ES 430

Electromagnetic

Chapter 1

Updated: 1/22/12

General Notes

- SI Units
- SI Prefixes
- Vectors

Applications of EM

Evolution of Electromagnetic

- Electromagnetic: Static or Dynamic (time varying)
  - Electric phenomena
  - Magnetic phenomena
- Classical period of EM evolution
  - Fundamentals of law of electricity, charges, electric current
- Modern history of EM→ New applications!

Classical History of EM

- 1820: Electric Battery [Volta]
- DC electric motor using the concept of inductance [Joseph Henry]
- Electric Generator; magnetic field ~~>electric field~~>Voltage [Faraday]
- 1894: Electric field ~~>magnetic field; showed the relation between Ampere; Faraday, Coulomb Law, Oersted through FOUR elegant equations!
  - Maxwell demonstrated that EM exists! (Father of EM theory)
- Proof of EM experimentally [Hertz]
- Invention of X-Rays (a form of EM) [Wilhelm Rontgen]
- Invention of AC motor [Tesla]
- Electrons identified as the carrier of electricity [Joseph Thomson]
- Formulation of quantum theory of matters [Plank]
- Electrons can be ejected using electromagnetic (light) – beginning of modern EM

Oersted: Danish scientist showed that when current passing through a wire it creates electric field using a compass!!

Fundamental Forces

- Nuclear Force
  - Subatomic scale / nuclear forces (1) – very strong
- EM Force
  - Molecules and atoms, microscopic scale (10^-2) → due to charges/ magnetic forces
- Interaction Force
  - Radio active elements (10^-14)
- Gravitational Force
  - Macroscopic scales (10^-41) → due to mass (solar system)

Some analogy between EM and Gravitational forces.

Fundamental Forces

- Remember that Force (N – Newton)
- Fem = Fe + Fm → Electrical Force + Magnetic Force
- These forces have magnitude and direction
- They change according to distance
- They have difference sources
- The medium that they are operating in impacts their magnitude

Static EM

- We first look at Electric component (force) part of EM
    - What is Coulomb's law?

Units: coulomb

One coulomb: amount of charge accumulated in one second by a current of one ampere. (in other words: $I = dq(t)/dt$)

1 coulomb represents the charge on ~ 6.241×10^{18} electrons

The coulomb is named for a French physicist, Charles-Augustin de Coulomb (1736-1806), who was the first to measure accurately the forces exerted between electric charges.

Charge of an electron

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

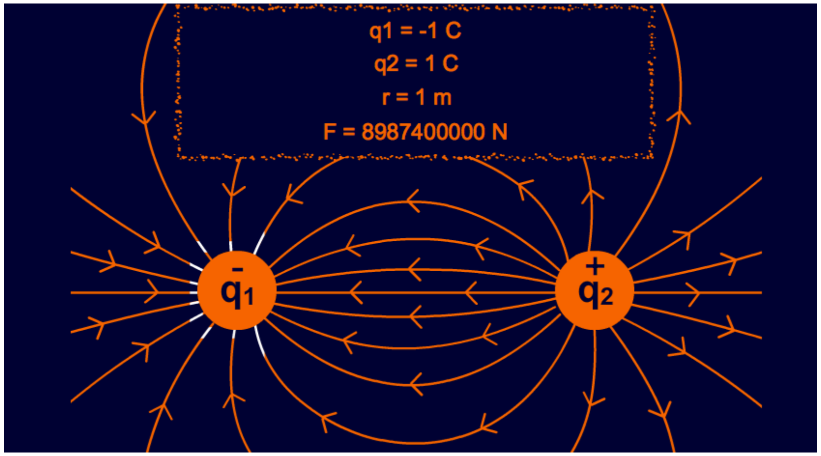
Charge conservation

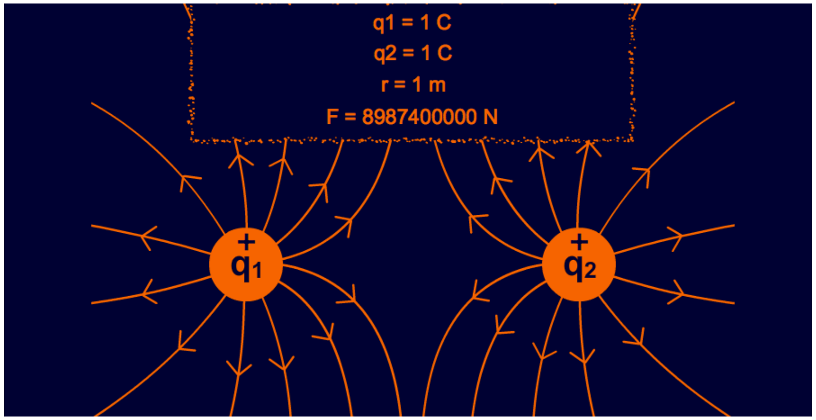
Cannot create or destroy charge, only transfer

Coulomb’s Law

Coulomb’s experiments demonstrated that:

(1) *two like charges repel one another, whereas two charges of opposite polarity attract,*





http://www.ilovemedia.es/force-calculator/

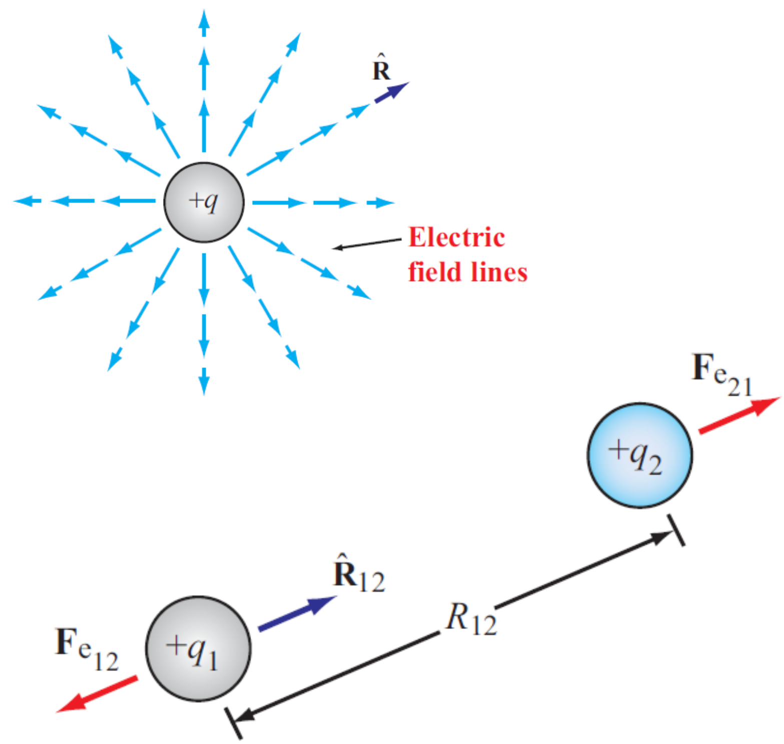
Coulomb's Law

Coulomb's experiments demonstrated that:

(1) *two like charges repel one another, whereas two charges of opposite polarity attract,*

(2) *the force acts along the line joining the charges, and*

(3) *its strength is proportional to the product of the magnitudes of the two charges and inversely proportional to the square of the distance between them.*



Unit vector from q1 to q2

$$\mathbf{F}_{e_{21}} = \hat{\mathbf{R}}_{12} \frac{q_1 q_2}{4\pi \varepsilon_0 R_{12}^2} \quad \text{(N)} \quad \text{(in free space)},$$

E-Force exerted on charge 2 by charge 1

Electrical permittivity of free space
8.854x10^-12 F/m **(Farads/meter)**

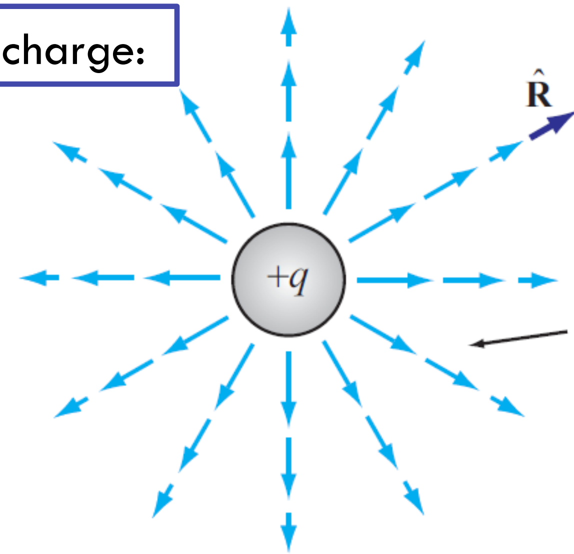
Electric Field Intensity (Volt per meter)

The electric field induced (in the medium) by an electric charge:

Radiated unit vector

$$\mathbf{E} = \hat{\mathbf{R}} \frac{q}{4\pi \varepsilon R^2} \qquad \text{(V/m)}$$

Permittivity of the material (F/m);
Relative permittivity of AIR is 1



Electric Flux Density (C per area)

Another quantity used in EM is the electric flux density **D**:

$$\mathbf{D} = \varepsilon \mathbf{E} \qquad (\mathrm{C/m^2})$$

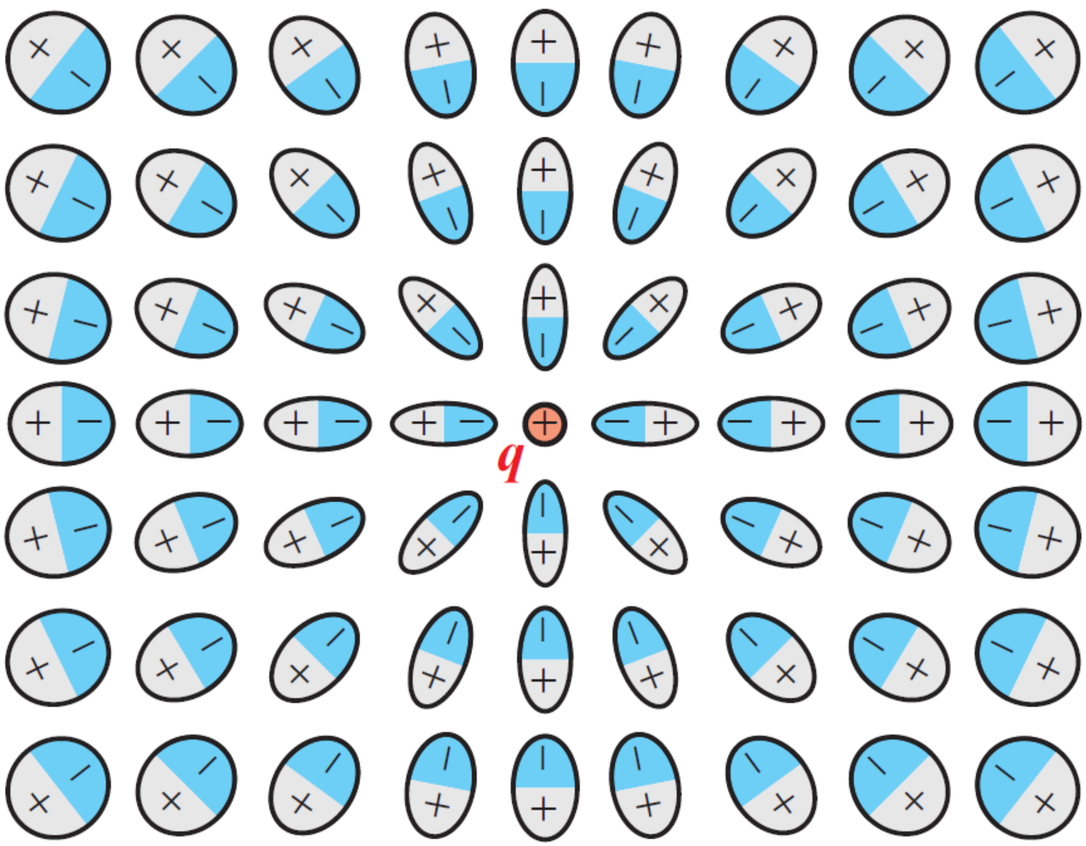
Remember: Flux is a quantity expressing the strength of a field of force in a given **area**

Electric Field inside Dielectric Medium

When a TEST charge is placed atoms are distorted → atoms are polarized →**electric dipole** is generated →we call this **polarization** →

Polarization of atoms changes electric field

$$\mathbf{E} = \hat{\mathbf{R}}\frac{q}{4\pi\varepsilon R^2} \qquad \text{(V/m)}$$



Magnetic Flux Density (Tesla)

Electric charges can be isolated, but magnetic poles always exist in ***pairs.***

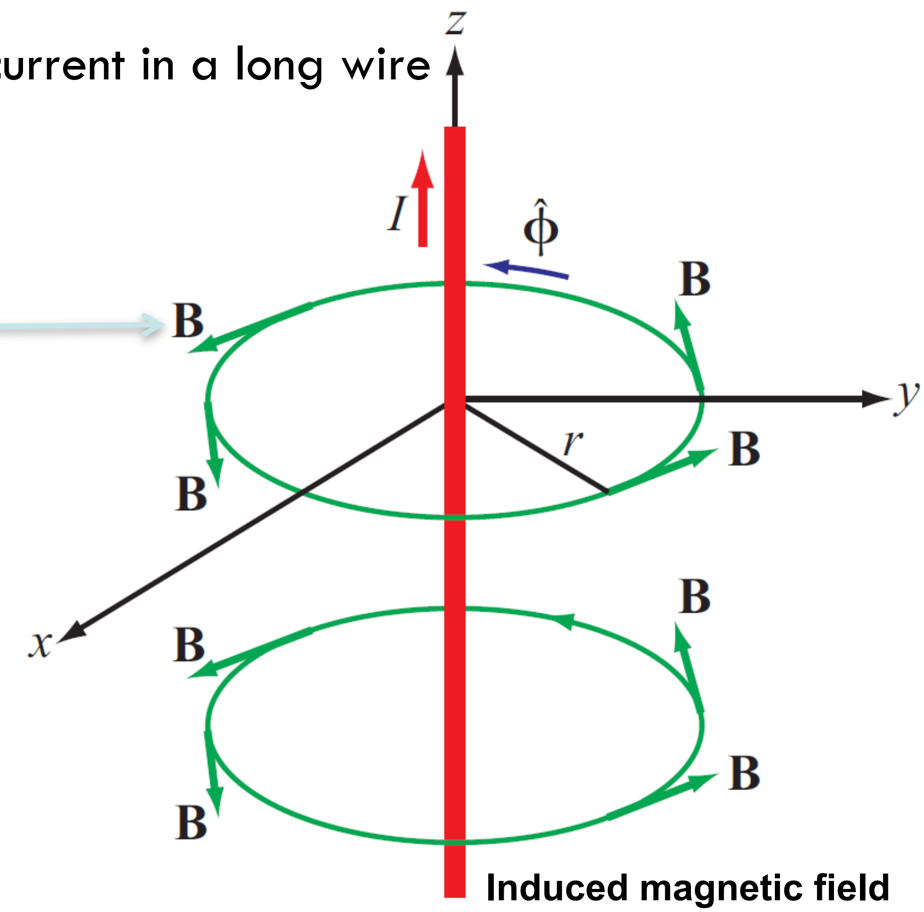
Magnetic field induced by a (steady state) current in a long wire

$$\mathbf{B} = \hat{\boldsymbol{\phi}} \frac{\mu_0 I}{2\pi r} \qquad \text{(T)}$$

Azimuthal unit vector

$$\mu_0 = 4\pi \times 10^{-7} \ \text{henry per meter (H/m)}$$

Magnetic permeability of free space



Electric and magnetic fields are connected through the speed of light:

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = 3 \times 10^8 \qquad \text{(m/s)}$$

Demonstration: http://www.falstad.com/vector3dm/

Magnetic Field Intensity (Ampere / meter)

Magnetic field intensity $\mathbf{H}$ (A/m)

$$\mathbf{B} = \mu \mathbf{H}$$

Static vs. Dynamic EM

Static conditions: charges are stationary or moving, but if moving, they do so at a constant velocity.

Branches of Electromagnetics

Branch	Condition	Field Quantities (Units)
Electrostatics	Stationary charges $(\partial q/\partial t = 0)$	Electric field intensity **E** (V/m) Electric flux density **D** (C/m^2) $\mathbf{D} = \varepsilon \mathbf{E}$
Magnetostatics	Steady currents $(\partial I/\partial t = 0)$	Magnetic flux density **B** (T) Magnetic field intensity **H** (A/m) $\mathbf{B} = \mu \mathbf{H}$
Dynamics (Time-varying fields)	Time-varying currents $(\partial I/\partial t \neq 0)$	**E**, **D**, **B**, and **H** (**E**, **D**) coupled to (**B**, **H**)

Under **static** conditions, induced electric and magnetic fields are independent; under **dynamic** conditions, fields become coupled

Remember: Static → DC; Dynamic (time varying) → AC/ Sinusoidal/Periodic waveforms

A bit about Units

Electric Field Intensity

$$\mathbf{E} = \hat{\mathbf{R}} \frac{q}{4\pi\varepsilon R^2} \quad \text{(V/m)}$$

= C/ [(F/m) . m^2] = C / (F.m)= V / m

Note: F = C/V = N;

Magnetic Flux Density

$$\mathbf{B} = \hat{\boldsymbol{\phi}} \frac{\mu_0 I}{2\pi r} \quad \text{(T)}$$

= (H/m).A / m = H.A / m^2 = T

Remember:

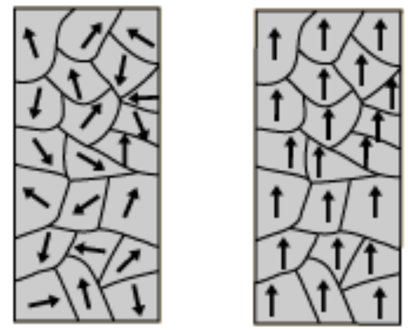
Permittivity → related to E fields which results in polarization (ε=F/m)

Permeability→ related to magnetic field (μ=H/m) [permeable ~ fluids]

Both are expressed per meter

Properties of Materials

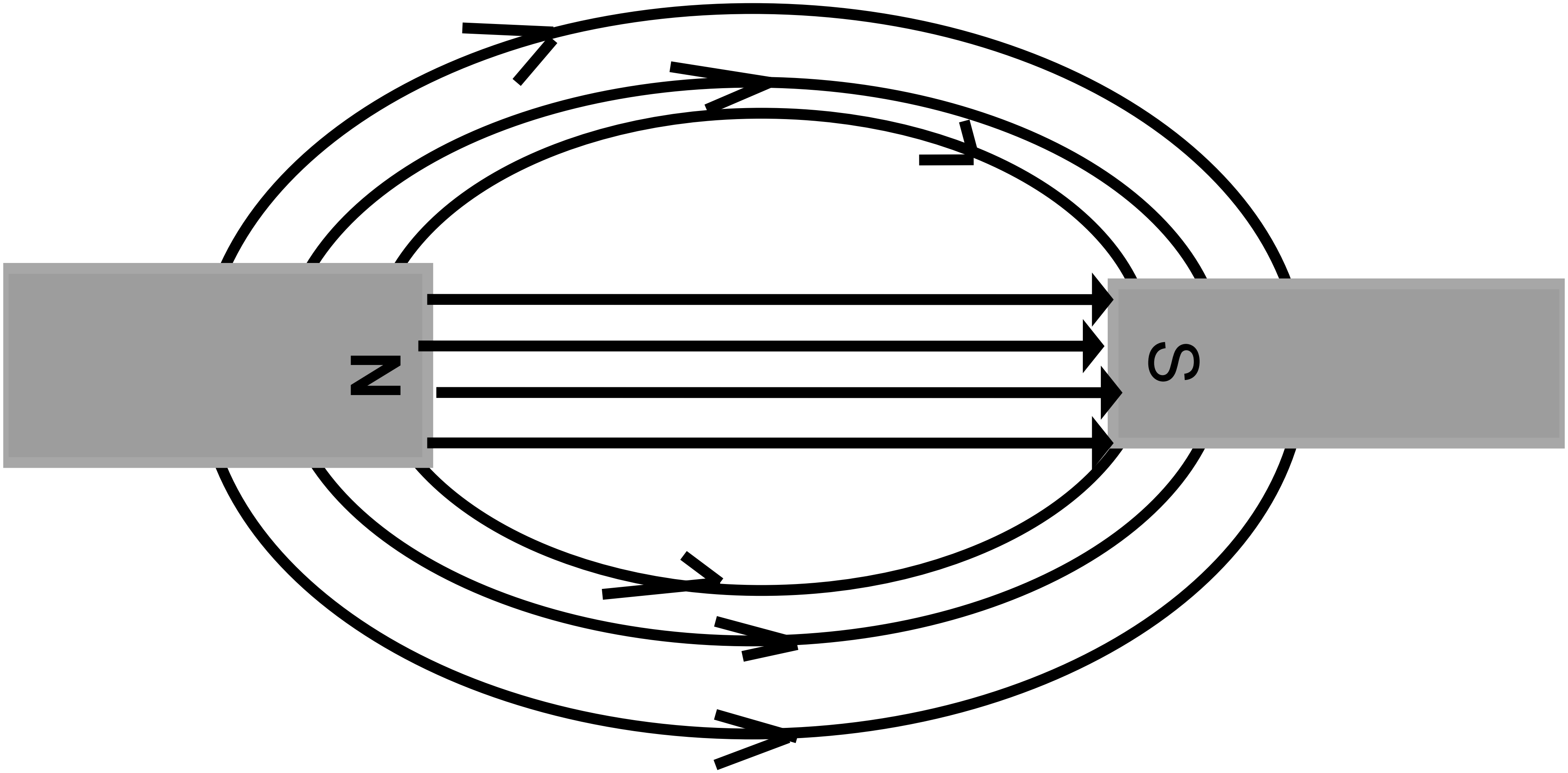
- The origin of the magnetic properties is a result of the spins of the unpaired electrons.
- When a material is not magnetized, the unpaired electrons spin in random directions, however in a magnet the spins of the unpaired electrons are all oriented in the same direction.



- In many materials, each electron is paired with another having an opposite spin.
- Magnetic effects mostly cancel each other.
- As a result, these materials have extremely weak magnetic fields.

- Some other materials, like nickel, cobalt and iron, have one or more unpaired electrons.
- The unpaired electrons produce magnetic fields.

Properties of Materials

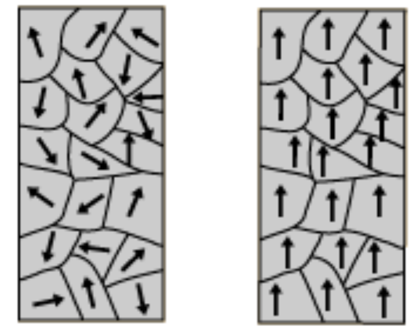


Properties of Materials

- Electric Permittivity ε (F/m) $\mathbf{E} = \hat{\mathbf{R}} \frac{q}{4\pi \varepsilon R^2}$ (V/m)
  - The higher it is, less E is induced, lower polarization
- Magnetic Permeability μ (H/m) $\mathbf{B} = \hat{\boldsymbol{\phi}} \frac{\mu_0 I}{2\pi r}$ (T)
  - Higher value → **more** retention of magnetic property can be experienced in the material after removing B field
    - For ferromagnetic materials (Nickel, Cobalt)
  - If diamagnetic (gold) and paramagnetic (air) μ ~1
- Conductivity (S/m = Siemens/meter)
  - σ = INF → perfect conductor
  - σ = 0 → perfect dielectric

Remember: **Homogenous** medium is medium with constant properties

Properties of Materials



- Ferromagnetic materials (Nickel, Cobalt, pure Iron) – magnetic material
  - Retain magnetic property
  - Higher μr→more retention
  - Electrons are unpaired orbiting around
- Diamagnetic materials (Gold, Copper) – non-magnetic material
  - Composed of atoms which have no net magnetic moments (i.e., all the orbital shells are filled and there are no unpaired electrons) - no net magnetic moment
  - When exposed to a field, a negative magnetization is produced
  - μr=1 (slightly less than 1)
- Paramagnetic materials (Air, Aluminum) – non-magnetic material
  - some of the atoms or ions in the material have a net magnetic moment due to unpaired electrons in partially filled orbitals
  - Magnetization is zero when the B field is removed
  - In the presence of a B field, there is a partial alignment of the atomic magnetic moments in the direction of the field, resulting in a net positive magnetization
  - μr=1 (slightly more than 1)

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Chart of the Electromagnetic Spectrum