ELEC1111 – Electrical Circuit Fundamentals

School of Electrical Engineering and Telecommunications

UNSW SYDNEY

Contents

Preface

How to use and navigate this manual

It is advised to download a digital copy of this manual on a personal device (e.g., laptop, tablet) that allows you to make annotations on it. For the duration of the term, you should use this copy to **submit the results** of your experiments (both analytical and practical parts) during the lab session and **get them marked off** by a lab demonstrator.

Answer boxes

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

Demonstrator checkpoints

When you come across either of the following checkpoints, you need to ask a lab demonstrator to assess your results and record your mark on your marking slip.

Check Point 1: Please ask a lab demonstrator to check your work before proceeding. You may continue working on the rest of the lab procedures while waiting for demonstrators.

Check Point 2: Please ask a lab demonstrator to check your work before proceeding. You may continue working on the rest of the lab procedures while waiting for demonstrators.

Video resources

When you come across the following icon, you will be linked to a video that demonstrates aspects of the operation of the laboratory equipment.

Topic of the video

It is important to familiarise yourself 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 ELEC1111 Electrical Circuit Fundamentals from a wide range of disciplines and laboratory experience. It is one of the aims of this course that all students develop confidence in individual work in a laboratory environment. This is not difficult if electronics has been a hobby before coming to UNSW. 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.

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

Make life easier for yourself; read ahead and get a feel of what is required in each lab. Also, keep in mind that the analytical part of each lab is 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.

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.

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 are of utmost 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** (if any) to solve questions posed in the lab. Teamwork 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:

- A **lab component kit**. This kit, which is available to purchase from the EE&T School Electronic Workshop (G17 building, ground floor, room G15), includes all the necessary components as well as a **prototyping board** (also known as **breadboard**). Resistors and capacitors will be available in all teaching lab rooms.
- **Protective eyewear**, which is mandatory for Lab 6, to prevent eye injuries. **Goggles** can be bought from the EE&T School Electronic Workshop.
- 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

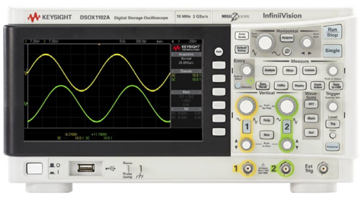
On each bench in the teaching laboratories, you will find the following lab equipment:

- An **oscilloscope** (Figure (a)).
- A **signal generator**, also known as a **function generator** (Figure (b)).
- A **DC power supply** with variable positive and negative voltages (Figure (c)).
- A **digital multimeter** (DMM) to measure voltage, current and resistance (Figure (d)).

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

- A dedicated place of **preferred-value resistors** (with power rating of $1/4$ W or 0.25 W) and **capacitors.**
- A precision **RLC meter** (known as **LCR Bridge**) to measure values of resistance, capacitance, and inductance (Figure (e)).
- **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

Record keeping

Attendance and hurdle

Your attendance, including prompt arrival and the efficient use of your laboratory periods, as well as your marks for each checkpoint will be recorded by the demonstrator every week on a marking slip.

⚠ A marking slip will be provided to you at the beginning of each laboratory session. This slip serves as proof of your attendance and work. Please retain these slips throughout the term to resolve any potential discrepancies in your marks.

⚠ You must **attend and attempt** at least 6 out of 7 weekly labs (Introductory Lab excluded) **AND pass the lab exam** to pass the course.

Results recording

All students should develop the discipline necessary to record their results neatly in the lab manual. This is not academic pedantry; it is part of becoming a professional engineer.

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

- Keep all your handwriting and records **neat and tidy** throughout the labs.
- **Scraps of paper** are **not allowed** for marking purposes. Recording of your results should be included in this manual.
- 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

⚠ You must complete the **Moodle OH&S Safety Course**[1] before starting the laboratory component.

⚠ 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 it online.

All your lab marks will be available on Moodle once all lab sessions in a week have finished. Please check your marks regularly, and if there is any mistake or missing mark, let the lecturer know via email. Do not forget to specify your zID and attach your marking slip so the proper actions are taken.

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

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

- Under **NO circumstance** is **230 V 50 Hz main power** to be used for any purpose other than that approved by the School of EE&T.
- Unless explicitly specified in the Lab Manual or by the demonstrators, **DO NOT change** your circuit setup/wiring while its power supply is on, as it might lead to an unnecessary injure. If you change your circuit setup/wiring while the power supply is on, you will get penalised for that lab mark.
- **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 body's resistance.
- Leave all **water bottles**, **bags**, **umbrellas**, etc. on the space **under the benches**.
- **Tampering** with or **removal** of any **laboratory equipment** is **forbidden**.
- You are expected to conduct yourself in a reserved manner at all times. **Noise** should be **kept to a minimum** as the lab rooms are teaching environments.
- Use of lab facilities for work not specifically associated with a School subject requires prior approval by a member of the academic staff.
- **Mobile phones** are **NOT to be used** at any time in a laboratory.
- You must **clean and tidy up your bench** when finishing the session. **Return** any required components before leaving the laboratory, including **equipment leads and cables**.
- **As you leave the laboratory, switch off all the equipment on the bench**.
- Please **advise** the lab demonstrators of any **equipment malfunction** or issues.
- Students are expected to **follow COVID-19 recommendations**.
- Students who **fail to abide** by these regulations will be told to **leave the laboratory**.

Lab 1: Familiarisation

Aims of this lab

The aim of this lab is to familiarise yourself with the following:

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

Videos and guides for review

Before doing this lab, you are expected to familiarise yourself with the laboratory equipment by reading the Appendix section of this manual and watching all the lab videos. Please make sure to revise the videos before commencing the 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 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

A. Analytical Part

You are **required** to carefully read all the sections of the Appendix and watch the videos linked in them **before starting the experiment**.

A.1 Draw the circuit represented in the breadboard layout below. Refer to the Breadboard/Prototyping board video and the corresponding section in the Appendix (Prototyping board (Breadboard)) for further details.

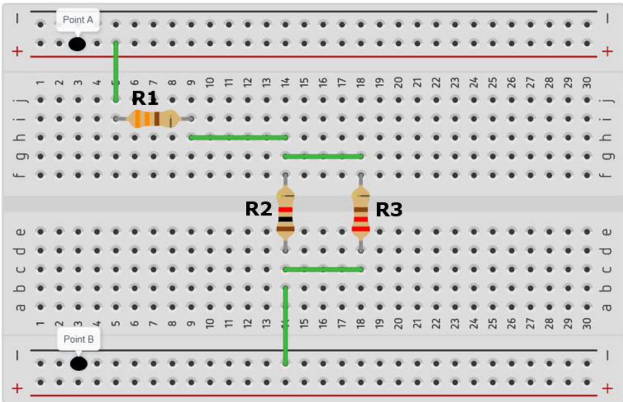


Figure 1.1: Breadboard layout

A.2 Complete the following Tables covering Resistor colour coding:

a. Find the value of each resistor.

Resistor	Band 1	Band 2	Band 3	Band 4	Resistor value
R_1	Blue	Grey	Gold	Gold	
R_2	Red	Red	Red	Red	
R_3	Brown	Green	Green	Silver	

b. 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. Consider a tolerance of 5% in all cases.

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

A.3 What is the current limit in a power supply and what is it used for? Refer to the Power supply video and the corresponding section in the Appendix (DC power supply) for further details.

A.4 Following the format and notation in Figure 1.2, draw how the voltage V_{cb} and the currents $I_{220\Omega}$ and $I_{1k\Omega}$ would be measured in the circuit shown in Figure 1.3. Refer to the Multimeter video and the corresponding section in the Appendix (Digital multimeter) for further details.

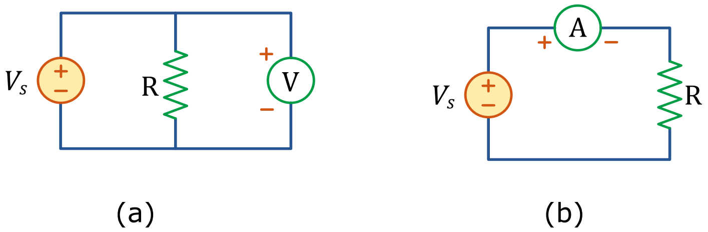


Figure 1.2: Connection of multimeter to measure voltage and current. Note that voltage is measured in parallel (see (a)), while current is measured in series and requires breaking the circuit to insert the multimeter (see (b)).

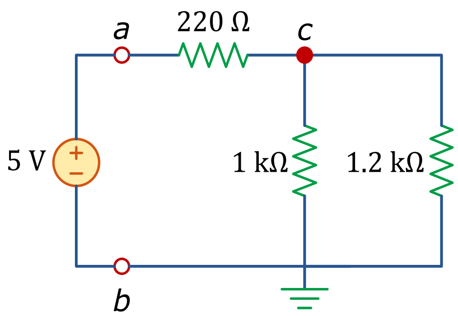


Figure 1.3: Resistive circuit for Lab 1 with DC power supply.

A.5 State what three types of periodic functions can be generated by the signal generator. Refer to the Signal generator video and the corresponding section in the Appendix (Signal/Function generator) for further details.

A.6 Explain each of the following concepts related to the Oscilloscope:

a. Scale (horizontal and vertical).

b. Measuring waveforms (comment on the three main ways to do this).

B. Experimental part

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

Required components

In this experiment, you require the following components:

- Your breadboard.
- $220\ \Omega$, $1\ \text{k}\Omega$, and $1.2\ \text{k}\Omega$ resistors from the resistor containers in the lab.

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

I. Resistance measurements

B.1 Complete the following Table by using the necessary resistors and measuring their resistance using the digital multimeter (DMM) on your bench.

Nominal resistance	Tolerance (from coloured band)	DMM value	Explain what causes the difference between the nominal resistance and the measured DMM value
$220\ \Omega$			
$1\ \text{k}\Omega$			
$1.2\ \text{k}\Omega$			

II. DC voltages and currents

B.2 Build the circuit shown in Figure 1.4 using a 5-V DC power supply ($\pm 0.1\ V$) with a current limit of $0.5\ \text{A}$. Measure voltages and currents shown in the Tables below

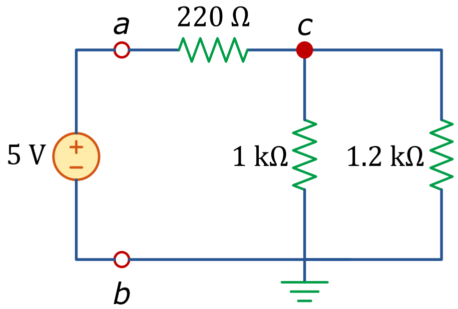


Figure 1.4: Resistive circuit for Lab 1 with DC power supply.

Voltage	DMM value
V_{ab}	
V_{cb}	
V_{ac}	

Current	DMM value
$I_{220\Omega}$	
$I_{1\mathrm{k}\Omega}$	
$I_{1.2\mathrm{k}\Omega}$	

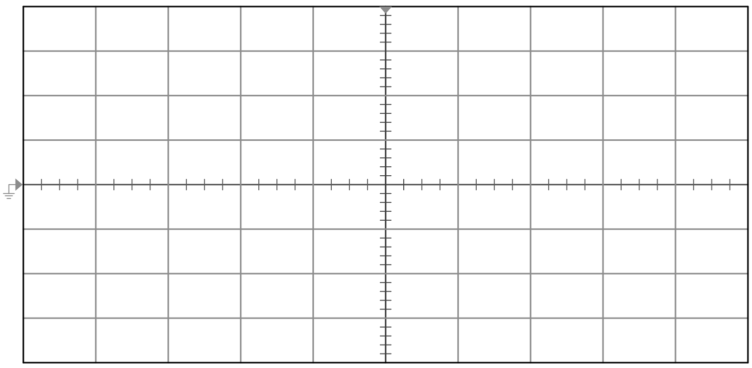
Check Point 1: Please ask a lab demonstrator to check your work before proceeding. You may continue working on the rest of the lab procedures while waiting for demonstrators.

III. AC voltages and currents

B.3 Set the **signal generator** to a sinusoidal output with a frequency of $1\ \mathrm{kHz}$ and at **maximum amplitude**, connect it to **channel 1** (**CH1**) of the oscilloscope. Configure the oscilloscope to display **at least 2 full periods** of the voltage signal. Measure and write down the amplitude (or peak value) of the AC signal using the three methods listed in the Table below.

	Volt per Division setting	Cursors	'Meas' button	Compare the accuracy of all three methods. Which method is the most accurate? Why?
Amplitude				

Sketch the observed waveform on the graph provided below. Clearly write down the horizontal and vertical scale.



Horizontal scale:________ Vertical scale:________

B.4 Repeat the same measurement with the same frequency and amplitude as before, but this time using the **multimeter**. Record the measured values in the Table provided, together with the amplitude/peak value from the previous question.

	Oscilloscope (**B.3**)	Multimeter	Explain why the AC measurement taken using the multimeter differs from the one taken using the oscilloscope.
Amplitude			

B.5 Using the AC power supply, connect a sinusoidal **1 kHz** and **15 V peak-to-peak** signal to the circuit as show in Figure 1.5. Measure the peak-to-peak value of voltages V_{ab} and V_{cb} using the **oscilloscope** and write your values in the Table below.

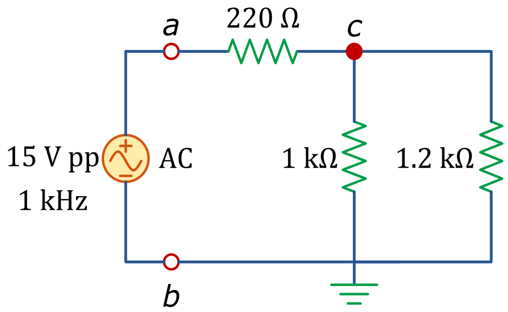


Figure 1.5: Resistive circuit for Lab 1 with AC voltage source.

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

B.6 In the same circuit shown in Figure 1.5, use the oscilloscope to measure the peak-to-peak voltage across the 220-Ω resistor, V_{ac}.

⚠ The oscilloscope **can only measure potentials with respect to ground (GND)**, therefore potential difference (between any two general points in the circuit) can only be measured through subtraction using the oscilloscope's **Math** feature.

Voltage	Peak-to-Peak measurement using oscilloscope
V_{ac}	

Check Point 2: Please ask a lab demonstrator to check your work before proceeding. You may continue working on the rest of the lab procedures while waiting for demonstrators.

Lab 2: Basic elements – Car rear lights

Aims of this lab

The aim of this lab is to understand basic circuit elements (sources, resistors and diodes) by designing and implementing the rear lights of a vehicle.

A. Analytical part

Conspicuity for the rear of a vehicle is provided by rear position lamps (or taillights). Rear position lamps may be combined with the vehicle's stop lamps or separated from them. In combined-function installations (as the one you will explore today), the lamps produce brighter red light for the stop lamp function and dimmer red light for the rear position lamp function. Regulations worldwide stipulate minimum intensity ratios between the bright (stop) and dim (rear position) modes.

In this lab, you will design and build the rear lights of a vehicle that meet the following specifications:

1. Needs to illuminate 6 LEDs distributed in a grid pattern (i.e., 3 rows × 2 columns).
2. The intensity ratio between the bright (stop) and dim (rear position) modes is $100/30$ (i.e., 100% intensity in stop mode and 30% intensity in rear position mode).
3. All LEDs are to have equal current flowing through them (equal brightness).
4. Current through each LED is to be no greater than $25\ \mathrm{mA}$.
5. The circuit is to be powered using a 12-V car battery.

To help you with the design task, you will analyse a circuit that illuminates a single LED functioning as a stop-rear light.

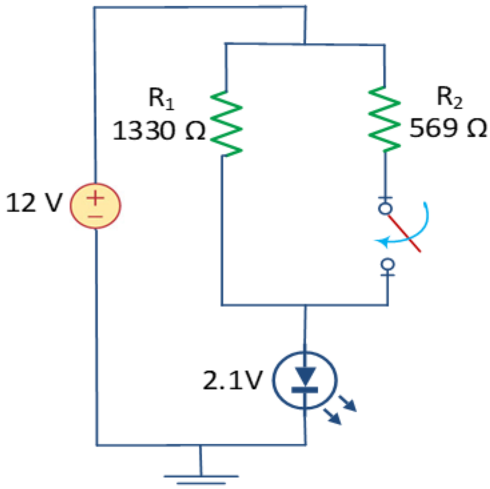


Figure 2.1. Single LED functioning as stop-rear light.

In this circuit, the stop mode occurs when the switch is closed since the value of the equivalent resistance decreases ($R_1 || R_2 < R_1$) and the current and brightness of each LED increases.

When doing the analysis, consider the following:

- When assuming ideal behaviour, a forward-biased LED behaves as a voltage source.
- LEDs to be used in Lab 2 for our taillights (OVFSRAC8) drop about $2.1\ \mathrm{V}$ across terminals for currents around $25\ \mathrm{mA}$.

A.1 Calculate the current in rear position mode (i_{rear}) and stop mode (i_{stop}) in the circuit shown in Figure 2.1. Check whether these currents conform to the specifications (i.e., they meet the required intensity ratio and maximum value).

Answer: $i_{rear} = 7.44\ \mathrm{mA}$; $i_{stop} = 24.84\ \mathrm{mA}$. Specifications are met.

A.2 Calculate the power dissipated by the LED and the two resistors in rear position mode and stop mode and check whether the resistor power requirements are met, considering that resistors to be used are rated at $0.25\ \mathrm{W}$.

Answer: Rear mode – $P_{LED_{rear}} = 15.62\ \mathrm{mW}$; $P_{R_1} = 73.7\ \mathrm{mW}$; $P_{R_2} = 0\ \mathrm{W}$.

Stop mode – $P_{LED_{stop}} = 52.16\ \mathrm{mW}$; $P_{R_1} = 73.7\ \mathrm{mW}$; $P_{R_2} = 172.25\mathrm{mW}$.

Power requirements are met.

A.3 Using the single LED circuit in Figure 2.1 as a starting point, design the rear lights of a vehicle, conforming to the specifications listed in the lab description. Note that the design implies adding additional LEDs and re-calculating the values of R_1 and R_2 so that the current requirements are met.

Calculate the power dissipation of your selected R_1 and R_2 and check whether the resistor power requirements are met (i.e., power less than 0.25 W). If not, propose a solution to meet the requirements without changing the resistor values.

A.4 Check your design using the following Falstad simulation: https://tinyurl.com/yetzp9t6. Comment on the accuracy of the calculated vs. simulated current and voltage values for the resistors and diodes. If the resistor values in your design are not the same as those in the simulation, change them accordingly in the simulation to answer the question.

B. Experimental part

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

Required components

In this experiment, you require the following components:

- Your breadboard.
- 6 LEDs (OVFSRAC8) from your **lab kit**.
- Resistors from the resistor containers in the lab.

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

Other relevant information

⚠ The schematic of the OVFSRAC8 LED, reproduced from its datasheet[2], is shown in Figure 2.2. Note that, even though it looks like a 4-terminal element, this LED is, in fact, a 2-terminal element (pins are connected 2 by 2). Note also the presence of a distinguishing mark of a flat side on the top left corner which indicates where the cathode is.

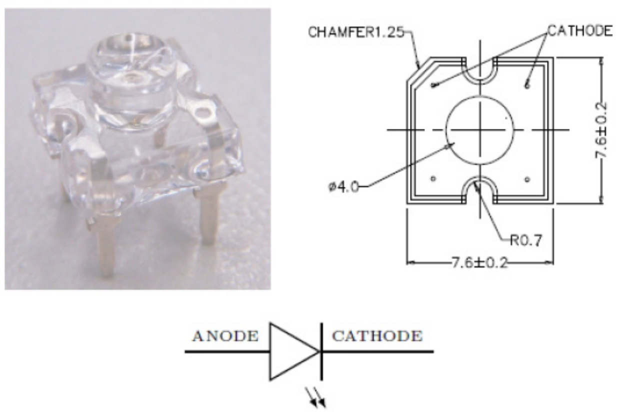
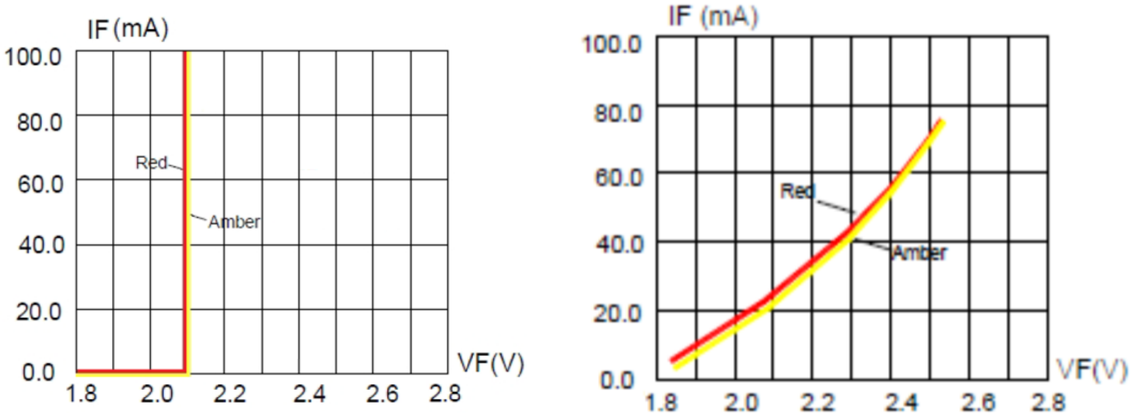


Figure 2.2. OVFSRAC8 LED schematic.

[2] OVFSRAC8 diode datasheet: https://www.ttelectronics.com/TTElectronics/media/ProductFiles/Optoelectronics/Datasheets/OVFSxxC8.pdf

⚠ LEDs in the analytical part of this lab (Section A), were treated as if they were a 2.1-V voltage source when forward biased. Nevertheless, the manufacturer reports in the datasheet[2] that the real voltage across the LED varies between 1.8 V and 2.6 V as a function of current, as shown in Figure 2.3.



(a) (b)

Figure 2.3. LED V-I characteristic. (a) ideal behaviour as voltage source assumed in theoretical calculations, and (b) real behaviour reported by the manufacturer[2].

I. Basic elements

B.1 Set up the circuit in Figure 2.4, keeping Figure 2.2 in mind to properly connect the LED and that the resistors are not preferred-value (standard) ones. You should use two standard resistors, and connected them properly, to obtain an equivalent R_1. For R_2, you can use the closest preferred-value resistor. Complete the Table below.

Required resistor	Preferred-value resistors		Connection of resistors
$R_1 = 1330\ \Omega$			
$R_2 = 569\ \Omega$			N/A

Adjust the output voltage of the DC power supply according to Figure 2.4 and set the current limit to 0.5 A (see Power Supply section in Appendix for details). Then, use the digital multimeter to measure the voltages and currents in **REAR POSITION mode**, and calculate the power as the product of the two. Write the values in the Table below.

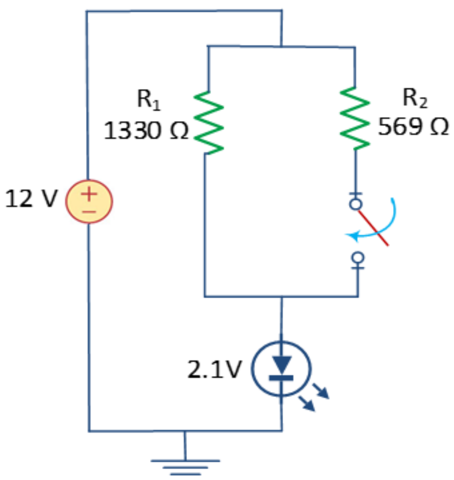


Figure 2.4. Single LED functioning as stop-rear light.

Element	Voltage	Current	Power (calculated)
Battery (12-V source)			
LED			
R_1			

Use the space provided to justify any discrepancies between your measurements of voltage, current and power for the LED and R_1 with their corresponding theoretical values from **A.1** and **A.2**. In addition, answer the following questions: How comparable is your LED voltage measurement to the LED V-I characteristic provided by Figure 2.3? Using Figure 2.3, justify the validity of your measured LED voltage.

B.2 Use the digital multimeter to measure the voltages and currents in **STOP mode**. Write the values in the Table below.

Element	Voltage	Current	Power (calculated)
LED			
R_1			
R_2			

Use the space provided to justify any discrepancies between your measurements of voltage, current and power for the LED, R_1 and R_2 and their corresponding theoretical values from **A.1** and **A.2.**

Check Point 1: Please ask a lab demonstrator to check your work before proceeding. You may continue working on the rest of the lab procedures while waiting for demonstrators.

II. Series and parallel connections

B.3 Set up the circuit in Figure 2.5 (which is the one you should have designed in **A.3**). Use the digital multimeter to measure the voltages and currents in **REAR POSITION mode**. Write the values in the Table below.

⚠ When measuring current in this circuit set the ammeter range to its maximum value manually by pressing [▲], this will minimise the ammeter internal resistance and result in a more accurate measurement.

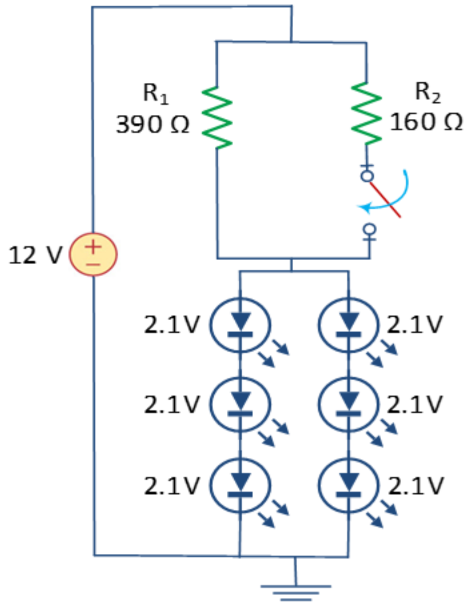


Figure 2.5. Stop-rear lights of a car.

Element	Voltage	Current
Top LED in column 1		
Bottom LED in column 1		
R_1		

Use the space provided to justify any discrepancies between your measurements and the theoretical values obtained in **A.3**. Does this design meet the specifications stated in the application description? Why or why not?

B.4 Use the space provided to justify any similarities or differences between the measured values of current flowing through the top and bottom LEDs in column 1 (from **B.3**) based on your knowledge of series and parallel connections.

B.5 Use the digital multimeter to measure the voltages and currents in **STOP mode**. Write the values in the Table below.

Element	Voltage	Current
Top LED in column 1		
Top LED in column 2		
R_1		
R_2		

B.6 Use the space provided to justify any similarities or differences between the measured values of current flowing through the top LEDs in column 1 and column 2 (from **B.5**) based on your knowledge of series and parallel connections. In addition, do the same for the voltage values across R_1 and R_2.

Check Point 2: Please ask a lab demonstrator to check your work before proceeding. You may continue working on the rest of the lab procedures while waiting for demonstrators.

Lab 3: V-I characteristics & basic laws – Solar-powered pet house

Aims of this lab

The relationship between the DC current through an electrical element or device and the DC voltage across its terminals is called a voltage-current (V-I) characteristic. Engineers use V-I characteristics to determine the basic parameters of a device and to model its behaviour in an electrical circuit. The aim of this lab is to examine the concept of V-I characteristic and understand basic laws, such as Ohm's law and Kirchhoff's Current and Voltage Laws (KCL and KVL) by implementing a solar-powered circuit for a pet house.

A. Analytical Part

The circuit in Figure 3.1 corresponds to a solar-powered pet house. The pet house has a solar panel on the roof to power a fan and an LED light.

The solar panel is composed of 36 solar cells, each of which is modelled as a current source connected in parallel with a diode, with a shunt and a series resistor used to represent the losses. The LED can be modelled as a voltage source, when forward biased. A resistor in series with the LED is used to set the current flowing through it. The output voltage of the fan behaves linearly with respect to the solar panel current, so it can be modelled by its effective resistance, 540 Ω. The solar panel, fan and LED light are connected close to each other, all outside the house.

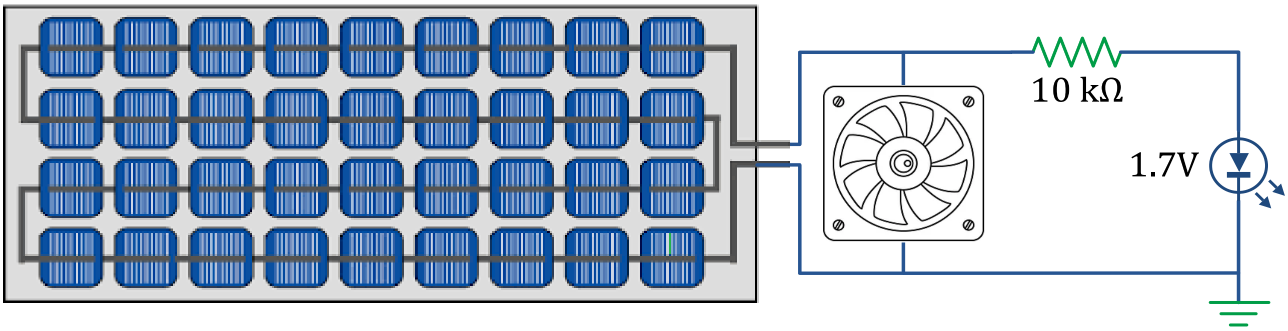


Figure 3.1. Circuit of solar-powered fan with LED light for pet house.

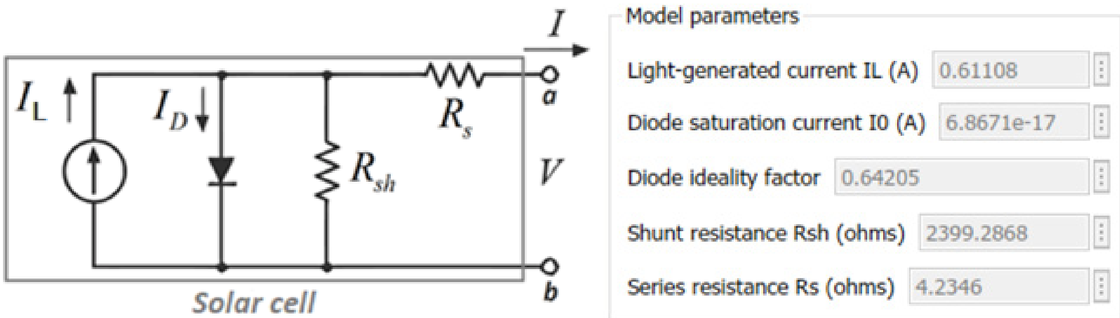


Figure 3.2. Model of a single cell and model parameters for each of the 36 cells of the 12-V 10-W solar panel to be used in Lab 3.

A.1 Given the solar cell model[3] and model parameters shown in Figure 3.2, calculate the maximum voltage available from each cell, v_{oc}. Note that the open circuit voltage, v_{oc}, is the voltage across the solar cell when the current through it is zero (i.e., when there is nothing connected to terminals *a*-*b*) and can be analytically calculated as:

$$v_{oc} = n\, V_T \ln\left(\frac{I_L}{I_0} + 1\right)$$

where n is the diode ideality factor; V_T is the thermal voltage, which, at $300\ \mathrm{K}$ ($27℃$) equals $25.86\ \mathrm{mV}$; I_L is the light-generated current; and I_0 is the diode saturation current.

Answer: $v_{oc_{cell}} = 0.61\ \mathrm{V}$.

A.2 Knowing that the solar panel has 36 solar cells connected in series (as can be seen in Figure 2.1), calculate the open circuit voltage of the solar panel. Compare your calculated value with the value provided by the manufacturer in the specifications[4].

Answer: $v_{oc_{panel}} = 21.96\ \mathrm{V}$.

A.3 Calculate the voltage across the fan and the $10\text{-k}\Omega$ resistor when the output voltage of the solar panel is $12.5\ \mathrm{V}$.

Answer: $v_{fan} = 12.5\ \mathrm{V}$; $v_{10k} = 10.8\ \mathrm{V}$.

A.4 Use the result from the previous question to calculate the current across the fan, the current across the LED light, and the output current of the solar panel.

Answer: $i_{fan} = 23.15\ \mathrm{mA}$; $i_{LED} = 1.08\ \mathrm{mA}$; $i_{panel} = 24.23\ \mathrm{mA}$.

[3] Note that the solar panel model used and the relation between its parameters is well documented in the literature (e.g., https://www.researchgate.net/publication/260939716_On_the_analytical_approach_for_modeling_photovoltaic_systems_behavior).

[4] Solar panel specifications can be found here: https://www.jaycar.com.au/12v-10w-solar-panel-with-clips/p/ZM9051.

A.5 Use the result of the previous two questions to calculate the power dissipated by the fan, the 10-kΩ resistor and the LED. Use power balance to calculate the power generated by the solar panel. Then, calculate the power transferred from the solar panel to the fan and LED light, η_{fan} and η_{LED} (i.e., power absorbed by each element over power supplied by the solar panel).

Answer: $P_{fan} = 289.38\ \mathrm{mW}; P_{10k} = 11.66\ \mathrm{mW};\ P_{LED} = 1.84\ \mathrm{mW}.$

$\eta_{fan} = 0.96;\ \eta_{LED} = 0.0061.$

A.6 You decide to illuminate the pet house with two LED lights instead of one, as shown in Figure 2.3. Use nodal analysis to calculate nodal voltages v_a to v_e knowing that the output voltage of the solar panel is $12.5\ \mathrm{V}$ (i.e., $v_a = 12.5\ \mathrm{V}$).

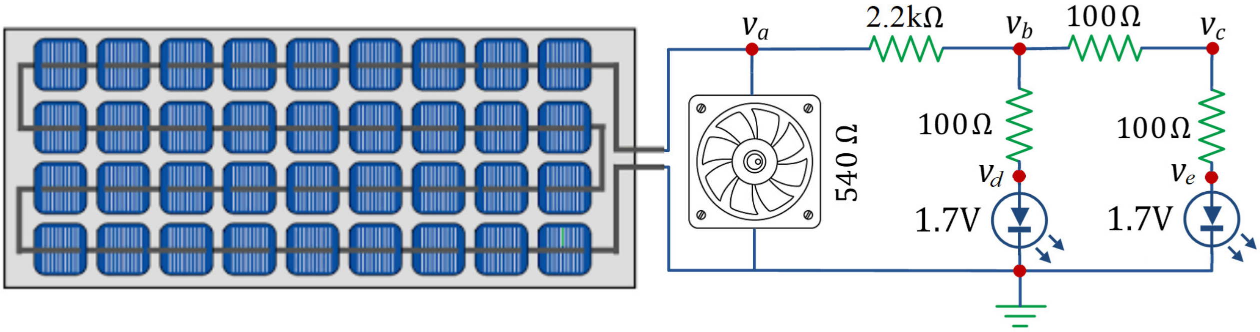


Figure 3.3. Circuit of solar powered fan with 2 LED lights for pet house.

Answer: $v_a = 12.5\ \mathrm{V}; v_b = 2.02\ \mathrm{V};\ v_c = 1.86\ \mathrm{V};\ v_d = 1.7\ \mathrm{V};\ v_e = 1.7\ \mathrm{V}.$

B. Experimental part

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

Required components

In this experiment, you require the following components:

- Your breadboard.
- Solar panel with lamp. The 55 W-rating light is used as the source of irradiance.
- 2 LEDs (OVFSRAC8) from your **lab kit**.
- $10\ \mathrm{k\Omega}$ resistor and $2.2\ \mathrm{k\Omega}$ resistors from the resistor containers in the lab.

Videos and guides for review

List of suggested videos:

Power supply

Multimeter

List of suggested guides from Appendix:

- DC power supply
- Digital multimeter

I. V-I Characteristics

In the first section of this lab experiment you will experimentally explore the V-I characteristics of the solar panel and the fan shown in Figure 3.1.

B.1 Set up the **lamp** attached to the solar panel to operate at **10 V**. Note that the lamp draws more current than the maximum current that can be supplied by each channel of the power supply in single mode. To increase the range of output current provided to your circuit beyond the limit of each power supply channel, you need to **increase the current limit to the maximum value (~3A) in the MASTER channel** (i.e., CH1) and set up the **power supply** in **parallel mode**[5]. By doing this, you are supplying twice the maximum current to your circuit, a total of 6 A, which is necessary given the high-power rating of the lamp.

⚠ The lamp attached to the solar panel needs to be connected to the power supply using the provided clips as shown in Figure 3.4 (after slightly unscrewing the output connectors).

⚠ **Ensure that the power connection to the lamp has the correct polarity.** The red terminal of the power supply should be connected to the red lamp clip. Likewise, the black terminal should be connected to the black lamp clip.

⚠ **NEVER increase the voltage supplied to the lamp over 12 V**, since it can get damaged. The **safest way to set up the lamp** is as follows: (1) set the current limit to 3 A before you switch on the power supply; (2) set the voltage value to the appropriate value (10 V in this case); (3) switch on the power supply.

[5] Further details of the different modes of the DC power supply and how they are selected can be found in the Appendix (DC power supply).

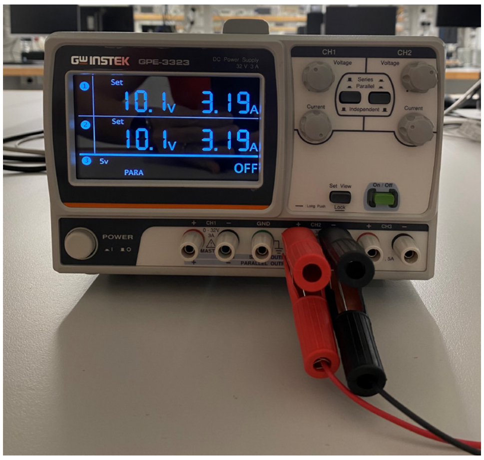


Figure 3.4. Connection of lamp clips to power supply.

B.2 Considering **<u>only</u>** the **solar panel** (i.e., when fan and LED light are not connected), measure the open circuit voltage (V_{OC}) of the solar panel for different light conditions. Record your measurements in the Table below.

⚠ Note that given the large internal resistance of the voltmeter, the open circuit voltage can be measured by directly connecting the voltmeter to the terminals of the solar panel.

Lighting conditions	Open circuit voltage, V_{oc}
Lamp @ 10 V (irradiance ≈ 20 W/m^2)	
Lamp @ 11 V (irradiance ≈ 25 W/m^2)	
Lamp @ 12 V (irradiance ≈ 30 W/m^2)	

Justify any discrepancies between your measured values and the theoretical value from **A.2** based on your understanding of any assumptions made to calculate the theoretical value and the extent of its validity. In addition, can you think of any external factors that would have an impact on your solar panel measurements?

B.3 Considering the same setup as in **B.2**. Measure the short circuit current (I_{SC}) that can be drawn from the solar panel for different light conditions. Record your measurements in the Table below.

⚠ Note that given the small internal resistance of the ammeter (i.e., almost a short circuit), the **short circuit current can be measured by directly connecting the ammeter to the terminals** of the solar panel.

Lighting conditions	Short circuit current, I_{sc}
Lamp @ 10 V (irradiance ≈ 20 W/m^2)	
Lamp @ 11 V (irradiance ≈ 25 W/m^2)	
Lamp @ 12 V (irradiance ≈ 30 W/m^2)	

B.4 Knowing that the effect of irradiation on PV cell's V-I characteristic is as shown in Figure 3.5, explain whether or not your measured short circuit currents (currents at $v = 0$ V) and open circuit voltages (voltages at $i = 0$ A) are consistent with this behaviour[6].

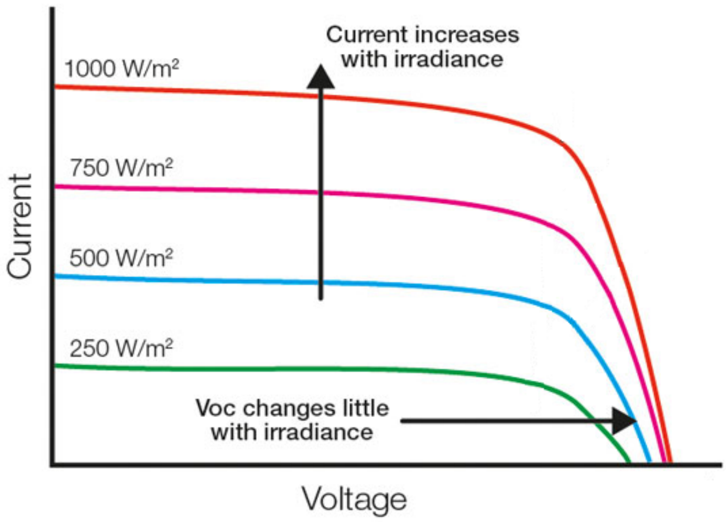


Figure 3.5. Effect of irradiation on PV cell's V-I characteristic

[6] Note that irradiance values obtained outdoors from the sun tend to be much higher than the ones in the lab, which lead to much higher short circuit currents, I_{SC}, as shown by the manufacturer in the specifications of the solar panel (https://www.jaycar.com.au/12v-10w-solar-panel-with-clips/p/ZM9051).

B.5 Connect the fan to the solar panel, as shown in Figure 3.6. Then, connect the lamp to the DC power supply and set up the lamp to work at $\mathbf{9\,V}$. Measure the voltage across the fan and the current through it when increasing the voltage of the lamp in steps of $1\,\mathrm{V}$ up to a maximum of $12\,\mathrm{V}$. Record all your measurements in the Table below and use the graph provided to plot the V-I characteristic of the fan.

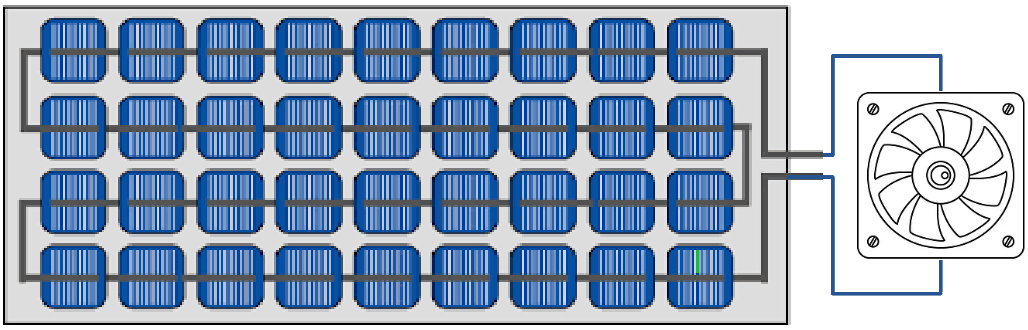
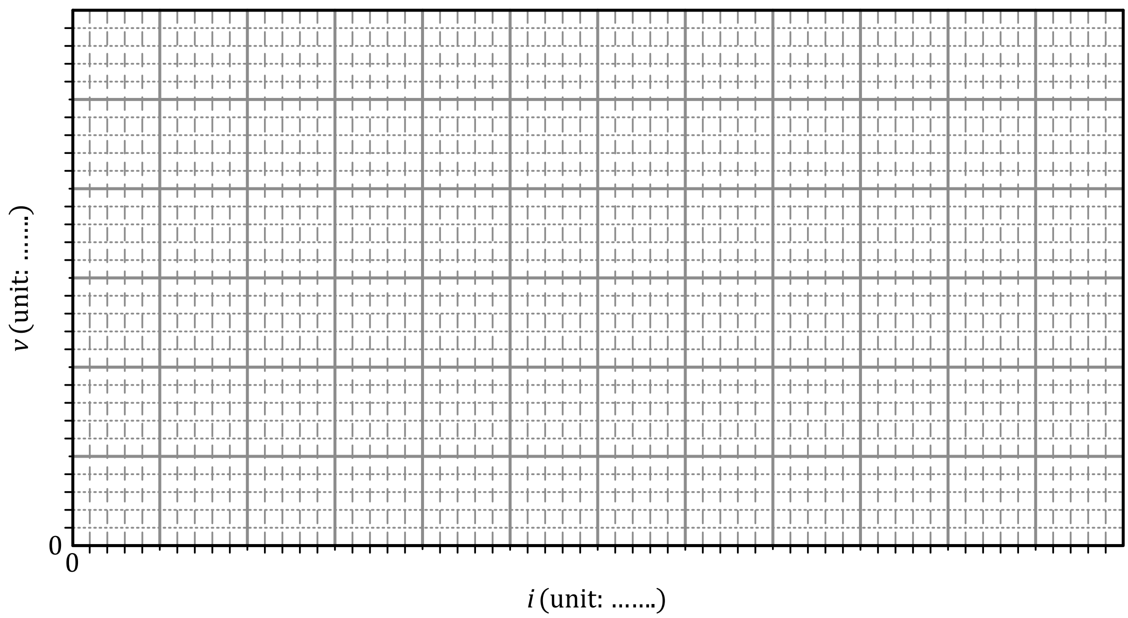


Figure 3.6. Circuit to explore fan's V-I characteristic.

Lighting conditions	Fan voltage	Fan current
Lamp @ 9 V (irradiance ≈ 15 W/m^2)		
Lamp @ 10 V (irradiance ≈ 20 W/m^2)		
Lamp @ 11 V (irradiance ≈ 25 W/m^2)		
Lamp @ 12 V (irradiance ≈ 30 W/m^2)		



What kind of relationship exists between the applied voltage and the current through the fan? Based on the gradient of your graph above, calculate the experimental value of the effective resistance of the fan. Write any necessary calculation(s) in the space below. Justify any discrepancies between the calculated value and the theoretical value provided in the lab description (i.e., 540 Ω).

Check Point 1: Please ask a lab demonstrator to check your work before proceeding. You may continue working on the rest of the lab procedures while waiting for demonstrators.

II. Kirchoff's laws

B.6 Build the circuit of Figure 3.7 on your prototyping board. Connect the lamp to the DC power supply and set up the lamp to work at $\mathbf{11\ V}$. Then, measure the voltages of nodes *a* and *b* with respect to reference node *G* and write them down in the Table below. Then measure the voltage across the $10\ k\Omega$ resistor, v_{ab}.

⚠ Note that due to the solar panel, voltage values will keep changing slowly. Ensure that you record the values once the changes start to stabilise.

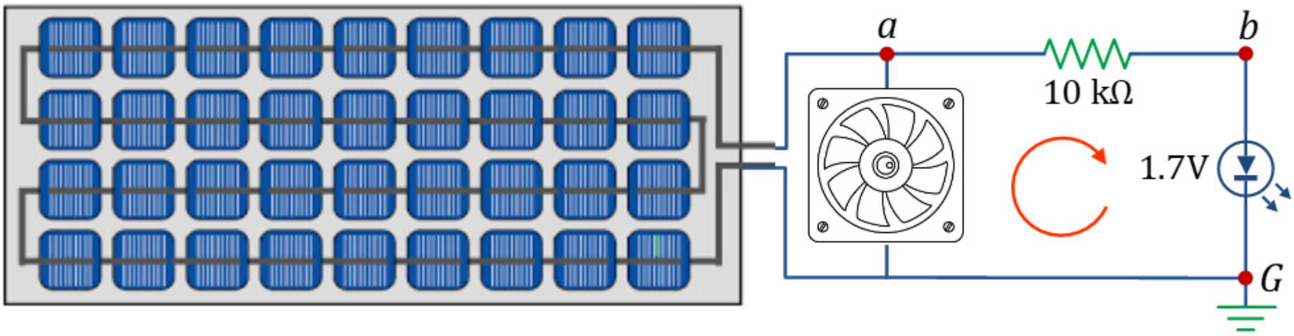


Figure 3.7. Circuit of solar powered fan with LED light for pet house.

Voltage	Calculated value (**A.3**)	Measured value	Justify any discrepancies between the measured values and the calculated values from **A.3**
V_{aG}			
V_{bG}			
V_{ab}			

B.7 Apply KVL for the mesh marked in red in Figure 3.7 (i.e., in the clockwise direction). Verify that KVL equations are satisfied using both sets of values (i.e., measured and calculated) and justify any discrepancies.

B.8 Measure the current through the solar panel, the fan and the LED light, as per Figure 3.8. Record all your results in the Table below.

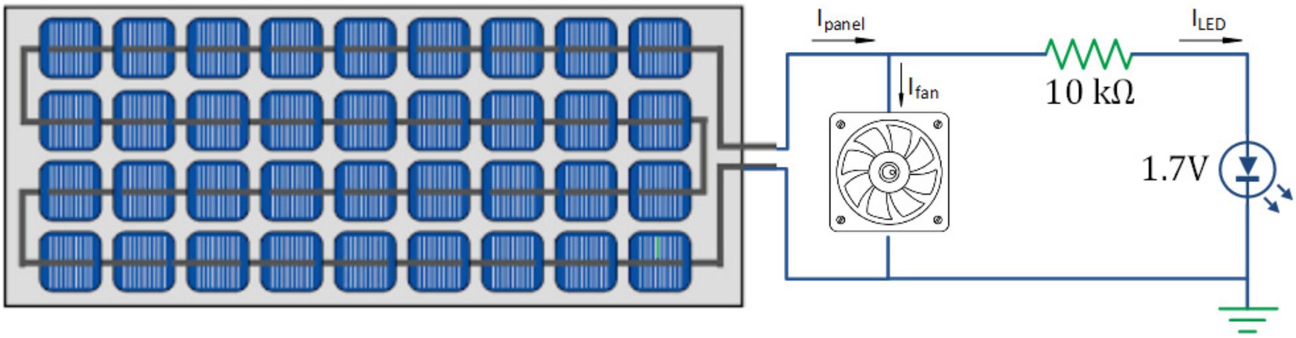


Figure 3.8. Circuit of solar powered fan with LED light for pet house.

Voltage	Calculated value (**A.4**)	Measured value	Justify any discrepancies between the measured values and the calculated values from **A.4**
I_{panel}			
I_{fan}			
I_{LED}			

B.9 Apply KCL at node *a* with the directions labelled in the previous question. Verify that KCL equations are satisfied using both sets of values (i.e., measured and calculated) and justify any discrepancies.

III. Nodal analysis

B.10 Build the circuit of Figure 3.9 on your prototyping board and measure the nodal voltages v_a to v_e. Record all your results in the Table below.

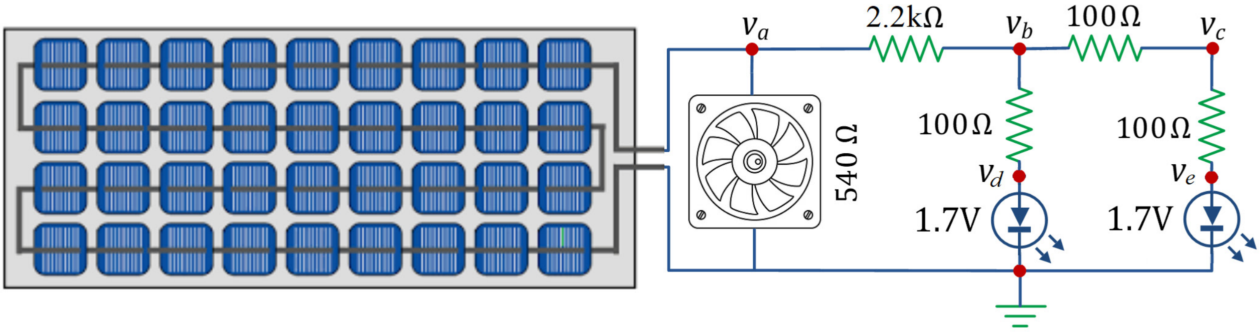


Figure 3.9. Circuit of solar powered fan with 2 LED lights for pet house.

Voltage	Calculated value (**A.6**)	Measured value	Justify any discrepancies between the measured values and the calculated values from **A.6**
v_a			
v_b			
v_c			
v_d			
v_e			

Check Point 2: Please ask a lab demonstrator to check your work before proceeding. You may continue working on the rest of the lab procedures while waiting for demonstrators.

Lab 4: Circuit theorems – Bicycle lighting system

Aims of this lab

The aim of this lab is to investigate the circuit theorems explained in Topic 3 (Thevenin's and Norton's theorem and maximum power transfer theorem) by analysing and implementing a model of a bicycle lighting system.

A. Analytical Part

The circuit in Figure 4.1 corresponds to a bicycle with front and rear bulb lights and a permanent magnet generator (hub dynamo) to power them.

The permanent magnet generator is in the front wheel hub, and acts as a voltage source where voltage is proportional to speed. The front light bulb has a resistance of 15 Ω and is attached to the handlebars, whereas the rear light bulb is mounted on the back wheel and has a resistance of 56 Ω.

The positive terminals of the lights and generator are connected in parallel by a thin wire; the negative terminals are all connected using the bicycle's conductive aluminium frame. The bicycle has a racing style frame with "700C" tyres. The diameter of the front wheel which has the generator is 670 mm.

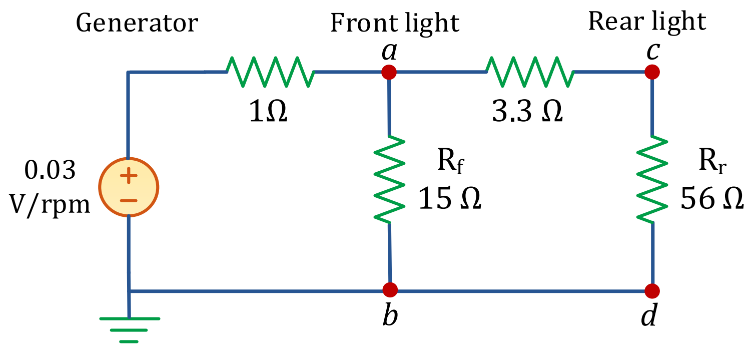


Figure 4.1. Bicycle's lighting system.

A.1 When the bicycle is travelling at 20 $\mathrm{km/h}$ (average cycling speed), the permanent magnet generator voltage is 4.75 V[7]. Using an analysis method of your choice, calculate the voltage and current flowing through each bulb when the bicycle is travelling at 20 $\mathrm{km/h}$. Then, calculate the power dissipated by each bulb.

Answer: Front light - $v_{front} = 4.38\ \mathrm{V}$; $i_{front} = 0.292\ \mathrm{A}$; $P_{front} = 1.28\ \mathrm{W}$.

Rear light - $v_{rear} = 4.14\ \mathrm{V}$; $i_{rear} = 0.074\ \mathrm{A}$; $P_{rear} = 0.31\ \mathrm{W}$.

[7] Demonstrate that the generator output voltage when the bicycle is travelling at 20 $\mathrm{km/h}$ is 4.75 V, knowing that the front wheel diameter is 670 mm and the permanent magnet generator works at 0.03 $\mathrm{V/rpm}$.

A.2 You realise that the rear light is not bright enough and decide to replace it. Given that brightness in a light bulb depends on its power, what rear light resistance will ensure the maximum transfer of power from the bicycle to the rear light? What will this maximum power be? Compare the power value with the one you obtained in **A.1**.

Note: calculate the Thevenin equivalent of the circuit from terminals *c*-*d* (without including R_r) to answer this question.

Answer: $R_{r_{new}} = R_{th} = 4.23\ \Omega \approx 4.3\ \Omega$; $V_{th} = 4.45\ \text{V}$; $P_{max} = 1.17\ \text{W}$.

B. Experimental part

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

Required components

In this experiment, you require the following components:

- Your breadboard.
- $100\ \Omega$ resistor from the resistor containers in the lab.
- $1\ \Omega$ (1W), $3.3\ \Omega$ (5W), $15\ \Omega$ (5W), $56\ \Omega$ (0.6W), $4.3\ \Omega$ (2W) and $47\ \Omega$ (0.6W) from your **lab kit**.

⚠ Note that these resistors require a higher power rating (indicated in brackets) than that of resistors from the containers in the lab (0.25 W).

Videos and guides for review

List of suggested videos:

Power supply

Multimeter

List of suggested guides from Appendix:

- DC power supply
- Digital multimeter

I. Thevenin's theorem

Build the circuit of Figure 4.2 on your breadboard, where R_r is the load resistor.

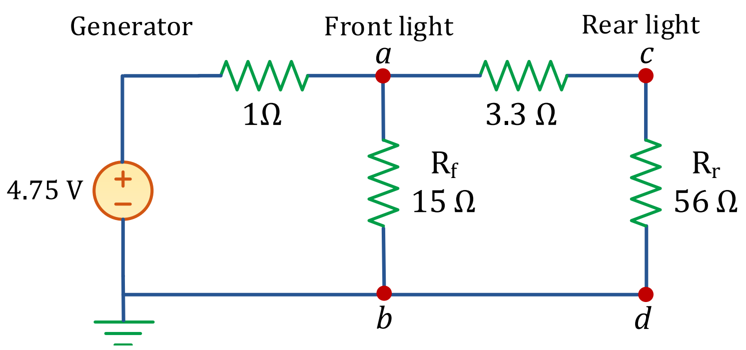


Figure 4.2. Bicycle's lighting system with permanent magnet generator voltage corresponding to a cycling speed of 20 km/h.

⚠ **DO NOT** touch the components or change the circuit when the power supply is on. The **components will be HOT**!

B.1 Adjust the output voltage of the DC power supply to approximately 4.75 V (with $\pm 0.1\,\mathrm{V}$ tolerance), as per Figure 4.2, and set the **current limit** to **1.3** $\mathbf{A}$. Then, measure the voltage across R_r and the current through it, and calculate the power consumed. Record your measurements in the Table below.

	Calculated value (**A.1**)	Measured value	Justify any discrepancies between the measured values and the calculated values from **A.1** based on your understanding of the impact that small resistor values have on a circuit
v_{rear}			
i_{rear}			
P_{rear}			

B.2 Now remove R_r from the terminals *c* and *d* (the terminals clearly become an open circuit). Measure the open circuit voltage. What does this voltage represent? Justify any discrepancies between the measured open circuit voltage and the voltage calculated in **A.2**.

B.3 Measure the Thevenin resistance R_{Th} by appropriately disabling the independent voltage source in your circuit. Justify any discrepancies between the measured R_{Th} and the R_{Th} value calculated in **A.2**.

B.4 Sketch the Thevenin equivalent circuit using the calculated values for v_{Th} and R_{Th} in the space provided below, build it on your breadboard, and connect it to the load resistance R_r.

⚠ DO NOT dismantle the circuit of Figure 4.2, since it will be used in the following sections. Simply, build the Thevenin equivalent circuit next to the circuit of Figure 4.2.

Measure the voltage across the load and compare it to the voltage you measured in question **B.1** and the voltage obtained in **A.1**. Record your measurements in the Table below.

	Calculated value (**A.2**)	Measured value (original circuit, **B.1**)	Measured value (Thevenin equivalent)	Justify any discrepancies between both the measured values and the calculated value from **A.1**
v_{rear}				

II. Norton's theorem

B.5 Consider the same circuit as in Figure 4.2. Measure the **short-circuit current** between terminals *c* and *d* (where R_r was connected). What does this current represent?

B.6 Calculate $i_{sc} = i_N = \frac{v_{\mathrm{Th}}}{R_{\mathrm{Th}}}$ and justify the cause of any discrepancies between the calculated value and the measured value obtained in the previous question. Why does the ammeter have a considerable impact on this circuit compared to those that you have made in previous labs?

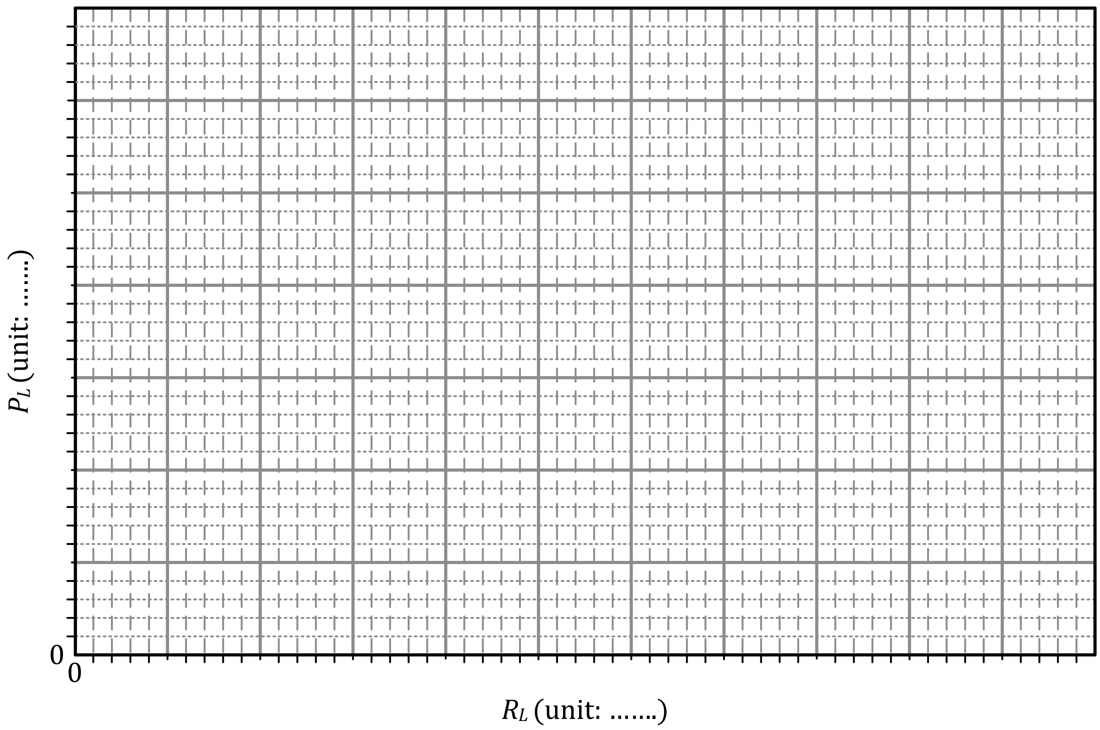
Check Point 1: Please ask a lab demonstrator to check your work before proceeding. You may continue working on the rest of the lab procedures while waiting for demonstrators.

III. Maximum power transfer

B.7 Consider the same circuit as in Figure 4.2. Replace the rear light resistor R_r with the values given in the Table below. Measure the voltage across R_r (v_L) and the current flowing through it (i_L), and then calculate the power consumed (P_L). Complete the Table below.

Load resistor R_r	Load voltage v_L	Load current i_L	Load power P_L (calculated)
$100\ \Omega$			
$56\ \Omega$			
$47\ \Omega$			
$4.3\ \Omega$			
$1\ \Omega$			

B.8 Plot the variation of the load power P_L with respect to the variation of the load resistor R_r using the collected data.



Using your graph, identify the load resistance value (R_r) at which maximum power transfer occurs, and the magnitude of power transferred at this load resistance. Why does maximum power transfer occur at this load resistance value? Justify any discrepancies between these identified values and their corresponding theoretical values from **A.2.**

Check Point 2: Please ask a lab demonstrator to check your work before proceeding. You may continue working on the rest of the lab procedures while waiting for demonstrators.

Lab 5: First-order circuits – Timers

Aims of this lab

The aim of this lab is to examine transient voltages and currents in simple RC and RL circuits working as timing circuits.

A. Analytical Part

RC and RL circuits are commonly used as timing circuits. The circuit in Figure 5.1 is used to generate periodic trigger pulses to be used as a timing signal. A piezoelectric AC buzzer is used to get acoustic feedback.

RC circuits behave as differentiators when the output is measured in the resistor, so when you feed a square pulse to an RC differentiator circuit and adjust the time constant, you can get sharp trigger signals at desired time intervals, as shown in Figure 5.2. These trigger signals are commonly used to activate other circuits.

Piezo buzzers are constructed by placing electrical contacts on the two faces of a disk of piezoelectric material. When a voltage is applied across the two electrodes, the piezoelectric material mechanically deforms. This movement of the piezo disk within the buzzer creates sound. Piezo buzzers are modelled as capacitors. Given that the capacitance of the piezo buzzer used for this application (ABT-431-RC)[8] is very small, the effect of the buzzer on the timer circuit will be disregarded.

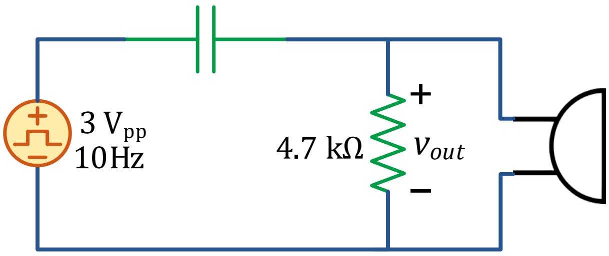


Figure 5.1. Timer circuit with buzzer.

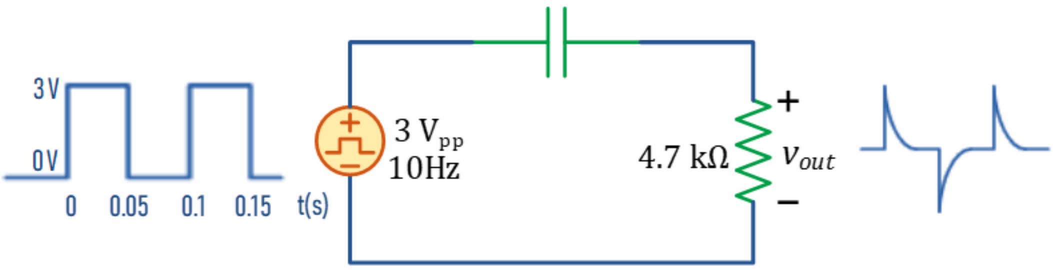


Figure 5.2. RC differentiator used to generate periodic trigger pulses[9].

[8] ABT-431-RC buzzer specifications can be found here: https://www.farnell.com/datasheets/2861428.pdf.
[9] You can observe the behaviour of this circuit in the following simulation: https://tinyurl.com/yalgsgha.

A.1 For the circuit in Figure 5.2, find $v_c(t)$ and $v_{out}(t)$ for $0 \leq \mathrm{t} < 0.05\,\mathrm{s}$, while the value of the square signal is $3\ \mathrm{V}$. Assume that the circuit has been in operation for a while. Let $t = 0\ s$ at an instant when the square signal changes from $0\ \mathrm{V}$ to $3\ \mathrm{V}$.

Answer: $v_c(t) = 3(1 - e^{-967t})\ \mathrm{V}$; $v_{out}(t) = 3e^{-967t}\ \mathrm{V}$.

A.2 For the same circuit, find $v_c(t)$ and $v_{out}(t)$ for $0.05 \leq \mathrm{t} < 0.1\,\mathrm{s}$, while the value of the square signal is $0\ \mathrm{V}$.

Answer: $v_c(t) = 3e^{-967(t-0.05)}\ \mathrm{V}$; $v_{out}(t) = -3e^{-967(t-0.05)}\ \mathrm{V}$.

A.3 Plot $v_{in}(t)$ and $v_{out}(t)$ in the same graph for $0 \leq \mathrm{t} \leq 0.1$ s. Ensure your plot is to scale and has at least three labelled values in each interval (i.e., $0 \leq \mathrm{t} < 0.05$ s and $0.05 \leq \mathrm{t} < 0.1$ s).

RL circuits also behave as differentiators when the output is measured in the inductor, so the same behaviour can be achieved with an RL circuit, as shown in Figure 5.3.

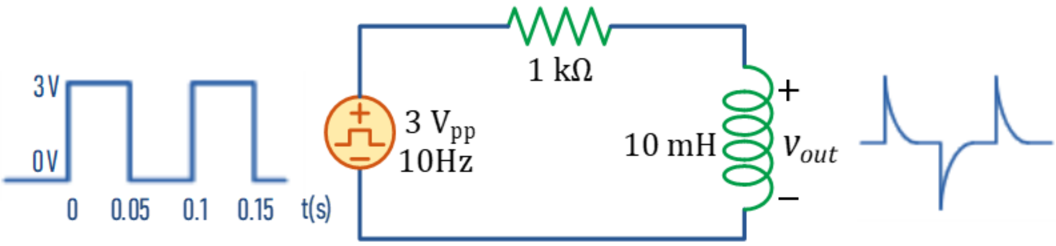


Figure 5.3. RL differentiator used to generate periodic trigger pulses[10].

A.4 Calculate the time constant of the circuit shown in Figure 5.3.

Answer: $\tau = 10\ \mu\mathrm{s}$.

[10] You can observe the behaviour of this circuit in the following simulation: https://tinyurl.com/yd9vglp3. Use the Run/STOP button to stop the simulation and check the time constant. You can modify the horizontal and vertical scale in the graphs by adjusting the Scope properties on the Settings icon (see below) on the bottom left of each graph.

B. Experimental part

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

Required components

In this experiment, you require the following components:

- Your breadboard.
- $4.7\ k\Omega$ and $1\ \mathrm{k}\Omega$ resistors from the resistor containers in the lab.
- $220\ \mathrm{nF}$ capacitor from the capacitor containers in the lab.
- One buzzer from your **lab kit**.
- $10\ \mathrm{mH}$ inductor from your **lab kit**.

Videos and guides for review

List of suggested videos:

Signal generator

Oscilloscope

List of suggested guides from Appendix:

- Signal/Function generator
- Oscilloscope

I. RC transients

B.1 Construct the RC circuit of Figure 5.4 on your breadboard. Adjust the output voltage of the DC power supply according to Figure 5.4 and set the current limit to $0.5\ \mathrm{A}$.

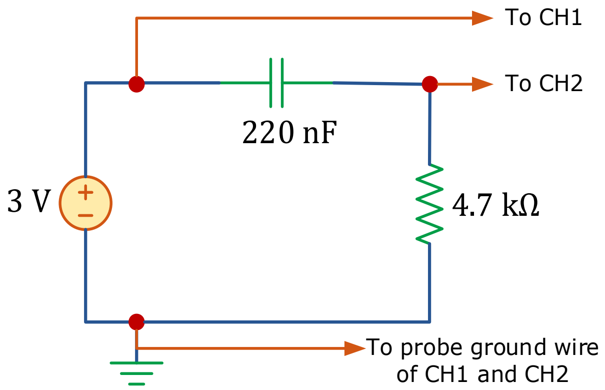


Figure 5.4. RC circuit to observe the transient behaviour with the oscilloscope.

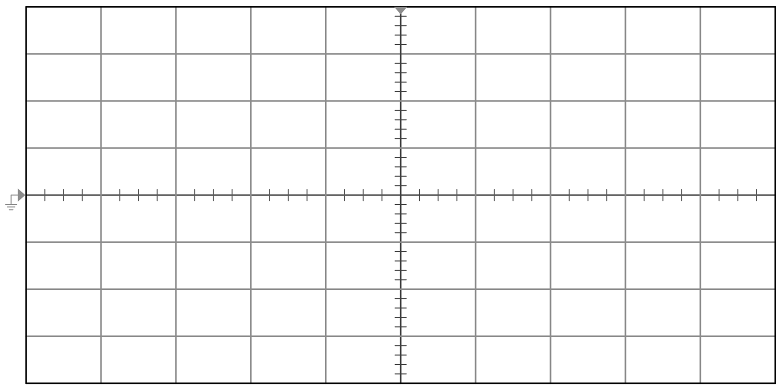
Connect the oscilloscope as indicated in Figure 5.4. Set the vertical scale of the oscilloscope to $\mathbf{1V/div}$ on both channels with **DC Coupling**. Also, set the horizontal scale to $\mathbf{2\ ms/div}$ and choose **CH1 as triggering source** on the **rising edge** with a **trigger level** of $\mathbf{0.5\ V}$. Finally, press the **"Single"** button to have the oscilloscope ready to be triggered. Once all these settings are in place, turn the power supply on and then use a wire to connect the RC circuit to the 3-V DC power supply and charge the capacitor, displaying the **transient voltage** of the capacitor on **CH2**.

Sketch the waveforms displayed on CH1 and CH2 of the oscilloscope in the graph provided below. Also, use the oscilloscope **Math** feature to display and sketch the voltage across the capacitor, v_{12}, using the same vertical scale as CH1 and CH2. Remember that as seen in Lab 1, the oscilloscope **can only directly measure potentials with respect to ground**, therefore potential difference (between any two general points in the circuit) can only be measured through subtraction using the oscilloscope's **Math** feature.

⚠ If no signal is displayed or you get a very noisy signal, you can repeat the test by disconnecting the power supply wire (so that there is time for the capacitor to discharge), pressing the "Single" button, and then use the same wire to reconnect your power supply to the circuit.

⚠ To avoid the impact of the gradual turning on of your power supply (i.e., soft startup) on your measurement, ensure that you disconnect and reconnect the wire rather than turning your power supply off and then back on.

CH1, CH2, v_{12}



Horizontal scale:________ Vertical scale:________

B.2 Explain how the settings of the oscilloscope (scale, coupling, and triggering source, edge and level) affect your measurements. **Note that not being able to trigger the oscilloscope properly is a very common mistake in the lab exam, so please ensure that you learn how to do this correctly**.

B.3 The current through the RC circuit of Figure 5.4 can be determined using Ohm's law. Using the waveforms from **B.1**, calculate the peak current through the resistor.

Check Point 1: Please ask a lab demonstrator to check your work before proceeding. You may continue working on the rest of the lab procedures while waiting for demonstrators.

B.4 Use the signal generator to supply voltage to the RC circuit, as shown in Figure 5.5. This circuit will be used to generate periodic trigger pulses.

Before connecting the signal generator to the circuit, connect its output directly to the oscilloscope to do the set up. Keep the vertical scale of the oscilloscope to $\mathbf{1V/div}$ on both channels, set the horizontal scale to $\mathbf{20\ ms/div}$ and set the oscilloscope back to **"Run"** mode. Set the signal generator output voltage to $\mathbf{3\ V}$ **peak-to-peak** and the frequency to $\mathbf{10\ Hz}$ and select the **square wave** output. Add a **DC offset** of $\mathbf{1.5\ V}$, in the signal generator, so that the input signal becomes a square wave in the range $0\ \mathrm{V}$ to $3\ \mathrm{V}$.

Connect the signal generator and oscilloscope as indicated in Figure 5.5. Observe the signal generator voltage and capacitor voltage displayed on the oscilloscope. Sketch both waveforms in the graph below (you can use the Run/Stop button to obtain a still image if needed).

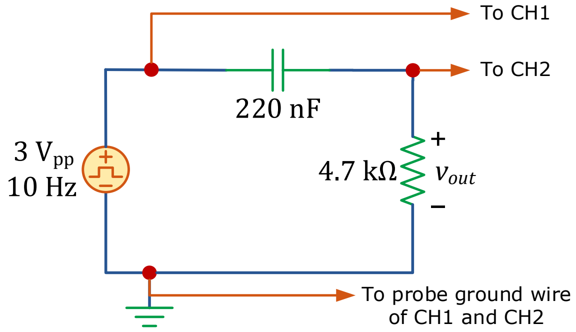
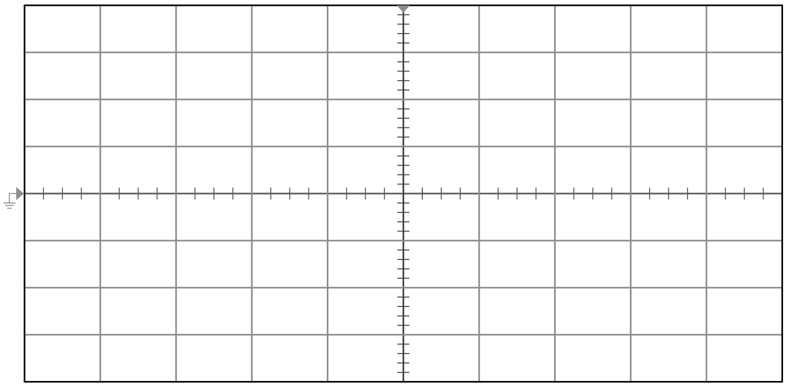


Figure 5.5. RC differentiator used to generate periodic trigger pulses.

CH1, CH2

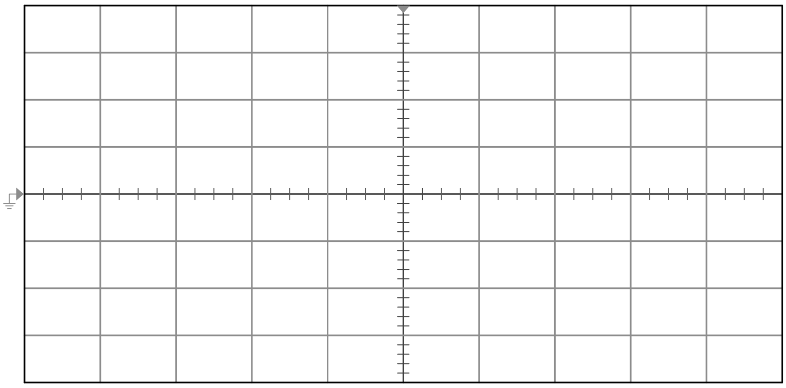


Horizontal scale:________ Vertical scale:________

Justify any differences in voltage amplitude and transient behaviour duration (what is the time constant of the circuit?) between your measurements and the theoretical values that you plotted in **A.3**.

B.5 Increase the frequency of the input signal to $\mathbf{1\ kHz}$ while the circuit is running and sketch the new waveforms in the graph provided (adjust the horizontal scale appropriately).

CH1, CH2



Horizontal scale:_______ Vertical scale:_______

Explain how varying the frequency of the voltage source impacts the voltage across the capacitor. What would happen to the capacitor voltage if you further increased the frequency of the voltage source? Why does this occur?

B.6 Decrease the frequency of the input signal to its original value (i.e., $\mathbf{10\ Hz}$) and add the buzzer to your circuit (as shown in Figure 5.6). Measure the time constant of your circuit using the corresponding channel of the oscilloscope. Justify any discrepancies between this value and the one you stated for the circuit without a buzzer in **A.1**. Based on this, explain whether disregarding the effect of the buzzer on the timer in the analytical part of the lab was a reasonable assumption. Once you finish, increase the frequency of the input signal progressively using the generator frequency range buttons (i.e., $100\ \mathrm{Hz}$, $1\ \mathrm{kHz}$, $10\ \mathrm{kHz}$ and $100\ \mathrm{kHz}$) to see the effect of frequency on the buzzer. Write down and justify your observations.

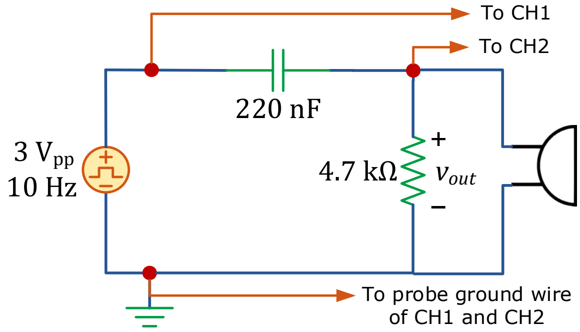


Figure 5.6. Timer circuit with buzzer.

II. RL transients

B.7 The transient response of an RL circuit will be observed in this section using an inductor of $10\ \mathrm{mH}$ and resistor of $1\ \mathrm{k\Omega}$. Measure the resistance of the inductor and note this as R_L. What formula is used to calculate the time constant of an RL circuit? Using this formula, describe the conditions under which R_L would have a considerable impact on the duration of the pulses in a RL differentiator circuit used to generate trigger pulses (like the one shown in Figure 5.7 below)?

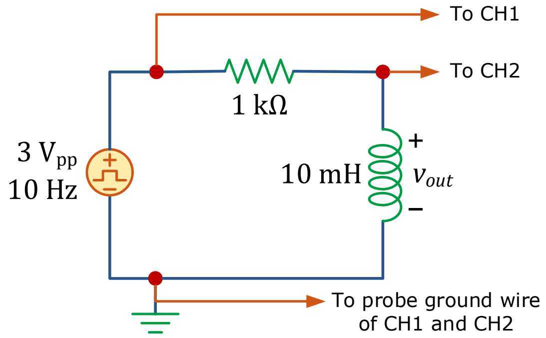
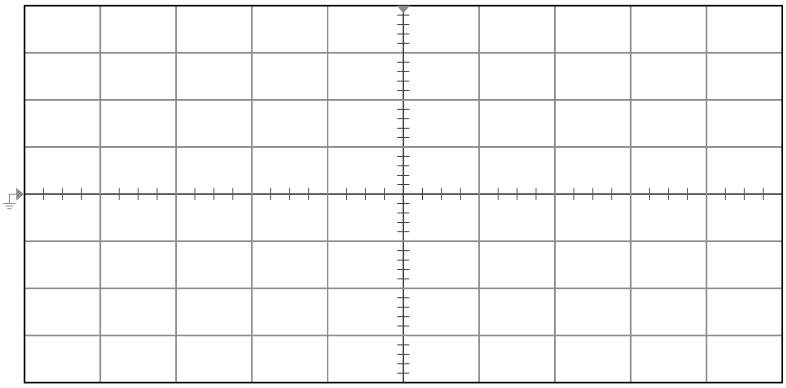


Figure 5.7: RL differentiator used to generate periodic trigger pulses.

B.8 Keeping the settings and connections of the signal generator and oscilloscope the same as in question **B.4**, replace the capacitor and resistor of Figure 5.5 with the inductor and the new resistor, as shown in Figure 5.7. Sketch the waveforms displayed on the oscilloscope in the provided space below (adjust the horizontal scale appropriately so you can observe the trigger pulses).

CH1, CH2



Horizontal scale:_______ Vertical scale:_______

How is the transient behaviour of the RL circuit compared to the RC one? Measure the time constant of your circuit using the corresponding channel of the oscilloscope. Justify any discrepancies between this value and the one obtained in **A.4**.

Check Point 2: Please ask a lab demonstrator to check your work before proceeding. You may continue working on the rest of the lab procedures while waiting for demonstrators.

Lab 6: Operational amplifiers – Doorbell

Aims of this lab

The aim of this lab is to investigate the behaviour of operational amplifiers (Op Amp), in both DC and AC conditions, by analysing and implementing a doorbell circuit.

A. Analytical Part

In this lab we will implement a doorbell circuit which allows the user to light a doorbell button with an LED, ring the doorbell, and speak to the visitor at the door, all using the original two wires to the doorbell button. To test the speaker functionality, we use a sinusoidal waveform. The circuit is shown below.

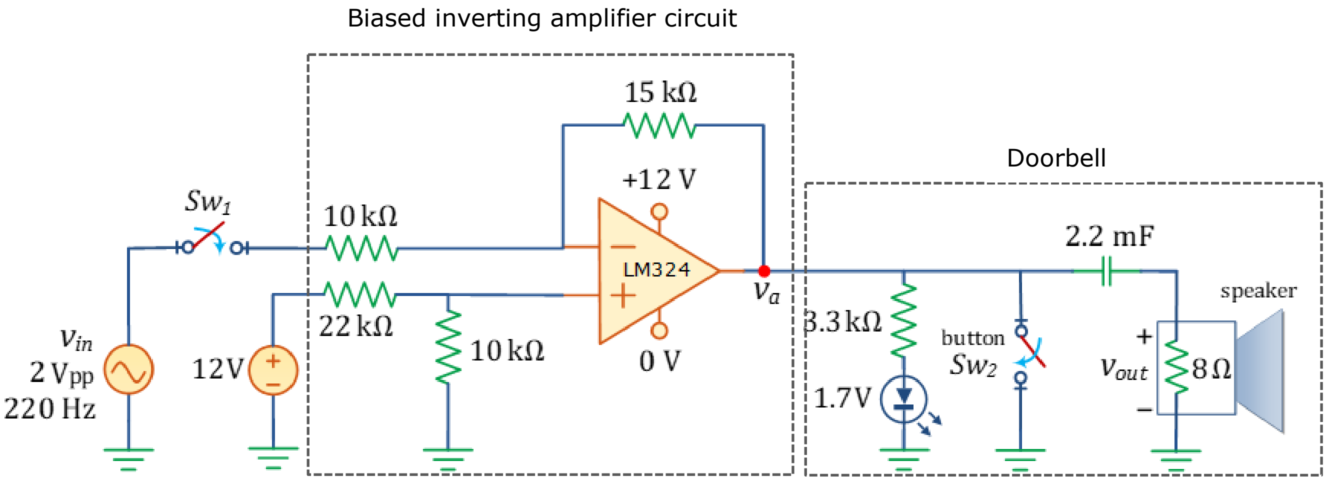


Figure 6.1. Doorbell circuit.

A.1 Calculate the voltage v_a when Sw₁ and Sw₂ are open.

Answer: $v_a = 3.75$ V.

A.2 Using the value of v_a from **A.1**, calculate the current (i_{LED}) and power (P_{LED}) in the LED. Also, calculate the current (i_{out}) and power (P_{out}) in the speaker. Note that switches Sw_1 and Sw_2 are still open.

Answer: $i_{LED} = 0.621 \text{ mA}; P_{LED} = 1.06\, m\text{W}; i_{out} = 0 \text{ A}; P_{out} = 0 \text{ W}.$

A.3 You push and hold the doorbell button Sw_2 (switch Sw_1 remains open). If the button is pushed at time $t = 0\,s$, calculate and plot the voltage across the speaker, v_{out}, for the first 100 ms. Ensure your drawing has at least three key values labelled.

Answer: $v_{out} = -3.75e^{-t/0.0176}$ V.

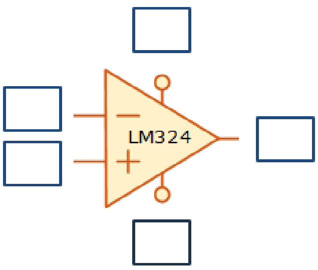
A.4 You push the doorbell button Sw_1 to speak. Express the voltages at the amplifier input, v_{in}, and output, v_a, as a function of time. Why is it important that v_a has a DC offset (i.e., a mean amplitude displacement from zero which is represented as a constant added/subtracted to the sinusoidal signal)?

Answer: $v_{in}(t) = \cos(440\pi t)$ V.

$v_a = 9.375 - 1.5v_{in}$ V.

$v_a(t) = 9.375 - 1.5\cos(440\pi t)$ V.

A.5 Label the pin connections for the operational amplifier based on the information given in Figure 6.2.



B. Experimental part

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

Required components

In this experiment, you require the following components:

- Your breadboard.
- $1\ \text{k}\Omega, 3.3\ \text{k}\Omega, 2 \text{ x } 10\ \text{k}\Omega,\ 15\ \text{k}\Omega$ and $22\ \text{k}\Omega$ resistors from the resistor containers in the lab.
- 1 LED (OVFSRAC8) from your **lab kit**.
- $2.2\ \text{mF}\ (2200\ \mu\text{F})$ capacitor from your **lab kit**.
- $8\ \Omega$ mini speaker from your **lab kit**.
- LM324 Op Amp from your **lab kit**.

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

Other relevant information

Figure 6.3 shows the physical layout of the LM324 Op Amp. The LM324 Op Amp is a quad Op Amp (i.e., it has 4 Op Amps), and can work in dual (i.e., from V_{CC} to V_{EE}) as well as single (i.e., from V_{CC} to GND) supply mode.

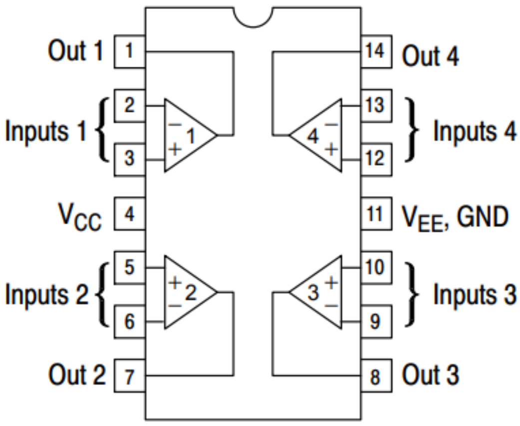
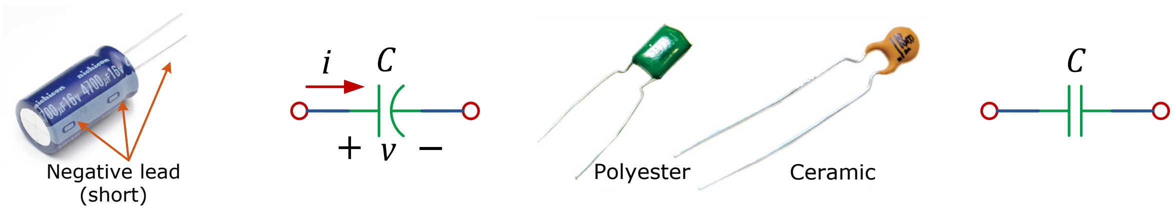


Figure 6.3: Physical layout of LM324 Operational Amplifier (note that V_{CC} and V_{EE}/GND are DC voltages from the power supply used to power up the Op Amp).

⚠ **Electrolytic** capacitors have **fixed polarity**, as shown in Figure 6.4(a) (note the circuit symbol for capacitors sensitive to reverse voltage in Figure 6.4(b)). If you connect the electrolytic capacitor the wrong way, large reverse current flow will cause **explosion.** Note that ceramic/polyester capacitors which are used in the lower range, e.g., nF and pF, are non-polarity devices (see examples in Figure 6.4(c), and circuit symbol for generic capacitors in Figure 6.4(d)).



(a) (b) (c) (d)

Figure 6.4: (a) Electrolytic capacitor, (b) Reverse-voltage sensitive capacitor circuit symbol, (c) Polyester and ceramic capacitors, (d) Generic capacitor circuit symbol.

⚠ **Protective eyewear is MANDATORY in this lab. Please make sure you always wear lightweight and impact-resistant safety glasses or goggles!**

I. Inverting amplifier

B.1 Build the **inverting amplifier** circuit shown in Figure 6.5 on your breadboard, using any of the Op Amps in Figure 6.3 (refer to the answer provided in **A.5**). Use the signal generator to provide a sinusoidal input voltage v_{in} with $\mathbf{2\ V}$ **peak-to-peak** and a frequency of $\mathbf{220\ Hz}$. Supply the Op Amp with $\pm\mathbf{12\ V}$ DC by configuring the DC power supply into **series mode**[11] with a current limit of $0.5\ \mathrm{A}$.

Display, on the oscilloscope and using the same scales, the input signal v_{in} on CH1 and the output signal v_{out} on CH2. Observe the 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.

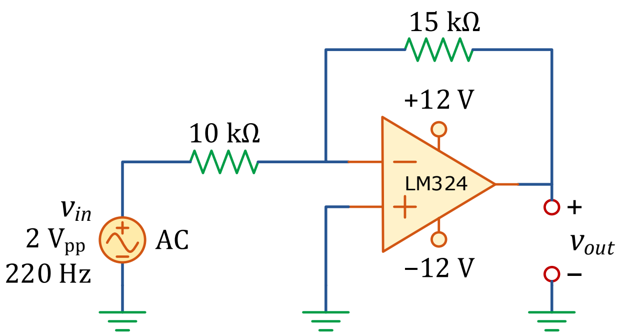
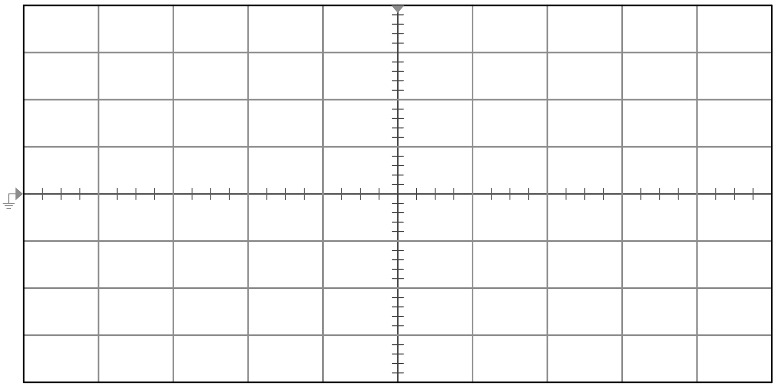


Figure 6.5: Inverting amplifier circuit with AC input and dual symmetrical voltage supply.

[11] Further details of the different modes of the DC power supply and how they are selected can be found in the Appendix (DC power supply).



Horizontal scale:________ Vertical scale:________

B.2 Using the same circuit, change the negative supply voltage to $\mathbf{0\ V}$ (instead of $-12\ \mathrm{V}$), as shown in Figure 6.6. When changing the negative supply of the Op Amp, <u>do not change the **series mode**</u> of the power supply. Instead, you should <u>just change the connections from $-\mathbf{12\ V}$ **to the ground** ($\mathbf{0\ V}$) **of the power supply**</u>.

Display the input signal v_{in} on CH1 and the output signal v_{out} on CH2 of the oscilloscope. Ensure that both channels have the same scales. Observe the 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.

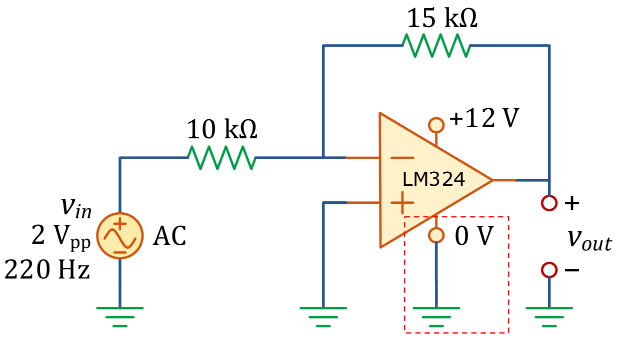
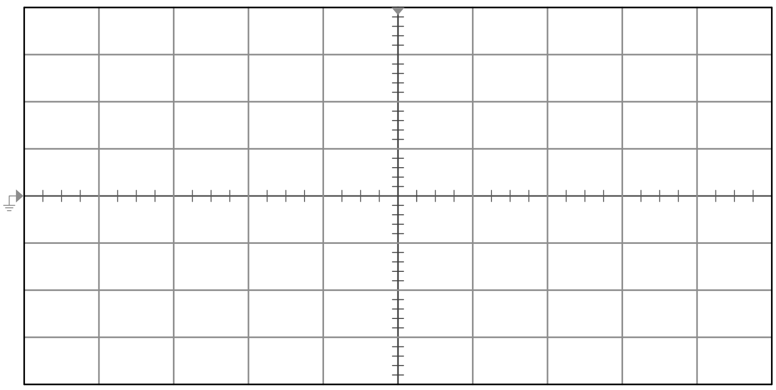


Figure 6.6: Inverting amplifier circuit with AC input and single asymmetrical voltage supply.



Horizontal scale:________ Vertical scale:________

B.3 Modify the previous circuit, as per Figure 6.7, to analyse the effect of biasing the Op Amp. Note that the same $+\mathbf{12\ V}$ DC voltage supply energising the Op Amp is connected to the 22 kΩ resistor.

Display the input signal v_{in} on CH1 and the output signal v_{out} on CH2. Set the vertical scale of the oscilloscope to $\mathbf{1V/div}$ on both channels with **DC Coupling**. Note that <u>the bias circuit will add a DC offset</u> to the output signal, so you will need to move the signal down using the small vertical knob for CH2 (shown in Figure 6.8) to see it.

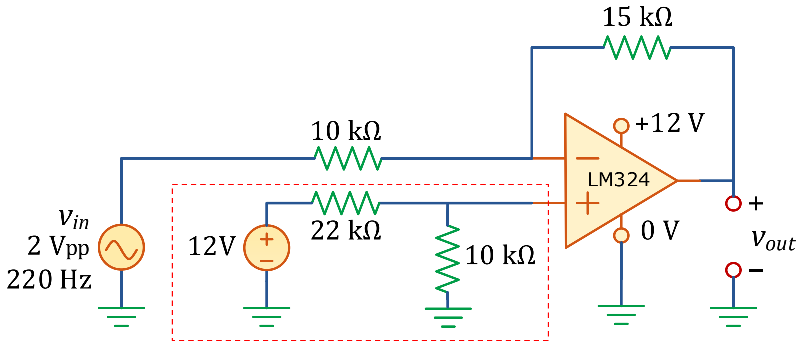


Figure 6.7: Biased inverting amplifier circuit with AC input and single asymmetrical voltage supply.

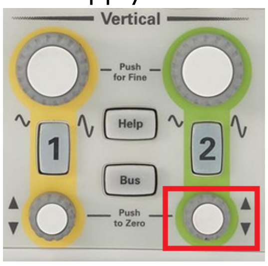
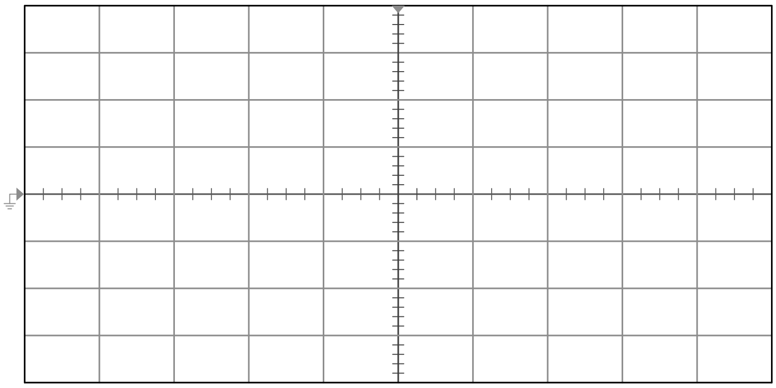


Figure 6.8: Small vertical knob for CH2 used to control the vertical position of CH2.

Observe the voltage waveforms and sketch them in the graph provided below. Clearly label the peak values and the fundamental time-period or frequency of the waveforms on the graphs.



Horizontal scale:________ Vertical scale:________

Use the space provided to justify any discrepancies between your measured v_{out} and the theoretical expression that you stated in **A.4**.

B.4 Explain the differences between the results obtained in **B.1**, **B.2** and **B.3** due to the difference circuit configurations. Justify why we need to use the biased amplifier to implement the doorbell circuit analysed in this lab[12]. Hint: the doorbell should work with a <u>single</u> 12-V battery.

Check Point 1: Please ask a lab demonstrator to check your work before proceeding. You may continue working on the rest of the lab procedures while waiting for demonstrators.

II. DC analysis of doorbell circuit

B.5 Use the same **inverting amplifier** circuit as before to build the doorbell circuit shown in Figure 6.9. Since we do not intend to test the speaker functionality at this stage, **there will not be any input voltage v_{in}** (i.e., v_{in} should be an open circuit). All other functionality (light and ringing sound) will be working, given that the 12-V battery is connected. Note that given the small time constant of the RC circuit formed by the 2.2 mF capacitor and the speaker (i.e., 8 Ω resistor), the speaker makes just a short "thud" sound.

Measure the current through and voltage across the LED and calculate the power dissipated by it. Then, measure the current through and voltage across the speaker, and calculate the power dissipated by it. Write the values in the Table below.

⚠ For convenience, <u>use a piece of wire as SW2</u> for your circuit (i.e., when the wire is connected, the switch is closed).

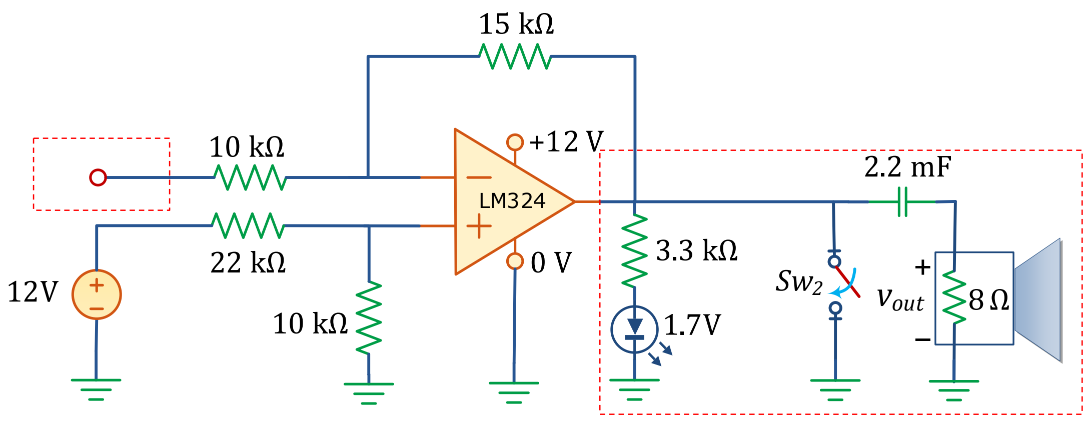


Figure 6.9. Doorbell circuit when no one is speaking to the visitor at the door.

Element	Voltage	Current	Power (calculated)
LED			
Speaker			

[12] A speech signal can be represented as a variation of amplitude with time, where the amplitude can be positive or negative, as shown in the following example: https://commons.wikimedia.org/wiki/File:Signal-speech-martin-de.png

Justify any differences between your measured values of voltage, current and power for the LED and speaker with their respective theoretical values in **A.2**.

B.6 Now, you will characterise the transient behaviour of the doorbell circuit when you close the switch (i.e., ringing) using the oscilloscope. Note that due to the small time constant of the RC circuit, it is difficult to hear an actual sound.

Use channel 1 (**CH1**) of the oscilloscope to measure the voltage v_{out} across the speaker. Set the vertical scale to $\mathbf{1V/div}$ and the horizontal scale to $\mathbf{50ms/div}$. Choose **CH1 as triggering** source on the **falling edge** with a **trigger level** of $\mathbf{0.5\ V}$. Finally, press the **"Single"** button to have the oscilloscope ready to be triggered. The **"Single"** button is yellow until the oscilloscope triggers.

Once all the settings are in place, close SW2. This should display the **transient voltage** of the capacitor. Use this waveform to find the **time constant** of this circuit. Justify any discrepancies between your measured time constant and the one you stated in **A.3**.

III. AC analysis of doorbell circuit and loading effects

B.7 To test the speaker functionality, you will use a sinusoidal waveform as input for the Op Amp (see red box in Figure 6.10). Use the signal generator to provide a sinusoidal input voltage v_{in} with $\mathbf{2\ V}$ **peak-to-peak** and a frequency of $\mathbf{220\ Hz}$.

Display, on the oscilloscope and using the same scales, the input signal v_{in} on CH1 and the output signal v_{out} on CH2. Observe the 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.

⚠ Note that in this question you would be expecting to see a sinusoidal output, but due to an undesirable **loading effect** caused by the small resistance of the speaker, v_{out} is not sinusoidal.

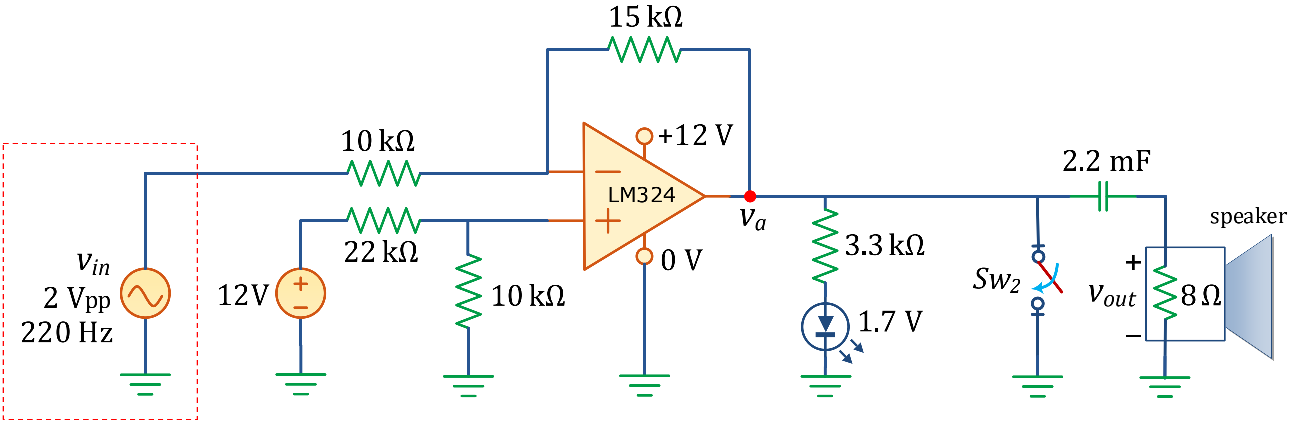
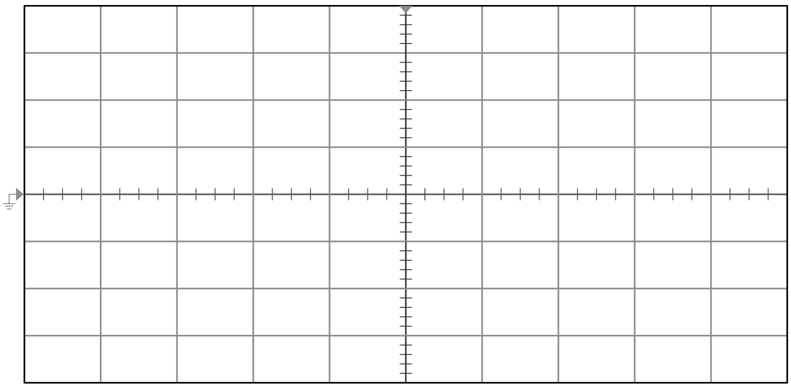


Figure 6.10. Doorbell circuit used to test speaker functionality (i.e., someone is speaking to the visitor at the door).



Horizontal scale:________ Vertical scale:________

B.8 To fix the loading effect problem, add a **1 kΩ resistor in series with the speaker**, as shown in Figure 6.11. Observe the input and output voltage waveforms (where the output includes both the 1 kΩ and the speaker). Use the space provided to describe both voltage waveforms. Are they sinusoidal now? In addition, explain the effect that this change has had on the speaker sound and why it is happening.

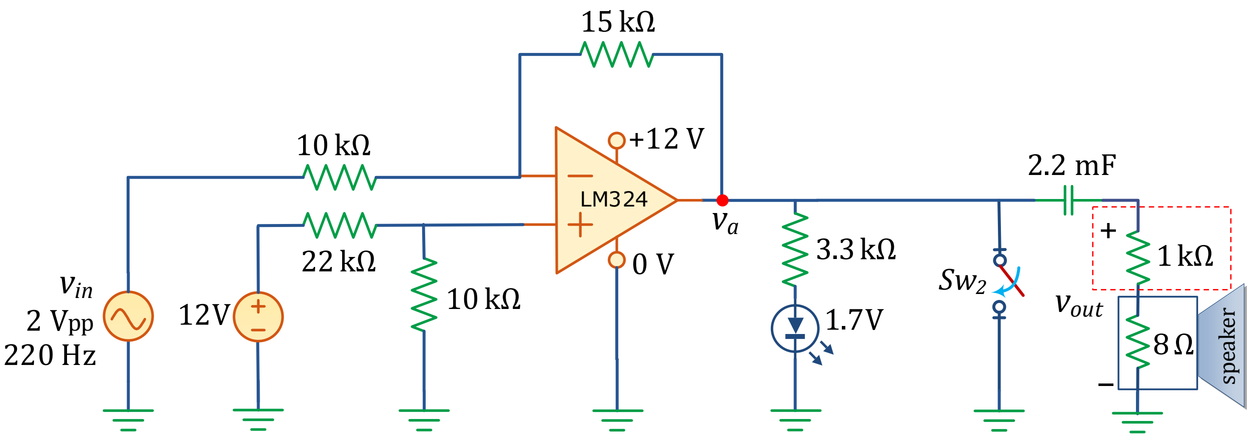


Figure 6.11. Doorbell circuit with additional load used to test speaker functionality (i.e., someone is speaking to the visitor at the door).

Check Point 2: Please ask a lab demonstrator to check your work before proceeding. You may continue working on the rest of the lab procedures while waiting for demonstrators.

Lab 7: AC circuits – Audio equaliser

Aims of this lab

The aim of this lab is to investigate frequency-dependent behaviour of AC circuits by analysing and implementing an audio equaliser.

A. Analytical Part

Audio equalisers allow to adjust the volume of different frequency bands within an audio signal. Sound consists of compressional waves. A microphone converts these waves to an electrical signal, whose amplitude and frequency are proportional to the sound.

The circuit in Figure 7.1 is a 3-channel audio equaliser, consisting of a bank of three filters. Each filter passes the portion of the signal present in its own frequency range or band. The low-pass filter (top) allows signals with frequencies up to $1\ \mathrm{kHz}$ to pass, the band-pass filter (middle) allows signals with frequencies between $1\ \mathrm{kHz}$ and $2.5\ \mathrm{kHz}$ to pass, and the high-pass filter (bottom) allows signals with frequencies over $2.5\ \mathrm{kHz}$ to pass. Signals with frequencies near those limits are partially passed, whereas signals far from those limits are attenuated or blocked. The amplitude passed by each filter is adjusted using a volume control (potentiometer or variable resistor) to control the power in each frequency band.

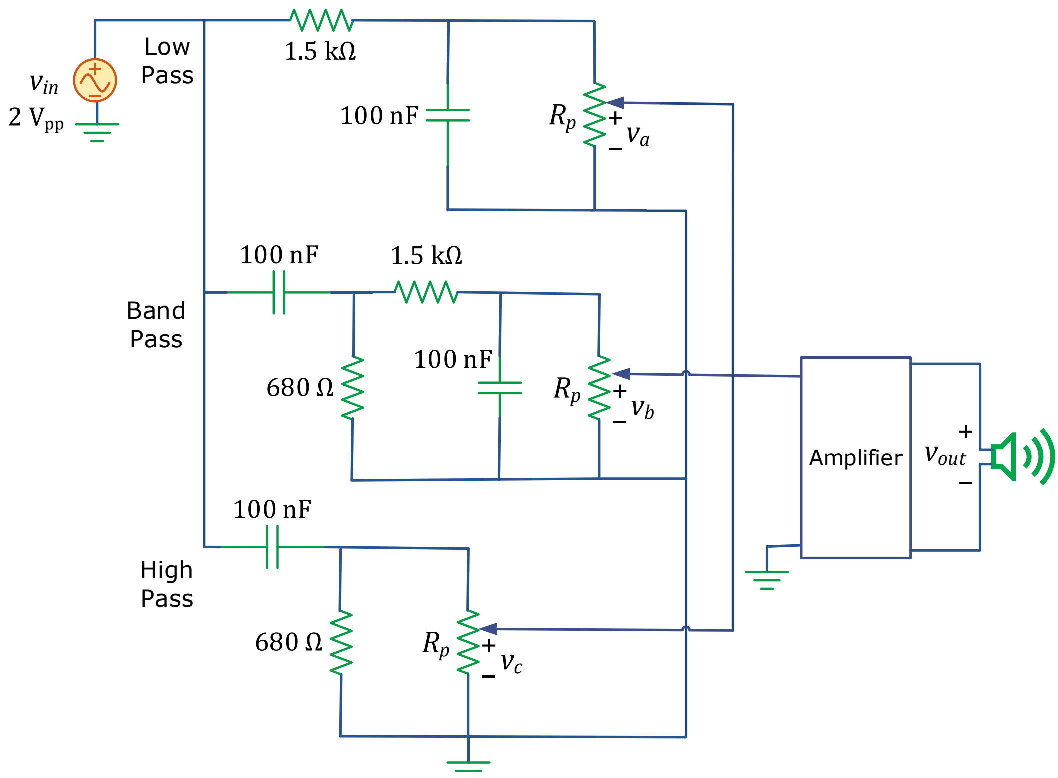


Figure 7.1. Three-channel audio equaliser[13].

[13] Adapted from https://www2.ece.ohio-state.edu/~anderson/Outreachfiles/AudioEqualizer.pdf

To make it possible to hear the effect of the equaliser, an amplifier is used. Note that the amplifier (see Figure 7.2) is pre-built and supplied to you to reduce the complexity of the set-up.

The equaliser can be tested using a sinusoidal wave, where the amplitude represents air pressure and the frequency relates to pitch, with lower frequencies relating to lower pitches.

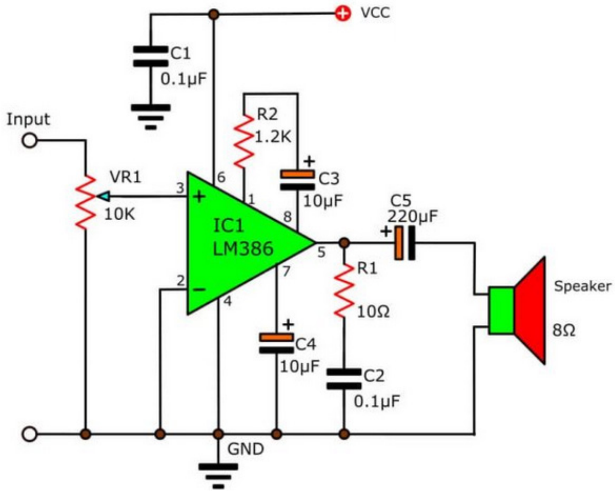


Figure 7.2. Amplifier circuit[14] for Lab 7. V_{CC} is set to 5 V and the input 10 kΩ potentiometer (or variable resistor) is replaced with a fixed resistor so that the behaviour of the amplifier is the same for all students.

A.1 Considering only the low pass filter stage of the audio equaliser (i.e., excluding the amplifier and speaker, as shown in Figure 7.3), calculate the voltage V_a as a phasor when the potentiometer (or variable resistor) value is $8\,\mathrm{k\Omega}$ (i.e., $R_p = 8\,\mathrm{k\Omega}$) and the frequency of the input signal is $100\,\mathrm{Hz}$, $1\,\mathrm{kHz}$ and $10\,\mathrm{kHz}$. What happens to the magnitude of V_a as frequency increases? Does this match the behaviour of a low pass filter (as per the explanation provided in the lab description in the previous page)?

NOTE: To avoid repeating the same calculation 3 times, you may opt to calculate V_a as a function of ω or f and then substitute the values.

Answer: $V_a(100\ \mathrm{Hz}) = 0.84\,\angle -4.54°\ \mathrm{V}$;
$V_a(1\ \mathrm{kHz}) = 0.66\,\angle -38.44°\ \mathrm{V}$;
$V_a(10\ \mathrm{kHz}) = 0.105\,\angle -82.82°\ \mathrm{V}$.

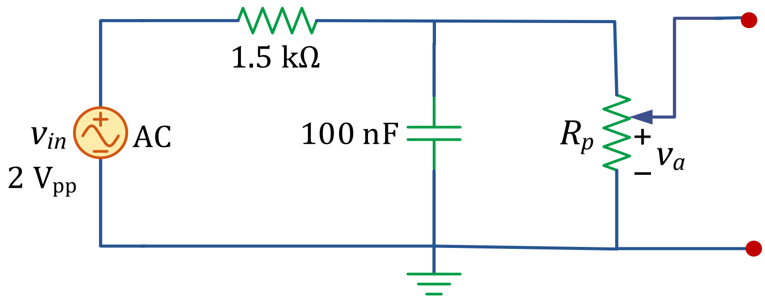


Figure 7.3: Low pass filter stage of audio equaliser. Note that R_p is a $10\,\mathrm{k\Omega}$ potentiometer used to control the volume.

[14] LM386 mini audio amplifier circuit from ElecCircuit.com.

A.2 Based on your result for **A.1**, express the voltage v_a as a function of time if the frequency of the input signal is 100 Hz, 1 kHz and 10 kHz.

Answer: $v_a(100 \text{ Hz}) = 0.84 \cos(200\pi t - 4.54°) \text{ V}$;

$v_a(1 \text{ kHz}) = 0.66 \cos(2000\pi t - 38.44°) \text{ V}$

$v_a(10 \text{ kHz}) = 0.105 \cos(20000\pi t - 82.82°) \text{ V}$.

B. Experimental part

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

Required components

In this experiment, you require the following components:

- Your breadboard.
- $2 \times 680\ \Omega$ resistors and $2 \times 1.5\ \mathrm{k}\Omega$ resistors from the resistor containers in the lab.
- $4 \times 100\ \mathrm{nF}$ capacitor from the capacitor containers in the lab.
- $3 \times 10\ \mathrm{k}\Omega$ trimmer potentiometers (supplied to you).
- $8\ \Omega$ mini speaker from your **lab kit**.
- Amplifier (pre-built and supplied to you).

Videos and guides for review

List of suggested videos:

Signal generator

Oscilloscope

List of suggested guides from Appendix:

- Signal/Function generator
- Oscilloscope

Other relevant information

Variable resistors or potentiometers are used in this laboratory (in particular, trimmer potentiometers or trim pots). The schematic and steps to set them are mentioned below.

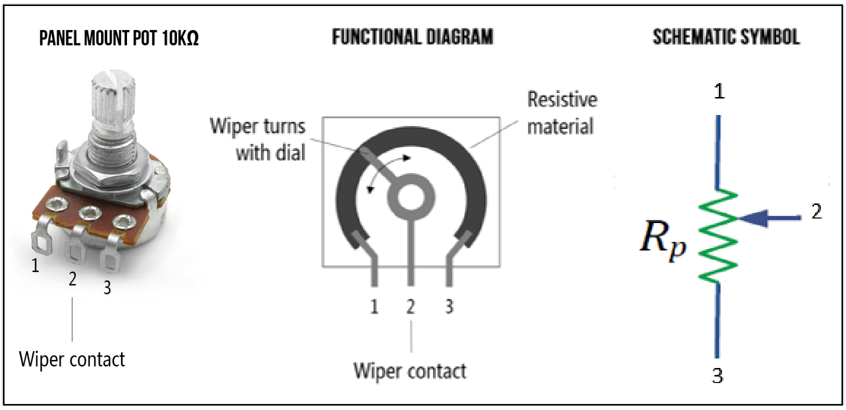


Figure 7.4. Potentiometer.

1. Place the potentiometer in the breadboard without a circuit.
2. Connect wires to terminal 1 and 2, measure the resistance (R_p).
3. Change the dial until you get the value that you need.
4. Place the potentiometer in the circuit and connect accordingly.

To hear the effect of the equaliser, an amplifier is used. The amplifier is pre-built and supplied to you to reduce the complexity of the set-up. The way to connect the amplifier to the circuit is shown in Figure 7.5.

Note that the grounds (GND) of the function generator and the DC source should be connected together and connected to the GND terminals.

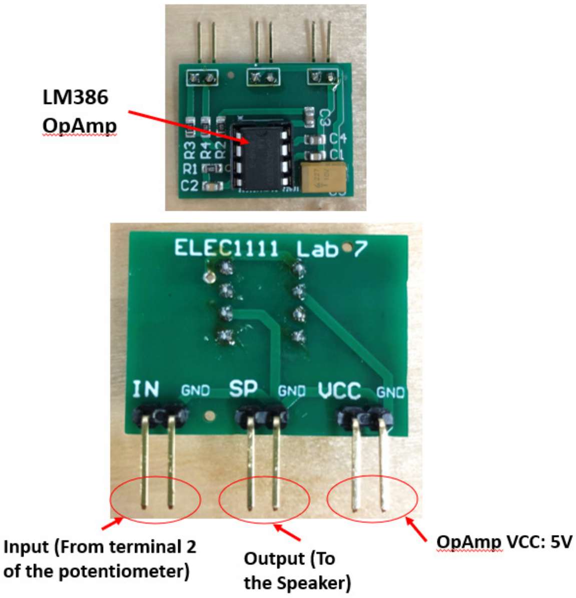


Figure 7.5. Pre-built amplifier for audio equaliser[15].

I. Frequency/Phasor domain analysis of AC circuits

B.1 Construct the low-pass filter of the audio equaliser, circuit show in Figure 7.6, on your breadboard. The first step will be to **observe the behaviour of the low-pass filter**, which is designed to allow signals with frequencies up to 1 kHz to pass.

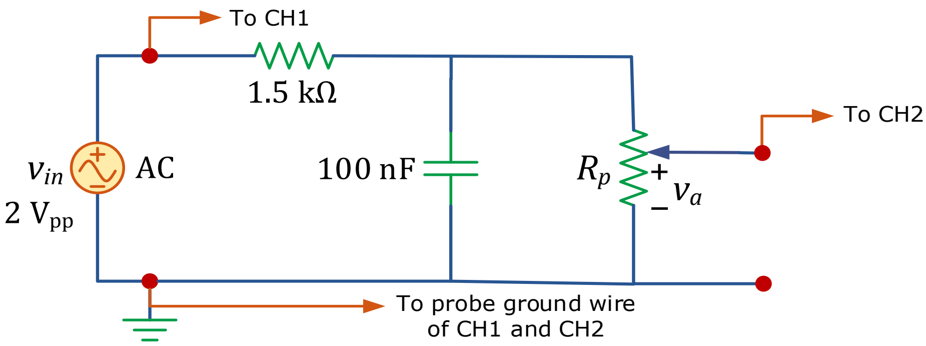


Figure 7.6: Low-pass filter stage of audio equaliser. Note that R_p is a $10\ \text{k}\Omega$ potentiometer used to control the volume.

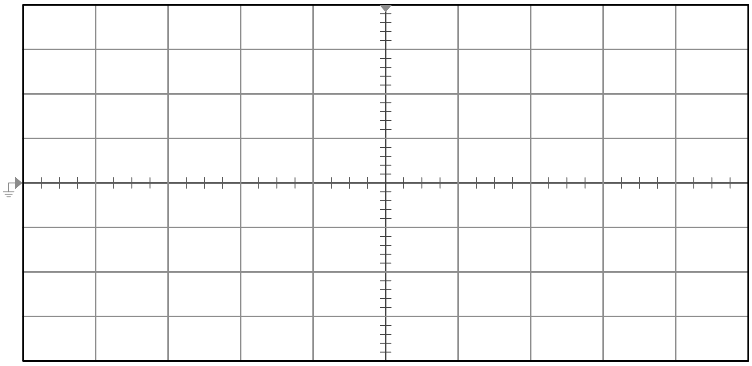
Use the signal generator to provide an input sinusoidal voltage v_{in} of **2 V peak-to-peak** with a frequency of **100 Hz**. Then, set the potentiometer value to **8 kΩ** (i.e., $R_p = 8\ \text{k}\Omega$).

Use **CH1** of the oscilloscope to measure the input voltage, v_{in}, and **CH2** to measure the filter output voltage waveform, v_a. Sketch the waveforms from both channels in the space provided below with at least **2 full periods** of each signal.

---

[15] LM386 mini audio amplifier circuit from ElecCircuit.com, shown in Figure 7.2.

CH1 and CH2



Horizontal scale:_______ Vertical scale:_______

Justify any discrepancies between the theoretical value of v_a obtained in **A.1** and your measured value from the oscilloscope.

B.2 Write the magnitude and phase values of the filter output voltage v_a obtained in **B.1** at $100\ \mathrm{Hz}$ in the Table below. Then, increase the frequency of the signal generator according to the Table and repeat the measurements looking at the effect on the v_a waveform. Compare the measured magnitude and phase values with the theoretical ones you calculated in **A.1**.

Frequency	Calculated filter output voltage magnitude $\lvert\mathbf{V}_a\rvert$ (peak value) (**A.1**)	Measured filter output voltage magnitude $\lvert\mathbf{V}_a\rvert$ (peak value)
$100\ \mathrm{Hz}$ (from **B.1**)		
$1\ \mathrm{kHz}$		
$10\ \mathrm{kHz}$		

Frequency	Calculated filter output voltage phase $\angle\mathbf{V}_a$ (**A.1**)	Measured filter output voltage phase $\angle\mathbf{V}_a$
$100\ \mathrm{Hz}$ (from **B.1**)		
$1\ \mathrm{kHz}$		
$10\ \mathrm{kHz}$		

B.3 Explain how and why the filter output voltage waveform v_a is changing as the frequency increases, particularly with respect to the magnitude. Describe how this behaviour matches that of a low-pass filter.

B.4 Add the pre-built amplifier (shown in Figure 7.7) and speaker circuit to your existing circuit, as shown in Figure 7.7. To power up the Op Amp, adjust the output voltage of the DC power supply to $5\,\mathrm{V}$ (with $\pm 0.1\,\mathrm{V}$ tolerance) and a current limit of $0.5\,\mathrm{A}$. Connect the supply to the VCC-GND terminals as shown in Figure 7.7. Complete the Table below.

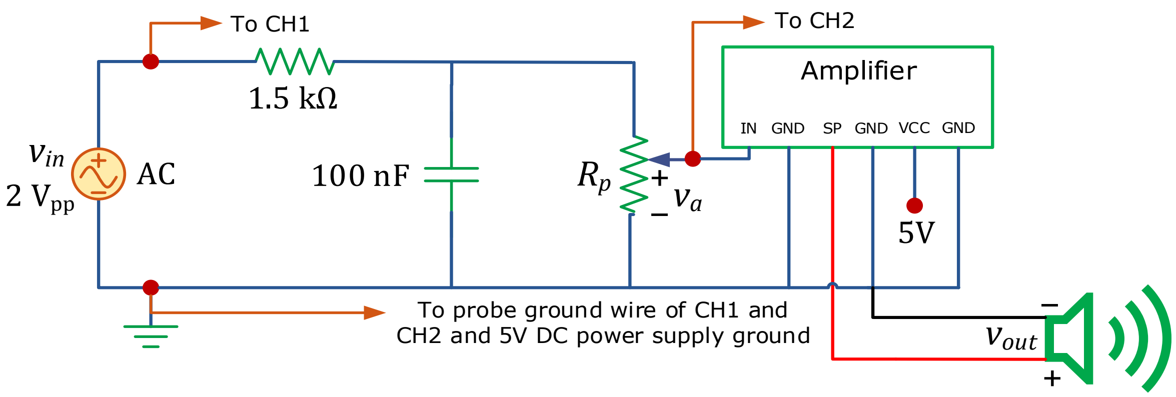


Figure 7.7: Low-pass filter stage of audio equaliser, including amplifier and speaker. Note that R_p is a $10\,\mathrm{k}\Omega$ potentiometer used to control the volume.

Frequency	Filter output voltage magnitude $\lvert\mathbf{V}_a\rvert$ (peak value)	Filter output voltage phase $\angle\mathbf{V}_a$
$100\,\mathrm{Hz}$		
$1\,\mathrm{kHz}$		
$10\,\mathrm{kHz}$		

Explain the effect of the amplifier circuit on the magnitude of the voltage v_a. In addition, explain the effect that frequency has on the pitch.

Check Point 1: Please ask a lab demonstrator to check your work before proceeding. You may continue working on the rest of the lab procedures while waiting for demonstrators.

B.5 Now, you will **observe the behaviour of the volume control**.

Keep the previous circuit set up and set the frequency of the sinusoidal input v_{in} back to $\mathbf{100\ Hz}$.

Write the magnitude and phase values of the voltage v_a obtained in **B.4** in the Table below. Then, set the value of the potentiometer according to the Table and look at the effect on the filter output voltage v_a.

Potentiometer value	Filter output voltage magnitude $\lvert\mathbf{V}_a\rvert$ (peak value)	Output voltage phase $\angle\mathbf{V}_a$
$4\ \mathrm{k\Omega}$		
$8\ \mathrm{k\Omega}$ (from **B.4**)		
$10\ \mathrm{k\Omega}$		

B.6 Based on your observations from **B.5**, explain the effect of the volume control potentiometer on the magnitude of the filter output waveform v_a when the frequency is kept constant.

B.7 The last step to fully characterise the behaviour of the low-pass filter stage of the audio equaliser is to observe the **gain of the amplifier**.

Set the frequency of the sinusoidal input v_{in} to $\mathbf{1\ kHz}$ and decrease the amplitude of v_{in} to $\mathbf{200\ mV}$ **peak-to-peak** to avoid saturation. Set the value of the potentiometer back to $\mathbf{8\ k\Omega}$. Use **CH1** of the oscilloscope to measure the filter output voltage v_a and **CH2** to measure the output voltage v_{out}, as shown in Figure 7.8. Sketch the waveforms from both channels in the space provided below with at least **2 full periods** of each signal.

⚠ Note that there might be some undesirable noise in v_{out}. You can ignore it when you sketch your graph.

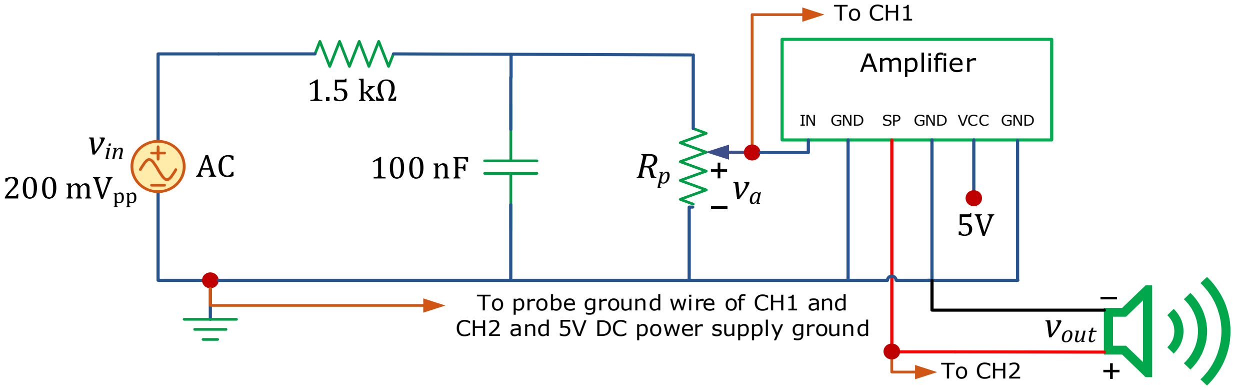
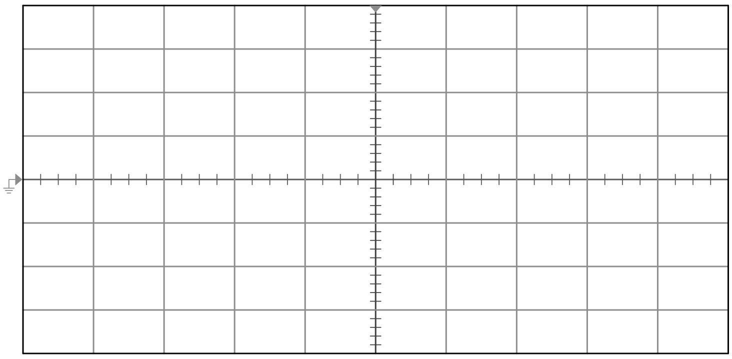


Figure 7.8: Low-pass filter stage of audio equaliser.

CH1 and CH2



Horizontal scale:________ Vertical scale:________

B.8 Based on your measurements of v_a and v_{out} in **B.7**, calculate the gain of the amplifier.

B.9 Construct the three-channel audio equaliser shown in Figure 7.9. Use the signal generator to provide a $\mathbf{2\,V}$ **peak-to-peak sinusoidal** with a frequency of $\mathbf{2\,kHz}$. Set the potentiometer value to $\mathbf{10\,k\Omega}$ (i.e., $R_p = 10\,\mathrm{k\Omega}$). Measure the voltages (magnitude and phase) obtained at the output of each of the filters, v_a, v_b and v_c **before connecting the amplifier.** Then, connect the amplifier and measure the voltage v_{out} in the speaker.

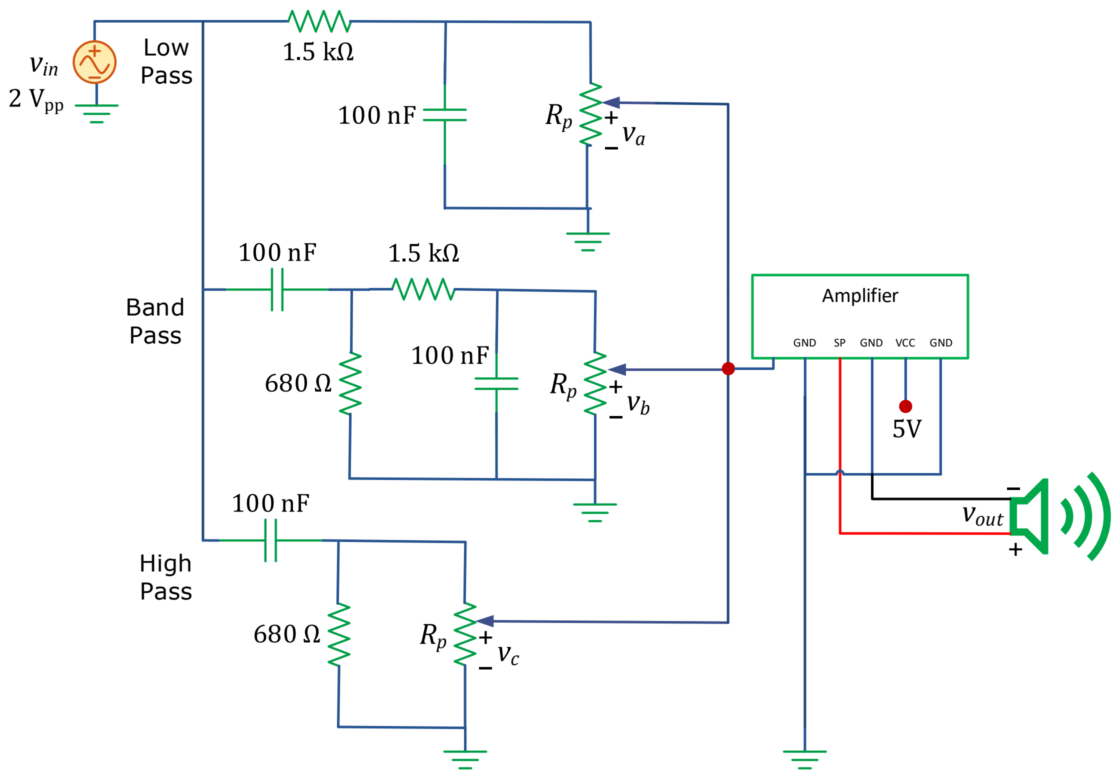


Figure 7.9. Three-channel audio equaliser.

Voltage	Magnitude $\|\mathbf{V}\|$ (peak value)	Phase $\angle\mathbf{V}$
v_a (no amplifier)		
v_b (no amplifier)		
v_c (no amplifier)		
v_{out} (with amplifier)		

Explain the significance of each of the three filters in the output voltage in the speaker, v_{out}, keeping in mind the cut-off frequencies for each of the filters [16]. Once completed, feel free to modify the frequency value and potentiometer values of each of the filters to gain a better understanding on how multi-channel equalisers work.

[16] Note that passive band-pass filters like the one in Figure 7.9 have a large band, so the theoretical and measured cut-off frequencies tend to differ considerably. If you want to check that, simply consider the output of the band-pass filter without the amplifier and change the frequency of the input progressively. The frequencies at which the output amplitude start to decrease will be the measured cut-off frequencies.

Check Point 2: Please ask a lab demonstrator to check your work before proceeding. You may continue working on the rest of the lab procedures while waiting for demonstrators.

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 2.54 mm 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.

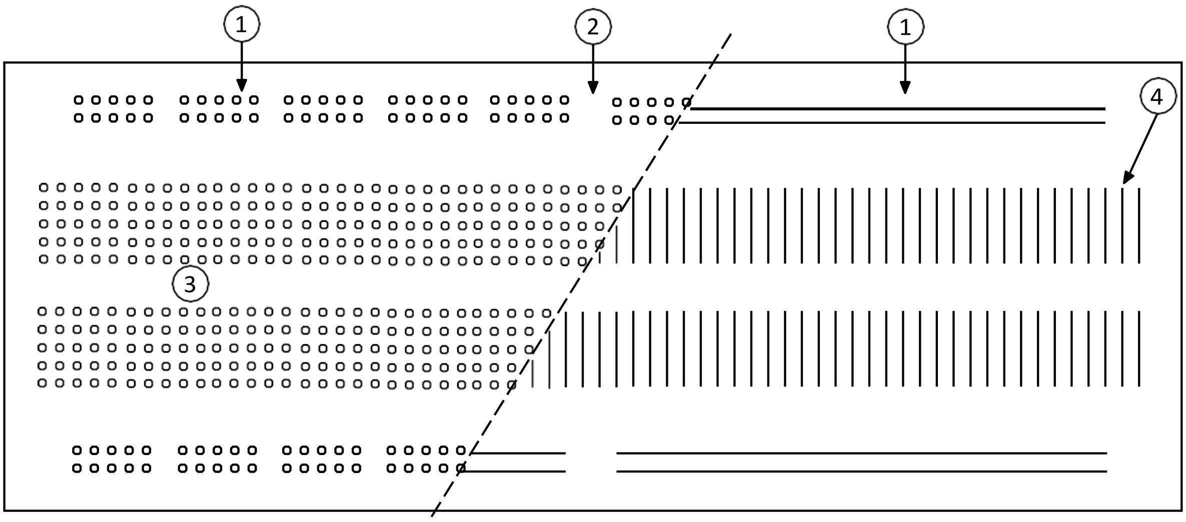


Figure A.1: The layout of the Prototyping Board, showing the hole placings on the left and inter-connecting conductors on the right of the figure.

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.

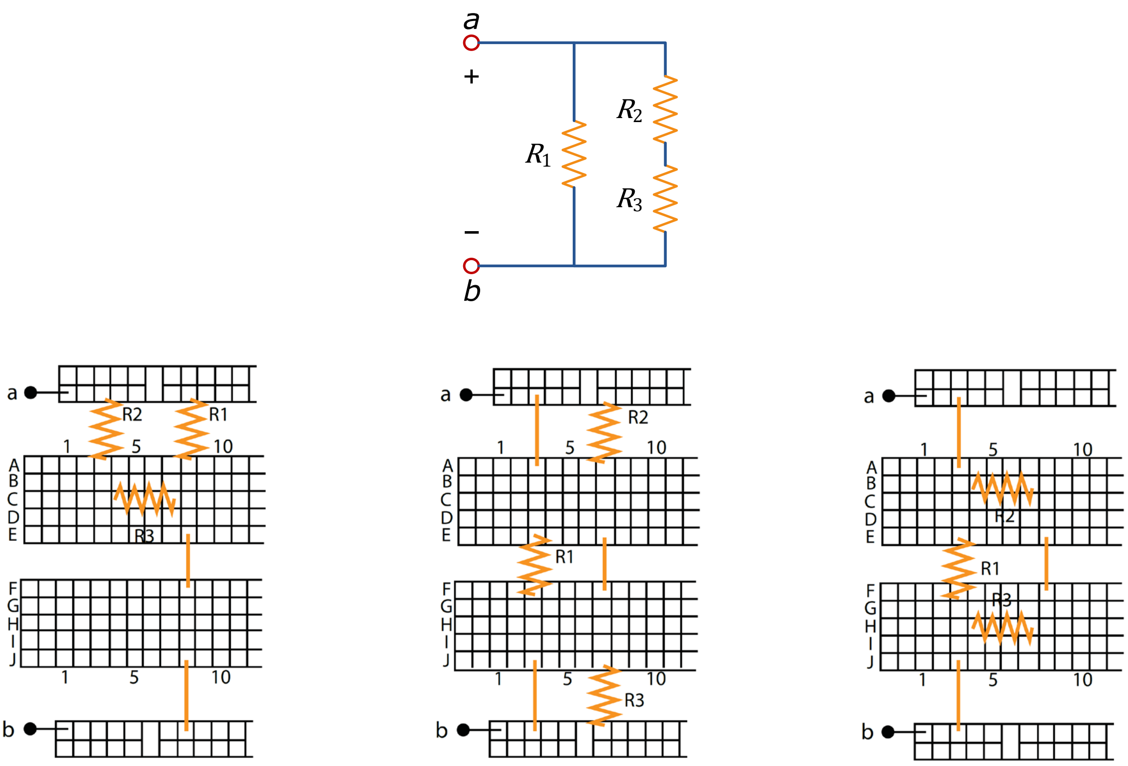
1. There are two rows of connections 1 across the top and bottom of the board. These are useful for power supply leads, earth lines and other connections that are required along the length of the board.
2. Note the gap 2 at the centre of these rows of holes. Use a wire bridge if you want the line to 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.:



(a) (b) (c)

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

Having a clear understanding of the circuit you are building helps in creating a well-planned breadboard layout:

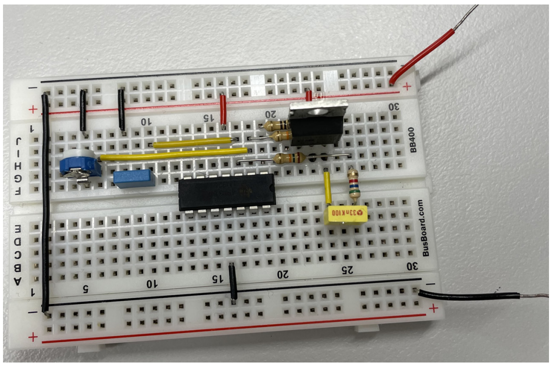


Figure A.3: Well-planned breadboard layout.

Resistor colour coding

The ordinary carbon composition fixed resistors that we use in the laboratory are characterised 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 $1/4\,\mathrm{W}$ 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.4. 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.

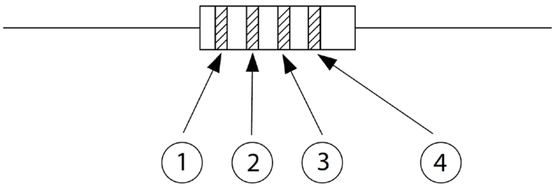


Figure A.4: Colour code bands on a resistor.

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.5.

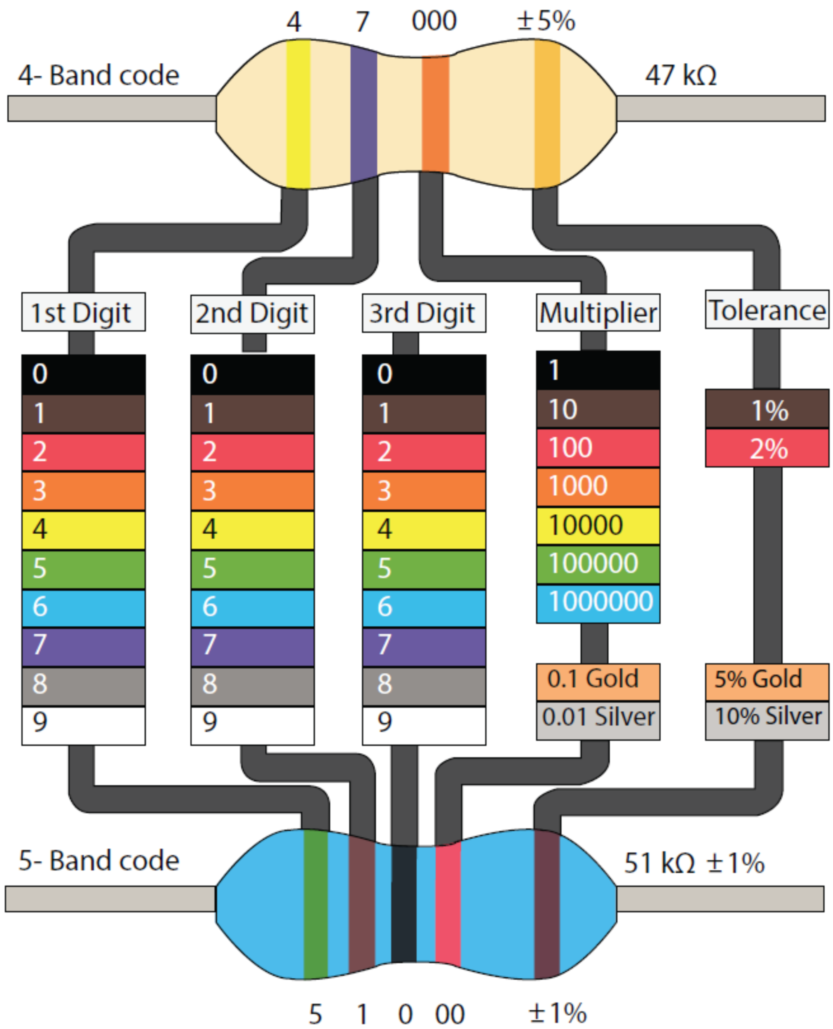


Figure A.5: Colour code bands on a resistor.

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 $1\,\Omega$ to $10\,\mathrm{M}\Omega$, with the lowest tolerance affordable. In our laboratories the resistors generally have a tolerance of $\pm 5\%$. 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 $150\,\Omega$ resistor. If this resistor has a tolerance of $\pm 10\%$, i.e. $\pm 15\,\Omega$, then its actual value may lie anywhere within the range $135\,\Omega$ to $165\,\Omega$. Now consider the $180\,\Omega\ \pm 10\%$ resistor which will have a value between $162\,\Omega$ and $198\,\Omega$. You will see that any resistance value between $150\,\Omega$ and $180\,\Omega$ 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.6. The multimeter connects to your circuit via banana cables, using the ports on the front panel.

Multimeter

Figure A.6: 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.7).

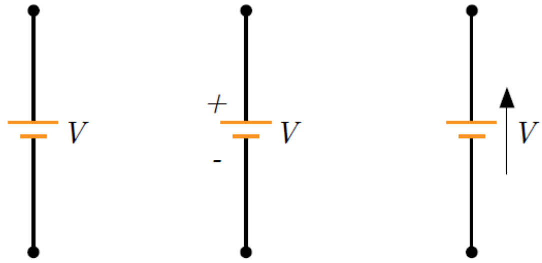


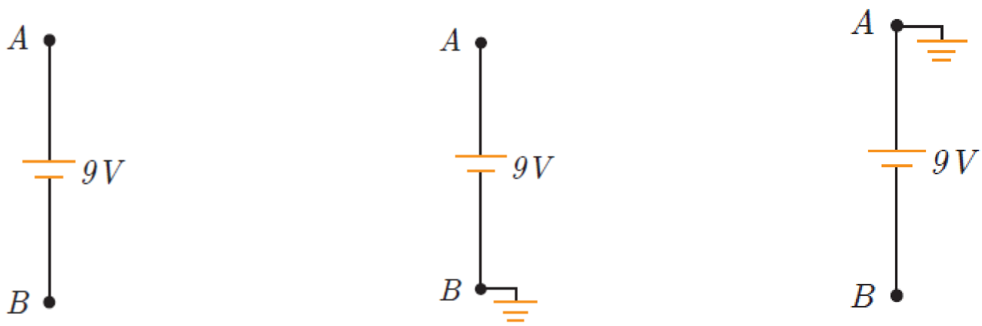
Figure A.7: Circuit symbols and equivalent notations for a battery.

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.8 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.8 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.9.

Power supply

Figure A.9: 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.9).

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. V_1 and V_2 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.10. The circuits you build should not require the use of this terminal.

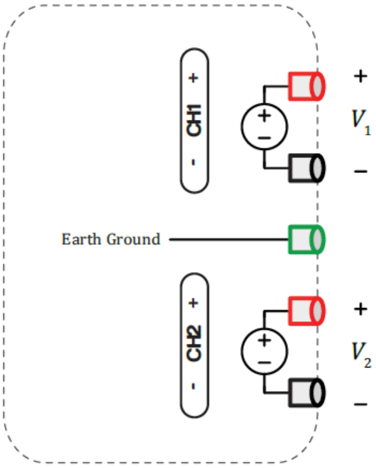


Figure A.10: Simplified diagram of the power supply acting in independent mode.

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.11. 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.

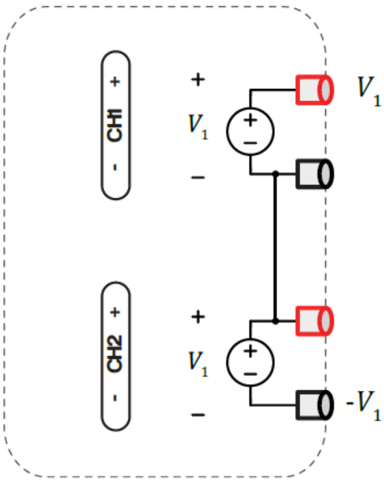


Figure A.11: Simplified diagram of the power supply whilst acting in series mode. Earth GND has been omitted.

⚠ 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.12. This allows you to supply twice the maximum current to your circuit, for a total of 6 A of current.

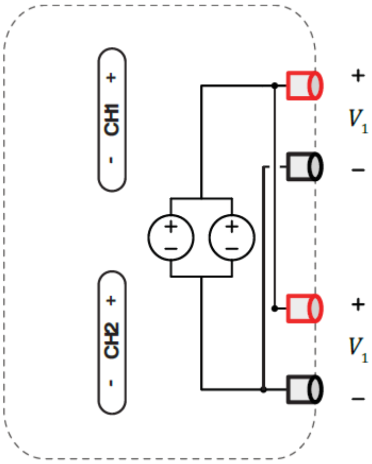


Figure A.12: Simplified diagram of the power supply when it is acting in parallel mode. Earth GND has been omitted.

⚠ 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. 6 A).

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.13.

Figure A.13: 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.14.

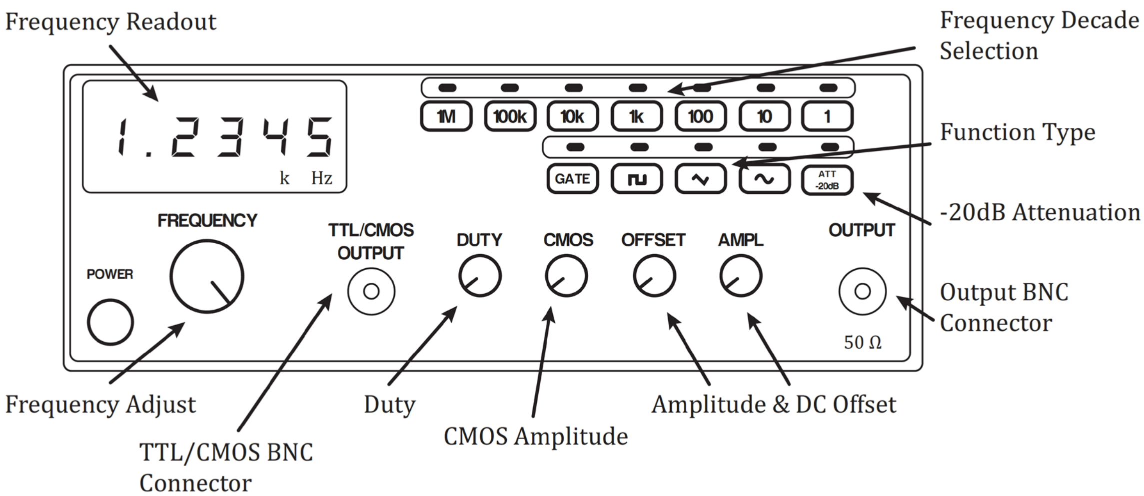


Figure A.14: The control panel with the functionality of each control labelled.

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/+5 V, so when the output is set to TTL, a 0-5 V square wave is provided. If the knob labelled "CMOS" is pulled out, it can be adjusted from 0 to +15 V; 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.15.

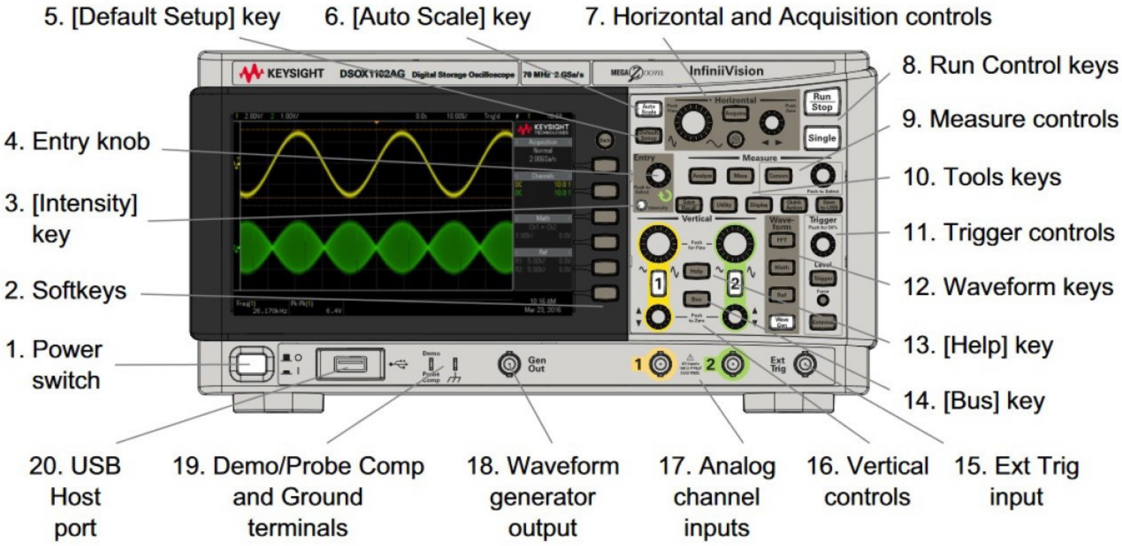
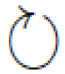


Figure A.15: The DSOX1102A oscilloscope front side.

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 $= 1 / 0.002 = 500$ Hz. 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 = 2 ms). 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 $10\ \mathrm{Hz}$ 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 $1\ \mathrm{M\Omega}$. This is in parallel with $\approx 16\ \mathrm{pF}$ 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 $150\ \mathrm{V}$ 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 centred on the midpoint of screen; Voltage cursor centred on channel ground level).
- Position of Cursor B (Time cursor centred on the midpoint of screen; Voltage cursor centred 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.15) 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.16).

⚠ 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.

Over compensated Correctly compensated Under compensated

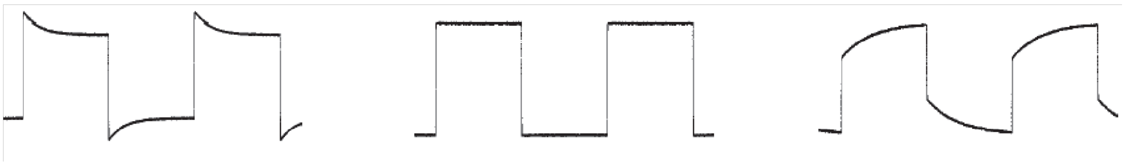


Figure A.16: Proper Calibration.

Mains Ground Input

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.