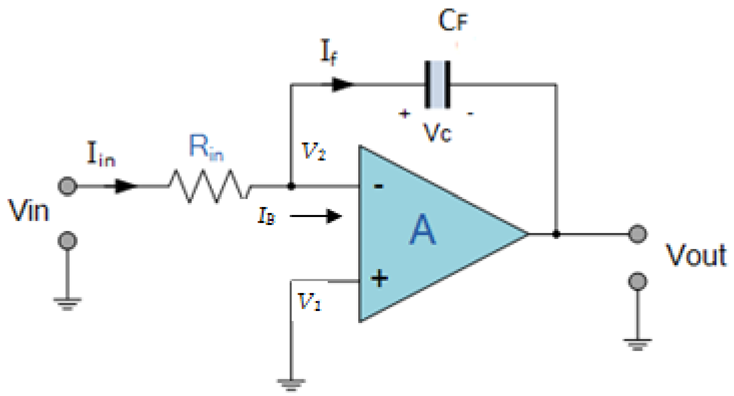
THE OPERATIONAL AMPLIFIER

THE INTEGRATOR

A circuit in which the output voltage waveform is the integral of the input waveform is the *integrator* or the *integration amplifier*. Such a circuit is obtained by using a basic inverting amplifier configuration if the feedback resistor R_F is replaced by a capacitor C_F.



The expression for the output voltage V_o can be obtained by writing Kirchhoff's current equation at node V_2

$$I_{in} = I_B + I_f$$

Since I_B is negligibly small,

$$I_{in} \cong I_f$$

The relationship between current through and voltage across the capacitor is

$$i_c = C\frac{dV_c}{dt}$$

Therefore

$$\frac{V_{in} - V_2}{R_{in}} = C_F \frac{d}{dt}(V_2 - V_{out})$$

However $V_1 = V_2 \cong 0$ because A (input impedance of OPAMP) is very large therefore

$$\frac{V_{in}}{R_{in}} = C_F \frac{d}{dt} (-V_{out})$$

The output voltage can be obtained by integrating both sides with respect to time

$$\int_0^t \frac{V_{in}}{R_{in}} dt = \int_0^t C_F \frac{d}{dt} (-V_{out}) dt$$

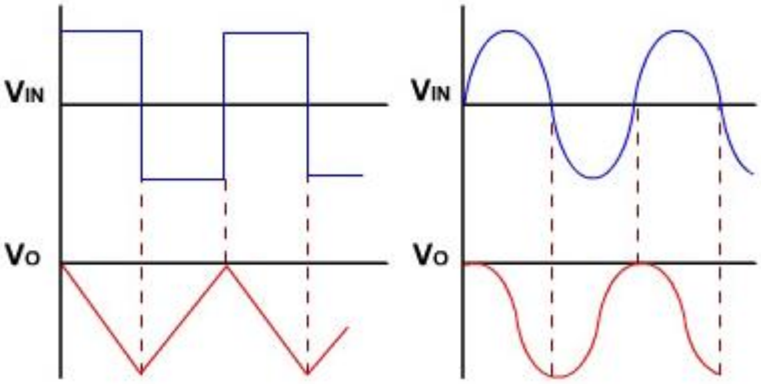
$$= C_F (-V_{out})$$

Therefore

$$V_{out} = -\frac{1}{R_{in} C_F} \int_0^t \frac{V_{in}}{R_{in}} dt + C \qquad [1]$$

Where C is the integration constant and is proportional to the value of the output voltage V_{out} at time t=0 seconds.

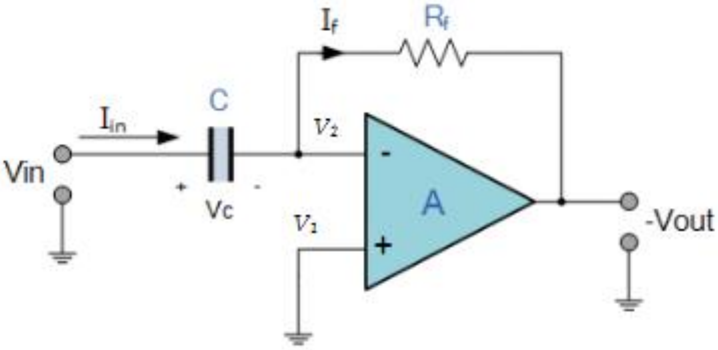
Equation [1] indicates that the output voltage is directly proportional to negative integral of input voltage and inversely proportional to time constant $(R_{in} C_F)$. For example, if the input is sine wave, the output is cosine wave; or if the input is square wave, the output will be triangular wave.



Operational Amplifier Integrator Waveforms

THE DIFFERENTIATOR

A circuit in which the output voltage waveform is the derivative of the input waveform is the *differentiator* or the *differentiation amplifier*. Such a circuit is obtained by using a basic inverting amplifier configuration if the input resistor Rin is replaced by a capacitor C.



The expression for the output voltage V_{out} can be obtained by writing Kirchhoff's current equation at node V_2

$$I_{in} = I_B + I_f$$

Since I_B is negligibly small,

$$I_{in} \cong I_f$$

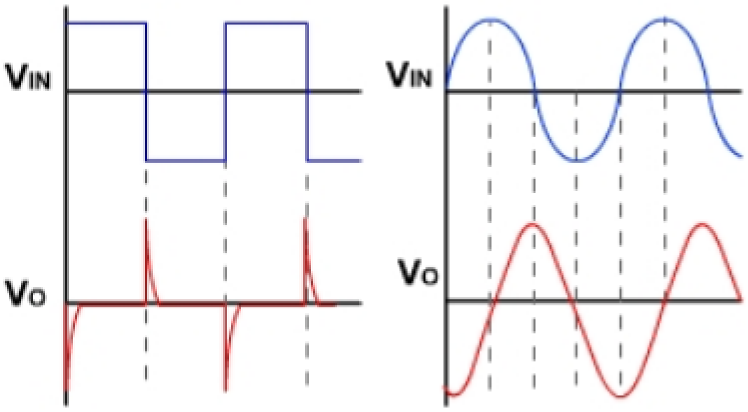
$$C\frac{d}{dt}(V_{in} - V_2) = \frac{V_2 - V_{out}}{R_f}$$

However $V_1 = V_2 \cong 0$ because A (input impedance of OPAMP) is very large therefore

$$C\frac{d}{dt}(V_{in}) = \frac{-V_{out}}{R_f}$$

$$V_{out} = -CR_f\frac{d}{dt}(V_{in}) \qquad [1]$$

Thus the output voltage V_{out} is equal to CR_f times negative instantaneous rate of change of input voltage V_{in} with time. The cosine wave produce sine output or square input will produce a spike wave output.



Operational Amplifier Differentiator Waveforms

COMPARATOR

A Comparator is a circuit which compares a signal voltage at one input of an OPAMP known as reference at the other input.

When the non-inverting voltage is greater than the inverting voltage, the comparator produces high output voltage equal to the positive saturation voltage.

When the non-inverting voltage is less than the inverting voltage, the comparator produces low output voltage equal to the negative saturation voltage.

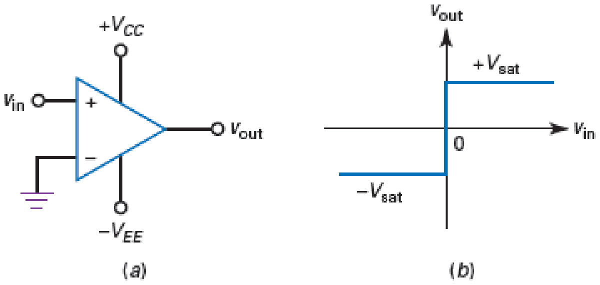
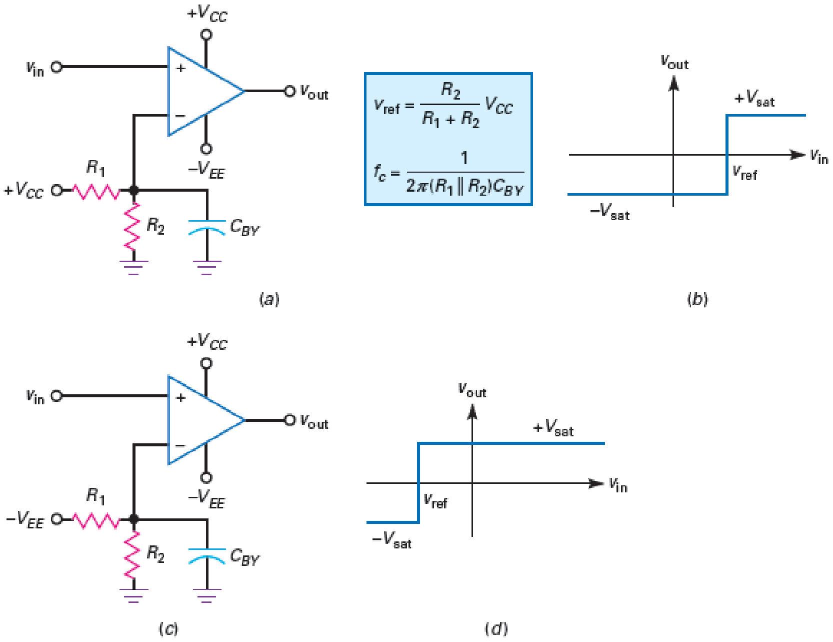


Fig. 1 (*a*) Comparator; (*b*) input/output response.

The simplest way to build a comparator is to connect an op amp without feedback resistors, as shown in Fig. 1(a). Because of the high open-loop voltage gain, a positive input voltage produces positive saturation, and a negative input voltage produces negative saturation. The comparator of Fig. 1(*a*) is called a **zero-crossing detector** because the output voltage ideally switches from low to high or vice versa whenever the input voltage crosses zero. Figure 1(b) shows the input-output response of a zero-crossing detector.

Comparators with Nonzero References



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

$$f_c = \frac{1}{2\pi(R_1 \| R_2)C_{BY}}$$

Figure 2 (*a*) Positive threshold; (*b*) positive input/output response; (*c*) negative threshold; (*d*) negative input/output response

The voltage divider produces the following reference voltage for the inverting input

$$V_{ref} = \frac{R2}{R1 + R2} Vcc$$

When V_{in} is greater than V_{ref}, the differential input voltage is positive and the output voltage is high. When V_{in} is less than V_{ref}, the differential input voltage is negative and the output voltage is low. Figure 2 (b) shows the **transfer characteristic** (input/output response).The trip point is now equal to V_{ref}. When V_{in} is greater than V_{ref}, the output of the comparator goes into positive saturation. When V_{in} is less than V_{ref}, the output goes into negative saturation.

If a negative limit is preferred, connect $-V_{EE}$ to the voltage divider, as shown in Fig. 2 (c). Now a negative reference voltage is applied to the inverting input. When V_{in} is more positive than V_{ref}, the differential input voltage is positive and the output is high, as shown in Fig. 2(d). When V_{in} is more negative than V_{ref}, the output is low.

SCHMITT TRIGGER

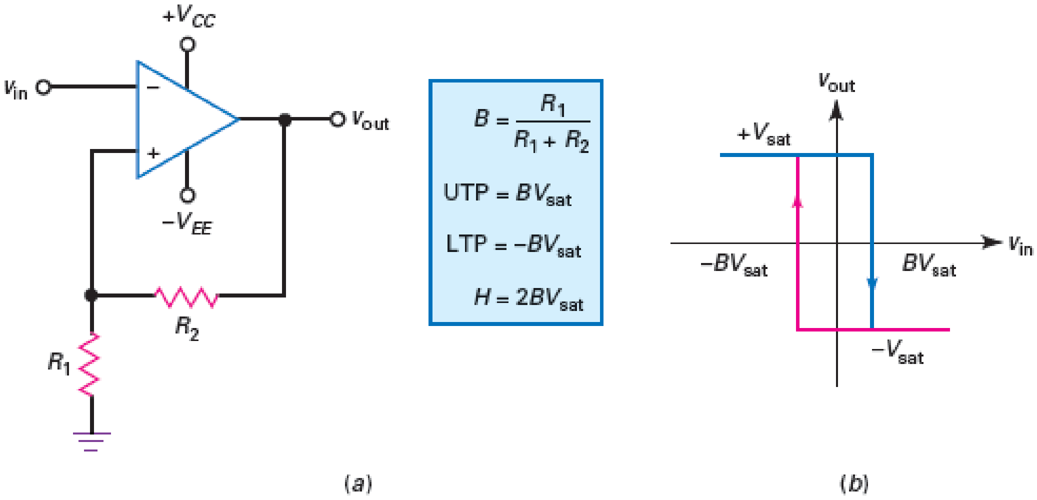


Figure 1: (*a*) Inverting Schmitt trigger; (*b*) input/output response has hysteresis.

The input voltage is applied to the inverting input. Because the feedback voltage at the non-inverting input is aiding the input voltage, the feedback is *positive.* A comparator using positive feedback like this is usually called a **Schmitt trigger.**

When the comparator is positively saturated, a positive voltage is fed back to the non-inverting input. This positive feedback voltage holds the output in the high state. Similarly, when the output voltage is negatively saturated, a negative voltage is fed back to the non-inverting input, holding the output in the low state. In either case, the positive feedback reinforces the existing output state. The feedback fraction is:

$$\beta = \frac{R1}{R1 + R2}$$

When the output is positively saturated, the reference voltage applied to the non-inverting input is $V_{ref} = +\beta V_{sat}$. When the output is negatively saturated, the reference voltage is $V_{ref} = -\beta V_{sat}$

The output voltage will remain in a given state until the input voltage exceeds the reference voltage for that state. For instance, if the output is positively saturated, the reference voltage is $+\beta V_{sat}$. The input voltage must be increased to slightly more than $+\beta V_{sat}$ to switch the output voltage from positive to negative, as shown in Fig. 1 (b). Once the output is in the negative state, it will remain there indefinitely until the input voltage becomes more negative than $-\beta V_{sat}$ Then, the output switches from negative to positive (Fig. 1*b*).

Hysteresis

The unusual response of Fig.1 (b) has a useful property called **hysteresis.** In Fig.1(b), the trip points are defined as the two input voltages where the output voltage changes states. The *upper trip point (UTP)* has the value

$$UTP=+\beta V_{sat}.$$

and the *lower trip point (LTP)* has the value

$$UTP= -\beta V_{sat}.$$

The difference between these trip points is defined as the hysteresis (also called the *dead band*):

$$H=UTP-LTP$$
$$H= +\beta V_{sat}. - (-\beta V_{sat}.)$$
$$H= 2\beta V_{sat}.$$