Electromagnetic Theory
PHYS 401/402

Fall 2018

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Electromagnetic Theory

- Welcome to electromagnetism.
- This is an upper level course covering principals of electromagnetism, primarily intended for physics majors.
- We will discuss basic principals and its mathematical formulation and applications in detail.
- Textbook: Introduction to Electrodynamics by D.J. Griffiths, 4th Edition (required).
  - Other supplementary reading material and links to online recourses will be recommended later as needed.

Grading/Homework

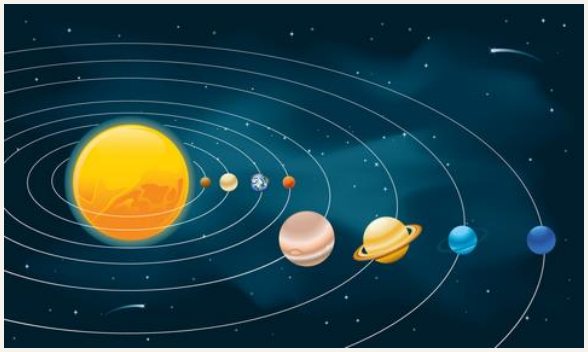
- **Grading:** There will be two in-class midterm tests and a final exam. The final grade is based on homework and tests.

Homework	30%
Midterm tests:	40%
Final exam	30%

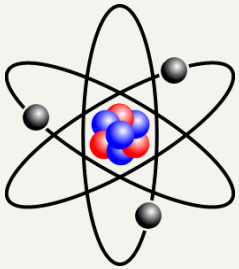
- **Homework:** There will be weekly homework assignments, which have to be turned in on time.
  - Solving homework problems is an essential, important part of the learning process.
  - You may (and are encouraged to) discuss homework problems with classmates or get help.
  - But should submit your own work describing detailed steps of the thought process and must have a full understanding of the concepts used in solving problems.

Electromagnetism

- Electromagnetism is **one of the four fundamental forces (interactions)** that govern the physical universe

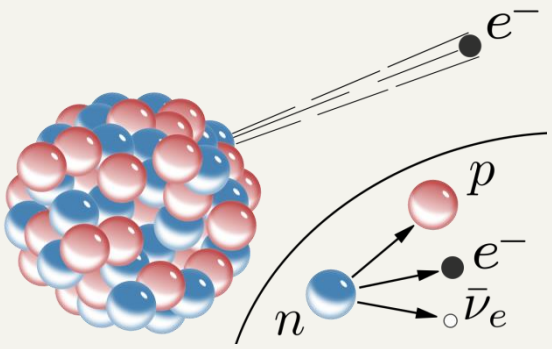


Gravity

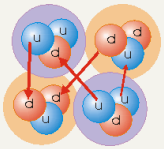


Electromagnetic

Long range $\frac{1}{r^2}$



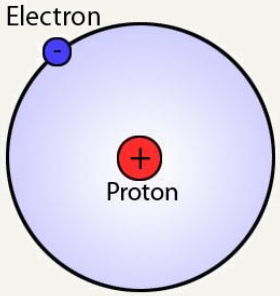
Weak



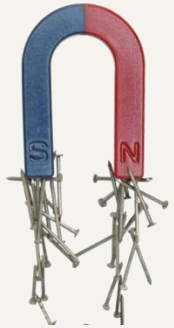
Strong

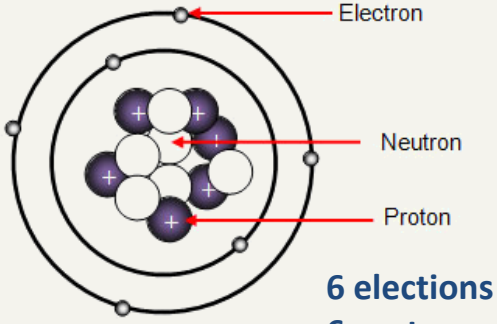
Short range ($\sim 10^{-15}$ m)

- We normally experience gravity, and effects of electromagnetism.
  - Electromagnetism is by far the strongest force we normally experience.

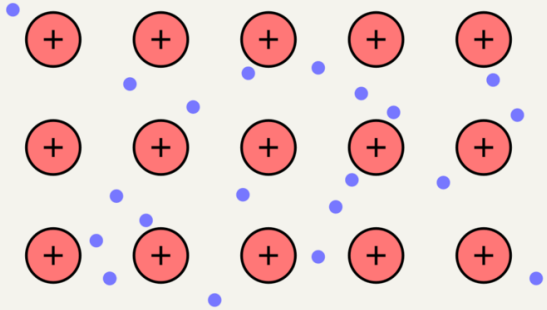


Electric attraction between the proton and election in a hydrogen atom is about $4x10^{40}$ times the gravitational pull between them





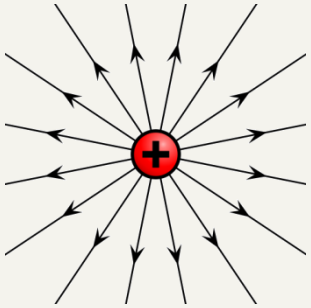
6 elections
6 protons



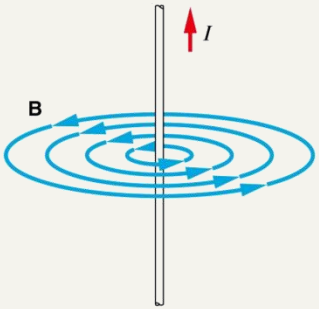
Electrostatic forces are usually cancelled or reduced because matter is **approximately electrically neutral**

Electromagnetic forces

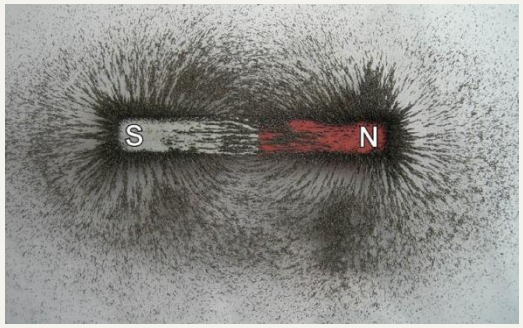
- In classical electromagnetic theory we consider that EM force is transmitted through an **electromagnetic field**



- An electric charge sets up an **electric field** in the region of space surrounding it
- Other charges, placed in an electric field, feel an **electrostatic force**

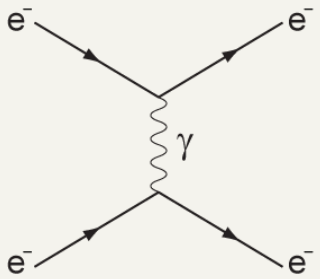


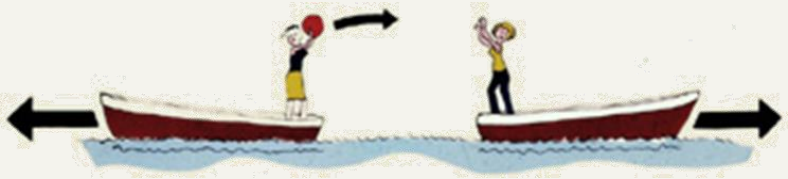
- An electric current (or magnet) sets up a **magnetic field** in the region of space around it
- Other currents (or magnets), placed in a magnetic field, will feel a **magnetic force**



What is a (EM) field?

- Electric and Magnetic forces acts at a distance, without contact. For a long time, this was difficult for people to accept.
- Michal Faraday introduced the concept of "Fields" (field lines or lines of force), but without an explanation what it is made of or how it is created.
    - But it felt a lot better with the concept of fields.





- The explanation is given in quantum field theory (quantum electrodynamics, QED). According to QED electromagnetic force is mediated by virtual photons.
- Classical electromagnetic theory (in this course) takes fields as abstract given entitles, and study their properties without worrying about what they are made of.

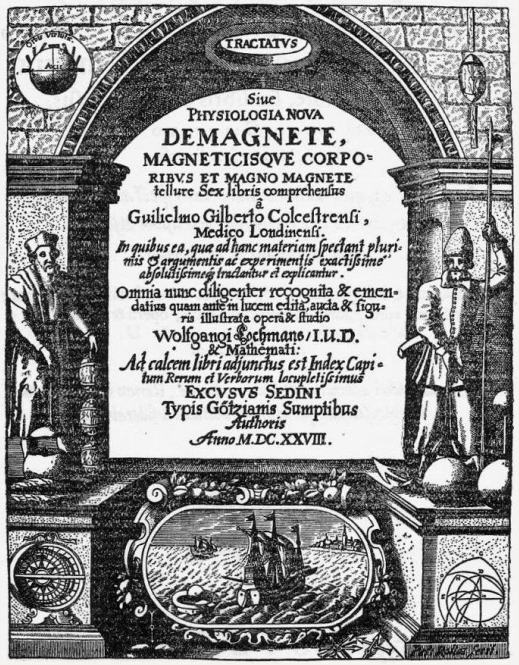
Key figures and events in the history of Electromagnetism

amber attracting a feather : electricity

lodestone attracting iron: magnetism

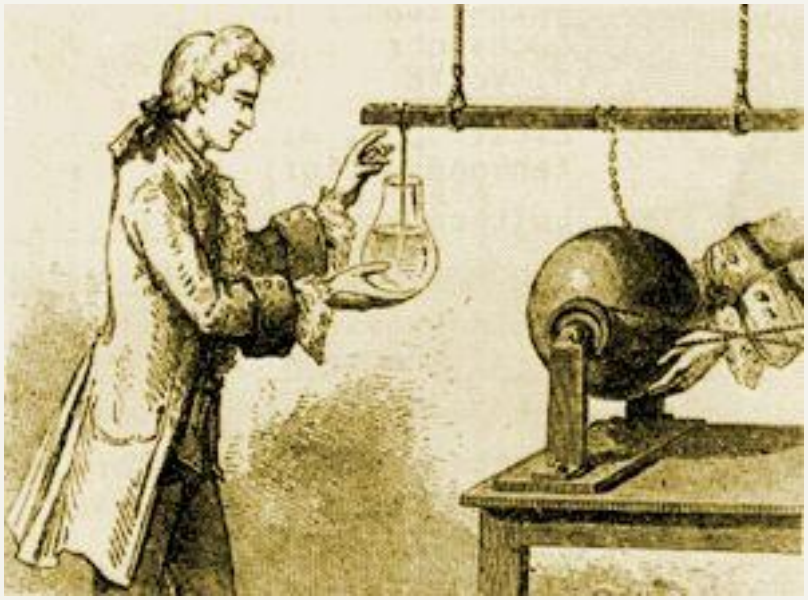
- Greek scholar Thales (6thc BCE) noted that amber attracts feathers and other light materials when rubbed with fur - The first historical reference to static electricity.
- Ancient Chinese, Greeks and many others had known *lodestone (*mineral magnetite) attracts iron; the magnetism.
  - They were used to make compasses.

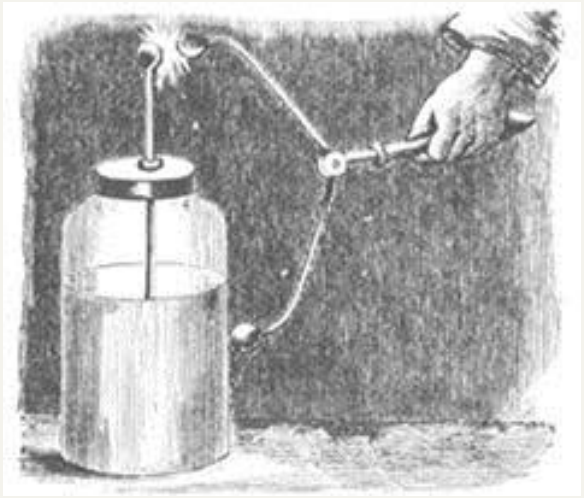
William Gilbert (1544-1603)



- An English scientist and a physician, William Gilbert did many studies of electricity and magnetism.
  - He coined the word *electricus (Latin)* for static electricity (*from Greek word elektron* for amber).
  - which later became ‘electricity’ in English.
- He discovered the geo-magnetism and showed that the earth was a giant magnet.
  - Reason why a compass points to north/south.

Pieter van Musschenbroek (1692 – 1761)





- Musschenbroek a Dutch physicist from Leiden, Netherlands, discovered *capacitance* and invented the *Leyden jar*. The first eclectic storage device (capacitor or electric condenser).

Benjamin Franklin (1706 – 1790)

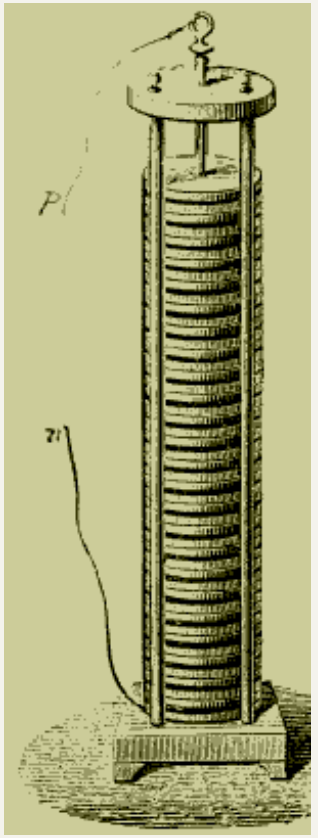
Franklin conducted many experiments on static electricity, he showed that lightning was due to electricity.

Charles Coulomb (1736 – 1806)

Using a torsion balance, Coulomb in 1784 experimentally determined how electrostatic force change with charge and distance, and showed it followed the inverse square law.

Coulomb's Law $$\mathbf{F} \propto \frac{q_1 q_2}{r^2}$$

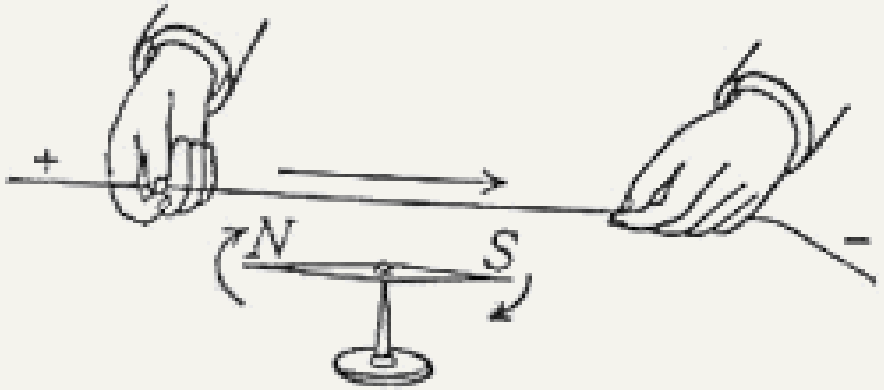
Alessandro Volta (1745 – 1827)



In 1799 Volta developed the first electric battery (voltaic pile).

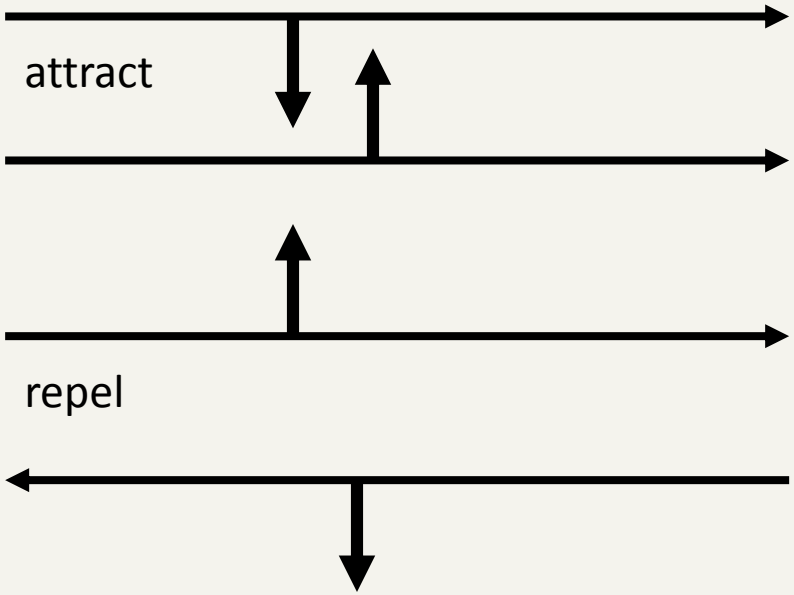
- It generated electricity (current) from the chemical reaction of zinc and copper discs separated from each other with cardboard discs soaked in a salt solution.

Hans Christian Oersted (1777 – 1851)



Danish scientist Oersted in 1820 showed that a current produces a magnetic field.

André-Marie Ampère (1775 – 1836)



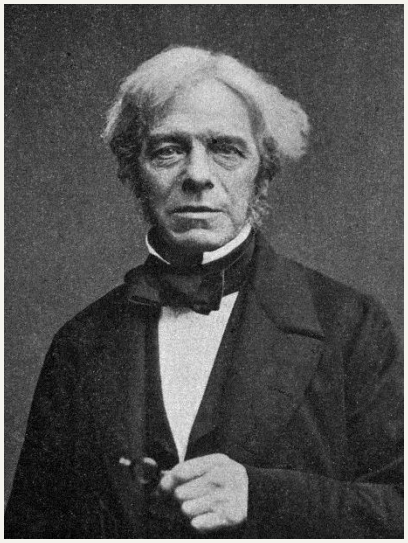
- Right after the Oersted's discovery in 1820, French physicist and mathematician Ampere demonstrated that parallel wires carrying currents attract/repel each other.

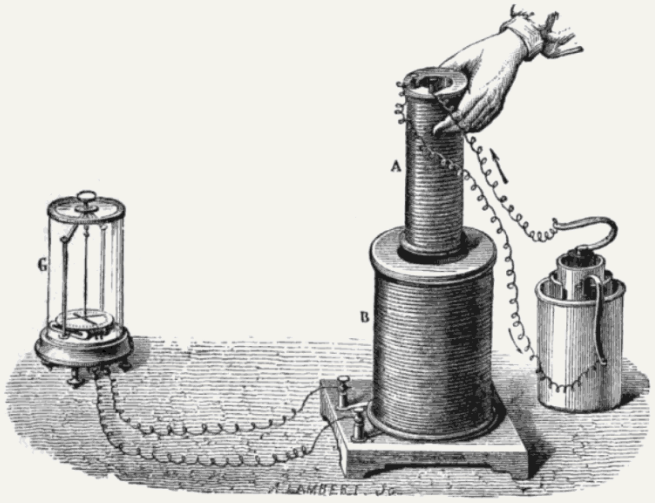
- From those experimental results Ampere formulated the physical principle that came to be called "Ampere's law.

Georg Simon Ohm 1789- 1854

1826: Georg Simon Ohm German mathematician and physicist, established the result now known as Ohm's law. V = IR

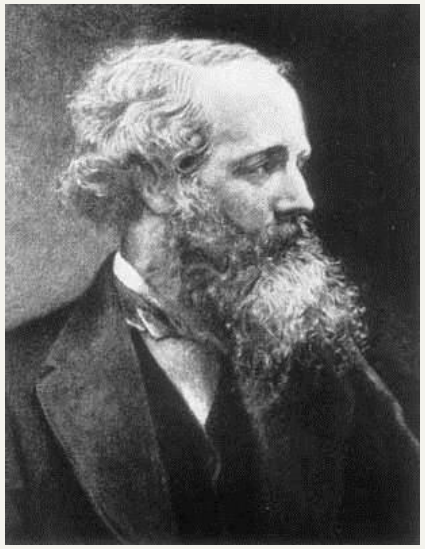
Michael Faraday (1791 – 1867)





- English chemist and physicist Faraday did many experimental studies of electricity and magnetism.
- He introduced the concept electric and magnetic fields (lines of force).
- His most significant discovery was the electromagnetic induction in 1831, *a changing magnetic field induces an electric field.*

James Clerk Maxwell (1831 – 1879)

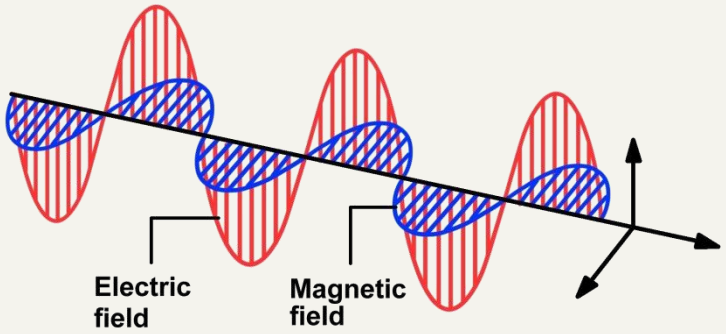


$$\nabla \cdot \mathbf{D} = \rho$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

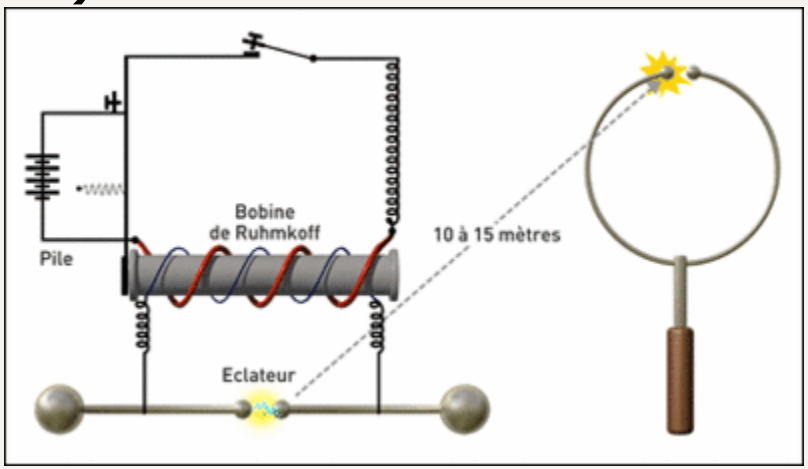


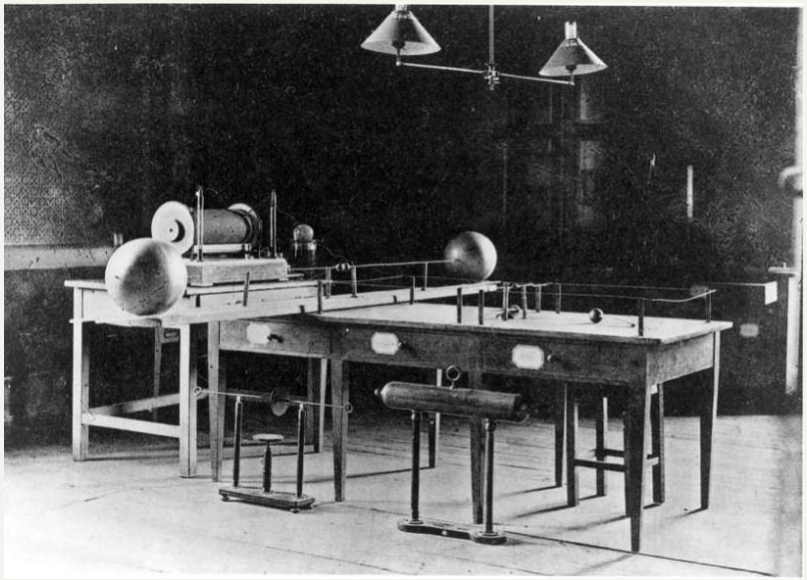
- Maxwell developed a mathematical description of Faraday's fields, and showed that electricity and magnetism are inter-related and they are different aspects of the same entity, the electromagnetism.

- He expressed all of the properties of electricity and magnetism in a set of differential equations, Maxwell equations.

- Using his formulation, Maxwell showed that light was an electromagnetic wave and predicted the existence of other types of electromagnetic waves.

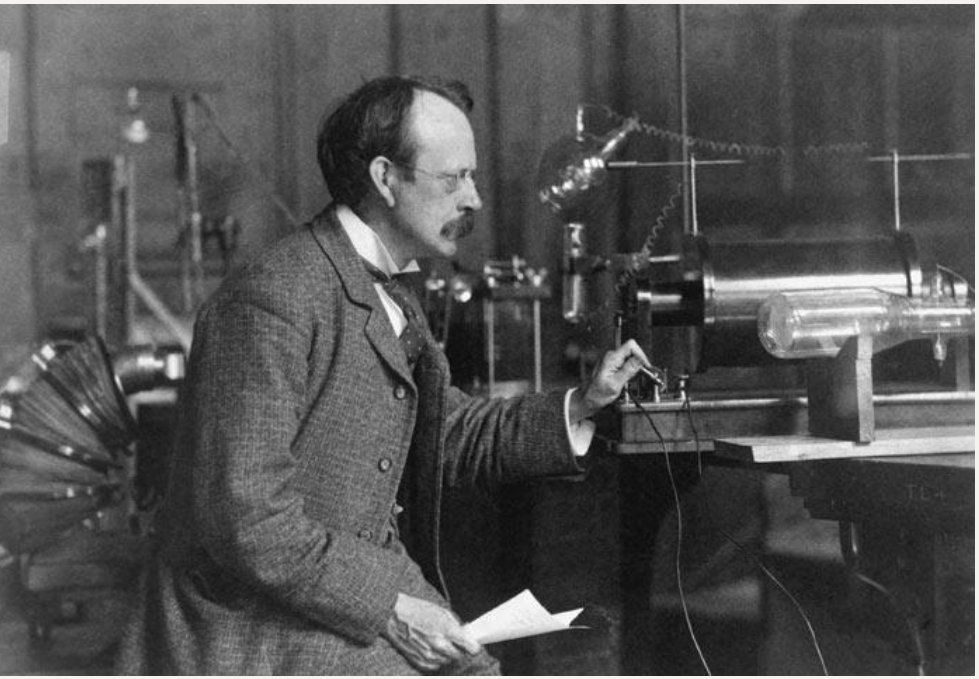
Heinrich Hertz (1857 – 1894)





In 1886 Hertz discovered (produced and detected) electromagnetic waves (radio waves) .

Joseph John Thomson (1856-1940)



- In 1887, J J Thomson showed that cathode rays were negatively charged particles which were later named electrons.

The story continues but we will stop here.

- A nice reference can be found at this web link: http://web.hep.uiuc.edu/home/serrede/P435/Lecture_Notes/A_Brief_History_of_Electromagnetism.pdf

Synthesis of ideas in physics

- **Electromagnetism** is a good example of synthesis of ideas in physics, understanding apparently different phenomena as a consequences of a deeper reality.
  - e.g: Newton showed that it the same force that cause apples to fall and that holds celestial objects (universe) together.

- Until 19th century, *electricity* and *magnetism* were considered separate phenomena. Work of Oersted, Ampere, Faraday… showed they were somehow related
  - a magnet, as well as a battery can drive an electric current
  - Electric currents produce magnetic fields

- This was cumulated with Maxwell's formulation of electromagnetism, which enabled him to realize the relation between light and electricity/magnetism, and laid the foundation of modern electromagnetic theory

$$\nabla \cdot \mathbf{D} = \rho, \quad \nabla \cdot \mathbf{B} = 0, \quad \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \quad \nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

- These elegant equations are written in the mathematical formulation of **vector calculus**, which we will first study.
- Later we will derive these equations, and discuss the physical phenomena they represent.

Outline of the Course

Very broadly we will be discussing following topics:

- An introduction to vectors and vector calculus
- How electric fields are produced by charges
- How magnetic fields are produced by currents
- How those fields are described in terms of potentials, how to evaluate them.
- How those fields are modified in materials.
- Electromagnetic forces, energy and conservation laws.
- How a changing magnetic field produces an electric field, and a changing electric field produces a magnetic field
- How these phenomena produce light (electromagnetic radiation) and how properties of light is explained in terms of electromagnetic theory.

Content of the Textbook

1. Vector Calculus
2. Vacuum Electrostatics, Gauss Law
3. Electrostatic Potential and Boundary Value Problems
4. Electrostatics in Matter, D Field
5. Magnetostatics (in Vacuum), Biot-Savart, Ampere's Law, Static Vector Potential
6. Magnetization-Static B Fields in matter, Susceptibility/Permeability, H field
7. Electrodynamics- EMF, Faraday's Law, Inductance, Amere-Maxwell, Maxwell Equations
8. Conservation Laws, Continuity Eqn, Poynting Theorem, Maxwell Stress Tensor, Linear and Angular Momentum of Fields
9. Electromagnetic Waves, Kinematics, Polarization, Wave Equations , Reflection and Transmission, Dispersion, Waveguides
10. Potentials and Fields- Dynamic Scalar and Vector Potential, Guage Transformations, Retarded Potentials, Leindard-Wiechert Potentials, Fields of Point Particles
11. Dipole Radiation
12. Electrodynamics and Relativity

- I am hoping that you will enjoy learning electromagnetism and exploring the phenomena it describes and look forward to working with you.

- Course web page: http://www.phy.olemiss.edu/~perera/EM