Laboratory Exercise 1 – ELECTRICAL MEASUREMENTS

Introduction

Electronic techniques and instrumentation are important in almost every branch of science. In this exercise you will meet some of the principles which govern the design and operation of such instruments. We restrict ourselves to circuits carrying steady, unchanging currents provided by constant voltage sources such as batteries (so-called **direct current** or **DC** circuits); in later exercises we meet time-varying currents in what are called, rather deceptively, **alternating current** or **AC** circuits.

Many substances can be loosely classified as **conductors**, which allow electric currents to pass relatively easily, or **insulators**, which offer much more resistance to current flow. Metals, with loosely bound electrons, are good conductors. So are various forms of carbon, such as graphite. An electronic component, manufactured to have a specific value of resistance, is called a **resistor**. When a current of I amps[1] passes through a resistor of value R ohms[2] there is a voltage drop or **potential difference** of V volts[3] across the resistor. The familiar relation known as **Ohm's Law**, $V = IR$, is satisfied by most conductors including all metals. (However, it must be stressed that Ohm's Law does not apply to all substances. Modern electronics is possible only because of the development in the last half-century of a wide range of materials and devices for which the 'law' does not hold.)

A part of a circuit whose resistance is infinite (a perfect insulator, or a badly made 'dry' solder joint) is called an **open circuit**; one whose resistance is negligible is termed a **short circuit**.

Resistors commonly have values between a few ohms and several tens of megohms (1 megohm = 10^6 ohms). Some precision resistors (such as those in the variable resistance box you will use) are made entirely of metal, but most of those found in low-power electronic circuits are made of carbon, or an insulator thinly coated with a film of metal. These almost always have their resistance values marked on them by a simple and universally recognised colour code. There are three coloured rings near one end (figure 1); from the end these signify the first digit, the second digit, and the number of zeros to follow. A fourth ring at the other end shows the accuracy, useful in precision circuit work. The code is:
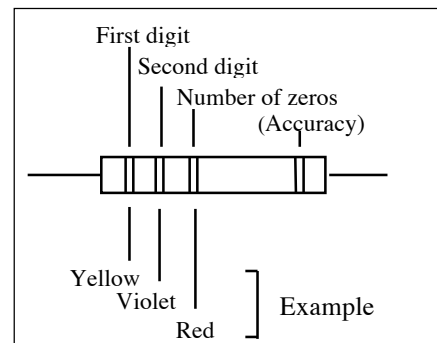

Figure 1 Resistance colour code

**Black = 0, Brown = 1, Red = 2, Orange = 3, Yellow = 4,
Green = 5, Blue = 6, Violet = 7, Grey = 8, White = 9**

A colour code chart is posted on the wall in the laboratory. In addition, there are several mnemonics for remembering this code.

In practice only a few resistance values are commonly used, selected so that each is about 20% larger than its predecessor. The basic ratios are 10, 12, 15, 18, 22, 27, 33, 39, 47, 56, 68 and 82. The resistor shown in figure 1 has a resistance of 4700 ohms = 4.7 kilo-ohms, usually read as '4.7 k', and often written as '4k7' to make the position of the decimal point more obvious on a crowded and perhaps poorly printed circuit diagram. (The 'k' is lower-case to distinguish it from 'K', the temperature unit degrees Kelvin.)

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[1] The unit of current, the amp, is usually abbreviated to the symbol A.
[2] The unit of resistance, the ohm, is usually abbreviated to the symbol Ω.
[3] The unit of voltage, the volt, is usually abbreviated to the symbol V.

Finally, we remind you that when resistors are joined in **series** (figure 2) the combined resistance is the sum of individual resistances:
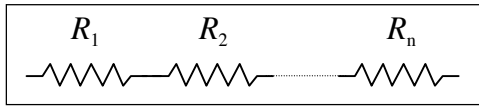
$$R = R_1 + R_2 + \ldots + R_n$$
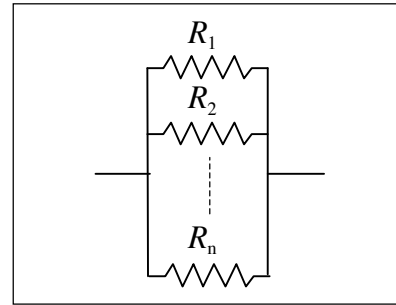

Figure 2 Resistors in series

Figure 3 Resistors in parallel

but when they are connected in **parallel** (figure 3) the result is:

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_1} + L + \frac{1}{R_n}$$

Making simple circuits

In this exercise you will connect resistors in various ways. A power supply provides the voltage, and you will measure currents and potential differences with a digital multimeter (DMM, sometimes called a DVM when used to measure voltage).

Circuits are constructed on a so-called **breadboard**, an insulated board containing a grid of interconnected small sockets into which you can push the leads of electronic components such as resistors. Figure 4 shows the layout of a breadboard. The top and bottom lines of sockets are usually connected to the positive and negative terminals of the voltage supply. By convention voltage levels in the circuit are usually measured with respect to the negative line; several circuits or instruments can use the same negative potential (when it is called the **common** potential or, if the connection is made through the ground, the **ground** or **earth** potential). The first exercise illustrates the use of the breadboard.
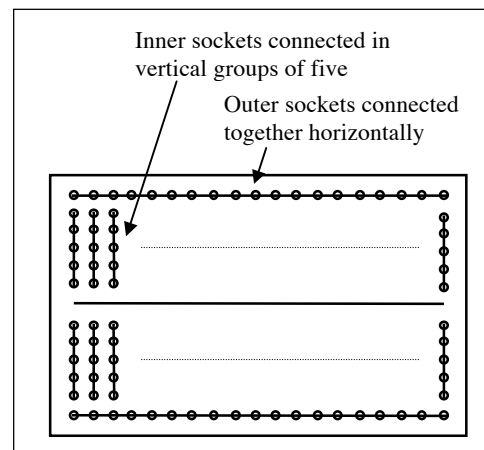

Figure 4 Breadboard connections

The potential divider

The simple circuit of figure 5 uses resistors in series to obtain a voltage lower than that directly available from the battery or other source. By Ohm's Law the current flowing is $I = V/(R_1 + R_2)$, so the potential difference between A and B is $V_{AB} = IR_1 = VR_1/(R_1 + R_2)$ while that between B and C is $V_{BC} = VR_2/(R_1 + R_2)$. Any voltage between ground potential and V can be obtained by an appropriate choice of R_1 and R_2.

• Connect the circuit of figure 5 using the voltage supply provided. For R_1 and R_2 use resistors of 2.2 kΩ and 4.7 kΩ, respectively.
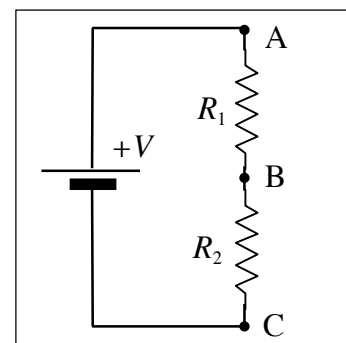
• First use the DMM to measure the actual resistances of R_1 and R_2. Then use the DMM to measure the potential differences V_{AB} and V_{BC}, and compare with calculated values.

Figure 5 Potential divider

• Replace R_1 by the resistor labelled X, measure V_{AB}, and hence deduce R_X.

The Wheatstone bridge

This simple circuit (figure 6) uses the principle that if two voltage dividers R_1R_2 and R_3R_4 side-by-side have the same resistance ratios, that is if R_1/R_2 is the same as R_3/R_4, then the voltages at points A and B must be equal. If three of the resistances are *known* then the fourth can be *calculated*.

This is an example of a **bridge** circuit. R_1R_2 and R_3R_4 are the two 'arms' of the bridge; when the bridge is 'balanced' there is no voltage between A and B so we don't need a highly accurate voltmeter. (The principle of measuring a zero value is used in many so-called **null** methods of measurement.) This particular bridge circuit was devised by Sir Charles Wheatstone for use by telephone engineers.
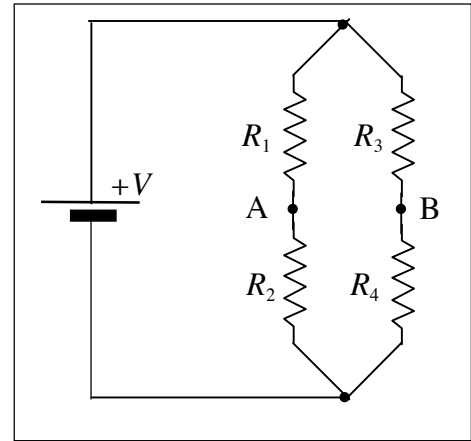

Figure 6 Wheatstone bridge

• Connect the circuit using equal resistors of 6.8 kΩ for R_1 and R_2, the resistor labelled **Y** for R_3, and the 1000 Ω variable resistor box for R_4.

• Vary R_4 until the potential difference between A and B is zero. Hence determine the resistance of **Y**=R_3.

Input resistance

When you make measurements, you must always be aware that the instruments you use can themselves have an effect that changes the readings. For example, some meters have an **internal resistance** which is comparable with the resistances you are using, so when you measure a voltage with it you are in effect placing another resistance in parallel. On the other hand, a modern DMM has a high internal resistance than the circuit you normally want to measure, so it usually has little effect when measuring voltages. Here we will measure the internal resistance of the DMM meter.

Figure 7 Input resistance

• Connect the circuit of figure 7 using four equal resistors of 10 MΩ each.

• Measure the potential differences AB, BC and CD, using the DMM. Since $1/R_2 + 1/R_3 = 1/R_{BC}$, the resistance of the parallel section R_{BC} is half that of the series sections R_{AB} and R_{CD}, so V_{BC} should be half of V_{AB} or V_{CD}.

• Measure the open circuit voltage of the battery, i.e. the voltage across the battery terminals when no circuit is connected.
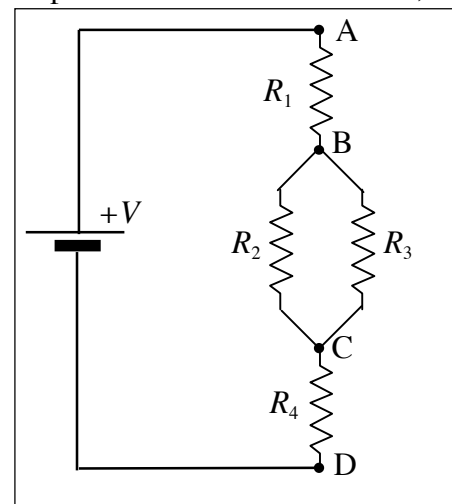
• From your results, and remembering that the total potential difference AD is constant, deduce the internal resistance of the DMM meter, and compare with the information given by the manufacturer on the back panel. Do this calculation twice, first using the value of V_{AB}, then V_{BC}. Your value of V_{CD} should be a useful check; is it?

The DMM has an internal resistance which is very high, so it has only a small effect on the voltage. An ideal voltmeter would have an infinite resistance and would then measure the **open circuit** voltage between two points. In practice, all instruments have some internal resistance

(usually called their **input resistance** or, when we are dealing with AC circuits, **input impedance**).

Output resistance

Any voltage source contains within itself some resistance to the flow of current, limiting the quantity of current that it can provide even when its output terminals are short-circuited. For many cells and batteries this **internal resistance** or **output resistance** is quite small, an ohm or less, as anyone who has accidentally dropped a spanner across the terminals of a car battery will appreciate.

• To measure the internal resistance R_{int} of the battery provided, connect it in series with the 1000 ohm variable resistance box and a switch (figure 8).

• With the switch open, measure the open circuit voltage.

• Then close the switch and vary the external resistance: (1) making a plot of R versus V, and (2) also finding the resistance, call it R, at which the measured voltage is *half* the open circuit value. Your circuit is then a potential divider in which half the voltage drop occurs across R_{int} and half across R, hence $R = R_{int}$.
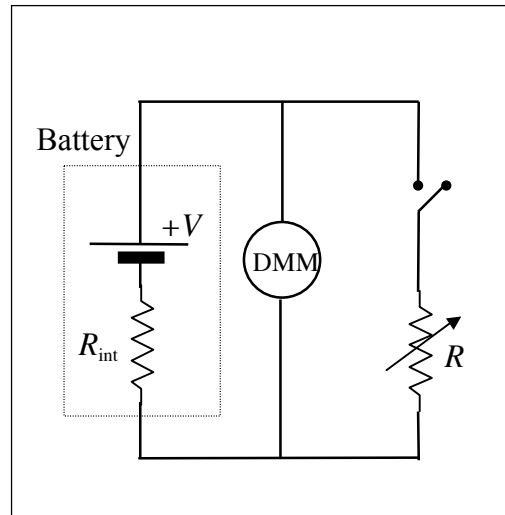

Figure 8 Output resistance

*Caution: when the external resistance is low, large currents can flow. Do **not** leave the switch closed for more than a few seconds, otherwise you are likely to discharge the battery or burn out the external resistance.*

Equivalent circuits

A theorem due to Thévenin states that a complex circuit of many voltage sources and resistors with two external terminals can be represented by a *single* output resistance R_T in series with a *single* voltage source V_T (provided it behaves linearly, i.e. obeys Ohm's Law). This very simple circuit is the **(Thévenin) equivalent circuit**. Another theorem states that the maximum power output of such a circuit occurs when the external, or **load**, resistance is equal to R_T. Given a two-terminal 'black box' containing an array of voltage sources and resistors, you are to measure V_T and R_T (that is, determine the equivalent circuit), and investigate its power output.

• Replace the battery of figure 8 by the 'black box'.

• With the switch open measure V_T, the open circuit voltage.

• Then with the switch closed reduce the load resistance R from 1000 Ω to a few Ω, recording both the potential difference V across R, and the value of V^2/R which is the power dissipated in the load resistance.

Plot the power output versus load resistance on two graphs (by hand – not computer):

• First, using **log–linear** graph paper, plot power (the **dependent variable** which you measure) along the linear axis versus resistance (the **independent variable** which you change) along the log axis to show the behaviour over a wide range of resistances. Use this graph to determine roughly the resistance range of the peak power.

• Second, using ordinary **linear** graph paper, plot an expanded (zoomed in) graph of power versus resistance showing only the region near the peak of the first curve. Take more data in the region of the peak to gain more accuracy. Use this second graph to find a value for the load resistance at maximum power output, and *compare this with R_T, which as we have seen is the load resistance when V is* $0.5V_T$.