The R-C Circuit

In this experiment we shall use the oscilloscope to study the behavior of a circuit consisting of a resistor and a capacitor (an R-C circuit).

I. Theory

One of the simplest circuits with time-varying voltages is the RC circuit, shown in figure 1a. If the capacitor \( C \) is initially charged, its charge drains off (from the positively charged plate to the negatively charged plate) through the resistor. The current through the resistor is proportional to the voltage across the capacitor, which in turn is proportional to the charge remaining on the capacitor. So, the voltage decreases, at a rate which is proportional to the voltage itself. This results in an exponential decrease of the voltage (and the current) with time:

\[
V(t) = V_0 e^{-\frac{t}{\tau}},
\]

where \( \tau = RC \) (called tau, rhymes with “ow”) is the characteristic time of the decay. (See section 21.7 of Walker for a more complete presentation of the theory of the RC circuit.)

The voltage across the capacitor as a function of time is plotted in figure 1b. Notice a useful fact: the decay time \( \tau = RC \) of the circuit is roughly equal to the time for the voltage to decrease from its initial value to 1/3 of its initial value. This provides an easy way of estimating the decay time, especially useful when observing the signal on an oscilloscope. Another way to determine the decay time uses the semi-log plot. If we take the natural logarithm of the equation above for \( V \), we get

\[
\ln V = \ln \left( V_0 e^{-\frac{t}{\tau}} \right) = \ln V_0 - \left( \frac{1}{\tau} \right) t
\]

\[
\ln V = \ln b + \left( \frac{-t}{\tau} \right) x
\]

From the equation in brackets, we see that we will get a straight line if we plot \( \ln V \) vertically and time horizontally. Then the slope is related to the decay time by

\[
\frac{-1}{\tau} = \text{slope}
\]

\[
RC = \frac{1}{\text{slope}}
\]
slope = \frac{1}{\tau}

II. Experimental Procedure

A. Decay of the R-C Circuit.

Set up the circuit shown in figure 2, drawing the circuit diagram in your lab book before actually hooking it up. For this part, use the 2-μF capacitor. Note that for a discharge resistor, we are using the internal resistance of the voltmeter. We will simulate the switch shown in figure 2(a) by connecting and disconnecting a wire. Be sure that the “+” end of the capacitor goes to the “+” side of the power supply.

With the power supply set to 10V, open the switch and take a series of readings of V versus t (about 10 points, spaced every 10 seconds). Open an EXCEL spreadsheet and set up your data table before opening the switch! [This part of the experiment, and the analysis, resemble the plotting exercise in the first lab, "Data Analysis." Look there for details on graphing and straight-line fits.]

Plot V (y-axis) versus t (x-axis).

Q1. From your graph, in what way does voltage depend on time (e.g. sinusoidally, linearly, exponentially)? (We call this “functional dependence”.)

Now plot ln V (y-axis) versus t (x-axis).

Q2. Do your data lie on a straight line? What does that tell you about the functional dependence of V on t?

Use TRENDLINE to draw the “best-fit” line through your data points and to determine its slope. Calculate the decay time, \( \tau = RC \), using the slope of your graph.

Q3. Does \( \tau \) agree with what you calculate from the nominal values for \( R \) and \( C \), within errors? (The internal resistance \( R \) of the multimeter is approximately 10 MΩ.)

Try the same experiment, with a variety of capacitors, ranging from very big to very small. Don’t take data, just watch and see what happens.

Q4. In general, which capacitors discharge faster, and which slower?
B. Oscilloscope waveforms.

Realistic electronic circuits usually involve much smaller capacitances, and thus shorter decay times. We can see such rapid changes of voltage with the oscilloscope. We will use a dual-trace scope. The upper trace should show the voltage applied by the signal generator (a square wave) across the series R-C combination, and the lower trace will show just the voltage across the capacitor.

Here’s what happens: When the voltage applied by the signal generator goes from zero to (say) five volts, the capacitor does not charge up instantaneously. Instead it charges gradually. The time for it to charge most of the way up is equal to the RC time. (“Most of the way up” means from zero to within a factor of 1/e of the final voltage. In this example, \(5V/e = 5V/2.71828 = 1.84V\), so in one RC time the voltage would go from zero to 3.16 V. It’s not usually important to be so precise, though.) On the scope it is fairly easy to make a rough estimate of the RC time for this circuit.

Note about coaxial cables: you have several cables for use in this electronic circuit which consist of a central wire, usually used for a signal, with a cylindrical metal shield surrounding it. You can't see either of these wires, unless your lab instructor has a cable cut open for you to look at. Some of these cables have red and black banana plugs on one end. The black plug is connected to the shield, and the red plug, to the inner conductor.

Hook up the circuit shown in figure 3, using the 1500-Ω resistor and the 0.1-μF capacitor. As before, draw the circuit out in your book before hooking it up, for best reliability. A good way is to connect a cable from the function generator to channel 1 of the scope. Get the picture of the waveform from the function generator on the screen. Then use the BNC "T" connector and a BNC-to-banana cable to continue the signal to breadboard. Then connect the R and C in series. Finally, connect channel 2 of the scope across the capacitor using another BNC-to-banana cable.

Display the driving signal on scope channel 1, in the top half of the screen, and the voltage on the capacitor on channel 2, on the bottom of the screen. Start with scales of 2 V/div and 0.5 ms/div on the scope, with the frequency at \(10 \times 10^1\) Hz. Then try different scales, especially for the time.

Sketch what you see in your lab book. Measure \(\tau\) from the graph on the scope; see figure 1b for help.

Q5. Compare \(\tau\) with the expected value.

Now replace the 0.1 µF capacitor with each of the others (except the 10 µF polarized capacitor, which might be damaged if connected in reverse polarity). You will probably have to change the time scale each time, to see the full exponential rise and drop of the signal on the screen.
Q6. Explain qualitatively what happens to the exponential response time when you change the capacitor. Is this what you expect from theory?

Finally, vary the frequency on the function generator. Here too you may have to change the time scale to see the trace properly.

Q7. Can you explain the behavior of the capacitor-voltage trace, qualitatively?

C. Flasher circuit.

Hook up the circuit shown in figure 4, using one of the capacitors on the capacitor board (any of them except the 10 μF polarized capacitor). Measure the rate at which the circuit blinks, approximately. Is it close to RC? Try another capacitor. Can you figure out what the role of the neon bulb is in the circuit? Try reducing the voltage.

![Figure 4. Flasher circuit.](image)

III. Equipment

- Multimeter (Metex 3850 D) (R_in = 10 MΩ)
- 10 μF capacitor
- Capacitors (0.1μF, 1μF, 2.2μF)
- Resistance (1.5 kΩ, 2 kΩ, 2.5 kΩ)
- Function generator
- Power supply
- Oscilloscope
- Patch cords: two short black, two short red
- 2 - BNC-to-banana cable
- 1 - BNC-to-BNC cable
- 1 - BNC “T” connector
- Wristwatch with second hand (supplied by a student)
- 100-V power supply
- Neon bulb