

# Electromagnetism

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# 1 Introduction

## 1.1 Charges and currents

*Electric charge* is a physical property of elementary particles. It is:

- (i) A signed quantity, it can either be positive, negative, or zero.
- (ii) It is quantised to integer multiples of the elementary charge.
- (iii) It is a conserved quantity even if particles are created or destroyed.

By convention the electron has charge  $-e$ , the proton has charge  $+e$  and the neutron has no charge. On macroscopic scales, the number of particles is so large that charge can be considered to have a continuous electric charge density  $\rho(\mathbf{x}, t)$ . The total charge in a volume  $V$  is then

$$Q = \int_V \rho dV.$$

The *electric current density*  $\mathbf{J}(\mathbf{x}, t)$  is the flux of electric charge per unit area. The current following through a surface  $S$  is

$$I = \int_S \mathbf{J} \cdot d\mathbf{S}.$$

Consider a time-independent volume  $V$  with boundary  $S$ . Since charge is conserved, we have that

$$\begin{aligned} \frac{dQ}{dt} &= -I \\ \frac{d}{dt} \int_V \rho dV + \int_S \mathbf{J} \cdot d\mathbf{S} &= 0 \\ \int_V \left( \frac{\partial \rho}{\partial t} + \nabla \cdot \mathbf{J} \right) dV &= 0 \end{aligned}$$

Since this is true for any  $V$ , we have that

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \mathbf{J} = 0.$$

This *equation of charge conservation* has the typical form of a conservation law.

The discrete charge distribution of a single particle of charge  $q_i$ ; and position vector  $\mathbf{x}_i(t)$ , is

$$\begin{aligned} \rho &= q_i \delta(\mathbf{x} - \mathbf{x}_i(t)), \\ \mathbf{J} &= q_i \dot{\mathbf{x}}_i \delta(\mathbf{x} - \mathbf{x}_i(t)). \end{aligned}$$

For  $N$  particles, it is

$$\begin{aligned} \rho &= \sum_{i=1}^N q_i \delta(\mathbf{x} - \mathbf{x}_i(t)) \\ \mathbf{J} &= \sum_{i=1}^N q_i \dot{\mathbf{x}}_i \delta(\mathbf{x} - \mathbf{x}_i(t)). \end{aligned}$$

As an exercise we can see that these satisfy the equation of charge conservation.

## 1.2 Fields and forces

Electromagnetism is a *field theory*.

Charged particles don't interact directly, but rather by generating fields around them, which are then experienced by other charged particles. In general we have two time-dependent vector fields, the electric field  $\mathbf{E}(\mathbf{x}, t)$ , and the magnetic field  $\mathbf{B}(\mathbf{x}, t)$ .

The *Lorentz force* on a particle of charge  $q$  and velocity  $\mathbf{v}$  is

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}).$$

## 1.3 Maxwell's equations

In this course we will explore some consequences of Maxwell's equations.

**Definition.** (Maxwell's equations)

$$\begin{aligned}\nabla \cdot \mathbf{E} &= \frac{\rho}{\varepsilon_0} \\ \nabla \cdot \mathbf{B} &= 0 \\ \nabla \times \mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t} \\ \nabla \times \mathbf{B} &= \mu_0 \left( \mathbf{J} + \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right).\end{aligned}$$

*Remark.* We have some properties about these equations.

- Coupled linear PDEs in space and time,
- Involve two positive constants:
  - (i)  $\varepsilon_0$  (vacuum permittivity)
  - (ii)  $\mu_0$  (vacuum permeability)
- Charges ( $\rho$ ) and currents ( $\mathbf{J}$ ) are the sources of electromagnetic fields.
- Each equation is an equivalent integral form (see later) related via the divergence or Stokes' theorem.
- These are the *vacuum* equations that apply on microscopic scales or in a vacuum. A related macroscopic version applies in media (Part II Electrodynamics).
- The equations are consistent with each other and with charge conservation. We will show this now.
  - (i) Taking the divergence of the third equation, this agrees with the time derivative of the second equation.
  - (ii) For charge conservation, we have that

$$\begin{aligned}\frac{\partial \rho}{\partial t} + \nabla \cdot \mathbf{J} &= \frac{\partial}{\partial t} (\varepsilon_0 \nabla \cdot \mathbf{E}) + \nabla \cdot \left( -\varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} + \frac{1}{\mu_0} \nabla \times \mathbf{B} \right) \\ &= 0.\end{aligned}$$

## 1.4 Units

The SI unit of electric charge is the coulomb ( $C$ ). The elementary charge is exactly

$$e = 1.602\,176\,634 \times 10^{-19} \text{ C}.$$

The SI unit of electric current is the ampere or amp ( $A$ ) which is equal to  $1 \text{ C s}^{-1}$ .

The SI base units needed in electromagnetism and then the second, metre, kilogram, and ampere. From the Lorentz force law we see that the units of  $\mathbf{E}$  and  $\mathbf{B}$  must be

$$\text{kg m s}^{-3} \text{A}^{-1} \quad \text{and} \quad \text{kg s}^{-2} \text{A}^{-1}.$$

We sometimes refer to the units of  $\mathbf{B}$  as the *Telsa* ( $T$ ).

From Maxwell's equations we can work out the units of  $\varepsilon_0$  and  $\mu_0$ . The values of these constants can be calculated via experimentation as

$$\begin{aligned}\varepsilon_0 &= 8.854 \dots \times 10^{-12} \text{ kg}^{-1} \text{m}^{-3} \text{s}^4 \text{A}^2 \\ \mu_0 &= 1.256 \dots \times 10^{-6} \text{ kg m s}^{-2} \text{A}^{-2}\end{aligned}$$

The speed of light is exactly

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = 299\,792\,458 \text{ m s}^{-1}.$$

## 2 Electrostatics

In a time-independent situation, Maxwell's equations reduce to

$$\begin{aligned}\nabla \cdot \mathbf{E} &= \frac{\rho}{\varepsilon_0} \\ \nabla \cdot \mathbf{B} &= 0 \\ \nabla \times \mathbf{E} &= 0 \\ \nabla \times \mathbf{B} &= \mu_0 \mathbf{J}\end{aligned}$$

Now  $\mathbf{E}$  and  $\mathbf{B}$  are decoupled so we can study them separately. Electrostatics is the study of the electric field generated by a stationary charge distribution. We'll be looking at

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}, \quad \nabla \times \mathbf{E} = 0.$$

### 2.1 Gauss' Law

Consider a closed surface  $S$  enclosing a volume  $V$ . Integrate over  $V$  and use the divergence theorem to obtain Gauss' law which is

$$\int_S \mathbf{E} \cdot d\mathbf{S} = \frac{Q}{\varepsilon_0},$$

Where

$$Q = \int_V \rho dV$$

is the total charge in  $V$ . Gauss' law is the integral version of the first of Maxwell's equations and is valid generally. We get that electric flux is proportional to the total charge enclosed.

In special situations we use Gauss' law together with symmetry to deduce from  $\rho$ , by choosing the *Gaussian surface*  $S$  appropriately.

### 2.1.1 Spherical symmetry

Consider a spherically symmetric charge distribution,  $\rho(r)$  in spherical polar coordinates with total charge  $Q$  contained within an outer radius  $R$ . To have spherical symmetry, the electric field should have the form

$$\mathbf{E} = E(r)\mathbf{e}_r.$$

This will satisfy  $\nabla \times \mathbf{E} = 0$  as required.

To find  $E(r)$  apply Gauss' law to a sphere of radius  $r$ . If  $r > R$  then we get that

$$\begin{aligned}\int_S \mathbf{E} \cdot d\mathbf{S} &= E(r) \int_S \mathbf{e}_r \cdot d\mathbf{S} \\ &= E(r) \int_S dS \\ &= E(r)4\pi r^2 = \frac{Q}{\epsilon_0}.\end{aligned}$$

Thus

$$\mathbf{E} = \frac{Q}{4\pi\epsilon_0 r^2}\mathbf{e}_r.$$

So the external electric field of a spherically symmetric body depends only on the total charge, and is equivalent to a point charge at the origin with all of the charge. The Lorentz force on a particle of charge  $q$  in  $r > R$  is

$$\mathbf{F} = q\mathbf{E} = \frac{Qq}{4\pi\epsilon_0 r^2}\mathbf{e}_r.$$

This is the *Coulomb force* between charge particles. The force is repulsive if the charges have the same sign and attractive if the charges have different sign.

In the limit as  $R \rightarrow 0$  we obtain the electric field at a *point charge*  $Q$ , corresponding to

$$\rho = Q\delta(\mathbf{x}).$$

There is a close analogy between the Coulomb force and the gravitational force between massive particles, recall from IA Dynamics and Relativity that

$$\mathbf{F} = -\frac{GMm}{r^2}\mathbf{e}_r.$$

Both involve an inverse-square law and the product of the charges, however there are some differences.

- (i) While gravity is always attractive, electric forces can be repulsive or attractive;
- (ii) Gravity is very much weaker, due to the much smaller constant of proportionality.

For example if we consider two protons, the ratio of the electric to gravitational force is  $10^{36}$ . On the atom scale, gravity is irrelevant. But the  $+$  and  $-$  charges balance so accurately, that they cancel on the planetary scale, and gravity is much more dominant.

### 2.1.2 Cylindrical symmetry

Consider a cylindrically symmetric charge distribution, with  $\rho(r)$  in cylindrical polar coordinates with total charge  $\lambda$  per unit length contained within an outer radius  $R$ . To have cylindrical symmetry again we have that

$$\mathbf{E} = E(r)\mathbf{e}_r.$$

Again this will satisfy  $\nabla \times \mathbf{E} = 0$ . To find  $E(r)$ , apply Gauss' law to a cylinder of radius  $r$  arbitrary length  $L$ .

If  $r > R$  then

$$\begin{aligned} \int_S \mathbf{E} \cdot d\mathbf{S} &= E(r) \int_S \mathbf{e}_r \cdot d\mathbf{S} \\ &= E(r) \int_S dS \\ &= E(r) 2\pi r L = \frac{\lambda L}{\epsilon_0}. \end{aligned}$$

Thus we have that

$$\mathbf{E} = \frac{\lambda}{2\pi\epsilon_0 r} \mathbf{e}_r.$$

In the limit as  $R \rightarrow 0$  we obtain the electric field of a line charge  $\lambda$  per unit length, corresponding to  $\rho = \lambda\delta(x)\delta(y)$ .

### 2.1.3 Planar symmetry

For a planar charge distribution, we have a charge density of  $\rho(z)$  in Cartesian coordinates with total charge  $\sigma$  per unit area contained within a region  $-d < z < d$  of thickness  $2d$ .

We will assume reflective symmetry, so  $\rho(z)$  is even.

To have planar symmetry, we have  $\mathbf{E} = E(z)\mathbf{e}_z$ . Again we have that  $\nabla \times \mathbf{E} = 0$ . The reflectional symmetry implies that  $E(-z) = -E(z)$ .

To find  $E(z)$  for  $z > 0$  apply Gauss' law to a "Gaussian pillbox" of height  $2z$  and arbitrary area  $A$ . If  $z > d$  then

$$\begin{aligned} \int_S \mathbf{E} \cdot d\mathbf{S} &= E(z)A - E(-z)A \\ &= 2E(z)A \\ &= \frac{\sigma A}{\epsilon_0} \end{aligned}$$

Thus we have that

$$\mathbf{E} = \begin{cases} \frac{\sigma}{2\epsilon_0} \mathbf{e}_z & z < d \\ -\frac{\sigma}{2\epsilon_0} \mathbf{e}_z & z < -d \end{cases}.$$

In the limit as  $d \rightarrow 0$  we obtain the electric field of a *surface charge*  $\sigma$  per unit area, corresponding to  $\rho = \sigma\delta(z)$ .

### 2.1.4 Surface charge and discontinuity

Let  $\mathbf{n}$  be a unit vector normal to the charged surface, pointing from region 1 to region 2. In our example we have that  $\mathbf{n} = \mathbf{e}_z$ .