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Electricity, Magnetism & Optics

Electric Charge and Electric Field

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Chapter Description

- Aims

  Students will understand basic concepts of electricity, i.e. the definition of elementary charge and the derivation of Coulomb's law.

- Expected Outcomes
  - Able to describe the concept of elementary charge
  - Able to apply Coulomb's law to calculate electrostatic forces
  - Able to draw electric field lines correctly from

- References
  - University Physics 14th Edition, Hugh D. Young, Roger A. Freedman, IOP Publishing Ltd, 2015
  - Physics for Scientists & Engineers 9th Edition, Raymond A. Serway & John W. Jewett, Cengage Learning, 2014

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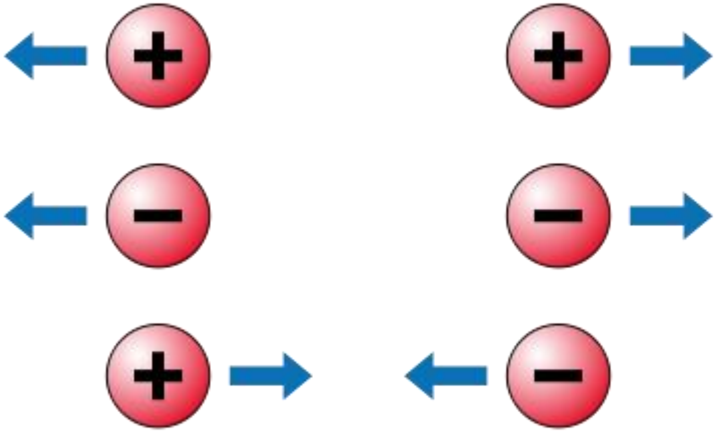

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1.1 Electric Charge

- The existence of electric force and electric charges can be demonstrated by a simple experiment using household items

- For example, if two glass rods are rubbed with silk and then brought close together, both glass rods will expel each other!

- This experiment shows the existence of some kind of force acting on both rod glasses.

- This force is called as the **electrostatic force**. So where does this force comes from??

Electrostatic force

- Let’s do another experiment. If two plastic rod is rubbed with fur, they too will repel each other.
- HOWEVER! If the glass rod rubbed with silk, and plastic rod rubbed with fur is brought together, they will attract each other!
- This clearly shows the are two variables at play in both the plastic and glass rods. One is repelling, and one is attracting.
- Scientists call both of these variables as **positive charge** and **negative charge**. And it is understood that same charges will attract each other, while opposite charges will repel.

Atomic Structure

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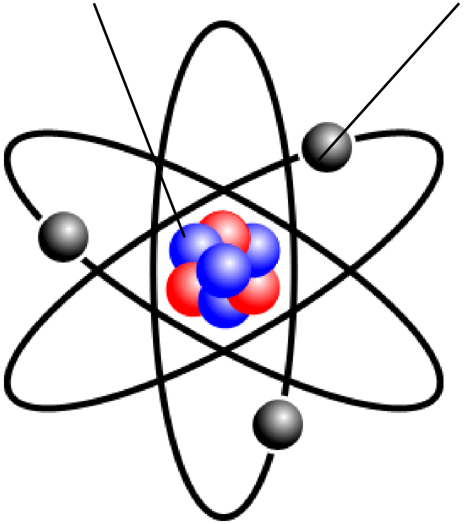
So, where does these charges come from?

- Everything is made up of atoms, and an atom is made up of a nucleus and electrons.
- The nucleus contains neutrons and protons which are positively charged.
- While the electrons occupy the region surrounding the nucleus and are negatively charged



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History of electron

- The electron was first discovered by J. J. Thomson in 1897 when he was studying about the cathode ray

- While in 1909, R. Millikan found the exact amount of charge in one electron from his famous oil drop experiment.

- It is found that one electron carries exactly 1.602×10^{-19} C
- "C" or Coulomb is the unit for charge
- A proton also carries the same amount of charge

This amount **1.602×10^{-19} C is referred to as elementary charge**. The symbol is ***e***. It is the smallest unit of charge found in nature.

$$1\,e = 1.602 \times 10^{-19}$$

Elementary charge

- Elementary charge is the building block for all charged objects
- That is, the charge in any object is the integer multiple of the elementary charge.

- For example, a charged object CAN ONLY HAVE charge of 0 *e*, or 2 *e*, or 73,472,480 *e*
- BUT it can never have charge of ½ *e*, or 0.47 *e*

- This is called quantization, i.e: charge can only exist in discreet amount

Discussion

How many electrons are inside an object with -3 C charge?

Protons vs Electrons

To avoid confusion, the default sign for *e* is positive. So, *e* is sometimes also referred to as elementary positive charge.

An electron therefore has charge of -1 *e*

Proton	Electron
Symbol: p	Symbol: e
Charge: $q = 1\ e$	Charge: $q = -1\ e$
Mass: $m = 1.67 \times 10^{-27}$ kg	Mass: $m = 9.11 \times 10^{-31}$ kg

Discussion

If protons and electrons carry charge, why are atoms neutral?

Principle of Conservation of Charge

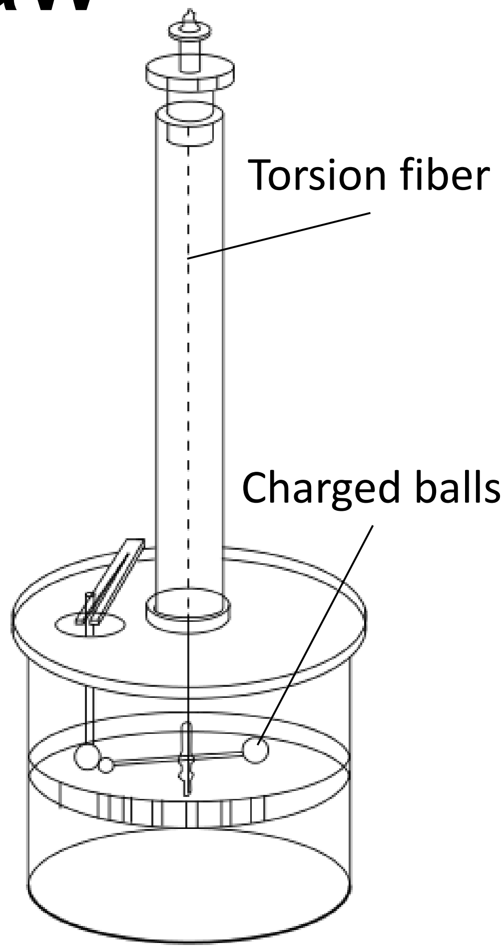
- Other than quantization, another property of charge is that electric charge is always conserved in an isolated or a closed system
- In other words, charge is not created nor destroyed, but it is transferred from one object to another.
- The charge in each objects has changed, but the total change of charge in both objects is zero
- Thus, the net amount of electric charge produced in any process is zero!

1.2 Coulomb's Law

- As stated before, electrostatic force is the reason why glass rod rubbed with silk repels each other, or is attracted to a plastic rod rubbed with fur.

- In 1784, a French scientist, Charles A. Coulomb investigated the electrostatic forces between two charged balls using torsion balance.

- He found that amount of charge and the force is related!



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Magnitude of electrostatic force

- Specifically, Coulomb found that the magnitude of the electrostatic force is:
  1. Proportional to the product of the charges of both balls.
  2. Inversely proportional to the square of the distance between them

$$F \propto \frac{|q_1 q_2|}{r^2}$$

- A proportionality constant, *k* can be introduced to turn this inequality into an equation.

Discussion

Try to find the dimension or unit of the proportionality constant, *k*

Coulomb's Law

The magnitude of the electrostatic force between two charged particles is proportional to the product of the charges of both particles and inversely proportional to the square of the distance between them

$$F = k\frac{|q_1 q_2|}{r^2}$$

or

$$F = \frac{1}{4\pi\varepsilon_0}\frac{|q_1 q_2|}{r^2}$$

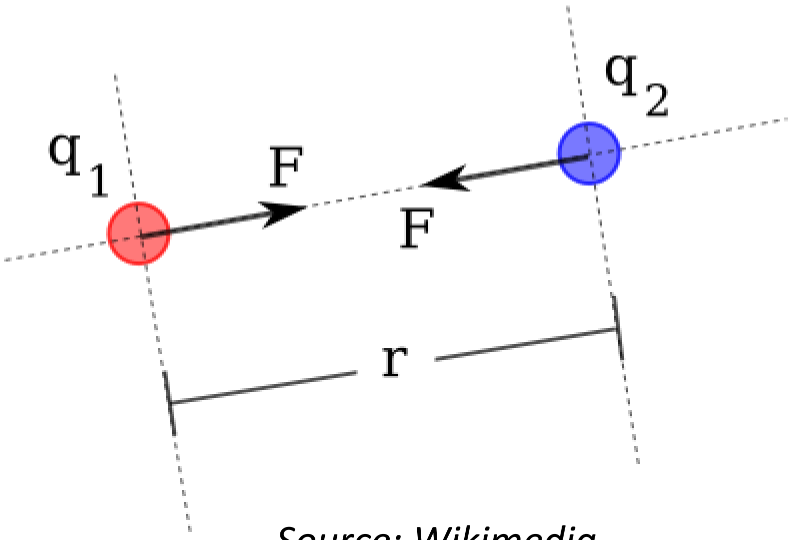
- In SI unit, *k* has the value of $k = 8.9875\times 10^9\ \mathrm{N\cdot m^2/C^2}$
- *k* can also be written as $k = \dfrac{1}{4\pi\varepsilon_0}$, where ε_0 is another constant called the permittivity of free space.

Direction of electrostatic force

- The equation of Coulomb's law only tells the magnitude, but NOT the direction of the force!

- The direction can be determined by drawing a line between both charged objects. The direction of the force will be along this line.

- The figure to the right shows an example of the direction of the attractive electrostatic force between two oppositely charged objects



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Coulomb's law: Vector form

- All forces can be expressed as a vector with magnitude and direction.

- The coulomb's law thus can be re-written in vector form as

$$\vec{\boldsymbol{F}}_{12}(r) = \frac{1}{4\pi\varepsilon_0}\frac{|q_1 q_2|}{r_{12}^2}\hat{\boldsymbol{r}}_{12}$$

- In this example, the force $\vec{\boldsymbol{F}}_{12}(r)$ refers to the electrostatic force of charge 1 acting on charge 2, while r_{12} refers to the distance between the two objects

Principle of superposition of forces

- But what about situations with more than two charged particles?
- Experiments show that when two charges exert forces on a third charge, the total force acting on the third charge is the vector sum of the forces by the two charges
- This is called the **principle of superposition of forces**, and is true for any number of charges.

- For example, if there are four point charges, the resultant force exerted by charge 2, 3 and 4 on charge 1 can be expressed as

$$\vec{F} = \vec{F}_{21} + \vec{F}_{31} + \vec{F}_{41} + \vec{F}_{51}$$

1.3 Electric Field

- The idea of a “force acting at a distance” was a difficult concept for early thinkers.
- A helpful way to look at the situations uses the concept of the electric field as introduced by Michael Faraday.
- Faraday stated that an electric field extend outward from every charged objects and permeates all of space surrounding the charged objects.

Imagining electric field

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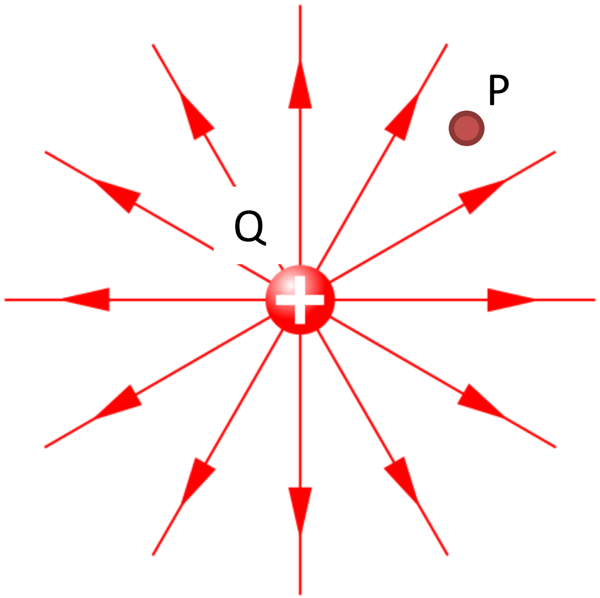
- For a positively charged object, Q, the electric field will permeate outward from the object.

- If another charged object, P, is placed somewhere near the first object, P will feel a force exerted on it by the electric field from Q. It can be said that the field from Q is interacting with P, and this solves the problem of “force acting at a distance”



Source: Victor Blacus, Wikimedia Commons

Defining electric field

- The field at point P is actually independent of the charge of P, and only depends on the charge of Q. Therefore, the electric field emanating from Q can be investigated using test charge. The test charge can be of any charge.

- Several test charges with charge *q* can be placed around the charged object that we would like to investigate. The force exerted on each test charges can be calculated using the Coulomb's law. And thus, the electric field can be defined as

$$F = \frac{1}{4\pi\varepsilon_0}\frac{|q_1 q|}{r^2} = \frac{1}{4\pi\varepsilon_0}\frac{|q_1|}{r^2}|q| = E|q|$$

$$E = \frac{1}{4\pi\varepsilon_0}\frac{|q|}{r^2}$$

Electric vector field

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- Since the electric field has a direction, it can also be written in vector form

$$\vec{\boldsymbol{E}} = \frac{1}{4\pi\varepsilon_0}\frac{|q|}{r^2}\hat{\boldsymbol{r}}$$

- The direction is always pointing away from a positive charge and pointing into negative charge.
- The electric field is not located in one single point, but it exists everywhere in the region surrounding the charged objects. It is actually an infinite set of vectors!
- This set of infinite vectors is referred to as a <u>vector field</u>, and the reason why the vectors in the region surrounding the charged object is called *electric field*

Principle of superposition of electric field

- Similar with electrostatic force, the electric field also follows the principle of superposition.

- If there are more than one charged object, the electric field at a point nearby all of the charged objects is the total vector sum of electric field from all charges.

$$\vec{E} = \frac{\vec{F}_0}{q_0} = \vec{E}_1 + \vec{E}_2 + \vec{E}_3 + \ldots$$

- This is referred to as **the principle of superposition of electric fields**

1.4 Electric Field Lines

- It is hard to visualize electric field just by calculating it at certain positions.
- The concept of electric field lines can be used to help us seeing the electric field surrounding a charged object.
- Electric field lines are an imaginary line connecting all the electric vector field, and is tangent to the direction of the electric field at that particular point.

Visualizing electric field lines

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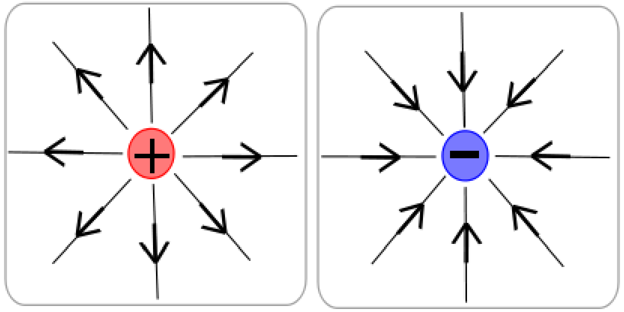
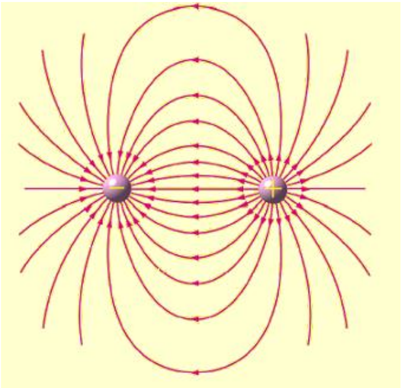
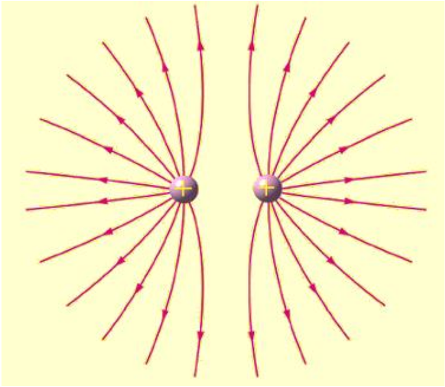


Electric field lines pointing away from positive charge, and pointing into negative charge. A higher charge can be represented by drawing more lines around the charge.



Electric field line for a positive charge and a negative charge placed nearby. This is also called a dipole.

Source: Chancocan, Wikimedia Commons



Electric field line for two positive charges, or two negative charge. Notice that the electric field is zero in the midpoint between the two charges

Conclusion

- Elementary charge
  - Electrons and protons are elementary charges
  - A charged object can only have multiple integer of elementary charge, depending on the amount of excess electrons or protons

- Coulomb's Law
  - Electrostatic force between two or more charged objects can be calculated using Coulomb's law

- Electric field
  - The electric fields are vector field surrounding the space around the charge
  - Electric field points away from positive charge, and into negative charge
  - It can be visualized using electric field lines.

Thank you!

Next chapter:
Gauss’s Law