General

Physics 101

Energy of a System

Prepared By

Prof. Rashad Badran

Work and Energy

- Work Done by a Constant Force and Some Applications
- Work Done by a Varying Force and Some Applications
- Potential Energy of a System
- Conservative and Non-conservative Forces
- Relationship Between Conservative Forces and Potential Energy
- Kinetic Energy and Work-Kinetic Energy Theorem
- Power

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Work Done by a Force

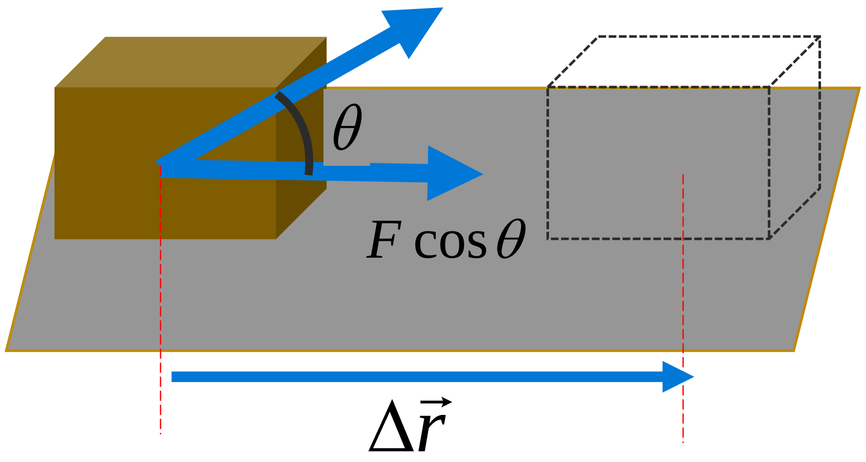
Work Done by a Constant Force:

$$W = \vec{F} \bullet \Delta\vec{r}$$

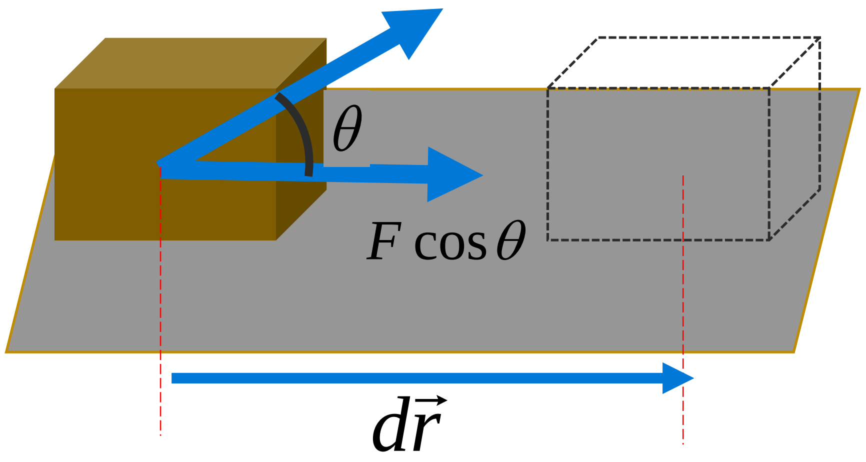
Work Done by a Varying Force:

$$W = \int_{r_1}^{r_2} \vec{F} \bullet d\vec{r}$$

$\vec{F} =$ **constant**



$\vec{F} =$ **variable**



- F is the magnitude of the force $\vec{F}$
- Δ r (or dr) is the magnitude of the object's displacement
- θ is the angle between $\vec{F}$ and $\Delta\vec{r}$ (or $d\vec{r}$)

Units of Work

Work = (Force) × (Displacement)

= (Newtons) × (meters) **(in SI Units)**

(Newton) × (meter) → **Joule (J)**

or (kg. m^2/s^2) → **Joule (J)** *

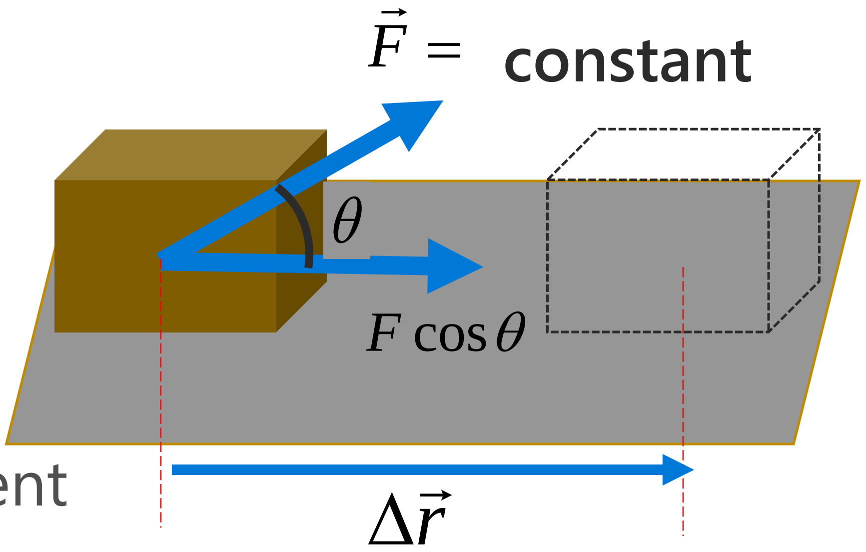
*** Joule is named after James Prescott Joule (1818-1889) who made major contributions to the understanding of energy, heat, and electricity**

Work Done by a Force

Work Done by a Constant Force: (A Scalar Quantity)

- The work, *W*, done by a constant force on an object is defined as the product of the component of the force along the direction of displacement and the magnitude of the displacement

$$W \equiv (F\cos\theta)\Delta r$$



- F is the magnitude of the force
- Δ r is the magnitude of the object's displacement
- θ is the angle between $\vec{F}$ and $\Delta\vec{r}$

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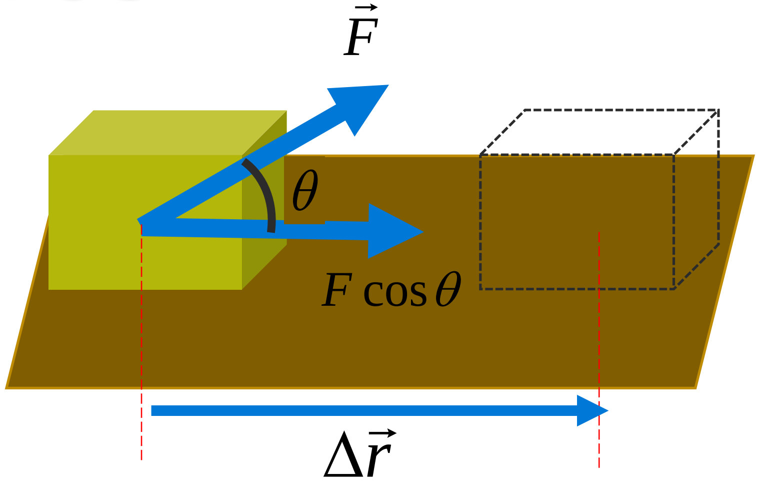
Work Done by a Force

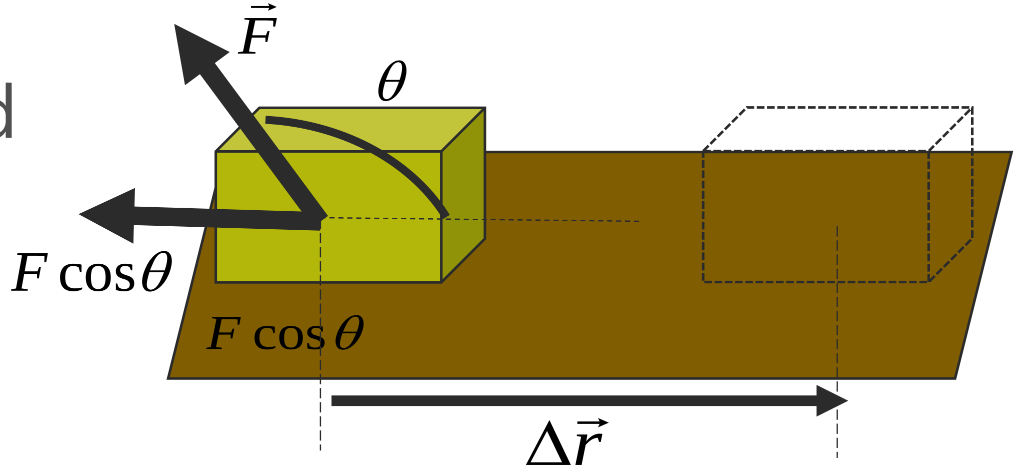
- Positive scalar quantity$\Rightarrow$ when force and displacement are both in the same direction

$$W = (F\cos\theta)\Delta r \equiv= +ve$$



- Negative scalar quantity $\Rightarrow$ when force and displacement are in opposite directions

$$W = (F\cos\theta)\Delta r \equiv= -ve$$



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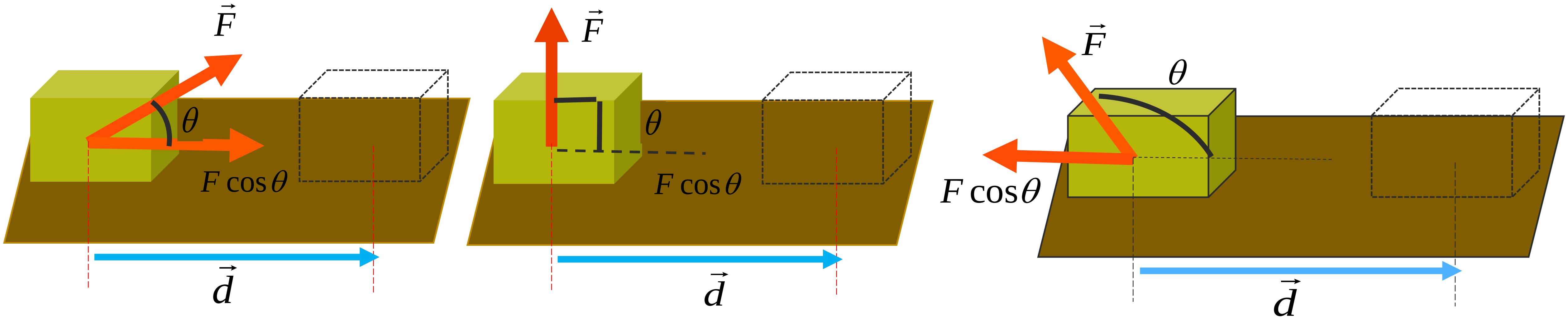
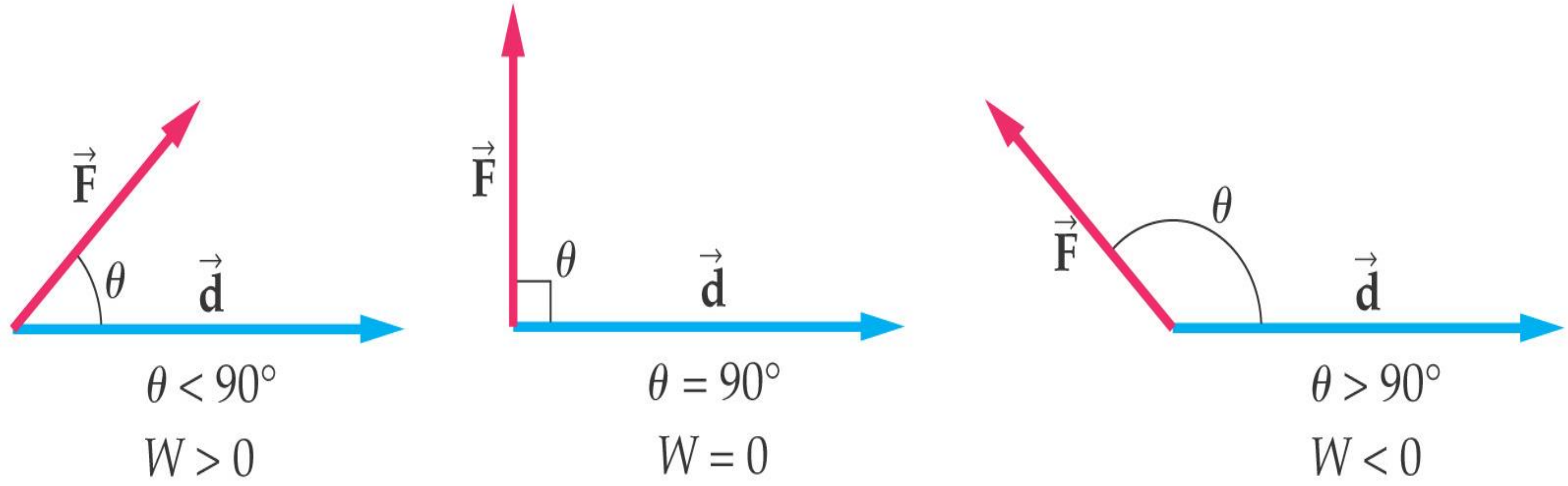
Work Done by a Force





Work Done by a Force

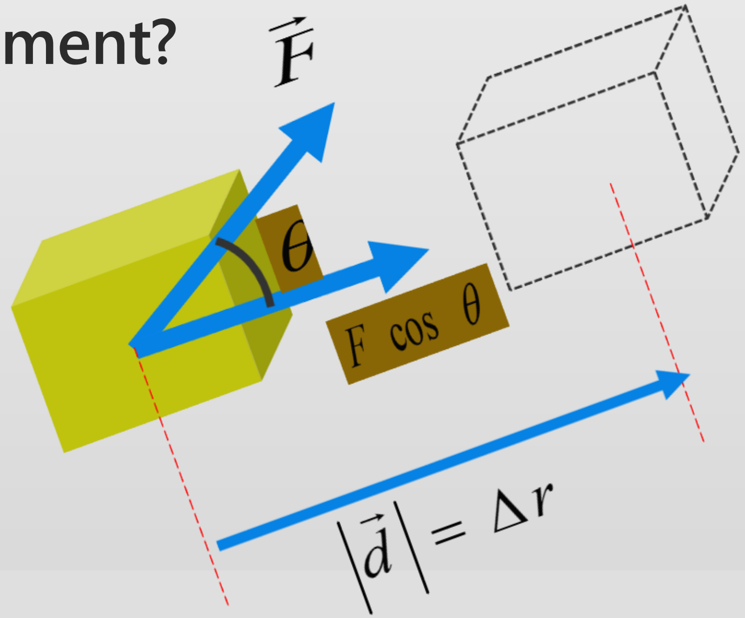
Example

A particle moving in the xy plane undergoes a displacement given by $\Delta\vec{r} = (2\hat{i} + 3\hat{j})m$ as a constant force $\vec{F} = (5\hat{i} + 2\hat{j})N$ acts on the particle.

(a) Calculate the magnitude of the force and the displacement of the particle.

(b) Calculate the work done by the force on the particle

(c) What is the angle between the force and displacement?



Work Done by a Force

Solution

Given: $\Delta\vec{r} = (2\hat{i} + 3\hat{j})m$ $\vec{F} = (5\hat{i} + 2\hat{j})N$

(a) To calculate the magnitude of the force and the displacement of the particle:

$$F = \sqrt{5^2 + 2^2} = 5.38N \qquad \Delta r = \sqrt{2^2 + 3^2} = 3.6m$$

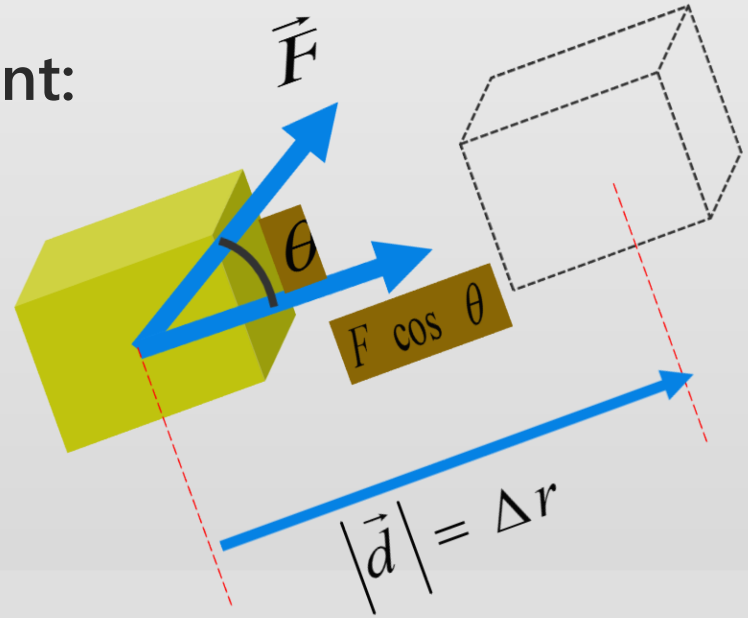
(b) To calculate the work done by the force on the particle:

$$W = \vec{F} \bullet \Delta\vec{r} \qquad \Rightarrow W = (5\hat{i} + 2\hat{j}) \bullet (2\hat{i} + 3\hat{j}) = 10 + 6 = 16J$$

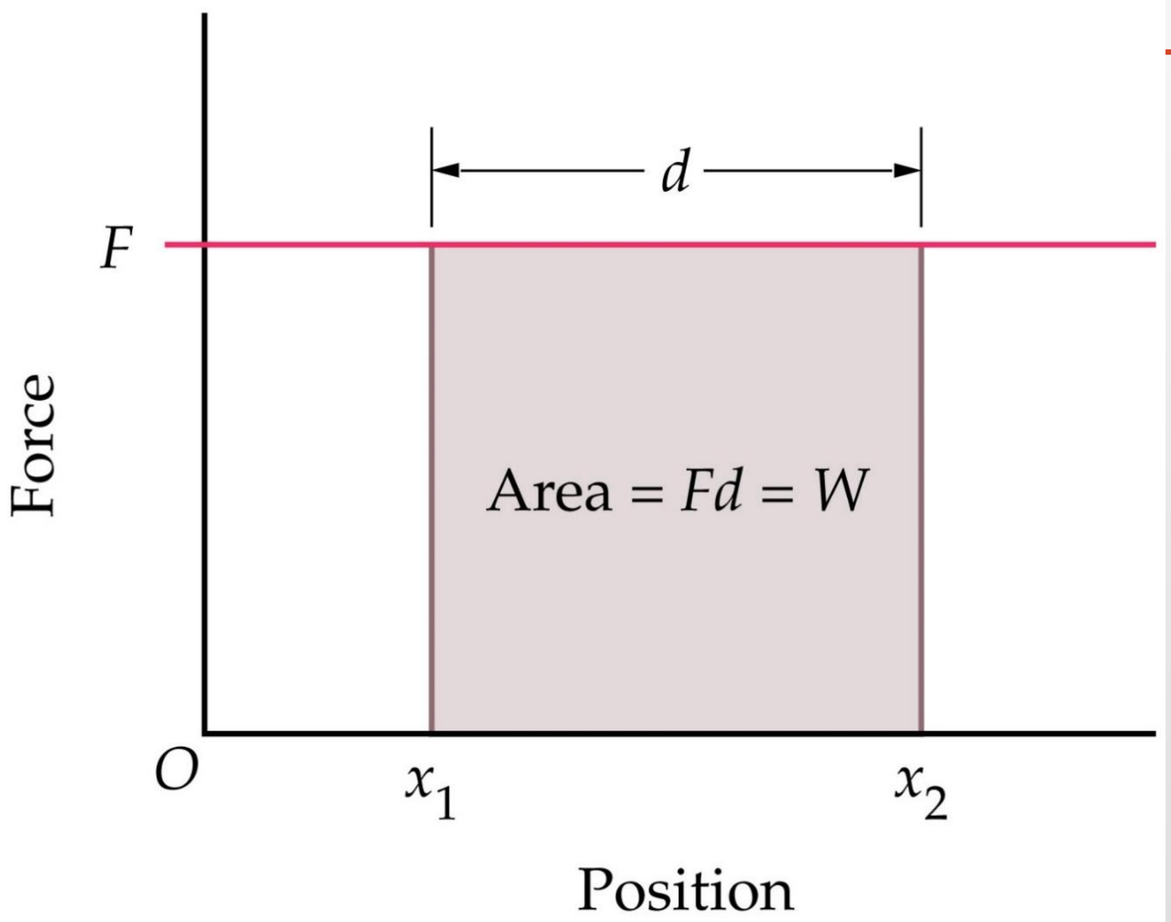
(c) To find the angle between the force and displacement:

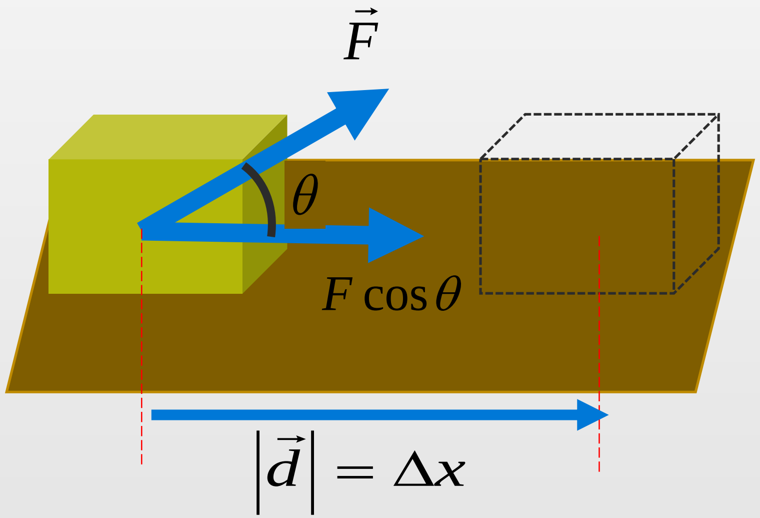
$$\cos\theta = \frac{\vec{F} \bullet \Delta\vec{r}}{(F)(\Delta r)} = \frac{16J}{(5.38N)(3.6m)}$$

$$\cos\theta = 0.826 \qquad \theta = \cos^{-1}(0.826) = 34.3^o$$



Work Done by a Force





$$W = F_x \Delta x = Fd$$

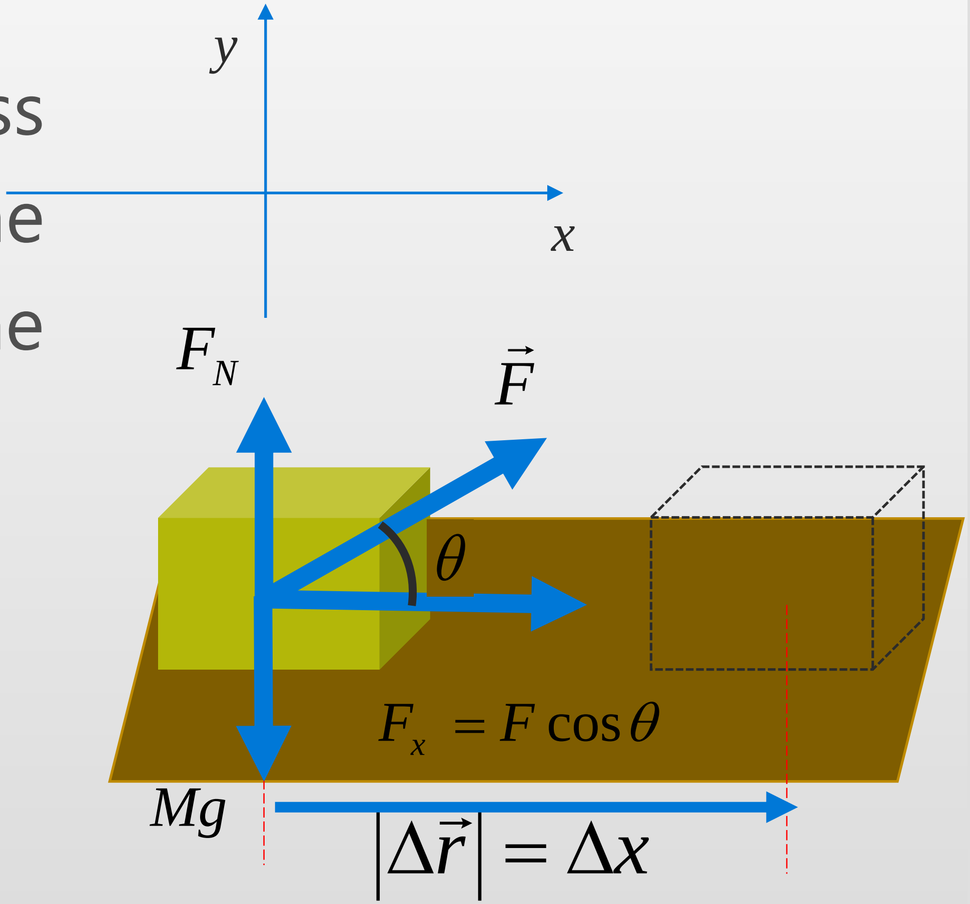
, where $F_x = F$ and $\Delta x = d$

Work Done by Several Forces

- If several forces act on an object of mass *M*, then the total work is equal to the algebraic sum of the work done by the individual forces

$$W_{net} = \sum_{i=1}^{m} W_i \qquad i = 1, 2, 3 \ldots m,$$

where m is the number of forces



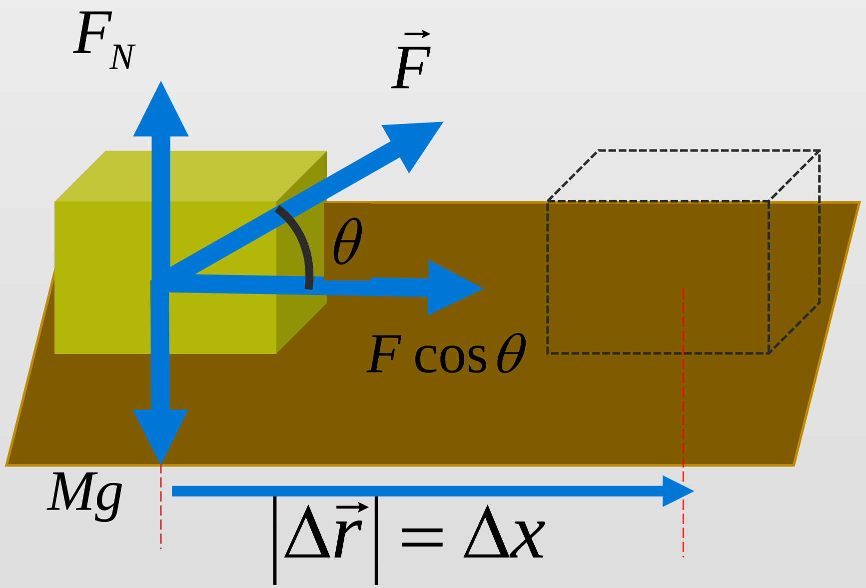
- In the shown figure, three forces act on the object of mass M, namely: F_N, Mg and $\vec{F}$

Work Done by Several Forces

- You should remember that the work is a scalar quantity, and the algebraic sum of the work done by the three forces is:

$$W_{net} = W_g + W_N + W_F$$

but, $W_g = W_N = 0$, because F_N and Mg are both perpendicular to $\Delta\vec{r}$.



Thus $W_{net} = W_F = (F\cos\theta)\Delta x$

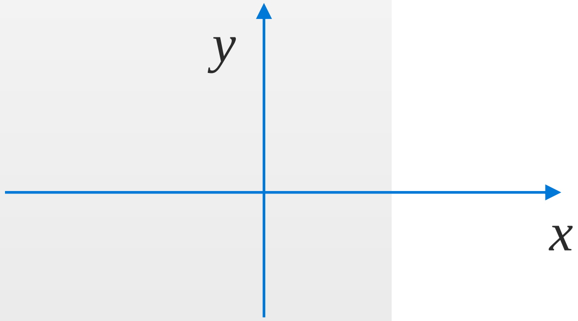
where $|\Delta\vec{r}| = \Delta x$

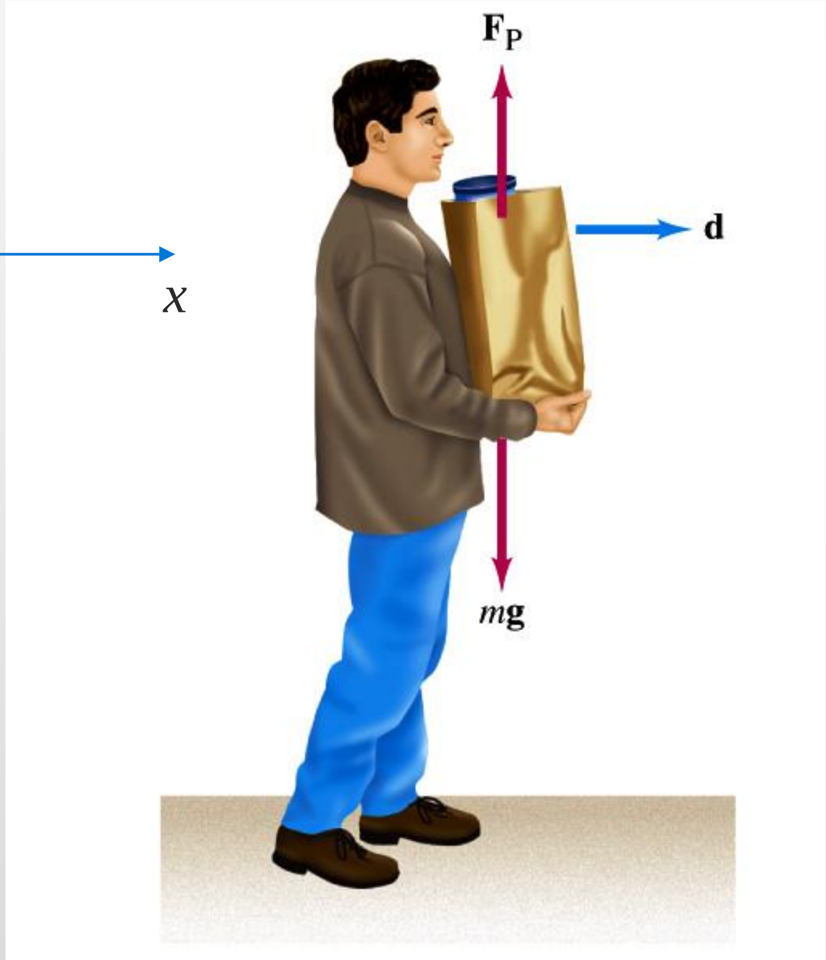
Work Done by Several Forces

Example In the figure shown, find the net work done on the bag.

Solution

$$W_{net} = W_{F_p} + W_g$$





$$W = (F\cos\theta)\Delta r$$

Here, $\Delta r = d$

$$W = (F\cos\theta)d$$

$$W_{F_p} = W_g = 0$$

Again this is because F_p and mg are perpendicular to d

$$W_{net} = 0$$

Conclusion: All forces perpendicular to the displacement do NOT give work.

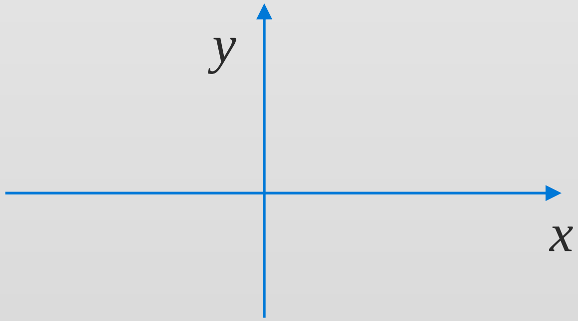
Satellite in a Circular Motion

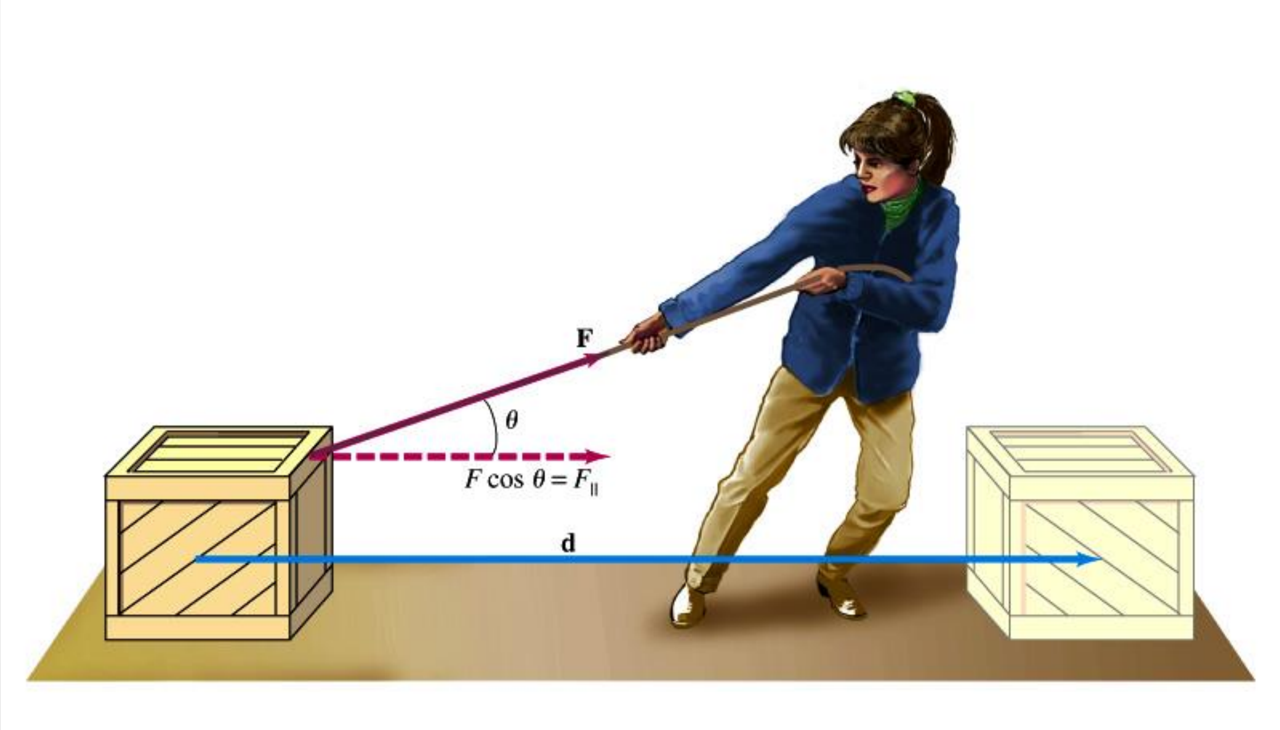
Does the Earth do work on the satellite?

Work Done by Several Forces

Example

A 50.0-kg crate is pulled 40.0 m by a person with a constant force (F = 100 N and θ = 37.0°). A friction force f_k = 50.0 N is exerted on the crate. Determine the work done by each force acting on the crate. What is the net work?





Work Done by Several Forces

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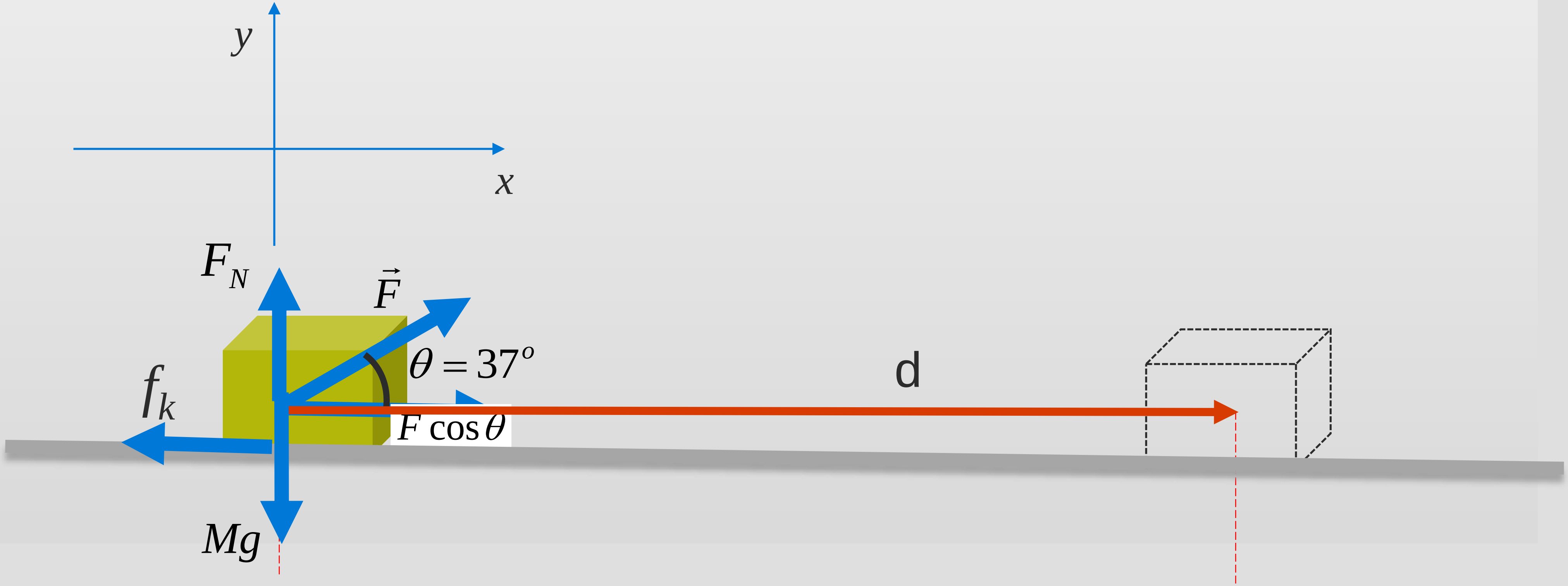


Work Done by Several Forces

A 50.0-kg crate is pulled 40.0 m by a person with a constant force (F = 100 N and θ = 37.0º). A friction force f_k = 50.0 N is exerted on the crate. Determine the work done by each force acting on the crate. What is the net work?

Solution

$$W = (F\cos\theta)\Delta r$$

$$W_{F_N} = W_g = 0$$

because F_N and mg are perpendicular to d.

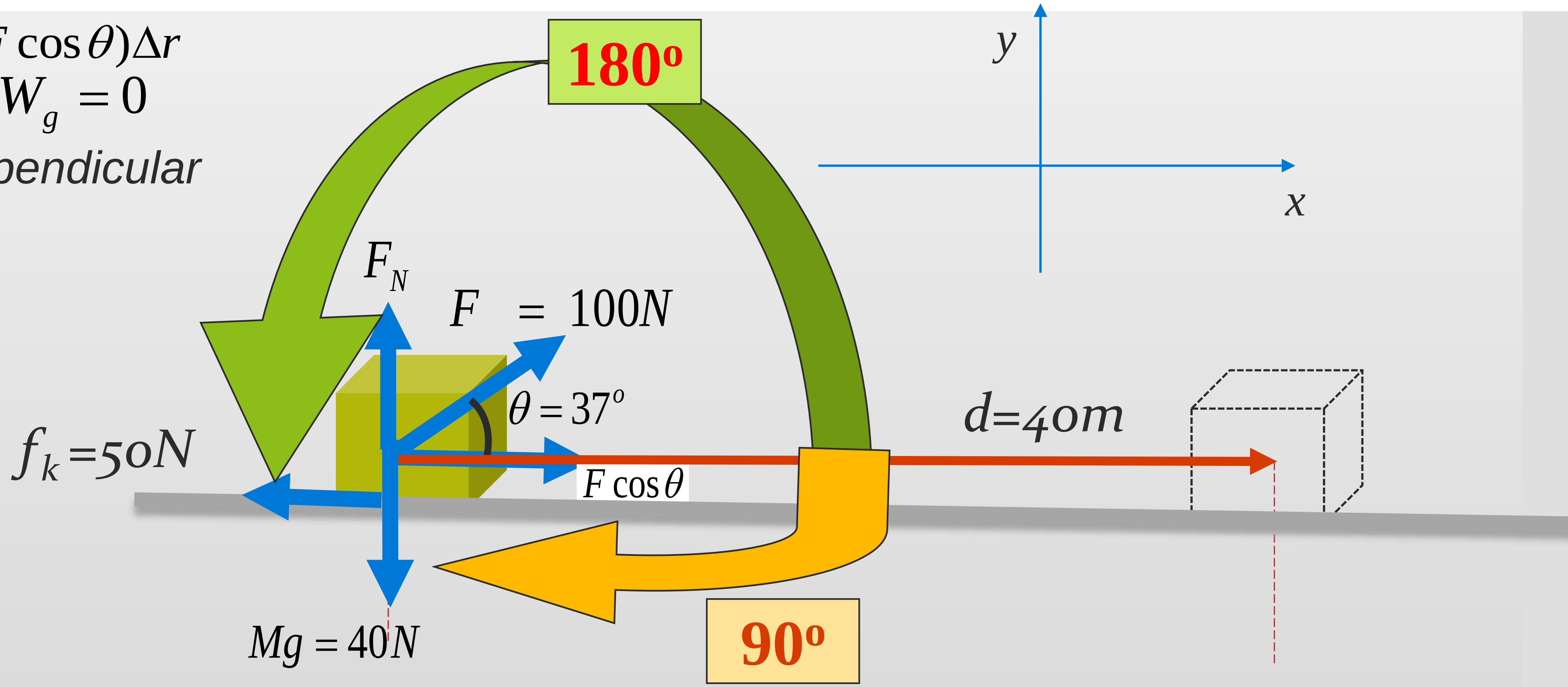
$$W_F = (F\cos\theta)d$$

$$\Rightarrow= (100N\cos 37^o)(40m)$$

$$W_F = 3194.5J$$

$$W_f = (f\cos 180^o)d$$

$$W_f = -(50N)(40m) = -2000J$$

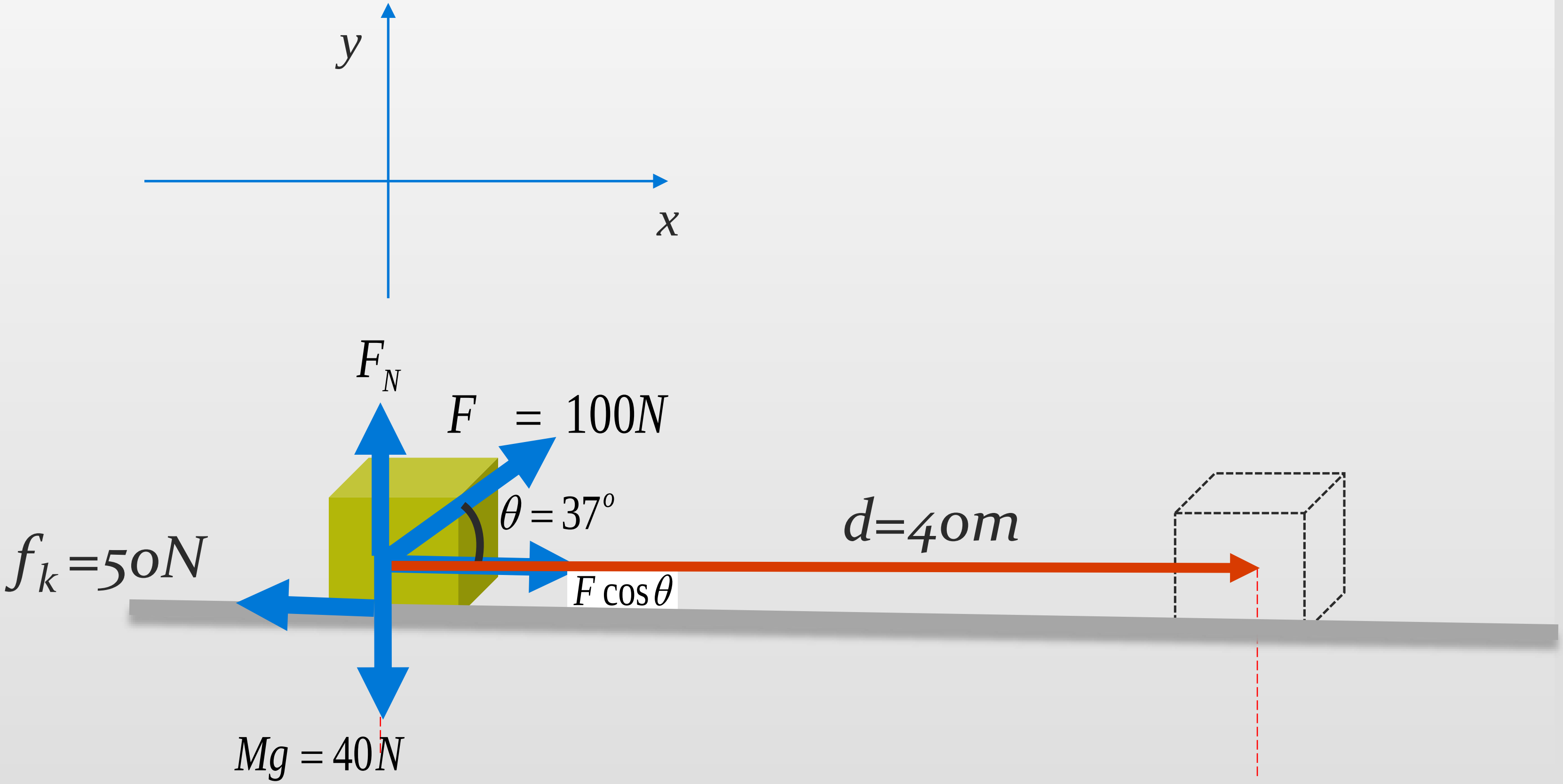


Work Done by Several Forces

Solution

$$W_{net} = \sum_{i=1}^{m} W_i$$

$$W_{net} = 3194.5 - 2000 = 1194.5J$$

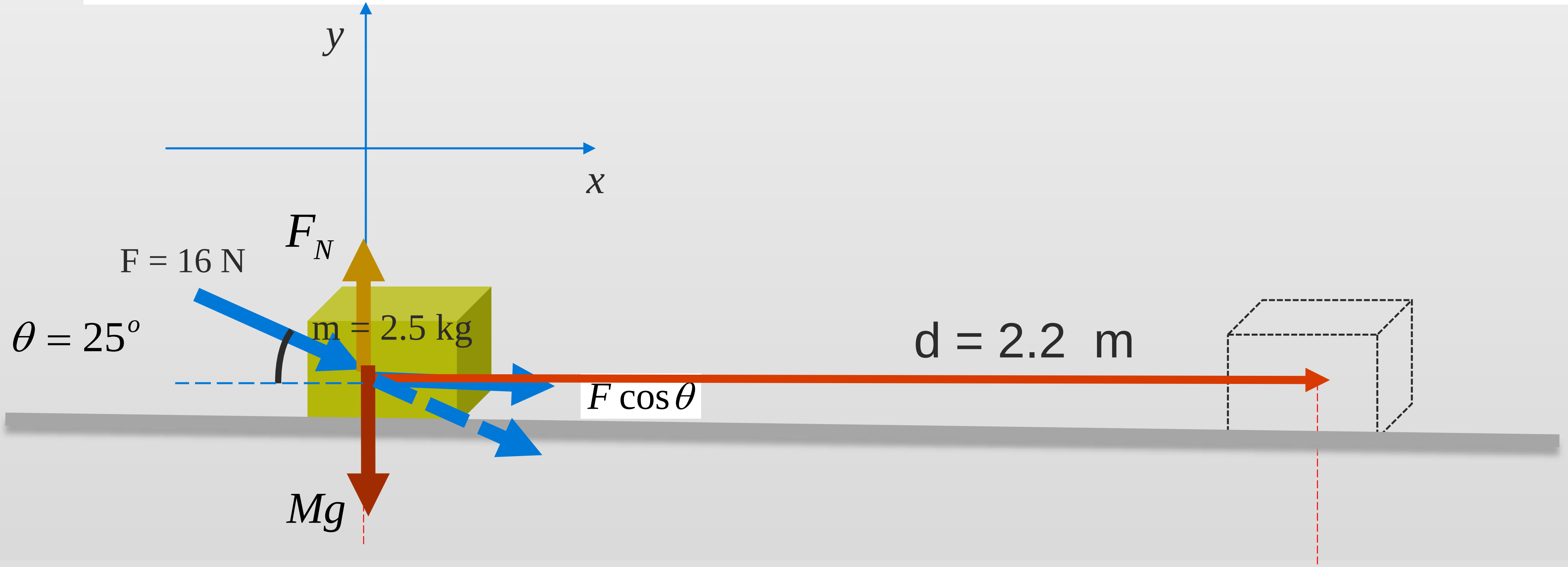


Note: The net work done on the crate is positive. There is an increase in the crate's velocity

Work Done by Several Forces

Example

A block of mass m = 2.5 kg is pushed a distance d = 2.2 m along a frictionless horizontal table by a constant applied force of magnitude F = 16 N directed at angle θ = 25.0º below the horizontal as shown. Determine the work done on the block by (a) the applied force, (b) the normal force exerted by the table, (c) the gravitational force, (d) the net force on the block, and (e) If a friction between block and table does exist and exerts a work of 11.2 J against the motion of the block find the coefficient of kinetic friction



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Work Done by Several Forces

Solution

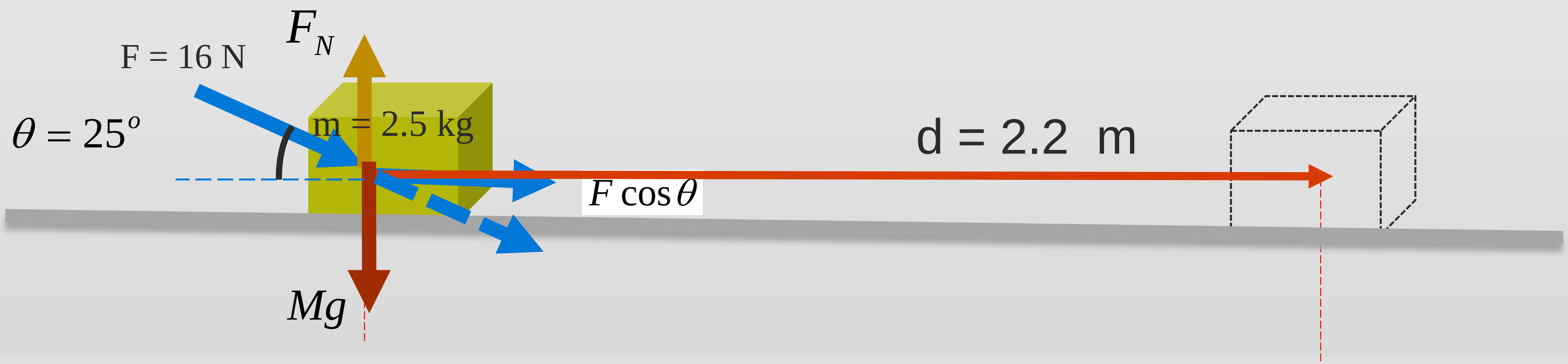
Given: m = 2.5 kg, d = 2.2 m, *F* = 16 N, θ = 25.0º

(a) To find the work done by the applied force:

$$W_F = (F\cos\theta)d$$

$$\Rightarrow = (16N\cos 25^o)(2.2m)$$

$$W_F = 70.2J$$



Work Done by Several Forces

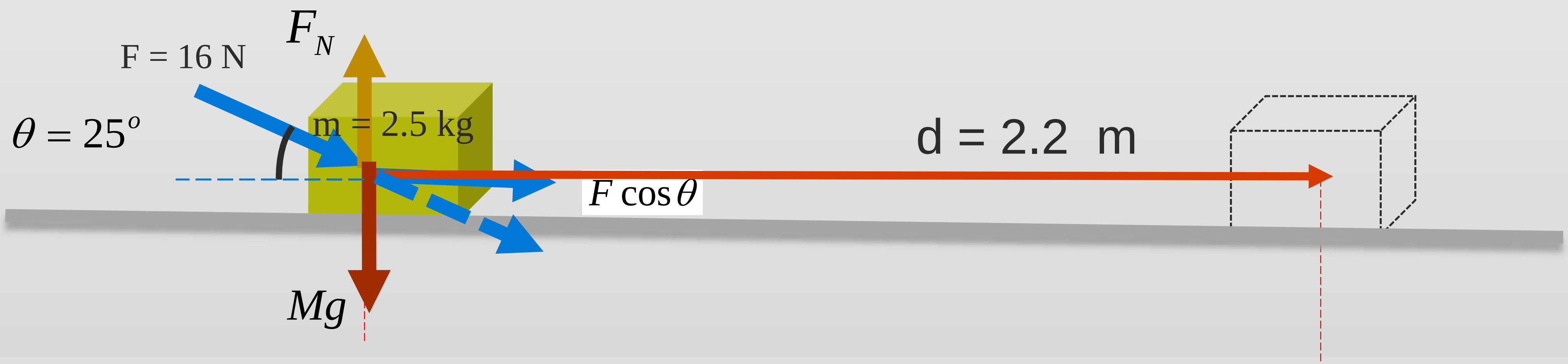
Solution

Given: m = 2.5 kg, d = 2.2 m, *F* = 16 N, θ = 25.0º

(b) , (c) To find the work done by the normal force exerted by the table and by the gravitational force:

$$W = (F\cos\theta)\Delta r$$

$$W_{F_N} = W_g = 0,$$ *because F_N and mg are perpendicular to d.*



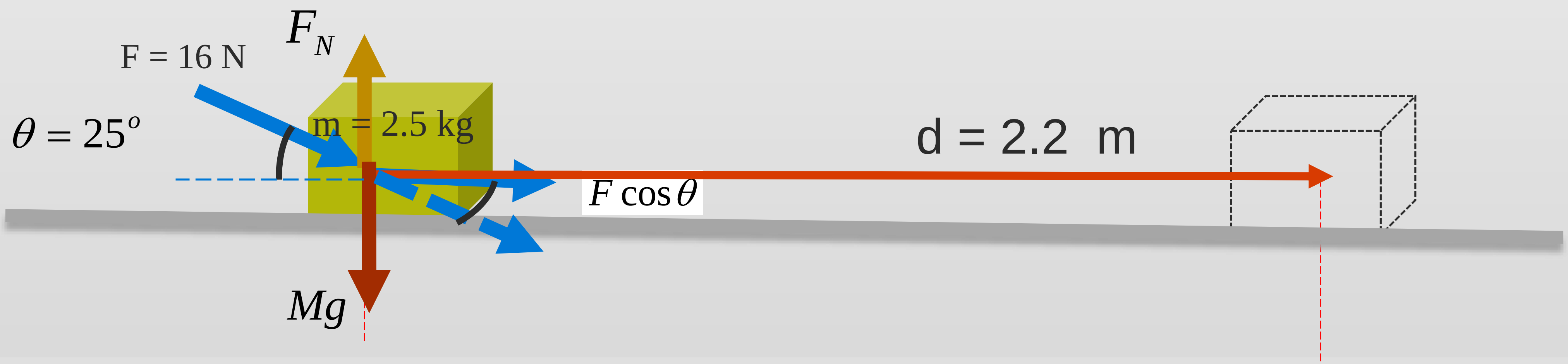
Work Done by Several Forces

Solution

Given: m = 2.5 kg, d = 2.2 m, F = 16 N, θ = 25.0º

(d) To find the work done by the net force on the block.

$$W_{net} = W_F = (F\cos\theta)d = 70.2J$$



Work Done by Several Forces

Solution

Given: m = 2.5 kg, d = 2.2 m, F = 16 N, θ = 25.0º

(e) To find the coefficient of kinetic friction when work done by frictional force is 11.2 J when friction between table and block does exist:

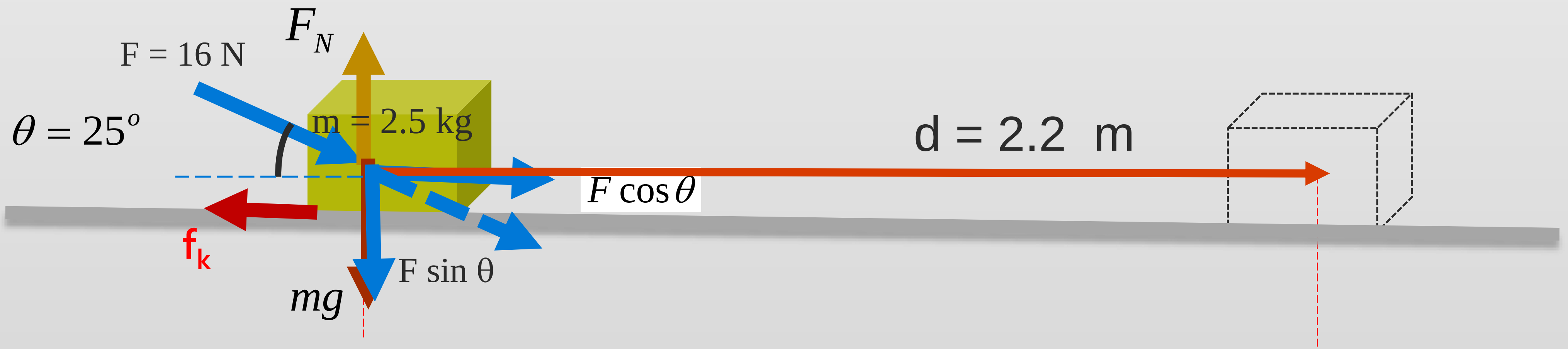
$$W_f = (f\cos 180^o)d$$
$$W_f = -f_k d$$
$$11.2J = -f_k(2.2m)$$
$$f_k = -5.1N$$
$$f_k = \mu_k F_N = 5.1\ N$$

$\Sigma F_y = 0 \Rightarrow F_N - mg - F\sin\theta = 0$

Or $\Rightarrow F_N = mg + F\sin\theta$

$\Rightarrow F_N = (2.5kg)(9.8m/s^2) + (16N)\sin 25 = 31.26N$

$\Rightarrow (5.1N) = \mu_k(31.26N) \Rightarrow \mu_k = 0.16$

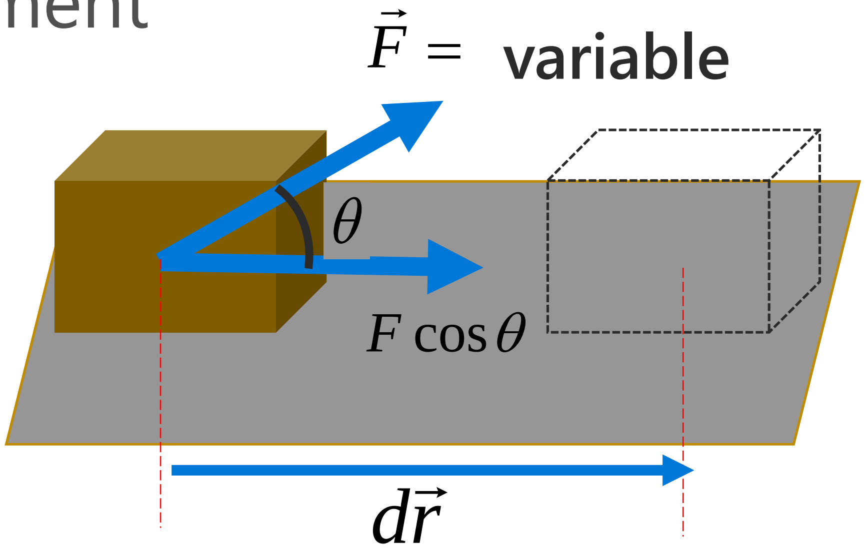


Work Done by a Varying Force

Work Done by a Varying Force: (A Scalar Quantity)

- Again the work, W_F, done by a varying force on an object is defined as the product of the component of the force along the direction of displacement and the magnitude of the displacement

$$W_F \equiv \int_{r_1}^{r_2} (F\cos\theta)\,dr$$



- F is the magnitude of the force
- dr is the magnitude of the object's displacement
- θ is the angle between $\vec{F}$ and $d\vec{r}$

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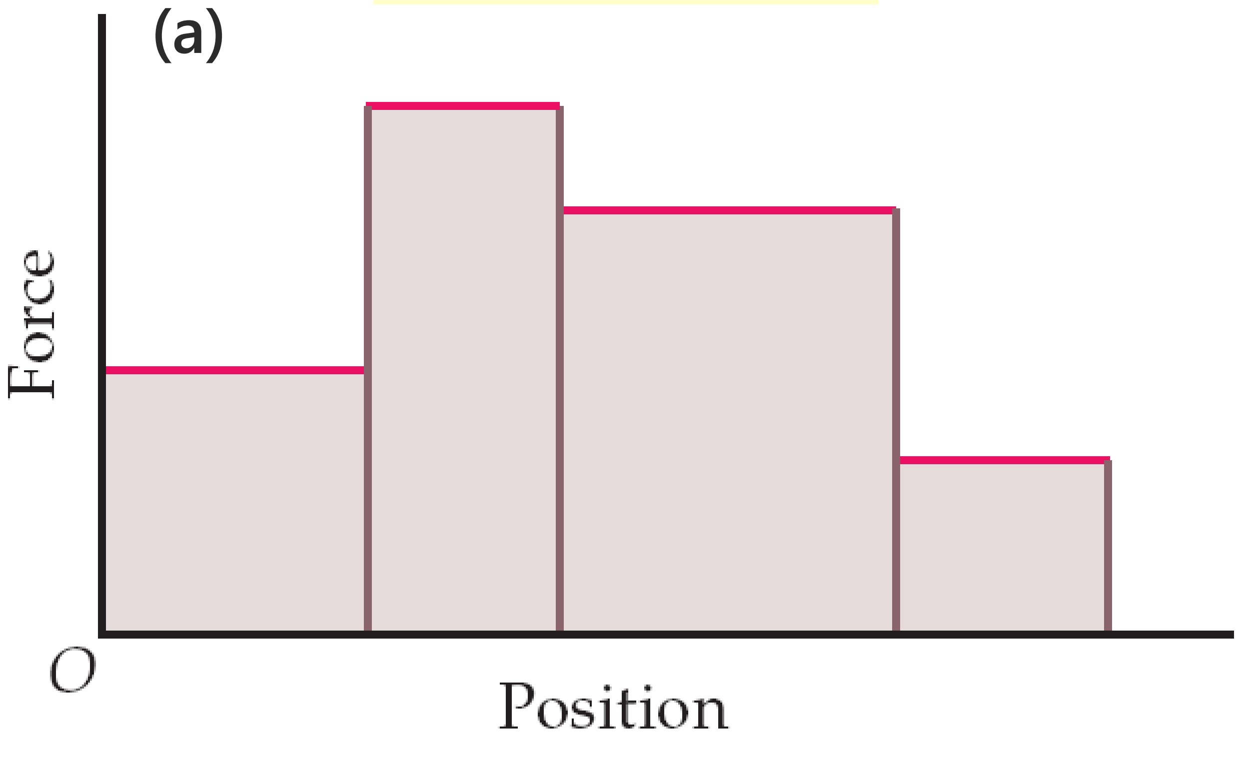
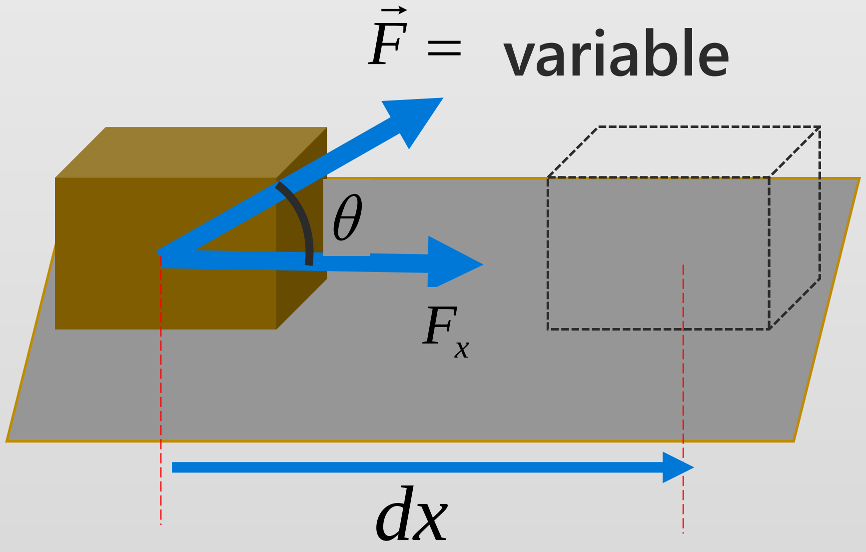
Work Done by a Varying Force

$$W_F \equiv \int_{x_1}^{x_2} F_x\,dx$$

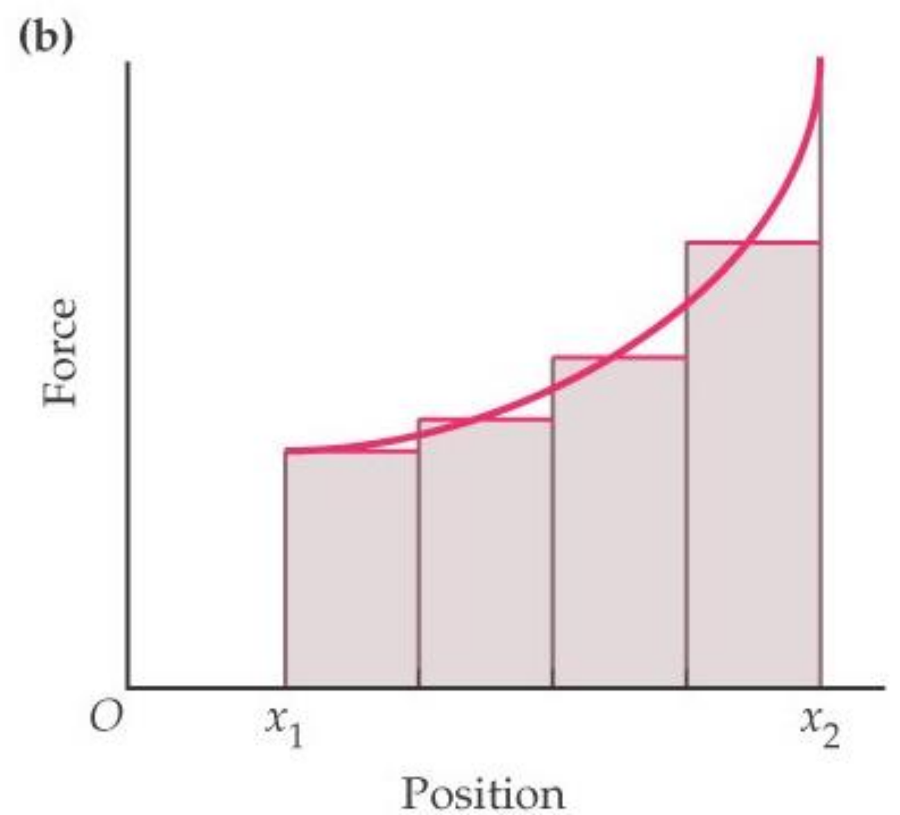


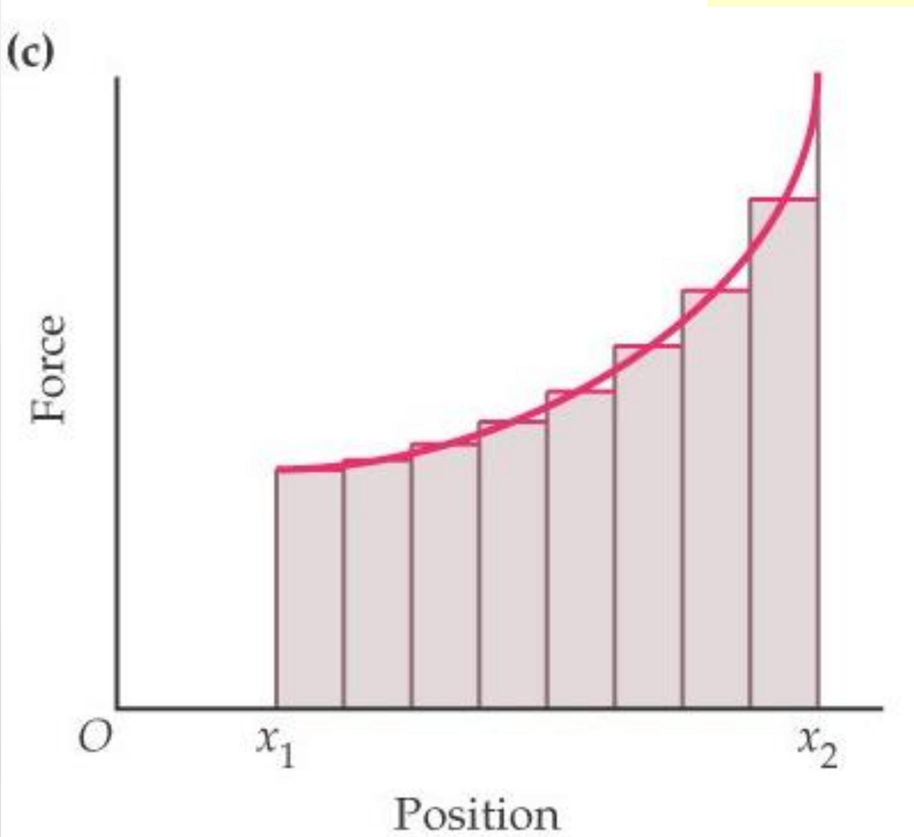


Work Done by a Varying Force

The sum of rectangular areas under the curve can be approximated as the area of the curve for a continuously varying force when number of rectangles increases (from Figure b to c). Thus

$$W_F \equiv \sum_i F_i (\Delta x)_i$$





$$W_F \equiv \int_{x_1}^{x_2} F_x dx$$

Work Done by Several Forces

Example

A force $\vec{F} = (4x\hat{i} + 3y\hat{j})N$, where x and y are in meters, acts on a an object as the object moves in the x- direction from the origin to $x = 5\ m$. Find the work done by the force on the object.

Solution

$$W_F = \int_{r_1}^{r_2} \vec{F} \bullet d\vec{r}$$

Since $d\vec{r} = dx\hat{i} + dy\hat{j}$ *, and the object moves in the x-direction and there is no change in y-direction, then dy = 0*

$$\therefore d\vec{r} = dx\hat{i}$$

$$\vec{F} \bullet d\vec{r} = (4x\hat{i} + 3y\hat{j}) \bullet dx\hat{i}$$

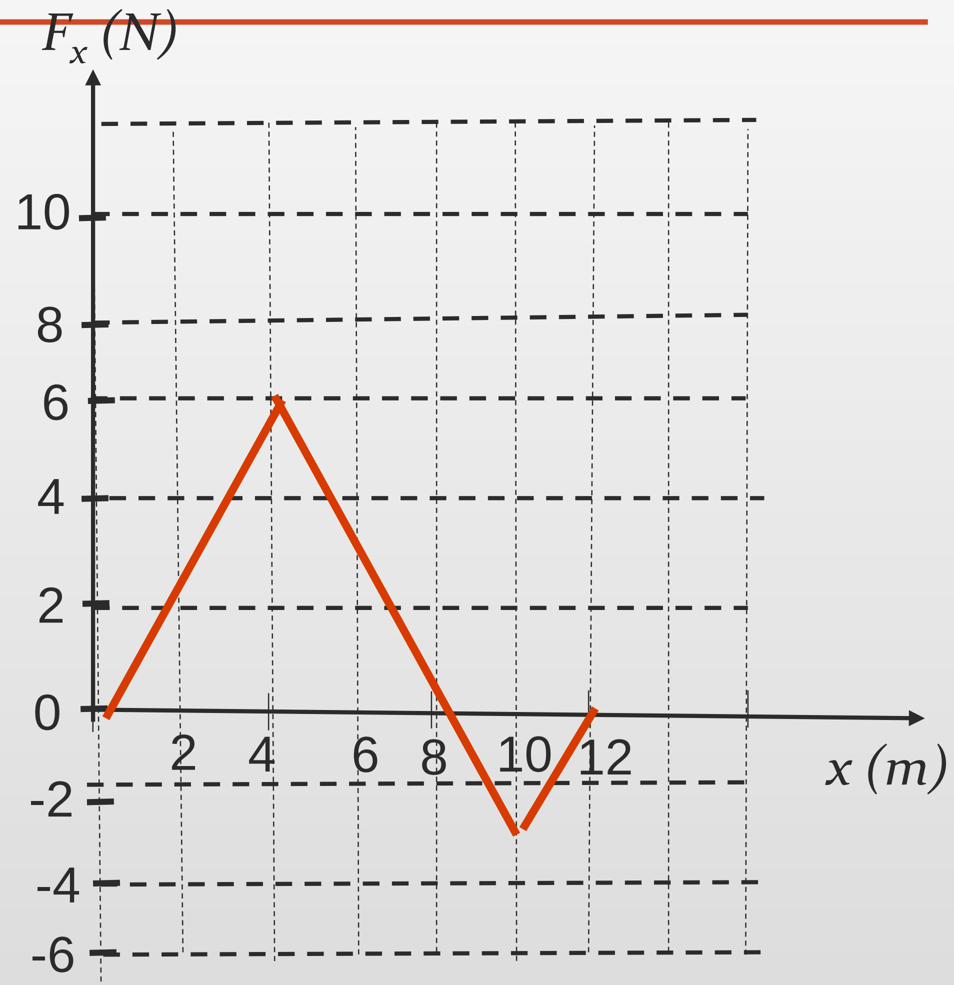
$$\Rightarrow \vec{F} \bullet d\vec{r} = 4xdx$$

$$\therefore W_F = \int_{x_1}^{x_2} F_x dx \qquad \Rightarrow W_F = 4\int_{x_1=0}^{x_2=5m} xdx \qquad \Rightarrow W_F = 50J$$

Work Done by Several Forces

Example

The force acting on a particle varies as shown. Find the work done by the force on the particle as it moves (a) from $x = 0$ to $x = 8\ m$, (b) from $x = 8\ m$ to $x = 10\ m$, and (c) from $x = 0$ to $x = 10\ m$.



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Work Done by Several Forces

Solution

(a) To find the work done by the force on the particle as it moves from $x = 0$ to $x = 8\ m$.

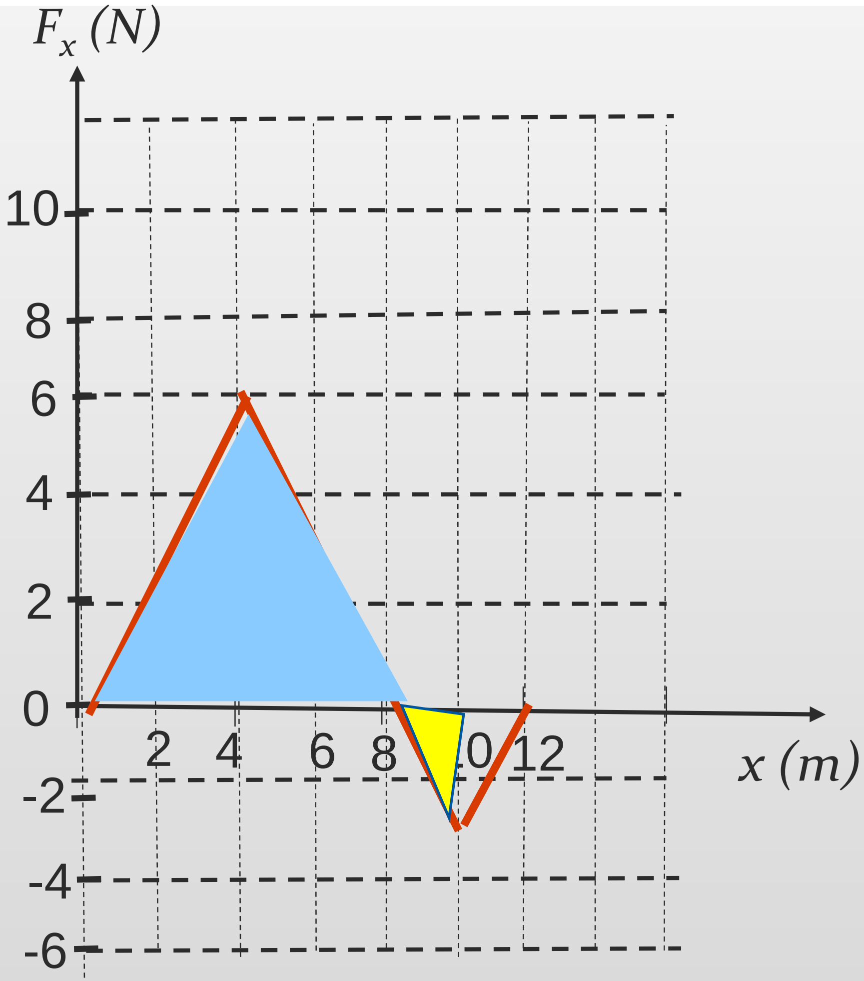
$$W_F = \int_{x_1=0}^{x_2=8m} F_x dx$$

W_F = Area under the curve of blue triangle=0.5(8m)(6N)=24J

(b) To find the work done by the force on the particle as it moves from $x = 8\ m$ to $x = 10\ m$.

$$W_F = \int_{x_1=8m}^{x_2=10m} F_x dx$$

W_F = Area under the curve of yellow triangle=0.5(2m)(-3N)=-3J



(c) To find the work done by the force on the particle as it moves from $x = 0$ to $x = 10\ m$.

$$W_F = \int_{x_1=0}^{x_2=10m} F_x dx$$

W_F = 24 - 3 = 21J

Note: It is the sum of work found in (a) and (b)

Work Done by a Varying Force: Spring Force

Spring Force: It is a restoring force

$$F_s = -kx \quad \text{(Hooke's Law)}$$

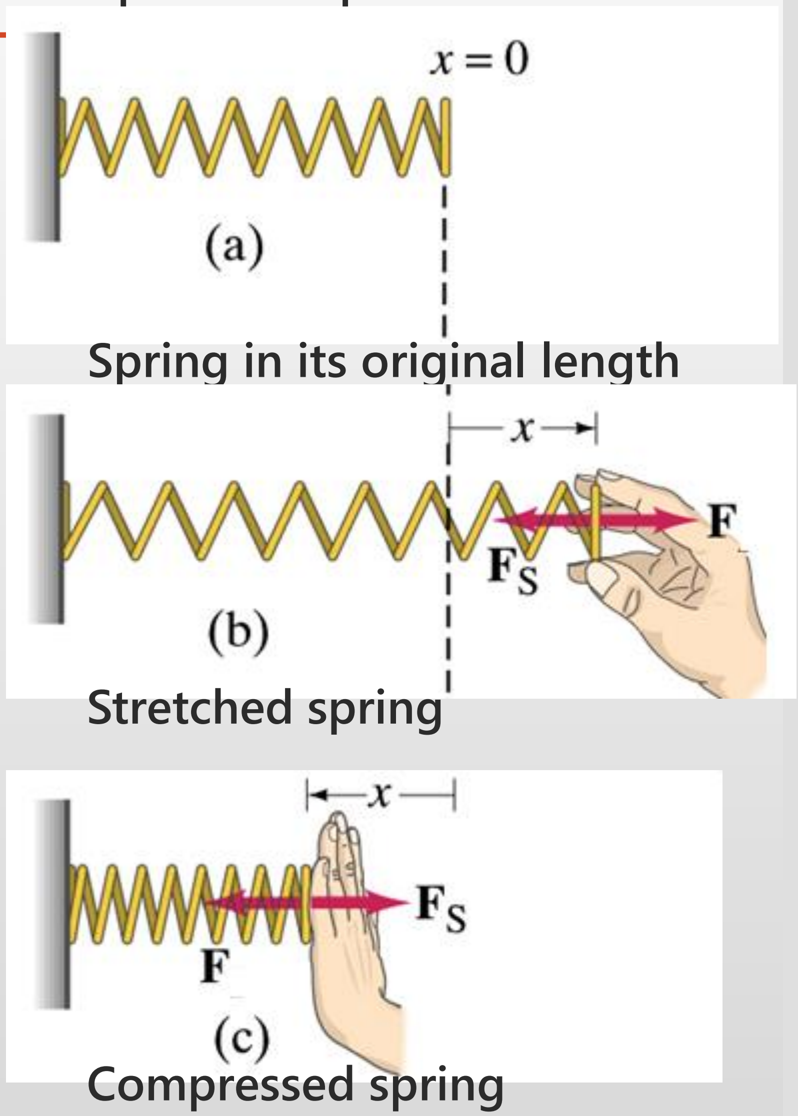
k is elastic (or spring) constant

Note: (1) The force exerted by spring is always opposite to the displacement from equilibrium.

(2) The applied force F_{app} has the same magnitude as the spring force but opposite in direction, namely,

$$F_{app} = kx$$

Equilibrium position



Work Done by a Varying Force: Spring Force

Work done by a Spring Force:

$$W = \int_{x_1}^{x_2} F_x dx$$

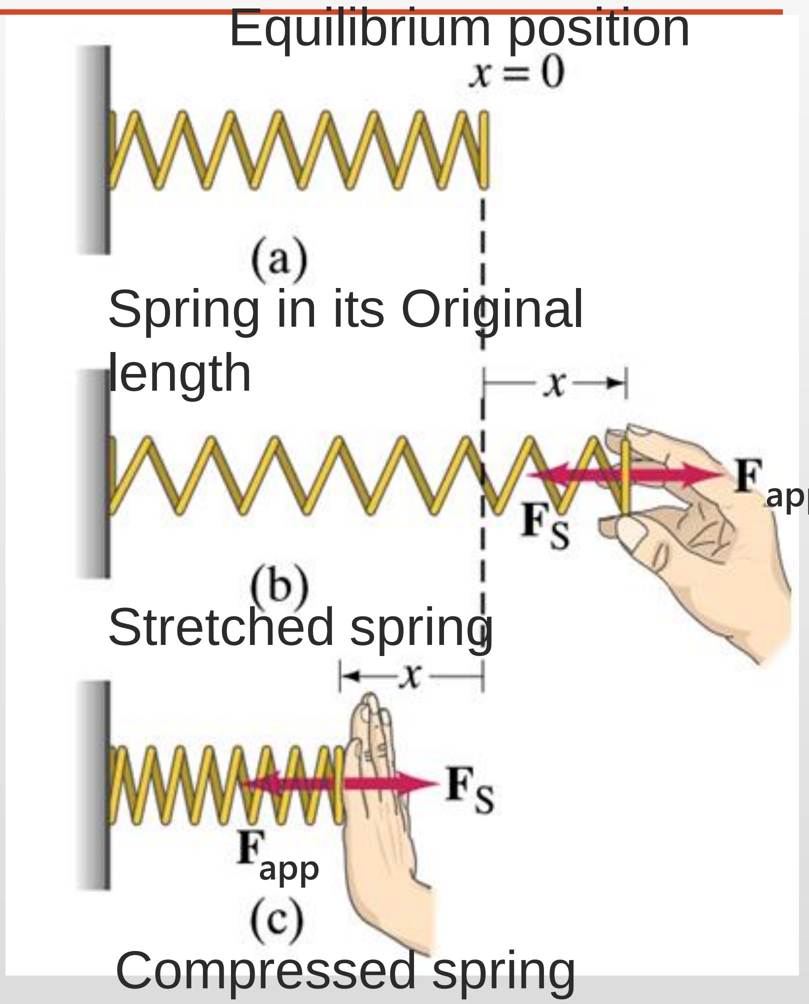
$$F_s = -kx$$

$$\therefore \quad W_s = \int_{x_1}^{x_2} (-kx) dx$$

$$W_s = -k\left(\frac{x^2}{2}\right) \Big|_{x_1}^{x_2}$$

$$\boxed{W_s = -\frac{k}{2}(x_2^2 - x_1^2)}$$

This expression can be applied for a stretched or a compressed spring



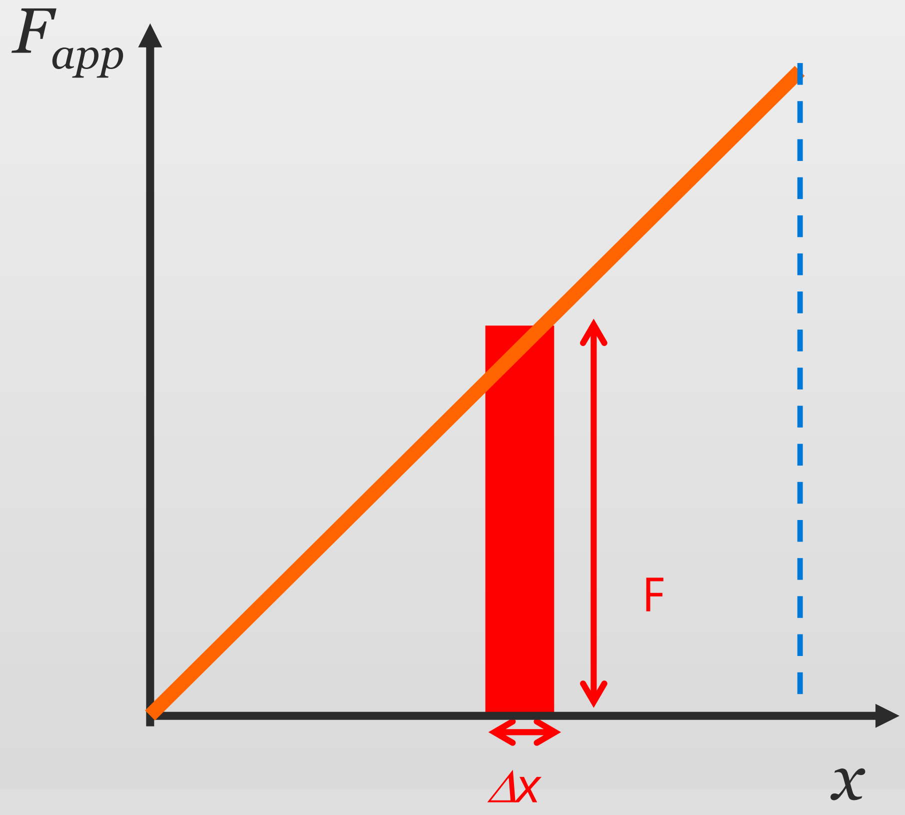
Work Done by Applied Force:

Work Done by Applied Force:

Work Done to Stretch or Compress Spring

$$\because \quad F_{app} = kx \quad \Rightarrow \quad \therefore \quad W_{app} = -W_s$$

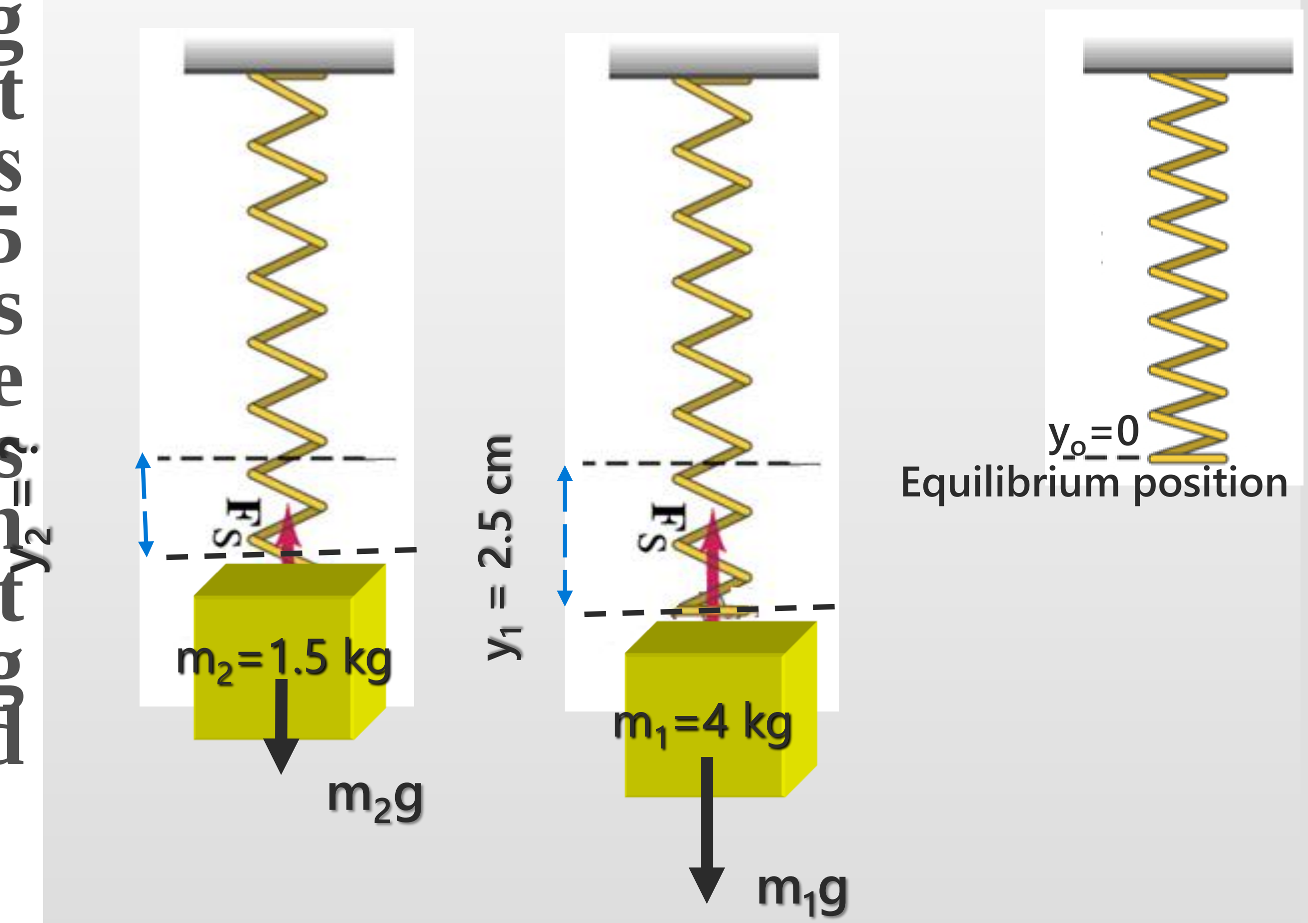
$$\boxed{W_{app} = \frac{k}{2}(x_2^2 - x_1^2)}$$



Work Done by Several Forces

Example

When a 4-kg object is hung vertically on a certain light spring that obeys Hooke's law, the spring stretches 2.5 cm. If the 4-kg object is removed, (a) how far will the spring stretch if a 1.5-kg is hung on it? (b) how much work must an external agent do to stretch the same spring 4 cm from its un-stretched position?



(c) stretched spring with y_2

(b) stretched spring With y_1

(a) Unstretched spring

Solution

For $m_1 = 4\ kg$, $y_1 = 2.5\ cm$.

(a) To find y_2 when the mass m_1 is replaced by $m_2 = 1.5\ kg$

For mass m_1:

$\Sigma F_y = 0 \Rightarrow F_s - m_1 g = 0$

Or $\Rightarrow ky_1 = m_1 g$

$\Rightarrow (0.025m)k = (4kg)(9.8m/s^2)$

$\Rightarrow k = 1568\ N/m$

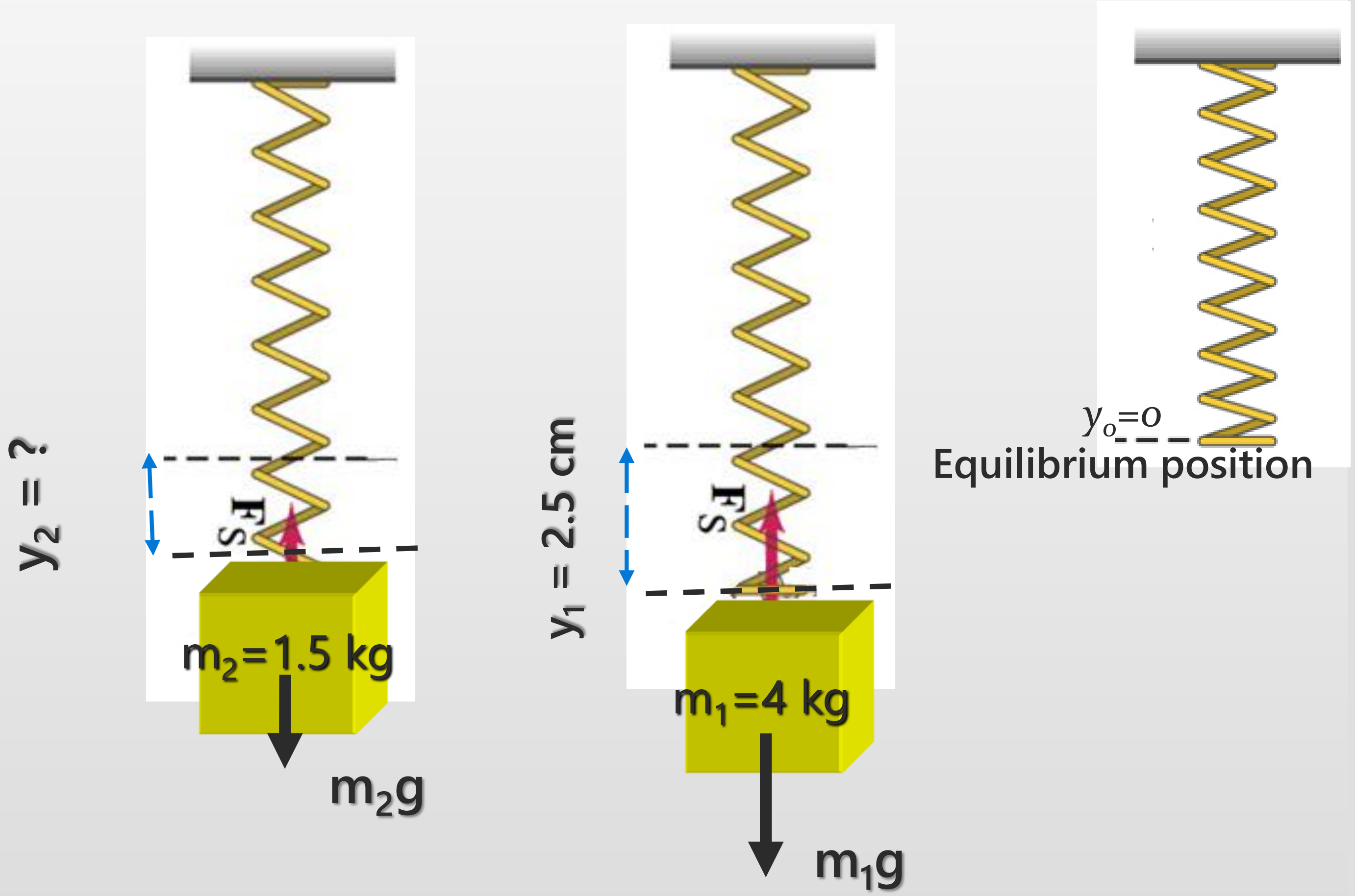
For mass m_2:

$\Sigma F_y = 0 \Rightarrow F_s - m_2 g = 0$

Or $\Rightarrow ky_2 = m_2 g$

$\Rightarrow (1568N/m)y_2 = (1.5kg)(9.8m/s^2)$

$\Rightarrow y_2 = 0.0094\ m = 0.94\ cm$



(c) stretched spring with y_2

(b) stretched spring With y_1

(a) Unstretched spring

Solution

(b) To find the work done by an external agent to stretch the spring *4 cm* from its un-stretched position. Knowing that *k = 1568 N/m*

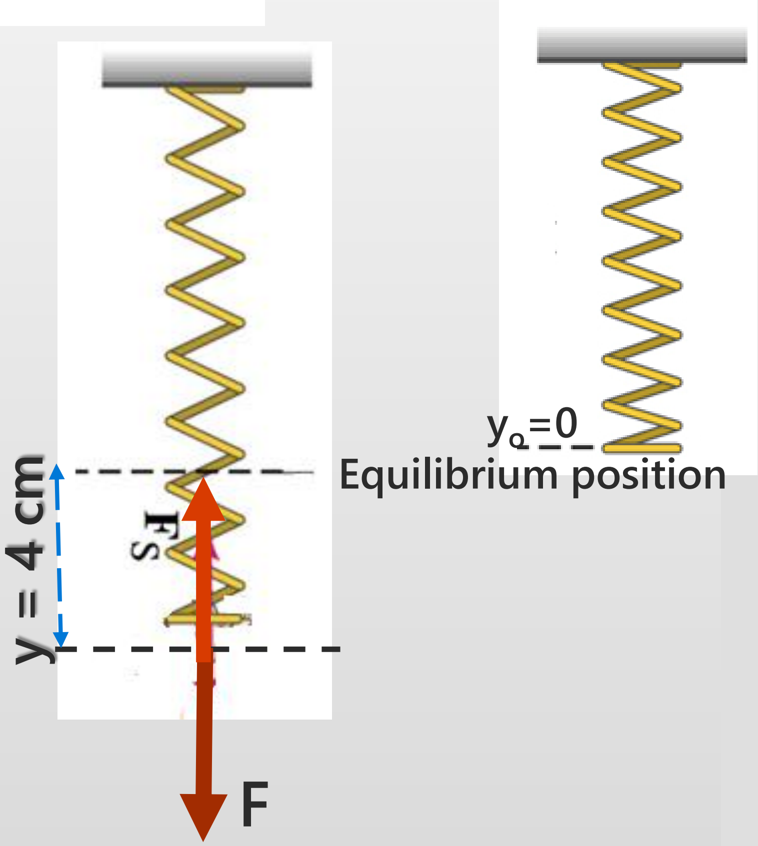
$$W_{app} = -W_s$$

$$W_s = -\frac{k}{2}(y^2 - y_o^2)$$

$$W_{app} = \frac{k}{2}(y^2 - y_o^2)$$

$y = 4\ cm = 0.04\ m,\ y_o = 0,\ k = 1568\ N/m$

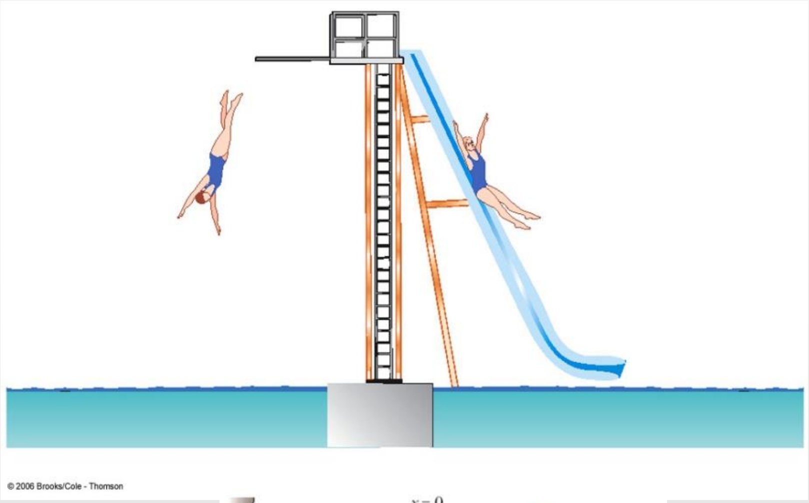
$$W_{app} = \frac{(1568\,N/m)}{2}((0.04)^2 - 0) = 1.28\,J$$

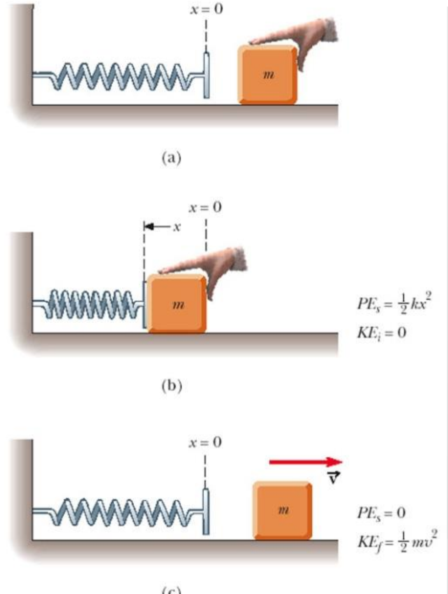


Types of Forces

- Conservative forces
  - Work and energy associated with the force can be recovered
  - Examples: Gravity, Spring Force

- Nonconservative forces
  - The forces are generally dissipative and work done against it cannot easily be recovered
  - Examples: Kinetic friction, air drag forces, normal forces, tension forces, applied forces …





Conservative Forces

- A force is conservative if the work it does on an object moving between two points is independent of the path the objects take between the points
  - ✓ The work depends only upon the initial and final positions of the object (it does not depend on the movement path)
  - ✓ The work done by this force in a closed path is zero
- ✓ Any conservative force can have a potential energy function associated with it
  - ✓ Work done by gravity

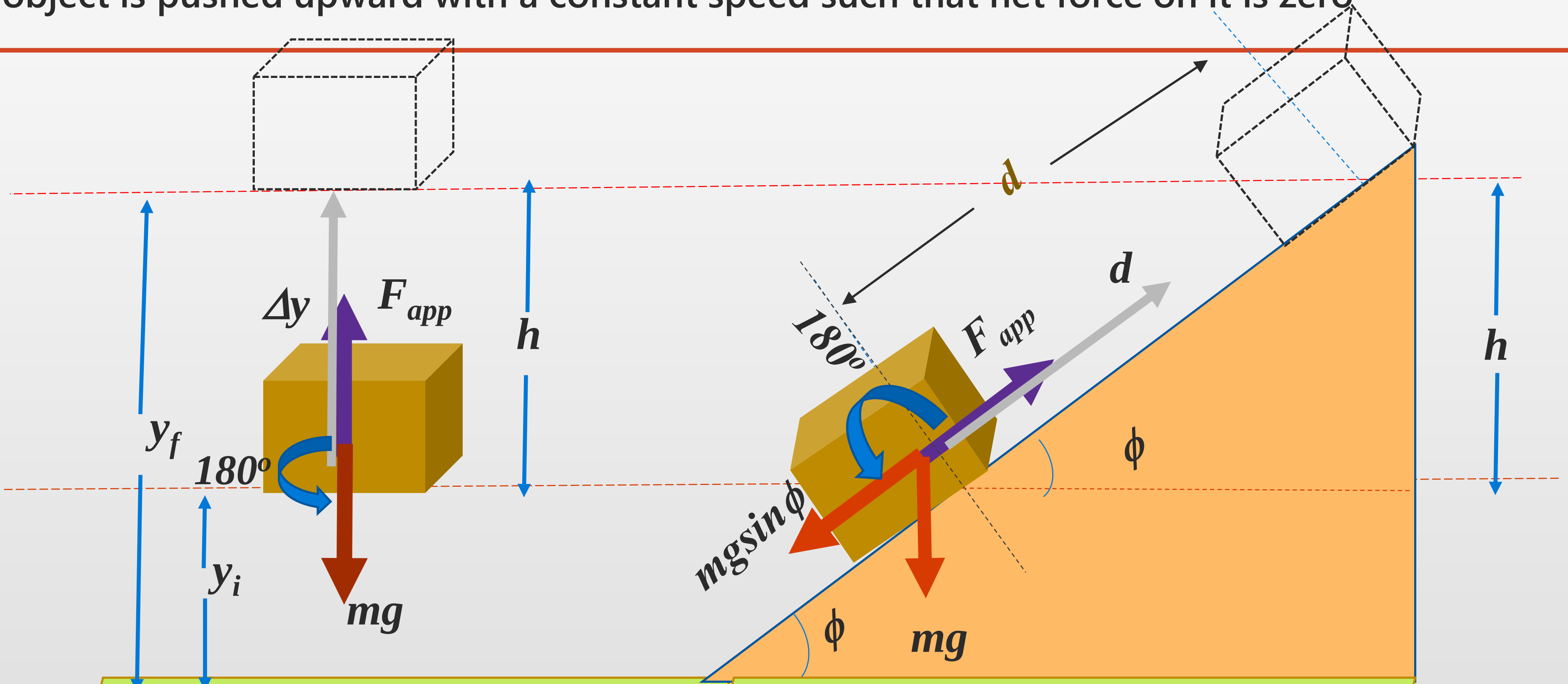
$$W_g = PE_i - PE_f = mgy_i - mgy_f$$

  - ✓ Work done by spring force

$$W_s = PE_{si} - PE_{sf} = \frac{1}{2}kx_i^2 - \frac{1}{2}kx_f^2$$

Conservative Forces

The object is pushed upward with a constant speed such that net force on it is zero



$$W_g = (F\cos\theta)\Delta y$$

$$F = mg, \quad \Delta y = h, \quad \theta = 180^o$$

$$W_g = (F\cos\theta)\Delta r$$

$$F = mg\sin\phi, \quad \Delta r = d, \quad \theta = 180^o$$

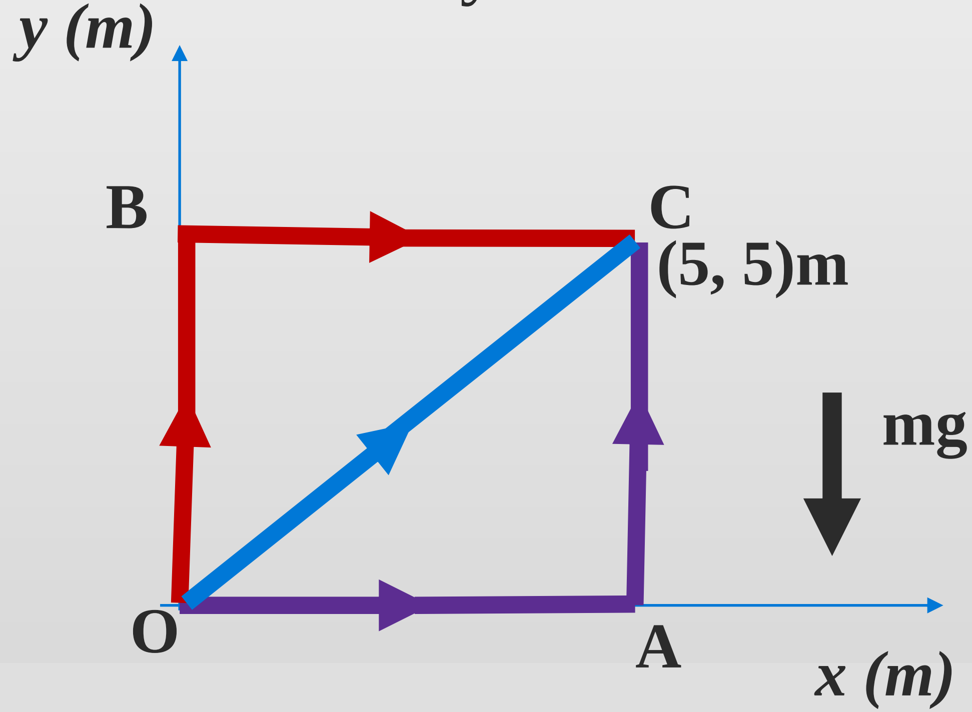
$$W = (mg\sin\phi)d\cos 180^o, \quad h = d\sin\phi$$

$$W_g = -mgh \quad \Leftrightarrow \quad W_g = -mgh$$

Conservative Forces

Example

A 4-kg object moves from the origin O to point C having coordinates x = 5 m and y = 5 m, as shown. One force on the object is the gravitational force acting in the negative y-direction. Using the relation $W = \vec{F} \bullet \Delta\vec{r}$ to calculate the work done by the gravitational force on the object as it goes from O to C along (a) the path OAC, (b) OC, and (c) OBC (d) Your results should be identical. Why?

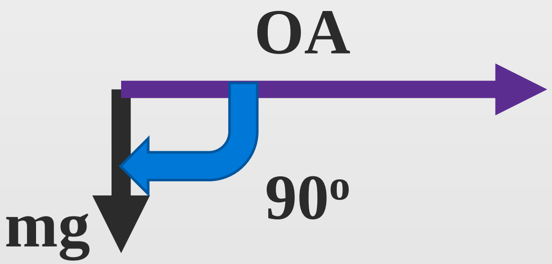


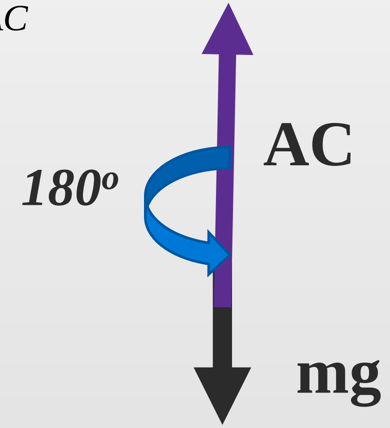
Conservative Forces

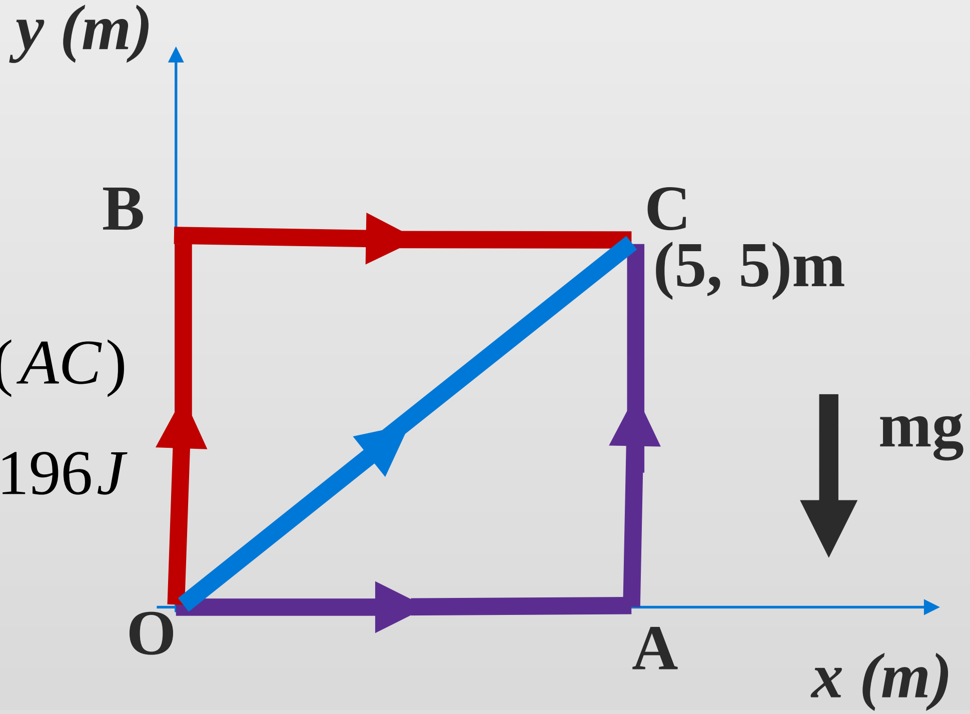
Solution

Given: m= 4 kg C (x = 5 m, y = 5 m). To calculate the work done by the gravitational force on the object as it goes from O to C along (a) the path OAC

$$W = \vec{F} \bullet \Delta\vec{r} \qquad W_{OAC} = W_{OA} + W_{AC}$$







$$W_{OA} = mg(OA)\cos 90 = 0$$

$$W_{AC} = mg(AC)\cos 180 = -mg(AC)$$

$$W_{AC} = -(4kg)(9.8m/s^2)(5m) = -196J$$

$$\therefore W_{OAC} = 0 + (-196J) = -196J$$

Conservative Forces

Solution

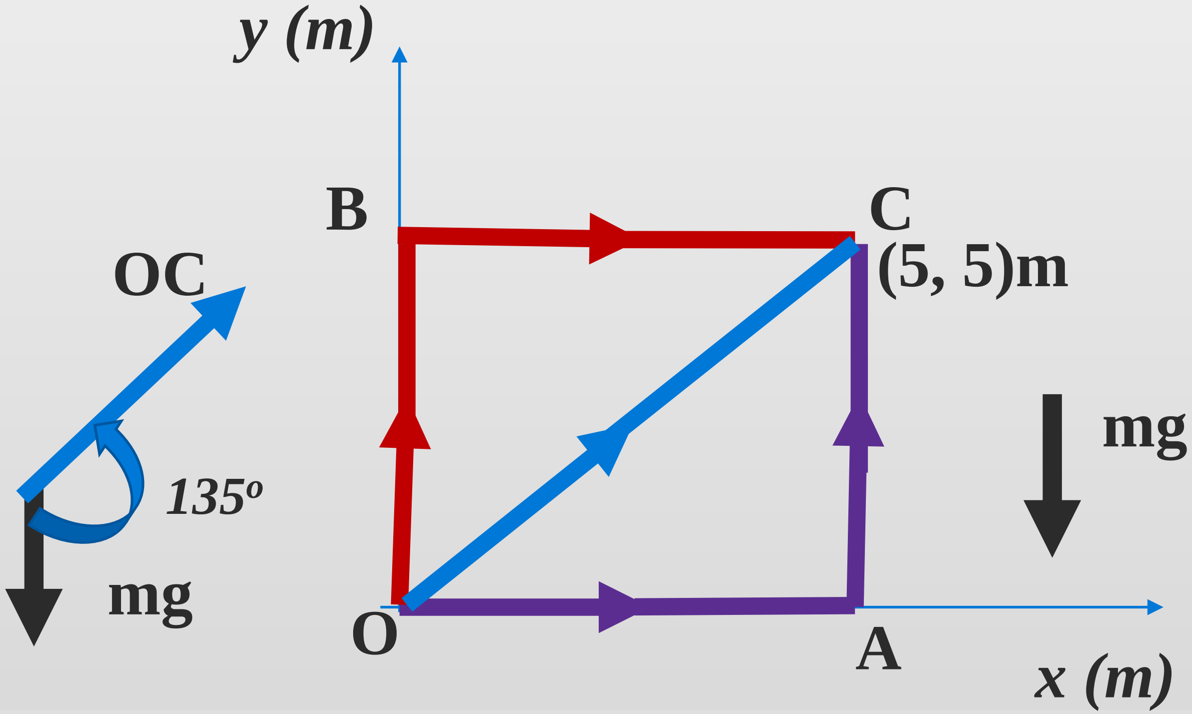
Given: m= 4 kg C (x = 5 m, y = 5 m). To calculate the work done by the gravitational force on the object as it goes from O to C along (b) the path OC

$$W = \vec{F} \bullet \Delta\vec{r}$$

$$W_{OC} = mg(OC)\cos 135$$

$$OC = \sqrt{(AC)^2 + (OA)^2} = \sqrt{5^2 + 5^2} = 5\sqrt{2}m$$

$$W_{OC} = (4kg)(9.8m/s^2)(5\sqrt{2})(-\frac{1}{\sqrt{2}}) = -196J$$



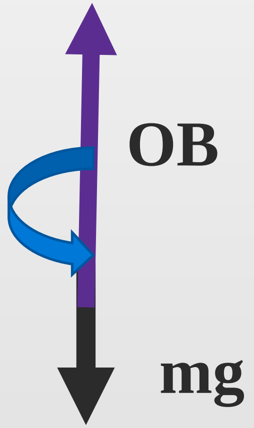
Conservative Forces

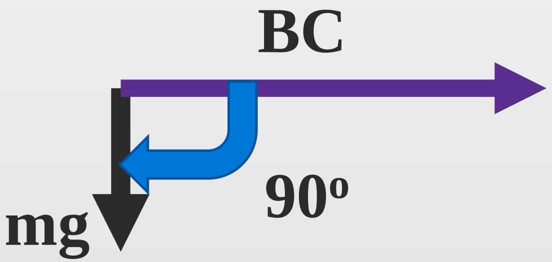
Solution

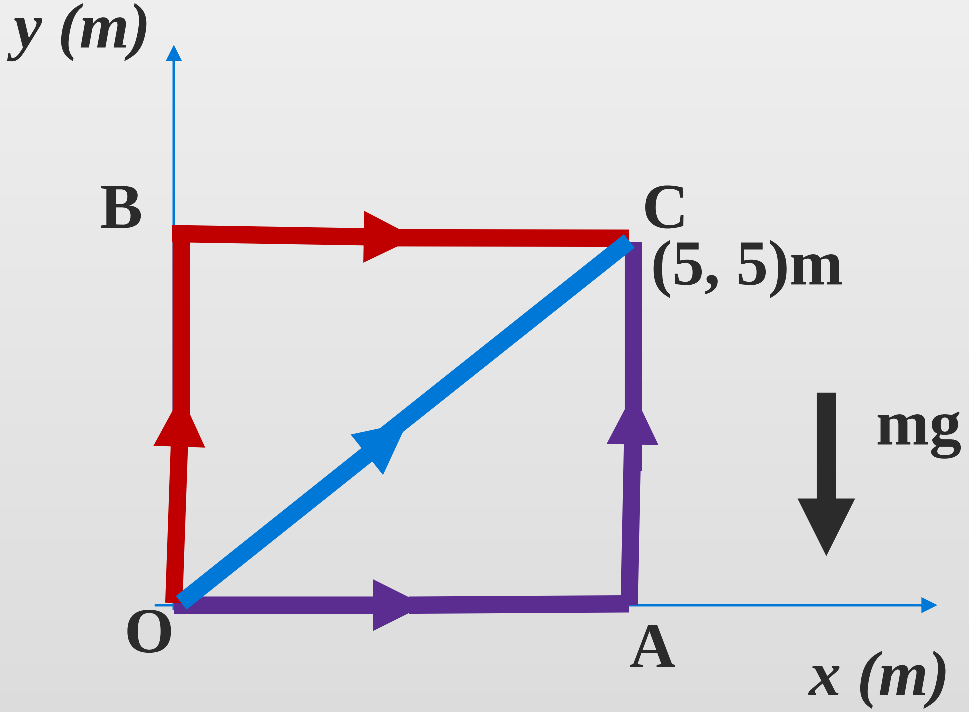
Given: m= 4 kg C (x = 5 m, y = 5 m). To calculate the work done by the gravitational force on the object as it goes from O to C along (c) the path OBC

$$W = \vec{F} \bullet \Delta\vec{r}$$

$$W_{OBC} = W_{OB} + W_{BC}$$







$$W_{OB} = mg(OB)\cos 180$$

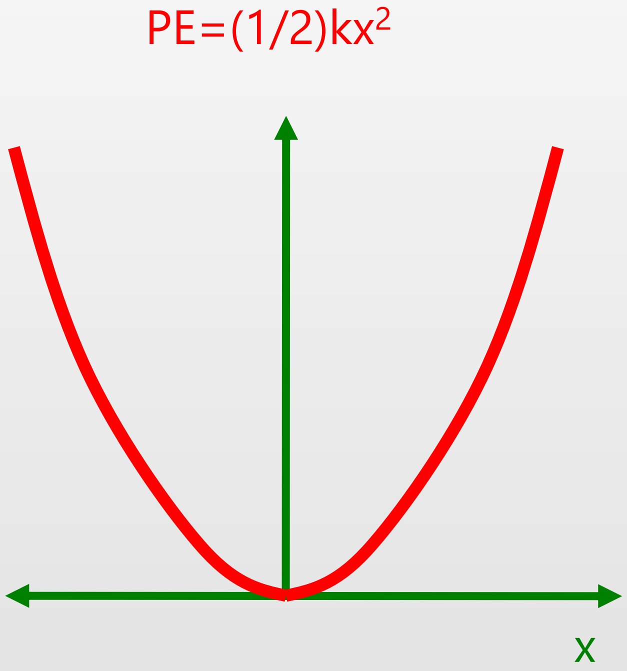
$$W_{BC} = mg(BC)\cos 90 = 0$$

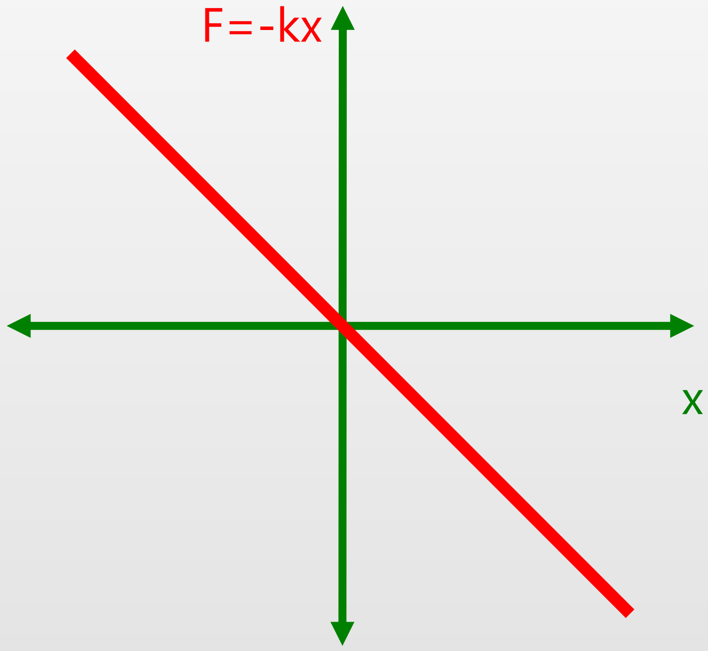
$$W_{OB} = -(4kg)(9.8m/s^2)(5m) = -196J$$

$$\therefore W_{OBC} = (-196J) + 0 = -196J$$

(d) The answer is the same in (a), (b) and (c) because the force is conservative

Plots for Potential Energy and Force of Spring





$$W_s = PE_{si} - PE_{sf} = \frac{1}{2}kx_i^2 - \frac{1}{2}kx_f^2$$

$$F_s = -kx$$

Relationship Between Conservative Forces and Potential Energy

When the PE (or U) is a function of one coordinate, say, x (i.e. $U=U(x)$) and this potential energy is related to a conservative force,

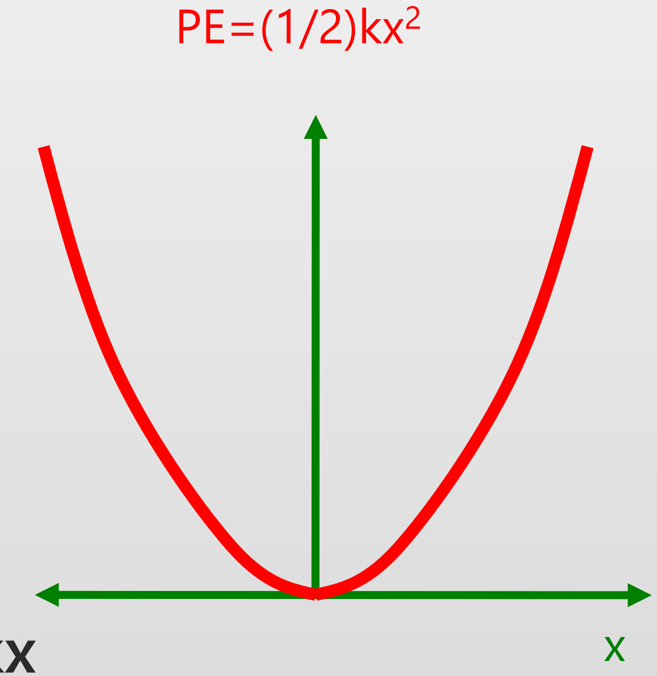
Where, $W_c = -\Delta PE = -\Delta U$
and $W_c = F_x\, dx$,

One can write $dU = -F_x\, dx$,

Or $\quad F_x = -dU/dx$

The potential energy stored in a spring is $U = (½)kx^2$

One can find the spring force using $F_x = -dU/dx$ to get $F_x = -kx$



Relationship Between Conservative Forces and Potential Energy

But if the PE (or U) is a function of two coordinates, say, x and y (i.e. $U=U(x, y)$) and this potential energy is related to a conservative force,

This force may have two components, namely:

$F_x = -\partial U(x, y)/\partial x$ and $F_y = -\partial U(x, y)/\partial y$

Relationship Between Conservative Forces and Potential Energy

Example

A potential energy function for a system in which a two dimensional force acts is of the form $U(x, y) = 3x^2y - 7x$. Find the force that acts at the point (x, y). What is the magnitude of this force when x = -1m and y= 2m?

Solution

The two components of this force, are:

$F_x = -\partial U(x, y)/\partial x = -6xy + 7$ and $F_y = -\partial U(x, y)/\partial y = -3x^2$

at the point (x =-1, y=2)m, $F_x = -(6(-1)(2) - 7) = 19N$ and $F_y = -3(2)^2 = -12N$

$$F = \sqrt{F_x^{\ 2} + F_y^{\ 2}} = \sqrt{(19)^2 + (-12)^2} = 22.5N$$

Kinetic Energy and Work-Kinetic Energy Theorem

- **Kinetic energy is defined as** $$K = \frac{1}{2}mv^2$$

Use the equation of motion $$v_f^2 = v_i^2 + 2a\Delta x$$

Divide both sides of this equation by m/2 to get:

$$\frac{mv_f^2}{2} = \frac{mv_i^2}{2} + ma\Delta x$$

Or $$ma\Delta x = \frac{m}{2}(v_f^2 - v_i^2)$$

- **The work-kinetic energy theorem can be written as:**

$$W = K_f - K_i = \Delta K$$

Note: This equation is correct whether the forces that act on an object are constant or variable

Work Done by Several Forces

Example

A 3-kg object has a velocity $(6\hat{i} - 1\hat{j})m/s$.

(a)What is its kinetic energy at this moment?

(b) what is the net work done on the object if its velocity changes to $(8\hat{i} + 4\hat{j})m/s$? .
[Note: Use the definition of the dot product, $v^2 = \vec{v} \bullet \vec{v}$**]**

Work Done by Several Forces

Solution

Given m= 3 kg and $\vec{v}_o = (6\hat{i} - 1\hat{j})m/s$

(a)To find the kinetic energy at this moment.

$$v_o^2 = \vec{v}_o \bullet \vec{v}_o$$

$$\vec{v}_o \bullet \vec{v}_o = (6\hat{i} - 1\hat{j}) \bullet (6\hat{i} - 1\hat{j}) = 37m^2/s^2$$

$$K_o = \frac{1}{2}mv_o^2 = \frac{1}{2}(3kg)(37m^2/s^2)$$

$$K_o = 55.5J$$

(b) To find the net work done on the object if its velocity changes to $\vec{v} = (8\hat{i} + 4\hat{j})m/s$

$$K = \frac{1}{2}mv^2 = \frac{1}{2}(3kg)(80m^2/s^2)$$

$$K = 120J$$

$$W_{net} = K - K_o = \Delta K$$

$$W_{net} = 120 - 55.5 = 64.5J$$

Work Done by Several Forces

Example

A 0.6-kg particle has a speed of 2 m/s at point A and kinetic energy of 7.5 J at point B, what is (a) its kinetic energy at A, (b) its speed at B, and (c) the net work done on the particle by external forces as it moves from A to B.

Work Done by Several Forces

Solution

Given m= 0.6 kg, v_A = 2 m/s K_B = 7.5 J

(a) To find the kinetic energy at A:

$$K_A = \frac{1}{2}mv_A^2 \qquad \Rightarrow K_A = \frac{1}{2}(0.6kg)(2m/s)^2 = 1.2J$$

(b)To find the speed at B:

$$v_B = \sqrt{\frac{2K_B}{m}} = \sqrt{\frac{2(7.5J)}{(0.6kg)}} = 5m/s$$

(c) To find the net work done on the particle by external forces as it moves from A to B.

$$W_{net} = \Delta K = K_B - K_A$$

$$\therefore W_{net} = 7.5 - 1.2 = 6.3J$$