RC Time Constant and the Oscilloscope
Student Activity

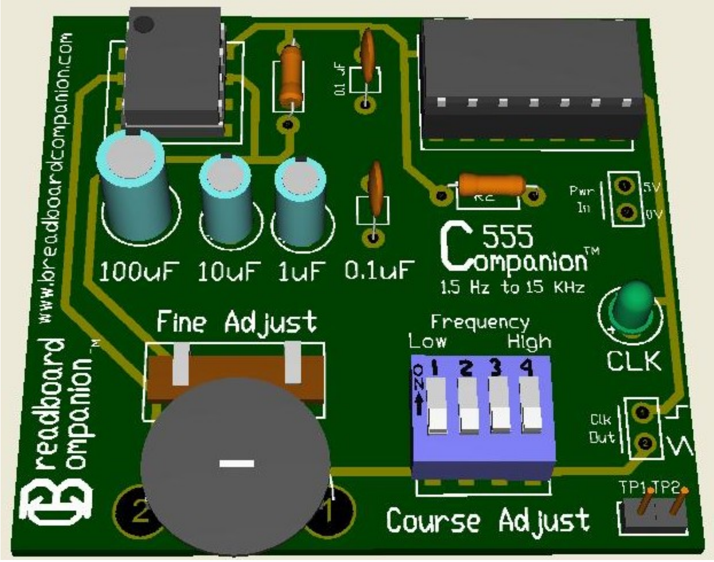
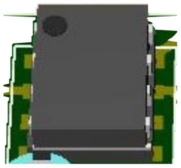


Figure 1

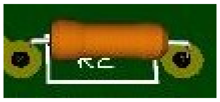
Objective:

To explore the RC time constant, theoretically and practically and to learn how to use an oscilloscope.

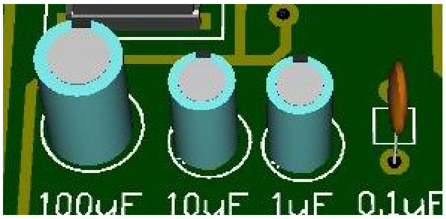
Background for the Activity:



555 Timer: The 555 Timer is a chip that regulates a square wave clock pulse. This means that it produces a wave with square edges, which is very useful in digital electronic design. The 555 timer needs to be consistent like a clock and is regulated by something called the RC time constant.



Resistors (R): A resistor slows down the flow of electricity. They are used to control the flow of electricity much like speed limit signs control the flow of automobiles.



Capacitors (C): A capacitor is two little metal plates that store a charge. One plate is positive and the other is negative and they are often rolled up and squeezed into a tiny little can. If a capacitor can discharge quickly, it can make a camera flash become very bright for a very short amount of time or unleash a painfully large voltage through a taser. The larger the capacitor, the more charge it can hold.

RC Time Constant: To charge a capacitor, it needs to be connected to a power source. Every connection has some sort of resistance (though some are extremely small) and this determines how quickly it charges. Similarly, the discharge of a capacitor requires some sort of connection between the two charged plates and this connection will have some sort of resistance as well. How quickly a capacitor can charge or discharge is determined by the size of the capacitor (a bigger capacitor would take longer to "fill up") and the size of the resistance in its particular path (more resistance means the charge is "moving slower").

Equation: Time for full charge = $5RC$ (Where "R" is the resistance of the path to power source)
Time for full discharge = $5RC$ (Where "R" is the resistance of the path between the plates)

555 Companion Layout:

Capacitors: The 555 Companion is designed so that four different capacitors can be used for the RC time constant. Their values are 100uF, 10uF, 1uF, and 0.1uF. Which capacitor is used is determined by which switch is selected on the dip switch. The left switch (as seen on Figure 1) selects the 100uF capacitor and so forth. Each step changes the RC time constant by a factor of ten.

Resistors: The 555 Companion is also designed to have a wide range of resistance. The resistance for each capacitor can change by spinning the thumb wheel on the potentiometer. A potentiometer is a variable resistor and the one on the 555 Companion can range from 0-10k Ohms.

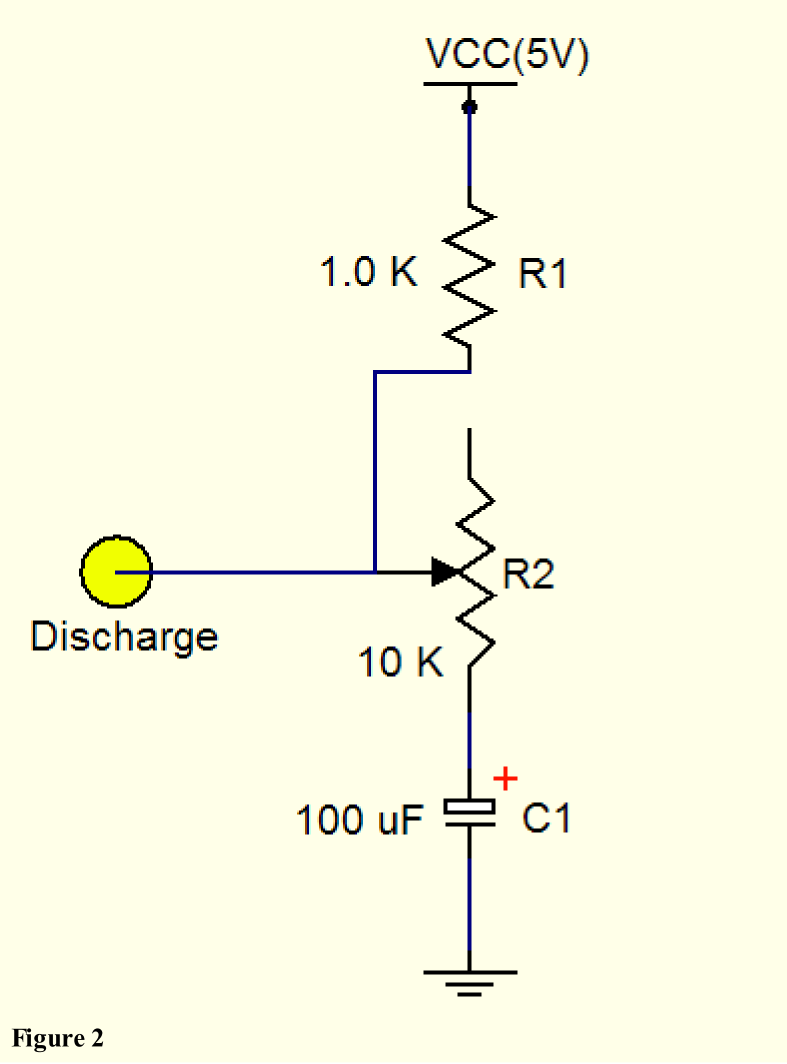


Figure 2

Schematic:
Illustrated in the schematic (Figure 2) is the basic layout of the 555 Companion with the 100uF capacitor "selected".

Charging:
The capacitor charges as the current runs from the voltage source (VCC) through the fixed resistor R1, the potentiometer R2 and then into the capacitor. The arrow on the potentiometer can move up or down as the thumb wheel is turned on the 555 Companion. As the arrow moves "up" on the schematic, the potentiometer's resistance increases to a maximum of 10k Ohms. As it moves "down" on the schematic, it decreases to a minimum of 0 Ohms.

Discharging:
One of the features of the 555 chip is to create a discharge "path" for the capacitor after it becomes 2/3 charged. Once this happens, the positive plate of the capacitor discharges through the potentiometer only (yellow dot represents discharge path). *Note: because R1 is fixed and only used in the charge path, the total resistance will always be different between the charge and discharge paths.*

Theoretical Calculation:

Theory: We can calculate how long it should take for the capacitor to charge and discharge. This will represent the "wavelength" of the square wave clock pulse as seen on the oscilloscope. How long it will take will depend on which capacitor is selected and where the potentiometer (thumb wheel) is at.

Example: Let us assume that switch 1 (Figure 1) is in the on position and the rest of the switches are in the off position. This means that the 100uF capacitor is the one that is being charged and discharged. If we want to know the range of wavelengths for the clock pulse on this setting, *we will have to look at the lowest setting of the potentiometer and at the highest setting.*

Potentiometer Resistance = 0 Ohms ***(Lowest Setting)***

Charge Resistance: Because the capacitor charges through R1 and R2 (Figure 2), the total charge resistance is 1k plus the resistance of the potentiometer. In this case, the potentiometer is set at 0 Ohms. Therefore, the charge resistance is **1k Ohms**.

Charge Time: Since charge time is ***5RC***, the time it will take the capacitor to charge is ***5 x 100u x 1k = 5 x 0.0001 x 1000 = 0.5 seconds.***

Discharge Resistance: Because the capacitor discharges through R2 only (Figure 2), the total discharge resistance is only that of the potentiometer. In this case, it is 0 Ohms. Therefore, the discharge resistance is **0 Ohms**.

Discharge Time: Since discharge time is ***5RC***, the time it will take the capacitor to discharge is ***5 x 100u x 0 = 5 x .0001 x 0 = 0 seconds.***

Total Wavelength of Clock Pulse: The total wavelength of the clock pulse is the amount of time it will take to charge and discharge (see Figure 3). In this case, it is **0.5 + 0 = 0.5 seconds**.

Frequency: Anything with consistent, repetitive cycles (such as a wave) can be characterized by something called a frequency. This is defined as "the number of cycles per second". The equation is

$$frequency = \frac{1}{wavelength}$$

In this case, frequency = 1/0.5 = **2 cycles/second**. This means that the square wave clock pulse will go up and down twice in one second. Similarly, the green LED will blink (on and off) twice in one second.

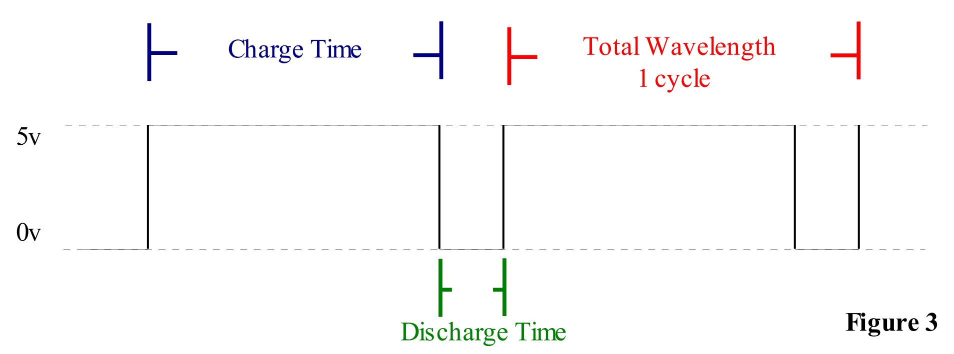


Figure 3

Potentiometer Resistance = 10k Ohms (Highest Setting)

Charge Resistance: 1k + 10k = 11k Ohms
Charge Time: 5 x 100u x 11k = 5 x .0001 x 11000 = **5.5 seconds**
Discharge Resistance: 10k Ohms
Discharge Time: 5 x 100u x 10k = 5 x .0001 x 10000 = **5 seconds**.
Total Wavelength: 5 + 5.5 = **10.5 seconds**.
Frequency: 1/10.5 = **0.095 cycles/second**

So when the potentiometer is set at 0k Ohms, the frequency is 2 cycles/second and when the potentiometer is set at 10k Ohms, the frequency is less than a 10th of a cycle/second. This means that it takes almost 11 seconds for the LED to flash once. This is the theoretical range of frequencies for the 100uF capacitor.

Experiment: Theory is only as good as the experiments that validate it. Let us test the theory, and see what we find. Connect the 555 Companion to a voltage source (see Figure 4), and select the 100uF capacitor (switch 1 on Figure 1). Now turn the thumb wheel on the 555 Companion until the LED flashes as fast as possible.

1. Does it appear that the light is flashing about 2 times per second?
2. Since the potentiometer is the only theoretical resistance to the discharge path, and the potentiometer is currently set at 0 ohms, does it appear that the discharge time is zero? In other words, does the light even flash? Should it?
3. Now spin the thumb wheel to the opposite extreme, does it appear that the light takes nearly 11 seconds to flash once?

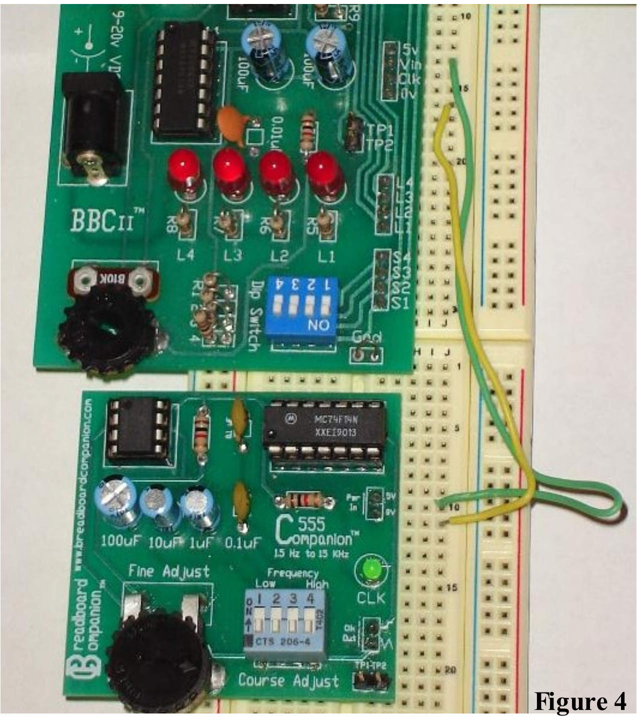


Figure 4

Theory vs. Reality: Theory is usually oversimplified. We seldom know all of the details of any single experiment and we hope our simplification does not get in the way of our measured results. In this case, something did get in the way. There are two correctable reasons for these theoretical inaccuracies.

1. The amount of time it takes a capacitor to *fully* discharge is approximately 5RC. The key word here is not approximately, but *fully*. If you connect the probe of an oscilloscope to TP2, you will see the charge and discharge of the capacitors. What you will find is that they do not charge *fully* to 5 volts and discharge *fully* to 0 volts. Instead, the capacitor begins to charge when it hits 1/3 of full capacity (5/3 volts) and begins to discharge when it hits 2/3 of full capacity (10/3 volts). This can be seen relatively easy by probing TP2 (lower right corner of the 555 Companion) with an oscilloscope.

What we need is a more general formula than the highly specific 5RC. The formula we are looking for is the following:

$$Time\ of\ discharge = RC \times \ln\left(\frac{V1}{V2}\right)$$

Where V1 is the starting voltage
V2 is the final voltage
"ln" is the natural log

Using this formula, discharging from 2/3 capacity (V1=10/3 volts) to 1/3 capacity (V2= 5/3 volts), we would arrive at a time of discharge of approximately 0.69RC. So we need to use 0.69RC for *our* calculations instead of 5RC since our capacitor is not *fully* discharging.

2. The second discrepancy we have found between theory and experiment was in the discharge time when the potentiometer was set to 0 Ohms. Theoretically, the resistance is zero and the discharge time should also be zero. However, there is a nonzero discharge time as evidenced by the discharge curve on TP2 and by the flashing of the LED even though the potentiometer is set to 0 Ohms. What this tells us is that every path in which electricity flows has some resistance, be it extremely small. Even copper wire has some resistance. In this case, the discharge path through the 555 chip proves to have a minimal resistance of 100 Ohms.

   Therefore, whenever we calculate the resistance of the discharge path, we must add the 100 Ohms of the path itself. This amount is somewhat insignificant when the potentiometer is set to 10k Ohms, but extremely significant when set to 0 Ohms.

Taking both of these theoretical oversights into account, we arrive at a wavelength of 1.46 seconds (see chart below) when the potentiometer is at its highest value of 10k Ohms. This means that it takes about 1.5 seconds for the LED to flash on and off. When the potentiometer is at its lowest value of 0 Ohms, we arrive at a frequency of 13.2 cycles/second. This means that the LED will flash about 13 times in one second. Both of these results should be consistent with the observations of our previous experiment.

Chart: Below is a chart in which we will calculate the theoretical values of the charge and discharge time for each capacitor—using (a) 0.69RC for the charge and discharge time and (b) 100 Ohms as an additional resistance of the discharge path. For each capacitor, we will analyze what the wavelength and frequency should look like when the potentiometer is at a minimum (0 ohms) and when it is at a maximum (10k Ohms). Fill out the chart below; the first two rows are filled out for you.

Capacitor Value	R1	R2	Charge Resistance	Charge Time	Discharge Resistance	Discharge Time	Wavelength of one Cycle	Frequency
100 uF	1 k	10 k	**11 k**	**0.759**	**10,100**	**0.7**	**1.46**	**0.69**
100 uF	1 k	0	**1 k**	**0.069**	**100**	**0.0069**	**0.076**	**13.2**
10 uF	1 k	10 k						
10 uF	1 k	0						
1 uF	1 k	10 k						
1 uF	1 k	0						
0.1 uF	1 k	10 k						
0.1 uF	1 k	0						

Experimental Observation with the Oscilloscope:

Oscilloscope: Obtain an oscilloscope and attach the probe to TP1 of the 555 Companion, making sure to attach the ground portion of the probe to 0 Volts. For each capacitor, try to find the trace on the oscilloscope by adjusting the time/division knob. Once a trace is found, record the amount of time it takes for the capacitor to charge (5v portion of square wave), the amount of time it takes to discharge (0v portion of square wave), the wavelength of one cycle, and the frequency in the chart below. If you are using a 2-Channel Scope, put the two channels on TP1 and TP2 and select "dual" channel for the mode. This will reveal the correspondence between the square wave clock pulse and the charging and discharging of the capacitor.

Because oscilloscopes are designed to observe waveforms at high frequencies, the slowest frequency on the chart will be impossible to pick up on with an oscilloscope (highlighted on chart). For this row, estimate only the wavelength using a stopwatch and observing the green LED.

Capacitor Value	R1	R2	Charge Time	Discharge Time	Wavelength of one Cycle	Frequency
100 uF	1 k	10 k	XXXXXXX	XXXXXXXXX		
100 uF	1 k	0				
10 uF	1 k	10 k				
10 uF	1 k	0				
1 uF	1 k	10 k				
1 uF	1 k	0				
0.1 uF	1 k	10 k				
0.1 uF	1 k	0				

Conclusion:

1. **In comparing the theoretical results with the experimental ones, in which cases were the frequencies the closest? In which ones were they the most apart?**

2. **Do you think the discrepancies between the theoretical and experimental results are due to theoretical oversights or observational errors and approximation? Explain your reasoning.**

3. **If we have the ability to measure something experimentally, is there any point to having a theoretical understanding of the subject? Is it necessary to have equations when we have tools to measure what the equations try to predict? Explain.**