1 Notes on Comparators and Schmidt Trigger

The Comparator is a special circuit (Figure 1) that incorporates an Op-Amp at high gain together with an internal inverter (A in Figure 1) and a NPN transistor (B in Figure 1) at the output. The voltage levels that are switched at the output are controllable, so that decisions on an analog input (V_- in Figure 1) relative to a threshold level (V_+ in Figure 1) may be transformed into voltages used to control different logic families, e.g., TTL uses 0 V and 3.2 V as logic "0" and "1".

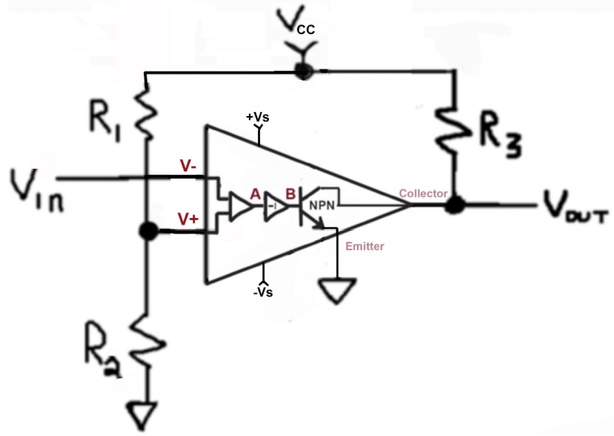

Figure 1.

2 Basic comparator

For the comparator circuit below (Figure 1), the collector of the NPN output transistor is connected to V_{CC} though a resistor, R_3, and the emitter is connected to ground, so that we have:

$$\begin{aligned} V_{out} &= 0 \qquad V_- > V_+ \\ &> 0 \qquad V_- < V_+. \end{aligned} \tag{2.1}$$

The threshold level is

$$V_+ = V_{CC} \frac{R_2}{R_1 + R_2}, \tag{2.2}$$

and any noise in the input is reflected as a chattering of voltage levels in the output (Figure 2).

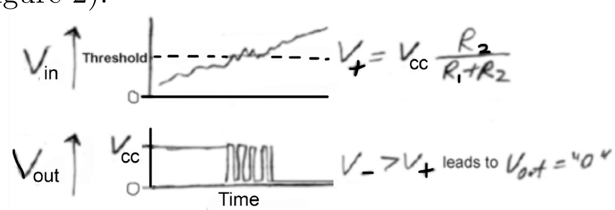

Figure 2.

3 Comparator with feedback

Let's now add a feedback resistor, R_4, so that the threshold will depends on the value of the output, V_{out} (Figure 3). There are two critical ingredients to make this work. First, the threshold must drop after the initially crossing of the input, V_-, as it increases past V_+. Contrawise, the threshold must increase when the input first decrease below V_+. This supplies hysteresis. We can achieve this goal noting that the comparator output decreases, i.e., from V_{CC} to 0 as the input crossed threshold from below (Figure 2), and vice versa. The second ingredient is that the value of the feedback is small, i.e., $R_4 >> R_1$, $R_4 >> R_2$, and $R_4 >> R_3$, so that the maximum output voltage is not substantially shifted from V_{CC}.

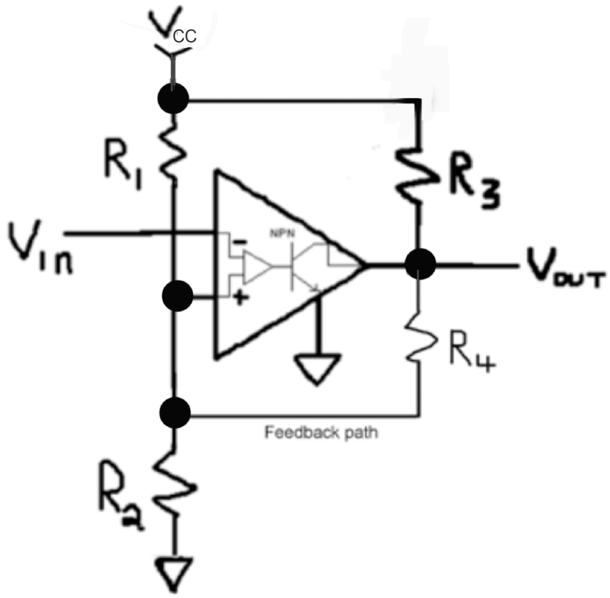

Figure 3.

Kirchoff's Current Law gives

$$0 = \frac{V_+ - V_{CC}}{R_1} + \frac{V_+}{R_2} + \frac{V_+ - V_{out}}{R_4} \tag{3.3}$$

so that

$$\begin{aligned} V_+ &= \frac{R_2 R_4 V_{CC} + R_1 R_2 V_{out}}{R_1 R_2 R_4} \\ &= \frac{R_2}{R_1 + R_2} \, \frac{V_{CC} + \frac{R_1}{R_4} V_{out}}{1 + \frac{1}{R_4} \frac{R_1 R_2}{R_1 + R_2}} \\ &\approx \frac{R_2}{R_1 + R_2} \left(V_{CC} + \frac{R_1}{R_4} V_{out} \right) \left(1 - \frac{1}{R_4} \frac{R_1 R_2}{R_1 + R_2} \right). \end{aligned} \tag{3.4}$$

where in the last step we used $1/(1+x) \approx 1 - x$ for small values of x.

3.1 Case of $V_{out} = 0$

$$V_+ = \frac{R_2}{R_1 + R_2} V_{CC} \left(1 - \frac{R_1}{R_4} \, \frac{R_2}{R_1 + R_2} \right). \tag{3.5}$$

3.2 Case of $V_{out} > 0$

We begin with Kirchoff's Current Law for the output, i.e.,

$$0 = \frac{V_{out} - V_{CC}}{R_3} + \frac{V_{out} - V_+}{R_4}. \tag{3.6}$$

Then

$$V_{out} = \frac{R_4}{R_3 + R_4} V_{CC} + \frac{R_3}{R_3 + R_4} V_+. \tag{3.7}$$

and

$$\begin{aligned} V_+ &\approx \frac{R_2}{R_1 + R_2}\left(V_{CC} + \frac{R_1}{R_3 + R_4}V_{CC} + \frac{R_1 R_3}{R_4(R_3 + R_4)}V_{CC}\right)\left(1 - \frac{1}{R_4}\frac{R_1 R_2}{R_1 + R_2}\right) \\ &\approx \frac{R_2}{R_1 + R_2}V_{CC}\left(1 + \frac{R_1}{R_4} - \frac{R_1 R_2}{R_4(R_1 + R_2)}\right) \\ &\approx \frac{R_2}{R_1 + R_2}V_{CC}\left(1 + \frac{R_1}{R_4}\frac{R_1}{R_1 + R_2}\right). \end{aligned} \tag{3.8}$$

where we dropped terms proportional to $1/R_4^2$. Note that, to the same approximation, the value of V_{out} of diminished so that

$$\begin{aligned} V_{out} &= 0 & V_- > V_+ \\ &= V_{CC}\left(1 - \frac{R_3}{R_4}\frac{R_2}{R_1 + R_2}\right) & V_- < V_+. \end{aligned} \tag{3.9}$$

The key result is that feedback adds hysteresis that shifts the threshold, and provides immunity to noise, independent of the detailed values of the components. The width of the hysteresis scales as R_1/R_2. An example with $R_1 = R_2 = R_3$ and $R_4 = 5R_1$ is shown in Figure 4.

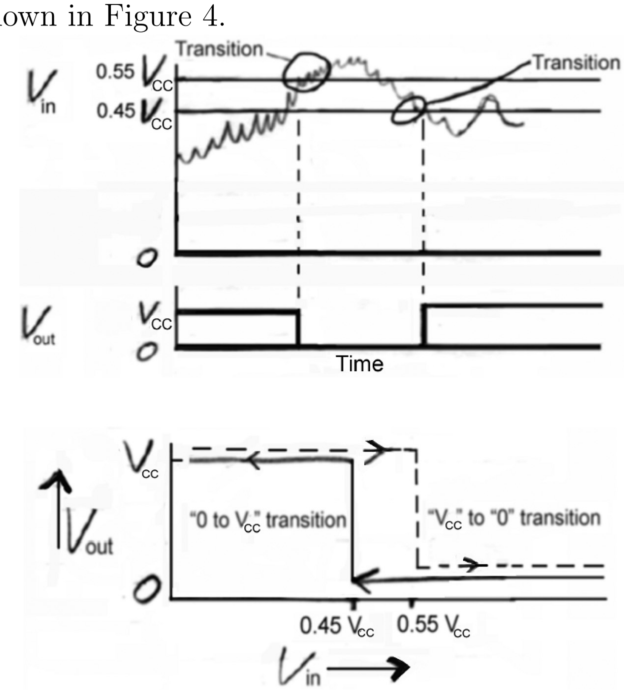

Figure 4.