In general, the three aspects for the internally assessed skill of data collection and processing are

- recording raw data including units and uncertainties where relevant
- processing raw data correctly
- presenting processed data including errors and uncertainties

In this investigation, the raw data consists of an appropriate set of readings for terminal p.d., V, and current, I. You must choose the best method of measuring and recording this data, and you should also use an appropriate number of significant figures for the data that you record. This data then needs to be processed, so you will need to decide on the best way to analyse the numbers to allow you to answer your initial question. Finally, when processing data, you need to take into account the uncertainties that you assessed in the raw data. Often, this is most clearly presented as a separate section in your write-up.

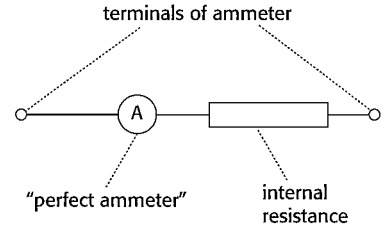
You can also take this experiment on to the conclusion and evaluation stage.

Real meters

As we saw on page 132, perfect voltmeters have infinite resistance and perfect ammeters have zero resistance. What happens if this is not the case?

The effect of adding the meter needs to be taken into consideration in the circuit calculations. It is usually necessary to start again with all of your calculations whenever a circuit is altered – it is not always possible to assume that an alteration (for example adding a voltmeter) in one part of the circuit will not effect another part of the circuit. It might help to image a real meter as a combination of a perfect meter and an "additional" resistor. For a real ammeter, the "additional" resistor is in series with the perfect meter, for the voltmeter it is in parallel.

(a) real ammeter:



(b) real voltmeter:

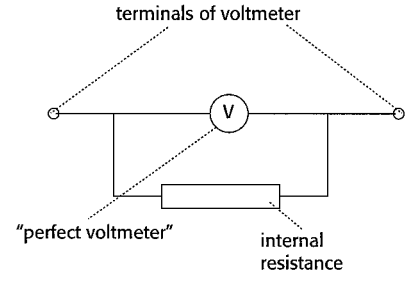
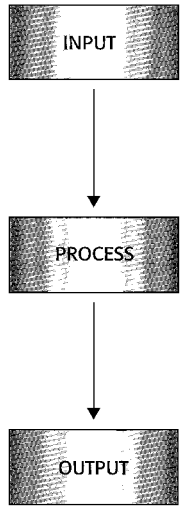


Figure 16

Potential dividers and sensors

For a circuit to be useful, it must interface with the real world; it must have at least one input and one output.

An input device could be as simple as a button or a switch. In a computer circuit, the input devices are things such as the keyboard, the mouse, or a DVD reader. Possible output devices include lights, buzzers, or, in the case of the computer, the screen, the printer, or the loudspeakers. The general name given to any electrical interface that converts energy between different forms is a **transducer**.



An electrical circuit involves electrical energy and thus input transducers, or **sensors**, are devices that convert some real everyday aspect of the physical world into electrical signals. Examples include microphones (sound into electrical), light sensors (light into electrical), and temperature sensors (thermal energy into electrical).

Sensors can facilitate a whole range of measurements that would be impossible for a lone physicist to observe with a single measuring

device. Electronic circuits can be designed in which the measurements are:

- **Automated**: multiple readings of a variable can be recorded over very short response (e.g. air pressure variations during a pulse of sound) or very long time intervals (e.g. the automatic recording of a patient's heart rate over a week).
- **Detailed**: they allow for a large number of precision multiple recordings to be taken at exactly the same time (e.g. the minute variations in the stresses and strains that take place in the body of an aircraft during takeoff).
- **Remote**: they allow for readings to be taken in difficult or even hostile locations (e.g. temperature measurements inside a reactor core or observations on another planet).

So what is happening when, for example, the breaking of a beam of light causes an alarm system to issue a warning?

Many sensors are just a resistor whose resistance varies in a predictable way in response to external factors. Two very important examples of this are *light-dependent resistors* (LDRs) and a type of temperature-dependent resistor called a *negative temperature coefficient* (NTC) *thermistor.*

In both of these devices, an increase in energy input to the device causes a large decrease in resistance. Thus when the amount of light shining on the LDR increases or the temperature of the thermistor goes up, the resistance goes down. In both cases this is because the devices are acting as semiconductors and the number of charge carriers has been affected (see page 129).

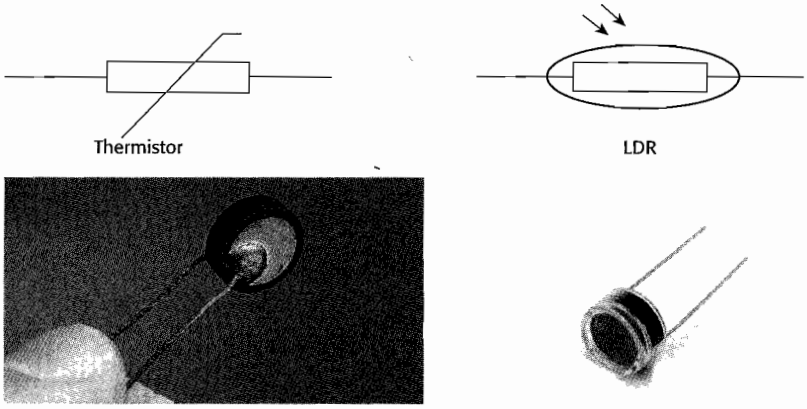


Figure 17

A simple way of utilizing this change in resistance is by employing a **potential divider** circuit using two resistors, R_1 and R_2 (see Figure 18).

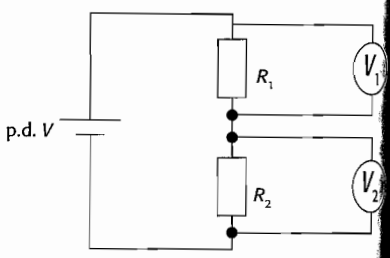


Figure 18

An analysis of the current flowing around the circuit, shows that the total potential difference that is available, V, divides up (hence the name of the circuit) with each resistor taking its "share" in proportion to its resistance.

$$\text{Since } V_1 = IR_1,\ V_2 = IR_2 \text{ and } I = \frac{V}{R_1 + R_2}$$

$$V_1 = \left(\frac{R_1}{R_1 + R_2}\right)V \text{ and } V_2 = \left(\frac{R_2}{R_1 + R_2}\right)V \qquad (5)$$

By analysing equation 5 we can see that the larger resistance takes the larger share of the total available p.d.

If either of these resistors was swapped for one of a different value, then the way the potential difference was shared would be different. The share of the p.d. would also vary if one of the resistors varied as a result of external conditions. For example, consider the circuit in Figure 19.

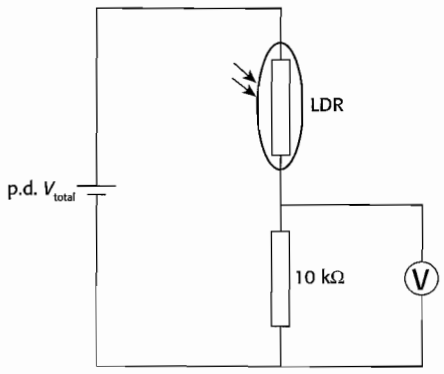


Figure 19

When light shines on the LDR, its resistance is comparatively small, say 200 Ω, but if no light shines then its resistance is greatly increased – perhaps to 20 kΩ.

In the light,

resistance of LDR ≈ 200 Ω
resistance of fixed resistor = 10 kΩ

∴ the resistance of the fixed resistor >> resistance of LDR
so $R_1/(R_1 + R_2) \approx 1$
and p.d. across the fixed resistor ≈ V_{total}

In the dark,

resistance of LDR ≈ 20 kΩ
resistance of fixed resistor = 10 kΩ

∴ the resistance of the fixed resistor ≈ resistance of LDR

p.d. across the fixed resistor $\approx \frac{V_{total}}{3}$

So when light stops shining on the LDR there will be a decrease in p.d. across the fixed resistor. An electrical circuit can be designed to compare this p.d. with a known fixed potential difference. We can create a system that will sound an alarm whenever the measured p.d. goes down. The system we are considering will sound an alarm whenever a beam of light that is arranged to shine on an LDR is broken.

To be useful, the circuit we have described still needs further modifications – the simple system would stop sounding the alarm as soon as the light shines on the sensor again. As long as each addition does not fundamentally affect this basic section, we can modify parts of the circuit to make it useful for our purpose.

Remember that it is not possible to assume that the current or potential difference remains constant after a change to the circuit. After a change, the only way to ensure a correct answer is to start the calculations again.

Sometimes the sensing device can be designed around a **potentiometer** circuit. This is just a potential divider created from a fixed resistor with a movable connection.

As the slider (represented by the arrow in Figure 20) moves from one end to the other, the p.d. measured by the voltmeter varies from the maximum, V_{total}, (when the movable connection is at the top end of the resistor) down to zero (when the movable connection is at the bottom end of the resistor). A simple circuit that uses this approach is the petrol gauge in a car. A device is arranged to float on top of the petrol in the tank. As it moves up and down, it varies the position of

the sliding contact on a potentiometer circuit and thus the p.d. recorded is dependent on the amount of petrol in the tank. This reading is calibrated so that it accurately represents the amount of petrol left.

A common sensor in everyday engineering use is the strain gauge. Linear strain is defined in the following way:

$$\text{strain} = \frac{\text{increase in length}}{\text{original length}}$$

A strain gauge measures any small extension or compression that occurs by measuring changes in resistance that take place when a resistor is increased or decreased in length. Often these changes in resistance are very small and so clever techniques need to be incorporated to allow these changes to be measurable.

Real voltmeters have high but not infinite resistance so that when we connect a voltmeter in parallel with a component we change the circuit. The p.d. that we end up measuring is different to the p.d. across the component before we connected the meter. If the resistance of the voltmeter is 10 times greater than the resistance of the device in question, then the maximum error in the reading of p.d. will be 10%. A voltmeter with a higher resistance would further reduce this error.

The same consideration needs to be borne in mind when choosing a potentiometer to use in a potential divider circuit. For example, the standard circuit in Figure 21 could be used for measuring the electronic characteristics for a bulb.

You can see that the circuit can be split into two halves. The left-hand side of the circuit allows you to fix a p.d. of your choice. When the right-hand side is added, this p.d. is connected to the bulb and meters. We have thus chosen and placed a p.d. across the bulb that will cause a current to flow through the bulb. Even if these meters were perfect, this way of visualizing the circuit is only useful if the resistances of the potentiometer and the bulb were appropriately selected in the first place.

We assume that the p.d. "fixed" by the left-hand side remained constant when the right-hand side of the circuit was added on. This will only be the case if the resistance of the right-hand circuit is significantly greater than the resistance of the potentiometer (like example (e) above). Normal laboratory potentiometers have a resistance across each end of about 1 Ω or 2 Ω and they are constructed to be able to carry a reasonably large current (5 A or so). This means that the resistance of the object under test (the bulb in the above example) should certainly be more than 10 Ω and ideally much larger.

This principle is also used when designing more complicated electric (and electronic) circuits. It is possible, within reason, to add different system "blocks" onto already existing circuits. If the resistance of the extra block is at least 10 times the resistance of the existing block, this addition can be done knowing that the first circuit will be largely unaltered by the addition.

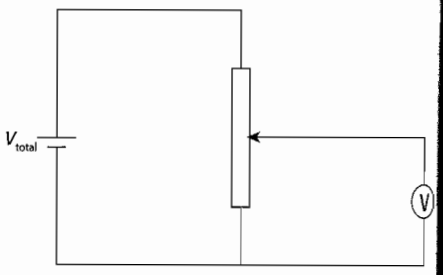


Figure 20

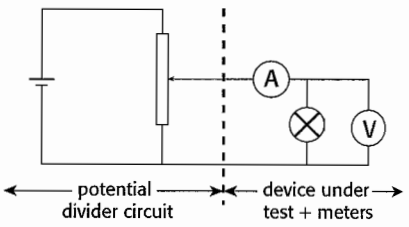


Figure 21