CG1111 Engineering Principles and Practice I

Principles of Capacitors and Inductors

(Week 5, Studio 2)

Time	Duration (mins)	Activity
0:00	20	Briefing
0:20	60	Activity #1: Applying DC transient analysis technique to derive the charging voltage characteristics of a capacitor in a given circuit (graded lab report)
1:20	70	Activity #2: Deriving the frequency of an oscillator circuit using the transient capacitor voltage equation (graded lab report)
	Homework	Activity #3 – Understanding the transient behaviour of an RL circuit **(not graded)** – You need to use your circuit from Activity #2

Introduction:

- When capacitors are being charged/discharged through a series RC circuit, the transient behaviour of the voltage change is not linear; instead, it changes exponentially with the following form:

$$v_C(t) = v_C(0)e^{-\frac{t}{\tau}} + v_C(\infty)\left(1 - e^{-\frac{t}{\tau}}\right), \tau = RC$$

- In Activity #1, you will first predict the charging voltage curve of a capacitor in a given circuit using DC transient analysis, and then verify its behaviour via experiments using the BitScope.

- In Activity #2, you will experience how a popular oscillator circuit utilizes a capacitor's transient voltage behaviour to control its oscillation frequency. You will derive the oscillation frequency and verify it experimentally with the help of the BitScope.

- Just like the transient voltage behaviour of a capacitor in a series RC circuit, an inductor's transient current in a series RL circuit also has a similar form:

$$i_L(t) = i_L(0)e^{-\frac{t}{\tau}} + i_L(\infty)\left(1 - e^{-\frac{t}{\tau}}\right), \tau = \frac{L}{R}$$

- In Activity #3, you will build an RL circuit, and observe its transient behaviour with the help of the BitScope. You will also try to estimate the inductance of the given inductor.

Objectives:

- To learn about the precautions when working with electrolytic capacitors
- To learn about the ***time-constant*** of series RC circuit, and series RL circuit
- To practise analysing DC circuits containing (i) **resistors and capacitors**, (ii**) resistors and inductors**, in both **steady-state** and **transient state**

Components:

- Protective goggles
- Breadboard and connecting wires
- USB breakout cable
- Digital multimeter
- BitScope
- 2200 μF electrolytic capacitor x 1
- 5% tolerance resistors {10 kΩ x 1, 100 kΩ x 1, 470 Ω x 1, 180 Ω x 2}
- Ceramic capacitors (100 nF x 1 [code 104], 10 nF x 1 [code 103])
- 555 timer IC x 1
- 820 μH inductor x 1

<u>Activity #1: Applying DC transient analysis technique to derive the charging voltage characteristics of a capacitor in a given circuit (60 mins)</u>

Note: Both Activity #1 and #2 will be assessed. Students are required to submit <u>individual</u> lab reports (upload in PDF format to submission folder) before the studio ends.

The circuit diagram in Figure 1 shows a capacitor charging circuit. When the switch is closed, the capacitor starts to get charged, and its voltage increases in a non-linear manner. From the e-lecture, we have learnt that the voltage of a capacitor in a <u>series RC</u> circuit during charging can be modelled using the following expression:

$$v_C(t) = v_C(0)e^{-\frac{t}{\tau}} + v_C(\infty)\left(1 - e^{-\frac{t}{\tau}}\right), \tau = RC$$

However, as can be seen in Figure 1, the capacitor is not in a series RC circuit for our case. In this part of the activity, you shall practice deriving the equivalent series RC circuit, so that you can apply the above transient voltage equation directly.

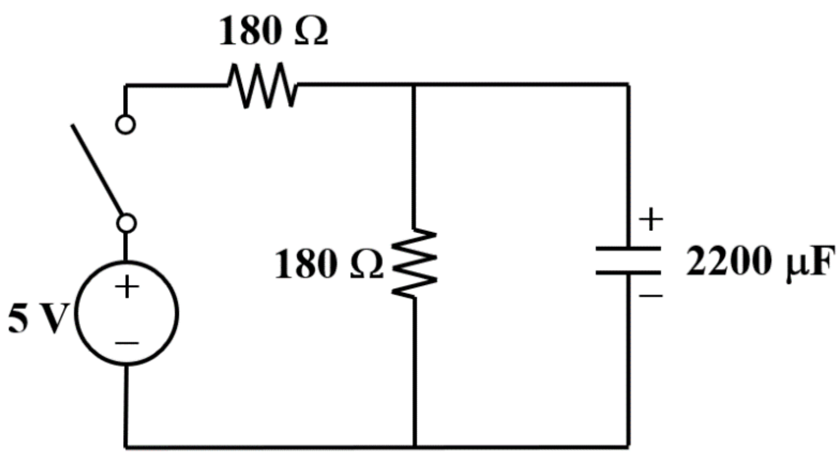


Figure 1: Circuit diagram for DC transient analysis on capacitor charging.

Procedure:

1. Write down the following precautions in your lab report:
    a. Electrolytic capacitors have polarity. I will ensure that the polarities are correct before turning on the power supply.
    b. I will wear protective goggles when the circuits are powered.

2. Spend some time to take note of the polarities of the 2200 μF electrolytic capacitor. There are '–' markings indicating which pin is the **negative** terminal (see Figure 2).

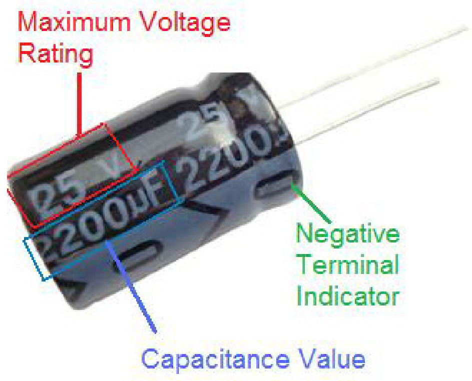


Figure 2: An electrolytic capacitor with '– ' markings identifying the negative pin.

3. Suppose the switch in Figure 1 has been opened for a very long period of time, and will be closed at time $t = 0$. What is the voltage $v_c(t)$ across the capacitor just before the switch is closed (i.e., at $t = 0^-$)? What is the voltage $v_c(t)$ just after the switch is closed (i.e., at $t = 0^+$)? What is the expected voltage $v_c(t)$ at steady-state after the switch is closed (i.e., at $t = \infty$)?

4. Derive the Thevenin equivalent circuit that the **capacitor sees**, for time $t \geq 0$ (i.e., after the switch is closed).

    Hint 1: The Thevenin voltage V_{Th} is the open-circuit voltage across the nodes where the capacitor was supposed to be connected (but removed for this analysis).
    Hint 2: The Thevenin resistance R_{Th} is the equivalent resistance seen across the nodes where the capacitor was supposed to be connected (but removed for this analysis), after we have "killed off" the effect of the voltage source by replacing it with a wire.
    Hint 3: An alternative way to find R_{Th} is to calculate the short-circuit current I_{SC} across the nodes where the capacitor was supposed to be connected (but removed for this analysis), and then use the equation $R_{Th} = V_{Th}/I_{SC}$ to get R_{Th}.

5. Draw the new representation of the circuit showing the capacitor connected in series with the Thevenin equivalent circuit, with the V_{Th} and R_{Th} values you have calculated in Step 4. Your circuit should look like Figure 3 below.

6. Now, write down the equation for the capacitor voltage $v_c(t)$, for time $t \geq 0$. Remember to include the numerical value of the time constant τ.

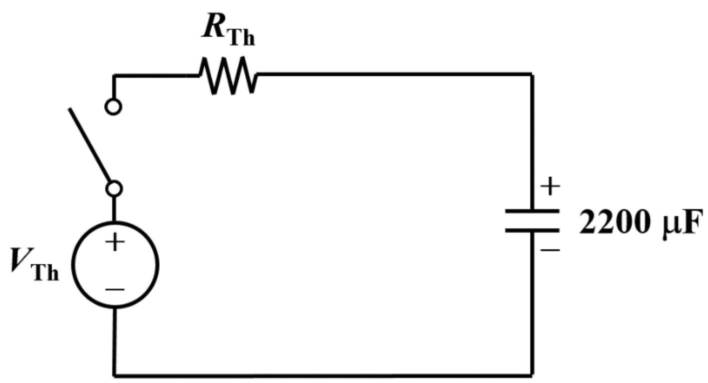


Figure 3: Circuit diagram showing the capacitor in series with a Thevenin equivalent circuit.

7. Using the breadboard, construct the circuit shown in Figure 1. **Check that the polarity of the capacitor is correct.** You can emulate the function of a switch by connecting everything else in the circuit except the "+" (i.e., red) wire of your USB breakout cable, and then finally connecting the "+" wire to the circuit only when you are ready to power up the circuit. You can leave the "+" wire disconnected for now.

8. We will now prepare to capture the capacitor's voltage waveform using the BitScope. Connect a test probe (the one with yellow wire is recommended so that it coincides with your waveform colour for easier debug) to the CHA pin (i.e., Channel A) of the BitScope. Connect another test probe (the one with black wire is recommended as black is normally used for ground) to the GND pin (i.e., Ground) directly below the CHA pin. Connect the mini-grabber of the yellow probe to the "+" terminal of the capacitor, and the mini-grabber of the black probe to the "–" terminal of the capacitor. Connect the BitScope to your computer, and run BitScope DSO. Click "POWER" to turn on your BitScope.

   Note: From now on, we will directly use the names of the various control panels in BitScope DSO in this handout. Please refer to the Appendix at the end of this handout for their locations on the screen.

9. In the "Timebase Control (6)" panel, set the timescale to **100 ms/Div**. Click on "REPEAT" to deactivate repetitive capture, because we will be doing a one-time waveform capture. In the "Channel Controls (7)" panel, for Channel A (i.e., CHA), set the **voltage per division** to **500 mV/Div**. Right-click on the offset entry (i.e., the box below "PRB"), select "REF". It should show "0 V" for now. Left click on the "0 V", and drag your mouse cursor down until the voltage offset becomes "**1 V**". The purpose is to lower the 0 V line downwards by 1 V so that the capacitor's voltage won't be clipped off at the top of the screen later.

10. Next, we shall adjust the trigger setting inside the "Trigger Controls (4)" panel. Left-click on the trigger voltage level (the yellow box inside the panel that shows a voltage), and drag your mouse slightly to change the value to anything between **40 mV** and **60 mV**. This sets the voltage level at which your BitScope will be triggered to capture the waveform.

11. You are now about to capture the capacitor's charging voltage waveform. Make sure the USB power adapter/charger is powered on. **Wear your goggles now.** With one hand

holding the "+" wire of the USB breakout cable, use the other hand to left-click on the "TRACE" button in the "Timebase Control (6)" panel. Immediately after, plug the "+" wire into your breadboard circuit to power up the capacitor charging circuit you have constructed in Step 7. If you have performed everything correctly, your BitScope DSO should have captured a single waveform, similar to the example shown in Figure 4. If you did not manage to capture the waveform correctly, remove the "+" wire from the circuit, wait for a few seconds for the capacitor to discharge, and repeat Step 11.

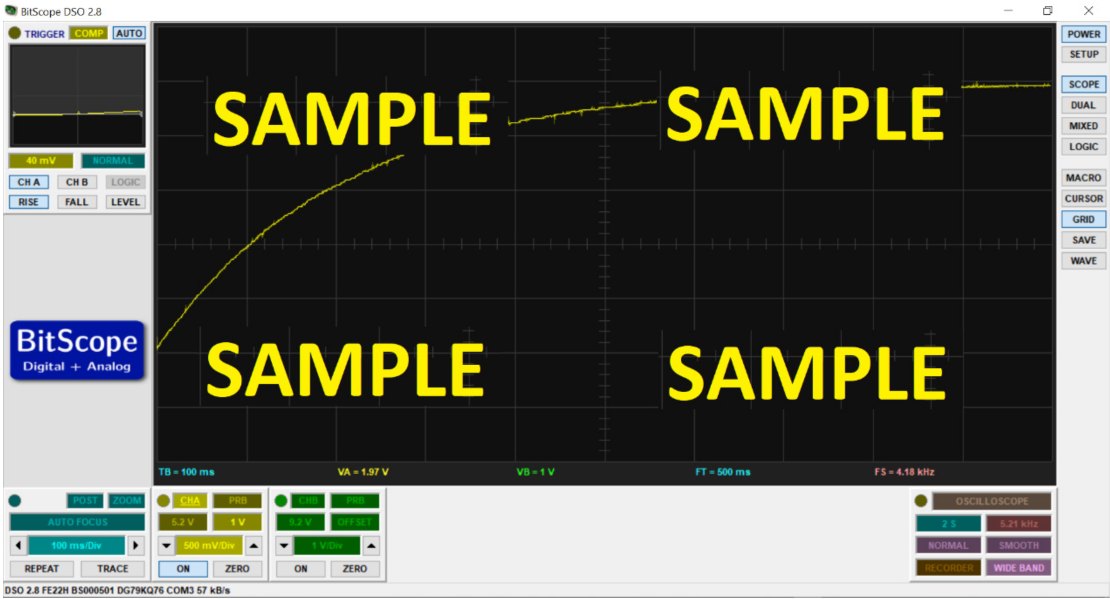


Figure 4: Sample waveform captured by BitScope.

12. Turn off the power to your capacitor charging circuit. You can now remove your goggles.

13. You will now use the "CURSOR" function in BitScope DSO to measure the time taken for the capacitor's voltage to rise to 63.2% of $v_c(t = \infty)$. To do so, click on the button "CURSOR" in the "Scope Selectors (2)" panel. Left-click on the *horizontal* orange cursor line on the "Main Display (1)", and drag it to coincide with the voltage corresponding to 63.2% of $v_c(t = \infty)$. The voltage value can be read from the "Cursor Measurements (5)" panel. Look for the voltage reading in orange. Next, left-click on the *vertical* orange cursor line on the main screen, and drag it to the time instant where the capacitor voltage reaches 63.2% of $v_c(t = \infty)$. The time measured can be read from the "Cursor Measurements (5)" panel as well. Do a screen capture of your BitScope DSO, and paste it into your report.

14. Answer the following questions:
<u>(i) Based on the equation you have written in Step 6, what is the theoretical value of this time (i.e., the time taken for the capacitor's voltage to reach 63.2% of $v_c(t = \infty)$)? Verify your experimental value against its theoretical value.</u>
<u>(ii) What are the possible sources of errors that could potentially cause a mismatch?</u>

Activity #2: Deriving the frequency of an oscillator circuit using the transient capacitor voltage equation (70 mins)

Note: This activity is also assessed, and must be included in your lab report for submission as well.

Background:

A common usage of the 555 timer chip is for generating square wave output waveforms. Figure 5 shows the block diagram of the 555 timer chip, with its corresponding pin layout. Notice that there is a **notch** on the chip near to pin 1 and pin 8. The notch helps you orientate the chip so that you know exactly where are pins 1 to 8.

So why is the chip called "555"? Looking at the block diagram, you can see that there are three 5 kΩ resistors in series between the ground (pin 1) and the voltage supply V_{cc} (pin 8). They form a nice potential divider circuit that yields reference voltages $\frac{1}{3}V_{CC}$ and $\frac{2}{3}V_{CC}$. (Note that pin 5 can overwrite these, but for our oscillator circuit, we won't be using pin 5 and will just connect it to a 10 nF capacitor to eliminate any noise.)

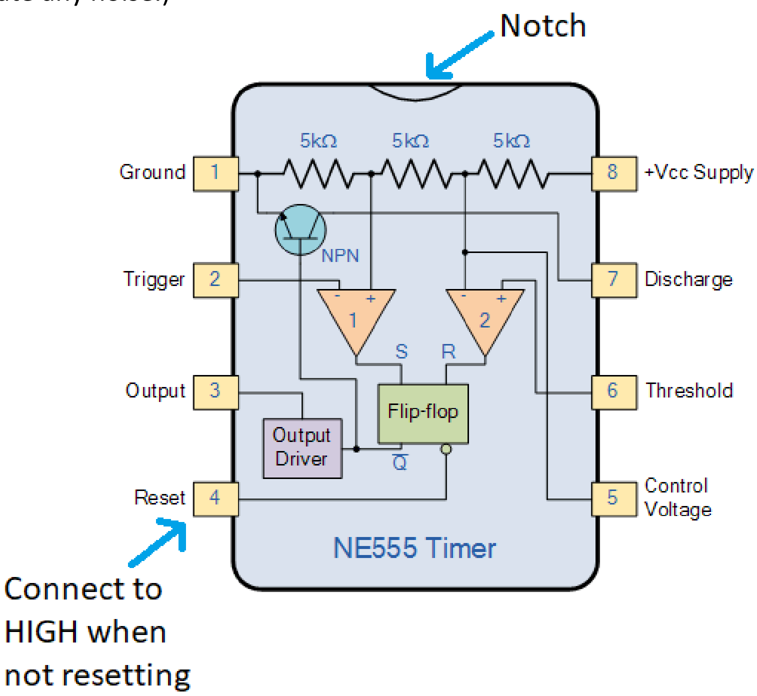


Figure 5: 555 Timer block diagram with pin layout.

The two triangles in the block diagram are comparators (which you will learn later in this module). They compare the voltages at pin 2 and pin 6 with the reference voltages $\frac{1}{3}V_{CC}$ and $\frac{2}{3}V_{CC}$, respectively. The following summarizes the behaviour of the chip:

- When the voltage at the "Trigger" (pin 2) falls below $\frac{1}{3}V_{CC}$, the Output (pin 3) flips from 0 V to HIGH (about $V_{CC} - 1.5$ V). It remains at HIGH until the voltage at the "Threshold" (pin 6) exceeds $\frac{2}{3}V_{CC}$.
- When the voltage at the "Threshold" (pin 6) exceeds $\frac{2}{3}V_{CC}$, the Output (pin 3) switches from HIGH to 0 V. It remains at 0 V until the voltage at the "Trigger" (pin 2) falls below $\frac{1}{3}V_{CC}$.

- When the Output is HIGH, the "Discharge" (pin 7) is open-circuit. When the Output is 0 V, the "Discharge" (pin 7) is connected to ground (hence 0 V).

If we connect the 555 timer chip using the connections shown in Figure 6, we can generate square wave output waveforms.

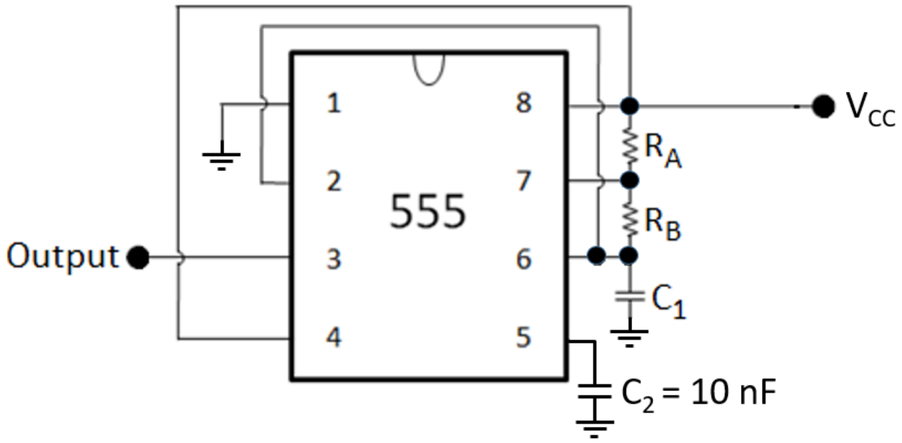


Figure 6: Connections for generating square wave output waveforms.

How does this circuit work? The 555 chip essentially permits capacitor C_1 to charge through resistors R_A and R_B with current flowing from the power supply V_{cc}. Pin 6 of the chip monitors the rising voltage on C_1 and when it reaches $\frac{2}{3}V_{CC}$, the capacitor is allowed to discharge through R_B into Pin 7. Once it has discharged to $\frac{1}{3}V_{CC}$, it is again allowed to charge, and the cycle repeats. Figure 7 below illustrates this mechanism. The size of the capacitance C_1 as well as the resistances R_A and R_B determine how long it will take for the capacitor to charge and discharge. While the capacitor is charging, the chip sets the output pin to HIGH; during discharging, the output pin is set to 0 V. The timer is thus nominally a square wave generator.

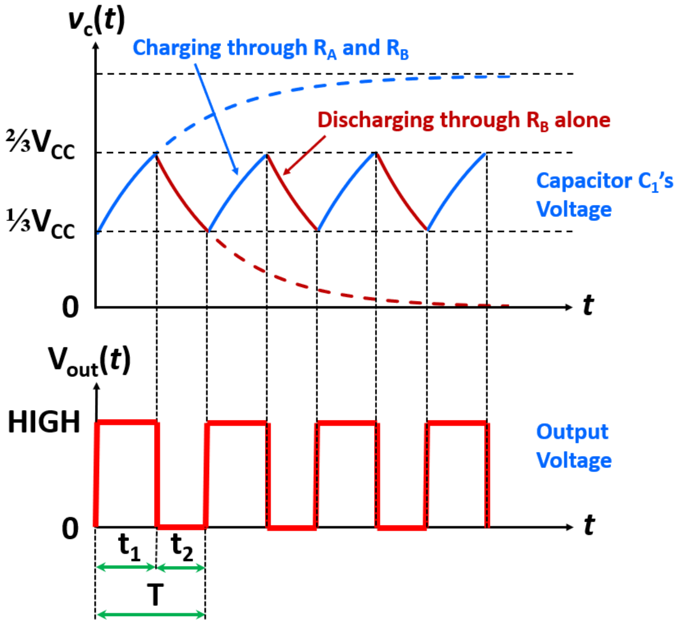


Figure 7: Relationship between Capacitor C_1's voltage (v_c) and the 555 IC's output voltage (V_{out}).

Procedure:

1. When capacitor C_1 is charging from $\frac{1}{3}V_{CC}$ to $\frac{2}{3}V_{CC}$, the charging source is $\mathbf{V_{cc}}$, and it is a **series RC circuit** with **resistors $\mathbf{R_A}$ and $\mathbf{R_B}$**. Using the transient capacitor voltage equation $v_C(t) = v_C(0)e^{-\frac{t}{\tau}} + v_C(\infty)\left(1 - e^{-\frac{t}{\tau}}\right), \tau = RC$, derive the time t_1 taken for v_C to charge from $\frac{1}{3}V_{CC}$ to $\frac{2}{3}V_{CC}$. Remember to use the correct $v_C(0)$ and $v_C(\infty)$ for the given conditions in this question.

2. When capacitor C_1 is discharging from $\frac{2}{3}V_{CC}$ to $\frac{1}{3}V_{CC}$, pin 7 is grounded and the discharging is done through it to **ground**. It is **a series RC circuit** with **resistor $\mathbf{R_B}$ only**. Derive the time t_2 taken for v_C to discharge from $\frac{2}{3}V_{CC}$ to $\frac{1}{3}V_{CC}$. Use the correct values for $v_C(0)$ and $v_C(\infty)$ for the given conditions in this question.

3. The period *T* of the square wave output is given by $t_1 + t_2$. Show that its frequency is:

$$f \approx \frac{1.44}{(R_A + 2R_B)C_1}$$

4. For the circuit shown in Figure 8 below, calculate the values of t_1, t_2, and *f*.

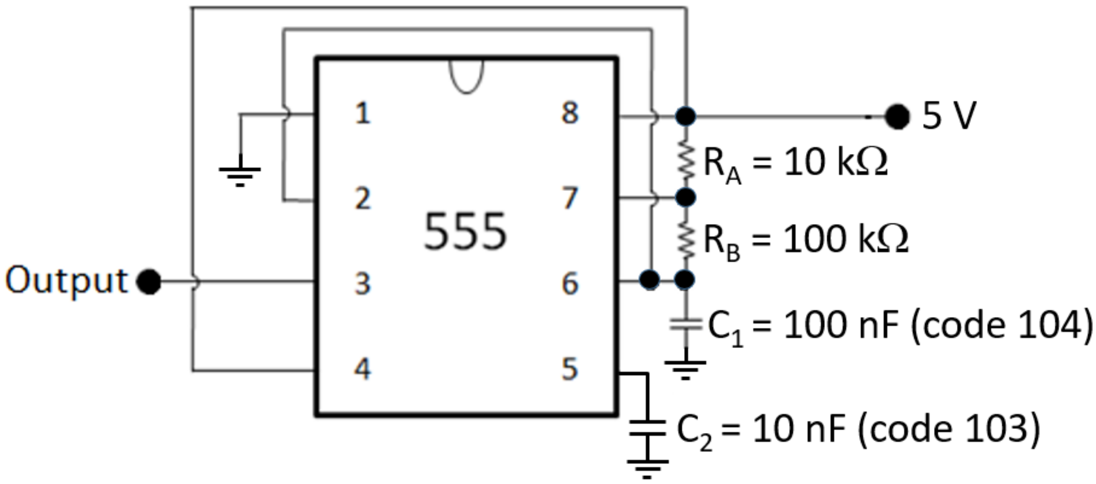


Figure 8: 555 timer circuit to be used for verifying your calculations.

5. You will now verify your calculations through experiments. Construct the circuit shown in Figure 8 on your breadboard. The '–' terminal of your USB breakout cable serves as the ground in this circuit. Ensure that all the grounds in the circuit are connected to this ground (i.e., they must have a **common** ground).

6. Next, you will use BitScope to observe the waveforms. For this activity, we will use both channels of the BitScope. Your Channel A already has a pair of probes from Activity #1. Now, connect another probe (green wire recommended) to Channel B (CHB) on your BitScope. Also connect a probe (dark brown wire recommended) to the ground (GND) pin below the CHB pin. Connect the mini-grabber of CHA to pin 6 of your circuit so as to observe the capacitor's voltage. Next, connect the mini-grabber of CHB to pin 3 of your circuit so as

to observe the 555 timer's output voltage. Finally, connect the mini-grabbers of the ground wires of both channels to the ground of your circuit.

7. Connect the BitScope to your computer, and run BitScope DSO. Turn on the power to your circuit, and the BitScope. Change the timescale in the "Timebase Control (6)" panel to **2 ms/Div**. Change the voltage scale of Channel A in the "Channel Controls (7)" panel to **500 mV/Div**. Click the "ON" button for Channel B in this panel to activate it. You can leave the voltage scale unchanged as **1 V/Div** for Channel B. The waveforms you see on the screen should now resemble the waveforms in Figure 7.

8. Click the "TRACE" button in the "Timebase Control (6)" panel to freeze the waveforms. You will now use the cursor functions to perform measurements. Click on "CURSOR" in the "Scope Selectors (2)" panel to turn it on. Left-click on the *vertical* orange cursor line on the main screen, and drag it to the time instant where the output's "falling edge" occurs. Next, left-click on the *vertical* dirty-green cursor line on the main screen (you should be able to find it at the extreme left), and drag it to the time instant where the output's "rising edge" occurs. Choose the rising edge that is immediately before the falling edge where the orange cursor was previously set. The duration of t_1 is now given in the "Cursor Measurements (5)" panel (look at the time shown in cyan colour). <u>Write down the value you have obtained.</u>

9. Now, use the cursors to measure the duration of t_2 using a similar approach, and <u>write down its value</u>. Finally, measure the duration of an entire period using a similar approach. Note that when you do this, the frequency is also automatically computed for you inside the "Cursor Measurements (5)" panel (shown in cyan colour). <u>Write down this frequency's value</u>. Take a screenshot of your BitScope DSO showing the waveforms, and include it in your report.

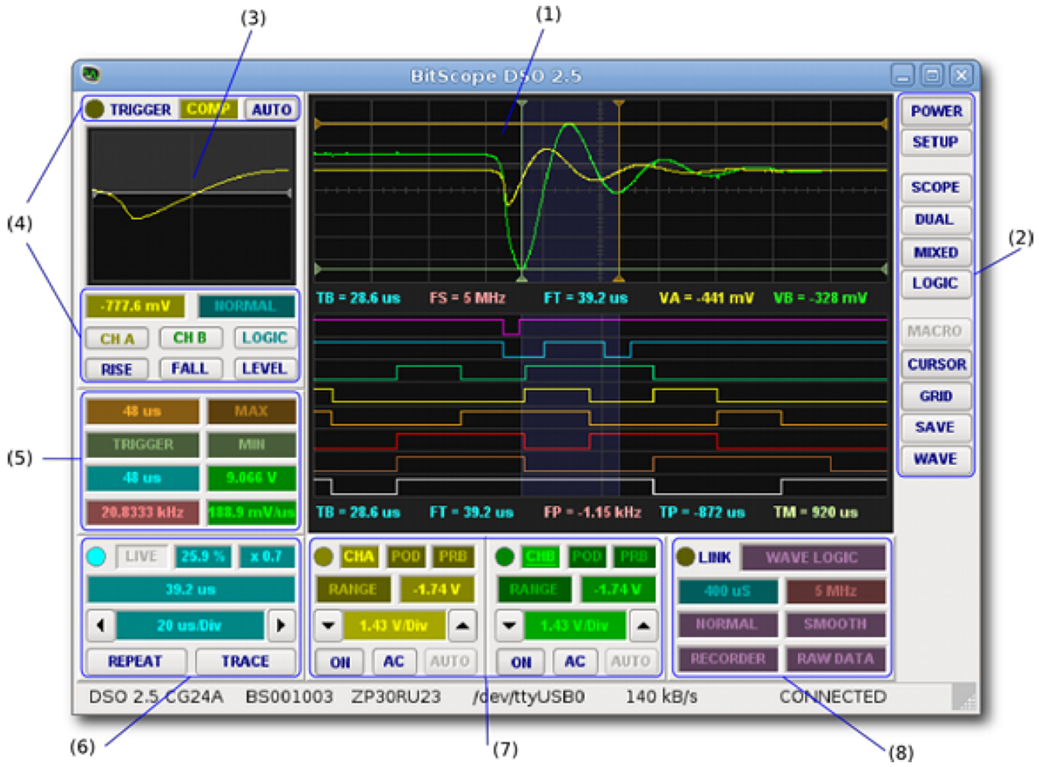
10. Verify the values of t_1, t_2, and f that you have obtained from measurements against the theoretical values you have calculated in Step 4. <u>What are the possible sources of errors that could potentially cause a mismatch?</u>

END OF GRADED STUDIO

<u>Activity #3: Understanding the transient behaviour of an RL circuit (60 mins)</u>

Note: This activity is not graded. The handout will be given to you as a separate document. Note that you need your 555 timer circuit from Activity #2.

APPENDIX: BITSCOPE DSO'S INTERFACE



ID	FEATURE	DESCRIPTION
(1)	Main Display	Waveform, logic and spectrum displays, measurements and cursors.
(2)	Scope Selectors	Virtual instruments, scope tools, presets, cursors, graticule etc.
(3)	Trigger Windows	Shows trigger levels, analog and logic waveforms at the trigger.
(4)	Trigger Controls	Controls trigger setup and displays trigger waveform and data.
(5)	Cursor Measurements	X and Y cursor values, voltage, time and rate measurements.
(6)	Timebase Control	Timebase, Zoom and Time Focus control parameters.
(7)	Channel Controls	Controls input source, range, vertical position and scaling.
(8)	Capture Control	Capture sample rate, duration, frame rate and display modes.