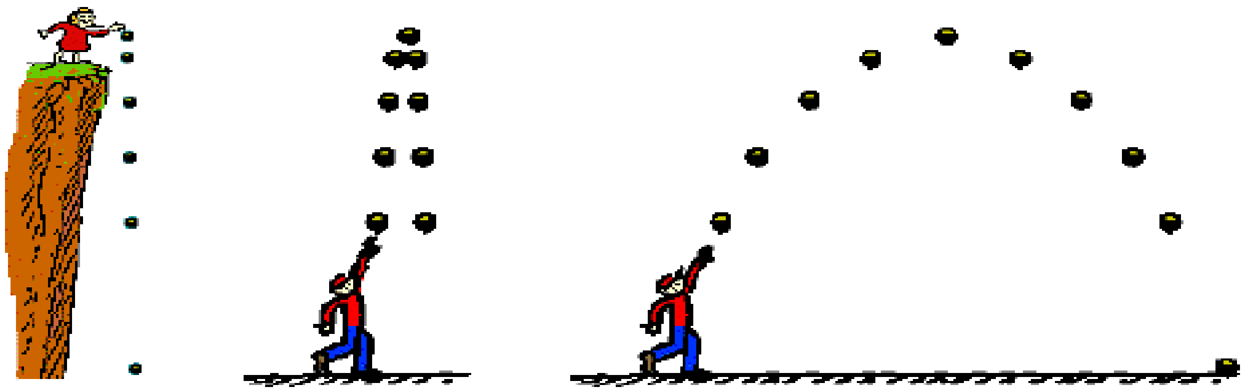
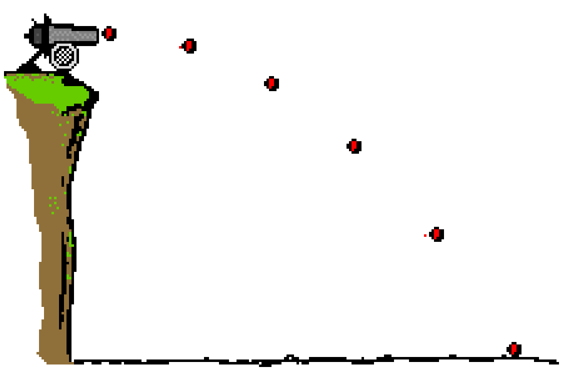
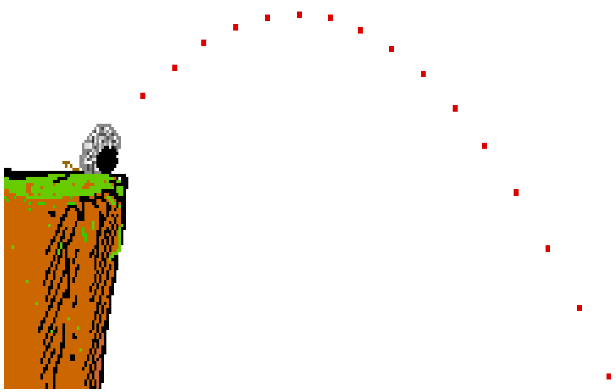


4 Motion in Two and Three Dimensions





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Learning Outcomes

By the end of the chapter student should be able:

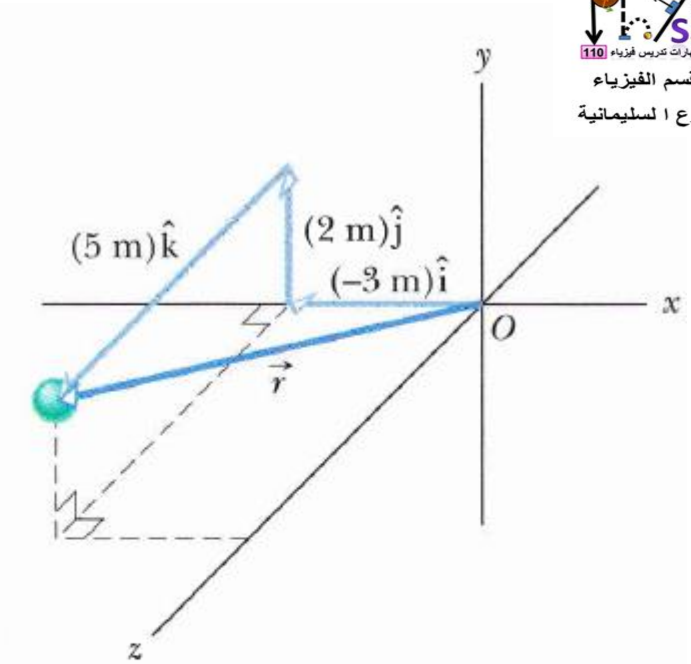
- to define the motion in two and three dimension.
- to locate a particle position in two and three dimension relative to the origin of coordinate system.
- to calculate the position vector at certain time, in magnitude- direction and write it in unit-vector notation.
- to calculate the displacement vector in magnitude- direction and write it in unit vector notation.
- to calculate the average velocity in magnitude- direction and in unit vector notation.
- to calculate the instantaneous velocity in magnitude- direction and write it in unit vector notation, and specify that the direction is always tangent to the particle's path.
- to calculate the average acceleration and its direction.
- to calculate the instantaneous acceleration and its direction
- .to define the projectile motion.
- to identify the launched angle of a projectile that measured from the horizontal.
- to resolve the initial velocity of the projectile into its components and write it in unit-vector notation.
- to analyze the projectile motion into two one dimensional independent motion: horizontal and vertical motions.
- to identify the horizontal and vertical components of the acceleration of the projectile.

Learning Outcomes

By the end of the chapter student should be able:

- to calculate the horizontal and vertical components of the final velocity of the projectile after time t.
- to calculate the horizontal and vertical displacement of the projectile after time t.
- to calculate the maximum height that the projectile can reach.
- to calculate the time that the projectile spend to reach any position.
- to define the horizontal Range of the projectile.
- to calculate the horizontal Range of the projectile.
- to calculate the maximum horizontal Range of the projectile.
- to describe the path of the projectile (trajectory).
- to define the uniform circular motion.
- to identify the particle's velocity in the uniform circular motion.
- to define the centripetal acceleration in magnitude and direction for a particle in uniform circular motion.
- to calculate the time of revolution (period) for a particle in uniform circular motion.
- to calculate the distance that the particle travels during one period in circular motion.
- to determine the velocity and acceleration vectors in a circular path in which the centre at the origin of xy plan.

4-2 | Position and Displacement



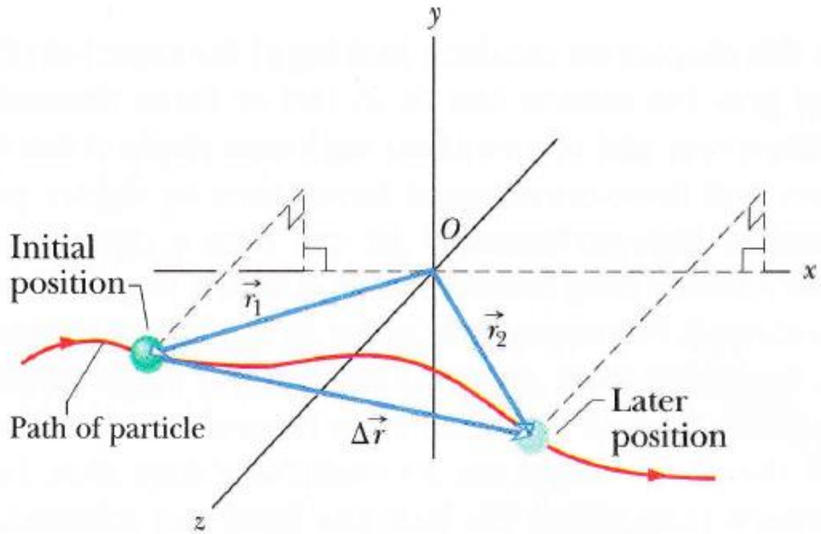
Position

$$\vec{r} = x\hat{\mathrm{i}} + y\hat{\mathrm{j}} + z\hat{\mathrm{k}}$$

Displacmen

$$\Delta\vec{r} = \vec{r}_2 - \vec{r}_1$$

$$\vec{r}_1 = x_1\hat{\mathrm{i}} + y_1\hat{\mathrm{j}} + z_1\hat{\mathrm{k}} \text{ and } \vec{r}_2 = x_2\hat{\mathrm{i}} + y_2\hat{\mathrm{j}} + z_2\hat{\mathrm{k}}$$



$$\Delta\vec{r} = (x_2\hat{\mathrm{i}} + y_2\hat{\mathrm{j}} + z_2\hat{\mathrm{k}}) - (x_1\hat{\mathrm{i}} + y_1\hat{\mathrm{j}} + z_1\hat{\mathrm{k}})$$

$$\Delta\vec{r} = (x_2 - x_1)\hat{\mathrm{i}} + (y_2 - y_1)\hat{\mathrm{j}} + (z_2 - z_1)\hat{\mathrm{k}}$$

$$\Delta\vec{r} = \Delta x\,\hat{\mathrm{i}} + \Delta y\,\hat{\mathrm{j}} + \Delta z\,\hat{\mathrm{k}}$$

Sample Problem 4-1

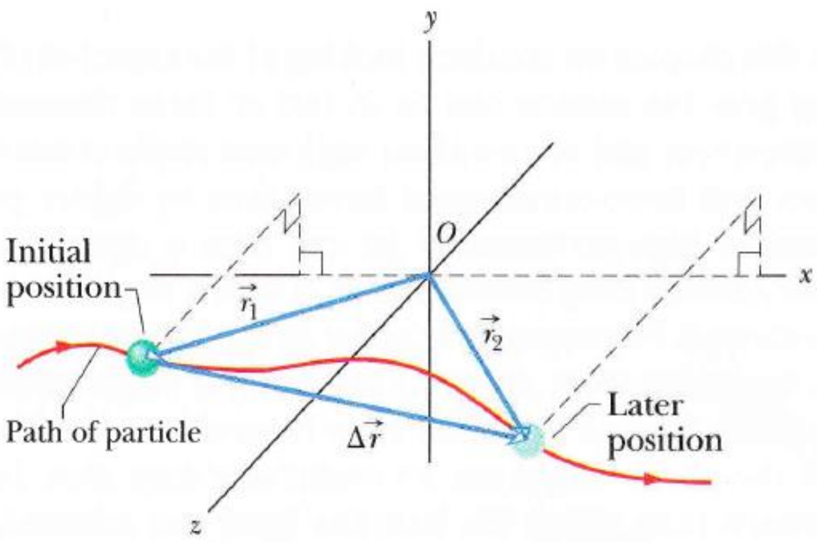
In Fig. 4-2, the position vector for a particle initially is

$$\vec{r}_1 = (-3.0\text{ m})\hat{\text{i}} + (2.0\text{ m})\hat{\text{j}} + (5.0\text{ m})\hat{\text{k}}$$

and then later is

$$\vec{r}_2 = (9.0\text{ m})\hat{\text{i}} + (2.0\text{ m})\hat{\text{j}} + (8.0\text{ m})\hat{\text{k}}.$$

What is the particle's displacement $\Delta\vec{r}$ from $\vec{r}_1$ to $\vec{r}_2$?



Sample Problem 4-2

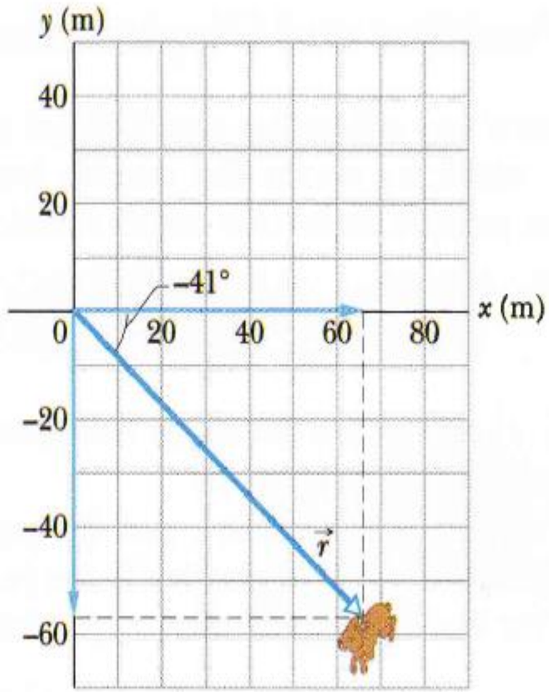
A rabbit runs across a parking lot on which a set of coordinate axes has, strangely enough, been drawn. The coordinates (meters) of the rabbit's position as functions of time t (seconds) are given by

$$x = -0.31t^2 + 7.2t + 28 \quad (4\text{-}5)$$

and

$$y = 0.22t^2 - 9.1t + 30. \quad (4\text{-}6)$$

(a) At $t = 15$ s, what is the rabbit's position vector $\vec{r}$ in unit-vector notation and in magnitude-angle notation?



4-3 | Average Velocity and Instantaneous Velocity

Average velocity

$$\vec{v}_{avg} = \frac{\Delta \vec{r}}{\Delta t}$$

$$\vec{v}_{avg} = \frac{\Delta x\hat{i} + \Delta y\hat{j} + \Delta z\hat{k}}{\Delta t}$$

$$= \frac{\Delta x}{\Delta t}\hat{i} + \frac{\Delta y}{\Delta t}\hat{j} + \frac{\Delta z}{\Delta t}\hat{k}$$

Example:

$$\vec{v}_{avg} = \frac{\Delta \vec{r}}{\Delta t} = \frac{(12\text{ m})\hat{i} + (3.0\text{ m})\hat{k}}{2.0\text{ s}}$$

$$= (6.0\text{ m/s})\hat{i} + (1.5\text{ m/s})\hat{k}.$$

Instantaneous velocity (Or velocity)

$$\vec{v} = \frac{d\vec{r}}{dt}$$

but $\vec{r} = x\hat{i} + y\hat{j} + z\hat{k}.$

$$\vec{v} = \frac{d}{dt}(x\hat{i} + y\hat{j} + z\hat{k})$$

$$= \frac{dx}{dt}\hat{i} + \frac{dy}{dt}\hat{j} + \frac{dz}{dt}\hat{k}$$

$$\vec{v} = v_x\hat{i} + v_y\hat{j} + v_z\hat{k}.$$

The direction of the Instantaneous velocity

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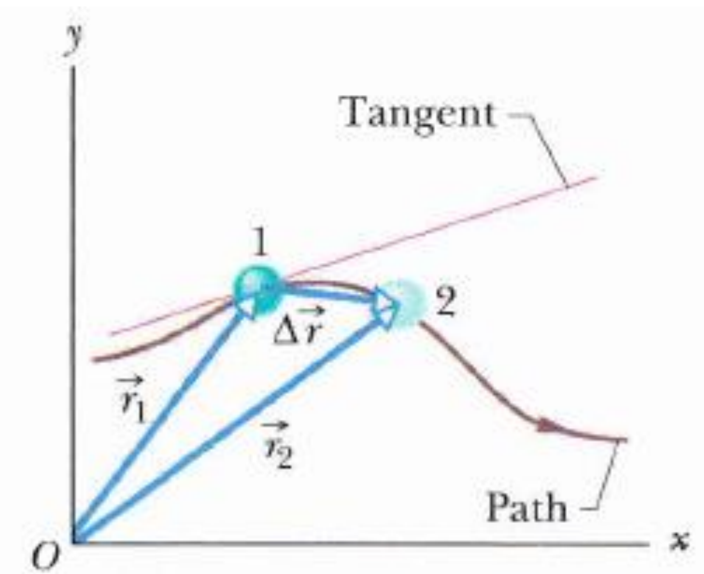
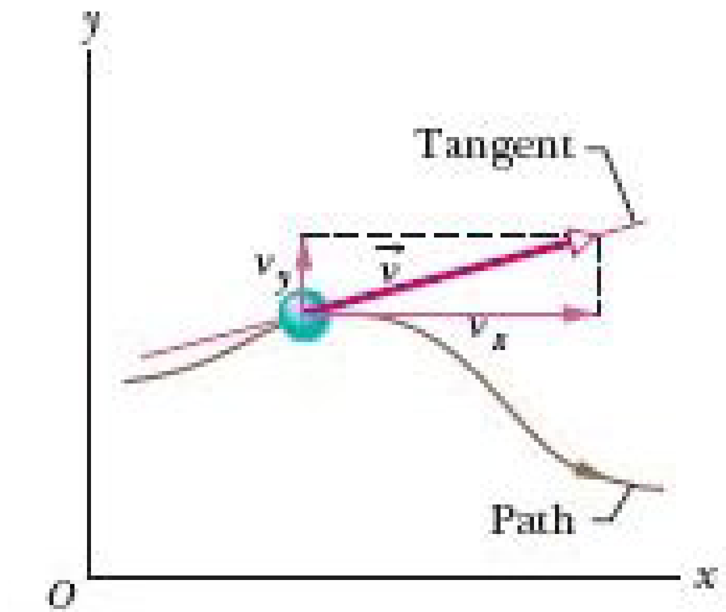
$$\vec{v} = v_x\hat{\mathrm{i}} + v_y\hat{\mathrm{j}} + v_z\hat{\mathrm{k}}$$



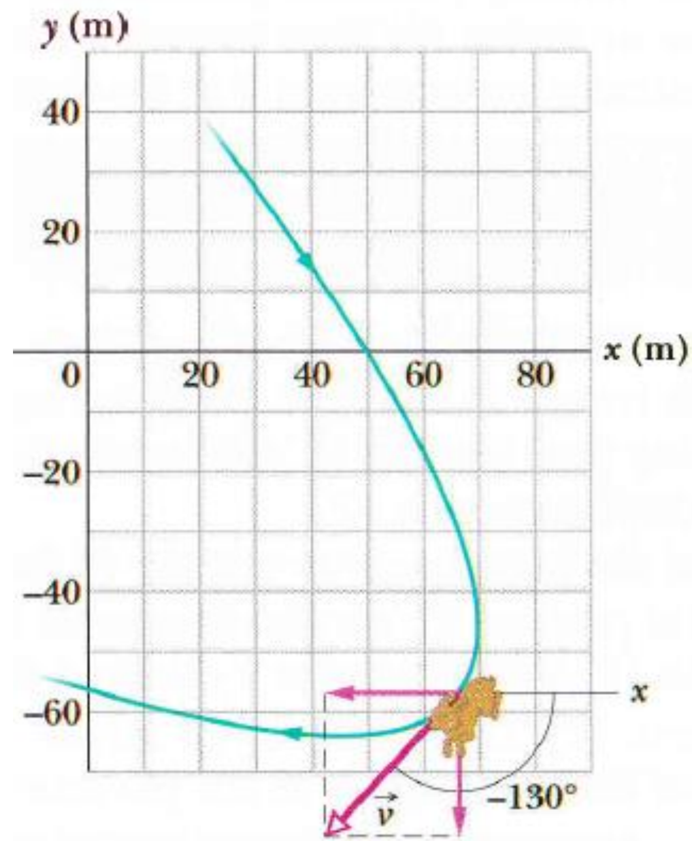


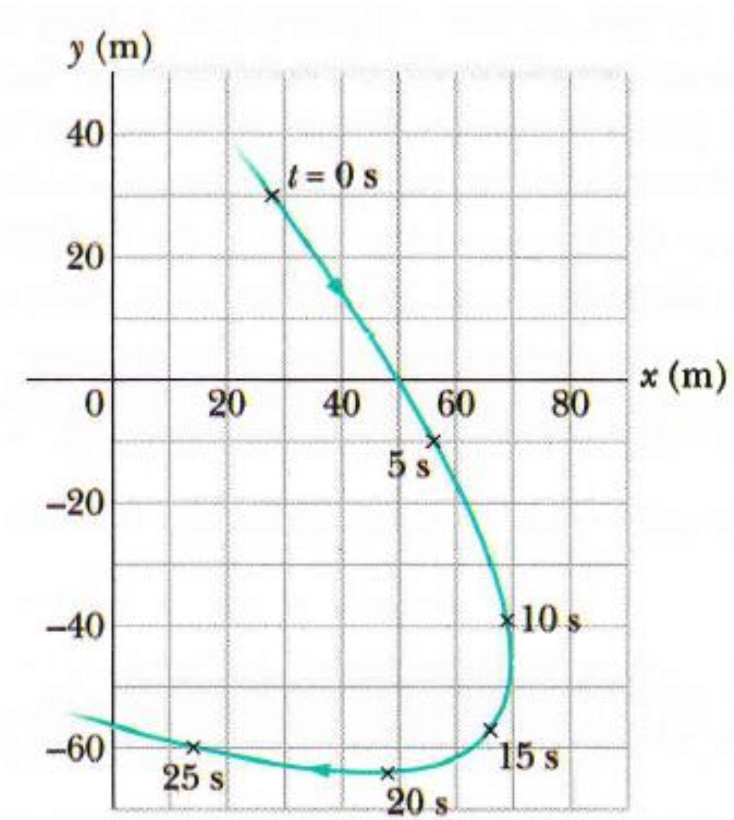
The direction of the instantaneous velocity $\vec{v}$ of a particle is always tangent to the particle's path at the particle's position.

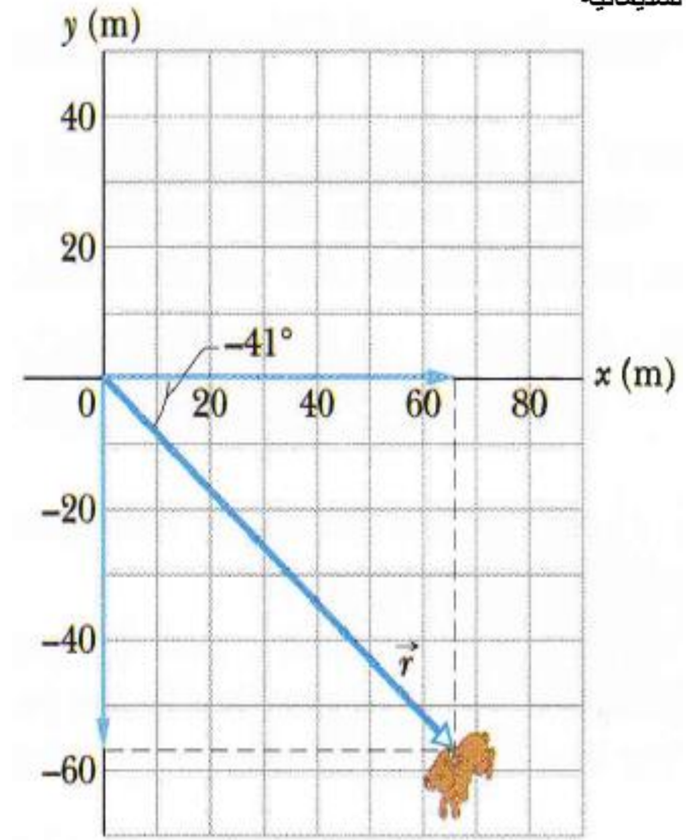
Sample Problem 4-3

For the rabbit in Sample Problem 4-2 find the velocity $\vec{v}$ at time $t = 15$ s.

$$x = -0.31t^2 + 7.2t + 28$$
$$y = 0.22t^2 - 9.1t + 30.$$




y (m)
40
20
0
20
40
60
80
x (m)
−20
−40
−60
t = 0 s
5 s
10 s
15 s
20 s
25 s


y (m)
40
20
−41°
x (m)
0
20
40
60
80
−20
−40
−60
$\vec{r}$

4-4 Average Acceleration and Instantaneous Acceleration

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Average Acceleration

$$\text{average acceleration} = \frac{\text{change in velocity}}{\text{time interval}}$$

$$\vec{a}_{\text{avg}} = \frac{\vec{v}_2 - \vec{v}_1}{\Delta t} = \frac{\Delta \vec{v}}{\Delta t}$$

Instantaneous Acceleration (Or acceleration)

$$\vec{a} = \frac{d\vec{v}}{dt}$$

but $\vec{v} = v_x\hat{i} + v_y\hat{j} + v_z\hat{k}$

$$\vec{a} = \frac{d}{dt}(v_x\hat{i} + v_y\hat{j} + v_z\hat{k})$$

$$= \frac{dv_x}{dt}\hat{i} + \frac{dv_y}{dt}\hat{j} + \frac{dv_z}{dt}\hat{k}$$

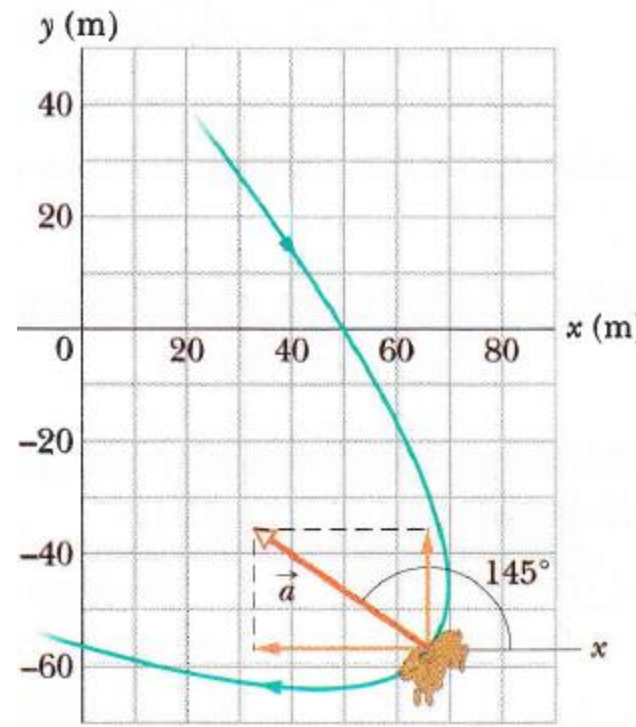
$$\vec{a} = a_x\hat{i} + a_y\hat{j} + a_z\hat{k}$$

Sample Problem 4-4

For the rabbit in Sample Problems 4-2 and 4-3, find the acceleration $\vec{a}$ at time $t = 15$ s.

$$x = -0.31t^2 + 7.2t + 28$$

$$y = 0.22t^2 - 9.1t + 30.$$



Sample Problem 4-5

A particle with velocity $\vec{v}_0 = -2.0\hat{\text{i}} + 4.0\hat{\text{j}}$ (in meters per second) at $t = 0$ undergoes a constant acceleration $\vec{a}$ of magnitude $a = 3.0\ \text{m/s}^2$ at an angle $\theta = 130°$ from the positive direction of the x axis. What is the particle's velocity $\vec{v}$ at $t = 5.0$ s?

4-5 | Projectile Motion

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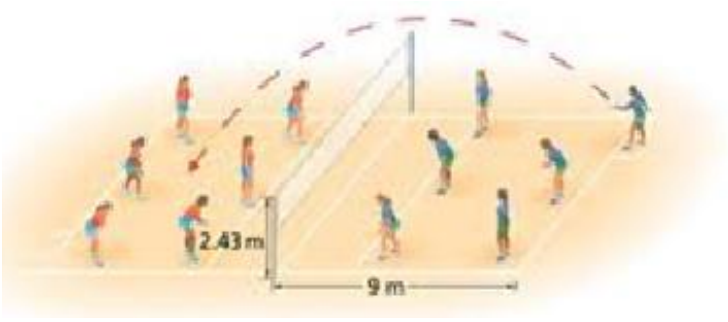
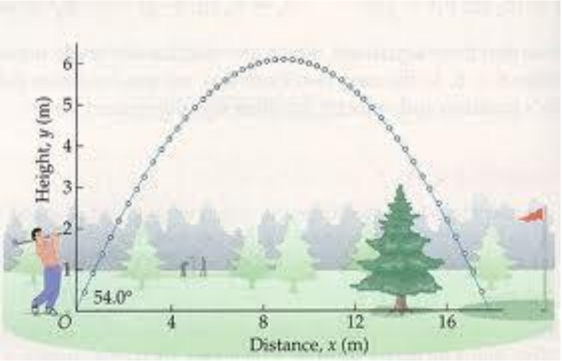
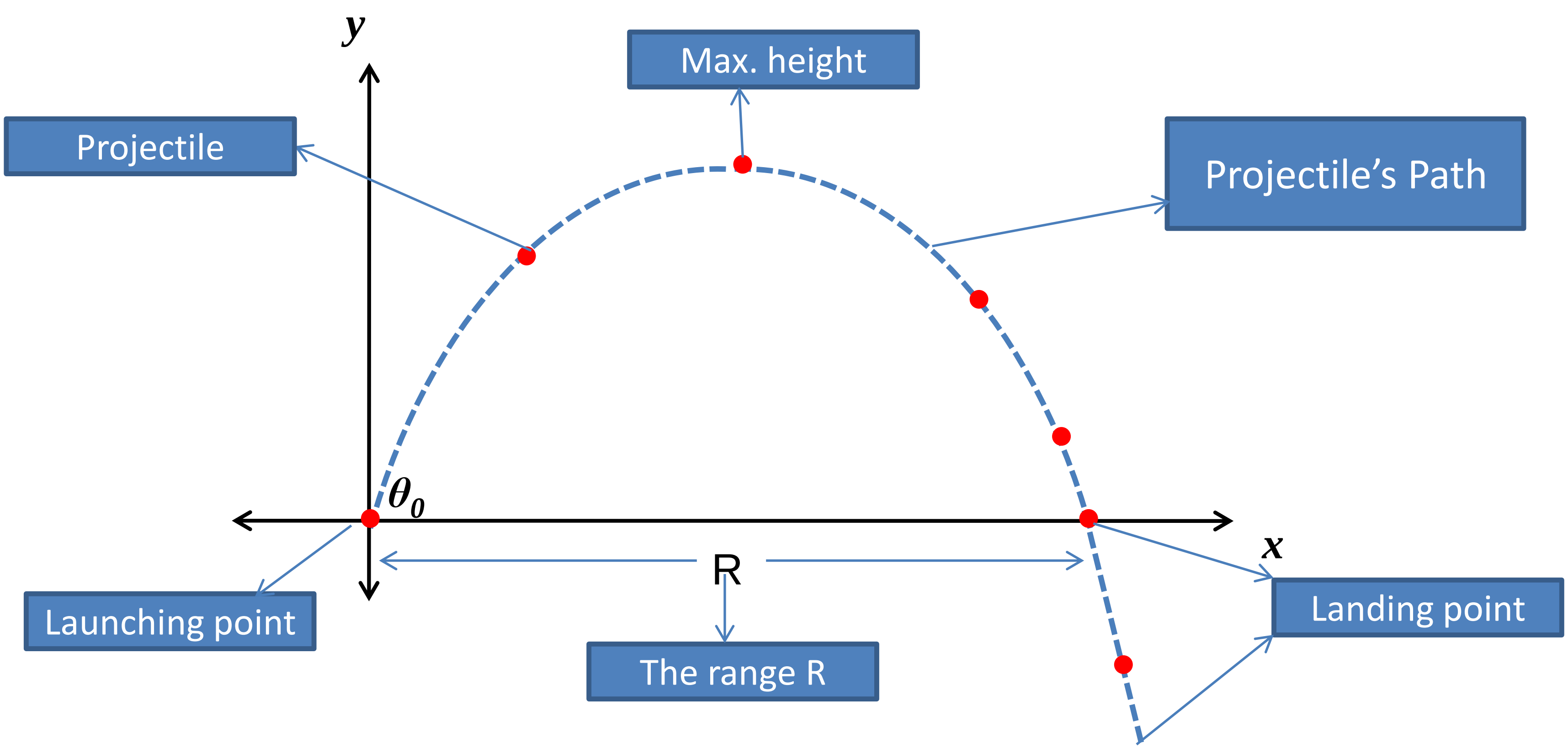
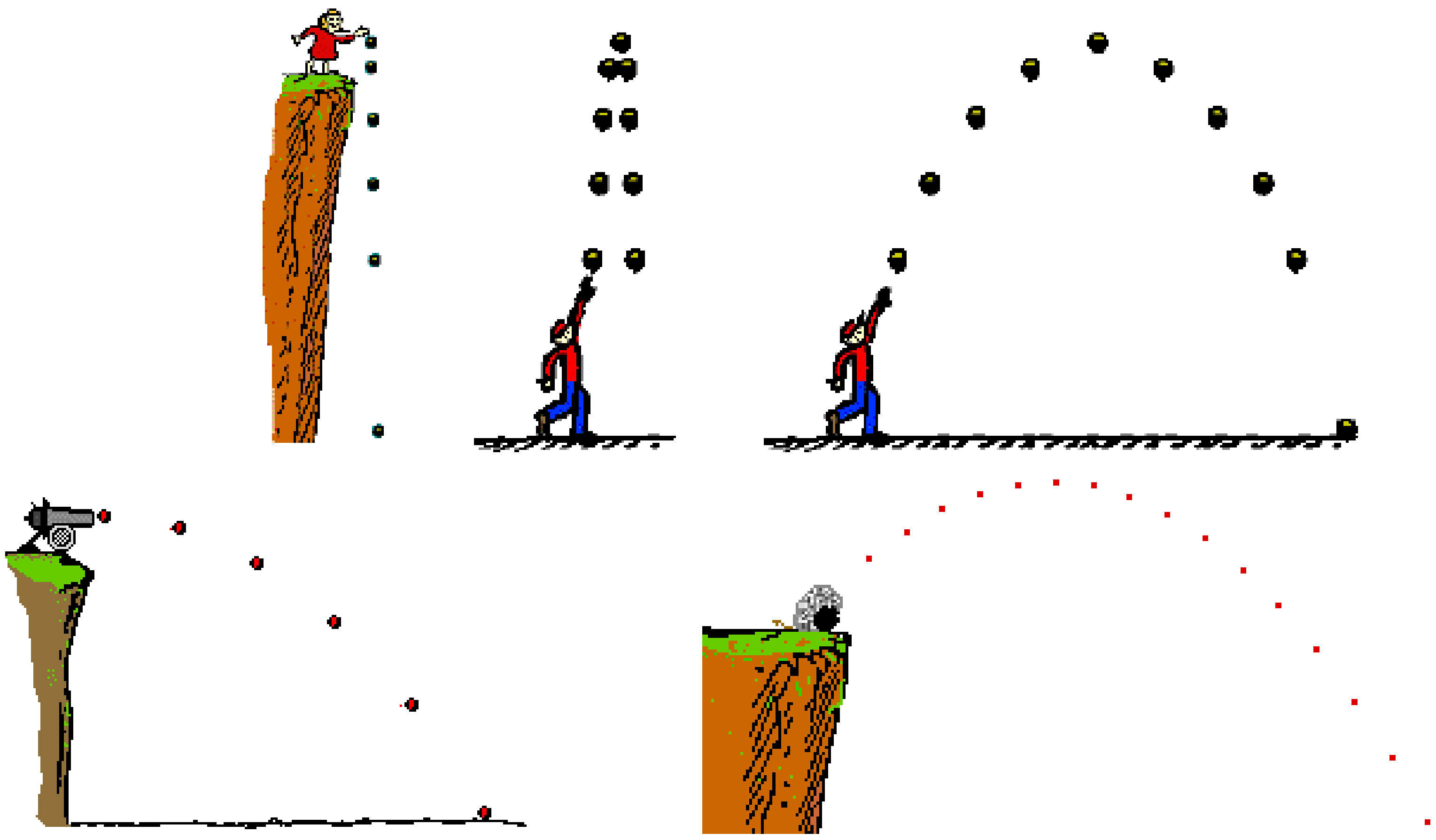
Projectile Motion *Projectile motion* is the motion of a particle that is launched with an initial velocity $\vec{v}_0$. During its flight, the particle's horizontal acceleration is zero and its vertical acceleration is the free-fall acceleration $-g$.






y
Max. height
Projectile
Projectile's Path
θ_0
x
R
Launching point
The range R
Landing point

Types of Projectiles

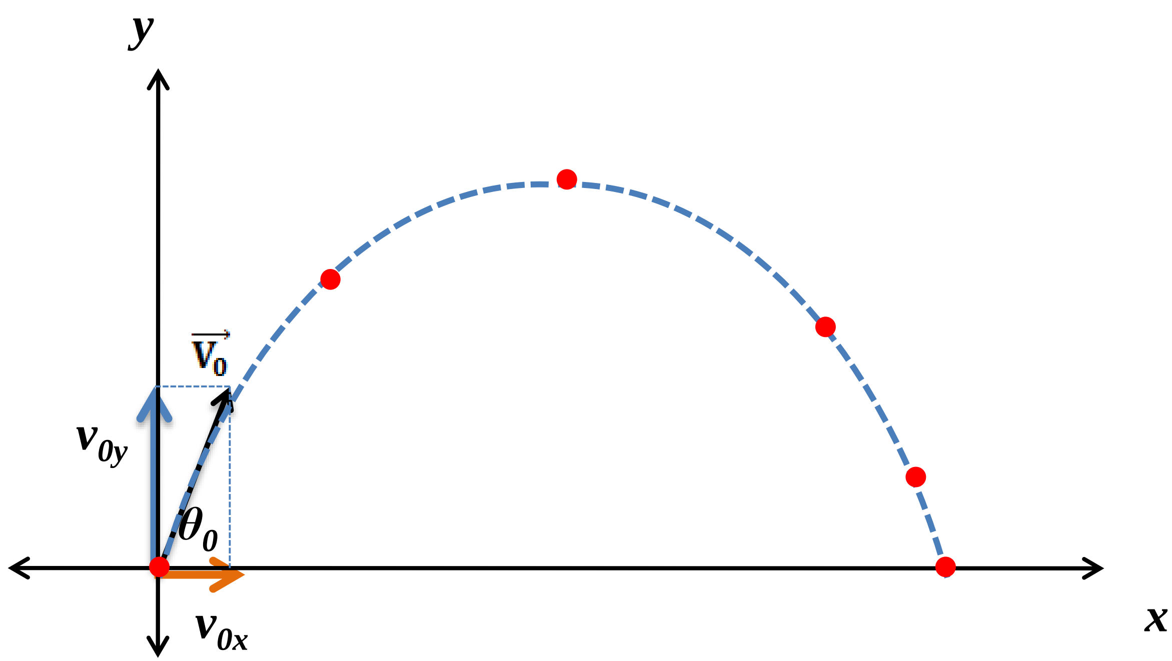


In projectile motion, the horizontal motion and the vertical motion are independent of each other; that is, neither motion affects the other.

$$\vec{v}_0 = v_{0x}\hat{\text{i}} + v_{0y}\hat{\text{j}}.$$

$$v_{0x} = v_0 \cos \theta_0$$

$$v_{0y} = v_0 \sin \theta_0$$



4-6 | Projectile Motion Analyzed

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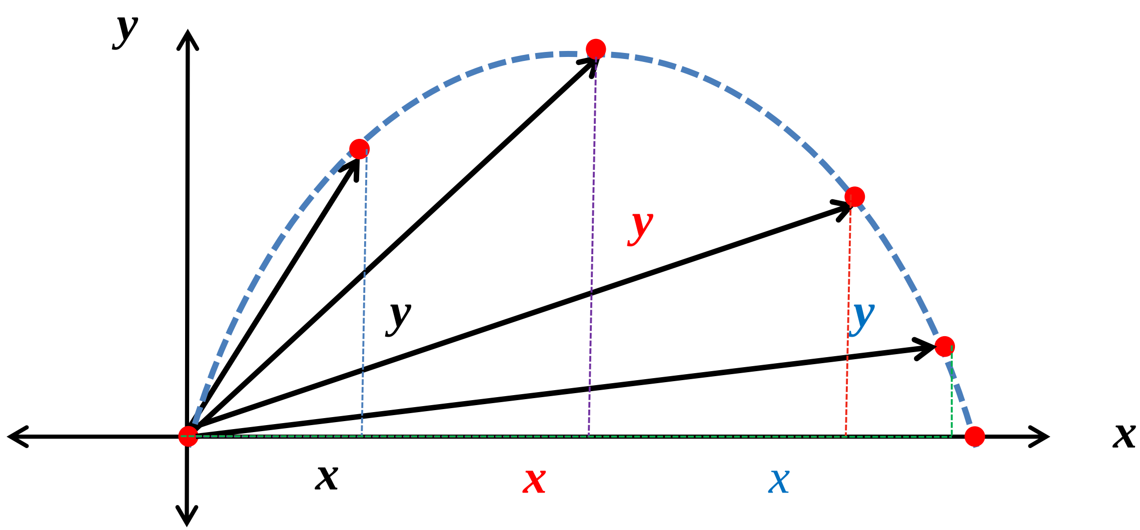

4-6 | Projectile Motion Analyzed

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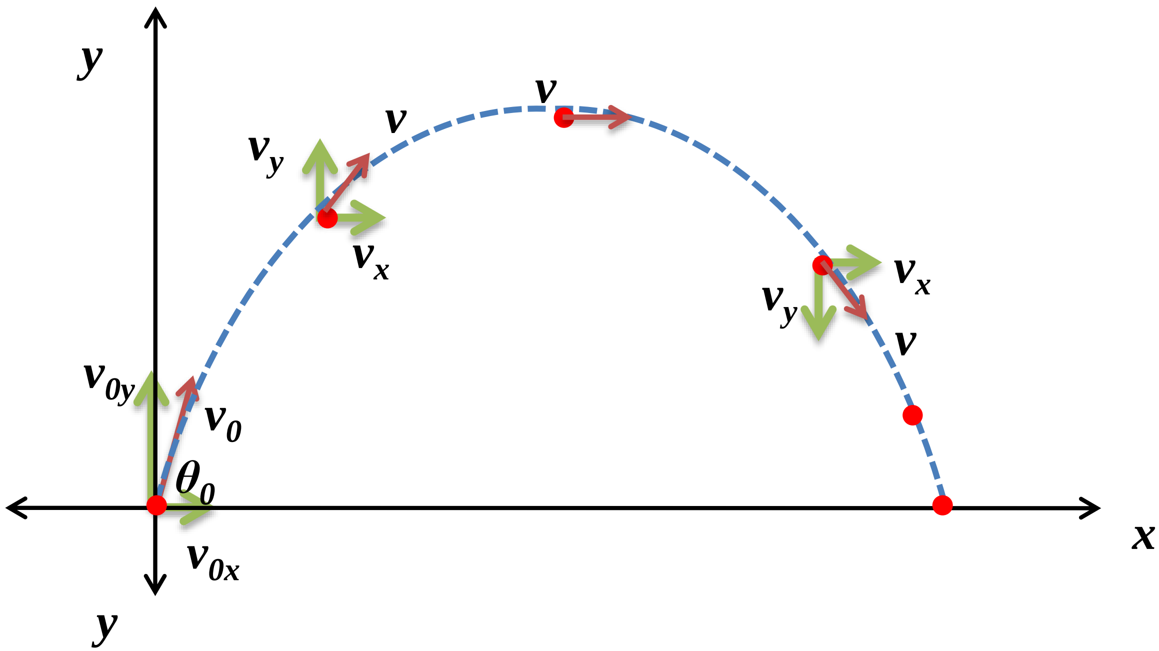

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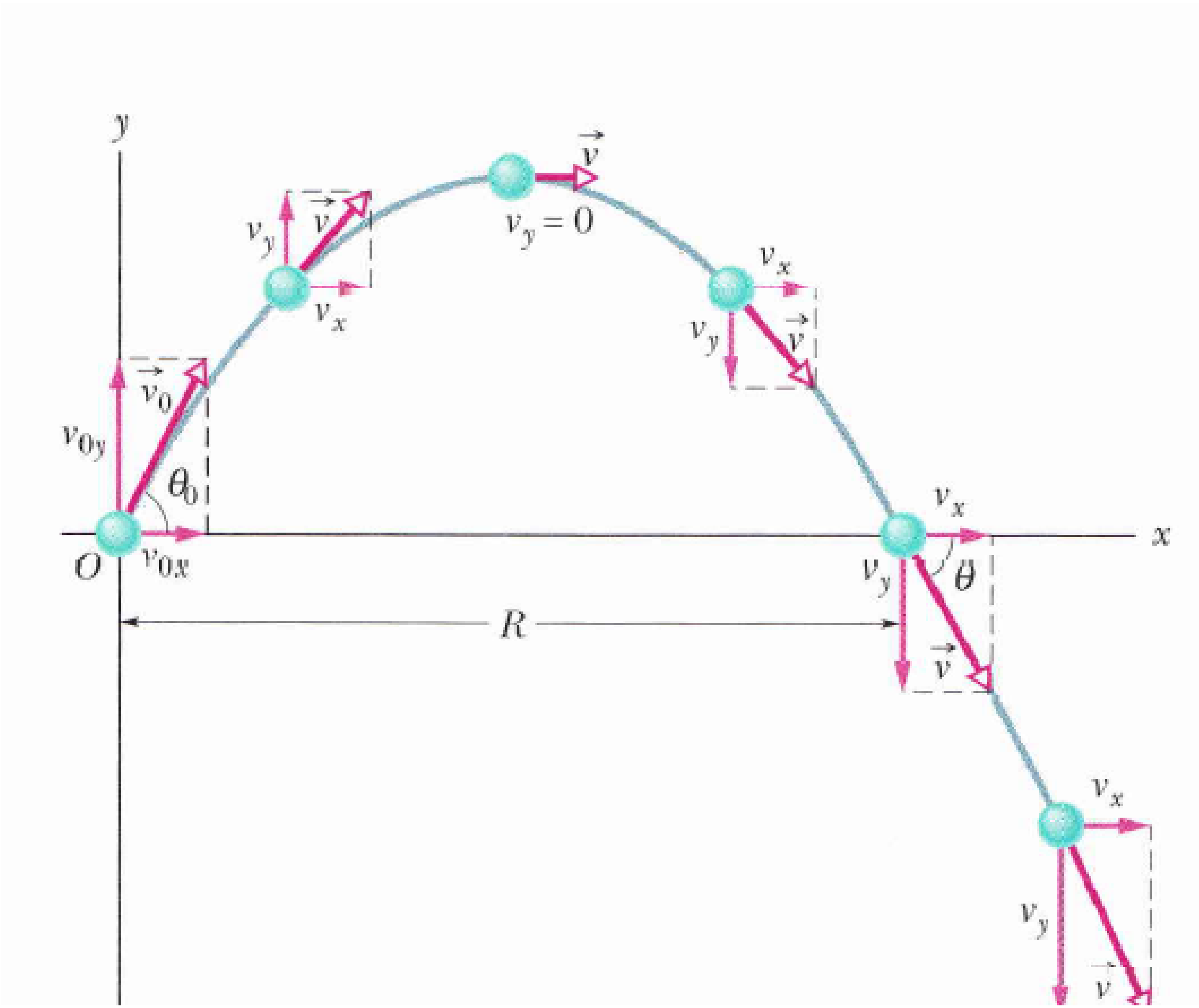

Projectile motion

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Horizontal Motion

$$a_x = 0$$

$$v_{0x} = v_0 \cos \theta_0$$

$$v_x = v_{0x}$$

$$x - x_0 = v_{0x} t.$$

$$x - x_0 = (v_0 \cos \theta_0) t.$$

$$v = v_0 + at$$

$$x - x_0 = v_0 t + \tfrac{1}{2} a t^2$$

$$v^2 = v_0^2 + 2a(x - x_0)$$

$$x - x_0 = \tfrac{1}{2}(v_0 + v)t$$

$$x - x_0 = vt - \tfrac{1}{2} a t^2$$

Vertical Motion

$$a_y = -g$$

$$v_{0y} = v_0 \sin \theta_0$$

$$v_y = v_{0y} - g\, t$$

$$v_y = v_0 \sin \theta_0 - g\, t$$

$$y - y_0 = v_{0y} t - \tfrac{1}{2} g t^2$$

$$= (v_0 \sin \theta_0) t - \tfrac{1}{2} g t^2,$$

Projectile motion

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Horizontal Motion

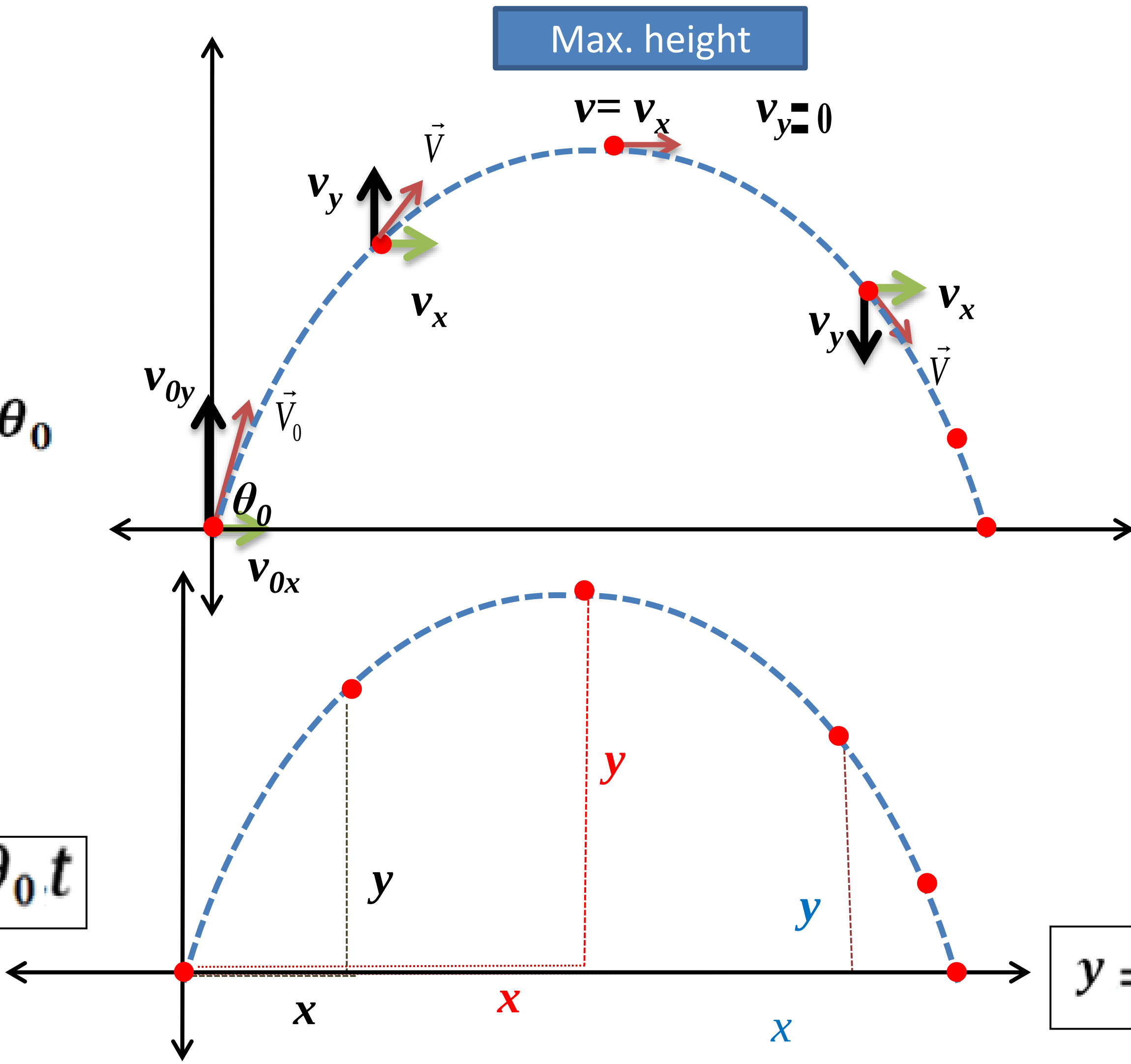
$a_x = 0$

$v_{0x} = v_0 \cos\theta_0$

$v_x = v_{0x}$

$x = v_{0x} t$

$x = v_0 \cos\theta_0 \, t$



Vertical Motion

$a_y = -g$

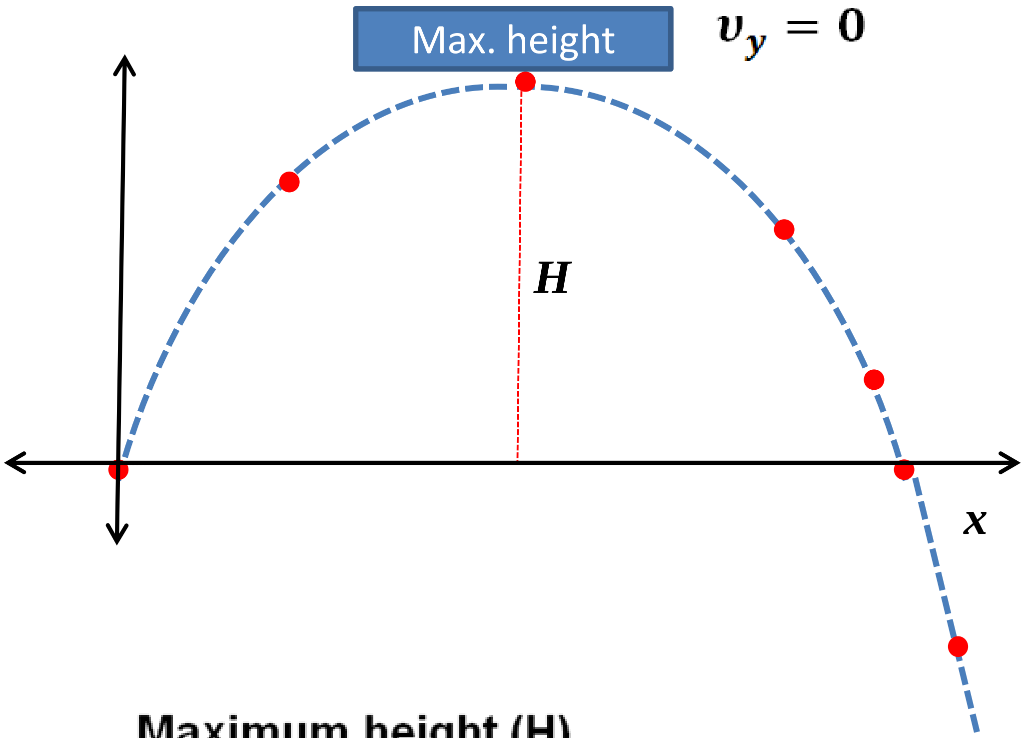
$v_{0y} = v_0 \sin\theta_0$

$v_y = v_{0y} - g\,t$

$v_y = v_0 \sin\theta_0 - g\,t$

$y = v_{0y} t - \frac{1}{2} g t^2$

$y = v_0 \sin\theta_0 \, t - \frac{1}{2} g t^2$



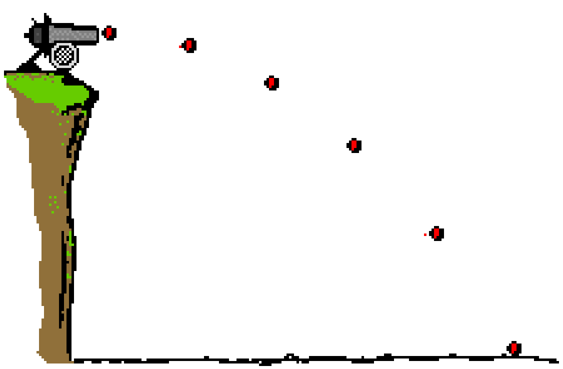
Maximum height (H)

$$H = \frac{(v_0 \sin \theta_0)^2}{2g}$$

PROBLEMS

•21 A projectile is fired horizontally from a gun that is 45.0 m above flat ground, emerging from the gun with a speed of 250 m/s. (a) How long does the projectile remain in the air?

(b) At what horizontal distance from the firing point does it strike the ground?



(c) What is the magnitude of the vertical component of its velocity as it strikes the ground?

••38 You throw a ball toward a wall at speed 25.0 m/s and at angle $\theta_0 = 40.0°$ above the horizontal (Fig. 4-38). The wall is distance $d = 22.0$ m from the release point of the ball. (a) How far above the release point does the ball hit the wall?

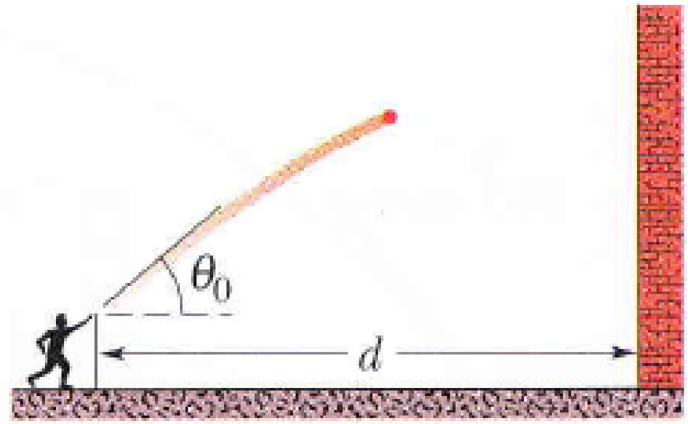


FIG. 4-38 Problem 38.

What are the (b) horizontal and (c) vertical components of its velocity as it hits the wall?

(d) When it hits, has it passed the highest point on its trajectory?

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

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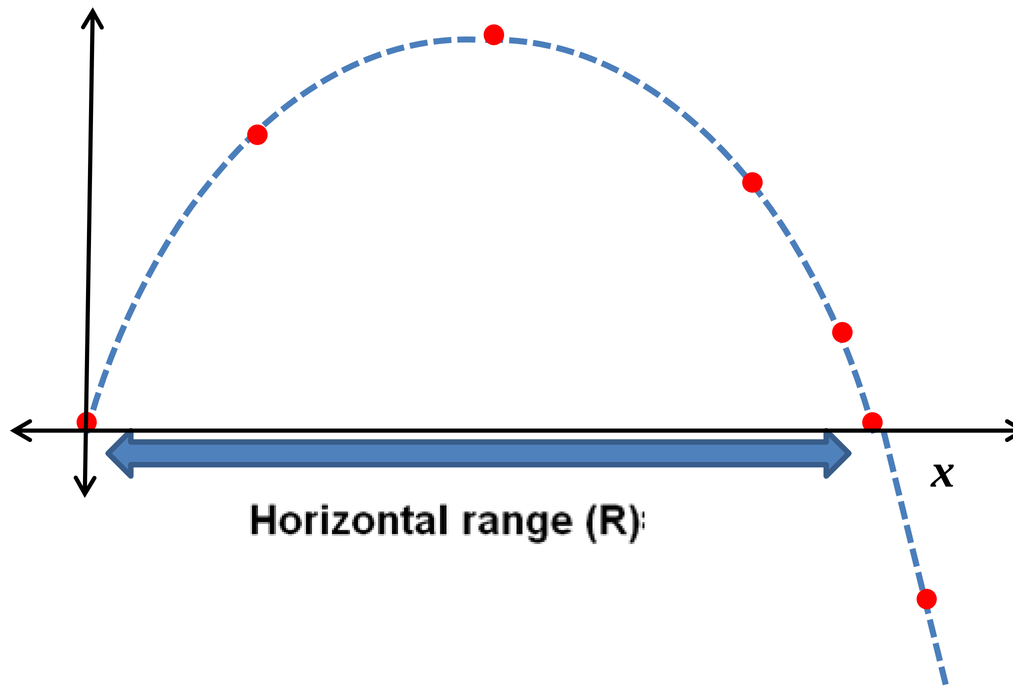
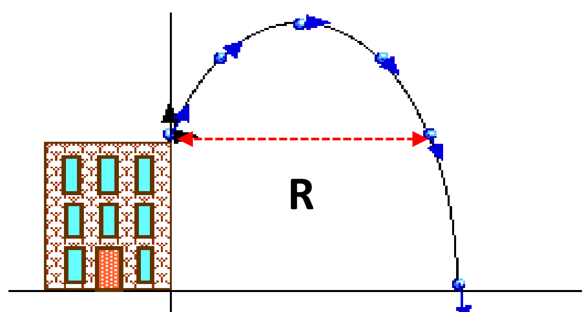
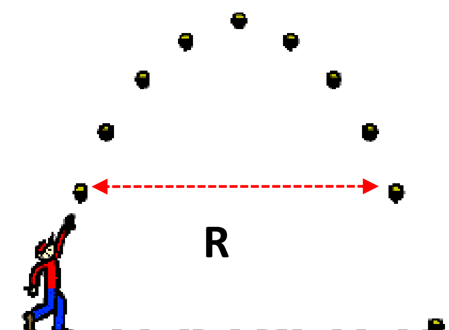
$$R = \frac{v_0^2}{g} \sin 2\theta_0$$

Maximum range

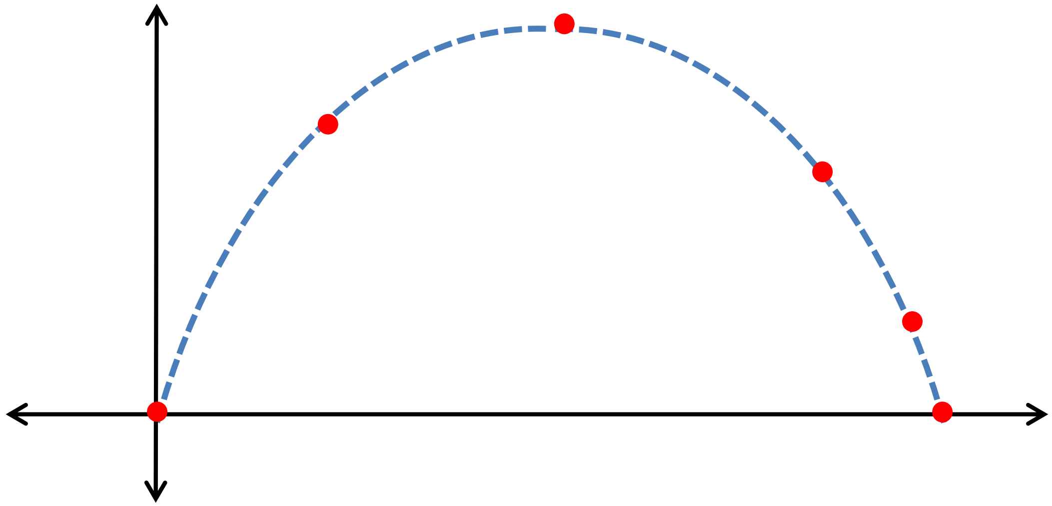
$$\theta_0 = 45^0 \rightarrow R_{max} = \frac{v_0^2}{g}$$







The equation of the projectile path (TRAJECTORY)



$$y = (\tan\theta_0)x - \frac{gx^2}{2(v_0\cos\theta_0)^2}$$

This is the equation of a parabola, so the projectile path is parabolic

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

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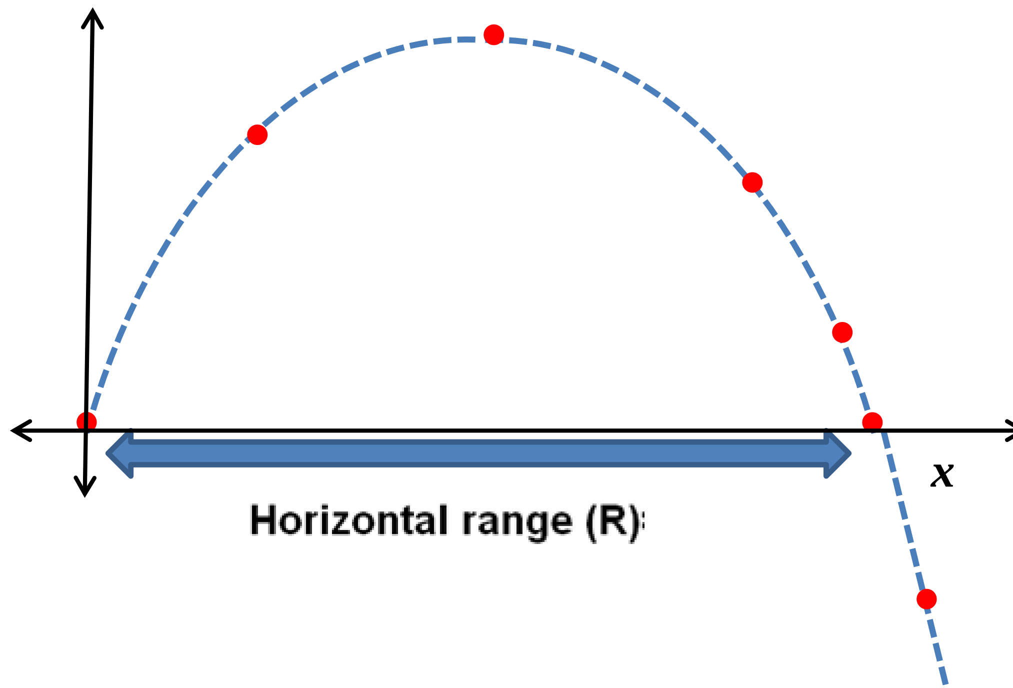
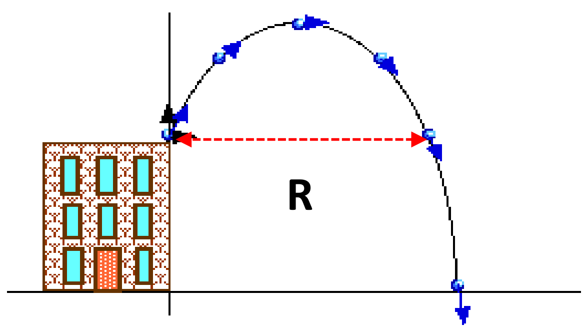
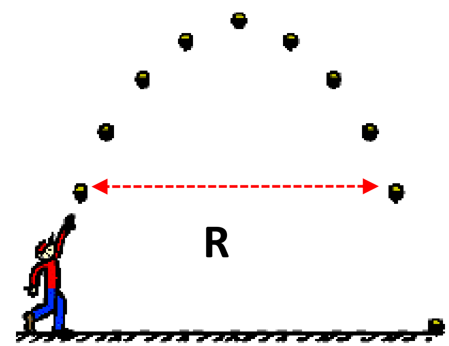
$$R = \frac{v_0^2}{g} \sin 2\theta_0$$



Maximum range

$$\theta_0 = 45^0 \rightarrow R_{max} = \frac{v_0^2}{g}$$

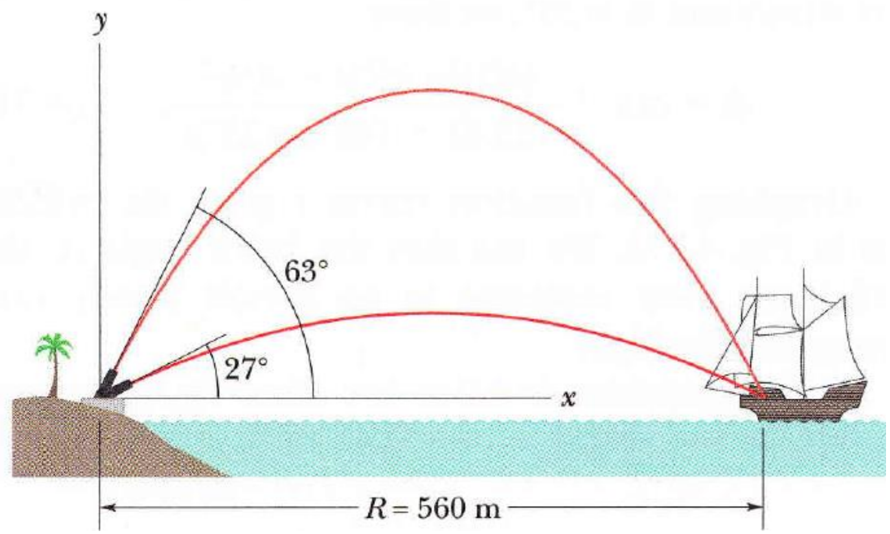




Sample Problem 4-7

Figure 4-16 shows a pirate ship 560 m from a fort defending a harbor entrance. A defense cannon, located at sea level, fires balls at initial speed $v_0 = 82$ m/s.

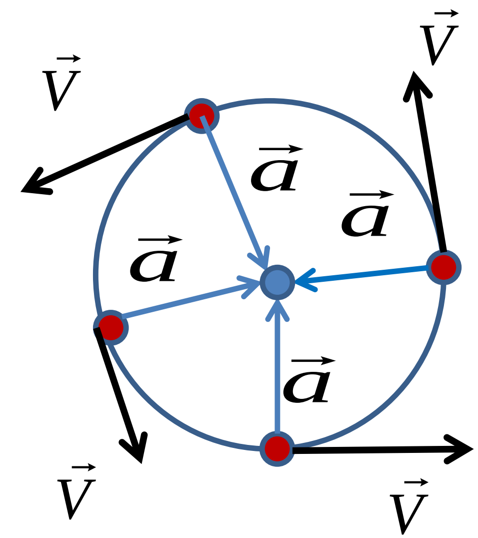
(a) At what angle θ_0 from the horizontal must a ball be fired to hit the ship?



(b) What is the maximum range of the cannonballs?

4-7 | Uniform Circular Motion

A particle is in uniform circular motion if it travels around a circle or circular arc at **constant speed.**



1-Velocity :

-magnitude constant v.

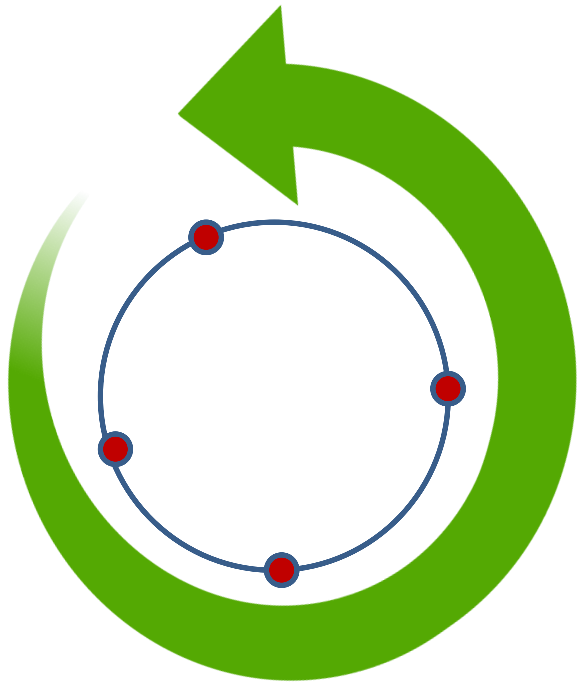
-direction :tangent to the circle in the direction of motion.

2- Acceleration:

Why is the particle accelerating even though the speed does not vary?

- magnitude $a = \frac{v^2}{r}$
- direction: toward the center.

- It is called **Centripetal acceleration(meaning seeking center)**



3- <u>Period:</u> is the time for a particle go around the circle once.

$$\text{Time} = \frac{\text{distance}}{\text{velocity}}$$

For one round $\Rightarrow$ distance = circumference of the circle

$$\boxed{T = \frac{2\pi r}{v}}$$

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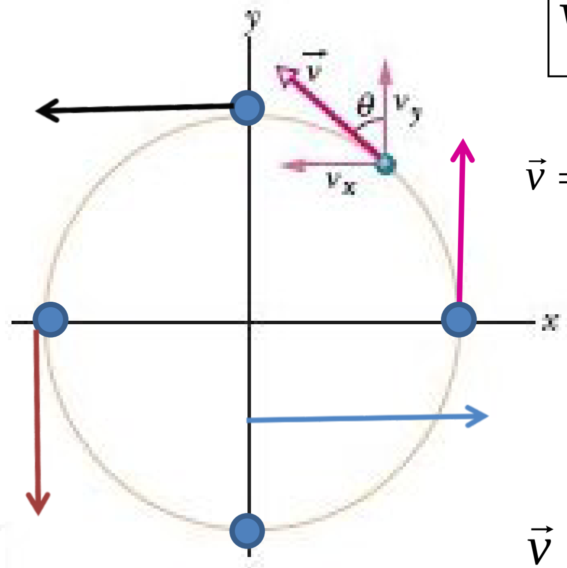
$$\vec{v} = v_x\hat{i} + v_y\hat{j}$$

$\vec{v} = -v\,\hat{\mathrm{i}}$

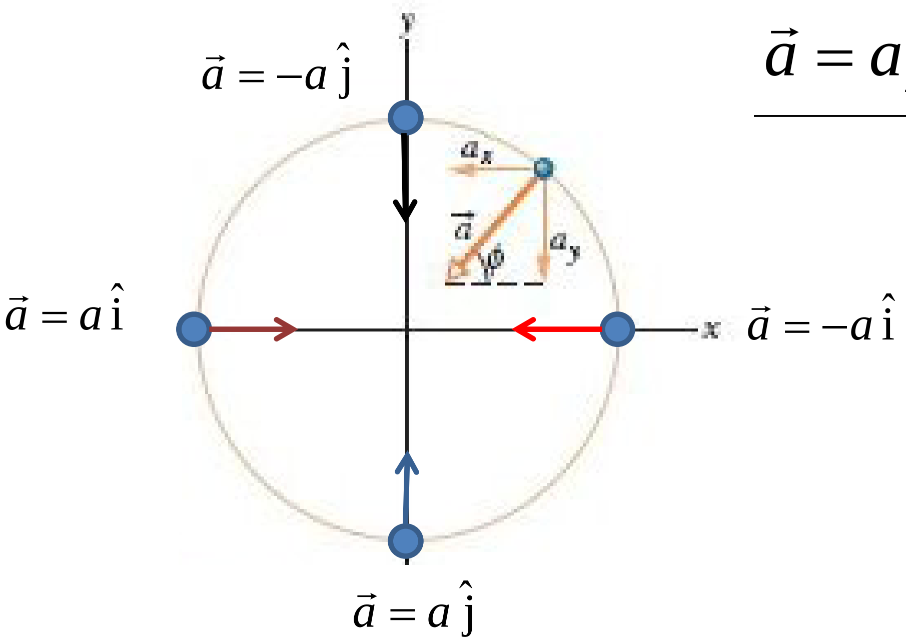
$\vec{v} = v\,\hat{\mathrm{j}}$



$\vec{v} = -v\,\hat{\mathrm{j}}$

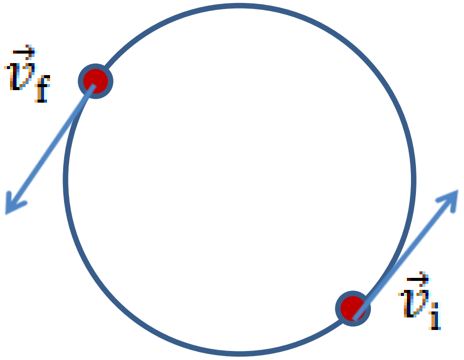
$\vec{v} = v\,\hat{\mathrm{i}}$

$$\vec{a} = a_x\hat{i} + a_y\hat{j}$$



Sample Problem 4-10

What is the magnitude of the acceleration, in g units, of a pilot whose aircraft enters a horizontal circular turn with a velocity of $\vec{v}_i = (400\hat{\mathrm{i}} + 500\hat{\mathrm{j}})$ m/s and 24.0 s later leaves the turn with a velocity of $\vec{v}_f = (-400\hat{\mathrm{i}} - 500\hat{\mathrm{j}})$ m/s?



Problem 21

(a) From Eq. 4-22 (with $q_0 = 0$),

h= (-gt^2)/2 , h= -45.0m

The time of flight is

$$t = \sqrt{\frac{2h}{g}} = \sqrt{\frac{2(45.0\text{ m})}{9.80\text{ m/s}^2}} = 3.03\text{ s.}$$

(b) From (Eq. 4-21)

$$\Delta x = v_0 t = (250\text{ m/s})(3.03\,\text{s}) = 758\text{ m.}$$

(c) from Eq.(4-23)

$$\left|v_y\right| = gt = (9.80\text{ m/s}^2)(3.03\,\text{s}) = 29.7\text{ m/s.}$$

Problem 38

(a) from Eq. 4-21

$$t = \frac{\Delta x}{v_x} = \frac{22.0 \text{ m}}{(25.0 \text{ m/s})\cos 40.0°} = 1.15 \text{ s}.$$

The vertical distance (from Eq. 4-22)

$$\Delta y = (v_0 \sin\theta_0)t - \frac{1}{2}gt^2 = (25.0 \text{ m/s})\sin 40.0°(1.15 \text{ s}) - \frac{1}{2}(9.80 \text{ m/s}^2)(1.15 \text{ s})^2 = 12.0 \text{ m}.$$

(b) $v_x = v_0 \cos 40.0° = 19.2$ m/s.

(c) from (Eq. 4-23)

$$v_y = v_0 \sin\theta_0 - gt = (25.0 \text{ m/s}) \sin 40.0° - (9.80 \text{ m/s}^2)(1.15 \text{ s}) = 4.80 \text{ m/s}.$$

(d) As $v_y > 0$ when the ball hits the wall, it has not reached the highest point yet.