Op Amp Circuits

Schmitt Trigger, Monostable, and Astable Circuits

Positive and negative feedback

The inverting amplifier circuit is shown in Fig. 1 (a). Let us show qualitatively that the

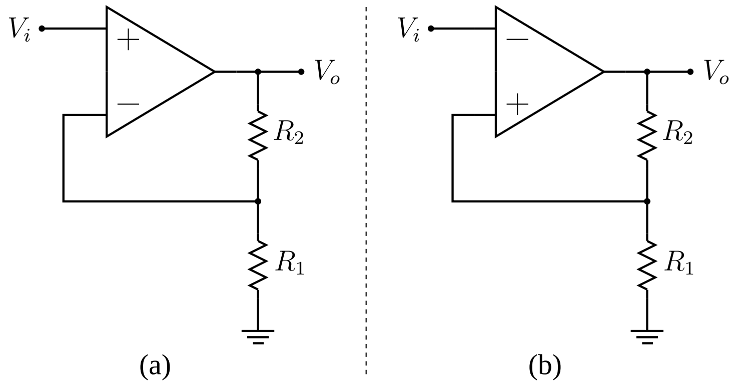

Figure 1: (a) Inverting amplifier, (b) Schmitt trigger.

feedback in this circuit is *negative*. Consider an increase in the output voltage V_o. This causes an increase in $V_- = \dfrac{R_1}{R_1 + R_2}\, V_o$. Since the op amp output is $V_o = A_V\,(V_s - V_-)$, an increase in V_- causes V_o to decrease. We see that there is a balancing process here: an increase in V_o has resulted in a decrease in V_o. The circuit is therefore stable, with the op amp operating in the linear region[1].

Consider now the circuit in Fig. 1 (b), which is identical to the inverting amplifier except that the inverting and non-inverting inputs of the op amp have been interchanged. Imagine once again V_o to have increased. Consequently, $V_+ = \dfrac{R_1}{R_1 + R_2}\, V_o$ also increases, and $V_o = A_V\,(V_+ - V_s)$ increases further. The feedback process is now *positive*, making the circuit unstable. In practice, the op amp output cannot increase or decrease indefinitely and saturates at $+V_{\rm sat}$ or $-V_{\rm sat}$.

Is such an unstable circuit of any use at all? It surely is, as we will see in this experiment.

V_o versus V_i relationship

When V_s is sufficiently large, the ouput voltage V_o of the circuit of Fig. 1 (b) (known as the "Schmitt trigger") is $-V_{\rm sat}$ as shown in Fig. 2. The voltage at the non-inverting input terminal of the op amp V_+ (with respect to ground) is then $V_+ \equiv V_{TL} = -V_{\rm sat}\, \dfrac{R_1}{R_1 + R_2}$. As V_i is reduced and becomes smaller than V_{TL}, the op amp output changes from $-V_{\rm sat}$ to $+V_{\rm sat}$ (since $V_- < V_+$), as shown in Fig. 2. Now, V_+ is equal to $V_+ \equiv V_{TH} = +V_{\rm sat}\, \dfrac{R_1}{R_1 + R_2}$. If V_i is reduced further, this state of affairs continues to hold. If V_i is increased, the output flips when V_i crosses V_{TH}.

[1]We will assume that the input voltage or the gain R_2/R_1 is small enough so that the op amp does not enter saturation.

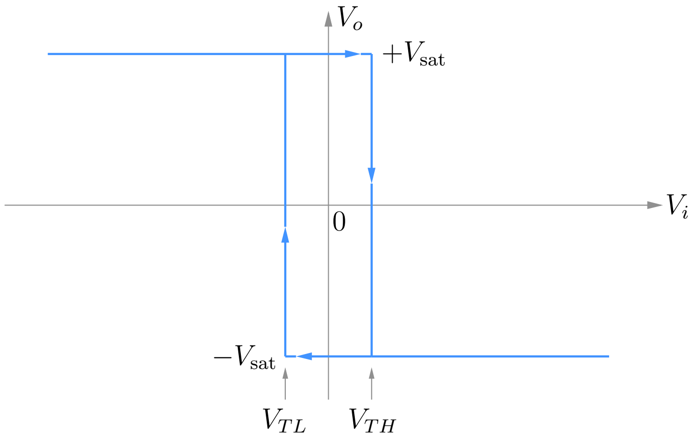

Figure 2: V_o versus V_i relationship for the Schmitt trigger of Fig. 1 (b).

We can see that the Schmitt trigger is a comparator with hysterisis (or "memory"). Since the input threshold voltage (V_{TH} or V_{TL}), at which the output flips, depends on the "state" of the circuit.

Note that the high and low threshold voltages, V_{TH} and V_{TL}, respectively, are symmetric about 0 V for the Schmitt trigger circuit of Fig. 1 (b), i.e., $V_{TH} = -V_{TL}$. By connecting a DC voltage source V_a, we can make them asymmetric (see Fig. 3), as shown below.

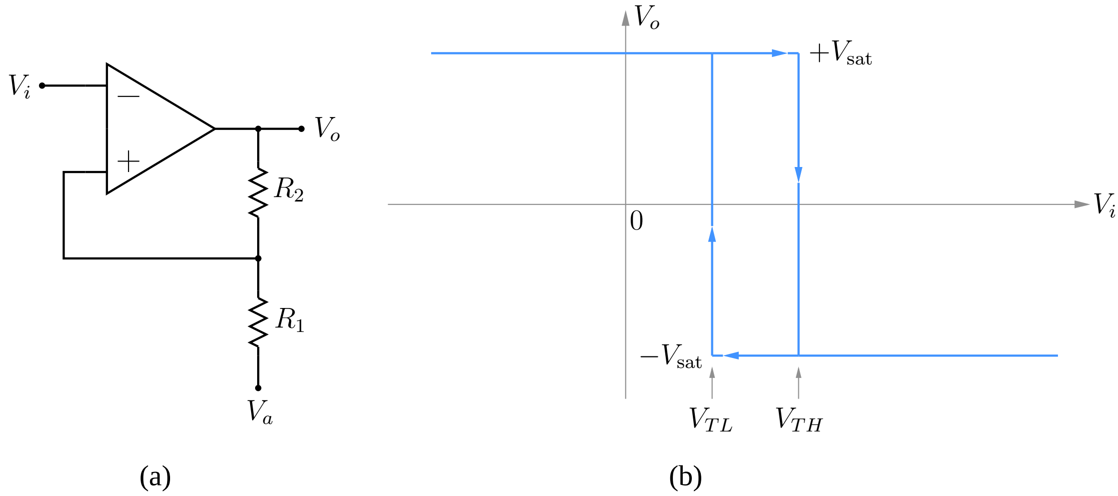

Figure 3: (a) Schmitt trigger circuit with asymmetric threshold voltages, (b) V_o versus V_i relationship. Note that $\dfrac{V_{TH}+V_{TL}}{2} = V_a \dfrac{R_2}{R_1+R_2}$.

When V_o is $+V_{\rm sat}$, we have

$$V_+ = +V_{\rm sat}\,\frac{R_1}{R_1+R_2} + V_a\,\frac{R_2}{R_1+R_2} \tag{1}$$

since the current entering the non-inverting input of the op amp can be neglected. Similarly, when V_o is $-V_{\rm sat}$, we have

$$V_+ = -V_{\rm sat}\,\frac{R_1}{R_1+R_2} + V_a\,\frac{R_2}{R_1+R_2}\,. \tag{2}$$

As an example, let $V_{\rm sat}=12\,{\rm V}$, $V_a=2\,{\rm V}$, $R_1=1\,{\rm k}\Omega$, $R_2=9\,{\rm k}\Omega$, then the threshold voltages can be calculated using Eqs. 1 and 2 as $V_{TH}=3\,{\rm V}$ and $V_{TL}=0.4\,{\rm V}$.

The output voltage of the Schmitt trigger can be limited by using a Zener pair as shown in Fig. 4. Let the breakdown voltage of the Zener diode be $V_Z=4.3\,{\rm V}$ and the turn-on voltage be $V_{\rm on}=0.7\,{\rm V}$. Consider the op amp output V_{o1} to be $+V_{\rm sat}$, say, $+12\,{\rm V}$. Because of the diode pair,

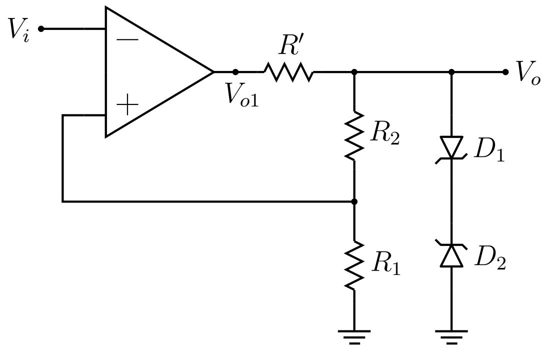

Figure 4: Schmitt trigger circuit with V_o limited to $\pm(V_Z+V_{\rm on})$.

the output voltage V_o gets limited to $V_{\rm on}+V_Z=5\,{\rm V}$, with D_1 in forward conduction, and D_2 in reverse breakdown. Note that the difference between V_{o1} and V_o appears across the resistor R' which must be chosen to limit the op amp output current to a reasonable value (a few mAs). Connecting the diode pair directly to the op amp output would lead to unhealthy events.

In a similar manner, when V_{o1} is $-V_{\rm sat}$ ($-12\,{\rm V}$), the output voltage V_o gets limited to $-(V_{\rm on}+V_Z)=-5\,{\rm V}$, with D_2 in forward conduction, and D_1 in reverse breakdown.

Astable multivibrator

The astable multivibrator (see Fig. 5 (a) is an oscillator which produces a square wave output voltage. Its frequency can be controlled by changing the R and C values. To understand the operation of this circuit, let us assume that $V_C=0\,{\rm V}$ and $V_o=V_m$ at $t=0$ (i.e., we are at $(0,V_m)$ in the V_C-V_o plane of Fig. 5 (c). Since the op amp input resistance is very large, we have a simple situation of a capacitor charging to $+V_m$ with a time constant $\tau=RC$, i.e., $V_C(t)=V_m\left(1-e^{-t/RC}\right)$, as shown in Fig. 6 (a). However, when V_C crosses V_{TH} (see Fig. 5 (c)), V_o changes to $-V_m$, and now the capacitor starts discharging toward $-V_m$ (again, with the same time constant $\tau=RC$). When V_C crosses V_{TL}, the output flips to $+V_m$, and this process continues, resulting in a square wave output.

To calculate the frequency of oscillation, let $V_C(0)=V_{TL}$, as shown in Fig. 6 (b). The capacitor voltage in the interval $0<t<t_1$ is given by

$$V_C(t) = A\,e^{-t/\tau} + B\,, \tag{3}$$

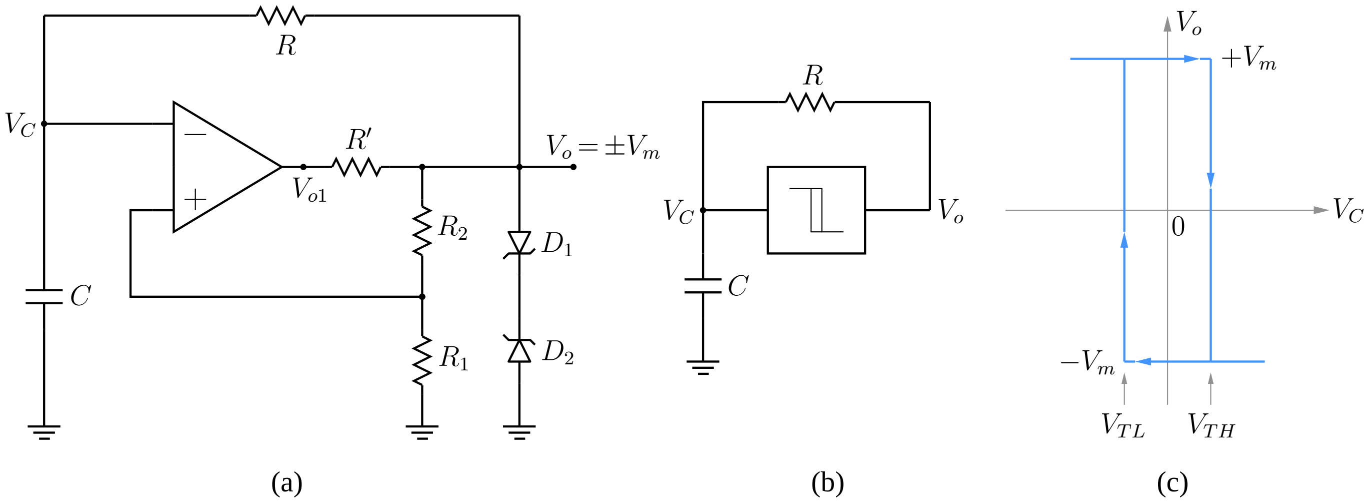

Figure 5: (a) Astable multivibrator circuit, (b) simplified diagram, (c) V_o versus V_C relationship.

where $A+B=V_{TL}$ (since $V_C(0)=V_{TL}$), and $B=V_m$ (since the capacitor is charging toward V_m), giving

$$V_C(t) = (V_{TL} - V_m)\, e^{-t/\tau} + V_m \quad \text{for} \;\; 0 < t < t_1\,. \tag{4}$$

At $t=t_1$, we have $V_C=V_{TH}$, i.e.,

$$V_{TH} = (V_{TL} - V_m)\, e^{-t_1/\tau} + V_m \quad \rightarrow \quad t_1 = \tau\, \log\left(\frac{V_m - V_{TL}}{V_m - V_{TH}}\right)\,. \tag{5}$$

In the interval $t_1 < t < T$, the capacitor discharges toward $-V_m$, and we can write

$$V_C(t) = A'\, e^{-(t-t_1)/\tau} + B'\,, \tag{6}$$

where $A'+B'=V_C(t_1)=V_{TH}$, and $B'=V_C(\infty)=-V_m$. We now get

$$V_C(t) = (V_{TH} + V_m)\, e^{-(t-t_1)/\tau} - V_m \quad \text{for} \;\; t_1 < t < T\,. \tag{7}$$

Since $V_C(T)=V_{TL}$, we can find $(T-t_1)$ as

$$V_{TL} = (V_{TL} + V_m)\, e^{-(T-t_1)/\tau} - V_m \quad \rightarrow \quad (T-t_1) = \tau\, \log\left(\frac{V_m + V_{TH}}{V_m + V_{TL}}\right)\,. \tag{8}$$

If $V_{TH}=-V_{TL}\equiv V_T$, the intervals t_1 and $(T-t_1)$ are equal, and we get

$$t_1 = T - t_1 \equiv \frac{T}{2} = \tau\left(\frac{V_m + V_T}{V_m - V_T}\right)\,, \tag{9}$$

and the period of oscillation is

$$T = 2\tau\left(\frac{V_m + V_T}{V_m - V_T}\right)\,. \tag{10}$$

Those who prefer dimensionless elegance can write T as

$$T = 2\tau\left(\frac{1+\beta}{1-\beta}\right)\,, \quad \text{with} \;\; \beta = \frac{V_T}{V_m}\,. \tag{11}$$

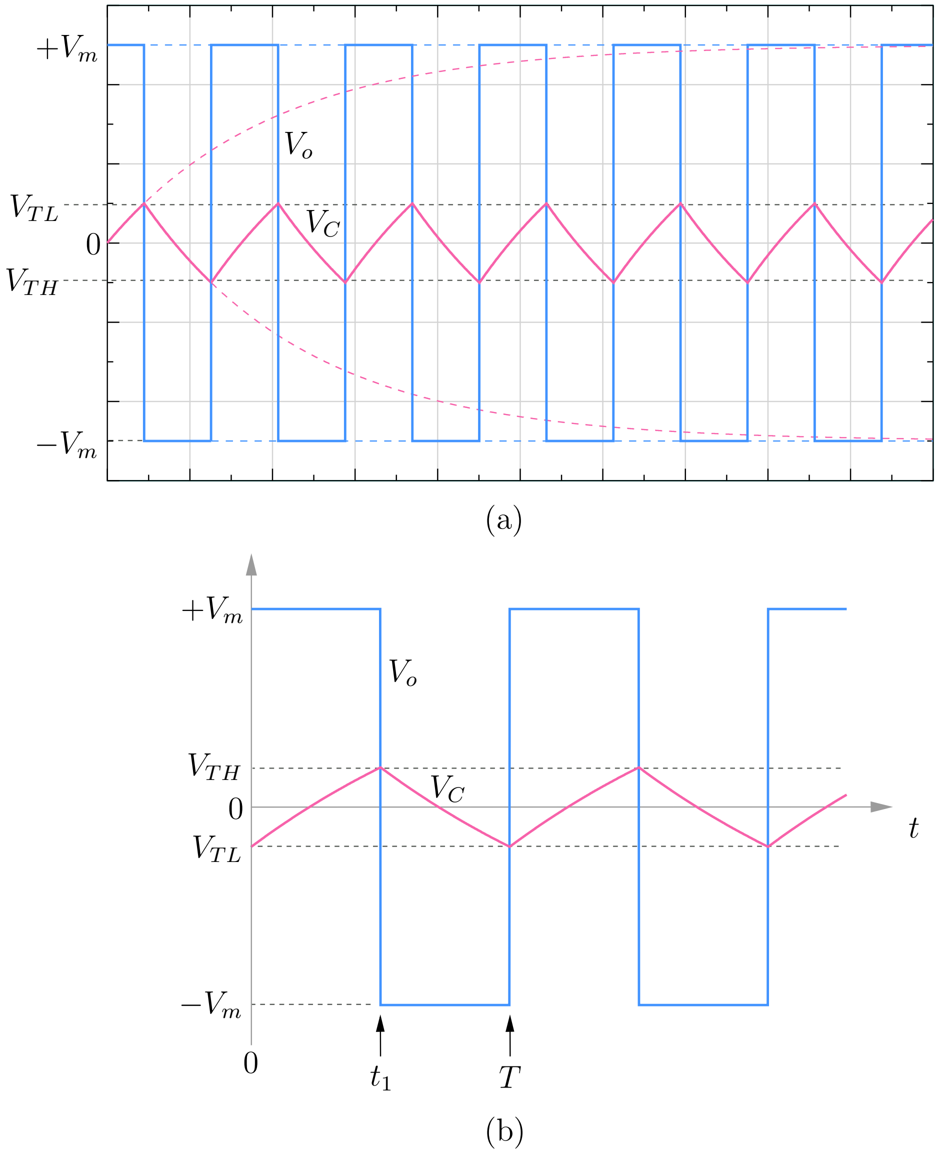

Figure 6: Waveforms for the astable multivibrator: (a) waveforms starting from $V_C(0) = 0\,\text{V}$, (b) waveforms in the steady state.

Monostable multivibrator

A monostable multivibrator has a "stable" state (say, $V_o = 0\,\text{V}$) and a "transient" state (say, $V_o = V_{\text{high}}$). Consider the circuit to be in the stable state (see Fig. 7) in the beginning. When a certain "event" occurs, it enters the transient state, remains in that state for a time interval T, and then returns to its stable state.

Fig. 8 (a) shows an implementation of the monostable multivibrator circuit using the Schmitt trigger of Fig. 4. Assume that the circuit is in the stable state in the beginning, viz., the push button is in the released state, the capacitor has charged to $+V' - (-V') = 2V'$, the input voltage V_- for the Schmitt trigger (with respect to ground) is $V_o = -V_m$ (with $V_m = V_Z + V_{\text{on}}$),

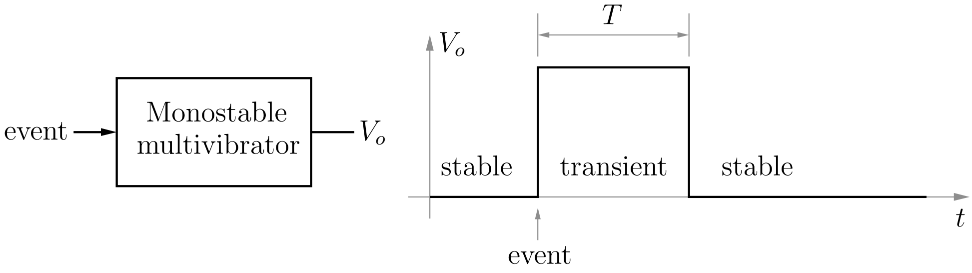

Figure 7: Operation of a monoastable multivibrator.

and $V_+ = -V_m \dfrac{R_1}{R_1 + R_2}$ (see Figs. 8 (c) and 8 (d)). At $t = t_1$, the push button is closed and released[2]. Closing the button discharges the capacitor, V_C becomes 0 V, V_- changes to $-V'$, and the output V_o to $+V_m$. When the push button is released, the capacitor starts charging. Since the input current of the op amp is negligibly small, the charging process can be described by

$$V_-(t) = A\, e^{-(t-t_1)/\tau} + B\,, \quad \text{for} \;\; t > t_1\,, \tag{12}$$

where $\tau = RC$. Using $V_-(t_1) = -V'$ and $V(\infty) = +V'$, we get $A = -2V'$, $B = V'$, i.e.,

$$V_-(t) = V'\,(1 - 2e^{-(t-t_1)})\,. \tag{13}$$

When V_- crosses V_{TH}, the output changes to $+V_m$ (at $t = t_1 + T$ in Fig. 8 (c)). The capacitor continues to charge, and in about five time constants, we have once again the original stable state that we started with at $t = 0$.

To calculate T, we simply substitute $V_-(t_1 + T) = V_{TH}$ in Eq. 13 and obtain

$$V_{TH} = V'\,(1 - e^{-T/\tau}) \quad \rightarrow \quad T = RC \times \log\left(\frac{V'}{V' - V_{TH}}\right)\,. \tag{14}$$

[2]We will assume that the time taken for pushing and releasing the button is much smaller than the time constant RC.

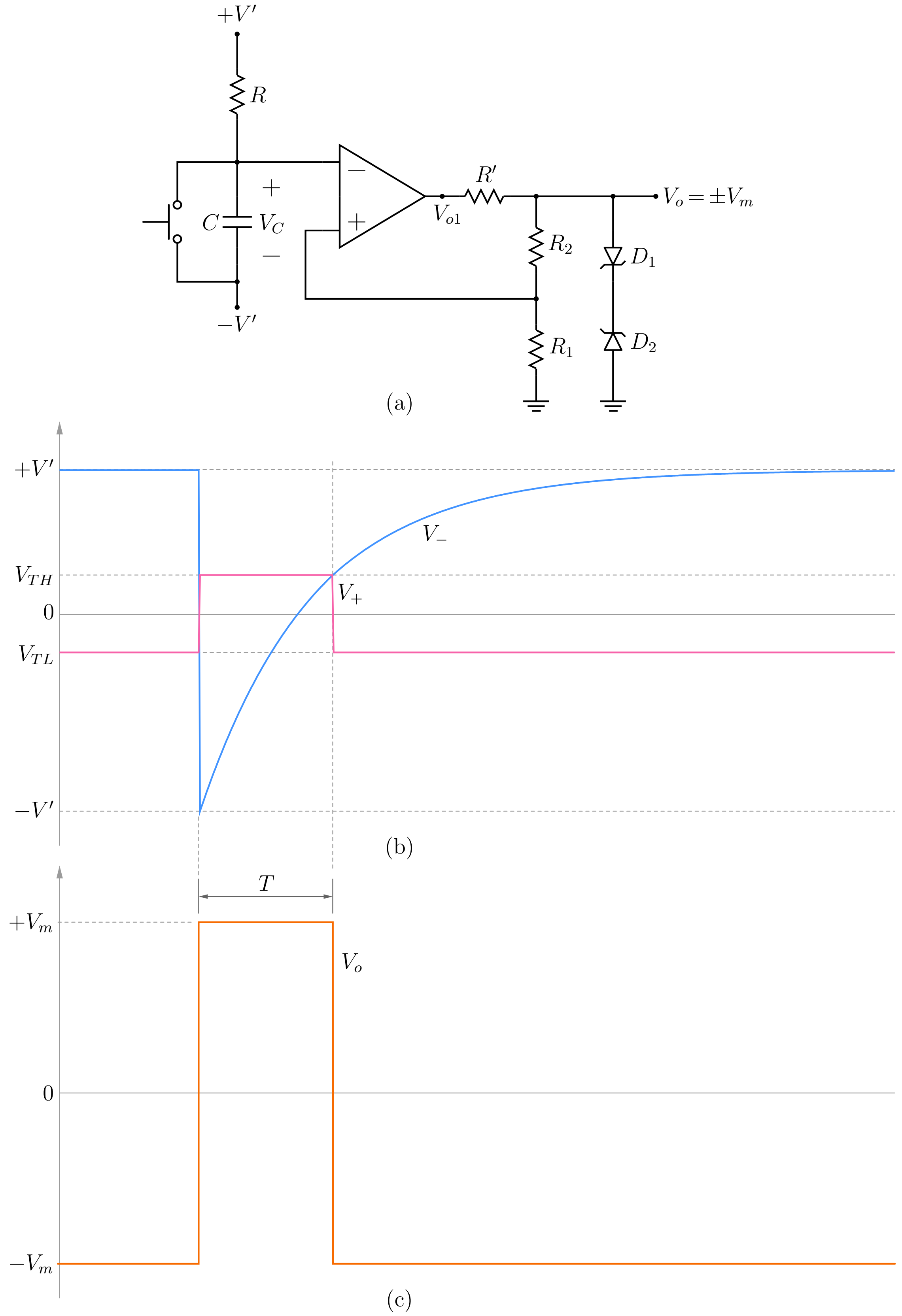

Figure 8: (a) Monoastable multivibrator circuit using a Schmitt trigger, (b) V_+ and V_- waveforms, (c) V_o waveform.