

# Fundamentals of Physics

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## 2 Motion along a straight line

### 2.1 Position, displacement, and average velocity

$$\text{Distance: } d = v \times t \quad \text{Time: } t = \frac{d}{v} \quad \text{Velocity: } v = \frac{d}{t}$$

$$\text{Magnitude} \Rightarrow \Delta x_1 - x_2$$

$$\text{Average velocity} \Rightarrow v_{\text{avg}} = \frac{\Delta x}{\Delta t} = \frac{x_2 - x_1}{t_2 - t_1}$$

$$\text{Magnitude} \Rightarrow \frac{\text{total distance}}{\Delta t}$$

### 2.2 Instantaneous velocity and speed

$$\text{Instantaneous velocity} \Rightarrow \lim_{\Delta t \rightarrow 0} \frac{\Delta x}{\Delta t} = \frac{dx}{dt}$$

### 2.3 Acceleration

$$\text{Average acceleration} \Rightarrow a_{\text{avg}} = \frac{v_2 - v_1}{t_2 - t_1} = \frac{\Delta v}{\Delta t}$$

$$\text{Acceleration at a point} \Rightarrow a = \frac{dv}{dt}$$

★ If the signs of the velocity and acceleration of a particle are the same, the speed of the particle increases. If the signs are opposite, the speed decreases.

### 2.4 Constant acceleration

The following five equations describe the motion of a particle with constant acceleration.

Nr	Equation	Missing quantity
1	$v = v_0 + at$	$x - x_0$
2	$x - x_0 = v_0 t + \frac{1}{2}at^2$	$v$
3	$v^2 = v_0^2 + 2a(x - x_0)$	$t$
4	$x - x_0 = \frac{1}{2}(v_0 + v_t)t$	$a$
5	$x - x_0 = vt - \frac{1}{2}at^2$	$v_0$

### 2.5 Free-fall acceleration

★ The free-fall acceleration near Earth's surface is  $a = -g = -9.8 \text{ m/s}^2$ , and the magnitude of the acceleration is  $g = 9.8 \text{ m/s}^2$ . Do not substitute  $-9.8 \text{ m/s}^2$  for  $g$ .

## 2.6 Graphical integration in motion analysis

- On a graph of acceleration  $a$  versus time  $t$ , the change in the velocity is given by:
- On a graph of velocity  $v$  versus time  $t$ , the change in the position is given by:

$$v_1 - v_0 = \int_{t_0}^{t_1} a \, dt.$$

$$x_1 - x_0 = \int_{t_0}^{t_1} v \, dt,$$

## 3 Vectors

### 3.1 Vectors and their components

- **Vector** - has magnitude and direction.
- **Scalar** - quantities that can be fully described by a magnitude (a numerical value alone), without any direction.
- **Vector sum (resultant)** - are the product from adding two or more vectors.

$$\vec{s} = \vec{a} + \vec{b},$$

$$\vec{a} + \vec{b} = \vec{b} + \vec{a} \quad (\text{commutative law})$$

$$(\vec{a} + \vec{b}) + \vec{c} = \vec{a} + (\vec{b} + \vec{c}) \quad (\text{associative law})$$

$$\vec{d} = \vec{a} - \vec{b} = \vec{a} + (-\vec{b}) \quad (\text{vector subtraction})$$

A component of a vector is the projection of a vector on an axis.

Finding the components:

$$a_x = a \cos \theta \quad \text{and} \quad a_y = a \sin \theta$$

If we know a vector's  $a_x$  and  $a_y$  and want magnitude or angle we can use:

$$a = \sqrt{a_x^2 + a_y^2} \quad \text{and} \quad \theta = \tan^{-1}\left(\frac{a_y}{a_x}\right)$$

### 3.2 Unit vectors, adding vectors by components

**Unit vector** - is a vector with magnitude of exactly 1.

$$\begin{aligned} r_x &= a_x + b_x \\ \vec{r} &= \vec{a} + \vec{b} \quad r_y = a_y + b_y \\ r_z &= a_z + b_z \end{aligned}$$

We can write a vector  $\vec{a}$  in terms of unit vectors as:  $\vec{a} = a_x \hat{i} + a_y \hat{j} + a_z \hat{k}$

### 3.3 Multiplying vectors

There are two ways of multiplying vectors, one way produces a scalar (scalar product) and the other way produces a new vector (vector product):

Feature	Scalar product (dot)	Vector product (cross)
Symbol	$\vec{A} \cdot \vec{B}$	$\vec{A} \times \vec{B}$
Result	Scalar (number)	Vector
Formula	$AB \cos \theta$	$AB \sin \theta$
Component form	$A_x B_x + A_y B_y + A_z B_z$	$(A_y B_z - A_z B_y, A_z B_x - A_x B_z, A_x B_y - A_y B_x)$

## 4 Motion in two and three dimensions

### 4.1 Position and displacement

**Position vector** - a vector that extends from a reference point (usually the origin) to the particle.

- **Unit vector notation:**  $\vec{r} = x\hat{i} + y\hat{j} + z\hat{k}$
- **Particle's displacement:**  $\Delta\vec{r} = \vec{r}_2 - \vec{r}_1$
- **Alternative form:**  $\Delta\vec{r} = (x_2 - x_1)\hat{i} + (y_2 - y_1)\hat{j} + (z_2 - z_1)\hat{k}$   
 $= \Delta x \hat{i} + \Delta y \hat{j} + \Delta z \hat{k}$

### 4.2 Average velocity and instantaneous velocity

- If a particle undergoes a displacement  $\Delta\vec{r}$  in time interval  $\Delta t$ , its average velocity  $\vec{v}_{avg}$  for that time interval is:  $\vec{v}_{avg} = \frac{\Delta\vec{r}}{\Delta t}$ .
- As  $\Delta t$  is shrunk to 0,  $\vec{v}_{avg}$  reaches a limit called either the velocity or the instantaneous velocity  $\vec{v}$ :  
 $\vec{v} = \frac{d\vec{r}}{dt} = v_x \hat{i} + v_y \hat{j} + v_z \hat{k}$

★ The direction of the instantaneous velocity  $\vec{v}$  of a particle is always tangent to the particle's path at the particle's position.

### 4.3 Average acceleration and instantaneous acceleration

- If a particle's velocity changes from  $\vec{v}_1$  to  $\vec{v}_2$  in time interval  $\Delta t$ , its average acceleration during  $\Delta t$  is:  
 $\vec{a}_{avg} = \frac{\vec{v}_2 - \vec{v}_1}{\Delta t} = \frac{\Delta\vec{v}}{\Delta t}$

## 4.4 Projectile motion

When you throw an object at an angle:

- It moves forward at a constant horizontal speed.
- It moves up and then down because of gravity pulling it downward.
- The path it follows is a parabola.

★ In projectile motion, the horizontal motion and the vertical motion are independent of each other; that is, neither motion affects the other.

The vertical motion of a projectile is governed by the following kinematic equations:

$$v_y = v_0 \sin \theta_0 - gt, \quad v_y^2 = (v_0 \sin \theta_0)^2 - 2g(y - y_0).$$

The trajectory (path) of a particle in projectile motion is parabolic and is given by

$$y = (\tan \theta_0)x - \frac{gx^2}{2(v_0 \cos \theta_0)^2}, \quad \text{if } x_0 \text{ and } y_0 \text{ are zero.}$$

The equations of motion for the particle (while in flight) can be written as

$$x - x_0 = (v_0 \cos \theta_0)t, \quad y - y_0 = (v_0 \sin \theta_0)t - \frac{1}{2}gt^2,$$

The particle's horizontal range  $R$ , which is the horizontal distance from the launch point to the point at which the particle returns to the launch height, is

$$R = \frac{v_0^2}{g} \sin 2\theta_0.$$

★ The horizontal range  $R$  is maximum for a launch angle of  $45^\circ$ .

## 4.5 Uniform circular motion

$$a = \frac{v^2}{r} \quad (\text{centripetal acceleration}), \quad T = \frac{2\pi r}{v} \quad (\text{period}).$$

## 4.6 Relative motion in one dimension

In relative motion, two reference frames moving at constant velocity measure different velocities for the same particle but the same acceleration. The relationship between the measured velocities is

$$\vec{v}_{PA} = \vec{v}_{PB} + \vec{v}_{BA},$$

and since the frames move at constant velocity,

$$\vec{a}_{PA} = \vec{a}_{PB}.$$

★ Observers on different frames of reference that move at constant velocity relative to each other will measure the same acceleration for a moving particle.

## 4.7 Relative motion in two dimensions

In two-dimensional relative motion, two reference frames moving at constant velocity measure different velocities for a particle but the same acceleration. The relationship between the measured velocities is

$$\vec{v}_{PA} = \vec{v}_{PB} + \vec{v}_{BA},$$

and since the frames move at constant velocity,

$$\vec{a}_{PA} = \vec{a}_{PB}.$$

## 5 Force and motion - I

### 5.1 Newton's first and second laws

★ **Newton's First Law:** If no *net* force acts on a body ( $\vec{F}_{\text{net}} = 0$ ), the body's velocity cannot change; that is, the body cannot accelerate.

★ An inertial reference frame is one in which Newton's laws hold.

★ **Newton's Second Law:** The net force on a body is equal to the product of the body's mass and its acceleration.

- The law can be written as:

$$\vec{F}_{\text{net}} = m\vec{a} \quad (\text{Newton's second law}).$$

- In component form:

$$F_{\text{net},x} = ma_x, \quad F_{\text{net},y} = ma_y, \quad F_{\text{net},z} = ma_z.$$

★ The acceleration component along a given axis is caused *only by* the sum of the force components along that *same* axis, and not by force components along any other axis.

### 5.2 Some particular forces

$$F_g = mg.$$

★ The weight  $W$  of a body is equal to the magnitude  $F_g$  of the gravitational force on the body.

$$W = mg \quad (\text{weight}),$$

★ When a body presses against a surface, the surface (even a seemingly rigid one) deforms and pushes on the body with a normal force  $\vec{F}_N$  that is perpendicular to the surface.



### 5.3 Applying Newton's laws

★ **Newton's Third Law:** When two bodies interact, the forces on the bodies from each other are always equal in magnitude and opposite in direction.

$$F_{BC} = F_{CB} \quad (\text{equal magnitudes})$$

## 6 Force and motion - II

### 6.1 Friction

Two types of friction:

- Static frictional force - Prevents motion when a body is at rest. Is written as  $\vec{f}_s$ .
- Kinetic frictional force - What friction becomes when sliding begins. Is written as  $\vec{f}_k$ .

Properties of friction:

1. If a body does not move, the static frictional force  $\vec{f}_s$  balances the component of the applied force that is parallel to the surface.
2. The maximum static friction is given by

$$f_{s,\max} = \mu_s F_N,$$

where  $\mu_s$  is the coefficient of static friction and  $F_N$  is the normal force.

3. Once the body starts sliding, the frictional force becomes kinetic and is given by

$$f_k = \mu_k F_N,$$

where  $\mu_k$  is the coefficient of kinetic friction.

### 6.2 The drag force and terminal speed

When a body moves through a fluid, it experiences a drag force  $\vec{D}$  opposing its motion. The drag magnitude depends on the relative speed  $v$  and is given by

$$D = \frac{1}{2} C \rho A v^2,$$

where  $C$  is the drag coefficient,  $\rho$  is the fluid density, and  $A$  is the cross-sectional area.

At terminal velocity, the drag force equals the gravitational force, and the speed becomes constant:

$$v_t = \sqrt{\frac{2F_g}{C\rho A}}.$$

## 6.3 Uniform Circular Motion

★ A centripetal force accelerates a body by changing the direction of the body's velocity without changing the body's speed.

A particle moving in a circle of radius  $R$  at constant speed  $v$  has a centripetal acceleration directed toward the center:

$$a = \frac{v^2}{R}.$$

This acceleration is caused by a net centripetal force of magnitude

$$F = \frac{mv^2}{R},$$

where  $m$  is the particle's mass.

## 7 Kinetic energy and work

### 7.1 Kinetic Energy

The kinetic energy  $K$  associated with the motion of a particle of mass  $m$  and speed  $v$ , where  $v$  is well below the speed of light, is

$$K = \frac{1}{2}mv^2 \quad (\text{kinetic energy}).$$

### 7.2 Work and kinetic energy

★ Work  $W$  is energy transferred to or from an object by means of a force acting on the object. Energy transferred to the object is positive work, and energy transferred from the object is negative work.

Work  $W$  is the energy transferred to or from an object by a force acting over a displacement  $\vec{d}$ . For a constant force,

$$W = Fd \cos \phi = \vec{F} \cdot \vec{d},$$

where  $\phi$  is the angle between  $\vec{F}$  and  $\vec{d}$ .

★ To calculate the work a force does on an object as the object moves through some displacement, we use only the force component along the object's displacement. The force component perpendicular to the displacement does zero work.

★ A force does positive work when it has a vector component in the same direction as the displacement, and it does negative work when it has a vector component in the opposite direction. It does zero work when it has no such vector component.

Only the component of  $\vec{F}$  along  $\vec{d}$  does work. The net work equals the change in kinetic energy:

$$\Delta K = K_f - K_i = \frac{1}{2}m(v_f^2 - v_i^2) = W.$$

### 7.3 Work done by the gravitational force

The work done by the gravitational force on an object of mass  $m$  over displacement  $\vec{d}$  is

$$W_g = mgd \cos \phi,$$

where  $\phi$  is the angle between  $\vec{F}_g$  and  $\vec{d}$ .

The work done by an applied force  $W_a$  and gravity are related by

$$\Delta K = K_f - K_i = W_a + W_g.$$

If  $K_f = K_i$ , then

$$W_a = -W_g,$$

meaning the applied force does as much work on the object as gravity removes.

### 7.4 Work done by a spring force

The force from a spring is given by Hooke's law:

$$\vec{F}_s = -k\vec{d}, \quad \text{or} \quad F_x = -kx,$$

where  $k$  is the spring constant and  $\vec{d}$  (or  $x$ ) is the displacement from equilibrium.

The work done by a spring when moving from  $x_i$  to  $x_f$  is

$$W_s = \frac{1}{2}kx_i^2 - \frac{1}{2}kx_f^2.$$

★ Work  $W_s$  is positive if the block ends up closer to the relaxed position ( $x = 0$ ) than it was initially. It is negative if the block ends up farther away from  $x = 0$ . It is zero if the block ends up at the same distance from  $x = 0$ .

If  $x_i = 0$  and  $x_f = x$ , then

$$W_s = -\frac{1}{2}kx^2.$$

★ If a block that is attached to a spring is stationary before and after a displacement, then the work done on it by the applied force displacing it is the negative of the work done on it by the spring force.

### 7.5 Work done by a general variable force

If the force  $\vec{F}$  on an object depends on position, the total work is found by integrating the force over the path:

$$W = \int_{x_i}^{x_f} F_x dx + \int_{y_i}^{y_f} F_y dy + \int_{z_i}^{z_f} F_z dz.$$

If the force acts only along the  $x$ -axis, this simplifies to

$$W = \int_{x_i}^{x_f} F(x) dx.$$

If this formula does not work, use formula:  $W = \Delta K$

## 7.6 Power

Power is the rate at which a force does work.

The *average power* over a time interval  $\Delta t$  is

$$P_{\text{avg}} = \frac{W}{\Delta t}.$$

The *instantaneous power* (rate at which a force does work) is

$$P = \frac{dW}{dt} = \vec{F} \cdot \vec{v}.$$

For a force  $\vec{F}$  making an angle  $\phi$  with velocity  $\vec{v}$ ,

$$P = Fv \cos \phi = \vec{F} \cdot \vec{v}.$$

## 8 Potential energy and conservation of energy

Types of energies and their formulas:

- Potential energy:  $U(y) = mgh$
- Kinetic energy:  $K = \frac{1}{2}mv^2$
- Spring energy:  $U(x) = \frac{1}{2}kx^2$

### 8.1 Potential energy

★ The net work done by a conservative force on a particle moving around any closed path is zero.

★ The work done by a conservative force on a particle moving between two points does not depend on the path taken by the particle.

★ The gravitational potential energy associated with a particle–Earth system depends only on the vertical position  $y$  (or height) of the particle relative to the reference position  $y = 0$ , not on the horizontal position.

A *conservative force* does zero net work around a closed path and depends only on position (e.g., gravity, springs).

The change in potential energy is related to work by

$$\Delta U = -W = - \int_{x_i}^{x_f} F(x) dx.$$

For potential energy (gravity):

$$\Delta U = mg(y_f - y_i) = mg\Delta y, \quad \text{and if } y_i = 0, \quad U(y) = mgy.$$

For a spring (elastic potential energy):

$$U(x) = \frac{1}{2}kx^2,$$

where  $U = 0$  when the spring is at its relaxed length.

## 8.2 Conservation of mechanical energy

★ In an isolated system where only conservative forces cause energy changes, the kinetic energy and potential energy can change, but their sum, the mechanical energy  $E_{\text{mec}}$  of the system, cannot change.

★ When the mechanical energy of a system is conserved, we can relate the sum of kinetic energy and potential energy at one instant to that at another instant without considering the intermediate motion and without finding the work done by the forces involved.

The total mechanical energy of a system is

$$E_{\text{mec}} = K + U,$$

where  $K$  is kinetic energy and  $U$  is potential energy.

In an isolated system (no external forces), mechanical energy is conserved:

$$K_1 + U_1 = K_2 + U_2,$$

or equivalently,

$$\Delta E_{\text{mec}} = \Delta K + \Delta U = 0.$$

## 8.3 Reading a potential energy curve

For a one-dimensional system, the force is related to the potential energy by

$$F(x) = -\frac{dU(x)}{dx}.$$

The kinetic energy is

$$K(x) = E_{\text{mec}} - U(x),$$

where  $E_{\text{mec}}$  is the total mechanical energy.

A *turning point* occurs when  $K = 0$ , and the particle reverses direction. An *equilibrium point* occurs where  $\frac{dU(x)}{dx} = 0$ , meaning  $F(x) = 0$ .

## 8.4 Work done on a system by an external force

Work is energy transferred to or from a system by means of an external force acting on that system.

If no friction is involved:

$$W = \Delta E_{\text{mec}} = \Delta K + \Delta U.$$

When friction is present, thermal energy changes as well:

$$W = \Delta E_{\text{mec}} + \Delta E_{\text{th}},$$

where the thermal energy increase is

$$\Delta E_{\text{th}} = f_k d,$$

with  $f_k$  being the kinetic friction force and  $d$  the displacement.

## 8.5 Conservation of energy

★ The total energy  $E$  of a system can change only by amounts of energy that are transferred to or from the system.

★ The total energy  $E$  of an isolated system cannot change.

★ In an isolated system, we can relate the total energy at one instant to the total energy at another instant without considering the energies at intermediate times.

The total energy of a system (mechanical + thermal + internal) can only change due to work done on it:

$$W = \Delta E = \Delta E_{\text{mec}} + \Delta E_{\text{th}} + \Delta E_{\text{int}}.$$

For an isolated system ( $W = 0$ ):

$$\Delta E_{\text{mec}} + \Delta E_{\text{th}} + \Delta E_{\text{int}} = 0.$$

**Power** is the rate of energy transfer. Average power:

$$P_{\text{avg}} = \frac{\Delta E}{\Delta t}.$$

Instantaneous power:

$$P = \frac{dE}{dt}.$$

On an energy–time graph, power equals the slope at a given point.

## 9 Center of mass and linear momentum

### 9.1 Center of mass

★ The center of mass of a system of particles is the point that moves as though (1) all of the system's mass were concentrated there and (2) all external forces were applied there.

The center of mass of a system of  $n$  particles is the weighted average of their positions:

$$x_{\text{com}} = \frac{1}{M} \sum_{i=1}^n m_i x_i, \quad y_{\text{com}} = \frac{1}{M} \sum_{i=1}^n m_i y_i, \quad z_{\text{com}} = \frac{1}{M} \sum_{i=1}^n m_i z_i,$$

or in vector form,

$$\vec{r}_{\text{com}} = \frac{1}{M} \sum_{i=1}^n m_i \vec{r}_i,$$

where  $M$  is the total mass of the system.

### 9.2 Newton's second law for a system of particles

The motion of a system's center of mass follows Newton's second law:

$$\vec{F}_{\text{net}} = M \vec{a}_{\text{com}},$$

where  $\vec{F}_{\text{net}}$  is the total external force,  $M$  is the total mass, and  $\vec{a}_{\text{com}}$  is the acceleration of the center of mass.

### 9.3 Linear momentum

★ The time rate of change of the momentum of a particle is equal to the net force acting on the particle and is in the direction of that force.

★ The linear momentum of a system of particles is equal to the product of the total mass  $M$  of the system and the velocity of the center of mass.

For a single particle, linear momentum is defined as

$$\vec{p} = m\vec{v},$$

a vector in the same direction as velocity. Newton's second law can be written as

$$\vec{F}_{\text{net}} = \frac{d\vec{p}}{dt}.$$

For a system of particles,

$$\vec{p} = M\vec{v}_{\text{com}}, \quad \vec{F}_{\text{net}} = \frac{d\vec{p}}{dt}.$$

### 9.4 Collision and impulse

Newton's second law in momentum form gives the impulse-momentum theorem:

$$\vec{p}_f - \vec{p}_i = \Delta\vec{p} = \vec{J},$$

where impulse is

$$\vec{J} = \int_{t_i}^{t_f} \vec{F}(t) dt.$$

For constant average force,

$$J = F_{\text{avg}}\Delta t.$$

When multiple bodies of mass  $m$  collide steadily with a fixed object,

$$F_{\text{avg}} = -\frac{n}{\Delta t}m\Delta v = -\frac{\Delta m}{\Delta t}\Delta v.$$

### 9.5 Conservation of linear momentum

★ If no net external force acts on a system of particles, the total linear momentum  $\vec{P}$  of the system cannot change.

★ If the component of the net external force on a closed system is zero along an axis, then the component of the linear momentum of the system along that axis cannot change.

In a closed and isolated system (no external forces), the total momentum remains constant:

$$\vec{P} = \text{constant}.$$

This can also be written as

$$\vec{P}_i = \vec{P}_f.$$

## 9.6 Momentum and kinetic energy in collisions

In an inelastic collision, kinetic energy is not conserved, but total momentum is:

$$\vec{p}_{1i} + \vec{p}_{2i} = \vec{p}_{1f} + \vec{p}_{2f}.$$

For motion along one axis:

$$m_1 v_{1i} + m_2 v_{2i} = m_1 v_{1f} + m_2 v_{2f}.$$

If the bodies stick together, the collision is *completely inelastic* and they share a common final velocity  $V$ . The velocity of the system's center of mass remains unchanged during the collision.

## 9.7 Elastic collisions in one dimension

★ In an elastic collision, the kinetic energy of each colliding body may change, but the total kinetic energy of the system does not change.

In an elastic collision, both kinetic energy and momentum are conserved. For a one-dimensional collision between two bodies (1 and 2), the final velocities are:

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

Elastic collisions conserve total energy and momentum within the system.

## 9.8 Collisions in two dimensions

If two bodies collide and their motion is not along a single axis, the collision is *two-dimensional*. For a closed and isolated system, momentum is conserved in both directions:

$$\vec{p}_{1i} + \vec{p}_{2i} = \vec{p}_{1f} + \vec{p}_{2f}.$$

In component form, this gives two equations (for  $x$  and  $y$  directions). If the collision is also elastic, kinetic energy is conserved:

$$K_{1i} + K_{2i} = K_{1f} + K_{2f}.$$

## 9.9 Systems with various mass: A rocket

In the absence of external forces, a rocket's acceleration is governed by the thrust equation:

$$Rv_{\text{rel}} = Ma,$$

where  $M$  is the rocket's instantaneous mass,  $R$  is the fuel consumption rate, and  $v_{\text{rel}}$  is the exhaust speed of the fuel relative to the rocket.

For a rocket with constant  $R$  and  $v_{\text{rel}}$ , whose mass changes from  $M_i$  to  $M_f$  while its velocity changes from  $v_i$  to  $v_f$ , the velocity change is given by:

$$v_f - v_i = v_{\text{rel}} \ln \frac{M_i}{M_f}.$$



## 10 Rotation

### 10.1 Rotational variables

- To describe the rotation of a rigid body about a fixed axis, we assume a reference line fixed in the body and perpendicular to the axis of rotation. The angular position  $\theta$  of this line is measured relative to a fixed direction.

$$\theta = \frac{s}{r} \quad (\text{radian measure})$$

where  $s$  is the arc length and  $r$  is the radius of the circular path.

- Radian measure is related to revolutions and degrees by

$$1 \text{ rev} = 360^\circ = 2\pi \text{ rad.}$$

- When a body rotates from  $\theta_1$  to  $\theta_2$ , its angular displacement is  $\Delta\theta = \theta_2 - \theta_1$ , where  $\Delta\theta$  is positive for counterclockwise rotation and negative for clockwise rotation.
- The average angular velocity  $\omega_{\text{avg}}$  is given by

$$\omega_{\text{avg}} = \frac{\Delta\theta}{\Delta t},$$

and the instantaneous angular velocity  $\omega$  is

$$\omega = \frac{d\theta}{dt}.$$

- Both  $\omega_{\text{avg}}$  and  $\omega$  are vectors whose directions are determined by the right-hand rule. Their magnitudes are the angular speed.
- If the angular velocity changes from  $\omega_1$  to  $\omega_2$  over a time interval  $\Delta t = t_2 - t_1$ , the average angular acceleration  $\alpha_{\text{avg}}$  is

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

and the instantaneous angular acceleration  $\alpha$  is

$$\alpha = \frac{d\omega}{dt}.$$

- Both  $\alpha_{\text{avg}}$  and  $\alpha$  are vectors.

## 10.2 Rotation with constant angular acceleration

- Constant angular acceleration ( $\alpha = \text{constant}$ ) is an important special case of rotational motion. The kinematic equations are analogous to those of linear motion:

$$\begin{aligned}\omega &= \omega_0 + \alpha t, \\ \theta - \theta_0 &= \omega_0 t + \frac{1}{2}\alpha t^2, \\ \omega^2 &= \omega_0^2 + 2\alpha(\theta - \theta_0), \\ \theta - \theta_0 &= \frac{1}{2}(\omega_0 + \omega)t, \\ \theta - \theta_0 &= \omega t - \frac{1}{2}\alpha t^2.\end{aligned}$$

## 10.3 Relating the linear and angular variables

- A point in a rigid rotating body, at a perpendicular distance  $r$  from the rotation axis, moves in a circle of radius  $r$ . If the body rotates through an angle  $\theta$ , the point moves along an arc of length

$$s = \theta r \quad (\text{radian measure}),$$

where  $\theta$  is in radians.

- The linear velocity  $\vec{v}$  of the point is tangent to the circular path, and its magnitude (the linear speed) is

$$v = \omega r \quad (\text{radian measure}),$$

where  $\omega$  is the angular speed (in radians per second).

- The linear acceleration  $\vec{a}$  of the point has both tangential and radial components. The tangential component is

$$a_t = \alpha r \quad (\text{radian measure}),$$

where  $\alpha$  is the angular acceleration (in radians per second squared). The radial component is

$$a_r = \frac{v^2}{r} = \omega^2 r \quad (\text{radian measure}).$$

- For uniform circular motion, the period  $T$  (time for one full revolution) is given by

$$T = \frac{2\pi r}{v} = \frac{2\pi}{\omega} \quad (\text{radian measure}).$$

## 10.4 Kinetic energy of rotation

- The kinetic energy  $K$  of a rigid body rotating about a fixed axis is given by

$$K = \frac{1}{2}I\omega^2 \quad (\text{radian measure}),$$

where  $I$  is the rotational inertia (moment of inertia) of the body.

- For a system of discrete particles, the rotational inertia is defined as

$$I = \sum m_i r_i^2,$$

where  $m_i$  is the mass of each particle and  $r_i$  is its perpendicular distance from the axis of rotation.

## 10.5 Calculating the rotational of inertia

- The rotational inertia  $I$  of a body is defined as

$$I = \sum m_i r_i^2$$

for a system of discrete particles, and as

$$I = \int r^2 dm$$

for a body with continuously distributed mass. In these expressions,  $r$  (or  $r_i$ ) is the perpendicular distance from the axis of rotation to each mass element. The integration extends over the entire body to include all mass elements.

- The parallel-axis theorem relates the rotational inertia  $I$  of a body about any axis to that of the same body about a parallel axis through the center of mass:

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

where  $h$  is the perpendicular distance between the two axes,  $I_{\text{com}}$  is the rotational inertia about the axis through the center of mass, and  $M$  is the total mass of the body. The quantity  $h$  represents how far the actual rotation axis is shifted from the center-of-mass axis.

## 10.6 Torque

- Torque is a turning or twisting action on a body about a rotation axis due to a force  $\vec{F}$ . If a force  $\vec{F}$  is applied at a point with position vector  $\vec{r}$  relative to the axis, the magnitude of the torque  $\tau$  is

$$\tau = rF_t = r_{\perp}F = rF \sin \phi,$$

where  $F_t$  is the component of  $\vec{F}$  perpendicular to  $\vec{r}$ , and  $\phi$  is the angle between  $\vec{r}$  and  $\vec{F}$ .

- The quantity  $r_{\perp}$  is the perpendicular distance between the rotation axis and the line of action of  $\vec{F}$ . This distance is called the *moment arm* of  $\vec{F}$ . Similarly,  $r$  is the moment arm of  $F_t$ .
- The SI unit of torque is the newton-meter (N·m). A torque  $\tau$  is positive if it tends to rotate a body counterclockwise, and negative if it tends to rotate the body clockwise.

## 10.7 Newton's second law for rotation

- The rotational analog of Newton's second law is

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

where  $\tau_{\text{net}}$  is the net torque acting on a particle or rigid body,  $I$  is the rotational inertia (moment of inertia) of the particle or body about the rotation axis, and  $\alpha$  is the resulting angular acceleration about that axis.

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