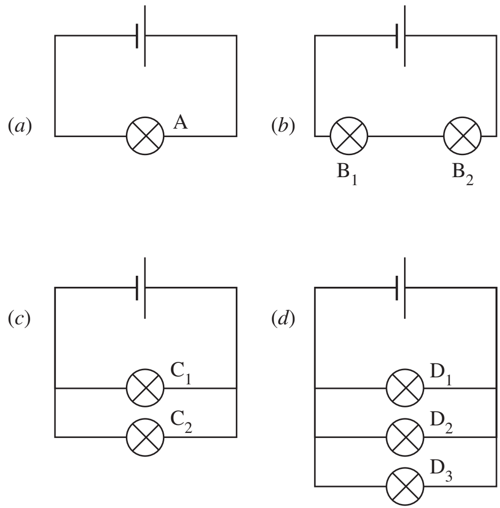
Teaching electricity

Attending a thoroughly enjoyable and stimulating Physics Update helped me clarify my ideas about the teaching of electricity in secondary school. Bob Kibble's 'Electrify your imagination' and Keith Taber's 'The physics teacher as a learning doctor' particularly informed this contribution. Often I have torn my hair out when faced yet again with 'the voltage flowing through the bulb …' and the inability of reasonably able students to solve the following problems. These questions can be used as a diagnostic tool to ascertain whether your students suffer from similar problems.

Question 1: 11–14 year-old pupils

In this question all the bulbs and cells are identical and the cells are 'ideal' with no internal resistance. If the current flowing through bulb A is 0.2 A and bulb A is at normal brightness, what is the current flowing through each of the other bulbs and what is their brightness and what is the current from each cell?

Often the answers pupils give indicate the confusion between current and voltage, with many pupils finding it difficult to shake off the idea that a particular cell will always provide the same current.



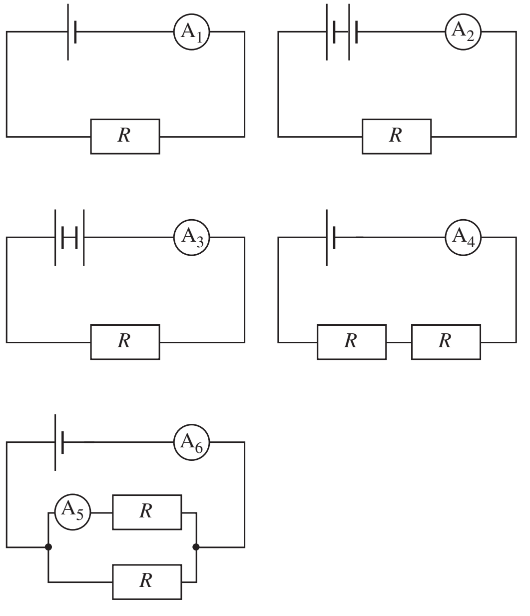
Question 1

Possible treatments

Discuss the answers to the questions carefully.

Answers.

In (*b*) the bulbs B_1 and B_2 are both dim because the current flowing through them is only 0.1 A because the cell has to push current through one difficult thing (the bulb) after another. The current



Question 2

flowing through the cell is 0.1 A.

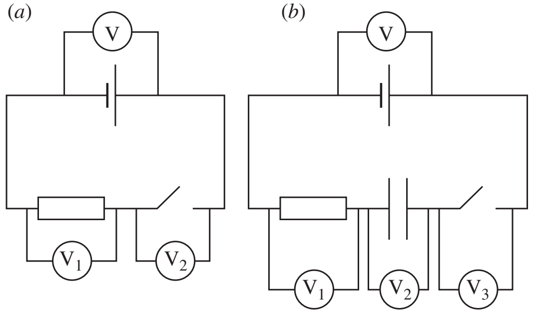
In (*c*) the bulbs C_1 and C_2 are both at normal brightness because the current flowing through each bulb is exactly 0.2 A. This is because each bulb is connected directly to the cell and so receives the full push caused by the voltage of the cell. The total current pushed around by the cell is 0.4 A.

In (*d*) all the bulbs D_1, D_2 and D_3 are normal because the current flowing through each bulb is 0.2 A. Adding an extra bulb in parallel provides another path for the current to flow through and so more current is pushed around by the cell, 0.6 A in this case.

Are we getting something, the extra light, for nothing when we connect the bulbs in parallel? Most pupils realize instinctively that there is no such thing as a free lunch, but it needs stressing that neither the current nor the voltage of the cell gets 'used up' when the cell pushes current around the circuit. However, the greater the current being pushed around the faster the chemical energy of the cell is used up.

I tell my pupils:

- that the cell provides a voltage or potential difference between its terminals that pushes the current around the circuit.
- that the amount of current pushed around



Question 3

depends on:
(1) the potential difference provided by the cell
(2) the total resistance of the circuit.

For example, the same 1.5 V cell can provide a huge current if it is short-circuited or a tiny current if connected across a large resistor.

Adding an extra resistance in parallel provides another path for the current to flow through and so more current is pushed around by the cell. This means that adding bulbs in parallel reduces the total resistance of the circuit.

The question I am then asked, if I am lucky enough to have pupils who want to think things out, is how does the cell know how much current to push around?[1]

Question 2: 14–16 year-old pupils

In this question all the cells are identical and have negligible resistances, the resistors are identical and the ammeters all have negligible resistances. If ammeter A_1 reads 1.0 A, find the readings on the other ammeters.

I usually find after teaching a class of about 20 year-10 girls in my own school, who on average will all go on to pass GCSE Physics with high grades, often more than half achieving A*, only one or two will get the correct answers to all of the above questions.

Possible treatments

Discuss the answers to the questions carefully.

Answers.

A_2 reads 2.0 A as the potential difference is doubled. (Everyone gets this correct.)

A_3 reads 0.0 A.

A_4 reads 0.5 A.

A_5 reads 1.0 A.
A_6 reads 2.0 A.

It is usually the last two questions that are answered incorrectly because of the poor understanding students have of voltage. See previous possible treatments and later for further treatment ideas.

Question 3: 15–18 year-old pupils

If in both circuits (*a*) and (*b*) the voltmeter V reads 1.5 V, find the reading on the other voltmeters,

(i) when the switches are open, before the capacitor has been charged up.

(ii) after the switches have been closed, allowing time for the capacitor to become fully charged.

Possible treatments

Discuss the answers to the questions carefully.

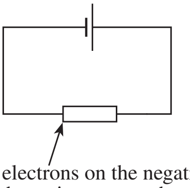
(*a*) (i) When the switch is open, V_1 reads 0.0 V because no current is flowing through the resistor and V_2 reads 1.5 V, but this p.d. cannot drive current through the open switch.
(ii) When the switch is closed, V_1 reads 1.5 V and this p.d. across the resistor drives current through it and V_2 reads 0.0 V because the closed switch has no resistance.

(*b*) (i) When the switch is open, V_1 reads 0.0 V, V_2 reads 0.0 V and V_3 reads 1.5 V.
(ii) When the switch is closed, V_1 reads 0.0 V, V_2 reads 1.5 V and V_3 reads 0.0 V.

The reason V_2 reads 1.5 V after the switch has been closed and time has passed to allow the capacitor to become fully charged is that there is now a build-up of charge on the plates of the capacitor, and it is this distribution of charge on its plates that is the cause of the p.d. between its plates. Similarly in (*a*) the cause of the p.d. across the open switch is the build-up of charge, but the open switch has a tiny capacitance and so very little charge is needed to provide the p.d.

Surely, when the switch is closed in (*a*) and a steady current is flowing, there must be a build-up of electrons on one side of the resistor to cause the p.d. across it. However, this is not usually mentioned in textbooks.

The reason so many students are unable to answer the questions correctly is that they have a very hazy concept of voltage. The definition of potential difference between two points as 'the work done per unit charge in moving the charge between the points' is not very helpful in understanding what is actually happening in the circuit. Pictures of Mr Coulomb carrying a full bag of energy into the resistor and leaving with an empty sack, which appear in many textbooks, beg the question exactly what is different about the way electrons move through a resistance as opposed to the way they move through connecting wire, given that the number of electrons passing any point in the circuit in one second is the same in the resistance as in the connecting wire.[2] Mr Coulomb is dropping off electrical energy, but what do we mean exactly by electrical energy and can we visualize it?


Excess electrons on the negative side of the resistor cause the p.d. across it and drive the electrons that are the current.

The above definition is only meaningful for me when introduced with electric fields and potential in the sixth form.

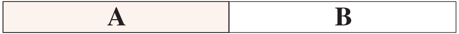
Most students can visualize current in metals as a flow of electrons moving around the circuit, colliding with the metal ions in the lattice, causing them to vibrate more rigorously and hence causing the heating effect. But what mental picture do we give our students to explain voltage and how do we answer the question 'what is voltage?'

I was taught that the negative terminal had a surplus of electrons and the positive terminal a deficiency and this was the cause of the potential difference because the electrons were repelled by the negative terminal and attracted to the positive. I was very happy to visualize this and with a bit of colour coding found most circuit problems easy. Why do we not tell our students the p.d. between two points is caused by the distribution of charge as we are happy to tell them this in the case of a charged capacitor?

Footnotes

1. In the very first few fractions of a second after the circuit is first set up, the cell tries to push a large current around, but it soon settles down to a steady value depending on the arrangement of the resistances in the circuit. (Fractions of a second because there will be very little capacitance in the circuit.)

2.



The above diagram represents two conductors, A and B, with the same dimensions, but different resistivities joined in series. For the sake of simplicity, imagine that the number of free electrons per metre^3 is the same in both conductors, as it would be if they were made from the same metal, but were maintained at different temperatures.

When a p.d. V is across the ends, then the same current flows through each, i.e. the same number of electrons per second passes a point in A as passes a point in B. Therefore the average drift velocity of the electrons must be the same in both conductors. The difference is that in the conductor with the higher resistivity, the distance the electrons travel on average before colliding with one of the ions in the metal lattice will be less. The force on the electron will be greater because this conductor will have a larger share of the voltage V, causing the acceleration of the electrons between collisions to be greater. However, the average drift velocity must be the same.

I think it is a pity that drift velocities are no longer included in the A-level syllabus, because thinking about what is happening to the electrons as a current flows is a very useful exercise. The interpretation of a mathematical formula into a picture, or model of what is actually happening, lies at the heart of physics.

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