Episode 125: Introducing capacitors

It is helpful to start this topic by discussing capacitors, rather than the more abstract notion of 'capacitance'.

Summary

Demonstration: A 'super-capacitor'. (10 minutes)

Demonstration: Some capacitors in use. (10 minutes)

Student experiment + discussion (40 minutes): Charging and discharging capacitors.

Student questions: Charge storage. (20 minutes)

Demonstration:

A super capacitor

You should be able to capture the attention of your students with a short demonstration of a 'super-capacitor'. This will allow the term 'capacitor' to be introduced and shows that (electrical) energy storage is one feature of these devices.

TAP 125-1: Super Capacitor

Demonstration:

Some capacitors in use

To emphasise the wide range of situations in which capacitors are used, show a few examples.

TAP 125-2 Where to find capacitors in everyday use

Student experiment + discussion (40 minutes):

Charging and discharging capacitors

The transient nature of the charge/discharge process can be looked at in a qualitative way using a range of capacitors and resistors and monitoring the current with an (analogue) ammeter. This is a good student experiment but you may have to give some initial guidance in how to discharge the capacitor between observations by connecting a lead across its terminals.
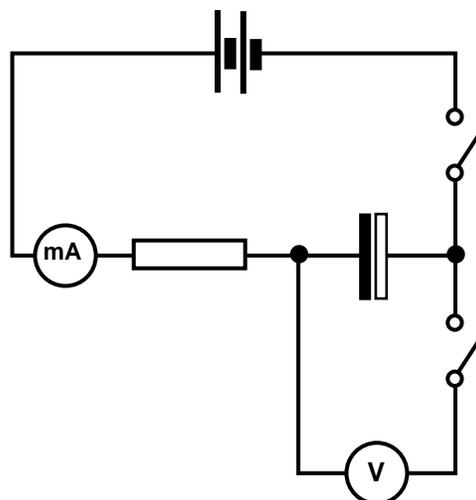
TAP 125-3 Charging and discharging capacitors

The experimental work can be followed by a discussion which should bring out the following observations:

- that current flows for a short time (meters deflect briefly)

- that the current is initially large and then decreases

- that there is the same current in the wires connecting the capacitor to both the positive and negative terminals of the supply (meters deflect identically)

- that the value of the capacitor and resistor alter the magnitude of the current and the time for which it flows.

- further discussion should emphasise the underlying physics explanations:

- that electrons are being removed from one plate, while others are being added to the other, during the 'charging' process

- that as this charge increases the potential difference across the capacitor increases. (The experiment uses a number of cells and assumes that each has the same emf)

- that this causes a reduction in the flow of charge

- until the pd across the capacitor equals the emf of the supply.

- thus a 'charged' capacitor has equal but opposite charges on the two plates so that the total charge is zero.

[There is some advantage in looking at the time variation of the current and/or voltage using either an oscilloscope or datalogger but this can be left until Episode 129.]

Student questions:

Charge storage

Questions will reinforce the discussion or get the students to think through the ideas about charge and its storage for themselves.

TAP 125-4   Questions on charging capacitors
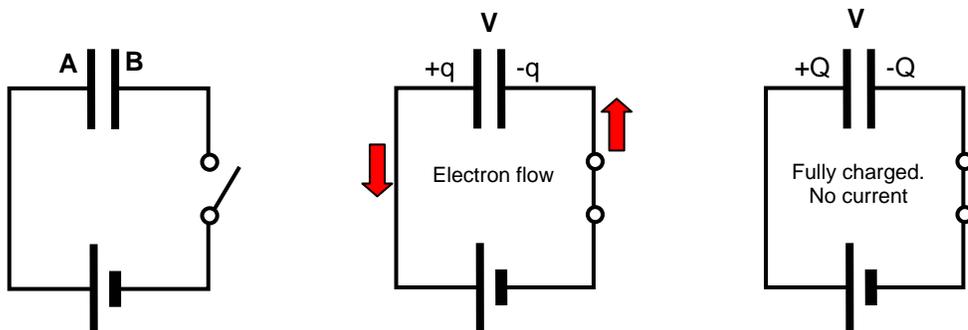
(resourcefulphysicss.org)

TAP 125- 1: Super-capacitor

All the essential ideas of a capacitor can be illustrated thorough a dramatic demonstration, with a large-scale capacitor connected to a high-voltage supply. Some of the effects are best seen in subdued lighting.

You will need

- ✓ two sheets of aluminium foil, approximately 50 cm × 150 cm
- ✓ a slightly larger sheet of heavy-gauge polythene (damp-course material works well or even a good bin liner)
- ✓ educational use EHT power supply, 0–5 kV, dc used with internal 50 MΩ resistor
- ✓ four leads, with no side screws.
- ✓ two crocodile clips, insulated ones are best

Safety

High voltage warning, capable of giving an unpleasant shock. To protect the teacher from accidental contact with the high voltage foil, support a glass or Perspex plate (a glass cupboard door is good) about 100 mm above the capacitor.

What to do

1. Make a crude capacitor by laying the polythene between the two sheets of aluminium on a bench. Ensure the top and bottom sheets of aluminium are not in contact anywhere.

2. Using crocodile clips, connect each aluminium sheet to a terminal of the power supply, set initially at 0 V. Make sure the negative terminal of the power supply is earthed and is connected to the sheet of aluminium on the bench.

3. Listen carefully and watch the foil as you gradually increase the potential difference. You should hear a crinkling sound and notice the foil is being pulled down flatter.

4. Why is this happening? The power supply removes electrons from one foil sheet and at the same time adds electrons to the other. They cannot move round the complete circuit because polythene is an electrical insulator. Charge is stored on the foil sheets in amounts + Q and – Q. Having opposite charges, the foil sheets attract.

5. You should notice that the force of attraction gets larger for larger potential difference, *V*. This suggests *Q* increases with *V*.

6. If you go on increasing the potential difference, there may be a sudden discharge (or discharges), almost explosive sparking. A channel through the polythene has been made conducting because of the high potential difference. This is just like lightning discharges through the (insulating) air.

7. If you look closely at where this happens, you will see it is where the foil sheets are closest together.

8. Turn the power supply off. Discharge the capacitor then examine the polythene. You will find it has holes in it! The polythene has been melted by the heating effect of each discharge. The capacitor clearly has stored energy as well as charge. (It could however be argued that this is resistive heating once breakdown has occurred, with energy transferred from the power supply directly, rather than from the capacitor.)

9.	At this point, look at a large-value commercial capacitor, say 100 mF. You will notice it is shaped like a cylinder. It has a similar structure to the 'super-capacitor', but has been rolled up to save space. The labelling on this capacitor includes a voltage: this is the maximum potential difference which can be applied in normal use, that is, without the insulator breaking down.

Steps 4 and 5 help to develop students' understanding of how capacitors work. You may wish to omit them at this stage.

External references

This activity is taken from Advancing Physics Chapter 10, 90D

TAP 125- 2: Capacitors in everyday use

By 'taking the back off' a number of common electrical appliances you should be able to find examples of capacitors in use. A wide range of capacitance is likely to be on show.

You could try:

- A laboratory power supply
- An ac to dc voltage converter
- A radio or TV
- A computer
- A VCR or audio amplifier
- A 'throwaway' flash camera

Safety

But be aware that if you use mains operated equipment great care is required if the cover is removed. Appliances **must not** be connected to the mains and a little time should be allowed to elapse before the cases are opened after disconnection, to allow any capacitors to discharge.

# TAP 125- 3: Charging and discharging capacitors

A foretaste

Using simply a milliammeter and stopwatch, you can study the changing currents which occur when a capacitor is charged or discharged in a simple circuit with a battery and resistor. This will enable you to explore the effects of three quantities: applied potential difference, capacitor value and resistor value.

You will need

- ✓ digital multimeter, used as milliammeter
- ✓ capacitors 47 μF, 100 μF, 220 μF, 470 μF
- ✓ clip component holder
- ✓ resistance substitution box
- ✓ variable power supply, 5 V dc(smooth and, ideally, stabilised as used for electronics) or 4 cell battery pack
- ✓ leads, 4 mm
- ✓ hand held stopwatch

Starting out

Choose a 100 μF capacitor, insert it in the component holder, set the resistance box to 1 kΩ and assemble the circuit as shown. Take care to connect the capacitor terminals with the correct polarity + and –.
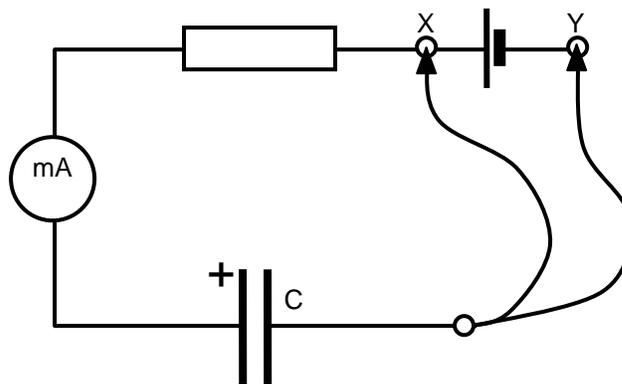
1. Briefly connect the flying lead to terminal Y. Watch the milliammeter carefully.

2. Briefly connect the flying lead to terminal X. Watch the milliammeter carefully.

Compare the similarities and differences between the magnitude, direction and duration of the current pulse in each case. Then consider how your results provide evidence for the following explanation:

Action 1 causes electric charge to flow onto one capacitor plate and off the other. The capacitor becomes 'charged' by keeping the equal and opposite charges separated. Action 2 has the

reverse effect; the separated charge flows away from one side of the capacitor via the circuit to the other side through the resistor and milliammeter. The capacitor becomes discharged.

You will repeat this basic experiment several times to find out the effects of varying the potential difference, capacitance and resistance.

The effect of changing the capacitance

Repeat the experiment with different capacitors: 47 μF, 220 μF, 470 μF.

In each case note the effects on the magnitude and duration of the current pulse. A stopwatch may help you observe the duration. Write a statement that summarises the effect of capacitance value on the discharge current.

The effect of changing the resistance

Using the 100 μF capacitor, repeat the experiment with different values of resistance: 2.2 kΩ, 4.7 kΩ, 10 kΩ.

In each case note the effects on the magnitude and duration of the current. Write a statement that summarises the effect of resistance value on the discharge current.

The effect of changing the potential difference

Connect the 100 μF capacitor and set the resistance box to 1 kΩ. Increase the number of cells to make a battery.
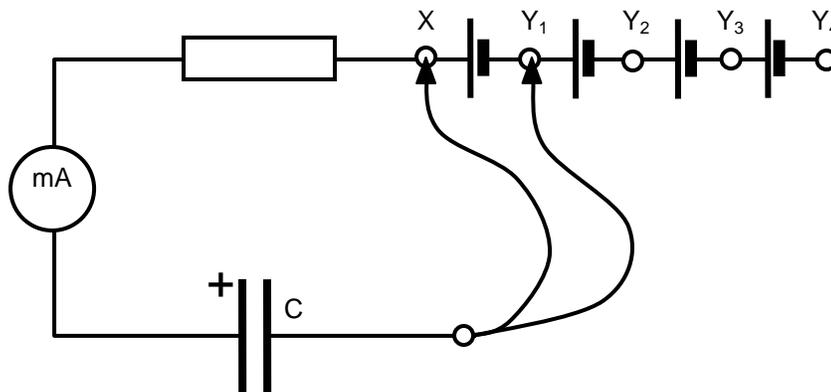
Repeat the experiment using a different Y terminal each time, providing different potential differences. In each case note the effects on the magnitude and duration of the current. Write a statement that summarises the effect of potential difference on the discharge current.

Thinking about the theory

To help make useful links with the theory of capacitors, use this chart to summarise your results; write a sentence in each cell to describe the effect.

	Magnitude of current	Duration of current
Effect of capacitance		
Effect of resistance		
Effect of potential difference		

Capacitance is defined and can be measured by dividing the charge Q stored on the capacitor by the potential difference V across its terminals. That is:

$$C = \frac{Q}{V}.$$

To help think about the effect of capacitance and potential difference on the charged stored, this can be rearranged to give:

$$Q = CV.$$

This implies that if either C or V is made larger, a larger charge Q would be stored on the capacitor. Explain how your results support this description. (Remember that when the capacitor is charged or discharged, Q coulombs of charge flow through the milliammeter.)

Theory predicts that the charging or discharging current is not steady but gradually decays over a period of time and the rate of decay depends upon R and C multiplied together. The rate appears not to depend upon the applied potential difference V. Explain how your results support these predictions.

You have learned

1.   When a capacitor is charged or discharged, a pulse of current flows which quickly rises to a peak and then gradually decays.

2.   The direction of the current pulse when the capacitor is charged is opposite to that of the discharge pulse.

3.   The magnitude of the current pulse is larger for larger value capacitors C.

4.   The magnitude of the current pulse is larger when a larger potential difference V is connected.

5.   The current pulse takes longer to decay when the product RC is larger.

Teacher's notes

Practical advice

If the multimeter does not have a prominent analogue bar display then you may prefer to use a

1 mA FSD analogue milliammeter.

The activities are intended to give students a 'feel' for the quantities that affect the current pulses when a capacitor is charged or discharged. The results point the way towards the time constant for measuring the rate of decay but RC is not explicitly defined here. Qualitative observations are intended; other activities provide quantitative approaches for studying the exponential form of the decay.

External references

This activity is taken from Advancing Physics Chapter 10, 100E

TAP 125- 4: Charging capacitors

Practising with current, charge and electron flow

You should already be familiar with the relationship between current, charge, potential difference and time. Try these few simple calculations as a reminder. You will have to recall or look up the value for the charge of the electron.

1.   How much charge passes a point in a circuit when a current of 8 A flows for 5 s?

2.   A charge of 120 C passes through a battery in 4 minutes.
        Calculate the average current?

3.   To start a car engine takes 80 A for 6 s.
        Calculate how much charge flows through the motor?

4.   The beam current in an oscilloscope is 2 mA.
        Calculate how many electrons strike the screen in 16 s.

5.   A charge of 20 C flows through a 1.5 V cell.
        Calculate how much energy has been transferred from the cell to a lamp connected across it?

The current in a hand calculator is very small, for example, 0.0006 mA.

6.   How many electrons per second does this represent?

7.   How long would it take for one coulomb of charge to flow?

The capacitor – an unusual circuit element

The diagram shows the symbol for a capacitor.
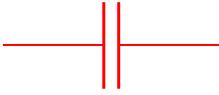
The symbol shows the idea behind the construction. There are two conducting surfaces with a non-conducting gap between them. This gap may literally be an air gap or it may be filled with an insulator, sometimes called a dielectric. It is important that this gap does not conduct when the capacitor is working. The construction means that charge can never flow **through** the capacitor, but can flow in the circuit **to** it (and **from** it).

In the circuit shown, an uncharged capacitor is connected to a battery.
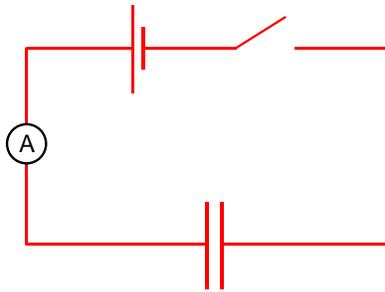
When the switch is closed, an ammeter will show a current. You may well have done or seen an experiment to demonstrate this.

8.   Which way will electrons flow? Redraw the circuit and put arrows on to show the direction of electron flow.

9.   If a current of 100 μA passes for 2 s, how much charge flows through the battery? How many electrons flow through the battery?

When a capacitor has been connected across a battery for some time, the flow of charge stops. The capacitor is said to be **charged**. We talk about the 'charge on the capacitor' and this is equal to the charge that has flowed through the battery during the charging process. The capacitor is left with one surface positively charged and the other negatively charged.

10.   Which surface (or plate) has gained electrons and which has lost electrons, and how many has each plate lost or gained?

11.   When the capacitor shown in the circuit above is charged, a charge of 150 μC flows through the battery. Redraw the diagram and mark on it the charge (with sign) on each plate. What is the net charge on the capacitor (i.e. taking account of the signs)?

You will perhaps have realised by now that what really happens when a capacitor is charged is that the pulse of current results in a redistribution of charge. The overall charge of the circuit is zero, as it was at the start of the process. One plate (or surface) of the capacitor has acquired a surplus of electrons at the expense of the other.

Two further questions, for discussion.

12.   How much charge is needed to charge a capacitor?

13.   Can we go on adding charge indefinitely to a capacitor?

Practical advice

It is intended that the first seven questions be used as a warm-up exercise to remind students about any previous work they will have done on electric current. They will have met the equation Q = It in their work on basic electricity and the questions are designed to test that they can handle charge confidently before moving on to capacitors.

The second section focuses on the flow of charge in a circuit containing a capacitor but stops short of using or developing Q = CV, which follows later. The idea of the questions, which are not all calculations, is to promote thinking about how the charging of a capacitor represents a redistribution of charge in a circuit in which nothing is either lost or gained. You may like in your teaching to sow the seed of how the redistribution of charge results in storage of energy which can be tapped into at any future time. Students also have opportunities in these questions to practise dealing with very small and very large numbers and with the use of standard form.

Solutions

1.   40 C
2.   0.5 A
3.   480 C
4. 2.0×10^{17}
5.   30 J
6. 3.75×10^{12}
7.   Approximately 19 days
8.   Arrows away from negative and towards the positive terminal

9. 2×10^{-4} C, 1.25×10^{15}

10.   The plate near the negative terminal has gained electrons, the other has lost electrons. The number in each case is 1.25×10^{15}

11.   Zero charge overall

Worked solutions

1.
$$Q = It = 8 \text{ A} \times 5 \text{ s} = 40 \text{ C.}$$

2.
$$I = \frac{Q}{t} = \frac{120 \text{ C}}{4 \times 60 \text{ s}} = 0.50 \text{ A.}$$

3.
$$Q = It = 80 \text{ A} \times 6 \text{ s} = 480 \text{ C.}$$

4.   Charge striking the screen in 16 s = 2×10^{-3} A $\times$ 16 s = 32×10^{-3} C, so the number of electrons striking the screen in 16 s is equal to:
$$\frac{32 \times 10^{-3} \text{ C}}{1.6 \times 10^{-19} \text{ C}} = 2.0 \times 10^{17}.$$

5. $W = QV = 20 \text{ C} \times 1.5 \text{ V} = 30 \text{ J.}$

6.   In 1s the charge flow is equal to 0.0006×10^{-3} C = 6.0×10^{-7} C, so the number of electrons is equal to
$$\frac{6.0 \times 10^{-7} \text{ C}}{1.6 \times 10^{-19} \text{ C}} = 3.75 \times 10^{12}.$$

7.   The time for 1 C is equal to
$$\frac{1 \text{ C}}{0.0006 \times 10^{-3} \text{ A}} = 19 \text{ days (approx.).}$$

8.   The circuit diagram should show arrows away from negative and towards the positive terminal of the cell.

9.
$$Q = It = 100 \times 10^{-6} \text{ A} \times 2 \text{ s} = 2 \times 10^{-4} \text{ C}$$
$$\text{number of electrons} = \frac{2 \times 10^{-4} \text{ C}}{1.6 \times 10^{-19} \text{ C}} = 1.25 \times 10^{15}.$$

10.   The plate near the negative terminal has gained electrons, the other has lost electrons. The number in each case is 1.25×10^{15}.

11.   The plate nearest the negative side of the cell will have -150 μC and the plate nearest the positive side of the cell will have $+ 150$ μC. Zero charge overall.

12.   Points raised might refer to the battery voltage available.

13.   Discussion expected to lead to discussion of electrical breakdown of dielectric.

External references

This activity is taken from Advancing Physics Chapter 10, 50S