Australian
National
University

Research School of Engineering
College of Engineering and Computer Science

ENGN1218 Introduction to Electronics

HLAB3 - First-order RC and RL Circuits

Week: 8

Lab Duration: 3 hours.

Due Date: Lab is marked during the lab time, based on completion of tasks.

Total Marks: 20

Contribution to Final Assessment: 3%

Attendance: To pass this course, students must attend and complete at least 8 out of 9 labs, including HLab5.

Pre-Lab Reading: The following resources will help you to successfully complete the lab:

- Lecture notes in week 6 and 7 (L21,L22,L25-L28)
- Lecture recordings in week 6 and 7
- Appendices in this lab manual
- Video lectures in echo360 on use of hardware instruments (especially oscilloscope)

Pre-Lab Tasks:

- Before coming to the lab, study the **Pre-Lab Reading** and read this entire lab manual carefully. Lab time is precious. Do not waste it reading the background material. If you do not do this minimum preparation, you may not be able to complete all the tasks in the lab time, resulting in loss of marks.
- Please print this manual and take one copy to the lab. The lab venue IR 105 does not have a printer. Hence, you need to make sure you print the manual before turning up for the lab. Alternatively, you can complete the lab manual electronically on your laptop/tablet.
- Parts of the Lab Tasks require basic theoretical calculations (i.e., Sections 2.1, 2.2.1, 2.3.1 and 2.4.1) and PSPICE simulations. Students should aim to complete the Pre-Lab Tasks BEFORE coming to the lab. Otherwise, you may not be able to complete the lab in 3 hours. This is especially important since the topics relevant to HLab3 were covered in weeks 6 and 7 when majority of students were busy with mid-semester exams so might not have time to study the topics.
- PSPICE schematic is provided for task 2.3.2. The schematic can be downloaded from the Wattle course website.

Instructions:

- Students will perform this lab in groups of two (or individually). Hence, both students will work together to assemble the circuit, take measurements and jointly complete the lab manual and will receive the same mark. There is no need to complete separate lab manuals or for two group members to individually assemble the same circuit.
- Use the lab time wisely. The focus should be taking measurements for the RC and RL circuits.
- With proper preparation, all students should be able to complete the lab in about 2.5 hours. The lab group is 3 hour duration to allow marking to be done during the lab time.

- Before leaving the lab, please make sure the tutors have recorded your attendance and marks. Return all cables/meters to their original position and clear your lab station. Log out of the lab computer (if applicable). Make sure to take all components used in the experiments with you (please DO NOT return them to their original boxes).

Important safety instructions:

Electrical safety and well-being of all students during the hardware lab time is of paramount importance and is taken seriously by myself, lab supervisors and lab tutors. In this regard, please:

- Wear (general) enclosed footwear with good sole during the lab time (no flip flops!).
- Wear safety goggles during the lab time. You can buy them for $5 from Co-op book shop. Note that if you wear prescription glasses then you do not need to wear safety goggles.
- Never place food or drink next to any equipment. Accidental spills can damage or destroy the equipment and your experiment and give you an electric shock.
- If you do not understand something, please ask the tutor immediately.
- If you are unsure, please ask the tutor to check your circuit, before you turn the power ON.
- When you are done for the day, make sure you power down all equipment.
- DANGER: This lab uses electrolytic capacitors, which have a polarity (the -ve terminal is marked on the capacitor and it is also the terminal which is shorter in length). If you insert the electrolytic capacitor in the circuit with incorrect polarity, it can explode and potentially cause serious damage to your eyes if you are not wearing safety goggles. If you are unsure, get the tutor to check the circuit before turning power ON.
- DANGER: When power is switched ON in RL circuits, it can theoretically cause arcing, since inductors oppose sudden changes in current. Please make sure to wear enclosed footware with rubber sole.

1 Learning Objectives

After completing this lab, students will be able to:

1. Recognizing types of capacitors (ceramic, electrolytic, green-cap) and practice of their safe handling.
2. Recognizing types of inductors (toroidal-core, ferrite-core).
3. Predict and measure the time constant of RC and RL circuits.
4. Combine capacitors and inductors in series/parallel.
5. Use oscilloscope and function generator to take lab measurements.

2 Pre-Lab Tasks

2.1 Self Test Questions

In a series RC circuit, what is the time constant τ and the duration of the transient, when

2.1.1 $R = 2k\Omega$, and $C = 1\mu$F. [**0.25 marks**]

2.1.2 $R = 20k\Omega$, and $C = 1$nF. [**0.25 marks**]

In a series RL circuit, what is the time constant τ and the duration of the transient, when

2.1.3 $R = 500\Omega$, and $L = 100\mu$H. [**0.25 marks**]

2.1.4 $R = 500\Omega$, and $L = 200\mu$H. [**0.25 marks**]

2.2 Charging a Capacitor (analogous to Step Response of a RC Circuit)

Consider the RC circuit shown in Fig. 1. Find the equation for the voltage across the capacitor.

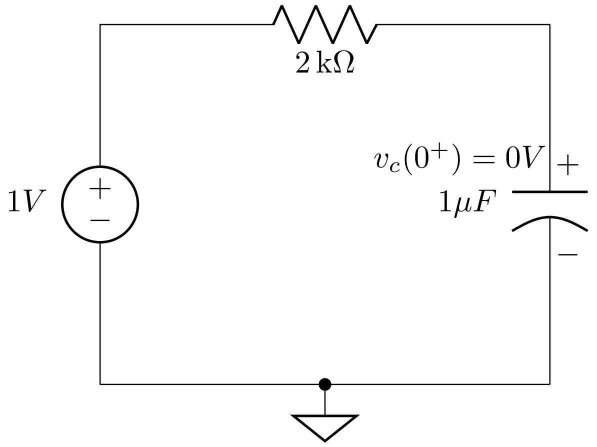


Figure 1: First-order RC circuit.

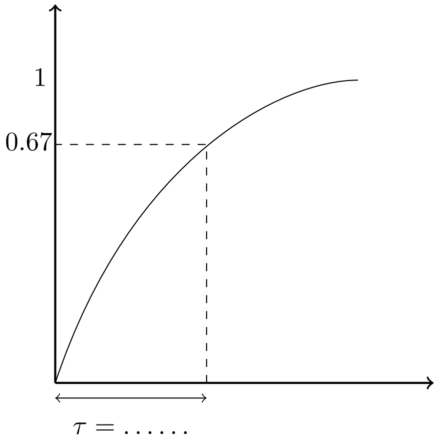


Figure 2: Time constant of an RC circuit.

2.2.1 Theoretical Calculations

Calculate the time constant of the RC circuit in Fig. 1. Assuming that the capacitor was fully discharged at $t = 0$, i.e., $v_c(0-) = v_c(0+) = 0$V, find the equation for the voltage across the capacitor. The generic equation for the voltage across a capacitor is given as [**1 marks**]

$$v_c(t) = \left[v_c\left(0+\right) - v_c\left(\infty\right)\right] e^{-\frac{t}{\tau}} + v_c\left(\infty\right). \tag{1}$$

2.2.2 PSPICE Procedure

2.2.2.1 Open a new schematic in PSPICE and save it as Hlab3-Task1.sch.

2.2.2.2 Construct the circuit shown in Fig. 1 in the PSPICE schematic. The PSPICE schematic should look similar to the one shown in Fig. 3.

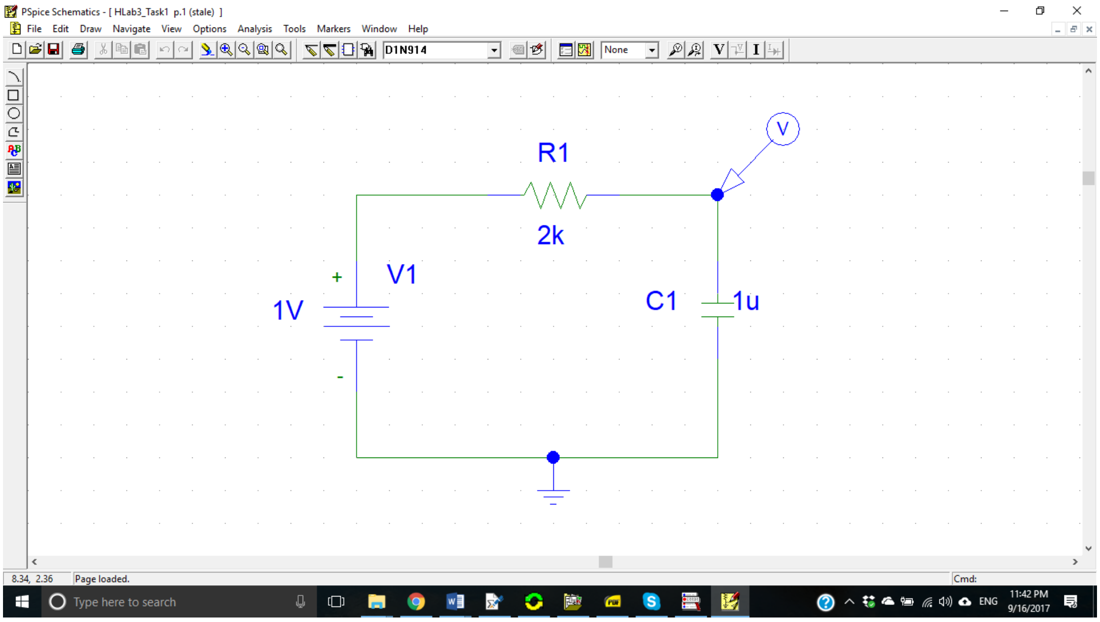


Figure 3: PSPICE schematic for circuit in Fig. 1.

2.2.2.3 In the schematic, double-click on the capacitor $C1$ to open the attributes. Set the value for the attribute named IC to zero. Note: IC stands for initial condition and its value is the initial voltage across the capacitor.

2.2.2.4 From the toolbar, select File, then Save to save the schematic.

2.2.2.5 Simulate the circuit and obtain the plot of the voltage across the capacitor. Using the plot from PSPICE, sketch and label the voltage across the capacitor in Fig. 4. [**1 marks**]

Figure 4: Plot for voltage across the capacitor.

2.2.2.6 From the simulated plot, enable Cursors and read the value of the time constant τ. Record the results in Fig.2. [**0.5 marks**]

2.2.2.7 Briefly discuss whether the theoretical value of the time constant matches the simulation results or not? [**0.5 marks**]

2.3 Discharging a Capacitor (analogous to Natural Response of a RC Circuit)

Consider the circuit shown in Fig. 5. Find the equation for the voltage across the capacitor.

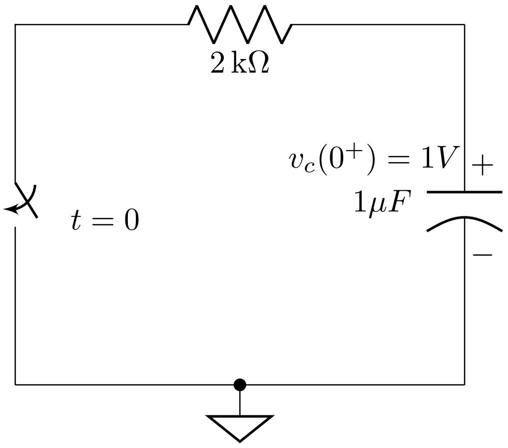


Figure 5: First-order RC circuit.

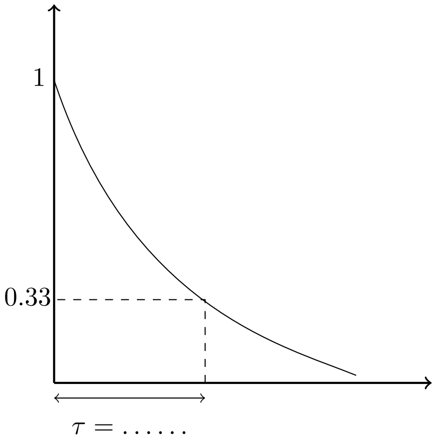


Figure 6: Time constant of an RC circuit.

2.3.1 Theoretical Calculations

Calculate the time constant of the RC circuit in Fig. 5. Using equation (1), find the equation for the voltage across the capacitor $v_C(t)$ when $v_c\,(0^+) = 1V$. [**1 marks**]

2.3.2 PSPICE Procedure

2.3.2.1 Load the schematic for Fig. 5 by selecting File, then Open, and then Hlab3-Task2.sch. Now click Open. The schematic will look similar to the one shown in Fig. 7.

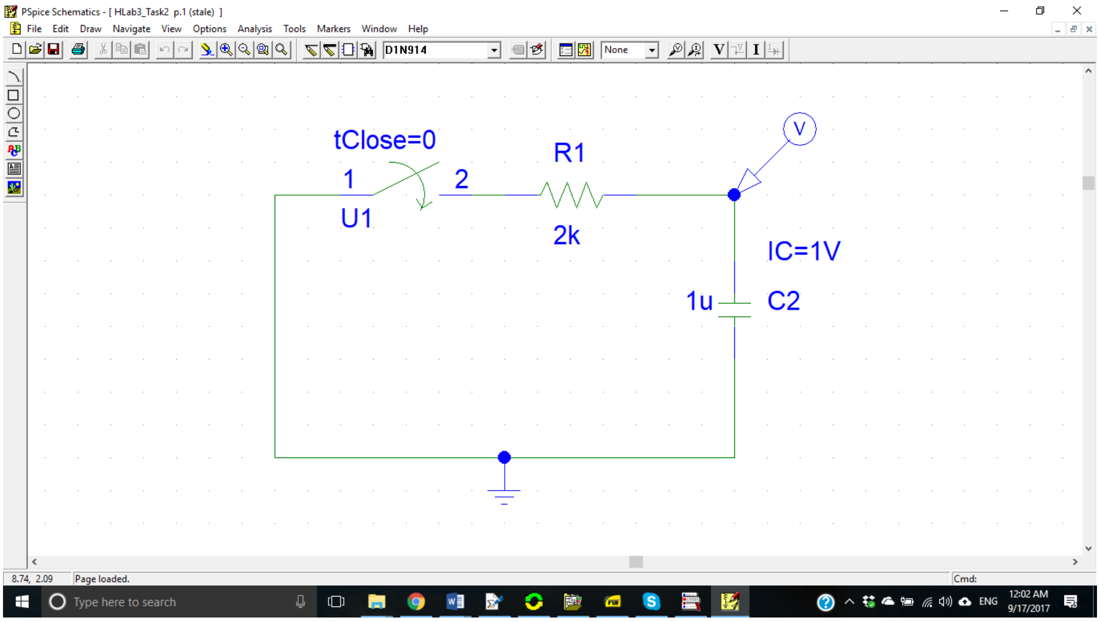


Figure 7: PSPICE schematic for Fig.5.

2.3.2.2 From the toolbar, select File, then Save to save the schematic.

2.3.2.3 Simulate the circuit and obtain the plot of the voltage across the capacitor. Using the plot from PSPICE, sketch and label the voltage across the capacitor in Fig. 8. [1 marks]

Figure 8: Plot for voltage across the capacitor.

2.3.2.4 From the simulated plot, enable Cursors and read the value of the time constant τ. Record the results in Fig.6. [0.5 marks]

2.3.2.5 Briefly discuss whether the theoretical results match the simulation results or not? [0.5 marks]

2.4 Charging and Discharging of a Capacitor

Consider the circuit shown in Fig. 9. Find the equation for the voltage across the capacitor for the charging and discharging phases.

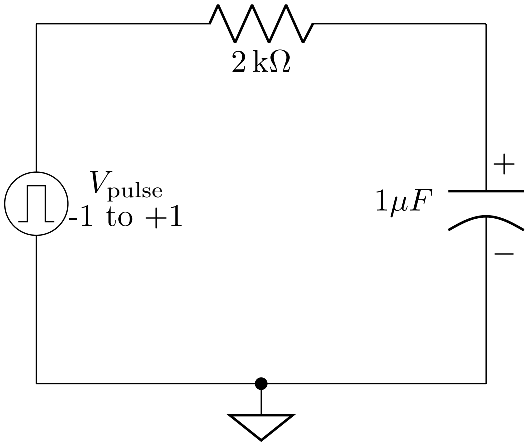


Figure 9: First-order RC circuit.

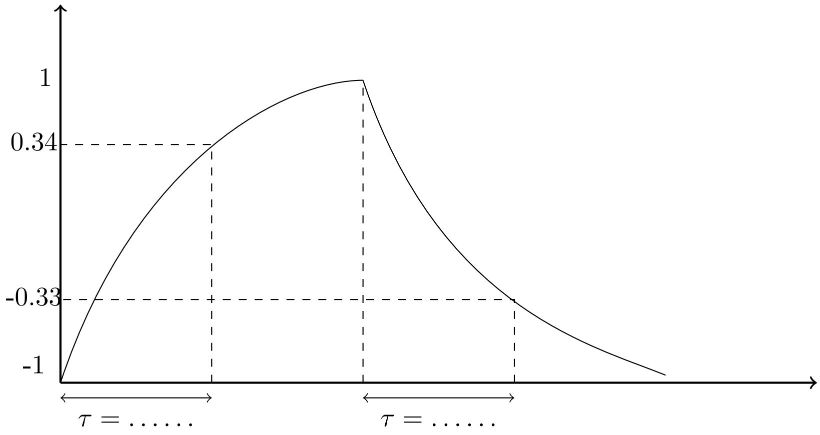


Figure 10: Time constant of an RC circuit.

2.4.1 Theoretical Calculations

Calculate the time constant of the RC circuit in Fig. 9. Using equation (1), find the equation for the voltage across the capacitor during the charging and discharging phase. Hint: For the charging phase, $v_c(0+) = -1$V and $v_c(\infty) = 1$V. Similarly, you need to determine the $v_c(0+)$ and $v_c(\infty)$ for the discharging phase, before you substitute in equation (1). [**1 marks**]

2.4.2 PSPICE Procedure

2.4.2.1 Open a new schematic in PSPICE and save it as Hlab3-Task3.sch.

2.4.2.2 Construct the circuit shown in Fig. 5 in PSPICE schematic. The PSPICE schematic should look similar to the one shown in Fig. 11. The voltage source to use is VPULSE.

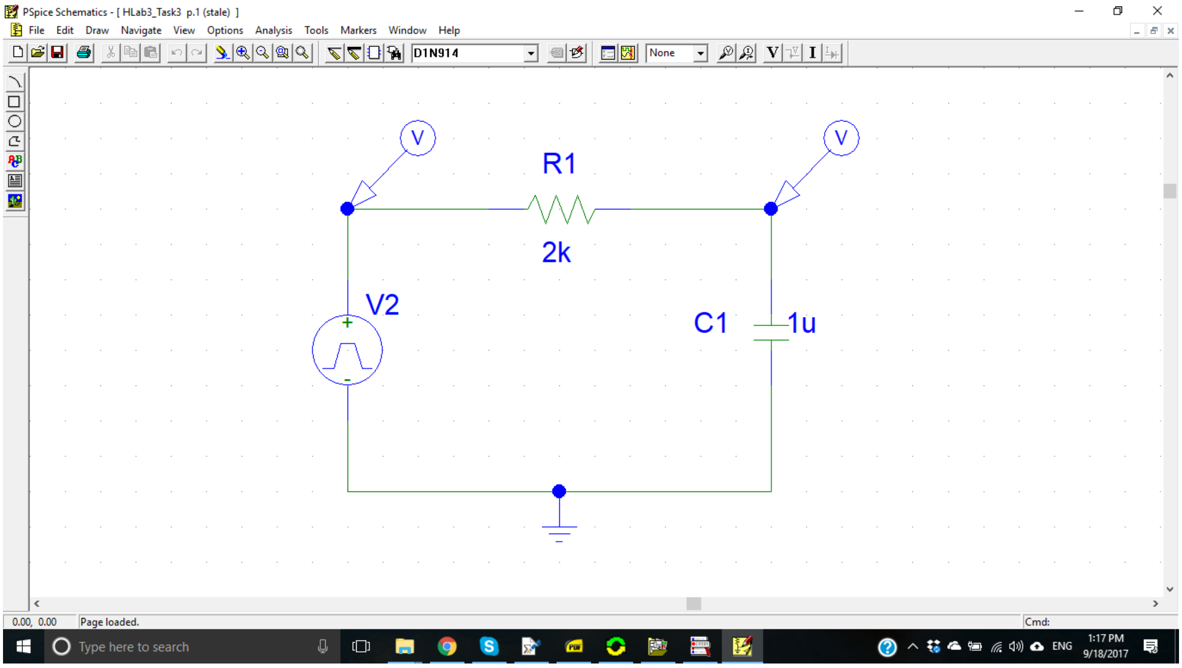
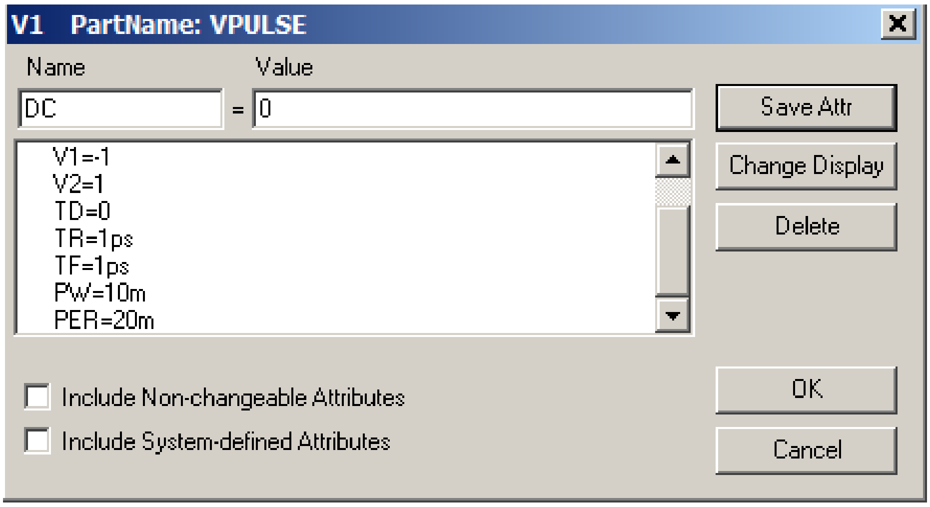


Figure 11: PSPICE schematic for circuit in Fig.9.

2.4.2.3 Double click on $V2$ to open the attributes. Set the values for the attributes DC and AC to 0. Set the remaining attributes as shown in Fig 12.



V1 PartName: VPULSE

Name: DC = Value: 0

V1=-1
V2=1
TD=0
TR=1ps
TF=1ps
PW=10m
PER=20m

☐ Include Non-changeable Attributes
☐ Include System-defined Attributes

Figure 12: Setting attributes for $V2$.

2.4.2.4 From the toolbar, select File, then Save to save the schematic.

2.4.2.5 Simulate the circuit and obtain the plot of the voltage across the capacitor. Using the plot from PSPICE, sketch and label the voltage across the capacitor in Fig. 13. [**1 marks**]

2.4.2.6 From the simulated plot, enable Cursors and read the value of the time constant τ for charging and discharging phase. Record the results in Fig.10. [**0.5 marks**]

Figure 13: Plot for voltage across the capacitor.

2.4.2.7 Why did we set the PERIOD of the input square wave (with ±1V amplitude) as 20ms? Give a reason for your answer. [**0.5 marks**]

3 Lab Tasks

You will be provided with a lab kit, which should include following components:

- Two $220pF$ ceramic capacitors
- One $120nF$ green polyester capacitor
- One $1uF$ electrolytic capacitor
- One $100\mu H$ chip inductor (looks like a resistor)
- One $100\mu H$ Ferrite core (toroidal) inductor
- Two $1k\Omega$ resistor
- One $2k\Omega$ resistors
- One $5k\Omega$ resistor
- Two $10k\Omega$ resistors
- One $20k\Omega$ resistor
- One $100k\Omega$ resistor

3.1 Charging and Discharging of a Capacitor

Consider the circuit shown in Fig. 14.

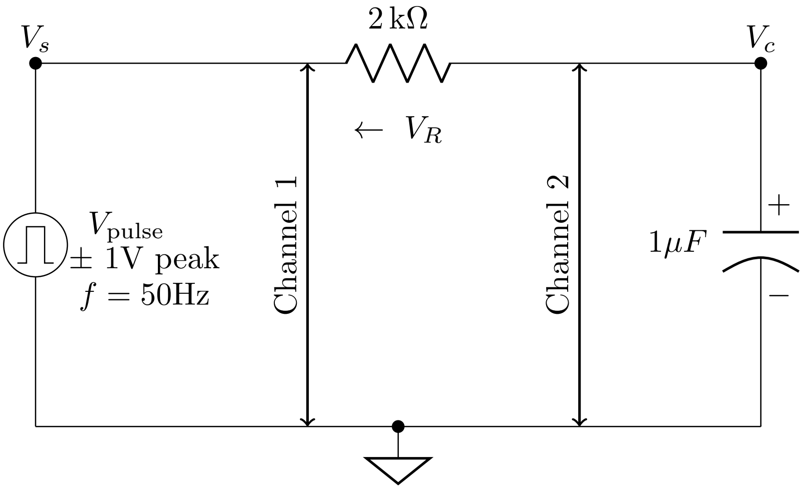


Figure 14: First-order RC circuit

3.1.1 For this task, you require the following components:

(a) A breadboard and an oscilloscope.
(b) Two oscilloscope probes.
(c) One 2kΩ resistor.
(d) One 1μF electrolytic capacitor.

3.1.2 Construct the RC circuit shown in Fig.14 on your breadboard. The red terminal of the signal generator output should be used to supply V_S and the black terminal should be connected to the ground rails on the breadboard. Connect the Channel 1 and Channel 2 oscilloscope probes to V_S and V_C. Connect both probe ground clips to the same signal ground (the same circuit node as the black terminal of the signal generator output, the ground symbol is attached for your reference). By viewing Channel 1 on your oscilloscope, adjust the signal generator to supply a 50 Hz square wave of $\pm 1V$ peak amplitude.

3.1.3 Note that, while V_C appears on Channel 2, V_R cannot actually be observed directly. If you repositioned the Channel 1 ground clip to the V_C side of the resistor, you would short circuit the capacitor. This is because the oscilloscope and signal generator grounds are joined because of the probe connections. However, V_R can be observed differentially by proceeding as follows.

3.1.4 Set Channel 1 and Channel 2 to the same Volts/Division (500mV). Set triggering to automatic by pressing Trigger–Mode/Coupling, then press Mode (on screen) as required to select Auto.

3.1.5 Trigger on Channel 1 by pressing the Trigger–Edge button, then choose 1 (on screen).

3.1.6 Press the Vertical–Math button, then press 1–2 (on screen), to subtract the signal on Channel 2 from the signal on Channel 1, to display V_R. Press Settings (on screen) and adjust the knob for the same Volts/Division as Channel 1 and Channel 2 (500mV).

3.1.7 The third trace is Channel 1–Channel 2 = V_R. Adjust the Channel 1 and Channel 2 Vertical positions for clarity, if necessary.

3.1.8 Sketch and label the waveforms obtained for V_C and V_R in Fig. 15 and Fig. 16, respectively.

Figure 15: Plot for V_C.

[**1 marks**]

3.1.9 Measure the time constant and record your result below. How does the measured value compare with the theoretical value and PSPICE simulation results in Section 2.4.1. [**1 marks**]

Figure 16: Plot for V_R.

[**1 marks**]

3.1.10 Now replace the capacitor in Fig. 14 with either $220pF$ or $120nF$ capacitor. Choose any resistance from the available set and compute the time constant and the minimum frequency of the square wave needed to properly show the results. Show your calculations in the space provided below. [**1 marks**]

3.1.11 Construct the circuit with your chosen capacitor and resistor values and measure V_C and V_R. Sketch and label the measured waveforms obtained for V_C and V_R with the new resistance and capacitance values in Fig. 17 and Fig. 18, respectively.

Figure 17: Plot for V_C.

[**1 marks**]

Figure 18: Plot for V_R.

[**1 marks**]

3.2 Measure Voltages in a RL Circuit

Consider the circuit shown in Fig. 19.

3.2.1 For this lab, you require the following components:

- (a) A breadboard and an oscilloscope.
- (b) Two oscilloscope probes.
- (c) One 500Ω resistor (connect two 1kΩ resistors in parallel).
- (d) Two 100μH inductors, connected in series (use the chip inductor and the toroidal inductors connected in series).

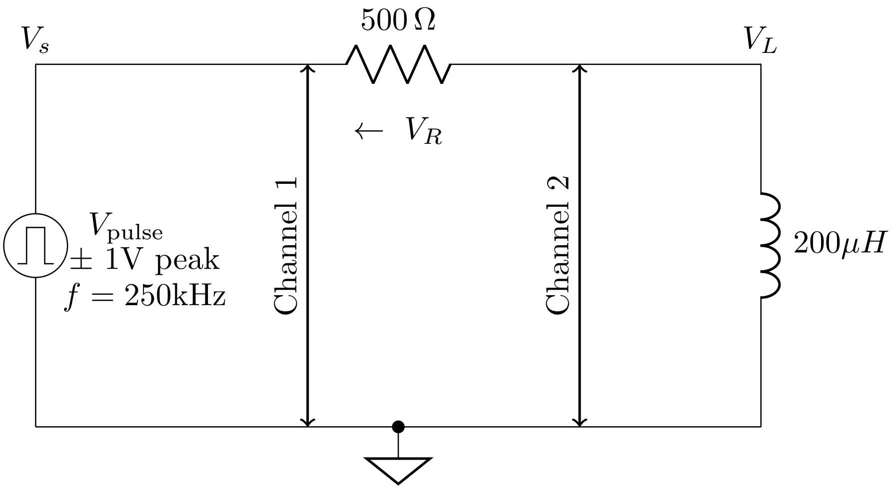


Figure 19: First-order RL circuit.

3.2.2 Construct the RL circuit shown in Fig. 19 on your breadboard. The red terminal of the signal generator output should be used to supply V_S and the black terminal should be connected to the ground rails on the breadboard. Connect the Channel 1 and Channel 2 oscilloscope probes to V_S and V_L. Connect both probe ground clips to the same signal ground (the same circuit node as the black terminal of the signal generator output, the ground symbol is attached for your reference). By viewing Channel 1 on your oscilloscope, adjust the signal generator to supply a 250kHz square wave of $\pm 1V$ peak amplitude.

3.2.3 Using the same procedure in Section 3.1, sketch and label the waveforms obtained for V_L and V_R in Fig. 20 and Fig. 21, respectively given on the next page. Note that at such high frequencies, stray effects can start to become significant so your measured waveforms may not be so smooth (see L22, slide 36). When sketching, you may just ignore any glitches and sketch the smooth waveforms.

Figure 20: Plot for V_L.

[**1 mark**]

3.2.4 From the waveform of the voltage across the resistor, measure the time constant (for both resistor voltage increasing and decreasing) and record your result below. How does the measured time constant compare with the theoretical value. If there is a difference, what could be the cause of this difference. [**2 marks**]

Figure 21: Plot for V_R.

[**1 mark**]

Appendices

A Capacitors and RC Circuits

The capacitor is a linear circuit component that stores energy in form of an electric field, producing a potential difference across its plates. An RC circuit can be made by simply putting a resistor and capacitor in series as shown in Fig. 22. There are many kinds of capacitor available on the market, some of which are polarized.

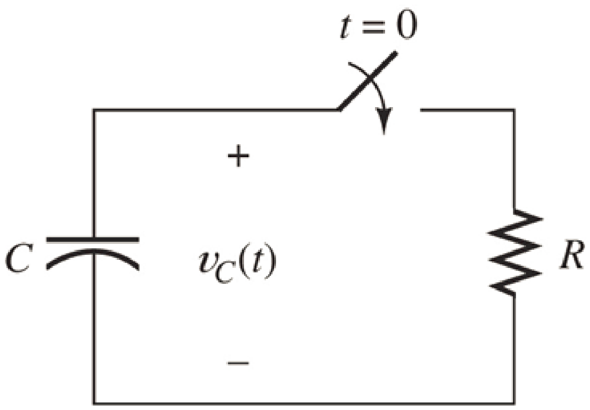


Figure 22: A simple RC circuit.

This means that a positive voltage can only be connected to the positive leg of the capacitor (cathode). This laboratory will make use of three common varieties, listed in Table 2.

A.1 Step Response

The time for a capacitor in an RC circuit to discharge to a factor of $e^{-1}(\approx 37\%)$ of the initial voltage is called the time constant τ. This can be computed as:

$$\tau = RC. \tag{2}$$

The response of such an RC circuit to an input step voltage can be given by the following expression:

$$v_c(t) = \left[v_c\left(0^+\right) - v_c\left(\infty\right)\right] e^{-\frac{t}{\tau}} + v_c\left(\infty\right), \tag{3}$$

where

- $v_c(t)$ is the capacitor voltage at time t
- $v_c(\infty)$ is the final voltage towards which the capacitor is charging.
- $v_c(0^+)$ is the initial voltage across the capacitor
- τ is the time constant of the RC circuit

A.2 Initial and Final Behaviours

It can be useful to model a capacitor in an RC circuit as other familiar circuit elements in order to describe initial and final response when a step input is applied or a switch is closed. Table x summarises these models for the case when the capacitor has some initial charge, and no charge. Note that $t(0^+)$ indicates the time just after the step is applied or switch is closed, while $t(\infty)$ indicates a “sufficiently long” period after the event. Note that in both cases, the capacitor acts like an open circuit when it has completely charged (or discharged) to some voltage over a long time. These observations are summarized in Table 3.

Table 1: Types of Capacitors.

Capacitor Type	Notes
 Ceramic	• Ceramic as a dielectric • Non-polarized • Small capacitance values of 1pf to 220nf • Small physical size • Low maximum rated voltage of 50V
 Polyester (Green-Cap)	• Polyester film as a dielectric • Non-polarized • Typical capacitance values between 1nF and 15uF • High maximum rated voltage of up to 1500V • Voltage ratings indicated by code on casing, where the code 2A, 2E, 2G, and 2J denotes a DC rating of 100V, 250V, 400V, and 630V, respectively.)
 Aluminium (Electrolyte)	• Strips of aluminium foil separated by paper soaked in electrolyte • Polarized–positive leg is generally longer while negative leg is indicated by coloured strip on casing • Typical capacitance range 0.1uF to 500,000uF • Poor tolerance on capacitance (10-20%) • Capacitance value drops with age and use of component

Table 2: Initial and final response of a capacitor in an RC circuit.

C (Initial Charge)	C
$t\,(0^+)$: Acts like a voltage source	$t\,(0^+)$: Acts like short circuit
$t\,(\infty)$: Acts like an open circuit	$t\,(\infty)$: Acts like open circuit

A.3 Parallel Capacitors

When capacitors are connected in parallel (e.g. Fig. 23), the equivalent capacitance is calculated as the sum of the individual capacitances. Intuitively this makes sense as it can be thought of as increasing the size of the capacitor plates, allowing more charge to be stored and hence increasing the capacitance.

$$C_{eq} = C_1 + C_2 + C_3 = \sum_{k=1}^{N} C_k \tag{4}$$

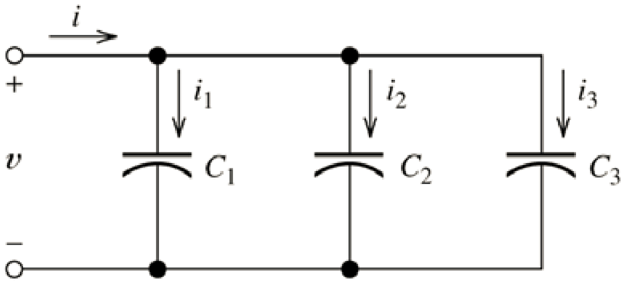


Figure 23: Capacitors in parallel combination.

A.4 Series Capacitors

When capacitors are connected in series (e.g. Fig. 24), the equivalent capacitance is calculated as the sum of inverse capacitances. Connecting capacitors in series can be intuitively thought of as increasing the distance between capacitor plates, thus leading to a reduced capacitance.

$$C_{eq} = \left(\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}\right)^{-1} = \left(\sum_{k=1}^{N} \frac{1}{C_k}\right)^{-1} \tag{5}$$

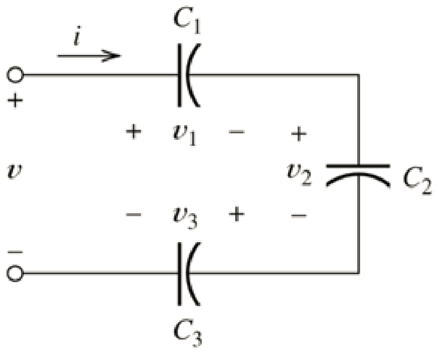


Figure 24: Capacitors in series combination.

B Inductors and RL Circuits

In its most basic form, an inductor (also called a choke) is a coil of wire wound around a central core. It works on the principle that a changing current through a coil of wire generates a changing magnetic flux, which in turn causes an opposing voltage across the inductor. An RL circuit can be made by simply connecting an inductor and resistor in series (see Fig. 25). Inductors are generally characterised by their core material and winding geometry. Some examples of inductors are presented in Table 4.

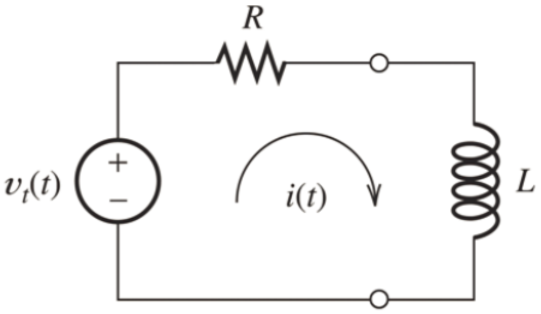
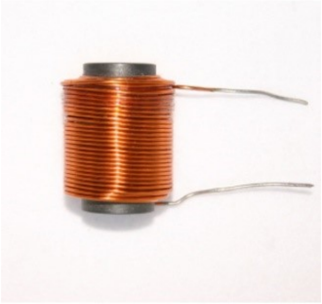


Figure 25: A simple RL circuit.

Table 3: Voltage measurement from the Voltmeters in Fig. 10 and Fig. 14.

Capacitor Type	Notes
 Air core	• No core material (air) • Small inductance value • Use in high-frequency applications like TV and radio receivers
 Ferrite core	• Ferrite core made of metal oxide ceramic • Core enables storage of additional magnetic energy leading to high inductance values • Used in transformers • Suffers from âĂŸiron lossâĂŹ through hysteresis and eddy currents
 Toroidal core	• Circular ring-formed magnetic core • Toroid shape reduces electromagnetic interference with adjacent components • High inductance for small physical size

B.1 Step response

The time for the voltage/current of an inductor in an RL circuit reduce by a factor of e^{-1} ($\approx 37\%$) of the initial value is called the time constant τ. This can be computed as:

$$\tau = \frac{L}{R}. \tag{6}$$

In an RL circuit, this leads to a current step response described by:

$$i_L(t) = i_L(\infty) + \left\{ i_L\left(0^+\right) - i_L(\infty) \right\} e^{\frac{-t}{\tau}}, \tag{7}$$

where,

- $i_L(\infty)$ is the final inductor current

- $i_L(0^+)$ is initial inductor current
- τ is the time constant of the RL circuit

B.2 Initial and Final Behaviours

It can be useful to model an inductor in an RL circuit as other familiar circuit elements in order to describe initial and final response when a step input is applied or a switch is closed. Table 4 summarises these models for the case when the inductor has some initial current, and no current. Note that $t(0^+)$ indicates the time just after the step is applied or switch is closed, while $t(\infty)$ indicates a "sufficiently long" period after the event. Note that in both cases, the inductor acts like a short circuit when the current has settled to a constant value and the magnetic flux has stopped changing. These observations are summarized in Table 5.

Table 4: Initial and final step response of an inductor in an RL circuit.

L (Initial Current)	L
$t(0^+)$: Acts like a current source	$t(0^+)$: Acts like an open circuit
$t(\infty)$: Acts like a short circuit	$t(\infty)$: Acts like a short circuit

B.3 Inductors in series

When inductors are connected in series (i.e. Fig. (26)), this can be thought of as additively increasing the length of the inductor (or the number of total windings). Thus the equivalent inductance is given by the sum of the individual inductances:

$$L_{eq} = L_1 + L_2 + L_3 = \sum_{k=1}^{N} L_k \tag{8}$$

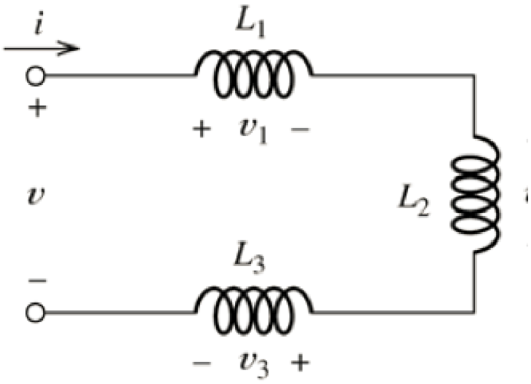


Figure 26: Inductors in series.

B.4 Inductors in parallel

When inductors are connected in parallel (i.e. Fig. (27)), they behave in a similar manner to parallel resistors in that the equivalent inductance is given by the sum of inverse inductances. It may be useful to think of this as providing more avenues for current to flow through, thereby reducing the opposing voltage generated for a given total current (i.e. reduced inductance).

$$L_{eq} = \left(\frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3}\right)^{-1} = \left(\sum_{k=1}^{N} \frac{1}{L_k}\right)^{-1} \tag{9}$$

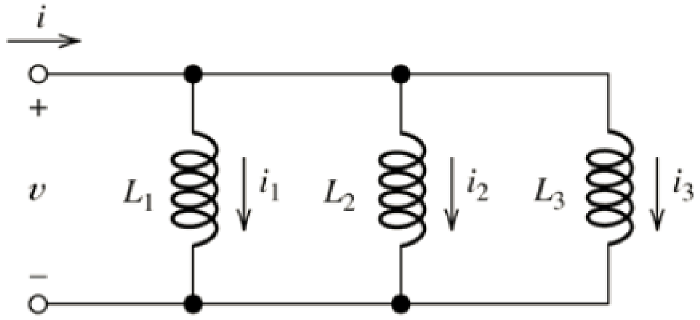


Figure 27: Inductors in parallel.

C Oscilloscope

Fig. 28 below shows the digital oscilloscope that you will be using in the labs.

- It enables you to view two independent signals at once, as well as some mathematical combination of the two. “Math” button in the Vertical section allows adding or subtracting two signals.
- A close-up of the main panel controls was shown in Fig. 29. Notice that the control panel is split up into different sections: Horizontal (time scaling), Run Control, Measure, Waveform, File, Trigger and Vertical (amplitude scaling).
- Channel 1 and Channel 2 share the same ground line internally which is also connected to the earth line. Thus they are “NOT FLOATING” unlike the triple power supply in the lab. Thus you need to be very careful that all probe grounds are connected to the same ground.

Figure 28: Digital oscilloscope.

C.1 Oscilloscope Probe

Fig. 30 shows a probe used together with the oscilloscope. Please note that it is not a mere tip and wire. It is an expensive device (cost around $300) in its own and contains a capacitor and resistor circuit called an attenuator (roughly it weakens signal to protect any sensitive device).

- The capacitor is used to match the input capacitance of the oscilloscope and the probe.

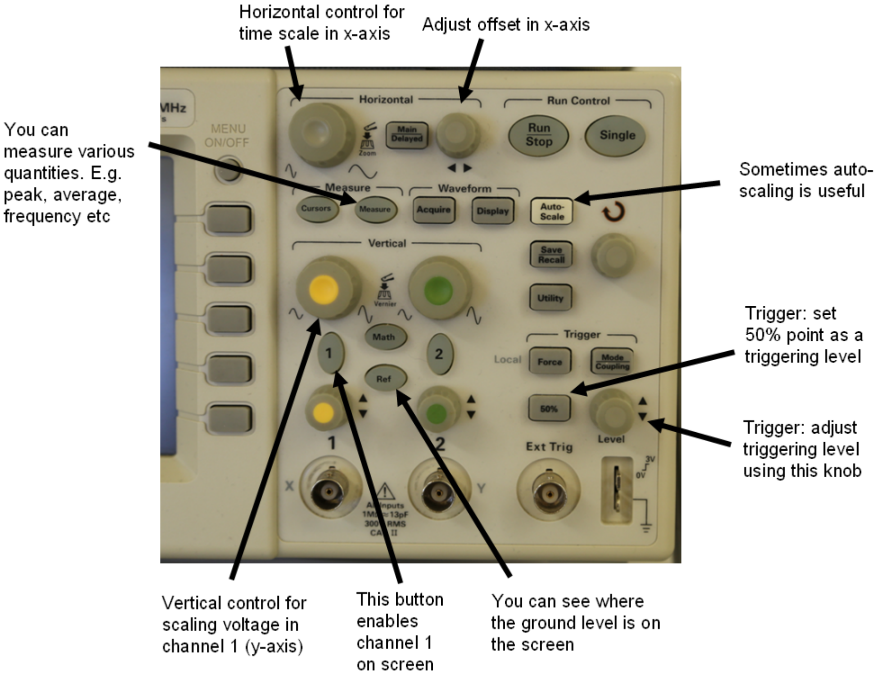


Figure 29: A closeup of the digital oscilloscope.

- There is a label “10:1” on this type of probe which is the attenuation ratio. Normal oscilloscope has $1M\Omega$ input resistance. This probe contains a $9M\Omega$ resistor in series to further attenuate any noises. The result is the magnitude of the input signal is scaled down to 1/10. If you observed this in your measurement, check the probe scale setting in your oscilloscope menu.
- Fig. 31 illustrates an incorrect and correct usage of the probe. The probe tip contains certain capacitance which is used for high-frequency signal. Never insert this tip into the breadboard which will damage the tip as well as the breadboard.

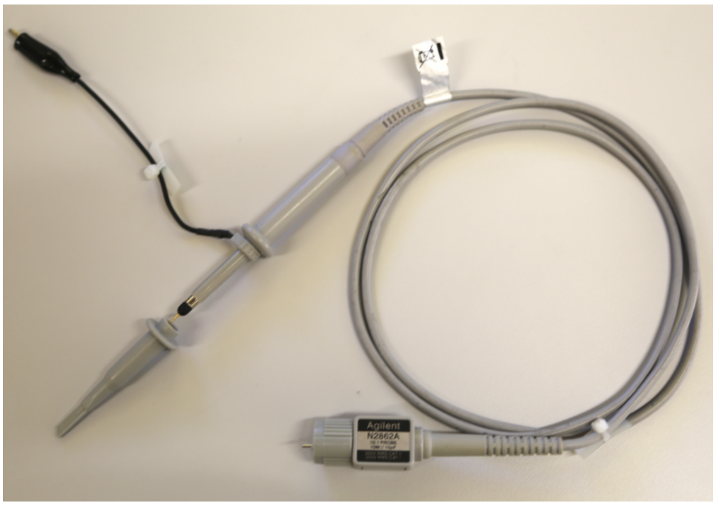


Figure 30: Oscilloscope probe.

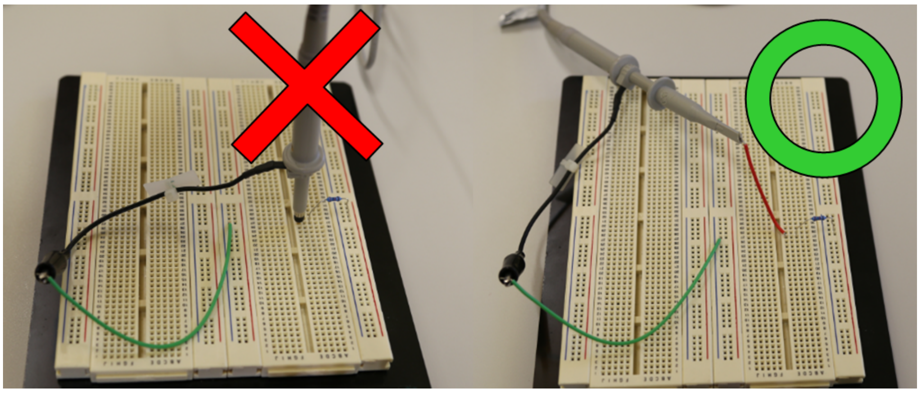


Figure 31: How to use the oscilloscope probe.