SPARKCHARTS™

PHYSICS FORMULAS

PHYSICAL CONSTANTS

Acceleration due to gravity	g	$9.8\,\mathrm{m/s^2}$
Avogadro's number	N_A	6.022×10^{23} molecules/mol
Coulomb's constant	k	$9\times10^{9}\,\mathrm{N\cdot m^2/C^2}$
Gravitational constant	G	$6.67\times10^{-11}\,\mathrm{N\cdot m^2/kg^2}$
Planck's constant	h	$6.63\times10^{-34}\,\mathrm{J\cdot s}$
Ideal gas constant	R	$8.314\,\mathrm{J/(mol\cdot K)}$ $= 0.082\,\mathrm{atm\cdot L/(mol\cdot K)}$
Permittivity of free space	ε_0	$8.8541\times10^{-12}\,\mathrm{C/(V\cdot m)}$
Permeability of free space	μ_0	$4\pi\times10^{-7}\,\mathrm{Wb/(A\cdot m)}$
Speed of sound at STP		$331\,\mathrm{m/s}$
Speed of light in a vacuum	c	$3.00\times10^{8}\,\mathrm{m/s}$
Electron charge	e	$1.60\times10^{-19}\,\mathrm{C}$
Electron volt	eV	$1.6022\times10^{-19}\,\mathrm{J}$
Atomic mass unit	u	$1.6606\times10^{-27}\,\mathrm{kg}$ $=931.5\,\mathrm{MeV}/c^2$
Rest mass of electron	m_e	$9.11\times10^{-31}\,\mathrm{kg}$ $=0.000549\,\mathrm{u}$ $=0.511\,\mathrm{MeV}/c^2$
...of proton	m_p	$1.6726\times10^{-27}\,\mathrm{kg}$ $=1.00728\,\mathrm{u}$ $=938.3\,\mathrm{MeV}/c^2$
...of neutron		$1.6750\times10^{-27}\,\mathrm{kg}$ $=1.008665\,\mathrm{u}$ $=939.6\,\mathrm{MeV}/c^2$
Mass of Earth		$5.976\times10^{24}\,\mathrm{kg}$
Radius of Earth		$6.378\times10^{6}\,\mathrm{m}$

DYNAMICS

NEWTON'S LAWS

1. **First Law:** An object remains in its state of rest or motion with constant velocity unless acted upon by a net external force.
2. **Second Law:** $F_{\text{net}} = ma$ $\qquad F = \dfrac{dp}{dt}$
3. **Third Law:** For every action there is an equal and opposite reaction.

Weight	$F_w = mg$
Normal force	$F_N = mg\cos\theta$ (θ is the angle to the horizontal)

FRICTION

Static friction $f_{s,\max} = \mu_s F_N$ $\qquad$ **Kinetic friction** $f_k = \mu_k F_N$

μ_s is the coefficient of static friction.
μ_k is the coefficient of kinetic friction.
For a pair of materials, $\mu_k < \mu_s$.

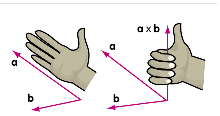
UNIFORM CIRCULAR MOTION

Centripetal acceleration $a_c = \dfrac{v^2}{r}$ $\qquad$ **Centripetal force** $F_c = \dfrac{mv^2}{r}$

VECTOR FORMULAS

Notation	$\mathbf{a} = a_x\hat{\mathbf{i}} + a_y\hat{\mathbf{i}} + a_z\hat{\mathbf{k}}$
Magnitude	$a = \lvert\mathbf{a}\rvert = \sqrt{a_x^2 + a_y^2 + a_z^2}$
Dot product (θ is the angle between a and b)	$\mathbf{a}\cdot\mathbf{b} = a_xb_x + a_yb_y + a_zb_z = ab\cos\theta$

Cross product $\lvert\mathbf{a}\times\mathbf{b}\rvert = ab\sin\theta$
$\mathbf{a}\times\mathbf{b}$ points in the direction given by the right-hand rule:

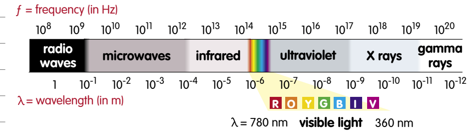


$$\mathbf{a}\times\mathbf{b} = (a_yb_z - a_zb_y)\,\hat{\mathbf{i}} + (a_zb_x - a_xbz)\,\hat{\mathbf{j}} + (a_xb_y - a_yb_x)\,\hat{\mathbf{k}} = \begin{vmatrix} a_x & a_y & a_z \\ a_x & a_y & b_z \\ \hat{\mathbf{i}} & \hat{\mathbf{j}} & \hat{\mathbf{k}} \end{vmatrix}$$

ELECTROMAGNETIC CONSTANTS

WAVELENGTHS OF LIGHT IN A VACUUM (m)

Red	$6.5-7.0\times10^{-7}$
Orange	$5.9-6.5\times10^{-7}$
Yellow	$5.7-5.9\times10^{-7}$
Green	$4.9-5.7\times10^{-7}$
Blue	$4.2-4.9\times10^{-7}$
Violet	$4.0-4.2\times10^{-7}$



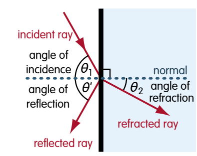
INDICES OF REFRACTION FOR COMMON SUBSTANCES ($\lambda = 5.9\times10^{-7}$ m)

Air	1.00	Alcohol	1.36
Corn oil	1.47	Diamond	2.42
Glycerol	1.47	Water	1.33

OPTICS

REFLECTION AND REFRACTION

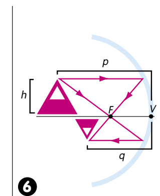
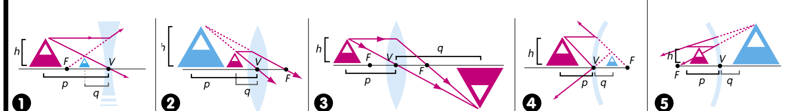
Law of Reflection	$\theta_{\text{incident}} = \theta_{\text{reflected}}$
Index of refraction	$n = \dfrac{c}{v}$ (v is the speed of light in the medium)
Snell's Law	$n_1\sin\theta_1 = n_2\sin\theta_2$
Critical angle	$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$



LENSES AND CURVED MIRRORS

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f} \qquad \frac{\text{image size}}{\text{object size}} = -\frac{q}{p}$$

Optical instrument	Focal distance f		Image distance q	Type of image
Lens:				
Concave	negative		negative (same side)	virtual, erect ❶
Convex	positive	$p < f$	negative (same side)	virtual, erect ❷
		$p > f$	positive (opposite side)	real, inverted ❸
Mirror:				
Convex	negative		negative (opposite side)	virtual, erect ❹
Concave	positive	$p < f$	negative (opposite side)	virtual, erect ❺
		$p > f$	positive (same side)	real, inverted ❻

WORK, ENERGY, POWER

Work	$W = \mathbf{F}\cdot\mathbf{s} = Fs\cos\theta$ $\quad W = \int \mathbf{F}\cdot d\mathbf{s}$
Kinetic energy	$KE = \dfrac{1}{2}mv^2 = \dfrac{p^2}{2m}$
Work-Energy Theorem (for conservative forces)	$W = \Delta KE$
Potential energy	$\Delta U = -W$
Gravitational potential energy	$U_g = mgh$
Total mechanical energy	$E = KE + U$
Average power	$P_{\text{avg}} = \dfrac{\Delta W}{\Delta t}$
Instantaneous power	$P = \mathbf{F}\cdot\mathbf{v}$

MOMENTUM AND IMPULSE

Linear momentum	$\mathbf{p} = m\mathbf{v}$
Impulse	$\mathbf{J} = \mathbf{F}t = \Delta\mathbf{p}$ $\quad \mathbf{J} = \int \mathbf{F}\,dt = \Delta\mathbf{p}$

COLLISIONS

All collisions $m_1\mathbf{v}_1 + m_2\mathbf{v}_2 = m_1\mathbf{v}_1' + m_2\mathbf{v}_2'$

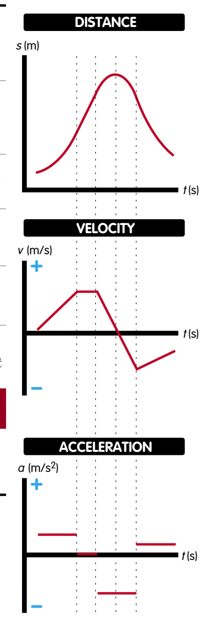
Elastic collisions

$$\frac{1}{2}m_1v_1^2 + \frac{1}{2}m_2v_2^2 = \frac{1}{2}m_1(v_1')^2 + \frac{1}{2}m_2(v_2')^2$$

$$v_1 - v_2 = -(v_1' - v_2')$$

KINEMATICS

Average velocity	$\mathbf{v}_{\text{avg}} = \dfrac{\Delta\mathbf{s}}{\Delta t}$
Instantaneous velocity	$\mathbf{v} = \dfrac{d\mathbf{s}}{dt}$
Displacement	$\Delta\mathbf{s} = \int \mathbf{v}\,dt$
Average acceleration	$\mathbf{a}_{\text{avg}} = \dfrac{\Delta\mathbf{v}}{\Delta t}$
Instantaneous acceleration	$\mathbf{a} = \dfrac{d\mathbf{v}}{dt}$
Change in velocity	$\Delta\mathbf{v} = \int \mathbf{a}\,dt$



CONSTANT ACCELERATION

$v_f = v_0 + at$

$v_{\text{avg}} = \dfrac{1}{2}(v_0 + v_f)$

$s = s_0 + v_0t + \dfrac{1}{2}at$

$\;\; = s_0 - v_ft + \dfrac{1}{2}at$

$\;\; = s_0 + v_{\text{avg}}t$

$v_f^2 = v_0^2 + 2a(s_f - s_0)$

CONTINUED ON OTHER SIDE

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WAVES

Amplitude A **Frequency** f **Wavelength** λ **Period** T **Angular frequency** ω

$$T = \frac{1}{f} = \frac{2\pi}{\omega} \qquad \omega = 2\pi f = \frac{2\pi}{T}$$

Wave speed $v = f\lambda$

Wave equation

$$y(x,t) = A\sin(kx - \omega t) = A\sin\left(2\pi\left(\frac{x}{\lambda} - \frac{t}{T}\right)\right)$$

WAVE ON STRING

Tension in string F_T **Length** L **Mass density** $\mu = \frac{\text{mass}}{\text{length}}$

Speed of standing wave $v = \sqrt{\frac{F_T}{\mu}}$

Wavelength of standing wave $\lambda_n = \frac{2L}{n}$

SOUND WAVES

Beat frequency $f_{\text{beat}} = |f_1 - f_2|$

DOPPLER EFFECT

Motion of observer	Motion of source: Stationary	Toward observer at v_s	Away from observer at v_s
Stationary	v λ f	$v_{\text{eff}} = v$ $\lambda_{\text{eff}} = \lambda\left(\frac{v - v_s}{v}\right)$ $f_{\text{eff}} = f\left(\frac{v}{v - v_s}\right)$	$v_{\text{eff}} = v$ $\lambda_{\text{eff}} = \lambda\left(\frac{v + v_s}{v}\right)$ $f_{\text{eff}} = f\left(\frac{v}{v + v_s}\right)$
Towards source at v_o	$v_{\text{eff}} = v + v_o$ $\lambda_{\text{eff}} = \lambda$ $f_{\text{eff}} = f\left(\frac{v + v_o}{v}\right)$	$v_{\text{eff}} = v \pm v_o$ $\lambda_{\text{eff}} = \lambda\left(\frac{v \pm v_s}{v}\right)$ $f_{\text{eff}} = f\left(\frac{v \pm v_o}{v \pm v_s}\right)$	
Away from source at v_o	$v_{\text{eff}} = v - v_o$ $\lambda_{\text{eff}} = \lambda$ $f_{\text{eff}} = f\left(\frac{v - v_o}{v}\right)$		

ROTATIONAL MOTION

Angular position $\theta = \frac{s}{r}$

Angular velocity $\omega = \frac{v}{r}$

$\omega_{\text{avg}} = \frac{\Delta\theta}{\Delta t}$ $\qquad \omega = \frac{d\theta}{dt}$

Angular acceleration $\alpha = \frac{a_t}{r}$

$\alpha_{\text{avg}} = \frac{\Delta\omega}{\Delta t}$ $\qquad \alpha = \frac{d\omega}{dt}$

CONSTANT α

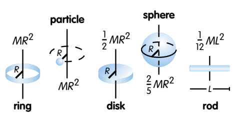
$\omega_f = \omega_0 + \alpha t \qquad \omega_{\text{avg}} = \frac{1}{2}(\omega_0 + \omega_f)$

$$\theta = \theta_0 + \omega_0 t + \frac{1}{2}\alpha t$$
$$= \theta_0 + \omega_{\text{avg}} t$$

$$\omega_f^2 = \omega_0^2 + 2\alpha(\theta_f - \theta_0)$$

MOMENTS OF INERTIA (I)

Moment of inertia $I = \int r^2 dm$



TORQUE AND ANGULAR MOMENTUM

Torque $\tau = Fr\sin\theta$

$\tau = \frac{d\mathbf{L}}{dt}$ $\qquad \tau = \mathbf{r} \times \mathbf{F}$

$\tau = I\alpha$

Angular momentum $L = pr\sin\theta$

$\mathbf{L} = \mathbf{r} \times \mathbf{p} \qquad \mathbf{L} = I\omega$

Rotational kinetic energy $KE_{\text{rot}} = \frac{1}{2}I\omega^2$

SIMPLE HARMONIC MOTION

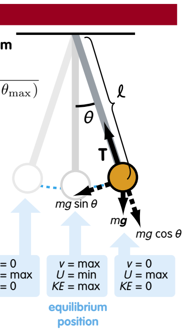
PENDULUM

Velocity at equilibrium position

$$v = \sqrt{2g\ell\,(1 - \cos\theta_{\max})}$$

Period

$$T = 2\pi\sqrt{\frac{\ell}{g}}$$



MASS-SPRING SYSTEM

Restoring force $F = -k(\Delta)x$

Δx is the distance the spring is stretched or compressed from the equilibrium position, and k is the spring constant.

Elastic potential energy $U_e = \frac{1}{2}k(\Delta x)^2$

Period $T = 2\pi\sqrt{\frac{m}{k}}$

Equation of motion $x = A\sin(\omega t)$

where $\omega = \frac{2\pi}{T} = \sqrt{\frac{k}{m}}$ is the angular frequency and $A = (\Delta x)_{\max}$ is the amplitude.

THERMODYNAMICS

1. **First Law**
   $\Delta\,(\text{Internal Energy}) = \Delta Q + \Delta W$
2. **Second Law:** All systems tend spontaneously toward maximum entropy.
   Alternatively, the efficiency $e = 1 - \frac{\Delta Q_{\text{out}}}{\Delta Q_{\text{in}}}$ of any heat engine always satisfies $0 \le e < 1$.

GAS LAWS

Universal Gas Law	$PV = nRT$	**Boyle's Law**	$P_1V_1 = P_2V_2$
Combined Gas Law	$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$	**Charles's Law**	$\frac{P_1}{T_1} = \frac{P_2}{T_2}$

ELECTRICITY

ELECTROSTATICS

Coulomb's Law $F = k\frac{q_1q_2}{r^2} = \frac{1}{4\pi\varepsilon_0}\frac{q_1q_2}{r^2}$

Electric field $\mathbf{E} = \frac{\mathbf{F}_{\text{on } q}}{q} \qquad \mathbf{F} = \mathbf{E}q$

Potential difference $\Delta V = \frac{W}{q}$

CIRCUITS

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

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

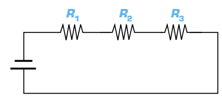
Ohm's Law $I = \frac{V}{R}$

Power dissipated by resistor $P = VI = I^2R$

Heat energy dissipated by resistor $W = Pt = I^2Rt$

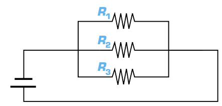
Series circuits

$I_{\text{eq}} = I_1 = I_2 = I_3 = \ldots$
$V_{\text{eq}} = V_1 + V_2 + V_3 + \cdots$
$R_{\text{eq}} = R_1 + R_2 + R_3 + \cdots$



Parallel circuits

$I_{\text{eq}} = I_1 + I_2 + I_3 + \cdots$
$V_{\text{eq}} = V_1 = V_2 = V_3 = \ldots$
$\frac{1}{R_{\text{eq}}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_2} + \cdots$



KIRCHHOFF'S RULES

Loop rule: The sum of all the (signed) potential differences around any closed loop is zero.
Node rule: The total current entering a juncture must equal the total current leaving the juncture.

MAGNETISM

Magnetic force on moving charge $F = qvB\sin\theta \qquad \mathbf{F} = q\,(\mathbf{v} \times \mathbf{B})$

Magnetic force on current-carrying wire $F = BI\ell\sin\theta \qquad \mathbf{F} = I\,(\ell \times \mathbf{B})$

MAGNETIC FIELD PRODUCED BY...

Magnetic field due to a moving charge $\mathbf{B} = \frac{\mu_0}{4\pi}\frac{q\mathbf{v} \times \hat{\mathbf{r}}}{r^2}$

Magnetic field produced by a current-carrying wire $B = \frac{\mu_0}{2\pi}\frac{I}{r}$

Magnetic field produced by a solenoid $B = \mu_0 nI$

Biot-Savart Law $d\mathbf{B} = \frac{\mu_0}{4\pi}\frac{I\,(d\ell \times \hat{\mathbf{r}})}{r^2}$

Lenz's Law and **Faraday's Law** $\varepsilon = -\frac{d\Phi_B}{dt}$

MAXWELL'S EQUATIONS

Gauss's Law $\oint_s \mathbf{E} \cdot d\mathbf{A} = \frac{Q_{\text{enclosed}}}{\varepsilon_0}$

Gauss's Law for magnetic fields $\oint_s \mathbf{B} \cdot d\mathbf{A} = 0$

Faraday's Law $\oint_c \mathbf{E} \cdot d\mathbf{s} = -\frac{\partial\Phi_B}{\partial t} = -\frac{\partial}{\partial t}\oint_s \mathbf{B} \cdot d\mathbf{A}$

Ampere's Law $\oint_c \mathbf{B} \cdot d\mathbf{s} = \mu_0 I_{\text{enclosed}}$

Ampere-Maxwell Law $\oint_c \mathbf{B} \cdot d\mathbf{s} = \mu_0 I_{\text{enclosed}} + \mu_0\varepsilon_0\frac{\partial}{\partial t}\oint_s \mathbf{E} \cdot d\mathbf{A}$

GRAVITY

Newton's Law of Universal Gravitation $F = G\frac{m_1m_2}{r^2}$

Acceleration due to gravity $a = \frac{GM_{\text{Earth}}}{r^2_{\text{Earth}}}$

Gravitational potential $U(r) = -\frac{GMm}{r}$

Escape velocity $v_{\text{escape}} = \sqrt{\frac{GM}{r}}$

KEPLER'S LAWS OF PLANETARY MOTION

1. Planets revolve around the Sun in an elliptical path with the Sun at one focus.
2. The imaginary segment connecting the planet to the Sun sweeps out equal areas in equal time.
3. The square of the period of revolution is directly proportional to the cube of the length of the semimajor axis of revolution: $\frac{T^2}{a^3}$ is constant.

SPARKCHARTS™

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