

Notes for PHYS 27200 - Electric And Magnetic Interactions

Ezekiel Ulrich

August 23, 2023

These are lecture notes for fall 2023 PHYS 27200 at Purdue. Modify, use, and distribute as you please.

Contents

Course Introduction 1

Equations 1

Electric charge 2

Electric field 2

Course Introduction

This is a calculus-based physics course using concepts of electric and magnetic fields and an atomic description of matter to describe polarization, fields produced by charge distributions, potential, electrical circuits, magnetic forces, induction, and related topics, leading to Maxwell's equations and electromagnetic radiation and an introduction to waves and interference. 3-D graphical simulations and numerical problem solving by computer are employed throughout. For more information, consult the syllabus.

Equations

1. Coulomb's Law: $\vec{F} = \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2}{r^2} \hat{r}$
2. Electric field: $\vec{E}_1 = \frac{1}{4\pi\epsilon_0} \frac{q_1}{r^2} \hat{r}$
3. Force due to electric field: $\vec{F}_2 = E_1 q_2$
4. Dipole moment between charges $-q$ and q separated by \vec{s} : $\vec{p} = q\vec{s}$
5. Electric field on dipole axis: $\vec{E} = \frac{1}{4\pi\epsilon_0} \frac{2sq}{r^3} \hat{p}$
6. Electric field on dipole bisecting plane: $\vec{E} = \frac{-1}{4\pi\epsilon_0} \frac{sq}{r^3} \hat{p}$

Electric charge

Electric Charge: Electric charge is an intrinsic characteristic of the fundamental particles that make up objects.

Conservation of charge: The net charge of a *closed system* never changes

Objects can have negative, zero, or positive charge. Charges are always multiples of the *elementary charge* $e = 1.60217662(63) \times 10^{-19} \text{C}$

Coulomb (C): One coulomb is the amount of charge that is transferred through the cross section of a wire in 1 second when there is a current of 1 ampere in the wire.

The charges of elementary particles are listed below.

Particle	Charge (elementary charge, e)
Electron (e^-)	-1
Positron (e^+)	+1
Proton (p^+)	+1
Anti-proton (p^-)	-1
Neutron	0
Anti-neutron	0
Photon	0

Point Charge: A charged object whose radius is much smaller than the distance between itself and all other objects of interest.

The magnitude of electric force between two point charges is directly proportional to the magnitude of each charge and inversely proportional to the distance squared. Specifically:

$$F = \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2}{r^2}$$

This is Coulomb's Law. Note the direction of the force changes with the sign of the charges involved. Like repels like and opposites attract.

Electric field

We can represent electric fields as lines emanating from a point charge. The greater the density of the lines, the greater the strength of the electric field. Note that at the origin, the force is undefined (infinite), since $|r| = 0$.

Consider the relative strengths of the electric and gravitational fields. The gravitational force is given by $F_g = G \frac{m_1 m_2}{r^2} \hat{r}$, with $m_{\text{electron}} = 9 \times 10^{-31} \text{kg}$ and $m_{\text{proton}} = 1.7 \times 10^{-27} \text{kg}$. If we consider a hydrogen

It was mentioned in class that mass is likewise intrinsic. However, when discussing the Higgs field's role in giving particles mass, the distinction between mass as an intrinsic or emergent property becomes more nuanced. The mass of elementary particles like electrons and quarks is emergent in the sense that it arises from their interaction with the Higgs field, which itself is a fundamental aspect of the universe.

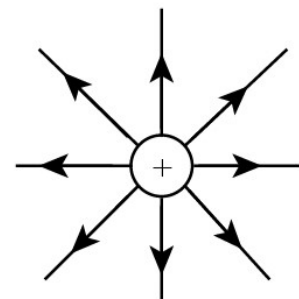


Figure 1: An electric field coming from point charge. Notice how the densities of the lines vary with distance from the source.

atom, then $r = 5.3 \times 10^{-11} \text{m}$. With $G = 6.7 \times 10^{-11}$, we have

$$F_g = \frac{(1.7 \times 10^{-27})(9 \times 10^{-31})(6.7 \times 10^{-11})}{(5.3 \times 10^{-11})^2} \approx O(10^{-46})N$$

Now, the electric force is given by $\vec{F} = \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2}{r^2} \hat{r}$. The charge of a proton and electron are $q_1 \approx q_2 \approx 1.6 \times 10^{-19} \text{C}$. Ergo, since $\frac{1}{4\pi\epsilon_0} \approx 8.99 \times 10^9 \frac{\text{Nm}^2}{\text{C}^2}$,

$$F_e = \frac{(8.99 \times 10^9 \frac{\text{Nm}^2}{\text{C}^2})(1.60 \times 10^{-19} \text{C})^2}{(5.3 \times 10^{-11} \text{m})^2} \approx O(10^{-17})N$$

This means that $\frac{F_e}{F_g} \approx 2.27 \times 10^{39}$, meaning the electric force is much stronger for these masses and charges than gravity. On scales as large as humans and planets, gravity is the dominant force because gravity is strictly additive.

For sufficient distances, the electric field of a uniformly charged spherical shell resembles the electric field of a point charge.

That means for $r \gg R$, $E_{\text{sphere}} = \frac{1}{4\pi\epsilon_0} \frac{q_1}{r^2} \hat{r}$. This holds only for outside the sphere. Inside, it can be shown that the electric field is zero.

Superposition Principle: The net electric field at a location in space is a vector sum of the individual electric fields contributed by all charged particles located elsewhere.

To introduce systems with multiple sources of electric field lines, consider the particle pair known as a dipole. Dipoles consist of one negatively charged and one positively charged particle, like so:

Dipole Moment: The dipole moment is a way of expressing asymmetrical charge distribution. It is a vector quantity, i.e. it has magnitude as well as definite directions.

On the axis of the dipole (i.e. the lines formed by the two particles), the electric field is

$$\vec{E} = \frac{1}{4\pi\epsilon_0} \frac{2sq}{r^3} \hat{p}$$

On the bisecting plane (i.e., the plane exactly halfway from each point) the field is given by

$$\vec{E} = \frac{-1}{4\pi\epsilon_0} \frac{sq}{r^3} \hat{p}$$



Figure 2: Notice how a circle resembles a point from a great distance.

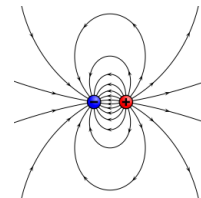


Figure 3: Two oppositely charged particles distanced from one another