Physics Formula Sheet

Unit Conversions

Length: 1 meter = 39.37 inches = 3.281 feet, 1 km = 0.621 miles, 1 mile = 5280 feet = 1609 meters

Mass: 1 amu (u) = 1.66×10^{-27} kg

Mass-Energy: (1 u) * 931.5 = Energy (MeV)

Time: 1 hour = 3600 seconds, 1 year = 365.25 days = 3.16×10^{7} sec

Volume: 1 Liter = 1000 cm^3 = 10^{-3} m^3, 1 gallon = 3.786 L = 3.786×10^{-3} m^3 = 231 in^3

Force: 1 Newton = 1 kg-m/s^2 = 0.2248 pounds

Angular Measure: 1 rev = 360° = 2π rad

Energy: 1 Joule = 0.239 cal = 0.738 ft·lb, 1 kw·hr = 3.6×10^{6} J, 1 eV = 1.60×10^{-19} J

Pressure: 1 atm = 1.013×10^{5} Pascals (N/m^2) = 29.92 inches or 760 mm of Hg

Temperature: $T_F = 1.8 * T_C + 32$, $T_C = 0.556 * (T_F - 32)$, $T_K = T_C + 273$

Density: 1 g/cm^3 = 1000 kg/m^3

Radioactivity: 1 Bq = 2.7×10^{-11} Ci

Physical Constants

Mass of Earth: $M_E = 5.98 \times 10^{24}$ kg
Mass of Sun: $M_S = 1.99 \times 10^{30}$ kg
Gravitational Constant: $G = 6.67 \times 10^{-11}$ N·m^2/kg^2

Radius of Earth: $R_E = 6.38 \times 10^{6}$ m
Earth-Sun distance: $r_E = 1.5 \times 10^{11}$ m
Speed of Light: $c = 3.0 \times 10^{8}$ m/s

Electon mass: m_e = 0.0005486 u = 9.11×10^{-31} kg
Neutron mass: m_n = 1.008665 u = 1.67×10^{-27} kg

Proton mass: m_p = 1.007276 u = 1.67×10^{-27} kg
Helium mass: m_{He} = 4.002602 u = 6.64×10^{-27} kg

Boltzmann's Constant: $k_B = 1.38 \times 10^{-23}$ J/K

Avogadro's #: $N_A = 6.023 \times 10^{23}$ molecules/mole

Ideal Gas Constant: R = 8.31 J/mol-K = 0.0821 L·atm/mol·K
Stefan-Boltzmann Radiation Constant: $\sigma = 5.67 \times 10^{-8}$ W/m^2·K^4

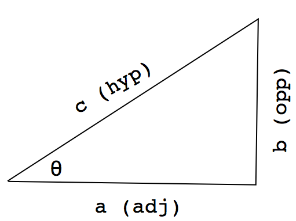
Specific heat of water: c_{water} = 4186 J/kg·°C
Specific heat of ice: c_{ice} = 2090 J/kg·°C
Specific heat of steam: c_{steam} = 2010 J/kg·°C

Latent heat of fusion: L_f = 333,000 J/kg
Latent heat of vaporization: $L_v = 2.26 \times 10^{6}$ J/kg

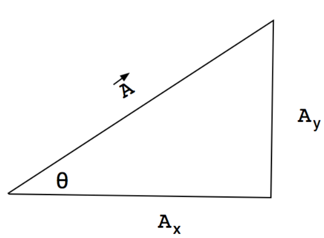
Coulomb constant: $k_C = 8.99 \times 10^{9}$ N·m^2/C^2
Fundamental charge: $e = 1.60 \times 10^{-19}$ C
Planck's constant: $h = 6.626 \times 10^{-34}$ J·s

Permittivity of free space: $\epsilon_0 = 8.85 \times 10^{-12}$ C^2/N·m^2
Permeability of free space: $\mu_0 = 1.26 \times 10^{-6}$ T·m/A
Rydberg constant: $R_H = 1.097 \times 10^{7}$ m^{-1}

Basic Trigonometry



$a^2 + b^2 = c^2$
$\cos\theta$ = adj/hyp
$\sin\theta$ = opp/hyp
$\tan\theta$ = opp/adj
$\theta = \tan^{-1}$(opp/adj)



$\mathbf{A_x} = \mathbf{A}\cos\theta$
$\mathbf{A_y} = \mathbf{A}\sin\theta$

$\theta = \tan^{-1}(|A_y|/|A_x|)$

Motion with Constant Acceleration

Average velocity: $\mathbf{v_{avg}} = \mathbf{\Delta x}/\Delta t$
Multi-part motion: $\mathbf{\Delta x_1} = \mathbf{v_{avg,1}} t_1$, $\mathbf{\Delta x_2} = \mathbf{v_{avg,2}} t_2$, …
$\mathbf{\Delta x_{tot}} = \mathbf{\Delta x_1} + \mathbf{\Delta x_2} + \ldots = \mathbf{v_{avg,tot}} t_{tot}$
Acceleration: $\mathbf{a} = \mathbf{\Delta v}/\Delta t = (\mathbf{v} - \mathbf{v_0})/t$
If $\mathbf{a}$ = constant, then $\mathbf{v_{avg}} = (\mathbf{v} + \mathbf{v_0})/2$
where $\mathbf{\Delta x}$ = displacement,
$\mathbf{v}$ = final velocity
$\mathbf{v_0}$ = initial velocity

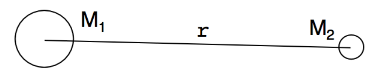
Equation of Motion	Missing
(1) $\mathbf{\Delta x} = \frac{1}{2}(\mathbf{v} + \mathbf{v_0})t$	$\mathbf{a}$
(2) $\mathbf{v} = \mathbf{v_0} + \mathbf{a}t$	$\mathbf{\Delta x}$
(3) $\mathbf{\Delta x} = \mathbf{v_0}t + \frac{1}{2}\mathbf{a}t^2$	$\mathbf{v}$
(4) $\mathbf{\Delta x} = \mathbf{v}t - \frac{1}{2}\mathbf{a}t^2$	$\mathbf{v_0}$
(5) $\mathbf{v}^2 = \mathbf{v_0}^2 + 2\mathbf{a}\mathbf{\Delta x}$	t

Forces (Newtons)

$\sum \mathbf{F} = m\mathbf{a} \implies \sum \mathbf{F_x} = m\mathbf{a_x}$, $\sum \mathbf{F_y} = m\mathbf{a_y}$ or $\sum \mathbf{F}_{/\!/} = m\mathbf{a}_{/\!/}$, $\sum \mathbf{F}_{\perp} = m\mathbf{a}_{\perp}$

<u>Force Definitions</u> (Magnitude and Direction)
<u>Gravity</u>: $\mathbf{F_g} = |mg|$, downward, where $g = 9.8\ m/s^2$
<u>Applied</u>: $\mathbf{F_{App}} = |variable|$, |variable| (must be defined in problem statement or solved for)
<u>Tension</u>: $\mathbf{F_T} = |variable|$, inward from each end of rope/string, equal and opposite at each end
<u>Normal</u>: $\mathbf{F_N} = |\sum \mathbf{F}_{\perp}|$ (sum of all other $\perp$ forces), $\perp$ to and out of surface.
<u>Kinetic Friction</u>: $\mathbf{F_{KF}} = |\mu_k \mathbf{F_N}|$, opposing motion, where μ_k is the coefficient of kinetic friction.
<u>Static Friction</u>: $\mathbf{F_{SF}} = |\sum \mathbf{F}_{/\!/}|$ (sum of all other $/\!/$ forces), opposite direction of $\sum \mathbf{F}_{/\!/}$.

Static Friction (max value): $\mathbf{F_{SF,max}} = |\mu_s \mathbf{F_N}|$ where μ_s is the coefficient of static friction.
<u>Spring</u>: $\mathbf{F_{spr}} = |k_s \boldsymbol{\Delta x}|$, restoring, k_s = spring constant (N/m) and $\boldsymbol{\Delta x}$ = displacement from equilibrium
<u>"Centrifugal"</u>: $\mathbf{F_{cf}} = |mv^2/r|$ or $|mr\omega^2|$, radially outward, where r = radius of circular motion
<u>Buoyancy</u>: $\mathbf{F_B} = |\rho_f V_f g|$, upward. ρ_f = fluid density, V_f = volume of displaced fluid
<u>Newtonian Gravity</u>: $F_{grav} = \left|\frac{GM_1M_2}{r^2}\right|$, attractive



where $G = 6.67 \times 10^{-11}\ N\text{-}m^2/kg^2$,
r = distance between centers of M_1 and M_2.

<u>Electric</u>: $F_{electric} = \left|\frac{k_c q_1 q_2}{r^2}\right|$, like charges repel, opposites attract.

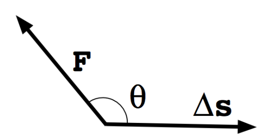
where k_c = Coulomb constant ($8.99 \times 10^9\ N\text{-}m^2/C^2$),
r = distance between centers of charges q_1 and q_2

More generally, $F_{Electric} = qE$, where E = Electric field in which q is immersed

<u>Magnetic</u>: $\mathbf{F_B} = q\mathbf{v} \times \mathbf{B}$ or $|q\mathbf{vB}\sin\theta|$ for moving charges,
or $\ell \mathbf{I} \times \mathbf{B}$ or $|\ell \mathbf{IB}\sin\theta|$ for current-carrying wires (ℓ = length of wire),
<u>direction</u>: right-hand rule #1 (**F** = palm, **v** or **I** = thumb, **B** = fingers)
where θ is the angle between **v** and **B** or between **I** and **B**. (cross product)

Energy and Work (Joules)

<u>Work done by a Force</u>



<u>Work/Energy Units</u>: 1 Joule = 1 kg-m²/s², 1 Watt = 1 Joule/sec
<u>Method #1</u>: $W_F = |\mathbf{F}| \cdot |\boldsymbol{\Delta s}| \cdot \cos\theta$, where θ is the angle between **F** and **Δs**
<u>Method #2</u>: $W_F = -\Delta U_F$ or $U_{initial} - U_{final}$, where U_F is the potential energy related to the force
<u>Method #3</u>: $W_{F1} + W_{F2} + W_{F3} = W_{tot}$. Find W_{F1}, W_{F2} and W_{tot}, then solve for W_{F3}.

<u>Potential Energy</u> (only conservative forces have an associated potential energy)
<u>Gravity</u> (relative): $\Delta U_{grav} = mg\boldsymbol{\Delta y}$ (only works for small distances over which $g = 9.8\ m/s^2$)
<u>Newtonian Gravity</u> (absolute): $U_{grav} = -\frac{GM_1M_2}{r}$ (see diagram above)
<u>Spring</u>: $U_{spr} = \frac{1}{2}k_s(\boldsymbol{\Delta x})^2$, where k_s = spring constant (N/m), $\boldsymbol{\Delta x}$ = displacement from equilibrium
<u>Electric</u> (relative): $\Delta U_{electric} = q_1 \Delta V_2$, where q_1 is a charge immersed in a potential V_2.
<u>Electric</u> (absolute): $U_{electric} = \frac{k_c q_1 q_2}{r}$, where r = distance between centers of charges q_1 and q_2

<u>Work-Energy and Energy Conservation</u>: U = potential energy, $K = \frac{1}{2}mv^2$, kinetic energy
<u>Mechanical Energy</u>: E = K + U. E is conserved ($\Delta E = 0$) if only conservative forces do work
<u>Work-Energy Theorem</u>: $W_{tot} = \sum W_F = \Delta K$.

<u>Power (Watts) and Energy</u>
<u>Power</u>: P = Energy/time or Work/time, $P = |\mathbf{F}| \cdot |\mathbf{v}| \cdot \cos\theta$, where θ is the angle between **F** and **v**

Momentum (kg-m/s) and Collisions

Momentum: $\mathbf{p} = m\mathbf{v}$, where $\mathbf{p}$ = momentum (kg·m/s), $\mathbf{p}$ and $\mathbf{v}$ share the same direction.

Impulse: $\Delta\mathbf{p} = \mathbf{F}_{avg}\Delta t$ or $\mathbf{F}_{avg} = \Delta\mathbf{p}/\Delta t$, where $\Delta\mathbf{p} = \mathbf{p}_{final} - \mathbf{p}_{initial}$.

Momentum Conservation: If $\sum\mathbf{F}_{ext} = 0$, then $\Delta\mathbf{p} = 0$, where $\sum\mathbf{F}_{ext}$ = sum of all external forces.

If $\Delta\mathbf{p} = 0$, then: $\Delta\mathbf{p}_x = 0$ or $m_1\mathbf{v}_{1i,x} + m_2\mathbf{v}_{2i,x} = m_1\mathbf{v}_{1f,x} + m_2\mathbf{v}_{2f,x}$

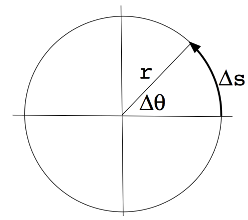
and $\Delta\mathbf{p}_y = 0$ or $m_1\mathbf{v}_{1i,y} + m_2\mathbf{v}_{2i,y} = m_1\mathbf{v}_{1f,y} + m_2\mathbf{v}_{2f,y}$

If masses stick together after collision, then $\mathbf{v}_{1f} = \mathbf{v}_{2f} = \mathbf{v}_f$

Elastic Collisions: If $\Delta\mathbf{p} = 0$ and $\Delta K = 0$, then:

$$v_{1f} = \frac{m_1 - m_2}{m_1 + m_2}v_{1i} + \frac{2m_2}{m_1 + m_2}v_{2i} \quad \text{and} \quad v_{2f} = \frac{2m_1}{m_1 + m_2}v_{1i} + \frac{m_2 - m_1}{m_1 + m_2}v_{2i}$$

Shortcut: Note that if $m_1 = m_2$, then $v_{1f} = v_{2i}$ and $v_{2f} = v_{1i}$.



Rotational Motion and Newtonian Gravity

Angular equivalents: $\Delta\theta = \Delta s/r$, $\omega = v/r$, $\alpha = a_{tan}/r$

Centripetal acceleration: $a_{cp} = v^2/r$ or $r\omega^2$, directed radially inward

"Centrifugal force": $F_{cf} = mv2/r$ or $mr\omega^2$, directed radially outward

Motion with Constant α

$\Delta\theta = \frac{1}{2}(\omega + \omega_0)t$

$\omega = \omega_0 + \alpha t$

$\Delta\theta = \omega_0 t + \frac{1}{2}\alpha t^2$

$\Delta\theta = \omega t - \frac{1}{2}\alpha t^2$

$\omega^2 = \omega_0^2 + 2\alpha\Delta\theta$

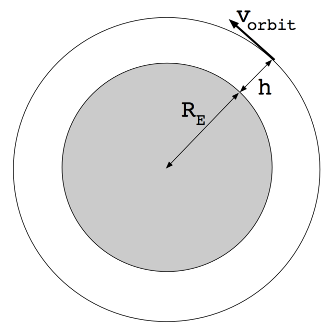
Orbital Motion (Earth)

$r_{orbit} = R_E + h$, where R_E = Radius of Earth, and h = altitude above surface

$2\pi r_{orbit} = v_{orbit}T$, where T = orbital period

Equation of Orbital Velocity: $v_{orbit} = \sqrt{\frac{GM}{r_{orbit}}}$

Kepler's 3rd Law of Orbits: $T^2 = \left(\frac{4\pi^2}{GM}\right)r_{orbit}^3$



Torque (Newton-meters)

Torque (Cross Product): $\tau = \mathbf{r} \times \mathbf{F}$ or $|\mathbf{r}|\cdot|\mathbf{F}|\cdot\sin\theta$, where

$\mathbf{r}$ = distance vector from pivot to point of application of the force, and

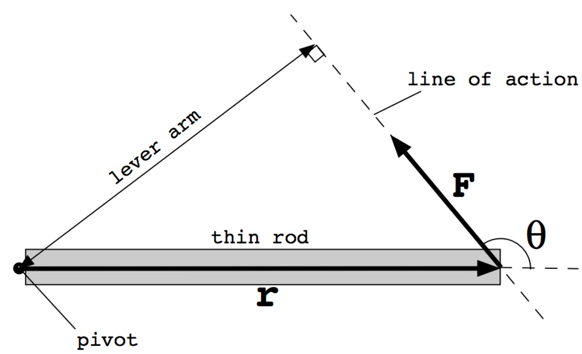
θ = angle between tails of vectors $\mathbf{r}$ and $\mathbf{F}$.

Torque (Lever Arm): $\tau = |\mathbf{F}\ell|$, where

ℓ = ⊥ distance to line of action or "lever arm".

Sign Convention: τ is negative if directed clockwise (cw)

τ is positive if directed counter-clockwise (ccw).



Moment of Inertia: $I = AMR^2$ (kg·m²), where

R = radius of object and A = number from 0-1 depending upon the nature of the object

$I_{ring} = MR^2$ $\quad$ $I_{point\ mass} = Mr^2$, where r = distance from object to axis object is revolving around

$I_{cylinder} = \frac{1}{2}MR^2$ $\quad$ $I_{sphere} = 0.4MR^2$

Newton's 2nd Law (Angular Version): $\sum\tau = I\alpha$

Static Equilibrium: $\sum F_x = \sum F_y = \sum\tau = 0$

Rotational Kinetic Energy (Joules) and Angular Momentum (kg-m/s)

Rotational Kinetic Energy: $K = \frac{1}{2}mv^2$ (translational KE) + $\frac{1}{2}I\omega^2$ (rotational KE)

Rolling without slipping: $\mathbf{v}_{center\text{-}of\text{-}mass} = \mathbf{v}_{tan}$, at rim $= r\omega$.

Angular Momentum: $\mathbf{L} = I\omega$. Just as $\mathbf{F}_{avg} = \Delta\mathbf{p}/\Delta t$, $\tau = \Delta\mathbf{L}/\Delta t$.

Conservation Laws: if $\sum\mathbf{F}_{ext} = 0$, then $\Delta\mathbf{p} = 0$ and if $\sum\tau_{ext} = 0$, $\Delta\mathbf{L} = 0$.

If $\Delta\mathbf{L} = 0$, then $I_{1i}\omega_{1i} + I_{2i}\omega_{2i} = I_{1f}\omega_{1f} + I_{2f}\omega_{2f}$.

Harmonic Motion

Spring Period: T = $2\pi\sqrt{\frac{m}{k_s}}$ Pendulum Oscillations: $T = 2\pi\sqrt{\frac{\ell}{g}}$

Spring Oscillations and Circular Motion:

Amplitude: $A = x_{max}$

Position: $x(t) = A \cos(\omega t)$

Velocity: $v(t) = r\omega = A\omega \sin(\omega t)$

Acceleration: $a(t) = r\omega^2 = A\omega^2 \cos(\omega t)$

Frequency: $f = 1/T$

Angular Frequency: $\omega = 2\pi f = 2\pi/T$

Mechanical Energy: $E = \frac{1}{2}mv^2 + \frac{1}{2}kx^2 = \frac{1}{2}kA^2$

Fluids

Density: ρ = Mass/Volume (kg/m^3). Since $m = \rho V$, $F_{grav} = mg = \rho V g$ for fluids.

Pressure: P = Force/Area (N/m^2 or Pascals)

Pascal's Principle: $P_{bot} = P_{top} + \rho gh$, "gauge pressure" = $P_{bot} - P_{top}$.

Continuity Equation: Q (flow rate) = (area)*(velocity) = Av (m^3/s), $A_1v_1 = A_2v_2$

Bernoulli's Equation: $P_{bot} + \rho g y_{bot} + \frac{1}{2}\rho v_{bot}^2 = P_{top} + \rho g y_{top} + \frac{1}{2}\rho v_{top}^2$

or $(P_{bot} - P_{top}) + \rho g(y_{bot} - y_{top}) + \frac{1}{2}\rho(v_{bot}^2 - v_{top}^2) = 0$

Thermal Physics

Thermal Expansion (length): $\Delta L = L_0\alpha\Delta T$, where α = linear expansion coefficient, ΔT in °C or K.

Thermal Expansion (area): $\Delta A = A_0(2\alpha)\Delta T$ or $A_0\beta\Delta T$, where β = area expansion coefficient

Thermal Expansion (volume): $\Delta V = V_0(3\alpha)\Delta T$ or $V_0\gamma\Delta T$, where γ = volume expansion coefficient

Calorimetry and Phase Changes

Heat: Q (Joules), $\Delta Q = mc\Delta T$, where c = specific heat (J/kg·°C), ΔT in °C or K.

Phase changes: $\Delta Q = +mL_f$ (melting, solid –> liquid), $-mL_f$ (freezing, liquid –> solid)

$\Delta Q = +mL_v$ (boiling, liquid –> gas), $-mL_v$ (condensing, gas –> liquid)

where L_f = latent heat of fusion, L_v = latent heat of vaporization

Thermal Equilibrium: $\Delta Q_1 + \Delta Q_2 + \Delta Q_3 + \ldots = 0$

Heat Transfer (Watts)

Conduction: Power (P) = $\Delta Q/\Delta t$ = Area*ΔT/R-value, where R-value = $\ell_1/k_1 + \ell_2/k_2 + \ell_3/k_3 + \ldots$

and ℓ = layer thickness, k = thermal conductivity (Joule/s·m·°C) of each layer

Radiation: Power (P) = $\Delta Q/\Delta t = \sigma$*(Area)*e*$(T^4 - T_0^4)$, where σ = S-B constant (5.67 x 10^{-8} W/m^2·K^4),

e = emissivity (0-1), T = object temperature, T_0 = temperature of surroundings

Ideal Gases

$PV = nRT$ or $PV = Nk_bT$	R = Ideal gas constant (see p1)	m = total gas mass (kg)
P = Pressure (N/m^2 or Pa)	k_b = Boltzmann's constant (see p1)	M = molar mass (kg/mole)
V = Volume (m^3)	n = # of moles	n = m/M
T = Temperature (K)	N = # of molecules	$n = N/N_A$ (see p1 for N_A)

Thermodynamics

Calculating Work: $W_{by\ gas} = +P_{avg}\Delta V$, $W_{on\ gas} = -P_{avg}\Delta V$

Internal Energy: $\Delta U = Q - W_{by\ gas} = Q + W_{on\ gas}$, where U = Internal Energy (Joules),

and Q = heat added to gas (system)

Cyclic Process: $\Delta U_{cycle} = 0$

Kinetic Energy of a Particle: $KE = \frac{1}{2}m_{particle}v_{rms}^2 = 1.5k_BT$

Internal Energy of a Gas: $U = 1.5nRT = 1.5PV$

Sound Waves

Sound Waves in Air: $v_{wave} = \sqrt{\frac{\gamma k_b T}{m}}$, γ = 5/3 for ideal monatomic gas, 7/5 for ideal diatomic gas

k_b = Boltzmann's constant (see p1), m = molecular mass (kg)

Sound Intensity: β (decibels) = 10 log (I/I_0), where I_0 = hearing threshold, 1.0 x 10^{-12} W/m^2.

$\Delta\beta$ (decibels) = 10 log (I_{big}/I_{small})

Intensity of a Point Source: I (Watts/m^2) = Power/$4\pi r^2$

Wave Equation: v = fλ

Electric Forces (Newtons) and Electric Fields (N/C or V/m)

Electric Field (point charge): $|\mathbf{E}| = k_c q/r^2$, direction: away from + charges, toward - charges

Electric Field (sheet of charge): $|\mathbf{E}| = 2\pi k_c \sigma$, where σ = surface charge density (Q/Area)

Parallel sheets/plates: $|\mathbf{E}| = 4\pi k_c \sigma$ inside, 0 outside, assuming equal and opposite Q on plates.

Conductors: $|\mathbf{E}|$ = 0 inside, all charge resides on surface, no charge enclosed by surface.

Electric Potential (Volts) and Electric Potential Energy (Joules)

Absolute Potential (point charges): $V_{abs} = k_c q/r$

Relative Potential: $\Delta U_E = q_1 \Delta V_2$ for charge q_1 immersed in potential from source 2.

Uniform Electric Fields: $\Delta V = \pm$ **E***(distance), **E** points from higher V to lower V.

Sign Conventions: + charges tend to follow E lines from higher to lower potential (voltage)

+ charges tend to follow E lines from higher to lower potential energy

If - charges follow E lines, they go against electric force and move from higher to lower potential (voltage), lower to higher potential energy

Work-Energy: $W_E = -\Delta U_E = -q_1 \Delta V_2$ for charge q_1 immersed in potential from source 2.

DC Circuits

Current: I (Amperes) = $\Delta Q/\Delta t$

Resistance: R (Ohms) = $\rho L/A$, where ρ = resistivity (Ohm·meters), L = wire length, A = wire area

Ohm's Law: ΔV (Volts) = $\pm IR$ (current travels from higher to lower voltage)

Power: P (Watts) = $I^2 R$ (power dissipated by resistor)

= $I\Delta V$ (power supplied by source)

Resistor Circuits

Series Resistors: $R_{tot} = R_1 + R_2$, $I_{tot} = I_1 = I_2$, $\Delta V_{tot} = \Delta V_1 + \Delta V_2$

Parallel Resistors: $1/R_{tot} = 1/R_1 + 1/R_2$, $I_{tot} = I_1 + I_2$, $\Delta V_{tot} = \Delta V_1 = \Delta V_2$

Kirchoff's Laws

Loop Rule: The sum of all voltage drops around a loop is zero. $\sum \Delta V = 0$.

Junction Rule: At any junction, the sum of incoming currents = sum of outgoing currents.

Capacitors

Capacitance: C (Farads) = $Q/\Delta V$ = Area*ϵ_0/d = Area/4π*k_c*d

Dielectrics: κ(kappa) = Dielectric constant. $C_{new} = \kappa C_{original}$

Energy Stored by a Capacitor: $U_E = \frac{1}{2}C\Delta V^2 = \frac{1}{2}Q\Delta V = Q^2/2C$

RC Circuits (initially uncharged)

Capacitive Time Constant: $\tau_C = RC$

Charge: $Q(t) = C\varepsilon(1 - e^{-t/\tau_C})$, $Q_{max} = C\varepsilon$

Current: $I(t) = \left(\varepsilon/R\right) e^{-t/\tau_C}$, $I_{max} = \varepsilon/R$

Capacitor Voltage: $\Delta V_C = \varepsilon(1 - e^{-t/\tau_C})$, $\Delta V_{max} = \varepsilon$

Resistor Voltage: $\Delta V_R = \varepsilon e^{-t/\tau_C}$, $\Delta V_{max} = \varepsilon$

RL Circuits (with $I_{initial} = 0$ at $t = 0$)

Inductive Time Constant: $\tau_L = L/R$

Current: $I(t) = \frac{\varepsilon}{R}(1 - e^{-t/\tau_L})$, $I_{max} = \varepsilon/R$

Inductor Voltage: $\Delta V_L = \varepsilon e^{-t/\tau_L}$, $\Delta V_{max} = \varepsilon$

Magnetic Fields (Tesla) and Magnetic Forces (Newtons)

Right-hand rules

RHR #1 (cross products): $\mathbf{A} = \mathbf{B} \times \mathbf{C}$, **A** = palm, **B** = thumb, **C** = fingers

RHR #2 (magnetic field of straight wire): **I** = thumb, **B** = curl of fingers of right hand

RHR #3 (magnetic field of wire loop): **I** = curl of fingers of right hand, $\mathbf{B}_{loop}$ = thumb

Magnetic Field of a Wire: $|\mathbf{B}| = \mu_0 \mathbf{I}/2\pi r$, Direction: RHR #2

Magnetic Field of a Loop: $|\mathbf{B}| = \mu_0 \mathbf{I}/2R$ within the plane of the loop and inside loop, where R = radius of loop, Direction: RHR #3

Magnetic Field of a Solenoid: $|\mathbf{B}| = \mu_0 N\mathbf{I}/L$ within the cylindrical volume of solenoid, N = # of turns, L = length of solenoid, use RHR #3

Magnetic Force

Force on a moving charge: $\mathbf{F_B} = q\mathbf{v} \times \mathbf{B}$, $|\mathbf{F_B}| = |q\mathbf{vB}\sin(\theta)|$, θ = angle between v and B. RHR #1

Circular motion: Circular path of charge in a magnetic field has radius $r = mv/qB$

Force on a current-carrying wire: $\mathbf{F_B} = \ell\mathbf{I} \times \mathbf{B}$, $|\mathbf{F_B}| = |\ell\mathbf{IB}\sin(\theta)|$, ℓ = length of wire. RHR #1

Magnetic Torque

Magnetic Moment: $\boldsymbol{\mu}$ ($T\cdot m^2$) = $N\mathbf{IA}$, where N = # of turns, **A** = area of loop, direction is consistent with $\mathbf{B}_{loop}$ from RHR #3.

Area vector: **A** is normal to plane of loop, typically same direction as magnetic moment

Magnetic Torque: $|\boldsymbol{\tau}_B| = |N\mathbf{B}_{ext}\mathbf{IA}\sin(\theta)|$, θ = angle between area vector and external magnetic field

$= \boldsymbol{\mu} \times \mathbf{B}_{ext} = |\boldsymbol{\mu}\mathbf{B}_{ext}\sin(\theta)|$

Direction: tends to align area vector (or $\boldsymbol{\mu}$) with $\mathbf{B}_{ext}$ direction.

Electromagnetic Induction

Magnetic Flux: $\boldsymbol{\Phi}_B = |\mathbf{B}|\cdot|\mathbf{A}|\cdot\cos(\theta)$, where θ = angle between **B** and Area vector (**A**).

Induced EMF: $\varepsilon_{ind} = N(\Delta\boldsymbol{\Phi}/\Delta t)$, opposes $\Delta\boldsymbol{\Phi}$.

Motional EMF: $\varepsilon_{ind} = BLv$, opposes $\Delta\boldsymbol{\Phi}$.

Self-induction: $\varepsilon_{ind} = L(\Delta I/\Delta t)$, where L = self-inductance (Henrys), $L_{loop} = N\boldsymbol{\Phi}/I$

Energy Stored by an Inductor: $E = \frac{1}{2}LI^2$

Finding direction of induced current:

1) Find initial direction of $\boldsymbol{\Phi}_B$.
2) Find direction of $\Delta\boldsymbol{\Phi}_B$.
3) B_{ind} opposed $\Delta\boldsymbol{\Phi}_B$.
4) I_{ind} is consistent with B_{ind} using RHR #3

Average voltage drop across inductor: $\Delta V_L = \pm L(\Delta I/\Delta t)$ (for instantaneous ΔV_L – see RL circuits)

Light and Optics

Energy Density of Light: $u_{tot} = u_{electric} + u_{magnetic} = \frac{1}{2}\epsilon_0 E_{rms}^2 + \frac{1}{2}(1/\mu_0)B_{rms}^2$ or $u_{tot} = \epsilon_0 E_{rms}^2 = (1/\mu_0)B_{rms}^2$

Intensity of Light: S = Power/Area = $c*u_{total}$, for light spread out over sphere, $S = \text{Power}/4\pi r^2$

Doppler Effect

General case (both source and observer moving):

Plus sign when source and observer come closer (blueshift)

Minus sign when source and observer move apart (redshift)

$$f_{obs} = f_{src}\left(1 \pm \frac{v_{rel}}{v_{wave}}\right)$$

Alternate formula for Doppler effect: $$\frac{\Delta\lambda}{\lambda} = \frac{v_{relative}}{c}$$

Wave Equation: $v = f\lambda$

Index of refraction: $n = c/v$, where c = speed of light in vacuum, v = speed of light in medium

Wavelength of light: $\lambda_n = \lambda_0/n$ (wavelength of light shortens when it enters some medium)

Snell's Law: $n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$, light turns toward normal when entering higher index

Critical Angle: $\theta_{crit} = \sin^{-1}(n_1/n_2)$, max angle of incidence for light to pass from $n_2 \rightarrow n_1$.

Polarization

Brewster's Angle: $\theta_B = \tan^{-1}(n)$. If $\theta_{incidence} = \theta_B$, ray is polarized parallel to surface

Unpolarized light through polarizer: $I_{final} = \frac{1}{2} I_{initial}$

Polarized light through polarizer: $I_{final} = I_{initial} \cos^2(\theta)$,

where θ = angle between polarized light and axis of polarizer

Lenses and Mirrors

p = object distance

q = image distance

f = focal length

R = radius of curvature = 2f

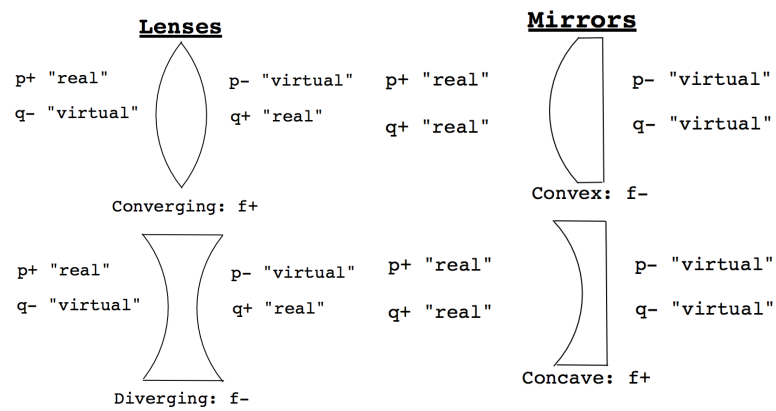
M = magnification = $-q/p$

If M+, image is upright

If M−, image is inverted

Image size: $h_{image} = |M| h_{object}$

Optics Equation: $$\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$$



Interference and Diffraction (light waves)

d = slit separation, L = distance to screen, y = distance from center of pattern on wall,

δ = path difference between two sources of light, θ = angular distance from center of pattern.

Two-slit interference (m = order number)

Constructive Interference (bright fringes) where $\delta = d\sin\theta = dy/L = 0, \lambda, 2\lambda, 3\lambda, \ldots (m\lambda)$

Destructive Interference (dark fringes) where $\delta = dy/L = 0.5\lambda, 1.5\lambda, 2.5\lambda, \ldots (m + \frac{1}{2})\lambda$

Single-slit interference

a = slit width, dark fringes where $a\sin\theta = ay/L = \lambda, 2\lambda, 3\lambda, \ldots$

Resolution: θ_{min} = separation/distance = λ/D (slit) or $1.22\lambda/D$ (circular aperture)

Diffraction grating

d = groove separation, bright light reflected where $d\sin\theta = \lambda, 2\lambda, 3\lambda, \ldots$

Thin Films

Phase shift due to reflection: $\delta = \frac{1}{2}$ wave if reflecting off higher index, otherwise 0

Phase shift due to extra distance in film: $\delta = 2tn/\lambda_0$ waves where t = film thickness

Constructive Interference (CI): $\delta_2 - \delta_1 = 0, 1, 2, \ldots$ waves, DI: $\delta_2 - \delta_1 = 0.5, 1.5, 2.5$ waves

Modern Physics

Photoelectric Effect

Photon Energy: $E = hf = hc/\lambda$, where h = Planck's constant (see p1)

Work Function: Φ = minimum KE needed for an electron to escape from a metal surface

Photoelectric Effect: $(KE)_{max} = hf - \Phi$ for max KE of electrons emerging from a surface

If $hf < \Phi$, then no electrons escape

$hf = \Phi$ at cutoff frequency: $f_{cutoff} = \Phi/h$

Momentum of a photon: $p = \text{Energy}/c = h/\lambda$

Hydrogen spectrum

Energy levels in Hydrogen: $E_n = -13.6/n^2$ eV, where 1 eV = 1.60×10^{-19} J

Electron absorption/emission: $\frac{1}{\lambda} = R_H\left|\frac{1}{n_1^2} - \frac{1}{n_2^2}\right|$, where R_H = Rydberg constant (1.097×10^7 m^{-1})

Blackbody Radiation – Wien's Law: $\lambda_{max}T = 0.029$ m·K

Radioactivity

Half-life: $T_{½}$ = Time for half of the remaining radioactive atoms in a sample to decay

Decay constant: $\lambda = 0.693/T_{½}$ s^{-1}

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

Radioactivity: $a(t) = \lambda N(t)$, $a(t) = a_0 e^{-\lambda t}$, units: Becquerels or Bq (decays/sec)

Biological Effects of Radiation

Radiation Absorbed Dose (Grays): Dose = (Absorbed Energy)/(Mass of absorbing material)

1 rad = 0.01 J/kg = 0.01 Grays

Biologically Equivalent Dose (rems) = Absorbed Dose * (Relative Biological Effectiveness)

Nuclear Physics

Binding Energy: $BE = \Delta mc^2$, where $\Delta m = M_{nucleus} - N_{protons}m_{proton} - N_{neutrons}m_{neutron}$

Mass-Energy calculations: E(MeV) = Mass (u) * 931.5 MeV/u·c^2

Masses of Selected Isotopes:

Proton: 1.007276 u

Neutron: 1.008665 u

Electron: 0.0005486 u

Hydrogen	(^{1}H): 1.007825 u	Deuterium (^{2}H): 2.014102 u	Tritium (^{3}H): 3.016050 u
Helium	^{3}He: 3.016030 u	^{4}He: 4.002602 u	
Boron	^{11}B: 11.009305 u		
Carbon	^{12}C: 12.000000 u	^{13}C: 13.003355 u	^{14}C: 14.003241 u
Manganese	^{55}Mn: 54.938047 u		
Iron	^{56}Fe: 55.934939 u		
Cobalt	^{59}Co: 58.933198 u	^{60}Co: 59.933819 u	
Strontium	^{90}Sr: 89.907738 u		
Krypton	^{92}Kr: 91.926270 u		
Barium	^{141}Ba: 140.914363 u		
Radium	^{226}Ra: 226.025402 u		
Uranium	^{235}U: 235.043924 u	^{238}U: 238.050784 u	
Plutonium	^{242}Pu: 242.058737 u		