Electromagnetism: testing Coulomb's law

About this free course

This free course is an adapted extract from the Open University course SM381 *Electromagnetism* www.open.ac.uk/courses/modules/sm381.

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Introduction

Electrical charges can be positive or negative. Charges of the same type repel each other, and charges of different types attract each other. For example, static electricity can cause hair to stand on end as similarly charged strands of hair all try to avoid each other, while in lightning a build up of negatively charged electrons moves rapidly to a region of positive charge.

Electrically charged particles exert forces on each other at a distance, that is they don't need to be touching each other. When these charged particles are stationary the force is referred to as electrostatic, and is described by Coulomb's law. Coulomb's law was established experimentally in the late eighteenth century, and is one of the building blocks of the theory of classical electromagnetism.

This course has four parts: a brief introduction to Coulomb's law in vector form, a video demonstration of an experiment, an exercise and a video solution. This gives you a practical demonstration of electrostatic forces and the opportunity to practise using the vector form of Coulomb's law. You will also be encouraged to think about the assumptions you make in your calculations and possible sources of experimental uncertainty.

Learning outcomes

After studying this course, you should be able to:

- describe the properties of Coulomb's law and electrostatic force
- determine the force exerted on one stationary charge by another using Coulomb's law
- explain some of the uncertainties and errors that can occur in experimental measurements of electrostatic properties.

This OpenLearn course is an adapted extract from the Open University course SM381 *Electromagnetism*.

1 Electric force – Coulomb's law

A **point charge** is a hypothetical charged particle that occupies a single point in space. It has no internal structure, motion or spin, so a stationary point charge is only affected by electric fields and not affected by magnetism. It is useful when defining the concept of electric force.

> **Definition of the electric force:** The electric force is defined as the electromagnetic force on a stationary point charge.

It is important to keep in mind, however, that the electric force is experienced not only by stationary point charges. The electric force is felt by all charges, whether they are moving or not.

Before looking at the electric force in more detail, it is useful to consider forces in general. Unlike charge, force is a vector quantity – it has a magnitude and a direction – and its conventional symbol is $\mathbf{F}$. The SI unit of force is the **newton** (N), where 1 N is equivalent to 1 kg m s^{-2}.

Newton's second law of motion states that the force on a particle is equal to its rate of change of momentum $\mathrm{d}\mathbf{p}/\mathrm{d}t$ or, when the force is applied to a body with a mass that does not change with time, its mass *m* multiplied by its acceleration $\mathbf{a}$. Mathematically this is written as

$$\mathbf{F} = \frac{\mathrm{d}\mathbf{p}}{\mathrm{d}t} = m\mathbf{a}. \tag{1}$$

Equation 1 gives an example of a vector quantity (in this case acceleration) multiplied by a scalar quantity (mass). The result of this operation is another vector (force).

Multiplying a vector by a scalar

If any vector $\mathbf{E}$ is multiplied by any scalar q, the result is another vector $\mathbf{F}$. The magnitude of $\mathbf{F}$ is equal to the scalar factor multiplied by the magnitude of the original vector. You can express this as $|\mathbf{F}| = q|\mathbf{E}|$ or $F = qE$.

If the scalar factor is positive then the product will be *parallel* to the original vector. If the scalar factor is negative then the product will be *antiparallel* to the original vector (Figure 1).

Also note the following general points, where $\mathbf{F}$ could represent any vector.

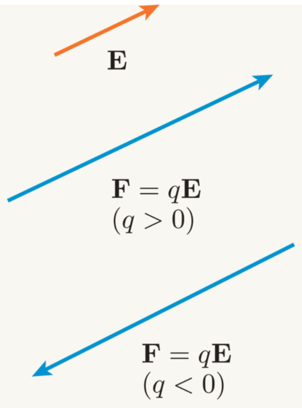


Figure 1 Multiplying a vector $\mathbf{E}$ by a scalar q. Here, the resultant vector $\mathbf{F} = \mathrm{q}\mathbf{E}$ is shown for $q > 0$ and $q < 0$.

- The quantity

  $$\widehat{\mathbf{F}} = \frac{\mathbf{F}}{|\mathbf{F}|} = \frac{\mathbf{F}}{F} \tag{2}$$

  is a vector of magnitude 1 (with no units) pointing in the same direction as $\mathbf{F}$. This vector is called the **unit vector** of $\mathbf{F}$ and is given the symbol $\widehat{\mathbf{F}}$ (pronounced F-hat).
- Writing

  $$\mathbf{F} = F\,\widehat{\mathbf{F}}, \tag{3}$$

  neatly splits a vector into a product of two terms:
  - F gives the magnitude of the vector
  - $\widehat{\mathbf{F}}$ gives its direction in space.
- The units of $\mathbf{F}$ are contained in the magnitude, F. Any unit vector is dimensionless and has magnitude 1; not 1 newton or 1 of anything else.
- Two vectors with the same magnitude and the same direction are defined as being equal, but remember that they can have different starting points.

The study of time-independent (static) electrical phenomena is known as **electrostatics**. The sections that follow focus on the electric force between static point charges. This so-called **electrostatic force** between two stationary point charges is given by **Coulomb's law**, which has the following observable properties.

Properties of Coulomb's law

The electrostatic force between two stationary point charges:

- acts along the line of separation between the charges
- is repulsive for charges of the same sign and attractive for charges of opposite sign
- has a magnitude that is proportional to the product of the charges and inversely proportional to the square of the distance between the charges.

In mathematical form, the scalar part of the electrostatic force F, acting on the line of separation between two charges, q_1 and q_2, separated by a distance r_{12} is written as

$$F = k_{\text{elec}} \frac{q_1 q_2}{r_{12}^2}, \tag{4}$$

where k_{elec} is a positive constant that will be defined later in this course. The denominator in Equation 4 characterises this expression as an **inverse square law**.

If q_1 and q_2 have the same sign, then Equation 4 predicts $F > 0$. This is interpreted as a repulsive force.

- What is the sign of F if q_1 and q_2 have opposite signs? How is this interpreted?
- If q_1 and q_2 have opposite signs, then $F < 0$. This is an attractive force.

1.1 Coulomb's law in vector form

Equation 4 is adequate for describing the interaction of two charges, but it cannot handle three or more charges that are not arranged in a straight line. Before considering a more general representation of Coulomb's law, you need to be familiar with vector addition and displacement vectors.

Adding and subtracting vectors

Suppose that a single particle simultaneously feels two different forces, $\mathbf{F}_1$ and $\mathbf{F}_2$. It responds just as if a single force, $\mathbf{F}_1 + \mathbf{F}_2$, had been applied to it. This is called the **vector sum** of the individual forces.

The geometric rule for adding two vectors is shown in Figure 2. Arrows representing the vectors are drawn with the head of the first arrow, $\mathbf{F}_1$, meeting the tail of the second arrow, $\mathbf{F}_2$. The arrow joining the tail of $\mathbf{F}_1$ to the head of $\mathbf{F}_2$ then represents the vector sum $\mathbf{F}_1 + \mathbf{F}_2$. This is called the **triangle rule**. Any number of vectors can be added by repeating the application of this rule.

Vector subtraction is defined by multiplying by a negative scalar and using vector addition. The vector $\mathbf{F}_1 - \mathbf{F}_2$ is interpreted as the sum of $\mathbf{F}_1$ and $-\mathbf{F}_2$.

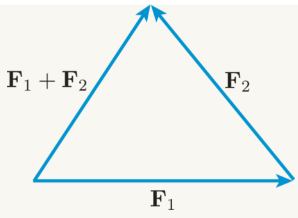


Figure 2 The triangle rule for vector addition.

An important use of vector subtraction is in describing the displacement of one point from another.

Working with displacement vectors

Figure 3 shows two vectors $\mathbf{r}_1$ and $\mathbf{r}_2$ whose arrows start at the origin O and end at charges q_1 and q_2. These vectors are called the **position vectors** of q_1 and q_2. A position vector has dimensions of length, where the SI unit of length is the metre (m).

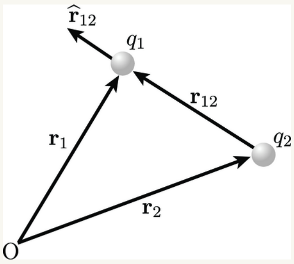


Figure 3 The vectors $\mathbf{r}_1$ and $\mathbf{r}_2$ define the positions of the point charges q_1 and q_2 with respect to the origin O. The displacement vector $\mathbf{r}_{12}$ points from q_2 to q_1, and is parallel to the unit vector $\widehat{\mathbf{r}}_{12}$.

The figure also shows $\mathbf{r}_{12}$, which is the **displacement vector** of q_1 from q_2. Using the triangle rule:

$$\mathbf{r}_1 = \mathbf{r}_2 + \mathbf{r}_{12}, \tag{5}$$

which rearranges to

$$\mathbf{r}_{12} = \mathbf{r}_1 - \mathbf{r}_2. \tag{6}$$

Using the unit vector $\widehat{\mathbf{r}}_{12}$, this becomes

$$r_{12}\,\widehat{\mathbf{r}}_{12} = \mathbf{r}_1 - \mathbf{r}_2. \tag{7}$$

This notation is convenient because the indices 1 and 2 are in the same order on both sides of the equation. However, remember that the displacement is *from* q_2 *to*

q_1. The left-hand index labels the end-point and the right-hand index labels the start-point.

Returning now to the discussion of Coulomb's law for the force between a pair of charged particles, suppose that charges q_1 and q_2 are at positions $\mathbf{r}_1$ and $\mathbf{r}_2$. The displacement vector of $\mathbf{r}_1$ from $\mathbf{r}_2$ makes it possible to express Coulomb's law as:

$$\mathbf{F}_{12} = k_{\text{elec}} \frac{q_1 q_2}{r_{12}^2} \,\widehat{\mathbf{r}}_{12}. \tag{8}$$

The left-hand side of this vector equation $\mathbf{F}_{12}$ is the electrostatic force *on* charge 1 *due to* charge 2. The force on charge 2 due to charge 1 is written as $\mathbf{F}_{21}$. The order of indices matters here because these two forces point in opposite directions.

The right-hand side of the equation is the product of the scalar factor $k_{\text{elec}} q_1 q_2 / r_{12}^2$ and the unit vector $\widehat{\mathbf{r}}_{12}$. The unit vector ensures that the force points in the correct direction. To see how this works, suppose that both charges in Figure 3 are positive. Since k_{elec} is positive, the unit vector is multiplied by a positive quantity, and the force on charge 1 points in the direction of $+\widehat{\mathbf{r}}_{12}$. This corresponds to a repulsion away from charge 2, as required for charges of the same sign.

It is conventional to write the constant k_{elec} as

$$k_{\text{elec}} = \frac{1}{4\pi\varepsilon_0},$$

where $\varepsilon_0 = 8.85 \times 10^{-12}$ C^2 N^{-1} m^{-2} (to 3 significant figures) is called the **permittivity of free space**. The definition of k_{elec} leaves you with the standard vector form of Coulomb's law for the electrostatic force between two charges.

Coulomb's law for two charges

$$\mathbf{F}_{12} = \frac{1}{4\pi\varepsilon_0} \frac{q_1 q_2}{r_{12}^2} \,\widehat{\mathbf{r}}_{12}. \tag{9}$$

- Using the definition of $\widehat{\mathbf{r}}_{12}$ (Equation 7), how can you write Equation 9 without a unit vector?
- Using Equation 7 and noting that $r_{12} = |\mathbf{r_1} - \mathbf{r_2}|$, the vector form of Coulomb's law for two charges becomes

$$\mathbf{F}_{12} = \frac{1}{4\pi\varepsilon_0} \frac{q_1 q_2}{|\mathbf{r}_1 - \mathbf{r}_2|^3} (\mathbf{r}_1 - \mathbf{r}_2). \quad (10)$$

You may find that working with this form of Coulomb's law speeds up some calculations.

2 Calculating the electric force between three or more charges

So far, this course has only considered Coulomb's law for a pair of point charges. The extension of this law to a collection of many particles requires vector addition. If $\mathbf{F}_i$ is the total electrostatic force on a charge i, this is calculated from the vector sum of the electrostatic forces that it experiences due to each of the other charges. Mathematically, this is written as

$$\mathbf{F}_i = \sum_{j \neq i} \mathbf{F}_{ij},$$

where $\mathbf{F}_{ij}$ is the electrostatic force on particle i due to particle j and the sum runs over all the particles j that exert an appreciable electrostatic force on particle i. Since the electrostatic force between each pair of charges obeys Coulomb's law, the total electrostatic force on charge i is written as follows.

Coulomb's law for multiple charges

$$\mathbf{F}_i = \frac{1}{4\pi\varepsilon_0} \sum_{j \neq i} \frac{q_i q_j}{|\mathbf{r}_i - \mathbf{r}_j|^3} (\mathbf{r}_i - \mathbf{r}_j). \quad (11)$$

- Why are terms with $i = j$ excluded from Equation 11?
- Because a point-like charged particle cannot exert a force on itself.

Now consider a small number of static point charges that are not arranged in a straight line. To work out the force on a given charge, you can begin by representing all the vectors in component form, as explained in the following box. Then you can use the rules of vector algebra to combine them according to the recipe given in Equation 11.

Cartesian components of a vector

It is often helpful to describe a vector in terms of its *components* along three standard directions. To do this, you can use **Cartesian coordinates**. This is a set of three mutually perpendicular axes (x, y and z) pointing outwards from an origin. The unit vectors pointing in the directions of these axes are denoted by $\mathbf{e}_x$, $\mathbf{e}_y$ and $\mathbf{e}_z$.

It is conventional to use a **right-handed coordinate system**, as described by the **right-hand rule**. Start by pointing the fingers of your right hand in the direction of the x-axis (indicated by the black dashed line in Figure 4). Then bend your fingers round to point in the direction of the y-axis, so that your hand is in the position shown in the figure. You might need to rotate your wrist to do this. Now your outstretched thumb points along the z-axis.

The crucial idea is that any vector can be split into a sum of three vectors that are aligned with each axis, as shown in Figure 4. It follows that any vector (in this case, a force $\mathbf{F}$) can be expressed as

$$\mathbf{F} = F_x\mathbf{e}_x + F_y\mathbf{e}_y + F_z\mathbf{e}_z. \quad (12)$$

The scalar quantities F_x, F_y and F_z are the **Cartesian components** of the vector $\mathbf{F}$ but they are usually just called its **components**. The vector components $F_x\mathbf{e}_x$, $F_y\mathbf{e}_y$ and $F_z\mathbf{e}_z$ are all positive in Figure 4 but, in general, vector components may be positive, negative or zero.

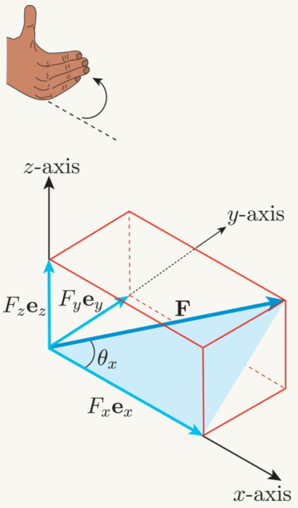


Figure 4 Splitting the vector $\mathbf{F}$ into the sum of three vectors: $F_x\mathbf{e}_x$, $F_y\mathbf{e}_y$, and $F_z\mathbf{e}_z$.

You can work out the relative orientations of the Cartesian axes using the right-hand rule, as explained in the text.

If you know the magnitude and direction of a vector, you can use trigonometry to find its components. For example, Figure 4 shows

$$F_x = F\cos\theta_x,$$

where F is the magnitude of the force and θ_x is the angle between $\mathbf{F}$ and the x-axis.

Similarly, if you know a vector's components then you can use Pythagoras' theorem to find its magnitude:

$$F = \sqrt{F_x^2 + F_y^2 + F_z^2}. \quad (13)$$

The vector operations introduced earlier in this chapter all have simple interpretations in terms of components. For example, if the position vectors of points 1 and 2 are

$$\mathbf{r}_1 = x_1\mathbf{e}_x + y_1\mathbf{e}_y + z_1\mathbf{e}_z \quad \text{and} \quad \mathbf{r}_2 = x_2\mathbf{e}_x + y_2\mathbf{e}_y + z_2\mathbf{e}_z,$$

then the displacement vector of point 1 from point 2 is

$$\mathbf{r}_{12} = \mathbf{r}_1 - \mathbf{r}_2 = (x_1 - x_2)\mathbf{e}_x + (y_1 - y_2)\mathbf{e}_y + (z_1 - z_2)\mathbf{e}_z. \tag{14}$$

Vector equations have the great advantage of brevity, but numerical calculations are usually carried out using components.

Now complete Exercise 1 where you will use the vector form of Coulomb's law to calculate the vector components of the electrostatic force on a charge due to two nearby charges.

Exercise 1

Two charges, $-16q$ and $3q$, where q is positive, are stationary at points $(2a, 0, 0)$ and $(0, a, 0)$, as shown in Figure 5.

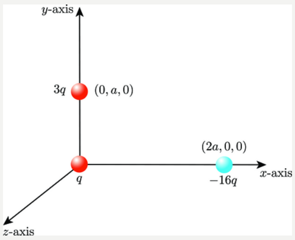


Figure 5 The positions of three stationary charges in the xy-plane.

Find the electrostatic force on a charge q placed at the origin $(0, 0, 0)$. Evaluate the magnitude of this force and specify its direction as a unit vector in Cartesian coordinates.

Discussion

All the charges lie in the xy-plane, so you can ignore the z-coordinates.

The electrostatic force $\mathbf{F}$ on charge q at the origin is given by the vector sum

$$\begin{aligned}\mathbf{F} &= \frac{1}{4\pi\varepsilon_0}\frac{-16q^2}{(2a)^2}(-\mathbf{e}_x) + \frac{1}{4\pi\varepsilon_0}\frac{3q^2}{a^2}(-\mathbf{e}_y)\\ &= \frac{1}{4\pi\varepsilon_0}\frac{q^2}{a^2}(4\mathbf{e}_x - 3\mathbf{e}_y).\end{aligned}$$

This force has magnitude

$$|\mathbf{F}| = \frac{1}{4\pi\varepsilon_0}\,\frac{q^2}{a^2}\,\sqrt{4^2 + (-3)^2}$$
$$= \frac{5}{4\pi\varepsilon_0}\,\frac{q^2}{a^2}$$

and is in the direction of the unit vector

$$\widehat{\mathbf{F}} = \frac{\mathbf{F}}{|\mathbf{F}|} = \frac{1}{5}\,(4\mathbf{e}_x - 3\mathbf{e}_y)$$
$$= (0.8\mathbf{e}_x - 0.6\mathbf{e}_y).$$

As a quick check, this is consistent with the charge q being attracted towards the $-16q$ charge on the x-axis and repelled from the $+3q$ charge on the y-axis.

3 Testing Coulomb's law and using vector components

This activity has three parts: a video demonstration of an experiment, an exercise and a video solution. The activity gives you a practical demonstration of electrostatic forces and the opportunity to practise using the vector form of Coulomb's law. It also encourages you to think about the assumptions in your calculations and possible sources of experimental uncertainty.

Activity Testing Coulomb's law and using vector components

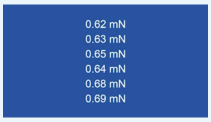
Allow up to 1 hour

Part 1 Measuring electrostatic forces

Watch Video 1, which shows Open University (OU) academics Sam Eden and Anita Dawes measuring one component of the electrostatic force that a charged sphere feels due to nearby charged spheres.

Video content is not available in this format.

Video 1 Filmed experiment: measuring electrostatic forces at the OU.



(The data shown on-screen during Video 1 are available in an Appendix to this activity.)

Part 2 Calculating electrostatic force components and comparing them with the measured values

Figure 1 shows the x-direction and the relative positions of the charged spheres in the filmed experiment.

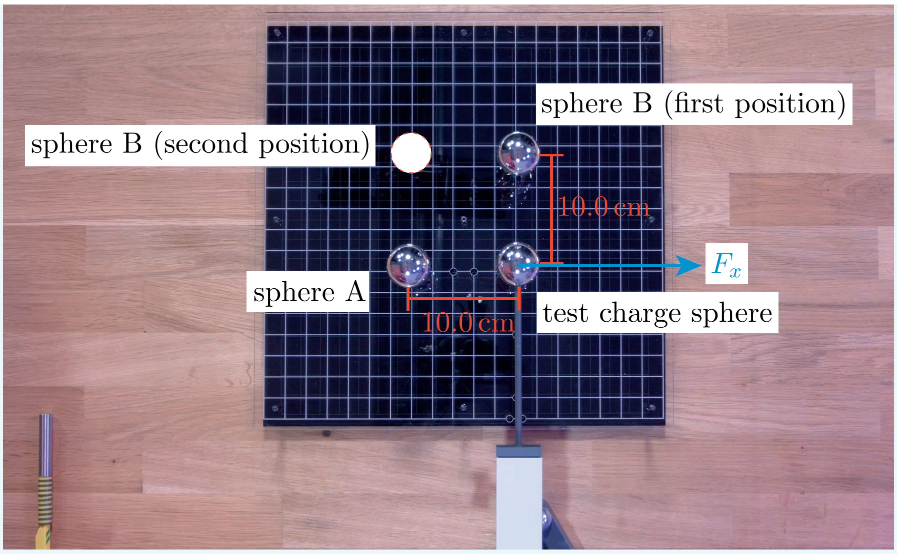


Figure 6 Annotated still image from Video 1 showing the positions of the test charge sphere, sphere A, and two possible positions for sphere B, as well as the force component F_x.

(a)

Use the vector form of Coulomb's law to predict the x-component F_x of the force that the test charge sphere feels in the three situations described below. All charges are given in units of nanocoloumbs (nC). Write your answers in millinewtons (mN) in Table 1.

i. The test charge sphere and sphere A are charged with $30\,\mathrm{nC}$ each. Sphere B is not present.
ii. The three spheres are charged with $30\,\mathrm{nC}$ each. Sphere B is in its first position (see Figure 1).
iii. The three spheres are charged with $30\,\mathrm{nC}$ each. Sphere B is in its second position (see Figure 1).

Table 1 Calculated force on the test charge.

situation	calculated F_x/mN
i	*Provide your answer...*
ii	*Provide your answer...*
iii	*Provide your answer...*

(b)

Comment briefly on possible reasons why your calculated F_x values may not agree exactly with the experimental values. Consider approximations in your calculations and experimental uncertainties that may have significant effects.

Provide your answer...

Discussion

Keep in mind that the discussion below only addresses a selection of issues; there are various other valid points that you might have raised in your answers.

The key assumption in the calculation is that the charged spheres can be treated as point charges located at the spheres' centres. At any position outside a spherically symmetric charge distribution, the field produced by the charge distribution is the same as the field that would be produced by a point charge located at its centre. This is a consequence of Gauss's law (one of the four key laws in electromagnetism known as Maxwell's equations). However, in this experiment the charge distribution around each sphere will not be perfectly spherically symmetric. This is partly because no manufactured sphere is perfect, but a more fundamental issue is that the electric field produced by one charged sphere will disrupt the spherical symmetry of the charge distribution on another.

Testing the experiment before filming indicated that most significant sources of experimental uncertainty were *unwanted forces* and *charge leakage*, as described below.

The test charge sphere can experience unwanted forces (that is, forces other than the electrostatic force due to nearby charged spheres). For example, air flow in the studio and vibrations transmitted from the floor had noticeable effects in the tests before filming.

Charge leakage occurs in the time between charging the spheres and measuring the forces. No insulator is perfect, and the rate at which charge dissipates from the spheres is sensitive to factors such as air humidity and the cleanliness of the plastic rods.

Further sources of experimental uncertainty include:

- The charge transferred to each sphere is known to a limited precision. This depends on the calibration procedure.
- No force meter is perfectly accurate, and the measured forces are displayed to a limited precision.
- Video 1 does not provide information on how precisely the test charge sphere has been positioned to measure the x-component of the force that it feels.
- The x- and y-positions of the spheres' centres are given to a limited precision, and the video does not provide information about precisely how they are situated on the xy-plane.

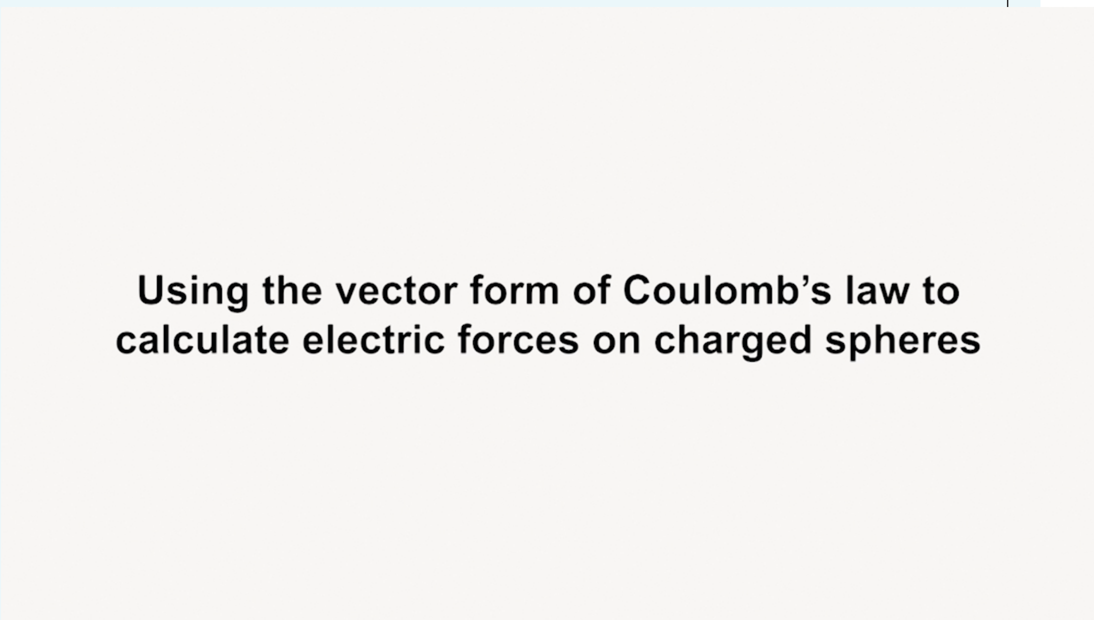
Part 3 Applying the vector form of Coulomb’s law – a model solution and discussion of the results

(a)

Watch Video 2 in which Sam presents model solutions for the three situations described in Part 2(a) of this activity. The video highlights the use of use of displacement vectors, position vectors, unit vectors and vector components.

Video content is not available in this format.

Video 2 Using the vector form of Coulomb’s law to determine theoretical force components for comparison with the measurements in Video 1.



The experimental results from Video 1 are summarised in Table 2 for the three situations described in Part 2(a). In each situation, F_x was recorded in mN before and after the spheres were charged. The results from Video 2 are also shown and your calculated values from Table 1 are also shown [please refresh the page if calculated values from Table 1 haven’t populated the boxes in the last column].

Table 2 Summary of the results from Videos 1 and 2.

situation	average measured F_x/mN			calculated F_x/mN values from Video 2	your calculated F_x/mN values from Table 1
	uncharged	charged	difference		
i	–0.058	0.65	0.71	0.81	*Display of content entered previously*

ii	–0.10	0.66	0.76	0.81	*Display of content entered previously*
iii	–0.057	0.99	1.0	1.1	*Display of content entered previously*

(b)

Compare the calculated F_x values in Table 2 with the experimental results (in the 'difference' column). Does this comparison support the validity of Coulomb's law and of your method for applying it in situations with more than two charges?

Provide your answer...

Discussion

For brevity, this discussion is limited to the point charge assumption, and the effects of charge leakage and unwanted forces.

Point charge assumption

The field produced by one charged sphere disrupts the spherical symmetry of the charge distribution on another. This causes the concentration of positive charge to be greatest on the side of each sphere that is furthest from the other positively charged spheres. Hence, treating the charged spheres as point charges located at the spheres' centres represents an underestimation of the separation of the charge distributions on each sphere.

Charge leakage

Charge leakage occurs during the time between charging the spheres and measuring the forces. This means that the magnitude of the charge on each sphere at the instant that the force is measured is lower than the $30\,\mathrm{nC}$ that was initially transferred.

It follows that the point charge assumption and charge leakage both cause the calculated forces to be higher than the forces in the experiment. This is broadly consistent with Table 2, where calculated forces are between 6% and 12% higher than the experimental values.

Unwanted forces

Table 2 shows that force measurements prior to charging the spheres vary over a range of $0.04\,\mathrm{mN}$. This provides a first approximation for the variation in the unwanted forces. The variation is close to the difference between the F_x values measured in situations (i) and (ii), which the calculations indicate should be the same.

Summary

This short discussion indicates that the key approximation in the calculation and the main sources of experimental uncertainty are broadly consistent with the differences between the calculated and measured forces in this activity. Therefore, the experimental results are broadly supportive of the validity of Coulomb's law and the present method for applying it in situations with more than two charges.

Conclusion

Coulomb's law for the force $\mathbf{F}_{12}$ on a point charge q_1 due to a point charge q_2 can be written as

$$\mathbf{F}_{12} = \frac{1}{4\pi\varepsilon_0} \frac{q_1 q_2}{r_{12}^2} \,\widehat{\mathbf{r}}_{12},$$

where ε_0 is the permittivity of free space, r_{12} is the magnitude of the displacement from charge q_2 to charge q_1, and $\widehat{\mathbf{r}}_{12}$ is the unit vector for this displacement.

You can use this form of Coulomb's law repeatedly with vector addition to find the force on a point charge due to a system of a few charges. However, when considering more complicated systems of charges or continuous charge distributions it is usually necessary to use computer based methods to determine the resulting force.

This OpenLearn course is an adapted extract from the Open University course SM381 *Electromagnetism*.

Appendix

Table A Measured forces F_x on a test charge sphere due to spheres A and B. The test charge and sphere A are fixed. Three situations for sphere B are considered (including not present and two different positions, as explained in Video 1 and Figure 1). In each situation, F_x is measured before and after the spheres are charged

sphere B	charge on each sphere/nC	measured F_x/mN					
not present	0	−0.05	−0.05	−0.07	−0.05	−0.07	−0.06
	30	0.62	0.63	0.65	0.64	0.68	0.69
first position	0	−0.08	−0.09	−0.11	−0.12	−0.11	−0.10
	30	0.65	0.64	0.64	0.65	0.67	0.68
second position	0	−0.04	−0.05	−0.06	−0.05	−0.07	−0.07
	30	0.98	0.99	0.99	0.99	0.98	1.00

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