Objectives:

- Charge, Electrostatics and Induction,
- Electric field and Forces on Charges,
- Conductors in Electric Fields,
- Lightning,
- Current, Resistance, Ohm’s Law,
- Power,
- Electrical Safety.
Electrostatics:  
As early as 600 BC, Ancient Greeks discovered that lumps of amber charged by friction (rubbing) would pick up small pieces of straw.  
Greek word for amber is "elektron"  
Magnetism discovered at about same time. Named after middle east region called Magnesia

Electric Force and Electric Charge: §26.2  
Ordinary matter composed of neutral atoms (no net charge). Particle scattering expts ⇒ atom composed of:  
• positively charged nucleus  
  • protons (+ve)  
  • neutrons (neutral)  
• surrounded by "cloud" of electrons (negatively charge)  
Neutral atom: # of electrons = # of protons  
Ion: imbalance in + and – charge due to excess or deficit of electrons (wrt # of protons)

Electric Force:  
Force of attraction b/w protons and electrons due to their electric charge (holds atoms together).

Electrostatics:  
Deals with forces b/w charges at rest (or nearly at rest: quasistatic)

Direction of Electric Force:  
Opposite charges attract  
Like charges repel

Unit of Electric Charge:  
Electric force b/w objects depends on their net electric charge.  
Minimum unit of charge found in nature (thus far) is:  
\[-e\] charge on electron  
\[+e\] charge on proton

Unit of Electric Charge:  
\[e = 1.60 \times 10^{-19} \, \text{C (Coulomb)}\]  
= magnitude of charge on electron or proton  
(Chosen so that current of 1 A (ampere) = 1 C.s\(^{-1}\))
**Charge Quantization:**

Electric charge is quantized (quantum unit is e)

<table>
<thead>
<tr>
<th>Charge</th>
<th>Particle</th>
</tr>
</thead>
<tbody>
<tr>
<td>-e</td>
<td>electron $e^-$, pion $\pi^-$, muon $\mu^-$</td>
</tr>
<tr>
<td>+e</td>
<td>proton $p^+$, pion $\pi^+$, positron $e^+$</td>
</tr>
<tr>
<td>0</td>
<td>neutron $n$, neutrino $\nu$, photon $\gamma$</td>
</tr>
</tbody>
</table>

(In particle theory, quarks postulated to have:

up (u)       +2/3 e  
down (d)      -1/3 e  (and antiparticles too)  
strange (s)  -1/3 e  

These have not yet been observed.)

**Conductors and Insulators:**

**Conductor:**

Outer shell electrons not involved in bonding ⇒ free to travel through volume of conductor ⇒ permits motion of electric charge through volume (In Cu ~10^{22} e’s per cm^3 available for conduction).

**Insulator:**

All electrons located in bonds b/w atoms ⇒ none free to move charge. (e.g. glass, plastic, very pure water)

**Semiconductor:**

Number of free electrons strongly dependent on doping (purity) of material. (Si, Ge, GaAs...)

**Charging:**

A surface charge can be produced on insulators by rubbing (e.g. rubbing glass rod with cat’s fur). This involves transfer of some surface electrons from one object to the other.

Aircraft can become charged due to electron transfer with air, dust + ice particles etc.

**Charging:**

Surface charge can be produced on insulators through charge transfer by friction: weak molecular bonds are formed and broken during contact and sometimes when the bond breaks an electron ends up swapping from one material to the other.

Rub the plastic rod with a piece of wood. This end is still neutral. The positive charge on the wool is equal to the negative charge on the rod.

The surface charge is immobile on an insulator.
Conductors can share charge by contact:

Equal charges on each.

... or charge can be induced:

Opposite charges on each.

electron transfer to/from "earth"

The Electroscope:

Charging by Induction: The Electrophorus

Fixed charge produced on paraffin surface.

Charge separation induced between top and bottom surfaces of metal plate.
Charging by Induction: The Electrophorus

Charge transfer between top plate and "Earth".

Net charge on plate.

Photocopiers and Laser Printers

(1) A photoconductive surface is given a positive charge (+).

(2) The image of a document is exposed on the surface. This causes the charge to drain away from the surface in all but the dark areas.

(3) Negatively charged toner powder is cascaded over the surface. It electrostatically adheres to the positively charged image area making a visible image.

(4) A piece of plain paper is placed over the surface and given a positive charge.

(5) The negatively charged powder image on the surface is electrostatically attracted to the positively charged paper.

(6) The powder image is fused to the paper by heat.
Electric Field:

Electric force is mediated by the **electric field**. Electric field is disturbance of space surrounding a charge due to its presence.

A second charge introduced into the space occupied by the electric field of the first charge experiences an electric force through an interaction with the field.

If a charge moves suddenly the change in the electric field propagates outward from the charge at the speed of light.

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Electric Field

**Electric field** defined as force per unit positive charge, \( q \):

\[
\vec{E} = \frac{\vec{F}}{q} \quad (\text{Units: } \text{N/C} \text{ or } \text{V/m})
\]

\[
\Rightarrow \vec{F} = \vec{E} q
\]

\( \Rightarrow \) find magnitude and direction of \( \vec{E} \) at some point in space by placing small +ve test charge, \( q \), at that point.

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Light Propagation (Qualitative)

- Changing electric electric field associated with an oscillating charge:

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Electric Dipole:

Many asymmetric molecules are electric dipoles e.g. \( \text{H}_2\text{O} \) molecule:

\[\text{H}_2\text{O} \]

Dipoles can also be induced by charge separation in an electric field e.g. on grass seeds or soot particles.
How big is the electric field?

- Inside copper wire of household circuits: $10^{-3}$ N/C (or V/m)
- Charged plastic comb: $10^3$
- Electron beam in TV; photocopier corona wire: $10^5$
- Electric breakdown in air: $3 \times 10^6$
- Hydrogen atom, at electron orbit radius: $5 \times 10^{11}$
- At uranium nucleus: $3 \times 10^{21}$

  - Force holding nucleus together is very strong!

Electric Field Lines:

- give graphical representation of electric field
- tangent to field line gives direction of $E$ at any point
- direction of arrows = direction +ve test charge would move if placed in field
- density of field lines proportional to field strength at any point (e.g. close to charge have high field density)

  - field lines originate on + charge
  - field lines terminate on - charge

Visualising Field Lines:

Field lines for pairs of point charges:

Pair of Like Charges

Pair of Opposite Charges

(Figs. 27-10 and 27.9b, Knight, Physics for Scientists and Engineers, 2nd Ed.)
Single Ion Implantation for Quantum Computer Fabrication:

Phosphorus Ions

Detector Electronics

Signal

5nm SiO₂

E-field established in substrate via metal contacts on silicon surface.
When ions enter silicon they lose energy and produce +ve and –ve charges that are separated by the E-field and transferred to the contacts where a current pulse is registered.

Induced Dipole Moment:
Separation of charges can occur in some molecules or bodies (e.g. metals) due to presence of E field. Charge separation ceases when field removed. Dipole moment is “induced” by field.

Charge separation in metal due to E field
(Also, small seeds, threads used to visualise field lines)

Electrostatics in Action – Continuous Inkjet Printer:

Ink droplets formed by shaking reservoir (piezoelectric crystal) or heating (microresistor).
Droplets charged by induction: charge separation along stream arising from E-field produced by charging electrode.
Charge on droplet selected by setting charging potential.
Fixed E-field between deflector plates: droplet steered according to its charge.

Electrostatics in Action – Continuous Inkjet Printer:

Droplets charged by induction: charge separation along stream arising from E-field produced by charging electrode.
Charge on droplet selected by setting charging potential.
Conductors in Electric Fields:
In conductor, large # of free electrons available ⇒ when conductor placed in \( E \)-field, free electrons move in opposite direction to field leaving one surface +vely charged and other -vely charged:

\[
\text{conductor} \quad \rightarrow \quad \begin{array}{c}
\varepsilon_{\text{ext}} \\
\varepsilon_{\text{int}}
\end{array}
\]

Charge separation generates internal \( E \)-field \( E_{\text{int}} \) opposite in direction to the external field.

Separation of charge continues until:

\[
\begin{align*}
|\varepsilon_{\text{int}}| &= |\varepsilon_{\text{ext}}| \\
\varepsilon_{\text{net}} &= 0
\end{align*}
\]

At equilibrium \( E_{\text{net}} = 0 \) everywhere inside conductor

Similarly, excess charge on conductor resides at the surface:

\[
\begin{array}{c}
\varepsilon_{\text{net}} = 0 \\
\varepsilon_{\text{int}} = 0
\end{array}
\]

(same equilibrium condition applies)

This is also what we would expect based on charge repulsion and minimisation of potential energy (see later).

Also, at equilibrium, field lines at surface of conductor are perpendicular to the surface at every point

(otherwise there would be net lateral force on charges and they would move)
Hollow Conductor:

Since excess charge resides on surface and $E=0$ everywhere inside conductor, must also be true for cavity anywhere inside conductor.

$\Rightarrow$ metal shell or cage "shields" interior from electric field

$\Rightarrow$ Faraday Cage

NB. The electrostatic potential will give us a better way of arguing that there can be no electric field lines within an empty cavity in a conductor.
Introduce charge into cavity of conducting shell.

Connect inner conductor to shell. Transfer charge to shell.

To add more charge start the whole process over again.

$E=0$ inside conducting shell.
Lightning:
When $E$-field exceeds $3 \times 10^6$ N/C (V/m) molecules in air can become ionised (neutral molecules broken into +vely and -vely charged ions):

$\text{these ions collide with neutral molecules } \Rightarrow \text{ more ions created } \Rightarrow \text{ collision cascade } \Rightarrow \text{ spark.}$

Sources of Mobile Charges:
Upper Atmosphere: Cosmic Rays (very swift particles from space, mostly protons) enter atmosphere and produce dense collision cascades of charged particles (+ve and -ve).

Terrestrial: Ions produced by natural radioactive decay and other ionisation processes including induced charge on droplets of water spray:

Earth = Giant Spherical Capacitor
Lightning = discharge through volume of capacitor

Current understanding is that: Small ice particles are being charged positively and rapidly transported upward.

Possible Charging Mechanisms

1. Ice particle polarised in E-field + charge exchange with water droplet or another ice particle.
2. Or -ve ions attracted towards ice particle and captured.

Lightning:

Just prior to flash, electron avalanche descends to ground
Charge density in column $\lambda \sim -1 \times 10^{-3}$ C.m$^{-1}$

Once column bridges gap, e- rapidly transported:
- current
- e- collisions with air molecules
- ionisation
- further current
- e- + air molecules
- atom excitation
- spontaneous decay
- photons
- flash
Discharge occurs first wherever E-field greatest:

so hit the deck if this happens to you!

(Fig 25-24, Halliday, Resnick and Walker, Fundamentals Of Physics, Wiley 2001)

**Insulators:**
- Electrons not free to move
- High resistance
- e.g. glasses, ceramics, most plastics, wood, pure water

**Conductors:**
- Many free electrons
- Low resistance
- e.g. metals, impure water, humans, ionized gas

**Semiconductors:**
- Pure semiconductors ~ insulators, presence of certain impurities (dopants) provides free electrons (or holes (+))
- Resistance strongly dependent on presence of dopants
- e.g. Si, Ge, GaAs, GaN, …

**Superconductors:**
- Resistance becomes zero below some critical temperature
- e.g. Hg, Nb, YBaCu₃O₇

**Current, Resistance and Ohm’s Law**
Knight: Chapter 31, 51-5

[Resistivity vs. Temperature graph for Hg]
Electric Current $i$:

Define Current $i = \frac{dq}{dt}$

Charge $dq$ passing through cross-sectional area of conductor in time $dt$

Units: 1 Ampere ($A$) = 1 C/s

Direction of current: arrows drawn in direction +ve charge would move if it constituted the current.

Charge Carriers:
- In a metal the charge carriers are electrons (−).
- In a liquid, the charge carriers are positive (cations) and/or negative ions (anions).
- In a semiconductor the charge carriers are (conduction band) electrons (−) and/or (valence band) holes (+) (bonds that are missing an electron).
- In a plasma (electrical discharge) both positive and negative charges can contribute to the current.
- In some solid-state materials such as those used in fuel cells or batteries both positive and negative charge carriers can contribute to the current.

Resistance:

Define resistance $R = \frac{V}{i}$

Units: 1 V/A = 1 Ω (ohm)

Resistors provide resistance values in circuits.
Ohm’s Law:

\[ i = \frac{V}{R} \]

where \( R \) = constant

(i.e. \( i \propto V \) for all values of \( \pm V \))

Ohmic device: one that obeys Ohm’s Law (e.g. carbon film resistor)

Non-ohmic device: one that doesn’t obey Ohm’s Law (e.g. semiconductor diode)

Fig. 31.22 Knight, Physics for Scientists and Engineers, 2nd Ed.

**Relationship b/w \( R \) and \( \rho \):**

For homogeneous, isotropic conductor:

\[ E = \frac{V}{l} \quad (V/m) \]

\[ \Rightarrow J = \frac{i}{A} = \frac{E}{\rho} = \frac{V}{l\rho} \]

\[ \Rightarrow R = \frac{V}{i} = \frac{\rho l}{A} \]

\( R \) depends directly on the resistivity of the material and the length of the conductor and inversely on the area through which the current is flowing. (Just as one would expect.)

**Resistance (and resistivity \( \rho \)) vs temperature:**

Resistance (and resistivity) of metal conductor increases with \( T \) since amplitude of vibration of lattice atoms increases \( \Rightarrow \) e’s collide with lattice atoms more often.

\[ R = \frac{\rho l}{A} \]

Resistivity depends on the properties of the material but not its geometry.

\[ V \approx 10^{8} \text{ m.s}^{-1} \]

Without E-field, motion is random, \( \sim 10^{14} \) collisions (with lattice atoms) per second (e in Cu) \( \Rightarrow \) direction constantly changing.

No net movement of e’s along conductor

**A model of conduction: Drift Speed \( v_d \):**

Free-electron model of conductor \( \Rightarrow \) e’s free to move throughout volume of solid (like molecules of gas in container). Thermal speed of electrons:

\[ v \approx 10^{8} \text{ m.s}^{-1} \]

Without E-field, motion is random, \( \sim 10^{14} \) collisions (with lattice atoms) per second (e in Cu) \( \Rightarrow \) direction constantly changing.

No net movement of e’s along conductor

With E-field:

- same random thermal motion
- drift speed \( v_d = 10^{-4} \text{ m.s}^{-1} \) superimposed on thermal motion
- Net movement of e’s in direction opposite to E-field
A model of conduction:

Fig. 31.13 Knight, Physics for Scientists and Engineers, 2nd Ed.

Temperature dependence of resistance:

source: http://www.tracielee.com/

Basic Circuit Elements: §32.1

Fig. 32.2 Knight, Physics for Scientists and Engineers, 2nd Ed.

Direct Current Circuits
Batteries and Electromotive Force (EMF):

Battery = an example of a device which is a source of emf (actually a source of energy rather than force)
- It is source of electric potential energy capable of pumping charge around an electric circuit while maintaining constant potential difference b/w its terminals.
- Batteries convert chemical energy to electric energy.

\[ \begin{align*}
\text{electrode: } & Pb + SO_4^{2-} \rightarrow PbSO_4 + 2e^- \\
+\text{electrode: } & PbO_2 + SO_4^{2-} + 4H^+ + 2e^- \rightarrow PbSO_4 + 2H_2O
\end{align*} \]

Define Current

\[ i = \frac{dq}{dt} \]

Units: 1 Ampere (A) = 1 C/s

Battery maintains electric field in conductor that keeps current flowing.

Equivalent Circuit of Battery:

\[ V = iR_{\text{int}} + iR_{\text{load}} \]

As \( R_{\text{int}} \) increases, less emf available for external load. In a battery, \( R_{\text{int}} \) tends to increase as the electrodes age i.e. with use.

Power in Electric Circuits:

\[ \Rightarrow dU = dqV \quad \text{and} \quad i = \frac{dq}{dt} \]

\[ \Rightarrow dU = i dt V \quad \Rightarrow \text{power } P = \frac{dU}{dt} = iV \]

\[ P = iV \]
Power in Electric Circuits:

For an **ohmic conductor**:

\[
\begin{align*}
  i &= \frac{V}{R} \Rightarrow P &= \frac{V^2}{R} = i^2 R = iV
\end{align*}
\]

Power dissipated in resistors in form of heat: conduction e’s lose energy to lattice atoms through collisions ⇒ lattice gains thermal energy.

\[P = iV\]

*Units:* 
1 A V = \(\frac{C J}{s C} = 1 J / s = 1 W\)

**E.g. Power lines:**

Electricity is transferred from power stations through transmission lines at very high voltages (e.g. 500 kV) and not at the 240 V used in houses. Why?

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**Power Lines**

- 1 cm radius cable, 20 km long from LaTrobe valley to Melbourne:

\[
R = \rho \frac{l}{A} = 17 \times 10^{-9} \frac{20000}{\pi (0.01)^2} = 1 \Omega
\]

- Total power output of Loy Yang: \(2200 \times 10^6\) W
- Transmission at 240 V:

\[
i_{\text{output}} = \frac{P_{\text{output}}}{V} = \frac{2200 \times 10^6}{240} = 9.2 \times 10^6 A
\]

---

**Power Lines**

- Power loss in transmission:

\[
P_{\text{loss}} = i^2 R = (9.2 \times 10^6)^2 \times 1 = 8.5 \times 10^{13} W
\]

which is far greater than the power output of the station!

- Alternatively, if we look at the current for transmission via a 1 ohm line at 240 V:

\[
i_{\text{transmission}} = \frac{V}{R} = 240 A
\]

- and that ain’t going to supply the needs of Melbourne!

---

**Power Lines**

- So, let’s try transmission at 500 kV:

\[
i_{\text{output}} = \frac{P_{\text{output}}}{V} = \frac{2200 \times 10^6}{5 \times 10^5} = 4,400 A
\]

\[
P_{\text{loss}} = i^2 R = (4.4 \times 10^3)^2 \times 1 = 1.9 \times 10^7 W
\]

- which is less than 1% of power output of the station. We can live with that!
**Electrical Safety:**
- Most electrical accidents involve AC (alternating current) rather than DC.
- Current enters a house through the ACTIVE wire.
- All current should return through the NEUTRAL wire.
- Any imbalance in ACTIVE/NEUTRAL indicates a fault!
- This “Earth Leakage” is detected by earth leakage protection circuitry and the ACTIVE is shut off.

- Current of 1 mA causes tingling sensation.
- Higher currents ⇒ pain and strong muscle contraction.
- Above 10 mA: severe muscle contractions and victim may not be able to let go of current source.
- 20 mA through body from hands to feet produces contractions of chest muscles that halt breathing.
- 70-100 mA results in heart fibrillation (heart stops pumping blood).
- Many electrical appliances will leak 1 mA to EARTH wire by capacitive coupling.
- Earth leakage protection circuits typically set to trip at 20-30 mA.
- Patients fitted with implanted electrodes can die from as little as 0.02 mA. Electrical equipment for surgery/monitoring must be well insulated.

Be sure, Be safe!