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Coulomb’s law and radial fields solutions

Electric fields 1 Calibrating an electrostatic sorting line

Matching answers and examiner-style commentary

OCR A H556 | A-level physics | Module 6 | 47 marks

Specification points covered

6.2.1(a–d) Charges, the spherical model, field lines and electric field strength.

6.2.2(a–d) Coulomb’s law, radial fields and comparison with gravitational fields.

Use $\varepsilon_0 = 8.85 \times 10^{-12}$ F m^{-1} and $k = 1/(4\pi\varepsilon_0) = 8.99 \times 10^{9}$ N m^2 C^{-2}.

1 Understand the calibration

An electrostatic sorter separates charged polymer fragments. Before use, an engineer tests uniformly charged insulating spheres. Assume the prescribed spherical charge distributions do not change. Small test charges do not disturb the source.

In Figure 1, A carries +8.0 nC and B carries −3.0 nC. Both radii are 8.0 mm. Unless a question states otherwise, use these charges.

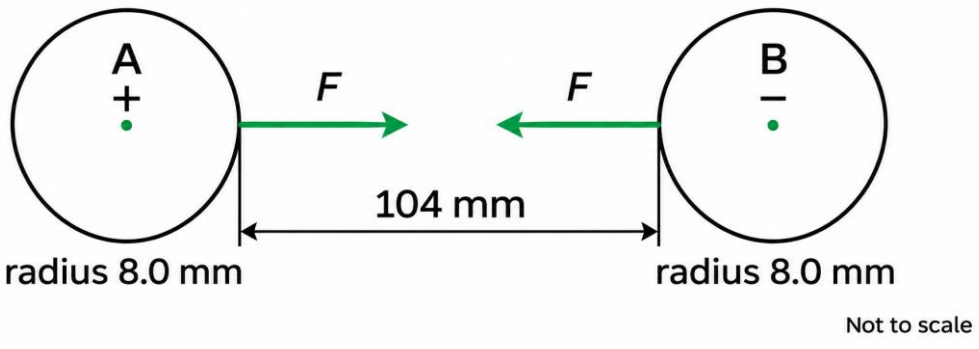


Figure 1 Calibration spheres

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1(a) Define electric field strength at a point. Include how its direction is defined. **[2 marks]**

Electric field strength is force per unit positive test charge, E = F/q. Its direction is the direction of the force on a positive test charge.

Marking guidance 1: force per unit charge. 1: direction defined using a positive test charge.

1(b) Figure 1 shows two calibration spheres. Calculate their centre-to-centre separation in metres and explain why this distance is used in the point-charge model. **[2 marks]**

The centre separation includes the gap and both radii.

r = 104 + 8.0 + 8.0 = 120 mm = 0.120 m.

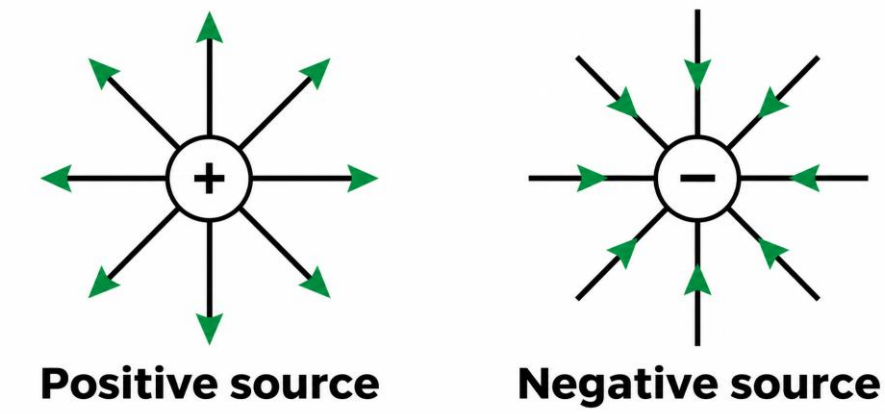
A uniformly charged sphere is modelled as a point charge at its centre.

Marking guidance 1: 0.120 m. 1: centre-point model explains the distance.

2 Map the field

2(a) In the space below, draw at least six field lines outside an isolated positively charged sphere. Show the direction and the symmetry. **[2 marks]**

Draw straight radial lines perpendicular to the spherical surface, distributed symmetrically, with arrows away from the positive sphere.



Model sketch Numerical calculations use the stated values and data tables

Marking guidance 1: radial, symmetric lines normal to the surface. 1: arrows outward.

2(b) A small negative test charge is placed to the right of that positive sphere. State the directions of the field and the electric force on the test charge. **[1 mark]**

The field points right, away from the source. The force on the negative test charge points left, towards the source, because F = qE reverses direction when q is negative.

Marking guidance 1: both directions correct.

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2(c) Now consider equal and opposite point charges: positive on the left and negative on the right. Explain the direction of the resultant field at their midpoint. **[2 marks]**

The positive charge produces a rightward field at the midpoint. The negative charge also produces a rightward field there, towards itself. The fields add, so the resultant points right.

Marking guidance 1: correct directions of the separate fields. 1: they add to give a rightward resultant.

2(d) Explain why the field line through a position does not necessarily show the trajectory of a particle launched through that position. **[2 marks]**

A field line gives the force direction for a positive test charge at each point. A moving particle also has an initial velocity, so its velocity need not point along the force. A negative particle experiences force opposite to the field.

Marking guidance 1: field line describes force/field direction. 1: trajectory also depends on initial velocity or charge sign.

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3 Predict the force

3(a) Calculate the magnitude of the electric force between the spheres in Figure 1. State whether the force is attractive or repulsive. **[2 marks]**

Use the centre distance 0.120 m and charge magnitudes 8.0×10^{-9} C and 3.0×10^{-9} C.

$|F| = k|Qq|/r^2 = (8.99 \times 10^{9})(8.0 \times 10^{-9})(3.0 \times 10^{-9})/(0.120)^2$.

$|F| = 1.498 \times 10^{-5}$ N $\approx 1.5 \times 10^{-5}$ N. The opposite charges attract.

Marking guidance 1: correct force magnitude. 1: attraction.

3(b) B is replaced by another negatively charged sphere. At the same centre separation, the force magnitude is 7.5×10^{-6} N. Determine the replacement sphere's charge. **[2 marks]**

Step 1 Make the unknown charge the subject of Coulomb's law.

$|q| = |F|r^2/(k|Q|)$.

Step 2 Substitute the measured force and known source charge.

$|q| = (7.5 \times 10^{-6})(0.120)^2/[(8.99 \times 10^{9})(8.0 \times 10^{-9})] = 1.502 \times 10^{-9}$ C.

The replacement charge is −1.5 nC; the negative sign comes from the stated charge type.

Marking guidance 1: valid rearrangement/substitution. 1: −1.5 nC.

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3 Predict the force continued

3(c) Return to the original charges and radii. The force must not exceed 5.0×10^{-6} N. Calculate the minimum centre separation and the corresponding clear surface gap. **[3 marks]**

Step 1 At the limiting force, rearrange for the centre distance.

$r^2 = k|Qq|/F$, so $r = \sqrt{(k|Qq|/F)}$.

$r = \sqrt{[(8.99 \times 10^{9})(8.0 \times 10^{-9})(3.0 \times 10^{-9})/(5.0 \times 10^{-6})]} = 0.2077$ m.

Step 2 Convert the centre distance to the surface gap.

gap $= r - 0.0080 - 0.0080 = 0.1917$ m ≈ 0.19 m.

A larger separation gives a smaller force, so this is a minimum separation.

Marking guidance 1: square-root rearrangement. 1: centre separation about 0.208 m. 1: gap about 0.192 m.

3(d) The charge on B is doubled and the centre separation is tripled. Find the new force as a fraction of the original force. **[1 mark]**

Force is proportional to charge product and inversely proportional to r^2.

$F_{new}/F_{old} = 2/3^2 = 2/9$.

Marking guidance 1: 2/9 with a valid ratio.

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4 Separate field from force

4(a) Sphere B is removed. Calculate the field strength 0.120 m from the centre of A. **[1 mark]**

$E = kQ/r^2 = (8.99 \times 10^9)(8.0 \times 10^{-9})/(0.120)^2 = 4.994 \times 10^3$ N C^{-1}, radially outward.

Marking guidance 1: about 5.0×10^3 N C^{-1}.

4(b) A test charge of −2.0 pC is placed at this position. Calculate its force magnitude and state the direction relative to A. **[2 marks]**

Convert −2.0 pC to -2.0×10^{-12} C. The field is determined by A.

$|F| = |q|E = (2.0 \times 10^{-12})(4.994 \times 10^3) = 9.989 \times 10^{-9}$ N.

The force is about 1.0×10^{-8} N towards A, opposite to the outward field.

Marking guidance 1: force magnitude. 1: towards A.

4(c) The test charge is replaced by −1.0 pC. Explain what happens to the field strength and to the force, assuming A is unchanged. **[2 marks]**

The field stays the same because A and the position are unchanged. The force magnitude halves because $|F| = |q|E$ and the test-charge magnitude halves. The force still points towards A.

Marking guidance 1: unchanged field, linked to source/position. 1: half the force, linked to the changed test charge.

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5 Combine fields along a line

5(a) Two point charges are now +8.0 nC at x = 0 and +2.0 nC at x = 0.300 m. Calculate the resultant field at x = 0.150 m. Show the direction of each contribution. **[2 marks]**

Take right as positive. Between two positive charges, the left source gives a rightward field and the right source gives a leftward field.

$E_A = k(8.0 \times 10^{-9})/(0.150)^2 = +3.196 \times 10^3$ N C^{-1}.

$E_B = -k(2.0 \times 10^{-9})/(0.150)^2 = -7.991 \times 10^2$ N C^{-1}.

$E = E_A + E_B = +2.397 \times 10^3$ N C^{-1} $\approx 2.4 \times 10^3$ N C^{-1}, rightward.

Marking guidance 1: opposing field directions and correct individual terms. 1: correct resultant and direction.

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5 Combine fields along a line continued

5(b) Find the zero-field point between these two positive charges. Let x be its distance from the +8.0 nC charge. **[3 marks]**

Step 1 Between like charges the fields oppose. Set their magnitudes equal.

$k(8.0 \times 10^{-9})/x^2 = k(2.0 \times 10^{-9})/(0.300 - x)^2$.

Step 2 Cancel common factors and take the positive square root, since both distances are positive.

$4/x^2 = 1/(0.300 - x)^2$, so $2/x = 1/(0.300 - x)$.

$2(0.300 - x) = x$, so $0.600 = 3x$ and $x = 0.200$ m.

This point is nearer the smaller charge, as a smaller distance is needed to make its field as strong.

Marking guidance 1: correct equality with both distances. 1: valid algebra. 1: x = 0.200 m in the stated region.

5(c) The charge at x = 0.300 m becomes −2.0 nC. Calculate the resultant field at the midpoint and explain why it cannot be zero anywhere between the charges. **[2 marks]**

Both fields now point right between the charges: away from the positive source and towards the negative source.

$E = k(8.0 + 2.0) \times 10^{-9}/(0.150)^2 = 3.996 \times 10^3$ N C^{-1}, rightward.

They have the same direction throughout the region between the charges, so they cannot cancel there.

Marking guidance 1: about 4.0×10^3 N C^{-1}, rightward. 1: same-direction fields cannot cancel.

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5 Combine fields along a line continued

5(d) The two original interacting spheres exert equal and opposite forces on each other. Explain why these forces do not give zero resultant force on either individual sphere. **[2 marks]**

The interaction forces act on different spheres. A resultant on A includes only forces acting on A, not the reaction force acting on B. Equal and opposite interaction forces therefore do not cancel in a free-body diagram of either sphere.

Marking guidance 1: forces act on different bodies. 1: resultant requires forces on the same body.

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6 Test the inverse-square model

A field sensor tests a single positively charged source. The centre distances and field magnitudes are recorded below.

Table 1

r / m	E / N C^{-1}
0.100	7200
0.150	3200
0.200	1800
0.250	1150

6(a) Use at least two pairs of readings from Table 1 to test whether E is inversely proportional to r^2. Show your numerical test. **[2 marks]**

For an inverse-square relationship, Er^2 should be constant.

At 0.100 m: $Er^2 = 7200 \times (0.100)^2 = 72.0$ N m^2 C^{-1}.

At 0.200 m: $Er^2 = 1800 \times (0.200)^2 = 72.0$ N m^2 C^{-1}.

The equal products support $E \propto 1/r^2$; the other readings give 72.0 and 71.9 to the stated precision.

Marking guidance 1: appropriate constant-product or equivalent factor test. 1: at least two correct numerical pairs.

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6 Test the inverse-square model continued

6(b) State a pair of axes that should give a straight line through the origin. Sketch the expected line, then calculate its gradient from Table 1 and use it to infer Q. **[3 marks]**

Plot E on the vertical axis against $1/r^2$ on the horizontal axis; $E = kQ(1/r^2)$. The expected line is straight through the origin.

Using r = 0.100 m and 0.200 m gives horizontal coordinates 100 and 25.0 m^{-2}.

gradient = (7200 − 1800)/(100 − 25.0) = 72.0 N m^2 C^{-1}.

Since gradient = kQ, $Q = 72.0/(8.99 \times 10^9) = 8.01 \times 10^{-9}$ C ≈ 8.0 nC.

Marking guidance 1: axes and straight origin line. 1: gradient about 72.0 with appropriate units. 1: Q about 8.0 nC.

6(c) Each E reading has a stated uncertainty of ±2%. Explain whether these data support the inverse-square model and whether they establish that every charged object can be treated as a point charge. **[2 marks]**

The calculated Er^2 values agree much more closely than 2%, so the data are consistent with this model over the measured range. They do not establish that every charged object is a point source: charge distribution, shape and distance still matter.

Marking guidance 1: agreement judged against uncertainty. 1: appropriately limited conclusion.

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7 Make a calibration decision

7(a) The sorter must attract negatively charged fragments. Choose the collector polarity. For calibration, compare centre separations of 0.200 m and 0.225 m using Q = +8.0 nC and |q| = 3.3 nC, the largest permitted test charge. The force limit is 5.0×10^{-6} N. Choose a separation and justify it numerically. **[3 marks]**

Use a positive collector so that negative fragments are attracted.

Step 1 Check the smaller separation at the largest charge.

$F = k|Qq|/r^2 = (8.99 \times 10^9)(8.0 \times 10^{-9})(3.3 \times 10^{-9})/(0.200)^2 = 5.93 \times 10^{-6}$ N. This exceeds the limit.

Step 2 Check the larger separation.

$F = (8.99 \times 10^9)(8.0 \times 10^{-9})(3.3 \times 10^{-9})/(0.225)^2 = 4.69 \times 10^{-6}$ N.

Choose 0.225 m: it remains below 5.0×10^{-6} N at the largest specified test charge.

Marking guidance 1: positive polarity. 1: both force comparisons correctly calculated. 1: justified 0.225 m choice against the limit.

7(b) Give one similarity and one difference between the field of a point electric charge and the gravitational field of a point mass. Make each comparison explicit. **[2 marks]**

Both are radial inverse-square fields outside the point/spherical source. A gravitational interaction between masses is always attractive, whereas electric interactions can attract or repel depending on charge signs. Mass is the gravitational source/test property; charge is the electric one.

Marking guidance 1: an explicit correct similarity. 1: an explicit correct difference.

7(c) Explain two conditions that make the calibration spheres and test charge suitable for the model used in this worksheet. **[2 marks]**

A prescribed uniform spherical charge distribution can be represented externally by a point at its centre; a strongly distorted or non-spherical distribution would not have this symmetry. The test charge must be small enough that it does not significantly change the source charge distribution. Keeping other charged conductors well away also reduces unwanted external fields.

Marking guidance 1 each for two explained, relevant conditions; accept equivalent limitations.

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