Permittivity of free space: $\epsilon_0 = 8.854 \times 10^{-12}$ — Proton mass: $1.673 \cdot 10^{-27}$
Elementary charge: $e = 1.602 \cdot 10^{-19}$ — Electron mass: $9.11 \cdot 10^{-31}$
Speed of light: $c = 3 \cdot 10^8$ — Permeability constant: $\mu_0 = 1.26 \times 10^{-6}$
$k = 9 \times 10^9$

$$\lambda = \frac{Q}{L} \quad \eta = \frac{Q}{A} \quad \rho = \frac{Q}{V}$$

$$E = \frac{kq}{r^2} \quad F = qE = \frac{kq_1q_2}{r^2} \quad V = \frac{kq}{r} \quad U = qV = \frac{kq_1q_2}{r} \quad \textbf{(point)}$$

$$E_{\text{wire}} = \frac{2k|\lambda|}{r} = \frac{2kQr^2}{R^3L} \quad E_{\text{plane}} = \frac{\eta}{2\epsilon_0} \quad E_{\text{ring}} = \frac{kzQ}{(z^2+r^2)^{3/2}}$$

$$E_{\text{disk}} = \frac{\eta}{2\epsilon_0}\left(1 - \frac{z}{\sqrt{z^2+R^2}}\right) \quad E_{\text{sphere}} = \begin{cases} \frac{kQ}{r^2} & \text{for } r >= R \\ \frac{kQr}{R^3} & \text{for } r < R \end{cases}$$

$$\text{Dipole} \begin{cases} p = qd \quad E = -\frac{2kp}{r^3}\text{(on axis)} \quad E = -\frac{kp}{r^3}\textbf{(on bisecting plane)} \\ \tau = pE\sin\theta \quad V = -pE\cos\theta \end{cases}$$

$$\text{Parallel-Plate Capacitor} \begin{cases} E = \frac{V}{d} = \frac{Q}{\epsilon_0 A}\textbf{(positive to negative plate)} \\ s = \text{distance from negative plate} \\ U = qEs = qV \quad V = \frac{s}{d}\Delta V_C \end{cases}$$

$$\Phi_{\text{enc}} = EA = \frac{Q_{\text{in}}}{\epsilon_0} \quad E_{\text{conductor surface}} = \frac{\eta}{\epsilon_0}$$

$$W = -q\Delta V \quad \Delta V = -Ed \quad V_{\text{sphere}} = \frac{4}{3}\pi r^3 \quad A_{\text{sphere}} = 4\pi r^2$$

$$W = Q \times V \quad C = \frac{Q}{\Delta V_C}$$

$$C = \frac{\epsilon_0 A}{d} \quad Q = \frac{\epsilon_0 A}{d}\Delta V_C \quad \textbf{(parallel-plate capacitor)}$$

$$C_{\text{eq}} = \begin{cases} C_1 + C_2 + \cdots & \textbf{(parallel)} \\ (\frac{1}{C_1} + \frac{1}{C_2} + \cdots)^{-1} & \textbf{(sequential)} \end{cases}$$

$$C = \kappa C_0$$

$$i_e = n_e A v_d \quad I = n \times A \times e \times v_d \quad n = \text{electron density}$$

$$\text{Current density} = J = \frac{I}{A} = n_e e v_d \quad I = JA = \sigma AE \quad \sigma = \text{conductivity}$$

$$\rho = \frac{1}{\sigma} = \text{resistivity} \quad R = \rho\frac{L}{A} \quad I = \frac{A}{\rho L}\Delta V \quad \Delta V = IR$$

$$R_{\text{eq}} = \begin{cases} (\frac{1}{R_1} + \frac{1}{R_2} + \cdots)^{-1} & \textbf{(parallel)} \\ R_1 + R_2 + \cdots & \textbf{(sequential)} \end{cases}$$

If one branch in a parallel circuit is opened, the current through the other stays the same

All parts of a sequential wire have the same current

$$P = \Delta V_R \times I = I^2 \times R = \frac{(\Delta V_R)^2}{R}$$

$$\tau = RC \quad Q = Q_0 e^{-t/\tau} \quad \Delta V_C = \Delta V_0 e^{-t/\tau}$$

Right-hand rule for wire (wrap fingers around wire): thumb points toward current and fingers point toward magnetic field

Right-hand rule for magnetic field: thumb points toward force, palm faces magnetic field, fingers point toward motion

$$\oint B \cdot dl = Bl = \frac{\mu_0 I}{2\pi r} \times 2\pi r = \mu_0 I \quad \Phi_m = BA\cos\theta$$

$$F_B = qv \times B = IL \times B$$

$$B_{\text{point charge}} = \frac{\mu_0 q(\vec{v} \times \vec{r})}{4\pi r^3} = \frac{\mu_0 qv\sin\theta}{4\pi r^2} \quad B_{\text{wire}} = \begin{cases} \frac{\mu_0 I}{2\pi r} & r >= R \\ \frac{\mu_0 Ir}{2\pi R^2} & r < R \end{cases}$$

$$B_{\text{center of current loop}} = \frac{\mu_0 NI}{2R} \quad B_{\text{solenoid}} = \mu_0 nI \quad n = N/L$$

$$\vec{B}_{\text{current segment}} = \frac{\mu_0 I\Delta\vec{s} \times \hat{r}}{4\pi r^2}$$

Magnetic dipole moment $= \vec{m} = (AI, \text{from south to north pole})$

$$\vec{B}_{\text{on axis of dipole}} = \frac{\mu_0\vec{m}}{2\pi z^3}$$

$$A \times B = (A_yB_z - A_zB_y)\mathbf{i} + (A_zB_x - A_xB_z)\mathbf{j} + (A_xB_y - A_yB_x)\mathbf{k}$$

Metal	Electron density (m^{-3})	Resistivity	Conductivity
Aluminum	18×10^{28}	2.8×10^{-8}	3.5×10^7
Iron	17×10^{28}	9.7×10^{-8}	1.0×10^7
Copper	8.5×10^{28}	1.7×10^{-8}	6.0×10^7
Gold	5.9×10^{28}	2.4×10^{-8}	4.1×10^7
Silver	5.8×10^{28}	1.6×10^{-8}	6.2×10^7

Kirchhoff's Law: Branch out from one terminal and set up equations for $\sum \Delta V_i = 0$

There is no current in the ground wire

$$\Delta V = \varepsilon = vlB \quad \textbf{(moving conductor)}$$

Increasing flux: induced magnetic field points opposite to applied
Decreasing flux: induced magnetic field points same direction to applied
Steady flux: no induced magnetic field

$$\varepsilon_{\text{induced}} = -\frac{d\Phi_m}{dt} \quad I_{\text{induced}} = \frac{\varepsilon_{\text{induced}}}{R}$$

$$E_{\text{inside}} = \frac{r}{2}\left|\frac{dB}{dt}\right| \quad \text{solenoid}$$

$$\frac{V_2}{V_1} = \frac{N_2}{N_1} \quad P_1 = P_2 \quad V_1I_1 = V_2I_2 \quad \frac{I_1}{I_2} = \frac{N_2}{N_1} \quad \textbf{(transformers)}$$

$$L = \frac{\Phi_m}{I} \quad \Delta V_L = -L\frac{dI}{dt} \quad U_L = L\int_0^I I\,dI = \frac{1}{2}LI^2 \quad \textbf{(inductors)}$$

$$I = -\frac{dQ}{dt} \quad Q(t) = Q_0\cos\omega t \quad \omega = \frac{1}{\sqrt{LC}} \quad \textbf{(LC circuits)}$$

$$I = I_0 e^{-t/\tau} \quad \tau = \frac{L}{R} \quad \textbf{(LR circuits)}$$

$$\vec{E}_B = \vec{E}_A + \vec{v}_{BA} \times \vec{B}_A \quad \vec{B}_B = \vec{B}_A - \frac{1}{c^2}\vec{v}_{BA} \times \vec{E}_A$$

Displacement current is from changing electric field rather than flow of charges.

$$I_{\text{disp}} = \epsilon_0\frac{d\Phi_e}{dt} = \epsilon_0 \cdot A\frac{dE}{dt}$$

$$\oint \vec{E} \cdot d\vec{A} = \frac{Q_{\text{in}}}{\epsilon_0} \quad \text{(Gauss's Law)}$$

$$\oint \vec{B} \cdot d\vec{A} = 0 \quad \text{(Gauss's Law for Magnetism)}$$

$$\oint \vec{E} \cdot d\vec{s} = -N\frac{d\Phi_m}{dt} \quad \text{(Faraday's Law)}$$

$$\oint \vec{B} \cdot d\vec{s} = \mu_0 I_{\text{through}} + \epsilon_0\mu_0\frac{d\Phi_e}{dt} \quad \text{(Ampere-Maxwell Law)}$$

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) \quad \text{(Lorentz Force Law)}$$

$$E(x,t) = E_0\cos(kx - \omega t + \phi) \quad c = \frac{\omega}{k} = \frac{\omega\lambda}{2\pi} = f\lambda = \frac{E}{B}$$

$$I = \frac{P}{4\pi r^2} = \frac{c\epsilon_0 E_0^2}{2}$$

Average value for $\sin\theta$ is $\frac{1}{2}$

$$\langle S\rangle = \frac{1}{\mu_0}EB\sin\theta \quad (\textbf{Poynting Vector} \text{ — energy flux of an EM wave})$$

Right-hand rule for electromagnetic waves: fingers point toward electric field, palm faces magnetic field, thumb points toward motion

$$I_{\text{transmitted}} = \frac{1}{2}I_0 \quad \textbf{(unpolarized)} \quad I_{\text{transmitted}} = I_0\cos^2\theta \quad \textbf{(polarized)}$$

$$\varepsilon = \varepsilon_0\cos\omega t \quad \omega = 2\pi f \quad X = \text{Reactance}$$

$$v_R = i_R R = V_{\max}\sin\omega t \quad p = i\varepsilon \quad \textbf{(AC circuit)}$$

$$\text{Capacitor circuit} \begin{cases} v_C = V_C\cos\omega t \quad q = Cv_C \quad X_C = \frac{1}{\omega C} \quad I_C = \frac{V_C}{X_C} \\ i_C = -\omega CV_C\sin\omega t = \omega CV_C\cos(\omega t + \frac{\pi}{2}) \end{cases}$$

$$\omega_C = \frac{1}{RC} \quad \textbf{(RC Circuit)}$$

An inductor is a coil of wire that generates a magnetic field when current flows through it and resist changes in current by inducing an emf opposite to the charge.

$$\text{Inductor circuit} \begin{cases} i_L = I_L\cos(\omega t - \frac{\pi}{2}) \quad V = L \cdot \frac{dI}{dt} \\ X_L = \omega L \quad I_L = \frac{V_L}{X_L} \end{cases}$$

$$\text{Series RLC Circuit} \begin{cases} Z = \sqrt{R^2 + (X_L - X_C)^2} \quad \textbf{(impedance)} \\ V = \sqrt{V_R^2 + (V_L - V_C)^2} \quad I_{\text{peak}} = \frac{\varepsilon_0}{Z} \\ \phi_{\text{between emf and current}} = \tan^{-1}\left(\frac{X_L - X_C}{R}\right) \\ \omega_0 = \frac{1}{\sqrt{LC}} = \textbf{resonance angular frequency} \end{cases}$$

Resonance frequency occurs when $X_L = X_C$ and $Z = R$. If $V_C > V_L$, the circuit operates below resonance frequency. If $V_L > V_C$, the circuit operates above resonance frequency.

$$P_R = \frac{1}{2}I_R^2 R = I_{\text{rms}}V_{\text{rms}} \quad x_{\text{rms}} = \frac{x}{\sqrt{2}}$$

$$P_{\text{source}} = \frac{1}{2}I\varepsilon_0\cos\phi = I_{\text{rms}}\varepsilon_{\text{rms}}\cos\phi = P_{\max}\cos^2\phi$$

where $\cos\phi$ is the power factor, ϕ is the phase between current and emf, and $P_{\max} = \frac{1}{2}I_{\max}\varepsilon_0$.

- AC circuit with capacitor: current leads voltage by $\frac{\pi}{2}$ (current reaches maximum $\frac{T}{4}$ before voltage)
- AC circuit with inductor: current lags voltage by $\frac{\pi}{2}$ (current reaches maximum $\frac{T}{4}$ after voltage)
- AC circuit with resistor: current is in phase with voltage