Diploma Programme

Physics data booklet

First assessment 2016

International Baccalaureate
Baccalauréat International
Bachillerato Internacional

Diploma Programme
Physics data booklet

Published February 2014

Published on behalf of the International Baccalaureate Organization, a not-for-profit educational foundation of 15 Route des Morillons, 1218 Le Grand-Saconnex, Geneva, Switzerland by the

International Baccalaureate Organization (UK) Ltd
Peterson House, Malthouse Avenue, Cardiff Gate
Cardiff, Wales CF23 8GL
United Kingdom
Website: www.ibo.org

4082

Contents

Fundamental constants 1

Metric (SI) multipliers 2

Unit conversions 3

Electrical circuit symbols 4

Equations—Core 5

Equations—AHL 8

Equations—Options 10

Fundamental constants

Quantity	Symbol	Approximate value
Acceleration of free fall (Earth's surface)	g	$9.81\ \mathrm{m\,s^{-2}}$
Gravitational constant	G	$6.67 \times 10^{-11}\ \mathrm{N\,m^2\,kg^{-2}}$
Avogadro's constant	N_A	$6.02 \times 10^{23}\ \mathrm{mol^{-1}}$
Gas constant	R	$8.31\ \mathrm{J\,K^{-1}\,mol^{-1}}$
Boltzmann's 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 vacuum	c	$3.00 \times 10^{8}\ \mathrm{m\,s^{-1}}$
Planck's 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	$1.20 \times 10^{-15}\ \mathrm{m}$

Metric （SI） multipliers

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

Unit conversions

1 radian (rad) $\equiv \frac{180°}{\pi}$

Temperature (K) = temperature (°C) + 273

1 light year (ly) = 9.46×10^{15} m

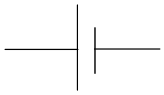
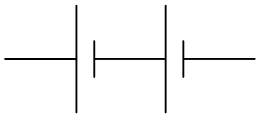
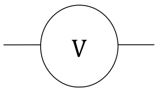
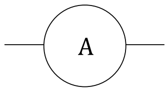
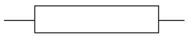
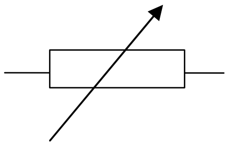
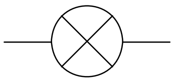
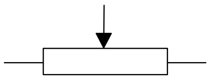
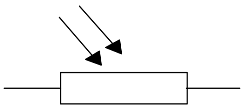
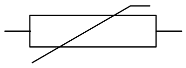
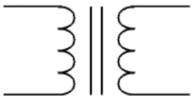
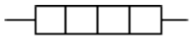
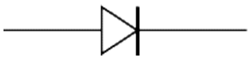
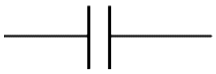
1 parsec (pc) = 3.26 ly

1 astronomical unit (AU) = 1.50×10^{11} m

1 kilowatt-hour (kWh) = 3.60×10^{6} J

$hc = 1.99 \times 10^{-25}$ J m = 1.24×10^{-6} eV m

Electrical circuit symbols

cell		battery	
ac supply		switch	
voltmeter		ammeter	
resistor		variable resistor	
lamp		potentiometer	
light-dependent resistor (LDR)		thermistor	
transformer		heating element	
diode		capacitor	

Equations—Core

Note: All equations relate to the magnitude of the quantities only. Vector notation has not been used.

Sub-topic 1.2 – Uncertainties and errors

If: $y = a \pm b$ — adding/subtracting

then: $\Delta y = \Delta a + \Delta b$ — add absolute uncertainty

If: $y = \frac{ab}{c}$ — multiplication/Division — add fractional uncertainty

then: $\frac{\Delta y}{y} = \frac{\Delta a}{a} + \frac{\Delta b}{b} + \frac{\Delta c}{c}$

If: $y = a^n$ — Power — fractional uncertainty · exponent

then: $\frac{\Delta y}{y} = \left| n \frac{\Delta a}{a} \right|$

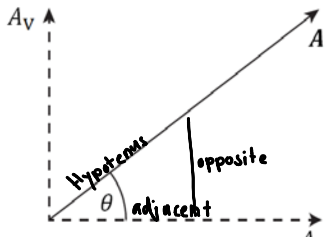
y = uncertainty

Δ = absolute uncertainty = $\frac{\text{uncertainty}}{\text{value}}$

a, b, c = given #

n = exponent

Sub-topic 1.3 – Vectors and scalars



SOH CAH TOA

A_H = X component (horizontal)

A_V = Y component (vertical)

A = vector quantity

Pythagorean therem

$A = \sqrt{(A_H)^2 + (A_V)^2}$

$A_H = A\cos\theta$ – cos θ relates to x-axis

$A_V = A\sin\theta$ – sin θ relates to y-axis

Sub-topic 2.1 – Motion

$v = u + at$

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

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

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

S = displacement (m)

U = intial velocity (m/s)

V = final velocity (m/s)

A = acceleration (m/s²)

T = time (s)

Sub-topic 2.2 – Forces

$F = ma$ — Newtons 2nd law

$F_f \le \mu_s R$

$F_f = \mu_d R$

μ_s = mu – coefficient of static friction

μ_d = mu – coefficient of dynamic friction

F = Force (Newtons or kg m/s²)

m = mass (kg)

a = acceleration (m/s²)

F_f = Friction Force (Newtons or kg m/s²)

R = Normal Force (N) Contact force

Sub-topic 2.3 – Work, energy and power

$W = Fs\cos\theta$

$E_K = \frac{1}{2}mv^2$

$E_P = \frac{1}{2}k\Delta x^2$

$\Delta E_P = mg\Delta h$

power $= Fv$

$$\text{Efficiency} = \frac{\text{useful work out}}{\text{total work in}} = \frac{\text{useful power out}}{\text{total power in}}$$

Work = Work Done (J or Nm)

F = Force (Newton or kg m/s²)

S = displacement (m)

cos θ = ∠ between force applied and direction of motion

E_K = Kinetic Energy (J or Nm)

E_p = Potential Energy

ΔE_p = Gravitational Potential Energy

Power = $\frac{\text{work}}{\text{time}}$ = $\frac{\text{Force} \cdot d}{t}$ = F · v (Watt or Joule/sec)

Sub-topic 2.4 – Momentum and impulse

$p = mv$

$F = \frac{\Delta p}{\Delta t}$ — Newtons 2nd law of momentum

$E_K = \frac{p^2}{2m}$

Impulse $= F\Delta t = \Delta p$

p = momentum (kg m/s) $v = \frac{d}{t} = \frac{m}{s}$

m = mass (kg)

v = velocity (m/s)

F = Force (Newtons or kg m/s²)

t = time (s)

E_k = kinetic energy (J or Nm)

Δt · $F = \frac{\Delta P}{\Delta t}$ · Δt how ΔP = F · Δt

Δ = change

m = mass (kg)

v = velocity (m/s)

k = Spring constant

x = extension (m)

g = gravitational acceleration (9.81 m/s²)

Spring Constant = F = –kx ← extension

(F = Force Applied, k = spring Constant)

Sub-topic 3.1 – Thermal concepts	Sub-topic 3.2 – Modelling a gas
$Q = mc\Delta T$ $Q = mL$ Q = Heat Energy (J) m = mass (kg) c = specific heat capacity (J/kg) ΔT = change in temp (°C) L = specific latent heat	$p = \frac{F}{A}$ p = Pressure F = Force A = Area $n = \frac{N}{N_A}$ n = # of moles N = # of atoms NA = Avogadro's Constant V = Volume $pV = nRT$ R = Gas Constant T = Temperature EK = Kinetic Energy $\bar{E}_K = \frac{3}{2} k_B T = \frac{3}{2} \frac{R}{N_A} T$ kB = Boltzmann's Constant

Sub-topic 4.1 – Oscillations	Sub-topic 4.4 – Wave behaviour
$T = \frac{1}{f}$ T = Period f = Frequency T = time taken to finish 1 cycle	$\frac{n_1}{n_2} = \frac{\sin\theta_2}{\sin\theta_1} = \frac{v_2}{v_1}$ n₁ = index of refraction (incident medium) n₂ = index of refraction (refractive medium) θ₁ = ∡ of incidence V = velocity (m/s) θ₂ = ∡ of refraction $s = \frac{\lambda D}{d}$ λ = wave length (m) D = screen & slit (m) d = slit spacing s = distance between bright spots Constructive interference: path difference $= n\lambda$ trough to trough (maxima) Destructive interference: path difference $= (n + \frac{1}{2})\lambda$ minima - double slit diffractions
Sub-topic 4.2 – Travelling waves	
$c = f\lambda$ c = speed of light (3·10⁸ m/s) f = frequency (Hz) λ = wavelength distance of wave	
Sub-topic 4.3 – Wave characteristics	
$I \propto A^2$ I = Intensity (W/m²) A = amplitude (m) proportional $I \propto x^{-2}$ x = distance from source I = original intensity $I = I_0 \cos^2\theta$ θ = ∡ below polarization below direction and transmission axis of polarizer Malus' Law	

Sub-topic 5.1 – Electric fields	Sub-topic 5.2 – Heating effect of electric currents
$I = \frac{\Delta q}{\Delta t}$ I = current (A) t = time (s) q = charge (c) $F = k\frac{q_1 q_2}{r^2}$ F = Electrical Force q = charge (c) r = distance between charges (m) k = coulomb's constant (8.99·10⁹ Nm²/C²) $k = \frac{1}{4\pi\varepsilon_0}$ k = coulomb's constant ε₀ = permitivity $V = \frac{W}{q}$ V = Volts (v) W = work done (J) q = charge (c) $E = \frac{F}{q}$ E = electric field strength (N/m) F = Force (N) q = charge (c) $I = nAvq$ I = current (A) v = drift velocity (m/s) n = # of charges q = charge (c) A = cross sectional charges (m²)	Kirchhoff's circuit laws: conservation of energy = Σvoltage = sum of $\Sigma V = 0$ (loop) all voltage drop $\Sigma I = 0$ (junction) conservation of charge - I exit + I enter = 0 $R = \frac{V}{I}$ V = volts I = current R = resistance V=IR $P = VI = I^2R = \frac{V^2}{R}$ Electrical Power P = Power R = resistance (Ω) V = Voltage (v) I = current (A) due to heat } powerloss $R_{total} = R_1 + R_2 + \cdots$ Series = total resistance $\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots$ Parallel = total resistance $\rho = \frac{RA}{L}$ ρ = resistivity of material R = resistance A = cross area (m²) L = Length (m)
Sub-topic 5.3 – Electric cells	**Sub-topic 5.4 – Magnetic effects of electric currents**
$\varepsilon = I(R + r)$ I = current (A) R = resistance ε = electromotive force (emf) Voltage r = internal resistance	$F = qvB\sin\theta$ - magnetic force of moving charge through magnetic field F = Force V = velocity q = charge B = magnitude of mag. field θ = ∡ between V & B $F = BIL\sin\theta$ Force on wire and current in magnetic field

B = magnitude of magnetic field
I = current (A) θ = ∡ between I and B
L = length (m)

Sub-topic 6.1 – Circular motion

$v = \omega r$ angular velocity

v= velocity (m/s)

$a = \frac{v^2}{r} = \frac{4\pi^2 r}{T^2}$ centripetal acceleration

ω = angular velocity (rad./sec)

r = radius (m)

a = acceleration = (m/s²)

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

T= period (sec.)

F= Force (N or kg m/s²)

m= mass (kg)

Sub-topic 6.2 – Newton's law of gravitation

$F = G\frac{Mm}{r^2}$ F= Force M = masses r=radius

G=gravitational constant (6.67·10⁻¹¹ N m²/kg²)

$g = \frac{F}{m}$ g=gravitational field strength

F= Force m = mass

$g = G\frac{M}{r^2}$ gravitational field strength at distance (r) from center of plant of mass (M)

Sub-topic 7.1 – Discrete energy and radioactivity

$E = hf$

$\lambda = \frac{hc}{E}$

Sub-topic 7.2 – Nuclear reactions

$\Delta E = \Delta m\, c^2$

Sub-topic 7.3 – The structure of matter

Charge	Quarks			Baryon number
$\frac{2}{3}e$	u	c	t	$\frac{1}{3}$
$-\frac{1}{3}e$	d	s	b	$\frac{1}{3}$

All quarks have a strangeness number of 0 except the strange quark that has a strangeness number of −1

Charge	Leptons		
−1	e	μ	τ
0	υ_e	υ_μ	υ_τ

All leptons have a lepton number of 1 and antileptons have a lepton number of −1

	Gravitational	Weak	Electromagnetic	Strong
Particles experiencing	All	Quarks, leptons	Charged	Quarks, gluons
Particles mediating	Graviton	W^+, W^-, Z^0	γ	Gluons

Sub-topic 8.1 – Energy sources

$\text{Power} = \frac{\text{energy}}{\text{time}}$

$\text{Power} = \frac{1}{2}A\rho v^3$

Sub-topic 8.2 – Thermal energy transfer

$P = e\sigma AT^4$

$\lambda_{\max}(\text{metres}) = \frac{2.90 \times 10^{-3}}{T(\text{kelvin})}$

$I = \frac{\text{power}}{A}$

$\text{albedo} = \frac{\text{total scattered power}}{\text{total incident power}}$

Equations—AHL

Sub-topic 9.1 – Simple harmonic motion	Sub-topic 9.2 – Single-slit diffraction
$\omega = \frac{2\pi}{T}$ ω= angular frequncy; T= Period $a = -\omega^2 x$ a= Acceleration $x = x_0 \sin \omega t$; $x = x_0 \cos \omega t$ X= Displacement from equilibrium $v = \omega x_0 \cos \omega t$; $v = -\omega x_0 \sin \omega t$ X0= maximum displacement $v = \pm\omega\sqrt{(x_0{}^2 - x^2)}$ t= Time elapsed $E_K = \frac{1}{2} m\omega^2 (x_0{}^2 - x^2)$ Ek= kinetic energy $E_T = \frac{1}{2} m\omega^2 x_0{}^2$ l= length of pendulum Pendulum: $T = 2\pi\sqrt{\frac{l}{g}}$ g= gravitational field; k= spring constant Mass–spring: $T = 2\pi\sqrt{\frac{m}{k}}$	$\theta = \frac{\lambda}{b}$ θ= angle λ= wavelength b= slit width **Sub-topic 9.3 – Interference** $n\lambda = d \sin \theta$ Constructive interference: $2dn = (m + \frac{1}{2})\lambda$ Destructive interference: $2dn = m\lambda$ n = # (diffraction grating) n= refractive index λ= wavelength m= # (TFI) d= split spacing θ= ∡ d= thickness of medium
Sub-topic 9.4 – Resolution	**Sub-topic 9.5 – Doppler effect**
$\theta = 1.22 \frac{\lambda}{b}$ θ= angle; λ= wavelength; m= diffraction order $R = \frac{\lambda}{\Delta\lambda} = mN$ b= slit width/diameter; N= # of slits illuminated R= Resolvance Δλ= smallest λ	Moving source: $f' = f\left(\frac{v}{v \pm u_s}\right)$ Moving observer: $f' = f\left(\frac{v \pm u_0}{v}\right)$ $\frac{\Delta f}{f} = \frac{\Delta\lambda}{\lambda} \approx \frac{v}{c}$

Sub-topic 10.1 – Describing fields	Sub-topic 10.2 – Fields at work
$W = q\Delta V_e$ electrostatic $W = m\Delta V_g$ gravitational } work done by mass/charge between 2 points W= Work (J) q= charge (C) V_e = electric potential m= mass (kg) V_g = gravitational potential	See table below

Potential	$V_g = -\frac{GM}{r}$	$V_e = \frac{kq}{r}$
Potential Gradient/ Field Strength	$g = -\frac{\Delta V_g}{\Delta r}$	$E = -\frac{\Delta V_e}{\Delta r}$
PE	$E_P = mV_g = -\frac{GMm}{r}$	$E_P = qV_e = \frac{kq_1q_2}{r}$
Force	$F_G = G\frac{m_1m_2}{r^2}$	$F_E = k\frac{q_1q_2}{r^2}$

$v_{esc} = \sqrt{\frac{2GM}{r}}$ Escape velocity of planet

$v_{orbit} = \sqrt{\frac{GM}{r}}$ Velocity of orbit around a body

V_g= gravitational potential
G= gravitational constant
M= mass (kg)
r= distance (m)
V_e= Electrical Potential
k= coulomb constant
q= charge
g= gravitational
E= Electric Field Strength
V_e= electric Potential
E_P= PE
F_g= Grav. Force
F_e= Electric Force

Sub-topic 11.1 – Electromagnetic induction

$\Phi = BA\cos\theta$ Φ = magnetic flux B = mag. magnetic field A = area of loop θ = ∠ A & B

$\varepsilon = -N\dfrac{\Delta\Phi}{\Delta t}$ ε = Emf N = # of loops Δt = time(s) Faraday's Law

$\varepsilon = Bvl$ v = speed of wire (m/s) – induced emf in straight wire

$\varepsilon = BvlN$ l = length of wire – induced emf in a coiled wire

Sub-topic 11.2 – Power generation and transmission

effective current → $I_{\mathrm{rms}} = \dfrac{I_0}{\sqrt{2}}$ I_0 = Peak current (square (RMS) of alternating current

effective voltage → $V_{\mathrm{rms}} = \dfrac{V_0}{\sqrt{2}}$ V_0 = Peak Voltage alternating Voltage

resistance → $R = \dfrac{V_0}{I_0} = \dfrac{V_{\mathrm{rms}}}{I_{\mathrm{rms}}}$

max power → $P_{\max} = I_0 V_0$

Power → $\bar{P} = \frac{1}{2} I_0 V_0$ Avg. Power

εp = emf (primary), εs = secondary

$\dfrac{\varepsilon_{\mathrm{p}}}{\varepsilon_{\mathrm{s}}} = \dfrac{N_{\mathrm{p}}}{N_{\mathrm{s}}} = \dfrac{I_{\mathrm{s}}}{I_{\mathrm{p}}}$ ratio of primary + secondary emf (transformer)

I = current

N = # of turns

Sub-topic 11.3 – Capacitance

$C = \dfrac{q}{V}$ C = capacities (Farads) V = voltage (V) q = charge (C)

$C_{\mathrm{parallel}} = C_1 + C_2 + \cdots$

$\dfrac{1}{C_{\mathrm{series}}} = \dfrac{1}{C_1} + \dfrac{1}{C_2} + \cdots$

\ similar to resistance /

$C = \varepsilon\dfrac{A}{d}$ parallel-plate capacitor ε: permittivity of dielectric A = area of plates d = distance between plates

$E = \frac{1}{2}CV^2$ E = energy stored in capacitor

$\tau = RC$ τ = time constant R = resistance

$q = q_0 e^{-\frac{t}{\tau}}$ q_0 = initial charge t = time(s)

$I = I_0 e^{-\frac{t}{\tau}}$ I_0 = initial max current I = current (A)

$V = V_0 e^{-\frac{t}{\tau}}$ V = Voltage

Sub-topic 12.1 – The interaction of matter with radiation

$E = hf$

$E_{\max} = hf - \Phi$

$E = -\dfrac{13.6}{n^2} eV$

$mvr = \dfrac{nh}{2\pi}$

$P(r) = |\psi|^2 \Delta V$

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

$\Delta E \Delta t \geq \dfrac{h}{4\pi}$

Sub-topic 12.2 – Nuclear physics

$R = R_0 A^{1/3}$

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

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

$\sin\theta \approx \dfrac{\lambda}{D}$

Equations—Options

Sub-topic A.1 – The beginnings of relativity	Sub-topic A.2 – Lorentz transformations
$x' = x - vt$ $u' = u - v$	$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$ $x' = \gamma(x - vt)$; $\Delta x' = \gamma(\Delta x - v\Delta t)$ $t' = \gamma(t - \frac{vx}{c^2})$; $\Delta t' = \gamma(\Delta t - \frac{v\Delta x}{c^2})$ $u' = \frac{u-v}{1-\frac{uv}{c^2}}$ $\Delta t = \gamma \Delta t_0$ $L = \frac{L_0}{\gamma}$ $(ct')^2 - (x')^2 = (ct)^2 - (x)^2$
Sub-topic A.3 – Spacetime diagrams	
$\theta = \tan^{-1}\left(\frac{v}{c}\right)$	
Sub-topic A.4 – Relativistic mechanics (HL only)	**Sub-topic A.5 – General relativity (HL only)**
$E = \gamma m_0 c^2$ $E_0 = m_0 c^2$ $E_K = (\gamma - 1)m_0 c^2$ $p = \gamma m_0 v$ $E^2 = p^2c^2 + {m_0}^2c^4$ $qV = \Delta E_K$	$\frac{\Delta f}{f} = \frac{g\Delta h}{c^2}$ $R_s = \frac{2GM}{c^2}$ $\Delta t = \frac{\Delta t_0}{\sqrt{1-\frac{R_s}{r}}}$

Sub-topic B.1 – Rigid bodies and rotational dynamics	Sub-topic B.2 – Thermodynamics
$\Gamma = Fr\sin\theta$ $I = \sum mr^2$ $\Gamma = I\alpha$ $\omega = 2\pi f$ $\omega_f = \omega_i + \alpha t$ $\omega_f^2 = \omega_i^2 + 2\alpha\theta$ $\theta = \omega_i t + \frac{1}{2}\alpha t^2$ $L = I\omega$ $E_{K_{rot}} = \frac{1}{2}I\omega^2$ ω= angular speed (θ/T) Γ = Torque (Nm) α=acceleration r=radius I = interia t=time θ=angle L= angular momentum I = rotational Inertia Ek=Kinetic Energy	$Q = \Delta U + W$ $U = \frac{3}{2}nRT$ $\Delta S = \frac{\Delta Q}{T}$ $pV^{\frac{5}{3}} = \text{constant (for monatomic gases)}$ $W = p\Delta V$ $\eta = \frac{\text{useful work done}}{\text{energy input}}$ $\eta_{Carnot} = 1 - \frac{T_{cold}}{T_{hot}}$ Q= internal Energy ΔV = Δ Heat Energy W= Work p= Pressure V= Volume

Sub-topic B.3 – Fluids and fluid dynamics (HL only)	Sub-topic B.4 – Forced vibrations and resonance (HL only)
$B = \rho_f V_f g$ $P = P_0 + \rho_f g d$ $Av = \text{constant}$ $\frac{1}{2}\rho v^2 + \rho g z + p = \text{constant}$ $F_D = 6\pi\eta r v$ $R = \frac{vr\rho}{\eta}$	$Q = 2\pi\frac{\text{energy stored}}{\text{energy dissipated per cycle}}$ $Q = 2\pi \times \text{resonant frequency} \times \frac{\text{energy stored}}{\text{power loss}}$

Sub-topic C.1 – Introduction to imaging	Sub-topic C.2 – Imaging instrumentation
$\frac{1}{f} = \frac{1}{v} + \frac{1}{u}$ $P = \frac{1}{f}$ $m = \frac{h_i}{h_o} = -\frac{v}{u}$ $M = \frac{\theta_i}{\theta_o}$ $M_{near\ point} = \frac{D}{f} + 1\ ;\ M_{infinity} = \frac{D}{f}$	$M = \frac{f_o}{f_e}$ **Sub-topic C.3 – Fibre optics** $n = \frac{1}{\sin c}$ $\text{attenuation} = 10\log\frac{I}{I_0}$ **Sub-topic C.4 – Medical imaging (HL only)** $L_I = 10\log\frac{I_1}{I_0}$ $I = I_0 e^{-\mu x}$ $\mu x_{\frac{1}{2}} = \ln 2$ $Z = \rho c$

Sub-topic D.1 – Stellar quantities	Sub-topic D.2 – Stellar characteristics and stellar evolution
$d\ (\text{parsec}) = \frac{1}{p\ (\text{arc–second})}$ $L = \sigma A T^4$ $b = \frac{L}{4\pi d^2}$	$\lambda_{\max} T = 2.9 \times 10^{-3}\ \text{m K}$ $L \propto M^{3.5}$
Sub-topic D.3 – Cosmology	**Sub-topic D.5 – Further cosmology (HL only)**
$z = \frac{\Delta\lambda}{\lambda_0} \approx \frac{v}{c}$ $z = \frac{R}{R_0} - 1$ $v = H_0 d$ $T \approx \frac{1}{H_0}$	$v = \sqrt{\frac{4\pi G \rho}{3}} r$ $\rho_\text{c} = \frac{3H^2}{8\pi G}$