Operational Amplifiers

Contents

1 Introduction

The operational amplifier (opamp) is a monolithic device, intended in the origin to be used in the so called analog computers. In fact is a very high gain dc-coupled differential amplifier with single-ended output. There are many (thousands) of operational amplifiers, but all of them are represented by symbol sketched in left side of figure 1, where the $+$ input is the non-inverting input the the $-$ is the inverting one. As it has been said an operational amplifier is a monolithic device build by some tenths of transistors and some resistors. In right side of figure 1 is shown a simplified schema of one of the most famous opamp the 741.

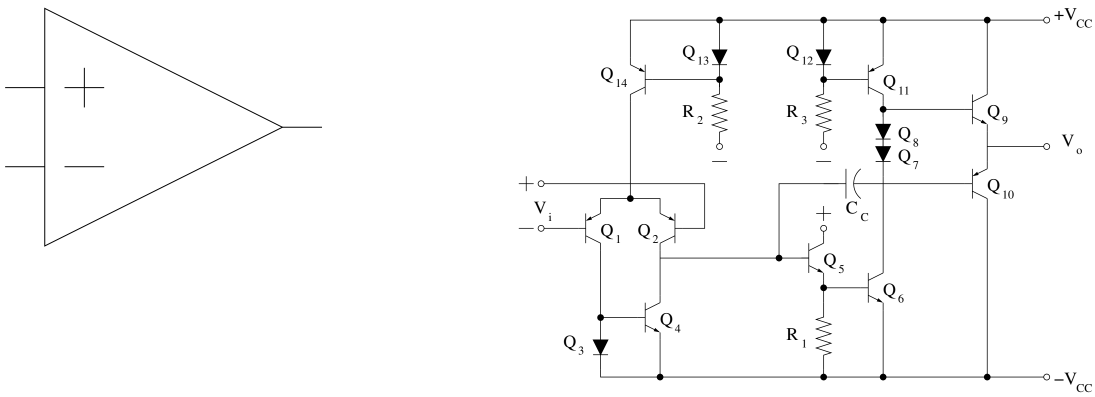


Figure 1: On left side is represented the schematic symbol of an opamp. On right side there is the simplified schematics of opamp 741.

In the figure 1 can be seen that the input stage is a differential amplifier and the output is a push-pull amplifier. The operational amplifier also can be considered almost as an ideal amplifier:

Ideal amplifier	Real amplifier
Infinite gain in voltage $A = \infty$	High gain in voltage $A \sim 10^5$
Infinite bandwith	Finite bandwidth
Infinite input impedance $Z_{in} = \infty$	High input impedance $Z_{in} \sim 10M\Omega$
Zero output impedance $Z_{out} = 0$	Low output impedance $Z_{out} \sim 0$

So even with the conditions of real amplifier, for normal situations an opamp can be considered as an ideal one.

The gain in voltage can be written as:

$$v_{out} = A(v_+ - v_-)$$

This gain is called open-loop amplifier. In the case of a real amplifier the gain will depend also with frequency, and can be parametrized as:

$$A(j\omega) = A_0 \frac{1}{1 + j\omega/\omega_c}$$

where $A_0 \sim 10^5$ and $\omega_c \sim 5Hz$. The fact that the gain is so big, makes that even the slightest noise made the circuit to saturate, what makes the setup not useful, at least to operate as linear amplifier. In order to control and stabilize is used the so called negative feedback, that is the connection of output to the non-inverting input, and in this case the gain will not depend on the amplifier characteristics. In figure 2 is shown the principe of negative feedback: the non-inverting input introduce a phase shift of 180^o that controls the output.

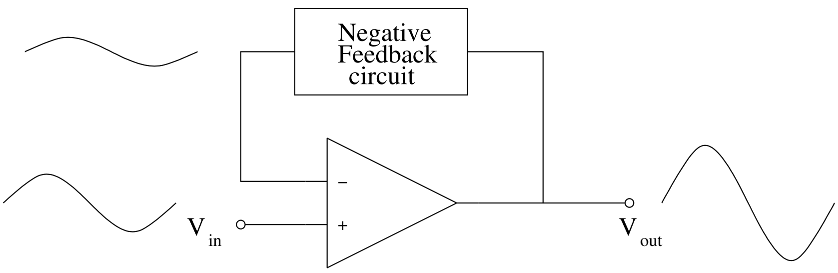


Figure 2: Principle of negative feedback

In case of negative feedback, and using the properties of an ideal amplifier the following rules can be applied to operational amplifiers:

Rule I: The voltages V_+ and V_- are equal $V_+ = V_-$.

Rule II: The input currents I_+ and I_- are zero $I_+ = I_- = 0$

Rule I is a direct consequence of $A = \infty$. This rule doesn't mean that the opamp actually changes the voltage. What it does is "look" at its input terminals and swing its output terminal around so that the external feedback network brings the input diffferential to zero (if possible).

Rule II is consequence of the high input impedance.

2 Basic op-amp circuits

2.1 Inverting amplifier

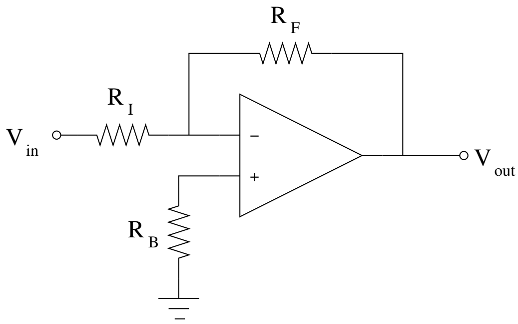


Figure 3: Inverting amplifier

Inverting amplifier is shown in figure 3. Analysis of the circuit gives

$$\frac{V_{in} - V_-}{R_I} = \frac{V_- V_{out}}{R_F}$$

Since $V_+ = V_- = 0$

$$\frac{V_{in}}{R_I} = -\frac{V_{out}}{R_F} \rightarrow A = \frac{V_{out}}{V_{in}} = -\frac{R_F}{R_I}$$

The resistor R_B is a compensation resistor and it reduces the current bias by eliminating non-zero current at the inputs. The optimal value for this resistor is $R_B = R_F || R_I$.

2.2 Non-inverting amplifier

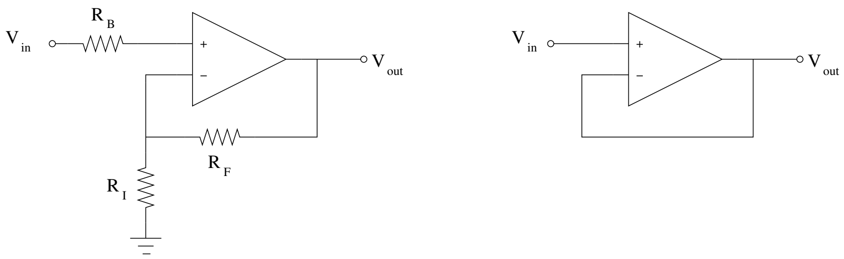


Figure 4: Non-inverting amplifier. On right side is shown a voltage follower or buffer

Non-inverting amplifier is shown in figure 4. For this circuit:

$$V_+ = V_- \rightarrow V_{in} = \frac{R_I}{R_I + R_F} V_{out}$$

$$\frac{V_{out}}{V_{in}} = 1 + \frac{R_F}{R_I}$$

The resistor R_B is a compensation resistors that reduces the current bias. The optimal value for this resistor is $R_B = R_F||R_I$.

An special case is when $R_F = 0$ and $R_I = \infty$. This setup is know as voltage follower or buffer. In this case the amplifier has a gain equal to one, that is there is no gain. On the other hand input impedance is very high and output impedance is almost zero. Such a device, when placed between source and load, protects the source from having to deliver high load currents, that would drom the voltage to the load to negligable levels. The power needed to deliver this load is delivered by the opamp.

2.3 Current-to-voltage converter

A current-to-voltage converter is shown in figure 5. Aplying our ideal amplifier rules gives

$$V_+ = V_- = 0 \rightarrow 0 - V_{out} = IR_F$$

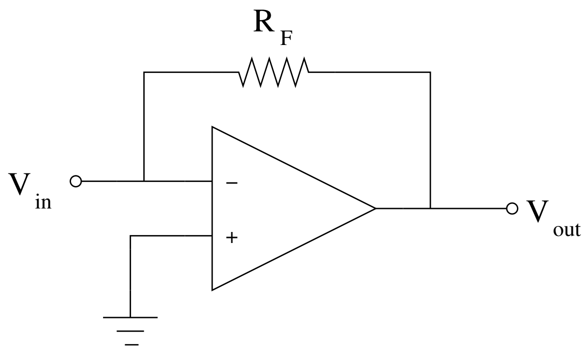


Figure 5: Current-to-voltage converter

2.4 Summers, subtracters

Figure 6-a shows several current sources driving the negative input of an inverting amplifier. Summing the current into the node gives:

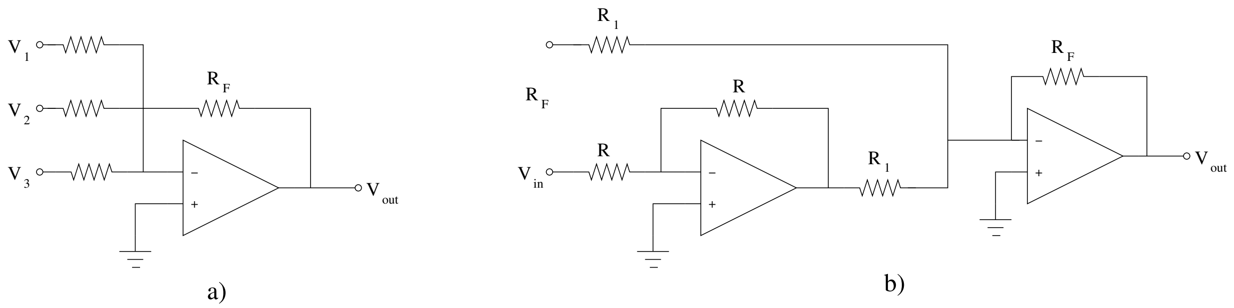


Figure 6: a) Summer amplifier b)Subtracter

$$\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} = -\frac{V_{out}}{R_F}$$

Therefore

$$V_{out} = -\left(\frac{R_F}{R_1}\right)V_1 - \left(\frac{R_F}{R_2}\right)V_2 - \left(\frac{R_F}{R_3}\right)V_3$$

if $R_1 = R_2 = R_3 = R$ then

$$V_{out} = -\frac{R_F}{R}(V_1 + V_2 + V_3)$$

and the output voltage is proportional to the sum of the input voltages. For only one input and a constant reference voltage

$$V_{out} = -\frac{R_F}{R_I}V_{in} - \frac{R_F}{R_R}V_{ref}$$

where the second term represents an offset voltage. This provides a convenient method tfor obtainint an output signal with any required voltage offset.

A substracter is shown in figure 6-b. Input v_1 passes throug an inverter, which has gain -1. The resulting output voltage is thus the difference of the two input voltages, or

$$v_{out} = -\frac{R_F}{R_1}(v_2 - v_1)$$

By choosing $R_F = R_1$, we would obtain a simple subtracted for which $v_{out} = v_2 - v_1$

2.5 Differentiating, integrating and logarithmic amplifiers

To obtain a differentiation circuit we replace the inpur resistor of the inverting amplifier with a capacitor as shown in figure 7-a Equating the currents that flow through the resistor and the

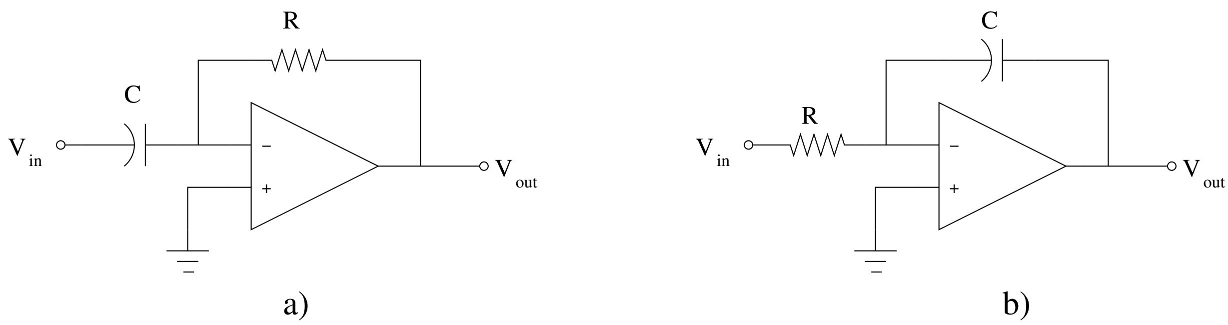


Figure 7: a)Differntiation circuit b) Integration circuit

capacitor, we obtain

$$C\frac{dv_{in}}{dt} = -\frac{v_{out}}{R} \rightarrow v_{out} = -RC\frac{dv_{in}}{dt}$$

Integration is obtained by reversing the resistor and the capacitor as shown in figure 7-b. Again equating currents

$$\frac{v_{in}}{R} = -C\frac{dv_{out}}{dt} \rightarrow \frac{dv_{out}}{dt} = -\frac{v_{in}}{RC} \rightarrow v_{out} = -\frac{1}{RC}\int v_{in}dt$$

Nonlinear input-output relationships can be produced by placing nonlinear elements in the feedback path of an opamp. A logarithmic amplifier gives an output voltage which is

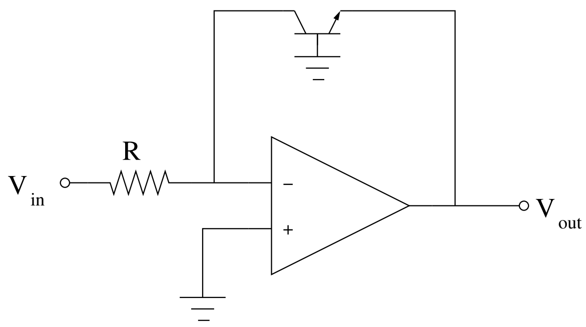


Figure 8: Logarithmic amplifier

proportional to the logarithm of the input voltage. A diode or a transistor can produce this effect. Figure8 shows a grounded base transistor for which we have

$$i_c = \alpha I_0 \exp(-ev_o/kT)$$

where v_o is the emitter-to-base voltage. The collector current can be expressed in terms of the input voltage as $i_c = v_{in}/R$ and taking into account that the inverting point is a virtual ground:

$$\frac{v_{in}}{R} = \alpha I_0 \exp(-ev_o/kT)$$

so taking logarithms we obtain:

$$v_{out} = -\frac{kT}{e} \ln \frac{v_{in}}{\alpha I_0 R}$$

If we were placed a diode or transistor in the input loop and a resistor in the feedback loop, we would obtain an exponential or antilog amplifier. Now that we have a log and an antilof amplifier we can construct a multiplier, that is, a circuit that can multiply two signals. If we sum the ouput of two logarithmic amplifiers and then pass the output of the combination through an antilog amplifier, the resulting signal will be proportional to the product of the two signals.

3 Active filters

As we have already seen filters are circuits able to allowing to pass certains frequencies and stopping signals with another circuits. Active filters uses opamps combined with passive circuits RC,RL or RLC. The active components provide a gain in tension and the passive ones make the frequency selection.

Some definitions before continue:

Cutoff frequency: Is the frequency at which the gain has decreased a factor $1/\sqrt{2} = 0.707$ or -3dB.

Bandwidth: Is the frequency range between the inferior and superior cutoff frequencies of a circuit.

Central frequency: In case that there are two cutoff frequencies (f_{c1} and f_{c2}), the central frequency can be defined as the geometrical mean of these frequencies:

$$f_0 = \sqrt{f_{c1} f_{c2}}$$

Quality factor: Also in case of two cutoff frequencies the quality factor Q is defined as the ratio between the central frequency(f_0) and the bandwidth (BW)

$$Q = \frac{f_0}{BW} = \frac{\sqrt{f_{c1} f_{c2}}}{f_{c1} - f_{c2}}$$

The value of Q informs about the selectivity if the filter, bigger is the Q value smaller is the bandwidth and much mor selective is for the frequency f_0.

dB/decade: A change by a factor 10 in frequency is called a decade. This value shows the slope of the attenuation as a function of the frequency before the inferior cutoff frequency or after the superior cutoff frequency. This value is usually -20 dB/decade.

db/octave: An octave (same term as in music) is a factor 2 in frequency. The attenuation in terms of octaves is -6db/octave.

Pole: It is each of the individual (passive) circuits used in a filter. Each pole usually have an attenuation of -20db/decade. If we combine two poles the attenuation achieved is -40db/decade and so forth. The name pole derives from the method of analysis that involves complex transfer functions in the complex frequency plane.

Basically we can found four kind of filters:

a) Low-Pass filters. Allow pass frequencies from 0 Hz to the superior frequency.

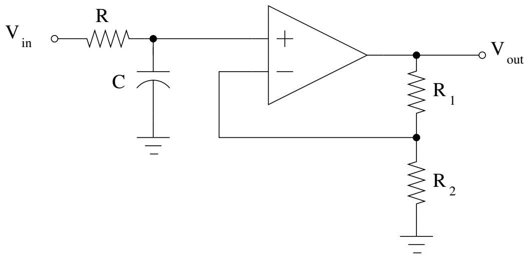
b) High-Pass filters. Allow pass frequencies from a inferior cutoff frequency to the infinity.

c) Band-pass filter. Allow pass just a band of frequencies between two cutoff frequencies.

d) Band-supress filter. Supress a band of frequencies between two cutoff frequencies.

3.1 Low-pass filters

3.1.1 1-pole filter

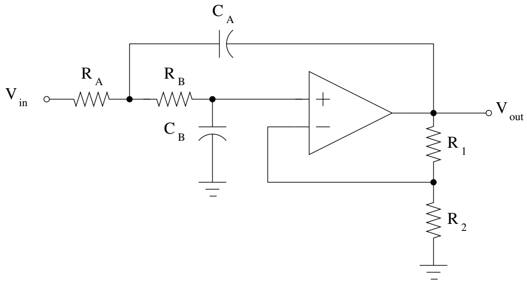


$$f_c = \frac{1}{2\pi RC}$$

$$Attenuation = -20dB/decade$$

$$A_{bf} = 1 + \frac{R_1}{R_2}$$

3.1.2 2-pole filter(Sallen-Key)



$$f_c = \frac{1}{2\pi\sqrt{R_A R_B C_A C_B}}$$

$$Attenuation = -40dB/decade$$

$$A_{bf} = 1 + \frac{R_1}{R_2}$$

4 Comparators

A comparator is a device that compares two input signals and as output gives a binary answer (high/low) depending if one signal is above or under the level fixed by the other called reference. The simplest form of such device is made with an opamp with no feedback as shown in figure 9. The reference voltage is set in the inverting inout and the input signal in the non-inverting input. If the input signal is above or under the reference, just only some tenths of milivolts, due to the high gain of the opamp, the output satures the opamp to the positive/negative value.

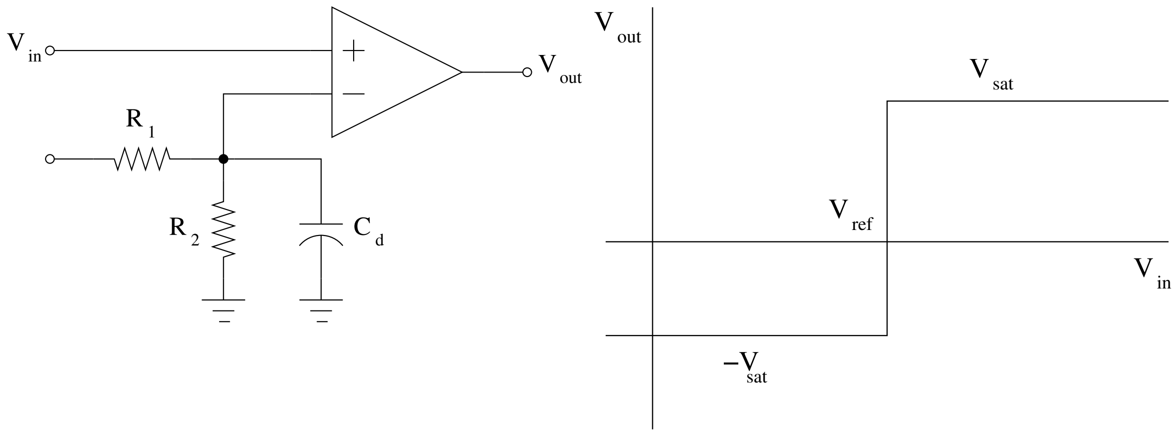


Figure 9: Comparator circuit

$$v_{ref} = \frac{R_2}{R_1 + R_2} V_{CC}$$

The capacitor connected to the inverting input is a decoupling capacitor that will reduce the power supply rippling and the noise in this input acting as a low-pass filter with the equivalent resistance $R_1||R_2$.

Although an ordinary opamp can be used as comparator, there are special integrated circuit intended for use as comparators designed to provide a high-speed response. The main difference between comparators and opamps is in the output stage. Opamps, as we have seen have a push-pull stage, but comparators usually have an “open-collector” output with grounded emitter (see figure 10. By supplying an external resistor connected to a voltage the positive output will be at that voltage and the negative one at ground. The external resistor “completes” the internal circuit providing a load resistor to a npn transistor. As the transistor operates as a saturated switch the value of the resistor is not critical. Open-collector output is a usual configuration that can be found in a lot of integrated circuits.

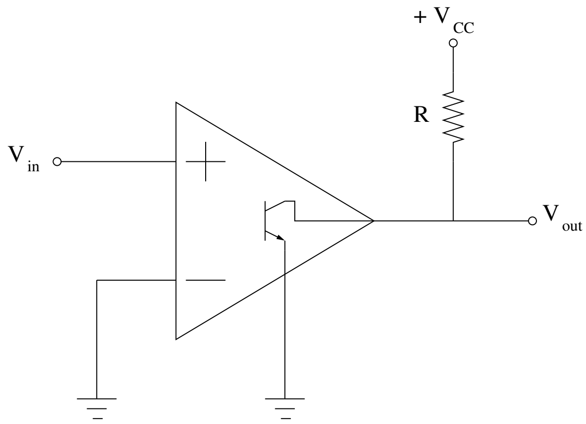


Figure 10: Comparatorn with an open collector output

5 Schmitt trigger

If the input of a comparator has noise, the output change almost randomly if the input is near the reference point. A positive feedback can solve this unconvinient behaviour. This setup is known as Schmitt trigger and is shown in figure 11-a

If the output is saturated positively then a positive voltage is reinjected to the non-inverting input. This reinjection makes the output to be positive. If the output is saturated negatively, is then a negative tension what is reinjected in the non-inverting input. In both cases the positive feedback reinforce the current output level. The effect of this is that there are two threshold for the comparator. The high threshold that applies when the ouput is saturated positively and the low threshold when is saturated negatively. In both cases, positive reaction reinforces the output voltage.

The two voltage thresholds are

$$V_{ref}^{high} = +BV_{sat} = \frac{R_2}{R_1 + R_2} V_{sat}$$

$$V_{ref}^{low} = -BV_{sat} = \frac{R_2}{R_1 + R_2} V_{sat}$$

This means that if the output is saturated positively then the inverting input should go a bit above V_{ref}^{high} to change to the negative level and if it is saturated negatively should go a bit belwo V_{ref}^{low} to change to the positive level. This behaviour produces a kind of hysteresis that avoids the random behaviour due to noise around a single threshold level, (see figure 11-b). The difefence between both reference voltages is known as hysteresis voltage. In figure 11-c is shown how it works this principle.

The threshold points can be easily translated with an extra resistor, as shown in figure 11-d, connected to a potencial, that set the center of the hystersis loop to

$$V_{cen} = \frac{R_2}{R_2 + R_3} V_{CC}$$

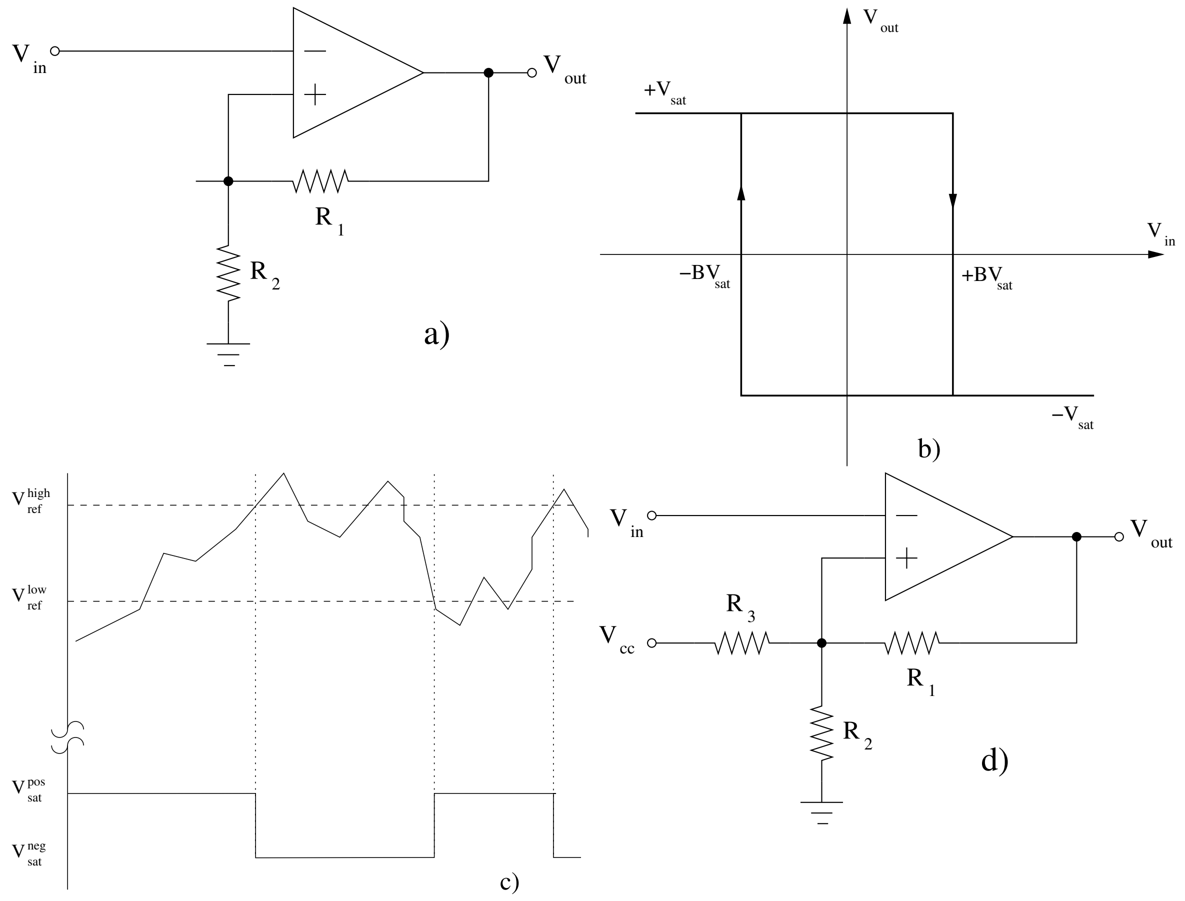


Figure 11: Scmitt trigger

The two thresholds are

$$V_{ref}^{high} = V_{cc} + BV_{sat} = \frac{R_2}{R_2 + R_3} V_{CC} + \frac{R_2||R_3}{R_1 + R_2||R_3} V_{sat}$$

$$V_{ref}^{low} = V_{cc} - BV_{sat} = \frac{R_2}{R_2 + R_3} V_{CC} - \frac{R_2||R_3}{R_1 + R_2||R_3} V_{sat}$$