Particles Cheat Sheet

Particle	Quarks	Anti-Par.	Quarks
p	uud	$\overline{p}$	$\overline{uud}$
n	udd	$\overline{n}$	$\overline{udd}$
π^0	$u\overline{u}$	π^0	$d\overline{d}$
π^+	$u\overline{d}$	π^-	$d\overline{u}$
K^0	$d\overline{s}$	$\overline{K^0}$	$s\overline{d}$
K^+	$u\overline{s}$	K^-	$s\overline{u}$

Exchange Particles

Force	Exchange Particle	Affected Particles
Strong	Pions	Hadrons
Weak	Bosons	All
Electro-magnetic	Virtual photons	Charges
Gravitational	Graviton (off-spec)	Masses

Conserved Quantities

In any interaction, the following quantities must be conserved: *mass-energy*, *charge*, *baryon number*, *lepton number*, and *strangeness*.

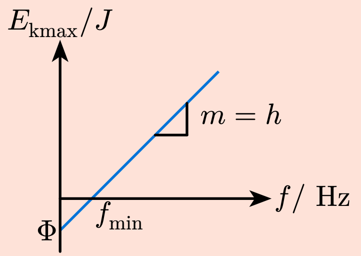
The only exception is that strangeness can change by ± 1 in a weak interaction if a down quark turns into a strange quark or vice versa.

Photoelectric Effect

This is evidence of the particulate nature of light.

$$hf = \Phi + E_{\text{kmax}}$$
$$hf - \Phi = E_{\text{kmax}}$$

Regardless of the intensity of the light, if the threshold frequency is not reached. This is because the photons undergo one-to-one interactions with the electrons.



The stopping potential required to stop the electrons from escaping is given by

$$eV_s = E_{\text{kmax}}$$

Electron Diffraction

This is evidence of the wave nature of electrons. We can model the de Broglie wavelength as

$$\lambda = \frac{h}{mv}$$

Faster velocity means smaller wavelength, so less diffraction and smaller diameter of rings.

Fluorescent Tube

1. Electrons are released from the cathode by thermionic emission and accelerated through the tube by a potential difference.
2. Electrons excite mercury atoms, which release UV photons when they de-excite.
3. UV photons excite phoshphorus atoms, which release visible photons when they de-excite.

Emission and Absorption Spectra

Emission Spectra
When atoms in a hot gas de-excite, electrons move to lower energy levels, releasing photons of certain frequencies. This produces an emission spectrum with the relevant colours.

Absorption Spectra
When atoms in a cold gas excite, electrons move to higher energy levels, absorbing photons of certain frequencies. This produces an absorption spectrum with the relevant colours missing.

Waves Cheat Sheet

Optical Fibres

Feature	Reason
Narrow diameter	Modal dispersion - rays of light incident at different angles take different paths
Monochro-matic light	Material dispersion - different wavelengths travel at different speeds (red > violet)
Cladding	Crosstalk - rays can cross between cores in a bundle

Refraction

The refractive index of a medium is how much faster light would travel outside of it.

$$n = \frac{c}{c_s}$$

The critical angle is defined passing from a more dense medium to a less dense medium.

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

- If $\theta_i > \theta_c$, total internal reflection occurs
- If $\theta_i = \theta_c$, the refracted ray passes along the boundary of the media
- If $\theta_i < \theta_c$, refraction occurs and the angles satisfy $n_1 \sin \theta_i = n_2 \sin \theta_r$

Stationary Waves

A stationary wave is formed

1. Waves are reflected at boundaries
2. Two waves travelling in opposite directions superpose/interfere
3. Fixed boundaries are nodes
4. Where the two waves are out of phase, destructive interference creates nodes
5. Where the two waves are in phase, constructive interference creates antinodes

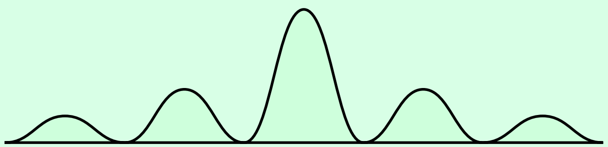
All non-node points are in phase or out of phase with each other.

$$f = \frac{1}{2l}\sqrt{\frac{T}{\mu}}$$

Diffraction

Diffraction is the spreading of waves as they pass through a gap of a similar magnitude as their wavelength. Higher wavelength diffracts more.

Single Slit Diffraction



Equally spaced maxima, getting progressively less intense from the centre.

Diffraction Grating

Angle of maxima given by $d \sin \theta = n\lambda$.

Progressive Waves

Longitudinal waves

- The oscillations are *parallel* to the direction of energy transfer
- Examples are sound waves and P waves

Transverse waves

- The oscillations are *perpendicular* to the direction of energy transfer
- Examples are EM waves and S waves
- Transverse waves can be polarised, restricting the oscillations to one plane only
- Definitions and equations

Definitions

- The phase difference between two points is the difference in phase in radians
- The path difference between two waves is how far ahead one is of the other in wavelengths

Interference

Two coherent sources are required:

- same frequency
- constant phase difference

The fringe spacing is given by $w = \frac{\lambda D}{s}$. Higher wavelength diffracts more.

We observe equally spaced maxima, getting progressively less intense from the centre.

- Where the two waves are out of phase, destructive interference creates minima
- Where the two waves are in phase, constructive interference creates maxima

Materials Cheat Sheet

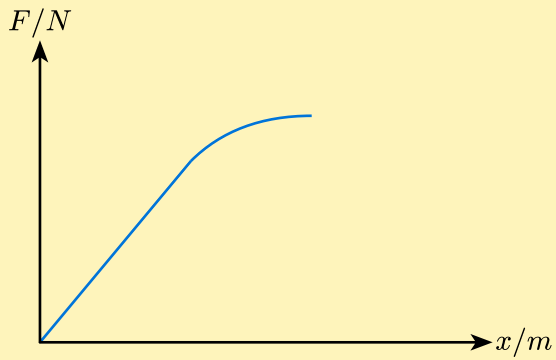
Hooke's Law

The extension of a spring is directly proportional to the force applied to it, up to its limit of proportionality.

$$F = kx$$

where k is the spring constant or stiffness.

Force-Extension Graph



The gradient of the linear section of the graph is the spring constant of the spring.

The area under the graph is the elastic energy stored in the spring.

Springs in Series and Parallel

The reciprocal of the spring constant in *series* is the sum of the reciprocal of the spring constant of each spring.

$$\frac{1}{k_{\text{total}}} = \frac{1}{k_1} + \frac{1}{k_2} + \frac{1}{k_3} + \ldots$$

The spring constant in *parallel* is the sum of the spring constant of each spring.

$$k_{\text{total}} = k_1 + k_2 + k_3 + \ldots$$

This is the opposite behaviour as resistors. To remember this, just remember that springs are not resistors.

Young's Modulus

Stress is force per unit cross-sectional area. (Pa)

$$\sigma = \frac{F}{A}$$

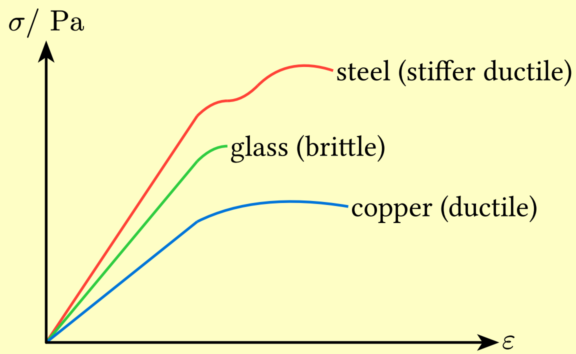
Strain is extension per unit original length. (∅)

$$\varepsilon = \frac{x}{L}$$

Young's modulus is stress per unit strain. (Pa)

$$E = \frac{\sigma}{\varepsilon} = \frac{FL}{Ax}$$

Stress-Strain Graph



The gradient of the linear section of each graph is the Young's modulus of the material. The area under each graph is work done per unit volume.

Properties of Materials

Key word	Definition
Tough	Requires a high amount of energy before breaking
Strong	Requires a high amount of stress before breaking
Ductile	Can withstand plastic tensile deformation without breaking
Malleable	Can withstand plastic comp. deformation without breaking
Brittle	Breaks with under stress with little plastic deformation
Stiff	Has a high Young's modulus
Hard	Difficult to scratch

Electricity Cheat Sheet

Current is the rate of flow of charge: $I = \frac{Q}{t}$

Potential difference is the work done per unit charge from one point to another: $V = \frac{E}{Q}$

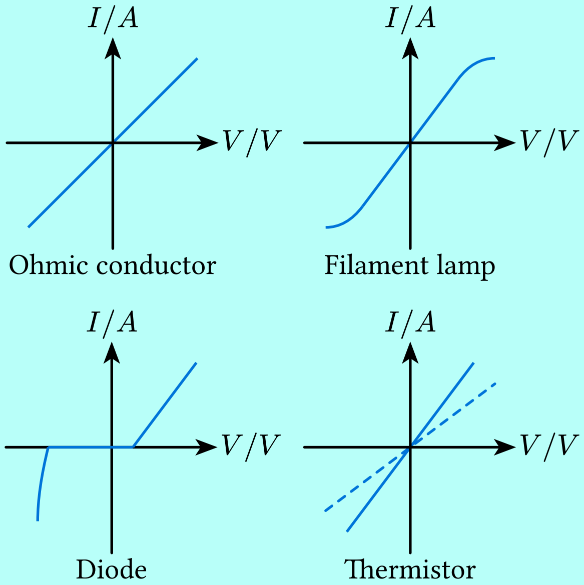
Resistance is a measure of how difficult it is for current to flow through a material: $R = \frac{V}{I}$

Power is the electrical work done in the circuit per unit time: $P = \frac{E}{t} = \frac{E}{Q} \times \frac{Q}{t} = VI$

A perfect ammeter has zero resistance.

A perfect voltmeter has infinite resistance.

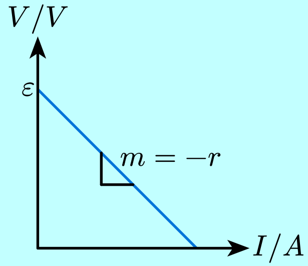
Current-Voltage Characteristics



Electromotive Force

$$\varepsilon = I(R + r)$$
$$\varepsilon = V_{\text{term}} + Ir$$
$$\varepsilon - Ir = V_{\text{term}}$$

The emf is the energy transferred by the battery per unit charge. However, internal resistance leads to lost volts and a lower terminal pd.



Resistivity

Resistivity is a physical quantity proportional to resistance and cross-sectional area and inversely proportional to length.

$$\rho = \frac{RA}{l}$$

- Typically, as temperature increases, resistivity also increases.
- An exception is the negative temperature coefficient thermistor, where resistivity actually decreases.
- Superconducting materials at extremely low temperatures have *zero* resistivity.

Potential Dividers

A potential divider consists of resistors in series with a fixed potential difference.

Potential dividers can be used to supply any pd between zero and the source pd.

$$I = \frac{V_0}{R_1 + R_2} = \frac{V_1}{R_1} = \frac{V_2}{R_2}$$

Series and Parallel

Kirchhoff's circuit laws:

1. The total current into a point equals the total current out of it.
2. The sum of the potential differences around a closed point is zero.

The resistance in *series* is the sum of the individual resistances.

$$R_{\text{total}} = R_1 + R_2 + R_3 + \ldots$$

The reciprocal of the resistance in *parallel* is the sum of the reciprocals of the indiv. resistances.

$$\frac{1}{R_{\text{total}}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots$$

CM and SHM Cheat Sheet

The angular speed/frequency is defined as

$$\omega = \frac{2\pi}{T} = 2\pi f$$

where
- T is the period of the motion
- f is the frequency of the motion

Circular Motion

A particle follows a circular path around a point.

For circular motion to take place, a centripetal force must provide centripetal acceleration.

$$F = \frac{mv^2}{r} = m\omega^2 r$$

$$a = \frac{v^2}{r} = \omega^2 r$$

The centripetal force is merely a label for whatever force provides centripetal acceleration, such as tension, gravity, or reaction force.

Simple Harmonic Motion

- Acceleration is directly proportional to displacement
- Acceleration is opposite in direction to displacement

$$a = -\omega^2 x$$

For example:
- $x = \cos(t)$
- $v = -\sin(t) = \cos\left(t + \frac{\pi}{2}\right)$
- $a = -\cos(t) = \cos(t + \pi)$

Springs and Pendulums

The period of a mass on a spring undergoing simple harmonic motion is given by

$$T = 2\pi\sqrt{\frac{m}{k}}$$

where m is the mass and k is the spring constant.

The period of a pendulum undergoing simple harmonic motion is given by

$$T = 2\pi\sqrt{\frac{l}{g}}$$

where l is the length and g is the gravitational field strength.

Damping

- Free oscillations: the total energy of the system is constant
- Damped oscillations: the total energy of the system decreases over time

Types of damping:
- Underdamping: the amplitude of oscillations decreases over time
- Overdamping: the system does not oscillate but tends towards the equilibrium position
- Critical damping: the system returns to the equilibrium position in the fastest possible time

Resonance

1. The frequency of the driving force matches the resonant/natural frequency of the system.
2. The driving force and restoring force are $\frac{\pi}{2}$ out of phase (just like velocity).
3. This leads to maximum energy transfer and maximum amplitude of oscillation.

Thermal Physics Cheat Sheet

The *heat* contained in a system (the *total internal energy* of the system) is the sum of

1. the *kinetic energies* of the molecules
   - related to changing the *temperature*
   - equation $Q = mc\Delta T$
2. the *potential energies* of the molecules
   - related to changing the *state of matter*
   - equation $Q = ml$

The temperature of a system is the *average* kinetic energy of the molecules. (Also, the state of matter of a system is related to the *average* potential energy of the molecules.)

Ideal Gas Law

The ideal gas law states that

$$\rho V = NkT$$

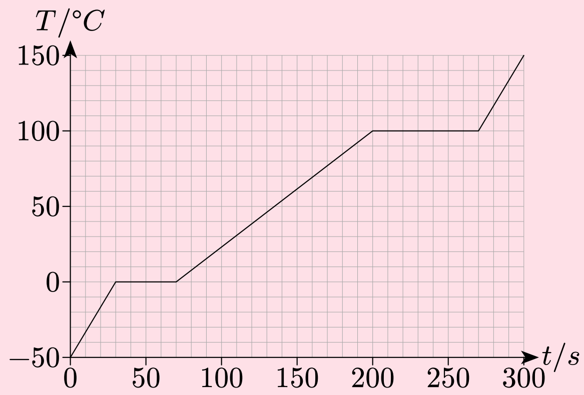
where N is the number of particles and k is the Boltzmann constant. (There is also a molar version that simply factors Avogadro's number into the constant.)

The ideal gas law is a consequence of any two of

1. Boyle's Law: $\rho \propto \frac{1}{V}$ when T is constant
2. Charles's Law: $V \propto T$ when ρ is constant
3. Pressure Law: $\rho \propto T$ when V is constant

You can remember which is which by memorising that Boyle's Law is the inverse one.

Temperature-Time Graphs



The graph shows that

1. when heating the substance increases kinetic energy, the temperature increases
2. when heating the substance increases potential energy, the substance melts or boils, so the temperature does not change

The Thermal Physics equations use Kelvins. Add 273.15 to convert from degrees Celsius to Kelvins.

The Mole

A *mole* is simply 6.02×10^{23} of something, usually molecules. It turns out that a mole of a substance has the same mass in *grams* as its molar mass in *atomic mass units*.

Ideal Gases

We make five assumptions about ideal gases.

1. The molecules are *point masses*.
2. There are *no intermolecular forces*.
3. The molecules are moving around with *continual random motion*.
4. The molecules undergo *elastic collisions* with each other and the container surface.
5. Each collision with the container surface is *much shorter* than the time between impacts.

Real gases do not follow these assumptions, but they can get quite close when the temperature is high and the pressure is low.

Ideal gases obey the *ideal gas law*.

Kinetic Energy

Using the statistics, mechanics, and the ideal gas assumptions, it can be derived that

$$\rho V = \frac{1}{3} N m (c_{\text{rms}})^2$$

where c_{rms} is the root mean square speed of the molecules in the system.

The mean kinetic energy of a molecule is thus

$$E_k = \frac{1}{2} m (c_{\text{rms}})^2 = \frac{3}{2} kT$$

Nuclear Physics Cheat Sheet

1. *Alpha radiation* is composed of helium nuclei. It is strongly ionising but easily stopped by a few centimetres of air.
2. *Beta radiation* is composed of fast moving electrons/positrons. It is moderately ionising and stopped by about a metre of air or a thin sheet of steel.
3. *Gamma radiation* is electromagnetic radiation composed of photons. It is stopped by a thick block of concrete.

Radioactive Decay

Since each undecayed nucleus has an equal chance of decaying at any given time,

$$\frac{dN}{dt} = -\lambda N$$

where N is the number of undecayed nuclei and λ is the decay constant. Solving this gives us

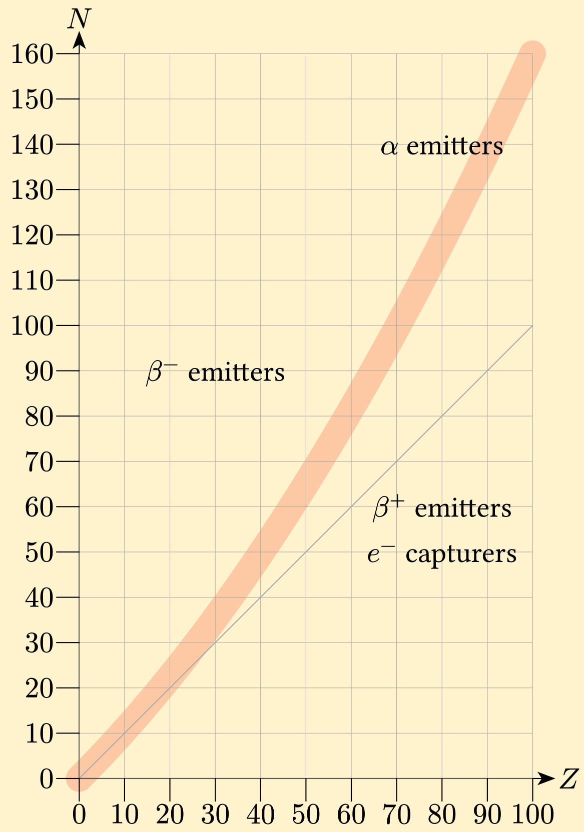
$$N = N_0 e^{-\lambda t}$$

where N_0 is the initial number of undecayed nuclei. We also define

$$A = \lambda N$$

as the activity of the sample, measured in Becquerels (Bq).

N-Z Graph



The graph of stable nuclei has slightly more neutrons (N) than protons (Z). This is because the strong attraction needs to overcome the electrostatic repulsion to keep the nuclei together.

Unstable nuclei will eventually decay to become more stable. Really unstable nuclei may undergo nuclear fission to produce two stabler daughter nuclei and several fast-moving neutrons.

Nuclear Reactors

In a nuclear fission reactor, slow-moving *thermal neutrons* are used to induce nuclear fission.

1. A thermal neutron is absorbed by a *fissile nucleus* (e.g. Uranium-235).
2. The nucleus splits into two smaller *daughter nuclei.*
3. This releases fast-moving neutrons.
   - Some neutrons undergo *elastic collisions* with *moderator* particles (usually water) to lose momentum.
   - Some neutrons are *absorbed* by *control rods* (usually boron) to avoid the chain reaction getting out of hand.
4. This creates a *chain reaction.*

Radioactive Waste

Radioactive waste is extremely dangerous.

1. *High-level* radioactive waste comes from spent fuel rods. They are removed by remote control and stored underwater to cool down. Then they are vitrified, sealed in steel drums, and buried deep underground.
2. *Medium-level* radioactive waste comes from materials with low activity and containers. They are sealed in steel drums and enclosed in concrete in special buildings.
3. *Low-level* radioactive waste comes from equipment and clothing. They are sealed in steel drums and buried in trenches.

Gravitational and Electric Fields Cheat Sheet

Gravitational Fields

Gravitational fields exert forces on masses.

- Gravitational field strength *at a point* is the gravitational force per unit mass acting at that point.
- Gravitational force acting *on a mass at a point* is its rate of change of momentum due to a gravitational field.
- Gravitational potential *at a point* is the work done per unit mass to move a mass from infinity to that point.
- Gravitational potential energy *of a mass at a point* is the work done to move a mass from infinity to that point.

Electric Fields

Electric fields exert forces on charges.

- Electric field strength *at a point* is the electric force per unit positive charge acting at that point.
- Electric force acting *on a mass at a point* is its rate of change of momentum due to an electric field.
- Electric potential *at a point* is the work done per unit charge to move a positive charge from infinity to that point.
- Electric potential energy *of a charge at a point* is the work done to move the charge from infinity to that point.

Field Equations

Field	Uniform G-Field	Uniform E-Field	Radial G-Field	Radial E-Field
Field Strength	g	E	$\frac{GM}{r^2}$	$\frac{kQ}{r^2}$
Force	mg	qE	$\frac{GMm}{r^2}$	$\frac{kQq}{r^2}$
Potential	gh	Ed	$-\frac{GM}{r}$	$\frac{kQ}{r}$
Potential Energy	mgh	qEd	$-\frac{GMm}{r}$	$\frac{kQq}{r}$

where $G \approx 6.67 \times 10^{-11}$ and $k = \frac{1}{4\pi\varepsilon_0} \approx 8.99 \times 10^9$

Capacitors

A capacitor is made of two parallel plates. When a potential difference is applied, electrons are forced onto one plate and off the other. This creates a uniform electric field between the plates and stores charge.

Capacitance is defined as charge stored per unit potential difference applied

$$C = \frac{Q}{V}$$

It depends on the cross-sectional area and the dielectric between the plates

$$C = \frac{A\varepsilon_0\varepsilon_r}{d}$$

Charging and Discharging

Charging is exponential

$$Q = Q_0\left(1 - e^{-\frac{t}{RC}}\right)$$

Discharging is also exponential

$$Q = Q_0 e^{-\frac{t}{RC}}$$

The time to halve is given by

$$T_{\frac{1}{2}} = 0.69RC$$

Magnetic Fields Cheat Sheet

Magnetic field strength is defined as force per unit current flowing per length of wire.

$$B = \frac{F}{Il}$$

Magnetic flux is defined as the magnetic field cutting a given surface.

$$\Phi = BA$$

Magnetic flux linkage is defined as the magnetic flux over several turns of coil.

$$\Psi = BAN$$

Alternating Current

Alternating current and alternating voltage follow a sine wave.

The average (root mean square) current is

$$I_{\text{rms}} = \frac{I_0}{\sqrt{2}}$$

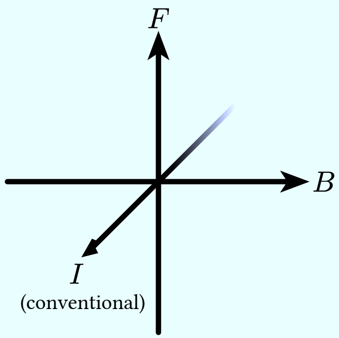
The average (root mean square) voltage is

$$V_{\text{rms}} = \frac{V_0}{\sqrt{2}}$$

The average (mean) power is

$$P_{\text{avg}} = \frac{P_0}{2}$$

The Motor Effect



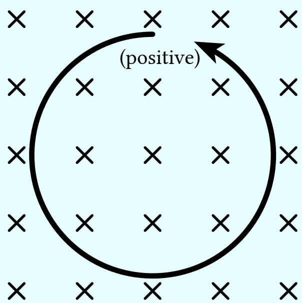
When a wire carries a current perpendicular to a magnetic field, there will be a magnetic force acting on the wire as shown.

$$F = BIl$$

Since current is defined as the rate of flow of charge, we can write a similar expression for force on a moving **positive** charge.

$$F = B\left(\frac{Q}{t}\right)l = BQv$$

This can lead to circular motion, used in cyclotrons and mass spectrometers.



Here the magnetic field lines (North to South) are going into the page, indicated by the crosses.

The Generator Effect

A changing magnetic field cutting a coil of wire will induce an emf across the wire, causing current to flow if the wire is in a circuit.

Lenz's Law
The direction of the induced emf will always oppose the change of flux that is producing it.

Faraday's Law
The induced emf will always be proportional to the change of flux that is producing it.

$$\varepsilon = N\frac{\Delta\Phi}{\Delta t}$$

Transformers

Transformers are used to transform the potential difference of alternating current.

$$\frac{N_s}{N_p} = \frac{V_s}{V_p}$$

The efficiency of a transformer is given by

$$\eta = \frac{P_s}{P_p} = \frac{I_s V_s}{I_p V_p}$$

The efficiency is not 100% because of eddy currents that dissipate energy as heat.

Transformers are used on the National Grid to transfer energy at a high potential difference.

Electrons and Relativity Cheat Sheet

Cathode Ray Tubes

1. A high potential difference between the anode and the cathode creates a strong electric field.
2. The electric field ionises the gas atoms, creating positive ions and electrons.
3. The positive ions are accelerated towards the cathode, releasing even more electrons.
4. The electrons (cathode rays) are accelerated towards the anode, exciting phosphor atoms.
5. The atoms de-excite and emit visible light, causing the tube to glow.

Thomson (1897)

1. They used an electron gun to release electrons.
2. The electrons entered a region with a zinc sulfide coated mica screen to become visible.
3. The mica screen had an electric field perpendicular to a magnetic field.
4. The electrons followed a parabolic path.
5. When the path was straight, the electric and magnetic forces were equal.
6. Substituting this into the electron gun equation we get $\frac{q}{m} = \frac{E^2}{2VB^2}$.

This supported Thomson's hypothesis that electrons have mass and charge, and gave a charge-to-mass ratio of $1.7 \times 10^{11} C\text{kg}^{-1}$.

Millikan (1909)

1. An atomiser created fine droplets in an electrically isolated chamber.
2. The oil droplets were negatively charged through friction.
3. Some oil droplets fell through a hole in the top plate and entered the electric field between the top and bottom plates, where they could be viewed through a microscope.
4. When the droplets were stationary, the electric and weight forces were equal.
6. When the droplets are falling at terminal velocity, the drag and weight forces were equal.

The results suggested that charge is quantised.

Michelson-Morley (1887)

1. A semi-silvered glass block split the monochromatic light beam into two.
2. The plane block ensured both beams pass through the same thickness of glass and air.
3. They observed the interference pattern from the two beams.
4. They rotated the apparatus by 90 degrees and observed the pattern again.
5. The pattern did not change.

This suggested that the ether does not exist, and the speed of light is invariant in all inertial reference frames.

Rossi-Hall (1940)

1. Cosmic rays of muons entered the atmosphere.
2. They measured the number of muons at a high altitude and a low altitude.
3. Most of the muons did not decay, despite having a short half-life.

This suggested that time passes slower for the muons than for the observers, because they move at relativistic speeds close to the speed of light.

Bertozzi (1962)

1. They fired electrons at an aluminium plate.
2. They measured the velocity of an electron by timing it over a fixed distance.
3. They measured the kinetic energy of the electron by measuring the temperature increase of an aluminium plate.
4. They plotted a graph of $\frac{v^2}{c^2}$ against E_k. The graph approximated a curve approaching 1.

This supported Einstein's prediction that no material object can reach the speed of light.