Force and Motion

Galileo (1564-1642): One of the first scientists to experiment on moving objects.

Sir Isaac Newton (1642-1727): Probably the greatest scientist of all time. Formulated the basic laws of motion.

Newton's first law (law of inertia):

An object will remain at rest or in uniform motion in a straight line unless acted upon by an external unbalanced force.

(Aristotle thought the natural state of objects was at rest. Galileo questioned this and Newton disproved it)

Uniform motion in a straight line -> constant velocity.

An object at rest also has constant velocity (v=0).

On Earth, because of friction and gravity, Newton's first law is not obvious. In space it is.

Force: changes velocity of an object. It is a vector quantity.

Even tug of war: balance of forces, no motion.

Uneven tug of war: unbalanced forces, net motion.

inertial: property of matter that resists changes in motion (Galileo).

mass: measure of motion (Newton)
Newton's second law of motion:

Force = mass x acceleration, \( F = m \cdot a \)

Force: unbalanced force

\( F \): mks units \( \text{kg} \cdot \text{m/s}^2 = 1 \text{ N (newton)} \)

\( F \): English units: 1 lb

weight: a force, can be expressed in newtons in MKS or in pounds in English system.

Average sized apple weighs about 1 N.

\[
\begin{align*}
F_1 &= 5.0 \text{ N} \\
\text{m}_1 &= 1.0 \text{ kg} \\
&<-
\end{align*}
\]

\[
\text{a} \rightarrow \begin{align*}
F_2 &= 8.0 \text{ N} \\
\text{m}_2 &= 1.0 \text{ kg} \\
&\rightarrow
\end{align*}
\]

Assume strings are massless and there is no friction

\[
(F_2 - F_1) = (m_1 + m_2) \cdot a \\Rightarrow a = \frac{(F_2 - F_1)}{(m_1 + m_2)} = \frac{3}{2} = 1.5 \text{ m/s}^2
\]

If the surface were not frictionless?
If string were not massless?

Additional forces are needed to model these effects.
Newton's second law is contained in Newton's first law.

We experience Newton's laws in our everyday lives; example: car mileage on highway compared with in city.

What is weight?

mass: amount of matter or inertia an object contains

weight: measure of the force of gravity

\[ w = m \cdot g; \quad g = 9.8 \text{ m/s}^2 \quad \leq g \text{ for Earth} \]

\[ F = m \cdot a; \quad w = F, \quad g = a \]

On moon, \( g = 9.8/6 \text{ m/s}^2 \)

mass is the same, however weight on the moon is 1/6 that of Earth

Computing weight

\[ m = 1 \text{ kg} \]

\[ w \text{ (Earth)} = 1 \text{ kg} \cdot 9.8 \text{ m/s}^2 = 9.8 \text{ N} \]

\[ w \text{ (moon)} = 9.8/6 = 1.6 \text{ N} \]
Work and Energy

work = force times parallel distance

\[ W = F \ d \]

**Diagram:**

- From 1 to 2 with distance \( d \)

**Example Diagrams:**

1. \( F \rightarrow \quad d \quad \rightarrow \quad W = F \ d \)
2. \( F \rightarrow \quad W = 0 \)
3. \( F \rightarrow \quad \rightarrow \quad F \rightarrow \quad F_h \quad d \quad W = F_h \ d \)

- Work: scalar quantity
- Force: vector quantity
- Parallel distance: vector quantity
Work: units are Joules = N·m

English: ft·lb

Ways in which work can be done:

1) against inertia

inertia: property of an object to stay at rest or in constant straight-line motion

When a force is applied to change the speed or direction of an object, work is done against inertia.

\[ W = F \cdot d \]

\[ v = 0 \quad \text{and} \quad v = 2 \text{ m/s} \]

2) Against gravity

3) Against friction

\[ W = \text{mgh} \]

\[ \text{work done against friction} \]
Kinetic energy and potential energy

Work and energy are related. When work is done, there is a change in energy

energy: the ability to do work (Joules)

work: The process by which energy is transferred from one object to another (Joules).

work, energy: scalar quantities

kinetic energy: energy of motion

\[ E_k = \frac{1}{2} m v^2 \]

\( E_k \) is the work that would have to be done to bring the object to rest.

work: change in kinetic energy

\[ W = \Delta E_k = E_{k2} - E_{k1} = \frac{1}{2} m v_1^2 - \frac{1}{2} m v_2^2 \]
Relating speed and kinetic energy

\[ v_1 = 30 \text{ km/h} \quad v_2 = 50 \text{ km/h} \]

By what factor is the kinetic energy increased?

\[ \frac{E_2}{E_1} = \left( \frac{v_2}{v_1} \right)^2 = \left( \frac{50}{30} \right)^2 = \frac{25}{9} \approx 2.8 \]

It takes an amount of work equal to the kinetic energy to stop a moving automobile. This work is provided by the tire friction.

breaking distance: distance, \( d_B \), a car travels after the break (breaking force, \( F_B \)) is applied.

The breaking distance increases with the square of the velocity:

\[ F_B d_B = \frac{1}{2} m v^2 \]

\[ d_B = \frac{1}{2} \frac{m v^2}{F_B} \]

20 mi/h : \( d_B = 8 \text{ m} \)

30 mi/h : \( d_B = 22 \text{ m} \)
Potential Energy

potential energy: energy that a body has that is not being spent.

![Diagram of a book being raised](image)

work was done against gravity to raise book, therefore book now has more potential energy. If book were to fall, it's velocity would be greater upon landing.

\[ E_p = W = m g h \]

potential energy due to gravity or work done against gravity

If \( m = 1.0 \text{ kg} \) and \( h = 1 \text{ m} \),

\[ E = W = 1.0 \text{ kg} \times 9.8 \text{ m/s} \times 1.0 \text{ m} = 9.8 \text{ J} \]

Other examples of potential energy:

- compression of stretching of a spring
- drawing back a bow
Conservation of Energy

conservation of energy: the total energy of an isolated system remains constant

\[
\text{(total energy)}_{\text{time 1}} = \text{(total energy)}_{\text{time 2}}
\]

\[
(E_k + E_p)_{\text{time 1}} = (E_k + E_p)_{\text{time 2}}
\]

conservation of mechanical energy:

\[
(1/2 \, m \, v^2 + m \, g \, h)_{\text{time 1}} = (1/2 \, m \, v^2 + m \, g \, h)_{\text{time 2}}
\]
Finding potential and kinetic energy

At point c: \[ E_k = \frac{1}{2} m v^2 = \frac{1}{2} (50 \text{ kg}) v_3^2, \]
\[ E_p = m g h = (50 \text{ kg})(9.8 \text{ m/s}^2)(10 \text{ m}) = 4900 \text{ J} \]

\[ E_k = \frac{1}{2} m v_3^2 = 12250 - 4900 \text{ J} = 7350 \text{ J} \]

\[ v_3 = \sqrt{\frac{(2)(7350 \text{ J})}{50 \text{ kg}}} = 17 \text{ m/s} \]

At point d: \[ E_k = \frac{1}{2} m v^2 = \frac{1}{2} (50 \text{ kg}) v_4^2, \]
\[ E_p = 0, \]
\[ v_4 = \sqrt{\frac{(2)(12250 \text{ J})}{50 \text{ kg}}} = 22 \text{ m/s} \]
Finding potential and kinetic energy

At point a: \( E_k = \frac{1}{2} m v^2 = 0 \),
\[ E_p = m g h = (50 \text{ kg})(9.8 \text{ m/s}^2)(15 \text{ m}) = 12250 \text{ J} \]
\[ E_k + E_p = 12250 \text{ J always} \]

At point b: \( E_k = \frac{1}{2} m v^2 = \frac{1}{2} (50 \text{ kg}) v_2^2 \),
\[ E_p = m g h = (50 \text{ kg})(9.8 \text{ m/s}^2)(15 \text{ m}) = 7350 \text{ J} \]
\[ E_k = \frac{1}{2} m v_2^2 = 12250 - 7350 \text{ J} = 4900 \text{ J} \]
\[ v_2 = \sqrt{(2)(4900 \text{ J}) / (50 \text{ kg})} = 14 \text{ m/s} \]
Power

power: time rate of doing work

\[ \text{power} = \frac{\text{work}}{\text{time}} \]

\[ p = \frac{W}{t} \text{ (Joules/s = Watt (W))} \]

Which requires more power?

a) To move furniture in one hour

b) To move the same furniture in three hours

The answer is a)

British system: ft-lb/s or horsepower

1 horsepower (hp) = 550 ft-lb/s = 746 W

The greater the power of an engine or motor, the faster it can do work.

2 hp motor can do twice as much work as a 1-hp motor in the same time.
Computing Power

\[ F = 50 \text{ N} \rightarrow \quad d = 10 \text{ m} \rightarrow \quad t = 20 \text{ s} \]

\[ p = \frac{(50 \text{ N})(10 \text{ m})}{20 \text{ s}} = 25 \text{ W} \]

(Note: \( W \) sometimes means work and sometimes means watts)

work: produces a change in energy

power = \frac{\text{energy produced or consumed}}{\text{time taken}}

\[ p = \frac{E}{t} \]

\[ E = p \times t \]

watt-hr: unit of energy

kilowatt-hr = 100 watt-hrs: unit of energy

Electric power companies charge for the electricity consumed in units of kilowatt-hrs.
Relating Power and Energy

1 hp motor operates for 10 hours. How much energy did it produce?

\[
E = 1 \text{ hp} \times 10 \text{ h} \times \frac{746 \text{ W}}{1 \text{ hp}} \times \frac{1 \text{ kW}}{1000 \text{ W}} = 7.5 \text{ kW-h}
\]