Chapter 12

Common Switching Functional Blocks

Voltage Comparators

In many applications, it is necessary to cause a digital switching action when an analog voltage rises above or drops below some value. An example would be a case when we wanted a digital signal to turn on a “discharge” light when the battery voltage dropped below a specific point, say 12.5 volts for an automotive application. In this case, we would want a logic high (or low) when the battery voltage dropped below 12.5 volts.

We have seen how diodes and BJT base-emitter junctions as well as enhancement MOSFETs have thresholds where they beging to conduct. It would be possible to construct a circuit to create an output transition from low to high as the input voltage crossed the trigger point. As simple example would be an appropriate voltage divider to drop the battery voltage down to an appropriate level and feed it into the base of a transistor inverter followed by several more inverters to provide gain and make the output rail-rail transistion occur for a very small transition of the input signal.

A few years ago, discrete devices were used as discussed to create this voltage comparison function. However, integrated circuits allow the voltage comparator function to be done in a single integrated circuit chip. These chips are based on operational amplifiers circuits with a switching transistor at the output. A functional representation is shown in Figure 1.

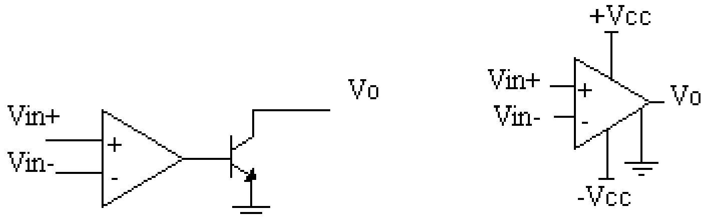

Figure 1. Functional representation of a voltage comparator and its symbol.

This circuit is simply an operational amplifier followed by a transistor whose emitter is connected to ground and whose collector is open. A typical application is shown in Figure 2. In this case a reference voltage is connected to the Vin- input or the inverting input. When the signal voltage at the Vin+ input rises above the reference, the output voltage goes high. What’s really happening is that the output of the op-amp goes low, cutting off the transistor so the external pull-up resistor causes the output voltage to go high. When the input voltage goes below the reference, the output of the op-amp goes high, causing the transistor to saturate and pull the output low. If you reversed the connection of the two input signals, the output function would switch directions. All of the internal buffering and interfacing is taken care of within the op-amp part of the circuit.

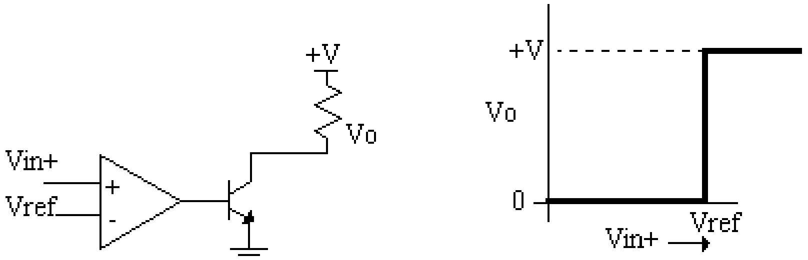

Figure 2. Typical application of a voltage comparator and its voltage transfer characteristic

The VTC shows an abrupt switch when the input voltage passes the reference voltage. The transition is not instantaneous, but occurs over a few millivolts of the input signal for most comparators. The LM311 whose data is given on page 100 of the “‘Design Compendium”, shows a minimum gain of 40 V/mV, or a gain of 40,000. Thus, for the example above, if +V is 5 volts, the transistion occurs with a change of 0.125 mV at the input.

The circuits shown above are typical of the LM319, and 339 voltage comparators. However, the LM311 is a little different in that the emitter of the output transistor is not connected to ground. It is left uncommitted, similar to the collector, so the user can have switching between other voltage ranges. An interface between positive voltage systems TTL or CMOS to the negative voltage ECL would be a typical application. It should be noted, however, that the emitter must be connected to a voltage within the +/- Vcc rails of the voltage comparator. Appropriate rails would be +5 and -5.2 volts of the two logic systems.

One problem using voltage comparators with very slowly varying input signals is output signal oscillation when the inputs are in close proximity of the switch point. All signals including power supplies have a smal amount of noise embedded on top of the desired signal. We saw earlier that the switching transition occurs with less than a millivolt change in the input voltage. If, for example, the input signal was just at the switch point and there was a small noise blip on it, the output would switch. This switching can, and often does, induce more noise on the system. This additional noise can cause the input signal to drop, causing another transition in the output. This second transistion can then again induce noise reversing the transisiton again. Such oscillations are frequently seen and cause many problem in the circuits.

Hysteresis

One way to prevent the spontaneouus oscillation of voltage comparator circuits is to introduce hysteresis as shown in Figure 3. In this case, two additional resistors are added to provide feedback. Typically, $R_2 >> R_3$ so only a small amount of feedback is provided. As far as the comparator is concerned, the voltage at the non-inverting input is the voltage that it sees and will control the output state.

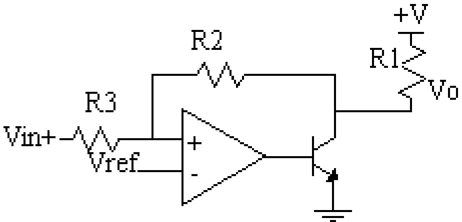

Figure 3. Voltage comparator with hysteresis

If Vin+ is just slightly below Vref, $V_o \approx 0$, the output transistor is saturated.

$$V_{noninv} = \frac{R_2}{R_2 + R_3} V_{in+}$$

As long as $R_2 >> R_3$, $V_{noninv} = V_{in+}$

If we now raise the input voltage slightly so the output switches state, then

$$V_{noninv} = \frac{R_2 + R_1}{R_3 + R_2 + R_1} V_{in+} + \frac{R_3}{R_3 + R_2 + R_1} V_{DD}$$

Again, as long as $R_1 + R_2 >> R_3$ then the first term is approximately V_{in+}. However, the second term adds to the voltage at the non-inverting terminal. Because R_3 is much smaller than the the sum of R_1 and R_2, this amount is quite small, but not zero. Typically, you want this amount to be a few millivolts to prevent oscillation.

Example:

Provide 10 mV of hysteresis with V_{DD} = 5 volts, R_1 = 1 kOhm, V_{REF} = 2.00 volts.

Solution:

We want $R_2 >> R_1$ so we choose R_2 = 1 MOhm.

Then to get 10 mV hysteresis,

$$10mV = \frac{R_3}{R_3 + R_2 + R_1} 5$$

$$\frac{R_3}{R_3 + 1.001 MOhm} = \frac{0.01}{5} = .002$$

$$R_3 \approx 0.002 x 1 MOhm = 2 KOhm$$

If we use R_3 = 2 KOhm, the actual hysteresis is 9.97 mV.

The voltage transfer characterisitc with hysteresis looks like that shown in Figure 4. Here we see that the high output transistion occurs at 2.00 volts as would have been the case without hysteresis, but the input voltage must drop significantly lower by the amount of hysteresis than before to cause the comparator to switch back.

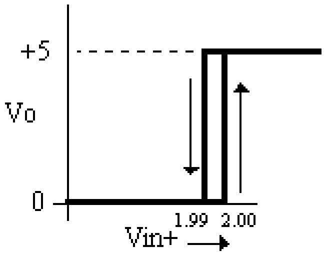

Figure 4. VTC with hysteresis for example.

Exercise

Draw the voltage transfer characterisitc for the voltage comparator circuit in Figure 5. Assume the transistor acts as a perfect switch, open or short. Note in this case, the reference is on the non-inverting input to the comparator and the input voltage is on the inverting input. The reference is supplied by a voltage divider from the power supply. (Hint: Convert the reference supply to it Thevenin equivalent.)

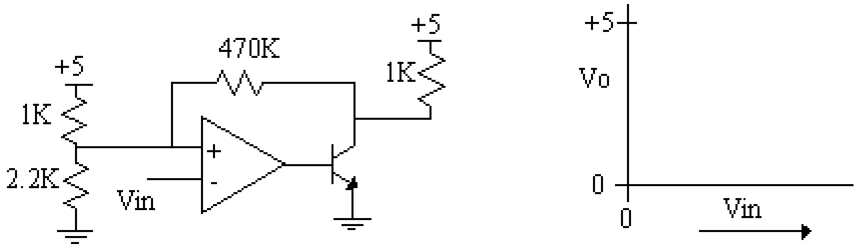

Figure 5. Voltage comparator circuit for Exercise.

The 555 Timer

The 555 timer is a functional block on a single integrated circuit chip that provides several timeing functions. The most common uses are as a square wave oscillator and as a source for a timed pulse or single-shot oscillator, astable and monostable multivibrators respectively. Timing and function are controlled by external componets and connections.

Figure 6 shows the functional block diagram of the 555's internal components. Comp A and compB are voltage comparators as discussed above. The three-5 KOhm resistor string provides two reference voltages for the voltage comparators at $2/3V_{CC}$ for comparator A and $1/3V_{CC}$ for comparator B. When the threshold input is above $1/3V_{CC}$, the flip-flop is reset, and when the trigger input is above $2/3V_{CC}$, the flip-flop is set. The ouptut comes from an interface/driver circuit which is driven by the flip-flop. The output is capable of sourcing or sinking current. The discharge output is used to discharge external timing capacitors as we will see when we discuss specific applications.

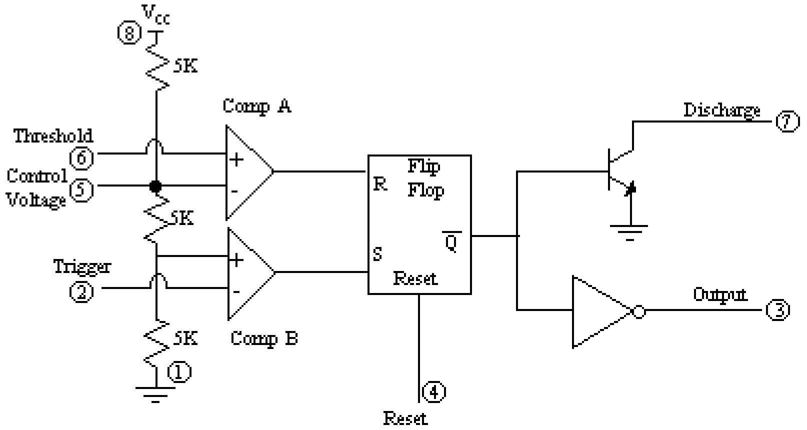

Figure 6. Functional block diagram of the 555 timer circuit

While the 555 timer is touted as being capable of sinking or sourcing 200 mA, that is with a 15 volts power supply and at that, the output voltage rises or falls substantially (typically 2.5 volts) from the rails. With a power supply of 5 volts, the consumer version of the chip can sink only 5 mA; still capable of driving TTL loads. Consult the data sheets from several manufacturers for complete specifications.

Monostable Application

In the this application, with the external connections shown in Figure 7, the timer circuit will operate as a single-shot multivibrator. Here, if the trigger gets a negative pulse, the flip-flop is set, making Q' high, truning off the discharge transistor, which then allows the capacitor to be charged up toward V_{CC}. When the capacitor voltage reaches $2/3V_{CC}$, the threshold signal causes the flip-flop to be reset, discharging the capacitor again. Typical waveforms are shown in Figure 8. It can be seen from the waveforms that the ouput remains low until a trigger signal is received. Then the output goes high while the capacitor charges and then goes back low where it remains until another trigger pulse is received. Hence, the name single-shot. Multiple triggers or continuous low voltage on the trigger input during charging have no effect, but the trigger signal must go back high again before the flip-flop can be reset by the threshold signal.

Timing is dependent on the time it takes the capacitor to charge up from a discharged state, or very near zero volts, to $2/3V_{CC}$. The charging equation is

$$v_C(t) = V_{CC}(1 - e^{-t/RC})$$

We solve this equation for $V_C = 2/3V_{CC}$.

$$0.667V_{CC} = V_{CC}(1 - e^{-t/RC})$$

and solve for t

$$1 - 0.667 = e^{-t/RC}$$

or

$$t/RC = - \ln(0.667) = 1.099$$

or the length of the pulse is

$$t = 1.099RC$$

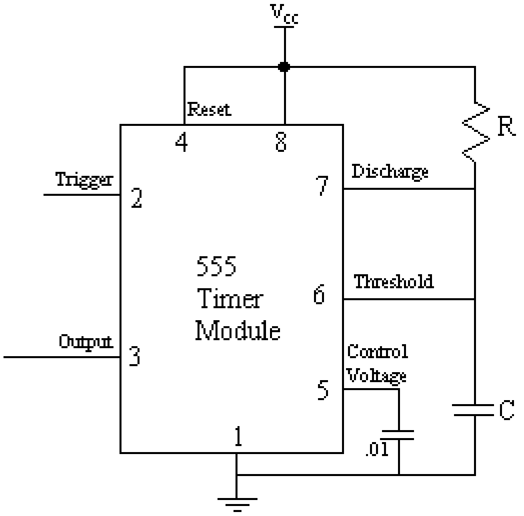

Figure 7. Connections for monostable operation.

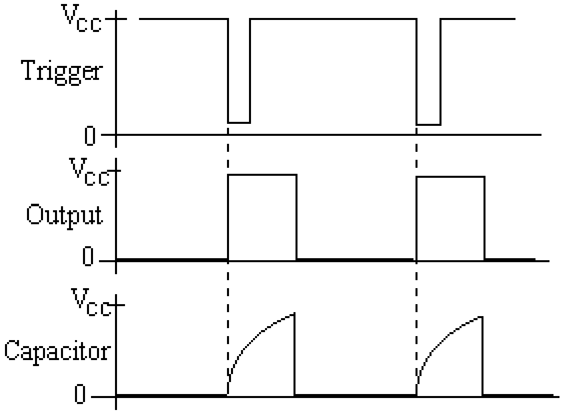

Figure 8. Wveforms for monostable operation.

The capacitor is shown as being discharged intstantaneously. However, the discharge current, and hence the rate, is limited by the β of the discharge transistor. In this mode of operation, the discharge is accomplished quickly, but it does limit how soon the cycle can be restarted. If a trigger signal is received during this discharge time, the flip-flop will be set and the capacitor recharged, this time, starting before it is completely discharged and shortening the output pulse.

Astable Application

Figure 9 shows the connections for astable or free-running operation. Both the trigger and threshold inputs are connected directly to the capacitor. There is an additional resistor, R_B, connected between the capacitor and the discharge transistor to slow the discharge. When the capacitor discharges to $1/3V_{CC}$, the trigger comparator switches and sets the flip-flop which in turn turns off the discharge transistor, allowing the capacitor to start charging up through both resistors, R_A and R_B. When the capacitor reaches $2/3V_{CC}$, the threshold input causes the flip-flop to reset which in turn turns on the discharge transistor and the capacitor discharges again. Thus, the capacitor charges and discharges back and forth between $1/3V_{CC}$ and $2/3V_{CC}$. Typical waveforms are shown in Figure 10.

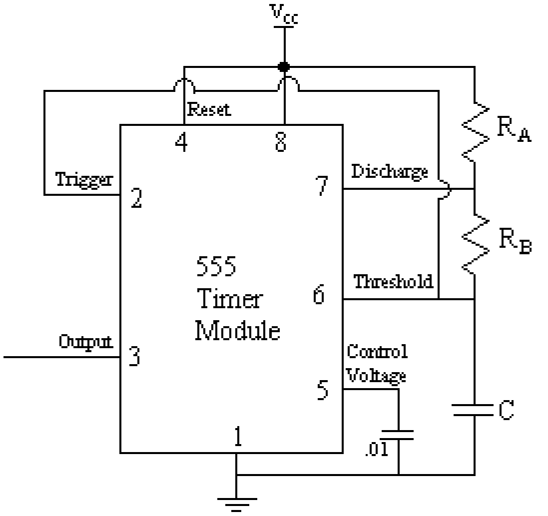

Figure 9. Astable Circuit

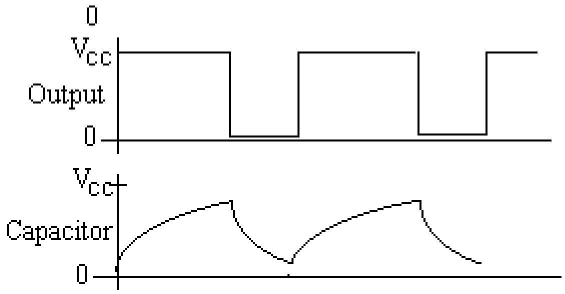

Figure 10. Astable waveforms

The discharge equation, starting at $2/3V_{CC}$ is

$$v_C(t) = \frac{2}{3}V_{CC}e^{-\frac{t}{R_BC}}$$

The capacitor discharges to $1/3V_{CC}$ at time = t_D, the time during discharge

$$\frac{1}{3}V_{CC} = \frac{2}{3}V_{CC}e^{-\frac{t_D}{R_B C}}$$

$t_D = R_B C(-\ln 0.5) = 0.693 R_B C$

During charging, the capacitor starts at $1/3V_{CC}$, and charges toward V_{CC}. The equation is

$$v_C(t) = V_{CC} - \frac{2}{3}V_{CC}e^{-\frac{t}{(R_B+R_A)C}}$$

The capacitor charges up to $2/3V_{CC}$ at time = t_C, the time during charge

$$\frac{2}{3}V_{CC} = V_{CC} - \frac{2}{3}V_{CC}e^{-\frac{t_C}{(R_B+R_A)C}}$$

$t_C = C(R_A + R_B)(-\ln 0.5) = 0.693(R_A + R_B)C$

The total period is the sum of the charge and discharge time

$t_T = 0.693(R_A + 2R_B)C$

It is important to note that the charging time will always be laronger than the discharging time with the result that the timer output will always be high longer than it will be low. From the equations, the only way to make a square wave is to make $R_A = 0$. But since R_A is connected from V_{CC} to the collector of the discharge transistor, that would result in very large currents through that transistor, which cannot be allowed.

Also note that the time is independent of the supply voltage, a very desirable result. The accuracy of the time, however, is dependent on not only the accuracy of the external resistor and capacitor values, but is dependent on the accuracy of the internal voltage divider string that set the voltage comparator reference levels for charge and discharge trigger points. This 3 resistor voltage divider string is made on the chip simultaneously so that the values tend to track. Any deviation from nominal value of one resistor tends to be seen by all resistors in the string so that the reference voltages are fairly accurate.

The control voltage input is connected directly to the reference voltage for the threshold voltage comparator. By external manipulation of this voltage, the thresholds for charge and discharge can be manipulated. The trigger point for discharge will be one-half the charge trigger point.

Does this control give the designer a means by which to make the charge and discharge times equal, producing a square wave at the timer output?

Exercises

1. You have a 0.1 μF, ±10% capacitor, all standard value 5% resistors, and a 555 timer integrated circuit. Design a monostable multivibrater circuit with a nominal pulse width of 20 ms. What are the worst case minimum and maximum pulse widths?

2. With the same components from the previous exercise, design an astable timing circuit with a nominal frequency of 1kHz.