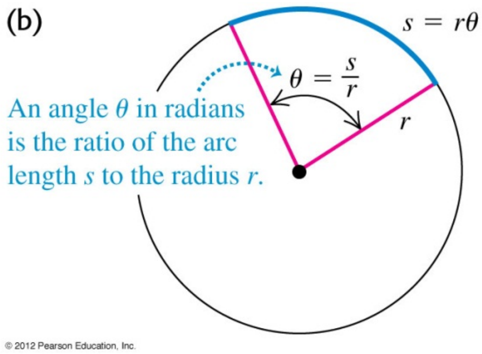
DYNAMICS OF RIGID BODIES I

Intended Learning Outcomes – after this lecture you will learn:
1. radian as a measure of angle
2. angular displacement, velocity and acceleration and their vector representation
3. angular motion as compared to rectilinear motion
4. rotational kinetic energy and moment of inertia

Textbook Reference: Ch 9.1 – 9.4

Measuring angles in radian



Define the value of an angle θ in **radian** as $\theta = \frac{s}{r}$, or arc length $s = r\theta$

- ⚠ a pure number, without dimension
- ⚠ independent of radius r of the circle
- ⚠ one complete circle

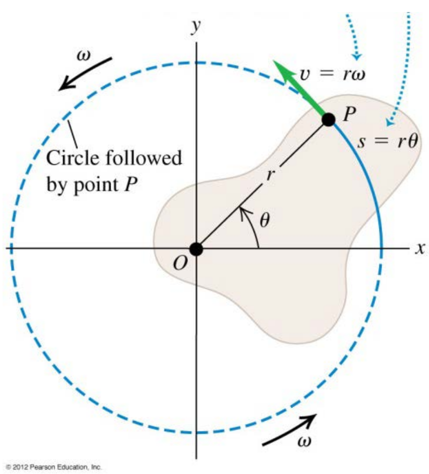
$$\theta = \frac{2\pi r}{r} = 2\pi \text{ (in radian)} \leftrightarrow 360°$$

$$\pi \text{ (in radian)} \leftrightarrow 180°$$

$$\pi/2 \text{ (in radian)} \leftrightarrow 90°$$

Consider a rigid body rotating about a fixed axis

<u>Convention</u>: θ measured from x axis in <u>counterclockwise</u> direction



angular displacement: $\Delta\theta = \theta_2 - \theta_1$

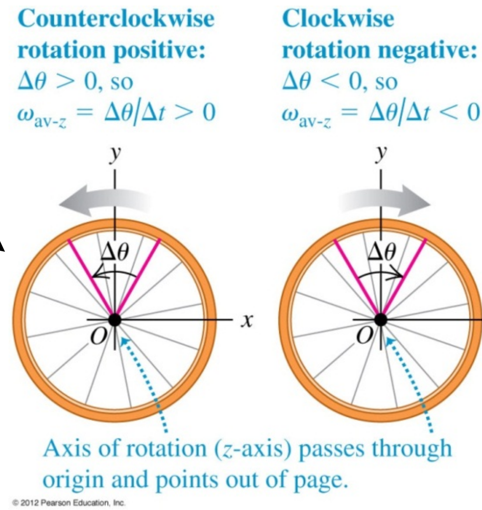
angular velocity:

$$\omega = \underset{\text{(average)}}{\frac{\Delta\theta}{\Delta t}} \xrightarrow{\Delta t \to 0} \underset{\text{(instantaneous)}}{\frac{d\theta}{dt}}$$

angular acceleration:

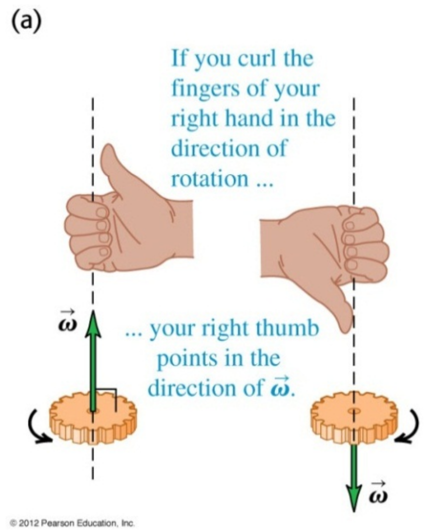
$$\alpha = \frac{d\omega}{dt} = \frac{d^2\theta}{dt^2}$$

$\Delta\theta = \theta_f - \theta_i > 0$



$\Delta\theta = \theta_f - \theta_i < 0$

Angular velocity is a vector, direction defined by the **right hand rule**

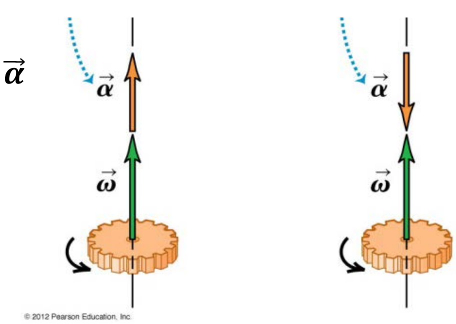


direction of $\vec{\boldsymbol{\omega}}$ represents sense of rotation

Angular acceleration is defined as $\vec{\boldsymbol{\alpha}} = d\vec{\boldsymbol{\omega}}/dt$

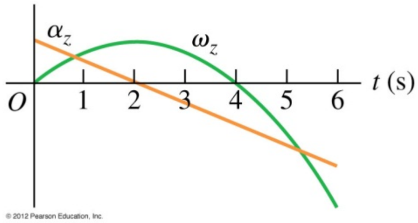
⚠ if rotation axis is fixed, $\vec{\boldsymbol{\alpha}}$ along the direction of $\vec{\boldsymbol{\omega}}$

Rotation speeding up, $\vec{\boldsymbol{\alpha}}$ and $\vec{\boldsymbol{\omega}}$ in the same direction



Rotation slowing down, $\vec{\boldsymbol{\alpha}}$ and $\vec{\boldsymbol{\omega}}$ in the opposite direction

Question:



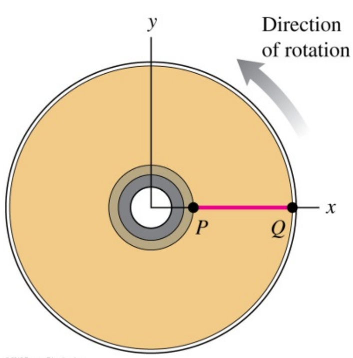
The figure shows a graph of ω and α versus time. During which time intervals is the rotation speeding up?
(i) $0 < t < 2$ s; (ii) 2 s $< t <$ 4 s; (iii) 4 s $< t <$ 6 s.

Answer: see inverted text on P. 305 of textbook

Rotation with constant angular acceleration

Straight-Line Motion with Constant Linear Acceleration		Fixed-Axis Rotation with Constant Angular Acceleration	
$a_x = \text{constant}$		$\alpha_z = \text{constant}$	
$v_x = v_{0x} + a_x t$	(2.8)	$\omega_z = \omega_{0z} + \alpha_z t$	(9.7)
$x = x_0 + v_{0x}t + \frac{1}{2}a_x t^2$	(2.12)	$\theta = \theta_0 + \omega_{0z}t + \frac{1}{2}\alpha_z t^2$	(9.11)
$v_x^2 = v_{0x}^2 + 2a_x(x - x_0)$	(2.13)	$\omega_z^2 = \omega_{0z}^2 + 2\alpha_z(\theta - \theta_0)$	(9.12)
$x - x_0 = \frac{1}{2}(v_{0x} + v_x)t$	(2.14)	$\theta - \theta_0 = \frac{1}{2}(\omega_{0z} + \omega_z)t$	(9.10)

Example 9.3 P. 306 Rotation with constant angular acceleration
A Blu-ray disc is slowing down to a stop with constant angular acceleration $\alpha = -10.0\ \mathrm{rad/s^2}$. At $t = 0$, $\omega_0 = 27.5\ \mathrm{rad/s}$, and a line PQ marked on the disc surface is along the x axis.



angular velocity at $t = 0.300$ s:

$$\omega = \omega_0 + \alpha t = 27.5\ \mathrm{rad/s} + (-10.0\ \mathrm{rad/s^2})(0.300\ \mathrm{s})$$
$$= 24.5\ \mathrm{rad/s}$$

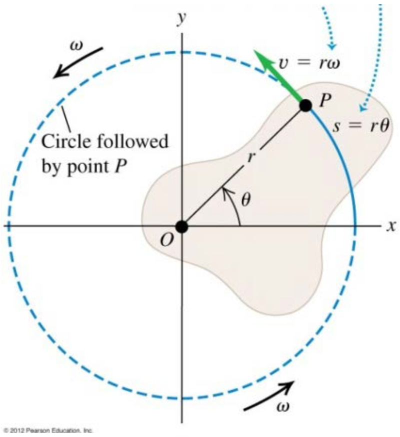
Suppose θ is the angular position of PQ at $t = 0.300$ s

$$\theta = \omega_0 t + \tfrac{1}{2}\alpha t^2 = 7.80\ \mathrm{rad} = (7.8\ \mathrm{rad})\left(\frac{360°}{2\pi\ \mathrm{rad}}\right) = 447°$$
$$= 87°$$

What are the directions of $\vec{\boldsymbol{\omega}}$ and $\vec{\boldsymbol{\alpha}}$?

Question:
In the above example, suppose the initial angular velocity is doubled to $2\omega_0$, and the angular acceleration (deceleration) is also doubled to 2α, it will take (more / less / the same amount of) time for the disc to come to a stop compared to the original problem.
Answer: see inverted text on P. 307 of textbook

Relation to linear velocity and acceleration

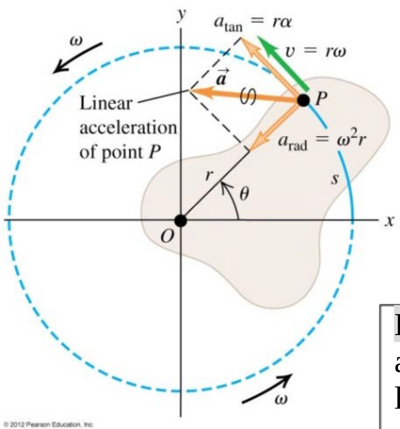


In time Δt, angular displacement is $\Delta\theta$,

tangential displacement (arc length) is $\Delta s = r\Delta\theta$

$$\therefore \text{ tangential speed } \; v = \frac{\Delta s}{\Delta t} = r\frac{\Delta\theta}{\Delta t} \to r\frac{d\theta}{dt} = r\omega$$

Linear velocity of point P, $\vec{\boldsymbol{v}}$, is tangential and has magnitude $v = r\omega$



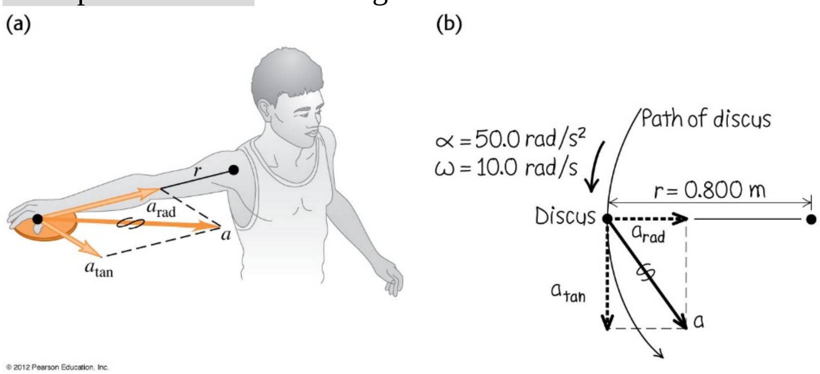
tangential acceleration $\boxed{a_{\text{tan}} = \frac{dv}{dt} = r\frac{d\omega}{dt} = r\alpha}$

radial acceleration $\boxed{a_{\text{rad}} = \frac{v^2}{r} = \omega^2 r}$

⚠ every point of the rigid body has identical $\vec{\boldsymbol{\omega}}$ and $\vec{\boldsymbol{\alpha}}$, but different $\vec{\boldsymbol{v}}$ and $\vec{\boldsymbol{a}}$

Demonstration: falling faster than g – same angular acceleration (same rod), the far end of the rod has linear acceleration larger than g.

Example 9.4 P. 309 Throwing a discus



An athlete whirls a discus in a circle of radius 80.0 cm. At some instant $\omega = 10.0$ rad/s, and $\alpha = 50.0$ rad/s^2. Then

$$a_{\text{tan}} = r\alpha = (0.800\text{ m})(50.0\ \text{rad/s}^2) = 40.0\text{ m/s}^2$$
$$a_{\text{rad}} = \omega^2 r = (10.0\ \text{rad/s})^2(0.800\text{ m}) = 80.0\text{ m/s}^2$$

Magnitude of the linear acceleration is

$$a = \sqrt{a_{\text{tan}}^2 + a_{\text{rad}}^2} = 89.4\text{ m/s}^2$$

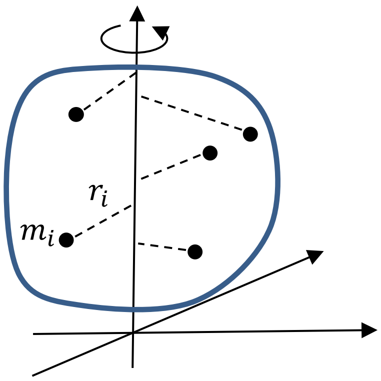
Rotational kinetic energy of a rigid body

Consider a rigid body as a collection of particles, the kinetic energy due to rotation is

$$K=\sum \tfrac{1}{2}m_i v_i^2=\sum \tfrac{1}{2}m_i r_i^2\omega^2=\frac{1}{2}\underbrace{\left(\sum m_i r_i^2\right)}\omega^2$$

c.f. in rectilinear motion, $K=\frac{1}{2}mv^2$

moment of inertia I, analogous to *mass* in rectilinear motion



$$\boxed{K=\tfrac{1}{2}I\omega^2, I=\sum m_i r_i^2}$$

⚠ When defining I, must specify a rotation axis. r_i is the $\perp$ distance to the rotation axis, not the distance from the origin.

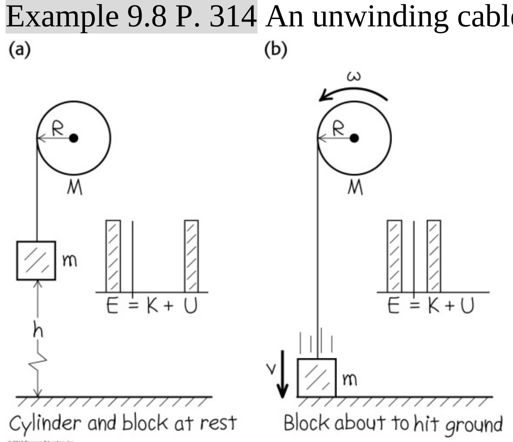
Gravitational potential energy of a rigid body

$$U=m_1gy_1+m_2gy_2+\cdots=(m_1y_1+m_2y_2+\cdots)g=Mgy_{\mathrm{cm}}$$

Gravitational PE is as if all the mass is concentrated at the CM.

Demonstration: Euler's disk to demonstrate the conservation of energy – the lower the CM of the disk, the faster it spin.

Example 9.8 P. 314 An unwinding cable



Assumption: rotation of cylinder is frictionless

no slipping between cylinder and cable

At the moment the block hits the ground, speed of block is v, angular speed of cylinder is ω

$$v=R\omega$$

$$0+\underbrace{mgh}_{\text{initial PE of block}}=\frac{1}{2}mv^2+\underbrace{\frac{1}{2}I\omega^2}_{\text{rotational KE}}$$

initial PE of block

rotational KE, $I=\frac{1}{2}MR^2$ (we will tell you why later)

$$\Rightarrow \quad v=\sqrt{\frac{2gh}{1+M/2m}}$$

⚠ if $M=0$, $v=\sqrt{2gh}$, same as free falling

Question: Is there friction between the string and pulley? Does it dissipate energy?

Questions:
Suppose the cylinder and block have the same mass, $m = M$. Just before the block hits the floor, its KE is (larger than / less than / the same as) the KE of the cylinder.
Answer: see inverted text on P. 315 of textbook

Clicker Questions:

Q9.2

A DVD is initially at rest so that the line *PQ* on the disc's surface is along the +*x*-axis. The disc begins to turn with a constant α_z = 5.0 rad/s^2. At t = 0.40 s, what is the angle between the line *PQ* and the +*x*-axis?

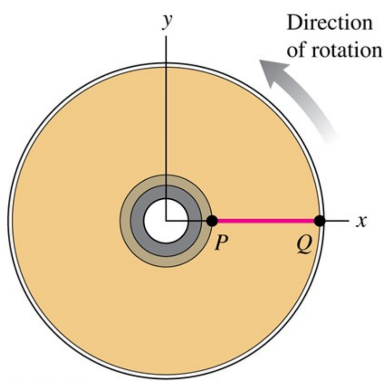
A. 0.40 rad

B. 0.80 rad

C. 1.0 rad

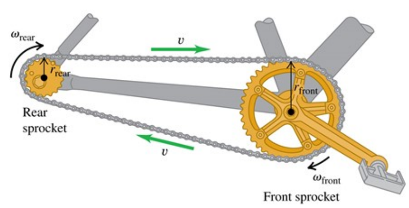
D. 1.6 rad

E. 2.0 rad



Q9.5

Compared to a gear tooth on the rear sprocket (on the left, of small radius) of a bicycle, a gear tooth on the *front* sprocket (on the right, of large radius) has



A. a faster linear speed and a faster angular speed.

B. the same linear speed and a faster angular speed.

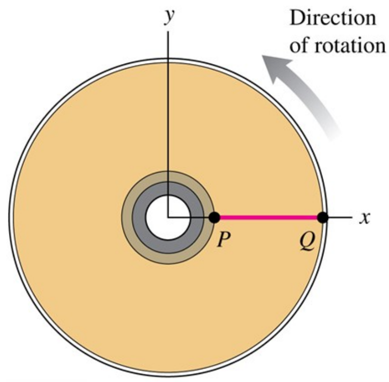
C. a slower linear speed and the same angular speed.

D. the same linear speed and a slower angular speed.

E. none of the above.

Q9.4

A DVD is rotating with an ever-increasing speed. How do the centripetal acceleration a_{rad} and tangential acceleration a_{tan} compare at points P and Q?



A. P and Q have the same a_{rad} and a_{tan}.

B. Q has a greater a_{rad} and a greater a_{tan} than P.

C. Q has a smaller a_{rad} and a greater a_{tan} than P.

D. Q has a greater a_{rad} and a smaller a_{tan} than P.

E. P and Q have the same a_{rad}, but Q has a greater a_{tan} than P.

Q9.6

You want to double the radius of a rotating solid sphere while keeping its kinetic energy constant. (The mass does not change.) To do this, the final angular velocity of the sphere must be

A. four times its initial value.

B. twice its initial value.

C. the same as its initial value.

D. half of its initial value.

E. one-quarter of its initial value.

Q9.7

The three objects shown here all have the same mass and the same outer radius. Each object is rotating about its axis of symmetry (shown in blue). All three objects have the *same* rotational kinetic energy. Which object is rotating *fastest*?

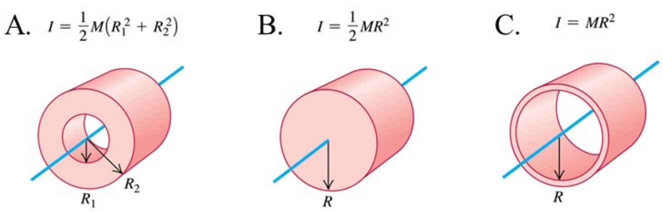
A. Object A is rotating fastest.

B. Object B is rotating fastest.

C. Object C is rotating fastest.

D. Two of these are tied for fastest.

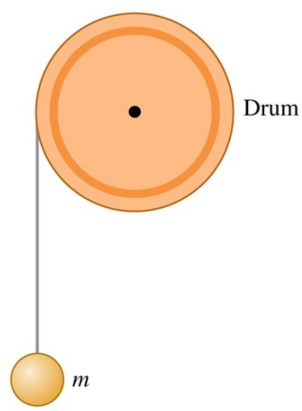
E. All three rotate at the same speed.



Q9.8

A thin, very light wire is wrapped around a drum that is free to rotate. The free end of the wire is attached to a ball of mass m. The drum has the same mass m. Its radius is R and its moment of inertia is $I = (1/2)mR^2$. As the ball falls, the drum spins.

At an instant that the ball has translational kinetic energy K, what is the rotational kinetic energy of the drum?



A. K B. $2K$ C. $K/2$ D. $K/4$

E. none of these

Ans: Q9.2) A, Q9.5) D, Q9.4) B, Q9.6) D, Q9.7) B, Q9.8) C