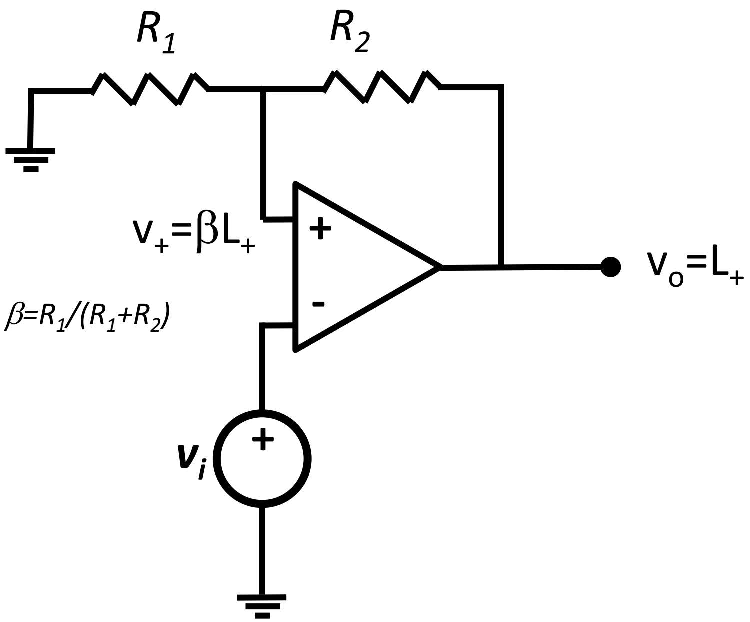
The bistable circuit has two stable states. The circuit can remain in either stable state indefinetely, and moves to the other state only when appropriately triggered



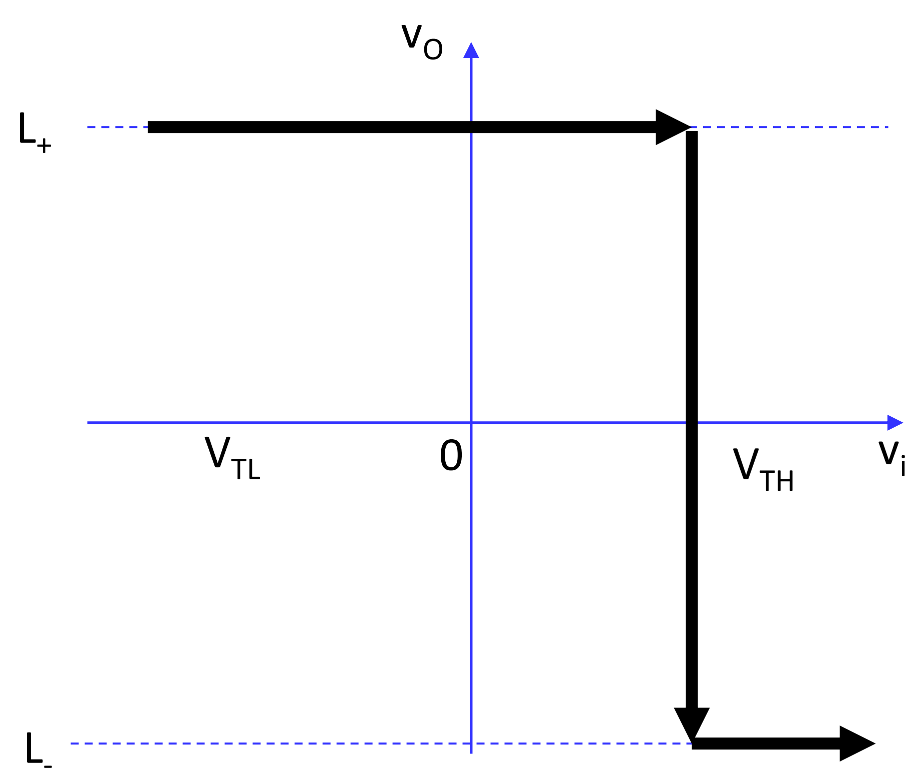




- The same happens in the equally-probable case that $v_+$ starts from a slightly negative value → In this case, the output voltage saturates to $v_o = L_-$
- The bistable circuit can remain in the saturated states indefinetely
- The circuit can not remain in the state where $v_+=0$ V and $v_o=0$ V → Unstable equilibrium (metastable state). Any disturbance leads to a transition (contrary to the case where the feedback is negative, where the virtual short circuit reduces disturbances)

# Transfer characteristics of the inverting bistable circuit




**How can we make this circuit change state?**



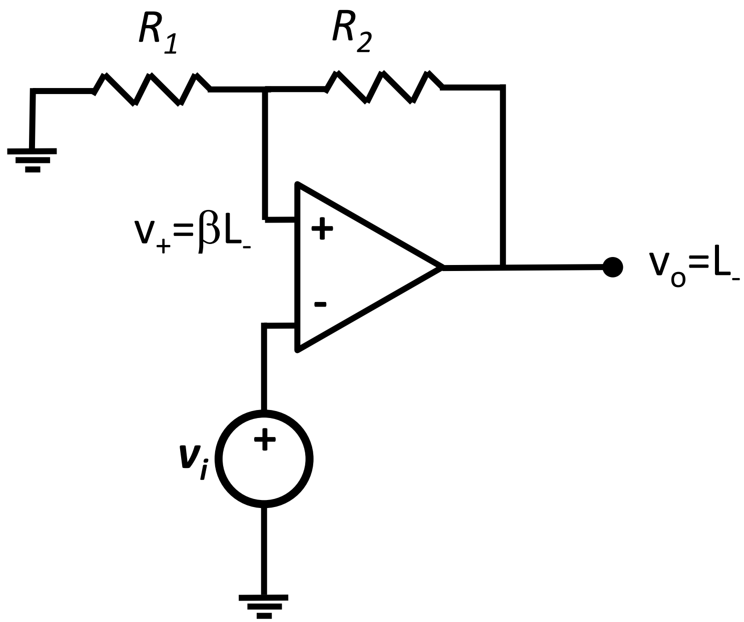

To derive the transfer characteristic we assume that $v_O$ is at $L_+$, and thus $v_+=\beta L_+$

As $v_i$ is increased from 0 V, nothing happens until $v_i$ reaches a value equal to $v_+=\beta L_+=V_{TH}$

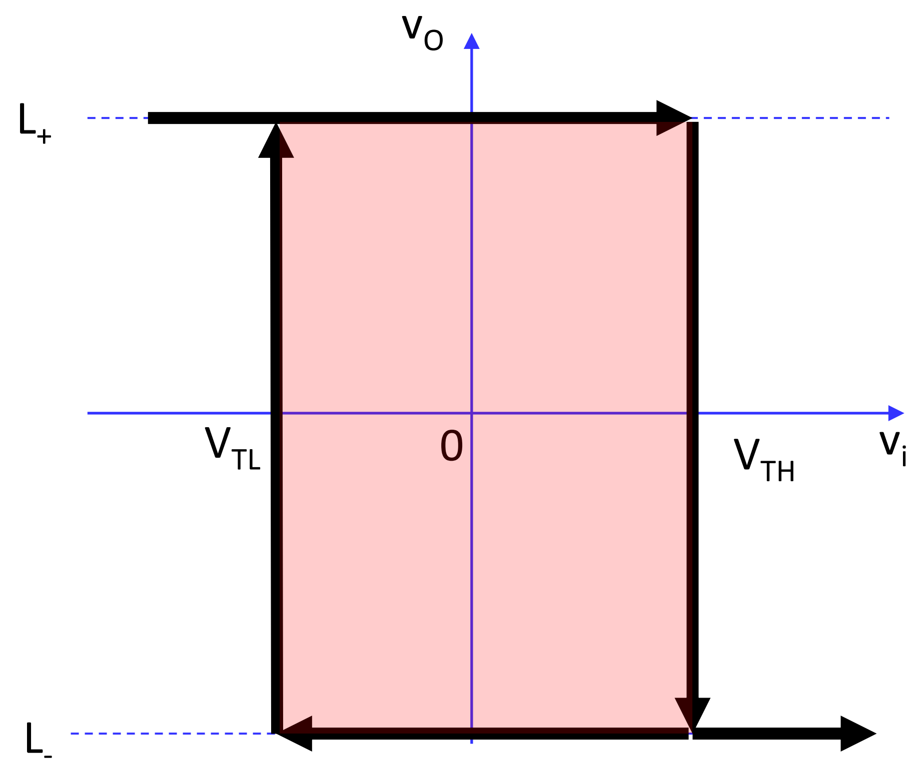
As $v_i$ exceeds this value, a net negative voltage appears at the input terminals of the op-amp, and $v_O$ goes negative

The voltage divider causes $v_+$ to go negative, thus increasing the net negative input of the op-amp, and the output saturates to $v_O=L_-$

# Transfer characteristics of the inverting bistable circuit




How can we make this circuit change state?



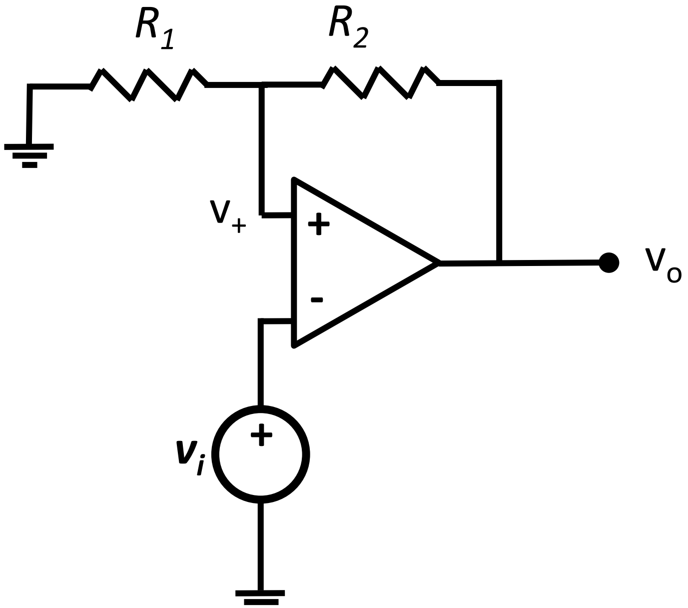

When $v_i$ is decreased → since $v_+=\beta L_-$, the output remains in negative saturation until $v_i$ goes below $V_{TL}=\beta L_-$

At this point, the output switches back to $L_+$

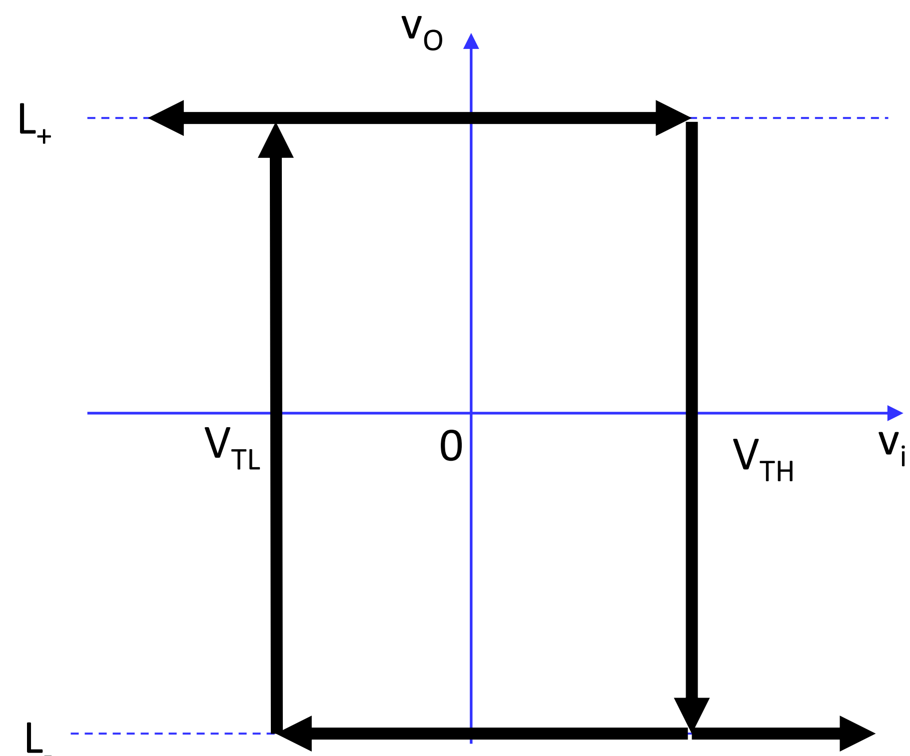
The circuit is said to exhibit hysteresis; the width of the hysteresis is the difference between the two thresholds, $V_{TH}$ and $V_{TL}$

This circuit is said to be inverting → output goes negative with positive input!

# Transfer characteristics of the inverting bistable circuit




How can we make this circuit change state?

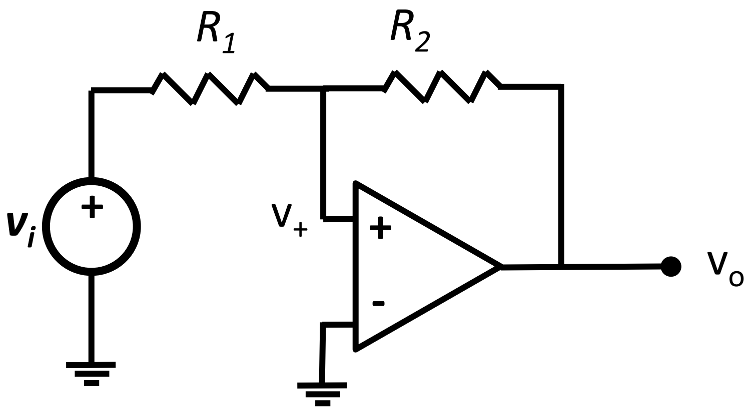



We note that to change state it is not necessary to keep the $v_i$ signal high or low → A pulse (trigger signal) is sufficient, then the system holds the new state until the input goes beyond the other threshold

The value of the output only depends on the previous value of the trigger signal (the trigger that caused the circuit to be in its current state) → thus the circuit exhibits **memory** (this is a basic memory element of digital systems)

In analog circuit applications, the bistable circuit is also known as Schmitt trigger

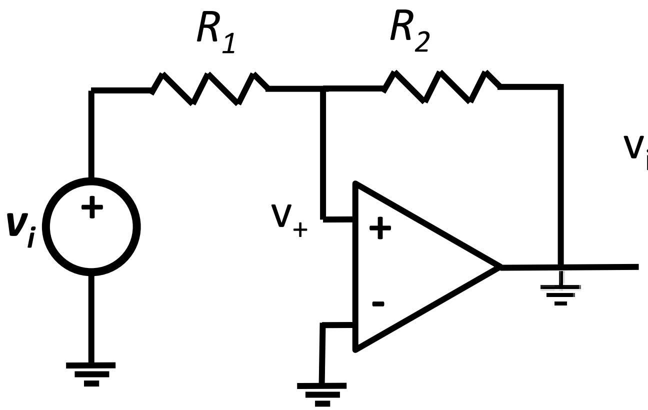
# Bistable circuit with non-inverting transfer characteristic




The basic bistable feedback loop can be used to derive a circuit with noninverting transfer characteristics, by applying the input signal $v_i$ to the terminal of $R_1$

To obtain the transfer characteristic we use the superposition

# Bistable circuit with non-inverting transfer characteristic

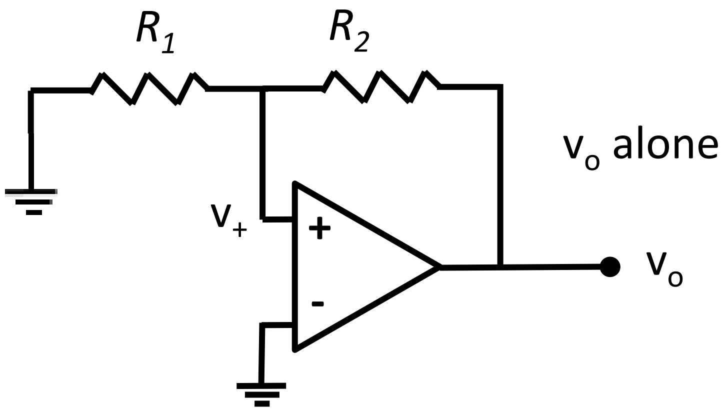



$v_i$ alone

The basic bistable feedback loop can be used to derive a circuit with noninverting transfer characteristics, by applying the input signal $v_i$ to the terminal of $R_1$

To obtain the transfer characteristic we use the superposition

# Bistable circuit with non-inverting transfer characteristic

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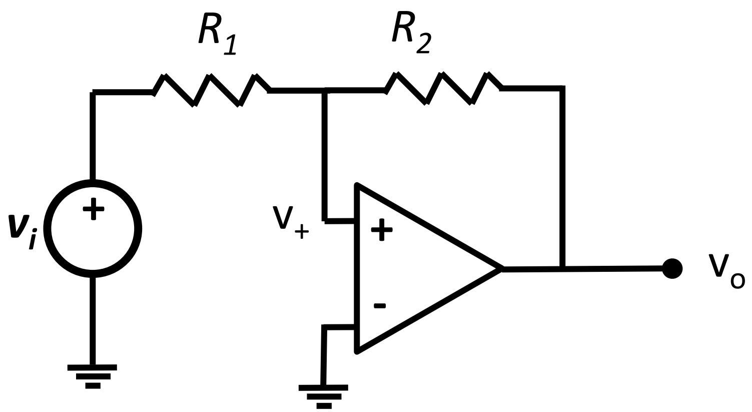
# Bistable circuit with non-inverting transfer characteristic




If $v_O$=$L_+$, positive values of $v_i$ will have no effect. To trigger the circuit into the $L_-$ state, $v_i$ must be made negative

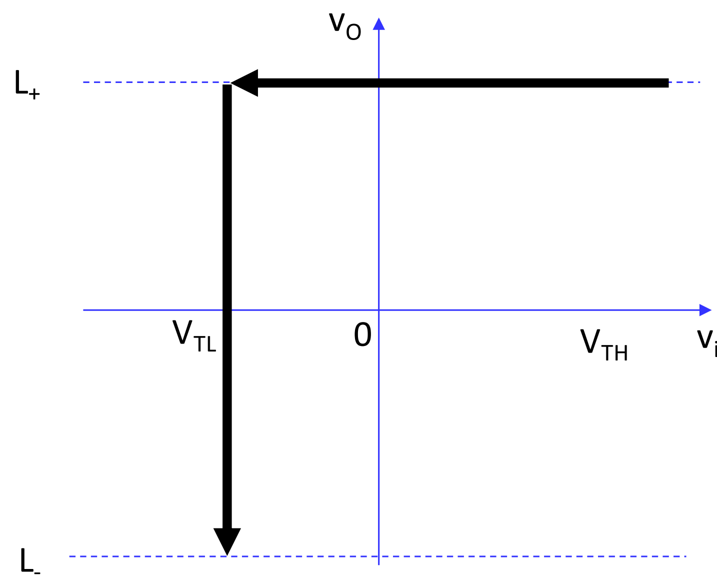
$V_{TL}$ can be found by substituting $v_O$=$L_+$, $v_+$=0, $v_i$=$V_{TL}$

And the result is $$V_{TL} = -L_+(R_1 / R_2)$$

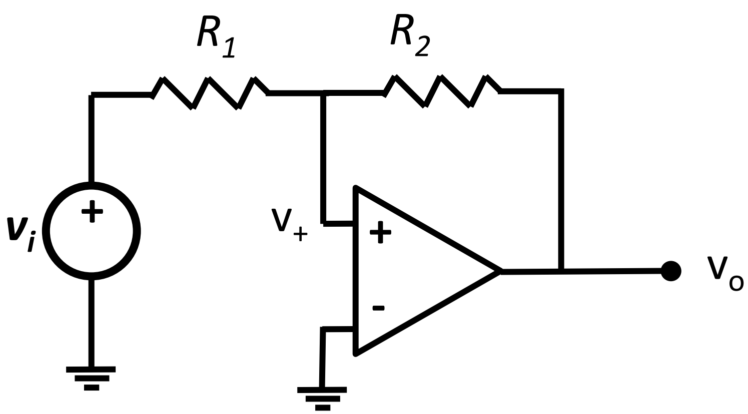
The basic bistable feedback loop can be used to derive a circuit with noninverting transfer characteristics, by applying the input signal $v_i$ to the terminal of $R_1$

To obtain the transfer characteristic we use the superposition:

$$v_+ = v_i \frac{R_2}{R_1 + R_2} + v_o \frac{R_1}{R_1 + R_2}$$



# Bistable circuit with noninverting transfer characteristic




Similarly, if $v_O=L_-$, negative values of $v_i$ will have no effect. To trigger the circuit into the $L_+$ state, $v_i$ must be made positive

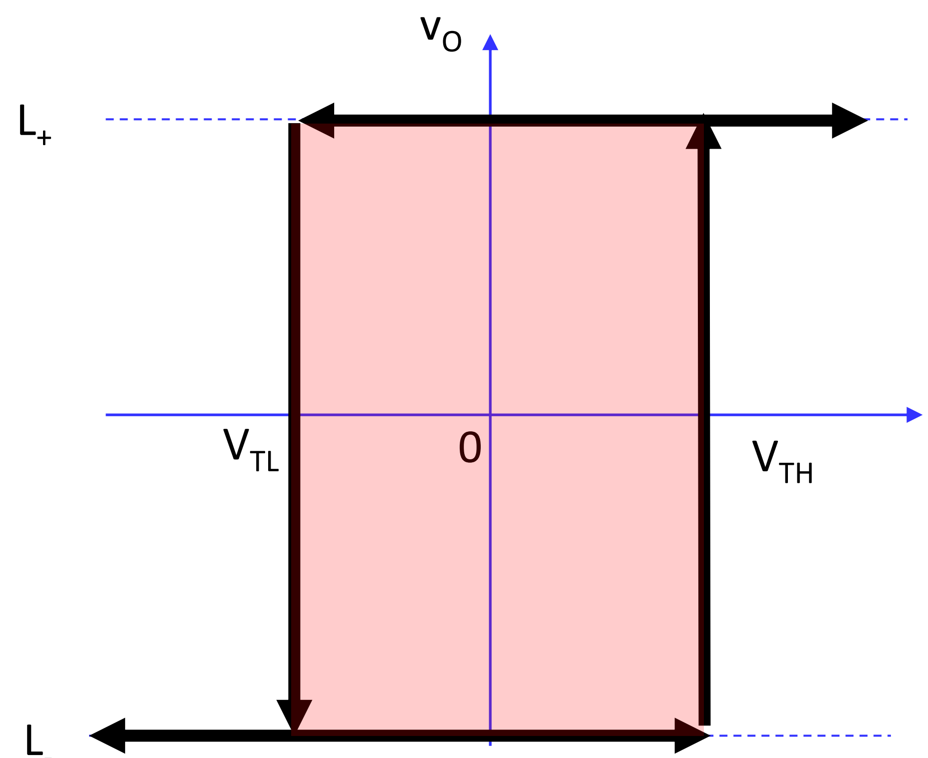
$V_{TH}$ can be found by substituting $v_O=L_-$, $v_+=0$, $v_i=V_{TH}$

And the result is $V_{TH} = -L_-(R_1 / R_2)$

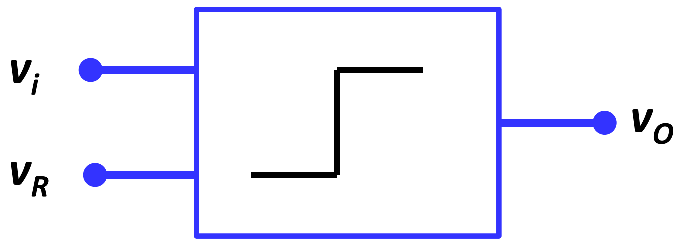
The basic bistable feedback loop can be used to derive a circuit with noninverting transfer characteristics, by applying the input signal $v_i$ to the terminal of $R_1$

To obtain the transfer characteristic we use the superposition:

$$v_+ = v_i \frac{R_2}{R_1 + R_2} + v_o \frac{R_1}{R_1 + R_2}$$

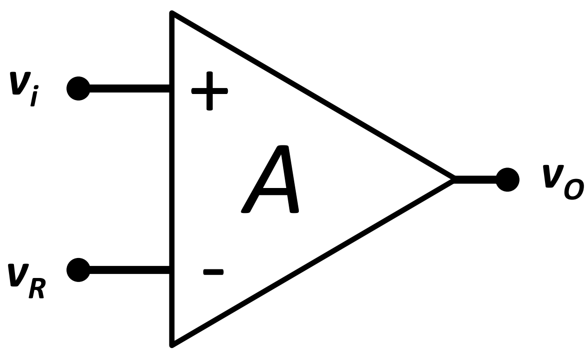


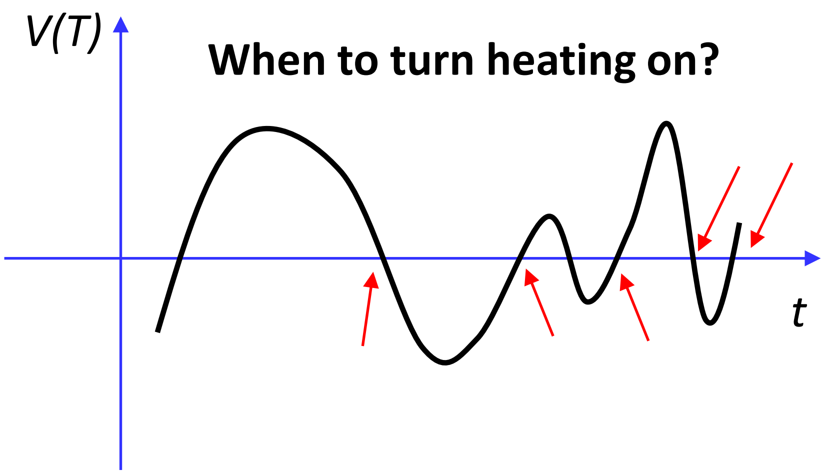
# Bistable circuit as comparator



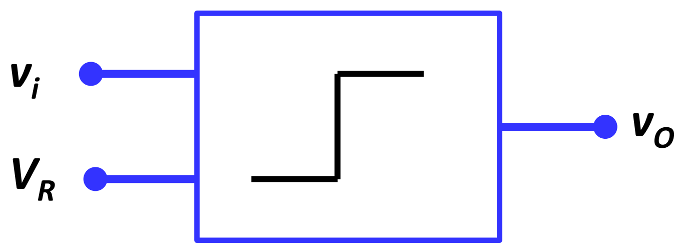

The comparator is an analog circuit building block that is used for several applications:

- Detecting the level of a signal with respect to a threshold
- Design of A/D converters
- …



# Bistable circuit as comparator

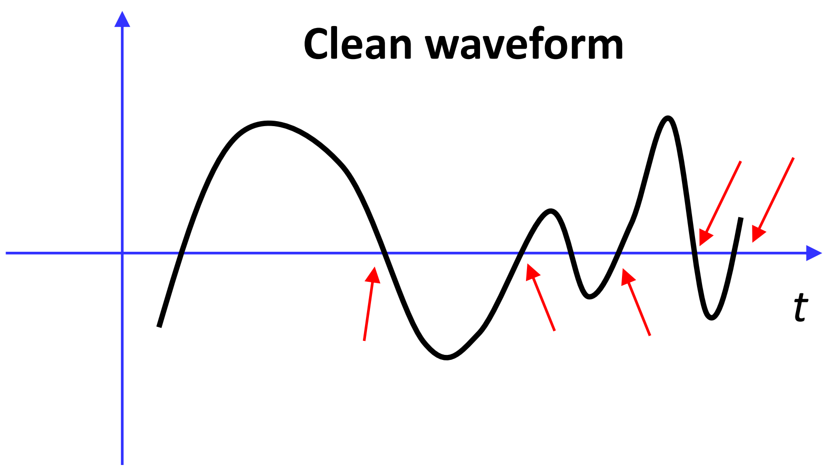


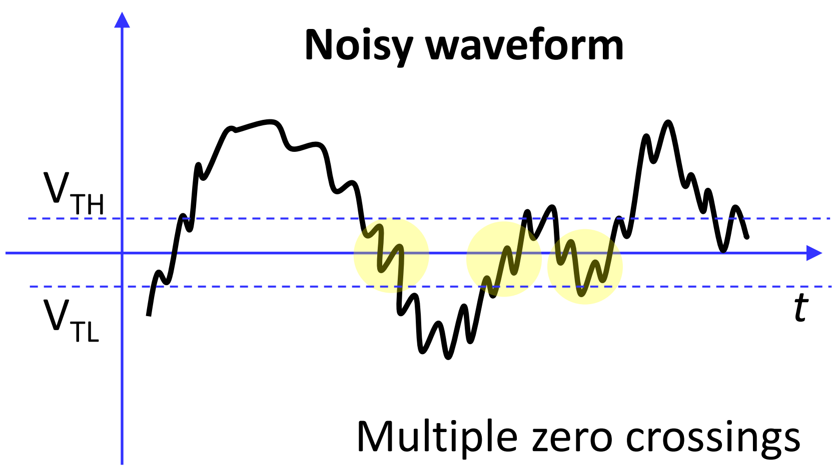

The comparator is an analog circuit building block that is used for several applications:

- Detecting the level of a signal with respect to a threshold
- Design of A/D converters
- …

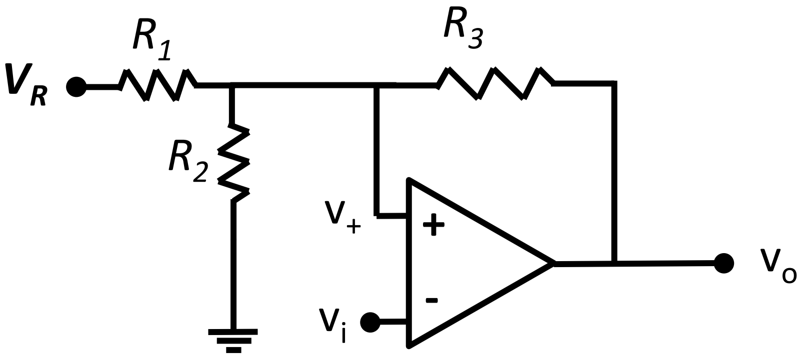
In several applications a single threshold is not sufficient, and hysteresis (i.e. two thresholds) can help!

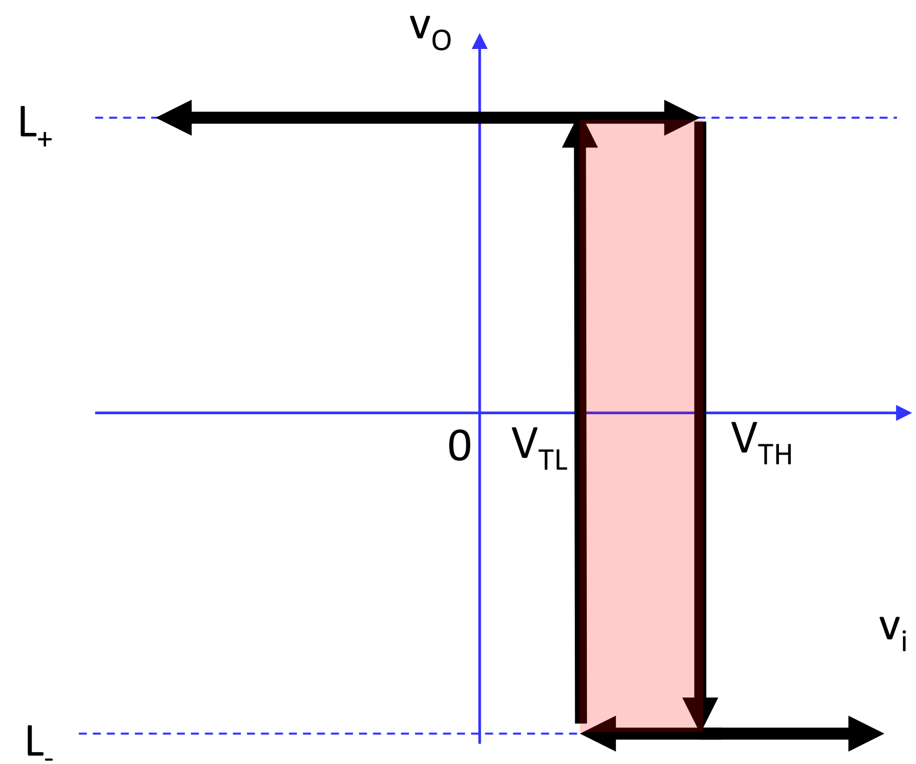
An example is the circuit for detecting the zero crossing of an arbitrary waveform



# Bistable circuit with offset (inverting)




To obtain the transfer characteristic we use the superposition:

$$v_+ = V_R \frac{R_2 \| R_3}{R_1 + R_2 \| R_3} + v_o \frac{R_1 \| R_2}{R_3 + R_1 \| R_2}$$

When $v_O = L_+$

$$V_{TH} = V_R \frac{R_2 \| R_3}{R_1 + R_2 \| R_3} + L_+ \frac{R_1 \| R_2}{R_3 + R_1 \| R_2}$$

When $v_O = L_-$

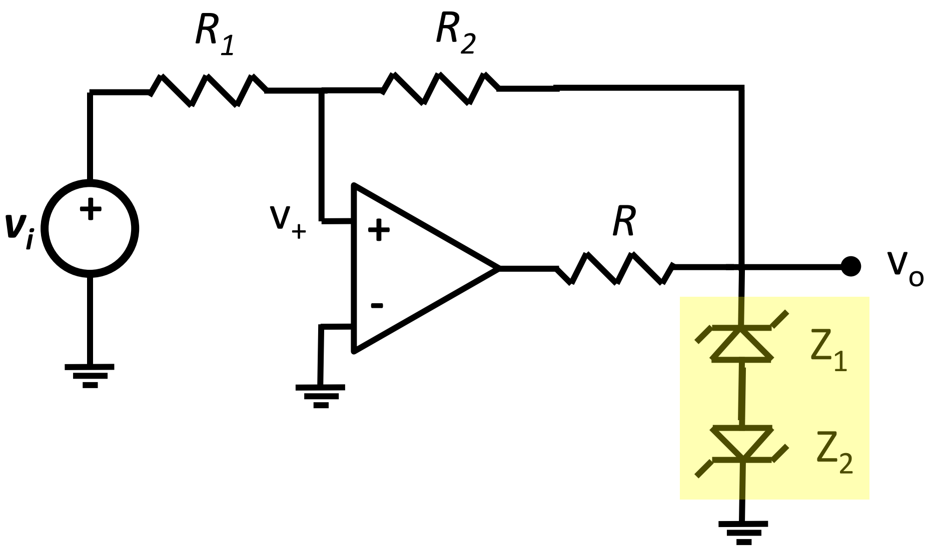
$$V_{TL} = V_R \frac{R_2 \| R_3}{R_1 + R_2 \| R_3} + L_- \frac{R_1 \| R_2}{R_3 + R_1 \| R_2}$$

**Numerical example:**
If $R_1$=10 kΩ, $R_2$=10 kΩ, $R_3$=100 kΩ, $V_R$=5 V, $L_+$=$L_-$=5 V, the two thresholds are:

$V_{TH}$=2.62 V
$V_{TL}$=2.14 V

# How to make the output voltage more accurate?

We know that the saturation voltage of the op-amp is never equal to $V_{CC}$/-$V_{EE}$… how to make the output more precise? → **By cascading the op-amp with a limiter circuit!**




In this circuit, the value of R should be chosen to yield the current required for the proper operation of the zener diodes ($I_z$>$I_{zmin}$)

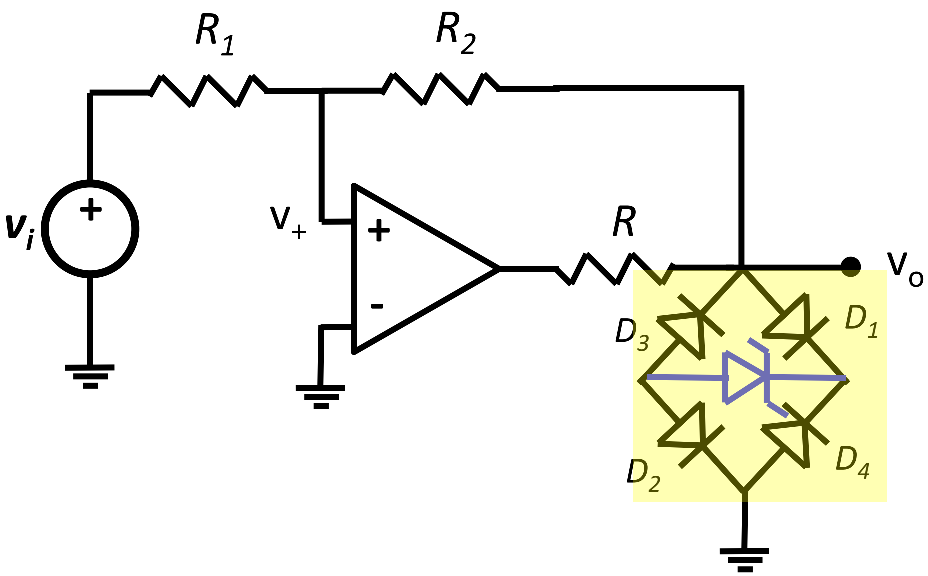
For this circuit:

- $L_+=V_{Z1}+V_D$
- $L_-=-(V_{Z2}+V_D)$

Where $V_D$ is the drop on a forward-biased diode

# How to make the output voltage more accurate?

We know that the saturation voltage of the op-amp is never equal to $V_{CC}$/-$V_{EE}$… how to make the output more precise? → **By cascading the op-amp with a limiter circuit!**

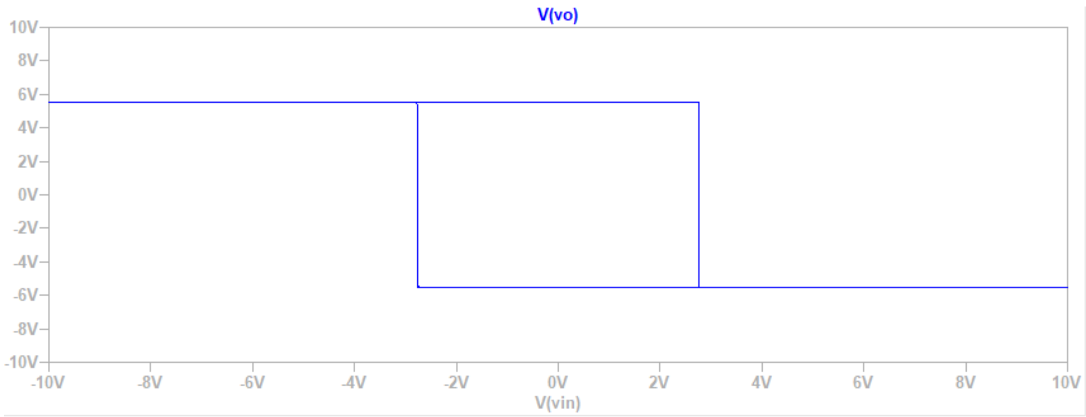


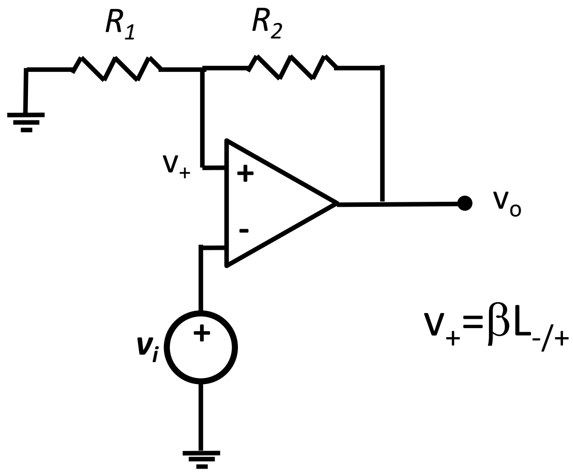

In this circuit, the value of R should be chosen to yield the current required for the proper operation of the zener diodes

For this circuit:

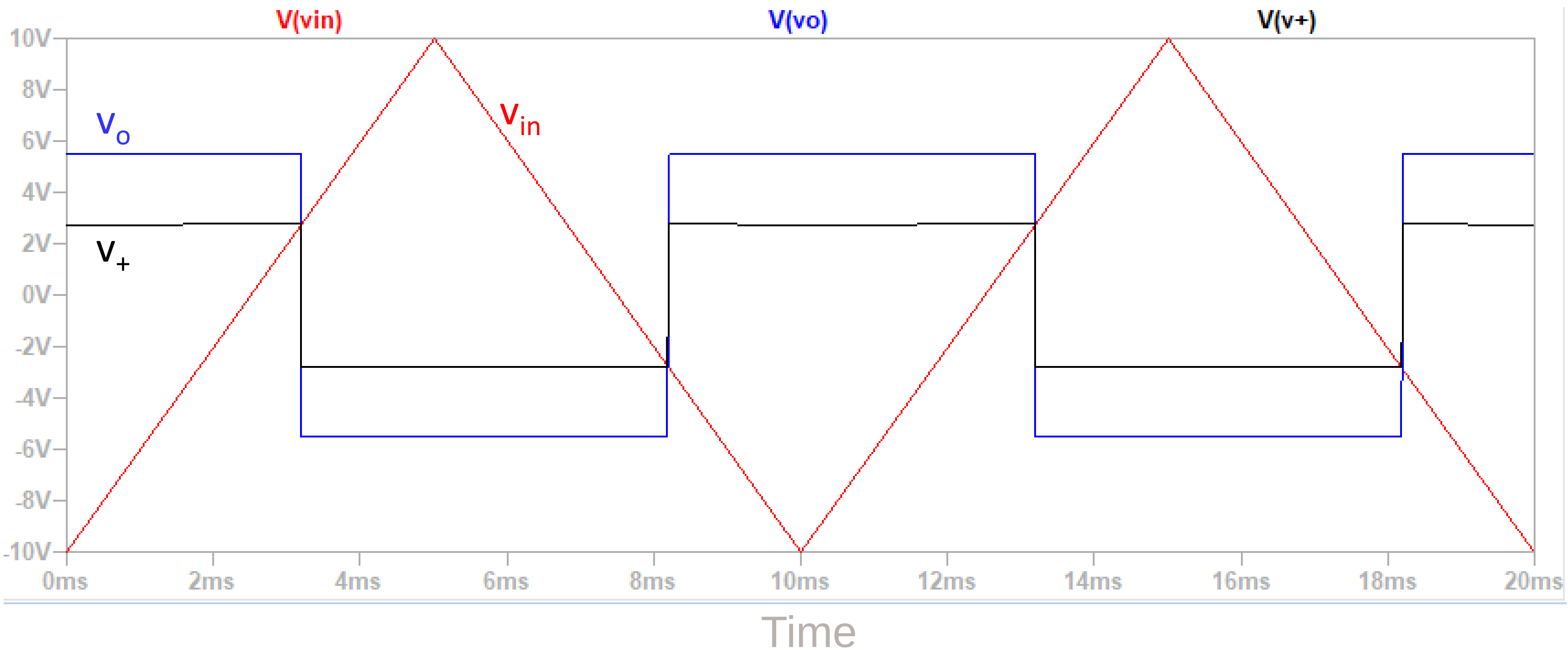
- $L_+ = V_Z + V_{D1} + V_{D2}$
- $L_- = -(V_Z + V_{D3} + V_{D4})$

# How to measure the transfer characteristics with LTspice?

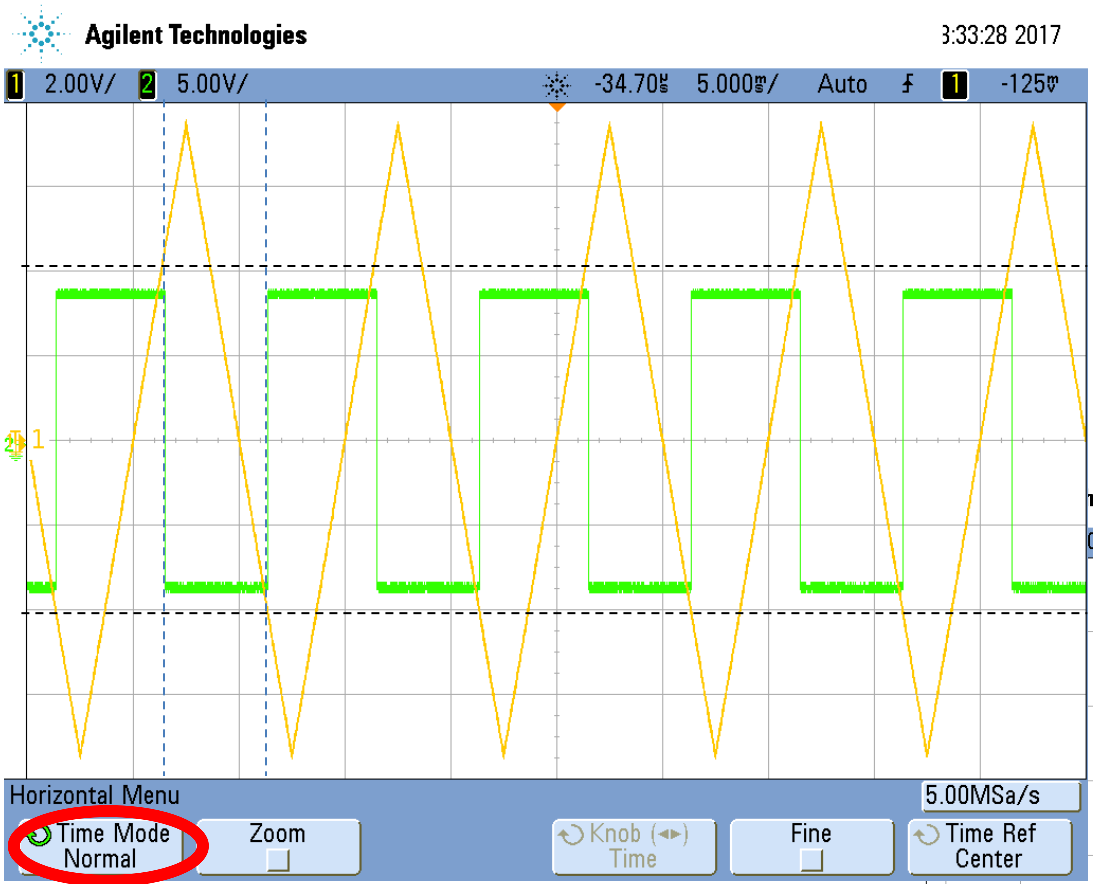


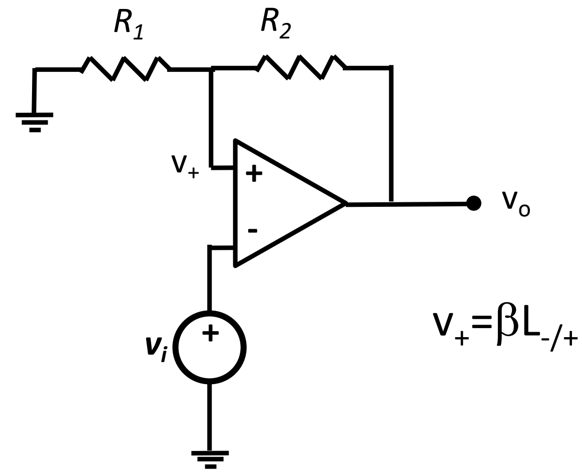



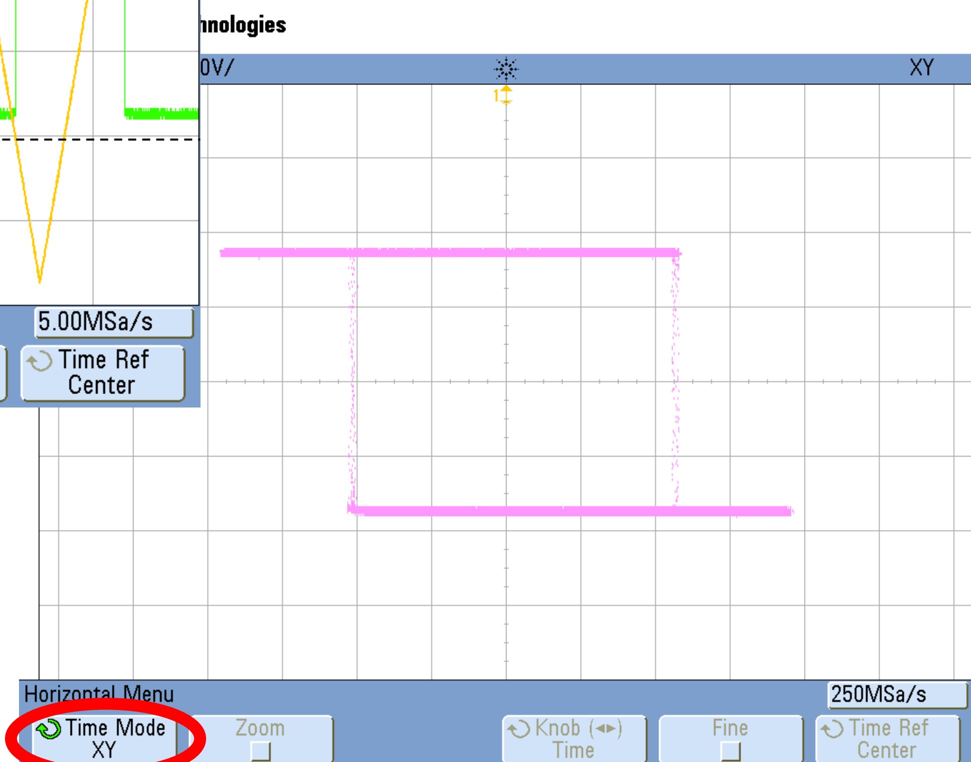

$v_+ = \beta L_{-/+}$



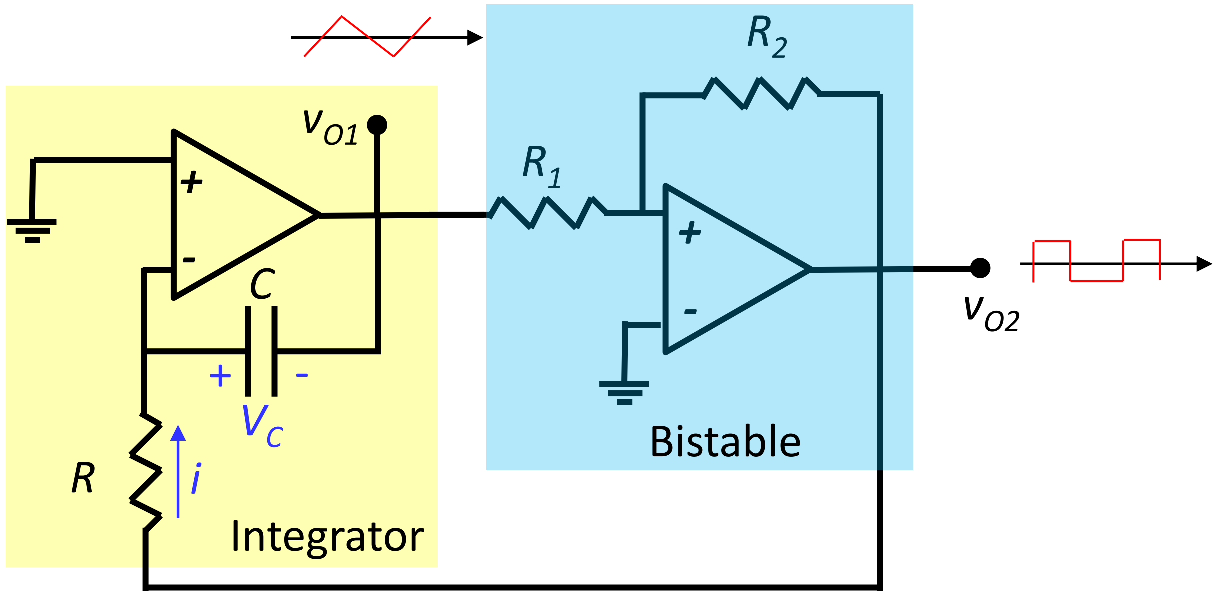
# How to measure the transfer characteristics with a scope?



# Generation of triangular waveforms

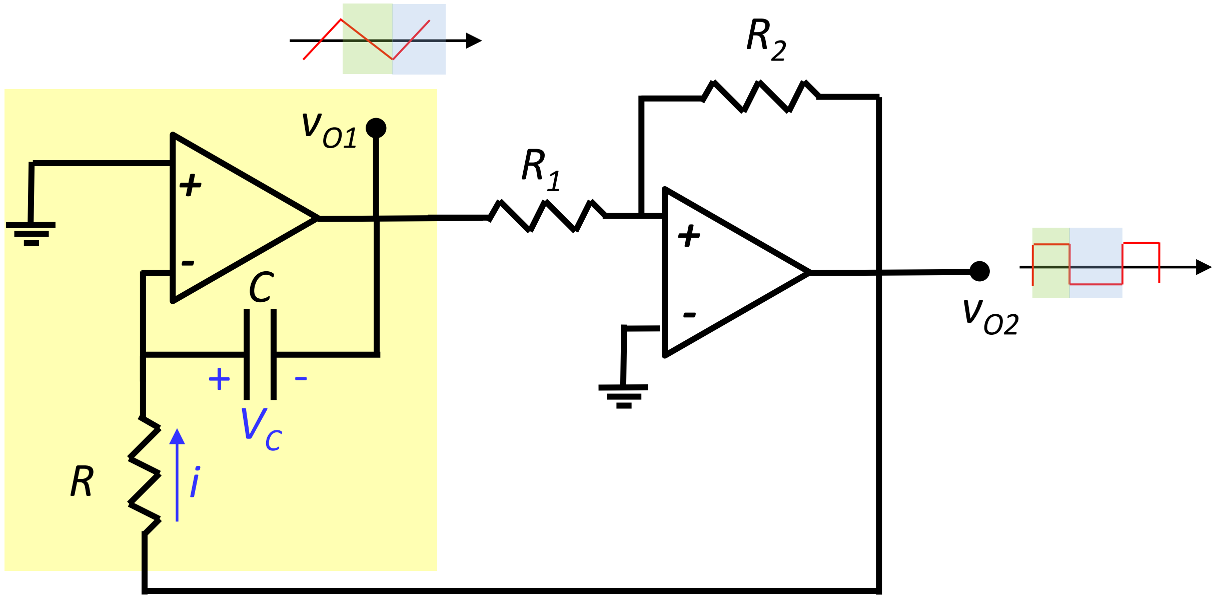


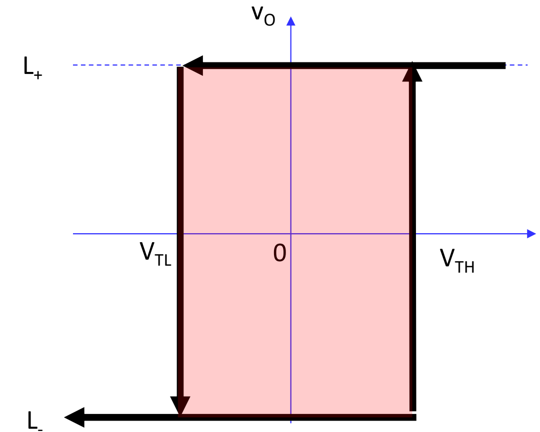

Square waves can be generated by forcing a bistable circuit to change state continuosly

In this case, an integrator is connected to the output of the bistable circuit to form a triangular wave

The circuit has two outputs: triangular wave and square wave. The timing (period) of the two waves is defined by the properties of the RC network

# Generation of triangular waveforms



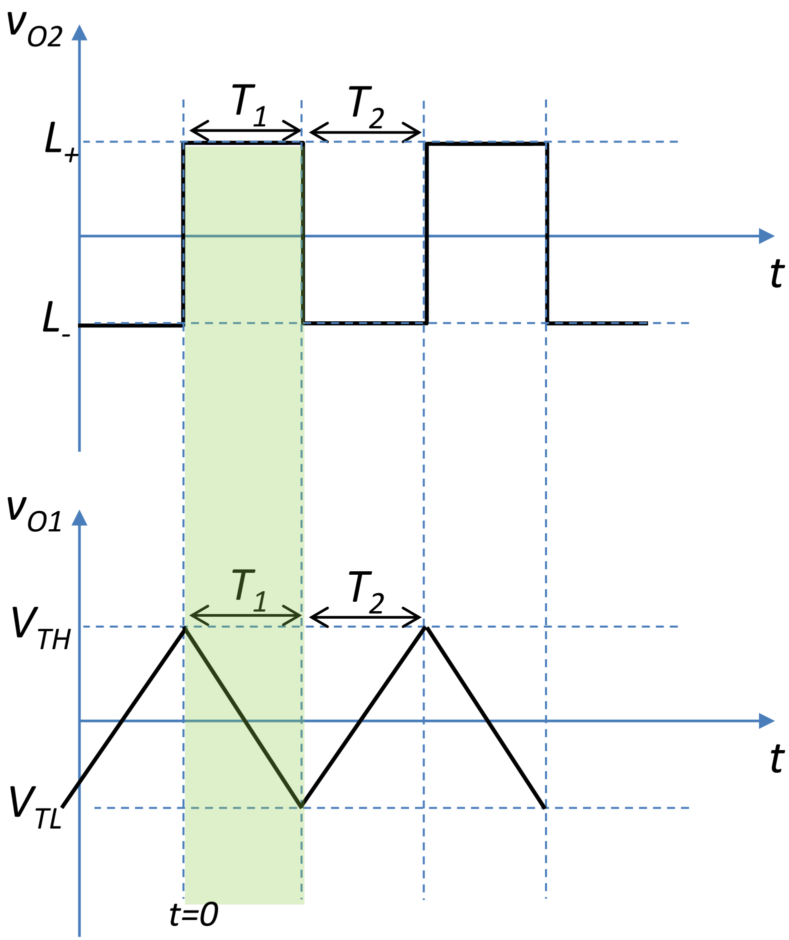

Consider the output $v_{O2}$ to be at $L_+$. The current on R is equal to $i=L_+/R$, and **is constant**

This will cause the output of the integrator **to linearly decrease** with a slope of $-L_+/RC$

$$\mathrm{i} = \mathrm{C}\frac{dV_C}{dt} = -\mathrm{C}\frac{dV_{O1}}{dt} = \frac{L_+}{R} \longrightarrow \frac{dV_{O1}}{dt} = -\frac{L_+}{RC} \longrightarrow V_{O1}(t) = V_{O1}(0) - \int \frac{L_+}{RC}dt = V_{O1}(0) - \frac{L_+t}{RC}$$

This process continues until $v_{O1}$ reaches the lower threshold of the bistable circuit, $V_{TL}$ at which point the bistable circuit will switch state, its output $v_{O2}$ becoming equal to $L_-$. The current on the capacitor will reverse direction, its absolute value becoming equal to $|L_-|/R$. The integrator output will start to increase linearly with slope equal to $|L_-|/RC$ until $V_{TH}$ is reached

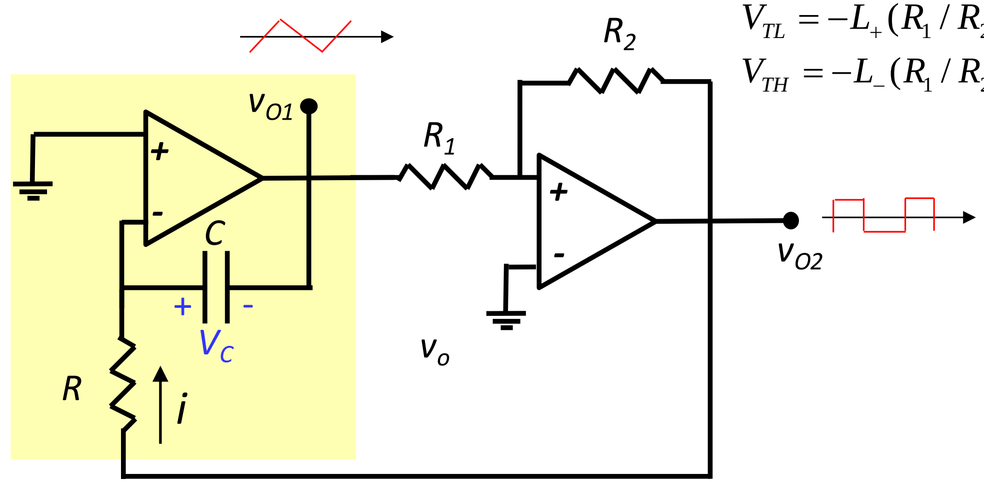
# Generation of triangular waveforms




$$i = C\frac{dV_C}{dt} = -C\frac{dV_{O1}}{dt} = \frac{L_+}{R} \longrightarrow \frac{dV_{O1}}{dt} = -\frac{L_+}{RC}$$

$$V_{O1}(t) = V_{TH} - \int \frac{L_+}{RC}dt = V_{TH} - \frac{L_+ t}{RC}$$

$$V_{TL} = -L_+(R_1/R_2)$$
$$V_{TH} = -L_-(R_1/R_2)$$




We can derive an expression for the period T of the square/triangular wave

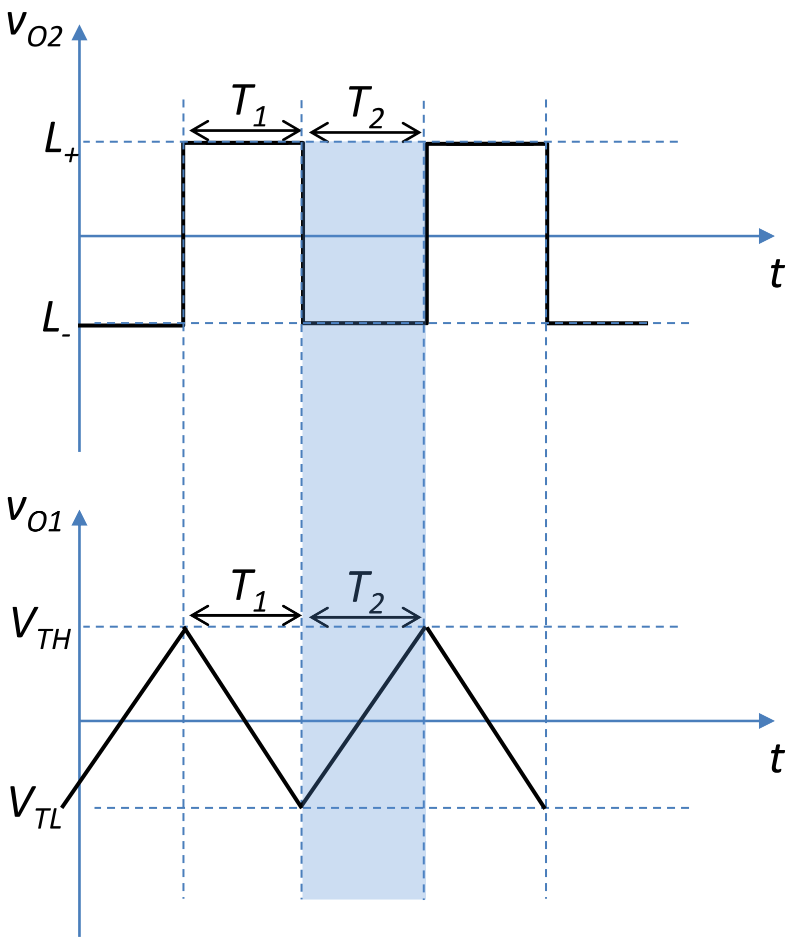
During $T_1$ we have

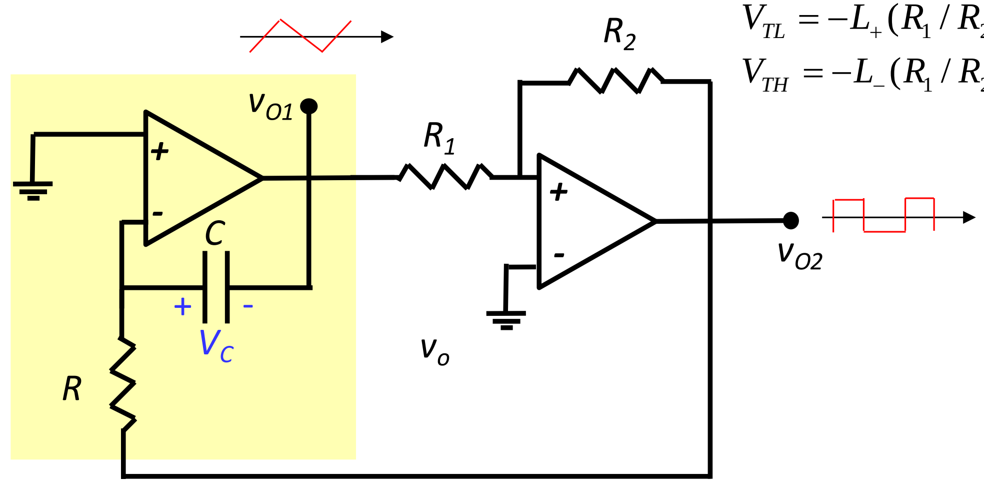
$$\frac{V_{TH} - V_{TL}}{T_1} = \frac{L_+}{RC}$$

From which we obtain

$$T_1 = RC\frac{V_{TH} - V_{TL}}{L_+}$$

# Generation of triangular waveforms




$V_{TL} = -L_+(R_1/R_2)$

$V_{TH} = -L_-(R_1/R_2)$

Similarly, during $T_2$ we have

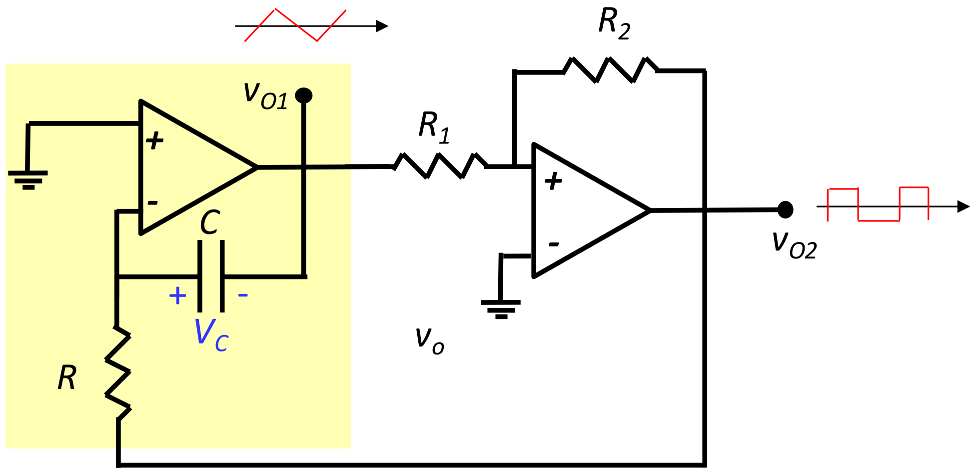
$$\frac{V_{TH}-V_{TL}}{T_2} = \frac{-L_-}{RC}$$

From which we obtain

$$T_2 = RC\frac{V_{TH}-V_{TL}}{-L_-}$$

To obtain symmetrical waves we design the bistable circuit to have $L_+=-L_-$ → $T = T_1 + T_2 = 2RC\dfrac{V_{TH}-V_{TL}}{L_+}$

# Numerical example




Considering the circuit in figure, the op-amps have saturation voltages of ±10 V, a capacitor C=10 nF and a resistor $R_1$=10 kΩ are used.

Find the values of R and $R_2$ such that the frequency of oscillation is 1 kHz and the triangular waveform has a 10 Vpp amplitude

**Solution**

We know that $T = \frac{1}{f} = 2RC\frac{V_{TH}-V_{TL}}{L_+} = 10^{-3}s$ → Thus $R = \frac{L_+}{2fC(V_{TH}-V_{TL})} = 50\ k\Omega$

The non-inverting bistable circuit has $V_{TH} = |L_\pm(R_1/R_2)| = 5V$

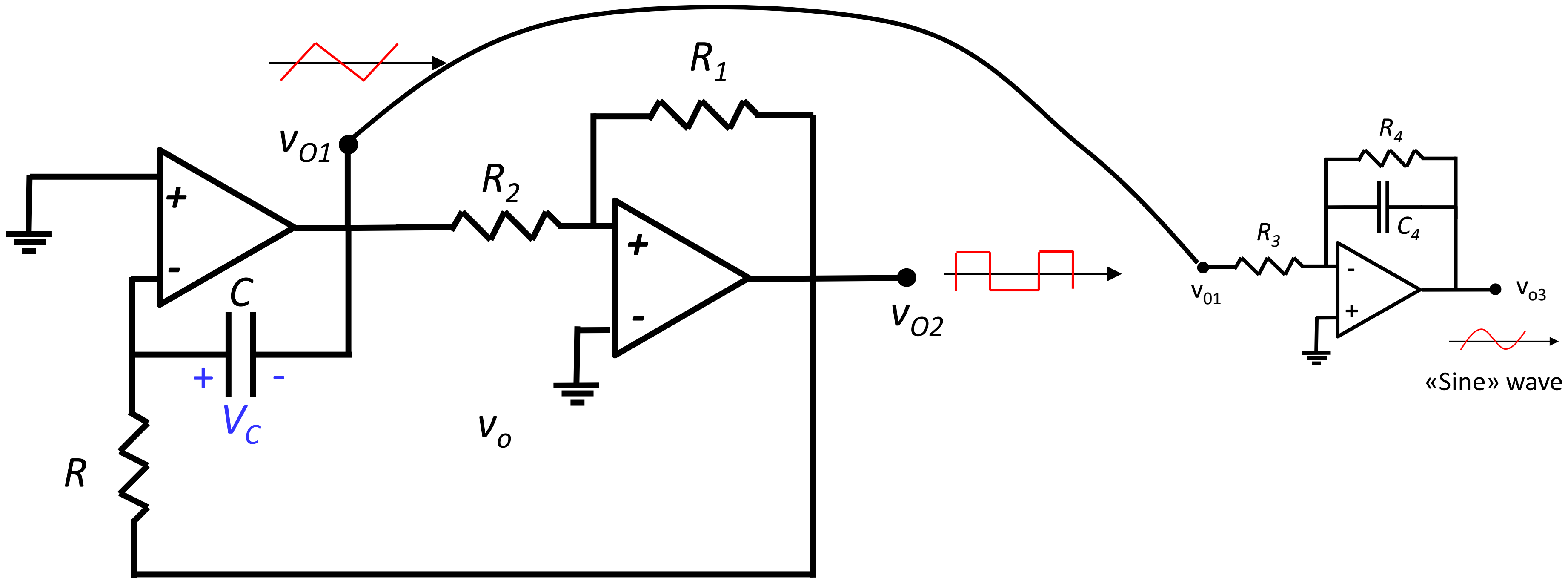
$R_1$ $R_2$

We can therefore calculate

$v_i$ + $v_+$ + - • $v_o$

$$R_2 = \frac{L_\pm R_1}{V_{TH}} = 20\ k\Omega$$

# How to generate a sine wave?

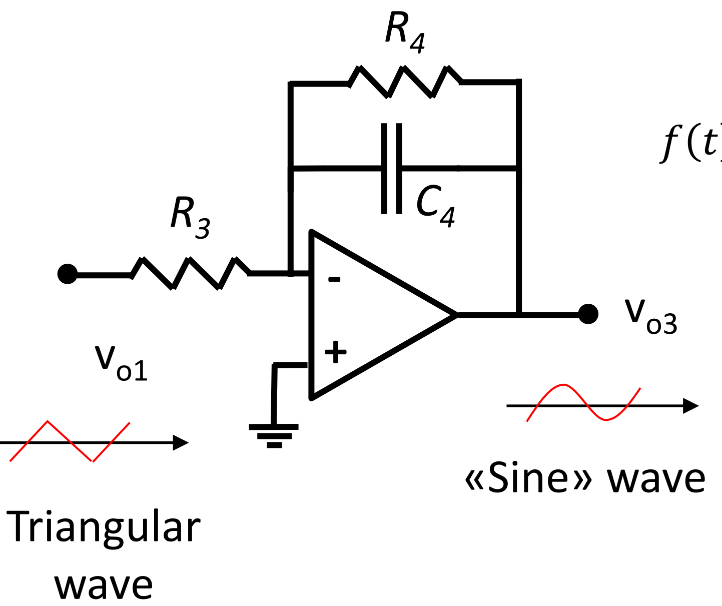



An effective way to create a sine wave is to start from a triangular wave and use a low-pass filter

This approach is relatively straightforward; the resulting sine-wave is not "ideal", we will evaluate it in detail

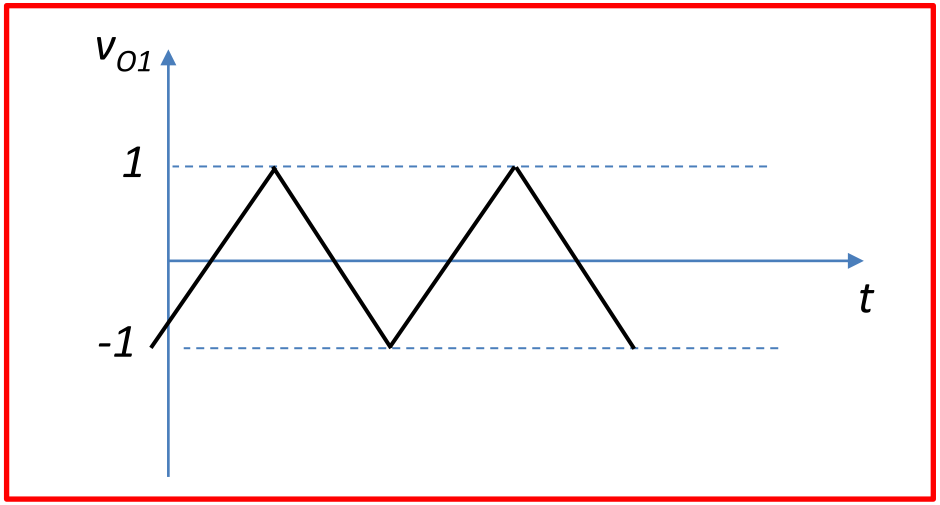
# Function generator based on the astable multivibrator

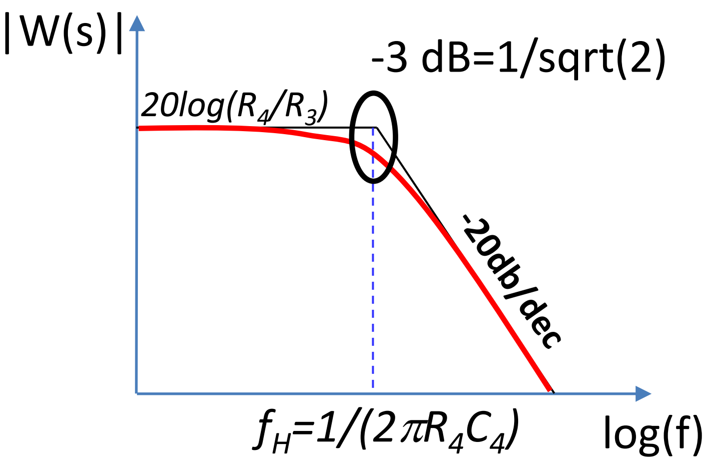
**Low-pass filter (first order)**

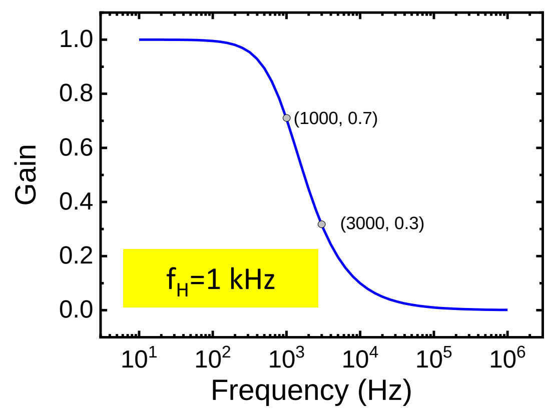



A triangular wave can be expressed as:

$$f(t) = \frac{8}{\pi^2}\left[\sin(\omega t) - \frac{1}{3^2}\sin(3\omega t) + \frac{1}{5^2}\sin(5\omega t) - \frac{1}{7^2}\sin(7\omega t) + \cdots\right]$$



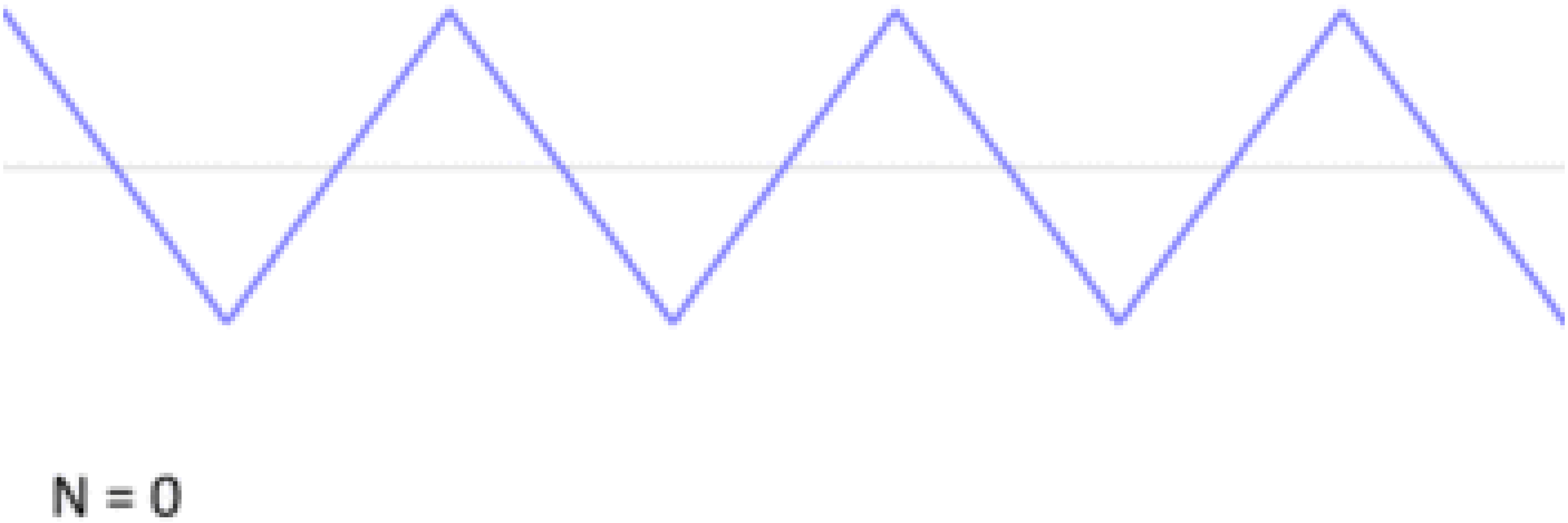




A simple low-pass filter may not be enough to obtain a good sine wave (3° harmonic is attenuated to 30%)

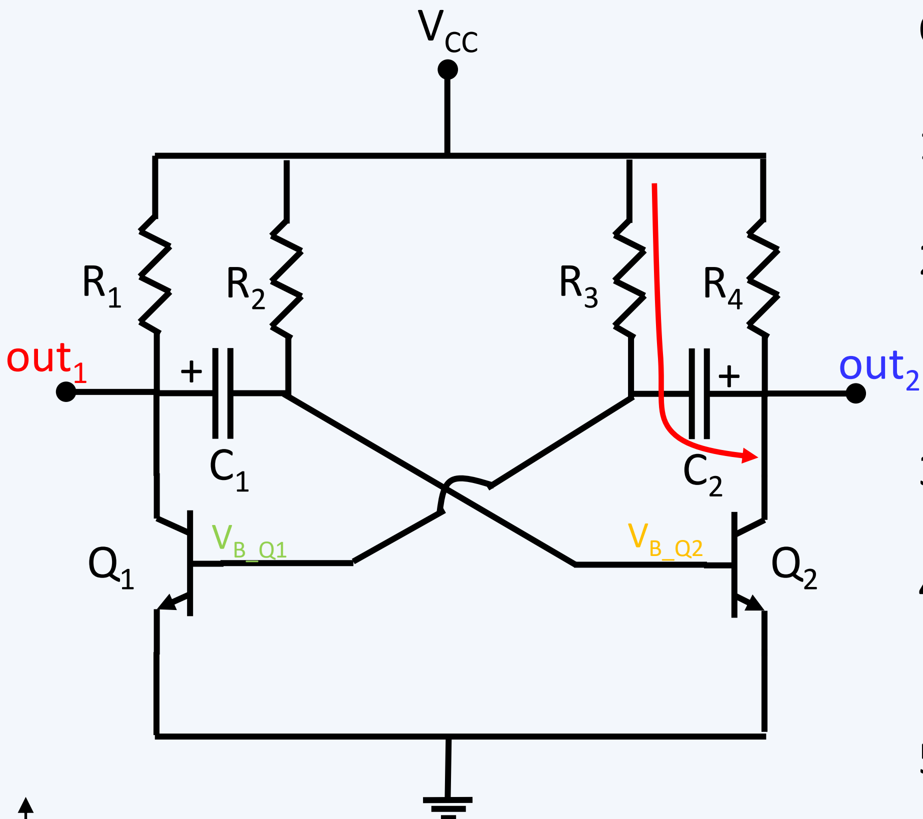
# From triangular wave to sine wave

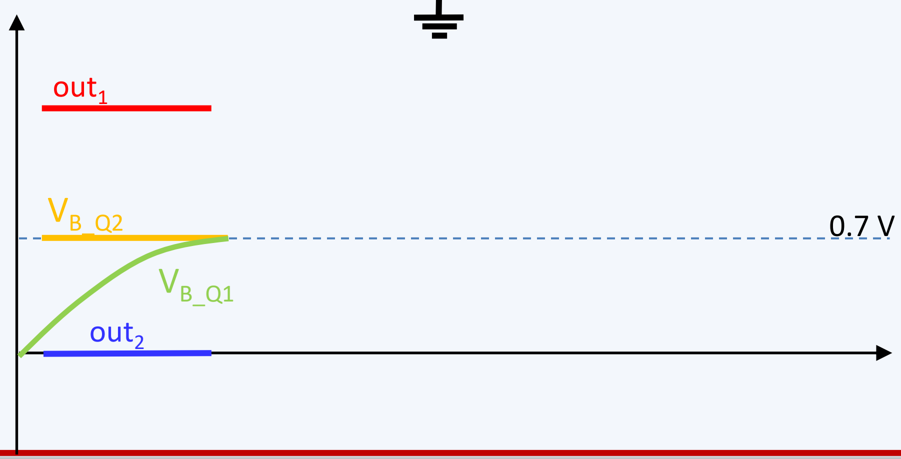
$$f(t) = \frac{8}{\pi^2}\left[\sin(\omega t) - \frac{1}{3^2}\sin(3\omega t) + \frac{1}{5^2}\sin(5\omega t) - \frac{1}{7^2}\sin(7\omega t) + \cdots\right]$$




https://en.wikipedia.org/wiki/File:Synthesis_triangle.gif

# Astable multivibrator without op-amps? (OPTIONAL)

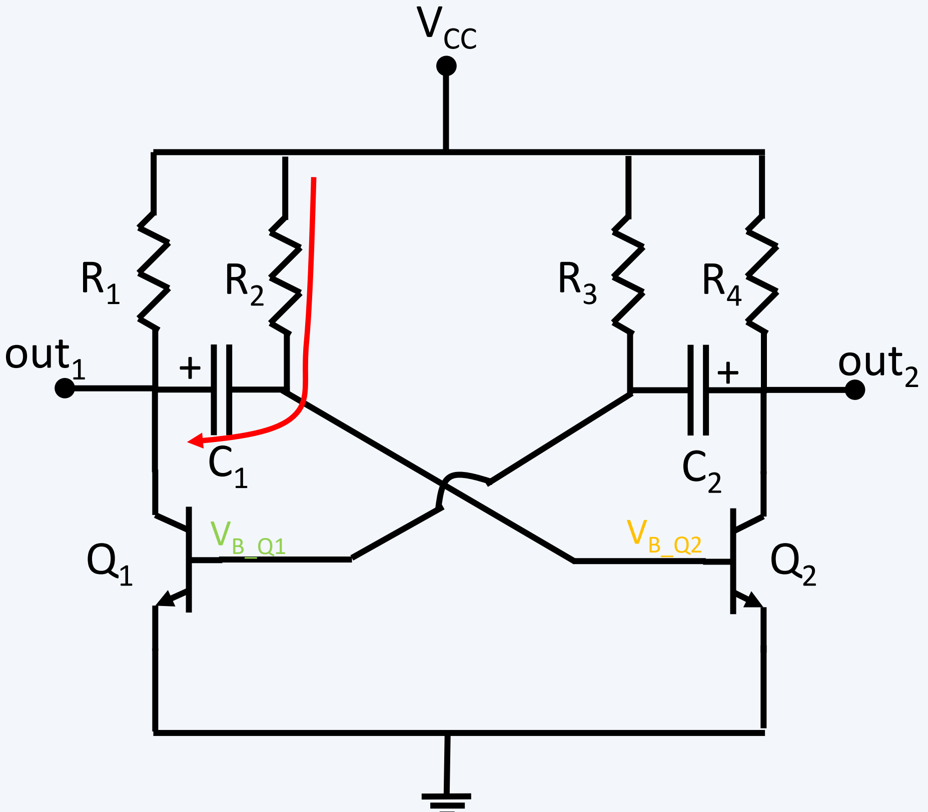


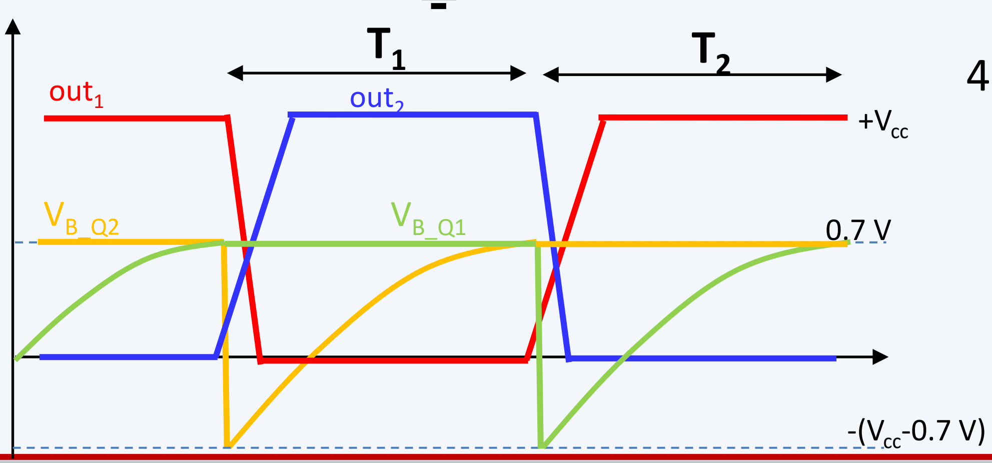




Operating principle (simplified description)

1. Before power is applied, both BJTs are off
2. When power is applied, $Q_1$ and $Q_2$ should turn-on; one will be faster, due to small differences → Assume it is $Q_2$ →$V_{B\_Q2}$=0.7 V
3. $out_2$ is then shorted to ground
4. Since $C_2$ is not charged yet, $V_{B\_Q1}$ is (initially) at ground potential, and $Q_1$ is off → $out_1=V_{CC}$
5. $C_2$ starts charging through $R_3$ (time constant $=R_3C_2$), and $V_{B\_Q1}$ increases gradually until it reaches 0.7 V
6. At the same time, $C_1$ also charges, through $R_1$, which is typically a small resistor (e.g. 100-1000 ohm). So $C_1$'s left lead ($out_1$) will quickly rise up to $V_{cc}$ and remain high

# Astable multivibrator without op-amps? (OPTIONAL)



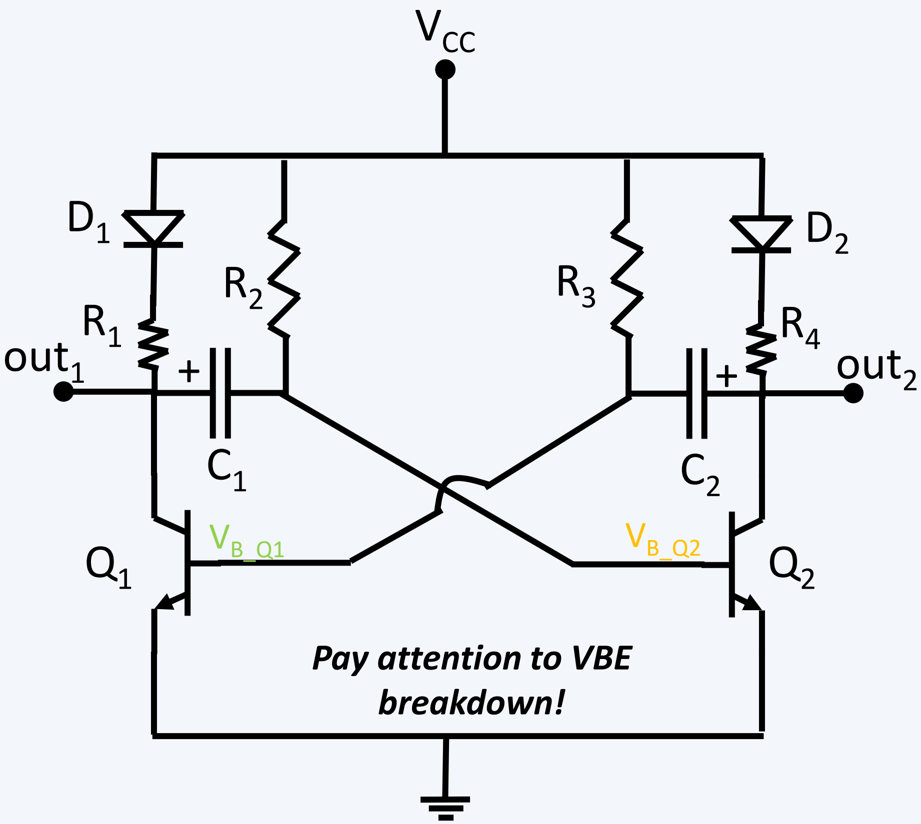

Operating principle (simplified description)

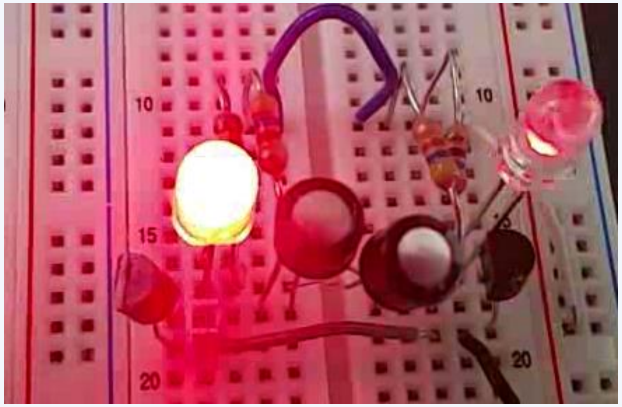
1. When $V_{B\_Q1}$ increases and reaches 0.7 V, $Q_1$ will turn on and its collector ($out_1$) will go to ground
2. Since $C_1$'s left lead is connected to $Q_1$'s collector, it will also drop to ground voltage
3. As $C_1$ is fully charged, its right lead ($V_{B\_Q2}$) will suddenly drop to a negative voltage (0.7 V-$V_{cc}$). This will shut off $Q_2$ firmly
4. During this period, $out_1$ will remain low, and $out_2$ will quickly rise to $V_{cc}$ (due to the charging of $C_2$ through a small resistor $R_4$)

It can be demonstrated that

$$t = T_1 + T_2 \sim \ln(2)(R_3C_2 + R_2C_1)$$

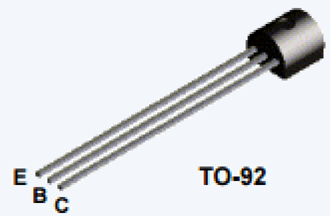
# Astable multivibrator without op-amps? (OPTIONAL)



This circuit blinks the two LEDs (D1 and D2) on and off continuosly

1. Try this circuit with




$R_1$=$R_4$=470 Ω
$R_2$=$R_3$=47 kΩ
$C_1$=$C_2$=10 µF
$Q_1$=$Q_2$=BC548
$V_{CC}$=9 V
$D_1$=$D_2$=red LEDs

And measure the collector and base voltages of the two transistors as a function of time

2. How can the switching frequency be calculated? Explain in the report!

It can be demonstrated that if we add the LEDs

$$T = -\ln\left(\frac{V_{CC} - V_{BE}}{2V_{CC} - V_{BE} - V_{LED}}\right)(R_3C_2 + R_2C_1)$$

# Source of these slides

The following texts have also been used to prepare this lecture:


- A. S. Sedra, and K. C. Smith, Microelectronic Circuits. Oxford, 2011
- R.C. Jaeger, T.N. Blalock, Microelettronica. McGraw-Hill
- Thomas L. Floyd, Electronic Devices. --: Pearson Prentice Hall, 2005
- P. Horowitz and W. Hill, The art of electronics. --: Cambrdige University Press, 2015
- Neil Storey, Electronics, A system approach. --: Pearson Prentice Hall, 2006
- V. K. Mehta, Principles of Electronics