Fields

Fairlight Tuition

Sevens

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Fields 1 [Concepts]

1. **Field definition:** A region in which a [mass/charge/moving charge] will experience a force. Field direction is that in which a [mass/positive charge/isolated north pole] would experience the force.

2. **Field similarities:** All act at a distance and obey the inverse-square law for variations in strength (with distance from a point source).

3. **Field differences (1):** Produced by and affect different quantities [mass (*g*)/charge (*E*)/moving charge (*B*)].

4. **Field differences (2):** *g* fields are only attractive; *E* and *B* fields are attractive or repulsive.

5. **Field differences (3):** *g* fields cannot be completely uniform and are not affected by the nature of medium; *E* and *B* fields can and are.

6. **Field graphs (all against 'd'):**

$$Force \underset{\Leftarrow\, gradient \,\Leftarrow}{\overset{\Rightarrow\, area \,\Rightarrow}{\overline{\qquad\qquad}}} Energy \qquad\qquad Field\ Strength \underset{\Leftarrow\, gradient \,\Leftarrow}{\overset{\Rightarrow\, area \,\Rightarrow}{\overline{\qquad\qquad}}} Potential$$

7. **The path of a charge** projected perpendicular to a uniform electric field is *parabolic* as the component of the velocity perpendicular to the field remains constant but its parallel component is accelerated by the field. The angle between the force and velocity vectors therefore reduces with motion.

Fields 2 [Gravitational]

1. **Newton's Law of Gravitational Force:** The gravitational force between two bodies is directly proportional to the product of their masses and inversely proportional to the square of the separation of their centres of mass:

$$F \propto \frac{m_1 m_2}{d^2} \qquad \left[= \frac{G m_1 m_2}{d^2} \right]$$

2. **Gravitational field strength** (*g*) newtons per kilogram [N kg $^{-1}$] + direction

3. **Gravitational field strength equation:** $g_1 = \frac{G m_1}{d^2}$ $\left[= \frac{F}{m_2} \right]$

4. **Gravitational potential definition:** The work done *on* unit test mass moving it from infinity (zero potential) to that point in the field. [Gravitational potential is therefore by default *negative* as work will be done *by* the test mass when moving through an *attractive* field.]

5. **Gravitational potential** (V_G) joules per kilogram [J Kg $^{-1}$]

6. **Gravitational potential equation:** $V_1 = (-)\frac{G m_1}{d}$

7. **Gravitational potential energy:** $E_{GP} = V_1 m_2$ $\left[= (-)\frac{G m_1 m_2}{d} \right]$

Fields 3 [Electric]

1. **Coulomb's Law of Electric Force:** The electric force between two bodies is directly proportional to the product of their charges and inversely proportional to the square of the separation of their centres of charge:
   $F \propto \frac{q_1 q_2}{d^2}$ $\left[= \frac{k q_1 q_2}{d^2}\right]$ $\left[= \frac{q_1 q_2}{4\pi\varepsilon_0 d^2}\right]$

2. **Electric field strength** (E) newtons per coulomb [N C $^{-1}$] + direction

3. **Electric field strength equation:** $E_1 = \frac{k q_1}{d^2}$ $\left[= \frac{F}{q_2}\right]$ $\left[= \frac{V}{d} \text{ (uniform)}\right]$

4. **Electric potential definition:** The work done *on* unit *positive* test charge moving it from infinity (zero potential) to that point in the field. [Electric potential is therefore by default *positive* as work will be done *on* the *positive* test charge when moving through a *repulsive* field.]

5. **Electric potential** (V_E) joules per coulomb [J C $^{-1}$]

6. **Electric potential equation:** $V_1 = (+)\frac{k q_1}{d}$

7. **Electric potential energy:** $E_{EP} = V_1 q_2$ $\left[= (+)\frac{k q_1 q_2}{d}\right]$

Fields 4 [Capacitance : Concepts]

1. **Capacitance** (C) farads [F]

2. **Capacitance Equation:** $C = \frac{Q}{V}$

3. **Time Constant** (τ [RC]) seconds [s]

4. **Time Constant Equation:** $\tau = RC$

5. **Half-life** ($T_{½}$) seconds [s]

6. **Half-life Equation:** $T_{½} = (ln2)(\tau)$ [$= (ln2)(RC)$]

7. **Permittivity of Free Space** (ε_0) farads per metre [F m $^{-1}$]

Fields 5 [Capacitance : Equations]

1. **Energy Stored:** $W = \frac{1}{2}VQ$ $\left[= \frac{1}{2}CV^2\right]$ $\left[= \frac{1}{2}\frac{Q^2}{C}\right]$

2. **Discharging:** $Q = Q_o e^{-\frac{t}{RC}}$ $\left[I = I_o e^{-\frac{t}{RC}}\right]$ $\left[V = V_o e^{-\frac{t}{RC}}\right]$

3. **Charge-time (*Q*-*t*) graphs:** gradient = I area = N/A

4. **Voltage-charge (*V*-*Q*) graphs:** gradient = $\frac{1}{C}$ area = energy stored.

5. **N-Q Analogy:** Number of undecayed nuclei (N) is analogous to charge stored (Q).

6. ***A*-*I* analogy:** Activity of source ($A = \Delta N/\Delta t = \lambda N$) is analogous to current ($I = \Delta Q/\Delta t = Q/RC$).

7. **λ- $^1/\tau$ analogy:** Decay constant (λ) is analogous to the *inverse* of the time constant ($^1/\tau$).

Fields 6 [Motor Effect]

1. **Magnetic flux density** (B) tesla [T] + direction

2. **Tesla:** A magnetic flux density of one tesla produces one newton force per unit length on a long wire carrying a current of one ampere placed perpendicular to the magnetic field.

3. **Corkscrew rule:** Current away = field clockwise. Current towards = field anti-clockwise.

4. **Force on a current carrying wire:** $F = (N)BIl(\sin\theta)$

5. **Force on a moving charge:** $F = Bqv(\sin\theta)$

6. **Fleming's left-hand (motor) rule:** se**C**ond = **C**urrent / **F**irst = **F**ield / **TH**umb = **TH**rust.

7. **The path of a charge** projected perpendicular to a uniform magnetic field is *circular* as the angle between the force and velocity vectors remains perpendicular with motion, exerting a radial resultant force on the charge.

Fields 7 [Dynamo Effect]

1. **Magnetic flux** (Φ) weber [Wb] [$= BA(\sin\theta)$]

2. **Magnetic flux linkage** ($N\Phi$) weber-turns [Wb-turns] [$= NBA(\sin\theta)$]

3. **Faraday's Law of Electromagnetic Induction:** The magnitude of the induced emf across a body is directly proportional to the rate of change of flux linkage through it (*or rate at which it cuts flux*).

$$\in \propto \frac{\Delta(NBA(\sin\theta))}{\Delta t}$$

4. **Lenz's Law:** The direction of the induced emf is such that its consequential effects will oppose the change in flux causing it. [Lenz's Law results from the application of the Law of Conservation of Energy to Faraday's Law.]

5. **Neumann's Equation:** $\in = (-)\frac{\Delta(NBA(\sin\theta))}{\Delta t}$

6. **Emf induced across a moving body:** $\in = (N)Blv(\sin\theta)$

7. **Fleming's right-hand (dynamo) rule:** thu**M**b = **M**ovement / **F**irst = **F**ield / s**E**cond = **E**mf.

Fields 8 [Motors]

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1. **Current is passed** through a rotor, creating a magnetic field around the rotor.

2. **This field** interacts with that of the permanent magnet, exerting a force [$F = (N)BIl(\sin\theta)$], and hence a couple, on the rotor (*motor effect*).

3. **This couple** causes the rotor to spin.

4. **If current direction** remains constant the rotor can only spin up to 180° (i.e. one half turn).

5. **A split-ring commutator** therefore reverses current direction every half turn (and hence also the force direction) by switching the brush-rotor contacts, allowing the rotor to keep spinning.

6. **As the rotor is spinning** in a magnetic field, however, the flux linkage through the rotor changes, inducing a *back emf* (according to Faraday's Law – *dynamo effect*).

7. **The direction of** this back emf opposes the original current (according to Lenz's Law), reducing the pd *across*, current *through* and force *on* the spinning rotor.

Fields 9 [Dynamos]

1. **A rotor is spun** in a magnetic field, changing the flux linkage through the rotor.
2. **This change in** flux linkage induces an emf in the rotor (according to Faraday's Law – *dynamo effect*).
3. **If the rotor** is a conductor, a current will therefore flow.
4. **The direction of** this current, however, opposes the change in flux causing it (according to Lenz's Law).
5. **The magnetic field** produced by the rotor current therefore interacts with that of the permanent magnet, creating a force that retards the rotor spin (*motor effect*).
6. **Some of the kinetic energy** put into a generator will therefore be converted into internal energy in the rotor before being dissipated as thermal energy to the cooler surroundings.
7. **This electromagnetic** retarding effect is used in systems such as *regenerative brakes.*

Fields 10 [Transformers : Function]

1. **Transformers are used** to change voltage (and hence also current) values by adjusting the ratio of turns in their primary and secondary coils.
2. **Alternating voltage** in the primary coil produces an alternating current (in which electrons oscillate with SHM).
3. **This alternating current** produces an alternating magnetic field around the primary coil.
4. **This alternating magnetic** field changes the flux linkage through the secondary coil, inducing an emf (according to Faraday's Law – *dynamo effect*).
5. **The magnitude of** this emf is proportional to the number of turns in the coils (*N*), and hence transformers with more secondary than primary turns will step-up the voltage (and *vice versa*).
6. **Transformer equation:** $$\frac{N_s}{N_p} = \frac{V_s}{V_p} = \frac{I_p}{I_s}$$
7. **Stepping-up** the voltage at a power station causes the current to be stepped-down, reducing Joule heating power losses in the national grid (as $P = I^2R$) .

Fields 11 [Transformers : Efficiency]

1. **Ideal transformers** are assumed to be 100% efficient ($I_P V_P = I_S V_S$).

2. **Real transformers** are generally 95-99% efficient. The five main sources of inefficiency are: Joule heating; eddy currents; flux leakage; magnetic hysteresis; and transformer hum.

3. **Joule [Resistive] Heating:** Currents in the primary and secondary coils do work on them, increasing their internal energy. (Minimise by using low resistance [low ρ high A] coils.)

4. **Eddy Currents:** Alternating magnetic fields around the primary coil induce small, circular eddy currents in the core, resulting in further Joule heating losses. (Minimise by laminating core with insulating material, greatly increasing its resistance.)

5. **Flux Leakage:** Physical separation may result in flux loss between the primary and secondary coils. (Minimise by winding coils close to each other around a common core.)

6. **Magnetic Hysteresis:** Energy is required to magnetise and de-magnetise the core, which increases in temperature as a result. (Minimise by using magnetically soft (low hysteresis) material for core, such as iron.)

7. **Transformer Hum:** Alternating magnetic forces cause vibrations in coils and core, leading to sound energy losses. [There is also some *magnetostriction* of the core.] (Minimise by tightening coils/ laminations and using materials and structures that do not resonate at mains frequency.)

Fields 12 [Hall Probe]

1. **A Hall Probe** measures the magnetic flux density within a region.

2. **A steady current** is driven through a semiconducting wafer in the tip of the probe.

3. **The charge carriers** in the wafer experience a lateral force due to the magnetic field in which the probe has been placed (*motor effect*).

4. **This lateral force** produces a surplus of charge on one side of the wafer and a deficit on the other, generating a pd – and hence an electric field – across the probe tip.

5. **The strength of** this field increases until the electric force on the charge carriers is equal and opposite to the lateral magnetic force, halting the relocation of charge.

$$\frac{Vq}{d} = Bqv$$

6. **For a steady current** and wafer width, *q*, *v* and *d* are all constant, and hence the 'Hall voltage' is directly proportional to the flux density ($V \propto B$). A voltmeter attached to the probe may therefore be calibrated to show magnetic flux density.

7. **Semiconducting wafers** are used because their charge carriers have a much higher drift velocity than metals, which produces a much larger 'Hall voltage' per tesla (and hence a lower uncertainty in the measurement).