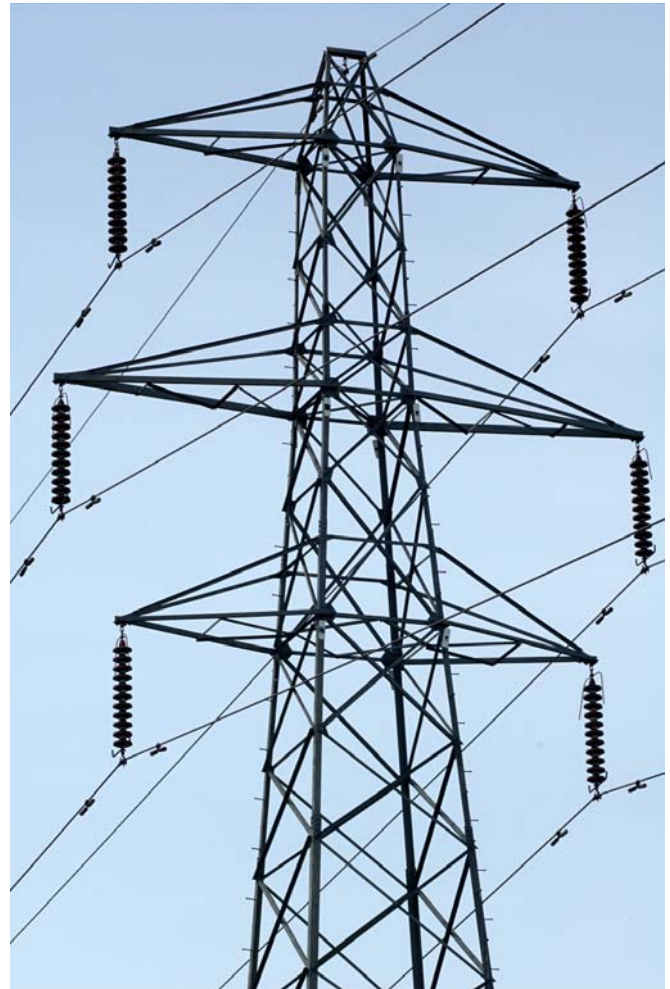


# Electricity

## Concepts and Circuits

Modern life depends upon electricity as a source of energy for lighting, heating, communications and a wide variety of machinery. Advances in understanding the nature of electricity and properties of substances which conduct electricity have facilitated the development of the electronics industry and the invention of numerous electrical machines. In everyday life, an understanding of basic concepts in electricity can contribute to the safe and efficient use of electrical devices.



# A. Introduction ●●

The theme of this module is the properties of simple electric circuits. To build an understanding, the basic electrical concepts are required: charge, current, energy, voltage, resistance and power. The activities exploit the use of ICT to stimulate thinking about how these concepts are used to understand the behaviour of electrical components and circuits. There are three types of activities:

## 1. **Data logging:** Four laboratory experiments:

- To investigate the relationship between voltage and current for a carbon resistor.
- To investigate the behaviour of two resistors connected in series or parallel.
- To investigate the relationship between voltage and current for a torch bulb.
- To investigate the relationship between voltage and current for a diode.

## 2. **Simulation:** Visual aids to assist understanding of the concepts of current and voltage and the interpretation of the data-logging experiments on simple circuits:

- To illustrate the behaviour of currents flowing in series and parallel circuits.
- To investigate the sharing of voltage in series circuit connections.
- To illustrate the concept of voltage as a measure of energy change in a circuit.
- To investigate resistors in series and parallel.
- To investigate power dissipated in a circuit

## 3. **Modelling:** Models to show the relationship between voltage and current for a bulb, to calculate the combined resistance of three resistors in parallel and to predict the voltage supplied to a circuit as the load resistance is varied.

# 1. Background theory

## 1. BASIC CONCEPTS IN ELECTRICITY

The basis of all electrical phenomena is the property of *electric charge*. It is very difficult to define what electric charge actually is; we cannot see it but we can observe its effects. It is better to think of it as a *property* of matter rather than like a substance, particle or fluid. Only two types of electric charge have been discovered and these have been named positive and negative. All matter is thought to contain electrically charged particles (protons and electrons in atoms), and the forces between them hold atoms and matter together. The normal presence of equal amounts of both positive and negative charge obscures their effect. It is only when charged particles move, or when there is an imbalance between the quantities of the two types that their effects can be easily observed. The effect of unbalanced charges leads to the phenomena of *electrostatics*. The effect of charge-on-the-move results in *electric currents*.

The unit for electric *charge* is the COULOMB, which is equivalent to the charge found on  $6.25 \times 10^{18}$  electrons.

*Current* is measured as the rate of flow of charge through a component. The unit for current is the AMPERE, (abbreviated to AMP) where 1 amp is the flow of 1 coulomb per second.

To obtain a flow of electric charge through a component, *electrical energy* is needed. As charge passes

through a component, some of its electrical energy becomes converted into a different form of energy (e.g. heat, light, sound, motion etc.). The difference in electrical energy of a coulomb of charge between entering and leaving the component is called the *potential difference*, or 'voltage' across the component. The unit of voltage is the VOLT, where 1 volt is the amount of energy (in joules) converted by 1 coulomb.

From the concept of voltage, it follows that the total *energy* converted by a component depends upon both the voltage across it and the number of coulombs flowing through it. If the voltage is  $V$ , the *energy* converted when  $Q$  coulombs flows through the component is the product  $QV$  (units: joules). Since current  $I$  is the number of coulombs flowing per second, we can further say that the *energy converted per second* is the product  $IV$  (units: joules per second or watts, where 1 watt = 1 joule /second). The rate of energy conversion is known as the *power* ( $P$ ) dissipated in the component. So we can say  $P = IV$ . When the power dissipated in a component is known, we can calculate the total energy converted using *power x time*.

## 2. ELECTRICAL CONDUCTORS AND COMPONENTS

Useful circuit components are conductors of electricity, that is, they allow current to flow through them. To describe how well a component conducts electricity, the concept of *resistance* is used. More precisely, resistance describes how poor a conductor is rather than how good it is at conducting. Thus resistance can be regarded as a measure of opposition to electric current. A larger resistance is a poorer conductor than a low resistance. Resistance is measured by the ratio *voltage / current*.

In symbols:  $R = V / I$  (units: ohm).

As a general principle voltage acts as a sort of 'driver' of current through a conductor. More voltage across a component causes more current. When the current varies in proportion to the voltage, the component is said to obey Ohm's Law. This makes the ratio  $V / I$  a constant value, so it is implicit that an ohmic conductor (one which obeys Ohm's Law) has a constant resistance. The law is conditional on the temperature and other physical conditions remaining constant, which is a problem for wires which get warm and light bulbs in which filaments get very hot. So strictly speaking, wires do not obey Ohm's Law when they get hot.

Electrical conductors owe their conductivity to the mobility of charge carriers. For most metals, the mobility of a certain proportion of

their electrons ('free' electrons) is responsible for current flow. The ease with which electrons can flow through a metal wire depends upon the state of vibration of the atoms in the wire. As the temperature of a wire increases, the amplitude of atomic vibrations increases making it more difficult for electrons to pass through. Thus the resistance of wire increases with temperature. The most common practical example of this is in a tungsten filament bulb. At its working temperature, its resistance is much greater than when cold. Thus in any experiments using bulbs, the resistance of a bulb is variable according to how much current passes and the consequent temperature of the filament. This can be a nuisance in experiments intended to investigate Ohm's Law which require resistors whose resistance does not change with different voltage and currents. The solution is to use carbon resistors which have a very low *temperature coefficient* of resistance, that is, their resistance hardly changes with temperature. Although Ohm's Law applies to many common conducting substances, there are also many examples of conducting materials for which the current does not vary in proportion to the voltage; for example, the gases in fluorescent tube lighting, ionic solutions, semiconductors in transistors, integrated circuits, diodes and LEDs.

### 3. ELECTRIC CIRCUITS

A fundamental condition for current flow is the provision of a complete circuit of conducting material, a continuous pathway along which charge can pass unimpeded. A circuit may be built from components in series or parallel, but it is crucial that at least one component is a source of electrical energy. The chemical battery is the most common example,

but other examples are dynamos and solar cells. To understand the properties and behaviour of circuits, all the basic concepts of charge, current, voltage, energy, resistance and power are required. The task of this module is to provide activities which help to illuminate the process of developing this understanding.

## 2. Pre-requisite knowledge required

- Experiments using batteries, bulbs and switches
- Continuity in circuits
- Current as a flow of electric charge
- Symbols used in circuit diagrams
- Use of ammeter for measuring current
- Series and parallel connections

## 3. Science concepts developed in the module

- Voltage, EMF, potential, p.d.
- Parallel connection of a voltmeter
- Energy, power
- Internal resistance of a battery
- Temperature coefficient of resistance

## 4. Other useful information

- Models of Electric Circuits - Appendix 1 taken from:  
[http://www.practicalphysics.org/go/Guidance\\_25.html?topic\\_id=8&guidance\\_id=1](http://www.practicalphysics.org/go/Guidance_25.html?topic_id=8&guidance_id=1)
- William Beaty "Misconceptions spread from K-6 textbooks"  
<http://amasci.com/miscon/elect.html>.

# B. Didactical approach ●●

## 1. Pedagogical context

The activities here concern basic concepts in electricity which form the foundation for understanding a wide range of electrical phenomena. Since electrical devices are such a common part of everyday life there are numerous contexts which may call upon basic principle for understanding. For example:

- Electricity in the home provides examples of electrical energy being converted into light, heat, sound and motion
- Despite the external appearance of a single cable used for connecting a mains electrical device, every electrical device needs a circuit in order to work
- Switches and fuses must be connected in series with a device
- Electric lights and other devices are connected in parallel to the mains supply
- Light bulbs of different power have different resistances

## 2. Common student difficulties

- Confusion between charge and current
- Appreciation the equivalence of 'electron flow' and 'conventional current'
- Understanding of voltage as a measure of energy conversion per coulomb
- Clarity of language: current *through* a component; voltage *across* a component
- Interpreting a relationship between two variables from a graph

## 3. Evaluation of ICT

This section considers some of the practical arrangements for exploiting the use of ICT to best effect, and discusses the qualities of the ICT methods which make a special contribution to students' learning.

### DATA-LOGGING

Voltage and current measurements are among the simplest to achieve with data-loggers, requiring fairly inexpensive sensors. Of course there are many traditional practical experiments which pupils can easily perform with batteries, bulbs and resistors, so what are the benefits of using sensors and data-loggers? When a few single measurements are required, it is difficult to justify the use of data-loggers, however, if a stream of measurements is useful then data-logging

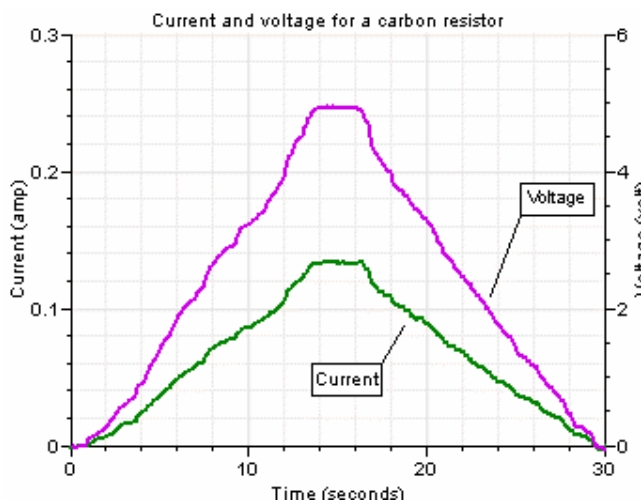
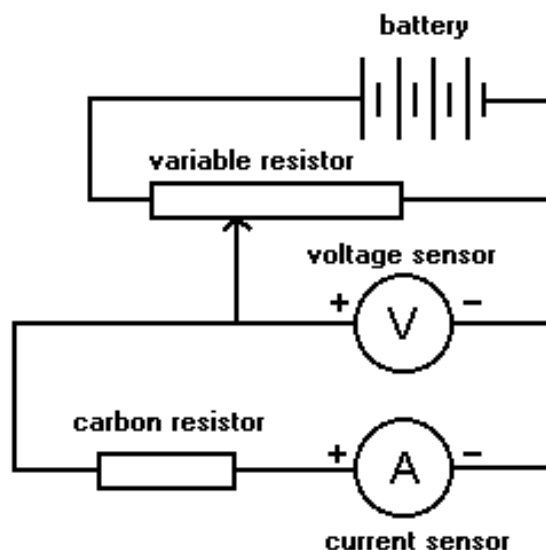
provides a valuable solution. Such is the case with investigating the current – voltage characteristics of components whereby a graph is obtained in real time whilst measurements are collected. The prompt display of the graph allows attention to be immediately focused on trends, changes and comparisons.

For the first activity a carbon resistor is recommended. This has the advantage of a very low temperature coefficient of resistance, thus maintaining a constant resistance over the normal working range of voltages and currents with batteries.

The first activity presents both voltage and current readings plotted against time, with the advantage that changes in one are simultaneously imitated by the other. This provides a meaningful experience of a proportional relationship; cursory inspection of the graph shows that if the *voltage* is doubled, the *current* also doubles, and similarly for other ratios. This is a powerful introduction to the relationship in preparation for the conventional *current vs. voltage* graph. The latter graph, being a straight line, has an instantly recognisable shape, but the fact that this represents a proportional relationship can be nurtured through the analysing activities suggested here.

The carbon resistor can be said to obey Ohm’s Law. As such, it is implicit that the resistance remains constant throughout the full range of current and voltage. Data-logging software makes this easily verifiable by calculating resistance and plotting this against voltage. Examples of non-ohmic components such

as a torch bulb or diode are readily investigated using the same circuit and experimental arrangement. Again the real-time plotting of the graphs allows results to be compared within a very short space of time. For the torch bulb, results may be compared with the modelling activity 3a which identifies the behaviour with the variation of resistance of the filament with temperature.





## SIMULATION

The simulations presented here are best used as teacher demonstrations for facilitating class discussions of the concepts involved. Their use needs to be carefully managed and integrated with discussion in order to develop clear logical thinking. Random clicking on the various program features is unlikely to benefit thinking about subtle concepts about which pupils often have very confused ideas, so a structured approach is essential.

The simulations for this module have been chosen to illustrate the power of this type of program to facilitate discussion leading to an understanding of abstract concepts. They provide visualisations of the internal working of circuits which are invisible in real life. They achieve this by much symbolism and use of analogy which demands expert interpretation and guidance by teachers through structured argument. All the examples may and should be set up as practical laboratory activities, but the use of simulation saves much time, allows changes to be made rapidly, and measurements to be easily and accurately compared. Together with various visual displays such as moving charges, analogue meters and energy bars, the simulation environment greatly assists comprehension.

### ***Circuit – current***

This simulation offers a visualisation of the difference between electrical *charge* and *current*. Charge (measured in *coulombs*) is the property of particles already present in all parts of the circuit ('free electrons') and *current* (measured in *amps*) is envisaged as the mobilisation of the charged particles to form a steady flow through wires and bulbs. As the *voltage* supplied is increased, the rate of flow of charges also increases, a result observed in the screen animation. In the context of this circuit, *voltage* may be seen as the 'driving force' causing the flow of charged particles (*current*) through the wires. The concept of *voltage* as a measure of energy changes in the circuit is not essential at this stage; in a simple circuit such as that used here, a simple cause (*voltage*) and effect (*current*) model is adequate to understand the behaviour of the currents and bulbs. The brightness of a bulb can be used as an informal indicator of *current* (when all the bulbs have similar resistance). (Later simulations in this series consider the dependence of brightness on the power dissipated in a bulb.)

The dial displays allow immediate observation of the magnitudes of *currents*; equal increases in *current* are observed when the *voltage* is increased in equal steps. It should be noted that this is not true bulb behaviour. Tungsten filament bulbs cannot be regarded as Ohmic conductors because their *resistance* increases with *temperature*. In order to offer simple patterns of results and encourage recognition of such patterns, the model for this and later simulations makes no allowance for this effect. However Activity 3b explicitly requires the model to take account of the temperature of the filament.

The dial displays also make it easy to compare currents in different parts of the circuit and when the number of bulbs is altered. When two bulbs are connected in series, the reduction in the current paves a way to developing ideas about resistance; it is 'harder' to drive current through two bulbs in series. However,



when bulbs are connected in parallel, the currents in the parallel branches may be seen to be independent of each other. Also observable are the branching and combining of currents at the T junctions so that the simple rule for summing currents applies at each junction.

**CAUTION:** The animated visualisation should not be interpreted too literally. As with many models and simulations, the graphics are symbolic and are chosen to assist thinking about particular themes, as described above. For example, the simulation does not attempt to represent the true number of charged particles nor their velocity associated with current flow in real wires; In reality the density of free electrons is enormous (typically about  $10^{18}$  electrons per millimetre of wire) and their drift velocity is very small (typically 1 mm/s.)

### ***Circuit – voltage***

This simulation is intended to prompt thinking about the role of voltage around the circuit. The voltage supplied by the battery is seen to be shared between the resistor and the bulb. The relative resistance of each component determines how voltage is shared between them. It is observed that, as the resistance is varied, not only does the current through the bulb vary but also the voltage across it. It needs to be emphasised that the brightness depends upon both current and voltage.

Discussion needs to develop ideas about electrical energy in the circuit: charge (measured in coulombs) collects electrical energy on passing through the battery and delivers it to the components on passing through them in the external circuit.

voltage = energy gained or lost per coulomb

current = rate of flow of coulombs through components per second

Note the correct use of language here: *current* flows through a component, but *voltage* has to be measured across the component. It is implicit that ammeters for measuring current must be connected in series, whereas voltmeters must be connected in parallel.

### ***Circuit – potential***

This simulation can be a powerful tool for developing an understanding of voltage, but it demands a carefully managed discussion with pupils.

The word voltage is used to describe two distinct concepts:

- EMF (electromotive force) is the electric potential energy gained by 1 coulomb of charge when passing through the battery. This is a measure of the energy *supplied* to the circuit.
- p.d. (potential difference) is the electric potential energy *converted* into heat and light) in each component when 1 coulomb passes.

The simulation distinguishes between these two concepts, allowing the EMF of the battery to be adjusted and the p.d.s across the components in the circuit to be measured. By displaying the electric energy as vertical bars, an analogy between electric potential energy and gravitational potential energy may be

invoked. In this view a lower point on a hill possesses less potential energy than the top of the hill and a downward slope represents a 'potential difference'. Just as a ball on a hillside will accelerate more quickly down a steeper slope compared with a more gentle slope, electric current is greater through a component when the p.d. is greater. The simulation shows the 'electrical hill' as a blue line and p.d. is represented by a downward drop shown as a blue arrow. The twin ideas of voltage (p.d.) causing current and voltage as a measure of energy changes may be developed in discussion of the analogy. The simulation permits the visualisation of these subtle concepts and assists the use of the gravitational analogy in developing an understanding of them.

An important principle implicit in this view of a circuit is the principle of Conservation of Energy: The electrical energy made available to the circuit as coulombs of charge pass through the battery, is completely accounted for as the sum of the energies lost by coulombs passing through each component. In other words, the sum of the p.d.s around the circuit is equal to the EMF of the battery.

Another important principle to emerge from discussing the simulation is that the rate of energy output from a bulb does not simply depend upon the current through it. It is clear that, being in series, the bulbs carry the same current, thus the difference in energy output of the bulbs also depends upon the voltages (p.d.s) across them.

### ***Circuit – resistance***

The main value of this simulation is to eliminate the multiplicity of measurements and calculations that are normally required in the practical experiments at the bench. The visual layout sets out the calculation method and demonstrates very clearly that the calculation result is independent of the voltage. Since current and voltage increase in the same ratio (assuming the resistors obey Ohm's Law), the resistance is a mathematical constant.

The ease with which different combinations of resistors may be selected, saves considerable amounts of time, ensures accuracy, and facilitates rapid comparison. A useful teaching tactic is to ask pupils to guess the likely current or resistance before each test setting. Pupils are often surprised when the combination in parallel yields a smaller resistance than either individual resistor. The visualisation in the simulation illustrates clearly that the additional resistor is in fact an additional conducting path available to current; therefore more current is able to flow rather than less, compared with an individual resistor. Although, these components are traditionally described as 'resistors' it is helpful to emphasise that they are employed as 'conductors'.

### ***Circuit – power***

This simulation helps to study the relationships between voltage, current and power in a simple circuit. The display dials and graph allow the changes to be compared instantly. If the voltage is increased in equal steps, the current dial is observed to increase in equal steps, but the power dial shows increases which get bigger with each step. Also, the display of values allows pupils to see that

increases occur in simple ratios for current and voltage, but according to the square for power and voltage. Compared with the real practical experiment, the appearance of simple values allows increases to be studied as simple ratios.

The previous simulation 'Current – potential' established the relationship between the brightness of the bulb and both voltage and current. Since the model for 'Circuit – power' calculates the electrical power as the product of voltage and current, this simulation emphasises that the brightness of bulb depends upon the rate of energy conversion and radiation as light.

## MODELLING

The purpose of the modelling activities is to give pupils an insight into the physical and mathematical basis of the calculations performed by the model. The essence of modelling is to experiment with adjusting the model so that it gives results which best match data from real experiments. The results from the first two models may be compared directly with those obtained from the data-logging activities.

### *Model – bulb*

The model is based upon two main assumptions:

1. The resistance of the filament increases as the filament gets hotter
2. The temperature of the filament depends upon the balance between the heat energy created by converting electric energy and that lost by radiation and convection to the surroundings.

The first effect is represented in the formula which calculates the change of resistance  $\Delta R$  as a result of the change in temperature  $\Delta T$ :

$$\Delta R = a \cdot \Delta T$$

where  $a$  is the temperature coefficient of resistance for the resistor.

The formula for calculating the change of temperature is more complex. It is composed of two parts; the first ( $c \cdot I \cdot V \cdot \Delta t$ ) relates to the production of heat in the filament and the second ( $b \cdot (T - 20) \cdot \Delta t$ ) relates to the loss of heat to the surroundings.

$$\Delta T = c \cdot I \cdot V \cdot \Delta t - b \cdot (T - 20) \cdot \Delta t$$

where

$c$  is a constant for obtaining the temperature rise from the electric power ( $I \cdot V$ ) dissipated in the bulb

$b$  is a constant for obtaining the temperature fall due to heat lost to the surroundings. The surrounding temperature is set to be 20 Celsius, so the assumption here is that the loss of heat varies in proportion to the excess temperature above the surroundings.

This is a simplification and ignores Stefan's Law of Radiation.

As the voltage is slowly increased, the current increases non-linearly: It rises less at higher currents due to the increase of resistance with temperature. Reducing the voltage gives a similar curve, but slightly below the first, a similar result to that obtained in the data-logging experiment.

### ***Model – resistors***

This model employs basic principles for the behaviour of simple circuits: There is a common voltage across resistors in parallel and the currents in each parallel branch combine as an arithmetic sum. Thus the method of calculation of the total resistance is completely transparent to pupils, but the results always seem to be surprising: more resistors in parallel give less resistance! The model is a development of the one employed in the simulation for Activity 2d.

### ***Model – battery***

This model takes account of the internal resistance of the battery, a factor ignored in all previous simulations and models. It distinguishes between the energy input to the circuit (EMF of the battery,  $E$ ) and the voltage,  $V$ , available to the external circuit across the terminals of the battery. The difference between these represents the energy per coulomb,  $v$ , dissipated as heat in the internal resistance of the battery.

Thus: 
$$V = E - v$$

The current in the circuit is calculated taking account of the total resistance in the circuit:

$$I = \frac{E}{(R_v + R + r)}$$

Where  $R_v$  and  $R$  are the resistances in the external circuit  
 $r$  is the internal resistance of the battery

The energy per coulomb,  $v$ , dissipated in the internal resistance of the battery is calculated:

$$v = I \cdot r$$

This clearly shows that the 'lost volts' due to the internal resistance increases according to the current through the battery and the magnitude of its internal resistance. A new battery has a low internal resistance, but during use, chemical changes in the battery cause this to increase. Thus an older, used battery tends to suffer a greater loss of voltage across its terminals. The model permits the ageing effect to be simulated by increasing the internal resistance.

## 4. Teaching approaches

The three groups of activities presented here offer distinctive but complementary insights into the science involved in this topic. For the activities to be effective for teaching and learning, it is helpful for teachers to consider two types of skills in using the software tools:

- **Operational skills** which concern the manipulation of the computer hardware and knowledge of the features in the software.
- **Procedural skills** which concern the manner in which the software tools are employed in the lesson context for the purpose of achieving learning benefits. A dominant aspect of these skills is the development of an inquiring approach to the analysis and interpretation of data and to making links with previous knowledge.

Such skills are important for the preparation of pupils for the activities, and the activity sheets below each contain indications of the skills needed for the particular activity.

For the teacher, there are further *pedagogical skills* which contribute to the effectiveness of the activities:

1. Clarity of learning objectives for each activity.
2. Understanding of the special value of the ICT method and exploiting its full potential in purposeful ways.
3. To manage the activity in a way which promotes 'appropriate' rather than 'indiscriminate' use of ICT.
4. To integrate the learning from each activity to develop pupils' understanding of the topic.

The development of the last of these is a particular aim of the IT for US Project, and the activities presented below have been specially selected to illustrate how integration might be achieved. The different types of activities are intended to be complementary both to each other and to further practical activities away from the computer. Teachers will usually have their preferred sequence of teaching themes involving, demonstrations, explanations, class experiments, but the table below suggests a suitable sequence exemplifying a logical development of concepts. The right hand column shows how the activities in this module may be chosen to enhance the teaching sequence.

Teaching sequence	IT for US Activities
<p>*Experiments with conductors and insulators</p> <p>*Experiments with batteries, bulbs &amp; switches</p> <p>Introduce concepts of charge and current</p> <p>Voltage as a 'driving force' causing current</p> <p>Concept of electrical energy: Voltage as energy per coulomb</p> <p>*Experiments measuring voltage across components in series</p> <p>*Experiments to measure electrical power</p>	<p>Simulation:2a Currents in circuits</p> <p>Simulation:2b Voltage in series</p> <p>Simulation:2c Elec. energy in circuits</p> <p>Simulation:2e Electric power</p>
<p>*Experiments to find relationships between current and voltage for components</p> <p>Define concept of resistance</p> <p>*Experiments with resistors in series and parallel</p>	<p>D-Logging:1a Resistor characteristics</p> <p>D-Logging:1b Resistors in series and parallel</p> <p>Simulation:2d Calculating resistance</p> <p>Model:3b Calculating resistance</p>
<p>*Experiment with a light bulb to observe effect of temperature on resistance</p> <p>*Experiments with coils of heated wire</p>	<p>D-Logging:1a Light bulb characteristic</p> <p>Model:3a Resistance of a light bulb</p>
<p>*Experiment to investigate internal resistance of a battery</p>	<p>Model:3c Internal resistance of battery and 'lost volts'</p>

The non-computer experiments (\*) are not described here, since their details are well established in conventional teaching schemes and text books.



Comparisons of the observations and results of each activity form a central role in this integration process. For example:

- Compare the graphs obtained in the data-logging experiments; different resistors and different combinations of resistors give different slopes of straight line; carbon resistors, torch bulbs and diodes produce different graph shapes;
- Compare the results from the simulations and data logging experiments to make links between the results of experiments and their theoretical explanation.

In these, the graph is a key tool in facilitating comparisons and interpretations and skills with graphs generally provide a common thread in exploiting IT for US activities.

In several cases, the graph is a key tool in facilitating comparisons and interpretations

and skills with graphs generally provide a common thread in exploiting IT for US activities.

The management of the classroom setting also has an important influence on the successful integration of activities. For this module, in view of the fact that an understanding of electricity requires clear thinking about several inter-related concepts, we suggest that the teacher needs to provide a strong guidance structure in the use of the activities. Most teachers will achieve this through didactic demonstrations linked with whole class discussion. However, there are still opportunities for follow-up work (reinforcement, extension, revision etc.) by pupils working individually or in pairs or in groups. Again, it is usually advisable to provide a structure for activities using some of the worksheet suggestions. In both planning and teaching, it is important to have clear learning objectives for the use of the activities, and to assist this, the table below summarises their distinctive potential learning benefits.

Activity	Potential learning benefits, 'ICT value'
<p>Data-logging</p> <ol style="list-style-type: none"> <li>1. Current – voltage graphs</li> <li>2. Resistors in series and parallel</li> </ol>	<p>Graph of current vs. voltage is displayed during experiment Changes are observable immediately.</p> <p>Graph analysis tools facilitate detailed investigation of data.</p>
<p>Simulation</p>	<p>Animated graphics provide visualisation of the abstract concepts involved in electrical theory:</p> <ul style="list-style-type: none"> <li>- Current as flow of charge</li> <li>- Conservation of current</li> <li>- Electric potential as electrical energy per coulomb</li> <li>- Voltage (EMF and PD) as energy transferred per coulomb</li> <li>- Conservation of energy in a circuit</li> </ul>
<p>Modelling</p> <ol style="list-style-type: none"> <li>1. Light bulb</li> <li>2. Resistors in parallel</li> <li>3. Internal resistance of battery</li> </ol>	<p>The models demonstrate how the relevant physical principles can be expressed in simple stages using mathematical formulae.</p> <p>The models calculate data which may be compared with data obtained from the real experiments (data-logging) with circuits.</p> <p>The effect of altering parameters such as surrounding temperature, mass of substance, thermal capacity and latent heat capacity may be investigated.</p> <p>Model 1 allows investigation of the change of resistance with temperature.</p> <p>Model 2 may be extended to any number of resistors of any value.</p> <p>Model 3 allows ageing effect of battery to be simulated.</p>

## 5. Resources for Student Activities

### USING INSIGHT SOFTWARE

Activity	Software program	Files available
1. Data-logging	Datalogging Insight	Set-up file: 'carbon resistor set-up' Open this file to configure the program ready for the experiments. Data files: 'carbon resistor data' <i>This file contains sample data.</i>
2. Simulation	Simulation Insight	'circuit – current' 'circuit – voltage' 'circuit – potential' 'circuit – resistance' 'circuit – power'
3. Modelling	Simulation Insight	'model – bulb' 'model – resistors' 'model – battery'

### EQUIPMENT AND MATERIALS FOR ACTIVITY 1 (DATA-LOGGING)

- Computer
- Software – *See table above*
- Interface (data-logger)
- Current and voltage sensors
- Two identical carbon resistors (e.g. 10 ohm)
- Variable resistor (rheostat e.g.20 ohm)
- Battery (e.g. 4.5V)
- Connecting leads
- Bulb (e.g. 3.5 V 0.2A)
- Thermistor
- LED (light emitting diode)

# C. Student Activities ●●

## ACTIVITY 1A. EXPERIMENT TO INVESTIGATE THE RELATIONSHIP BETWEEN CURRENT AND VOLTAGE FOR A CARBON RESISTOR

### Learning Objectives:

1. To obtain graphs of voltage, current and time as the voltage across a carbon resistor is varied.
2. To interpret the graphs so as to describe the relationship between voltage and current.
3. To derive graphs showing the resistance of the resistor and the power dissipated.

APPLIED ICT TECHNOLOGY:  
DATA LOGGING

STUDENT LEVEL:  
AGE 14-17

RECOMMENDED SETTINGS:  
STUDENT ACTIVITY IF  
ENOUGH EQUIPMENT IS  
AVAILABLE, OTHERWISE  
TEACHER DEMONSTRATION

### Operational Skills:

- Connecting sensors and interfaces
- Choosing logging parameters
- Starting and finishing real-time logging
- Using the cursor tools for obtaining measurements from the graph
- Changing the designation of the graph axes
- Deriving secondary data by calculation

### Procedural Skills:

- Evaluating measurement quality
- Analysing data using graph
- Reading values/slopes

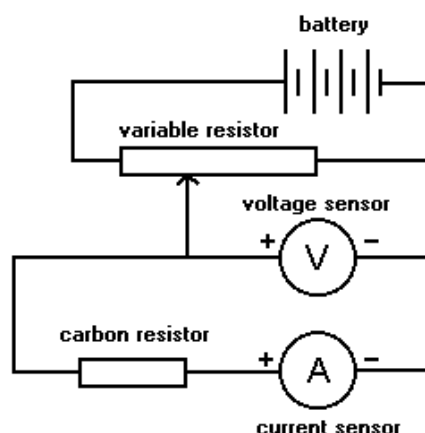
### Materials:

- Interface (data-logger)
- Current and voltage sensors
- Carbon resistor (e.g. 10 ohm)
- Variable resistor (rheostat e.g.20 ohm)

- Battery
- Connecting leads

### Activity method:

1. Connect the fixed ends of the variable resistor to the battery as shown.
2. Connect the slider contact on the variable resistor to the carbon resistor and complete the circuit with the sensors in place as shown. (Take care to observe the polarity of the connections to the sensors as shown.)



3. Set the data logging software to record both current and voltage for about 60 seconds. Adjust the graph to plot the values of *current* and *voltage* against *time*. Start recording.
4. Slowly adjust the variable resistor slider so that the voltage varies from zero to its maximum and back to zero again.
5. Observe the graph showing current and voltage rising and falling with Time.

### Analysing activities:

1. *Sweeping cursors*  
After the experiment, the real-time experience can be re-lived to a certain extent using the graph cursors and bar display: Drag the X cursor slowly across the screen, and note how the bars grow and shrink in the same manner as the changes of the values recorded during the experiment, creating an 'action replay' effect. In particular, pupils should notice that the increases and decreases of voltage and current always occur in the same direction. This is a useful indicator of the relationship; the changes in current seem to imitate changes in voltage in the same pattern.
2. *Take readings from the graph*  
Record the current values when the voltage is 1.0, 2.0 and 3.0 volts and look for the pattern in the results.
3. *Change the axes*  
Change the axes of the graph to show *current vs. voltage*. The shape of the graph line is an important indicator of the relationship. Take readings using the cursors to confirm that the results are the same as those obtained in Analysis task 2.

4. *Calculate resistance*

Use the readings taken in Task 3 to calculate the *resistance* of the resistor from the formula:

$$R = V / I$$

Alternatively, use the software to derive a set of data for *resistance* using the same formula. The graphs of *resistance vs voltage* or *resistance vs time* show how constant or variable the resistance is during the experiment.

5. *Calculate power dissipated*

Use the software to derive a further set of data using the formula  $P = I * V$ . Plot the graph of power vs voltage and compare its shape with the previous graph of *current vs. voltage*. Use cursors to take readings of *power* when the voltage is 1.0, 2.0 and 3.0 volts. Look for the pattern in the results and compare this with the pattern of results obtained in Analysis tasks 2 and 3.

**Further work:**

- Discuss how well the results confirm Ohm's Law for the resistors.
- Repeat the experiment with a resistor of different value and compare the results.
- The same method may be used for a variety of components such as torch bulbs, diodes, LEDs and thermistors. (See Activity 1c.).



# ACTIVITY 1B. EXPERIMENT TO COMPARE THE BEHAVIOUR OF TWO RESISTORS CONNECTED IN SERIES OR IN PARALLEL

## Learning Objectives:

1. To obtain graphs of *current* against *voltage* for a single resistor, for two similar resistors in series and two similar resistors in parallel.
2. To interpret the graphs so as to describe the resistance of the combination of resistors.
3. To predict the gradient of the graph before each test.

APPLIED ICT TECHNOLOGY:  
DATA LOGGING

STUDENT LEVEL:  
AGE 14-17

RECOMMENDED SETTINGS:  
STUDENT ACTIVITY IF  
ENOUGH EQUIPMENT IS  
AVAILABLE, OTHERWISE  
TEACHER DEMONSTRATION

## Operational Skills:

- Connecting sensors and interfaces
- Choosing logging parameters
- Starting and finishing real-time logging
- Using the cursor tools for obtaining measurements from the graph

## Procedural Skills:

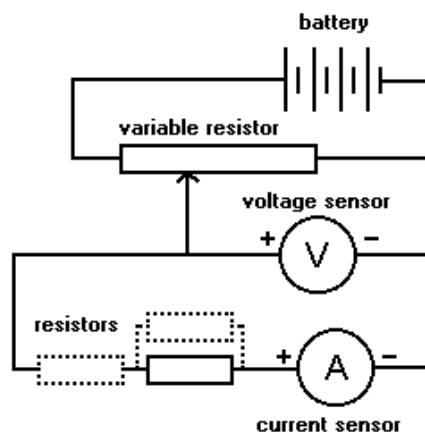
- Evaluating measurement quality
- Analysing data using graph
- Reading values/slopes

## Materials:

- Interface (data-logger)
- Current and voltage sensors
- Two identical carbon resistors (e.g. 10 ohm)
- Variable resistor (rheostat e.g. 20 ohm)
- Battery
- Connecting leads

### Activity method:

1. Connect the fixed ends of the variable resistor to the battery as shown.
2. Connect the slider contact on the variable resistor to the carbon resistor and complete the circuit with the sensors in place as shown. (Take care to observe the polarity of the connections to the sensors as shown.)
3. Set the data logging software to record both current and voltage for about 60 seconds. Adjust the graph to plot the values of *current* against *voltage*. Start recording.
4. Slowly adjust the variable resistor slider so that the voltage varies from zero to its maximum and back to zero again.
5. Observe the graph and consider how the value of the resistor affects the gradient of the graph line.
6. Connect a second carbon resistor in series with the first and record data as before. Observe the gradient of the new graph line and compare it with the first line for the single resistor.
7. Repeat Instruction 6 but with the second resistor in parallel with the first.



### Analysing activities:

1. *Take readings from the graph*  
For each graph line, record the current values when the voltage is 1.0, 2.0 and 3.0 volts and look for the pattern in the results.
2. *Compare the graphs*  
Notice that the three graphs (for a single resistor, two resistors in series and two resistors in parallel) each have a different gradient. Deduce which graph shows the largest resistance. Deduce which graph shows the lowest resistance.
3. *Calculate resistance*  
Use the readings taken in Task 1 to calculate the *resistance* of the resistor or combination of resistors from the formula:  $R = V / I$   
Deduce which arrangement of resistors has the highest resistance.  
Deduce which arrangement of resistors has the lowest resistance.

# ACTIVITY 1C. EXPERIMENT TO INVESTIGATE THE RELATIONSHIP BETWEEN CURRENT AND VOLTAGE FOR A TUNGSTEN BULB

## Learning Objectives:

1. To obtain graphs of voltage, current and time as the voltage across a tungsten bulb is varied.
2. To interpret the graphs so as to describe the relationship between voltage and current.

APPLIED ICT TECHNOLOGY:  
DATA LOGGING

STUDENT LEVEL:  
AGE 14-17

RECOMMENDED SETTINGS:  
STUDENT ACTIVITY IF  
ENOUGH EQUIPMENT IS  
AVAILABLE, OTHERWISE  
TEACHER DEMONSTRATION

## Operational Skills:

- Connecting sensors and interfaces
- Choosing logging parameters
- Starting and finishing real-time logging
- Using the cursor tools for obtaining measurements from the graph
- Changing the designation of the graph axes

## Procedural Skills:

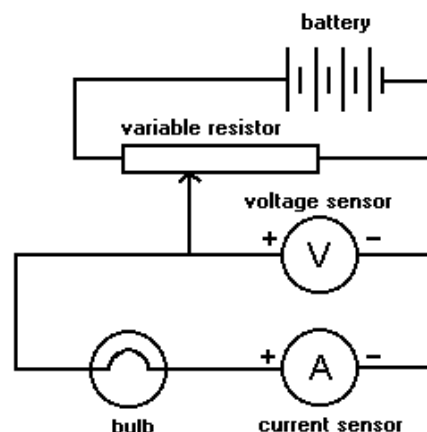
- Evaluating measurement quality
- Analysing data using graph
- Reading values/slopes

## Materials:

- Interface (data-logger)
- Current and voltage sensors
- Torch bulb (3.5 V)
- Variable resistor (rheostat e.g.20 ohm)
- Battery
- Connecting leads

### Activity method:

1. Connect the fixed ends of the variable resistor to the battery as shown.
2. Connect the slider contact on the variable resistor to the bulb and complete the circuit with the sensors in place as shown. (Take care to observe the polarity of the connections to the sensors as shown.)
3. Set the data logging software to record both current and voltage for about 60 seconds. Adjust the graph to plot the values of *current* and *voltage* against *time*. Start recording.
4. Slowly adjust the variable resistor slider so that the voltage varies from zero to its maximum and then slowly back to zero again.
5. Observe the graph showing current and voltage rising and falling with Time.



### Analysing activities:

1. *Sweeping cursors*  
Notice that the shapes of the graph lines are not as orderly as the ones for the carbon resistors. More information about the difference can be obtained using the cursors:  
Drag the X cursor slowly across the screen, and note how the bars grow and shrink in the same manner as the changes of the values of current and voltage recorded during the experiment, creating an 'action replay' effect. In particular, pupils should notice that the increases and decreases of voltage and current occur at different rates, in contrast with the behaviour with carbon resistors. This is a first indicator of a non-linear relationship; the changes in current seem to become smaller than corresponding changes in voltage.
2. *Take readings from the graph*  
Record the current values when the voltage is 1.0, 2.0 and 3.0 volts and look for the pattern in the results which confirm a non-linear relationship.
3. *Change the axes*  
Change the axes of the graph to show *current vs. voltage*. The shape of the graph line clearly indicates a non-linear relationship. It also shows a slightly different shape according to whether the voltage was increased or

decreased: The current tends to be lower when the voltage is decreased. Pupils may be prompted to think about the effect of temperature changes on the resistance of the bulb filament.

#### 4. Calculate resistance

Use the software to derive a set of data for *resistance* using the formula:

$$R = V / I$$

The graphs of *resistance vs voltage* or *resistance vs time* confirm the changes of resistance during the experiment.

#### Further work:

- Find out how the graphs are affected by the speed with which the voltage is increased or decreased in the experiment. The results may be explained by thinking about the temperature changes in the filament and their effect on its resistance.
- Repeat the experiment using the same method with a thermistor. Consider the role of temperature and compare the results with those for the carbon resistors and the bulb.
- Repeat the experiment with a diode or LED, making sure that an additional safety resistor is connected in series with the diode. Compare the results with previous experiments and discuss how applicable is Ohm's Law for each type of component.

## ACTIVITY 2A. UNDERSTANDING CURRENTS IN SERIES AND PARALLEL CIRCUITS

### Learning Objectives:

1. To understand electric current as a flow of electrical charge.
2. To understand that, since the total charge in a circuit is conserved, current is also conserved through series and parallel connections.
3. To understand that the current through two components in series is the same
4. To understand that voltage is a cause of the flow of current.

APPLIED ICT TECHNOLOGY:  
SIMULATION

STUDENT LEVEL:  
AGE 14-17

RECOMMENDED SETTINGS:  
TEACHER DEMONSTRATION  
AND CLASS DISCUSSION

### Operational Skills:

- Using the software controls for running the simulation

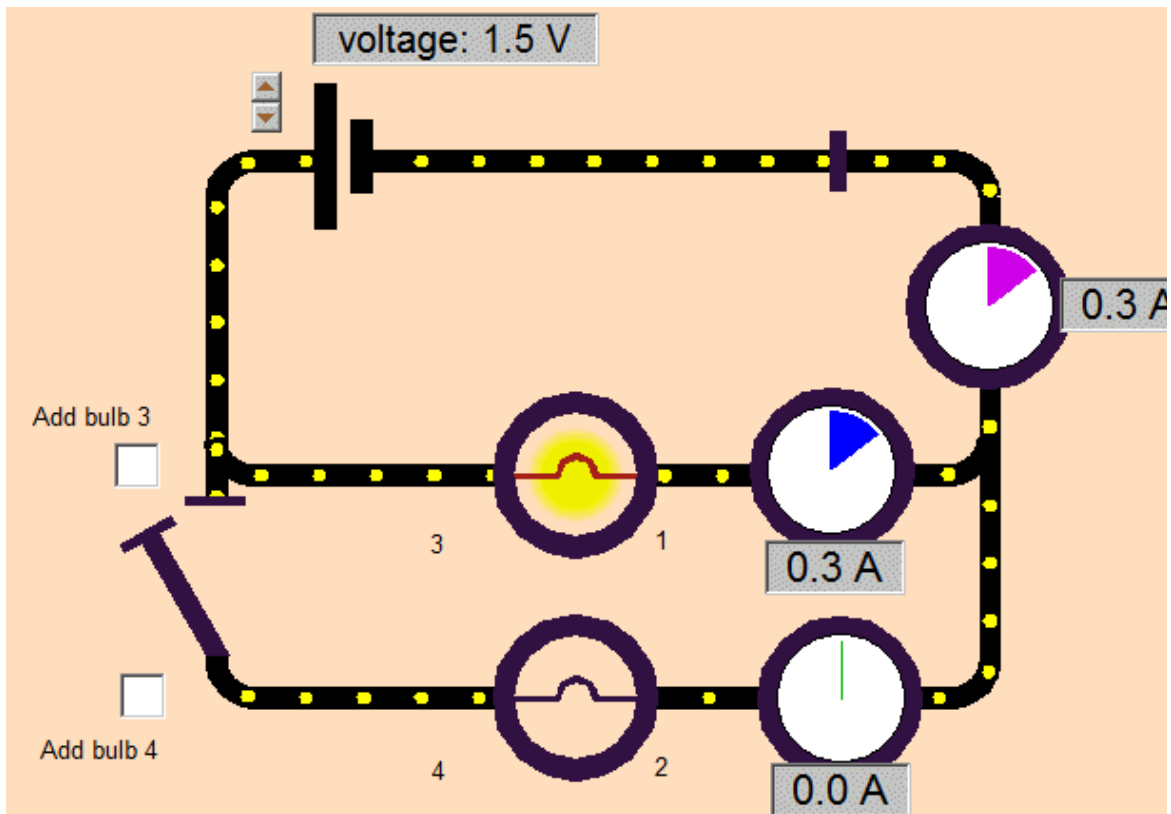
### Procedural Skills:

- Describe observations and link these with theoretical explanation

### Activity method:

1. Open the *Insight* file 'Circuit -current'
2. Look carefully at the circuit in the simulation window and notice that it contains a battery, two light bulbs, two switches and three ammeters. Two further bulbs may be added to the circuit by ticking the check boxes to the left.
3. Close the switch next to the battery, and adjust the voltage supplied by the battery. Observe the effect on the current through the bulb and the brightness of the bulb.
4. Add bulb 3 in series with the first bulb. Observe the effect on the flow of current through both bulbs and the brightness of the bulbs. Observe the further effect of adjusting the voltage.
5. Remove bulb 3 and close the lower switch so that current flows in the second branch of the circuit. Compare the three currents indicated by the meters. Compare the brightness of the bulbs as the voltage is adjusted.
6. Experiment with different combinations of bulbs and voltage, each time comparing the currents and brightness.





### Discussion:

Thinking about your observations, discuss the correctness of the following statements:

- As the voltage supplied increases, the current through a bulb also increases.
- The brightness of a bulb depends upon the current passing through it.
- For a given voltage, when two bulbs are in series, the current is reduced.
- The current passing through the battery is equal to the sum of the currents passing through the bulbs.

## ACTIVITY 2B. UNDERSTANDING VOLTAGE SHARING IN SERIES CIRCUITS

### Learning Objectives:

1. To understand electric current as a flow of electrical charge.
2. To understand that, since the total charge in a circuit is conserved, current is also conserved through series and parallel connections.
3. To understand that the current through two components in series is the same.
4. To understand that voltage is a cause of the flow of current.

APPLIED ICT TECHNOLOGY:  
SIMULATION

STUDENT LEVEL:  
AGE 14-17

RECOMMENDED SETTINGS:  
TEACHER DEMONSTRATION  
AND CLASS DISCUSSION

### Operational Skills:

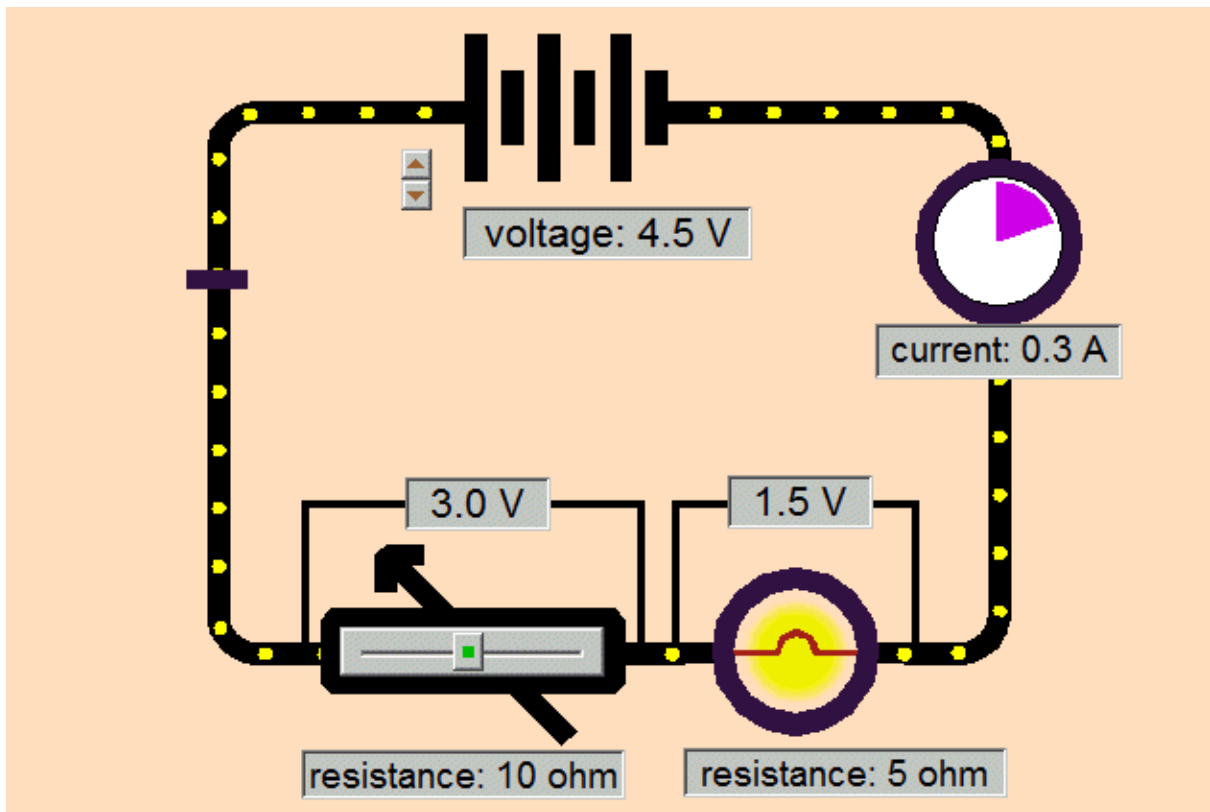
- Using the software controls for running the simulation

### Procedural Skills:

- Describe observations and link these with theoretical explanation

### Activity method:

1. Open the *Insight* file 'Circuit -voltage'
2. Look carefully at the circuit in the simulation window and notice that it contains a battery, variable resistor, light bulb and an ammeter.
3. Close the switch and adjust the voltage supplied by the battery. Observe the effect on the current through the bulb and the brightness of the bulb.
4. Vary the resistor and observe the effect on the flow of current, the brightness of the bulb, and the voltages across the resistor and bulb.
5. Think about the relationship between the voltage and resistance.



### Discussion:

Thinking about your observations, discuss the correctness of the following statements:

- The brightness of a bulb depends upon the current passing through it and the voltage across it.
- The sum of the voltages across the resistor and bulb is equal to the voltage supplied by the battery.
- The voltage supplied by the battery is shared equally between the resistor and bulb.
- The voltage across the resistor increases as its resistance is increased.
- The current in the circuit reduces as the total resistance is increased.

## ACTIVITY 2C. UNDERSTANDING THE CONCEPTS OF VOLTAGE AND CURRENT

### Learning Objectives:

1. To understand electric current as a flow of electrical charge.
2. To understand that voltage is a cause of the flow of current and is a measure of electrical energy change as current flows around a circuit.
3. To understand that a battery donates electrical energy to charge flowing through it and that components in the circuit convert that energy into other forms.
4. The rate of energy conversion in each bulb depends upon the voltage across it as well as the current through it.

APPLIED ICT TECHNOLOGY:  
SIMULATION

STUDENT LEVEL:  
AGE 14-17

RECOMMENDED SETTINGS:  
TEACHER DEMONSTRATION  
AND CLASS DISCUSSION

### Operational Skills:

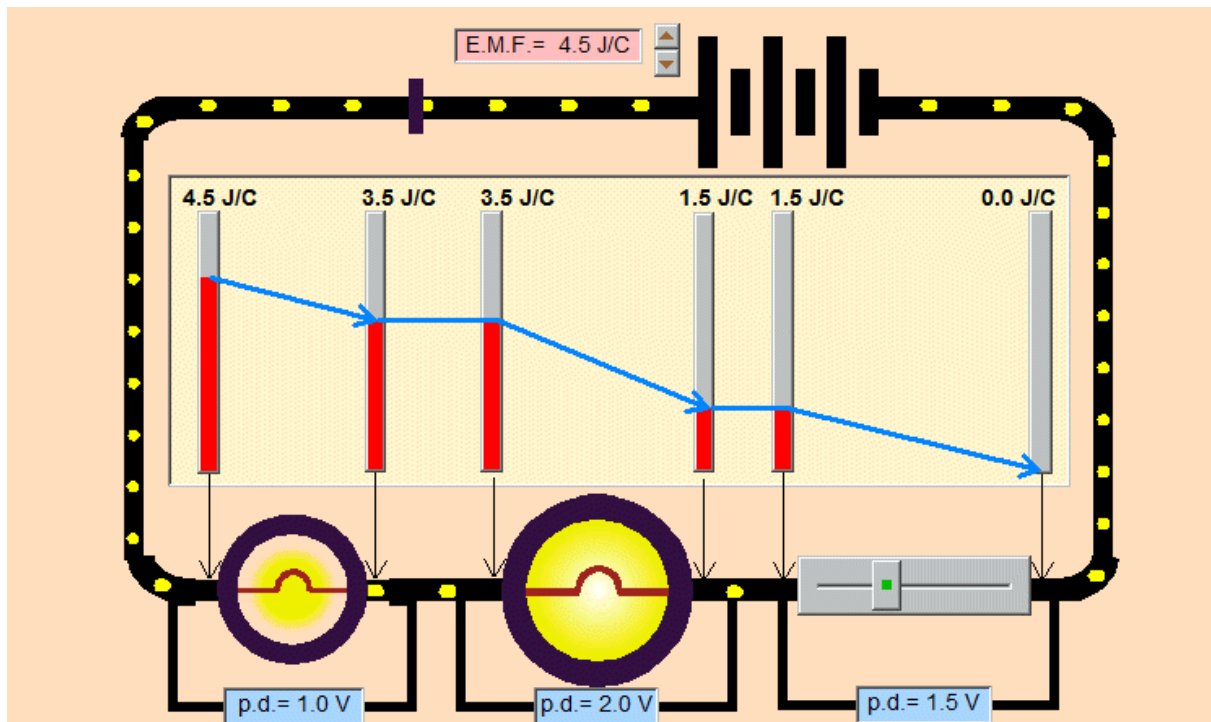
- Using the software controls for running the simulation

### Procedural Skills:

- Describe observations and link these with theoretical explanation

### Activity method:

1. Open the *Insight* file 'Circuit – potential'.
2. Look carefully at the circuit in the simulation window and notice that it contains a battery, two light bulbs and a variable resistor, all in series. In the middle of the circuit, a panel shows a series of bars indicating the energy of 1 coulomb at various points in the circuit.
3. Close the switch, and adjust the EMF of the battery. Observe the effect on the energy bars.
4. Notice that the blue lines and arrows help to show how the energy changes from one point to another. Each arrow indicates the potential difference (voltage) across a bulb or resistor.



### Discussion:

Thinking about your observations, discuss the correctness of the following statements:

- The 'EMF' is the electrical energy donated to each coulomb of charge flowing through the battery.
- The energy bars show that the electrical energy of 1 coulomb diminishes as it passes around the circuit.
- The current through the bulbs is the same.
- The rate of energy conversion in each bulb depends upon the voltage across it as well as the current through it.

## ACTIVITY 2D. INVESTIGATING RESISTORS IN SERIES AND PARALLEL

### Learning Objectives:

1. To understand how resistance is calculated from current and voltage measurements.
2. To deduce rules for the combined resistance of resistors in series and in parallel

APPLIED ICT TECHNOLOGY:  
SIMULATION

STUDENT LEVEL:  
AGE 14-17

RECOMMENDED SETTINGS:  
TEACHER DEMONSTRATION  
AND CLASS DISCUSSION

### Operational Skills:

- Using the software controls for running the simulation

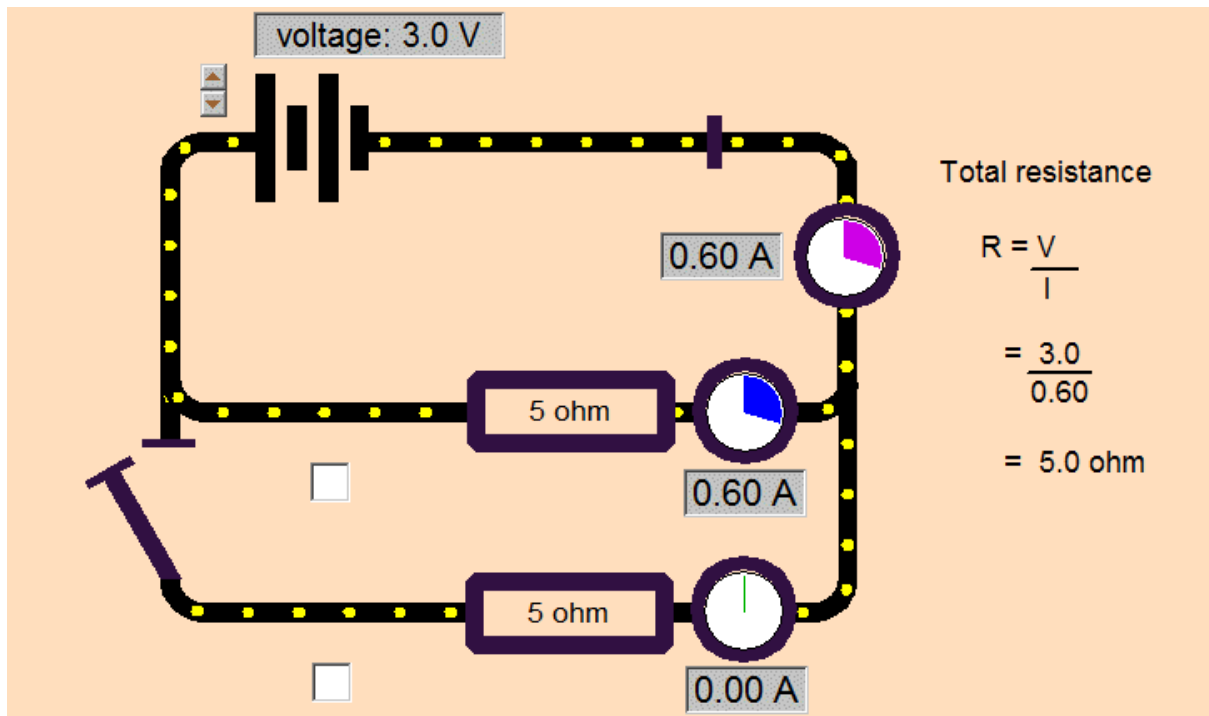
### Procedural Skills:

- Describe observations and link these with theoretical explanation

### Activity method:

1. Open the *Insight* file 'Circuit – resistance'
2. Look carefully at the circuit in the simulation window and notice that it contains a battery, two resistors, two switches and three ammeters.
3. Close the switch next to the battery, and adjust the voltage of the battery. Observe how the resistance is calculated from the measurements of current and voltage. Compare the calculations as the voltage is varied.
4. Add a second resistor in series with the first and observe the new calculation.
5. Remove the second resistor and close the second switch so that two resistors are shown in parallel. Observe the new calculation and compare it with those previous.
6. Try various combinations of resistors, each time observing the calculation and comparing the results.





### Discussion:

Thinking about your observations, discuss the correctness of the following statements:

- Changing the voltage supplied by the battery has no effect on the calculated value of the resistance.
- When two resistors are connected in series, less current flows.
- When the resistance of the circuit is doubled, the current is reduced to half its former value.
- When two resistors are connected in parallel, more current flows in the circuit.

## ACTIVITY 2E. INVESTIGATING THE POWER DISSIPATED IN A CIRCUIT

### Learning Objectives:

1. To understand electric current as a flow of electrical charge.
2. To understand that, since the total charge in a circuit is conserved, current is also conserved through series and parallel connections.
3. To understand that voltage is a cause of the flow of current is a measure of electrical energy changes as current flow around a circuit.

APPLIED ICT TECHNOLOGY:  
SIMULATION

STUDENT LEVEL:  
AGE 14-17

RECOMMENDED SETTINGS:  
TEACHER DEMONSTRATION  
AND CLASS DISCUSSION

### Operational Skills:

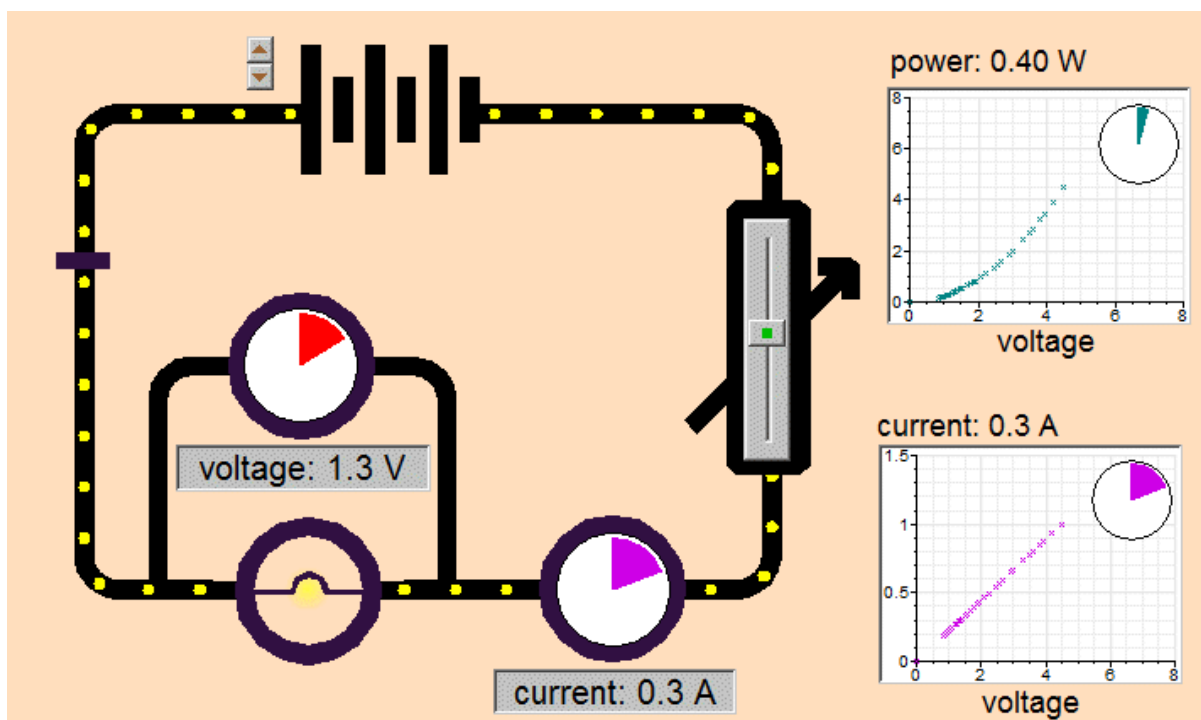
- Using the software controls for running the simulation

### Procedural Skills:

- Describe observations and link these with theoretical explanation

### Activity method:

1. Open the *Insight* file 'Circuit – current'
2. Open the *Insight* file 'Circuit – power'
3. Look carefully at the circuit in the simulation window and notice that it contains a battery, switch, light bulb, variable resistor, ammeter and voltmeter. The graphs indicate power and current plotted against voltage.
4. Close the switch, and adjust the voltage of the battery. Observe the effect on the current and power.
5. Slowly increase the resistor and observe and compare the two graphs. Adjust the battery voltage back to zero.
6. Reduce the resistance to zero, set the battery to contain one cell and note the values for power and current. Repeat this for two, three and four cell and compare the pattern of the increases for current and power.



### Discussion:

Thinking about your observations, discuss the correctness of the following statements:

- When the voltage is increased in the ratios 2, 3 and 4 times, the power increases in the ratios 4, 9 and 16 times.
- Current increases in the same ratio as the voltage increases.
- Power increases in proportion to the square of voltage increases.

# ACTIVITY 3A. INVESTIGATING A MODEL OF THE ELECTRICAL PROPERTIES OF A FILAMENT LIGHT BULB

## Learning Objectives:

1. To understand that the resistance of a filament light bulb changes as the bulb heats up and that this makes the current-voltage relationship non-linear.
2. To understand that the temperature of a light filament reaches equilibrium when the energy radiated by the bulb is equal to the electrical energy supplied.
3. To understand that when the voltage supplied to the bulb changes there is a time delay with changes in current.

APPLIED ICT TECHNOLOGY:  
MODELLING

STUDENT LEVEL:  
AGE 14-17

RECOMMENDED SETTINGS:  
STUDENT ACTIVITY OR  
TEACHER-LED CLASS  
DISCUSSION

## Operational Skills:

- Using the software controls for running the simulation
- Using the cursor tools for obtaining readings from the graph

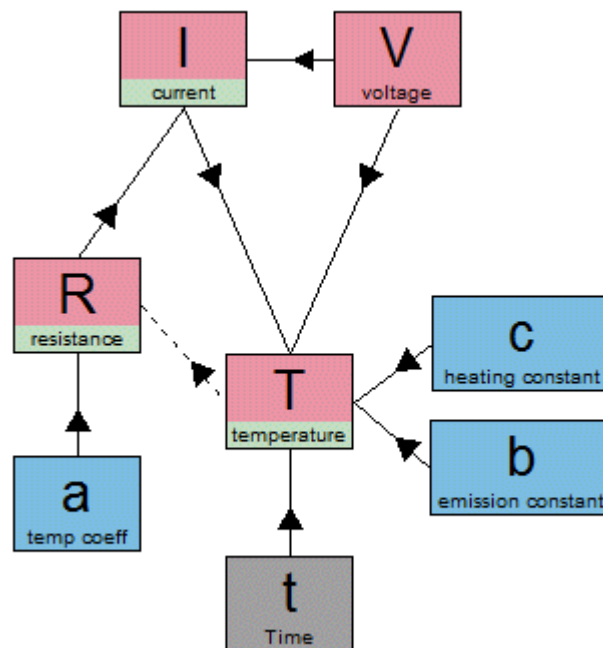
## Procedural Skills:

- Use the shape of the graph to make predictions about the resistance of the bulb
- To link the shape of the graph with the formulae in the model
- To use the model to explain the behaviour of the bulb

## Activities (using *Simulation Insight*)

1. Open the *Insight* file 'model – bulb'.
2. Click on the START button to run the simulation.
3. Slowly increase the *voltage* up to a maximum, then slowly reduce it to zero. [Right click on the voltage block to show the slide adjuster.]

4. Observe the shape of the *current vs. voltage* graph and deduce what happened to the value of the *resistance* during the experiment.
5. Plot the graph of *resistance vs. voltage* to check your prediction.
6. Explain why the graph line for *voltage increasing* is different from the line for *voltage decreasing*.
7. Stop the simulation and inspect the formulae used to calculate *resistance*, *temperature* and *current*. Try to explain what each formula tells you about these variables.
8. Double click on the 'temperature coefficient' and set its value to zero. This means that the resistance will not change with temperature but remains constant.
9. Restart the simulation and repeat instruction 3. Explain why the new graph has a different shape. Explain the connection between this graph and Ohm's Law.



# ACTIVITY 3B. INVESTIGATING A MODEL TO CALCULATE THE COMBINED RESISTANCE OF THREE RESISTORS IN PARALLEL

## Learning Objectives:

1. To apply the rules for current and voltage in circuits with parallel connections to calculate the combined resistance of three resistors in parallel.

APPLIED ICT TECHNOLOGY:  
MODELLING

STUDENT LEVEL:  
AGE 14-17

RECOMMENDED SETTINGS:  
STUDENT ACTIVITY OR  
TEACHER-LED CLASS  
DISCUSSION

## Operational Skills:

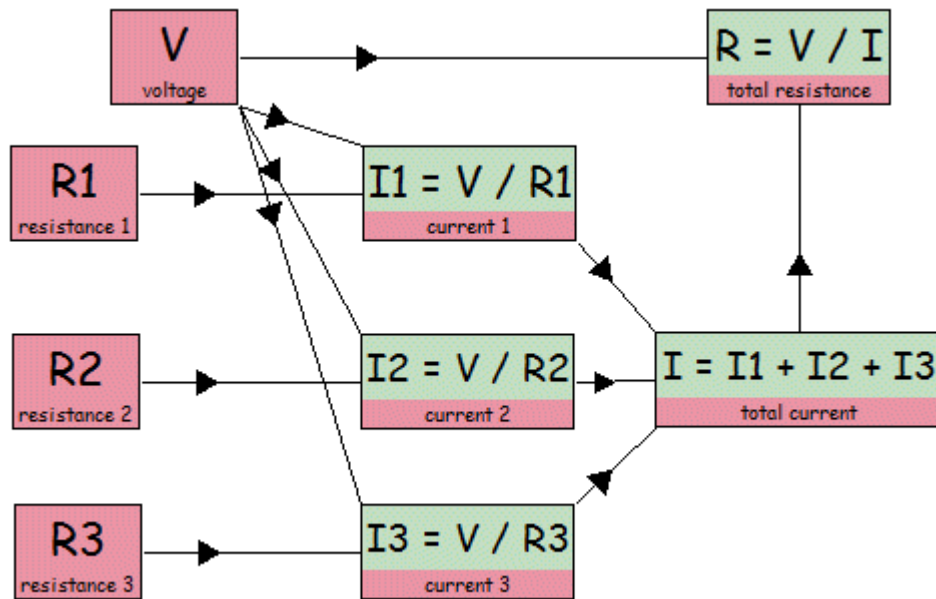
- Using the software controls for running the simulation

## Procedural Skills:

- Explaining the physical basis of each formula employed in the model

## Activities (using *Simulation Insight*)

1. Open the *Insight* file 'model – resistors'.
2. Look carefully at the model and notice the method of calculations: current 1, current 2 and current 3 are calculated for each resistor, these currents are combined to give the total current and this is then used to calculate the total resistance
3. Observe what happens to all the calculated currents and total resistance as you set in turn each resistor to 3 ohm.
4. Think about the effect of adding more resistors to produce less total resistance. Try to explain this.
5. Experiment with different values of resistance to deduce a rule for predicting the total resistance.



## ACTIVITY 3C. INVESTIGATING A MODEL OF A BATTERY SUPPLYING A CURRENT TO A CIRCUIT. THE PROBLEM OF 'LOST' VOLTS

### Learning Objectives:

1. To understand that the internal resistance of a battery affects the output voltage supplied to an external circuit.
2. To understand that the reduction in voltage across the terminals of a battery depends upon the current flowing and magnitude of the internal resistance.

APPLIED ICT TECHNOLOGY:  
MODELLING

STUDENT LEVEL:  
AGE 14-17

RECOMMENDED SETTINGS:  
STUDENT ACTIVITY OR  
TEACHER-LED CLASS  
DISCUSSION

### Operational Skills:

- Using the software controls for running the simulation
- Using the cursor tools for obtaining readings from the graph

### Procedural Skills:

- Explaining the physical basis of each formula employed in the model

### Activities (using *Simulation Insight*)

1. Open the *Insight* file 'model - battery'.
2. Look carefully at the model and observe the formulae used to calculate EMF, voltage and current.
3. Take a quick look at the circuit in the Scene window, then return to the Model window.
4. Set the switch to '1' (on) and observe the current and the voltage across the battery as you increase the number of cells in the battery.
5. Increase the value of the internal resistance and again observe the effect on the battery voltage. The difference between the EMF of the battery and the voltages across its terminals is shown as 'lost volts'.
6. Deduce a simple rule for predicting the value of 'lost volts',



