I INTRODUCTION

1.1 Overview

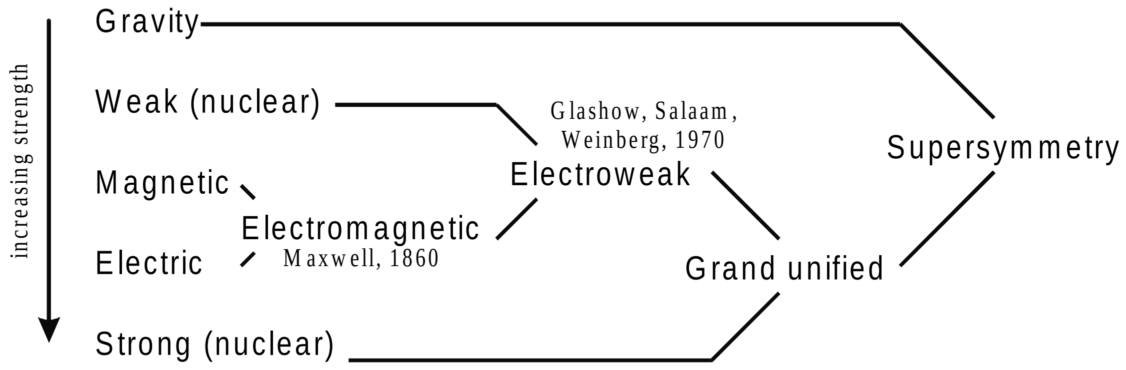
Electromagnetism is the study of Electricity and Magnetism

– and their unification

– and the consequences which flow from this.

Historically electricity and magnetism were regarded as separate and independent phenomena until their complete unification by Maxwell in ~1860.

Unification of the forces of Nature is one of the important challenges tackled by Physics. Currently it is believed that there are five (regarding the electric and the magnetic forces separately) fundamental forces – unified according to the following scheme:



The Forces of Nature and their unification

The unification of electricity and magnetism resulted in the interpretation of light as an electromagnetic wave, the prediction of the possibility of radio communication and ultimately in Einstein's theory of relativity. What technological developments will follow from further unifications remain to be seen.

1.2 History of the ideas of electromagnetism

Magnetic and electric effects were known to the Ancients: they had Lodestone and Amber.

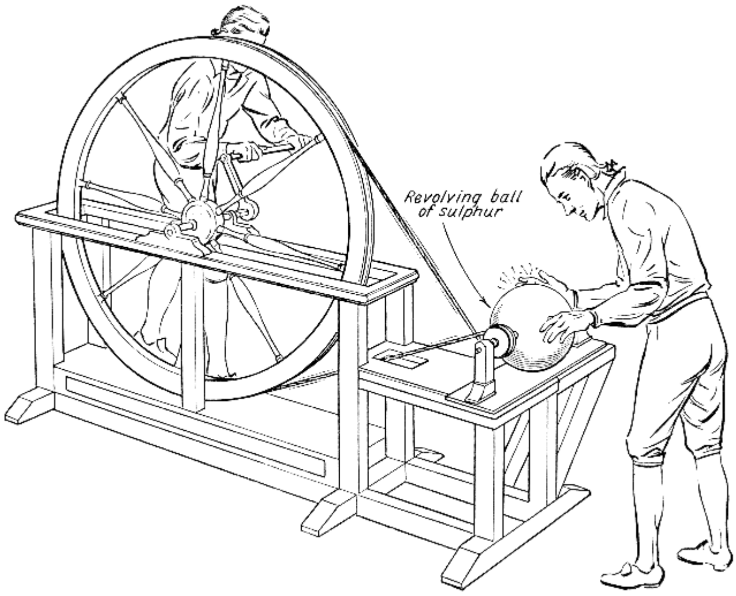
Lodestone – attracted iron and pointed in the same direction: *magnetic* effects. Named after *Magnesia* in Asia Minor where the first magnetic rocks were found.

Amber – when rubbed it attracted dried straw, leaves etc: *electric* effects. Named after *elektron*, which is the Greek word for amber.

There was then no real progress for some 2,000 years, until…

1600 WILLIAM GILBERT (1540-1603), physician to Queen Elizabeth I discovered that the property of Amber was shared by such things as sulphur, glass, precious stones, sealing wax, etc. He coined the word *electric* – meaning 'like amber'.

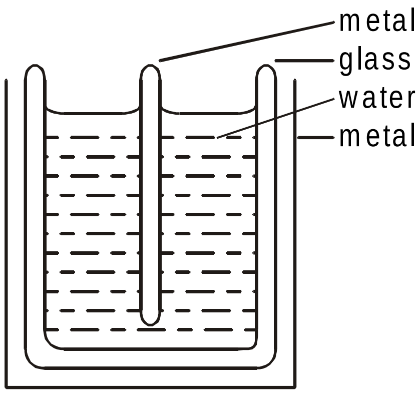
Soon after, OTTO von GUERICKE (1602-1686), of Magdeburg Hemisphere fame, invented the first electric 'machine'.



von Guericke's electric machine

When the sulphur ball is rotated and rubbed it emits sparks! – An amusing entertainment.

1745 The LEYDEN JAR was invented independently by Ewald von Kleist in 1745 and by Pieter van Masschenbroek of Leyden in 1746. This is a form of primitive capacitor; it could store electric charge. If many are connected in series then one can get a big electric shock. The *jar* was the Imperial unit of capacitance, used by the Royal Navy until the 1950s.

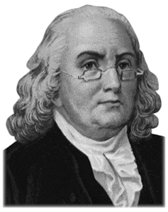


construction of a Leyden jar

1746 CARTHUSIAN MONKS formed a line some 300 metres long holding iron wires connecting each to his neighbour on either side. The Abbot, Jean-Antoine Nollet (1700-1770) then connected the wires to a number of Leyden jars in series. The monks all jumped high into the air upon receiving the electric shock. The important demonstration here was that the electricity flowed along the wires almost instantaneously.

1733 CHARLES DUFAY (1698-1739) discovered that static charge came in two types and that like charges repel while unlike charges attract.

1748 JOHN CANTON (1718-1772) invented the pith-ball electroscope, enabling him to *measure* electric charge. He was interested in thunderstorms; his work influenced Benjamin Franklin.



1752 BENJAMIN FRANKLIN (1706-1790) performed his famous kite experiment – flying a kite in a thunderstorm. He concluded that lightning was the same phenomenon as the sparks from an electric machine. More importantly, it was he who realised that the one type of charge cancelled the other type; he introduced the designation of *positive* and *negative* electric charge.

1791 LUIGI GALVANI (1737-1798), professor of anatomy at Bologna University, showed that the legs of a dead frog would twitch on connecting them to a charged Leyden jar – muscular action is caused by electrical stimulus. The legs also twitched when dissimilar metals were connected and touched the muscle. He concluded that the two metals produced electricity.

1797 ALESSANDRO VOLTA (1745-1827) extended Galvani's work and he developed this into the invention of the electric cell and the battery.

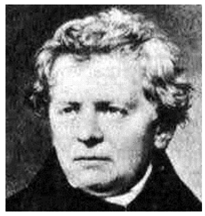
1800 HUMPHREY DAVEY (1778-1829) invented the electric carbon arc lamp, but thus far there was no generator to power it!

The picture shows Davey experimenting with laughing gas.

1800 CHARLES COULOMB (1736-1806) studied the force between charged objects and obtained his famous inverse square law.

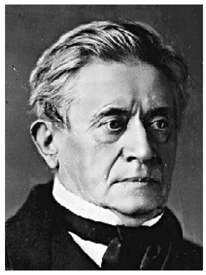
1819 HANS OESTERD (1771-1851) showed that an electric current has a magnetic effect associated with it. When a current flowed Oesterd observed a nearby compass needle to deflect.

1820 ANDRÉ-MARIE AMPÈRE (1775-1836) studied the force between current-carrying wires. He saw that a solenoid behaved rather like a bar magnet, which led him to speculate on the origins of magnetism as microscopic electric currents within materials.

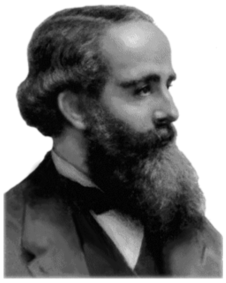


1826 GEORG OHM (1787-1854) observed that the current flowing in a conductor is proportional to the applied voltage: Ohm's law.

1831 MICHAEL FARADAY (1791-1867) discovered that a moving magnet could induce an electric voltage: magnetic motion causes an electric effect. Thus he invented the dynamo. When 12 years old he had attended Davy's lectures at the Royal Institution, and he was so impressed that he wrote to him asking for a job! In 1813, he was appointed a laboratory technician and he subsequently worked his way up to become Director of the Royal Institution and a fellow of the Royal Society.

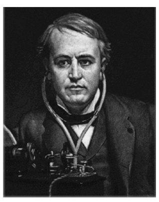


JOSEPH HENRY (1797-1878) did similar work in the USA – duplication, hampered by poor transatlantic communication.

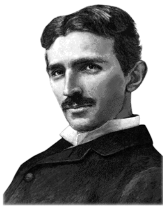


1873 JAMES CLERK MAXWELL (1831-1879) synthesised all the previous knowledge of electric and magnetic effects, and with significant developments of his own he formulated a set of equations (Maxwell's equations) which describe electromagnetic effects correctly. He predicted that even away from charges and magnets, varying electric fields cause magnetic fields and vice-versa. A consequence of this was that these varying, interrelated fields, could propagate with a wave-like motion, travelling at the speed of light. He concluded that light was probably a form of electromagnetic radiation. He predicted radio communication and his work also led, eventually, to Einstein's theory of relativity.

1887 HEINDRICH HERTZ (1857-1894) generated and detected radio waves in the laboratory. He established that they could be reflected, refracted and polarised. He also demonstrated their diffraction and interference – just like light. Hertz's work provided experimental verification of Maxwell's theory.

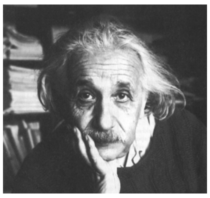


1879 THOMAS EDISON (1847-1931) developed the electric incandescent lamp. He also pioneered DC mains electricity distribution. He advocates the introduction of the electric chair as a method of execution.

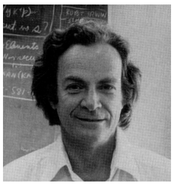


NIKOLA TESLA (1856-1943) invented the induction motor, AC mains electricity, 3 phase motors, fluorescent lighting and hydroelectric generators. He probably preceded Röntgen in the discovery of X-rays and Marconi in the demonstration of radio communication.

1895 GUGLIELMO MARCONI (1874-1937) established the practicality of radio communication culminating in the transmission and reception of radio waves across the Atlantic Ocean in 1901. However Tesla claimed to have preceded Marconi in this.



1905 ALBERT EINSTEIN (1879-1955) realised that Maxwell's equations were inconsistent with Newton's laws. Einstein had the geniusto realise that it was Newton's laws rather than Maxwell's equations that needed modifying. Einstein thus arrived at the special theory of relativity.



1949 RICHARD FEYNMAN (1918-1988) established the *quantum* theory of electromagnetism. He won the Nobel Prize for Physics in 1965 for this work.

1.3 Structure of the course

The aim of the course is the understanding of electric and magnetic phenomena, up to their unification in the so-called Maxwell equations. Along the way we shall develop the language for describing these things, namely fields and vectors: vector algebra and vector calculus.

1.3.1 Fields and matter

The philosophy of our approach to the electromagnetism of matter is a little different from the conventional view. The behaviour of charges and currents is complicated by the presence of material media (matter). The effect of matter is, conventionally, introduced at an early stage through the use of the dielectric constant ε and the magnetic permeability μ as phenomenological constants. We will not adopt this procedure. The first part of this course will concentrate on charges and currents in free space (in a vacuum). Only when the laws of electromagnetism are established for this simpler system, will the effects of matter be considered.

But at that stage matter may be regarded as nothing more than a collection of charges and currents. Then the previously established ideas can be easily extended to the case of material media.

This does go against the historical development of the subject, but it makes for considerable simplification in the numbers of ideas being developed at the same time.

1.3.2 The path to Maxwell's equations

Most treatments of electromagnetism start from Coulomb's inverse square law for the electric force between two charges. The traditional treatment introduces a further experimental observation: Ampère's formula for the magnetic force between electric currents. Since electric currents are no more than charges in motion it follows that these forces might well be related. And indeed special relativity provides the connection; Ampère's formula may be obtained from Coulomb's law through a Lorentz transformation.

In this course we shall follow the traditional approach of regarding Coulomb's law and Ampère's formula as two separate experimental observations upon which the subject of electromagnetism is based. The key steps leading to Maxwell's equations are:

1. Coulomb's inverse square law for the force between (stationary) charges

2. The existence of electric currents (moving charges)

3. Ampère's formula for the force between electric currents

4. Faraday's law of electromagnetic induction

5. The displacement current

You ought to be familiar with the ideas underlying the phenomena of 1 – 4. You should learn, in this course, how these phenomena can be integrated into a coherent mathematical description. You will then, at the appropriate stage, see how the displacement current is needed to make the description consistent. From these the Maxwell equations and their consequences follow.

When you have completed this chapter you should:

- be able to list the various forces of nature;

- know the relative magnitude of the electromagnetic force compared with other forces of nature;

- be able to describe the development of ideas leading from the primitive concepts of electric and magnetic phenomena to the current understanding;

- have a knowledge of some of the technologies following from the above ideas;

- appreciate that within the context of electromagnetism, matter is no more than a collection of charges and currents.

More generally, you should begin to see how electromagnetism fits into the structure of physics.