Fields

IB Diploma Physics

> *The data booklet is on the desk in every paper, so the useful question is what you have to supply yourself: the definitions, the decay bookkeeping, and the results you are expected to derive. Compiled by GioPhysics from the published syllabus. This is an independent study aid, not an IB document; the official syllabus is the authority.*

D.1 Gravitational fields

SL

Newton's law of gravitation

$$F = GMm / r^2$$

- F — gravitational force between the two masses (N)
- G — gravitational constant (N m^2 kg^{-2})
- M, m — the two masses (kg)
- r — separation of their centres (m)

For point masses, and for uniform spheres measured centre to centre.

SL

Gravitational field strength

$$g = F / m = GM / r^2$$

- g — gravitational field strength (N kg^{-1}, m s^{-2})
- M — mass producing the field (kg)
- r — distance from its centre (m)

The force per unit mass, and numerically the same as the acceleration of free fall at that point.

SL
DERIVED

Speed in a circular orbit

$$v = \sqrt{GM / r}$$

- v — orbital speed (m s^{-1})
- M — mass being orbited (kg)
- r — orbital radius (m)

Not printed in the data booklet: it comes from setting the gravitational force equal to the centripetal force, $GMm/r^2 = mv^2/r$. The orbiting mass cancels.

SL
DERIVED

Kepler's third law

$$T^2 = 4\pi^2 r^3 / (GM)$$

- T — orbital period (s)
- r — orbital radius (m)
- M — mass being orbited (kg)

Not marked given here because the booklet's coverage of it has not been confirmed. It follows from $GMm/r^2 = 4\pi^2 mr/T^2$, and the useful form is that T^2 is proportional to r^3 for everything orbiting the same central mass.

HL

Gravitational potential

$$V_g = -GM / r$$

- V_g — gravitational potential (J kg^{-1})
- M — mass producing the field (kg)
- r — distance from its centre (m)

Higher level only. Negative because the zero is taken at infinity and gravity only attracts.

HL

Gravitational potential energy

$$E_p = -GMm / r$$

E_p — potential energy of the pair (J)
M, m — the two masses (kg)
r — their separation (m)

Higher level only. This replaces $\Delta E_p = mg\Delta h$ once the field can no longer be treated as uniform.

HL

Field as potential gradient

$$g = -\Delta V_g / \Delta r$$

g — gravitational field strength ($N\ kg^{-1}$)
$\Delta V_g/\Delta r$ — potential gradient ($J\ kg^{-1}\ m^{-1}$)

Higher level only. The field is the gradient of the potential graph, and equipotential surfaces are everywhere perpendicular to the field lines.

HL

Work done moving a mass in a field

$$W = m\Delta V_g$$

W — work done (J)
m — mass moved (kg)
ΔV_g — change in gravitational potential ($J\ kg^{-1}$)

Higher level only. No work is done moving along an equipotential.

HL

Escape speed

$$v_{esc} = \sqrt{2GM / r}$$

v_{esc} — escape speed ($m\ s^{-1}$)
M — mass of the planet or star (kg)
r — distance from its centre (m)

Higher level only. The speed at which kinetic energy just cancels the negative potential energy, so the total energy reaches zero.

HL

Total energy of an orbiting body

$$E_T = -GMm / (2r)$$

E_T — total energy of the orbiting body (J)
M — mass being orbited (kg)
m — mass in orbit (kg)
r — orbital radius (m)

Higher level only. Kinetic plus potential. It is negative for a bound orbit, and a satellite losing energy to drag falls to a smaller r and speeds up.

D.2 Electric and magnetic fields

SL

Coulomb's law

$$F = kQ_1Q_2 / r^2, \text{ with } k = 1 / (4\pi\varepsilon_0)$$

F — force between the charges (N)
k — Coulomb constant ($N\ m^2\ C^{-2}$)
Q_1, Q_2 — the two point charges (C)
ε_0 — permittivity of free space ($C^2\ N^{-1}\ m^{-2}$)
r — separation (m)

Same inverse square shape as gravitation, but this one can repel as well as attract.

SL

Electric field strength

$$E = F / q = kQ / r^2$$

E — electric field strength (N C^{-1}, V m^{-1})
F — force on the test charge (N)
q — test charge (C)
Q — charge producing the field (C)

Force per unit positive charge, so the field direction is the direction of the force on a positive charge.

SL

Uniform field between parallel plates

$$E = V / d$$

E — field strength (V m^{-1})
V — potential difference between the plates (V)
d — plate separation (m)

HL

Electric potential

$$V_e = kQ / r$$

V_e — electric potential (V, J C^{-1})
Q — charge producing the field (C)
r — distance from it (m)

Higher level only. Unlike gravitational potential this can be positive or negative, following the sign of Q.

HL

Electric potential energy

$$E_p = kQq / r$$

E_p — potential energy of the pair of charges (J)
Q, q — the two charges (C)
r — their separation (m)

Higher level only. Positive for two like charges, which is why they fly apart when released.

HL

Field as potential gradient

$$E = -\Delta V_e / \Delta r$$

E — electric field strength (V m^{-1})
$\Delta V_e/\Delta r$ — potential gradient (V m^{-1})

Higher level only. In a uniform field this is exactly $E = V/d$.

HL

Work done moving a charge

$$W = q\Delta V_e$$

W — work done (J)
q — charge moved (C)
ΔV_e — change in electric potential (V)

Higher level only.

D.3 Motion in electromagnetic fields

SL

Energy gained by an accelerated charge

$$\Delta E_k = qV$$

ΔE_k — kinetic energy gained (J, eV)
q — charge (C)
V — accelerating potential difference (V)

This is what the electronvolt is: the energy an electron gains across one volt.

SL

Force on a moving charge in a magnetic field

$$F = qvB \sin \theta$$

- F — magnetic force (N)
- q — charge (C)
- v — speed ($m\ s^{-1}$)
- B — magnetic flux density (T)
- θ — angle between the velocity and the field (°)

The force is perpendicular to both v and B, so it does no work and cannot change the speed — only the direction.

SL

Force on a current-carrying conductor

$$F = BIL \sin \theta$$

- F — force on the conductor (N)
- B — magnetic flux density (T)
- I — current (A)
- L — length of conductor in the field (m)
- θ — angle between the conductor and the field (°)

Direction from the left-hand rule for conventional current.

SL
DERIVED

Radius of a charged particle's circular path

$$r = mv / (qB)$$

- r — radius of the path (m)
- m — mass of the particle (kg)
- v — speed ($m\ s^{-1}$)
- q — charge (C)
- B — magnetic flux density (T)

Not printed in the data booklet: it is $qvB = mv^2/r$ rearranged, for a particle moving at right angles to the field.

SL

Force between parallel current-carrying wires

$$F / L = \mu_0 I_1 I_2 / (2\pi r)$$

- F/L — force per unit length ($N\ m^{-1}$)
- μ_0 — permeability of free space ($T\ m\ A^{-1}$)
- I_1, I_2 — the two currents (A)
- r — separation of the wires (m)

Currents in the same direction attract; opposite directions repel.

D.4 Induction

HL

Magnetic flux

$$\Phi = BA \cos \theta$$

- Φ — magnetic flux (Wb)
- B — magnetic flux density (T)
- A — area of the loop (m^2)
- θ — angle between the field and the normal to the area (°)

Higher level only. Note that θ is measured from the normal, so the flux is greatest when the field is perpendicular to the plane of the loop.

HL

Flux linkage

$$\text{flux linkage} = N\Phi$$

- N — number of turns in the coil
- Φ — flux through one turn (Wb)

Higher level only.

HL

Faraday's law

$$\varepsilon = -N \, \Delta\Phi / \Delta t$$

- ε — induced electromotive force (V)
- N — number of turns
- $\Delta\Phi/\Delta t$ — rate of change of flux ($Wb\ s^{-1}$)

Higher level only. The magnitude is the rate of change of flux linkage; the minus sign is Lenz's law, which is conservation of energy — the induced current opposes the change that made it.

HL

e.m.f. induced in a moving conductor

$$\varepsilon = BvL$$

- ε — induced e.m.f. (V)
- B — magnetic flux density (T)
- v — speed of the conductor ($m\ s^{-1}$)
- L — length of the conductor in the field (m)

Higher level only. For a rod moving at right angles to a uniform field, sweeping out area as it goes.