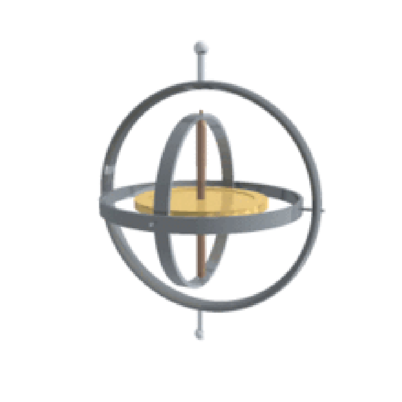
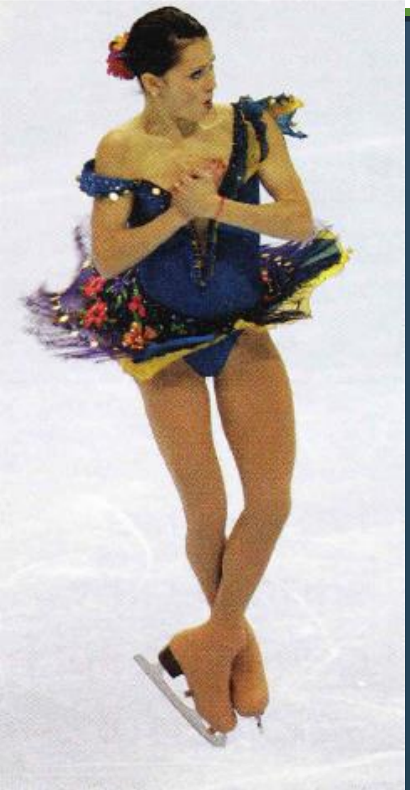


Chapter 10

Rotation 轉動



10-1 Rotational Varibles

Learning Objectives

10.01 Identify that if all parts of a body rotate around a fixed axis locked together, the body is a rigid body.

10.02 Identify that the angular position of a rotating rigid body is the angle that an internal reference line makes with a fixed, external reference line.

10.03 Apply the relationship between angular displacement and the initial and final angular positions.

10.04 Apply the relationship between average angular velocity, angular displacement, and the time interval for that displacement.

10.05 Apply the relationship between average angular acceleration, change in angular velocity, and the time interval for that change. (more …)

10-1 Rotational Variables

- We now look at motion of **rotation**
- We will find the same laws apply
- But we will need new quantities to express them
  - Torque τ ←→ F
  - Rotational inertia I ←→ m
- A **rigid body** (剛體) rotates as a unit, locked together(每一點之角速度'、角加速度均相同)
- We look at rotation about a **fixed axis (有一固定轉動軸)**
- These requirements exclude from consideration:
  - The Sun, where layers of gas rotate separately
  - A rolling bowling ball, where rotation and translation occur (CH11)

10-1 Rotational Variables

- The fixed axis is called the **axis of rotation**
- Figs 10-2, 10-3 show a *reference line*
- The **angular position** of this line (and of the object) is taken relative to a fixed direction, the **zero angular position**

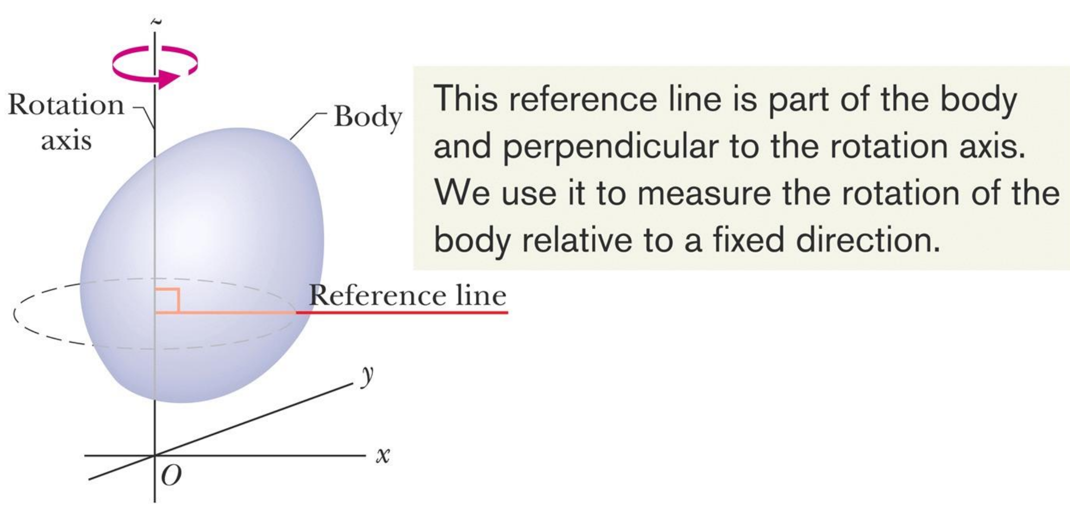


Figure 10-2

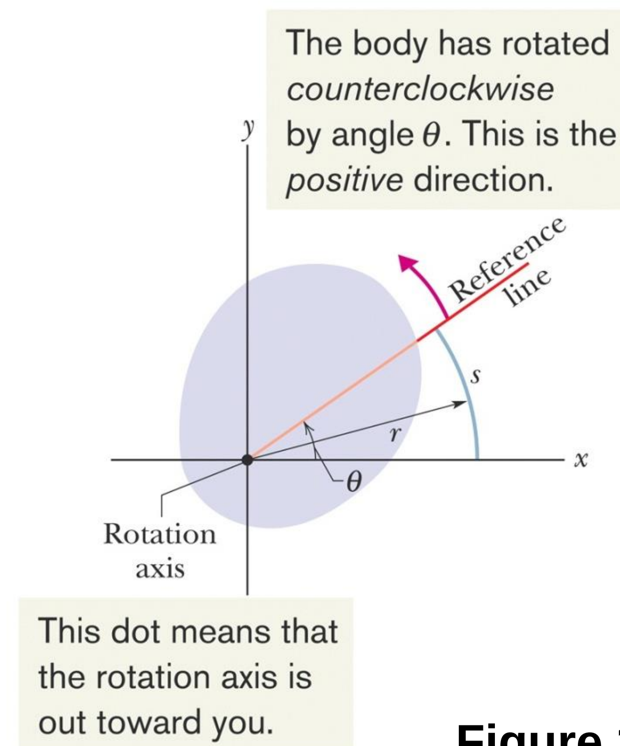


Figure 10-3

10-1 Rotational Variables

Measure using **radians** (徑度量rad): dimensionless

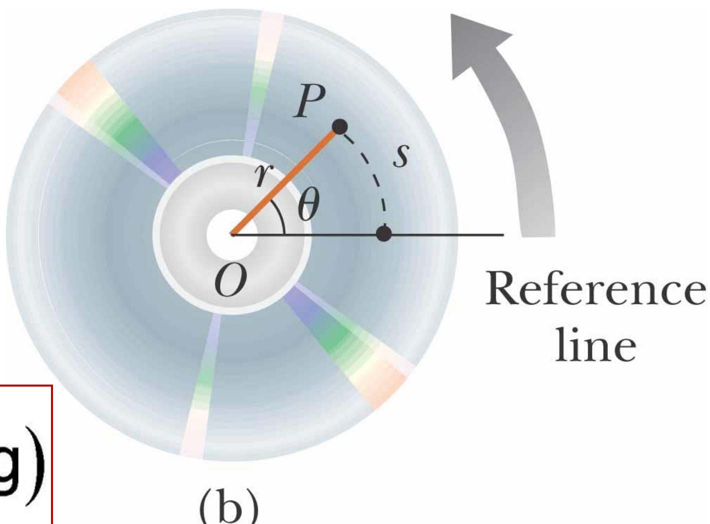
$$\theta = \frac{s}{r}$$ **Eq. (10-1)**

$$\boxed{1 \text{ rev} = 360^\circ = \frac{2\pi r}{r} = 2\pi \text{ rad},}$$ (rpm: rev per minute) **Eq. (10-2)**

Do not reset θ to zero after a full rotation

- We know all there is to know about the kinematics of rotation if we have $\theta(t)$ for an object
- Define angular displacement as:

$$\boxed{\Delta\theta = \theta_2 - \theta_1.}$$ **Eq. (10-4)**



(b)

$$\boxed{1\,\text{rad} = \frac{360^\circ}{2\pi\,\text{rad}} \approx 57.3^\circ}$$

$$\boxed{\theta\,(\text{rad}) = \frac{\pi}{180^\circ}\,\theta\,(\text{deg})}$$

10-1 Rotational Variables

- **Average angular velocity(角速度)**: angular displacement during a time interval

  SI unit: rad/s

$$\omega_{avg} = \frac{\theta_2 - \theta_1}{t_2 - t_1} = \frac{\Delta\theta}{\Delta t}, \qquad \text{Eq. (10-5)}$$

- **Instantaneous angular velocity**: limit as $\Delta t \rightarrow 0$

$$\boxed{\omega = \lim_{\Delta t \to 0} \frac{\Delta\theta}{\Delta t} = \frac{d\theta}{dt}.} \qquad \text{Eq. (10-6)}$$

- If the body is rigid, these equations hold for all points on the body**(剛體:**每一點之角速度' 均相同**)**
- Magnitude of angular velocity = **angular speed**

10-1 Rotational Variables

- Figure 10-4 shows the values for a calculation of average angular velocity

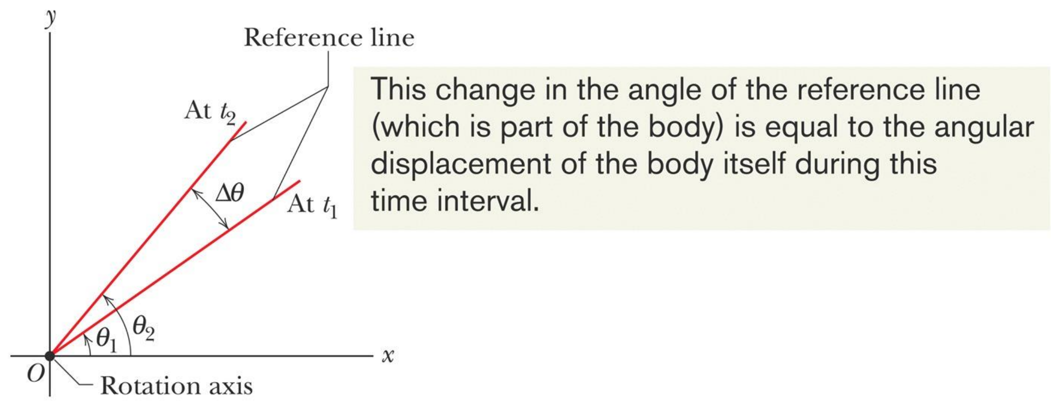


Figure 10-4

~Rotation is counterclockwise (CCW): $\omega > 0$, is clockwise (CW): $\omega < 0$.

- **Average angular acceleration**: angular velocity change during a time interval

$$\alpha_{avg} = \frac{\omega_2 - \omega_1}{t_2 - t_1} = \frac{\Delta\omega}{\Delta t}, \qquad \textbf{Eq. (10-7)}$$

10-1 Rotational Variables

- **Instantaneous angular velocity**: limit as $\Delta t \to 0$

$$\alpha = \lim_{\Delta t \to 0} \frac{\Delta \omega}{\Delta t} = \frac{d\omega}{dt}. \qquad \text{Eq. (10-8)}$$

- If the body is rigid, these equations hold for all points on the body(剛體:每一點之角加速度’ 均相同)
- With right-hand rule to determine direction (右手螺旋定則定之!,) angular velocity & acceleration can be written as vectors

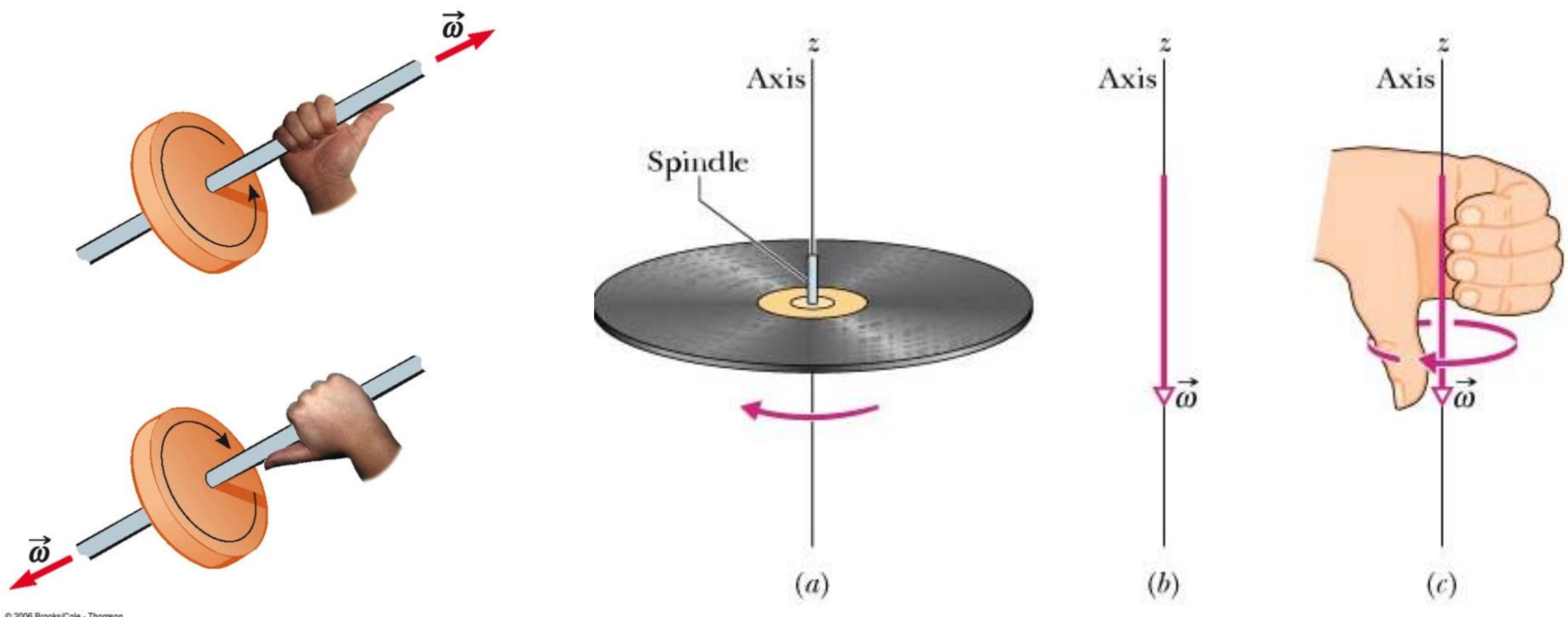


Figure 10-6

Angular displacement *cannot* be treated as a vector! ~ depends on it's rotating order!

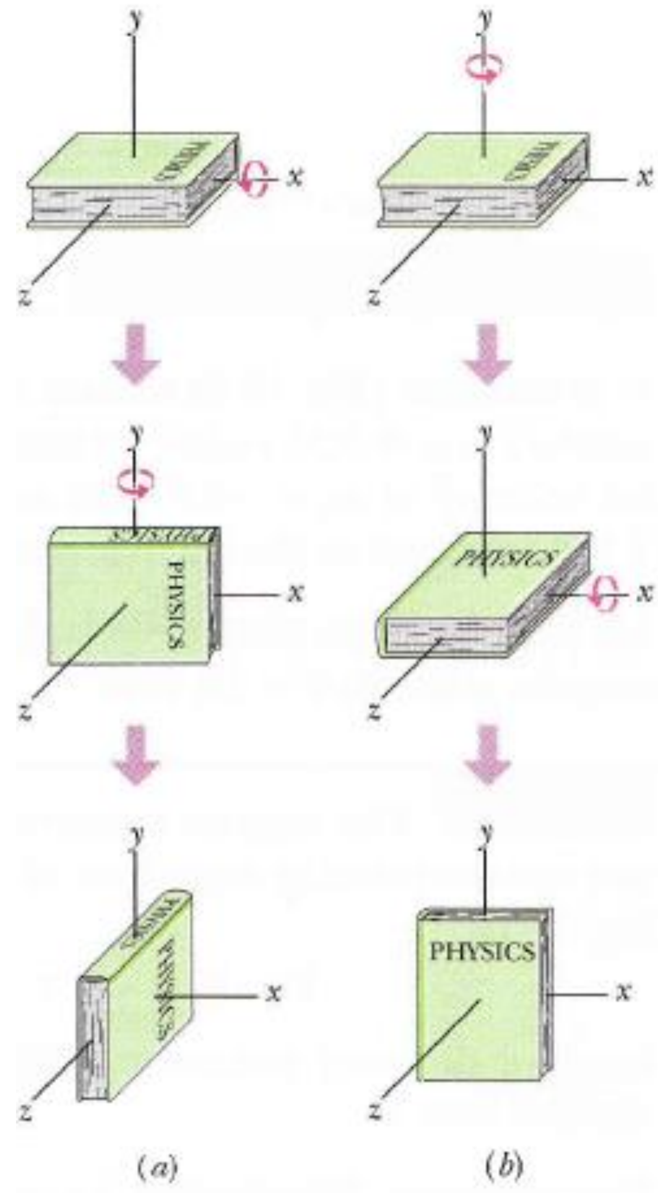


FIG. 10-7 (*a*) From its initial position, at the top, the book is given two successive 90° rotations, first about the (horizontal) x axis and then about the (vertical) y axis. (*b*) The book is given the same rotations, but in the reverse order.

10-2 Rotation with Constant Angular Acceleration

Learning Objectives

10.14 For constant angular acceleration, apply the relationships between angular position, angular displacement, angular velocity, angular acceleration, and elapsed time (Table 10-1).

Table 10-1 Equations of Motion for Constant Linear Acceleration and for Constant Angular Acceleration

Equation Number	Linear Equation	Missing Variable		Angular Equation	Equation Number
(2-11)	$v = v_0 + at$	$x - x_0$	$\theta - \theta_0$	$\omega = \omega_0 + \alpha t$	(10-12)
(2-15)	$x - x_0 = v_0 t + \frac{1}{2}at^2$	v	ω	$\theta - \theta_0 = \omega_0 t + \frac{1}{2}\alpha t^2$	(10-13)
(2-16)	$v^2 = v_0^2 + 2a(x - x_0)$	t	t	$\omega^2 = \omega_0^2 + 2\alpha(\theta - \theta_0)$	(10-14)
(2-17)	$x - x_0 = \frac{1}{2}(v_0 + v)t$	a	α	$\theta - \theta_0 = \frac{1}{2}(\omega_0 + \omega)t$	(10-15)
(2-18)	$x - x_0 = vt - \frac{1}{2}at^2$	v_0	ω_0	$\theta - \theta_0 = \omega t - \frac{1}{2}\alpha t^2$	(10-16)

Table 10-1

10-2 Rotation with Constant Angular Acceleration

Equations of Rotational Kinematics (轉動力學):

Translational Motion		Rotational Motion	
x	$\leftrightarrow$	θ	
v	$\leftrightarrow$	ω	
a	$\leftrightarrow$	α	
$v = v_0 + at$	$\leftrightarrow$	$\omega = \omega_0 + \alpha t$	(eqs.1)
$x = x_o + v_o t + \frac{at^2}{2}$	$\leftrightarrow$	$\theta = \theta + \omega_o t + \frac{\alpha t^2}{2}$	(eqs.2)
$v^2 - v_o^2 = 2a(x - x_o)$	$\leftrightarrow$	$\omega^2 - \omega_o^2 = 2\alpha(\theta - \theta_o)$	(eqs.3)

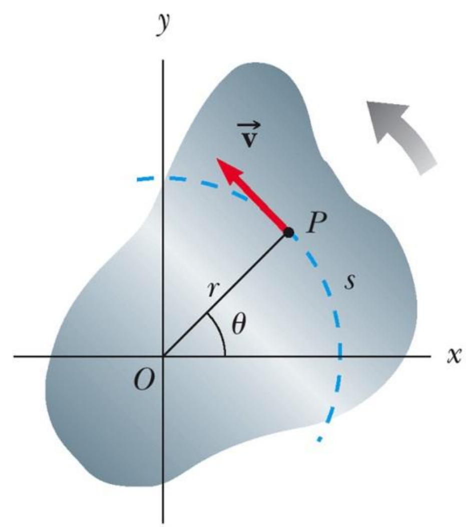
10-3 Relating the Linear and Angular Variables

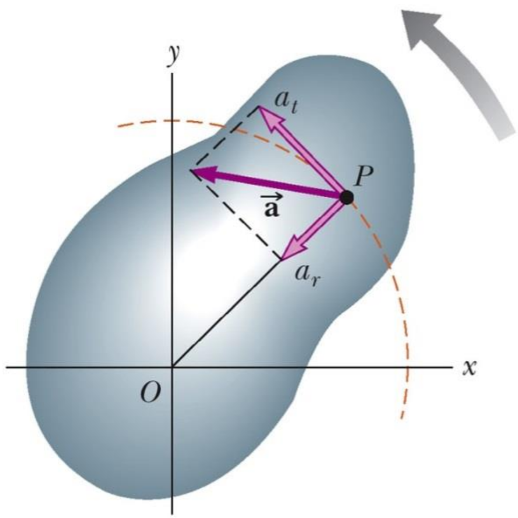
Learning Objectives

10.15 For a rigid body rotating about a fixed axis, relate the angular variables of the body (angular position, angular velocity, and angular acceleration) and the linear variables of a particle on the body (position, velocity, and acceleration) at any given radius.

10.16 Distinguish between tangential acceleration and radial acceleration, and draw a vector for each in a sketch of a particle on a body rotating about an axis, for both an increase in angular speed and a decrease.

- 角度變量與線性移動變量之比較: 兩者差一 “長度”之單位!





§10-3 Relating the Linear and Angular Variables

Relation between angular velocity and speed

The arc length s and the angle θ are connected by the equation:

$s = r\theta$ where r is the distance OP. The speed of point P $v = \frac{ds}{dt} = \frac{d(r\theta)}{dt} = r\frac{d\theta}{dt}$

$$\boxed{v = r\omega} \qquad \boxed{\omega = 2\pi f} \qquad (10\text{-}18)$$

The period T of revolution is given by: $T = \frac{\text{circumference}}{\text{speed}} = \frac{2\pi r}{v} = \frac{2\pi r}{\omega r} = \frac{2\pi}{\omega}$

$$\boxed{T = \frac{2\pi}{\omega}} \qquad \boxed{T = \frac{1}{f}} \qquad (10\text{-}20)$$

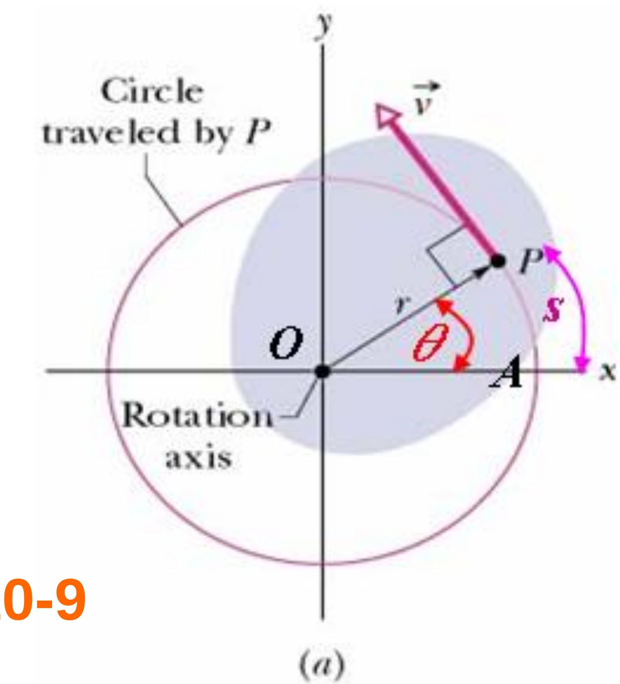


Figure 10-9

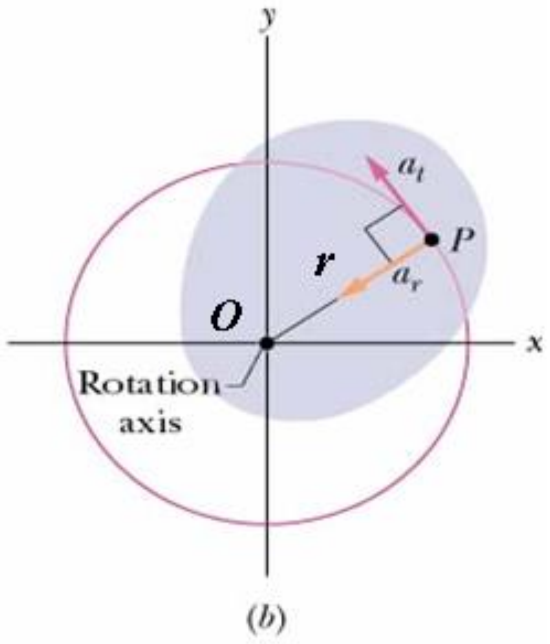


Figure 10-9

The Acceleration

The acceleration of point ***P*** is a vector that has two components. **A** "radial" componet along the radius and pointing towards point ***O***. We have encountered this component in chapter 4 where we called it "centripetal" acceleration. Its magnitude is:

$$\boxed{a_r = \frac{v^2}{r} = \omega^2 r} \qquad (10\text{-}23)$$

The second component is along the tangent to the circular path of ***P*** and is thus known as the "tangential" component. Its magnitude is:

$$a_t = \frac{dv}{dt} = \frac{d(\omega r)}{dt} = r\frac{d\omega}{dt} = r\alpha \qquad \boxed{a_t = r\alpha} \qquad (10\text{-}22)$$

The magnitude of the acceleration vector is: $\boxed{a = \sqrt{a_t^2 + a_r^2}}$

物體(剛體)每一點之角速度、角加速度均相同。

10-4 Kinetic Energy of Rotation轉動動能

Learning Objectives

10.17 Find the rotational inertia of a particle about a point.

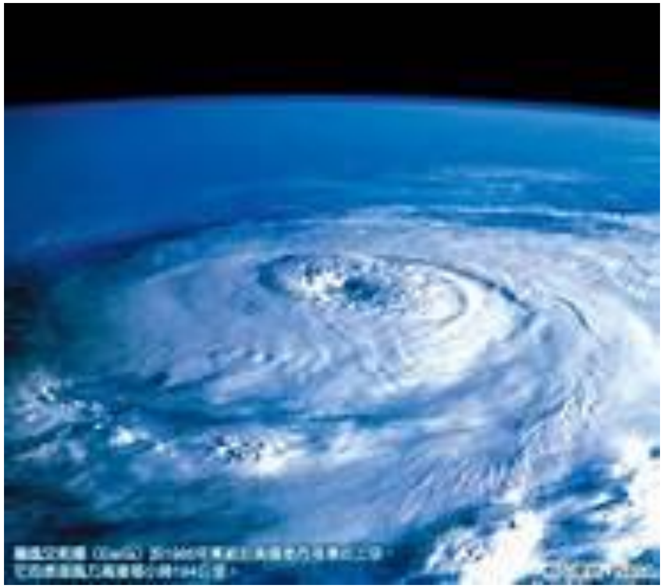
10.18 Find the total rotational inertia of many particles moving around the same fixed axis.

10.19 Calculate the rotational kinetic energy of a body in terms of its rotational inertia and its angular speed.

(六)颱風之結構：~轉動動能 =?

颱風範圍很大，普通半徑有200~300公里，在天氣圖上，我們僅能用密集近似圓形等壓線來表示颱風的位置和暴風範圍。從氣象衛星所攝照片可以看出颱風的頂部是大致圓形呈螺旋狀旋轉著的雲，颱風內的風向在北半球是繞颱風中心作反時針方向旋轉（在南半球則繞中心作順時針方向旋轉）。在颱風內部，過去由氣象偵察飛機從各種不同的高度、不同的方向，飛進颱風內部觀測的結果，得知颱風大致為一半徑甚大的雲柱，自頂端至地面的高度不等，曾觀測到有18,000餘公尺之高，這龐大的雲柱中央無雲或雲層很薄，沒有風雨現象，這就是颱風眼。從颱風眼向外，離開颱風眼不遠處，雲層最厚而風雨亦最大，再向外風雨漸弱

https://www.cwb.gov.tw/V7/knowledge/encyclopedia/me_all.htm



10-4 Kinetic Energy of Rotation

$$K = \sum \tfrac{1}{2} m_i (\omega r_i)^2 = \tfrac{1}{2}\left(\sum m_i r_i^2\right)\omega^2,$$ **Eq. (10-32)**

$K = \sum_i \frac{1}{2} m_i v_i^2$ The speed of the i-th element $v_i = \omega r_i \rightarrow K = \sum_i \frac{1}{2} m_i \left(\omega r_i\right)^2$

$\boxed{K = \frac{1}{2}\left(\sum_i m_i r_i^2\right)\omega^2 = \frac{1}{2} I\omega^2}$ The term $\boxed{I = \sum_i m_i r_i^2}$ is known as rotational inertia or moment of inertia about the axis of rotation. The axis of rotation must be specified because the value of I for a rigid body depends on its mass, its shape as well as on the position of the rotation axis. The rotational inertia of an object describes how the mass is distributed about the rotation axis

Moment of Inertia轉動慣量: The dimensions of moment of inertia are ML^2 and its SI units are $kg.m^2$

10-4 Kinetic Energy of Rotation

- We can write:

$$\boxed{I=\sum_i m_i r_i^2} \quad \text{or} \quad \boxed{I=\int r^2\,dm}$$

Eq. (10-33)

- And rewrite the kinetic energy as:

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

Eq. (10-34)

- Use these equations for a finite set of rotating particles
- Rotational inertia corresponds to how difficult it is to change the state of rotation (speed up, slow down or change the axis of rotation)

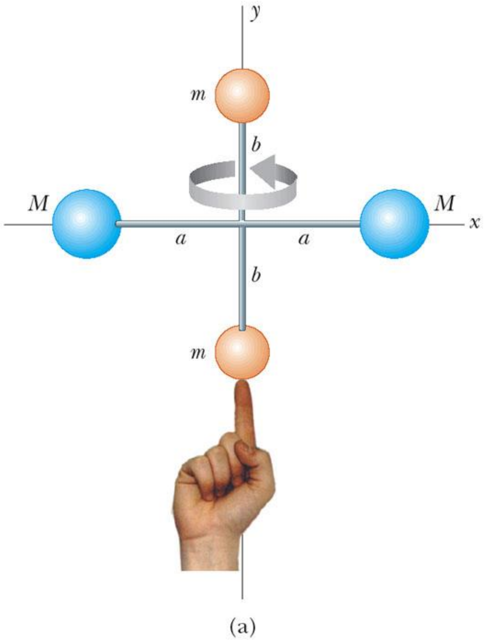
10-5 Calculating the Rotational Inertia

Learning Objectives

10.20 Determine the rotational inertia of a body if it is given in Table 10-2.

10.21 Calculate the rotational inertia of body by integration over the mass elements of the body.

10.22 Apply the parallel-axis theorem for a rotation axis that is displaced from a parallel axis through the center of mass of a body.



10-5 Calculating the Rotational Inertia

- Integrating Eq. 10-33 over a continuous body:

$$\boxed{I = \int r^2\, dm \qquad \text{(rotational inertia, continuous body).}}$$

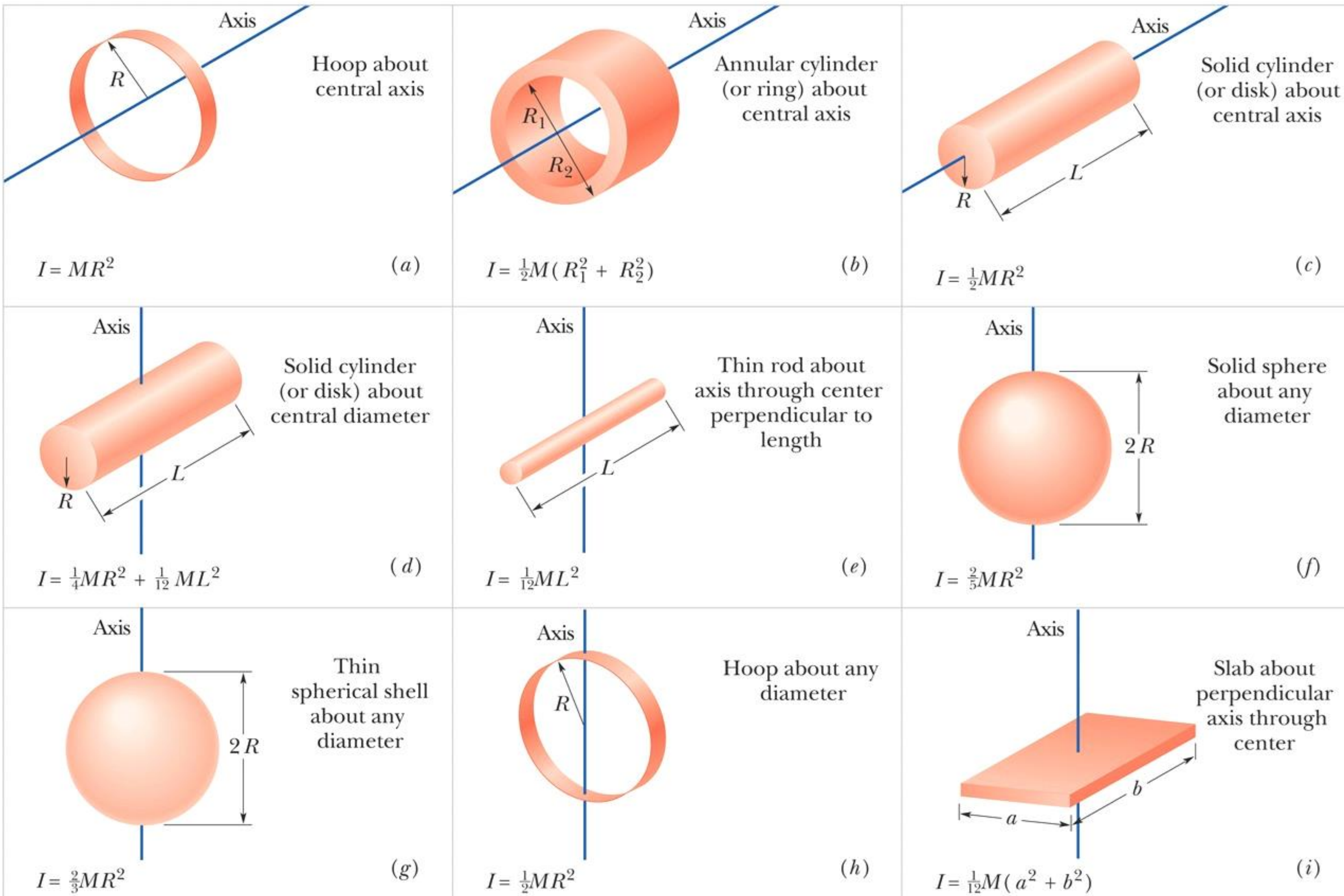
Eq. (10-35)

$$\boxed{I = \int \rho r^2 dV}$$

- In principle we can always use this equation
- But there is a set of common shapes for which values have already been calculated (Table 10-2) for common axes

10-5 Calculating the Rotational Inertia

Table 10-2 Some Rotational Inertias



Hoop about central axis $I = MR^2$ (a)	Annular cylinder (or ring) about central axis $I = \frac{1}{2}M(R_1^2 + R_2^2)$ (b)	Solid cylinder (or disk) about central axis $I = \frac{1}{2}MR^2$ (c)
Solid cylinder (or disk) about central diameter $I = \frac{1}{4}MR^2 + \frac{1}{12}ML^2$ (d)	Thin rod about axis through center perpendicular to length $I = \frac{1}{12}ML^2$ (e)	Solid sphere about any diameter $I = \frac{2}{5}MR^2$ (f)
Thin spherical shell about any diameter $I = \frac{2}{3}MR^2$ (g)	Hoop about any diameter $I = \frac{1}{2}MR^2$ (h)	Slab about perpendicular axis through center $I = \frac{1}{12}M(a^2 + b^2)$ (i)

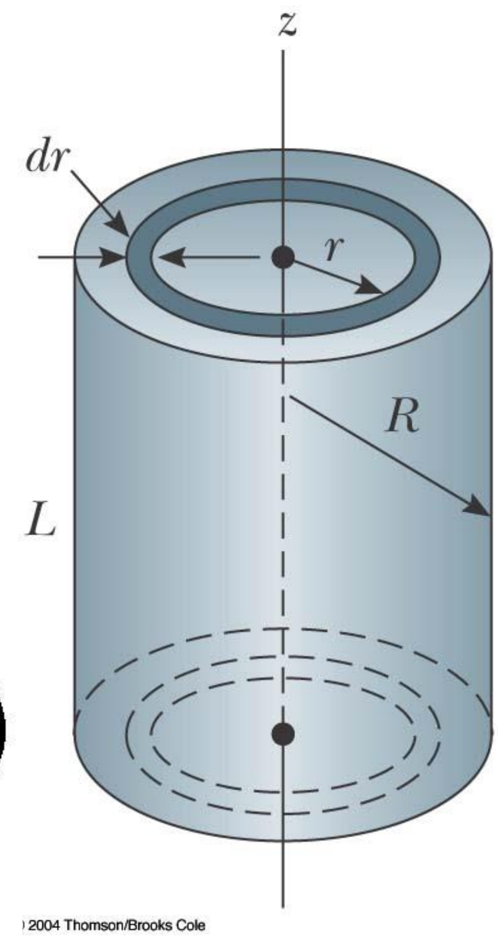
Table 10-2

Moment of Inertia of a Uniform Solid Cylinder轉動慣量之計算:

- Divide the cylinder into concentric shells with radius *r*, thickness *dr* and length *L*
- Then for *I*

$$I = \int r^2 dm = \int r^2 (2\pi\rho L r \, dr)$$

$$I_z = \frac{1}{2} M R^2$$



$$
\begin{aligned}
I &= \int \rho r^2 \, dV = \int_0^R \rho r^2 (2\pi r L) \, dr \\
&= 2\pi\rho L \int_0^R r^3 \, dr = \tfrac{1}{2}\pi\rho L R^4
\end{aligned}
$$

The volume of the entire cylinder is $\pi R^2 L$, so the density is $\rho = M/V = M/\pi R^2 L$. Substituting this value of ρ in the above result gives

$$
I = \tfrac{1}{2}\pi \left(\frac{M}{\pi R^2 L} \right) L R^4 = \boxed{\tfrac{1}{2} M R^2}
$$

Note that this result, which appears in Table 10.2, does not depend on L. Therefore, it applies equally well to a long cylinder and a flat disk.

10-5 Calculating the Rotational Inertia

- If we know the moment of inertia for the center of mass axis, we can find the moment of inertia for a parallel axis with **the parallel-axis theorem**:

$$\boxed{I = I_{com} + Mh^2}$$

Eq. (10-36)

- Note the axes *must* be parallel, and the first *must* go through the center of mass
- This does *not* relate the moment of inertia for two arbitrary axes

We need to relate the rotational inertia around the axis at *P* to that around the axis at the com.

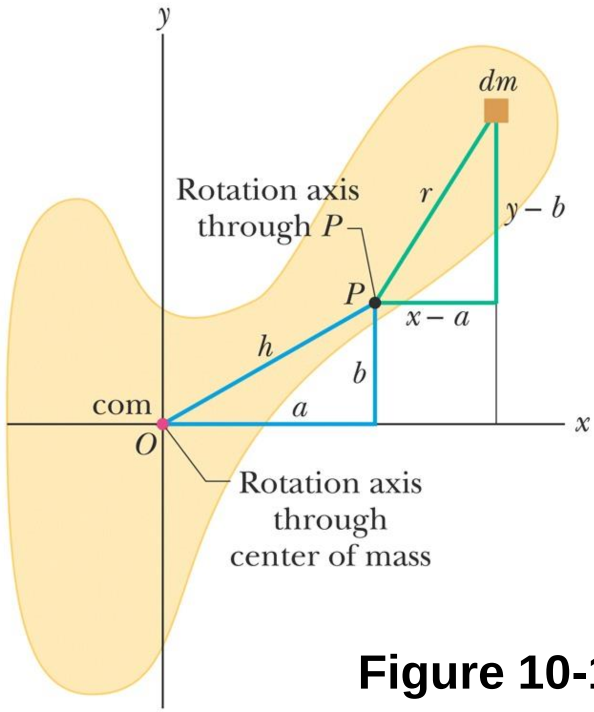


Figure 10-12

Proof of the Parallel-Axis Theorem

We take the origin *O* to coincide with the center of mass of the rigid body shown in the figure. We assume that we know the rotational inertia I_{com} for an axis that is perpendicular to the page and passes through *O*.

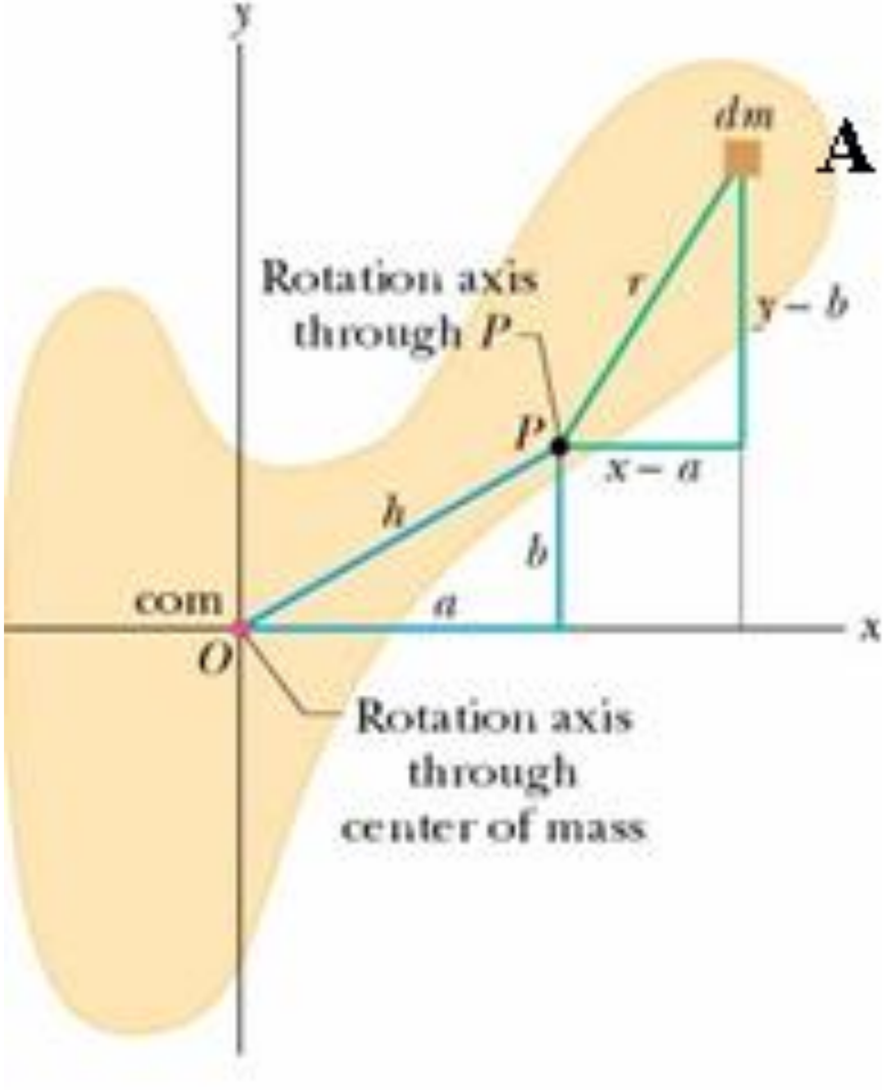


Figure 10-12

We wish to calculate the rotational ineria I about a new axis perpendicular to the page and passes through point P with coodrinates (a,b). Consider an element of mass dm at point A with coordinates (x,y). The distance r between points A and P is: $r=\sqrt{(x-a)^2+(y-b)^2}$

Rotational Inertia about P: $I=\int r^2 dm=\int\left[(x-a)^2+(y-b)^2\right]dm$ (10-37)

$I=\int\left(x^2+y^2\right)dm-2a\int xdm-2b\int ydm+\int\left(a^2+b^2\right)dm$ The second and third integrals are zero. The first integral is I_{com}. The term $\left(a^2+b^2\right)=h^2$

Thus the fourth integral is equal to $h^2\int dm=Mh^2 \rightarrow$ $\boxed{I=I_{com}+Mh^2}$

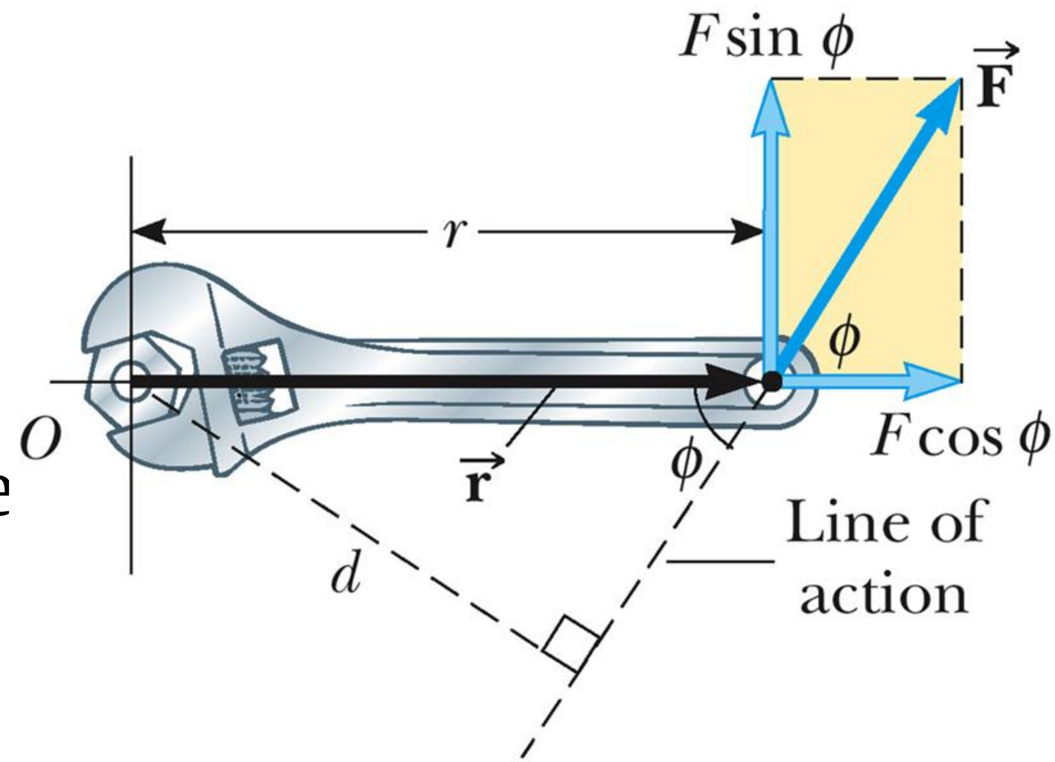
10-6 Torque力矩:

Learning Objectives

- $\tau = r\,F \sin\phi = F\,d$

The moment arm, *d*, is the *perpendicular* distance from the axis of rotation to a line drawn along the direction of the force

$d = r \sin\phi$

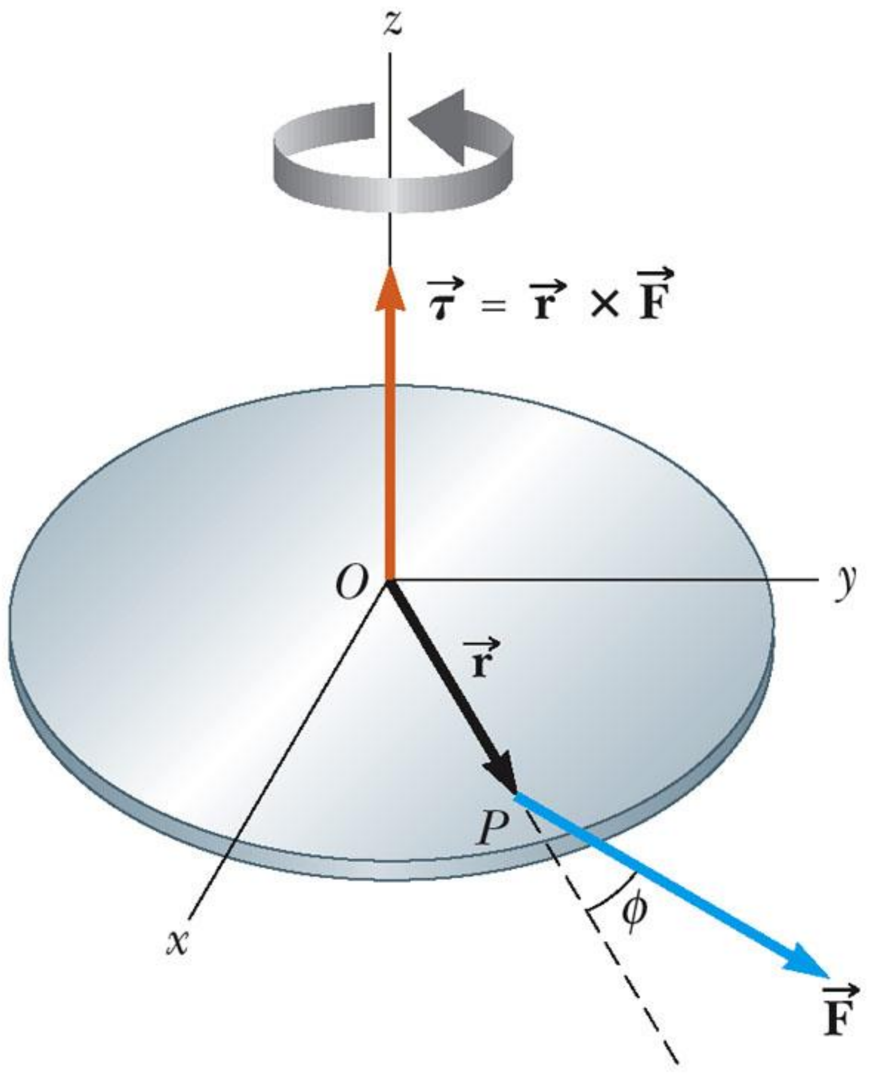


Torque as a Vector Product

- Torque is the **vector product** or **cross product** of two other vectors
- $$\boxed{\vec{\tau} = \vec{\mathbf{r}} \times \vec{\mathbf{F}}}$$

Eq. (10-39)

以右手螺旋定則判定力矩造成之轉動方向!

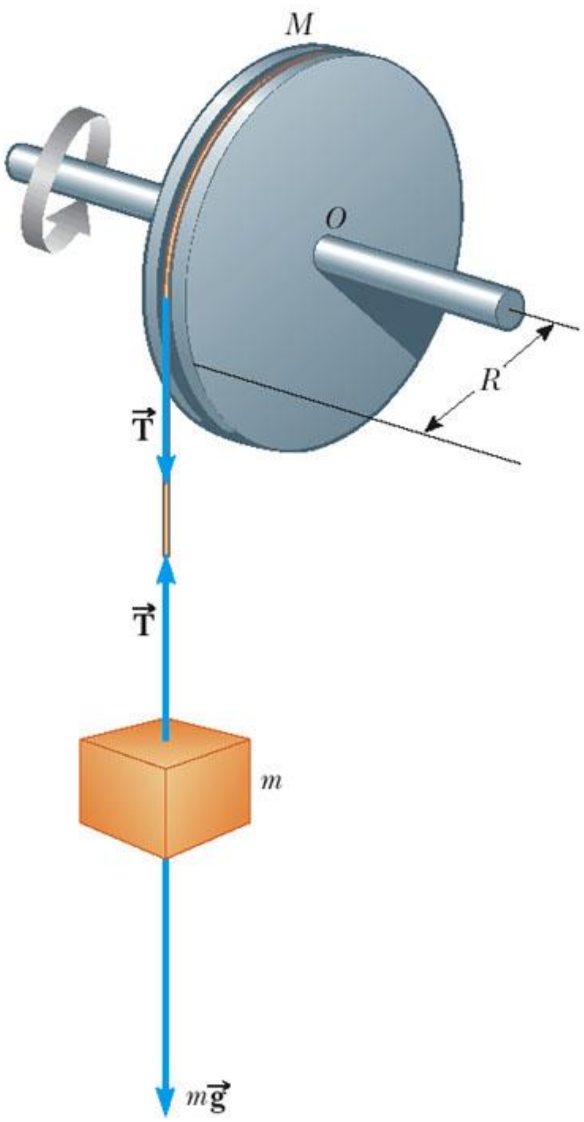


Note that 1 J = 1 N m, but torques are *never* expressed in joules, torque is not energy

10-7 Newton's Second Law for Rotation

Learning Objectives

10.28 Apply Newton's second law for rotation to relate the net torque on a body to the body's rotational inertia and rotational acceleration, all calculated relative to a specified rotation axis.



10-7 Newton's Second Law for Rotation

- Rewrite *F* = *ma* with rotational variables:

$$\boxed{\tau_{\text{net}} = I\alpha}$$

Eq. (10-42)

- For translational motion Newton's second law connects the force acting on a particle with the resulting acceleration
- It is torque that causes angular acceleration

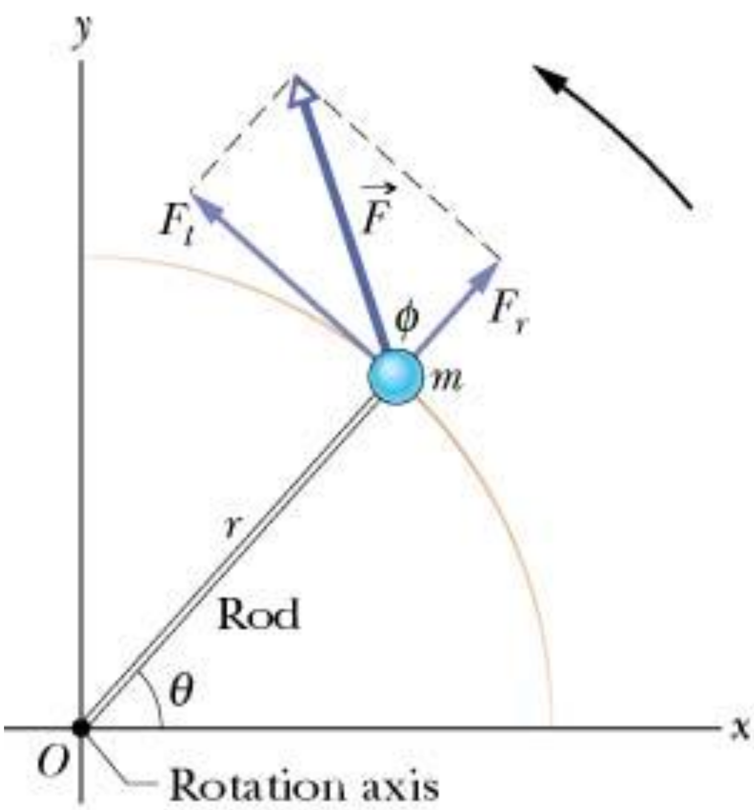


Figure 10-17

~Torque and Angular Acceleration on a Particle力矩與角加速度:

- The magnitude of the torque produced by a force around the center of the circle is
  - $\tau = F_t\, r = (ma_t)\, r$
- The tangential acceleration is related to the angular acceleration
  - $\Sigma\tau = \Sigma(ma_t)\, r = \Sigma(mr\alpha)\, r = \Sigma(mr^2)\, \alpha$
- Since mr^2 is the moment of inertia of the particle,
  - $\Sigma\tau = I\alpha$

Sample Problem 10-9 10.10 ur skill

Figure 10-18*a* shows a uniform disk, with mass $M = 2.5$ kg and radius $R = 20$ cm, mounted on a fixed horizontal axle. A block with mass $m = 1.2$ kg hangs from a massless cord that is wrapped around the rim of the disk. Find the acceleration of the falling block, the angular acceleration of the disk, and the tension in the cord. The cord does not slip, and there is no friction at the axle.

$$T - mg = ma.$$

$$-RT = \tfrac{1}{2}MR^2\alpha.$$

$$\alpha = a/R.$$

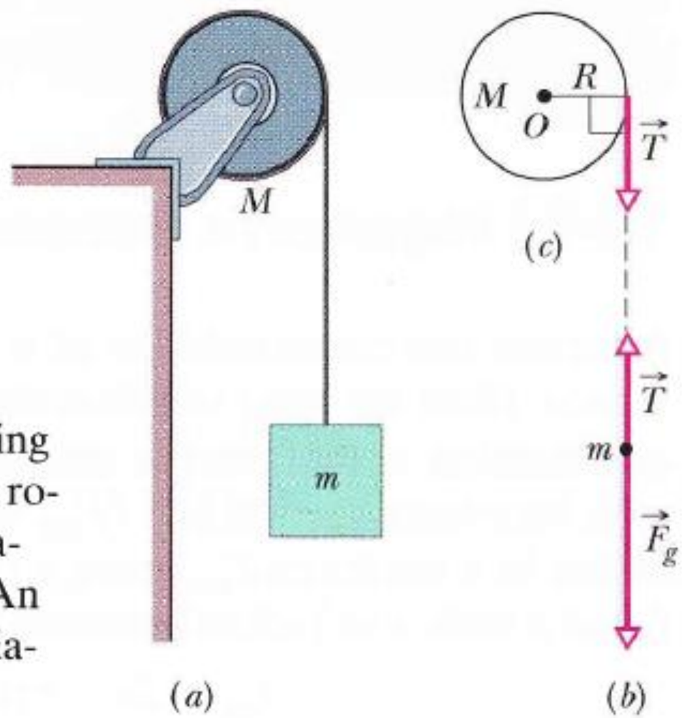


FIG. 10-18 (*a*) The falling block causes the disk to rotate. (*b*) A free-body diagram for the block. (*c*) An incomplete free-body diagram for the disk.

$$a = -g\frac{2m}{M + 2m} = -(9.8\ \text{m/s}^2)\frac{(2)(1.2\ \text{kg})}{2.5\ \text{kg} + (2)(1.2\ \text{kg})}$$

$$= -4.8\ \text{m/s}^2. \qquad \text{(Answer)}$$

We then use Eq. 10-48 to find T:

$$T = -\tfrac{1}{2}Ma = -\tfrac{1}{2}(2.5\ \text{kg})(-4.8\ \text{m/s}^2)$$

$$= 6.0\ \text{N}. \qquad \text{(Answer)}$$

$$\alpha = \frac{a}{R} = \frac{-4.8\ \text{m/s}^2}{0.20\ \text{m}} = -24\ \text{rad/s}^2.$$

Answer:
-4.8 m/s^2
6.0 N
-24 rad/s^2

10-8 Work and Rotational Kinetic Energy

Learning Objectives

10.29 Calculate the work done by a torque acting on a rotating body by integrating the torque with respect to the angle of rotation.

10.30 Apply the work-kinetic energy theorem to relate the work done by a torque to the resulting change in the rotational kinetic energy of the body.

10.31 Calculate the work done by a *constant* torque by relating the work to the angle through which the body rotates.

10.32 Calculate the power of a torque by finding the rate at which work is done.

10.33 Calculate the power of a torque at any given instant by relating it to the torque and the angular velocity at that instant.

10-8 Work and Rotational Kinetic Energy

- The rotational work-kinetic energy theorem states:

$$\boxed{\Delta K = \frac{1}{2} I \omega_f^2 - \frac{1}{2} I \omega_i^2}$$

Eq. (10-52)

- The work done in a rotation about a fixed axis can be calculated by:

$$\boxed{W = \int_{\theta_i}^{\theta_f} \tau \, d\theta}$$

Eq. (10-53)

- Which, for a constant torque, reduces to:

$$W = \tau(\theta_f - \theta_i)$$

Eq. (10-54)

or $dW = \tau \, d\theta$

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10-8 Work and Rotational Kinetic Energy

- We can relate work to power with the equation:

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

Eq. (10-55)

- Table 10-3 shows corresponding quantities for linear and rotational motion:

Table 10-3 Some Corresponding Relations for Translational and Rotational Motion

Pure Translation (Fixed Direction)		Pure Rotation (Fixed Axis)	
Position	x	Angular position	θ
Velocity	$v = dx/dt$	Angular velocity	$\omega = d\theta/dt$
Acceleration	$a = dv/dt$	Angular acceleration	$\alpha = d\omega/dt$
Mass	m	Rotational inertia	I
Newton's second law	$F_{net} = ma$	Newton's second law	$\tau_{net} = I\alpha$
Work	$W = \int F\,dx$	Work	$W = \int \tau\,d\theta$
Kinetic energy	$K = \frac{1}{2}mv^2$	Kinetic energy	$K = \frac{1}{2}I\omega^2$
Power (constant force)	$P = Fv$	Power (constant torque)	$P = \tau\omega$
Work–kinetic energy theorem	$W = \Delta K$	Work–kinetic energy theorem	$W = \Delta K$

Tab. 10-3

Analogies between translational and rotational Motion

Translational Motion		Rotational Motion
x	$\leftrightarrow$	θ
v	$\leftrightarrow$	ω
a	$\leftrightarrow$	α
$v = v_0 + at$	$\leftrightarrow$	$\omega = \omega_0 + \alpha t$
$x = x_o + v_o t + \frac{at^2}{2}$	$\leftrightarrow$	$\theta = \theta_o + \omega_o t + \frac{\alpha t^2}{2}$
$v^2 - v_o^2 = 2a\left(x - x_o\right)$	$\leftrightarrow$	$\omega^2 - \omega_o^2 = 2\alpha\left(\theta - \theta_o\right)$
$K = \frac{mv^2}{2}$	$\leftrightarrow$	$K = \frac{I\omega^2}{2}$
m	$\leftrightarrow$	I
$F = ma$	$\leftrightarrow$	$\tau = I\alpha$
F	$\leftrightarrow$	τ
$P = Fv$	$\leftrightarrow$	$P = \tau\omega$

10 Summary

Angular Position

- Measured around a **rotation axis**, relative to a **reference line**:

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

Eq. (10-1)

Angular Displacement

- A change in angular position

$$\Delta\theta = \theta_2 - \theta_1.$$

Eq. (10-4)

Angular Velocity and Speed

- Average and instantaneous values:

$$\omega_{\text{avg}} = \frac{\theta_2 - \theta_1}{t_2 - t_1} = \frac{\Delta\theta}{\Delta t},$$

Eq. (10-5)

$$\omega = \lim_{\Delta t \to 0} \frac{\Delta\theta}{\Delta t} = \frac{d\theta}{dt}.$$

Eq. (10-6)

Angular Acceleration

- Average and instantaneous values:

$$\alpha_{\text{avg}} = \frac{\omega_2 - \omega_1}{t_2 - t_1} = \frac{\Delta\omega}{\Delta t},$$

Eq. (10-7)

$$\alpha = \lim_{\Delta t \to 0} \frac{\Delta\omega}{\Delta t} = \frac{d\omega}{dt}.$$

Eq. (10-8)

10 Summary

Kinematic Equations

- Given in Table 10-1 for constant acceleration
- Match the linear case

Linear and Angular Variables Related

- Linear and angular displacement, velocity, and acceleration are related by *r*

Rotational Kinetic Energy and Rotational Inertia

$$K = \tfrac{1}{2} I\omega^2 \qquad \text{(radian measure)}$$

Eq. (10-34)

$$I = \sum m_i r_i^2 \qquad \text{(rotational inertia)}$$

Eq. (10-33)

The Parallel-Axis Theorem

- Relate moment of inertia around any parallel axis to value around com axis

$$I = I_{\text{com}} + Mh^2$$

Eq. (10-36)

10 Summary

Torque

- Force applied at distance from an axis:

$$\tau = (r)(F \sin \phi).$$ **Eq. (10-39)**

- Moment arm: perpendicular distance to the rotation axis

Work and Rotational Kinetic Energy

$$W = \int_{\theta_i}^{\theta_f} \tau \, d\theta$$ **Eq. (10-53)**

$$P = \frac{dW}{dt} = \tau\omega$$ **Eq. (10-55)**

Newton's Second Law in Angular Form

$$\tau_{\text{net}} = I\alpha$$ **Eq. (10-42)**

CH10 習題:

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