



ARRL Morse Code Oscillator, How It Works

By: Mark Spencer, WA8SME

This supplement is intended for use with the ARRL Morse Code Oscillator kit, sold separately.

I hope that you found your kit building experience a rewarding one and that you are on your way to learning Morse code. Perhaps now that the resin smoke has cleared and the soldering iron has cooled, you'll want to learn a little bit about how your code practice oscillator (CPO) works. That is the purpose of this tutorial note.

Below you will find two instructional sections on how the circuit of your CPO works, the first is a simple overview, the second, is more detailed and technical. In the simple overview discussion it is assumed that you have a basic knowledge of electronic vocabulary words such as frequency, period, resistance, capacitance, and voltage and that you can follow along the circuit diagram of your CPO. In the more detailed and technical discussion on how your CPO works, it is assumed that you have a higher level of understanding of the basic electronics concepts and are comfortable with learning about some higher level electronics concepts such as comparators, flip-flops, voltage dividers, resistor-capacitor (RC) time constants, and doing some rudimentary mathematics.

Simplified how it works. If you take a look at the circuit diagram in figure 1 you will see that the focal point, and main component of your CPO, is U1, a NE555 Timer integrated circuit. An integrated circuit (IC) is a collection of electronic components (transistors, resistors, etc.) that are interconnected to perform a specific task, and these components are manufactured in an integrated package (and thus the name).

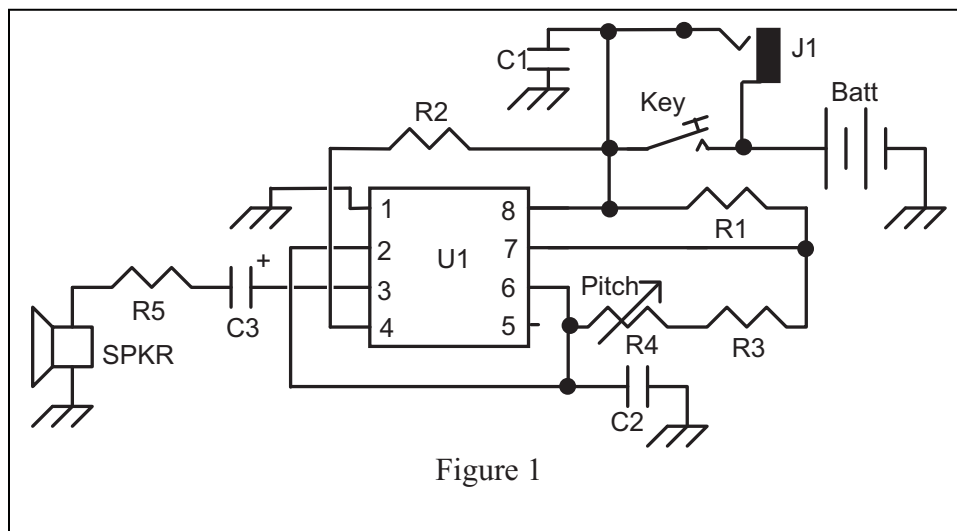


Figure 1

The 555 timer is basically an oscillator. The purpose of an oscillator is to convert direct current (DC) into alternating current (AC). In the case of your CPO, when you press the key down, a connection is made between the 9-volt battery and the 555 timer IC to power the circuit. The 555 timer converts the DC from the battery into the AC that you hear as the tone in the speaker. In the simplest terms, that is how the circuit works. But let's take a little closer look at some of the individual components that surround the 555 timer and see what part those components play in the circuit.

The 555 timer performs the oscillator function by switching on and off an internal switch (actually a transistor) that allows a capacitor (C2) to charge and discharge through resistors R1, R3, and R4. The rate at which C2 charges and discharges determines the frequency, or pitch, of oscillator of the 555 timer and you control that rate by adjusting the variable resistor R4. The higher the resistance value of R4, the lower the frequency or pitch that you hear in the speaker. So you can consider the components R1, R3, R4, and C2 the primary supporting components of the circuit that allow the 555 timer to work.

The resistor R2 provides a voltage on pin 4 of the 555 timer IC with limited current, the technical term for what R2 does is it is a "pull-up resistor." The voltage on pin 4 of the IC keeps resetting the 555 timer to keep it in constant oscillation while power is applied to the circuit through the Morse key.

Because there are some AC currents generated in the oscillator, we need to keep those currents from getting into the DC power source of the circuit which could cause feedback interference and distortion. That is the purpose of the capacitor C1. C1 is called a bypass capacitor because it provides a path to ground for the unwanted AC (filtering out the unwanted AC), while passing the wanted DC to the circuit.

The last two components of the circuit are resistor R5 and capacitor C3 between the output pin of the 555 timer and the speaker. The output of the 555 timer is a square wave. When square waves are applied to a speaker, they tend to be raspy and not very pleasant to listen to. A better wave for audio purposes is the sine wave. The purpose of R5 and C3 is to act as a simple filter circuit that takes some of the "edge" off the square wave to make the tones generated sound a little more pleasing (however this simple filter circuit does not convert the square wave into a sine wave...a much more complicated filter than this would be required).

So let's summarize. When you press the Morse key down, power is applied to the 555 timer and the timer begins to oscillate. The frequency of the oscillation depends on the charging and discharging of the capacitor C2 through the combined resistance of R1, R3, and R4 with R4 being the resistor that you control to change the pitch of the oscillation. The other components of the circuit provide some filtering of unwanted AC currents, some softening of the square wave that is fed to the speaker, and a voltage that keeps the 555 timer oscillating. Now, would you like a little more detail? Then read on.

Detailed technical discussion on how it works. The 555 timer is a very versatile IC and has many, many uses. The 555 timer has two basic overall timer modes, the monostable (one shot) and the astable (multi-vibrator) modes. In monostable operation, the 555 timer will produce a single output pulse of fixed duration when triggered by an input pulse. In astable operation, the 555 timer will produce an output that flips back and forth between two possible states (on or off, high or low). The output is a square wave with a frequency set by the rate at which the input changes. Consider the astable multi-vibrator as a self triggered monostable one-shot circuit. The CPO circuit uses the 555 timer in the astable mode. Before we can take a detailed look at the astable operation of the 555 timer, we need to review some of the electronic building blocks that make up the 555 timer IC in some detail.

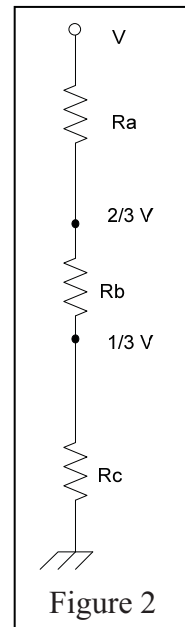


Figure 2

The resistance ladder or voltage divider. One common technique to manipulate voltages is to use resistors in series that create the desired voltage drop across each resistor in the series. This is called a voltage divider circuit. In figure 2, three resistors are in series and there is a voltage drop across each resistor that is proportional to the value of the resistor with the total voltage drop across all the resistors in the series equal to the overall voltage applied to the circuit. If the resistors are all equal in value, the voltage drop across each individual resistor will be $1/3V$, you might confirm this with a simple Ohms law calculation.

The transistor as an electronic switch. The British call transistors and vacuum tubes “valves.” This is a very accurate description of the function of transistors in an electronic circuit, a transistor is an electrically controlled valve where a tiny control current is used to control the flow of a much larger current. If this electronically controlled valve has only two states, full-on or full-off, then the transistor is essentially an electrically controlled switch. In figure 3, if a positive current is applied to the base of the transistor, the transistor will turn on and provide a path for current to flow between the emitter and collector. If zero current is applied to the base, the transistor will turn off and the current path between the emitter and collector will open preventing current flow.

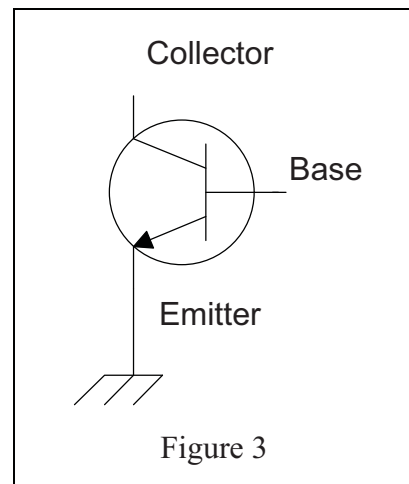


Figure 3

The comparator op-amp circuit. A comparator is an operational amplifier circuit configured to operate at saturation, in other words the output of the op-amp is either full on (full positive) or full off (full negative or zero). The comparator does what the name implies, it compares the relative values of the input voltages and will provide a corresponding output of one allowed state or the other. There are two inputs to the comparator, the non-inverting input labeled with a +, and the inverting input labeled with a - (see figure 4). There is a truth table

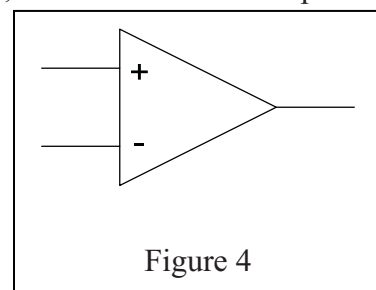


Figure 4

associated with the comparator. A truth table details the output state as a function of the inputs to the comparator.

non-inverted (+)	inverted (-)	output
+ < -		low / 0
+ > -		high / 1
+ = -		unknown

If the non-inverting input voltage is less than the inverting input voltage then the comparator output would be low, negative, or zero as appropriate (to the supply voltage). If the non-inverting input voltage is greater than the inverting input voltage then the comparator output would be high, positive, or one as appropriate. If the two input voltages are equal, the comparator output would be unpredictable at that specific point because the change in the state of the comparator output would be in transition.

The RS Flip-Flop circuit. A flip-flop circuit is a member of the digital logic family of circuits. In digital logic, the input and output of the circuits have one of two states, either high (1), or low (0), and nothing else. In an RS Flip-Flop (Reset-Set Flip-Flop), the two input states to the circuit will cause the output to “flip” from one state and “flop” to the opposite state as dictated by the appropriate truth table for the RS Flip-Flop. The R and S lines are the input to the circuit, and the Q and \bar{Q} (not-Q) are the outputs. The \bar{Q} (not-Q) output is simply the opposite state of the Q output. The not-Q line is often indicated by the over strike of the letter (I am using \bar{Q} because that is what my word processor will produce).

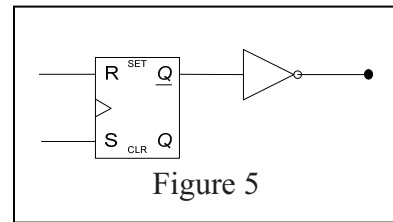


Figure 5

R (reset)	S (set)	Q	\bar{Q} (not-Q)
0	0	NC	NC
1	0	0	1
0	1	1	0
1	1	X	X

For example, if the R input is high, the S input is low, then the Q output will be low and the \bar{Q} output will be the opposite or high. One of the more useful characteristics of the RS Flip-Flop is that the output state will remain unchanged from the previous state if both the R and S inputs go low. Conversely, care must be taken to avoid both R and S inputs being high simultaneously because the Q output states will be unpredictable. In the circuit of figure 5, there is an inverting gate depicted that is not part of the RS Flip-Flop. This inverting gate is left in this diagram because it is an integral part of the Flip-Flop circuit when employed in the 555 timer which will be explained below. The operation and function on an inverter is straight forward, the output is opposite the input state (a 1 input becomes a 0 output, a 0 input becomes a 1 output).

All together as a 555 timer, astable multi-vibrator (oscillator). Now let's put all these parts together to form the 555 timer circuit that is encapsulated in the IC package (figure 6). The components that make up the 555 timer are inside the heavy black box outline that represents the casing of the IC device. Notice that there is a voltage divider circuit that divides the voltage applied (V_{cc}) into thirds. These fractional parts of V_{cc} are in turn connected to the inverting input of one comparator and the non-inverting input of another comparator. The other two inputs to the comparators are connected to another external voltage divider and capacitor that will be described later. There is an RS Flip-Flop that has its inputs coming from the comparators and only the not-Q (\bar{Q}) output is connected through an inverter to the outside world. And finally, there is a transistor that is controlled by the output of the RS Flip-Flop that is connected to the base of the transistor.

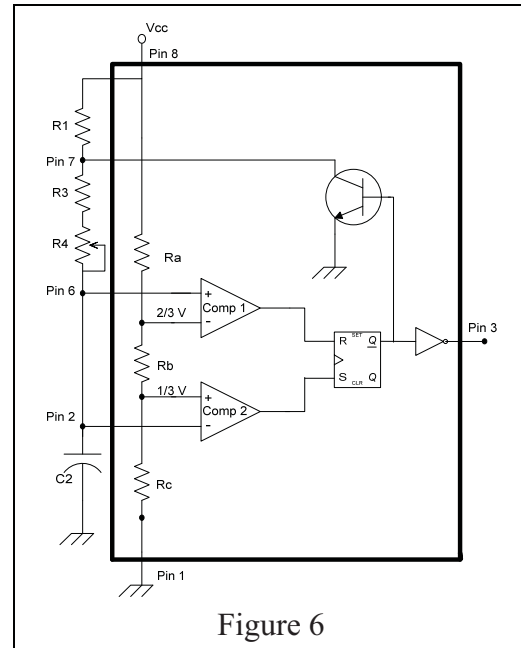


Figure 6

The external components. The series resistors R1, R3, and R4 along with the capacitor C2 form an RC circuit that is used to trigger the 555 timer to generate and control the output frequency of device. When the voltage V_{cc} is applied to the top of R1, the current passes through the resistors in series to charge the capacitor C2. The formula that describes the rate of charge as a function accumulated in C2 is:

$$V(t) = E \left(1 - e^{-\frac{t}{RC}} \right) \text{ where } t \text{ is time, } E \text{ is the supply voltage (} V_{cc} \text{), } R \text{ is in ohms, } C \text{ is in farads, and } R = R1 + R3 + R4$$

The value $R \cdot C$ is defined as the time constant of the circuit, the time when the voltage across the capacitor equals 63.2% of the applied voltage. You control the time constant of this circuit, the time it takes for the voltage across C2 to reach 63.2% of V_{cc} , by varying the setting of R4.

Notice that the transistor inside of the 555 timer IC is connected via pin 7 of the device to the junction between R1 and R3. If the transistor is turned on by applying a positive current to the transistor base, the transistor will in turn connect that junction between R1 and R3 to ground. In this condition, C2 will begin to discharge through R3 and R4 (the current flowing through R1 from the supply is also shorted to ground and no longer is supplying current to keep C2 charging). The formula that describes the rate of discharge C2 as a function of time is the function:

$$V(t) = E \left(e^{-\frac{t}{RC}} \right) \quad R \text{ is now } R3+R4$$

The result is that when the transistor is off, C2 will charge and the voltage across C2 increases at a rate that is set by the values of resistors R1, R3 and R4 (you control the value of R4). Conversely, when the transistor is on, C2 will discharge and the voltage across C2 decreases at a rate that is set by the values of resistors R3 and R4. Keep this in mind as we now take a detailed look at the operation of the 555 timer.

555 Timer operation. Basically, the 555 timer is designed to change the output state in response to the changes to the input to the device. Refer to figure 7 which is an oscilloscope display of the input and output of the 555 timer. The bottom trace is the input voltage applied to pins 2 and 7 (the comparator inputs), this voltage is generated by the RC circuit. Notice that the voltage rise (charging cycle) and the voltage fall (discharging cycle) follow the logarithmic functions above. The top square wave trace is the output pin 3. By design, if the voltage applied to the inputs of the internal comparators is less than $1/3V_{cc}$, the output will be low or zero volts. As the input voltage rises above $1/3V_{cc}$ up to $2/3V_{cc}$, the output flips high (V_{cc}) and remains high. As the input voltage rises just above $2/3V_{cc}$, the output flops low or 0 volts. As the input voltage falls below $2/3V_{cc}$ down to just above $1/3V_{cc}$, the output remains low. Finally, as the voltage falls just below $1/3V_{cc}$ and begins to rise again, the output flips to the high state to complete one cycle of oscillation. The rate of the input voltage change is determined by the RC constant of the resistor-capacitor circuit connected to the input pins of the 555 timer and the switch between charging and discharging of C2 is the result of flipping the internal switch (the transistor) of the 555 timer. Let's take a closer, step by step look and the internal logic of the device as a function of time.

Time T0. During the following step by step discussion of the 555 timer operation, you will need to refer to the truth tables for the comparator and RS Flip-Flop previously presented. In figure 8,

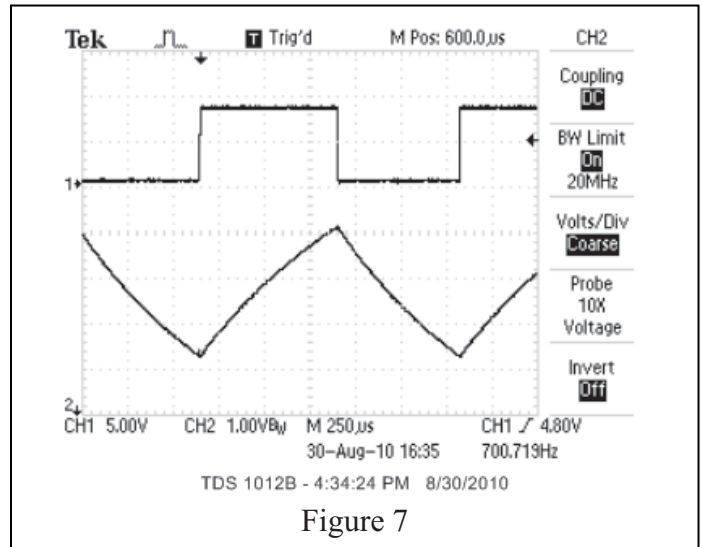


Figure 7

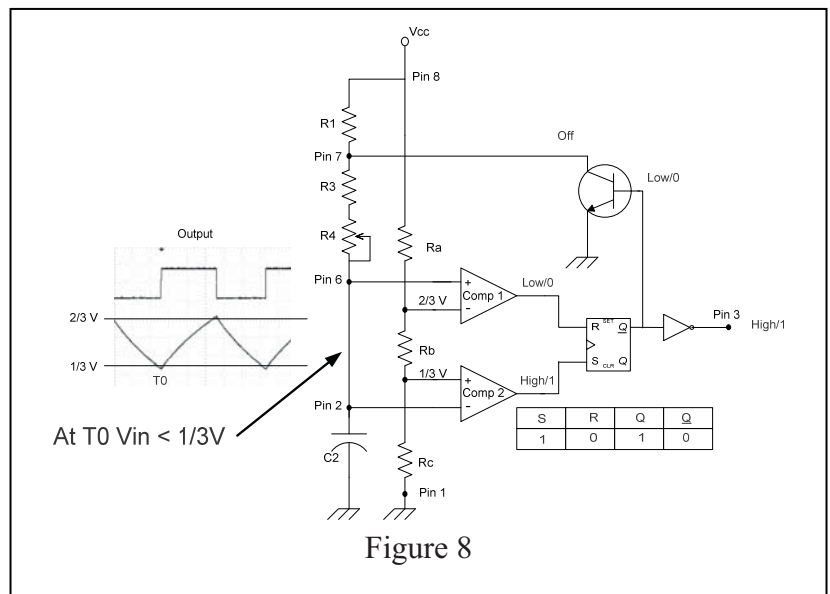


Figure 8

which is a snap shot at time 0, note that by design, the reference voltage applied to Comparator 1 of the device is $2/3V_{cc}$ and applied to Comparator 2 is $1/3V_{cc}$ (the result of the internal voltage divider). We will start at an arbitrary point on the input voltage of the RC circuit curve when the voltage across C2 is just **below** $1/3V_{cc}$. The voltage just below $1/3V_{cc}$ applied to the non-inverting input of Comp1 is less than $2/3V_{cc}$ that is the reference voltage on the inverting input of Comp1. From the truth table, this would result in a low output on Comp1. Conversely, the voltage just below $1/3V_{cc}$ applied to the inverting input of Comp2 is less than the $1/3V_{cc}$ voltage that is the reference voltage on the non-inverting input of Comp2. From the truth table, this would result in a high on the output of Comp 2.

In turn, the R input to the RS Flip-Flop is low, the S input is high, from the truth table, the Q output is therefore low. The low output of the flip-flop will turn off the transistor (allowing C2 to continue to be charged). When the low output of the flip-flop passes through the inverter, the output on pin 3 of the 555 timer is high (V_{cc}).

Time $T_0 < T < T_1$. Let's move on to the next time interval in figure 9. As C2 charges and the voltage rises, we are looking at the time interval when the voltage across C2 is between $1/3V_{cc}$ and $2/3V_{cc}$. That voltage, as applied to the non-inverting input of Comp1 is still less than the $2/3V_{cc}$ voltage applied to the inverting input, therefore the output of Comp1 remains unchanged at low (0). However, the applied voltage to the inverting input of Comp2 is now above the $1/3V_{cc}$ voltage applied to the non-inverting input of that comparator and the output of Comp2 snaps to low. The R and S inputs to the Flip-Flop are now both low, and from the truth table, the output of the flip-flop will remain unchanged from the

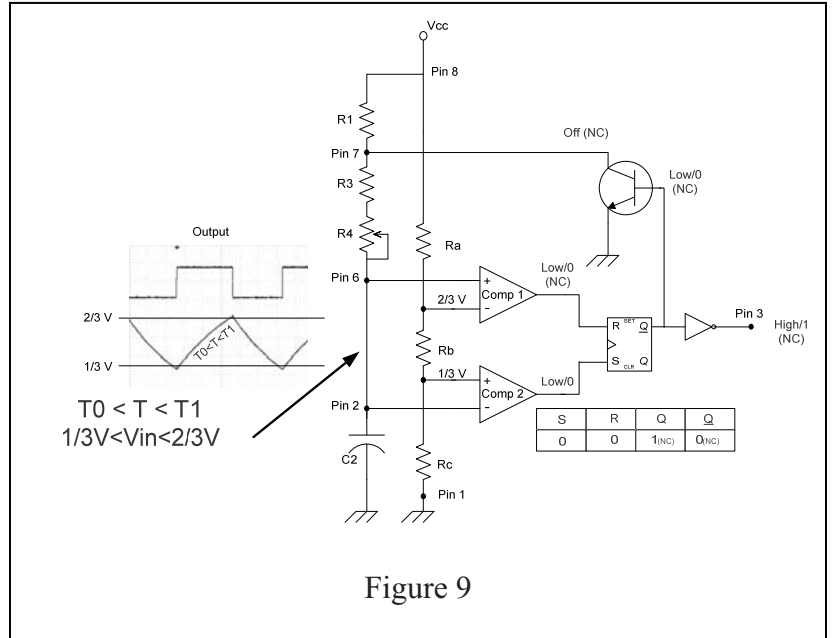


Figure 9

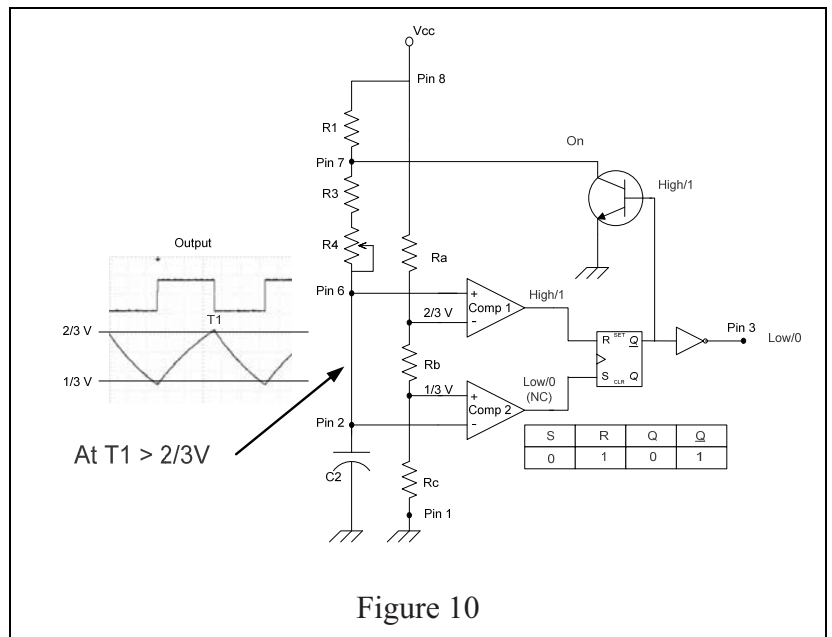


Figure 10

previous setting which was Q low. The state of the transistor remains off meaning $C2$ will continue to charge, and the output on pin 3 also remains unchanged at high.

Time $T1$. At time $T1$, the voltage across $C2$ has risen to just **above** $2/3V_{cc}$ (figure 10). This voltage applied to the inverting input of $Comp2$ is well above the $1/3V_{cc}$ reference voltage applied to the non-inverting input and the output of $Comp2$ remains unchanged at low. This voltage when applied to the non-inverting input of $Comp1$ is greater than the $2/3V_{cc}$ reference voltage applied to the inverting input causing the output of $Comp1$ to change to high. With the R input now 1, and the S input now 0 on the flip-flop, the Q output flips to high. This high when passed through the inverter produces a low on the pin 3 output. But now, this same high output from the flip-flop turns on the transistor allowing for the grounding of the junction between $R1$ and $R3$ and $C2$ begins to discharge.

Time $T1 < T < T0$. Now on to the last time interval. $C2$ is discharging because the transistor switch is turned on and the voltage falls between $2/3V_{cc}$ and $1/3V_{cc}$. This falling voltage, when applied to the inverting input of $Comp2$ is still above the reference voltage so the output of $Comp2$ remains unchanged at low. The falling voltage is on the non-inverting input of $Comp1$ is now below the $2/3V_{cc}$ reference voltage and the output of $Comp1$ changes to low also. When the two lows are applied to the inputs of the flip-flop, the output of the flip-flop remains unchanged from the previous state, the output on pin 3 is unchanged at low, and the transistor remains

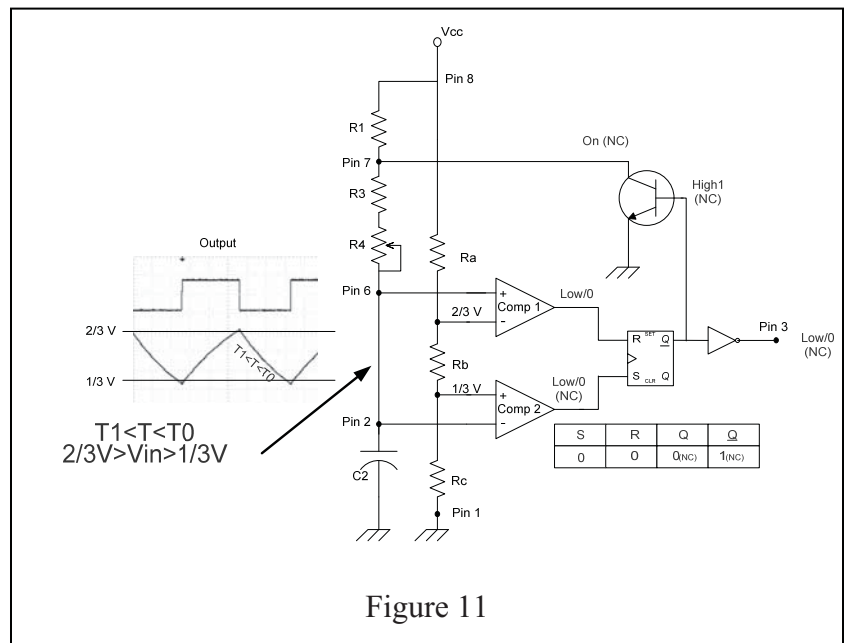


Figure 11

turned on to continue the discharge of $C2$. This state remains until the cycle is repeated at $T0$ when the voltage drops slightly below $1/3V_{cc}$.

So as the voltage across $C2$ varies between the limits of just below $1/3V_{cc}$ and just above $2/3V_{cc}$, the output of the 555 timer changes in step to produce a square wave that has a frequency dependent on the time constant of the RC circuit (that you control through the variable resistor) connected to the device inputs.

On to some math. The oscillating frequency of the 555 timer can be precisely predicted and controlled by manipulating the resistance and capacitor values of the RC circuit. The documentation for the 555 timer provides the mathematical relationship between the values of the resistance and capacitance to the on and off time periods. This in turn can be used to calculate the period of the square wave and therefore the frequency of

oscillation. Let's take a look at the math using measurements from the actual CPO circuit.

The 555 timer documentation indicates the following:

The on-time of the device (when C2 is charging through R1, R3, and R4) is:

$$T_{on} = 0.693(R1 + R3 + R4)C2$$

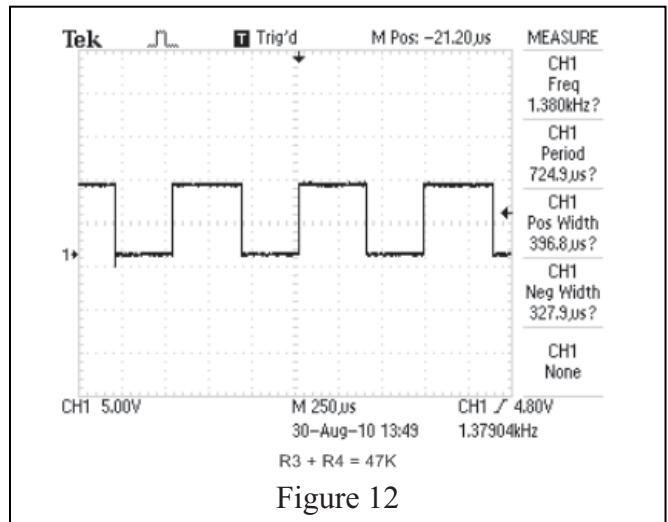
The off-time of the device (when C2 is discharging through R3 and R4) is:

$$T_{off} = 0.693(R3 + R4)C2$$

The total period of the square wave output then is:

$$T_{Period} = T_{on} + T_{off}$$

Figure 12 is an oscilloscope screen shot with the variable resistor R4 set to 0 ohms. On the right side of the scope display are the auto measurements of the high period (396.8 uS), the low period (327.8 uS), the overall square wave period is 724.9 uS, and the wave frequency is 1380 Hz. Let's insert some numbers into the formulas and see how well they work to predict the performance of the 555 timer.



Plugging the values R1 = 10 K, R3 = 47 K, R4 = 0 (the variable resistor is set to 0 ohms), and C2 = .01 uF (or 1x10⁻⁸F) into the on-time formula, the result is 395.0 uS. [Remember the units must be in Ohms and Farads for the formulas to work]

Plugging the values R3 = 47 K, R4 = 0, and C2 = .01 uF into the off-time formula, the result is 325.7 uS. The comparison to the measured are remarkably close.

Continuing, the calculated period is 720.7 uS versus the measured period of 724.9 uS.

The calculated frequency ($freq = \frac{1}{period}$) is 1387 Hz versus the measured frequency of 1380 Hz.

One more time. To reinforce the math, I set the value of the variable resistor to 53 K (using a VOM). The resulting screen shot with the CPO operating with this resistance setting is in figure 13. Doing the same calculations above but with R4 = 53 K, the following results were obtained:

On-time period calculated = 762.3 uS versus measured = 745.0 uS

Off-time period calculated = 693.0 uS versus measured = 679.0 uS

Calculated square wave period = 1433.3 uS
versus measured 1424 uS

Calculated square wave frequency = 687
Hz versus measured = 702. Hz

These values are still remarkable close considering there is an added variable, the accuracy of measuring the variable resistance value.

Conclusion. I hope that you have had fun with your soldering experience. Now you can claim with pride that your code practice oscillator is homebrew. I also hope that

you have taken, and enjoyed, the step beyond the homebrew experience and have learned a little bit about the CPO circuit, and some basic, and not so basic electronics. If anything, I hope you have gained some appreciation for the elegance and versatility of the 555 timer integrated circuit. You may have to revisit this tutorial from time to time to refresh your memory about how the 555 timer operates, don't worry, I have to. Perhaps with this understanding of the internal workings of this device you'll find other ways to apply the technology around your shack, build your own circuit from scratch, and homebrew your own 555 timer based project that you can share with others.

73,

Mark Spencer, WA8SME

