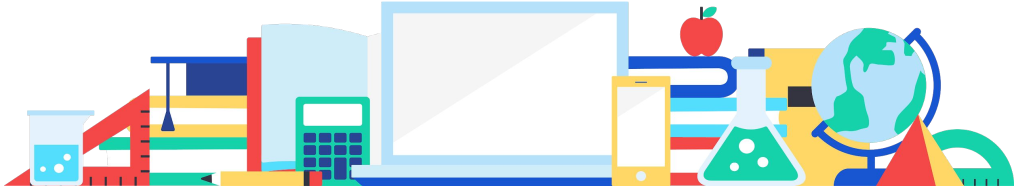
Physics 2 Concepts & Vocab

Updated July 2020



Electricity & Circuits

Electricity & Circuits: Electric Field

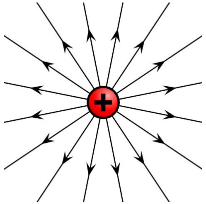
Key Concept

➔ **Coulomb's Law** gives us the **electrostatic force** on a small test charge q from another charge Q as

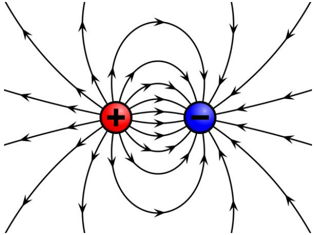
$$F = \frac{kQq}{r^2}$$

➔ We can represent the **force per (positive) unit charge** due to charge Q as an **electric field**

$$\vec{E} = \frac{\vec{F}}{q}$$



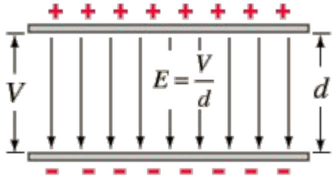
➔ **Field lines** are always perpendicular to the surface of the source. Electric fields due to multiple sources can be summed by vector addition (**superposition**)



Electricity & Circuits: Electric Potential

Key Vocabulary

- The force due to an electric field is **conservative** (work done is **independent** of path taken) $W = Eq\Delta r$
  where Δr is the displacement in the direction of the field
- **Electric potential** is the **potential energy per unit charge** : the work done between 2 points per unit charge (in J/C or volts) is the **potential difference** or **voltage**. If one electron (q= -1.6×10^{-19} C) moves through a voltage of 1V then the WD is 1 electron volt, 1 eV = 1.6×10^{-19} J
- Surfaces with the same PE are **equipotentials** (eg spherical shells for a point charge). Potential is relative (eg zero may be set at infinite distance or at the negative terminal of a battery)
- Work done by the field is the negative of the change in PE
  $$W = -\Delta PE = q\Delta V$$
- Two **charged plates** produce a **uniform field** as shown below



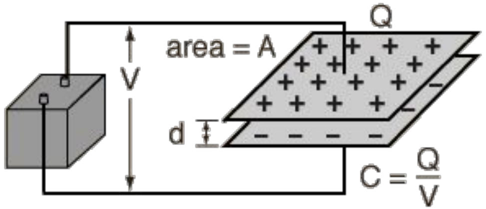
Electricity & Circuits: Capacitance

Key Concept

➔ If two **parallel metal plates** are connected to a voltage V, opposite charges ±Q will accumulate according to the **capacitance** (in Farads F)

$$C = \frac{Q}{V} = \frac{\epsilon_0 A}{d}$$

where A and d are the area and separation of the plates and ϵ_0 is the permittivity of free space $\epsilon_0 = 8.85\times10^{-12}\ C^2/Nm^2$



➔ The **energy** stored on a charged capacitor is given by

$$E = \frac{1}{2}CV^2$$

which is the area under the linear graph of charge vs voltage as the charge builds up on the plates from zero to its eventual value of CV

Electricity & Circuits: Capacitors in Circuits

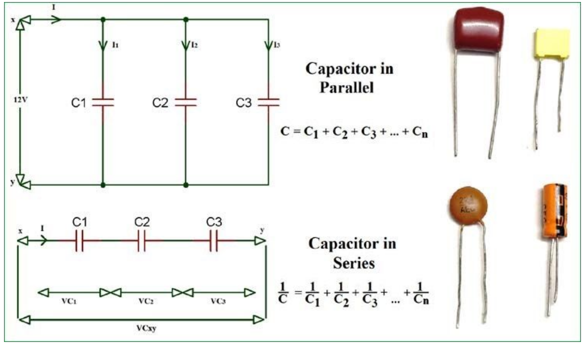
Key Concepts

- For capacitors in **parallel**, since the voltage across each is V, and the total charge is the sum of each charge Q=CV, the **capacitance sums**

$$C = C_1 + C_2 + C_3$$

- For capacitors in **series**, since each section remains net neutral the charge Q = CV on each capacitor is the same, and as the potential differences across each must sum to the total potential difference

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$



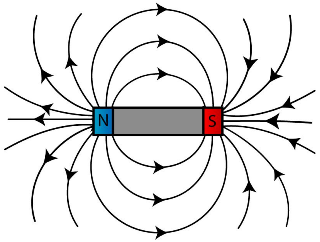
- For a **capacitor and resistor** in series, the initial current I=V/R will gradually decline to zero as charge on the capacitor builds from 0 to CV

Electromagnetism

EM : Magnetic Fields

Key Vocabulary

- **Magnets** have North and South poles.
  - **Like poles repel** and **opposite poles attract**
- **Magnetic field lines** show the **direction** (North to South) and **strength** (through their density) of the field
- Field lines form **closed loops** (even if partly internal to the magnet)



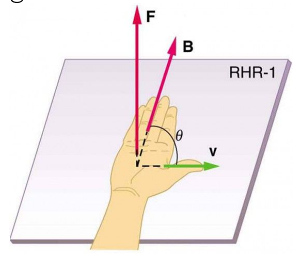
- The ability of a metal to be **magnetized** is called **permeability**. Metals which can be magnetized are called **ferromagnets** and include iron, cobalt and nickel

Key Concept

➔ A **charge** q moving at velocity v at angle θ to a magnetic field B experiences a force

$$F = qvB\sin\theta$$

with direction given by the "**right hand rule**" as illustrated (note for -ve charge the direction of the force would be reversed)

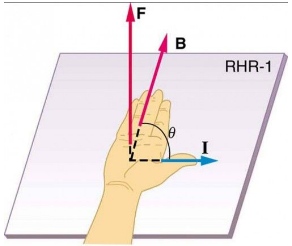


$F = qvB\sin\theta$

F $\perp$ plane of **v** and **B**

➔ For a **wire** of length l carrying a **current** I, the force is given by

$$F = IlB\sin\theta$$



$F = I\ell B\sin\theta$

F $\perp$ plane of **I** and **B**

➔ A charge entering a magnetic field with velocity **perpendicular** to it will experience a force perpendicular to the velocity producing **circular motion**

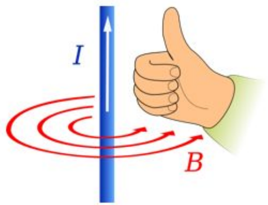
EM : Force on Moving Charge

EM : Field due to Current

Key Concept

➔ A long straight **current-carrying wire** produces a **magnetic field**

$$B = \frac{\mu_0 I}{2\pi r}$$



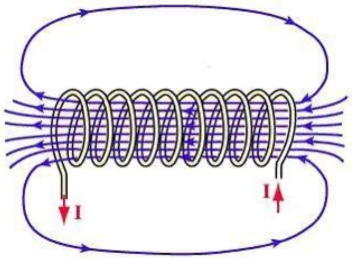
where r is the distance from the wire, μ_0 is the permeability (for air approx $4\pi \times 10^{-7}$ N/A^2) and the direction is given by another RH rule (illustrated)

➔ A **circular loop** (radius r) of wire with N turns produces a magnetic field at its center of

$$B = \frac{\mu_0 N I}{2r}$$

➔ If the loop is stretched into a long **spiral** of length L this is called a **solenoid** and has an approximately **uniform magnetic field** inside it given by

$$B = \mu_0 \frac{N}{L} I$$



Using a higher permeability core (eg iron) will produce a proportionally stronger field

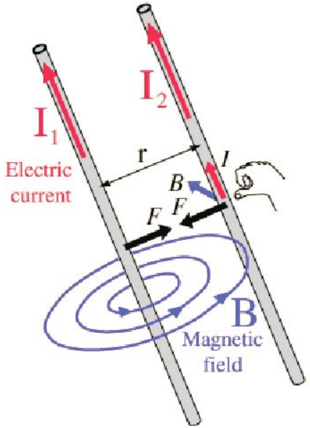
EM : Force between 2 Wires

Problem Solving

- ➔ Two **parallel current carrying wires** will experience a **force** due to each other's magnetic fields and combining

$$F = IlB \quad \text{and} \quad B = \frac{\mu_0 I}{2\pi r}$$

we obtain $$F_{12} = \frac{\mu_0 I_1 I_2 l}{2\pi r}$$



- ➔ Using the RH rule for field direction and then for force direction
  - Currents in **same direction attract**
  - Currents in **opposite directions repel**

EM : Induced EMF & Faraday's Law

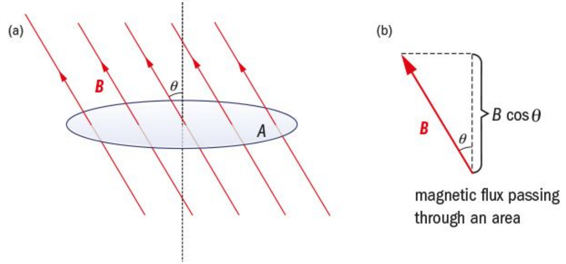
Key Concept

- ➔ A length of wire l moving at velocity v perpendicular to a magnetic field B experiences an induced voltage or "**electromotive force**" (**emf**) given by

$$\epsilon = Blv$$

- ➔ We define the **magnetic flux** of a field B through an area A as

$$\Phi = BA\cos\theta$$



- ➔ **Faraday's Law** of **electromagnetic induction** states that induced emf is equal to the rate of change of magnetic flux

$$\epsilon = -\left(\frac{\Delta\Phi}{\Delta t}\right)$$

- ➔ **Lenz's Law** states that the **induced current** always flows in the direction such that its own magnetic field **opposes** the field that induced it

Physical Optics

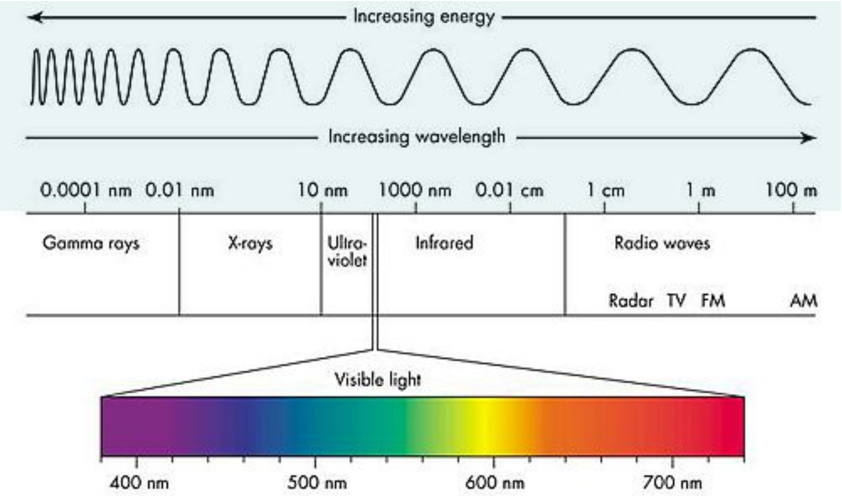
Physical Optics : EM Waves

Key Vocabulary

- **Electromagnetic waves** are **transverse waves** of oscillating EM fields
- EM waves transfer **energy**, and require no medium in which to propagate
- Their frequency f and wavelength λ are related by

$$c = f\lambda$$

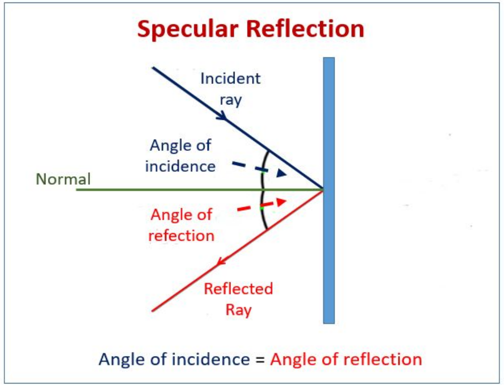
where in vacuum the **speed of light** c = 3×10^8 m/s
- Radio waves, microwaves, visible light, X-rays and gamma rays are all part of the **electromagnetic spectrum** as shown below



Physical Optics : Reflection

Key Vocabulary

- **Reflection** off a **smooth** surface is **specular** with angle of reflection equal to the angle of incidence



- Reflection off a **rough** surface is **diffuse** (at various angles)
- The **color** of an opaque object is dictated by which wavelengths it reflects
- Light consisting of a single wavelength is **monochromatic**
- Light where all waves are in phase is **coherent**. Laser light is both monochromatic and coherent

Physical Optics : Refraction & Total Internal Reflection

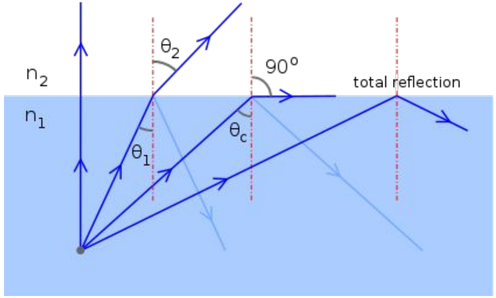
Key Concept

- ➔ The speed of light varies in different media, as measured by the **refractive index** $n=c/v$, where $n \geq 1$ and c and v are the speed of light in vacuum and the medium. Note that the frequency of a wave cannot change and thus it is the wavelength that changes in different media
- ➔ Light passing between media of different refractive indices will be **bent** towards or from the normal according to **Snell's Law**

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

- ➔ When light enters a medium of lower refractive index (is bent away from the normal), for the **critical angle** of incidence θ_c it will have an angle of refraction equal to 90^0, and for angles of incidence greater than the critical angle the light will undergo **total internal reflection**

$$\sin\theta_c = \frac{n_2}{n_1}$$



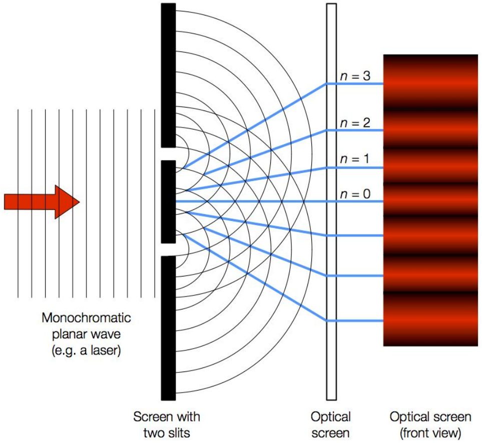
Physical Optics : Diffraction & Interference

Key Concept

- ➔ **Diffraction** occurs when waves encounter a boundary or narrow opening causing the waves to bend around corners
- ➔ The circular waves formed by diffraction from a **double slit** (illustrated) generate an **interference pattern** (constructive interference where crests meet crests and destructive interference where crests meet troughs)
- ➔ **Constructive interference** will occur where the **path-length difference** from the two slits is an **integer** number of wavelengths
- ➔ If the slits are a distance d apart, and the screen is a distance L away, the bright peaks therefore occur at

$$\frac{n\lambda}{d} = \frac{x}{L} \quad \text{Or} \quad n\lambda = d\sin\theta$$

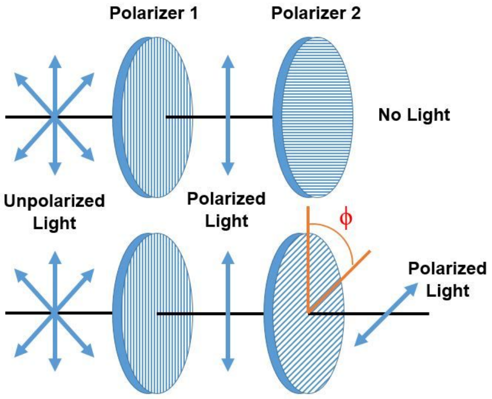
where x or ϑ is the distance or angle of the peak from the center



Physical Optics : Polarization

Key Vocabulary

- ➔ Transverse EM waves can oscillate in any direction perpendicular to the direction of travel
- ➔ **Polarization** by a filter selects only one plane of oscillation
- ➔ Unpolarized light will be completely blocked by “crossed polars” (at 90^0)



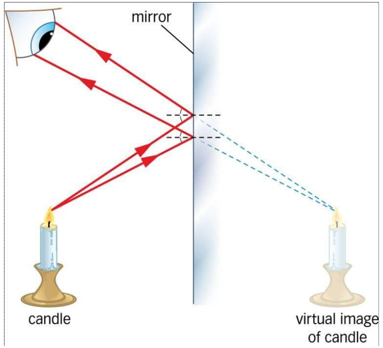
- ➔ Polarized sunglasses transmit only vertically polarized light thereby reducing the glare of reflected light from horizontal surfaces which tends to be polarized horizontally

Ray Optics

Ray Optics : Images and Plane Mirrors

Key Vocabulary

- **Real images** are formed by **converging** light rays. They can be projected onto a screen and are always **inverted** (upside down)
- **Virtual images** occur when **diverging** rays are perceived to converge back to a point. They cannot be projected and are always **upright**
- The image formed by a **plane mirror** is **virtual** - no actual light is emerging from the other side. The image is the same size and distance from the mirror, and is upright but has left-right reversal

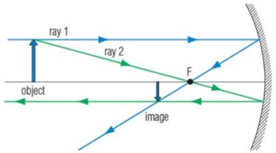


Ray Optics : Concave and Convex Mirrors

Key Concepts

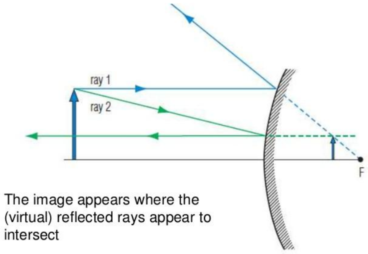
- **Concave mirrors** cause parallel rays to **converge** at a **real focal point**
- **Convex mirrors** cause parallel rays to **diverge** from a **virtual focal point**
- The focal point is halfway to the **center of curvature** of the mirror
- Image formation can be analyzed by considering two rays from a point on the object, one parallel to the lens axis and one through the focal point

Concave Mirror Ray Diagrams



The point where the two reflected rays converge will be the location of the image

Ray Diagrams for Convex Mirrors



The image appears where the (virtual) reflected rays appear to intersect

- The distance to the focal point F, object S_o and image S_i, and the magnification m are related by

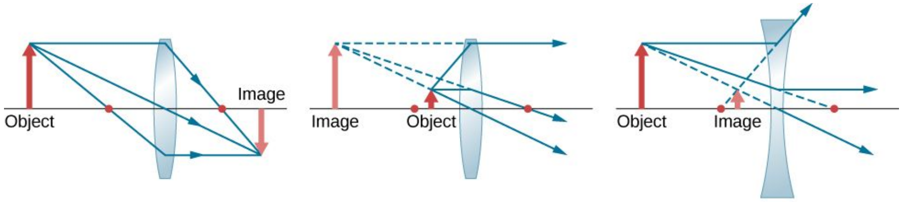
$$\frac{1}{F} = \frac{1}{S_o} + \frac{1}{S_i} \qquad m = -\frac{S_i}{S_o}$$

where a negative F or S indicate virtual (behind the mirror) and a negative magnification indicates inversion

Ray Optics : Converging and Diverging Lenses

Key Concepts

- ➔ **Lenses** focus light by **refraction**. In the **thin lens approximation** the light is assumed to refract from the center of the lens
- ➔ **Converging lenses** cause parallel rays to **converge** at a **real focal point**
- ➔ **Diverging lenses** cause parallel rays to **diverge** from a **virtual focal point**
- ➔ Image formation can be analyzed by considering two rays from a point on the object, one parallel to the lens axis and one through the focal point



Converging lens Real image (a) | Converging lens Virtual image (b) | Diverging lens Virtual image (c)

- ➔ A... magnification m are related by

$$\frac{1}{F} = \frac{1}{S_o} + \frac{1}{S_i} \qquad m = -\frac{S_i}{S_o}$$

where -ve F or S are virtual (in front of lens) and -ve m means inversion

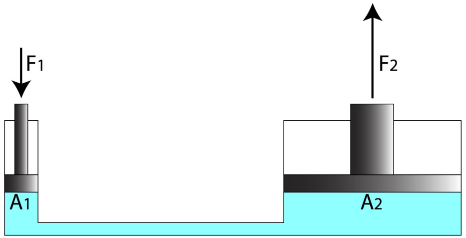
Fluids

Fluids : Pascal's Principle & Static Pressure

Key Concepts

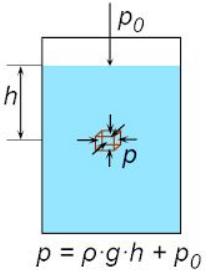
- **Fluids** are **liquids** (incompressible) and **gases** (compressible)
- **Pascal's Principle** states that **external pressure** (force per unit area) applied to a fluid is transmitted uniformly to all parts of it

$$\frac{F_1}{A_1} = \frac{F_2}{A_2}$$



- **Static pressure** at a given **depth** is calculated by considering a column of liquid
- The forces from external pressure and weight are balanced by the pressure upwards on the column

$$p = p_0 + \rho g h$$



Fluids : Buoyancy & Fluid Motion

Key Concepts

- **Archimedes' Principle** states that the upward **buoyant force** on an **immersed object** equals the weight of its own volume V_d of liquid (density ϱ) that it displaces

$$F_B = \rho g V_d$$

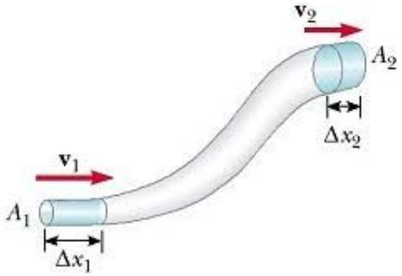
- For **liquids in motion** at speed v, incompressibility implies that the **flux** (volume of flow Q through a cross-sectional area A per second)

$$Q = \frac{v \Delta t A}{\Delta t} = vA$$

must be constant, yielding the **equation of continuity**

$$v_1 A_1 = v_2 A_2$$

ie as cross-sectional area decreases the velocity increases



Fluids : Bernoulli's Equation

Key Concept

- **Bernoulli's Equation** describes liquid moving between two points through an irregularly shaped pipe of varying height
- If we consider the volume flowing in at point 1 and out at point 2 per unit time, its net change in mechanical energy (PE+KE) is the work done on it

$$WD = (mgh_2 - mgh_1) + \left(\frac{1}{2}mv_2^2 - \frac{1}{2}mv_1^2\right)$$

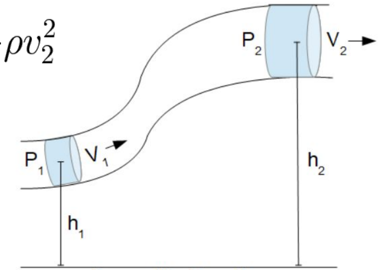
but also

$$WD = F_1d_1 - F_2d_2 = P_1A_1v_1t - P_2A_2v_2t$$

and since $A_1v_1t = A_2v_2t = \frac{m}{\rho}$

we obtain Bernoulli's Equation

$$P_1 + \rho g h_1 + \frac{1}{2}\rho v_1^2 = P_2 + \rho g h_2 + \frac{1}{2}\rho v_2^2$$



Bernoulli's Equation

Fluids : Applications of Bernoulli

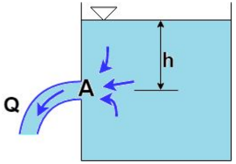
Problem Solving

➔ For a **fluid at rest** the Bernoulli equation reduces to

$$\Delta P = P_2 - P_1 = \rho g \Delta h = \rho g (h_2 - h_1)$$

➔ For **fluid escaping a hole** in the side of a tank, the external (atmospheric) pressure is the same at the top and the hole and therefore

$$\frac{1}{2}\rho v^2 = \rho g \Delta h \qquad v = \sqrt{2g\Delta h}$$

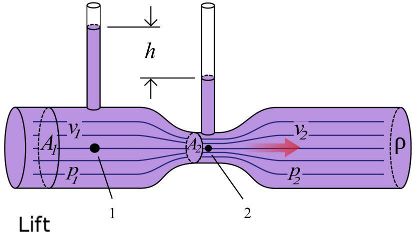


with a rate of flow Q=vA

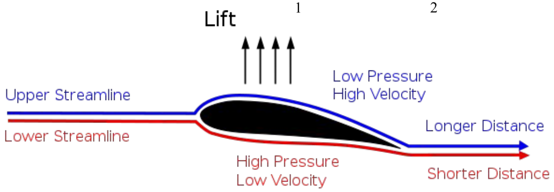
➔ For **fluid moving horizontally**

$$\Delta P = P_1 - P_2 = \frac{1}{2}\rho(v_2^2 - v_1^2)$$

ie pressure decreases as velocity increases as shown by a **Venturi tube** (illustrated)



➔ A **wing** produces **lift** since higher velocity above the wing causes lower pressure



Thermodynamics

Thermodynamics : Temperature & Moles

Key Vocabulary

- **Temperature** is a relative measure of **heat** indicating the direction in which **thermal energy** will flow. The temperature in Kelvin is given by the temperature in Celsius plus 273 (such that 0K is absolute zero)
- A **mole** of an element contains $N_0 = 6.02 \times 10^{23}$ molecules (**Avogadro's Number**) : the mass of 1 mole is given by the standard atomic mass of the atoms in grams (e.g. 1 mol of oxygen O_2 has a mass of 32g)
- An **ideal gas** is assumed to have only elastic molecular collisions, no intermolecular forces, and negligible volume of molecules themselves
  1 mole of ideal gas has volume 22.4 litres at 0^0C and 1 atmos pressure
- **Kinetic-molecular theory** assumes that the thermal **internal energy** U of a gas is equal to the **kinetic energy** of the molecules which is proportional to temperature T in Kelvin: $U = \frac{3}{2}nRT$
  where n is number of moles ($=N/N_0$ for N molecules) and R is the universal gas constant 8.31 J/mol K.
- KE_{avg} the **average KE per molecule** is $KE_{avg} = \frac{3}{2}kT$ $\quad v_{rms} = \sqrt{\frac{3kT}{m}}$
  where k is the Boltzmann constant ($=R/N_0$) 1.38×10^{-23} J/K, and v_{rms} is the root mean square average velocity of the molecules of mass m

Thermodynamics : Ideal Gas Law

Key Concept

➔ The **ideal gas law** for pressure P, volume V and temperature T of a gas (with n moles or N molecules) can be expressed in the following forms

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \qquad PV = nRT \qquad PV = NkT$$

If temperature is constant, then the product PV is constant (**Boyle's Law**)
If volume is constant, then P is proportional to T (the **Pressure Law**)
If pressure is constant, then V is proportional to T (**Charles' Law**)

➔ If a **gas expands** it does **work** on its environment equal to the pressure times the change in volume, or more generally the area under the graph of P vs V between two points. This energy comes from the internal energy (KE of the molecules)

➔ If a gas is **compressed** then work is done on the gas

Thermodynamics : 1st Law of Thermodynamics

Key Concept

- The **First Law of Thermodynamics** states that the change in **internal energy** U equals the **heat energy** Q transferred to the gas plus the **work** W done on the gas
$$\Delta U = Q + W$$
The First Law is a statement that **energy is conserved**

- For an **isothermal** process (constant temp), $\Delta U = 0$ and $P \propto 1/V$: the transfer of heat to the gas equals the work done by the gas expanding

- For an **isobaric** process (constant pressure) $W = -P\Delta V$

- For an **isochoric** process (constant volume) $W = 0$ and thus $\Delta U = Q$

- For an **adiabatic** process there is no heat transfer ($Q=0$) so $\Delta U = W$: if the gas expands, doing work on its surroundings, then the temperature drops

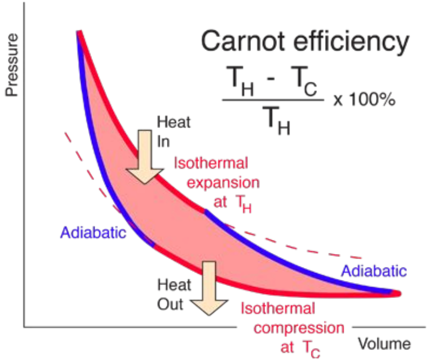
Thermodynamics : 2nd Law of Thermodynamics

Key Concept

The **Second Law of Thermodynamics** can be stated in many forms

- **Entropy** (randomness or disorder) of an isolated system cannot decrease, and is only constant if all processes are reversible
- **Heat** never flows from a cooler to hotter body of its own accord
- It is impossible for a **heat engine** to convert all of the thermal energy absorbed into work done

➔ The **Carnot cycle** involves **adiabatic** and **isothermal** compression and expansion and illustrates the maximum possible theoretical **efficiency** η of a heat engine. The work done is the area enclosed on the PV graph and equals the net heat energy transferred in and so



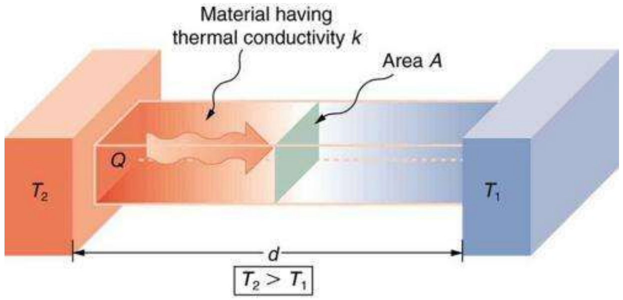
$$\eta = \frac{W}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}} = 1 - \frac{T_C}{T_H}$$

Thermodynamics : Heat Transfer

Key Vocabulary

- **Conduction** is the transfer of heat from a hotter to cooler material by physical contact. The rate of heat flow

$$H = \frac{Q}{t} = \frac{kA(T_2 - T_1)}{d}$$



- **Convection** is the transfer of heat by the movement of fluids - for example via thermal expansion as when “hot air rises”

- **Radiation** is the transfer of heat by electromagnetic waves - for example infrared waves from the Sun heating the atmosphere of the Earth

Modern Physics

Modern Physics : Quantum Theory

Key Concepts

- ➔ The **photoelectric effect** (electrons are only ejected from metals by EM radiation beyond a threshold frequency f_0, regardless of intensity) led Einstein to realize that light was quantized in packets (photons). The **photon energy** is E=hf where h is the **Planck constant** 6.63×10^{-34} Js
- ➔ The maximum KE of ejected electrons by the photoelectric equation is

$$KE_{max} = hf - hf_0$$

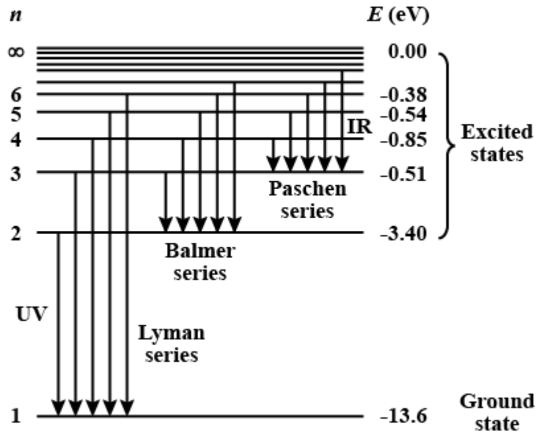
where hf_0 is the material dependent "work function"
- ➔ Compton established via collision experiments that photons have **momentum** $p=h/\lambda$ again showing how waves could behave as particles
- ➔ deBroglie found that **electrons** passing through a double slit generated a **diffraction pattern** of interference with $\lambda=h/mv$: showing that particles could behave as waves
- ➔ The **Heisenberg Uncertainty Principle** states that it is impossible to precisely determine both position and momentum simultaneously

$$\Delta x \Delta p \geq \frac{h}{4\pi}$$

Modern Physics : Atomic Structure

Key Concept

- ➔ Rutherford found that positively charged alpha particles (He nuclei) fired at a thin gold film were mostly not deflected and deduced the presence of a small **positively charged nucleus** orbited by negative electrons
- ➔ Bohr proposed that **electrons** have discrete (**quantized**) energy states and emit EM waves when transitioning from a higher to lower energy state where the photon energy equals the energy difference (f = ΔE/h)
- ➔ The Bohr model explained why characteristic **spectral lines** are seen for each element when electrically sparked (eg Hydrogen below)
- ➔ The energy required to free an electron (raise it to E=0) from a given state is called the **ionization energy**



Modern Physics : Nuclear Structure

Key Concepts

- **Atomic nuclei** consist of positively charged **protons** and neutral **neutrons**
- The **atomic number** specifies the number of protons (charge) and thus the element, and the **mass number** specifies total nucleons (protons plus neutrons) eg $^{64}_{28}\mathrm{Ni}$ denotes Nickel with 28 protons and 36 neutrons
- Different **isotopes** of the same element have varying numbers of neutrons

- **Electric force** causes protons to **repel** each other but shorter range nuclear **strong force attracts** all nucleons to each other. Heavier nuclei therefore require more neutrons than protons to be stable
- The mass of a nucleus is less than the summed mass of its protons and neutrons - this difference is called the **mass defect** and can be equated with the nuclear **binding energy** according to **mass-energy equivalence**

$$E = mc^2$$

Modern Physics : Radioactive Decay

Key Concept

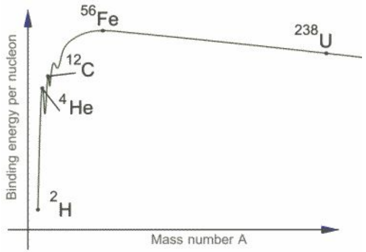
- **Radioactive decay** is the spontaneous breakdown of a nucleus involving the release of energy (EM radiation) and matter
  - **Alpha decay** involves the emission of a Helium nucleus ${}_2^4\mathrm{He}$
  - **Beta decay** involves a neutron decaying into a proton and electron (plus an antineutrino)
  - Decay can also occur by **electron capture** or **positron emission**
- **Fission** involves a nucleus splitting into lighter nuclei eg

$$ {}^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{140}_{54}\mathrm{Xe} + {}^{94}_{38}\mathrm{Sr} + 2{}^{1}_{0}\mathrm{n} + {}^{0}_{0}\gamma $$

  where binding energy is released as radiation (gamma rays) and the production of two further neutrons can cause a **chain reaction**
- **Fusion** occurs when nuclei combine eg

$$ {}^{1}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} + {}^{0}_{0}\gamma $$

- **Binding energy per nucleon** (shown right) peaks for iron (atomic number 56) and thus fusion only occurs for elements lighter than iron and fission only occurs for elements heavier than iron



Modern Physics : Special Relativity

Key Concept

- Einstein's **Theory of Special Relativity** results from the observation that the speed of light in a vacuum is the same for all observers regardless of the velocity of their reference frame
- In order for this to be the case, intervals of time and distance as measured by observers in different reference frames differ
- Two consequences of special relativity are **time dilation** and **length contraction**

$$\Delta t' = \gamma \Delta t \qquad \Delta x' = \frac{\Delta x}{\gamma} \qquad \gamma^2 = \frac{1}{\left(1 - \frac{v^2}{c^2}\right)}$$

where $\Delta t'$, Δt, $\Delta x'$ and Δx are time and distance intervals as measured in a moving (at speed v) or at rest reference frame respectively, with $\Delta x = 0$ in the first case and $\Delta t'=0$ in the second

- Time dilation implies that the time between two ticks of a clock is longer in a frame in which the clock is moving (explaining why high speed muons decay more slowly)
- Length contraction implies that a train moving extremely fast past a station would appear shorter than in its own at rest reference frame

Additional Resources

Physics 2

Additional Resources

- https://apstudents.collegeboard.org/courses/ap-physics-2-algebra-based
- https://www.khanacademy.org/science/ap-physics-2
- https://en.wikipedia.org/wiki/AP_Physics_2