SI Units

- 10^{12} - tera (T)
- 10^{9} - giga (G)
- 10^{6} - mega (M)
- 10^{3} - kilo (k)
- 10^{0}
- 10^{-3} - mili (m)
- 10^{-6} - micro (μ)
- 10^{-9} - nano (n)
- 10^{-12} - pico (p)
- 10^{-15} - femto (f)

Particles & Radiation

Particles

Leptons

- Fundamental (cannot be broken down any further)
- Do not 'feel' the strong force
- Lepton numbers are conserved separately (so the electron lepton number is unrelated to the muon lepton number)

Lepton	Charge	Lepton No.
Electron	-1	+1
Muon	-1	+1
Positron	+1	-1
Electron neutrino (v_e)	0	1
Electron antineutrino ($\bar{v_e}$)	0	-1

Hadrons

- Not fundamental particles (made of quarks)
- 'Feel' the strong force

Quarks

Quark	Charge	Baryon No.	Strangeness
Up	$+\frac{2}{3}$	$+\frac{1}{3}$	0
Down	-$\frac{1}{3}$	$+\frac{1}{3}$	0
Strange	-$\frac{1}{3}$	$+\frac{1}{3}$	-1
Anti-up	-$\frac{2}{3}$	-$\frac{1}{3}$	0
Anti-down	$+\frac{1}{3}$	-$\frac{1}{3}$	0

Quark	Charge	Baryon No.	Strangeness
Anti-strange	$+\frac{1}{3}$	-$\frac{1}{3}$	+1

Baryons

- Made of 3 quarks or antiquarks

Baryon	Charge	Baryon No.	Quark Composition
Proton	+1	+1	uud
Neutron	0	+1	udd
Anti-proton	-1	-1	$\bar{u}\bar{u}\bar{d}$
Anti-neutron	0	-1	$\bar{u}\bar{d}\bar{d}$

Mesons

- Made of a quark-antiquark pair
- Always have a baryon number of 0

Pions

- Mesons that do not have strangeness

Meson	Charge	Quark Composition
π^+	+1	$u\bar{d}$
π^0	0	$u\bar{u}$ or $d\bar{d}$
π^-	-1	$d\bar{u}$

Kaons

- Mesons that do have strangeness

Kaon	Charge	Strangeness	Quark Composition
K^+	+1	+1	$u\bar{s}$
K^0	0	+1	$d\bar{s}$
K^0	0	-1	$s\bar{d}$
K^-	-1	-1	$s\bar{u}$

Pair Production and Annihilation

- If a particle and its anti-particle collide, they annihilate each other, releasing 2 high-energy photons
  - $e^- + e^+ \rightarrow \gamma + \gamma$

- Pair production is when a high-energy photon produces a particle-antiparticle pair (they are not bonded like in mesons)
  - $\gamma \rightarrow e^- + e^+$
- These are not limited to electrons

Radiation

Conservation Laws

- Charge is always conserved
- Baryon number is always conserved
- Lepton numbers are conserved separately (L_e and L_μ)
- Strangeness is only conserved in strong interaction

Interactions

(this is where the Feynman diagrams would go but I don't know how to get pictures working on this when I export it so I'll just be describing them)

- **Beta-minus decay** – $n \rightarrow p + e^- + \bar{v}_e$
  - A down quark in the neutron becomes an up quark forming a proton, both of these are on the left
  - From where the neutron becomes a proton, a W^- boson moves to the right and an electron and anti-electron neutrino come from the end of the line
- **Beta-plus decay** – $p \rightarrow n + e^+ + v_e$
  - An up quark in the proton becomes a down quark, forming a proton.
  - W^+ boson moves to the right and a positron and electron neutrino come from the end of the line
- **Electromagnetic repulsion** – it shows the collision of 2 protons or electrons
  - The 2 identical particles come close to each other, a virtual photon is drawn between them (with no direction) and then they move away from each other
- **Electron-proton collision** – $p + e^- \rightarrow n + v_e$
  - The proton an electron move towards each other, then a W^- boson moves from the electron to the proton.
  - On the proton side after the boson is a neutron, and on the electron side is an neutrino.
- **Electron capture** – $p + e^- \rightarrow n + v_e$
  - The exact same ***except*** that a W^+ boson moves from the proton to the electron.

Photon Emission and Energy Levels

- Electrons reside at different energy levels around the nucleus

- When these electrons absorb energy, they are excited and move up to the next or multiple energy levels. They then de-excite and emit photons of the same wavelength and frequency that they absorbed.
- **Absorptions spectra** – this is the spectrum that is shone at a gas. Any wavelengths that are absorbed will be shown as black lines (because they didn't pass through the gas and were absorbed)
- **Emission spectra** – this is the spectrum that results from the de-excitation of the electrons as they emit the wavelengths they previously absorbed. The coloured wavelengths in the emission spectrum match the black lines in the absorption spectrum exactly.

Wave-particle duality

Particles behaving as waves

- Electron diffraction is an example of particles behaving as waves (diffraction is a wave-like property)
- **de Broglie wavelength** – wavelength of a particle is given by: $\lambda = \frac{h}{mv}$

Waves behaving as particles (Photoelectric effect)

- The photoelectric effect is an example of waves (photons) behaving as particles.

Photoelectric effect

- If light is shone on a metal surface, it should release more electrons as intensity is increased (which is wave-like behaviour), but this does not happen.
- The light must first have a certain energy (work function), which means it must have a frequency (threshold frequency), only then will increasing the intensity increase the amount of electrons liberated.
- This is because each individual photon will collide with an electron, and if it does not have enough energy to liberate it, it won't and it does not "contribute" to liberating (so if you needed 3 photons to liberate it, having all 3 hit the same electron one after the other will not liberate it)
- The equation relating to the photoelectric effect is:

$$hf = \phi + E_{\text{k max}}$$

Where f is the frequency of the photon, ϕ is the work function (minimum energy needed to liberate the electron) and $E_{\text{k max}}$ is the maximum kinetic energy of the electron once it is liberated.

Waves

Terminology

- **Phase** - the position along a cycle of a wave, measured in degrees or radians
- **Phase difference** - the difference in phase between 2 waves
- **Principle of superposition** - when waves overlap, the displacement of the new "composite" wave is the sum of the displacement of the other waves at that point. Constructive interference is when the composite wave has a large amplitude than the individual waves that make it up, destructive interference is when the composite wave has a smaller amplitude than the individual waves that make it up. Total destructive interference is when the composite wave has 0 amplitude.
- **Path difference** - the difference in distance travelled by 2 waves
- **Coherent source** - one that only emits light of the same frequency and wavelength and with a fixed phase difference

Progressive Waves

- Transfer energy
- Longitudinal waves - oscillate parallel to the direction of energy transfer (e.g. sound waves)
- Transverse waves - oscillate perpendicular to the direction of energy transfer (e.g. EM waves)
- If 2 waves are in phase, then the phase difference is a multiple of 360^o or 2π radians.
- If 2 waves are completely out of phase, then the phase difference is an odd multiple of 180^o or π radians (180^o or $\pi, 540^o$ or 3π, etc.)

Stationary Waves

- Do not transfer energy (in an ideal environment)
- Formed when 2 progressive waves with the same wavelength and frequency are moving in opposite directions superpose on each other
- Where the 2 waves constructively superpose on each other are where the antinodes form (this happens where they are in phase)
- Where total destructive interference occurs are where the nodes form (this happens when they are completely out of phase)
- The lowest frequency at which a stationary wave can occur on a string is given by the equation:

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

Where f is the frequency of the first harmonic (also called the fundamental frequency), L is the length of the string, T is the tension on the string and μ is the mass per unit length of the string.

Interference and Diffraction

- **Young's Double Slit**
  - Laser is shone on a double slit, the light diffracts when it meets the slits and now the 2 slits act as coherent sources of light.
  - Bright spots (maxima) show up on the screen where the 2 sources constructively interfere. These occur where the path difference is an integer multiple of the wavelength ($n\lambda$)
  - Dark spots (minima) show up on the screen where the 2 sources destructively interfere. These occur where the path difference is an integer multiple plus a half of the wavelength ($(n + \frac{1}{2})\lambda$)
  - Using white light instead of monochromatic light gives wider maxima and each maxima will be a spectra of colours instead of a single colour
  - Increasing slit width decreases the amount of diffraction and the width of the central maximum, but its intensity increases
  - Increasing the wavelength increases the amount of diffraction and the width of the central maximum, but its intensity decreases (opposite of slit width)
- A diffraction grating is many very thin slits very close together that are equally spaced
  - Monochromatic light in a diffraction grating results in a sharper and brighter maxima than a double slit
  - The equation relation to diffraction gratings is:

$$dsin\theta = n\lambda$$

Where d is the distance between the slits, θ is the angle between the maximum and the normal, n is the order of the maximum and λ is the wavelength of the light.

Refraction

- When light moves into a material with a different optical density, its speed changes.
- Less dense $\rightarrow$ more dense = slow down and move towards the normal
- More dense $\rightarrow$ less dense = speed up and move away from the normal
- The refractive index is a ratio of the speed of light in the material compared to a vacuum

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

Where n is the refractive index of the substance, c is the speed of light in a vacuum and c_s is the speed of light within the substance. If a material has a refractive index of 1.47 then light is 1.47 times slower in the material than in a vacuum.

- **Snell's Law** $- n_1 sin\theta_1 = n_2 sin\theta_2$
  - This equation relates to the behaviour of light at the boundary of 2 substances.
  - n_1 is the refractive index of the substance the light is currently in, θ_1 is the angle the light makes with the normal to the boundary it collides with.
  - n_2 is the refractive index of the substance light is entering, and θ_2 is the angle that light makes with the normal to the boundary after it has refracted
- **Total Internal Reflection** - this is when light that hits the boundary of 2 substance reflects and stays inside the same medium instead of refracting into the substance
  - This only occurs if the angle to the normal is greater than the **critical angle** and the light is travelling from a more dense medium into a less dense medium.
  - The critical angle is given by the equation $sin\theta = \frac{n_1}{n_2}$ where n_2 is the substance with the greater refractive index.
  - If the angle to the normal is *equal* to the critical angle then the light will travel along the boundary of the substances

Optical Fibres

- An optical fibre is used to transmit information in the form of light.
- It has 2 components, an optically dense core and less optically dense cladding
  - This results in the critical angle being very small, so the only way for the light to escape is for it to be essentially perpendicular to the boundary (in theory, in practice light escapes in other ways)
- The cladding also protects the core and reduces signal degradation
- Signal degradation
  - Absorption - part of the signal is absorbed by the optical fibre, reducing its amplitude and making it potentially lose the information it is carrying, can be reduced with signal boosters along the optical fibre
  - Dispersion - this causes pulse broadening (the signal is wider and its amplitude is also decreased). Broadened signals can overlap causing a loss of information
    * Modal dispersion - caused by light entering the optical fibre at different angles, meaning they take different paths so they take different amounts of time to travel along the fibre.
      · This can be reduced with monomodal optical fibres (the core is very thin so the different paths they take are not significantly

different.)

  * Material dispersion - caused by light consisting of different wavelengths which refract by different amounts and will take different paths and travel at different speeds
    - This can be prevented by using monochromatic light

Electricity

I-V Characteristics

- Ohm's Law $-$ $V = IR$
- An ohmic conductor is one that follows Ohm's law
- The I-V graph of an ohmic conductor is a directly proportional relationship, it is a linear line that goes through the origin
- The I-V graph of a filament bulb is more complicated than I can be asked to describe (google it)
- The I-V graph of a diode is flat when the voltage is negative (flowing the opposite way that is desired) and then its like an exponential after $V = 0$ (just google it again) (if the voltage across a diode is in the wrong direction but its high enough, current will flow anyway)

Resistivity

- Resistivity is an inherent property of a material which is a measure of how easily it conducts electricity. It is given by the equation:

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

- Where ρ is the resistivity, R is the resistance, A is the cross-sectional area and L is the length.
- As the temperature of a component increases, its resistance will also increase (the particles have more energy and vibrate more, so they are more likely to collide with the electrons)
- For thermistors, as temperature increases, resistance decreases
- A superconductor is a material which has 0 resistance once below a certain temperature (critical temperature)
  - They are useful because they can produce very strong magnetic fields
  - They do not waste a lot of energy as a result of heating

Circuit Laws

	Current	Voltage	Resistance
Series	$I_1 = I_2 = I_3$	$V_T = V_1 + V_2 + V_3$	$R_T = R_1 + R_2 + R_3$

	Current	Voltage	Resistance
Parallel	The current going into a junction is the same as the current going out of a junction. It is split along the different branches.	$V_1 = V_2 = V_3$	$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$

- **Kirchhoff's First Law** - current into a junction = current out of a junction
- **Kirchhoff's Second Law** - the sum of all voltages in a series circuit (excluding the terminal voltage) is equal to the terminal voltage

Potential Dividers

- A circuit with 2 or more resistors in parallel so that a desired fraction of the terminal voltage can be produced.
- Can be any 2 kinds of resistors.

Mechanics & Materials

Mechanics

SUVAT

$$v^2 = u^2 + 2as$$

$$v = u + at$$

$$s = (\frac{u+v}{2})t$$

$$s = ut + \frac{1}{2}at^2$$

$$s = vt - \frac{1}{2}at^2$$

Newton's Law of Motion

- **Newton's First Law** – an object will remain at rest or travelling at a constant velocity unless a resultant force is acting on it
- **Newton's Second Law** – $F = ma$
- **Newton's Third Law** – if object A exerts a force on object B, object B will exert an equal and opposite force on object A.

Collisions

- Momentum is always conserved
- Elastic collisions conserve kinetic energy
- Inelastic collisions do not conserve kinetic energy

Materials

Hooke's Law

- $F = kx$

Bulk Properties of Solids

- $Density = \frac{mass}{volume}$
- **Limit of proportionality** – the point at which Hooke's Law no longer applies
- **Limit of elasticity** – the point at which the object will deform plastically
- Tensile stress $(\varepsilon) = \frac{Force}{Area}$
- Tensile strain $(\sigma) = \frac{\Delta l}{l}$
- Elastic strain energy $= \frac{1}{2}F\Delta l$
- If an object has deformed plastically, when the force on it is removed, it will "de-extend" to a certain extent and the gradient will be parallel to the linear part of the Force-extension graph. (google it)

Young's Modulus

- Describes the stiffness of a material
- $E = \frac{\varepsilon}{\sigma}$
- Can be found by calculating the gradient of the linear part of a stress-strain graph

Further Mechanics

Circular Motion

- Angular speed $(\omega) = \frac{v}{r} = 2\pi f = \frac{\Delta\theta}{\Delta t}$
- The unit for angular speed is $rad\ s^-1$
- Centripetal acceleration is always directed towards the centre of the circle

- Centripetal force is always perpendicular to the velocity and pointing towards the centre of the circle

Simple Harmonic Motion

- SHM is any motion in which:
  - Acceleration is directed towards a fixed point
  - AND acceleration is directly proportional to the negative of the displacement
- If an object is in SHM its displacement can be found with $x = Acos(\omega t)$ where x is displacement, A is amplitude, ω is the angular speed and t is time.
- The acceleration-displacement graph of an object in SHM is a straight line with a negative gradient going through the origin.
- In a pendulum in SHM:
  - E_k is at a maximum and E_g is at a minimum at the equilibrium position.
  - E_g is at a maximum and E_k is 0 at the maximum displacement

Damping

- A damping force is any force that opposes the movement of an object
- **Light Damping**
  - Small amount of damping
  - Still oscillates
  - Takes a long time to stop
- **Heavy Damping**
  - No oscillations
  - Slowly returns to equilibrium
- **Critical Damping**
  - Returns to equilibrium as quickly as possible

Resonance

- When a new frequency is applied to an oscillating system its amplitude will change
- If the applied frequency is close to the natural frequency (resonance frequency) then the amplitude will increase (this is resonance)
- If the applied frequency is not close to the natural frequency, the amplitude will be reduced to a minimum
- The amplitude of oscillations can be plotted against frequency, creating a resonance curve which shows that the close the applied frequency is to the natural frequency, the greater the amplitude of the oscillations
- On a resonance curve, more damping reduces the height of the peak (amplitude) and widens the peak