PROCEDURES OF EMPIRICAL CONCEPT FORMATION IN PHYSICS INSTRUCTION

Example 2: Electricity[1]

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Basic perception. Studying of electric current is started with simple equipment like a battery, a lamp, some wires, compass, and salt water. One sees the effects: light, heat, magnetic interaction, and electrolysis. These are recognised to be manifestations of a single phenomenon, electric current. The entities of the systems in which the phenomenon occurs are found to be a (closed) circuit, and a current source (battery). The circuit may consist of wires, lamps, or other electrical devices, like electromagnets, buzzers, etc. The devices and also batteries are found to always have two terminals.

It is obvious that the electric current has strength, because the effects of the current (for example, the brightness of a lamp) can vary. Electric current also has direction, which can be seen by observing the magnetic or chemical effects. Different batteries in otherwise similar circuits cause different current strengths; on the other hand, a similar battery causes different current strengths in different circuits. So batteries have a property, which determines their ability to cause current, and circuits have a property that determines their effect on the current that a certain battery causes.

Prequantification of the laws of current. Lamps are used for determining the current strength. The lamps are first tested to verify that their brightnesses are equal, when they are connected to a same battery one at the time. When the lamps are simultaneously on, one may then judge if the currents of the lamps are equal, or if one is smaller than the other is.

Several lamps are connected in series. One finds that all lamps light up and go out simultaneously, and they shine with equal brightness. So the current strength is the same everywhere in the circuit - also in the battery, which can be verified by studying how the compass needle turns near the leads and the battery.

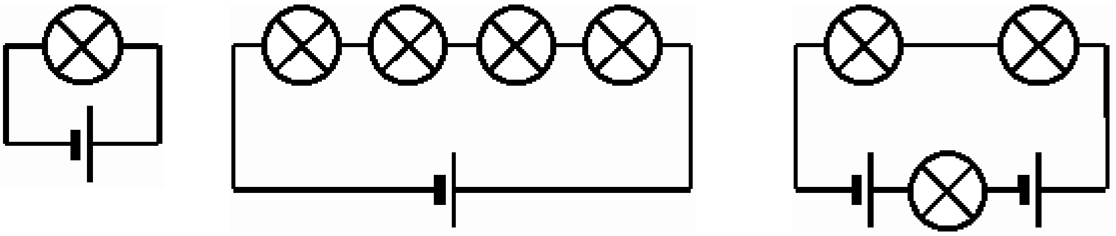

Fig. 1

With a branching circuit (Fig. 2) is found that when more lamps are connected in parallel, the parallel lamps shine dimmer, and the other lamps brighter. So the current is obviously divided between the parallel lamps.

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[1] Addendum to our article in Physics Teacher Education Beyond 2000 Conference, held in Barcelona from August 27 to September 1, 2000.

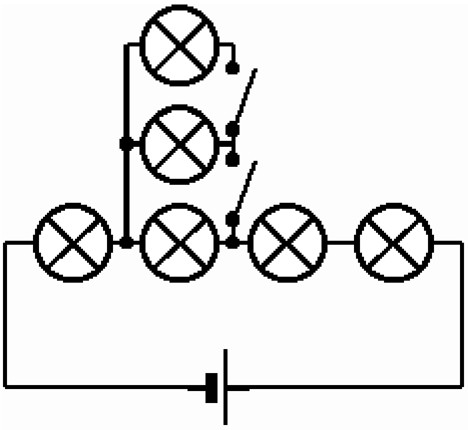


Fig. 2

Quantification of the current. When one wants to define a quantity that describes the strength of the electric current, one has to define the value of the new quantity to be proportional to a measurable property of one of the effects of the phenomenon. We choose the magnetic interaction.

A practical set-up for the quantifying experiment is shown in Fig. 3. A set of similar lamps is connected in parallel. The brightnesses of the lamps are the same, so it is obvious that the current in every lamp is also the same. A coil is then connected as part of the circuit so that the current of a number of lamps is also the current in the coil. By varying the coil connection, the current in the coil can be made the same as the current in 1, 2, 3, 4, or 5 lamps. The magnetic interaction between the coil and a bar magnet is measured, i.e. with a scale. One finds that the interaction is proportional to the magnitude of the current. So we may define the electric current to be proportional to the magnetic force of the current, $I \sim F$. Typical results of an experiment are seen in Fig. 4. The coil used has 60 turns; the force was measured with an Ohaus triple-beam balance, whose resolution is 0,1 N.

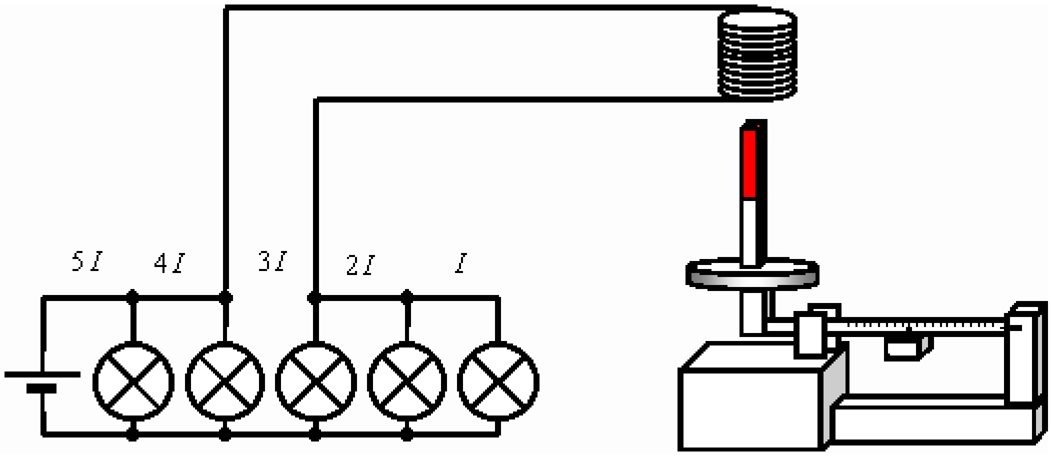


Fig. 3

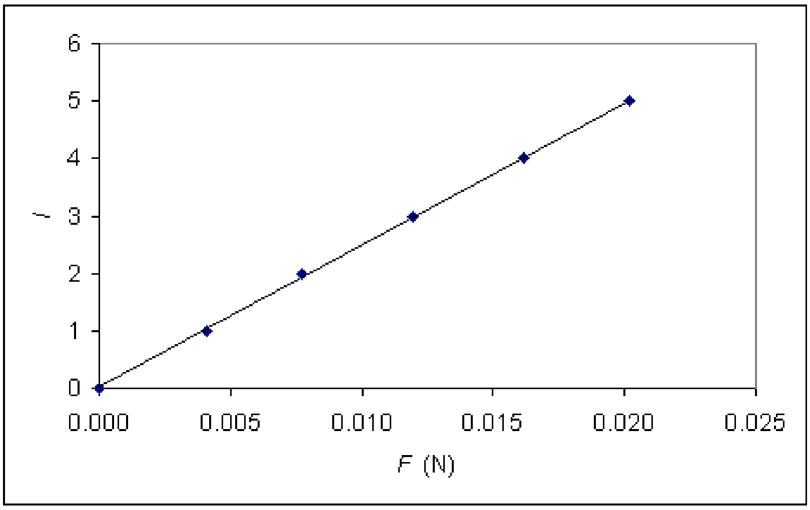


Fig. 4

Voltage. Previously we have found that batteries have a property to cause electric current in a closed circuit. With experiments of Fig. 5, one finds that the more batteries are connected in series in the same direction, the brighter the lamp shines. So the magnitude of the current-generating property (which can be called voltage) is increased.

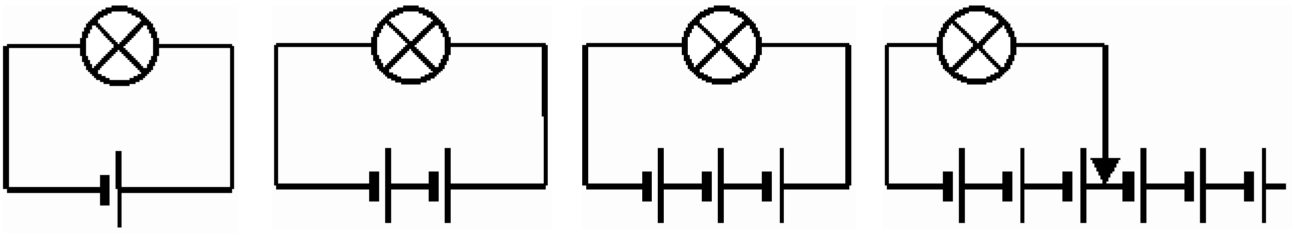

a) b) c) d)

Fig. 5

Fig. 6 shows experiments that indicate that potential has direction: if two similar batteries are connected in series in opposite direction, they cancel each other out. In Fig. 6a), the lamp shines as bright as with a single battery; in Fig. 6b), the lamp does not shine at all, and the galvanometer shows no current.

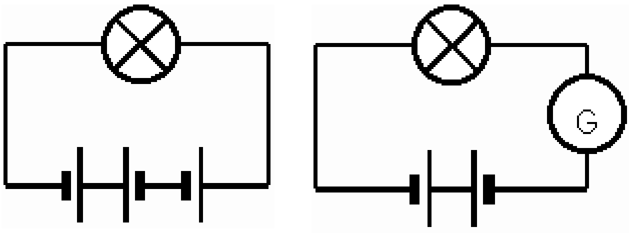

a) b)

Fig. 6

Experiments in Fig. 7 show that when more than one battery is connected in parallel, the brightness of a lamp and thus the voltage across the lamp does not change.

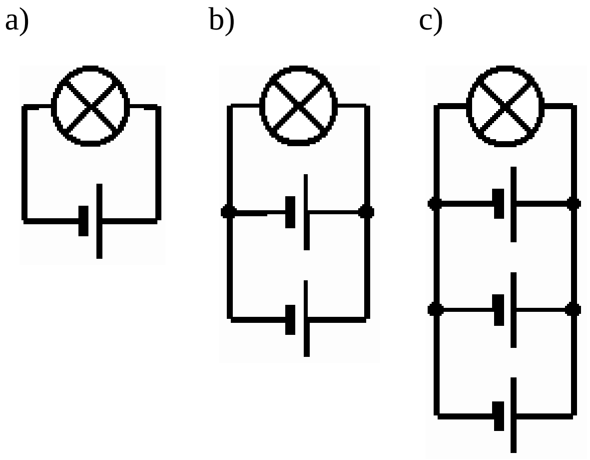


Fig. 7

By connecting several lamps in series to a single battery, one finds that they shine the dimmer the more lamps there are. On the other hand, if one adds to the circuit one lamp plus one battery at a time (Fig. 8), one sees that the brightness of the lamps remains the same. This indicates that in every case, the voltage across every lamp is the same.

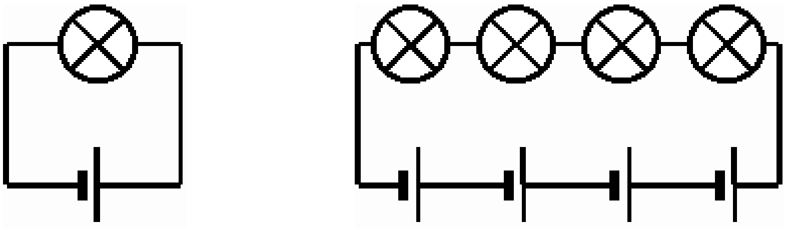


Fig. 8

So it is obvious that not only the batteries, but also the lamps have an effect to the current. One can make a generalisation: voltage is a property of not only a battery, but any pair of points in a circuit. Thus, a step-and-level model starts to form. In the experiments of Fig. 9, the voltage across a lamp is equal with the voltage between the terminals of a battery. A reasonable requirement is that in a closed circuit, the sum of the steps must be zero. We may also take a single point of the circuit as a reference, and call the voltage between the reference and another point as the potential of the point. The potential of the reference point can be defined to be any suitable value, usually zero.

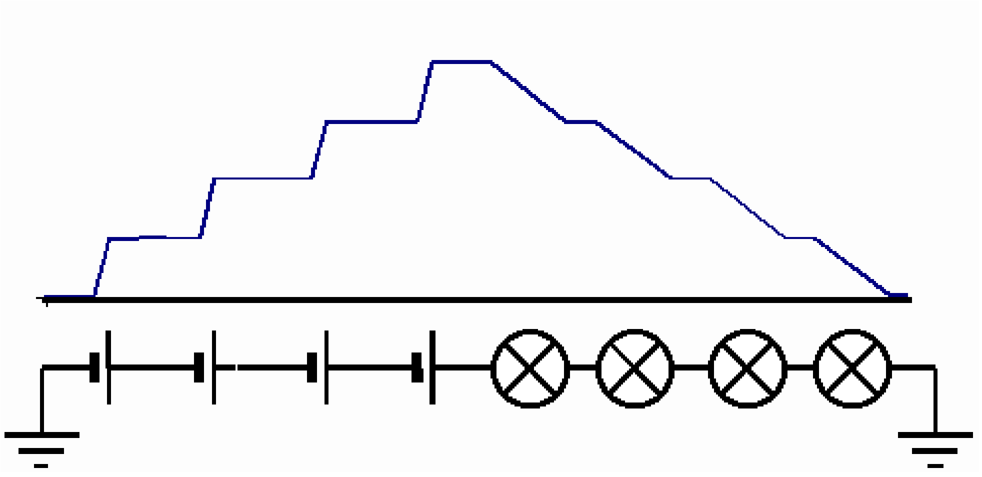


Fig. 9

The model can be tested with an experiment shown in Fig. 10, by connecting a battery and a galvanometer in series across one of the lamps. The galvanometer shows no current, so the potential between the lamp terminals must be equal with the potential of the battery.

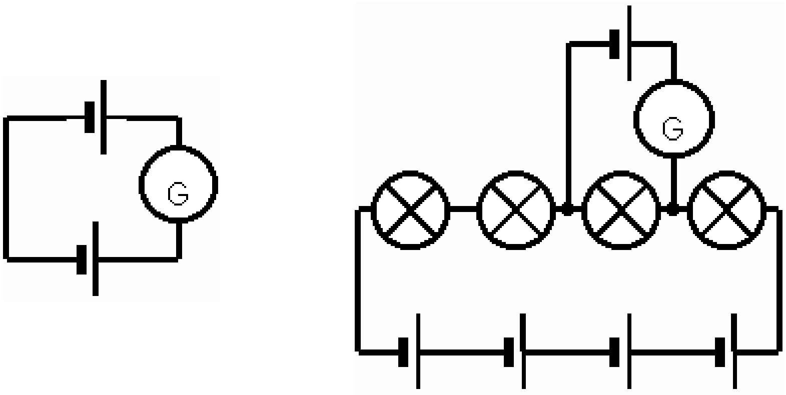


Fig. 10

Quantification of voltage. At this point, based on the previous experiments, it is obvious that voltage is proportional to the number of batteries in series. One could define an unknown voltage, using a lamp or a galvanometer as a zero instrument, presuming that the unknown voltage is a multiple of the voltage of a standard battery. But for a better quantifying experiment, one needs a way to produce a continuously altering potential.

See Fig. 11 and Fig. 12. The series of lamps in Fig. 9 has been replaced with a homogenous wire. It is expected that the potential must now change uniformly as a function of the position in the wire.

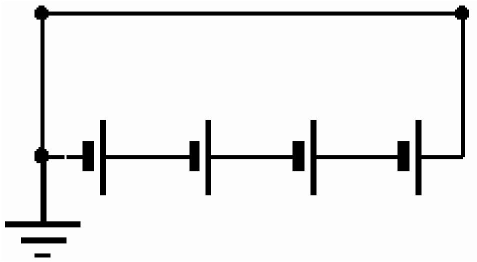


Fig. 11

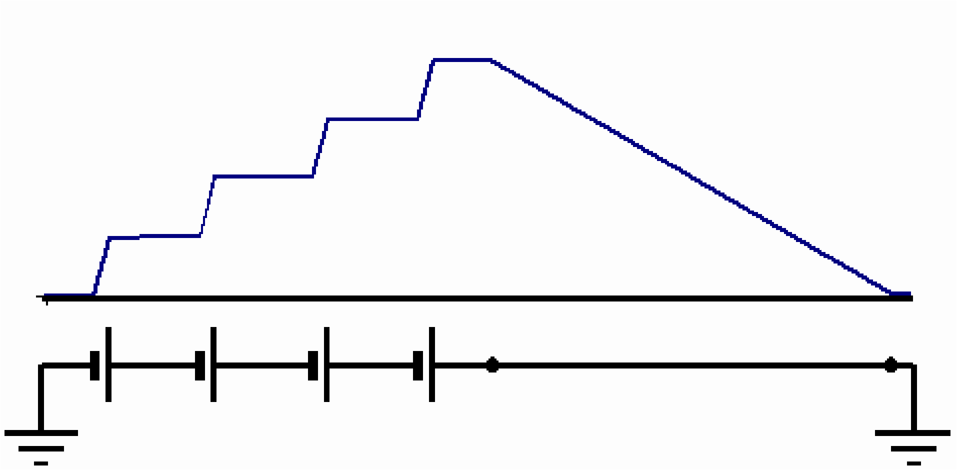


Fig. 12

Fig. 13 shows the quantifying experiment. With a galvanometer, one finds that the potential in the wire is proportional to the position. Thus, we may define the quantity potential of a point in the wire to be proportional to the position of the point, measured from the reference, whose potential is 0. Thus the defining law of the potential is $U \sim L$ (Fig. 14).

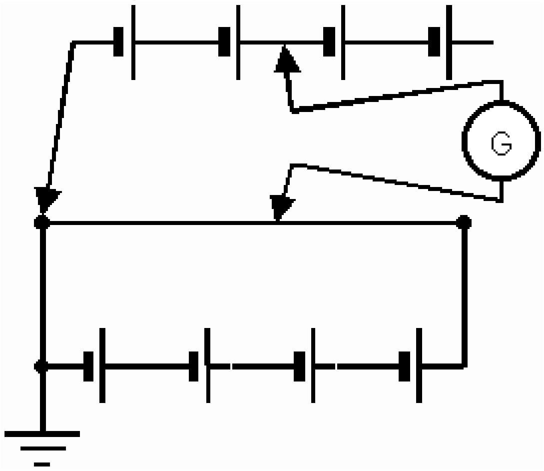


Fig. 13

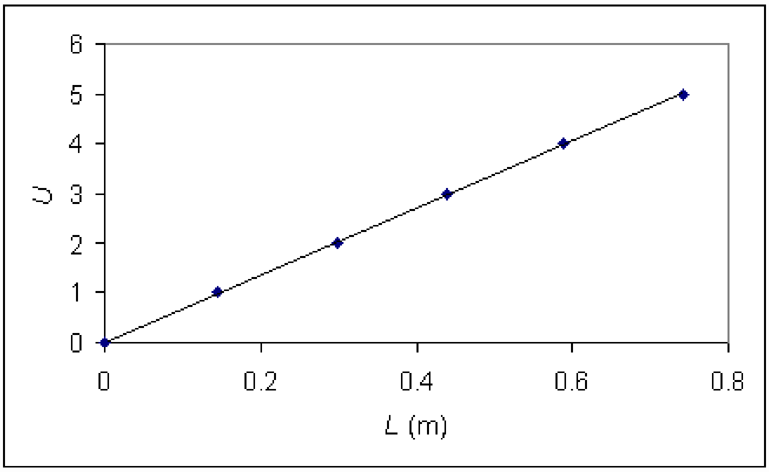
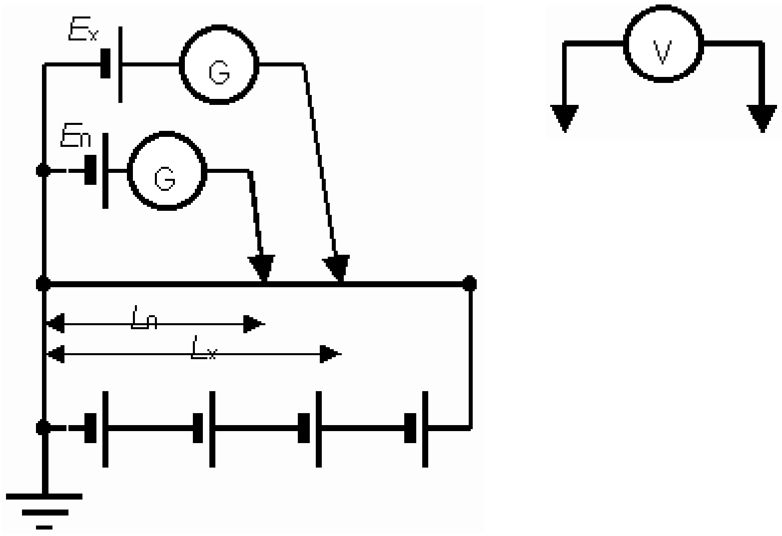


Fig. 14

Fig. 15a) shows the principle of how to measure an arbitrary unknown voltage E_x. When both galvanometers show zero current, $E_x = (L_x/L_0)E_0$



a)

b)

Fig. 15

In practice, this is a way too tedious method for voltage measurements. Therefore, at this point one may take a voltmeter into use, even if its operating principle is still unknown. One must check the operation of the voltmeter with the set-up in Fig. 15, and find that the meter measures voltage.

Prequantification of resistance. The next thing to study is the component's ability to resist the flow of the current. The effects of wire length, thickness, material and temperature are studied, by varying one of these qualities constant at the time, and keeping the rest constant. All of these properties are found to affect the wire's ability to resist the current. Next, the voltage across the component is varied, and the voltage and the current through the component are measured. A higher potential difference is found to cause a larger current. A second component is added in series with the original (first) component, keeping the terminal voltage of the power source constant. The current through the components is found to be smaller, and the voltage across the first component is also smaller. The terminal voltage is increased, until the current is the same as before the addition of the second component. The voltage across the first component is now again the same as before the addition of the second component. Also, the current through a component and voltage across the component depend on each other in a way that is not affected by the rest of the circuit. Several components with varying ability to resist current are connected in series, so that equal current now flows through every component. The voltages across the components are measured. It is found that the greater ability to resist current a component has, the higher the voltage across the component is.

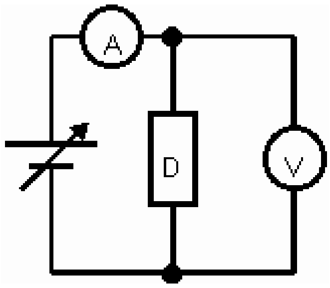


Fig. 16. The circuit for resistance experiments. D is the device under investigation.

Ohm's Law. Prequantification indicates that the ratio of the voltage across a component and the current through the component might be a good candidate as the quantity that describes the components ability to resist the current. For the quantifying experiment, idealisations are necessary. Since the temperature is found to have an effect to the conducting capability, one must either keep the temperature of the component constant, or use current that is small enough not to heat the component significantly.

Fig. 16 is a schematic diagram of the circuit that can used in quantitative measurements. A metal wire is connected to a power source. The voltage across the ends of the wire U and the current through the wire I are recorded, while the terminal voltage of the power source is gradually altered. The (I, U) graph is drawn, and the graph is found to be a straight line that goes through the origin (Fig. 17). This indicates the proportionality $U \sim I$. The experiment is repeated for different wires. One finds that the graphs for these are also straight lines, but have different slopes. Based on prequantification, the slopes of the graphs are found to characterise the wires' ability to resist the current. The ratio $R = U/I$ is invariant for each wire.

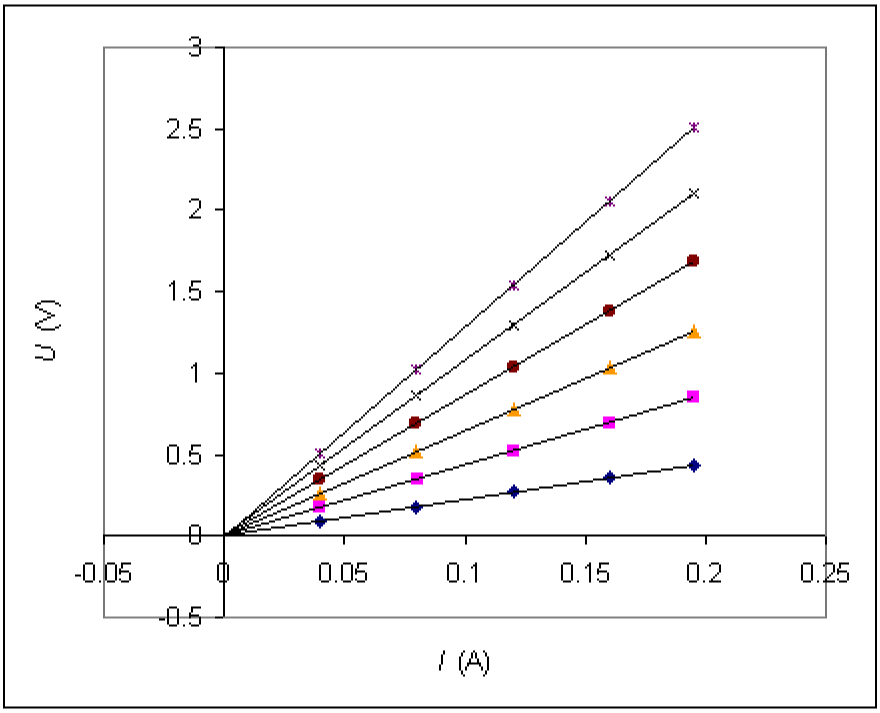


Fig. 17

Resistivity. The resistances of wires of similar material and cross-section but different lengths *L* are defined. The (*L*, *R*) graph is drawn, and the data points are found to lie on a straight line that goes through the origin (Fig. 18). The experiment is repeated for a wire made of different material. Its (*L*, *R*) graph is another line going through the origin. Thus $R \sim L$.

A similar series of measurements is performed by varying the cross-section area of the wire, and keeping the length constant. This is best done both by connecting several wires in parallel, and also by using wires of varying thicknesses. One finds the resistance getting smaller, as the cross-section area increases. By drawing the (1/*A*, *R*) graph one finds the proportionality $R \sim 1/A$. The results can be merged as a law $R \sim L/A$. The slope of the proportionality line is the resistivity: $\rho = (A/L)R$.

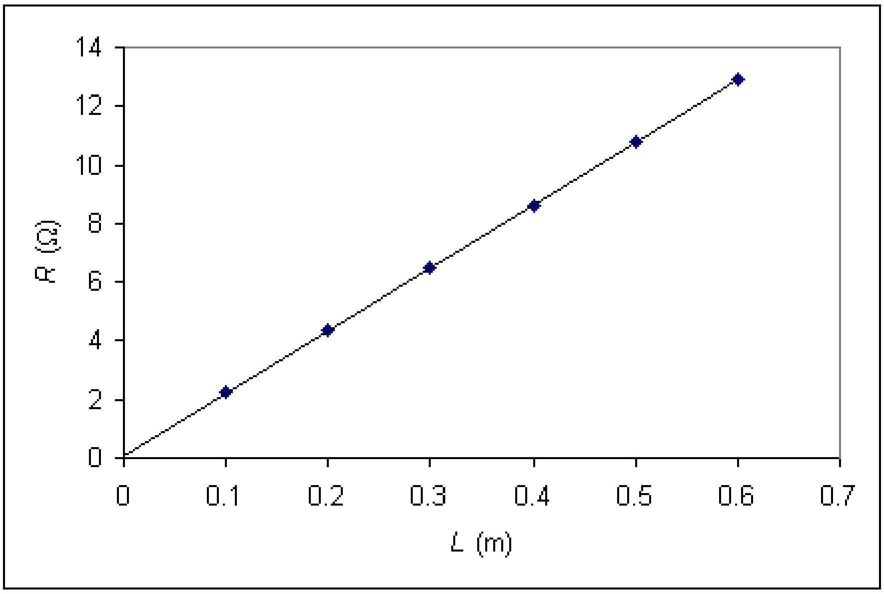


Fig. 18

Components that do not obey the macroscopic Ohm's Law. For metal wires, $U \sim I$ only at constant temperature. The filament of a light bulb is a tungsten wire, whose temperature rises considerably, when the current is increased from zero to the nominal operating current of the bulb.

The operating voltage of the bulb is increased from 0 to its nominal value, and decreased back to 0. The current through the filament and voltage across it are recorded. It is found that the (I, U) graph is now not a straight line, and there is hysteresis; the (I, U) graph follows different paths when the current is increased or decreased. It is found that the hysteresis vanishes, if the current is varied very slowly.

Fig. 19 shows the results of an experiment, where a signal generator (an AC power source with adjustable amplitude and frequency) has been used to power the bulb. This set-up gives a smoother curve than would be possible to get by adjusting the voltage by hand, and also provides the additional information that the graph is symmetric with respect to the origin. For some other components, like diodes, the curve is not symmetric.

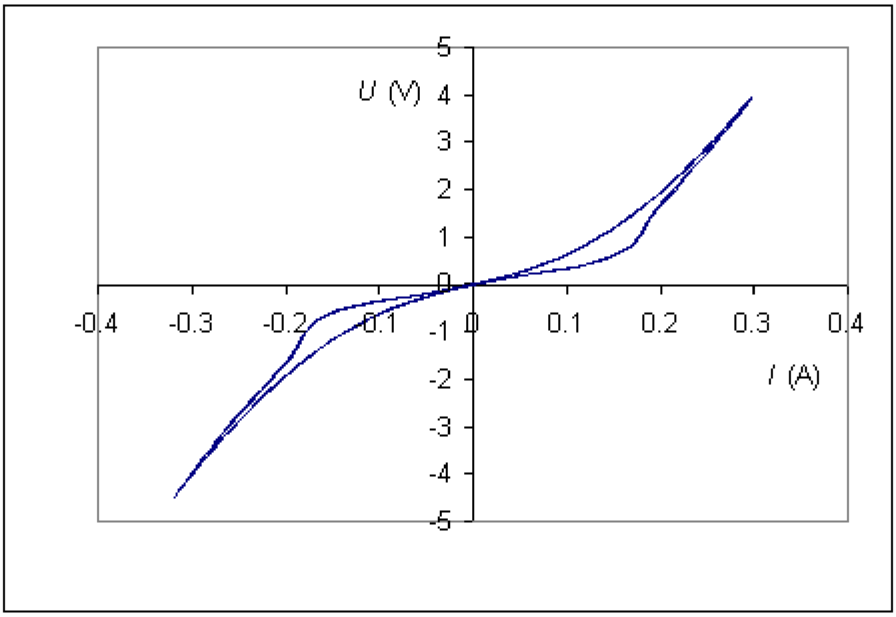


Fig. 19

It is obvious that the hysteresis is caused by the filament's slowness to change its temperature according to the heating power; that is, the heat capacity of the filament. If a constant current has been applied to the bulb for some time, the temperature of the filament has stabilised which means that the electric power heating the filament is equal to the radiating power of the filament.

Differential (dynamic) resistance can be defined as $R_d = \mathrm{d}U/\mathrm{d}I$, which describes the local behaviour of the voltage as a function of the current. The global behaviour is characterised by the static resistance $R_s = U(I)/I$ ..