

Episode 102: Current as a flow of charge

Here, you are trying to illustrate the idea of electric charge and its relationship to a flow of current.

Summary

Demonstration: Spooning charge. (15 minutes)

Worked example: Calculating numbers of electrons. (10 minutes)

Demonstration: The shuttling ball. (15 minutes)

Worked example: Calculating charge per second. (10 minutes)

Discussion: Defining current, the coulomb. (10 minutes)

Student questions: On charge and current. (30 minutes)

Demonstration:

Spooning charge

Start by reminding your students of the nature of electric charge. They should be familiar with the concept of charge from pre-16 science course. Remind them that this is a fundamental property of some types of particles (e.g. protons and electrons) and that there is a law of force: like charges repel, unlike charges attract. These are the forces that push charges around electric circuits.

Use the 'Spooning Charge' demonstration to reinforce the idea that charge can be taken from one place to another and does not just disappear.

TAP 102-1: Spooning Charge.

Worked example:

Calculating numbers of electrons

Remind them that charge is measured in coulombs and tell them that the size of the charge on an electron is a tiny fraction of a coulomb (1.6×10^{-19} C). A quick calculation will confirm that even tiny charge transfers on our scale involve enormous numbers of electrons.

Calculate the number of electrons transferred when you 'spoon' charge and show that this depends on the voltage of the supply. (The result is, of course, linked to capacitance; this could be mentioned for a strong group.)

Demonstration:

The shuttling ball

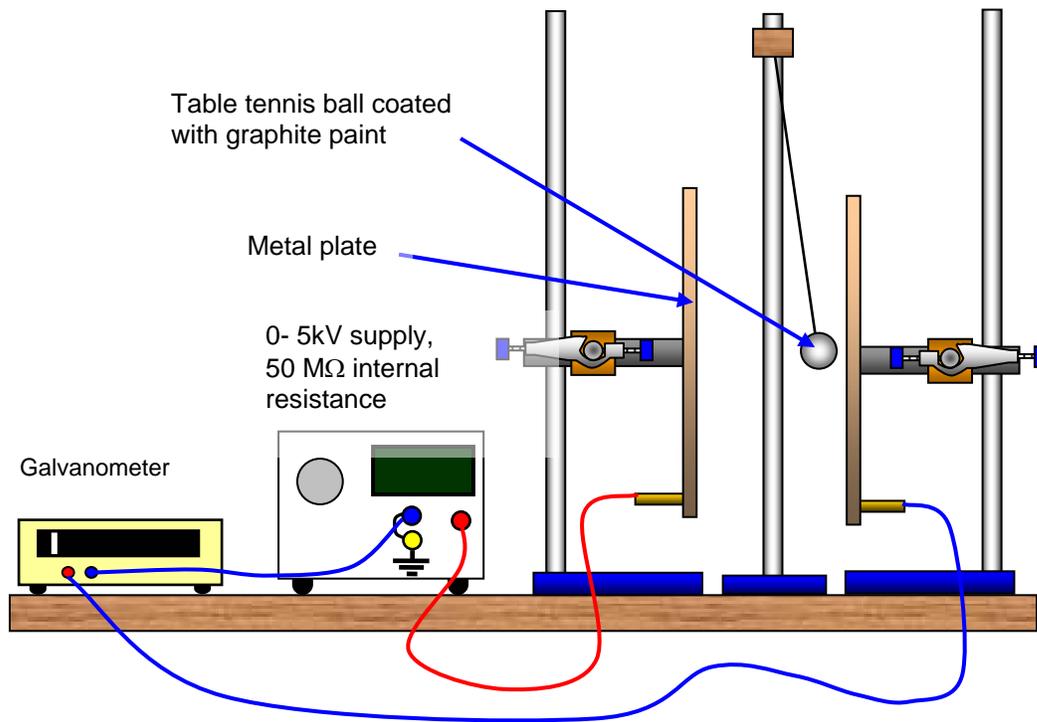
Use the 'Shuttling Ball' demonstration to link charge and current. The greater *the rate of transfer* of charge the greater the current.

TAP 102-2: Shuttling ball

Worked Example:

Calculating charge per second

Calculate the charge transferred per second in the shuttling ball experiment. To do this, use a coulomb-meter to measure the charge on the ball and then measure the number of transfers in a given time. Alternatively you could work back from the current.



Discussion:

Defining current, the coulomb

Define current as rate of change of charge. At this level it might be best to do this graphically. Current is the gradient of a graph of charge transferred against time, leading to $I = \Delta Q / \Delta t$ or (in the limit) $I = dQ/dt$. Exactly how you represent this will depend on the requirements of your specification and the mathematical experience of your students. The idea of the gradient can be introduced by asking how the charge transferred by the shuttling ball increases with time - it will go up in a series of steps but, given a large number of transfers, these will approximate to a constant slope. The average current is equal to its gradient. The essential outcome is that they realise that a current of one amp is equivalent to a flow of one coulomb per second. The equation $I = Q/t$ (familiar from pre-16 science lessons) is useful but stress that this refers to an average current I and they must take care when I is changing.

Define the coulomb as the charge passed by a current of 1 A in 1 s, i.e. $1 \text{ C} = 1 \text{ A s}$. (Note that the ampere is an SI base unit, and its definition is beyond requirements at this stage.)

Student questions:
On charge and current

TAP 102-3: Introductory Questions on Charge and Current

TAP 102-1: 'Spooning' charge

What kind of thing is charge?

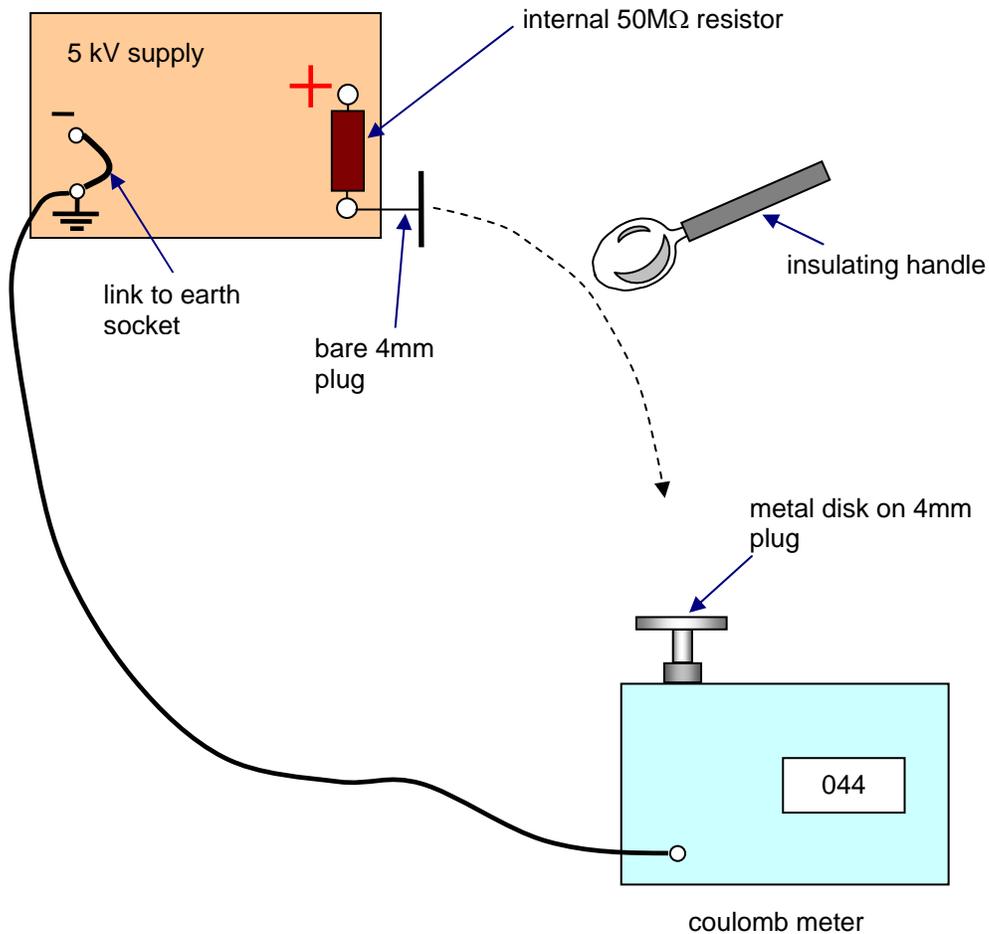
Long ago it was known that when materials like amber are rubbed they become 'electrified'. But since the Greek word for amber was 'elektron', this only means that what happens is what happens to amber! There was no real understanding at this point. Gradually, the 'whatever it is' on the amber became called 'electric charge'. The word 'charge' suggests 'an amount of something powerful', as in 'a charge of gunpowder'. This demonstration helps to show that it makes sense to think of charge as an amount of 'something' which can go from place to place.

Requirements

- ✓ digital coulomb-meter
- ✓ plastic rods: polythene and acetate or Perspex with cotton cloth
- ✓ EHT power supply, 0 – 5 kV dc metal disc on 4 mm plug to fit coulomb-meter
- ✓ uninsulated 4 mm plug to fit EHT power supply
- ✓ leads, 4 mm (N.B. no side screws in plugs)
- ✓ teaspoon and tablespoon each mounted on insulating polythene rods

Safety Note	The EHT power supplies approved for use in schools are safe but can give a shock large enough to make a person jump.
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'Spooning' amounts of charge



Electric charge can be picked up and carried by a spoon, just as if it were sugar or milk. Fix a metal spoon to an insulating handle, touch it onto the terminal of a high voltage supply, and carry the spoon across to a charge-measuring instrument, onto which the charge is dumped. Repeat the action: the charge measured increases by the previous amount. You can go on transferring charge like this in equal amounts several times.

Try the spoon upside down. The charge carried is the same, so it is not completely like milk or sugar! But it can be moved around in 'spoonfuls', though any metal object will do as a 'spoon'.

Try a bigger spoon. More charge is transferred. Try a bigger potential difference from the supply. Again more charge is transferred. So the amount of charge on a conductor depends on both the potential difference and on the size of the conductor.

Knowing that the charge on an electron is -1.6×10^{-19} C, you can calculate the number of electrons in a 'spoonful' of charge. A typical spoonful of negative charge is -2 nC. So the number of electrons is:

$$\frac{\text{charge on spoon}}{\text{charge on electron}} = \frac{2 \text{ nC}}{1.6 \times 10^{-19} \text{ C}} = 1.2 \times 10^{10} \text{ electrons}$$

Charges can be produced also in the 'old fashioned way', by rubbing insulators like polythene or Perspex with a cloth. This strips a few electrons off one material and leaves them on the other. The piece with extra electrons is negatively charged; the piece with fewer is positively charged.

Outcomes

1. Charges, which you cannot see, are real enough and can be ladled around and measured, just like other more tangible physical quantities.
2. Charges are either positive or negative.
3. The electron has a very small charge. A 'charged object' is one with a slight excess or deficit of electrons.

External references

This activity is taken from Advancing Physics Chapter 2, 30D

TAP102- 2: Shuttling ball and ions in flame

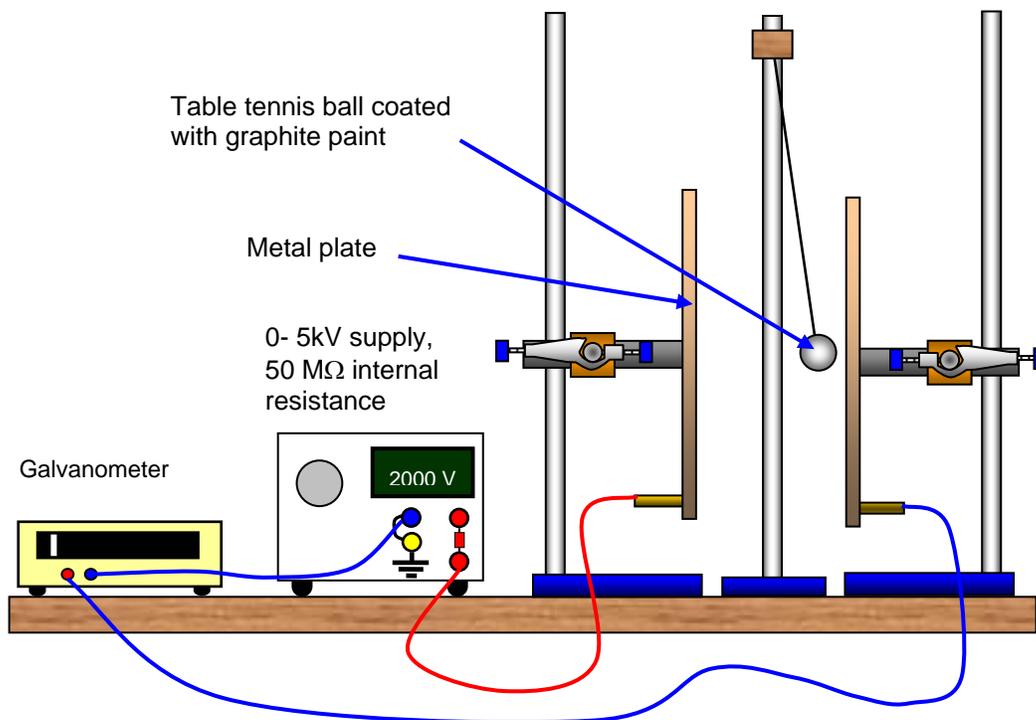
Charges carried by a moving object

An electric current is just a charge moving from one place to another. This charge can be carried by anything, in this case a table tennis ball.

Requirements

- ✓ EHT power supply, 0 – 5 kV dc
- ✓ pair of conducting discs, insulated and clamped vertically
- ✓ leads, 4 mm (N.B. no side screws in 4mm plugs)
- ✓ colloidal graphite coated table tennis ball suspended on 1.5 m of nylon monofilament
- ✓ very tall retort stand, boss and clamp to support nylon monofilament
- ✓ light-spot galvanometer
- ✓ stroboscope candle and matches

Safety Note	The EHT power supplies approved for use in schools are safe but can give a shock large enough to make a person jump.
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A shuttling charge is an electric current

Connect a pair of metal plates across a large potential difference. No current passes across the gap between them, unless there is a spark. But hang a conducting ball in the gap and let it touch one plate. It picks up charge from that plate. Charged, the ball is repelled by that plate and attracted by the other one. So it swings across until it touches the second plate. There, it delivers its charge, and is pulled back to the first plate. The sequence repeats, and the ball shuttles to and fro between the plates.

A sensitive current meter connected between the plates shows that a current is flowing. It is likely to be only a few microamperes.

You can calculate the charge carried by the ball if you know the current and the time of travel of the ball between the plates, because the current is the rate at which the ball carries charge across the gap.

Remove the ball. Now put a candle flame in the gap. The flame is hot enough for atoms in it to be ionised. These ions will also travel across the gap. Now you cannot see them move, but you can see the current indicated on a meter. The current will be considerably larger than that carried by the shuttling ball. Soot from positive carbon ions (candle wax contains carbon) will be deposited on the negatively charged plate.

Things to remember

1. You will have seen a moving charge-carrying ball deliver an electric current which can be detected on a meter.
2. You should have calculated charges and currents using $I = Q/t$ and numbers n of electrons transported per second.
3. You should be getting used to calculating with very large and very small numbers.
4. You should know that a hot flame can ionise atoms within it, so that flames can be electrical conductors.

Practical advice

A Van de Graaff generator may be used instead of the 5 kV power supply. Ensure that the galvanometer is earthed and that no sparks jump to it. Start with the plates close enough together (about 6 cm apart) for the ball to shuttle automatically. If the stroboscope is to be used to measure the frequency of movement of the ball, the laboratory needs to be darkened.

It may be helpful to have the whole of the plates and the retort stand on a large sheet of insulator, to permit rotation of the whole apparatus in order to allow the entire class a clear view of the volume between the plates.

Here the emphasis is on current as a flow of charge with a visible carrier in the form of a shuttling ball, and then as ions in a flame.

A graphite painted table tennis ball (use colloidal graphite paint) is suspended on a 1.5 m of insulating nylon thread, suspended between two metal plates held on insulating rods about 6-8 cm apart. The dome of the Van de Graaff generator is connected to the nearest plate, and the far plate is earthed to the base of the generator. The ball shuttles between the plates and charge is clearly set in motion. The frequency of shuttling can be increased by increasing the potential

difference (faster motion of belt, or increased output from EHT supply), or by moving the plates closer. The current can be measured by placing a sensitive light beam galvanometer in the earth return circuit. The meter indication shows that a moving charge constitutes an electric current. The direction of the charge flow and the sign of charge on the generator dome can be found. Such a galvanometer has a typical sensitivity of 25 mm / μA , and a current of a few μA can usually be achieved.

A stroboscope can be used to find the frequency of shuttling. It is important to freeze the motion at one end rather than the middle to avoid visual aliasing (increase strobe rate until two images of the ball, one at each plate, are seen and then drop to half this rate).

A number of calculations are worth doing:

- Number of coulombs flowing per second
- Number of electrons flowing per second
- Charge on the ball (typically about 10 nC)

The demonstration can be completed by replacing the shuttling ball with a candle flame, and measuring the ionisation current carried by the ions in the hot gases of the flame. The current from the ions in the hot flame will conduct a current several orders of magnitude larger, so the sensitivity of the galvanometer will need to be decreased to measure current of the order of milliamperes. The ions are produced in oppositely charged pairs from the originally neutral candle wax. The C^+ ions responsible for the brightness of the flame will be attracted to the negatively charged plate and will deposit as carbon black when they hit the plate and become neutralised.

Alternative approaches

The slow but visible movement of coloured ions as current carriers is a good alternative. The ionisation current in a miniature neon indicator lamp taken above its striking voltage (about 60 V), could also be demonstrated, using an EHT supply and suitable 50 mA meter.

Be safe

If a 5 kV supply is used, ensure that the large series resistor (typically 50 M Ω) is included in the output circuit to limit shocks to very mild ones. A teacher should do this demonstration, but the activity could be repeated by a post 16 student under close supervision.

External references

This activity is taken from Advancing Physics Chapter 2, 40D, which was an adaptation of Revised Nuffield Advanced Physics experiment E1.

TAP: 102-3: Introductory questions on charge and current

1. Convert 25 mA to A
2. Convert 0.50 A to mA
3. A torch bulb passes a current of 120 mA.
 - (a) How many coulombs of charge flow through the lamp in 1 minute?
 - (b) How many coulombs of charge flow through the lamp in 1 hour?
 - (c) How many electrons leave the negative terminal of the cell each second?
4. A car battery is rated as 36 A h. In principle this means it could pass a current of 1 A for 36 h before it runs down. How much charge passes through the battery if it is completely run down?
5. An electron beam in a beam tube carries a current of 125 μA .
 - (a) What charge is delivered to the screen of the tube every second?
 - (b) How many electrons hit the screen each second?

Solutions to introductory questions on charge and current

1. 0.025 A

2. 500 mA

3. (a) $Q = It = 0.120 \times 60 = 7.2 \text{ C}$

(b) $Q = It = 0.120 \times 60 \times 60 = 432 \text{ C}$

(c) $N = Q/e = It/e = (0.120 \times 1) / 1.6 \times 10^{-19} = 7.5 \times 10^{17} \text{ s}^{-1}$

4. $Q = It = 36 \times 60 \times 60 = 129\,600 = 130\,000 \text{ (2 sf.)}$

5. (a) $Q = It = 1.25 \times 10^{-4} \times 1 = 1.25 \times 10^{-4} \text{ C}$

(b) $N = Q/e = 1.25 \times 10^{-4} / 1.6 \times 10^{-19} = 7.8 \times 10^{14} \text{ s}^{-1}$