Waveshaping Circuits and Data Converters

Lesson #19
Timers
Section 12.3
555 Timer

• An device introduced by Signetics in 1972
• An economical and convenient way to design multivibrator circuits.
• Consists of voltage divider string, two comparators, a RS flip-flop and a switching transistor
• RS flip-flop is a device which can attain one of two states based on the states of its inputs RS.
RS Flip-Flop

<table>
<thead>
<tr>
<th>Clr</th>
<th>R</th>
<th>S</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>x</td>
<td>x</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>NC</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>?</td>
</tr>
</tbody>
</table>

x - don’t care
NC – No Change
? - indeterminate
555 Timer

- **Reset** – will always reset the flip-flop and usually set to Vcc.

- **Threshold** – Value > 2/3 Vcc then flip-flop is RESET, Q=0 and NotQ =1 and transistor Q1 conducts.

- **Trigger** – Value < 1/3 Vcc then flip-flop is SET, Q=1 and NotQ=0 and transistor Q1 is cutoff. Note that the flip-flop will be “triggered” on the falling edge of a pulse applied to this input.

- **Control** – probe to test threshold value.

- **Discharge** – is the Q1 output and presents a short to ground when Q1 conducts.

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555 Monostable

- A monostable produces a single pulse for every trigger signal applied. Only two external components: $R_A$ and $C$.

- When the trigger drops below $1/3 \text{ Vcc}$, the comparator $CP_2$ causes the flip-flop to be SET and Q1 opens and C begins to charge through $R_A$. When the voltage of the capacitor reaches $2/3 \text{ Vcc}$, the comparator $CP_1$ causes the flip-flop to be RESET and Q1 saturates presents a “zero” resistance to ground for the capacitor to discharge through.

- As a result a single pulse of width $T=R_A C \ln(3)$ is produced.

\[ v_c(t) = K_1 + K_2 e^{-t/[R_A C]} \]
\[ v_c(0) = 0 = K_1 + K_2 \]
\[ v_c(\infty) = +A = K_1 \]
\[ v_c(t) = A(1 - e^{-t/[R_A C]}) \]
\[ v_c(T) = \frac{2A}{3} = A(1 - e^{-T/[R_A C]}) \]
\[ \therefore T = R_A C \ln(3) \]
555 Monostable

<table>
<thead>
<tr>
<th>Monostable</th>
<th>State</th>
<th>1</th>
<th>2</th>
<th>2a</th>
<th>3</th>
<th>4</th>
<th>1</th>
</tr>
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<tbody>
<tr>
<td>Vin</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
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<tr>
<td>S</td>
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<td>1</td>
<td>0</td>
<td>0</td>
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<td>0</td>
</tr>
<tr>
<td>R</td>
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<td>0</td>
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</tr>
<tr>
<td>Q</td>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Qnot</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Transistor</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
<td>ON</td>
<td>1</td>
</tr>
<tr>
<td>Vcap</td>
<td>0</td>
<td>0</td>
<td>&lt;2/3 Vcc</td>
<td>&lt;2/3 Vcc</td>
<td>2/3 Vcc</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>
A second resistor is added and the capacitor is connected to the trigger input.

- At startup the capacitor voltage is less than 1/3 Vcc, the flip-flop is SET (via the trigger comparator), Q1 opens and C begins to charge through RA and RB.

\[
T_H = (R_A + R_B)C \ln(2)
\]

\[
T_L = R_B C \ln(2)
\]

\[
T = T_H + T_L
\]

\[
= (R_A + 2R_B)C \ln(2)
\]

- As the capacitor voltage reaches 2/3 Vcc, the flip-flop is RESET (via the threshold comparator), Q1 saturates, and the capacitor starts to discharge through RB.

- When the capacitor voltage drops below 1/3 Vcc, the flip-flop is SET again, Q1 reopens, and the process restarts again.
555 Astable

<table>
<thead>
<tr>
<th>State</th>
<th>1</th>
<th>2a</th>
<th>2b</th>
<th>3</th>
<th>4</th>
<th>2a</th>
<th>2b</th>
<th>3</th>
<th>4</th>
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<tbody>
<tr>
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<td>=1/3Vcc</td>
<td>&lt;2/3Vcc</td>
<td>&lt;2/3Vcc</td>
<td>&lt;1/3Vcc</td>
<td>&lt;2/3Vcc</td>
<td>&lt;2/3Vcc</td>
<td>&lt;2/3Vcc</td>
<td>&lt;2/3Vcc</td>
</tr>
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<td>0</td>
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<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
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<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Q</td>
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<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Qnot</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Transistor</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
<td>ON</td>
</tr>
<tr>
<td>RC</td>
<td>(Ra+Rb)C</td>
<td>(Ra+Rb)C</td>
<td>(Ra+Rb)C</td>
<td>RbC</td>
<td>(Ra+Rb)C</td>
<td>RbC</td>
<td></td>
<td></td>
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</table>
A VCO circuit diagram is shown with the following components:

- **Input Voltage:** $V_{in} = T_2$ volts
- **Control Line:** Trigger [2]
- **Threshold Line:** [6]
- **Discharge Line:** [7]
- **Reset Line:** [4]
- **Ground Line:** [1]
- **Power Supply:** [8]
- **RS Flip-Flop:**
  - Output [3]
  - Control [5]
  - Trigger [2]
  - Threshold [6]
  - Reset [4]
  - Ground [1]

The circuit includes resistors $R_A$ and $R_B$, capacitors $C$, and a voltage-controlled oscillator (VCO) with output $Q_1$. The control lines and thresholds are connected to the flip-flop, which outputs $Q$ and $\overline{Q}$.
VCO

\[ v_s(t) = K_1 + K_2 e^{-\frac{t}{(R_A + R_B)C}} \]

Low To High

\[ v_s(0) = K_1 + K_2 = T_1 \]

\[ v_s(\infty) = K_1 = V_{CC}; K_2 = T_1 - V_{CC} \]

\[ v_s(T_H) = V_{CC} + (T_1 - V_{CC}) e^{-\frac{T_H}{(R_A + R_B)C}} = T_2 \]

\[ (T_1 - V_{CC}) e^{-\frac{T_H}{(R_A + R_B)C}} = T_2 - V_{CC}; \]

\[-\frac{T_H}{(R_A + R_B)C} = \ln\left(\frac{T_2 - V_{CC}}{T_1 - V_{CC}}\right)\]

\[ T_H = (R_A + R_B)C \ln\left(\frac{V_{CC} - T_1}{V_{CC} - T_2}\right) \]

\[ T_2 = xV_{CC}; T_2 = 2T_1 \]

\[ T_H = (R_A + R_B)C \ln\left(\frac{1 - 0.5x}{1 - x}\right) \]

High To Low

\[ v_c(0) = K_1 + K_2 = T_2 \]

\[ v_c(\infty) = K_1 = 0; K_2 = T_1 \]

\[ v_c(T_L) = T_1 e^{-\frac{T_L}{R_B C}} = T_2 \]

\[ T_1 e^{-\frac{T_H}{R_B C}} = T_2; \]

\[ e^{-\frac{T_H}{R_B C}} = \frac{T_2}{T_1} = 2 \]

\[ T_L = R_B C \ln(2) \]
VCO

\[ T = T_L + T_H \]

\[ T_H = (R_A + R_B)C \ln\left(\frac{1 - 0.5x}{1 - x}\right) \]

\[ T_L = R_B C \ln(2) \]

\[ T = R_B C \ln(2) + (R_A + R_B)C \frac{\ln(1 - 0.5x)}{\ln(2)} \]

\[ = R_B C \ln(2) + (R_A + R_B)C \frac{\ln(1 - 0.5x)}{\ln(2)} \ln(2) \]

\[ = [R_B + (R_A + R_B)\lambda(x)]C \ln(2) \]

\[ \lambda(x) = \frac{\ln(1 - 0.5x)}{\ln(2)} \]
\[ VCO \]

**Standard Astable**

\[
T_{\text{stand}} = R_B C \ln(2) + (R_A + R_B)C \ln(2) ; \quad f_{\text{stand}} = \frac{1}{[2R_B + R_A]C \ln(2)}
\]

**VCO**

\[
T_{\text{VCO}} = R_B C \ln(2) + (R_A + R_B)C \ln\left(\frac{1 - 0.5x}{1 - x}\right) ; \quad f_{\text{VCO}} = \frac{1}{[R_B + (R_A + R_B)\lambda(x)]C \ln(2)}
\]

\[
\frac{f_{\text{VCO}}}{f_{\text{stand}}} = \frac{1}{[R_B + (R_A + R_B)\lambda(x)]C \ln(2)} \times \frac{1}{[2R_B + R_A]C \ln(2)}
\]

\[
= \frac{[2R_B + R_A]C \ln(2)}{[R_B + (R_A + R_B)\lambda(x)]C \ln(2)} = \frac{[2R_B + R_A]C \ln(2)}{[R_B + (R_A + R_B)\lambda(x)]C \ln(2)}
\]

\[
\lambda(x) = \frac{\ln(\frac{1 - 0.5x}{1 - x})}{\ln(2)}
\]

When \( \lambda = 1 \), then \( f_{\text{VCO}} = f_{\text{stand}} \)

\[
\lambda(x) = 1 = \frac{\ln(\frac{1 - 0.5x}{1 - x})}{\ln(2)} \quad \Rightarrow \quad \frac{1 - 0.5x}{1 - x} = 2 \quad \Rightarrow \quad x = \frac{2}{3}
\]
\[ T_{\text{stand}} = R_B C \ln(2) + (R_A + R_B) C \ln(2) ; \]
\[ f_{\text{stand}} = \frac{1}{[2R_B + R_A]C \ln(2)} \]

\[ T_{\text{VCO}} = R_B C \ln(2) + (R_A + R_B) C \ln\left(\frac{1 - 0.5x}{1 - x}\right) ; \]
\[ f_{\text{VCO}} = \frac{1}{[R_B + (R_A + R_B)\lambda(x)]C \ln(2)} \]

\[ \% \text{Change} = \frac{f_{\text{stand}} - f_{\text{VCO}}}{f_{\text{stand}}} = \frac{1}{[2R_B + R_A]C \ln(2)} - \frac{1}{[R_B + (R_A + R_B)\lambda(x)]C \ln(2)} \]
\[ = 1 - \frac{[2R_B + R_A]}{[R_B + (R_A + R_B)\lambda(x)]} \]
\[ = \ln\left(\frac{1 - 0.5x}{1 - x}\right) \]
\[ \lambda(x) = \frac{\ln(\frac{1 - 0.5x}{1 - x})}{\ln(2)} \]
VCO

\[ \frac{T_2 - V_{in}}{R_s} + \frac{T_2 - V_{cc}}{R} + \frac{T_2}{2R} = 0 \]

\[ T_2 \left( \frac{1}{R_s} + \frac{1}{R} + \frac{1}{2R} \right) = \frac{V_{in}}{R_s} + \frac{V_{cc}}{R} \]

\[ T_2 = \frac{R V_{in} + R_s V_{cc}}{R + \frac{3}{2} R_s} ; V_{in} = x V_{cc} \]

\[ T_2 = \left( \frac{R_x + R_s}{R + \frac{3}{2} R_s} \right) V_{cc} \]
\[ v_c(t) = K_1 + K_2 e^{-\frac{t}{(R_A + R_B)C}} \]

**Low To High**

\[ v_c(0) = K_1 + K_2 = T_1 \]

\[ v_c(\infty) = K_1 = V_{CC} ; K_2 = T_1 - V_{CC} \]

\[ v_c(T_H) = V_{CC} + (T_1 - V_{CC}) e^{-\frac{T_H}{(R_A + R_B)C}} = T_2 \]

\[ (T_1 - V_{CC}) e^{-\frac{T_H}{(R_A + R_B)C}} = T_2 - V_{CC} ; \]

\[ e^{-\frac{T_H}{(R_A + R_B)C}} = \frac{T_2 - V_{CC}}{T_1 - V_{CC}} \]

\[ -\frac{T_H}{(R_A + R_B)C} = \ln\left(\frac{T_2 - V_{CC}}{T_1 - V_{CC}}\right) \]

\[ T_H = (R_A + R_B)C \ln\left(\frac{V_{CC} - T_1}{V_{CC} - T_2}\right) \]

\[ T_2 = \left(\frac{R_x + R_s}{R + \frac{3}{2}R_s}\right)V_{CC} ; T_2 = 2T_1 ; T_1 = \left(\frac{R_x + R_s}{2R + 3R_s}\right)V_{CC} \]

\[ T_H = (R_A + R_B)C \ln\left(1 - \left(\frac{R_x + R_s}{2R + 3R_s}\right)\right) = (R_A + R_B)C \ln\left(\frac{2R + 3R_s - (R_x + R_s)}{2[R + \frac{3}{2}R_s - (R_x + R_s)]}\right) \]

\[ = (R_A + R_B)C \ln\left(\frac{(2 - x)R + 2R_s}{2(1 - x)R + R_s}\right) \]

\[ \text{where } R_s = yR \]

\[ = (R_A + R_B)C \ln\left(\frac{2 - x + 2y}{2 - 2x + y}\right) \]

---

VCO

\[ V_{cap} \]

\[ T_2 \]

\[ T_L = 0.5T_2 \]

\[ V_{out} \]

\[ V_{o} \]

\[ \text{To } V_{cc} \]

\[ T_H \]

\[ \text{Output} \]

\[ \text{BME 373 Electronics II – J.Schesser} \]
$v_c(t) = K_1 + K_2 e^{-\frac{t}{R_B C}}$

High To Low

$v_c(0) = K_1 + K_2 = T_2$

$v_c(\infty) = K_1 = 0; K_2 = T_1$

$v_c(T_L) = T_i e^{-\frac{T_L}{R_B C}} = T_2$

$T_i e^{-\frac{T_H}{R_B C}} = T_2$;

$e^{-\frac{T_H}{R_B C}} = \frac{T_2}{T_1}$

$T_L = R_B C \ln(2)$

$T = T_L + T_H$

$T_H = (R_A + R_B) C \ln(\frac{2 - x + 2 y}{2 - 2 x + y})$

$T_L = R_B C \ln(2)$

$T = R_B C \ln(2) + (R_A + R_B) C \ln(\frac{2 - x + 2 y}{2 - 2 x + y})$

$\lambda(x, y) = \frac{\ln(\frac{2 - x + 2 y}{2 - 2 x + y})}{\ln(2)}$

$T = [R_B + (R_A + R_B) \lambda(x, y)] C \ln(2)$
**VCO**

**Standard Astable**

\[ T_{stand} = R_s C \ln(2) + (R_s + R_g)C \ln(2); \]

\[ f_{stand} = \frac{1}{[2R_s + R_g]C \ln(2)} \]

**VCO**

\[ T_{vco} = [R_s + (R_s + R_g)\lambda(x, y)]C \ln(2); \]

\[ f_{vco} = \frac{1}{[R_s + (R_s + R_g)\lambda(x, y)]C \ln(2)} \]

\[ \lambda(x, y) = \ln\left(\frac{2 - x + 2y}{2 - 2x + y}\right) \]

\% Change = \frac{f_{vco} - f_{vco}}{f_{vco}} = \frac{1}{[2R_s + R_g]C \ln(2)} - \frac{1}{[2R_s + R_g]C \ln(2)} \]

\[ = \frac{1}{[2R_s + R_g]} \left[ \frac{[R_s + (R_s + R_g)\lambda(x, y)]}{[2R_s + R_g]} \right] \]

\[ = 1 - \frac{[2R_s + R_g]}{[R_s + (R_s + R_g)\lambda(x, y)]} \]
555 Schmitt Trigger

<table>
<thead>
<tr>
<th>Schmitt Trigger</th>
<th>Schmitt Trigger</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>State</strong></td>
<td><strong>Vin going from 0 to Vcc</strong></td>
</tr>
<tr>
<td><strong>Vin</strong></td>
<td>&lt;1/3Vcc</td>
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<tr>
<td>CP2</td>
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<tr>
<td>Set</td>
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<tr>
<td>CP1</td>
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<td>Reset</td>
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<td>Q</td>
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<tr>
<td>Qnot</td>
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<tr>
<td><strong>State</strong></td>
<td><strong>Vin going from Vcc to 0</strong></td>
</tr>
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Homework

• 555 Timer
  – Problems: 12.18-20