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Electric Charge and Electric Field

$F_{\text{Coulomb}} = k\frac{|Q_1 Q_2|}{r^2}$, $k = 9 \times 10^9\ N \cdot m^2/C^2$

$\varepsilon_0 = \frac{1}{4\pi k} = 8.85 \times 10^{-12}\ C^2/(N \cdot m^2)$

$e = 1.602 \times 10^{-19}\ C$

$E = k\frac{|Q|}{r^2}$, point charge

$E = \frac{\sigma}{2\varepsilon_0}$, $\sigma = \frac{\Delta Q}{\Delta A}$, infinite charged plane

$F_e = |q|\,E$

$\sum_{\substack{\text{closed} \\ \text{surface}}} E_\perp \Delta A = \frac{Q_{\text{encl}}}{\varepsilon_0}$, Gauss' Law 1

$\Phi_e = EA\cos\phi$, electric flux

$p = Qd$, electric dipole moment

$U_{\text{e-dipole}} = -pE\cos\phi$, dipole potential energy

$\tau = pE\sin\phi$, torque on dipole

Electric Potential

$W_e = -\Delta U_e$

$U_e = k\frac{Qq}{r}$, point charges

$\Delta U_e = q\Delta V$

$V = k\frac{Q}{r}$, point charge wrt ∞

$W^* = \Delta KE + \Delta U_e$

$1\ eV = 1.6 \times 10^{-19}\ J$

$\bar{E}_\ell = -\frac{\Delta V}{\Delta \ell}$

$C = \frac{Q_{\text{free}}}{\Delta V}$, $U_C = \frac{1}{2}\frac{Q^2}{C}$ } capacitor

$C = \kappa\frac{\varepsilon_0 A}{d}$, $E = \frac{\sigma_{\text{total}}}{\varepsilon_0}$ } parallel plate capacitor

$u_e = \frac{1}{2}\varepsilon_0 E^2$, E-field energy density

Electric Current

$I = \frac{\Delta Q}{\Delta t}$

$v_{\text{drift}} = \frac{1}{fnq}\frac{I}{A}$

$\Delta V = IR$, resistor

$R = \rho\frac{L}{A}$

$P = I\Delta V$

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Electric Circuits

$R = R_1 + R_2$, in series

$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$, in parallel

$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2}$, in series

$C = C_1 + C_2$, in parallel

$\Delta V_{terminal} = \mathcal{E} - Ir$

Kirchhoff's Rules: $\begin{cases} \text{loop: } \sum_{\substack{\text{closed} \\ \text{loop}}} \Delta V = 0 \\ \text{junction: } \sum I_{in} = \sum I_{out} \end{cases}$

series RC dc-circuit: $I(t) = \frac{\Delta V}{R} e^{-t/\tau}$, $\tau = RC$, $\Delta V = \begin{cases} \mathcal{E}, & \text{charging} \\ Q_0/C, & \text{discharging} \end{cases}$

$\Delta V_R = \begin{cases} -IR, & \text{with current} \\ +IR, & \text{against current} \end{cases}$

$\Delta V_{battery} = \begin{cases} +\mathcal{E}, & \text{from - to + terminal} \\ -\mathcal{E}, & \text{from + to - terminal} \end{cases}$

$\Delta V_C = \begin{cases} +\frac{Q}{C}, & \text{from - to + plate} \\ -\frac{Q}{C}, & \text{from + to - plate} \end{cases}$

Magnetism

$F = |q|vB\sin\phi$

$F = I\ell B\sin\phi$

$\sum_{\substack{\text{closed} \\ \text{surface}}} B_\perp \Delta A = 0$, Gauss' Law 2

$2\pi f_{cyclotron} = \frac{|q|B}{m} = \frac{v}{R}$

$\sum_{\substack{\text{closed} \\ \text{loop}}} B_\parallel \Delta\ell = \mu_0 I_{encl}$, Ampere's Law $(\mu_0 = 4\pi \times 10^{-7}\ T\cdot m/A)$

$\frac{F}{\ell} = \frac{\mu_0 I_1 I_2}{2\pi d}$

$B = \frac{\mu_0 I}{2\pi r}$, long straight wire

$B_{center} = \frac{\mu_0 I}{2R}$, loop

$B_{center} = \frac{\mu_0 N I}{\ell}$, solenoid

$\mathfrak{M} = NIA$, magnetic dipole moment

$U_{m\text{-}dipole} = -\mathfrak{M}B\cos\phi$, dipole potential energy

$\tau = \mathfrak{M}B\sin\phi$, torque on magnetic dipole

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EM Induction

Lenz: A changing flux gives rise to a current whose flow opposes the original change

$\Phi_m = BA\cos\phi$, magnetic flux

$\mathcal{E} = \sum_{\substack{\text{area's}\\ \text{boundary}}} E_{\parallel}^{(\text{ind})}\Delta\ell = -N\frac{\Delta\phi_m}{\Delta t}$, Faraday's Law

$\mathcal{E} = B\ell v$, motional emf

$\mathcal{E} = \omega NBA$, ac generator

$\frac{\Delta V_s}{\Delta V_p} = \frac{I_p}{I_s} = \frac{N_s}{N_p}$, transformer

$L_{\text{solenoid}} = \frac{\mu N^2 A}{\ell}$

$u_m = \frac{1}{2}\frac{B^2}{\mu_0}$, B-field energy density

$$\left.\begin{aligned}\Delta V &= L\frac{\Delta I}{\Delta t}\\ U_L &= \tfrac{1}{2}LI^2\end{aligned}\right\}\ \text{inductor}$$

$$\Delta V_L = \begin{cases} -L\frac{\Delta I}{\Delta t}, & \text{with current}\\ +L\frac{\Delta I}{\Delta t}, & \text{against current}\end{cases}$$

series LR dc-circuit: $I_{\text{with emf}} = \frac{\mathcal{E}}{R}\left(1 - e^{-t/\tau}\right),\ \tau = \frac{L}{R}$

AC Circuits

series LRC ac-curcuit:

$$\begin{cases} Z = \sqrt{R^2 + (X_L - X_C)^2}\\ \Delta V_{RLC} = \Delta V_S = IZ, \quad \overline{P}_S = \frac{1}{2}I\Delta V_S\cos\phi = I_{\text{rms}}\Delta V_{S,\text{rms}}\cos\phi\\ \Delta V_R = IR, \quad \overline{P}_R = \frac{1}{2}I^2R = I_{\text{rms}}^2R\\ \Delta V_L = IX_L, \quad \overline{P}_L = 0\\ \Delta V_C = IX_C, \quad \overline{P}_C = 0\\ \cos\phi = \frac{R}{Z}, \quad \tan\phi = \frac{X_L - X_C}{R}\end{cases}$$

$X_L = \omega L$

$X_C = \frac{1}{\omega C}$

$\omega = 2\pi f$

resonance: $\begin{cases} X_L = X_C\\ \omega_0 = \frac{1}{\sqrt{LC}}\end{cases}$

$I_{\text{rms}} = \frac{I}{\sqrt{2}}$

$\Delta V_{\text{rms}} = \frac{\Delta V}{\sqrt{2}}$

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Electromagnetic Waves

$\sum_{\text{closed loop}} B_{\parallel}\Delta\ell = \mu_0 I_{\text{encl}} + \mu_0\varepsilon_0 \frac{\Delta\Phi_e}{\Delta t}$, Ampere's (generalized) Law

$c = \frac{1}{\sqrt{\varepsilon_0\mu_0}} = 2.998 \times 10^8\ m/s$ | $f\lambda = c$ | $E = cB$, EM wave

$\bar{u}_{\text{EM}} = \frac{1}{2}\varepsilon_0 E^2_{\text{rms}} + \frac{1}{2}\frac{1}{\mu_0}B^2_{\text{rms}}$, EM wave energy density | $I = \bar{S} = \frac{1}{\mu_0}E_{\text{rms}}B_{\text{rms}}$, (Poynting) intensity

$P = \begin{cases} \frac{S}{c}, & \text{absorbing} \\ 2\frac{S}{c}, & \text{reflecting} \end{cases}$, radiation pressure on surfaces

Geometric Optics

$\theta_{\text{Reflected}} = \theta_{\text{Incident}}$

$n_1 \sin\theta_1 = n_2 \sin\theta_2$

$\sin\theta_{\text{critical}} = \frac{n_2}{n_1}$ | $n = \frac{c}{v}$, $c = 3 \times 10^8\ m/s$

$\lambda' = \frac{n\lambda}{n'}$

$f' = f$

$\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$

$\frac{1}{f_{\text{lens}}} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$

$\frac{1}{f_{\text{mirror}}} = \frac{2}{R}$

$m = \frac{h_I}{h_O} = -\frac{q}{p}$

$P\ [Diopter] = \frac{1}{f\ [m]}$

$P_{\text{lenses in contact}} = P_1 + P_2$

conventions for light incident from left:

- mirror: $R > 0$, concave surface; $q > 0$, left of vertex
- thin lens: $R > 0$, convex surface; $q > 0$, right of vertex

Wave Nature of Light

$\phi_{\text{path}} = 2\pi\left(\frac{ns}{\lambda_{\text{vac}}}\right)$, 1 medium

$\phi_{\text{refl.}} = \begin{cases} 0, & \text{high} \to \text{low} \\ \pi, & \text{low} \to \text{high} \end{cases}$

$\Delta\Phi_{\text{total}} = \begin{cases} 2m\pi,\ m \in \mathbb{Z} \Rightarrow & \text{constructive} \\ (2m+1)\pi,\ m \in \mathbb{Z} \Rightarrow & \text{destructive} \end{cases}$

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Double slit interference: $d\sin\theta_m = \begin{cases} m\lambda, & \text{bright} \\ \left(m+\frac{1}{2}\right)\lambda, & \text{dark} \end{cases}, \; m \in \mathbb{Z}$

$y = L\tan\theta$

single slit diffraction: $a\sin\theta_m = m\lambda$, dark, $m \in \mathbb{Z} - \{0\}$

diffraction grating: $\frac{1}{\nu}\sin\theta_m = m\lambda$, bright, $m \in \mathbb{Z}$

Raleigh resolution criterion: $\theta_{\min} = \begin{cases} \frac{\lambda}{D}, & \text{slit of width } D \\ 1.22\frac{\lambda}{D}, & \text{circle of diameter } D \end{cases}$

$I = I_0\cos^2\theta$

Brewster's (polarization) angle: $\tan\theta_P = \frac{n_2}{n_1}$, $\theta_P + \theta_R = 90^o$

Optical Instruments

camera: $f - stop = \frac{f}{D}$

eye: myopia: $p = \infty$, $q = -d_{f.p.}$
hyperopia: $p = d_{\text{reading}} \approx 25\ cm$, $q = -d_{n.p.}$

magnifying glass: $M = \begin{cases} \frac{N}{f}, & \text{eye relaxed} \\ \frac{N}{f} + 1, & \text{eye focused at } N \end{cases}$

telescope: $M = -\frac{f_o}{f_e}$

microscope: $M \approx \frac{N(L-f_e)}{f_o f_e}$

Special Relativity

$\Delta t = \gamma\Delta t_0$

$L = \frac{L_0}{\gamma}$

$\gamma = \frac{1}{\sqrt{1-(v/c)^2}}$

$u = \frac{u'+v}{1+\frac{vu'}{c^2}}$

$p = \begin{cases} \gamma_u m u \\ mu, & \text{if } u \ll c \end{cases}$

$E = \begin{cases} KE + mc^2 \\ \gamma_u mc^2 \\ \sqrt{(mc^2)^2 + (pc)^2} \end{cases}$

$KE = \begin{cases} (\gamma_u - 1)mc^2 \\ \frac{1}{2}mu^2, & \text{if } u \ll c \end{cases}$

$\gamma_u = \frac{1}{\sqrt{1-(u/c)^2}}$

$E_0 = mc^2$

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Quantum Physics

$\lambda_{max}T = 2.90 \times 10^{-3}\ m \cdot K$

$c = \lambda f$

$E = hf,\ h = 6.63 \times 10^{-34}\ J \cdot s$

$\lambda = \frac{h}{p}$

$\hbar = \frac{h}{2\pi}$

$hc = 1240\ eV \cdot nm$

Compton scattering: $\lambda' - \lambda = \frac{h}{m_e c}(1 - \cos\theta)$, $\lambda_e = \frac{h}{m_e c} = 2.426 \times 10^{-12}\ m$

photoelectric effect:

$$KE_{max} = e\Delta V_s = hf - \Phi_0$$

$$f_{thresh} = \frac{\Phi_0}{h}$$

Bohr H-atom:

$$E_n = -\frac{13.6\,Z^2}{n^2}\ [eV]$$

$$r_n = n^2 r_1,\ r_1 = 0.529 \times 10^{-10}\ m$$

$$L_n = n\hbar$$

$$\frac{1}{\lambda} = R_H\left(\frac{1}{n_{fin}^2} - \frac{1}{n_{ini}^2}\right),\ R_H = 1.097 \times 10^7\ m^{-1}$$

H-atom quantum nos.:

$$n = 1, 2, 3, \ldots$$

$$\ell = 0, 1, 2, \ldots, n-1$$

$$m_\ell = -\ell, -\ell+1, \ldots, +\ell$$

$$m_s = -\tfrac{1}{2}, +\tfrac{1}{2}$$

$$L = \sqrt{\ell(\ell+1)}\hbar$$

$$L_z = m_\ell \hbar$$

$$S = \sqrt{s(s+1)}\hbar$$

$$S_z = m_s \hbar$$

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

$$\Delta t \Delta E \geq \frac{\hbar}{2}$$

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Nuclear Physics

$^A_Z X,\ A = Z + N$

$B_X = (Zm_H + Nm_n - M_X)c^2, \quad \begin{Bmatrix} m_H = 1.007825\ u \\ m_n = 1.008665\ u \end{Bmatrix}$

$R = R_0 A^{1/3},\ R_0 = 1.2 \times 10^{-15}\ m$

$(KE_a)_{min} = \left(1 + \frac{m_a + \frac{|Q|}{2c^2}}{m_A}\right)|Q|$

$Q = KE_f - KE_0 = (\sum m_P - \sum m_D)c^2$, for $P_1 + P_2 + \cdots \rightarrow D_1 + D_2 + \cdots$

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

$\left|\frac{\Delta N}{\Delta t}\right| = \lambda N(t)$

$t_{1/2} = \frac{\ln 2}{\lambda}$

$\tau = \frac{1}{\lambda}$

$D[Gray] = \frac{\text{radiation energy absorbed } [Joule]}{\text{absorber mass } [kg]}$, dose

$H \begin{bmatrix} Sievert \\ rem \end{bmatrix} = Q \times D \begin{bmatrix} Gray \\ rad \end{bmatrix}$, human-equivalent dose

Radiation type	Q quality factor
photons (X, γ)	1
β	1-1.5
slow neutrons	3-5
fast neutrons	10
protons	10
α	10-20
heavy ions	20

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General

$$\Delta s = v_0 t + \frac{1}{2}at^2$$

$$v = v_0 + at$$

$$v^2 = v_0^2 + 2a\Delta s$$

$F_{\text{net}} = ma$

$w = mg$, weight

$KE = \frac{1}{2}mu^2$

$U_g = mgy$

$P = \frac{\Delta E}{\Delta t}$, power

$P = \frac{F}{A}$, pressure

$\Delta P_{\text{fluid}} = \rho_{\text{fluid}} gh$

$P_{\text{abs}} = P_{\text{atm}} + P_{\text{gauge}}$

$I = \frac{P}{S}$ (if spherical wave, $S = 4\pi r^2$), intensity

Constants and Conversions

$$m_e = 9.109 \times 10^{-31}\ kg = 0.511\ MeV/c^2 = 0.000549\ u$$

$$m_p = 1.673 \times 10^{-27}\ kg = 938.3\ MeV/c^2 = 1.007276\ u$$

$$m_n = 1.675 \times 10^{-27}\ kg = 939.6\ MeV/c^2 = 1.008665\ u$$

$1\ nm = 10^{-9}\ m$

$$m_\alpha = 6.645 \times 10^{-27}\ kg = 3.727\ GeV/c^2 = 4.001506\ u$$

$$1\ eV = 1.602 \times 10^{-19}\ J$$

$$1\ MeV = 10^6\ eV$$

$1\ u = 1.660565 \times 10^{-27}\ kg = 931.5\ MeV/c^2$

$$1\ Bq = 1\ decay/sec$$

$$1\ \text{Ci} = 3.70 \times 10^{10}\ Bq$$

$$1\ Gy = 1\ J/kg = 100\ rad$$