Electric & Magnetic Fields

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Course	HL IB Physics
Section	Fields
Topic	Electric & Magnetic Fields
Difficulty	Medium

To be used by all students preparing for HL IB Physics
Students of other boards may also find this useful

1

The correct answer is **C** because:

- When the conducting spheres X and Y are brought into contact, they end up with the same charge, because they are identical
    - Therefore, at the point of contact, the total charge –8 μC + 12 μC = +4 μC is distributed equally across them
    - This means each sphere is charged with +2 μC after being separated again

The underlying principle that will help you understand this question is the conservation of charge. Charge is always carried in units of the elementary charge ($e = \pm 1.6 \times 10^{-19}$ C) so since the conducting spheres in this question are identical, when they are brought into contact a **finite** amount of charge will spread evenly across them. The total charge is therefore distributed symmetrically.

2

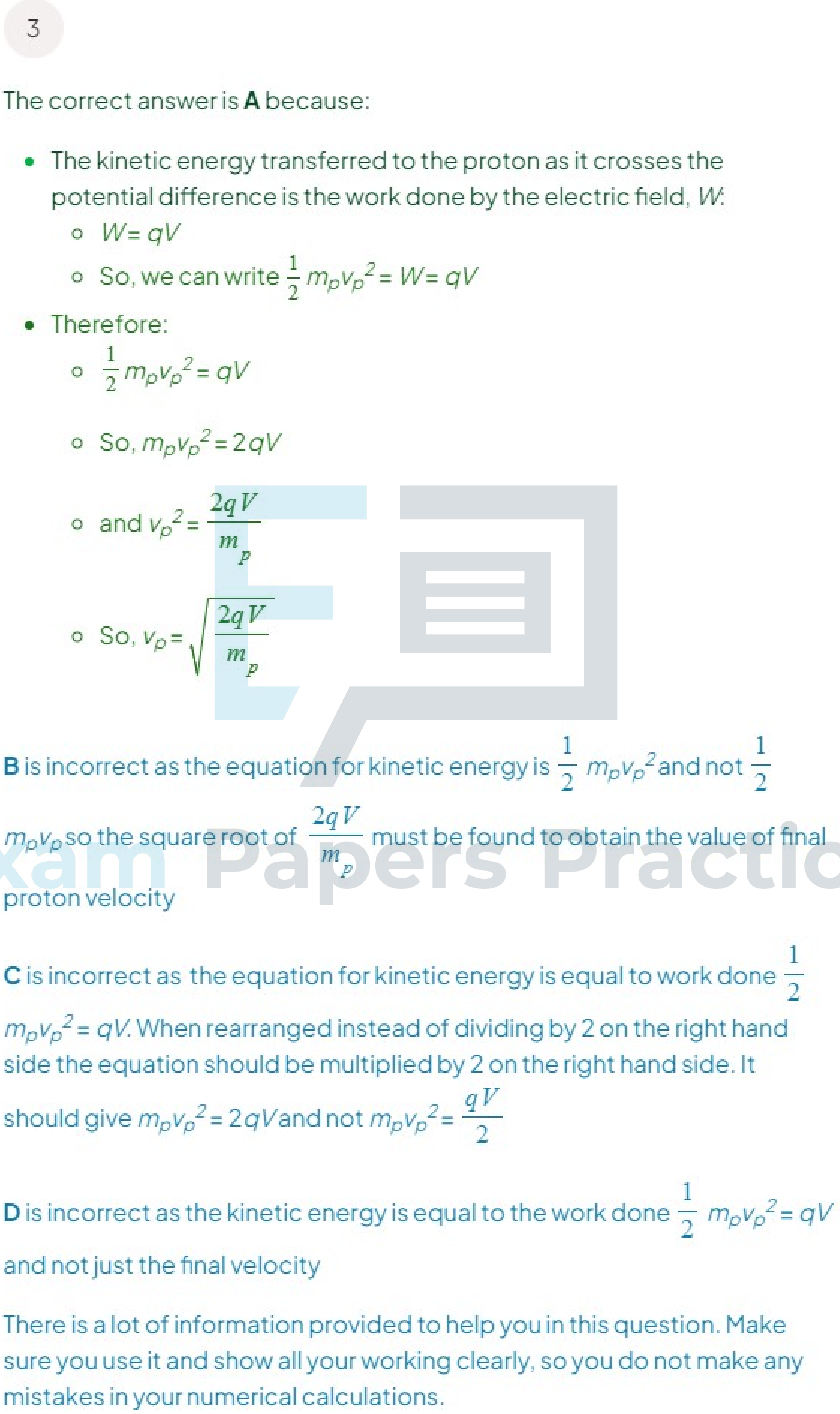
The incorrect answer is **C** because:

- The work done (or energy transferred) on or by an electron as it moves across a potential difference is independent of the path taken
    - The potential difference, and hence the energy transferred, is only dependent on the initial and final position of the electron

A is incorrect as a potential difference occurs whenever there is a separation of charge. If charge is separated, an electric field is set up, directed from positive to negative

B is incorrect as $V = \frac{W}{q}$ therefore $W = qV$, so if the charge $q = e$ (the elementary charge on an electron), then $W = eV$ is the work on or by an electron across a potential difference V

D is incorrect as the electric field has both magnitude and direction



3

The correct answer is **A** because:

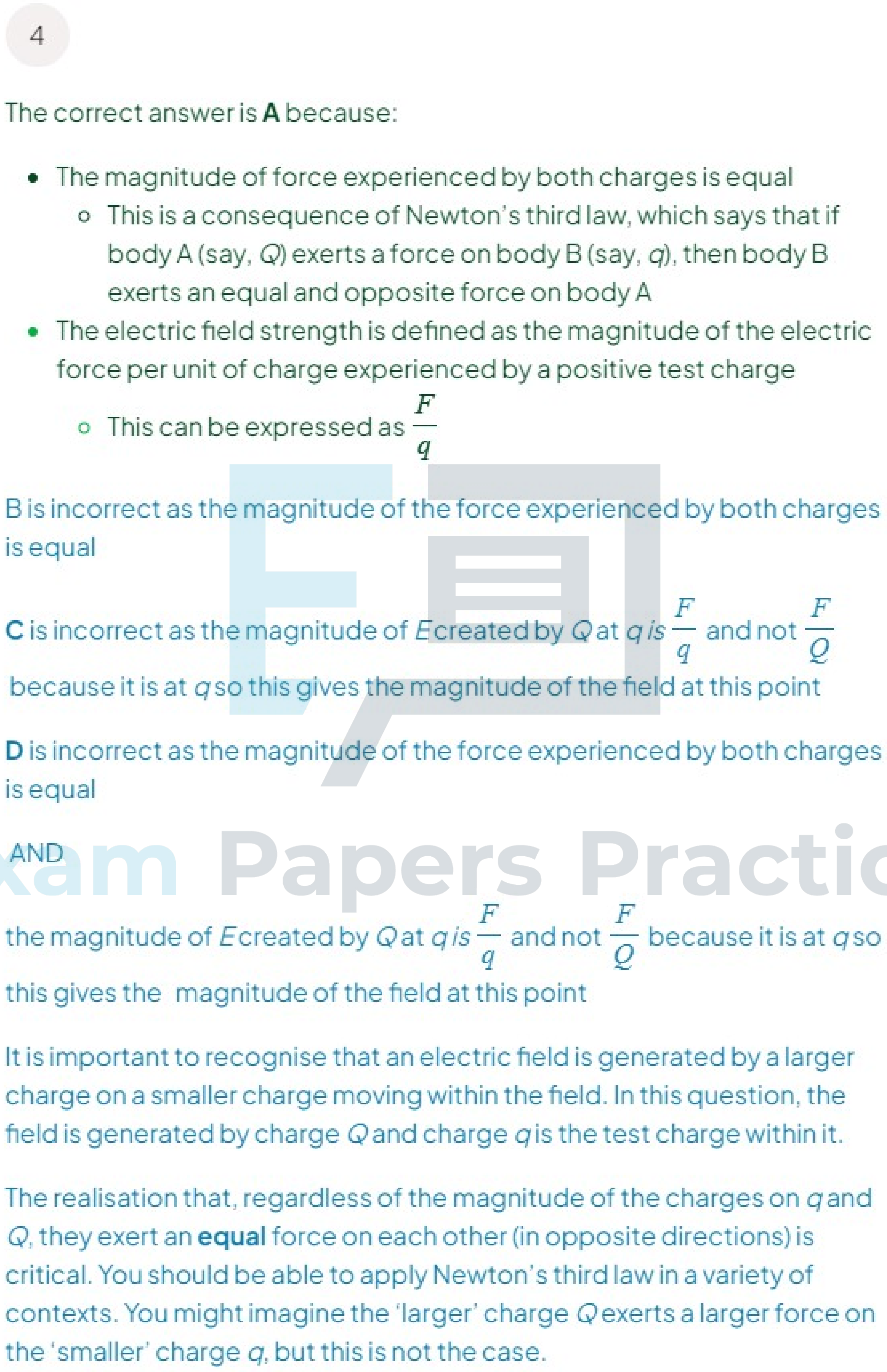
- The kinetic energy transferred to the proton as it crosses the potential difference is the work done by the electric field, W:
  - $W = qV$
  - So, we can write $\frac{1}{2} m_p v_p^2 = W = qV$
- Therefore:
  - $\frac{1}{2} m_p v_p^2 = qV$
  - So, $m_p v_p^2 = 2qV$
  - and $v_p^2 = \frac{2qV}{m_p}$
  - So, $v_p = \sqrt{\frac{2qV}{m_p}}$

B is incorrect as the equation for kinetic energy is $\frac{1}{2} m_p v_p^2$ and not $\frac{1}{2} m_p v_p$ so the square root of $\frac{2qV}{m_p}$ must be found to obtain the value of final proton velocity

C is incorrect as the equation for kinetic energy is equal to work done $\frac{1}{2} m_p v_p^2 = qV$. When rearranged instead of dividing by 2 on the right hand side the equation should be multiplied by 2 on the right hand side. It should give $m_p v_p^2 = 2qV$ and not $m_p v_p^2 = \frac{qV}{2}$

D is incorrect as the kinetic energy is equal to the work done $\frac{1}{2} m_p v_p^2 = qV$ and not just the final velocity

There is a lot of information provided to help you in this question. Make sure you use it and show all your working clearly, so you do not make any mistakes in your numerical calculations.



4

The correct answer is **A** because:

- The magnitude of force experienced by both charges is equal
  - This is a consequence of Newton's third law, which says that if body A (say, *Q*) exerts a force on body B (say, *q*), then body B exerts an equal and opposite force on body A
- The electric field strength is defined as the magnitude of the electric force per unit of charge experienced by a positive test charge
  - This can be expressed as $\frac{F}{q}$

B is incorrect as the magnitude of the force experienced by both charges is equal

C is incorrect as the magnitude of *E* created by *Q* at *q* is $\frac{F}{q}$ and not $\frac{F}{Q}$ because it is at *q* so this gives the magnitude of the field at this point

D is incorrect as the magnitude of the force experienced by both charges is equal

AND

the magnitude of *E* created by *Q* at *q* is $\frac{F}{q}$ and not $\frac{F}{Q}$ because it is at *q* so this gives the magnitude of the field at this point

It is important to recognise that an electric field is generated by a larger charge on a smaller charge moving within the field. In this question, the field is generated by charge *Q* and charge *q* is the test charge within it.

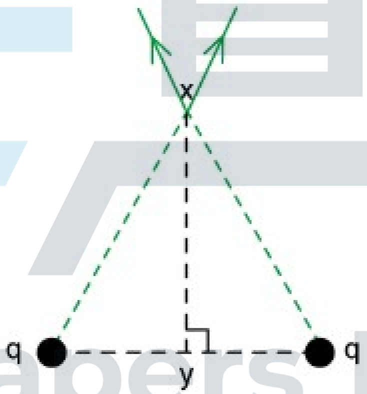
The realisation that, regardless of the magnitude of the charges on *q* and *Q*, they exert an **equal** force on each other (in opposite directions) is critical. You should be able to apply Newton's third law in a variety of contexts. You might imagine the 'larger' charge *Q* exerts a larger force on the 'smaller' charge *q*, but this is not the case.

However, the electric field strength, here, is **due to the charge Q,** which we can imagine as 'creating the field' (in reality, both charges have an electric field around them). Therefore, the electric field strength due to charge Q is the force experienced per unit of charge **at that point in the field,** i.e., $E = \frac{F}{q}$ and **not** $E = \frac{F}{Q}$

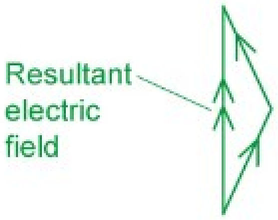
5

The correct answer is **B** because:

- The electric field from each charge q is radially outward, such that the two electric field vectors at point **X** is shown as below:



- The vector sum of these gives a resultant vector that is vertically upward, shown by the double headed arrow below:



A, C & D are incorrect as according to the vector triangle the resultant force is along the line YX away from the point charges.

You should remember the electric field due to a point charge is **radial**. That means, it is directed outwards, in all directions, from the point charge – therefore, in this question, there are two 'outward' vectors from both point charges at the point **X**. These should be added, 'tip-to-tail', to work out the direction of the resultant electric field vector.

6

The correct answer is **C** because:

- The force between two charges $F = \frac{kQ_1Q_2}{r^2}$ where k is a constant
    - Therefore, the force between the two charges Q_1 and Q_2 when separated by a distance r is given by $F = \frac{k(q)(4q)}{r^2} = \frac{4kq^2}{r^2}$
- If $Q_1 \rightarrow 2Q_2 = 2q$ and $r \rightarrow 3r$, then $F \rightarrow F'$, where:
    - $F = \frac{k(2q)(4q)}{(3r)^2} = \frac{2 \times 4kq^2}{9r^2} = \frac{2}{9} \times \frac{4kq^2}{r^2} = \frac{2}{9}F$

A is incorrect as the charge on q doubles, so q becomes 2q so the fraction becomes $\frac{2}{9}$ and not $\frac{2}{3}$

B is incorrect as the equation is $F = \frac{kQ_1Q_2}{r^2}$ and not $F = \frac{kQ_1Q_2}{r}$ so the fraction becomes $\frac{2}{9}$ and not $\frac{2}{3}$

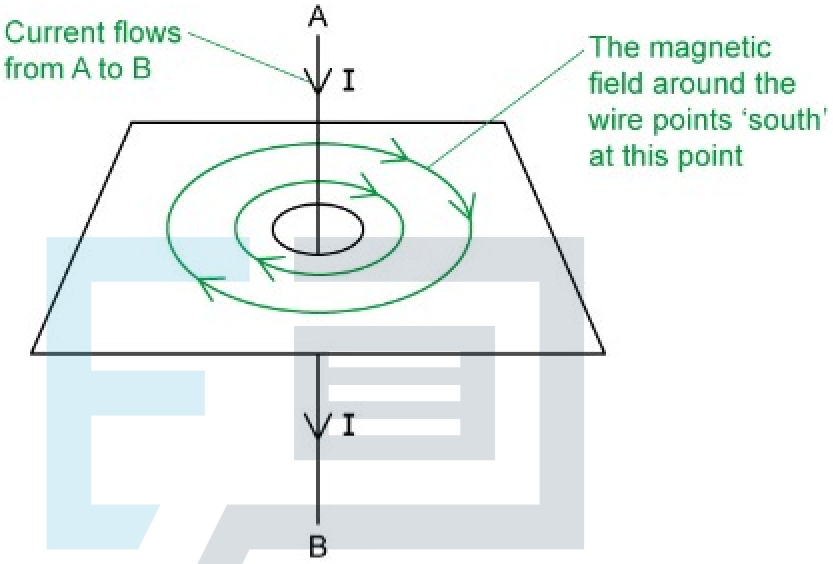
D is incorrect as the distance between the charges is also trebled, so this needs to be considered

This question requires you to find an equation in terms of the original variables, then an equation in terms of the new variables and use the multiplication of fractions to find the difference between them.

7

The correct answer is **A** because:

- The magnetic field around the wire, when a current flows from A to B, is shown in the image below:



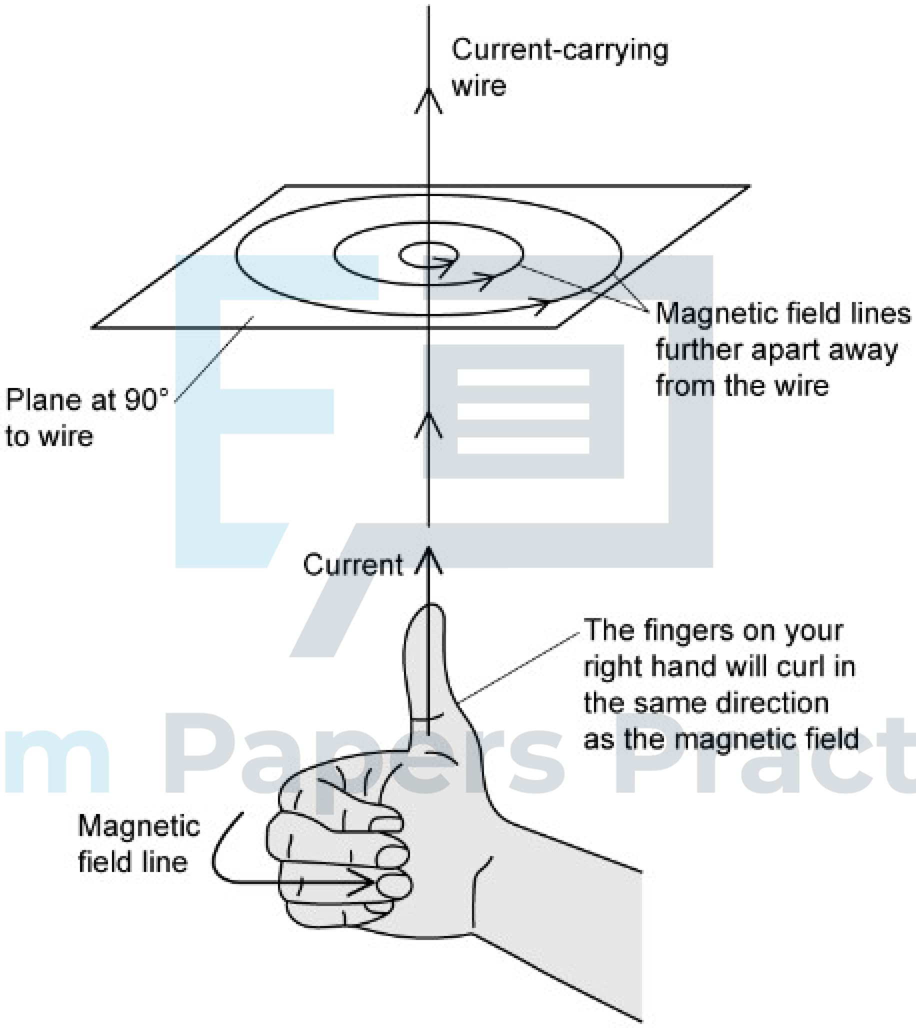
- The magnetic field caused by the current through the wire would cause the arrow to point to the 'south'
- The 'south' pointing magnetic flux density from the current in the wire offsets the original 'north' direction caused by the external magnetic field
    - Therefore, the arrow in the compass would be horizontal, which corresponds to **A**

B is incorrect as the arrow on the needle will be part way between the 'south' facing magnetic flux density and the original 'north' facing arrow

C is incorrect as the current in the wire would cause the needle to point 'south' but this does not take into consideration the original 'north' direction of the needle from the external field

D is incorrect as this is the original 'north' direction of the needle but it does not take into consideration the 'south' pointing magnetic flux density

Remember the right-hand grip rule is used to determine the direction of circular magnetic field lines around a current-carrying conductor! You should be able to direct your thumb downwards (the direction of current flows 'down', from A to B in the wire) and observe your fingers curling in a **clockwise** direction. Therefore, the magnetic field lines around a current from A to B are in a clockwise direction.



Crucially, in this question, there are **two** competing magnetic fields: the original external field, which causes a 'north' deflection, and the field due to the current-carrying wire, which causes a 'south' deflection. The overall deflection is thus horizontal! If the external field wasn't there, the needle would point south.

8

The correct answer is **A** because:

- The metal plates are not parallel, therefore, the electric field strength should be stronger where they are closer together
    - This is because the electric field strength between parallel plates $E = \frac{V}{d}$ and so is inversely proportional to the distance *d* between the plates
- Therefore, the field lines should be more densely packed together where the plates are closer together
    - This rules out options B and C
- The metal plates are lines of equipotential
    - Therefore, the electric field lines should meet the plates at 90°
    - This rules out option D
- Therefore, the correct diagram is given by option A

B is incorrect as the field lines are equally spaced, but the field strength is greater where the plates are closer together. Therefore, the field lines should be more densely packed here. Also, the field lines are not meeting the plates at 90°

C is correct as the field lines meet the plates at 90° but they are equally spaced

D is correct as the field lines are more densely packed where the plates are closer together, but the field lines do not meet the plates at 90°

9

The correct answer is **B** because:

- At position B:
    - The electric field E_7 due to the +7 μC charge has magnitude $\frac{7k}{r^2}$ where *r* is the distance between the charge and position B and *k* is the coulomb constant $k = \frac{1}{4\pi\varepsilon_0}$

  - The electric field $E_{-3.5}$ due to the −3.5 μC charge has a magnitude $\frac{3.5k}{r^2}$ where *r* is the distance between the charge and position B
  - Therefore, the resultant electric field $E = E_7 + E_{-3.5} = \frac{10.5k}{r^2}$
- By inspection, no combination of the fields due to both charges is greater than $\frac{10.5k}{r^2}$
  - This is because B is the only position at which the distance to each charge is *r*
  - For every other position, the distance to one of the charges is greater than *r*
  - Hence, the contributing electric field strength is weaker

A is incorrect as the electric field strength due to the +7 μC charge has a magnitude $\frac{7k}{r^2}$ and the electric field strength due to the −3.5 μC charge has a magnitude $\frac{3.5k}{(3r)^2}$. In total, the sum is $\frac{7k}{r^2} + \frac{3.5k}{9r^2} = \frac{66.5k}{9r^2} \approx \frac{7.4k}{r^2}$ which is less than $\frac{10.5k}{r^2}$

C is incorrect as the electric field strength due to the −3.5 μC charge has a magnitude $\frac{3.5k}{r^2}$ and the electric field strength due to the +7 μC charge has a magnitude $\frac{7k}{(far)^2}$ which is less than $\frac{7k}{r^2}$. Therefore, the sum will be less than $\frac{10.5k}{r^2}$

D is incorrect as the electric field strength due to the −3.5 μC charge has a magnitude $\frac{3.5k}{r^2}$ and the electric field strength due to the +7 μC charge has a magnitude $\frac{7k}{(3r)^2}$ which is less than $\frac{7k}{r^2}$. Therefore, the sum will be less than $\frac{10.5k}{r^2}$

Make sure you are comfortable with applying the equation for electric field strength, $E = \frac{kQ}{r^2}$ and working out **resultant** electric fields, by adding the contribution from each charge present in the situation. In this case, the key is recognising that each position labelled is a distance r **from the nearest charge**. This enables you to determine resultant electric fields.

Of course, you could also do this question by inspection: the electric field is going to be strongest nearest to the larger magnitude of charge (+7 μC) but **not at position A**, because the electric field due to the –3.5 μC acts in the same direction.

10

The correct answer is **C** because:

- The work done ΔW (or energy transferred) by the electric field on the helium nucleus as it moves across the potential difference ΔV_e is given by $\Delta W = q\Delta V_e$
  - The energy is transferred to the particle's kinetic energy, given by $\frac{1}{2}mv^2$
  - Therefore, $\frac{1}{2}mv^2 = q\Delta V_e$
  - Hence, $v = \sqrt{\frac{2q\Delta V_e}{m}}$
- The known quantities are:
  - $\Delta V_e = 5\text{ kV} = 5000\text{ V}$
  - $m = 2m_p + 2m_n$ (where m_p is the mass of a proton and m_n is the mass of a neutron)
  - $q = 2e$ (where e is the elementary charge)
- Hence:
  - $v = \sqrt{\frac{2 \times (2e) \times 5000}{(2m_p + 2m_n)}} = \sqrt{\frac{4 \times 5000e}{2(m_p + m_n)}} = \sqrt{\frac{10\,000e}{m_p + m_n}} = 100\sqrt{\frac{e}{m_p + m_n}}$

You are expected to know that a helium nucleus is an **alpha particle**, and that alpha particles comprise of **two protons and two neutrons.**

11

The correct answer is **D** because:

- Since the equipotential encircles both charges, the electric field lines must be radial to them
    - This is as expected, since the electric field and equipotentials must intersect at 90°
- Since P and Q are of the same sign, there can be no resultant electric field between them
    - This is indicated correctly by a space between horizontal equipotentials

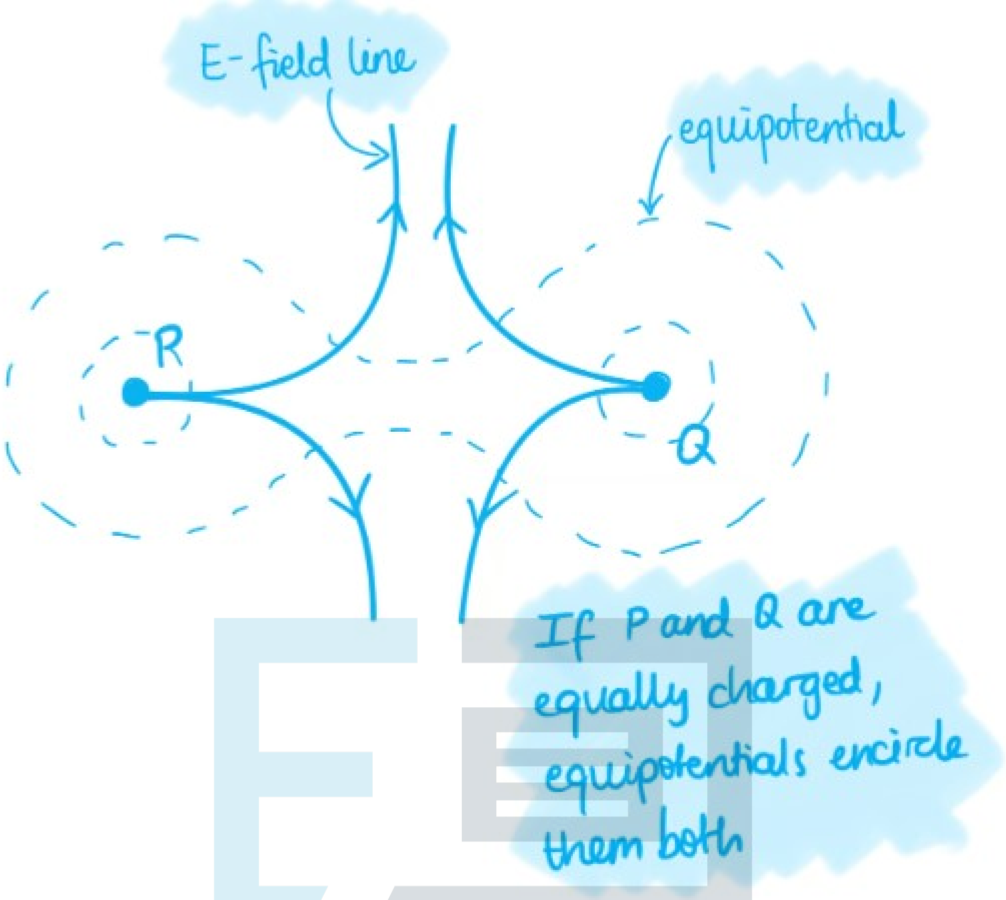
A is incorrect as a vertical equipotential between two charges indicates that the charges are oppositely charged. This is because field lines connect oppositely charged particles

B is incorrect as equipotential lines cannot join charges because this would indicate the electric field is parallel to them at their surface (since the equipotential intersects them at 90°). This is not the case

C is incorrect as the equipotential lines intersect the charges at 90°. This is not true of equipotential lines, because this would indicate the electric field is parallel to the surface of the charge (which is not the case)

Take great care not to mix up electric field lines and equipotentials!

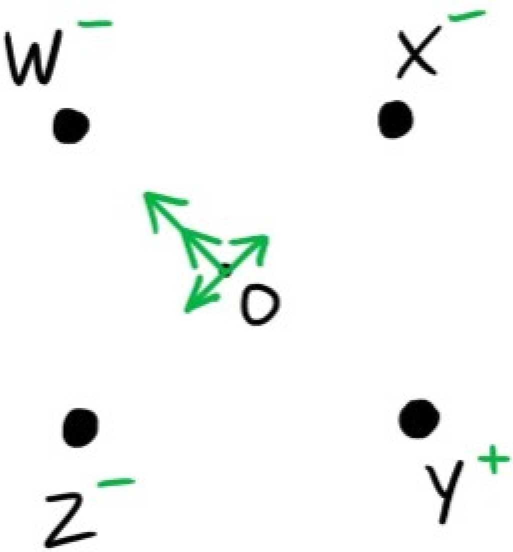
A diagram of the electric field superimposed on top of the equipotentials in option **D** should convince you that this is correctly drawn for two charges of equal sign:



12

The correct answer is **A** because:

- Drawing the electric field due to each of W, X, Y and Z in turn gives a diagram as shown below:



- Each electric field line is directed from positive charge toward negative charge
- There is no resultant field due to charges Z and X, because they are equal and in opposite directions at position O
- Therefore, the resultant field is only due to charge Y and W
    - Since these charges are oppositely charged, their electric field acts in the same direction
    - Therefore, the resultant electric field is directed from Y, towards charge W
    - Hence, the correct answer is **A**

You should be able to analyse diagrams like this "by inspection", and spot symmetries (like the resultant field due to Z and X being zero, because they are the same charge and O is the midpoint between them). This skill will drastically simplify similar problems; this is a popular exam question, so even if you have to do a bit of trial and error, practice drawing field lines is worthwhile!

13

The correct answer is **B** because:

- If equipotentials encircle two sources, they must correspond (i.e., be point masses or charges of the same sign)
    - Field lines and equipotentials are always perpendicular to each other
    - Hence, if equipotentials encircle sources of a field, this must mean field lines never connect the sources (otherwise, they would not intersect at 90°)

A is incorrect as while the equipotentials would be correct for two equal point masses, they would not be correct for two equal charges that are oppositely charged. There is a field line connecting two opposite charges: hence, the equipotential between them is vertical

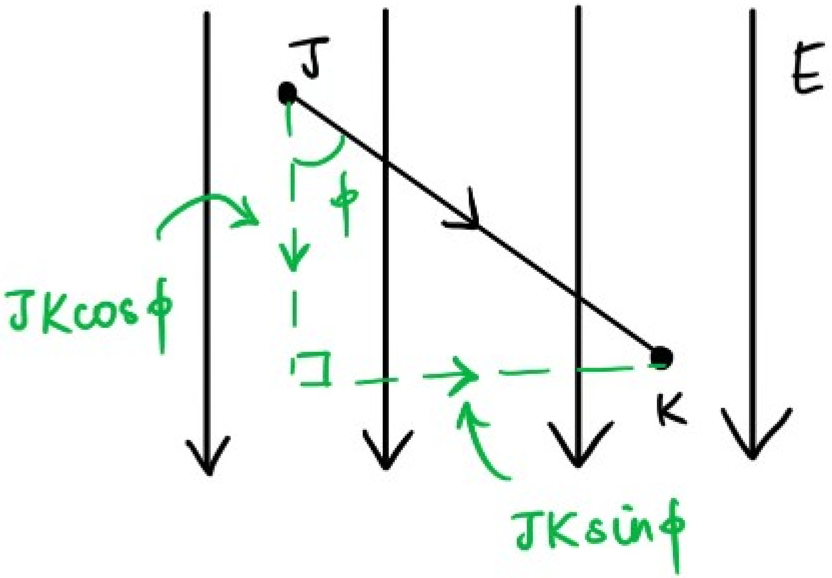
C is incorrect as the equipotentials are valid for two equal point masses (and invalid for two equal opposite charges). This is because the field lines for equal point masses oppose each other, therefore, the equipotentials encircle the sources

D is incorrect as the equipotential lines are valid for two equal charges of the same sign, but are also valid for two equal point masses. Point masses in this case are equivalent to charged bodies of the same sign (since field lines, in both contexts, oppose each other)

14

The correct answer is **A** because:

- The charge moving from J to K in the electric field is equivalent to moving along two components one parallel and one perpendicular to the field:
    - The vertical distance travelled in the electric field, parallel to field lines, is $JK\cos\Phi$
    - The horizontal distance travelled, perpendicular to field lines, is $JK\sin\Phi$
    - This is shown in the image below:



- The work done *W* (or energy transferred) is a product of force *F* and distance travelled *d* parallel to that force
  - The force *F* exerted on *q* by the electric field is given by $F = qE$
  - The distance travelled parallel to the force (i.e. parallel to the field lines) is $JK\cos\Phi$
- The energy transferred is the change in the charge's electric potential energy, and is given by:
  - $W = Fd = (qE) \times (JK\cos\Phi) = EqJK\cos\Phi$
  - Therefore, the correct answer is **A**

B is incorrect as the quantity $JK\sin\Phi$ is the distance travelled perpendicular to field lines – i.e., along an **equipotential.** There is no work done along an equipotential (because there is no change in potential), therefore no energy is transferred and this cannot be an expression for the charge's change in electric potential energy

C is incorrect as the quantity $\tan\Phi$ is a ratio of the two vertical and horizontal distances, of no physical importance. It is included purely as a 'distractor'!

D is incorrect as the quantity *EqJK* is the product of force exerted by the electric field *Eq* and the distance *JK*. Since this distance is not parallel to the force exerted, it does not correctly determine the change in the charge's potential energy

15

The correct answer is **D** because:

- Since the particles reach the negatively charged plate at the same time, they must have the same acceleration
- Acceleration is the ratio of resultant force F to mass m
  - The question allows us to neglect gravitational effects
  - Hence, the only (and hence, resultant) force acting on each charge is that from the electric field: $F_1 = Eq_1$ on charge q_1 and $F_2 = Eq_2$ on charge q_2
- Since the acceleration is the same, then the ratio of F to m is the same for both charges:
  - $a = \dfrac{Eq_1}{m_1}$ for charge q_1 of mass m_1
  - $a = \dfrac{Eq_2}{m_2}$ for charge q_2 of mass m_2
- Therefore, equating expressions gives:
  - $\dfrac{Eq_1}{m_1} = \dfrac{Eq_2}{m_2}$
  - $\dfrac{q_1}{m_1} = \dfrac{q_2}{m_2}$
- Hence, the correct answer is **D**

Note that the **ratio** of charge-to-mass must be equal, **not** the individual charges and masses. This is a surprising result: one which only arrives after careful consideration that acceleration **must be the same** for both charges if they travel the same distance in the same amount of time.

Recall, $s = ut + \frac{1}{2}at^2$, so if both charges start from rest, and the distance travelled s and time taken t for each charge is equal, then their acceleration must be equal too. Crucially, this acceleration is given by the ratio of **resultant force** in the electric field to each particle's **mass**: which is actually a ratio of charge to mass in this uniform electric field.

16

The correct answer is **B** because:

- Between two plates, the electric field strength is uniform: $E = \frac{V}{d}$
- Gradient of the electric potential: $E = -\frac{\Delta V_e}{\Delta r}$
- Plate X is charged to –180 V and plate Y is charged to +180 V
    - Therefore, the change in potential from plate X to plate Y, ΔV_e = final potential – initial potential
    - So, $\Delta V_e = (180) - (-180) = 360$ V
- The distance between this change in electric potential Δr is 2.0 m
    - Therefore the gradient $\frac{\Delta V_e}{\Delta r} = \frac{360}{2} = 180$ V m^{-1}
    - This eliminates options **C** and **D**
- The electric field is always directed from positive charge to negative charge
    - Therefore, the electric field must be directed to the **left**
- Hence, the correct answer is **B**

Determine the direction of an electric field, first of all, wherever possible. This will provide a starting point from which to consider things like the directions and shape of equipotentials. For this question, which may seem complicated at first glance, you should remember the crucial fact that the electric field strength is proportional to the **gradient** of a potential. Gradients are very simply calculated: the change in electric potential ΔV_e with distance Δr.