PHYS 122 Electromagnetism

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Electrical Charge and Electric Field

Quantity	Unit	Definition
Electrical field (point charge)	$\mathrm{N/C}$ $(\mathrm{V/m})$	$\vec{E}_s = \frac{\vec{F}_0}{q_0} = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2}\hat{r}$
Linear charge density	$\mathrm{C/m}$	$\lambda = \frac{dQ}{dl}$
Surface charge density	$\mathrm{C/m^2}$	$\sigma = \frac{dQ}{dA}$
Volume charge density	$\mathrm{C/m^3}$	$\rho = \frac{dQ}{dV}$
Electric dipole moment (direction from - to +)	$\mathrm{C \cdot m}$	$\vec{p} = q\vec{d}$
Induced dipole moment (direction from - to +)	$\mathrm{C \cdot m}$	$\vec{p} = \alpha\vec{E}$

Description	Equations
Coulomb's law	$F = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2}\hat{r}$
Force on test charge by an electric field	$\vec{F}_0 = q_0\vec{E}$
Superposition of electric forces	$\vec{F} = \sum_i \vec{F}_i$
Superposition of electric fields	$\vec{E} = \sum_i \vec{E}_i$
Torque on an electric dipole in an uniform electrical field	$\vec{\tau} = \vec{p} \times \vec{E}$
Potential energy of an electric dipole in an uniform electric field	$U = -\vec{p} \cdot \vec{E}$
Electric field of test charge on x axis caused by dipole at origin oriented in + y direction	$E_x = 0$ $E_y = -\frac{kp}{\lvert x\rvert^3}$
Electric field of test charge on y axis caused by dipole at origin oriented in + y direction	$E_x = 0$ $E_y = \frac{2kp}{\lvert y\rvert^3}$

Gauss's Law

Quantity	Unit	Definition
Electric flux through a surface	$\mathrm{N \cdot m^2/C}$ $(\mathrm{V \cdot m})$	$\Phi_E = \int \vec{E} \cdot d\vec{A}$

Description	Equations
Electric flux of a uniform electric field	$\Phi_E = \vec{E} \cdot \vec{A}$

Description	Equations
Electric flux of a nonuniform electric field	$\Phi_E = \int \vec{E} \cdot d\vec{A} = \int E \cos\theta \, dA$
Gauss's law Electric flux through a closed surface	$\Phi_E = \oint \vec{E} \cdot d\vec{A} = \oint E \cos\theta \, dA = \frac{Q}{\varepsilon_0}$

Electric field of uniform *spherical* charge distributions

- charged = *uniformly* charged throughout (insulating)
- conducting = charge only on surface

Charge Distribution	Point in Electric Field	Electric Field Magnitude
Point charge	-	$E = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2}$
Solid conducting sphere Hollow charged sphere	Outside sphere, $r > R$	$E = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2}$
Solid conducting sphere Hollow charged sphere	Inside sphere, $r < R$	$E = 0$
Solid charged sphere	Outside sphere, $r > R$	$E = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2}$
Solid charged sphere	Inside sphere, $r < R$	$E = \frac{1}{4\pi\varepsilon_0}\frac{r}{R^3}q$

Electric field of uniform *cylindrical* charge distributions

Charge Distribution	Point in Electric Field	Electric Field Magnitude
∞ wire/rod	-	$E = \frac{1}{2\pi\varepsilon_0}\frac{\lambda}{r} = \frac{2k\lambda}{r}$
∞ solid conducting cylinder ∞ hallow charged cylinder	Outside cylinder, $r > R$	$E = \frac{1}{2\pi\varepsilon_0}\frac{\lambda}{r} = \frac{2k\lambda}{r}$
∞ solid conducting cylinder ∞ hallow charged cylinder	Inside cylinder, $r < R$	$E = 0$
∞ solid charged cylinder	Outside cylinder, $r > R$	$E = \frac{1}{2\pi\varepsilon_0}\frac{\lambda}{r} = \frac{2k\lambda}{r}$
∞ solid charged cylinder	Inside cylinder, $r < R$	$E = \frac{1}{2\pi\varepsilon_0}\frac{r}{R^2}\lambda = \frac{2k\lambda r}{R^2}$

Electric field of uniform *planar* charge distributions

Charge Distribution	Point in Electric Field	Electric Field Magnitude
∞ charged sheet/plate	-	$E = \frac{\sigma}{2\varepsilon_0}$
∞ conducting sheet/plate	-	$E = \frac{\sigma}{\varepsilon_0} = \frac{q}{2\varepsilon_0 A}$ (q spreads at each surface)

Charge Distribution	Point in Electric Field	Electric Field Magnitude
Two oppositely charged conducting plates	Between plates	$E = \frac{\sigma}{\varepsilon_0}$
Charged conductor	At surface	$E = \frac{\sigma}{\varepsilon_0}$

Electric Potential

Quantity	Unit	Definition
Electric potential energy (point charge) (choose $U = 0$ at ∞)	J	$U = \frac{1}{4\pi\varepsilon_0}\frac{q_s q_0}{r}$
Electric potential (point charge) (choose $V = 0$ at ∞)	V $(\mathrm{J/C})$	$V = \frac{U}{q_0} = \frac{1}{4\pi\varepsilon_0}\frac{q_s}{r}$

Description	Equations
Electric potential energy of a test charge due to many source charges	$U = \frac{q_0}{4\pi\varepsilon_0}\sum_i \frac{q_i}{r_i}$
Total electric potential energy of all source charges	$U = \frac{1}{4\pi\varepsilon_0}\sum_{i<j} \frac{q_i q_j}{r_{ij}}$
Electric potential due to many source charges	$V = \frac{1}{4\pi\varepsilon_0}\sum_i \frac{q_i}{r_i}$
Electric potential due to continuous distribution of charges	$V = \frac{1}{4\pi\varepsilon_0}\int \frac{dq}{r}$
Electric potential and potential energy of point charges	$U = q_2 V_1$
Work by electric force and electric field	$W_{a\to b} = \int_a^b \vec{F}\cdot d\vec{l} = q\int_a^b \vec{E}\cdot d\vec{l}$
Work by electric force on a closed path	$W_{a\to b\to a} = q\oint \vec{E}\cdot d\vec{l} = 0$
Work by electric force and change in potential energy	$W_{a\to b} = -\Delta U$
Potential difference	$V_{ab} = V_b - V_a$
Potential difference between terminals of battery	$V_{\mathrm{batt}} = V_{-+} = V_+ - V_-$
Potential difference and work, potential energy difference	$V_{ab} = \frac{\Delta U}{q_0} = -\frac{W_{a\to b}}{q_0}$
Potential difference and electric field	$V_{ab} = -\int_a^b \vec{E}\cdot d\vec{l} = -\int E\cos\theta\, dl$
Electric field and potential gradient	$\vec{E} = -\vec{\nabla}V = \left\langle -\frac{\partial V}{\partial x}, -\frac{\partial V}{\partial y}, -\frac{\partial V}{\partial z}\right\rangle$

Capacitance and Dielectrics

Quantity	Unit	Definition

Quantity	Unit	Definition
Capacitance (in vacuum)	F $(\mathrm{C/V} = \mathrm{C^2/J})$	$C = \dfrac{Q}{V_{-+}} = \dfrac{Q}{V_+ - V_-}$
Electric energy density (in vacuum)	$\mathrm{J/m^3}$	$u = \dfrac{U}{Ad} = \dfrac{1}{2}\varepsilon_0 E^2$

Description	Equations
Capacitance of a parallel-plate capacitor in vacuum	$C = \dfrac{Q}{V_{-+}} = \varepsilon_0 \dfrac{A}{d}$
Potential energy stored in a charged capacitor (define $U_{\text{uncharged}} \equiv 0$)	$U = \dfrac{Q^2}{2C} = \dfrac{1}{2}CV^2 = \dfrac{1}{2}QV$
Electric energy density in vacuum	$u = \dfrac{U}{Ad} = \dfrac{1}{2}\varepsilon_0 E^2$
Dielectric constant	$\kappa = \dfrac{C}{C_0} = \dfrac{V_0}{V} = \dfrac{E_0}{E}$
Induced surface charge density on a dielectric in an isolated capacitor	$\sigma_{\text{induced}} = \sigma_{\text{bound}}$ $\sigma_0 = \sigma_{\text{free}}$ $\sigma_{\text{induced}} = \sigma_0 \left(1 - \dfrac{1}{\kappa}\right)$
Permittivity of a dielectric	$\varepsilon = \kappa\varepsilon_0$
Capacitance of a parallel-plate capacitor with dielectric between plates	$C = \kappa C_0 = \kappa\varepsilon_0 \dfrac{A}{d} = \varepsilon \dfrac{A}{d}$
Electric energy density in a dielectric	$u = \dfrac{1}{2}\kappa\varepsilon_0 E^2 = \dfrac{1}{2}\varepsilon E^2$
Gauss's law in dielectrics	$\oint \vec{E} \cdot d\vec{A} = \dfrac{q_{\text{free,enc}}}{\kappa\varepsilon_0}$

Current, Resistance, and emf

Quantity	Unit	Definition
Current	A $(\mathrm{C/s})$	$I = \dfrac{dQ}{dt}$
Current density (per unit cross-section area)	$\mathrm{A/m^2}$	$\vec{J} = nq\vec{v}_d$ $J = \dfrac{I}{A} = n\lvert q\rvert v_d$
Conductivity (intrinsic to a material)	$(\Omega \cdot \mathrm{m})^{-1}$ $\mathrm{A/(V \cdot m)}$	$\sigma = \dfrac{J}{E}$
Resistivity (intrinsic to a material)	$\Omega \cdot \mathrm{m}$	$\rho = \dfrac{E}{J}$
Resistance	Ω	$R = \dfrac{V}{I} = \dfrac{\rho L}{A} = \dfrac{L}{\sigma A}$

Description	Equations
Drift velocity of charge carrier	$\vec{v}_d = -\dfrac{q\vec{E}}{m}\tau$
Current and conductor properties	$I = \dfrac{dQ}{dt} = n\lvert q\rvert v_d A = JA$

Description	Equations
Current density (per unit cross-section area)	$\vec{J} = nq\vec{v}_d$ $J = \frac{I}{A} = n\lvert q\rvert v_d = \frac{nq^2\tau}{m_q}E$
Conductivity (intrinsic to a material)	$\sigma = \frac{J}{E} = \frac{nq^2\tau}{m_q}$
Temperature dependence of resistivity	$\rho(T) = \rho_0(1+\alpha(T-T_0))$
Temperature dependence of resistance	$R(T) = R_0(1+\alpha(T-T_0))$

Direct-Current (DC) Circuits

| Circuit analysis

Description	Equations
Circuit elements in series $\lvert Q\rvert, I$ - Equal V, R - Add C - Reciprocal	$\lvert Q\rvert = \lvert Q_1\rvert = \ldots = \lvert Q_i\rvert$ $I = I_1 = \ldots = I_i$ $V = \sum_i V_i$ $R = \sum_i R_i$ $\frac{1}{C} = \sum_i \frac{1}{C_i}$
Circuit elements in parallel V - Equal Q, I, C - Add R - Reciprocal	$V = V_1 = \ldots = V_i$ $Q = \sum_i Q_i$ $I = \sum_i I_i$ $C = \sum_i C_i$ $\frac{1}{R} = \sum_i \frac{1}{R_i}$
Algebra of reciprocal values of two elements	$\frac{1}{A} = \frac{1}{A_1} + \frac{1}{A_2} \Rightarrow A = \frac{A_1 A_2}{A_1 + A_2}$
Kirchhoff's junction rule (conservation of charge)	$\sum I = 0$
Kirchhoff's loop rule (conservation of energy)	$\sum V = 0$
Battery $(- \rightarrow +)$	$+\mathcal{E}$
Resistor (along reference direction)	$-IR$
Capacitor $(- \rightarrow +)$	$+\frac{q(t)}{C}$

| Ohm's law and power

Description	Equations
Ohm's law	$V = IR$
Potential difference of source with internal resistance	$V_{-+} = \mathcal{E} - Ir = IR$
Current of source with internal resistance	$I = \frac{\mathcal{E}}{R+r}$

Description	Equations
Power delivered to or extracted from a circuit element	$P = IV$
Power delivered to a resistor (Note: both I and V depend on R)	$P = IV = I^2R = \frac{V^2}{R}$
Power output of a source	$P = I\mathcal{E} = IV + I^2r = I^2(R+r)$

| R-C circuit

Description	Equations
Time constant	$\tau = RC$
Charge when charging capacitors	$q(t) = C\mathcal{E}(1 - e^{-t/RC}) = Q_f(1 - e^{-t/RC})$
Current when charging capacitors	$i(t) = \frac{\mathcal{E}}{R}e^{-t/RC} = I_0e^{-t/RC}$
Charge when discharging capacitors	$q(t) = Q_0e^{-t/RC}$
Current when discharging capacitors	$i(t) = -\frac{Q_0}{RC}e^{-t/RC} = I_0e^{-t/RC}$
Power of battery in R-C circuit	$P = i\mathcal{E} = i^2R + \frac{iq}{C}$
Total energy stored in capacitor	$U = \frac{1}{2}QV = \frac{1}{2}Q_f\mathcal{E}$

Magnetic Force and Motion

Quantity	Unit	Definition
Magnetic force	N	$\vec{F} = q\vec{v} \times \vec{B} = \lvert q\rvert vB\sin\theta$
Magnetic flux through a surface	Wb $(\mathrm{T \cdot m^2})$	$\Phi_B = \int \vec{B} \cdot d\vec{A}$
Magnetic dipole moment (direction from S to N)	$\mathrm{A \cdot m^2}$ $\mathrm{J/T}$	$\vec{\mu} = I\vec{A}$

| Magnetic interactions of charged particles

Description	Equations
Magnetic force on a charged particle	$\vec{F} = q\vec{v} \times \vec{B} = \lvert q\rvert vB\sin\theta$
Radius of a circular orbit in a magnetic field (charge where $v \perp B$)	$R = \frac{mv}{\lvert q\rvert B}$
Angular speed (frequency) of circular motion	$\omega = 2\pi f = \frac{2\pi}{T} = \frac{\lvert q\rvert B}{m}$
Frequency of circular motion	$f = \frac{1}{T} = \frac{\omega}{2\pi} = \frac{\lvert q\rvert B}{2\pi m}$
Period of circular motion	$T = \frac{1}{f} = \frac{2\pi}{\omega} = \frac{2\pi m}{\lvert q\rvert B}$

Description	Equations
Velocity selector	$v = \dfrac{E}{B}$
Thompson's experiment	$v = \sqrt{\dfrac{2qV}{m}}$ $\dfrac{q}{m} = \dfrac{E^2}{2VB^2}$
Mass spectrometers	$m = \dfrac{\lvert q \rvert B^2 R}{E}$

| Magnetic interactions of current-carrying conductor

Description	Equations
Magnetic force on a straight wire segment	$\vec{F} = I\vec{l} \times \vec{B}$
Magnetic force on an infinitesimal wire segment	$d\vec{F} = I\, d\vec{l} \times \vec{B}$
Magnetic dipole moment	$\vec{\mu} = I\vec{A}$
Magnetic torque on a current loop	$\vec{\tau} = \vec{\mu} \times \vec{B} = IAB\sin\theta$
Magnetic torque on a solenoid	$\vec{\tau} = N\vec{\mu} \times \vec{B} = NIAB\sin\theta$
Potential energy for a magnetic dipole in B field	$U = -\vec{\mu} \cdot \vec{B} = -\mu B\cos\theta$

| Magnetic flux and other effects

Description	Equations
Magnetic flux through a surface	$\Phi_B = \displaystyle\int \vec{B} \cdot d\vec{A}$
Gauss's law for magnetism	$\displaystyle\oint \vec{B} \cdot d\vec{A} = 0$
Electromagnetic (Lorentz) force	$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$
Hall effect	$nq = \dfrac{-J_x B_y}{E_z}$

Magnetic Field

Quantity	Unit	Definition
Magnetic field	T $\mathrm{N/(A \cdot m)}$ $1\mathrm{G} = 10^{-4}\mathrm{T}$	$\vec{B} = \dfrac{\mu_0}{4\pi} \displaystyle\int \dfrac{Id\vec{l} \times \hat{r}}{r^2}$

Description	Equations
Ampere's law	$\displaystyle\oint \vec{B} \cdot d\vec{l} = \mu_0 I$
Magnetic field of a point charge	$\vec{B} = \dfrac{\mu_0}{4\pi} \dfrac{q\vec{v} \times \hat{r}}{r^2}$
Biot-Savart law Magnetic field of infinitesimal length of wire	$d\vec{B} = \dfrac{\mu_0}{4\pi} \dfrac{Id\vec{l} \times \hat{r}}{r^2}$

Description	Equations
Force on two ∞ parallel wires per unit length	$\vec{F} = q\vec{v} \times \vec{B}$ $\frac{F}{l} = \frac{\mu_0 I_1 I_2}{2\pi d}$
Force on two moving charges	$\vec{F} = I\vec{l} \times \vec{B}$ $\vec{F}_{1\to 2} = \frac{\mu_0}{4\pi}\frac{q_1 q_2}{r}\vec{v}_2 \times \vec{v}_1 \times \hat{r}$

| Magnetic field of *linear* conductors

Conductor Form	Magnetic Field Magnitude
∞ straight wire	$B = \frac{\mu_0 I}{2\pi r}$
∞ current-conducting plane	$B = \frac{1}{2}\mu_0 K$

| Magnetic field of *circular* conductors

Conductor Form	Magnetic Field Magnitude
On the axis of circular wire loop	$B_x = \frac{\mu_0 I R^2}{2(x^2 + R^2)^{3/2}}$
On the axis of N circular wire loops	$B_x = \frac{N\mu_0 I R^2}{2(x^2 + R^2)^{3/2}} = \frac{\mu_0 \mu}{2\pi(x^2 + R^2)^{3/2}}$
At the center of N circular wire loops	$B_x = \frac{N\mu_0 I}{2a}$
At the center of a circular arc	$B = \frac{\mu_0 I\theta}{4\pi r}$
Inside cylindrical conductor	$B = \frac{\mu_0 I}{2\pi}\frac{r}{R^2} \quad (r < R)$
Outside cylindrical conductor	$B = \frac{\mu_0 I}{2\pi r} \quad (r > R)$
Inside ∞ solenoid	$B = N\mu_0 I$
Inside finite length solenoid	$B = \frac{N\mu_0 I}{l}$
Inside toroid	$B = \frac{N\mu_0 I}{2\pi r}$

Changing Magnetic Field (Induction)

Quantity	Unit	Definition
Inductance	H $\mathrm{V \cdot s/A}$	$L = \frac{\Phi_B}{i}$

Description	Equations
Faraday's law	$\mathcal{E} = -\frac{d\Phi_B}{dt}$
Motional emf	$\mathcal{E} = \oint (\vec{v} \times \vec{B}) \cdot d\vec{l}$ $\mathcal{E} = vBl$

Description	Equations
Faraday's law for stationary integration path (Induced electric field and magnetic flux)	$\oint \vec{E} \cdot d\vec{l} = -\frac{d\Phi_B}{dt}$
Inductance of a solenoid	$L = \frac{\mu_0 N^2 A}{l}$
Inductance as amount of change in current associated with change in magnetic flux	$\mathcal{E} = -L\frac{di}{dt}$ $\frac{d\Phi_B}{dt} = L\frac{di}{dt}$
Magnetic potential energy	$U = \frac{1}{2}LI^2$
Magnetic energy density	$u = \frac{1}{2}\frac{B^2}{\mu_0}$

Changing Electric Field

Description	Equations
Conduction current	$i_C = \frac{dq}{dt} = \varepsilon_0 \frac{d\Phi_E}{dt}$
Displacement current	$i_D = \varepsilon_0 \frac{d\Phi_E}{dt}$
Maxwell-Ampere's law	$\oint \vec{B} \cdot d\vec{l} = \mu_0(i_C + i_D)$ $= \mu_0 i_C + \mu_0 \varepsilon_0 \frac{d\Phi_E}{dt}$
Magnetic field inside a circular capacitor	$B = \frac{\mu_0 I r}{2\pi R^2} \ (r < R)$ $B = \frac{\mu_0 I}{2\pi R} \ (r \geq R)$
Maxwell's Equations	$\oint \vec{E} \cdot d\vec{A} = \frac{Q}{\varepsilon_0}$ $\oint \vec{B} \cdot d\vec{A} = 0$ $\oint \vec{E} \cdot d\vec{l} = -\frac{d\Phi_B}{dt}$ $\oint \vec{B} \cdot d\vec{l} = \mu_0 \left(i_C + \varepsilon_0 \frac{d\Phi_E}{dt} \right)$
Maxwell's equation in empty free space	$\oint \vec{E} \cdot d\vec{A} = 0$ $\oint \vec{B} \cdot d\vec{A} = 0$ $\oint \vec{E} \cdot d\vec{l} = -\frac{d\Phi_B}{dt}$ $\oint \vec{B} \cdot d\vec{l} = \mu_0 \varepsilon_0 \frac{d\Phi_E}{dt}$

Alternating-Current (AC) Circuits

Quantity	Unit	Definition
Capacitive reactance	Ω	$X_C = \frac{1}{\omega C}$
Inductive reactance	Ω	$X_L = \omega L$
Impedance	Ω	$Z = \frac{\mathcal{E}_{\max}}{I}$

Description	Equations
AC source in AC circuit	$\mathcal{E} = \mathcal{E}_{\max}\sin(\omega t)$
Angular frequency of oscillation	$\omega = 2\pi f$
Resistor in AC circuit (i and v in phase)	$v_R = \mathcal{E}_{\max}\sin(\omega t)$ $i = I\sin(\omega t)$ $V_R = IR$
Capacitor in AC circuit (i leads v by 90 deg)	$v_C = \mathcal{E}_{\max}\sin(\omega t)$ $i = I\sin(\omega t + 90^\circ)$ $V_C = IX_C = \frac{I}{\omega C}$
Inductor in AC circuit (i lags v by 90 deg)	$v_L = \mathcal{E}_{\max}\sin(\omega t)$ $i = I\sin(\omega t - 90^\circ)$ $V_L = IX_L = I\omega L$
RC series AC circuit	$Z_{RC} = \sqrt{R^2 + 1/(\omega C)^2}$ $\tan\phi = -\frac{V_C}{V_R} = -\frac{1}{\omega RC}$
RLC series AC circuit	$Z_{RLC} = \sqrt{R^2 + (\omega L - 1/\omega C)^2}$ $\tan\phi = \frac{V_L - V_C}{V_R} = \frac{\omega L - 1/\omega C}{R}$
RC filters	$V_C = V_R$ $\omega_{\text{cutoff}} = \frac{1}{RC}$ High pass measures R Low pass measures C
RL filters	$V_R = V_L$ $\omega_{\text{cutoff}} = \frac{R}{L}$ High pass measures L Low pass measures R
Trigonometric identities	$\sin\theta = \cos(\frac{\pi}{2} - \theta)$ $\cos\theta = \sin(\frac{\pi}{2} - \theta)$ $\sin(-\theta) = -\sin\theta$ $\cos(-\theta) = \cos\theta$

Special Relativity

Description	Equations
Lorentz factor	$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}}$
Time dilation	$\Delta t_v = \gamma \Delta t_{\text{proper}}$
Length contraction	$l_v = \frac{l_{\text{proper}}}{\gamma}$
Space-time interval	$s^2 = (c\Delta t)^2 - (\Delta x)^2$
Lorentz transformation	$x' = \gamma(x - ut)$ $y' = y$ $z' = z$ $t' = \gamma(t - ux/c^2)$

Description	Equations
	$v'_x = \dfrac{v_x - u}{1 - uv_x/c^2}$
Relativistic inertia	$m_v = \gamma m$
Relativistic momentum	$p = \gamma mv$
Relativistic kinetic energy	$K = (\gamma - 1)mc^2$
Internal (rest) energy	$E_{\text{int}} = mc^2$
Total energy	$E = K + E_{\text{int}}$ $E^2 = (mc^2)^2 + (pc)^2$

Appendix: List of Constants

Quantity	Value
Coulomb constant	$k = 8.99 \times 10^9\ \mathrm{N \cdot m^2/C^2}$
Electric constant	$\varepsilon_0 = 8.85 \times 10^{-12}\ \mathrm{F/m}$
Magnetic constant	$\mu_0 = 1.26 \times 10^{-6}\ \mathrm{H/m}$
Elementary charge	$q_e = 1.60 \times 10^{-19}\ \mathrm{C}$
Mass of electron	$m_e = 9.11 \times 10^{-31}\ \mathrm{kg}$
Speed of light in vacuum	$c = 3.00 \times 10^8\ \mathrm{m/s}$