ENGG1000 Electrical Lab Program

The motivation behind these laboratory exercises is to expose you to some of the technical concepts and ideas that will be useful for you in designing the electronics in your project. Due to time and space limitations we cannot provide more than an introduction and brief explanation of these concepts, and our aim here is more to expose you to some basic features of electronics. For more detailed explanation you are encouraged to consult textbooks and websites on this material.

Your most important resource in the labs is the lab tutors. You're wasting a valuable and important resource if you are not regularly asking these tutors questions and for explanations.

The second point to emphasize is to take accurate notes when you work through these exercises. Many of the ideas you see here will be useful in your design project, and you want to make sure you can accurately repeat what you do here in your design development work. A journal recording your circuits, settings, and measurement results will be a valuable asset to you later on, and is something that should become a habit whenever you do experimental work in the laboratory.

Assessment Guidelines:

- Checkpoints are listed throughout the lab programs. Show your functioning circuits to a lab demonstrator to be marked off. The accumulation of these checkpoint marks for either Lab 2, 3, or 4 will constitute your mark for the lab part of this technical stream, along with your lab book. It is recommended that every individual perform Lab 1, to gain basic familiarity with the lab equipment and lab environment (unless, for instance, you are familiar with the equipment through a course like ELEC1111).
- There will be a short laboratory skills test, examining your competency in using basic lab equipment and circuit analysis. These labs are more than sufficient preparation for this test, and it necessary that any student wishing to undertake this test has successfully completed Lab 1.
- There will be a short multiple choice quiz on Moodle, to assess the theoretical concepts you've learnt during these lab exercises.
- You can move through these lab checkpoints as fast or as slowly as you wish. There is no requirement for an individual or group to complete all experiments and all checkpoints. Each laboratory exercise may have circuit ideas that could prove useful in your design project.

General Guidelines for Electronics

- Your breadboard and the various electronic components you use are quite delicate, so be careful and make sure that each connection is firm.
- Particularly when you begin to work on larger, more complex circuits, there are many things that can go wrong. It is unrealistic to expect to connect all the components together and expect them to immediately work. It is important that you incrementally test every component and connection as you build your circuit.
- Only if every unit works can you expect the entire circuit to function properly. When debugging a circuit bear this in mind, and progressively check each component to verify that it is working as expected and that they are connected in the correct orientation.
- As a last resort, ask a demonstrator for assistance.

Laboratory Safety

You will already have watched a video of the Lab Safety Regulations prior to being admitted to the laboratory; however it is always worth emphasizing the importance of safe practices in an electrical engineering laboratory.

To begin with, please note that use of the EE&T laboratory facilities is conditional on adhering to the following rules:

- You may not smoke, eat or drink in the laboratories.
- Covered footwear must be worn at all times.
- Bags and loose clothing must be stored under the benches. The most common form of accident in laboratories is tripping, so this rule is much more important than you may think.
- You may not, under any circumstances, wire your own project directly to the mains. For this subject, all designs are to be powered either by batteries or from the power supplies provided in the labs.
- Please report any equipment failures or unsafe mains cords to laboratory technical staff or to one of the laboratory demonstrators.

In addition to the above safety guidelines, you should remember that the School's laboratories are a shared resource, to be treated with care and respect. Before leaving the laboratory, please

- turn off and unwire any equipment you have used;

- put all equipment, leads and components away; and

- store all lab stools under the benches.

Laboratory Journal Assessment

You may have either Lab 2, 3, or 4 completed (in terms of checkpoints, and not the additional exercises) and your lab journal submitted to obtain marks for one of the assessments within the Electrical Stream. To have your Lab Journal marked off for marks, here are some basic requirements:

- All of the checkpoints within that particular lab must have been marked off by a lab demonstrator.
- Each time your conducted experimental work in the lab must be dated.
- All circuits, components used, component values, measurement equipment used, and measuring equipment settings must be accurately recorded.
- Measured quantities, including correct units, and results must be accurately recorded.
- Waveforms should be printed from the CROs and pasted neatly into your book (ask a demonstrator to show you how).

It is not expected that you re-write your lab exercises after the end of the exercise for submission – the record you keep while doing the lab should be accurate and complete enough to be marked. Documentation is an important activity in engineering – your records should be accurate enough to be followed and reproduced by a team member, should you happen to be absent for any reason.

Electronic Component Pack

The lab demonstrators will be able to give you the special components as you need them – in the notes below this is referred to as the 'component pack'. Common components, like resistors, capacitors, and diodes, will be available from the shelves on the wall in each of the electronics laboratories. Once you have taken a component be sure to hold onto it, as you will likely need it in a future part of an experiment.

If you are unsure where to obtain a component, ask a demonstrator.

ENGG1000 Electrical Engineering Stream, Session 1, 2016

Lab Exploration Tutorial 1

An Introduction to Electronics

1. Lab Equipment

It is important firstly to introduce you to the main lab equipment that you'll use to conduct your experimental investigation. These devices are widely used throughout the university, even in schools other than Electrical Engineering, and more importantly for you, are the staple of engineers in many industries.

A) DC Power Supply

In your component kit you are provided with a connector to allow you to use a couple of batteries to provide electrical power, in the form of electrical current, to portable devices. These batteries are limited in that they are only able to supply one single voltage to an electrical circuit (9 Volts in the case of the rectangular shaped and aptly named 9V battery), and relatively limited electrical current. The DC Power Supply available to you in the lab provides you much greater flexibility, as it can provide any voltage to the circuit (within its operating range), and considerably more current, as it is ultimately powered from the Mains (the standard 240 V plugs that you run all of your household equipment from).

Some chips that you may use, called integrated circuits, require supplied voltages of ±6 V as well as ground (the 0V reference). To achieve this make sure that the power supply is in series mode (an appropriate selection on the front panel can achieve this), then use the left-most negative terminal as the negative supply (-6 V source), the right-most positive terminal as the positive supply (+6 V point), and either the left-positive or right-negative terminals as ground (the 0V reference point

The DC power supply configured to provide 6V or 12V as just described is illustrated in Figure 1. Note that the dashed connection does not need to be made externally, as is actually connected inside the Power Supply when series mode is connected.). It is always a good idea to verify that the voltage out of the Power Supply is what you intend using the Digital Multimeter.

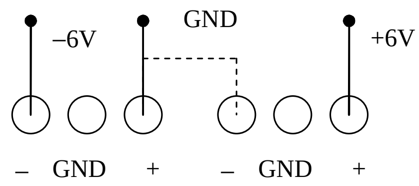

Figure 1 – Using the DC Power Supply to provide -6 V, 0 V and +6 V

B) Digital Multimeter

The digital multimeter is a simpler alternative to the oscilloscope for measuring voltages that do not change over time (or that change relatively slowly with time). Most voltages you will use in this course will be DC, so ensure that the AC/DC button is set accordingly. Also ensure that you have the leads connected to the correct sockets and the right voltage range set. This is the most common mistake in using a Multimeter – trying to measure a voltage when the leads are connect to the current terminal, or vice versa. Multimeters can also measure resistance and current, but this is rarely done, because the LCR bridge is more accurate for measuring resistance and current is usually measured in terms of voltage across a known resistance.

C) Signal Generator

In some instances, you will want to produce voltages that *vary with time* in order to test your circuits. For example, you may want to turn an LED or a motor on once every second. For this purpose, the standard piece of test equipment is the signal generator, also known as a function generator. The signal generator can produce various types of waveforms, including square waves, sinusoids and triangular waves. For these laboratory exercises, you will mostly use a square wave – the main characteristics of this are as follows:

- The maximum voltage (known as amplitude, if the wave if symmetrical about zero Volts): Make sure you know how to control this on the signal generator.
- The minimum voltage: See if you can figure out how to control this.
- The period T, measured in seconds — equivalently, the frequency $f = 1/T$, measured in Hz (cycles/second).
- The duty cycle, meaning the percentage of each period spent in the high voltage state — typically 50%.

Be careful not to use the “TTL output” – this output is designed to produce a 0V / 5V square wave for use with logic circuits.

Depending on the path you follow in this laboratory program, you may also find yourself using the sine wave output.

D) Cathode Ray Oscilloscope

Having generated periodic test signal like the square wave, we need a piece of equipment that allows us to visualize them. The oscilloscope does this, by locking on to a periodic signal (a process known as 'triggering') and displaying usually just a few periods of it. Early oscilloscopes used a cathode ray tube for the display, and were known as cathode ray oscilloscopes (CROs) - there are still a few of these in the labs. You may have watched a video showing you how to use the CRO to display signal waveforms.

CROs are only useful in displaying periodic signals. An electron beam is periodically deflected horizontally at a constant speed, leaving a glowing trace on the phosphorescent screen. The input signal is used to deflect this same beam in the vertical direction. If on each sweep the beam passes over the same trajectory on the screen a stable waveform is obtained. This is the role (or really art) of triggering, to make the sweeps follow the same trajectory and hence view a stable waveform.

Old Televisions worked on exactly the same principle, though in TVs the trajectory of the electron beam is always the same and its intensity (or current) is varied (we say modulated) based on the information signal. A large current produces a bright spot on the screen, while a small current will leave the screen dark in this region. Together, these bright and dark spots combine to produce the visual image you look at everyday on the TV. Colour TVs actually use three beams, for the Red, Blue, and Green colours.

Nowadays most oscilloscopes (and TVs for that matter) are digital, although the principles of operation are similar. The key features of the oscilloscope are:

- You can adjust the horizontal time base of the oscilloscope manually. Make sure you know how.

- You can adjust the vertical (voltage) scale of the oscilloscope manually. Make sure you know how.

- Manual adjustment alone cannot be expected to yield an exact lock with the periodicity of the signal under test. For this reason, all oscilloscopes provide an electronic triggering mechanism which automatically adjusts the flyback period (by a small amount) so that the start of the trace is aligned with a defined event. Typically, this event is based upon the rate at which the input waveform rises (or falls). Play around with the triggering features on the oscilloscope.

- The oscilloscopes in the lab provide at least two separate channels, so you can observe and compare multiple signals together. Both channels share the same horizontal time base. For each channel, you can adjust the vertical gain, controlling the way in which input signal voltage is converted into vertical displacement on the screen. You can also adjust the vertical offset of each channel, allowing you to separate the channels on the screen. Make sure you know how to do these things.

- Be aware of the difference between the DC and AC coupling settings on the CRO. For AC coupling the waveform is displayed so that the average value of the waveform is aligned to 0Volts on the display. For DC coupling, however, the actual voltage at the probe input is displaced, relative to the GND input.

You will regularly need a tutor's help to display signals on the oscilloscope. Do not be afraid to ask them – this all part of the learning process, and they are there to help you learn.

2. Alternating Current Signals

Turn the Signal Generator on and select the sine wave generator. Adjust the generating frequency to 1 kHz (1000 Hz). Now connect the signal generator outputs directly to the input of the CRO (Cathode Ray Oscilloscope) – use Channel 1.

Use the oscilloscope to display the 1 kHz sine wave signal. Sketch this waveform in your lab book, recording the CRO settings you use (the y-axis, expressed as Volts/Div, and the x-axis, expressed as µs/Div). Note that you can vary the amplitude of the signal generated by the Signal Generator using the 'Gain' knob. Set the voltage produced by the Signal Generator to 2 V peak to peak.

Now repeat for a 100 kHz sine wave produced by the signal generator. Then generate a 1 kHz square wave – such square-wave signals are important in Integrated Circuits (ICs) as Clock signals (for example, what is the clock speed of your computer?). Sketch of these in your note book, along with the CRO settings used.

3. Breadboards

The breadboard is your flexible platform for constructing multiple electric circuits in the lab. Its internal connections are as shown in Figure 2. The top and bottom railings are connected together internally in a horizontal direction – shown as red and black connections in Figure 2. These top and bottom railings are often used as the positive (+) and negative (-) voltage supply terminals for the circuit. The middle holes are connected vertically in groups of five, shown in blue in Figure 2.

These internal connections are important in allowing you to connect various electrical components together to build your circuit. You can plug one component into a hole, another into another hole, and the internal connection of the breadboard will allow current to flow from one component into the other, making a connection in your circuit.

Search through your component pack for the little 12V incandescent lamp. It is the little clear plastic device (the one with the smallest head in your component pack) – ask a demonstrator if you're not sure. Note that all the data sheets for components you will use in the labs can be found on the subject website. These data sheets generally have diagrams and pictures showing what each device looks like...

Use the breadboard to connect this lamp to the DC power supply. Initially have the DC power supply configured to give zero output voltage. You'll need to cut a few wires to make the connections from the supply leads to the breadboard.

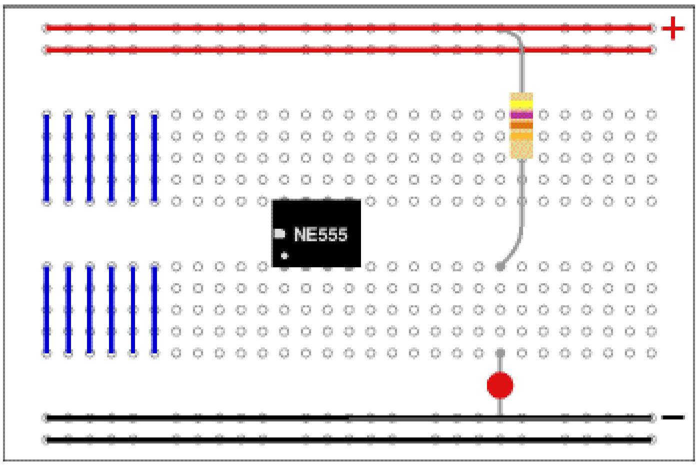

Figure 2 – Internal Connections in a Breadboard (lines in red, black, and blue are the internal connections)

Then turn up the voltage from the DC power supply until you see the lamp shine brightly. Note the supply voltage at which this happens. It is at your discretion the interpretation of 'shine brightly'.

The circuit you have constructed is illustrated in Figure 3 below. The DC power supply is represented as the battery here.

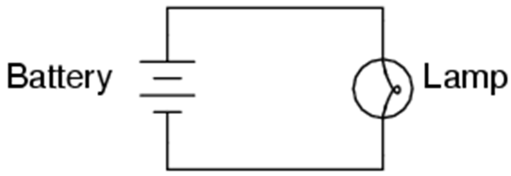

Figure 3 – Simple Lamp circuit

Now turn on the Digital Multimeter. Set the device to measure DC current. Note that the current range will determine which terminal you plug the leads into when measuring current. Cut yourself some more wires and connect the DC multimeter, configured as an Ammeter (or current measuring device), in series to the lamp. The circuit is shown in Figure 4 below.

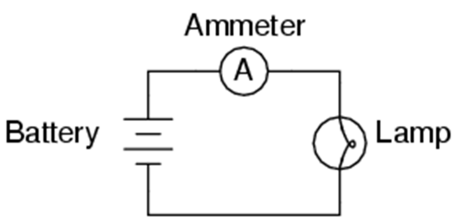

Figure 4 – Measurement of Lamp current

Use the ammeter to measure the current through the lamp at your supply voltage from before. Use Ohm's law to determine the resistance of the lamp. Recall Ohm's law defines the resistance of a device as the voltage across the device, *V*, divided by the electrical current that flows through the device, *I*:

$$R = \frac{V}{I}$$

Now, reduce the supply voltage to the incandescent lamp to one half of the value you used earlier. You will naturally see the lamp shine only very dimly. Measure the current through the lamp for this voltage, and determine the resistance of the lamp at this supply voltage. Is it what you expected? What does this tell you about Ohm's law for an incandescent lamp?

Calculate the electrical power dissipated by the lamp under both supply voltage settings. The electrical power, *P*, dissipated by a device (measured in Watts) is the product of the voltage across the device, *V*, and the current flowing through the device, *I*:

$$P = VI$$

4. Resistors

In the lab in one of the corners you'll see a shelf filled with little resistors of many different values. How do determine which is which? A coding scheme using coloured bands on the resistor is used to mark their respective values, in terms of resistance and the manufacturing tolerance. Figure 5 below illustrates how this coding scheme works.

For example, if a resistor has the following coloured bands: Red, red, brown, space, and then gold, then its resistance is calculated as:

$$R = 22 \times 10 = 220\Omega$$

The manufacturing tolerance is 5%, which means the real precise resistance of any resistor with these marking could be any value between 209 Ω and 231Ω – that is, it varies within 5% of the nominal resistance of 220Ω. In the laboratory you have access to an LCR bridge which can be used to measure the resistance of a resistor more precisely, should you choose.

Resistors are an important circuit component, and are used in everything from power plants to pacemakers. The unit of resistance is the Ohm (Ω), and the range of practical resistances is typically from around 1Ω to around 100 MΩ (10^8). Smaller and larger values are possible, but are not commonly seen in the electronics labs. Within this range, obviously it not possible to manufacture every single value of resistance, so a system of preferred values is used:

1.0Ω 1.2Ω 1.5Ω 1.8Ω 2.2Ω 2.7Ω 3.3Ω 3.9Ω 4.7Ω 5.6Ω 6.8Ω 8.2Ω 10Ω . . . . .

Other resistance values are multiples of ten of these values, and the set of preferred values is known as the E-12 series. For this reason, you will only find certain values of resistance available in the lab.

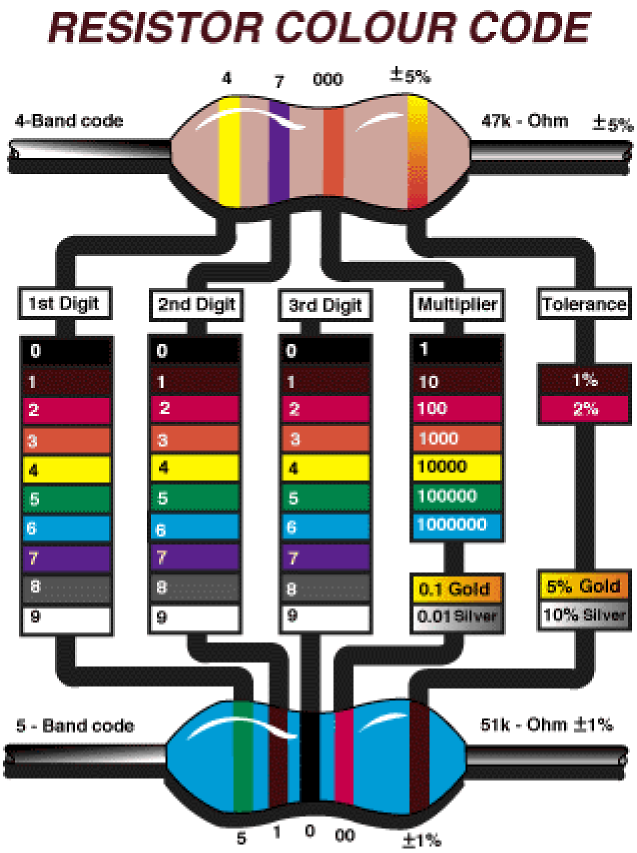

Figure 5 – Resistor Colour Coding

You should familiarize yourself with the above resistor colour coding, which can be found on many websites, and is also displayed on posters in the laboratory. Given a resistor you can look at the chart and the various colour bands will indicate its value, order of magnitude, and finally its tolerance.

Find yourself a 1 kΩ and a 2.2 kΩ resistor. Take one of the 9V batteries from your component pack, and connect up the circuit shown in Figure 6. The 9V battery is the supply, and the resistors can be connected in any order of your choice.

This circuit is a simple voltage divider circuit. Use the Digital Multimeter to measure the voltage across the 2.2 kΩ resistor. Verify that it indeed satisfies the above equation:

$$V_{out} = \frac{R_2}{R_1 + R_2} V_{in}$$

Which resistor is R_1 and which is R_2?

This basic voltage divider circuit and the principles underlying it have many practical applications in electronic circuits. In your component pack you'll find a small DC motor. This motor is rated to operate with an input voltage of 3 V, and when operating without load will draw a current of 0.22 A. You'll need to cut a couple of wires and solder them to the ends of the motor, to make it easier to connect it to the breadboard.

Determine a pair of resistors, from the available sequence of values that will divide the 9V supply voltage from the battery into 3V to supply the motor. This is not quite as easy as it looks, since when you connect the motor across the resistor you've chosen, the voltage you measure across this resistor will change (since the resistance of the motor is finite). Can you determine what the resistance of the motor is, and account for it? Do your best to design a simple circuit that will supply the DC motor with a voltage of 3V, using a pair of resistors as voltage dividers and a 9V battery. Record your design in your notebook.

In your above circuit you'll probably notice that the motor turns fairly slowly, as it is not getting sufficient current from the 9V source. You, of course, have two 9V batteries in your component kit. Design a very simple modification to your above circuit such that you can double the current supplied to the DC motor, using two 9V batteries instead of one. (Hint: think terms of connecting the batteries either in series or in parallel)

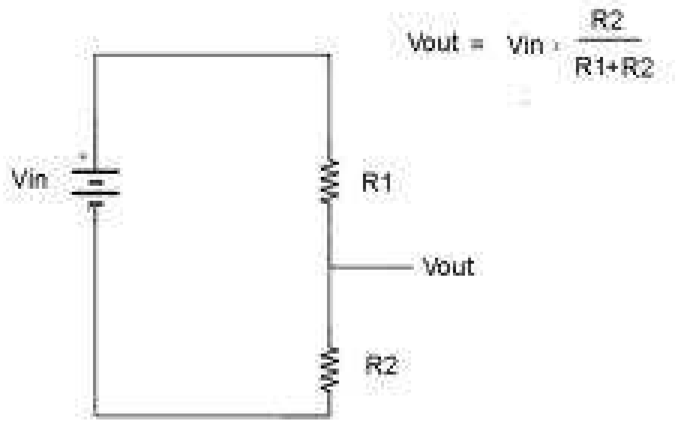

Figure 6 – Voltage Divider Circuit

5. Current Divider

The natural analogy to the voltage divider is the current divider. Such a circuit is illustrated below in Figure 7.

Select a 1kΩ, 2.2kΩ, and 3.3kΩ resistor and connect them to the 9V battery as in the circuit above. Use an ammeter to measure the current flowing through each of the resistors in this circuit. Show that, for each of the resistors, the current through it, *I*, times its resistance, *R*, is equal to 9V. That is,

$$9\text{ V} = RI$$

What is the total current being supplied by the battery? What is the effective total resistance of this circuit? Explain this in terms of fundamental circuit principles.

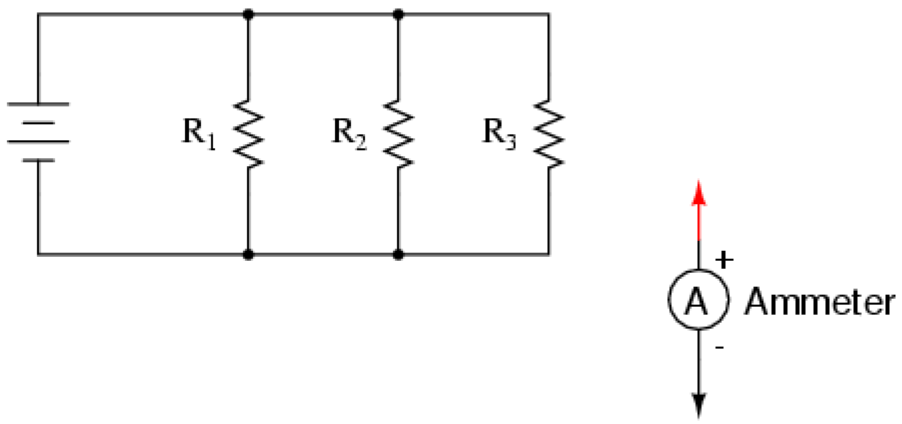

Figure 7 – Current Divider

One device for which we seek to control the current supplied to it is a Light Emitting Diode, or LED for short. Unlike a resistor, the relationship between voltage and current in a diode is not linear. As a first order approximation, assuming the diode is forward-biased, you may think of diodes as devices which like to maintain a constant voltage between their two terminals, regardless of the amount of current which flows through the diode. An LED is a special type of diode which emits light as electrons move across the electric potential between the terminals. Current will flow through a diode only in one direction, from the anode to the cathode, which means that they can only consume power.

Understanding the operation of an LED, and of diodes in general, requires some knowledge of semiconductors, and for proper detailed treatment, a knowledge of quantum physics. We don't have time or space to go into these details here, and will limit ourselves to understanding how we can use these devices rather than how and why they work the way they do. The interested student can find many good textbooks and websites that attempt to explain the inner workings of diodes and LEDs.

As stated earlier, LEDs are essentially just diodes (electrical devices that allow current to flow through them in only one direction, called the forward-biased mode) that are designed to give off light in the forward-biased mode. They require an externally applied voltage to turn-on voltage, and this voltage varies between make and colour (including infra-red and ultraviolet), and is typically of the order of 1.6 to 3.5 V. The circuit symbol and the physical device layout are shown in Figure 8.

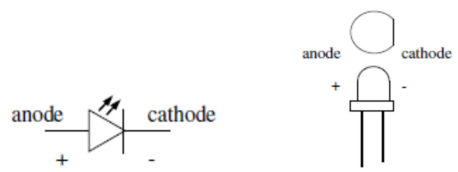

Figure 8 - LED circuit symbol and physical housing

A simple model for the current-voltage characteristics of an ideal diode is shown in Figure 9. The diode requires a certain externally applied voltage, V_{on}, to turn on begin to conduct current. Once the diode is 'on' and conducting, the voltage drop across it is approximately constant and independent of the actual current flowing through the device.

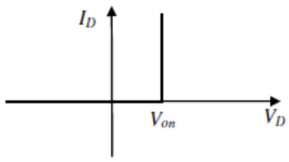

Figure 9 – I-V characteristics of an ideal Diode

Real diodes exhibit some slight differences in behaviour than this very basic ideal diode model. When conducting there will be a slight dependence of voltage on the forward current; there is always a small current, often called the dark current, when the diode is reverse-biased; and finally, the is a maximum voltage that can be applied in the reverse direction before the device will 'breakdown' and a large current will flow – this is naturally called the reverse breakdown voltage.

To turn on an LED, a voltage greater than or equal to the turn-on (forward) voltage (sometimes indicated as V_F) must be applied, and a current of typically 10-20mA must be supplied. To determine the correct turn-on voltage and supply current for your LED, consult the data sheets. It is an important habit to get into when dealing with electronics – consulting data sheets for information on how to operate devices. The data sheets are produced by the device manufacturer to tell you important information like the maximum and minimum voltages and currents that must be supplied to the device for it to operate as designed, how the device will operate under specific conditions, and so forth. The data sheets of all devices you will encounter in this lab program can be downloaded from the subject website.

You are actually provided with two different types of LEDs – one emits principally red light, while the other emits in the infra-red portion of the electromagnetic spectrum. The red LED will be of interest to us initially, since it will give us the visual confirmation and satisfaction that our circuit is functional. [Note: depending on availability, the 'red LED' may sometimes be an 'orange LED', or another colour.]

Find the red LED, and identify the anode as the longer leg. It is very, very small, and indicates the cathode with a band – that is, the cathode is the end that has the band. If you are unsure consult the data sheet on the course website, which has a diagram of what this LED looks like. It is almost the smallest component you have in your package.

The anode must be connected to the positive (higher) voltage for the LED to emit light. Proceed as outlined below:

1) Select resistor R_1 and a signal generator output voltage so that the current through the LED is of the order of 30 mA. The circuit used to drive the LED can be illustrated as in Figure 10. Note that the source for this circuit is the Signal Generator

   When operating the LED it will have a voltage drop of V_{on} across it, where V_{on} is the forward bias voltage that can be read off the data sheet. Ohm's law across the resistor then gives the current through the circuit,

$$I = \frac{V_{in} - V_{on}}{R}$$

Ask a tutor if you are unsure of your calculation. For the little red LED, the forward bias voltage drop is $V_{on} = 1.9\text{V}$.

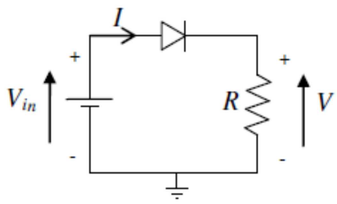

Figure 10 – LED driving circuit analysis

2) Start with a very low frequency square wave so that you can see the LED turn on and off with your naked eye. One or two flashes per second might be reasonable here, so the signal generator frequency should be set somewhere between 1 to 5 Hz, say.

3) Now use the multimeter to measure the current and the voltage across the LED.

4) What happens to the voltage across the LED and to the current through it as the signal generator output voltage is adjusted? Does this match what you expect, based on the diagram shown in Figure 9?

5) Replace the Signal Generator with the DC Power Supply set to give the same output voltage as the maximum voltage of the square wave out of the signal generator. The LED will now flash continually.

In your component pack you are given a green coloured LED, with quite a large head and with the shape as shown in Figure 8. Verify that this LED emits light in the same circuit as you used for the Remove the resistor *R* and connect the LED directly to the DC power supply set. Slowly increase the voltage applied to the LED and watch as the LED begins to change colour before 'fizzing out'. Observe that the LED is 'fried', and that it will not function anymore, even if the resistor R is replaced back in the circuit.

This illustrates the importance of the resistor *R* in the above circuit to limit the current into the LED and so protect this device. There are many other ways to protect electrical devices and circuits, like fuses and circuit-breakers, such as the ones you have connected to the mains supply in your homes for safety reasons. Bear this in mind when you proceed in your lab work and with your design project. Any further devices you blow must be paid for yourself (though these devices are not exactly expensive).

As a matter of satisfaction, show your demonstrator the fried LED. You should be proud – this is probably the first time you will have destroyed an electronic component in the lab. If you plan to take any more courses in Electrical Engineering, it won't be your last!

Now, let’s turn our attention back to the current divider circuit and design a circuit to power the little red LED from the 9V battery. The circuit we’re after is illustrated below in Figure 11. You’re aim is to select resistors R_1 and R_2 to power the little red LED, by ensuring the current through it is 30mA. Note that it will have a voltage drop of $V_{on} = 1.9\text{V}$ across when operational, so you must account for this forward bias voltage in your circuit analysis.

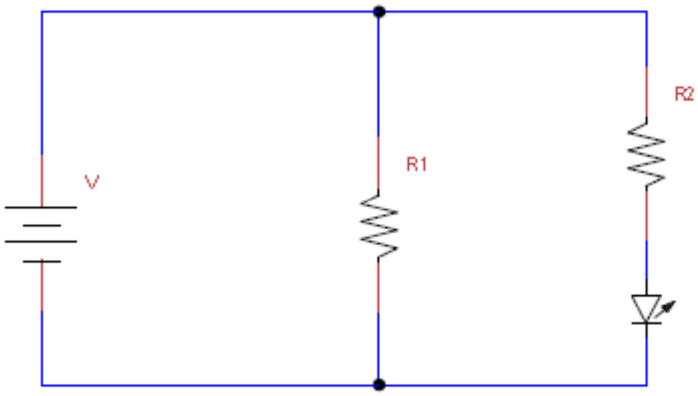

Figure 11 – LED current divider circuit

6. Capacitors

Capacitors are a fundamental circuit element, which physically consist of two conducting plates very close to each other (separated by a dielectric material), as suggested by their circuit symbol, shown in Figure 12. The plates are not connected (i.e. there is an open circuit between them), however if positive charges were to accumulate on one of the plates, then due to the proximity of the other plate, negative charges would be attracted to it, producing a current. The charge accumulation effect occurs when a voltage is applied to the capacitor, which creates an electric field between the plates, encouraging charge accumulation at the plates. If charges are stored at the plates and then the voltage is removed, the charges will flow away from the plates again. This behaviour leads us to think of the capacitor as a charge storage device.

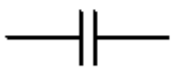

Figure 12 – Capacitor Circuit Symbol

The relationship between charge stored q and the voltage across a capacitor V is given by $q = CV$, where C is the *capacitance* of the device, in Farads (F). Since current is the rate of flow of charge, this leads us to the voltage-current relationship for the capacitor:

$$I(t) = C\frac{dV(t)}{dt}$$

Where $I(t)$ and $V(t)$ are the capacitor current and voltage as a function of time t. What does this mean? If the voltage across the capacitor is constant, then no current flows. If the voltage changes linearly, then a constant current flows.

Practical capacitors are generally formed from two conductive "plates," separated by a small gap which is filled with an insulating material known as a dielectric. The capacitance turns out to be proportional to the area of the plates and inversely proportional to the distance between the plates. In order to make very large capacitances, therefore, a large amount of plate area is required and the plates should be separated by very small distances. For reference, we note that parallel plates with area 1 cm^2, separated by 1 mm of free space, would yield a capacitance on the order of 1 pF (pico-Farad). Carefully selected dielectric materials can yield larger capacitors, but the main aim of the game is to design a large plate area and extremely close plates.

The plates are commonly made from aluminum foil, with a dielectric material which is also thin and flexible, so that the arrangement can be coiled up to accommodate large plate areas in a comparatively small package. The pressure to minimize the separation between the conductive plates brings a number of adverse consequences for practical capacitors:

1. It is hard to control the very small plate separation precisely during manufacture, which means that typical capacitors have capacitance values which may vary by 10% or 20% from the stated (nominal) values.

2. Since there is only a very thin layer of insulating material between the plates, the insulation is not quite perfect and a small amount of current can flow (leak) between the plates. This is typically modeled by a high (yet not infinite) resistance, in parallel with the capacitor.

3. With the plates separated by very small distances, large voltages can create enormous electric fields between the plates, which can cause destructive ionization (arcing) inside the capacitor. For this reason, large capacitors often have very small breakdown voltages and the circuit designer must be careful to avoid destructive voltages appearing in the circuit.

As a general rule, large capacitors in smallish containers have the following limitations:

- Reduced breakdown voltages.

- Reduced leakage resistances (i.e., higher leakage currents).

- Large capacitors generally involve large coiled up conductors, which generate magnetic fields. It turns out that the rise and fall of these magnetic fields limit the rate at which the capacitor current can change, so that large capacitors often have poor performance when presented with very high frequency signals.

- For very large capacitances (values significantly larger than $1\mu\mathrm{F}$), a special dielectric material is often required, which can only withstand voltages in one direction. These capacitors are said to be "polarized" or "electrolytic." They have a positive terminal and a negative terminal and the voltage on the positive terminal must not become less than that on the negative terminal (doing so may destroy the capacitor). Be very aware of this when you use these capacitors in your circuits! If you connect one of these electrolytic capacitors the wrong way around they can EXPLODE. The polarity of these capacitors is clearly marked on the side of these capacitors, so make sure you connect them the correct way.

The interesting feature of capacitors that we will utilize in the construction of filters is their frequency dependence. Consider a sinusoidal input voltage signal into a capacitor with a frequency *f* (measured in Hertz),

$$V(t) = V_0 \cos(2\pi f t)$$

The current through the capacitor is then

$$I(t) = -2\pi f C V_0 \sin(2\pi f t)$$

The first insight here is that the current and the voltage across a capacitor are out of phase – one is the sine while the other is the cosine, so when one peaks the other is zero. This is illustrated in Figure 13. The second point is that the effective resistance, called the impedance in this case, is $|Z| = 1/2\pi f C$. This relates the magnitude of the current through the capacitor to the resultant voltage across the capacitor (and vice versa). Note that as the frequency of the sinusoid increases the effective resistance of the capacitor decreases. Capacitors are an important building block of a class of devices known collectively as filters – devices whose purpose is to select certain frequency ranges of signals at preference to others. Naturally filters are critical in radio communications to select the desired channel and suppress neighbouring, interfering channels.

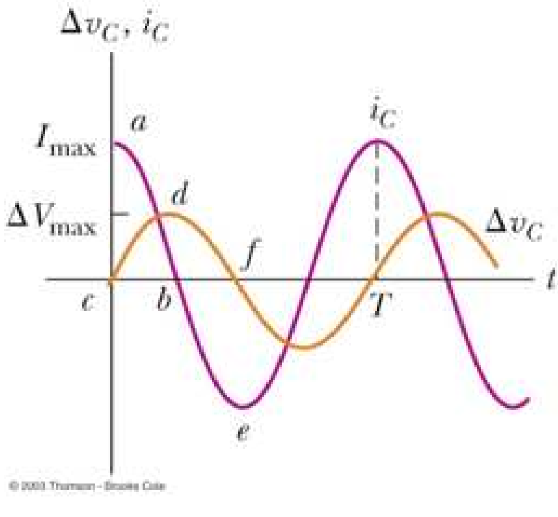

Figure 13 – Current and Voltage across a capacitor

Connect up the circuit shown in Figure 14. Use one of the non-electrolytic capacitors of value 0.047 µF and a resistor of value 1 kΩ, as a way of measuring the current through the capacitor. You can refer to the subject website for information on how to determine capacitance values from the information printed on its housing, so you use the correct capacitor. The requisite information is shown in Figure 15 below.

The voltage source is the signal generator, tuned initially to produce a sinusoidal output at frequency 1 kHz and amplitude of 1 V. Display the input voltage from the signal generator and the voltage across the resistor on the CRO simultaneously. Observe what happens to the output voltage as the frequency of the input is increased to 10 kHz. How does this relate to the theory you have read above?

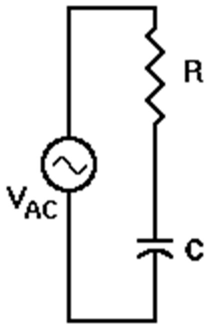

Figure 14 – Capacitor test circuit

Determine the effective resistance of this capacitor (called the impedance) at frequencies of 1 kHz and 10 kHz. How do the values you obtain compare with the theory above?

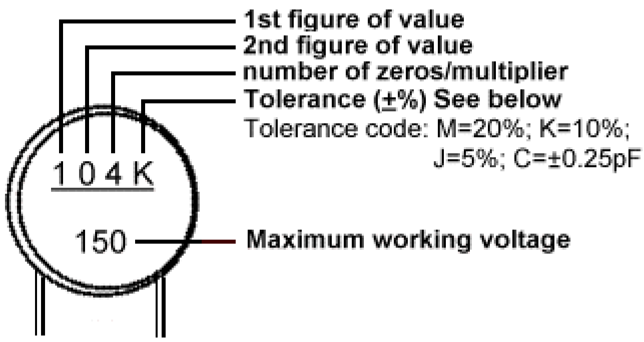

Figure 15 – Reading Capacitance Values