# Physics

Cambridge GCE A-Levels

Grass

# Contents

# Kinematics

- *Distance* is defined as the total length of *path* travelled.
- *Velocity* is defined as the rate of change of displacement.
- *Acceleration* is defined as the rate of change of velocity.

# Dynamics

- *Newton's First Law of Motion* states that an object at rest will remain at rest and an object in motion will remain in motion at constant velocity in a straight line in the absence of an *external* resultant force.
- The *linear momentum* of a body is the product of its mass and velocity. The linear momentum is in the *same direction* as it velocity.
- *Newton's Second Law of Motion* states that the rate of change of momentum of a body is directly proportional to the resultant force acting on the body and occurs *in the direction* of the resultant force.
- *Newton's Third Law of Motion* states that if body A exerts a force on body B, then body B exerts a force of the *same type* that is equal in magnitude and opposite in direction on body A.
- *Impulse* is defined as the product of *average* force acting on an object and the time for which the force acts.
- The *Principle of Conservation of Linear Momentum* states that the total momentum of a system remains constant provided no *external* resultant force acts on the system.

# Forces

- *Hooke's Law* states that the force is directly proportional to the extension in a material if its *limit of proportionality* is not exceeded.
- The *center of gravity* of an object is the point at which the entire weight of a body may be considered to act.
- The *moment* of a force is equal to the product of the force and the *perpendicular* distance of the *line of action* of the force from the pivot. It is also the turning effect of a force.
- *Torque of a couple* is defined as the product of one of the forces and the *perpendicular* distance between the *lines of action* of the forces.
- The *Principle of Moments* states that if a body is in equilibrium, the sum of all the clockwise moments about *any axis* must be equal to the sum of anticlockwise moments about the *same axis*.
- *Density* is defined as the mass per unit volume of a substance.
- *Pressure* is defined as force per unit area, where the force is *acting perpendicularly* to the area.
- Deriving $p = \rho g h$:
  1. Consider a point at a depth $h$ below the surface of a liquid of density $\rho$.
  2. The force $F$ acting perpendicularly on a surface area $A$ at depth $h$ is due to the weight of the liquid column above $A$ to give pressure $p$. Thus, $p = \frac{F}{A} = \frac{mg}{A} = \frac{\rho A h}{g} = \rho g h$.
- *Upthrust* is the upward force exerted by a fluid on a body immersed in the fluid (due to pressure difference in the fluid).
- *The origin of upthrust:* Upthrust is a result of the pressure difference between top and bottom surfaces of the body, resulting in a net upwards force being exerted on the body by the third medium in which the body is located.
- *Archimedes' Principle* states that when a body is totally or partially immersed in a fluid, it experiences an upward force (upthrust) equal to the weight of fluid displaced.
- *The Principle of Floatation* states that, for any object floating in *equilibrium*, the upthrust is equal to the weight of the object.

# Work, Energy, and Power

- *Work done* is defined as the product of a force and the displacement in the direction of the force.
- *One joule of work* is defined as the work done by a force of 1 Newton when its *point of application* moves through a distance of 1 metre in the direction of the force.
- *Energy* is defined as the ability to do work.
- *The Principle of Conservation of Energy* states that energy can neither be created or destroyed in *any process*. It can be transformed from one form to another, and transferred from one body to another.
- Deriving $E_k = \frac{1}{2}mv^2$:
  1. Consider a constant horizontal applied force $F$ acting on an object of mass $m$ travelling with initial velocity $u$ to reach a final velocity $v$ over a displacement $s$.
  2. For uniform acceleration, $v^2 = u^2 + 2as$ so $as = \frac{1}{2}(v^2 - u^2)$. Combined with Newton's Second Law, $W = Fs = mas = \frac{1}{2}mv^2 - \frac{1}{2}mu^2$. When the object starts from rest, $u = 0$.
  3. By conservation of energy, *the work done by force* $F$ *must be converted into the kinetic energy* $E_k$ *of the object*. Hence, $E_k = W = \frac{1}{2}mv^2 - \frac{1}{2}m(0)^2 = \frac{1}{2}mv^2$.
- The *Work-Energy Theorem* states that the net work done by *external* forces acting on a particle is equal to the change in kinetic energy of the particle.
- Deriving $E_p = mgh$:
  1. Consider an object from the Earth's surface — which is taken as the reference for zero gravitational potential energy — raised up by a *constant force* $F$ *equal to and opposite to the weight* $mg$ of the object such that the object moves up at *constant velocity* to a height $h_2$.
  2. Thus, the object moves at constant speed so $\Delta E_k = 0$. Therefore,

  $$\begin{aligned} \Delta E_p &= W \\ E_p - 0 &= Fs \\ E_p &= mgh. \end{aligned}$$

     Where $E_p$ is the gravitational potential energy at height $h$ above the Earth's surface.
- Know how to $\Delta E_p = \frac{1}{2}kx^2$ from area under graph.
- *Power* is defined as the rate of doing work.
- Derive $P = Fv$: $P = \frac{dW}{dt} = \frac{Fds}{dt} = Fv$.

# Temperature and Ideal Gases

- The *Zeroth Law of Thermodynamics* If bodies $A$ and $B$ are separately in thermal equilibrium with body $C$, then bodies $A$ and $B$ are in thermal equilibrium with each other.
- *One mole* is defined as the amount of substance that contains as many elementary particles as there are atoms in 0.012kg of carbon-12.
- *Avogadro's Constant* $N_A$ is the number of atoms in 0.012kg of carbon-12.
-

| | Assumptions of the Kinetic Theory of Gases |
|---|---|
| **M** | The molecules of the gas are in *rapid* and *random* motion. |
| **A** | There are *no intermolecular* attractive forces. |
| **N** | Any gas consists of a *very large number* of molecules. |
| **T** | The duration of collisions is negligible compared to the time interval between collisions. |
| **E** | The collisions between gas molecules, and between gas molecules and the container walls are *perfectly elastic*. |
| **V** | The volume of the gas molecules themselves is negligible compared to the volume of the container. |

- When do real gases behave like ideal gases: At high temperatures and low pressures.
- Deriving $p = \frac{1}{3}\frac{Nm}{V}\langle c^2\rangle$:
  1. Consider a cubic container of side $l$ containing $N$ molecules, each of mass $m$.
  2. Change in momentum due to *elastic* collision between wall and molecule = $2mc_x$
  3. Time interval between collisions, $\Delta t = \frac{2l}{c_x}$.
  4. By Newton's 2nd Law, $F = \frac{2mc_x}{\frac{2l}{c_x}} = \frac{mc_x^2}{l}$.
  5. Since $A = l^2$, Pressure due to 1 particle, $p = \frac{mc_x^2}{l^3} = \frac{mc_x^2}{V}$.
  6. Pressure due to $N$ particles, $p_N = \frac{Nmc_x^2}{V}$.
  7. By Pythagoras'Theorem, $c^2 = c_x^2 + c_y^2 + c_z^2$. The average speed in the $x$, $y$, and $z$ directions can be taken to be $c_x = c_y = c_z$ so $c^2 = 3c_x^2$. Now, $p_N = \frac{Nm\langle\frac{1}{3}c^2\rangle}{V} = \frac{1}{3}\frac{Nm\langle c^2\rangle}{V}$.

# First Law of Thermodynamics

- The *heat capacity* of a body is defined as the amount of thermal energy required to raise its temperature by one Kelvin / degree Celsius.
- The specific *heat capacity* of a body is defined as the amount of thermal energy required to raise the temperature of one unit mass of the substance by one Kelvin / degree Celsius.
- The *specific latent heat* of a body is defined as the thermal energy required to change *phase* of one unit mass of a substance, *without a change in temperature*.
- *Internal energy* of a system is a sum of *random distribution* of kinetic and potential energy *associated with the molecules* of the system.
- The *First Law of Thermodynamics* states that the *increase* in internal energy of a closed system is the *sum* of heat *supplied* to the system and the work done *on* the system.

# Circular Motion

- *Angular displacement* is the angle through which an object turns *with respect to the center* of the circular path.
- *The radian* is defined as the angle *subtended* at the *center* of a circle by an *arc* of length equal to the radius of the circle.
- *Angular velocity* is the rate of change of angular displacement.

- ☐

| | | | |
|---|---|---|---|
| $\omega = \dfrac{2\pi}{T} = 2\pi f$ | $v = r\omega$ | $a_c = \dfrac{v^2}{r} = r\omega^2 = v\omega$ | $F_c = ma_c$ |

- ☐ Common formulae: $\theta = \tan^{-1}\left(\frac{v^2}{rg}\right)$, $v = \sqrt{rg}$.
- ☐ Water in bucket at top position: $F_c = N + W$ (where $N \geqslant 0$) so $\omega > \sqrt{\frac{g}{r}}$.
- ☐ Need to write "Centripetal force is provided by ______"

# Gravitational Fields

- *Newton's Law of Gravitation* states that the force of attraction between any two point masses is directly proportional to the product of their masses and inversely proportional to the square of their separation.
- A *gravitational field* is a region in space where mass experiences a gravitational force acting on it.
- Gravitational field strength at a point is defined as the gravitational force per unit mass acting on a small mass placed at that point
- The *gravitational potential energy* of a mass at a point is defined as the work done by an *external agent* in bringing the mass *from infinity* to that point (without any change in kinetic energy).
- *Gravitational potential* at a point is defined as the work done per unit mass by an *external agent* in bringing a mass *from infinity* to that point (without a change in kinetic energy).
- Escape velocity is the *minimum* velocity a mass needs to be projected from the *surface* of the moon in order to have sufficient kinetic energy to overcome the gravitational field it experiences and *move to infinity*.
- Escape velocity $v_{\text{min}} = \sqrt{\frac{2GM}{r}}$ (where Min $E_k$ needed is the gain in $E_p$ to reach infinity).

□

$$\begin{tikzcd}
U_G = -\frac{GMm}{r} \arrow[r, "-\frac{d}{dr}"] \arrow[d, "\frac{1}{m}"'] & F_G = -\frac{GMm}{r^2} \arrow[d, "\frac{1}{m}"'] \\
\phi = -\frac{GM}{r} \arrow[r, "-\frac{d}{dr}"] & g = -\frac{GM}{r^2}
\end{tikzcd}$$

□ $U_G = m\phi$ & $\Delta U_G = m\Delta\phi$.

□ $U_G$ is negative because infinity is taken as the reference point for zero potential energy. The work done against gravitational force in bringing a mass from infinity to that point is negative.

□ Gravitational force provides the centripetal force:

$$\begin{aligned}
F_G &= F_c \\
\frac{GMm}{r^2} &= mr\omega^2 = mr\left(\frac{2\pi}{T}\right)^2 \\
T^2 &= \frac{4\pi^2}{GM}r^3 \\
T^2 &\propto r^3
\end{aligned}$$

□ Gravitational force provides the centripetal force:

$$F_G = F_c$$

For A: $$\frac{Gm_A m_B}{(r_A + r_B)^2} = m_A r_A \omega^2$$

For B: $$\frac{Gm_A m_B}{(r_A + r_B)^2} = m_B r_B \omega^2$$

The center of mass of the system is at point $P$ where

$$m_A r_A = m_B r_B$$

such that both stars have the same angular velocity $\omega$.

- For binary star systems, notice that *orbital radius is replaced by the stars' separation*:

$$\begin{aligned} m_A r_A &= m_B r_B \\ r_A + r_B &= \frac{m_B}{m_A} r_B + r_B \\ r_B &= \frac{m_A}{m_A + m_B}(r_A + r_B) \end{aligned} \qquad \text{so} \qquad \begin{aligned} \frac{G m_A m_B}{(r_A + r_B)^2} &= m_B r_B \omega^2 \\ &= \frac{m_A m_B}{m_A + m_B}(r_A + r_B)\omega^2 \end{aligned}$$

So, rearranging, we have

$$\omega^2 = \frac{G(m_A + m_B)}{(r_A + r_B)^3} = \frac{G m_A}{r_B (r_A + r_B)^2} \qquad \text{and} \qquad T^2 = \frac{4\pi^2}{G(m_A + m_B)}(r_A + r_B)^3.$$

- Geostationary orbit facts:

  1. Only one such orbit at a *fixed* distance of $4.2 \times 10^7$m from Earth's center,
  2. Orbital period of 24 hours,
  3. Satellite's plane of orbit coincides with the equatorial plane of the Earth,
  4. Orbits West to East (in the same direction as Earth's rotation).

- Equipotential lines are not equally spaced because the gravitational field strength is not constant but decreases as one goes away from the Earth.

- Assumptions made in the theory (e.g. in deriving $g = -\frac{GM}{r^2}$):

  1. The bodies are separated by distances so large they can be considered as point particles (i.e. separation » radius).
  2. The bodies are homogenous spheres (constant density throughout the sphere).
  3. The bodies have masses distributed symmetrically around the center in uniform layers.
  4. In the absence of other masses.

# Oscillations

- *Simple harmonic motion* is defined as the motion of a body whose acceleration is directly proportional to its displacement from a fixed point (equilibrium position) and is always directed towards that fixed point.
- A *freely oscillating* system oscillates at its own *natural frequency* without *external* influences other than the *initial impulse when displaced* from its equilibrium position, with *no dissipation* of energy.
- *Damped oscillations* are oscillations in which the amplitude diminishes with time as a result of *dissipative forces* that reduce the total energy of the oscillations.
- A system is in *forced oscillations* when it is forced to oscillate at a frequency other than the natural frequency by a *periodic external* force.
- *Resonance* is a phenomenon that occurs when the frequency at which an object is being made to vibrate (the forced frequency of vibration) is equal equal to its natural frequency of vibration.

□

| | | Spring-Mass | Pendulum |
|---|---|---|---|
| $v = \pm\omega\sqrt{x_0^2 - x^2}$ | $a = -\omega^2 x$ | $T = 2\pi\sqrt{\frac{m}{k}}$ | $T = 2\pi\sqrt{\frac{l}{g}}$ |

□

| | $E_k$ | $E_p$ | $E_T$ |
|---|---|---|---|
| $t$ | $\frac{1}{2}m\omega^2 x_0^2 \cos^2(\omega t)$ | $\frac{1}{2}m\omega^2 x_0^2 \sin^2(\omega t)$ | $\frac{1}{2}m\omega^2 x_0^2$ |
| $m$ | $\frac{1}{2}m\omega^2(x_0^2 - x^2)$ | $\frac{1}{2}m\omega^2 x^2$ | $\frac{1}{2}m\omega^2 x_0^2$ |

□ Simple pendulums and mass spring systems can be approximated to be SHM when the angle of oscillation ($\leqslant 20°$) and oscillation amplitude are small, respectively.

□

| | In Phase | Antiphase | Out of Phase |
|---|---|---|---|
| $\Delta\phi$/rad | 0 | $\pi$ | nonzero |

□ When damping increases:

- Amplitude at *all* frequencies decreases.
- (Resonance) frequency at max amplitude shifts gradually to lower frequencies.
- Peak (max amplitude) becomes flatter.

# Wave Motion

- A *progressive* wave is a wave in which *energy is carried* from one point to another by means of *vibrations or oscillations* within the wave. Particles within the wave are *not transported along* the wave.
- A *phase* is an angle which gives a measure of the *fraction of a cycle* that has been *completed* by an oscillating particle or by a wave.
- *Intensity* of a wave is the wave energy incident per unit time per unit area *normal* to the wave.
- *Polarisation* of a wave refers to the *confinement* of oscillations in *only* one plane. The plane of oscillations is *parallel* to the direction of energy transfer.
- Malus' Law states that the intensity of a beam of *plane polarised light* after passing through a rotatable polariser is directly proportional to the square of the cosine of the angle through which the polariser is rotated from the position that gives maximum intensity.
  ($I = I_{max} \cos^2(\theta)$)

□

| | | |
|---|---|---|
| Phase Difference $\Delta\phi$ | $\frac{2\pi}{\lambda}\Delta x$ | $\frac{2\pi}{T}\Delta t$ |

□

| Intensity | | | |
|---|---|---|---|
| Amplitude | Wave | | |
| | Spherical | Circular | Plane |
| $I \propto A^2$ | $I \propto \frac{1}{r^2}$ | $I \propto \frac{1}{r}$ | I is constant (No spreading of waves) |

☆ When unpolarised light passes through a polariser, the average value of $\cos^2(\theta)$ is $\frac{1}{2}$ so $I_{new} = \frac{1}{2} I_{max}$.

# Superposition

- *Principle of Superposition*: When two or more waves of the *same type*, meet at *a point in space*, the *resultant displacement* of the waves at any point is the *vector sum* of the *displacements* due to *each wave acting independently* at that point.
- *Stationary waves* are waves whose *waveforms does not advance* and there is *no net translation of energy*. The *amplitude* of the waves varies according to *position* from zero at the nodes to a maximum at the antinodes.
- A stationary wave is formed when two *progressive* waves
  1. Having the *same frequency* and *same speed*
  2. Travel in *opposite directions* towards each other
  3. Have *similar amplitudes*
  4. Are unpolarised, or polarised along the same axis
  5. Are *superposed*
-

| Properties | Reflection Surface | |
|---|---|---|
| | Loose End[1] | Fixed End |
| Allows for Oscillations? | Yes | No |
| Will Reflected Wave be Inverted (phase change of $\pi$)? | No | Yes |

- Characteristics of Stationary Waves:
  1. Displacement node = Pressure antinode
  2. Displacement antinode = Pressure node

| Properties | Stationary Wave | Progressive Wave |
|---|---|---|
| Energy | No net transfer of energy | Energy is transferred in the direction of propagation of the wave. |
| Phase | □ Adjacent nodes: In phase<br>□ Adjacent segments: Antiphase. (Fig 12.1) | All points within one wavelength have different phases. |
| Amplitude | Varies: 0 @nodes to max @antinodes. | Same for all particles. |
| Wavelength | Twice the distances between adjacent nodes or adjacent antinodes. | Distance between adjacent in-phase particles. |
| Frequency | Same for all particles | |
| Nodes[1]/Antinodes[2] | ✓ | × |

[1]Particles of the wave can move about freely.

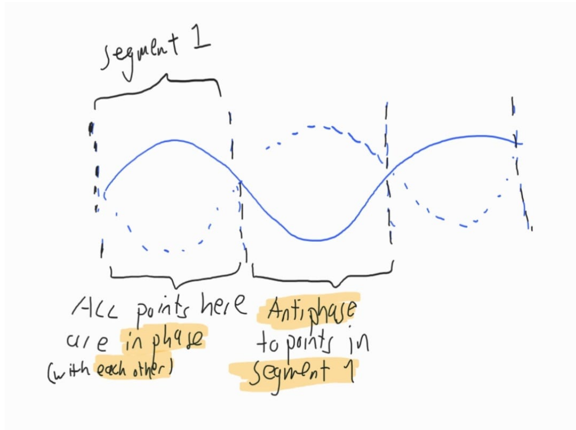



**Figure 12.1:** Phases in Stationary Waves

| | Modes | | Diagrams | Wavelength | Frequency |
|---|---|---|---|---|---|
| | Overtone | Harmonic | | | |
| Strings/Open Pipes | nth | $(n+1)$th | 12.2 & 12.3 | $\lambda = \frac{2L}{n+1}$ | $f = (n+1)\frac{v}{2L}$ |
| Pipes Closed at One End | | $(2n+1)$th | 12.4 & 12.5 | $\lambda = \frac{4L}{2n+1}$ | $f = (2n+1)\frac{v}{4L}$ |

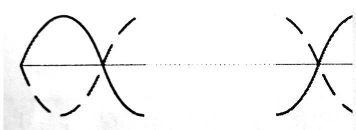


**Figure 12.2:** String

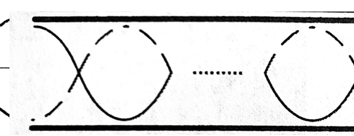


**Figure 12.3:** Open Pipe

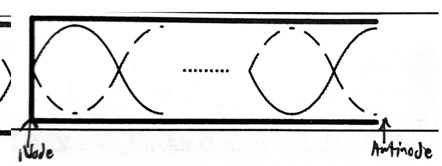



**Figure 12.4:** Pipe Closed at One End

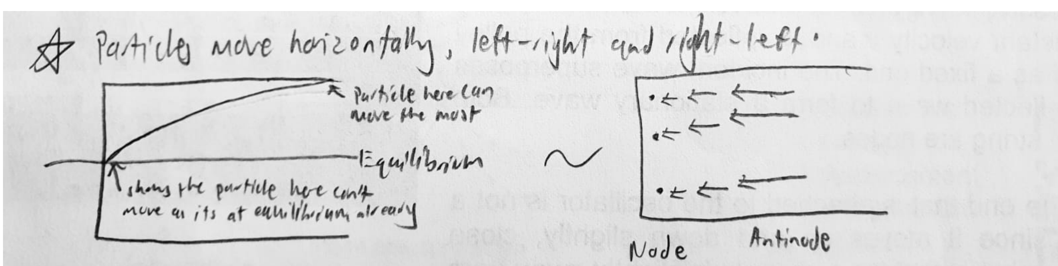



**Figure 12.5:** Movement of Particles In Pipe

- Resonance length[2] with pipes closed at one end
$$L = \frac{\lambda}{4} = \frac{v}{4f}.$$
- *Diffraction* is the *bending or spreading out* of waves when they travel through a *small opening* or when they pass round a *small obstacle*.
- Single Slit Diffraction: Let $b$ be the slit width, and $L$ the slit-screen distance.
  1. For all nonzero integers $m$, the angular positions $\theta$ of the $1 \leqslant m$th order minima satisfies
  $$\sin(\theta) = \frac{m\lambda}{b}.$$

[2]End correction: Actual length of vibration is $L + 2c$ for open pipes, and $L + c$ for closed pipes.

2. Distance $y_1$ of the first minima from either side of the central bright fringe is

$$y_1 = \frac{\lambda L}{b}.$$

(figure)

- *Circular* aperture: $\theta \approx \frac{\lambda}{b}$.
- *Rayleigh's Criterion* is the *minimum separation* between two objects in order to be distinguished as two *distinct* objects:

$$\theta \approx \frac{\lambda}{b}.$$

- Sources are *coherent* if they have a *constant phase difference* with respect to time.
- *Interference* is the *superposing* of two or more waves to produce *regions of maxima and minima* in space, according to the *Principle of Superposition*.
- Conditions for an *observable* interference pattern:
  1. The waves must *overlap* to produce regions of maxima and minima.
  2. The *sources* must be *coherent*.
  3. The waves must have approximately the *same amplitude*.
  4. The waves, if transverse, must be *unpolarised* or have the *same plane of polarisation*.
- For $n \in \mathbb{Z}_0^+$, representing the $n$th order max/min, we have

| Sources' Phase Difference | Path Difference | |
|---|---|---|
| | Constructive Interference (maxima) | Destructive Interference (minima) |
| In phase | $\Delta = n\lambda$ | $\Delta = (n + 1/2)\lambda$ |
| Out-of-phase | $\Delta = (n + 1/2)\lambda$ | $\Delta = n\lambda$ |

- Double-slits: For[3] a slit separation $a$ and slit-screen distance $D$, the fringe separation

$$x = \frac{\lambda D}{a}.$$

- Diffraction grating: For a slit-separation $d$ and $n \in \mathbb{Z}_0^+$, the angular positions for the $n$th order maxima satisfies

$$d \sin(\theta_n) = n\lambda.$$

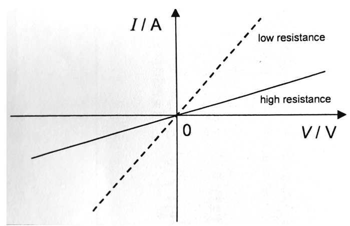
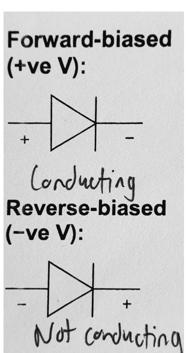
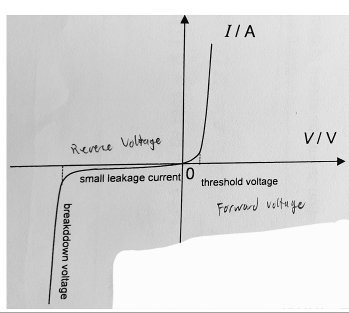
- Check answer: For visible light, $400\text{nm} \leqslant \lambda \leqslant 700\text{nm}$.

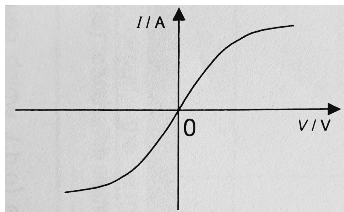
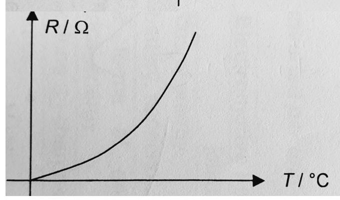
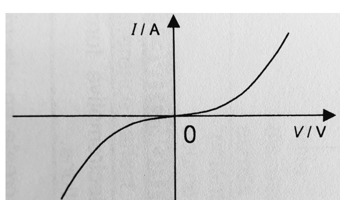
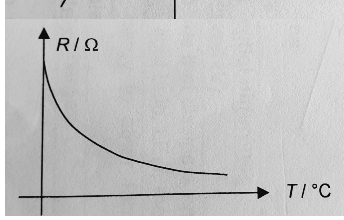
[3]Typical values: $a \approx 0.5$mm, $D \approx 1$m, and $\lambda \approx 600$nm. In any case, using the equation requires $a << D$.
[4]The intensity of the double-slit interference pattern is not constant because of single-slit diffraction effects.

# Currents of Electricity

- The *number density* $n$ is defined as the number of particles per unit volume.
- The *drift velocity* $v$ is the *average* velocity at which *charge carriers* move through a *conductor* when there is *electric current in the conductor*.
- Deriving the equation $I = nAvq$:
  1. Assume that the *current is constant*. Then, $I = \frac{Q}{t}$.
  2. Assume that there are $N$ charge carriers, *each* carrying carry an *equal amount of charge* $q$. Then, the *total charge* that passes through a cross-sectional area $A$ is
  $$Q = Nq.$$
  3. Assume that the *number density* $n$ of charge carriers is *uniform*. Then, the number of charge carriers passing through $A$ in a time interval $t$ is
  $$N = nV,$$
  for the volume $V$ covered by the current in that time.
  4. But $V$ is just $A\Delta x$. Moreover, since the current travels at some velocity $v$, we have
  $$V = A\Delta x = Avt$$
  5. Therefore,
  $$I = \frac{Q}{t} = \frac{Nq}{t} = \frac{nVq}{t} = \frac{nAvtq}{t} = nAvq.$$
- Elementary charge $e = 1.6 \times 10^{-19}$C (Charge of an electron/proton).
- The *potential difference* between *two points* of a circuit is defined as the amount of electrical energy *converted* to other forms of energy *per unit charge* moved *between* the two points.
- *Ohm's Law* states that the *current* flowing in a *conductor* is *directly proportional* to the *potential difference across it* under *constant physical conditions*.
- *Resistance* is defined as the *ratio* of the *potential difference across* the conductor to the *current* flowing through it.
- *Resistivity* $\rho$ is the *proportionality constant* between the *dimensions of a specimen of a material* and its *resistance* such that
$$R = \frac{\rho L}{A}.$$

- Electrical Components

| Types of Conductors | Changes to Resistance | Reason |
|---|---|---|
| Metallic conductor at constant temperature | – At *constant temperature* this is an Ohmic conductor.<br>– Has *constant resistance*. Ratios of V/I is constant.<br> | – At *constant temperature*, the *number of free electrons* and the *rate of atomic vibration* is constant.<br>– A resistor at a different constant temperature will have a difference resistance, and hence, V/I ratio. |
| Semiconductor Diode<br> | – Forward-biased: *Resistance decreases* when *p.d. increases*. In fact, if the forward-biased p.d. goes past its *threshold voltage*, *resistance* becomes very low.<br>– Reverse-biased: *Very high resistance*. But, there will be a *small leakage current*.<br>– If the reverse-biased p.d. is so high that it exceeds the *breakdown voltage*, the diode will *break down* and *conduct electricity*.<br> | – When connected in *forward bias*, the circuit's *electric field set up* allows for available *charge carriers to flow* through |

| | | |
|---|---|---|
| Filament Lamp | – When *p.d. increases*, *current increases*, with *decreasing* I – V *ratio*.<br>– The *resistance* of a metallic conductor *increases* with an increase in *temperature*.<br><br><br><br> | – As *current increases*, *power dissipated increases* since $P = I^2R$. Heat is generated so *equilibrium temperature rises* — as electrons drift through the metal, they collide with the metal lattice and transfers energy to it.<br>– The *lattice ions vibrate more vigorously*. This *hinders the flow* of 'charge carriers'. Therefore, *resistance is increased*.<br>– Ohmic conductors do *not* obey Ohm's Law at *high* voltages/currents for this reason. |
| Negative Temperature Coefficient (NTC) Thermistor | – When *p.d. increases*, *current* through the thermistor also *increases*, with *increasing* I – V *ratio*.<br>– The *resistance* of a thermistor *decreases* with an *increase* in *temperature* (This is the meaning of NTC).<br><br><br><br> | – As *current increases*, *power dissipated increases*. *More heat* is generated, leading to a *rise* in *equilibrium temperature*.<br>– Thus, the *mean kinetic energy* of the electrons and lattice ions *increases*. So,<br>1. The *bonded electrons break free* from bonds, increasing the *number* of 'mobile charge carriers'. Therefore, *resistance decreases*.<br>2. The *lattice ions vibrate more vigorously*, *hindering the flow* of 'mobile charge carriers'. Thence, resistance increases.<br>– The first effect is much more significant than the second. So, there is a net *decrease in resistance*. |

- The *electromotive force* (e.m.f) of a *source* is defined as the amount of *energy converted* from *non-electrical* forms of energy to *electrical* energy *per unit charge* as the *charge passes through a complete circuit*.
- Internal resistance: the p.d. across a component is given by $V = E - Ir$.
- Power dissipated $P = IV$.
- Power delivered is *maximum* when $R = r$, such that

$$P_{max} = \frac{E^2}{4r}.$$

- Efficiency of the source
  - *Increases* when external load/*resistance increases*.
  - Is halved when $R = r$.
    *Note:* Maximum power $\neq$ maximum efficiency.

# Electric Fields

- *Coulomb's Law* states that the *magnitude* of the *electric force* between two *point charges* is directly proportional to the product of the charges, and inversely proportional to the square of their separation.
- The formula is

$$F_E = \frac{Q_1 Q_2}{4\pi\varepsilon_0 r^2}$$

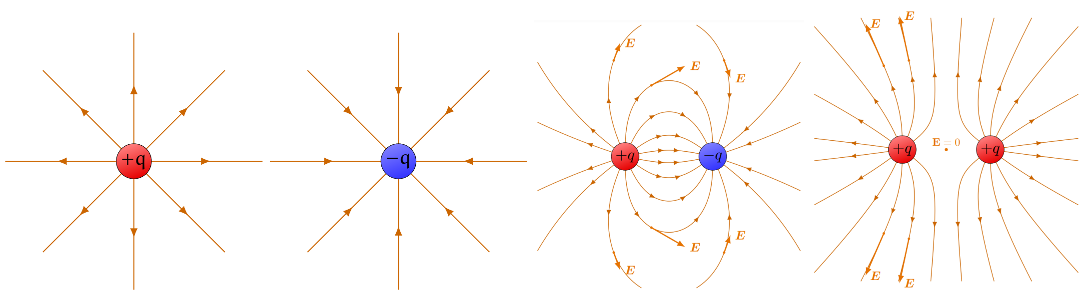
  where $\varepsilon_0$ is the permittivity of *free space* ($\varepsilon_0$ is applicable for vacuum and air only).
- Sign of $F_E$:

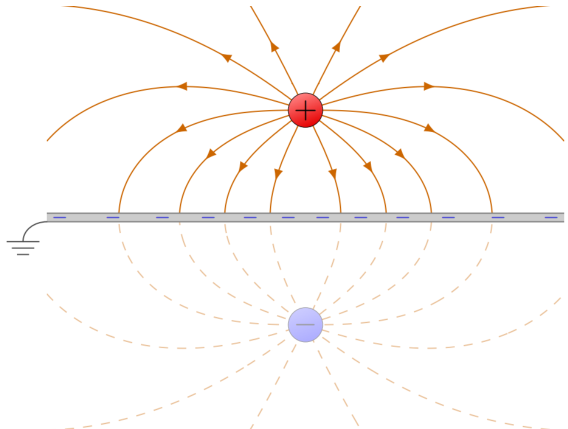
| $F_E$ | Direction |
|---|---|
| Positive | Repulsive |
| Negative | Attractive |

- Comparison between E-fields and G-fields:

| Sim/Diff | E-field | G-field |
|---|---|---|
| S | For both Column's Law and Newton's Law of Gravitation, $r$ is the *center to center separation* of the objects. | |
| S | By Newton's Third Law, the *forces* that masses and charges on each other is *equal in magnitude* and *opposite in direction*. | |
| D | Gravitational force is *always attractive*. | Electric Force can be *attractive or repulsive*. |

- An *electric field* is a *region in space* where a *charge experiences an electric force*.
- How to draw electric field lines:
  - *Lines cannot intersect* one another.
  - Lines must *begin from positive charges* and *end on negative charges*.
  - Arrows show the *direction of force* exerted on a positive test charge.
  - The *greater* the electric field strength, the *closer* together field lines are drawn.
  - Lines leave/end on *conducting surfaces* at *right angles*

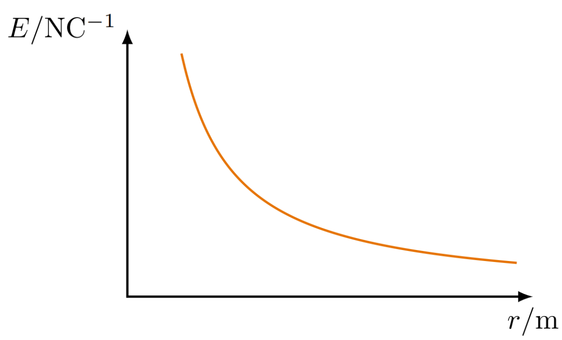




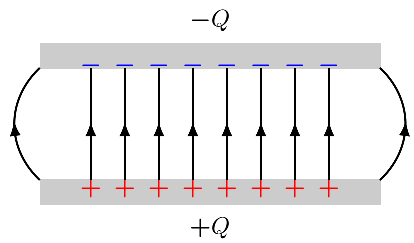
- The *electric field strength* at a point is defined as the *electric force* per *unit positive charge* placed at that point.
- The formula is, for a small stationary test charge q,

$$E = \frac{F_E}{q}.$$

- Electric field strength of a positive point charge:




- Charge distribution on a conducting sphere:
  - Excess charges are forced to the surface of the conductor until the electric field inside the conductor is zero.
  - *Outside* the conductor, the electric field is the *same* as that of an isolated point charge equal to the excess charge.
- Properties of conductors in *electrostatic equilibrium*:
  - The *electric field is zero inside* a conductor (regardless of shape).
  - So, the *entire conductor* is at the *same potential*.
  - Just outside the conductor, the e-field lines are *perpendicular to its surface*, starting and ending on charges on the surface.
  - *Excess charges* resides exclusively on *the surfaces* of a conductor.
- Electric field strength between two charged parallel plates is uniform everywhere between the plates, except at both ends of the plates.
- Also, *charges* between the plates experience *uniform acceleration*.




- Magnitude of electric field strength between the plates:

$$E = \frac{dV}{dr} = \frac{\Delta V}{d}.$$

# Bibliography

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4. Electric field plots https://tikz.net/electric_field_plots/
5. Electric field lines between parallel plates https://tex.stackexchange.com/a/488802