Chapter 8

RC Circuits and The Oscilloscope

There are two important concepts involved in this experiment. In part "A" we examine an effect which occurs with its own unique "clock", a "clock" whose basic time unit (the time constant, τ) is determined by the electrical characteristics of the circuit, i.e. by the particular values of "R" and "C". A common graph for many kinds of time-varying phenomena can be produced in terms of the intervals called time constants. We can relate these graphs to our own time system (sec., min., hrs., etc.) by knowing how a time constant is related to the electrical characteristics of a particular circuit. In part "B" we see how we can use our knowledge of electricity and magnetism to create an important instrument for measuring effects which change with time. Like many modern instruments, the oscilloscope requires us to convert the effect which we wish to observe into a voltage. This is quite easy for this particular experiment, but that is not always the case.

Objective

1. To study charging and discharging of a capacitor.

2. To perform basic electrical measurements using an oscilloscope.

Apparatus   Battery, capacitors, resistors, two-pole switch, digital multimeter, stop watch, connecting wires, linear and semi-log paper.

Digital Oscilloscope, signal generator, coaxial cables.

This lab consists of three parts. Part A: RC Circuits (manual), part B: RC Circuits (computer-based) and part C: Oscilloscope.

8.1   A: RC Circuits

8.1.1   Introduction

A capacitor consists of two metal surfaces separated by a non-conductor. The electric charge can be stored on the metal surfaces of the capacitor. The amount of charge Q stored is proportional to the voltage V applied across the capacitor:

$$Q = CV$$

The proportionality constant C in the above relation is the capacitance. The SI unit of capacitance is the Farad [F]. Subunits of Farad are frequently used: $\mu F = 10^{-6}F$ (micro Farad), $pF = 10^{-12}F$ (pico Farad). The capacitance of a capacitor is determined by the geometry of the conductor(s) and the material separating them. Commercial capacitors are often made by spacing two metallic foils with a sheet of paraffin-coated paper. These layers are then rolled into the shape of a cylinder to form a small package. For such a capacitor the capacitance is given by:

$$C = \frac{k\epsilon_0 A}{d}$$

$$A = \text{ Surface area of the metal plate } (m^2)$$
$$d = \text{ separation between plates } (m)$$
$$k = \text{ dielectric constant (for paper k} = 3.7)$$
$$\epsilon_0 = 8.85 \times 10^{-12} F/m \text{ - constant called permittivity of free space}$$

High-voltage capacitors consist of interweaving metal plates immersed in silicon oil. Small capacitors are constructed using ceramic materials (e.g. $BaTi0_3$), which have a high dielectric constant $k \approx 1 \times 10^{-8}F/m$. The process of charging or discharging a capacitor doesn't happen instantaneously. It takes some time. This time is determined by the resistance in the circuit and the capacitance (Fig. 8.1).
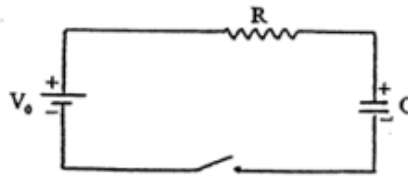

Figure 8.1: Simple RC circuit.

The sum of voltages (Conservation of Energy) around the circuit shown in Fig. 8.1 leads to the following equation:

$$V_0 = V_R + V_C = IR + \frac{Q}{C}$$

Immediately after closing the switch, $Q = 0$, so that $V_R = V_0$, and the current I jumps to its maximum value $I = V_0/R$. As the capacitor accumulates charge, it begins to resist

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the flow of charge because the positive side tends to hold electrons, and the negative side tends to oppose the addition of more electrons. The complete mathematical treatment of charging of a capacitor (see the textbook) shows that the magnitude of charge accumulated by the capacitor changes with time according to the equation.

$$Q = Q_0(1 - e^{-t/RC})$$
$$\text{Where } Q_0 = CV_0$$
$$\text{and } e = \text{base of natural logarithm} = \sim 2.72$$

Since $Q = CV$, C - being constant, the voltage across the capacitor changes with time in a similar way as the charge changes.

$$V = V_0(1 - e^{-t/RC})$$

The product RC, called the time constant τ, has the dimensions of time (seconds). The time constant $\tau = RC$ determines the rate of the charging process. Now let's consider a charged capacitor being discharged through resistor R. The initial charge on the capacitor is Q_0. When the switch is closed, the charge begins to move through the resistor, and the current is maximum. The initial current is not constant, since as charge leaves the capacitor the voltage across the capacitor decreases; therefore, the current decreases as well. The theory shows that charge on the capacitor during the discharge changes according to the equation:

$$Q = Q_0 e^{-t/RC} \quad \text{Where } Q_0 \text{ is the initial charge on the capacitor}$$

The time constant $\tau = RC$ determines how quickly the capacitor will discharge. The voltage across the capacitor is given by an analogous formula since $Q = CV$, C - constant.

$$V = V_0 e^{-t/RC}$$

The current I for the charging and discharging processes is given by the same formula:

$$I = I_0 e^{-t/RC}$$

Obviously, the direction of current for charging and discharging is opposite.

8.1.2   Prelab Exercise 1

1. If the experimental set up in Fig. 8.2 has a 12.0V battery and a 10µF capacitor, determine the time it would take for the fully charged capacitor to decrease the voltage from 12.0V to 8.0V (switch will be in the discharging position A-C).

2. The two resistors, 1$k\Omega$ and 10$M\Omega$, in this circuit (Fig.8.2) are different by many orders of magnitude. Explain why?
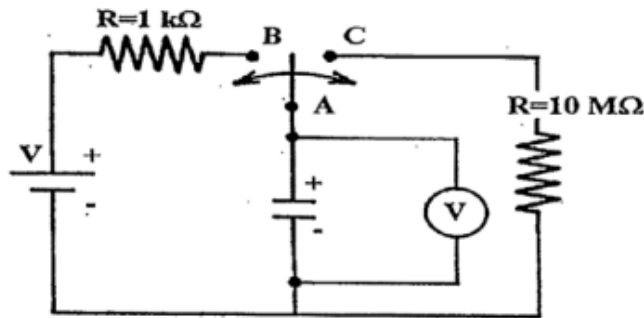
Figure 8.2: Circuit for studying charging and discharging of an RC circuit.

8.1.3   Measurements and Calculations

1. Connect the circuit as shown. Refer to Fig. 7.3 for a reminder on how the solderless breadboard is designed.

2. Charge the capacitor by moving the two-pole switch to the position B. The time constant for charging is very short because of the small value of the resistance $1k\Omega$. After about 1 second the voltage across the capacitor is essentially identical to that of the battery

3. Move the switch quickly to the position C, starting the clock at the same time. The capacitor will discharge through the $10M\Omega$ resistor and through the internal resistance of the digital voltmeter, also $10M\Omega$. Both resistors are connected in parallel so the equivalent resistance of both is $5M\Omega$. Take about 6-10 readings of voltage vs. time. Take the readings every 15-20 seconds. Remember that all discharges are identical, so you can use several discharge sequences to obtain the necessary readings.

4. In this experiment, the voltage discharges exponentially (not a straight line on a graph of V vs T). To extract useful information, please plot $ln(V)$ vs. T. This should give a straight line whose slope is $-1/RC$. Determine the slope and compute τ. You do not need to perform any uncertainty analysis on the slope.

5. Determine the value of the capacitor, C, from the time constant.

6. Sketch what you think the Current vs Time graph would look like.

8.2   B: RC Circuits- (computer-based measurement)

1. Using the setup in Fig. 8.2, replace the $10M\Omega$ discharging resistor with a $1M\Omega$ resistor.

2. Add a second capacitor in series with the existing capacitor, and monitor the voltage across the pair.

3. Rather than using the multimeter to measure voltage, attach the Voltage Probe at-

tached to the computer interface. The voltage probes take measurements at regular time intervals (20 times per second). The data is then transmitted through the interface to the computer to be displayed and analyzed. The colour-coded test leads should be connected across capacitors in the following way: red lead to the positive end of the capacitor and black lead to the negative end of the capacitor.

4. If it is not already open, open the file *Capacitors* on the desktop. Clear existing data if necessary.

5. Charge the capacitor for about two seconds.

6. Switch to discharging, then select the ▶ Collect button soon afterwards.The experimental data will be plotted on the screen while it is collected. The time and voltage are recorded in the table on the left-hand side of the screen. Once the data collection is completed, move the cursor and observe how time and voltage are displayed on the upper-right side of the graph window.

7. Autoscale the plot by selecting ⊞. Then, to fit the data to an exponential, click on ⋀⋀. Scroll down the options for functions and select the formula called *Natural Exponent*. Click on the *TRY Fit* button. A black fit line should appear over the red collected data points in the small window. Click *OK*, and the black fit line will now appear in the main window, along with a fit function and values for fit parameters.

8. Print your results in Landscape format. In the window that pops up, select Print Footer, and enter your name. print one copy with your name and one copy with your partner's name.

9. Compare the equation
$$V = V_0 e^{-t/RC}$$
with the equation displayed on the graph and compute the equivalent capacitance C. Here, we use $R = 0.91 \times 10^6 \Omega$ since we have a $1M\Omega$ resistor in parallel with our $10M\Omega$ voltage probe.

10. Compare it with the value of capacitance C determined in Section 8.1.3 above.

8.2.1 Questions

1. If a $10\mu F$ capacitor is replaced by a $1\mu F$ capacitor, can you still perform the experiment manually? Explain!

8.3 Oscilloscope

8.3.1 Introduction

On oscilloscope is a device which is used to display a voltage vs time graph in real time. It is particular useful when investigating voltages which change with time in a periodic

manner. In modern digital oscilloscopes, this is done using an on-baord fast analog-to-digital converter, and a colourful display screen. The parameters such as the scales of the axes, offsets can be set by the user. In addition, there are many other useful functions which you may wish to investigate such as cursors, and automatic measurements. In addition, a digital oscilloscope has a multitude of other functions which more advanced users would appreciate.
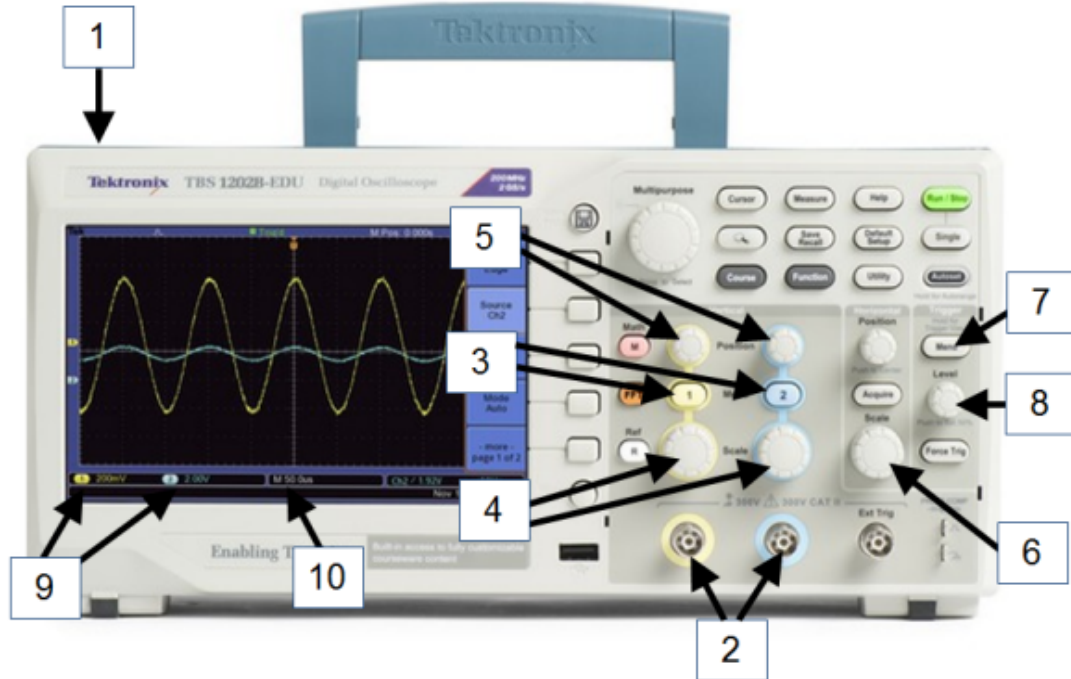
8.3.2 Experimental

Figure 8.3: Digital Oscilloscope

1. Power Switch

2. Input signals attached here. This oscilloscope can display two signals simultaneously.

3. Show Channel input.

4. Adjust the y-axis (Voltage/Division) scaling Channels. Use to "zoom in" on waveform.

5. Adjust the y position on the screen of the Channel.

6. Adjust the x-axis (Time/Division)

7. Set the triggering of the oscilloscope (see below)

8. Trigger Level control (see below)

9. Volt/Div for each channel are displayed here. (Each division is one large square).

10. Time/Div is displayed here. (Each division is one large square).

- To **measure the amplitude** of the voltage signal (waveform) count the number of divisions (large squares) from peak-to-trough and multiply by the selected value of the Volts/Div displayed in the bottom left corner of the screen. Divide this result by 2 to obtain the amplitude. Alternatively, you can use the built-in measurement

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functions by selecting the *Meas* button on the right and figuring out how the measure amplitude.
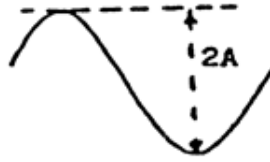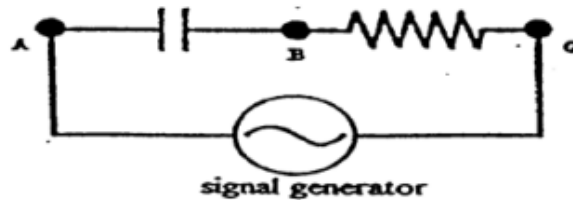

- To **measure the frequency**, count the number of divisions (large squares) from peak-to-peak and multiply by the selected value of the Time/Div displayed in the bottom left corner of the screen. The frequency is $f = 1/T$.
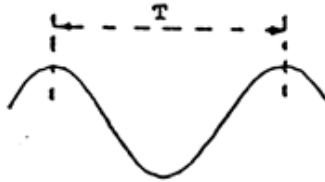
8.3.3   Measurement and Calculations

1. Connect the following circuit. This RC circuit is similar to the circuits studied in

signal generator

the first part of this lab. The only difference is that the battery (source of constant voltage) has been replaced by a signal generator (source of variable voltage).

2. Select sinusoid signal on the signal generator and adjust its frequency to about 1000 Hz (push the ∼ button and the 1k button.) Connect the signal AG to CH 1 of the oscilloscope and measure the frequency and the amplitude of the signal displayed on the oscilloscope.

3. Connect the capacitor at points AB to CH 1 with a coaxial cable. Select a square wave on the signal generator and adjust its frequency to about 300 Hz. The alternating voltage from the signal generator will charge the capacitor when the voltage is not equal to zero. When the voltage is momentarily equal to zero, the capacitor discharges through the resistor in this RC circuit.

Sketch the signal you observe on the screen of the oscilloscope. Using the charging and discharging portions of the signal on the screen (Fig.8.4) estimate the time constant

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of your RC circuit. Remember that the time constant τ is the time for the voltage to drop to 37% of its maximum value during the discharging process, and the time to increase to 63% of its maximum value during the charging process.
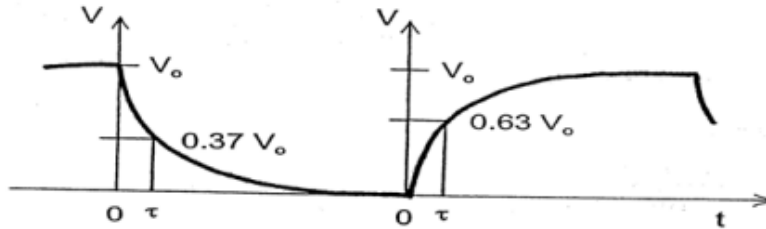

Figure 8.4: Charging and discharing of a capacitor

Use the relation $\tau = RC$ to determine the capacitance C. With the resistance R already known from the colour code chart, what is the value of C?

8.3.4   Questions

1. Would your measurements of amplitude and frequency be different if you set VOLTS/DIV and the TIME/DIV differently? Explain!

2. What is the largest and the smallest voltage (full signal displayed) that can be measured with your oscilloscope? What is the lowest and the highest frequency that can be measured with your oscilloscope?

END OF LAB

Was this lab useful, instructive, and did it work well? If not, send an email to thatlabsucked@gmail.com and tell us your issues. In the subject line, be sure to reference the your course, the experiment, and session. example subject: *PHYS1010 Linear Motion monday 2:30.* We won't promise a response, but we will promise to read and consider all feedback.