LABORATORY MANUAL

ELEC1111 – Electrical and Telecommunications Engineering

School of Electrical Engineering and Telecommunications

Contents

Preface

How to use and navigate this manual

It is advised to use this manual both in **printed version** and in **digital version** as PDF file on Moodle.

The **printed** version will be used for **marking** your pre-lab exercises, **submitting the results** of your experiments during the lab session and getting them marked off by a lab demonstrator.

The **digital** version provides direct links to useful videos and other resources relevant to your lab.

Answer Boxes

It is important that your answers are neatly written within the provided spaces for each question/exercise. Your laboratory manual and your lab books are your "professional documents" and should be treated appropriately. The answer boxes look like a simple box as shown below.

Demonstrator Checkpoints

When you come across the following Table, you need to ask a lab demonstrator to assess your results and record your mark in the given space in your lab manual.

Pre-Lab/ Lab work No#	Date:	Assessor name and signature:	Mark:

Video Resources

In the digital version of lab manual, when you come across the following icon, you will be linked to a video that demonstrates aspects in the operation of the laboratory equipment.

Topic of the video

It is important to familiarize yourselves with the basic functions of each device and lab equipment before your first session so that you can spend your lab time more efficiently and become proficient with the equipment.

Key points

This icon ⚠ demonstrates important parts of your laboratory experiment. If you are unsure about the necessary steps, please consult with your lab demonstrators.

Overview

Students come into Electrical Engineering and Telecommunications from a wide range of backgrounds in laboratory experience. This is most apparent each year in ELEC1111. It is one of the aims of this course that all students develop confidence at individual work in a laboratory environment. This is not difficult if electronics has been a hobby before coming to University. For those students with minimal previous laboratory experience, including those who would say that they rely on the ability of a laboratory partner, here are some words of encouragement:

1 A lot of students in a similar situation have shown that they can succeed in this component of the course without any previous laboratory experience.

2 Make life easier for yourself; read ahead and get a feel of what is required of you in each lab experiment. Also, keep in mind that pre-lab exercises are there to prepare you for the theory to be used in each lab. Remember that the lab equipment is used by many students each year and, as such, should be robust enough for sensible use. Measurements that are not supposed to be made with any piece of equipment will be clearly stated in the instructions.

3 Do not be afraid to experiment. Everything should be safe at the voltages you are using. Nevertheless, there may be an occasional (non-serious) bang as an incorrectly connected electrolytic capacitor gets too hot, or smoke as an incorrectly rated resistor undergoes a high electric current, much to the embarrassment of the perpetrator and to the education of all in the laboratory.

4 The lab demonstrators are there to help you gain a better understanding of the material. You can encourage your lab demonstrators to be more active and helpful by showing that you genuinely attempt to understand the experiment and try to ask specific questions rather than posing a general question such as "What should I do in the laboratory today?" In any case, if you are genuinely lost when doing an experiment, your lab demonstrators will be there to guide you in completing and understanding the different parts of it.

Aims of the laboratory sessions

This course provides the first of many electrical engineering laboratory experiences that you will encounter both here and in your future career. From now on, you are building a foundation of experimental attitudes and abilities that is of upmost importance when it comes to any engineering discipline.

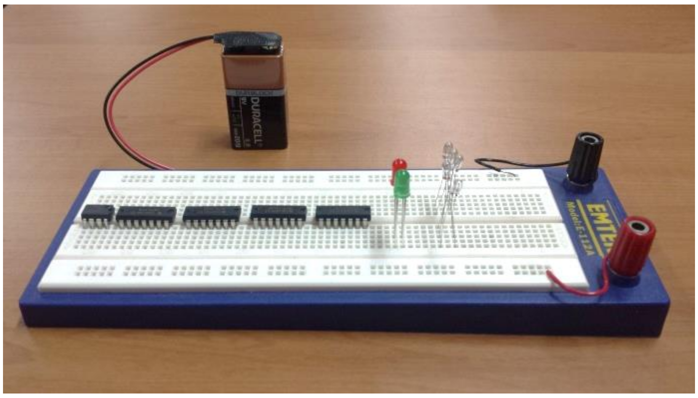
The main aims of the laboratory component are:

- To **gain** familiarity with basic laboratory equipment and measurement techniques.
- To **reinforce** concepts presented in lectures.
- To **stimulate** a scientific curiosity and help provide answers to how things work.
- To **observe** and **question**. Never simply accept any results, for instance, ask yourself *why that waveform has a big bump in it*.
- To **construct**, **test**, and get circuits **working**, and learn how to **resolve** an issue with a circuit that is not working as it should be (**debugging**).
- To **work** equally with your **team member** to solve questions posed in the lab. Team work is highly encouraged.
- To **develop** a professional attitude to laboratory preparation, circuit design, measurement, and recording of results,
- And finally, to **enjoy** the labs and **have some fun!**

Requirements

There are several items that are required for laboratory practices, these items are:

1 A **lab component kit**. This kit, which is available to purchase from the School Electronic Workshop, includes all the necessary components as well as a **prototyping board** (also known as **breadboard**), as shown in the Figure below (note that some components in the figure may vary depending on availability from the School, and there may be more essential components inside the kit). Resistors and capacitors will be available in all teaching lab rooms. However, you are recommended to bring a component box to keep any resistor and capacitor that you pick for your future use in each lab experiment.



Lab component kit with prototyping board

2 For students continuing in Electrical Engineering and Telecommunications, it is also recommended to purchase a **small pair of wire strippers** for cutting and trimming component wires, and a **small pair of long-nose pliers** for inserting components into a prototyping board. You can also purchase **small jumper cables** for more convenience in wiring your circuit. These items may be purchased from most electronics or hardware stores and will be used extensively in this and future laboratory courses.

Laboratory equipment

On each bench in the teaching laboratories, you will find the following lab equipment:

1 An **oscilloscope** (Figure (a)).

2 A **signal generator**, also known as a **function generator** (Figure (b)).

3 A **DC power supply** with variable positive and negative voltages (Figure (c)).

4 A **digital multimeter** (DMM) to measure voltage, current and resistance (Figure (d)).

In addition, in each teaching laboratory room you may find the following:

5 A dedicate place of **preferred-value resistors** (with power rating of $1/4$ W or 0.25 W) and **capacitors.**

6 A precision **RLC meter** (known as **LCR Bridge**) to measure values of resistance, capacitance, and inductance (Figure (e)).

7 **Soldering irons**.

8 **Computers** to access any necessary document online or review the lecture notes on Moodle.

Further detailed descriptions of this equipment are provided in the Appendix section at the end of this manual as well as in short videos available on Moodle. If necessary, other relevant laboratory hardware information will be given at the appropriate time during lab sessions.

(a) Oscilloscope

(b) Signal/Function generator

(c) DC power supply

(d) Digital multimeter

(e) LCR Bridge

Laboratory record keeping

Attendance

Your attendance, including prompt arrival and the efficient use of your laboratory periods, will be recorded by the demonstrator every week in the attendance sheet as well as your lab marks. It is essential that you complete the **pre-lab exercises** and any necessary laboratory preparation before coming to the lab.

⚠ You must **attend** at least 7 of the 8 labs **AND** attain a pass assessment in labs **AND** pass the lab exam to pass the course.

Lab results recording

All students should develop the discipline necessary to record their results neatly both in the lab book and the results sheet. This is not academic pedantry, it is part of becoming a professional engineer.

⚠ All lab results must be recorded in the **answer boxes of your lab** manual for proper marking and record keeping purposes.

- Keep all your handwritings and records **neat and tidy** throughout the labs. As there will be a lab exam, you need to be able to read your own notes later for lab exam revision.
- **Scraps of paper** are **not allowed** for recording results at the bench. Any loose sheets should be pasted into your lab book.
- All results of measurements and calculations should clearly show the **measurement units** and should be to an **appropriate precision**.
- All **circuit diagrams** should be drawn with the measurement points clearly labelled, including the earth or common ground if appropriate.
- Use a **ruler** when drawing a straight line in any diagram or graph.
- When drawing graphs, **numerical scales** must be shown together with a **label** for each axis. Every graph must have a **complete title** and a statement of any special measurement conditions that apply.

Laboratory rules for proper conduct

⚠ Students must complete the **Moodle OH&S Safety Course**[1] before starting the laboratory component. If a student attends any laboratory session without having completed the safety declaration, the marks for that session will be zero.

⚠ The **OH&S certificate** must be submitted before you start working in the labs. There is a dedicated OH&S submission portal on Moodle where you can upload the certificate and submit online.

All your lab marks will be available on Moodle by the end of each week. Please check your marks regularly, and if there is any mistake or missing mark, let the head lab demo and/or the lecturer know as soon as possible.

The following **rules** need to be observed for a safe and amenable working environment:

- Under **NO circumstance** is **230V 50Hz mains power** to be used for any purpose, other than that approved by the School of EE&T.
- **NO smoking**, **eating** or **drinking** in the laboratory.
- Safety regulations require that proper **enclosed footwear** is **always** worn in the laboratory.
- Take care not to let your hair loose as it might be tangled with your circuit wires.
- Be cautious of rings, watches and necklaces. These are good conductors. Moreover, skin beneath a ring or watch is damp and lowers the body resistance.
- Leave all **water bottles**, **bags**, **umbrellas**, etc. on the space **under the benches**.
- **Tampering** with or **removal** of any **laboratory equipment** is **forbidden**.
- Students are expected to conduct themselves in a reserved manner at all times. **Noise** is to be **kept to a minimum** as the lab rooms are teaching environments.
- Use of lab facilities for work that is not specifically associated with a School subject requires prior approval by a member of academic staff.
- **Mobile phones** are **NOT to be used** at any time in a laboratory.
- Students should **clean and tidy up benches** when they have finished their experiments and **return** any required components before they leave the laboratory, which include **equipment leads and cables**, **high-power resistors**, and **inductors**. You may **keep** the resistors and capacitors for later use in your component box.
- As you leave the laboratory, **switch off** all the instruments. In particular, switch off handheld multimeters (if there is any). Being battery powered, it is most frustrating for the next student to find an instrument not working because of flat batteries.
- Please **advise** the lab demonstrators of any **equipment malfunction** or issues.
- Students who **fail to abide** by these regulations will be told to **leave the laboratory**.

[1] Follow instructions on your course Moodle page to complete the OH&S Safety Course.

Lab Experiment 1: Familiarisation

Aims of this experiment

The aim of this first lab experiment is to familiarize yourselves with the following:

1. Basic concepts of electric circuits.
2. Equipment in the laboratory and their features, functions, and operation.

Videos and guides for review

You are expected to familiarise yourselves with the laboratory equipment by reading the Appendix section of this manual and watching all the lab videos before attending the first lab. Nevertheless, a list of suggested lab videos and subsections of the Appendix explaining the relevant laboratory equipment will be provided for each lab experiment. Please make sure to revise them before commencing the laboratory session.

List of suggested videos:

- Breadboard/Prototyping board
- Multimeter
- Power supply
- Signal generator
- Oscilloscope
- Debugging tips

List of additional videos:

The following videos address different aspects of the laboratory equipment with a high level of detail. Please note that while the videos have been recorded using different pieces of equipment than those available in the lab, they are also very useful to improve your understanding, since the operation is essentially the same.

- Prototyping board
- Introduction to the power supply
- Limiting current in power supply
- Introduction to the multimeter
- Measuring resistance with a multimeter
- Measuring voltage with a multimeter
- Measuring current with a multimeter
- Introduction to the signal generator
- Introduction to the oscilloscope
- Displaying a waveform
- Adjusting scales in oscilloscope
- AC and DC coupling in oscilloscope
- Using two channels in oscilloscope
- Adjusting scales with two channels

List of suggested guides from Appendix:

- Prototyping board (Breadboard)
- Resistor colour coding
- DC power supply
- Digital multimeter
- Signal/Function generator
- Oscilloscope

Lab 1: Pre-lab work

As part of your lab preparation, you are required to carefully read all the sections of the Appendix and watch all the corresponding lab videos before attending your first lab session.

Please answer the following questions **before coming to the lab**.

1 What is a periodic signal/waveform? Provide an example by sketching an arbitrary periodic signal (e.g., a sinusoid or square wave signal).

2 Explain how the frequency (f) and the period (T) are defined for a periodic signal, and what is the relationship between them. Then, use your sketch from the previous question and label the period.

3 What is the frequency of the voltage provided by a battery? Provide any necessary explanations.

4 Is the voltage supplied by a normal household power outlet periodic? If your answer is yes, what is the frequency of this voltage? If your answer is no, explain why.

5 A 12-V battery has its positive terminal connected to the ground. Draw a diagram of the connection and find the voltage of the two terminals with respect to the ground.

6 Find the value of the resistors in the following Table and write them down in the "Resistor value" column.

Resistor	Band 1	Band 2	Band 3	Band 4	Resistor value?
R_1	Blue	Grey	Gold	Gold	
R_2	Yellow	Violet/Purple	Yellow	Gold	
R_3	Red	Red	Red	Red	
R_4	Brown	Green	Green	Silver	

7 If a circuit design requires the non-critical and non-standard resistors given in the Table below, what would be the closest resistance that can be chosen from the list of preferred-value (standard) resistors? Write down the colour band of the preferred-value resistance as well as the preferred value itself for each case.

Required resistor	Preferred value	Band 1	Band 2	Band 3	Band 4
560 kΩ					
25 Ω					
970 Ω					
18.5 kΩ					
1.1 MΩ					
36 kΩ					

8 Calculate the input resistance R_{in} as seen from terminals *a* and *b* of the circuit shown in Figure 1.1.

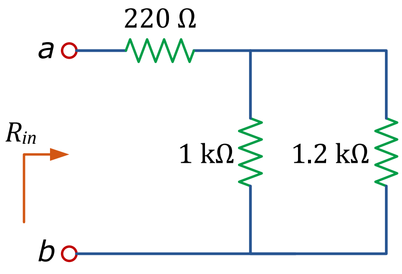


Figure 1.1: Resistive circuit for Pre-Lab 1.

Pre-Lab 1	Date:	Assessor name and signature:	Mark:

Lab 1: Experimental procedure

Please complete all the tasks given in this section during the lab session. Do not forget to watch the related lab videos and guides that are suggested for this lab experiment.

Required components

In this experiment you will be required to use the following components:

- Your breadboard.
- $220\ \Omega$, $1\ \mathrm{k}\Omega$, and $1.2\ \mathrm{k}\Omega$ resistors.

⚠ Remember that all results of measurements and calculations should clearly show the **measurement units** and should be to an **appropriate precision**.

I. Resistance measurements

1 Consider the circuit given in Figure 1.2. Complete the following Table by collecting the resistors from the resistor containers in the lab and measuring their resistance with the precision LCR Bridge at each room and then with the digital multimeter (DMM). Compare and comment on the results, i.e., explain the factors that cause the difference between the measured values and the nominal ones.

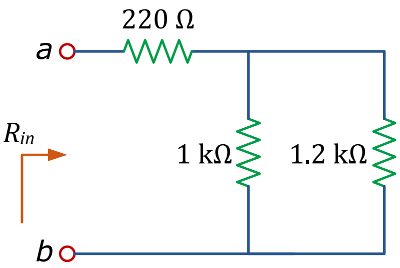


Figure 1.2: Resistive circuit for Lab Experiment 1.

Nominal resistance	Tolerance	DMM Value	LCR Bridge value	Comments
$220\ \Omega$				
$1\ \mathrm{k}\Omega$				
$1.2\ \mathrm{k}\Omega$				

2 Calculate the input resistance R_{in} in the circuit of Figure 1.2 using your measured values from the Table above.

R_{in} with DMM values:

R_{in} with LCR Bridge values:

3 Build the circuit of Figure 1.2 on your boards and measure the input resistance R_{in} using the digital multimeter. Compare its value with your pre-lab work in question **8** and your calculations from the previous question (question **2**), and comment on the results.

II. DC voltages and currents

4 Adjust the output voltage of the DC power supply to approximately 5 V (with $\pm 0.1\text{ V}$ tolerance) and connect it to the resistive circuit that you built for the last question, as shown in Figure 1.3. Calculate the voltages at nodes *a* and *c* with respect to node *b* (V_{ab} and V_{cb}), as well as the voltage from node *c* to node *a* (V_{ca}), using the measured resistance values from the **LCR Bridge** in question **1**. Then, measure the same voltages using the digital multimeter and write them down in the Table below. Compare and comment on the calculated and measured voltage values.

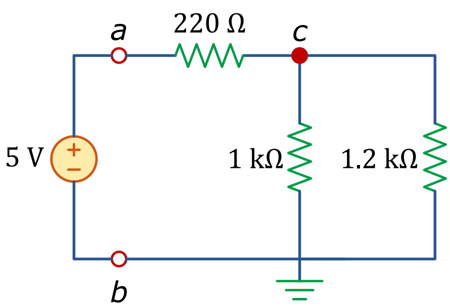


Figure 1.3: Resistive circuit for Lab Experiment 1 with DC power supply.

Voltage	Calculated using LCR Bridge resistance values	Direct measurement using multimeter	Comments
V_{ab}			
V_{cb}			
V_{ac}			

5 Using the measured resistance values from the **LCR Bridge** in question **1**, calculate the current through each of the three resistors in Figure 1.3 (choose an arbitrary direction for each current and label them clearly on the circuit diagram in the figure). Then, measure the current through each of the three resistors, using the digital multimeter and write the values down in the Table below. Compare and comment on the calculated and measured voltage values.

Current	Calculated using LCR Bridge resistance values	Direct measurement using multimeter	Comments
$I_{220\Omega}$			
$I_{1\text{k}\Omega}$			
$I_{1.2\text{k}\Omega}$			

6 What is the relation between the current through the $220\text{-}\Omega$ resistor and the currents through the $1\text{-k}\Omega$ resistor and $1.2\text{-k}\Omega$ resistor?

7 When you have finished measuring a current, please disconnect the meter and return its settings to either the **OFF** position or to a high voltage range. Why is this important?

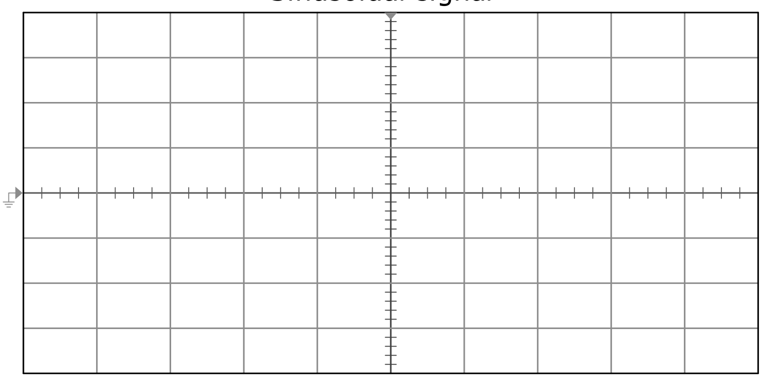
III. AC voltages and currents

8 Set the signal generator to a sinusoidal output with a frequency of **1 kHz** and at **maximum amplitude** and connect it to **channel 1** (**CH1**) of the oscilloscope. Configure the oscilloscope to display **at least 2 full periods** of the voltage signal. Identify the amplitude or peak value and peak-to-peak value of the sinusoidal signal and write them down in the Table below (you may use the Measure or Cursor functions in the oscilloscope). Repeat the measurement for the square and triangular signals and sketch all three waveforms in the spaces provided below using the same settings mentioned above.

⚠ When sketching or drawing waveforms from the oscilloscope, it is important to clearly read the settings of the vertical/Y axis, known as **Volt per Division** setting (e.g., $5\mathrm{V/div}$ as vertical scale), and horizontal/X axis, known as **Time per Division** setting (e.g., $10\mathrm{ms/div}$ as horizontal scale).

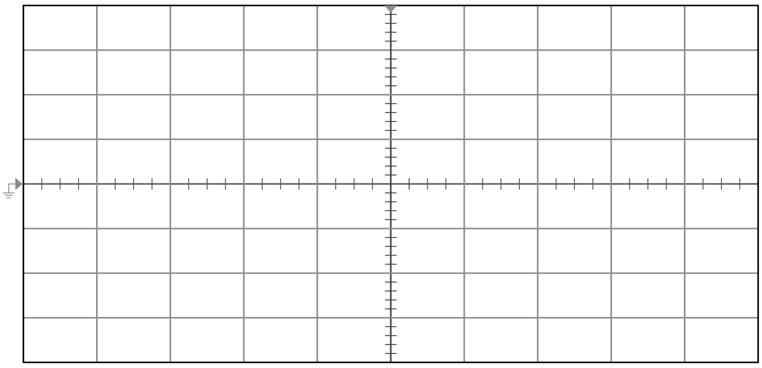
Voltage signal	Amplitude/Peak value	Peak-to-Peak value
Sinusoidal		
Square		
Triangular		

Sinusoidal signal



Horizontal scale:---------- Vertical scale:----------

Square signal



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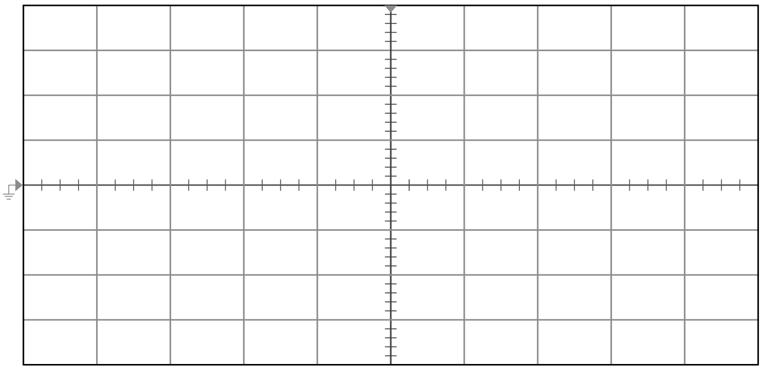
Triangular signal



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9 Repeat the same measurements of the three AC signal types with the same frequency and amplitude as before, but this time by using the **multimeter**. Record the measured values in the Table below, together with the amplitude/peak values from the previous question. Explain why the AC values measured using the multimeter are different to the amplitude/peak values measured using the oscilloscope.

⚠ You have been using the multimeter to measure DC values so far, but now you are asked to measure AC values, so make sure to properly set up your multimeter for AC measurement.

Voltage signal	Amplitude/peak value using multimeter	Amplitude/peak value using oscilloscope	Comments
Sinusoidal			
Square			
Triangular			

10 Set the signal generator to a **sinusoidal** output with a frequency of $1\ \mathbf{kHz}$ and $15\ \mathbf{V}$ **peak-to-peak**. Then, connect the output signal of the signal generator to your circuit, as shown in Figure 1.4. Measure the peak-to-peak value of voltages V_{ab} and V_{cb} using the **oscilloscope** and write your values in the Table below.

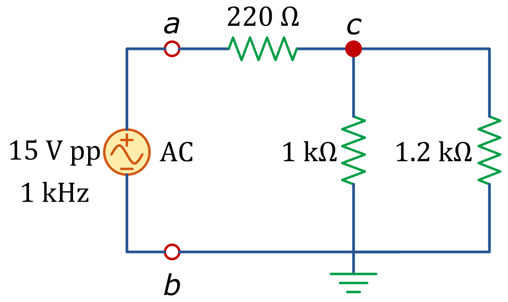


Figure 1.4: Resistive circuit for Lab Experiment 1 with AC voltage source.

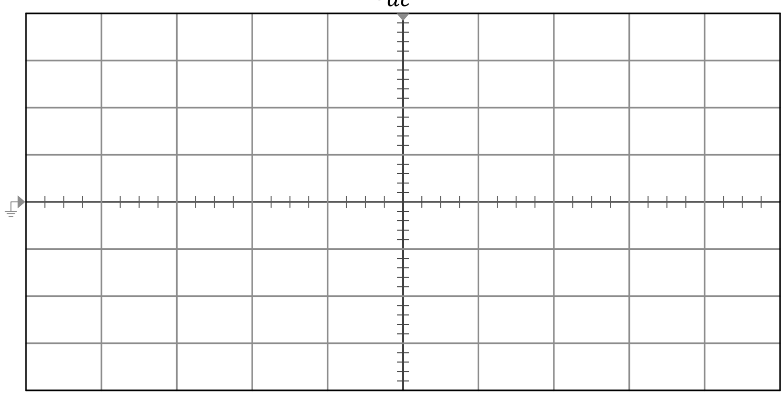
Voltage	Peak-to-Peak measurement using oscilloscope
V_{ab}	
V_{cb}	

11 Explain why the measured V_{ab} in the circuit is not equal to the initial 15 V peak-to-peak that you adjusted before connecting the signal generator to the circuit. What do you need to do to compensate this voltage drop?

12 In the same circuit shown in Figure 1.4, use the oscilloscope to measure the peak-to-peak voltage across the 220-Ω resistor, V_{ac}, and sketch the voltage signal in the space below with proper scales. Explain why you cannot measure this voltage directly by using only one channel of the oscilloscope.

⚠ The oscilloscope can only measure directly the *potentials* of the signals with respect to earth and **not the potential difference** between any two general points in a circuit. It is however capable of monitoring two signals at the same time and, by subtracting one signal from the other, a potential difference can be measured.

V_{ac}



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13 Explain the steps required to perform this measurement including connections of the circuit, settings of the oscilloscope and use of the oscilloscope functions.

⚠ Please note that the bonus questions below will not be marked. They are intended to deepen your understanding of the topic and should be done only if the rest of the questions (which will be marked) have been completed.

14 (**Bonus question**) If you were asked to measure the period of an AC signal (e.g., V_{ac} in the previous question) manually by only counting the boxes and ticks shown on the oscilloscope display, what would be the maximum resolution or precision of your measurement? Provide any necessary explanation.

15 (**Bonus question**) Is it possible to directly measure a current through a resistor using the oscilloscope (AC or DC)? If not, explain how the oscilloscope can be used to measure current and comment on the accuracy of the obtained current value.

Lab work 1	Date:	Assessor name and signature:	Mark:

Lab Experiment 2: Series and Parallel Circuits

Aims of this experiment

The aim of this lab experiment is to:

1. Study the properties of series and parallel combination of resistors.
2. Validate voltage and current division laws.

Videos and guides for review

List of suggested videos:

- Breadboard/Prototyping board
- Power supply
- Multimeter

List of suggested guides from Appendix:

- Prototyping board (Breadboard)
- DC power supply
- Digital multimeter

Lab 2: Pre-lab work

For your pre-lab work, please answer the following questions **before coming to the lab**.

1 How can you identify whether two electric elements are connected in parallel or in series? Is there any other form of connection between electric elements?

2 Draw the circuit for a **current divider** with resistors R_1 and R_2 and derive the equations for the currents going through these resistors.

3 Draw the circuit for a **voltage divider** with resistors R_1 and R_2 and derive the equations for the voltages across these resistors.

4 Consider the circuits given in Figure 2.1. Calculate the equivalent resistance of the circuits as seen from the voltage source V_s if all lightbulbs are of equal resistance R.

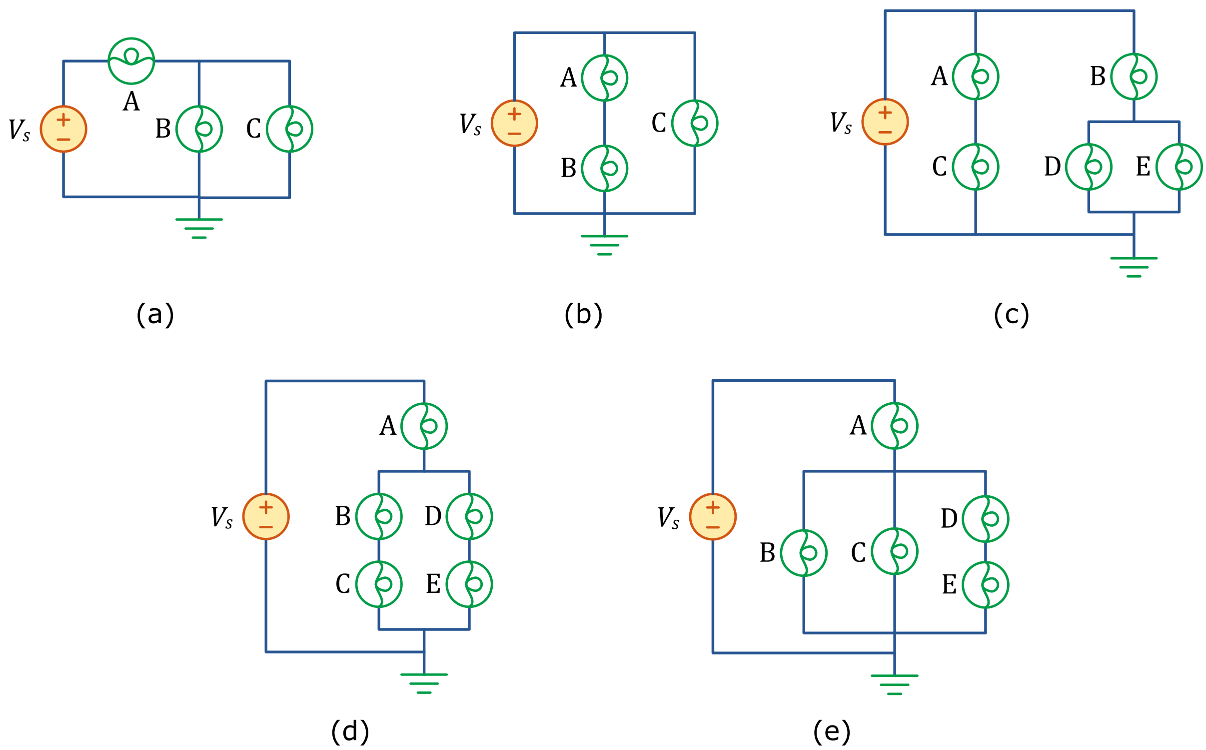


Figure 2.1: Circuits for Pre-Lab 2.

Pre-Lab 2	Date:	Assessor name and signature:	Mark:

Lab 2: Experimental procedure

Please complete all the tasks given in this section during the lab session. Do not forget to watch the related lab videos and guides that are suggested for this lab experiment.

Required components

In this experiment you will be required to use the following components:

- Your breadboard.
- Miniature lightbulbs.
- $220\ \Omega$ resistor.

I. Series and parallel connections

1 Connect a lightbulb to the DC power supply as shown in Figure 2.2(a). Start with $V_S = 2\ \mathrm{V}$ and measure the voltage across lightbulb A and the current through it using the digital multimeter. Increase the voltage in steps of $2\ \mathrm{V}$ up to a maximum of $10\ \mathrm{V}$, and for each voltage measure the current through the lightbulb. Record all your measurements in the Table below. Then, calculate the resistance of the lightbulb for each set of measured voltage and current.

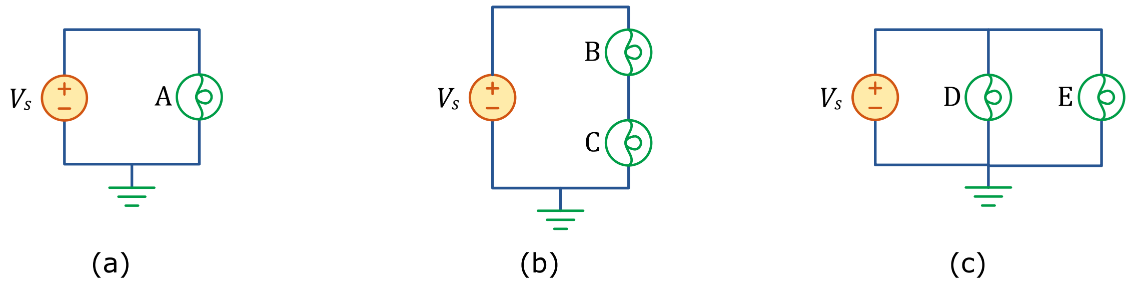


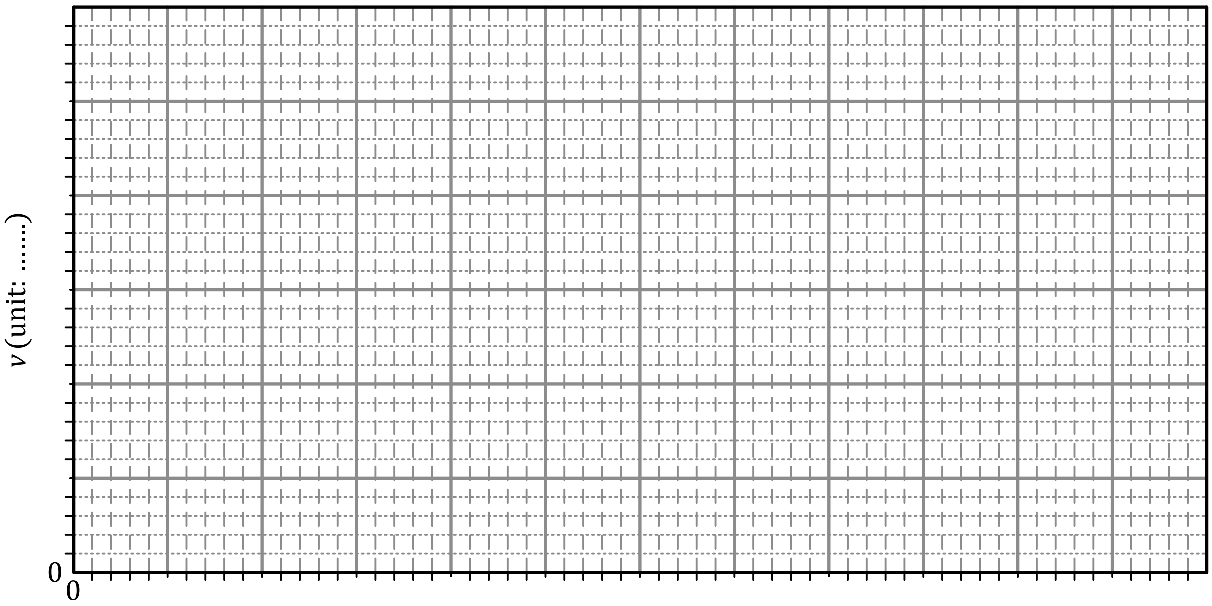
Figure 2.2: Simple circuits with lightbulbs and DC power supply for Lab Experiment 2: (a) Single lightbulb, (b) two lightbulbs in series, and (c) two lightbulbs in parallel.

Voltage	Current	Resistance
$V_S = 2\ \mathrm{V}$		
$V_S = 4\ \mathrm{V}$		
$V_S = 6\ \mathrm{V}$		
$V_S = 8\ \mathrm{V}$		
$V_S = 10\ \mathrm{V}$		

2 Repeat the previous experiment using a $220\ \Omega$ resistor instead of lightbulb A in the circuit shown in Figure 2.2(a). Record all your measurements in the following Table, and then calculate the resistance for each set of measured voltage and current.

Voltage	Current	Resistance
$V_S = 2\ \mathrm{V}$		
$V_S = 4\ \mathrm{V}$		
$V_S = 6\ \mathrm{V}$		
$V_S = 8\ \mathrm{V}$		
$V_S = 10\ \mathrm{V}$		

3 Sketch the i-v curves of the lightbulb and the resistor in the graph below and explain your observation in terms of the behaviour of both lightbulb and resistor under different voltages and currents, particularly for the resistance of the lightbulb. Does it remain constant? Why?



4 Build the circuits shown in Figure 2.2(b) and Figure 2.2(c) side-by-side on your breadboard and supply them with $12\ \mathrm{V}$ ($V_S = 12\ \mathrm{V}$). Observe the brightness of lightbulbs B, C, D, and E and make comparisons between their brightness by adequately describing what you mean in your comparison, i.e., use adjectives such as "*the same brightness as*", "*brighter than*", "*dimmer than*", and so on. Provide all necessary explanations to justify your comparison.

5 Based on your observations from previous results, which electrical parameter impacts the brightness? Use your measurements in the Table of question **1** and calculate the values of that parameter to justify your reasoning.

6 In the circuit of Figure 2.2(b), increase the applied voltage to $24\ \mathrm{V}$ while keeping the applied voltage in the circuit of Figure 2.2(c) at $12\ \mathrm{V}$. Now compare the brightness of lightbulbs (B,C) with (D,E). Record your observations and reasoning (provide any necessary explanation to justify your reasoning by collecting relevant measurements and numerical values for the electrical parameter impacting the brightness of each lightbulb).

7 Now build the circuits given in Figure 2.3 and set the power supply to $12\ \mathrm{V}$ ($V_S = 12\ \mathrm{V}$). Compare the brightness of the lightbulbs in these two circuits with the ones in Figure 2.2(b) and Figure 2.2(c).

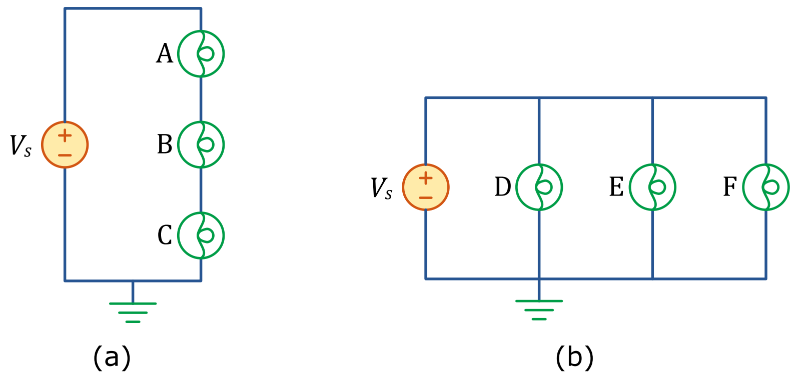


Figure 2.3: Simple circuits with lightbulbs and DC power supply for Lab Experiment 2: (a) Three lightbulbs in series and (b) three lightbulbs in parallel.

8 What happens to the overall resistance connected to the power supply as you add more lightbulbs in **series**? How does it impact the brightness of the lightbulbs? What happens to the current supplied by the power supply as you add more lightbulbs in **series**?

9 What happens to the overall resistance connected to the power supply as you add more lightbulbs in **parallel**? How does it impact the brightness of the lightbulbs? What happens to the current supplied by the power supply as you add more lightbulbs in **parallel**?

10 Can you add unlimited number of bulbs in parallel? Why?

11 Explain why all the wirings in buildings are done in parallel.

Please note that the bonus question below will not be marked. It is intended to deepen your understanding of the topic and should be done only if the rest of the questions (which will be marked) have been completed.

12 (**Bonus question**) Consider the circuits shown in Figure 2.4. Explain which lightbulb in each circuit is the brightest. Provide any necessary calculation and measurement to justify your reasoning.

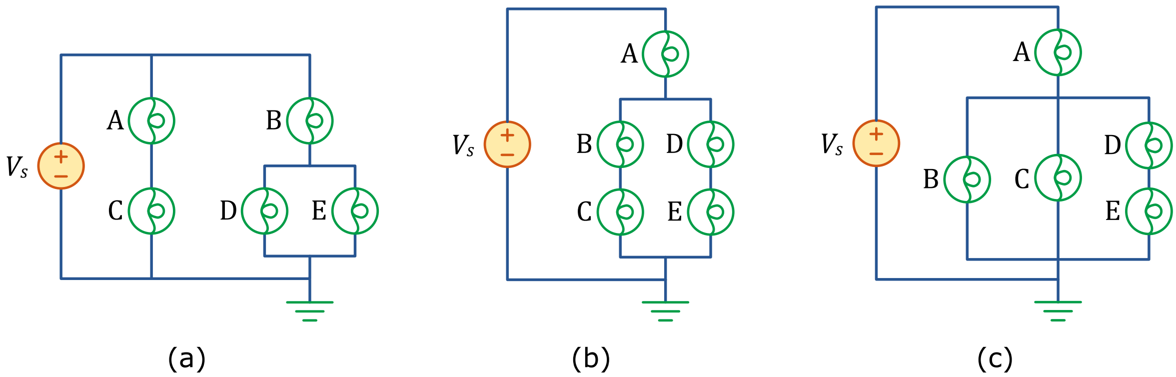


Figure 2.4: Circuits for bonus question.

Circuit of Figure 2.4(a)

Circuit of Figure 2.4(b)

Circuit of Figure 2.4(c)

Lab work 2	Date:	Assessor name and signature:	Mark:

Lab Experiment 3: Kirchhoff’s Laws

Aims of this experiment

The aims of this lab experiment are to:

1. Investigate the properties of a simple battery and a voltage source.
2. Examine and verify Kirchhoff’s Current and Voltage Laws (KCL and KVL).

Videos and guides for review

List of suggested videos:

Power supply

Multimeter

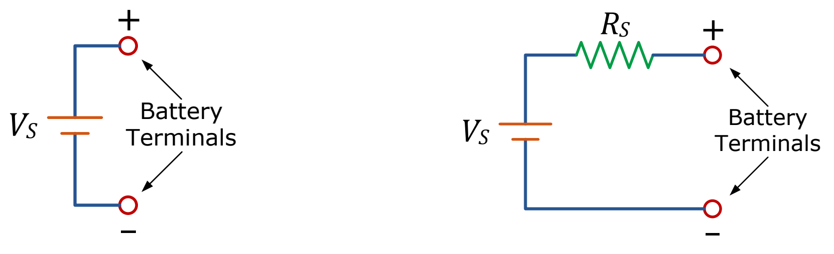
List of suggested guides from Appendix:

- DC power supply
- Digital multimeter

Introduction: Circuit models for batteries

A battery is a convenient way of storing electrical energy in a portable form. It can be used as a DC voltage source. In the first part of this lab experiment, you should examine the properties of a dry cell battery by applying KVL, KCL and Ohm’s Law. Such batteries are used as the power source in many everyday household and personal products.

The two battery models that will be considered are illustrated in Figure 3.1. Figure 3.1(a) shows the **ideal model for the battery**, being represented as a voltage source V_s that is independent of any variable, such as temperature, external load, etc. This model may be used in circuit analysis where imperfections will not affect the analysis of the circuit. The **equivalent circuit of the battery** includes an **internal resistor** R_s, as shown in Figure 3.1(b). This resistor accounts for the voltage drop at the terminals of the battery as current is drawn from the battery and is a significant improvement to the battery model. V_s and R_s are affected by the state of the battery, i.e., they can change as the battery discharges or gets older. They can also depend on the amount of current being drawn from it. Therefore, these equivalent circuit components will be considered at a specific operating point.



(a) (b)

Figure 3.1: Equivalent circuits of a battery: (a) Ideal model, and (b) model with internal resistance.

Lab 3: Pre-Lab work

For your pre-lab work, please answer the following questions **before coming to the lab**.

Batteries

1 Consider a typical 9 V battery. What sort of information can you get from the package and what additional information would be important to know?

2 Consider the simple circuit of Figure 3.2. What is the current that flows through resistor R_L?

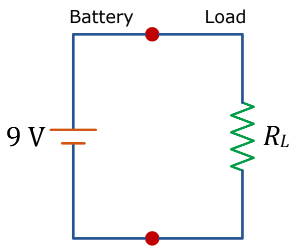


Figure 3.2: Simple circuit with ideal battery connected to a load.

3 What is the power consumed by the load?

4 What is the power supplied by the battery and how does it relate to the power consumed by the load?

5 Consider a more practical model of the battery with a given load resistor, as shown in Figure 3.3. When **no load** is connected to the battery, the terminal voltage is measured at $8.8\,\mathrm{V}$. Find the value of V_s.

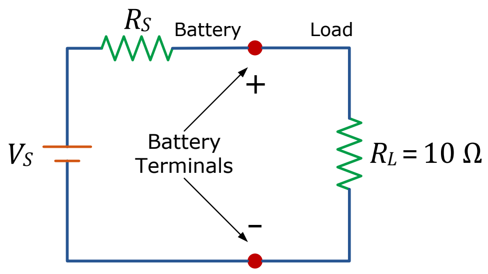


Figure 3.3: Simple circuit with non-ideal battery connected to a load.

6 When a $\mathbf{10}$-Ω resistor is connected to the battery, the voltage at the terminals is measured at $8\,\mathrm{V}$. Calculate the current flowing in the circuit.

7 Calculate the internal resistance of the battery R_s.

KVL and KCL

8 Consider the circuit of Figure 3.4. Calculate the resistance seen from the terminals of the 10-V DC source.

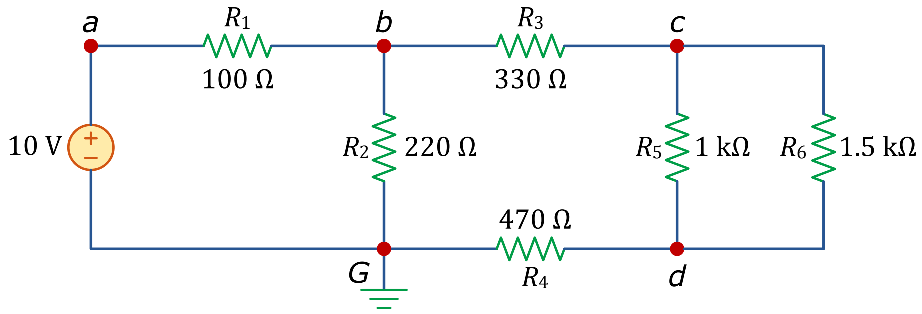


Figure 3.4: Resistive circuit for Pre-Lab 3.

9 Calculate the voltages of nodes *a*, *b*, *c* and *d* with respect to the reference node *G* (ground).

10 Calculate the currents through all the resistors in the circuit (choose the directions as you see fit).

Pre-Lab 3	Date:	Assessor name and signature:	Mark:

Lab 3: Experimental procedure

Please complete all the tasks given in this section during the lab session. Do not forget to watch the related lab videos and guides that are suggested for this lab experiment.

Required components

In this experiment you will be required to use the following components:

- Your breadboard.
- A 9-V Battery.
- A $10\text{-}\Omega$ resistor with $10\ \text{W}$ power rating (please return this resistor at the completion of the experiment).
- $100\ \Omega$, $220\ \Omega$, $330\ \Omega$, $470\ \Omega$, $1\ \text{k}\Omega$, and $1.5\ \text{k}\Omega$ resistors.

I. Batteries

1 Measure the output voltage of the 9-V battery with no external load connected using the digital multimeter.

2 Draw the circuit to illustrate how you will measure the output voltage of the battery when there is a $10\text{-}\Omega$ resistor connected to the battery (**MAKE SURE THE RESISTOR IS OF APPROPRIATE POWER RATING!**). Explain why you cannot use normal resistors for this part of the experiment.

3 Connect the 9-V battery to the $10\text{-}\Omega$, 10-W resistor for a short amount of time and measure the output voltage from the terminals of the battery (about **2 seconds is sufficient**, even though the voltage may still be changing slowly). Then, calculate the internal resistance of the battery.

4 Refer back to Figure 3.1(b) and draw the equivalent circuit of the battery showing the value of the components you obtained in the previous question. From the equivalent circuit values just derived for your battery, estimate the short circuit current that should be available from the battery.

II. KVL and KCL

5 Build the circuit of Figure 3.5 on your prototyping board, using the laboratory power supply as the 10 V source. Then, using the digital multimeter, measure the voltages of nodes *a*, *b*, *c* and *d* with respect to reference node *G* and write them down in the Table below. How do they compare with the calculated values in Lab 3: Pre-Lab work?

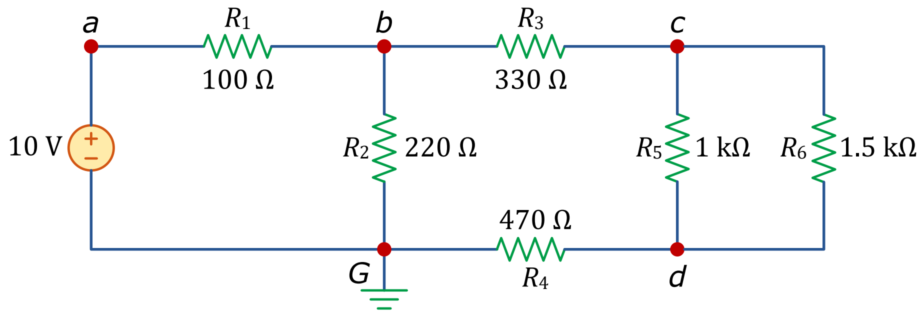


Figure 3.5: Resistive circuit for Lab Experiment 3.

Voltage	Calculated value	Measured value	Comments
V_{aG}			
V_{bG}			
V_{cG}			
V_{dG}			

6 Use the digital multimeter to measure the voltages V_{ab}, V_{bc}, V_{cd}, and V_{ac}.

Voltage	Measured value
V_{ab}	
V_{bc}	
V_{cd}	
V_{ac}	

7 Find the current through the $100\text{-}\Omega$, $220\text{-}\Omega$ and $330\text{-}\Omega$ resistors, (a) using the measured voltage across the resistances from the previous question (use actual measured values for resistors), and (b) by directly measuring them using the multimeter. Record all your results in the following Table and compare them with the calculated values in Lab 3: Pre-Lab work. Make sure to label the current directions that you chose for calculation and measurements on the circuit of Figure 3.5.

Current	Measured voltage	Measured resistance	Measured current using measured voltage	Measured current using multimeter	Calculated current
$I_{100\Omega}$					
$I_{220\Omega}$					
$I_{330\Omega}$					

8 Apply KCL at node *b* using the current values measured with the multimeter and the calculated ones, with the directions that you have chosen and labelled in the previous question. Verify that the KCL equations are satisfied using both sets of values (measured and calculated) and comment on the differences in the equations.

9 Apply KVL for loops 1 and 2 as shown in Figure 3.6 (i.e., in the clockwise direction), using both the measured and calculated voltage values. Verify that the KVL equations are satisfied using both sets of values (measured and calculated) and comment on the differences in the equations.

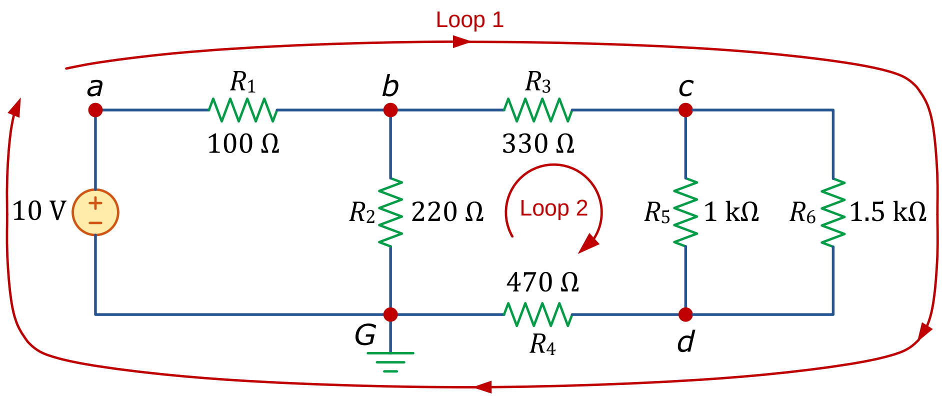


Figure 3.6: Resistive circuit with given outer and inner loops for applying KVL.

Lab work 3	Date:	Assessor name and signature:	Mark:

Lab Experiment 4: Circuit theorems

Aims of this experiment

The aim of this lab experiment is to investigate the following circuit theorems:

1. Thevenin's theorem.
2. Norton's theorem.
3. Superposition.
4. Maximum power transfer theorem.

Videos and guides for review

List of suggested videos:

Power supply

Multimeter

List of suggested guides from Appendix:

- DC power supply
- Digital multimeter

Lab 4: Pre-Lab work

For your pre-lab work, please answer the following questions **before coming to the lab**.

1 Consider the circuit of Figure 4.1. Find the Thevenin and Norton equivalent circuits from across terminals *c* and *d* (i.e., assuming R_6 to be a load resistor), as shown in Figure 4.2. Show all working and sketch the equivalent circuits.

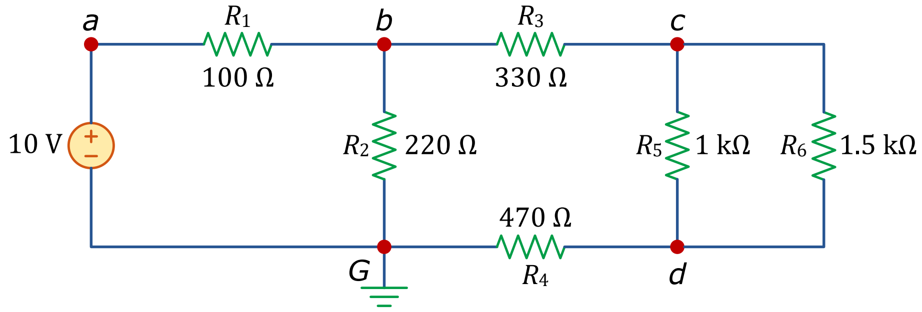


Figure 4.1: Resistive circuit for Pre-Lab 4.

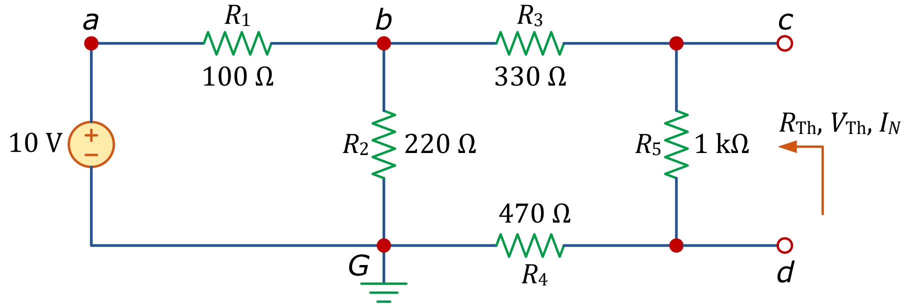


Figure 4.2: Resistive circuit used to calculate Thevenin and Norton equivalent circuits from terminals *c* and *d*.

2 Find the Thevenin and Norton equivalent circuits from across terminals *b* and *c* (i.e., assuming R_3 to be a load resistor), as shown in Figure 4.3. Show all working and sketch the equivalent circuits.

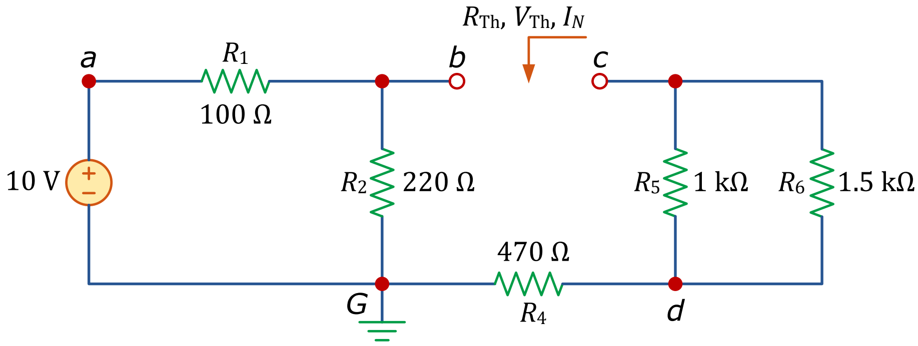


Figure 4.3: Resistive circuit used to calculate Thevenin and Norton equivalent circuits from terminals *b* and *c*.

3 State the **principle of superposition** and explain how it can be used to analyse electric circuits.

4 Explain how Norton's and Thevenin's theorems can be used to analyse electric circuits.

5 Explain how a DC linear circuit or network can deliver maximum power to a resistive load. Sketch any necessary equivalent circuit and provide the maximum power transfer formula to elaborate your answer (you do not have to prove the theorem).

Pre-Lab 4	Date:	Assessor name and signature:	Mark:

Lab 4: Experimental procedure

Please complete all the tasks given in this section during the lab session. Do not forget to watch the related lab videos and guides that are suggested for this lab experiment.

Required components

In this experiment you will be required to use the following components:

- Your breadboard.
- $100\ \Omega$, $220\ \Omega$, $330\ \Omega$, $470\ \Omega$, $680\ \Omega$, $1\ \text{k}\Omega$, and $1.5\ \text{k}\Omega$ resistors.

I. Thevenin's theorem

1 Build the circuit of Figure 4.4 on your breadboard. Consider R_6 to be the load resistor. Measure the voltage across R_6 and the current through it (V_L and I_L), and calculate the power consumed (P_L).

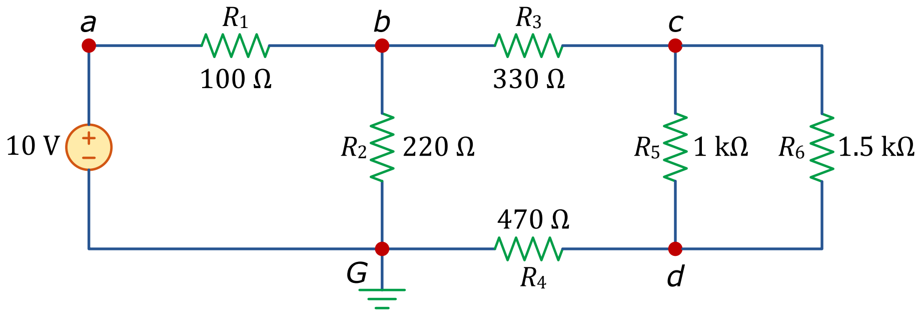


Figure 4.4: Resistive circuit for Lab Experiment 4.

2 Now remove R_6 from the terminals *c* and *d* (the terminals clearly become an open circuit). Measure the open circuit voltage across terminals *c* and *d*. What does this voltage represent?

3 Compare the measured open circuit voltage with the voltage that you calculated in Lab 4: Pre-Lab work question **1**. Provide any necessary explanations and comments.

4 Measure the Thevenin resistance R_{Th} by appropriately disabling all independent sources in your circuit. Compare the result with the R_{Th} that you calculated in Lab 4: Pre-Lab work question **1**. Provide any necessary explanations and comments.

5 Sketch the Thevenin equivalent circuit, build it on your breadboard, and connect it to the load resistance R_6. Measure the voltage across the load and compare it to the voltage you measured in question **1**. Provide any necessary explanations and comments.

II. Norton's theorem

6 Consider the same circuit as in Figure 4.4. Measure I_N as the **short-circuit current** between terminals *c* and *d* (where R_6 was connected).

7 Calculate $I_N = \frac{V_{\mathrm{Th}}}{R_{\mathrm{Th}}}$ and compare it to the measured value obtained in the previous question.

III. Superposition theorem

8 Build the circuit of Figure 4.5 on your breadboard. Set V_{s_1} and V_{s_2} to be $10\ \mathrm{V}$ and $15\ \mathrm{V}$, respectively. Then, measure the currents I_1, I_2, and I_3 with the given directions.

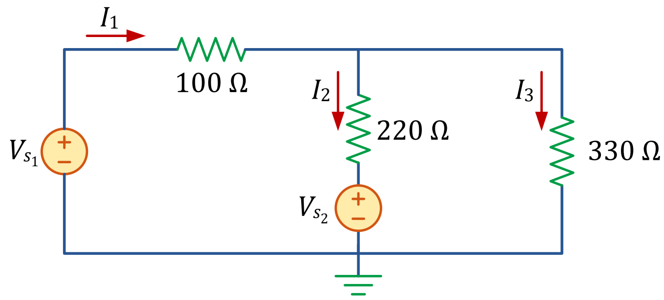


Figure 4.5: Resistive circuit to verify the superposition theorem.

9 Disable V_{s_1} and measure the same currents but label them as I_1', I_2', and I_3'.

10 Disable V_{s_2} and measure the same currents but label them as I_1'', I_2'', and I_3''.

11 Confirm the principle of superposition using your previous measurements.

IV. Maximum power transfer

12 Build the resistive circuit shown in Figure 4.6 on your breadboard. Measure the voltage across R_L (V_L) and the current flowing through it (I_L), and then calculate the power consumed (P_L) for the different values of R_L given in the Table below. Write down all your measurements and calculations in the Table.

Hint: To complete this experiment faster you can place all resistors in the breadboard next to each other and use a wire as a switch to connect one resistor at a time and then measure voltage and current for each load separately.

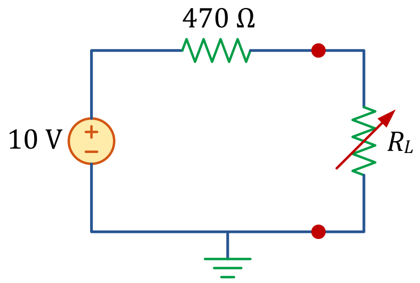
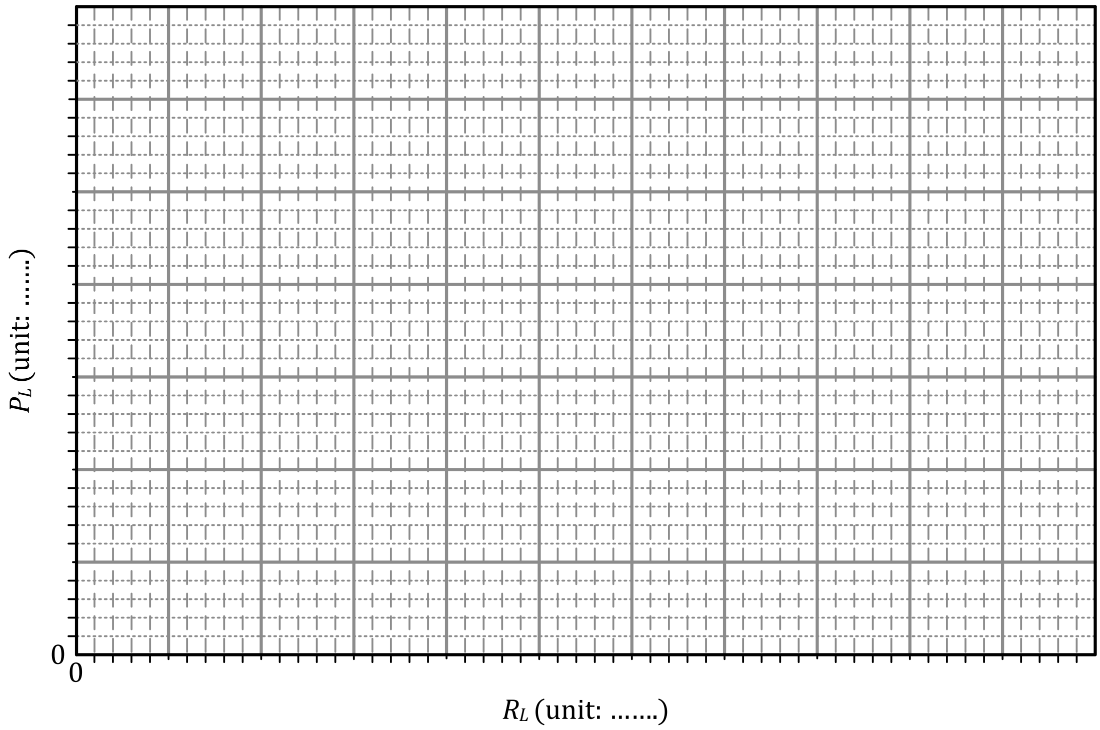


Figure 4.6: Resistive circuit to examine maximum power transfer theorem.

Load resistor R_L	Load voltage V_L	Load current I_L	Load power P_L
$100\ \Omega$			
$220\ \Omega$			
$470\ \Omega$			
$680\ \Omega$			
$1\ \mathrm{k}\Omega$			

13 Plot the variation of the load power P_L with respect to the variation of the load resistor R_L using the collected data. Identify at what point the power is maximum. Calculate the theoretical value for the maximum power transferred for the circuit of Figure 4.6 and compare it with your experimental value.



Lab work 4	Date:	Assessor name and signature:	Mark:

Lab Experiment 5: First-order circuits

Aims of this experiment

The aim of this lab experiment is to examine the following features of first-order circuits:

1. Transient voltages and currents in simple RC and RL circuits.
2. Natural and step responses of RC and RL circuits.
3. Transient response of simple RC and RL circuits to a square wave voltage input.

Videos and guides for review

List of suggested videos:

Signal generator

Oscilloscope

List of suggested guides from Appendix:

- Signal/Function generator
- Oscilloscope

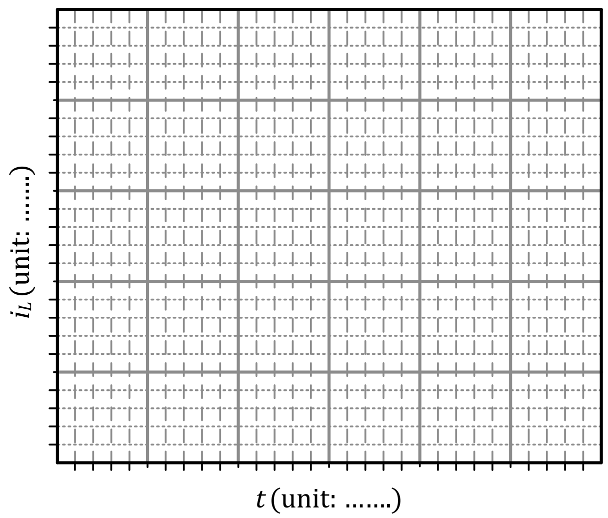
Lab 5: Pre-Lab work

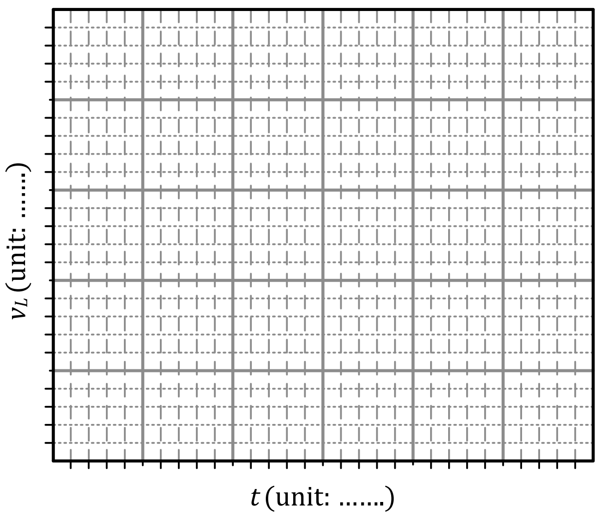
For your pre-lab work, please answer the following questions **before coming to the lab**.

1 An initially charged capacitor is connected through a switch to a resistive circuit without a source. The switch is in the open position for a long time and closes at $t = 0$. Draw the circuit and calculate the **steady-state voltage** of the capacitor in this RC circuit, i.e., $v_C(\infty)$ or v_C when $t \to \infty$.

2 Explain the physical meaning of the steady-state voltage value in the previous question. What does this mean for the energy stored in the capacitor?

3 Consider a series RL circuit with a DC voltage source and a switch. Draw the circuit and sketch the variation of current and voltage of the inductor, i_L and v_L, respectively, before and after the switch closes at $t = 0$. Assume $i_L(0) = 0$. Provide any necessary labels on the graphs and explanations for the variations of waveforms.





4 An RC switching circuit has a capacitance of $100\ \mu\mathrm{F}$ and is required to have a time constant of $5\ \mathrm{ms}$. What is the required value of resistance in the circuit? What is the inductance value required to achieve the same time constant in an RL switching circuit using the same resistor?

Pre-Lab 5	Date:	Assessor name and signature:	Mark:

Lab 5: Experimental procedure

Please complete all the tasks given in this section during the lab session. Do not forget to watch the related lab videos and guides that are suggested for this lab experiment.

Required components

In this experiment you will be required to use the following components:

- Your breadboard.
- $1\ \mathrm{k\Omega}$ and $100\ \mathrm{k\Omega}$ resistors.
- $220\ \mu\mathrm{F}$ and $220\ \mathrm{nF}$ capacitors.
- $10\ \mathrm{mH}$ inductor (please **return** the inductor to its bin at the end of the experiment).
- Green-light and red-light LEDs.

I. RC transients – First measurements

⚠ Light-emitting diodes (**LEDs**) should be connected in the correct direction to work properly, otherwise they cannot emit light. Figure 5.1(a) illustrates the **positive** (Anode) and **negative** (Cathode) leads in an LED which can also be detected by the **flat spot** on the LED side. The LED symbol is shown in Figure 5.1(b).

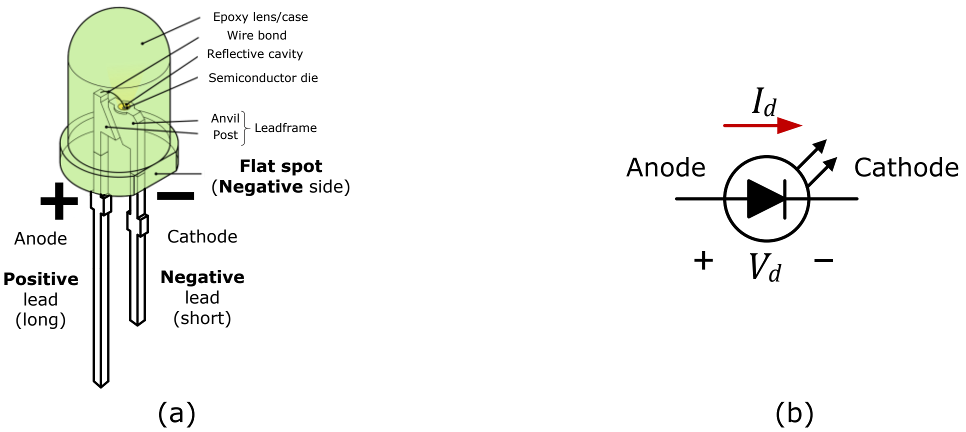


Figure 5.1: (a) Light-emitting diode (LED) (source Wikipedia), (b) LED circuit symbol.

⚠ **Electrolytic** capacitors have **fixed polarity**, as shown in Figure 5.2(a) (note the circuit symbol for capacitors sensitive to reverse voltage in Figure 5.2(b)). If you connect the electrolytic capacitor the wrong way, it will **explode.** Note that capacitors in the lower range, e.g., nF and pF, are not sensitive to reverse voltage (see examples in Figure 5.2(c), and circuit symbol for generic capacitors in Figure 5.2(d)).

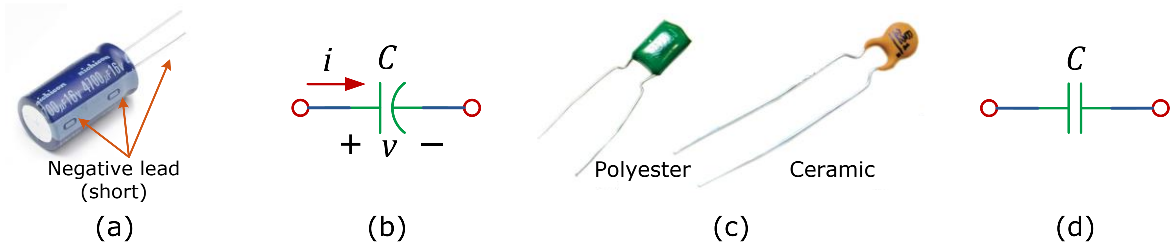


Figure 5.2: (a) Electrolytic capacitor, (b) Reverse-voltage sensitive capacitor circuit symbol, (c) Polyester and ceramic capacitors, (d) Generic capacitor circuit symbol.

1 Build the RC circuit shown in Figure 5.3 on your breadboard, making sure to connect the **negative lead** of the 220 μF capacitor to the **common ground** (terminal *b* in Figure 5.3). The LEDs are used to indicate the presence of current and its direction as they light up when current flows through either of them.

Connect the multimeter across the capacitor to measure its voltage (note the given **polarity**). Turn on the power supply and set its voltage to 15 V. Then, connect the wire from the power supply to terminal *a*. What happens to the voltage of the capacitor? Which LED does light up and approximately for how long?

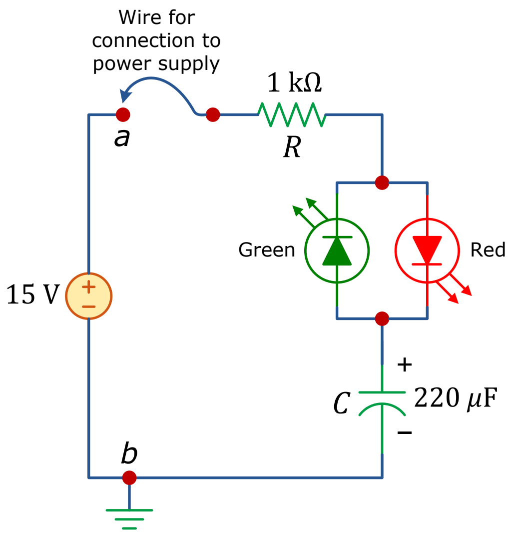


Figure 5.3: RC circuit with LEDs to observe the direction of current during a transient stage.

2 Now disconnect the wire from terminal *a* (i.e., disconnect the power supply) and connect the wire to ground (terminal *b*). What happens to the voltage of the capacitor? Which LED does light up and approximately for how long? Is the time that LEDs light up the same as the time constant of the circuit? Explain your answer.

3 Why do the LEDs light up at different stages?

II. RC transients – Waveforms

Now you are going to use the oscilloscope to explore the charging and discharging of a capacitor.

4 Construct the RC circuit of Figure 5.4 on your breadboard. Connect channel 1 (**CH1**) of the oscilloscope to **node 1** on the circuit and channel 2 (**CH2**) to **node 2**, and the ground of both CH1 and CH2 to the common ground of your circuit. Set the vertical scale of the oscilloscope to $\mathbf{2V/div}$ on both CH1 and CH2 with **DC Coupling**. Also, set the horizontal scale to $\mathbf{20ms/div}$ and choose **CH1 as triggering source** on the **rising edge** with a **trigger level** of $0.5\,\mathrm{V}$. Finally, press the **"Single"** button to have the oscilloscope ready to be triggered. Once all the settings are in place, use the wire to connect the RC circuit to 5-V DC power supply and charge the capacitor. This should display the **transient voltage** of the capacitor on **CH2**.

Find the time constant for this circuit and compare it with the approximate time constant of the previous circuit in Figure 5.3.

⚠ If no signal is displayed, you must discharge the capacitor before repeating the test by simply disconnecting the wire from the power supply and connecting it to the ground.

⚠ Recall that an **oscilloscope** channel can **only measure node voltage**, which is the voltage at the point of connection to the **common ground**. You can refer back to "AC voltages and currents" section in Lab 1: Experimental procedure to review how to do measurements with the oscilloscope (particularly question **12)**.

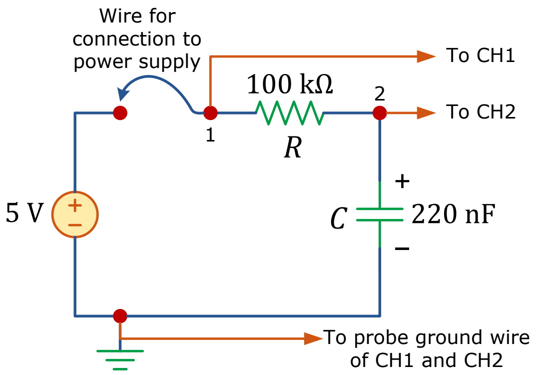
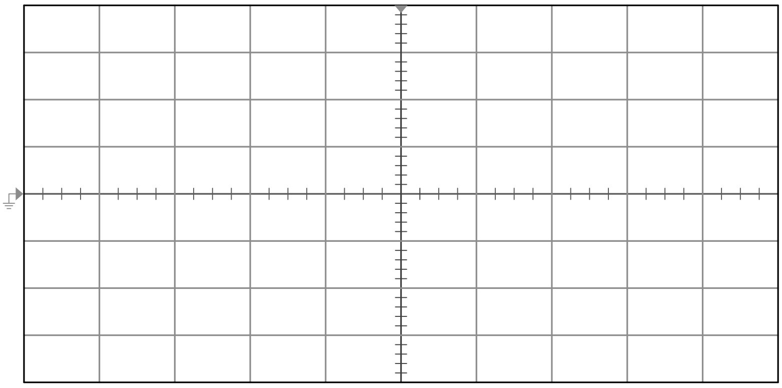


Figure 5.4: An RC circuit to observe the transient behaviour with the oscilloscope.

5 Explain how the settings of the oscilloscope affect your measurements. Refer to the "Oscilloscope" and "Triggering the oscilloscope" videos. Note that not being able to trigger the oscilloscope properly is a very common mistake in the lab exams.

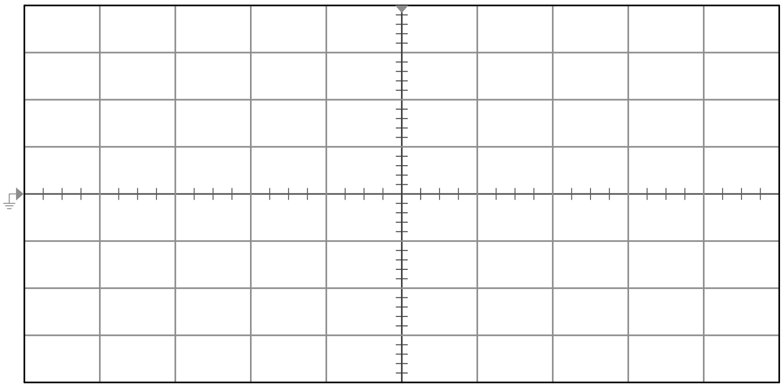
6 Sketch the waveforms displayed on CH1 and CH2 of the oscilloscope in the spaces provided below. Also, use the oscilloscope **Math** feature to display and the sketch the voltage across the $100\text{-k}\Omega$ resistor, V_{12}.

CH1, CH2



Horizontal scale:---------- Vertical scale:----------

V_{12}



Horizontal scale:---------- Vertical scale:----------

7 The current through the RC circuit of Figure 5.4 can be determined using Ohm's law. Using the waveforms above, calculate the peak current in the resistor.

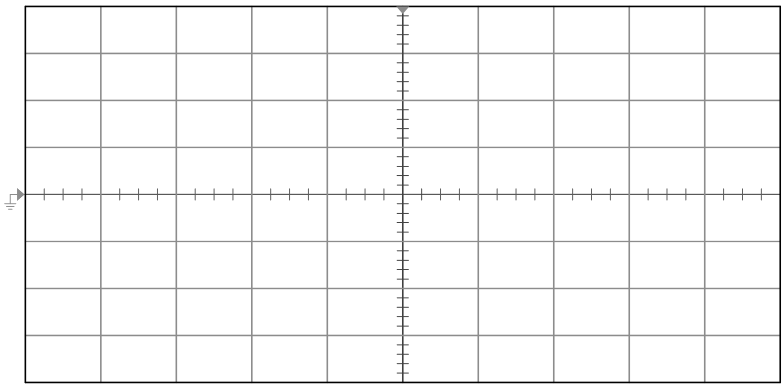
8 This simple experiment demonstrates the first order transient response of a simple RC circuit and shows the exponential response of both the voltage and the current. How does the current across the capacitor change? Can the voltage across the capacitor change in a similar manner? Explain your answer.

9 Would the current through the capacitor and the voltage across it be different if the resistor R and capacitor C were swapped (i.e., the resistor is connected to ground and the capacitor to the power supply)?

III. RC transients - Switching RC circuits

10 Use the signal generator to supply voltage to the circuit of Figure 5.4. Set the output voltage to $\mathbf{15\ V}$ **peak-to-peak** and the frequency to $\mathbf{5\ Hz}$ and select the **square wave** output. Then, connect the output of the signal generator to node 1. Set the oscilloscope back to **"Run"** mode (Run/Stop button should be green) and observe the signal generator voltage and capacitor voltage displayed on the oscilloscope via CH1 and CH2 (you may need to readjust the vertical scale in CH2). Sketch both waveforms in the graph below.

CH1, CH2



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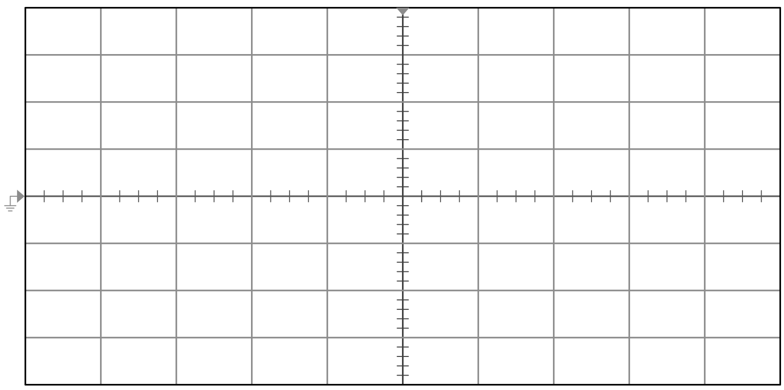
11 Increase the frequency to $\mathbf{25\ Hz}$ while the circuit is still working and sketch the new waveforms in the graph provided. Explain the differences between the waveforms at low frequency, as observed in the previous question, and at higher frequency. What would happen to the capacitor voltage as you further increase the frequency of the voltage source?

CH1, CH2



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IV. RL transients

12 The transient response of an RL circuit will be observed in this section using $L = 10\,\mathrm{mH}$ and $R = 1\,\mathrm{k\Omega}$. Before continuing with the experiment, measure the resistance of the inductor and note this as R_L.

13 Keeping the settings and connections of the signal generator and oscilloscope the same as in question **10**, replace the capacitor and resistor of Figure 5.4 with the inductor and the new resistor, as shown in Figure 5.5. Sketch the waveforms displayed on oscilloscope in the provided space.

Find the time constant of your circuit using the displayed signal on CH2 and compare it with the calculated one using the numerical values of the inductance and resistance. Based on your measurements of the inductor and resistor values, what is an important parameter to consider when finding the time constant?

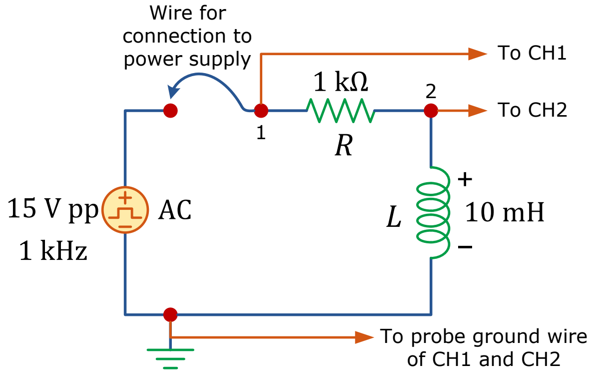
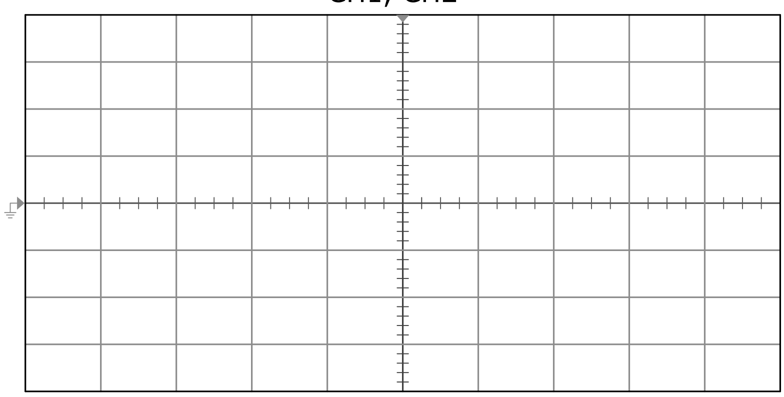


Figure 5.5: An RL circuit to observe the transient behaviour with the oscilloscope.

CH1, CH2



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14 How does an inductor voltage in an RL circuit, differ from the capacitor voltage in an RC circuit?

Lab work 5	Date:	Assessor name and signature:	Mark:

Lab Experiment 6: Operational amplifiers

Aims of this experiment

The aim of this lab experiment is to design and test the following Operational Amplifier (Op Amp) circuits:

1. Inverting amplifier.
2. Non-inverting amplifier.
3. Differentiator.
4. Integrator.

Videos and guides for review

List of suggested videos:

- Power supply
- Signal generator
- Oscilloscope

List of suggested guides from Appendix:

- Power supply
- Signal/Function generator
- Oscilloscope

Introduction: Physical layout of LM741 Op Amp

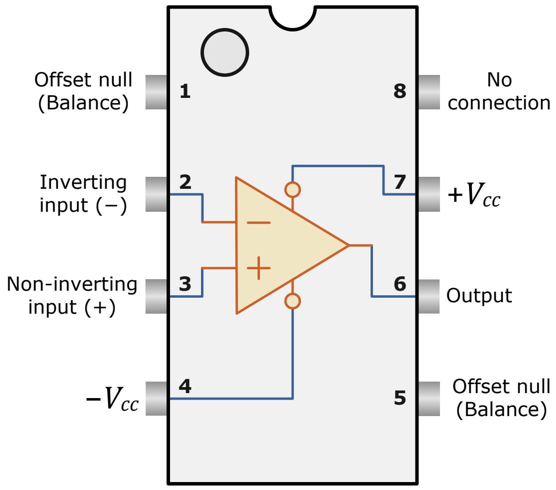


Figure 6.1: Physical layout of LM741 Operational Amplifier (note that V_{cc} and $-V_{cc}$ are DC voltages from the power supply used to power up the Op Amp).

Lab 6: Pre-Lab work

For your pre-lab work, please answer the following questions **before coming to the lab**.

1 What are the characteristics of an ideal Op Amp?

2 Considering the physical layout of the LM741 Op Amp shown in Figure 6.1, how many and which pins of the LM741 do you have to connect in a functional Op Amp circuit?

3 How do you need to connect the DC power supply in order to power up the Op Amp?

4 Under what circumstances does an Op Amp become saturated? Explain your answer.

5 Derive the gain (ratio of v_{out} to v_{in}) for the **inverting amplifier** circuit of Figure 6.2 using nodal analysis.

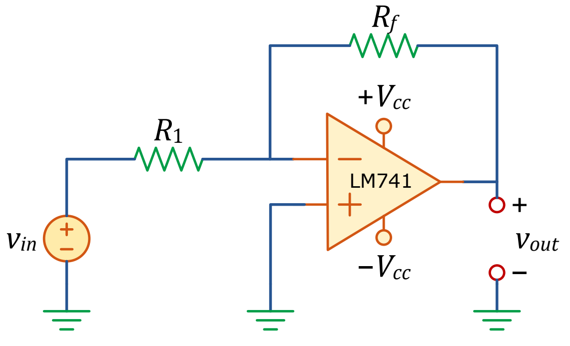


Figure 6.2: Inverting amplifier circuit with Op Amp.

6 For the inverting amplifier shown in Figure 6.2, what would happen under the following conditions?

a The input resistance R_1 is removed and replaced with an open circuit.

b The input resistance R_1 is removed and replaced with a short circuit.

c The feedback resistance R_2 is removed and replaced with an open circuit.

d The feedback resistance R_2 is removed and replaced with a short circuit.

7 Sketch the standard circuit of a **non-inverting amplifier** using Op Amps and derive the equation relating the output voltage v_{out} to the input voltage v_{in} using nodal analysis.

8 Sketch the standard circuit of a **differentiator** using Op Amps and derive the equation relating the output voltage v_{out} to the input voltage v_{in} using nodal analysis.

9 Sketch the standard circuit of an **integrator** using Op Amps and derive the equation relating the output voltage v_{out} to the input voltage v_{in} using nodal analysis.

Pre-Lab 6	Date:	Assessor name and signature:	Mark:

Lab 6: Experimental procedure

Please complete all the tasks given in this section during the lab session. Do not forget to watch the related lab videos and guides that are suggested for this lab experiment.

Required components

In this experiment you will be required to use the following components:

- Your breadboard.
- $470\ \Omega$, $1\ \mathrm{k\Omega}$, $10\ \mathrm{k\Omega}$, $15\ \mathrm{k\Omega}$, $100\ \mathrm{k\Omega}$ and $1\ \mathrm{M\Omega}$ resistors.
- Op Amp LM741.
- $1\ \mathrm{nF}$ and $4.7\ \mathrm{nF}$ capacitors.

I. Inverting amplifier

1 In the circuit of Figure 6.3, find the feedback resistor R_f such that the **amplifier gain** is equal to $\mathbf{15}$, i.e., $\frac{v_{out}}{v_{in}} = 15$.

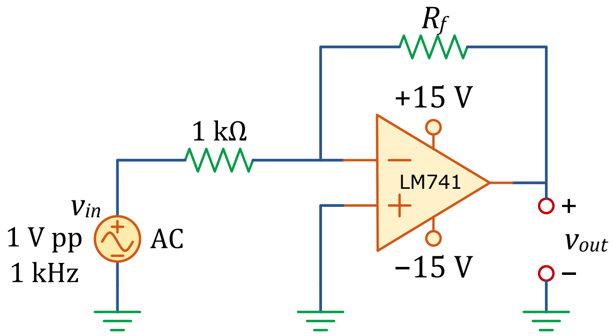


Figure 6.3: Inverting amplifier circuit with Op Amp and AC sinusoidal input voltage.

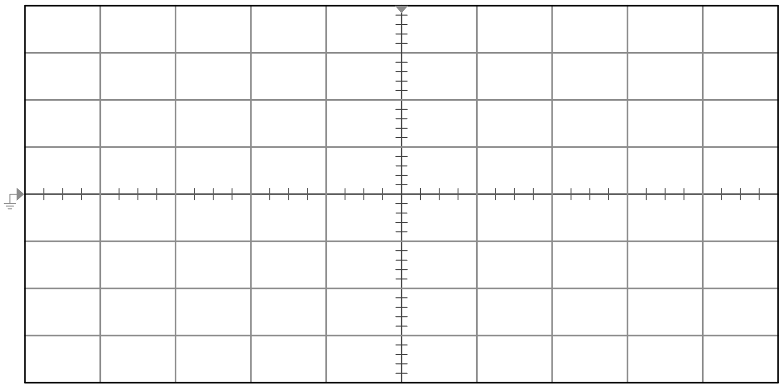
2 Build the **inverting amplifier** circuit shown in Figure 6.3 on your breadboard. Use the signal generator to provide the input voltage v_{in} with $\mathbf{1\ V}$ **peak-to-peak** and a frequency of $\mathbf{1\ kHz}$. Select **sine wave** output. Supply the Op Amp with $\pm\mathbf{15\ V}$ DC by configuring the DC power supply into **series mode**. Configure the oscilloscope so that the input signal v_{in} is displayed on CH1 and the output signal v_{out} is displayed on CH2. Observe the input and output voltage waveforms and sketch them in the provided space. Clearly label the peak values and the fundamental time-period or frequency of the waveforms on the graphs.

⚠ Make sure to properly connect $+\mathbf{15\ V}$ DC voltage supply to **pin 7** and $-\mathbf{15\ V}$ to **pin 4** according to the LM741 layout given in Figure 6.1.

⚠ **Turn down the current nob** on your power supply to **one fourth** of its maximum position to protect your circuit from any accidental or inadvertent short circuit and monitor the current output.

⚠ Make sure that the peak-to-peak value of the input voltage is correct when connecting the signal generator to your circuit.

v_{in} (CH1)



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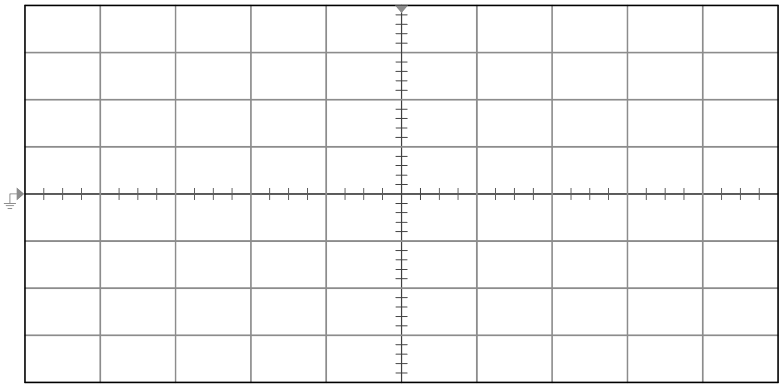
v_{out} (CH2)



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3 Use theoretical calculations to find the peak value of the output voltage v_{out} in the circuit of Figure 6.3 and then compare it with the experimental results you obtained in the previous question.

II. Non-inverting amplifier

4 Build the **non-inverting amplifier** circuit shown in Figure 6.4 on your breadboard. Use the same settings for DC power supply, signal generator, and oscilloscope as in question **2**. Observe the input and output voltage waveforms (v_{in} and v_{out}, respectively) and sketch them in the provided space. Clearly label the peak values and the fundamental time-period or frequency of the waveforms on the graphs.

⚠ Make sure to properly connect $+\mathbf{15\,V}$ DC voltage supply to **pin 7** and $-\mathbf{15\,V}$ to **pin 4** according to the LM741 layout given in Figure 6.1.

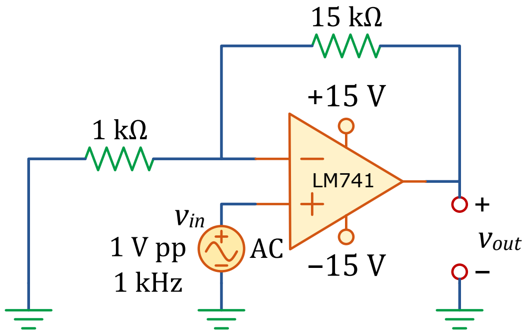
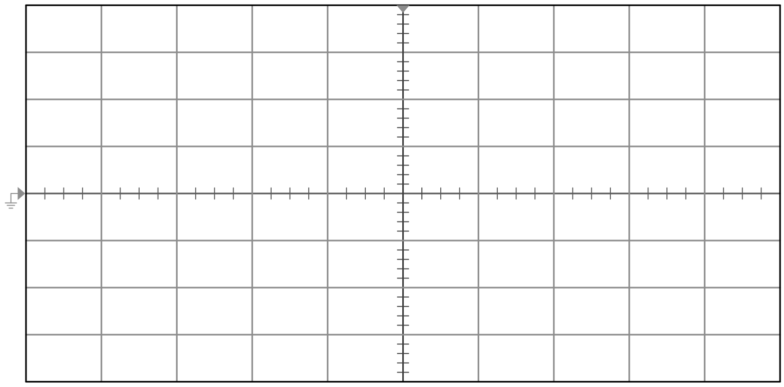


Figure 6.4: Non-inverting amplifier circuit with Op Amp and AC sinusoidal input voltage.

v_{in} (CH1)



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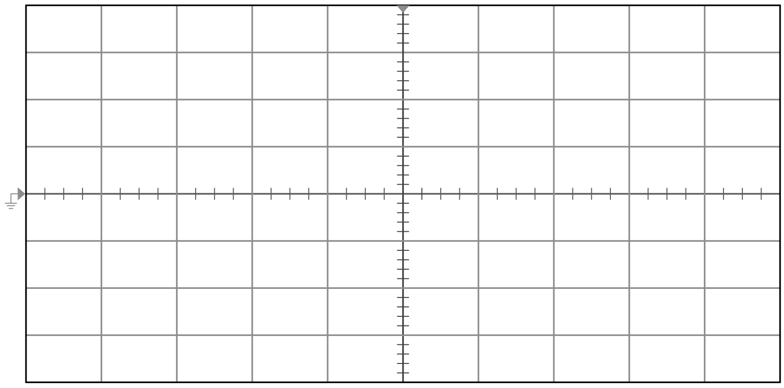
v_{out} (CH2)



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5 Use theoretical calculations to find the peak value of the output voltage v_{out} in the circuit of Figure 6.4 and then compare it with the experimental results you obtained in the previous question.

6 Increase the input voltage signal v_{in} by **20 percent** and observe the response of the non-inverting amplifier in the oscilloscope. Provide an explanation on what happens to the output of the amplifier v_{out}.

7 If you were asked to do the same thing on the inverting amplifier of Figure 6.3, would you expect to observe a similar result? Explain your answer.

III. Differentiator

8 The circuit shown in Figure 6.5 is the **practical** form of an **Op Amp differentiator circuit.** Unlike the standard form of the circuit seen in the lecture, it contains a resistance R_s in series with the capacitance C to avoid high frequency noise and stability problems.

Build the practical Op Amp differentiator in Figure 6.5 with $C = 4.7\ \mathrm{nF}$, $R_f = 10\ \mathrm{k\Omega}$, and $R_s = 470\ \Omega$. Use the signal generator to provide an input voltage v_{in} with $\mathbf{1\ V}$ **peak-to-peak** and a frequency of $\mathbf{1\ kHz}$, and select **triangle wave** output. Supply the Op Amp with $\pm\mathbf{15\ V}$ DC voltage by configuring the DC power supply into **series mode**. Configure the oscilloscope so that the input signal v_{in} is displayed on CH1 and the output signal v_{out} is displayed on CH2. Observe the input and output voltage waveforms and sketch them in the provided space. Clearly label the peak values and the fundamental time-period of the waveforms on the graphs.

⚠ Make sure to properly connect $+\mathbf{15\ V}$ DC voltage supply to **pin 7** and $-\mathbf{15\ V}$ to **pin 4** according to the LM741 layout given in Figure 6.1.

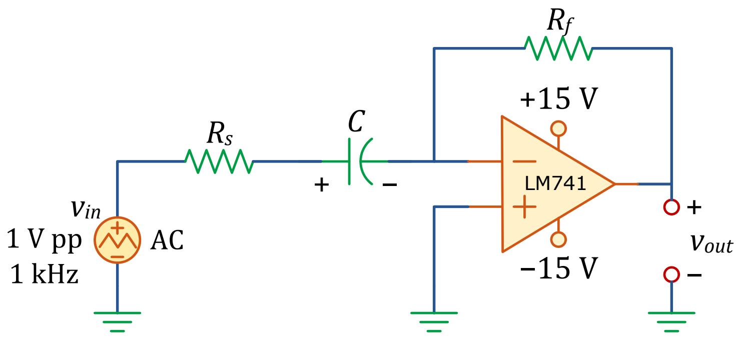
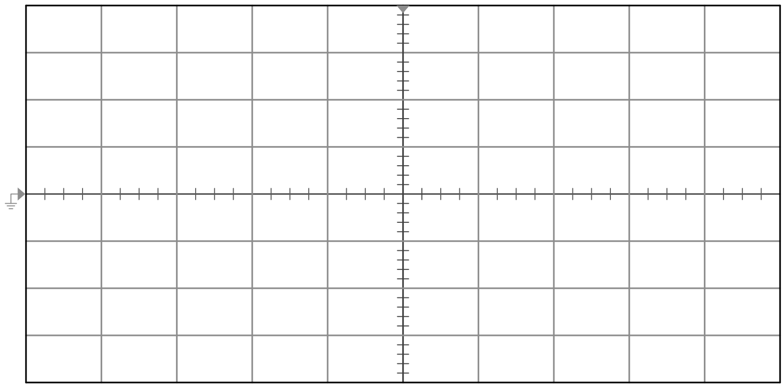


Figure 6.5: Practical differentiator circuit using Op Amp and AC triangle input voltage.

v_{in} (CH1)



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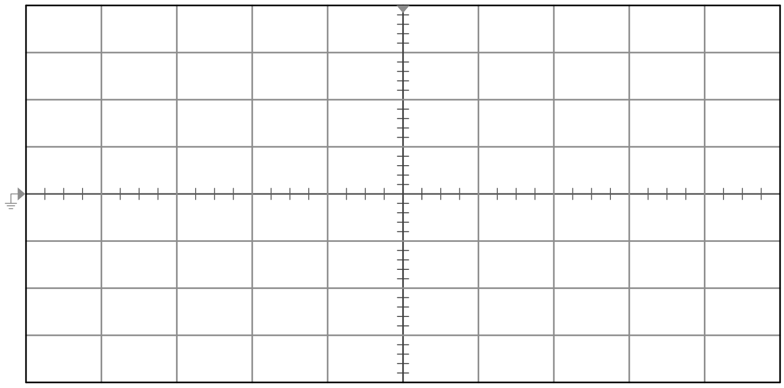
v_{out} (CH2)



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9 What is the noticeable difference between the experimental output signal of the practical Op Amp differentiator and the theoretical output signal?

10 Remove the series resistor R_s and directly connect the input signal v_{in} to the capacitor (i.e. implement a standard Op Amp differentiator). Observe the result and explain what happens to the output signal.

⚠ Please note that the bonus questions below will not be marked. They are intended to deepen your understanding of the topic and should be done only if the rest of the questions (which will be marked) have been completed. These include the questions related to the integrator circuit in the next section.

11 (**Bonus question**) Based on your understanding of capacitor behaviour against sudden voltage changes and the results from the previous question, explain why it is not practical to use the ideal/standard Op Amp differentiator circuit (refer to your answer in Lab 6: Pre-Lab work question **7**), and how adding the series resistor R_s can fix the problem.

12 (**Bonus question**) **Noise** in electrical signals is generally defined as an unwanted and random **high-frequency** signal with **small magnitude** which is mostly generated by electromagnetic interferences. What is the main problem of Op Amp differentiator circuits regarding signals containing electrical noise[1]? How can we reduce the effect of noise in the output of the differentiator by using the series resistor? Provide any necessary explanation and/or formula to support your answer. (**Hint**: Use superposition theorem to explain the effect of noise in the output).

IV. Integrator

13 The circuit shown in Figure 6.6 is the **practical** form of an **Op Amp integrator circuit.** Unlike the standard form of the circuit seen in the lecture, it contains a resistance R_p in parallel with the capacitance C to limit the gain of the integrator at low frequencies.

Build the practical Op Amp integrator circuit shown in Figure 6.6, with $C = 1\ \mathrm{nF}$, $R_1 = 100\ \mathrm{k\Omega}$, and $R_p = 1\ \mathrm{M\Omega}$. Use the signal generator to provide an input voltage v_{in} with **$\mathbf{1\ V}$ peak-to-peak** and a frequency of **$\mathbf{1\ kHz}$**, and select **square wave** output. Supply the Op Amp with $\pm\mathbf{15\ V}$ DC voltage by configuring the DC power supply into **series mode**. Configure the oscilloscope so that the input signal v_{in} is displayed on CH1 and the output signal v_{out} is displayed on CH2. Observe the input and output voltage waveforms and sketch them in the provided space. Clearly **label** the **peak values** and the **fundamental time-period** of the waveforms on the graphs.

[1] In this course we assume ideal Op Amps, which means that their output is independent of input frequency, whereas in practice, Op Amps have a limited bandwidth, meaning that their output can change if the frequency is increased beyond a specific value.

⚠ Make sure to properly connect $+15\,\mathbf{V}$ DC voltage supply to **pin 7** and $-15\,\mathbf{V}$ to **pin 4** according to LM741 layout given in Figure 6.1.

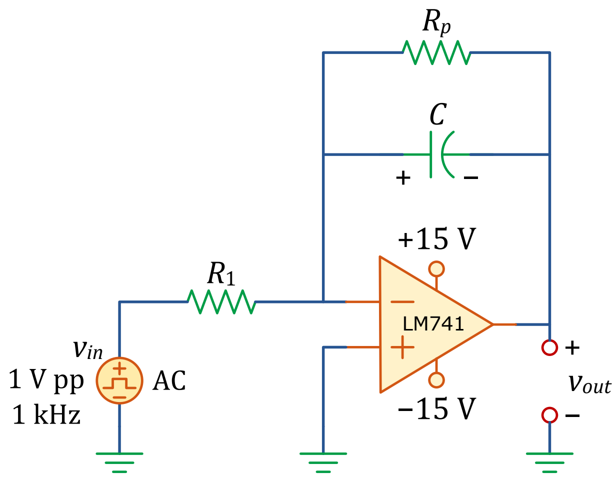
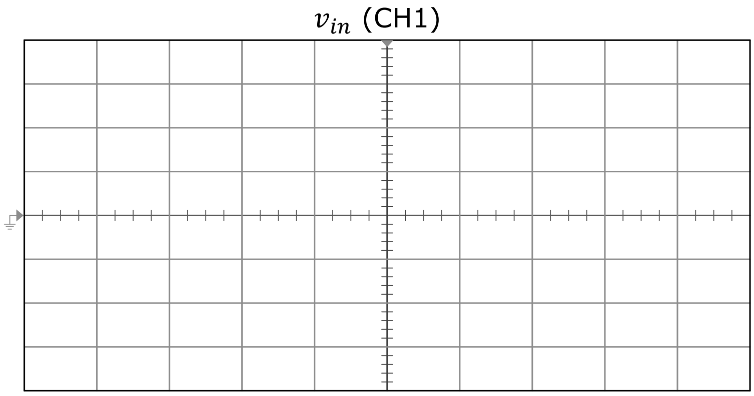


Figure 6.6: Practical integrator circuit using Op Amp and AC square-wave input voltage.



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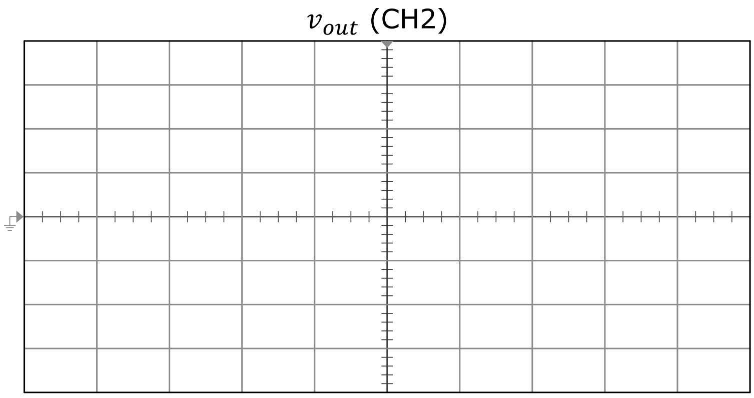

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14 Remove the parallel resistor R_p (i.e. implement a standard Op Amp integrator). Observe the result and explain what happens to the output signal.

⚠ Please note that the bonus question below will not be marked. It is intended to deepen your understanding of the topic and should be done only if the rest of the questions (which will be marked) have been completed.

15 (**Bonus question**) Based on your observation from the previous questions and the behaviour of capacitors against low frequency signals (such as DC signals), explain why it is not practical to use the ideal/standard Op Amp integrator (refer to your answer in Lab 6: Pre-Lab work question **9**), and how adding the parallel resistor R_p can fix the problem.

Lab work 5	Date:	Assessor name and signature:	Mark:

Lab Experiment 7: AC circuits

Aims of this experiment

The aim of this lab experiment is to investigate the following concepts in AC circuits:

1. Frequency-dependent behaviour of RC circuits.
2. RMS value of AC signals.
3. Average power.
4. Maximum average power transfer

Videos and guides for review

List of suggested videos:

Signal generator

Oscilloscope

List of suggested guides from Appendix:

- Signal/Function generator
- Oscilloscope

Lab 7: Pre-Lab work

For your pre-lab work, please answer the following questions **before coming to the lab**.

1 In questions **8** and **9** of "AC voltages and currents" section in Lab Experiment 1, you generated three different AC signals (sinusoidal, square, and triangle waveforms) via the signal generator and measured them using the oscilloscope and the multimeter. You should have noticed that with the multimeter you can directly measure RMS value of AC signals. Using the frequency and amplitude of the signals in question **8** of Lab Experiment 1, calculate their numerical RMS values and compare them with the measured ones in question **9** of Lab Experiment 1. Provide any necessary calculations and sketches of signals.

2 How does frequency affect the impedance of the following elements?

a A resistor

b An inductor

c A capacitor

Explain your answers by providing any necessary equations.

3 Consider the RC circuit given in Figure 7.1. The input voltage v_{in} is a 10 V peak-to-peak sinusoidal with a frequency of 100 Hz. Draw the circuit in the phasor domain and calculate the impedance of the capacitor as well as output voltage v_{out} across terminals *a* and *b*, i.e., $v_{out} = |\mathbf{V}_{out}|\cos(2\pi f + \angle\mathbf{V}_{out})$.

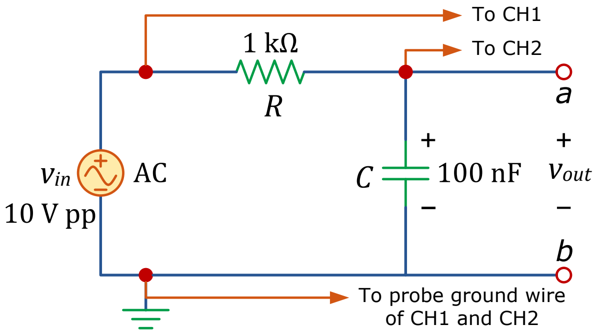


Figure 7.1: AC RC circuit for Pre-Lab 7.

4 How much average power[1] does a $10\text{-}\Omega$ resistor consume when it is connected to a 100-V (rms) sinusoidal voltage source with a frequency of 50 Hz? Explain your answer.

5 How much average power does a 3-mH inductor consume when it is connected to a 100-V (rms) sinusoidal voltage source with a frequency of 50 Hz? Explain your answer.

[1] Please note that in the context of power engineering, if the power supply is an AC source, **the exact term "average power" may not** always be used, and instead it is simply referred to as just **"power"**. You may also see **"active power"** or **"real power"**, but they all mean the same thing, which is **average power for an AC signal**.

6 How much average power is supplied by a 100-V (rms) sinusoidal voltage source with a frequency of $50\ \mathrm{Hz}$ that is connected to a parallel combination of the 10-Ω resistor and 3-mH inductor? Explain your answer.

7 What is the practical meaning of the RMS value in AC analysis?

8 Explain how an AC linear circuit or network can deliver **maximum average power** to an impedance as a load. Sketch any necessary equivalent circuit and provide the maximum average power transfer formula to elaborate your answer (you do not have to prove the theorem).

9 What is the condition for maximum average power transfer if the AC circuit/network is connected to a resistive load?

Pre-Lab 7	Date:	Assessor name and signature:	Mark:

Lab 7: Experimental procedure

Please complete all the tasks given in this section during the lab session. Do not forget to watch the related lab videos and guides that are suggested for this lab experiment.

Required components

In this experiment you will be required to use the following components:

- Your breadboard.
- $1\ \mathrm{k\Omega}$ resistor.
- $100\ \mathrm{nF}$ capacitor.
- $10\ \mathrm{mH}$ inductor.

I. Frequency/Phasor domain analysis of AC circuits

1 Construct the RC circuit of Figure 7.2 on your breadboard. Use the signal generator to provide a **$10\ \mathrm{V}$ peak-to-peak sinusoidal** with a frequency of **$100\ \mathrm{Hz}$**. Use **CH1** of the oscilloscope to measure the input voltage v_{in} and CH2 to measure the output voltage v_{out}. Sketch the waveforms from CH1 and CH2 in the space provided below with at least **2 full periods** of each signal. Compare the theoretical value of v_{out} that you obtained in Pre-Lab 7 question **3** with your measured one from the oscilloscope. Explain any potential discrepancy or difference between the calculated and measured output voltages.

⚠ The source is assumed to be a **sine** function **NOT cosine.** Take this into account.

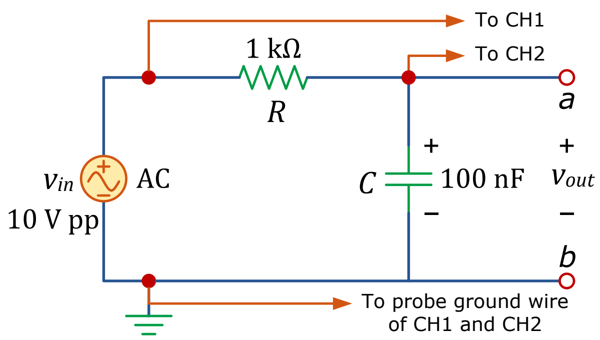
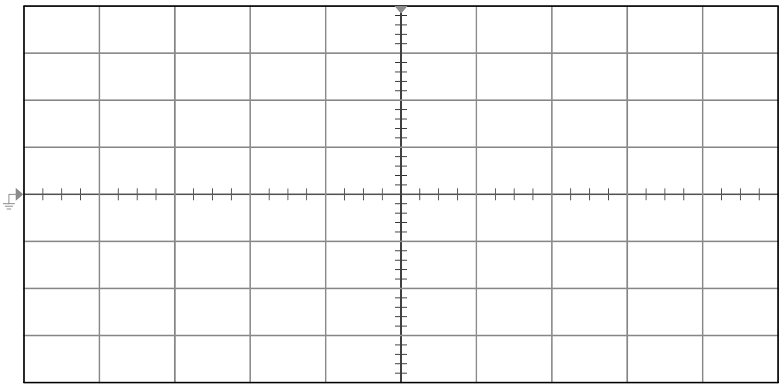


Figure 7.2: RC circuit for frequency/phasor domain analysis.

CH1 and CH2



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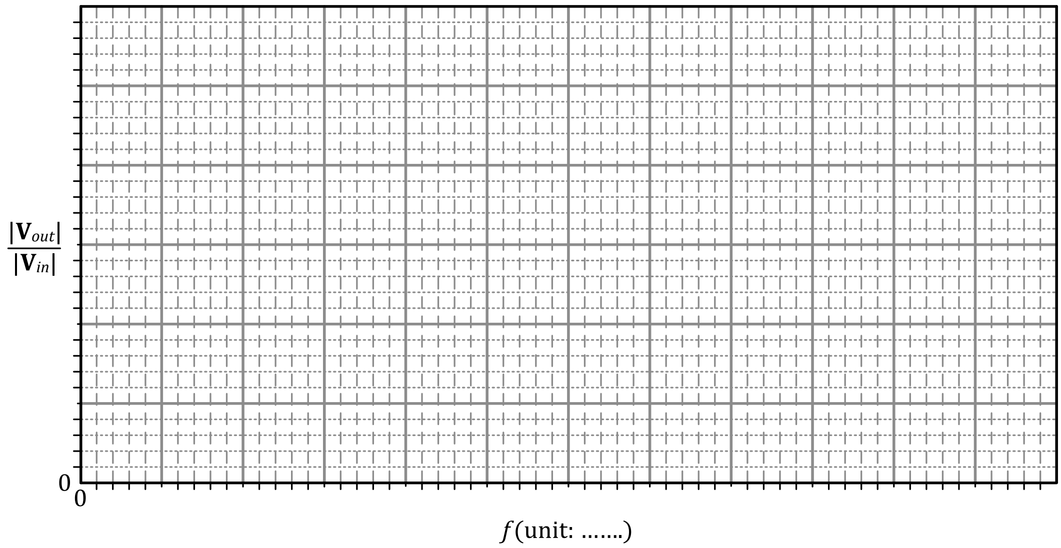
2 Increase the frequency of the signal generator according to the Table below and repeat the measurements looking at the effect on the output waveform.

Frequency	Output voltage magnitude $|\mathbf{V}_{out}|$ (peak-to-peak)	Output voltage phase $\angle\mathbf{V}_{out}$	Frequency	Output voltage magnitude $|\mathbf{V}_{out}|$ (peak-to-peak)	Output voltage phase $\angle\mathbf{V}_{out}$
0 Hz			1.6 kHz		
100 Hz			2 kHz		
400 Hz			2.4 kHz		
800 Hz			2.8 kHz		
1.2 kHz			3 kHz		

3 Explain why the output voltage waveform is changing as frequency increases, particularly the magnitude. What would be one possible practical application of such a circuit based on your observations?

4 Use your measurements in question **2** to sketch the **ratio** of output voltage magnitude to input voltage magnitude $|\mathbf{V}_{out}|/|\mathbf{V}_{in}|$ as a function of frequency in the graph provided. Find an approximate frequency at which the ratio drops by 70.71%, (i.e., $1/\sqrt{2}$ of the maximum value, which is known as **cut-off frequency** f_c) and label it on the graph.



II. AC Power

5 In the RC circuit of Figure 7.2, measure the **RMS values** of the voltages and currents for the resistor, capacitor, and voltage source. Use a sinusoidal input voltage frequency of **100 Hz** with the same **10 V peak-to-peak** amplitude. Which equipment would be suitable to directly measure RMS values? Record your results in the Table below and then find **average power** consumed by each element using your results. Verify the **conservation of energy/power** in AC circuits.

R	Measured value	C	Measured value	v_{in}	Measured value
V_{rms}		V_{rms}		V_{rms}	
I_{rms}		I_{rms}		I_{rms}	
P_{avg}		P_{avg}		P_{avg}	

III. Maximum average power transfer

6 Consider the AC circuit shown in Figure 7.3, where an inductive load is connected to the output terminals *a* and *b*. The inductive load has an unknown load resistance R_L and inductance of $L = 10\,\text{mH}$. Calculate the value of R_L and the source frequency **in Hertz** such that the circuit can deliver **maximum average power** to the inductive load. Then calculate the maximum average power $P_{\max}$.

⚠ Note that the voltage source value is given in **peak-to-peak**, but you need the **magnitude** for average power calculation.

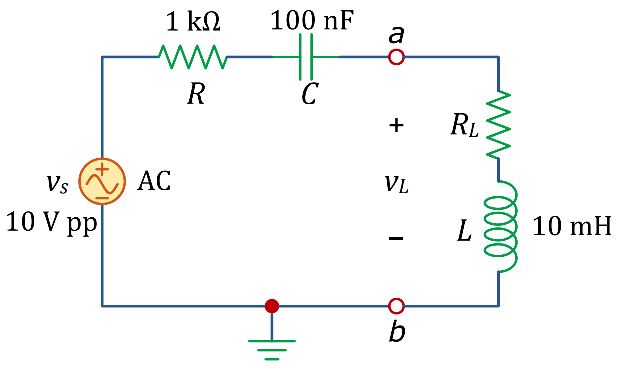


Figure 7.3: AC circuit with inductive load to examine maximum average power transfer.

7 Build the AC circuit of Figure 7.3 and set the signal generator v_s to $\mathbf{10\ V}$ **peak-to-peak sinusoidal** input voltage. Use the frequency and load resistance R_L that you obtained in the previous question. Find the average power consumed by the inductive load using a suitable measurement and compare it with your calculated maximum average power in the previous question. Explain any difference between these values.

⚠ Think of **what** voltage or current you need to measure in the circuit and the **equipment** you have to use to be able to easily determine the average power consumed by the inductive load.

Lab work 7	Date:	Assessor name and signature:	Mark:

Lab Experiment 8: Digital logic circuits

Aims of this experiment

The aims of this lab experiment are as follows:

1. Study the truth tables of various basic logic gates.
2. Verify DeMorgan's theorem.
3. Implement a circuit to control a light.

Introduction: Logical gates ICs

⚠ It is important to verify the **connections** of the specific IC you are using with its datasheet. Figure 8.1 shows the internal pin connections of four most-commonly used digital logic ICs.

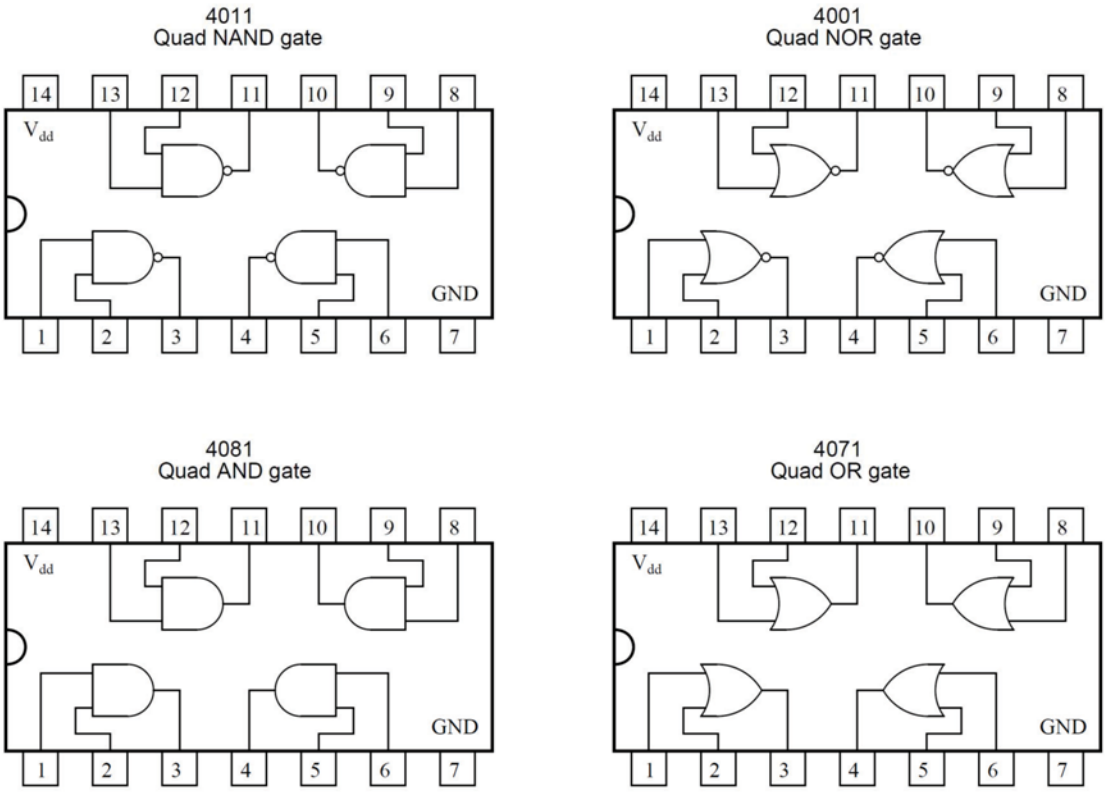


Figure 8.1: Examples of logical gates ICs and their pin connections.

Lab 8: Pre-Lab work

For your pre-lab work, please answer the following questions **before coming to the lab**.

1 Obtain the Boolean expressions and write the Truth Tables for the digital logic circuits shown in Figure 8.2.

2

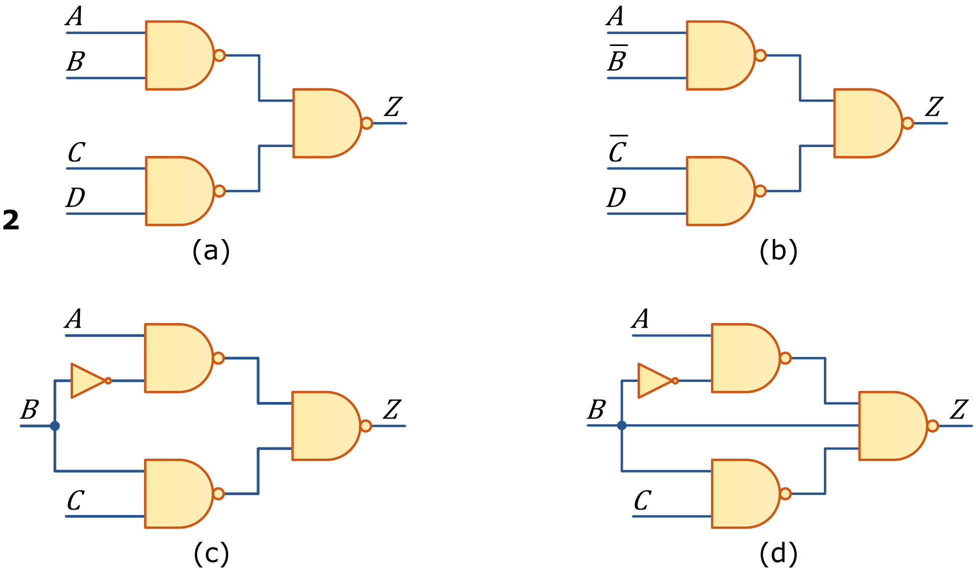


Figure 8.2: Logic circuits for Pre-lab 8.

3 Write the expressions that define DeMorgan's Theorem.

4 Draw the logic gate equivalent circuits for DeMorgan's Theorem expressions.

Pre-Lab 8	Date:	Assessor name and signature:	Mark:

Lab 8: Experimental procedure

Please complete all the tasks given in this section during the lab session.

Required components

In this experiment you will be required to use the following components:

- Your breadboard.
- Multiple digital gates ICs (7408 AND, 7432 OR, 7404 NOT, and 7486 XOR).
- Green/Red-light LED and/or lightbulb.

I. Analysis of basic logic gates

1 Assign lines for the V_{cc} and ground terminals of your breadboard and connect an IC (say 7408). Connect **pin 7** to **ground** and **pin 14** to V_{cc}. Apply suitable voltages to the inputs of the logic gates and measure the output voltage. Write down your results in the Tables below.

⚠ Think about what **voltage levels** should be used to represent **logic 1** and **logic 0** in the practical circuits and set the power supply voltage V_{cc} accordingly. You only need to use one of the logic gates in each IC to run this experiment.

Gate: 7408 **AND**

Input A	Input B	Output Z

Gate: 7432 **OR**

Input A	Input B	Output Z

Gate: 7404 **NOT**

Input A	Output Z

Gate: 7486 **XOR**

Input A	Input B	Output Z

II. Verifying DeMorgan's Theorem

2 Build the logic gate equivalent circuits for the DeMorgan's Theorem expressions you drew in question 4 of Lab 8: Pre-Lab work on your breadboard. Apply **logic 1** and **logic 0** voltages to their inputs and measure their outputs for all four logic circuits to verify DeMorgan's Theorem. Write down your measurements in the Tables below.

DeMorgan's Theorem - **First** rule

Logical expression:		
Input A	Input B	Output Z

Logical expression:		
Input A	Input B	Output Z

DeMorgan's Theorem - **Second** rule

Logical expression:		
Input A	Input B	Output Z

Logical expression:		
Input A	Input B	Output Z

III. Logic Circuits

3 You are going to build and test a circuit designed to control one light. The light has **three control switches** *A*, *B*, and *C*. The circuit must be designed based on the following logic:

- **a** If *C* is OFF, then the light is OFF.
- **b** If *C* is ON, then the light should be ON if:
  A is ON **and** *B* is OFF **or** *A* is OFF **and** *B* is ON.
- **c** If *C* is ON, then the light should be OFF if:
  A is ON **and** *B* is ON **or** *A* is OFF **and** *B* is OFF.

Using the above rules, complete the Truth Table given below for this logic circuit.

Input A	Input B	Input C	Output Z

4 Design and draw a logic circuit that operates based on the above Truth Table.

5 Implement the logic circuit you designed in the previous question using the logic ICs.

⚠ Ask one of the lab demonstrators to check and confirm the operation of your circuit.

Lab work 8	Date:	Assessor name and signature:	Mark:

Appendix: Laboratory equipment

Prototyping board (Breadboard)

The prototyping board gives the circuit designer a convenient base on which to construct circuits. The holes are set at 2.54mm intervals and are compatible with the pin spacings on integrated circuits. Inter-component wiring is achieved through the conductors that are already built into the layout of the board. The holes readily accept integrated circuit pins and leads from low-power diodes, 1/4 W resistors and small capacitors. However, if difficulty is experienced with larger diameter leads, solder a smaller diameter lead onto it for use instead.

Although several manufacturers make these boards, they will all have the same general characteristics and layout as illustrated in Figure A.1.

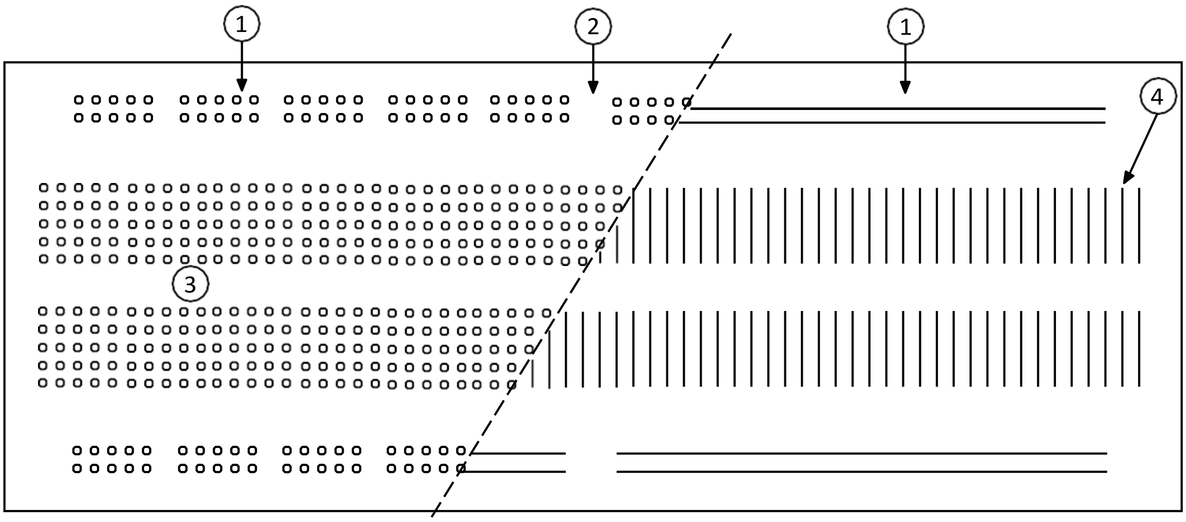


Figure A.1: The layout of the Prototyping Board, showing the hole placings on the left and inter-connecting conductors on the right of the figure.

Features of the prototyping board

These features are described in terms of the numbers shown on the board that is illustrated in Figure A.1.

1. There are two rows of connections 1 across the top and bottom of the board. These are useful for power supply leads, earth lines and other connections that are required along the length of the board.
2. Note the gap 2 at the centre of these rows of holes. Use a wire bridge if you want the line to pass right across the board.
3. The gap 3 across the centre of the board is suitable for inserting integrated circuits with the two rows of pins on opposite sides of the gap.
4. On each side of the centre gap 3, the holes are connected in groups of five at right angles to the gap 4.

Breadboard/Prototyping board

Suggestions for using the board

Consider if you want to build a simple circuit as shown in Figure A.2.

- Use the upper and lower rows of holes for power supply and earth connections.
- Keep the component leads short. Long leads may touch and give short circuits. Circuit construction is easier to follow later if neat wiring is used in the first place.
- Insert the components gently but firmly and vertically into the holes on the board. Use your small pair of long-nose pliers to insert the components. A positive electrical contact must be made and maintained with the conductors beneath the holes.
- Arrange the layout of the components on your board to be similar to that of your circuit diagram, e.g.

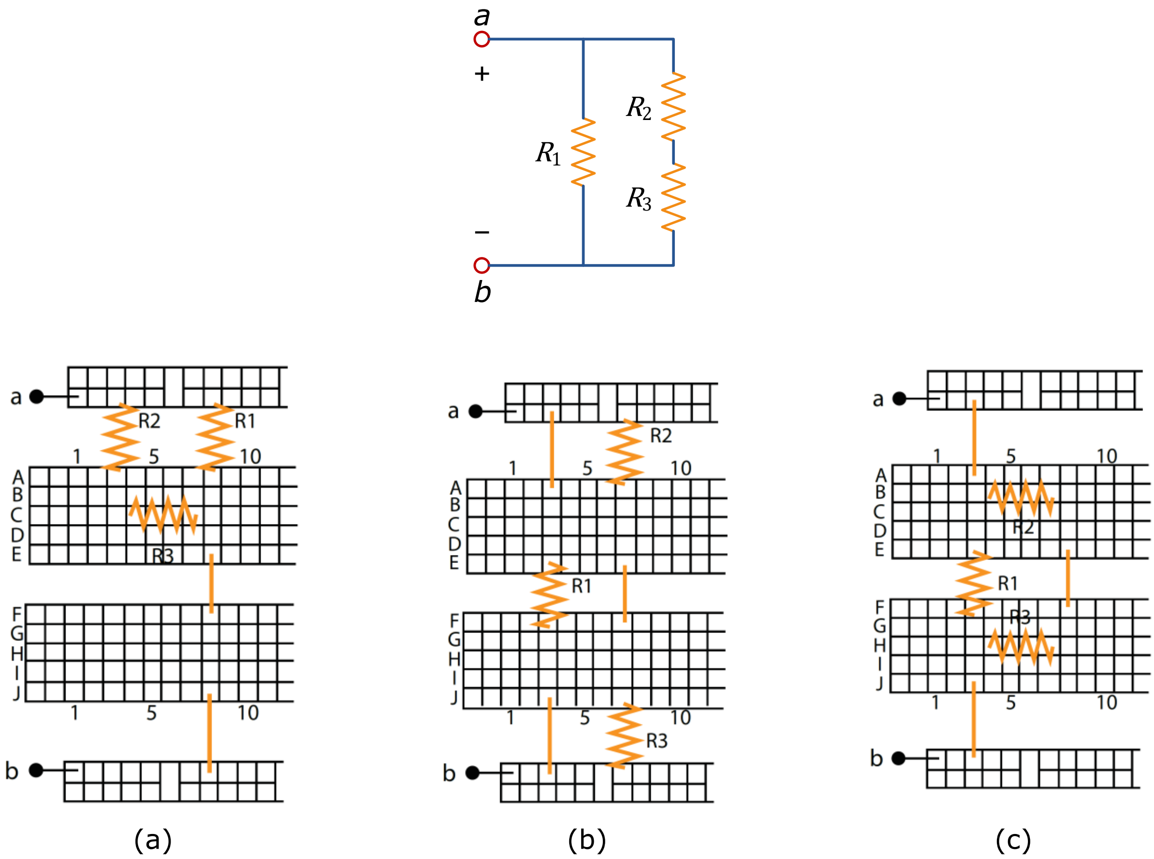


Figure A.2: Circuit diagram with equivalent breadboard layouts. Case (b) shows a preferred layout that reflects the circuit diagram on the board.

Resistor colour coding

The ordinary carbon composition fixed resistors that we use in the laboratory are characterized by three quantities,

1. Their **resistance** value in ohms, (Ω),
2. Their **tolerance** as a percentage (%) and
3. Their **power dissipation** in watts (W).

The power dissipation capability is determined mainly by the physical size of the resistor. General purpose resistors with $1/4$ W dissipation will be used unless a higher power rating is required.

The nominal value for the resistor and its tolerance are described by the colour bands on the resistor as shown in Figure A.3. Normally, there will be four bands on each resistor placed towards one end of the resistor (if there is enough room). Commencing with the band closest to a lead of the resistor, the interpretation of each band is given in the Table below.

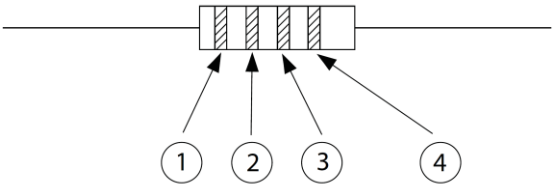


Figure A.3: Colour code bands on a resistor.

Band / Colour	First single digit 1	Second single digit 2	Multiplier 3	Tolerance (%) 4
Black		0	$10^0=1$	
Brown	1	1	$10^1=10$	1
Red	2	2	10^2	2
Orange	3	3	10^3	3
Yellow	4	4	10^4	4
Green	5	5	10^5	
Blue	6	6	10^6	
Violet/Purple	7	7	10^7	
Grey	8	8	10^8	
White	9	9	10^9	
Gold			0.1	5
Silver			0.01	10
No colour				20

It is important that you know how to use this table, and with practice, you should remember the numerical value assigned to each colour. The first two bands give the significant digits of the resistance value (the second digit may be zero) while the third band gives the exponent for the multiplying power of ten, i.e. the third band tells you how many additional zeroes must be added to the significant digits. The fourth band gives the tolerance or range in which an actual resistor may be found with respect to its nominal value. Most resistors used in the laboratory have gold ($\pm$5%) for this tolerance band. A 20% tolerance is assumed if the fourth band is missing. Below are some examples to see how the resistance is obtained using the colour band readings.

Resistor	Band 1	Band 2	Band 3	Band 4	Resistor value
R_1	Brown	Red	Black	Gold	$12 \times 10^0 = 12\ \Omega \pm 5\%$
R_2	Red	Violet/Purple	Brown	Gold	$27 \times 10^1 = 270\ \Omega \pm 5\%$
R_3	Orange	While	Orange	Red	$39 \times 10^3 = 39\ \mathrm{k}\Omega \pm 2\%$

A much better representation of resistance colour bands is illustrated in Figure A.4.

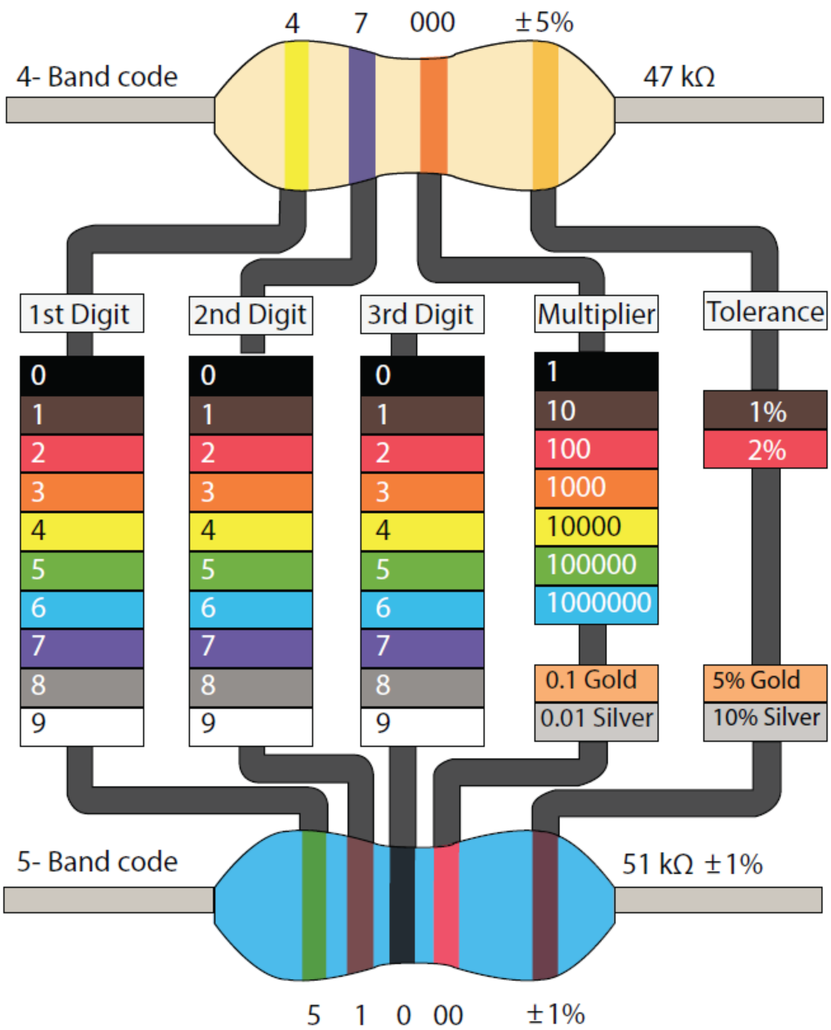


Figure A.4: Colour code bands on a resistor.

There is a compromise in selecting the values for any store of resistors that are kept in the laboratory. It is desirable to cover all resistance values, say from 1 Ω to 10 MΩ, with the lowest tolerance affordable. In our laboratories the resistors generally have a tolerance of ±5%. To maintain stock at a reasonable level we do not keep all resistors from the 5% range, preferring instead to omit every second value and retaining the values that would be kept in a complete 10% range. What is the 10% range of resistors?

Consider the 150 Ω resistor. If this resistor has a tolerance of ±10%, i.e. ±15 Ω, then its actual value may lie anywhere within the range 135 Ω to 165 Ω. Now consider the 180 Ω ±10% resistor which will have a value between 162 Ω and 198 Ω. You will see that any resistance value between 150 Ω and 180 Ω is within 10% of a **preferred value**.

Most of your electronic circuit designs will use preferred value resistors given in the next table, unless a precise value of resistance is required.

PREFERRED VALUE RESISTORS in Ohms (Ω)												
1	1.2	1.5	1.8	2.2	2.7	3.3	3.9	4.7	5.6	6.8	8.2	10
10	12	15	18	22	27	33	39	47	56	68	82	100
100	120	150	180	220	270	330	390	470	560	680	820	1k
1 k	1.2 k	1.5 k	1.8 k	2.2 k	2.7 k	3.3 k	3.9 k	4.7 k	5.6 k	6.8 k	8.2 k	10 k
10 k	12 k	15 k	18 k	22 k	27 k	33 k	39 k	47 k	56 k	68 k	82 k	100 k
100 k	120 k	150 k	180 k	220 k	270 k	330 k	390 k	470 k	560 k	680 k	820 k	1 M
1 M	1.2 M	1.5 M	1.8 M	2.2 M	2.7 M	3.3 M	3.9 M	4.7 M	5.6 M	6.8 M	8.2 M	10 M

Digital multimeter

Introduction

Multimeters are indispensable measurement tools that allow you to accurately measure currents and voltages, both DC and AC, and resistance. The digital multimeter that you will use in the laboratories is the GWInstek GDM-8245. It is shown in Figure A.5. The multimeter connects to your circuit via banana cables, using the ports on the front panel.

Multimeter

Figure A.5: Front panel of multimeter GWInstek GDM-8245.

Measuring Voltage

The procedure for taking a voltage measurement is as follows:

1. Plug a red banana cable into the red topmost port marked V - Ω.
2. Plug a black banana cable into the black port marked with a ground symbol. Reserving black for ground connections is good practice.
3. Press the DCV button if you want to take a DC measurement, or the ACV button if you want to take an AC measurement.
4. Press [AUTO/MAN] button for manual or auto-ranging selection. If you choose manual selection, press [▲] or [▼] to the desired range (if you have no idea about the value of input, it is recommended that you start at the highest range).
5. Connect the red cable to the positive measurement point in your circuit, and the black cable to the negative measurement point in your circuit.

Measuring Resistance

To measure resistance:

1. Plug a red banana cable into the red topmost port marked V - Ω.
2. Plug a black banana cable into the black port marked with a ground symbol.
3. If the resistor you are measuring is in a circuit, take it out.
4. Connect the cables across the resistor and press the Ω button.
5. Press [AUTO/MAN] button for manual or auto-ranging selection. If you choose manual selection, press [▲] or [▼] to the desired range.

Measuring Current

Since current is measured in series, make a break in your circuit, and bridge the gap through the multimeter. Current is measured using the current ports and the black port marked with a ground symbol.

You will not often be measuring any significant amount of current, hence you should use the current port marked "2 A". For future use, if you have no idea about the value of input current, it is recommended that you start with the highest range port (marked "20 A"). This is particularly important, since applying a higher current than the selected range will blow the protection fuses in the device. If the current is less than 2 A, change to the lower range port (marked "2 A") to increase the precision.

1. Plug a red banana cable into the middle red port marked "2 A".
2. Plug a black banana cable into the black port marked with a ground symbol. Reserving black for ground connections is good practice.
3. Press the DCA button if you want to take a DC measurement, or the ACA button if you want to take an AC measurement.
4. Press [AUTO/MAN] button for manual or auto-ranging selection. If you choose manual selection, press [▲] or [▼] to the desired range (if you have no idea about the value of input, it is recommended that you start at the highest range).
5. Connect the multimeter in series with the element whose current you need to measure. Current flowing into the multimeter through the red cable will be measured as positive.

RMS Measurements

When you measure AC signals with the multimeter, the reading you get is the RMS value of the signal. In fact, the benchtop multimeters in the laboratories are true RMS meters, which means that the RMS value of the signal is calculated accurately from digitally sampled readings. In cheaper or older multimeters, the signal is assumed to be purely sinusoidal, and hence the RMS value is computed by multiplying the average value by a correction factor. This method works well if the signals you are measuring are sinusoidal, but produces incorrect readings for other kinds of signals, or if there is a significant amount of noise present in the signal.

The AC+DC button is used to set the AC/DC coupling of the RMS measurements. If any DC is present in the input signal, it will be included in the RMS measurement given by the multimeter.

DC power supply

The purpose of the first part of this section is to point out some of the general features of a power supply. Then, the specific characteristics of the DC power supply used in the laboratory will be explained.

Battery

A battery is a source of electricity that gives a constant DC voltage, where DC (direct current) means that the current produced by the source does not change its direction with respect to time. Remember, **a battery has two terminals, but no earth** (see Figure A.6).

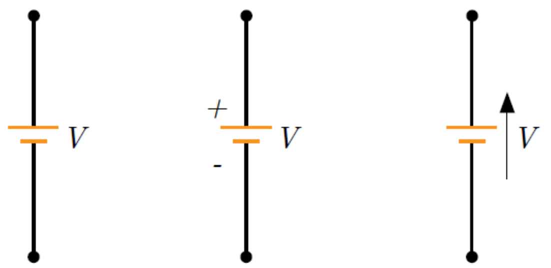


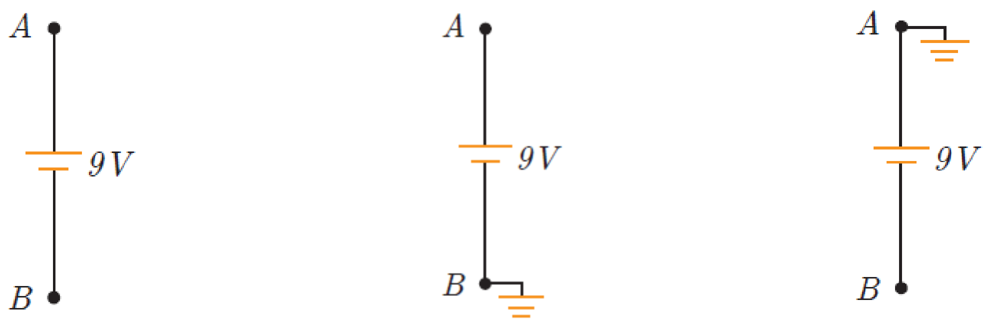
Figure A.6: Circuit symbols and equivalent notations for a battery.

Voltage conventions

A voltage with a single subscript specifies the potential of the subscripted point in the circuit with respect to earth. Thus, V_A specifies the potential of A with respect to earth and V_B specifies the potential of B with respect to earth. A voltage with a double subscript, for example V_{AB}, specifies the potential difference between A and B. The potential difference is the potential of the first subscripted point with respect to the second point. Thus $V_{AB} = V_A - V_B$.

If the negative (−) or the positive (+) terminal of a battery (not both) are connected to earth, then the battery is said to be **EARTHED**. A battery which is not earthed gives a **FLOATING** voltage and is known as a floating battery.

The example in Figure A.67 shows three different configurations of a 9-V battery. The corresponding voltages are shown in the Table below, to help you better understand the concept of floating and earthed battery.



(a) (b) (c)

Figure A.7 Voltages and potential differences for three battery configurations.

Battery / Voltage	(a)	(b)	(c)
V_A	? (floating)	9 V	0 V
V_B	? (floating)	0 V	−9 V
V_{AB}	9 V	9 V	9 V

Power Supply

This section will explain how to use the dual-output benchtop DC power supply. The one that you will use in the laboratories is the GWInstek GPE-3323, shown in Figure A.68.

Power supply

Figure A.8: Control panel of benchtop power supply GWInstek GPE-3323.

The supply has two variable outputs, Channels one (CH1) and two (CH2), as well as a third fixed 5-V output (CH3). Note that each output has its own set of controls (see Figure A.68).

To set the output voltage of one of the channels, turn the corresponding 'VOLTAGE' knob and watch the voltage readout until it settles on the desired voltage.

Along with this, you also need to set the current limit by increasing the "CURRENT" knob. The current limit is the maximum current allowed to be delivered to the circuit, with the purpose of protecting it from harmful effects due to a short-circuit or similar problem. If too much demand is placed on the power supply, and you attempt to draw more current than what is set by the current limit, the supply enters constant current mode, and the CC indicator LED will come on.

The power supply can be operated in three different modes, and each mode changes the way both channels behave. You can change the mode by using the two mode select switches on the top right corner of the power supply.

Independent Mode

In independent mode, the two supply channels are operated completely independently. Figure A.9 shows how the supply voltages are taken at the output posts. V1 and V2 can be set from 0 to 32 V independently. Adjusting the current knob for either channel sets the current limit for that channel alone.

⚠ Notice that the green GND earth connection is physically isolated from the positive and negative output posts and connected to the metal case of the power supply, and to the building earth, as shown in Figure A.69. The circuits you build should not require the use of this terminal.

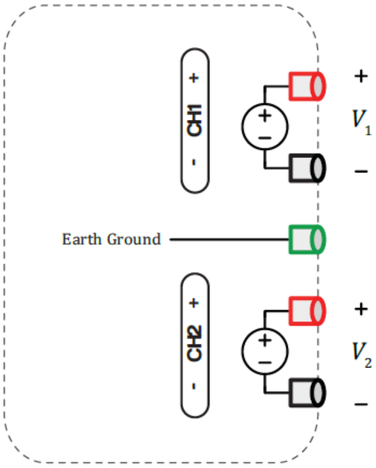


Figure A.9: Simplified diagram of the power supply acting in independent mode.

Series Mode

When in series mode, the positive (red) terminal of channel two is connected to the negative (black) terminal of channel one, as shown in Figure A.100. In this mode, the voltage setting for channel two (the slave) will mimic the setting for channel one (the master). This means that the voltage V1 appears on both channels, creating a virtual ground in the middle. The voltage at the positive terminal of channel one will be at V_1 V, whilst the voltage at the negative terminal of channel two is $-V_1$ V.

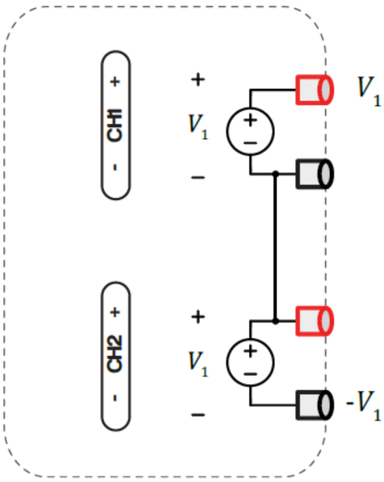


Figure A.10: Simplified diagram of the power supply whilst acting in series mode. Earth GND has been omitted.

⚠ Series mode is useful when you need to power an op-amp with **both positive** and **negative supplies**, and also provide the circuit with a ground (0 V). The overall output current will be limited by the lowest set current knob. You can also use this mode when you need to **increase the range of output voltage** provided to your circuit **beyond the limit of each channel** (up to double the limit, i.e., 64 V).

Parallel Mode

While in parallel mode, both positive terminals, and both negative terminals, are connected together, as shown in Figure A.111. This allows you to supply twice the maximum current to your circuit, for a total of 6 Amps of current.

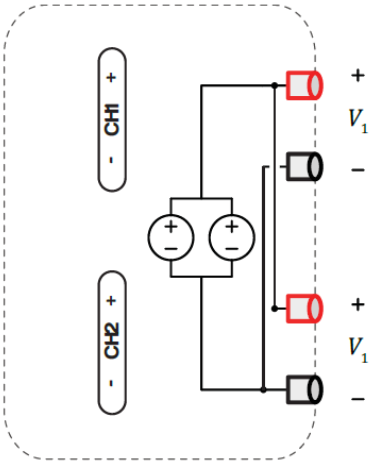


Figure A.11: Simplified diagram of the power supply when it is acting in parallel mode. Earth GND has been omitted.

⚠ Parallel mode is useful when you need to **increase the range of output current** provided to your circuit **beyond the limit of each channel** (up to double the limit, i.e. 6A).

Signal/Function generator

The signal generators in the labs can provide sine, triangle and square waves at frequencies from 0.5 Hz to 5 MHz. The one that you will use is the GWInstek GFG-8250A, shown in Figure A.12.

Figure A.12: The interface of the signal generator.

Signal generator

Using the Signal Generator

The frequency of the output signal is displayed on the six-digit LED display on the top left of the control panel. To adjust the frequency, first press the frequency decade selection button corresponding to the order of magnitude required. Then use the frequency adjustment knob to tune the generator to the desired frequency. You can change the function type using the buttons indicated by "Function Type" in Figure A.13.

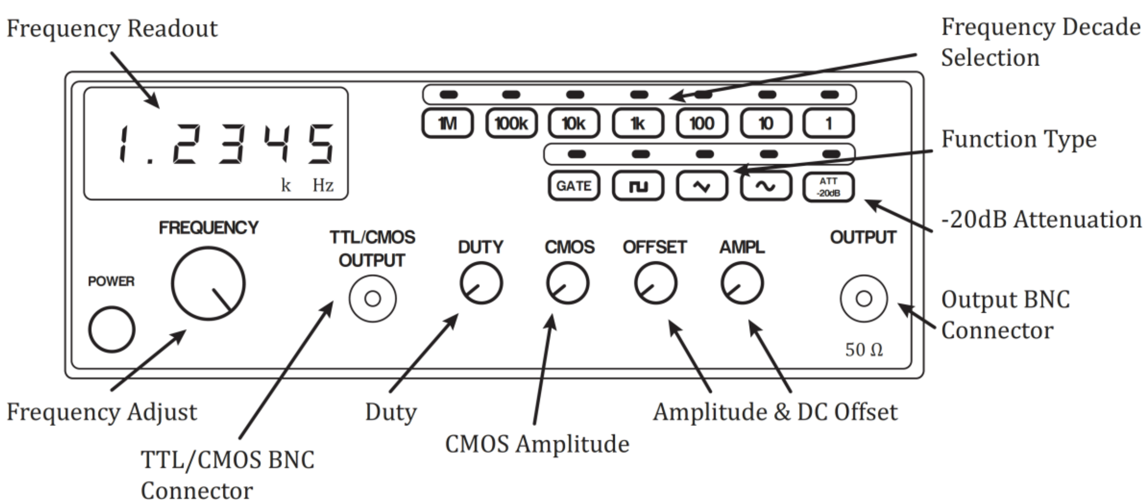


Figure A.13: The control panel with the functionality of each control labelled.

There are four smaller knobs used to further adjust the output signal, labelled "DUTY", "CMOS", "OFFSET" and "AMPL". The black text next to these adjustments is applicable when the knobs are in the pushed-in position, and the orange text is applicable when the knobs have been pulled outwards. The amplitude knob changes the amplitude of the output signal. The maximum amplitude the function generator can provide is 10 V. If you need a very low voltage signal, you can use the -20dB button to attenuate the signal further. If you require a DC offset in your signal, pull out the DC offset knob and adjust accordingly. To adjust the duty cycle of the waveform, pull out the "DUTY" knob and adjust accordingly.

The signal generator connects to your circuit from the output connector on the right side of the control panel using a BNC cable. The other BNC connector is used for the TTL/CMOS output.

Using the wrong BNC connector is a common mistake in the labs.

TTL/CMOS Output

The other BNC connector labelled "TTL/CMOS OUTPUT" provides a clock (square wave) output at the currently selected frequency, for circuits containing TTL or CMOS family logic. If the "CMOS" knob is pushed in, the function generator is set to output a TTL compatible clock signal. TTL Logic operates on 0/+5V, so when the output is set to TTL, a 0-5V square wave is provided. If the knob labelled "CMOS" is pulled out, it can be adjusted from 0 to +15V; as a range of logic voltage levels can be used with CMOS logic.

Oscilloscope

Introduction

The oscilloscope is one of the most important tools you will use in these labs, and your career as an electrical engineer. Oscilloscopes allow you to inspect circuit voltages as they vary over time, and measure just about everything you wanted to know about them, from their average value to their frequency. Almost all oscilloscopes have two input channels, allowing you to plot two signals together so that you can compare them. The oscilloscope display is broken up into a number of horizontal and vertical divisions, marked by the dotted lines on the display.

The oscilloscope that you will use in the laboratories is the Keysight DSOX1102A. It is a dual-trace oscilloscope that can display two independent voltage waveforms as a function of time.

The oscilloscope, as any other piece of measuring equipment, should not change the operation of your circuit or any of the voltages in it.

⚠ The oscilloscope can only measure directly the *potentials* of the signals with respect to earth and **not the potential difference** between any two general points in a circuit. It is however capable of monitoring two signals at the same time and, by subtracting one signal from the other, a potential difference can be measured.

Oscilloscope

Oscilloscope Layout

The DSOX1102A oscilloscope front panel is shown in Figure A.14.

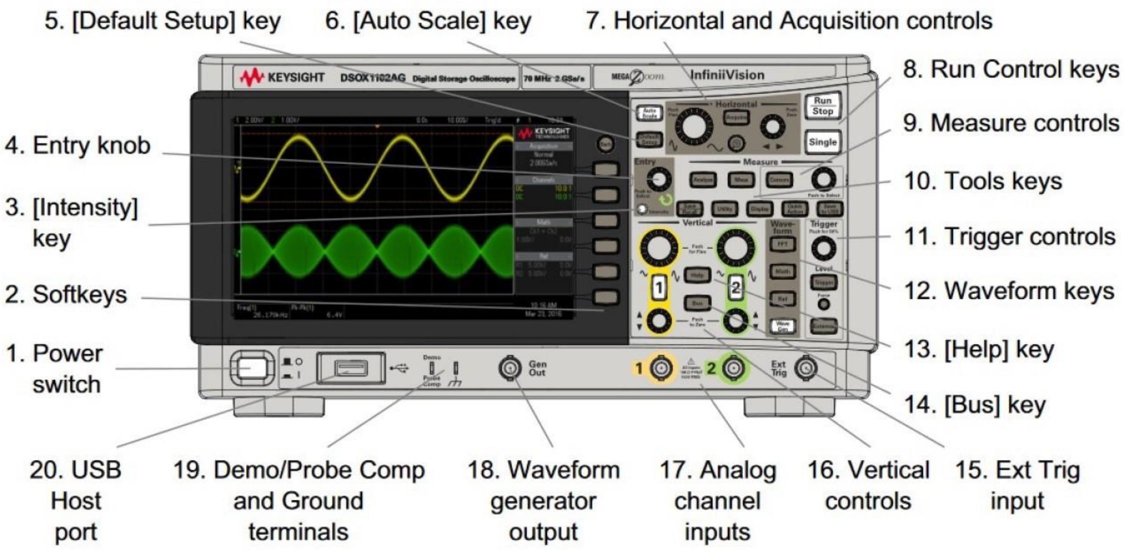


Figure A.14: The DSOX1102A oscilloscope front side.

Function of Oscilloscope Knobs

Carefully examine the front panel of the oscilloscope and make sure you identify all the knobs and their functions:

Horizontal	Large knob	Horizontal time scale - Timebase
	Small knob	Horizontal position
Vertical	Large knob 1	Vertical scale CH 1
	Small knob 1	Vertical position CH1
	Large knob 2	Vertical scale CH 2
	Small knob 2	Vertical position CH2
Trigger	Small Knob	Trigger Level
	Entry Knob	Value selection

Horizontal Controls

The Horizontal Position knob controls the horizontal (or X) position of the waveform on the screen and may be used to align the waveform as you wish with the screen graticule. Turn it left and right to see its effects, but initially leave it near the centre of its travel. Clicking the offset knob inwards sets the offset back to zero.

The Horizontal Scale - Time Base (TIME/DIV) knob determines the sweep rate across the screen and is given as a time per division for the horizontal display. For example: a waveform is displayed on the oscilloscope with a scale set at 0.5ms/div. If the period of the waveform is found to be 4 divisions, then the period is $4 \times 0.5 = 2.0$ ms. The frequency of the waveform is given by the reciprocal of the period, that is frequency = 1 / 0.002 = 500Hz. As mentioned previously, the oscilloscope should not affect your circuit and does not change the time or voltage of the signal that it measures. If the switch is changed from 0.5ms/div to 1ms/div, the waveform will now be 2div long (2div × 1ms/div = 2ms). The symbols under the knob indicate that this control has the effect of spreading out or zooming in on the waveform using the horizontal scale. Push the channel's horizontal scale knob to toggle between fine and coarse adjustment.

Vertical Controls

The Vertical Position knob controls the vertical (or Y) position of the waveform. Clicking the offset knob inwards sets the offset back to zero.

The Vertical Scale - (VOLTS/DIV) knob determines volts/div for the vertical axis of the display. Push the channel's vertical scale knob to toggle between fine and coarse adjustment.

Channel Coupling

Push the “1” button under the vertical scale knob. This will display the menu for Coupling, Channel bandwidth limit, Vertical scale fine adjustment, Channel Invert and Channel Probe. The coupling menu determines if the DC component of the signal will be displayed on the screen.

DC: All components of the signal (that is, DC and AC) are displayed on screen. Note that **DC** does not mean that this position is to measure DC only. *Generally, this is the setting to use.*

AC: The DC component of the input signal is decoupled (that is, blocked off) by a large internal capacitor, leaving the signal AC component only. Also, signals slower than 10Hz are attenuated. AC coupling is sometimes called capacitive coupling, because a capacitor is added in series with the measurement to achieve the DC blocking required. AC coupling is useful when you need to study a small AC signal superimposed on a large DC voltage.

Channels Inputs

The oscilloscope resistance at the input socket is 1 MΩ. This is in parallel with ≈16 pF input capacitance for the oscilloscope. Depending on the magnitude of the circuit components, either or both the resistance and capacitance may affect the circuit being examined. The maximum allowable input voltage is 150 V RMS. For any high voltage measurements, be sure about your equipment capabilities *AND your safety procedures*.

Triggering the Oscilloscope

The trigger defines when the acquisition system begins acquiring, which means that it defines what is displayed on screen and what data is available to make measurements on.

The trigger level is simply adjusted with the trigger level knob. There are two different modes (sweep modes) the trigger can operate in. Each mode changes what the oscilloscope does once a trigger condition occurs.

Normal Mode: Triggers and acquisitions only occur when the specified trigger conditions are found. Once a trigger condition is met, the oscilloscope graphs a single time period and leaves this on the display until another trigger condition is met. Once the new trigger event occurs, the oscilloscope graphs the signal again. Periodic waveforms will appear stationary, because they will cross the trigger level at routine intervals.

Auto Mode: If the specified trigger conditions are not found, triggers are forced, and acquisitions are made so that signal activity is displayed on the oscilloscope.

If the oscilloscope does not trigger, you can press [Force Trigger] to trigger on anything and make a **single acquisition.** This is useful for catching infrequent or non-periodic events. You can also force a **single acquisition** by pressing the **[Single]** key in the top right corner of the Oscilloscope front panel (note that the key will be yellow until the oscilloscope triggers).

Measuring Waveforms

Once your waveforms are scaled and triggered appropriately, you can configure the oscilloscope to perform measurements using the ‘Meas’ button in the Measure control. You can change the source you are measuring by pressing the ‘Type’ option when the measure menu opens. Selecting ‘Voltage’ allows you to display peak voltages, RMS and average values, percentage overshoot and more. Selecting ‘Time’ allows you to measure the frequency, duty cycle and many other time-related properties of the waveform.

It is important to realise that the measurements and their accuracy depend on the degree to which the signal is present on the screen. If you wanted to measure the amplitude of a sine wave accurately, you should scale the waveform so that it fills the display, without clipping at the top.

You can measure a waveform quickly using the *Volts/div* setting of the X and Y Axis and the boxes in the screen of the Oscilloscope. However, to achieve accurate measurements, the Oscilloscope provides cursors, which are enabled by pressing the "Cursors" button in the Measure control.

Cursors are horizontal and vertical markers that indicate X-axis values (usually time) and Y-axis values (your voltages or currents) on a selected waveform source.

The cursor measurement has three modes: Manual, Track Waveform and Measure.

- **Manual**
  In this mode, the screen displays two parallel cursors. Move the cursors to make custom voltage or time measurements of the signal. Use Cursors knob to select and adjust.
- **Track Waveform**
  In this mode, the screen displays two cross cursors. The cross cursor sets the position on the waveform automatically.
- **Measure**
  In this mode, cursors show locations used for the most recently added measurement.

When using the cursors, you can get measurements by:

- Position of Cursor A (Time cursor centered on the midpoint of screen; Voltage cursor centered on channel ground level).
- Position of Cursor B (Time cursor centered on the midpoint of screen; Voltage cursor centered on channel ground level).
- Read the horizontal space between Cursor A and B (ΔX): Time between cursors, units in seconds.
- ($1/\Delta X$), units in Hz, kHz, MHz, GHz.
- Vertical space between cursor A and B (ΔY): Voltage between cursors, units in V.

Some Other Facilities

Compensate Passive Probes

How do you know that your oscilloscope is not faulty? You could

(a) ask the tutor;

(b) try another oscilloscope;

(c) test it;

(d) none of the above.

On each occasion that you use an oscilloscope, **the answer must be (c)**. This can be done, because in most oscilloscopes there is a probe compensation socket or terminal (see number 19 in Figure A.14) which generates a known waveform at a specified voltage and frequency. If you observe your oscilloscope carefully, you would find the peak-to-peak value of the voltage for a square wave. You can use this signal to test your oscilloscope, both Channel 1 and Channel 2. Should your oscilloscope not read the voltage specified by the compensation output, it is out of calibration and it needs to be calibrated (see Figure A.15).

⚠ It is a good habit to test your oscilloscope before taking your measurements, otherwise you may have to repeat all your measurements should your oscilloscope be out of calibration.

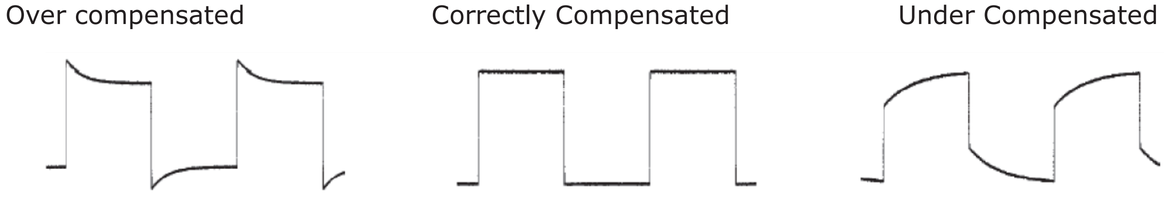


Figure A.15: Proper Calibration.

<u>Mains Ground Input</u>

The oscilloscope amplifiers are CONNECTED INTERNALLY to the mains earth of the power point, as is the chassis-frame of the oscilloscope. When the oscilloscope leads are plugged into the Channel 1 and Channel 2 sockets, all the black crocodile clips or hooks, but not the probe, are also connected internally to earth.

⚠ **Important: There must be only one earth in your circuit.**

All the earth leads from the oscilloscope must be connected to the one point in your circuit, where the earth symbol is shown. The terms "Floating" and "Earthed" may be confusing and should be clearly understood. Refer to the notes on DC power supply, for more information.