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# PH105 Final Exam

## Instructions

1. Answer all questions.
2. Record your responses on a scantron sheet.
3. On your scantron sheet, be sure to bubble in your **full name and CWID**.

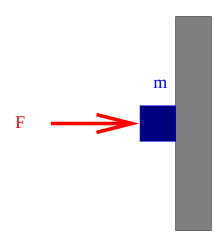
**1.** A projectile is fired from ground level on a broad level plain. The initial speed is $v_o$ and the projectile is fired at an angle $\theta$ with respect to the horizontal. Which of the following statements is INCORRECT? Neglect air resistance.

a) The horizontal component of the projectile's velocity is constant.
b) The distance it will fly depends on the angle $\theta$.
c) The speed of the projectile never exceeds $v_o$.
d) The acceleration of the projectile at the peak of its trajectory is zero.
e) The angle $\theta$ for which the time in the air is maximum is not the same as the angle $\theta$ for which the range is maximum.

**2.** Two identical balls, initially at rest, are thrown directly upward, ball A at speed $v$ and ball B at speed $2v$, and they feel no air resistance. Which statement about these balls is correct?

a) The balls will reach the same height
b) At their highest point, the acceleration of each ball is instantaneously equal to zero.
c) Ball B will go four times as high as ball A.
d) At its highest point, ball B will have twice as much gravitational potential energy as ball A.
e) Ball B will go twice as high as ball A.

**3.** A 0.50 kg block is pushed by a horizontal force against a vertical wall. The coefficient of static friction, $\mu_s$, between the block and the wall is 0.90. Which minimum horizontal force do you have to apply in order to prevent the block from sliding down the wall?




a) 4.9 N  b) 5.44 N  c) 4.41 N  d) 10.34 N  e) None of these

**4.** A ball of mass 500 g is dropped from a height of 9.2 m. If it is found to reach the ground with a final speed of 8.5 m/s, calculate the work done by the air resistance that it must have experienced on its descent.

a) 18 J  b) 45 J  c) 0 J  d) 27 J  e) 27,000 J

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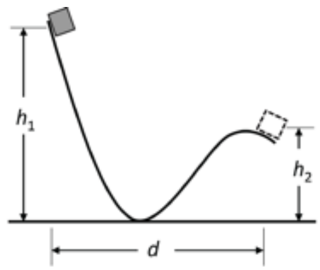
**5.** A block of mass m = 100 g slides down a frictionless track, as shown in the figure. The block has an initial height of 5 m and is initially at rest. What will be its speed when it reaches the end of the track where its height is 2 m and its horizontal displacement is 6 m?




a) 3.7 m/s   b) 6.3 m/s   c) 7.7 m/s   d) 9.9 m/s   e) 10.8 m/s

**6.** An object moving with an initial velocity $v_0$ on a rough horizontal surface, stops in a distance d due to the force of kinetic friction. The amount of work done by the force of kinetic friction to stop the object is equal to the:

a) initial velocity of the object
b) initial kinetic energy of the object
c) mass of the object times its acceleration
d) mass of the object times its initial velocity
e) square of the initial velocity of the object

**7.** A 300 g bat flying at 6.00 m/s swallows a 15 g insect that was heading straight toward it with a speed of 3.00 m/s. What is the bat's speed immediately after swallowing the insect?

a) 5.86 m/s   b) 5.71 m/s   c) 5.14 m/s   d) 5.57 m/s   e) 6.00 m/s

**8.** A satellite is in circular orbit around a spherical asteroid, at an altitude of 100 km above the surface, moving at a uniform speed of 80 m/s. If the asteroid has a radius of 321 km, what is the mass of the asteroid? (use $G = 6.67 \times 10^{-11}\,\mathrm{Nm^2/kg^2}$)

a) $4.04 \times 10^{19}$ kg   b) $3.08 \times 10^{19}$ kg   c) $9.60 \times 10^{18}$ kg   d) $4.04 \times 10^{16}$ kg   e) $9.60 \times 10^{15}$ kg

**9.** A rotating gas cloud with initial rotational (moment of) inertia $I_0$ and initial angular speed $\omega_o$ collapses under the influence of internal forces until its rotational (moment of) inertia is $I_0/3$. What is its final angular speed?

a) $\omega/3$   b) $3\omega$   c) $\omega_o/\sqrt{3}$   d) $\sqrt{3}\omega_o$   e) $\omega_o$

**10.** A harmonic wave travels in a wire with amplitude 6.00 mm, wavelength 120 cm, and period of $1.05 \times 10^{-2}$ s. What is the speed with which the wave travels?

a) 3.60 m/s   b) 114 m/s   c) 720 m/s   d) 11500 m/s   e) 72000 m/s

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**11.** In simple harmonic motion, the displacement is maximum when the:

a) acceleration is zero
b) force is at its positive maximum
c) velocity is zero
d) kinetic energy is maximum
e) kinetic energy equals the potential energy stored in the spring

**12.** A solid rock, suspended in air by a spring scale, has a measured mass of 9.00 kg. When the rock is completely submerged in water, the scale reads 3.30 kg. If the density of the water is 1000 kg/m$^3$, what is the density of the rock?

a) 2.73 x 10$^3$ kg/m$^3$ b) 1.00 x 10$^3$ kg/m$^3$ c) 0.732 x 10$^3$ kg/m$^3$
d) 1.58 x 10$^3$ kg/m$^3$ e) 9.00 x 10$^3$ kg/m$^3$

**13.** An ideal monatomic gas expands at a constant pressure of 10 kPa from 10 liters to 30 liters. If absorbs 500 J of heat during this process, what is its change in internal energy?

a) 200 J b) 300 J c) -200 kJ d) 500 J e) 700 J

**14.** If the fastest you can safely drive is 65 mi/h, what is the longest time you can stop for dinner if you must travel 541 mi in 9.6 h total?

a) 1.0 h b) 1.3 h c) 1.6 h d) You can't stop at all.

**15.** A car accelerates from 10.0 m/s to 30.0 m/s at a rate of 3.00 m/s$^2$. How far does the car travel while accelerating?

a) 80.0 m b) 399 m c) 226 m d) 133 m

**16.** A 480-kg car moving at 14.4 m/s hits from behind a 570-kg car moving at 13.3 m/s in the same direction. If the new speed of the heavier car is 14.0 m/s, what is the speed of the lighter car after the collision, assuming that any unbalanced forces on the system are negligibly small?

a) 5.24 m/s b) 19.9 m/s c) 13.6 m/s d) 10.5 m/s

**17.** Jacques and George meet in the middle of a lake while paddling in their canoes. They come to a complete stop and talk for a while. When they are ready to leave, Jacques pushes George's canoe with a force $\vec{F}$ to separate the two canoes. What is correct to say about the final momentum and kinetic energy of the system if we can neglect any resistance due to the water?

a) The final momentum is zero and the final kinetic energy is zero.
b) The final momentum is in the direction of F and the final kinetic energy is positive.
c) The final momentum is in the direction opposite of F but the final kinetic energy is zero.
d) The final momentum is in the direction of F but the final kinetic energy is zero.
e) The final momentum is zero but the final kinetic energy is positive.

**18.** A 2000-kg truck is sitting at rest (in neutral) when it is rear-ended by a 1000-kg car going 26 m/s .

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After the collision, the two vehicles stick together. What is the final velocity of the combined mass after the collision?

a) 2.9 m/s  b) 15 m/s  c) 13 m/s  d) 8.7 m/s  e) 26 m/s

**19.** A 1.00-kg particle that moves with potential energy given by $U(x) = (-2.00\,\mathrm{J}\cdot\mathrm{m})/x + (4.00\,\mathrm{J}\cdot\mathrm{m}^2)/x^2$. Suppose the particle is moving with a speed of 3.00 m/s when it is located at x = 1.00 m. What is the speed of the object when it is located at x = 5.00 m?

a) 4.68 m/s  b) 3.67 m/s  c) 3.00 m/s  d) 2.13 m/s

**20.** An object attached to an ideal massless spring is pulled across a frictionless surface. If the spring constant is 45 N/m and the spring is stretched by 0.88 m when the object is accelerating at 2.0 m/s$^2$, what is the mass of the object?

a) 22 kg  b) 20 kg  c) 17 kg  d) 26 kg

**21.** At the end of a delivery ramp, a skid pad exerts a constant force on a package so that the package comes to rest in a distance d. When the pad is replaced by one that requires a distance of 7d to stop the same package, what happens to the length of time it takes for the package to stop?

a) decreases by a factor of 7  b) increases by a factor of 7
c) increases by a factor of $\sqrt{7}$  d) decreases by a factor of $\sqrt{7}$

**22.** What is the maximum distance we can shoot a dart, from ground level, provided our toy dart gun gives a maximum initial velocity of 2.78 m/s and air resistance is negligible?

a) 0.789 m  b) 0.394 m  c) 1.39 m  d) 1.58 m

**23.** A uniform solid cylinder of radius R and a thin uniform spherical shell of radius R both roll without slipping. If both objects have the same mass and the same kinetic energy, what is the ratio of the linear speed of the cylinder to the linear speed of the spherical shell?

a) $\frac{4}{3}$  b) $\sqrt{\frac{4}{3}}$  c) $\frac{4}{\sqrt{3}}$  d) $\frac{\sqrt{3}}{2}$  e) $\frac{\sqrt{10}}{3}$

**24.** A 0.25 kg ideal harmonic oscillator has a total mechanical energy of 4.0 J. If the oscillation amplitude is 20.0 cm, what is the oscillation frequency?

a) 3.2 Hz  b) 2.3 Hz  c) 1.4 Hz  d) 4.5 Hz

**25.** A heavy stone of mass m is hung from the ceiling by a thin 8.25-g wire that is 65.0 cm long. When you gently pluck the upper end of the wire, a pulse travels down the wire and returns 7.84 ms later, having reflected off the lower end. The stone is heavy enough to prevent the lower end of the wire from moving. What is the mass m of the stone?

a) 23.1 kg  b) 349 kg  c) 35.6 kg  d) 8.90 kg  e) 227 kg

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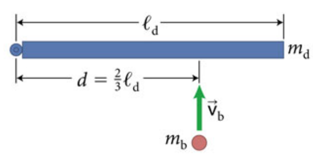
**26.** A 12,000-N car is raised using a hydraulic lift, which consists of a U-tube with arms of unequal areas, filled with incompressible oil and capped at both ends with tight-fitting pistons. The wider arm of the U-tube has a radius of 18.0 cm and the narrower arm has a radius of 5.00 cm. The car rests on the piston on the wider arm of the U-tube. The pistons are initially at the same level. What is the initial force that must be applied to the smaller piston in order to start lifting the car? (For purposes of this problem, you can neglect the weight of the pistons.)

a) 3330 N b) 2900 N c) 926 N d) 1.20 kN e) 727 N

**27.** An open door of inertia $m_d$ and width $l_d$ is at rest when it is struck by a thrown ball of clay of inertia $m_b$ that is moving at speed $v_b$ at the instant it strikes the door (see figure below). The impact location is a distance $d = \frac{2}{3} l_d$ from the rotation axis through the hinges. The clay ball strikes perpendicular to the door face and sticks after it hits. What is the angular velocity of the system about the hinges after the impact? Do not ignore the inertia $m_b$.

a) $\omega = \frac{4 m_b v_b}{(m_b + 2 m_d) l_d}$ b) $\omega = \frac{6 m_b v_b}{(4 m_b + 3 m_d) l_d}$ c) $\omega = \frac{3 m_b v_b}{(2 m_b + m_d) l_d}$ d) $\omega = \frac{12 m_b v_b}{(8 m_b + 3 m_d) l_d}$



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# Formula sheet

$$g = 9.81\,\mathrm{m/s^2} \quad G = 6.67\times10^{-11}\,\mathrm{N\,m^2/kg^2}$$

$$N_A = 6.022\times10^{23}\,\text{things/mol} \qquad 1\,\mathrm{L} = 10^{-3}\,\mathrm{m^3}$$

$$k_B = 1.38065\times10^{-23}\,\mathrm{J\cdot K^{-1}} = 8.6173\times10^{-5}\,\mathrm{eV\cdot K^{-1}}$$

$$\text{sphere} \quad V = \frac{4}{3}\pi r^3 \quad A = 4\pi r^2$$

$$ax^2 + bx^2 + c = 0 \Longrightarrow x = \frac{-b\pm\sqrt{b^2-4ac}}{2a}$$

$$\sin\alpha \pm \sin\beta = 2\sin\frac{1}{2}(\alpha\pm\beta)\cos\frac{1}{2}(\alpha\mp\beta)$$

$$\cos\alpha \pm \cos\beta = 2\cos\frac{1}{2}(\alpha+\beta)\cos\frac{1}{2}(\alpha-\beta)$$

$$c^2 = a^2 + b^2 - 2ab\cos\theta_{ab}$$

$$\frac{d}{dx}\sin ax = a\cos ax \qquad \frac{d}{dx}\cos ax = -a\sin ax$$

$$\int\cos ax\,\mathrm{dx} = \frac{1}{a}\sin ax \qquad \int\sin ax\,\mathrm{dx} = -\frac{1}{a}\cos ax$$

$$\sin\theta\approx\theta \qquad \cos\theta\approx 1-\frac{1}{2}\theta^2 \qquad \text{small } \theta$$

$$\vec{\mathbf{v}} = \lim_{\Delta t\to0}\frac{\Delta\vec{\mathbf{r}}}{\Delta t} \equiv \frac{d\vec{\mathbf{r}}}{dt}$$

$$a_x = \lim_{\Delta t\to0}\frac{\Delta v_x}{\Delta t} \equiv \frac{dv_x}{dt} = \frac{d}{dt}\left(\frac{dx}{dt}\right) = \frac{d^2x}{dt^2}$$

$$\Delta v_x = \int_{t_i}^{t_f} a_x(t)\,dt \qquad \Delta x = \int_{t_i}^{t_f} v_x(t)\,dt$$

$$x(t) = x_i + v_{x,i}t + \frac{1}{2}a_x t^2$$

$$v_x(t) = v_{x,i} + a_x t$$

$$v_{x,f}^2 = v_{x,i}^2 + 2a_x\Delta x$$

$$a_{x,\text{ramp}} = g\sin\theta$$

$$\Delta U^G = mg\Delta x \qquad \frac{a_{1x}}{a_{2x}} = -\frac{m_2}{m_1}$$

$$E_{\text{mech}} = K + U \quad K = \frac{1}{2}mv^2$$

$$\Delta E = \Delta K + \Delta U = 0 \quad \text{non-dissipative, closed}$$

$$\Delta E = W \qquad P = \frac{dE}{dt}$$

$$\Delta U_{\text{spring}} = \frac{1}{2}k\,(x-x_o)^2$$

$$P = F_{\text{ext,x}}\,v_x \quad \text{one dimension}$$

$$W = \left(\sum\vec{\mathbf{F}}\right)\Delta x_F \quad \text{constant force 1D}$$

$$W = \int_{x_i}^{x_f} F_x(x)\,dx \quad \text{nondiss. force, 1D}$$

$$\Delta\vec{\mathbf{p}} = \vec{\mathbf{0}} \quad \text{isolated system}$$

$$\vec{\mathbf{p}}_f = \vec{\mathbf{p}}_i \quad \text{isolated system}$$

$$\vec{\mathbf{p}} \equiv m\vec{\mathbf{v}}$$

$$m_u = -\frac{\Delta v_{s,x}}{\Delta v_{u,x}}m_s$$

$$\vec{\mathbf{J}} = \Delta\vec{\mathbf{p}}$$

$$v_{1f} = \left(\frac{m_1-m_2}{m_1+m_2}\right)v_{i1} + \left(\frac{2m_2}{m_1+m_2}\right)v_{2i} \quad \text{1D elastic}$$

$$v_{2f} = \left(\frac{2m_1}{m_1+m_2}\right)v_{1i} + \left(\frac{m_2-m_1}{m_1+m_2}\right)v_{2i} \quad \text{1D elastic}$$

$$\Delta E = 0 \quad \text{isolated system}$$

$$K = \frac{1}{2}mv^2$$

$$\vec{v}_{12} = \vec{\mathbf{v}}_2 - \vec{\mathbf{v}}_1 \quad \text{relative velocity}$$

$$\vec{\mathbf{a}} = \frac{\sum\vec{\mathbf{F}}}{m} \qquad \vec{\mathbf{a_{cm}}} = \frac{\sum\vec{\mathbf{F}}_{\text{ext}}}{m} \qquad \sum\vec{\mathbf{F}} \equiv \frac{d\vec{\mathbf{p}}}{dt}$$

$$\vec{\mathbf{J}} = \left(\sum\vec{\mathbf{F}}\right)\Delta t \quad \text{constant force}$$

$$\vec{\mathbf{J}} = \int_{t_i}^{t_f}\sum\vec{\mathbf{F}}(t)\,dt \quad \text{time-varying force}$$

$$\vec{\mathbf{F}}_{12} = -\vec{\mathbf{F}}_{21} \qquad F_{\text{grav}} = -mg \qquad F_{\text{spring}} = -k\Delta x$$

**Rotation: we use radians**

$$s = \theta r \quad \leftarrow \text{arclength}$$

$$\omega = \frac{d\theta}{dt} = \frac{v_t}{r} \qquad \alpha = \frac{d\omega}{dt}$$

$$a_t = \alpha r \quad \text{tangential} \qquad a_r = -\frac{v^2}{r} = -\omega^2 r \quad \text{radial}$$

$$v_t = r\omega \qquad v_r = 0 \qquad \omega_f^2 = \omega_i^2 + 2\alpha\Delta\theta$$

$$\left(F_{12}^s\right)_{\max} = \mu_s F_{12}^n$$

$$F_{12}^k = \mu_k F_{12}^n$$

$$W = \vec{\mathbf{F}}\cdot\Delta\vec{\mathbf{r}}_F \quad \text{const non-diss force}$$

$$W = \int_{\vec{\mathbf{r}}_i}^{\vec{\mathbf{r}}_f}\vec{\mathbf{F}}(\vec{\mathbf{r}})\cdot d\vec{\mathbf{r}} \quad \text{variable nondiss force}$$

$\downarrow$ launched from origin, level ground

$$y(x) = (\tan\theta_o)\,x - \frac{gx^2}{2v_o^2\cos^2\theta_o}$$

$$\text{max height } = H = \frac{v_i^2\sin^2\theta_i}{2g}$$

$$\text{Range } = R = \frac{v_i^2\sin 2\theta_i}{g}$$

$$(F_{12}^2)_{\max} = \mu_s F_{12}^n \qquad F_{12}^k = \mu_k F_{12}^n$$

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**fluids:**

$$P = F/A \qquad P(d) = P_{\text{surface}} + \rho g d$$

$$\frac{F_1}{A_1} = \frac{F_2}{A_2} \quad F_1 x_1 = F_2 x_2 \qquad \text{hydraulics}$$

$$B = \text{buoyant force} = \text{weight of water displaced} = \rho_f V_{\text{displ}} g$$

$$P = P_{\text{gauge}} + P_{\text{atm}} \qquad \rho = M/V$$

$$I = \sum_i m_i r_i^2 \Rightarrow \int r^2\, dm = kmr^2 \qquad I = mr^2 \quad \text{point particle}$$

$$I_z = I_{com} + md^2 \quad \text{axis } z \text{ parallel, dist } d$$

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

$$K = \frac{1}{2}I\omega^2 = L^2/2I$$

$$\Delta K = \frac{1}{2}I\omega_f^2 - \frac{1}{2}I\omega_i^2 = W = \int \tau\, d\theta$$

$$P = \frac{dW}{dt} = \tau\omega$$

$$\tau = rF\sin\theta_{rF} = r_\perp F = rF_\perp$$

$$\tau_{net} = \sum \vec{\boldsymbol{\tau}} = I\vec{\boldsymbol{\alpha}} = \frac{d\vec{\mathbf{L}}}{dt}$$

$$K_{\text{tot}} = K_{cm} + K_{rot} = \frac{1}{2}mv_{cm}^2 + \frac{1}{2}I\omega^2$$

**Oscillations:**

$$T = \frac{1}{f} = \frac{2\pi}{\omega} \quad \omega = \frac{2\pi}{T} = 2\pi f \quad k = \frac{2\pi}{\lambda}$$

$$x(t) = A\sin(\omega t + \varphi_i)$$

$$v(t) = \frac{dx}{dt} = \omega A\cos(\omega t + \varphi_i)$$

$$a(t) = \frac{d^2x}{dt^2} = -\omega^2 A\sin(\omega t + \varphi_i)$$

$$\varphi(t) = \omega t + \varphi_i$$

$$a = -\omega^2 x = \frac{d^2x}{dt^2} \qquad \frac{d^2\theta}{dt^2} = -\omega^2\theta$$

$$E = \frac{1}{2}m\omega^2 A^2 \quad F_{\text{spring}} = -kx$$

$$\omega = \sqrt{k/m} \quad \text{spring.}$$

$$T = \begin{cases} 2\pi\sqrt{L/g} & \text{simple pendulum} \\ 2\pi\sqrt{I/mgl_{cm}} & \text{physical pendulum} \end{cases}$$

**Gravitation**

$$F_{12}^G = G\frac{m_1 m_2}{r_{12}^2} \quad G = 6.67 \times 10^{-11}\,\text{N m}^2/\text{kg}^2$$

$$U^G(r) = -G\frac{m_1 m_2}{r_{12}}$$

$$E_{\text{mech}} = \frac{1}{2}mv^2 - G\frac{m_1 m_2}{r_{12}} \begin{cases} < 0 & \text{bound; ellipse} \\ = 0 & \text{parabola} \\ > 0 & \text{hyperbola} \end{cases}$$

**Waves:**

$$y = f(x - ct) \quad \text{along +x} \qquad y = f(x + ct) \quad \text{along -x}$$

$$k = \frac{2\pi}{\lambda} \quad \lambda = cT \quad \omega = \frac{2\pi}{T} \quad c = \lambda f$$

$$y(x,t) = f(x,t) = A\sin(kx - \omega t + \varphi_i)$$

$$y(x,t) = 2A\sin kx\cos\omega t \quad \text{standing wave}$$

$$\text{nodes at } x = 0, \pm\frac{\lambda}{2}, \pm\lambda, \pm\frac{3\lambda}{2}$$

$$v = \sqrt{T/\mu} \quad \mu = M_{\text{string}}/L_{\text{string}} \quad T = \text{tension} \qquad \text{strings}$$

$$P_{\text{av}} = \frac{1}{2}\mu\lambda A^2\omega^2/T = \frac{1}{2}\mu A^2\omega^2 c$$

$$\frac{\partial^2 f}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2 f}{\partial t^2}$$

$$f_n = \frac{nv}{\lambda} = \frac{nv}{2L} \quad \lambda_n = \frac{2L}{n} \quad n = 1, 2, 3\ldots \qquad \text{strings \& open-open pipe}$$

$$f_n = \frac{nv}{\lambda} = \frac{nv}{4L} \quad \lambda_n = \frac{4L}{n} \quad n = 1, 3, 5\ldots \qquad \text{closed-open pipe}$$

**thermal stuff:**

$$PV = Nk_BT = nRT$$

$$W = P\Delta V$$

$$T(K) = T(^\circ C) + 273.15^\circ$$

$$Q = mc\Delta t \quad c = \text{specific heat} \qquad \text{no phase chg}$$

$$Q = \pm mL \qquad \text{phase chg}$$

**Isolated systems:** $\vec{\mathbf{p}}$, $E = K + PE$, $L$ are all conserved.
**Static equilibrium:** $\sum F = 0$ and $\sum \tau = 0$ about any axis.
**Elastic collision:** KE and $p$ are both conserved.
**Inelastic collision:** only $p$ is conserved, not KE.

| **Derived unit** | **Symbol** | **equivalent to** |
|---|---|---|
| newton | N | $\text{kg}\cdot\text{m/s}^2$ |
| joule | J | $\text{kg}\cdot\text{m}^2/\text{s}^2 = \text{N}\cdot\text{m}$ |
| watt | W | $\text{J/s} = \text{m}^2\cdot\text{kg/s}^3$ |

| **Power** | **Prefix** | **Abbreviation** |
|---|---|---|
| $10^{-6}$ | micro | µ |
| $10^{-3}$ | milli | m |
| $10^{-2}$ | centi | c |
| $10^{3}$ | kilo | k |
| $10^{6}$ | mega | M |

Moments of inertia of things of mass $M$

| **Object** | axis | **dimension** | **I** |
|---|---|---|---|
| solid sphere | central axis | radius $R$ | $\frac{2}{5}MR^2$ |
| hollow sphere | central axis | radius $R$ | $\frac{2}{3}MR^2$ |
| solid disc/cylinder | central axis | radius $R$ | $\frac{1}{2}MR^2$ |
| hoop/pipe | central axis | radius $R$ | $MR^2$ |
| point particle | pivot point | distance $R$ to pivot | $MR^2$ |
| rod | center | length $L$ | $\frac{1}{12}ML^2$ |
| rod | end | length $L$ | $\frac{1}{3}ML^2$ |

Thermodynamic processes

| **Process** | **const** | $W$ | $Q$ | $\Delta E_{\text{th}}$ | ideal gas $E$ law |
|---|---|---|---|---|---|
| isochoric | $V$ | 0 | $NC_V\Delta T$ | | $\Delta E_{\text{th}} = Q$ |
| isobaric | $P$ | $-Nk_B\Delta T$ | $NC_P\Delta T$ | $NC_V\Delta T$ | $\Delta E_{\text{th}} = W + Q$ |
| isothermal | $T$ | $-Nk_BT\ln\left(\frac{V_f}{V_i}\right)$ | | 0 | $Q = -W$ |