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Physics

Constants, unit conversions and the equations for Themes A to E

SL HL

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JUMP TO Fundamental constants · Geometry, trigonometry and uncertainties · Space, time and motion · The particulate nature of matter · Wave behaviour · Fields · Nuclear and quantum physics

REFERENCE DATA

Fundamental constants

Quantity	Symbol	Approximate value
Acceleration of free fall at Earth's surface	g	$9.8\ \mathrm{m\,s^{-2}}$
Gravitational constant	G	$6.67 \times 10^{-11}\ \mathrm{N\,m^2\,kg^{-2}}$
Avogadro constant	N_A	$6.02 \times 10^{23}\ \mathrm{mol^{-1}}$
Molar gas constant	R	$8.31\ \mathrm{J\,K^{-1}\,mol^{-1}}$
Boltzmann constant	k_B	$1.38 \times 10^{-23}\ \mathrm{J\,K^{-1}}$
Stefan–Boltzmann constant	σ	$5.67 \times 10^{-8}\ \mathrm{W\,m^{-2}\,K^{-4}}$
Coulomb constant	k	$8.99 \times 10^{9}\ \mathrm{N\,m^2\,C^{-2}}$
Permittivity of free space	ε_0	$8.85 \times 10^{-12}\ \mathrm{C^2\,N^{-1}\,m^{-2}}$
Permeability of free space	μ_0	$4\pi \times 10^{-7}\ \mathrm{T\,m\,A^{-1}}$
Speed of light in a vacuum	c	$3.00 \times 10^{8}\ \mathrm{m\,s^{-1}}$
Planck constant	h	$6.63 \times 10^{-34}\ \mathrm{J\,s}$
Elementary charge	e	$1.60 \times 10^{-19}\ \mathrm{C}$
Electron rest mass	m_e	$9.110 \times 10^{-31}\ \mathrm{kg} = 0.000549\ \mathrm{u} = 0.511\ \mathrm{MeV\,c^{-2}}$
Proton rest mass	m_p	$1.673 \times 10^{-27}\ \mathrm{kg} = 1.007276\ \mathrm{u} = 938\ \mathrm{MeV\,c^{-2}}$
Neutron rest mass	m_n	$1.675 \times 10^{-27}\ \mathrm{kg} = 1.008665\ \mathrm{u} = 940\ \mathrm{MeV\,c^{-2}}$
Unified atomic mass unit	u	$1.661 \times 10^{-27}\ \mathrm{kg} = 931.5\ \mathrm{MeV\,c^{-2}}$
Solar constant	S	$1.36 \times 10^{3}\ \mathrm{W\,m^{-2}}$
Fermi radius	R_0	$1.20 \times 10^{-15}\ \mathrm{m}$

Unit conversions

Quantity	Equivalent
1 radian	$\frac{180^\circ}{\pi}$
Temperature in kelvin	$T(\mathrm{K}) = \theta(^\circ\mathrm{C}) + 273$
1 light year (ly)	$9.46 \times 10^{15}\ \mathrm{m}$
1 parsec (pc)	$3.26\ \mathrm{ly}$
1 astronomical unit (AU)	$1.50 \times 10^{11}\ \mathrm{m}$
1 kilowatt-hour (kWh)	$3.60 \times 10^{6}\ \mathrm{J}$
hc	$1.99 \times 10^{-25}\ \mathrm{J\,m} = 1.24 \times 10^{-6}\ \mathrm{eV\,m}$

Metric (SI) prefixes

Prefix	Symbol	Factor	Prefix	Symbol	Factor
peta	P	10^{15}	deci	d	10^{-1}
tera	T	10^{12}	centi	c	10^{-2}
giga	G	10^{9}	milli	m	10^{-3}
mega	M	10^{6}	micro	μ	10^{-6}
kilo	k	10^{3}	nano	n	10^{-9}
hecto	h	10^{2}	pico	p	10^{-12}
deca	da	10^{1}	femto	f	10^{-15}

TOOLKIT

Geometry, trigonometry and uncertainties

Circle	$C = 2\pi r \qquad A = \pi r^2$ C = circumference, A = area, r = radius
Triangle	$A = \frac{1}{2}bh$ b = base, h = perpendicular height
Cylinder	$A_{\text{curved}} = 2\pi rh \qquad V = \pi r^2 h$
Sphere	$V = \frac{4}{3}\pi r^3$
Prism and cuboid	$V = Ah \qquad V = lwh$ A = cross-sectional area; l, w, h = length, width, height
Trigonometric relationships	$\tan\theta = \dfrac{\sin\theta}{\cos\theta} \qquad \sin^2\theta + \cos^2\theta = 1$
Resolving a vector into components	$A_H = A\cos\theta \qquad A_V = A\sin\theta$ A_H, A_V = horizontal and vertical components of A; θ = angle measured from the horizontal
Uncertainty: sums and differences	$y = a \pm b \quad \Rightarrow \Delta y = \Delta a + \Delta b$
Uncertainty: products and quotients	$y = \dfrac{ab}{c} \quad \Rightarrow \dfrac{\Delta y}{y} = \dfrac{\Delta a}{a} + \dfrac{\Delta b}{b} + \dfrac{\Delta c}{c}$
Uncertainty: powers	$y = a^n \quad \Rightarrow \dfrac{\Delta y}{y} = \left\lvert n\dfrac{\Delta a}{a}\right\rvert$ Δa, Δb, Δc, Δy = absolute uncertainties in a, b, c and y

THEME A

Space, time and motion

A.1 Kinematics

A.1 **Equations of motion for uniform acceleration**	$v = u + at \qquad s = ut + \frac{1}{2}at^2 \qquad v^2 = u^2 + 2as \qquad s = \frac{(v+u)}{2}t$ u = initial velocity, v = final velocity, a = acceleration, s = displacement, t = time

A.2 Forces and momentum

A.2 **Friction**	$F_f \leq \mu_s F_N \qquad F_f = \mu_d F_N$ F_f = frictional force, F_N = normal reaction, μ_s / μ_d = coefficients of static / dynamic friction
A.2 **Hooke's law**	$F_H = -kx$ F_H = restoring force, k = spring constant, x = extension from equilibrium
A.2 **Viscous drag (Stokes' law)**	$F_d = 6\pi\eta r v$ η = fluid viscosity, r = radius of the sphere, v = speed relative to the fluid
A.2 **Buoyancy (upthrust)**	$F_b = \rho V g$ ρ = density of the displaced fluid, V = volume displaced, g = gravitational field strength
A.2 **Weight**	$F_g = mg$
A.2 **Momentum and impulse**	$p = mv \qquad J = F\Delta t$ p = momentum, J = impulse, F = net force acting for time Δt
A.2 **Newton's second law**	$F = ma = \frac{\Delta p}{\Delta t}$
A.2 **Centripetal acceleration**	$a = \frac{v^2}{r} = \omega^2 r = \frac{4\pi^2 r}{T^2}$ r = radius of the circle, ω = angular speed, T = period
A.2 **Linear and angular speed**	$v = \frac{2\pi r}{T} = \omega r$

A.3 Work, energy and power

A.3 **Work done by a force**	$W = Fs\cos\theta$ θ = angle between the force and the displacement s
A.3 **Kinetic energy**	$E_K = \frac{1}{2}mv^2 = \frac{p^2}{2m}$
A.3 **Change in gravitational potential energy (uniform field)**	$\Delta E_p = mg\Delta h$
A.3 **Elastic potential energy**	$E_H = \frac{1}{2}k(\Delta x)^2$ Δx = extension or compression of the spring
A.3 **Power**	$P = \frac{\Delta W}{\Delta t} = Fv$
A.3 **Efficiency**	$\eta = \frac{\text{useful work out}}{\text{total work in}} = \frac{\text{useful power out}}{\text{total power in}}$

A.4 Rigid body mechanics HL

A.4 HL **Torque**	$\tau = Fr\sin\theta$ r = distance from the axis, θ = angle between F and the radius vector
A.4 HL **Uniform angular acceleration**	$\Delta\theta = \frac{\omega_f + \omega_i}{2}t \qquad \omega_f = \omega_i + \alpha t \qquad \Delta\theta = \omega_i t + \frac{1}{2}\alpha t^2$ $\omega_f^2 = \omega_i^2 + 2\alpha\Delta\theta$ $\Delta\theta$ = angular displacement, ω_i / ω_f = initial / final angular speed, α = angular acceleration
A.4 HL **Moment of inertia**	$I = \sum mr^2$
A.4 HL **Newton's second law for rotation**	$\tau = I\alpha$
A.4 HL **Angular momentum**	$L = I\omega \qquad \Delta L = \tau\Delta t = \Delta(I\omega)$
A.4 HL **Rotational kinetic energy**	$E_K = \frac{1}{2}I\omega^2 = \frac{L^2}{2I}$

A.5 Galilean and special relativity HL

A.5 HL **Galilean transformations**	$x' = x - vt \qquad t' = t \qquad u' = u - v$ x, t, u = position, time and velocity in frame S; primed values are measured in frame S′, moving at velocity v relative to S
A.5 HL **Lorentz transformations**	$x' = \gamma(x - vt) \qquad t' = \gamma\left(t - \frac{vx}{c^2}\right) \qquad u' = \frac{u - v}{1 - \frac{uv}{c^2}}$
A.5 HL **Lorentz factor**	$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$
A.5 HL **Spacetime interval**	$(\Delta s)^2 = (c\Delta t)^2 - (\Delta x)^2$ invariant for all inertial observers
A.5 HL **Time dilation and length contraction**	$\Delta t = \gamma \Delta t_0 \qquad L = \frac{L_0}{\gamma}$ Δt_0 = proper time, L_0 = proper length
A.5 HL **Angle between axes on a spacetime diagram**	$\tan\theta = \frac{v}{c}$

THEME B

The particulate nature of matter

B.1 Thermal energy transfers

B.1 **Density**	$\rho = \frac{m}{V}$
B.1 **Mean kinetic energy of particles in an ideal monatomic gas**	$\bar{E}_k = \frac{3}{2}k_B T$ T = absolute temperature (K)
B.1 **Specific heat capacity and specific latent heat**	$Q = mc\Delta T \qquad Q = mL$
B.1 **Rate of thermal conduction**	$\frac{\Delta Q}{\Delta t} = kA\frac{\Delta T}{\Delta x}$ k = thermal conductivity, A = cross-sectional area, ΔT = temperature difference across a thickness Δx
B.1 **Stefan–Boltzmann law**	$L = \sigma A T^4$ L = luminosity (radiated power), A = surface area
B.1 **Apparent brightness**	$b = \frac{L}{4\pi d^2}$ d = distance from the source
B.1 **Wien's displacement law**	$\lambda_{\max} T = 2.9 \times 10^{-3}\ \mathrm{m\,K}$ $\lambda_{\max}$ = wavelength of peak emission from a black body

B.2 Greenhouse effect

B.2 **Emissivity**	$e = \frac{\text{power radiated per unit area}}{\sigma T^4}$
B.2 **Albedo**	$\text{albedo} = \frac{\text{total scattered power}}{\text{total incident power}}$

B.3 Gas laws

B.3 **Pressure**	$P = \frac{F}{A}$

B.3 **Amount of substance**	$n = \frac{N}{N_A}$ N = number of particles
B.3 **Combined gas law (fixed amount of gas)**	$\frac{PV}{T} = \text{constant}$
B.3 **Ideal gas equation of state**	$PV = nRT = Nk_BT$
B.3 **Pressure from kinetic theory**	$P = \frac{1}{3}\rho\overline{v^2}$ $\overline{v^2}$ = mean square speed of the particles
B.3 **Internal energy of an ideal monatomic gas**	$U = \frac{3}{2}nRT = \frac{3}{2}Nk_BT$

◆ B.4 Thermodynamics HL

B.4 HL **First law of thermodynamics**	$Q = \Delta U + W$ Q = thermal energy supplied to the gas, W = work done by the gas
B.4 HL **Work done by a gas at constant pressure**	$W = P\Delta V$
B.4 HL **Change in internal energy (ideal monatomic gas)**	$\Delta U = \frac{3}{2}nR\Delta T = \frac{3}{2}Nk_B\Delta T$
B.4 HL **Entropy change**	$\Delta S = \frac{\Delta Q}{T}$
B.4 HL **Entropy (statistical definition)**	$S = k_B \ln \Omega$ Ω = number of possible microstates
B.4 HL **Adiabatic process (ideal monatomic gas)**	$PV^{5/3} = \text{constant}$
B.4 HL **Efficiency of a heat engine**	$\eta = \frac{\text{useful work}}{\text{input energy}}$ $\eta_{\text{Carnot}} = 1 - \frac{T_c}{T_h}$ T_c = cold reservoir temperature, T_h = hot reservoir temperature (both in K)

B.5 Current and circuits

B.5 **Electric current**	$I = \dfrac{\Delta q}{\Delta t}$
B.5 **Potential difference**	$V = \dfrac{W}{q}$
B.5 **Resistance and resistivity**	$R = \dfrac{V}{I} \qquad \rho = \dfrac{RA}{L}$ ρ = resistivity, A = cross-sectional area, L = length of the conductor
B.5 **Electrical power**	$P = IV = I^2R = \dfrac{V^2}{R}$
B.5 **Resistors in series**	$I = I_1 = I_2 = \cdots \qquad V = V_1 + V_2 + \cdots \qquad R_s = R_1 + R_2 + \cdots$
B.5 **Resistors in parallel**	$I = I_1 + I_2 + \cdots \qquad V = V_1 = V_2 = \cdots \qquad \dfrac{1}{R_p} = \dfrac{1}{R_1} + \dfrac{1}{R_2} + \cdots$
B.5 **Cells with internal resistance**	$\varepsilon = I(R + r)$ ε = emf, R = external resistance, r = internal resistance

THEME C

Wave behaviour

C.1 Simple harmonic motion

C.1 **Defining condition for SHM**	$a = -\omega^2 x$ ω = angular frequency, x = displacement from equilibrium
C.1 **Period, frequency and angular frequency**	$T = \frac{1}{f} = \frac{2\pi}{\omega}$
C.1 **Mass–spring oscillator**	$T = 2\pi\sqrt{\frac{m}{k}}$
C.1 **Simple pendulum**	$T = 2\pi\sqrt{\frac{l}{g}}$ l = length of the pendulum
C.1 HL **Displacement and velocity against time**	$x = x_0 \sin(\omega t + \phi)$ $\quad v = \omega x_0 \cos(\omega t + \phi)$ x_0 = amplitude, ϕ = phase angle
C.1 HL **Velocity at displacement x**	$v = \pm\omega\sqrt{x_0^2 - x^2}$
C.1 HL **Energy in SHM**	$E_T = \frac{1}{2}m\omega^2 x_0^2$ $\quad E_p = \frac{1}{2}m\omega^2 x^2$ E_T = total energy, E_p = potential energy at displacement x

C.2 Wave model

C.2 **Wave equation**	$v = f\lambda = \frac{\lambda}{T}$

C.3 Wave phenomena

C.3 **Snell's law**	$\frac{n_1}{n_2} = \frac{\sin\theta_2}{\sin\theta_1} = \frac{v_2}{v_1}$ n = refractive index, θ = angle to the normal, v = wave speed in each medium

C.3 **Conditions for interference**	constructive: path difference $= n\lambda$ destructive: path difference $= \left(n + \frac{1}{2}\right)\lambda$ n = an integer
C.3 **Double-slit fringe spacing**	$s = \frac{\lambda D}{d}$ D = slit-to-screen distance, d = separation of the slits
C.3 HL **Single-slit diffraction: first minimum**	$\theta = \frac{\lambda}{b}$ b = slit width, θ = angle from the central maximum (radians)
C.3 HL **Diffraction grating (multiple slits)**	$n\lambda = d\sin\theta$ n = order, d = slit spacing

C.5 Doppler effect

C.5 **Doppler effect for light**	$\frac{\Delta f}{f} = \frac{\Delta\lambda}{\lambda} \approx \frac{v}{c}$ v = relative speed of source and observer ($v \ll c$)
HL C.5 **Doppler effect for sound**	moving source: $f' = f\left(\frac{v}{v \pm u_s}\right)$ moving observer: $f' = f\left(\frac{v \pm u_o}{v}\right)$ f' = observed frequency, v = wave speed, u_s / u_o = speed of source / observer

THEME D

Fields

D.1 Gravitational fields

D.1 **Newton's law of gravitation**	$F = G\frac{m_1 m_2}{r^2}$
D.1 **Gravitational field strength**	$g = \frac{F}{m} = G\frac{M}{r^2}$ M = mass producing the field, m = test mass
D.1 HL **Gravitational potential energy of two masses**	$E_p = -G\frac{m_1 m_2}{r}$
D.1 HL **Gravitational potential**	$V_g = -G\frac{M}{r}$
D.1 HL **Field strength from potential gradient**	$g = -\frac{\Delta V_g}{\Delta r}$
D.1 HL **Work done moving a mass**	$W = m\Delta V_g$
D.1 HL **Escape speed and orbital speed**	$v_{\text{esc}} = \sqrt{\frac{2GM}{r}} \qquad v_{\text{orbit}} = \sqrt{\frac{GM}{r}}$ r = distance from the centre of the central mass M

D.2 Electric and magnetic fields

D.2 **Coulomb's law**	$F = k\frac{q_1 q_2}{r^2} \qquad k = \frac{1}{4\pi\varepsilon_0}$
D.2 **Electric field strength**	$E = \frac{F}{q} \qquad E = \frac{V}{d}$ (parallel plates) V = potential difference across plates separated by d
D.2 HL **Electric potential energy of two charges**	$E_p = k\frac{q_1 q_2}{r}$
D.2 HL **Electric potential**	$V_e = k\frac{Q}{r}$

D.2 HL **Field strength from potential gradient**	$E = -\frac{\Delta V_e}{\Delta r}$
D.2 HL **Work done moving a charge**	$W = q\Delta V_e$

D.3 Motion in electromagnetic fields

D.3 **Force on a moving charge**	$F = qvB\sin\theta$ θ = angle between velocity and field
D.3 **Force on a current-carrying conductor**	$F = BIL\sin\theta$ θ = angle between current and field
D.3 **Force per unit length between parallel wires**	$\frac{F}{L} = \mu_0\frac{I_1 I_2}{2\pi r}$ r = separation of the wires

D.4 Induction HL

D.4 HL **Magnetic flux**	$\Phi = BA\cos\theta$ θ = angle between the field and the normal to the area
D.4 HL **Faraday's law with Lenz's law**	$\varepsilon = -N\frac{\Delta\Phi}{\Delta t}$ N = number of turns
D.4 HL **Emf induced in a moving conductor**	$\varepsilon = BvL$

THEME E

Nuclear and quantum physics

E.1 Structure of the atom

E.1 Photon energy	$E = hf$
E.1 Nuclear radius HL	$R = R_0 A^{1/3}$ A = nucleon number, R_0 = Fermi radius
E.1 Energy levels in the Bohr hydrogen atom HL	$E = -\frac{13.6}{n^2}\ \text{eV}$ n = principal quantum number
E.1 Quantised angular momentum (Bohr model) HL	$mvr = \frac{nh}{2\pi}$

E.2 Quantum physics HL

E.2 Photoelectric equation HL	$E_{\max} = hf - \Phi$ $E_{\max}$ = maximum kinetic energy of emitted electrons, Φ = work function
E.2 de Broglie wavelength HL	$\lambda = \frac{h}{p}$
E.2 Compton scattering HL	$\lambda_f - \lambda_i = \Delta\lambda = \frac{h}{m_e c}(1 - \cos\theta)$ θ = scattering angle of the photon

E.3 Radioactive decay

E.3 Mass–energy equivalence	$E = mc^2$
E.3 Radioactive decay law HL	$N = N_0 \mathrm{e}^{-\lambda t}$ N_0 = initial number of undecayed nuclei, λ = decay constant
E.3 Activity HL	$A = \lambda N = \lambda N_0 \mathrm{e}^{-\lambda t}$
E.3 Half-life HL	$T_{1/2} = \frac{\ln 2}{\lambda}$

E.5 Fusion and stars

E.5

Distance from stellar parallax

$$d\,(\text{pc}) = \frac{1}{p\,(\text{arcsecond})}$$

p = parallax angle

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