**Chapter 20: Potential Difference and Capacitance**

***Please remember to photocopy 4 pages onto one sheet by going A3→A4 and using back to back on the photocopier***

**The potential difference** (p.d.) between two points is the work done when a charge of 1 coulomb moves from one point to the other\*.

The unit of potential difference is **the volt (symbol V)**

**The volt**

The potential difference between two points is one volt if one joule of work is done when bringing a charge of one coulomb from one point to another.

A more common (but less correct) word for the term ‘potential difference’ is ‘voltage’.

Note that potential difference is always between two points.

**Relationship between work, charge and potential difference**

work = potential difference × charge:

**W = V × Q**

**Potential at a point\***

The potential at a point refers to the work done in bringing a positive charge from that point to earth.

We come back to this when covering the electric circuit questions in the ‘Resistance’ chapter.

**Leaving Cert Physics Syllabus: Potential Difference**

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| --- | --- | --- | --- |
| **Content** | **Depth of Treatment** | **Activities** | **STS** |
|  | Definition of potential difference:work done per unit charge totransfer a charge from one pointto another.Definition of volt.Concept of zero potential. | Appropriate calculations. |  |

**Capacitance\***

**The symbol for capacitance is C**

Please don’t confuse ‘capacitance’ (symbol C) with ‘charge’ (symbol Q).

A capacitor is an electrical device used to store separated charge

**The capacitance of a conductor** is the ratio of the charge on the conductor to its potential\*.

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

The unit of capacitance is the farad; symbol is F.

(This is similar to the definition for resistance; $R= \frac{V}{I}$ which we will come across in the next chapter.)

**A parallel plate capacitor**

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**The parallel plate capacitor\***

Consider two oppositely charged parallel plates as shown\*



From the diagram we can see that the capacitance will increase if the common area between plates (A) increases, or if the distance between plates (d) decreases.

Therefore C ∝ A and C ∝ $\frac{1}{d}$ ⇒ C ∝ $\frac{A}{d}$ ⇒ C = k $\frac{A}{d}$

The proportional constant turns out to be ε (remember we came across this in the last chapter as part of Coulomb’s Law) and represents the permittivity of the medium between the two plates.

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**⇒**

**To demonstrate the factors affecting the capacitance of a parallel plate capacitor\***

 Multimeter (set to read *capacitance*)

1. Connect the two parallel plates to a multi-meter set to read capacitance. Note the capacitance.
2. Increase the distance between them – note that the capacitance decreases.
3. Move one plate slightly to the side (decreasing the overlap area) – note that the capacitance decreases.
4. Place different slabs of insulating material between the plates – note that the capacitance is lowest when nothing (air) is between the plates\*.

**So the three factors that affect the capacitance of a parallel plate capacitor are**

1. **Overlap area**
2. **Distance between the plates**
3. **Permittivity of the medium**

**Exam tip:** “medium” is not an acceptable answer

**The energy stored in a capacitor\***

$$W=\frac{1}{2}CV^{2}$$



**To show that a charged capacitor stores energy**

* Set up as shown.
* Close the switch to charge the capacitor.
* Remove the battery and connect the terminals together to ‘short’ the circuit.
* The bulb will flash as the capacitor discharges, showing that it stores energy.

**Common uses of capacitors**

1. The ‘flash’ on a camera
2. Tuning into a radio station (for an explanation see the link on the *Capacitance* page of thephysicsteacher.ie).
3. Allows alternating current (a.c.) to pass through it but blocks direct current (d.c.)\*.
4. Smoothing out variations in direct current.
5. Used in circuits to only allow alternating current of a specific frequency to flow.\*

|  |  |  |  |
| --- | --- | --- | --- |
| **Quantity** | **Symbol** | **Unit** | **Symbol of unit** |
| ***Charge*** | Q | *coulombs* | C |
| ***Current*** | I | *amps* | A |
| ***Capacitance*** | C | *farads* | F |
| ***Electric Field Strength*** | E | *newton per coulomb* | N/C |

**Leaving Cert Physics Syllabus: Capacitance**

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| --- | --- | --- | --- |
| **Content** | **Depth of Treatment** | **Activities** | **STS** |
|  |  |  |  |
| Capacitors andcapacitance | Definition: *C* = *Q/V*Unit of capacitance. |  |  |
|  | Parallel plate capacitor.**Use of**  | **Demonstration that capacitance depends on the common area, the distance between the plates, and the nature of the dielectric.****Appropriate calculations.** | Common uses of capacitors:• tuning radios• flash guns• smoothing• filtering. |
|  | Energy stored in a capacitor.**Use of *W* = ½ *CV 2***Capacitors – conduct a.c. but notd.c. | Charge capacitor–discharge through lamp or low-voltage d.c. motor.**Appropriate calculations.**Demonstration. |  |

**Extra Credit**

**\*Definition of potential difference**

Note:

If the +1 charge is going to a positive point then work has to be done to get it there, but if it’s going to a negative point then *it* (the +1 charge)does the work.

This is similar to saying that a rock on top of a cliff has a potential energy of, say, 100 Joules.

 To get the rock up there you have to do 100 Joules of work on the rock, or alternatively if the rock fell to the ground *it* would do 100 Joules of work.

**\*W = V Q**

Now if you know how much gravitational energy the rock has (from the formula for gravitational potential energy E = mgh), you can calculate the velocity at which it will hit the ground (from the formula for kinetic energy E = ½ mv2).

From Conservation of Energy; Potential Energy = Kinetic Energy: mgh = ½ mv2

Just as the rock will accelerate towards the ground, so the positive charge will accelerate towards the negative point.

In fact, if you know how much potential energy the charge had to begin with, i.e. the potential between the two points (from the formula W = QV) you can calculate its velocity when it reaches the second point (if you know its mass) by again using

Potential Energy = Kinetic Energy, or QV = ½ mv2

**\*Potential at a Point**

Remember above that we noted potential difference is always between two points?

Well quite often we need to know how difficult it is to bring positive charge from the earth to a positive object.

Because this occurs so often, we dispense with the term ‘potential difference’ and just refer to the potential difference between the earth and the object as ‘the potential of the object’ – this is also known as ‘the potential at a point’.

From this it should be obvious that the more positive charge an object has, the more work will have to be done in bringing another positive charge up to it, and so the potential at that point will be greater.

You might now want to challenge yourself to explain how a Gold Leaf Electroscope can be used to compare the potential difference between one object and the earth versus another object and the earth.

**\*Capacitance**

Picture a water container.

If the capacity of the container is 2 litres then we know that the container will only hold 2 litres of water. But we can’t say that for an object that stores charge; we can theoretically put an infinite amount of charge on (say) a euro coin – the charge won’t ‘fall off’, but it will make it harder to put further charger on the coin (the potential of the coin increases). Now picture a 1 euro and a large 2 euro coin. As we put more charge on both coins, the potential of the 1 euro coin will increase more quickly than the potential of the 2 euro coin (because the charge density is greater on the 1 euro coin). It is this concept which we use to help us define the capacitance of a capacitor.

If the addition of a small charge results in a large increase in potential then we say that the capacitance is small; the ratio of Q to V is a small number.

If however if the addition of a large charge results in a small increase in potential then we say that the capacitance is large; the ratio of Q to V is a large number.

So we define the capacitance of a capacitor to be the ratio of Q to V. C = Q/V

So for example if a capacitor has a capacitance of 2 farads, then putting a charge of 6 coulombs on it will increase its potential by 3 volts (from C = Q/V, so V = Q/C).

However if the capacitor had a capacitance of 200 farads, putting a charge of 6 coulombs on it would only raise its potential by 0.03 volts.

**\*Definition of capacitance**

If, when asked to define Capacitance, you answer that “*it is used to store charge”*, you will get zero marks, because this is not a definition.

**\*C = Q/V**

It’s easier to remember the formula C = Q/V if you re-arrange it as Q = CV

**\*The parallel plate capacitor**



The potential of a positively charged object is an indication of how much work will have to be done to bring another positively charged object up to it.

Therefore the more positive charge that is on the object, the greater its potential will be.

If however we bring a negatively charged object up close to the positively charged object, their electricity fields will tend to cancel each other out, and it will then become easier to bring more positive charge up to the original – positively charged – object.

This means that the potential of the original object becomes reduced simply by bringing an oppositely charged conductor up close to it.

This is the principle upon which a parallel plate capacitor is based.

**\*Consider two oppositely charged parallel plates as shown**

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The key to this is to remember that the more their electric fields cancel each other out, the greater will be the capacitance of the system.

**\*Two formulae for the energy stored in a capacitor**

**W = ½ CV2, W = Q2/2C**

You don’t need to know how to derive these formulae, but it is actually very straightforward and, for me at least, it’s easier to derive them from scratch than to remember them.

They derivation incorporates the formulae W = QV, and C = Q/V.

I can show you on the board in 5 minutes if you ask me.

Note that if you start with Q = CV, and substitute this into W = QV, you get W = CV, with no factor of ½!

To explain where the factor of ½ comes from requires going over the derivation, so go on – ask me!

By the way, the text-books don’t explain this apparent anomaly.

**\*Allows alternating current (a.c.) to pass through it but blocks direct current (d.c.)\*.**





In the first diagram (direct current) once the circuit is complete there is a sudden movement of electrons, but because the circuit is not complete there is no further flow.

In the second diagram the plates are continuously charging and discharging; the time this takes (and therefore the frequency) depends upon the size of the plates (see next point).

Strictly speaking the current is not ‘passing through’ the capacitor, but merely acts as though it is.

**\*Used in circuits to only allow alternating current of a specific frequency to flow**

This in turn is **used in radios to only receive certain frequencies**, corresponding to radio waves coming from a specific radio station.

The part of an electronic circuit responsible for this is called an ‘RC’ circuit (for Resistance, Capacitance).

When changing stations in a radio, you are really changing the capacitance of this part of the circuit.

How does this work?

Well the larger the size of the capacitor, the longer it takes to discharge (and charge). Now if the time it takes to charge and discharge corresponds to the frequency of the alternating current – which in turn is carrying the sound information from the radio station – then this signal will be allowed to pass and ultimately to reach the speakers.

**Electrical resonance – Using capacitors to ‘tune in’ a radio or television**
Tuning a radio or television involves selecting a particular transmission frequency from all the incoming frequencies received by the aerial by matching the natural frequency of the detecting circuit in the radio or TV with the desired incoming frequency. This can be achieved by varying the capacitance of the detecting circuit. It will only produce a large oscillating voltage, i.e. resonance occurs, for the incoming frequency equal to its own natural frequency. The circuit will produce only small oscillating voltages for other frequencies.

**\*To demonstrate the factors affecting the capacitance of a parallel plate capacitor**

Note: An alternative demonstration is given on page 242, but it is difficult to understand what’s going on – the textbook does not explain it fully.

The demonstration described is perfectly adequate and is much more straightforward.

**\*Place different slabs of insulating material between the plates – Note that the capacitance is lowest when nothing (or air) is between the plates.**

This may seem confusing, so if it’s bothering you, ask me to explain why.

 **Exam questions**

1. [2005][2004][2009][2002 OL]

Define potential difference.

1. [2007 OL]

Name an instrument used to measure potential difference.

1. [2009][2008][2004] [2002 OL]

Define capacitance.

1. [2004 OL]

Name the electrical component represented in the diagram.

1. [2010]

Which of the following devices is adjusted when tuning into a radio station?

Transformer, diode, capacitor, rheostat

1. [2006]

List the factors that affect the capacitance of a parallel plate capacitor.

1. [2008]

How would you demonstrate that the capacitance of a parallel plate capacitor depends on the distance between its plates?

1. [2010]

What is the positive charge stored on a 5 μF capacitor when connected to 120 V d.c. supply?

1. [2006]
2. The plates of an air filled parallel plate capacitor have a common area of 40 cm2 and are 1 cm apart. The capacitor is connected to a 12 V d.c. supply. Calculate the capacitance of the capacitor.

(Permittivity of free space = 8.85 × 10-12 F m-1)

1. Calculate the magnitude of the charge on each plate.
2. What is the net charge on the capacitor?
3. [2004][2009][2002 OL]

Describe an experiment to demonstrate that a capacitor can store energy.

1. A capacitor is connected to a switch, a battery and a bulb as shown in the diagram. When the switch is moved from position A to position B, the bulb lights briefly.
2. What happens to the capacitor when the switch is in position A?
3. Why does the bulb light when the switch is in position B?
4. When the switch is in position A the capacitor has a charge of 0.6 C, calculate its capacitance.
5. [2007]

Calculate the energy stored in a 5 μF capacitor when a potential difference of 20 V is applied to it.

1. [2005]

A capacitor of capacitance 100 μF is charged to a potential difference of 20 V. What is the energy stored in the capacitor?

1. [2002]

How much energy is stored in a 100 μF capacitor when it is charged to a potential difference of 12 V?

1. [2009]

The ability of a capacitor to store energy is the basis of a defibrillator. During a heart attack the chambers of the heart fail to pump blood because their muscle fibres contract and relax randomly. To save the victim, the heart muscle must be shocked to re-establish its normal rhythm.

A defibrillator is used to shock the heart muscle.

A 64 μF capacitor in a defibrillator is charged to a potential difference of 2500 V.

The capacitor is discharged in 10 milliseconds through electrodes attached to the chest of a heart attack victim.

1. Calculate the charge stored on each plate of the capacitor.
2. Calculate the energy stored in the capacitor.
3. Calculate the average power generated as the capacitor discharges.
4. [2004]
5. The circuit diagram shows a 50 μF capacitor connected in series with a resistor, a 6 V battery and a switch.

The potential difference across the capacitor is initially 2.24 V.

Calculate the charge on the capacitor at this instant.

1. Calculate the energy stored in the capacitor *when it is fully charged*.
2. Describe what happens in the circuit when the 6 V d.c. supply is replaced with a 6 V a.c. supply.
3. [2002 OL]

Diagram A shows a capacitor connected to a bulb and a 12 V a.c. supply.

Diagram B shows the same capacitor connected to the bulb, but connected to a 12 V d.c. supply.

What happens in each case when the switch is closed? Explain your answer.

1. [2006 OL][2006 OL][2007 OL][2010]

Give one use of a capacitor.

**Exam Solutions**

1. The potential difference between two points is the work done in bringing a charge of 1 Coulomb from one point to the other.
2. A voltmeter
3. The capacitance of a conductor is the ratio of the charge on the conductor to its potential.
4. A capacitor
5. Capacitor
6. Common area of plates, distance apart, permittivity of dielectric between plates.
7. Connect the two parallel plates to a digital multi-meter (DMM) set to read capacitance.

Note the capacitance.

Increase the distance between them – note that the capacitance decreases.

1. Q = CV = (5 × 10–6)(120)

Q = 6.0 × 10–4 C

1. *C=*ε*A/d*

C = [(8.85 × 10-12)(40 × 10-4)] / (0.01)

C = 3.54 × 10-12 F

1. Q = C V

Q = (3.54 x 10-12)(12) = 4.2(5) x 10-11 C

1. ****Zero
* Set up as shown.
* Close the switch to charge the capacitor.
* Remove the battery and connect the terminals together to ‘short’ the circuit.
* The bulb will flash as the capacitor discharges, showing that it stores energy.
1. It charges (charge builds up on the plates).
2. The capacitor discharges so current briefly runs through the bulb.
3. C = Q/V = 0.6/6 = 0.1 Farads
4. E = ½ CV2 = ½ (5 x 10-6)(20)2 = 1.0 x 10-3 J
5. E = ½CV2   E = ½(100 × 10-6)(20)2  = 0.02 J
6. E = ½ CV2 = ½ (100 × 10-6)(12)2 = 7.2 × 10-3 J
7. C = Q/v  q = CV  q = (64 × 10-6)(2500)  q = 0.16 C
8. E = ½ CV2 = ½ (64 × 10-6)(2500)2 = 200 J
9. P = W/t = (200)/(10 × 10-3) = 20000 W
10. C = Q/V  Q = CV = (50 ×10−6)(2.24) = 1.12 × 10-4 C
11. E = ½ CV2 = ½ (50 ×10− 6)(6 )2 = 9 ×10−4 J

Note that here we use 6 Volts as the potential difference across the capacitor because although the potential difference at the beginning is 2.24 V, when the capacitor is fully charged it takes the maximum amount of energy to put more charge on.

1. The current will flow continually.
2. In diagram A the bulb lights because a capacitor ‘conducts’ a.c. (it is continually charging and discharging).

In diagram B the bulb does not light because a capacitor does not conduct d.c.

1. Store charge / (radio) tuning / Smoothing out variations in direct current / store energy / flash guns for cameras, phone charger, blocks d.c.