

Physics data booklet

First assessment 2016



Diploma Programme Physics data booklet

Published June 2014
Revised edition published November 2016

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

© International Baccalaureate Organization 2014

The International Baccalaureate Organization (known as the IB) offers four high-quality and challenging educational programmes for a worldwide community of schools, aiming to create a better, more peaceful world. This publication is one of a range of materials produced to support these programmes.

The IB may use a variety of sources in its work and checks information to verify accuracy and authenticity, particularly when using community-based knowledge sources such as Wikipedia. The IB respects the principles of intellectual property and makes strenuous efforts to identify and obtain permission before publication from rights holders of all copyright material used. The IB is grateful for permissions received for material used in this publication and will be pleased to correct any errors or omissions at the earliest opportunity.

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, without the prior written permission of the IB, or as expressly permitted by law or by the IB's own rules and policy. See <http://www.ibo.org/copyright>.

IB merchandise and publications can be purchased through the IB store at <http://store.ibo.org>.

Email: sales@ibo.org

Contents

| | |
|--------------------------------------|----|
| Mathematical equations | 1 |
| Fundamental constants | 2 |
| Metric (SI) multipliers | 3 |
| Unit conversions | 3 |
| Electrical circuit symbols | 4 |
| Equations—Core | 5 |
| Equations—AHL | 9 |
| Equations—Options | 12 |



Mathematical equations

| | |
|---------------------------|--|
| Area of a circle | $A = \pi r^2$, where r is the radius |
| Circumference of a circle | $C = 2\pi r$, where r is the radius |
| Surface area of a sphere | $A = 4\pi r^2$, where r is the radius |
| Volume of a sphere | $V = \frac{4}{3}\pi r^3$, where r is the radius |

Fundamental constants

| Quantity | Symbol | Approximate value |
|---|--------------|---|
| Acceleration of free fall (Earth's surface) | g | 9.81ms^{-2} |
| Gravitational constant | G | $6.67 \times 10^{-11}\text{Nm}^2\text{kg}^{-2}$ |
| Avogadro's constant | N_A | $6.02 \times 10^{23}\text{mol}^{-1}$ |
| Gas constant | R | $8.31\text{JK}^{-1}\text{mol}^{-1}$ |
| Boltzmann's constant | k_B | $1.38 \times 10^{-23}\text{JK}^{-1}$ |
| Stefan–Boltzmann constant | σ | $5.67 \times 10^{-8}\text{Wm}^{-2}\text{K}^{-4}$ |
| Coulomb constant | k | $8.99 \times 10^9\text{Nm}^2\text{C}^{-2}$ |
| Permittivity of free space | ϵ_0 | $8.85 \times 10^{-12}\text{C}^2\text{N}^{-1}\text{m}^{-2}$ |
| Permeability of free space | μ_0 | $4\pi \times 10^{-7}\text{TmA}^{-1}$ |
| Speed of light in vacuum | c | $3.00 \times 10^8\text{ms}^{-1}$ |
| Planck's constant | h | $6.63 \times 10^{-34}\text{Js}$ |
| Elementary charge | e | $1.60 \times 10^{-19}\text{C}$ |
| Electron rest mass | m_e | $9.110 \times 10^{-31}\text{kg} = 0.000549\text{u} = 0.511\text{MeVc}^{-2}$ |
| Proton rest mass | m_p | $1.673 \times 10^{-27}\text{kg} = 1.007276\text{u} = 938\text{MeVc}^{-2}$ |
| Neutron rest mass | m_n | $1.675 \times 10^{-27}\text{kg} = 1.008665\text{u} = 940\text{MeVc}^{-2}$ |
| Unified atomic mass unit | u | $1.661 \times 10^{-27}\text{kg} = 931.5\text{MeVc}^{-2}$ |
| Solar constant | S | $1.36 \times 10^3\text{Wm}^{-2}$ |
| Fermi radius | R_0 | $1.20 \times 10^{-15}\text{m}$ |

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

$$1 \text{ radian (rad)} \equiv \frac{180^\circ}{\pi}$$

$$\text{Temperature (K)} = \text{temperature (}^\circ\text{C)} + 273$$

$$1 \text{ light year (ly)} = 9.46 \times 10^{15} \text{ m}$$


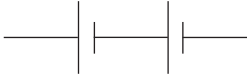

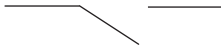

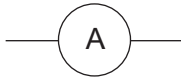

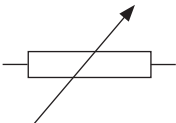

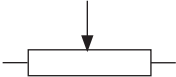
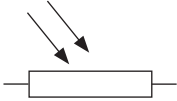
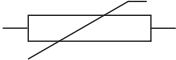
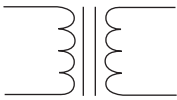

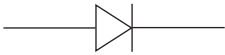

$$1 \text{ parsec (pc)} = 3.26 \text{ ly}$$

$$1 \text{ astronomical unit (AU)} = 1.50 \times 10^{11} \text{ m}$$

$$1 \text{ kilowatt-hour (kWh)} = 3.60 \times 10^6 \text{ J}$$

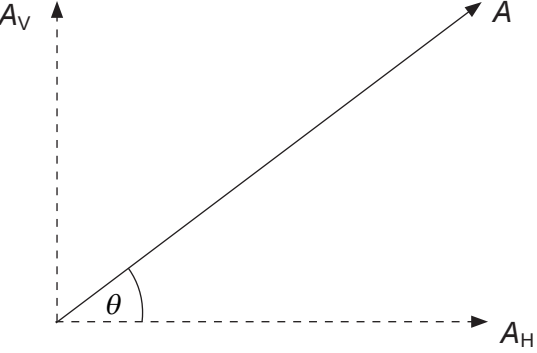
$$hc = 1.99 \times 10^{-25} \text{ Jm} = 1.24 \times 10^{-6} \text{ eVm}$$

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 | Sub-topic 1.3 – Vectors and scalars |
|---|--|
| <p>If: $y = a \pm b$ then: $\Delta y = \Delta a + \Delta b$</p> <p>If: $y = \frac{ab}{c}$ then: $\frac{\Delta y}{y} = \frac{\Delta a}{a} + \frac{\Delta b}{b} + \frac{\Delta c}{c}$</p> <p>If: $y = a^n$ then: $\frac{\Delta y}{y} = \left n \frac{\Delta a}{a} \right$</p> |  <p>$A_H = A \cos \theta$</p> <p>$A_V = A \sin \theta$</p> |

| Sub-topic 2.1 – Motion | Sub-topic 2.2 – Forces |
|--|--|
| <p>$v = u + at$</p> <p>$s = ut + \frac{1}{2}at^2$</p> <p>$v^2 = u^2 + 2as$</p> <p>$s = \frac{(v + u)t}{2}$</p> | <p>$F = ma$</p> <p>$F_f \leq \mu_s R$</p> <p>$F_f = \mu_d R$</p> |
| Sub-topic 2.3 – Work, energy and power | Sub-topic 2.4 – Momentum and impulse |
| <p>$W = F s \cos \theta$</p> <p>$E_k = \frac{1}{2}mv^2$</p> <p>$E_p = \frac{1}{2}k\Delta x^2$</p> <p>$\Delta E_p = mg\Delta h$</p> <p>power = Fv</p> <p>efficiency = $\frac{\text{useful work out}}{\text{total work in}}$ $= \frac{\text{useful power out}}{\text{total power in}}$</p> | <p>$p = mv$</p> <p>$F = \frac{\Delta p}{\Delta t}$</p> <p>$E_k = \frac{p^2}{2m}$</p> <p>impulse = $F\Delta t = \Delta p$</p> |

| Sub-topic 3.1 – Thermal concepts | Sub-topic 3.2 – Modelling a gas |
|----------------------------------|--|
| $Q = mc\Delta T$ $Q = mL$ | $p = \frac{F}{A}$ $n = \frac{N}{N_A}$ $pV = nRT$ $\bar{E}_k = \frac{3}{2}k_B T = \frac{3}{2} \frac{R}{N_A} T$ |

| Sub-topic 4.1 – Oscillations | Sub-topic 4.4 – Wave behaviour |
|--|---|
| $T = \frac{1}{f}$ | $\frac{n_1}{n_2} = \frac{\sin \theta_2}{\sin \theta_1} = \frac{v_2}{v_1}$ |
| Sub-topic 4.2 – Travelling waves | $s = \frac{\lambda D}{d}$ Constructive interference: path difference = $n\lambda$ Destructive interference: path difference = $\left(n + \frac{1}{2}\right)\lambda$ |
| $c = f\lambda$ | |
| Sub-topic 4.3 – Wave characteristics | |
| $I \propto A^2$ $I \propto x^{-2}$ $I = I_0 \cos^2 \theta$ | |

| Sub-topic 5.1 – Electric fields | Sub-topic 5.2 – Heating effect of electric currents |
|---|--|
| $I = \frac{\Delta q}{\Delta t}$ $F = k \frac{q_1 q_2}{r^2}$ $k = \frac{1}{4\pi\epsilon_0}$ $V = \frac{W}{q}$ $E = \frac{F}{q}$ $I = nAvq$ | Kirchhoff's circuit laws: $\Sigma V = 0 \text{ (loop)}$ $\Sigma I = 0 \text{ (junction)}$ $R = \frac{V}{I}$ $P = VI = I^2R = \frac{V^2}{R}$ $R_{\text{total}} = R_1 + R_2 + \dots$ $\frac{1}{R_{\text{total}}} = \frac{1}{R_1} + \frac{1}{R_2} + \dots$ $\rho = \frac{RA}{L}$ |
| Sub-topic 5.3 – Electric cells | Sub-topic 5.4 – Magnetic effects of electric currents |
| $\varepsilon = I(R + r)$ | $F = qvB \sin \theta$ $F = BIL \sin \theta$ |
| Sub-topic 6.1 – Circular motion | Sub-topic 6.2 – Newton's law of gravitation |
| $v = \omega r$ $a = \frac{v^2}{r} = \frac{4\pi^2 r}{T^2}$ $F = \frac{mv^2}{r} = m\omega^2 r$ | $F = G \frac{Mm}{r^2}$ $g = \frac{F}{m}$ $g = G \frac{M}{r^2}$ |

| Sub-topic 7.1 – Discrete energy and radioactivity | Sub-topic 7.2 – Nuclear reactions |
|---|-----------------------------------|
| $E = hf$ $\lambda = \frac{hc}{E}$ | $\Delta E = \Delta mc^2$ |

Sub-topic 7.3 – The structure of matter

| Charge | Quarks | | | Baryon number | Charge | Leptons | | |
|--|--------|---|---|---------------|--|---------|-----------|------------|
| $\frac{2}{3}e$ | u | c | t | $\frac{1}{3}$ | -1 | e | μ | τ |
| $-\frac{1}{3}e$ | d | s | b | $\frac{1}{3}$ | 0 | ν_e | ν_μ | ν_τ |
| All quarks have a strangeness number of 0 except the strange quark that has a strangeness number of -1 | | | | | 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 | Sub-topic 8.2 – Thermal energy transfer |
|---|--|
| $\text{power} = \frac{\text{energy}}{\text{time}}$ $\text{power} = \frac{1}{2} A \rho v^3$ | $P = e\sigma AT^4$ $\lambda_{\text{max}}(\text{metres}) = \frac{2.90 \times 10^{-3}}{T(\text{kelvin})}$ $I = \frac{\text{power}}{A}$ $\text{albedo} = \frac{\text{total scattered power}}{\text{total incident power}}$ |

Equations—AHL

| Sub-topic 9.1 – Simple harmonic motion | Sub-topic 9.2 – Single-slit diffraction |
|---|---|
| $\omega = \frac{2\pi}{T}$ $a = -\omega^2 x$ $x = x_0 \sin \omega t; x = x_0 \cos \omega t$ $v = \omega x_0 \cos \omega t; v = -\omega x_0 \sin \omega t$ $v = \pm \omega \sqrt{(x_0^2 - x^2)}$ $E_k = \frac{1}{2} m \omega^2 (x_0^2 - x^2)$ $E_T = \frac{1}{2} m \omega^2 x_0^2$ <p>pendulum: $T = 2\pi \sqrt{\frac{l}{g}}$</p> <p>mass-spring: $T = 2\pi \sqrt{\frac{m}{k}}$</p> | $\theta = \frac{\lambda}{b}$ |
| | Sub-topic 9.3 – Interference |
| | $n\lambda = d \sin \theta$ <p>Constructive interference: $2dn = \left(m + \frac{1}{2}\right)\lambda$</p> <p>Destructive interference: $2dn = m\lambda$</p> |
| Sub-topic 9.4 – Resolution | Sub-topic 9.5 – Doppler effect |
| $\theta = 1.22 \frac{\lambda}{b}$ $R = \frac{\lambda}{\Delta\lambda} = mN$ | <p>Moving source: $f' = f \left(\frac{v}{v \pm u_s} \right)$</p> <p>Moving observer: $f' = f \left(\frac{v \pm u_o}{v} \right)$</p> $\frac{\Delta f}{f} = \frac{\Delta \lambda}{\lambda} \approx \frac{v}{c}$ |

| Sub-topic 10.1 – Describing fields | Sub-topic 10.2 – Fields at work | |
|--|---|------------------------------------|
| $W = q\Delta V_e$ $W = m\Delta V_g$ | $V_g = -\frac{GM}{r}$ | $V_e = \frac{kQ}{r}$ |
| | $g = -\frac{\Delta V_g}{\Delta r}$ | $E = -\frac{\Delta V_e}{\Delta r}$ |
| | $E_p = mV_g = -\frac{GMm}{r}$ | $E_p = qV_e = \frac{kQq}{r}$ |
| | $F_g = \frac{GMm}{r^2}$ | $F_e = \frac{kQq}{r^2}$ |
| | $v_{\text{esc}} = \sqrt{\frac{2GM}{r}}$ $v_{\text{orbit}} = \sqrt{\frac{GM}{r}}$ | |

| Sub-topic 11.1 – Electromagnetic induction | Sub-topic 11.3 – Capacitance |
|--|--|
| $\Phi = BA \cos \theta$ $\varepsilon = -N \frac{\Delta \Phi}{\Delta t}$ $\varepsilon = Bvl$ $\varepsilon = BvIN$ | $C = \frac{q}{V}$ $C_{\text{parallel}} = C_1 + C_2 + \dots$ $\frac{1}{C_{\text{series}}} = \frac{1}{C_1} + \frac{1}{C_2} + \dots$ |
| Sub-topic 11.2 – Power generation and transmission | |
| $I_{\text{rms}} = \frac{I_0}{\sqrt{2}}$ $V_{\text{rms}} = \frac{V_0}{\sqrt{2}}$ $R = \frac{V_0}{I_0} = \frac{V_{\text{rms}}}{I_{\text{rms}}}$ $P_{\text{max}} = I_0 V_0$ $\bar{P} = \frac{1}{2} I_0 V_0$ $\frac{\varepsilon_p}{\varepsilon_s} = \frac{N_p}{N_s} = \frac{I_s}{I_p}$ | $C = \varepsilon \frac{A}{d}$ $E = \frac{1}{2} CV^2$ $\tau = RC$ $q = q_0 e^{-\frac{t}{\tau}}$ $I = I_0 e^{-\frac{t}{\tau}}$ $V = V_0 e^{-\frac{t}{\tau}}$ |

| Sub-topic 12.1 – The interaction of matter with radiation | Sub-topic 12.2 – Nuclear physics |
|--|---|
| $E = hf$ $E_{\text{max}} = hf - \Phi$ $E = -\frac{13.6}{n^2} \text{eV}$ $mvr = \frac{nh}{2\pi}$ $P(r) = \psi ^2 \Delta V$ $\Delta x \Delta p \geq \frac{h}{4\pi}$ $\Delta E \Delta t \geq \frac{h}{4\pi}$ | $R = R_0 A^{\frac{1}{3}}$ $N = N_0 e^{-\lambda t}$ $A = \lambda N_0 e^{-\lambda t}$ $\sin \theta \approx \frac{\lambda}{D}$ |

Equations—Options

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

| Sub-topic B.1 – Rigid bodies and rotational dynamics | Sub-topic B.2 – Thermodynamics |
|---|---|
| $\Gamma = Fr \sin \theta$ $I = \sum mr^2$ $\Gamma = I\alpha$ $\omega = 2\pi f$ $\omega_f = \omega_i + \alpha t$ $\omega_f^2 = \omega_i^2 + 2\alpha\theta$ $\theta = \omega_i t + \frac{1}{2}\alpha t^2$ $L = I\omega$ $E_{K_{\text{rot}}} = \frac{1}{2}I\omega^2$ | $Q = \Delta U + W$ $U = \frac{3}{2}nRT$ $\Delta S = \frac{\Delta Q}{T}$ $\rho V^{\frac{5}{3}} = \text{constant (for monatomic gases)}$ $W = p\Delta V$ $\eta = \frac{\text{useful work done}}{\text{energy input}}$ $\eta_{\text{Carnot}} = 1 - \frac{T_{\text{cold}}}{T_{\text{hot}}}$ |
| 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 |
|---|---|
| $\frac{1}{f} = \frac{1}{v} + \frac{1}{u}$ $P = \frac{1}{f}$ $m = \frac{h_i}{h_o} = -\frac{v}{u}$ $M = \frac{\theta_i}{\theta_o}$ $M_{\text{near point}} = \frac{D}{f} + 1; M_{\text{infinity}} = \frac{D}{f}$ | $M = \frac{f_o}{f_e}$ |
| | 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) |
| | $L_1 = 10 \log \frac{I_1}{I_0}$ $I = I_0 e^{-\mu x}$ $\mu x_{\frac{1}{2}} = \ln 2$ $Z = \rho c$ |

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