Conceptual Physics Fundamentals

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Chapter 6:

GRAVITY, PROJECTILES, AND SATELLITES

This lecture will help you understand:

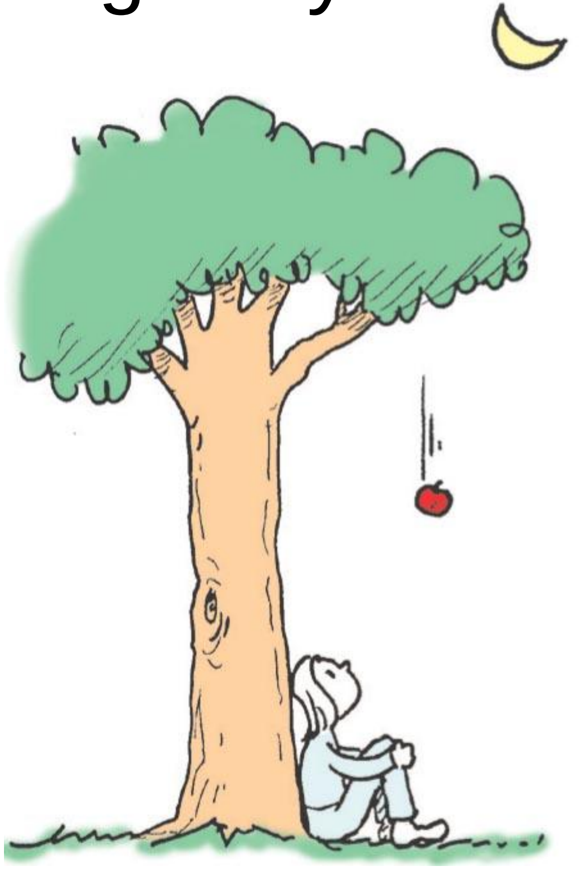
- The Universal Law of Gravity
- The Universal Gravitational Constant, *G*
- Gravity and Distance: The Inverse-Square Law
- Weight and Weightlessness
- Universal Gravitation
- Projectile Motion
- Fast-Moving Projectiles—Satellites
- Circular Satellite Orbits
- Elliptical Orbits
- Energy Conservation and Satellite Motion
- Escape Speed

Gravity, Projectiles, and Satellites

"The greater the velocity…with (a stone) is projected, the farther it goes before it falls to the Earth. We may therefore suppose the velocity to be so increased, that it would describe an arc of 1, 2, 5, 10, 100, 1000 miles before it arrived at the Earth, till at last, exceeding the limits of the Earth, it should pass into space without touching." —Isaac Newton

The Universal Law of Gravity

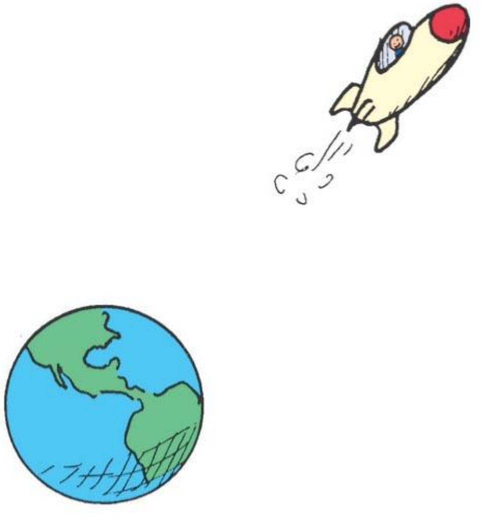
- Newton was not the first to discover gravity. Newton discovered that gravity is *universal.*
- Legend—Newton, sitting under an apple tree, realized that the force between Earth and the apple is the same as that between moons and planets and everything else.



The Universal Law of Gravity

Law of universal gravitation

- everything pulls on everything else
- every body attracts every other body with a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance separating them



The Universal Law of Gravity

- in equation form:

$$force \sim \frac{(mass_1 \times mass_2)}{distance^2}, \text{ or } F \sim \frac{m_1 m_2}{d^2},$$

where *m* is mass of object and *d* is the distance between their centers

examples:

- the greater the masses m_1 and m_2 of two bodies, the greater the force of attraction between them
- the greater the distance of separation *d*, the weaker the force of attraction

The Universal Law of Gravity
CHECK YOUR NEIGHBOR

Newton's most celebrated synthesis was and is of

A. earthly and heavenly laws.
B. weight on Earth and weightlessness in outer space.
C. masses and distances.
D. the paths of tossed rocks and the paths of satellites.

CHECK YOUR ANSWER

Newton's most celebrated synthesis was and is of

A. earthly and heavenly laws.

B. weight on Earth and weightlessness in outer space.

C. masses and distances.

D. the paths of tossed rocks and the paths of satellites.

Comment:

This synthesis provided hope that other natural phenomena followed universal laws, and ushered in the "Age of Enlightenment."

The Universal Gravitational Constant, *G*

- Gravity is the weakest of four known fundamental forces
- With the gravitational constant *G*, we have the equation:

$$F = G\frac{m_1 m_2}{d^2}$$

- Universal gravitational constant,

  $G = 6.67 \times 10^{-11}\ \mathrm{Nm^2/kg^2}$

- Once value was known, mass of Earth was calculated as 6×10^{24} kg

The Universal Gravitational Constant, *G*
CHECK YOUR NEIGHBOR

The universal gravitational constant, *G*, which links force to mass and distance, is similar to the familiar constant

A. π.
B. *g*.
C. acceleration due to gravity.
D. speed of uniform motion.

The Universal Gravitational Constant, *G*
CHECK YOUR ANSWER

The universal gravitational constant, *G*, which links force to mass and distance, is similar to the familiar constant

A. π.

B. g.

C. acceleration due to gravity.

D. speed of uniform motion.

Explanation:

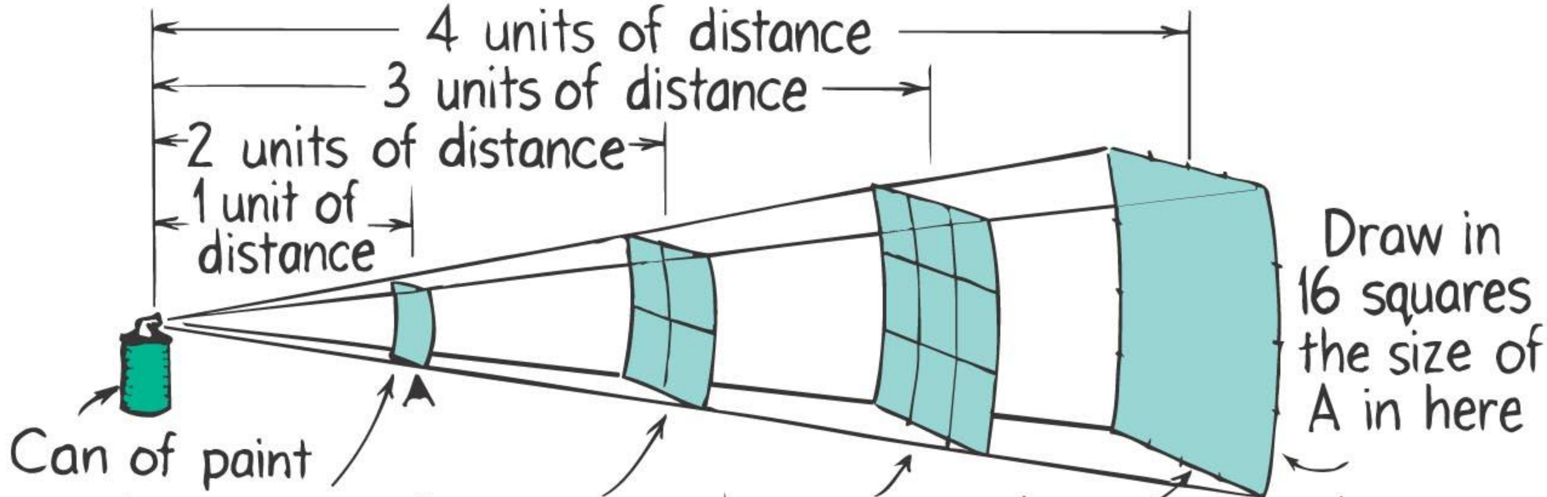
Just as π relates the circumference of a circle to its diameter, *G* relates force to mass and distance.

Gravity and Distance: The Inverse-Square Law

Inverse-square law

- relates the intensity of an effect to the inverse-square of the distance from the cause
- in equation form: *intensity* = 1/*distance*^{2}
- for increases in distance, there are decreases in force
- even at great distances, force approaches but never reaches zero

Inverse-Square Law



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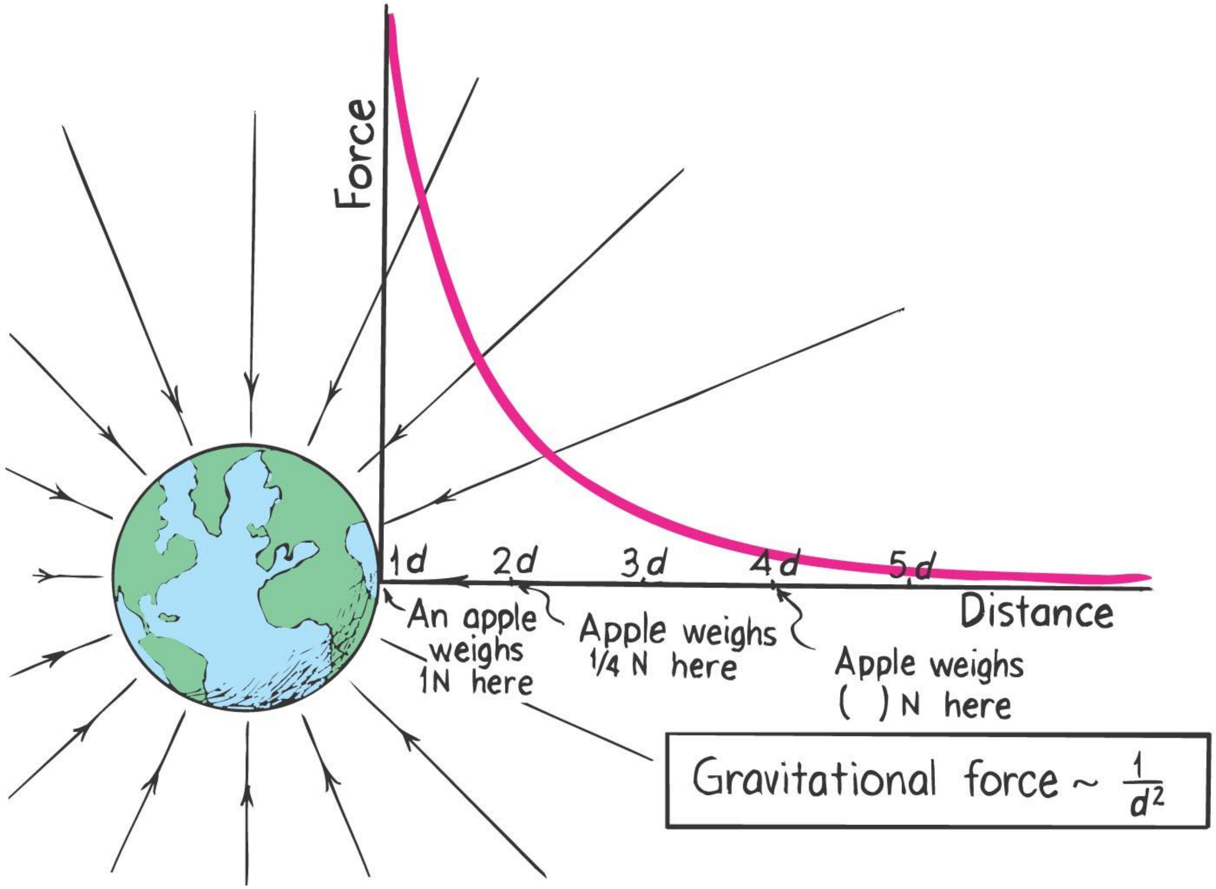
Paint spray	1 layer thick	¼ layer thick	( ) layer thick	( ) layer thick

Inverse-Square Law



Gravity and Distance: The Inverse-Square Law
CHECK YOUR NEIGHBOR

The force of gravity between two planets depends on their

A. masses and distance apart.
B. planetary atmospheres.
C. rotational motions.
D. all of the above

Gravity and Distance: The Inverse-Square Law
CHECK YOUR ANSWER

The force of gravity between two planets depends on their

A. masses and distance apart.

B. planetary atmospheres.

C. rotational motions.

D. all of the above

Explanation:

The equation for gravitational force, $F = G\frac{m_1 m_2}{d^2}$ cites only masses and distances as variables. Rotation and atmospheres are irrelevant.

Gravity and Distance: The Inverse-Square Law

CHECK YOUR NEIGHBOR

If the masses of two planets are each somehow doubled, the force of gravity between them

A. doubles.
B. quadruples.
C. reduces by half.
D. reduces by one-quarter.

Gravity and Distance: The Inverse-Square Law
CHECK YOUR ANSWER

If the masses of two planets are each somehow doubled, the force of gravity between them

A. doubles.

B. quadruples.

C. reduces by half.

D. reduces by one-quarter.

Explanation:

Note that both masses double. Then double × double = quadruple.

Gravity and Distance: The Inverse-Square Law
CHECK YOUR NEIGHBOR

If the mass of one planet is somehow doubled, the force of gravity between it and a neighboring planet

A. doubles.
B. quadruples
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Gravity and Distance: The Inverse-Square Law
CHECK YOUR ANSWER

If the mass of one planet is somehow doubled, the force of gravity between it and a neighboring planet

A. doubles.
B. quadruples.
C. reduces by half.
D. reduces by one-quarter.

Explanation:

Let the equation guide your thinking: $F = G\frac{m_1 m_2}{d^2}$

Note that if one mass doubles, then the force between them doubles.

Weight and Weightlessness

Weight

- force an object exerts against a supporting surface

  examples:

  - standing on a scale in an elevator accelerating downward, less compression in scale springs; weight is less
  - standing on a scale in an elevator accelerating upward, more compression in scale springs; weight is greater
  - at constant speed in an elevator, no change in weight

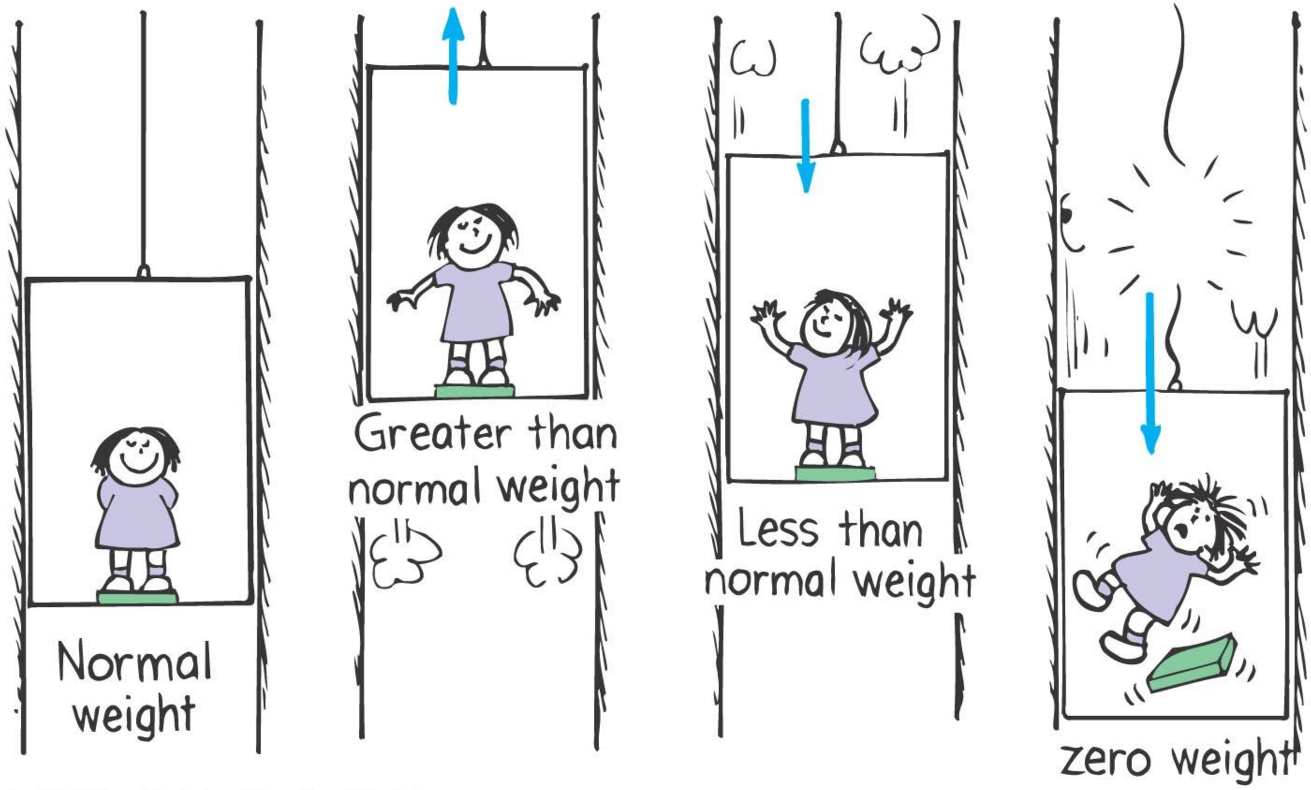
Weight and Weightlessness

Weightlessness

- no support force, as in free-fall

example: astronauts in orbit are without support forces and are in a continual state of weightlessness

Weight and Weightlessness



Weight and Weightlessness
CHECK YOUR NEIGHBOR

When an elevator accelerates upward, your weight reading on a scale is

A. greater.
B. less.
C. zero.
D. the normal weight.

Weight and Weightlessness
CHECK YOUR ANSWER

When an elevator accelerates upward, your weight reading on a scale is

A. greater.
B. less.
C. zero.
D. the normal weight.

Explanation:
The support force pressing on you is greater, so you weigh more.

Weight and Weightlessness
CHECK YOUR NEIGHBOR

When an elevator accelerates downward, your weight reading is

A. greater.
B. less.
C. zero.
D. the normal weight.

Weight and Weightlessness
CHECK YOUR ANSWER

When an elevator accelerates downward, your weight reading is

A. greater.
B. less.
C. zero.
D. the normal weight.

Explanation:

The support force pressing on you is less, so you weigh less. Question: Would you weigh less in an elevator that moves downward at constant velocity?

Weight and Weightlessness
CHECK YOUR NEIGHBOR

When the elevator cable breaks, the elevator falls freely, so your weight reading is

A. greater.
B. less.
C. zero.
D. the normal weight

Weight and Weightlessness
CHECK YOUR ANSWER

When the elevator cable breaks, the elevator falls freely, so your weight reading is

A. greater.
B. less.
C. zero.
D. the normal weight.

Explanation:

There is still a downward gravitational force acting on you, but gravity is not felt as weight because there is no support force, so your weight is zero.

Weight and Weightlessness
CHECK YOUR NEIGHBOR

If you weigh yourself in an elevator, you'll weigh more when the elevator

A. moves upward.
B. moves downward.
C. accelerates upward.
D. all of the above

Weight and Weightlessness
CHECK YOUR ANSWER

If you weigh yourself in an elevator, you'll weigh more when the elevator

A. moves upward.

B. moves downward.

C. accelerates upward.

D. all of the above

Explanation:

The support provided by the floor of an elevator is the same whether the elevator is at rest or moving at constant velocity. Only accelerated motion affects weight.

Universal Gravitation

Universal gravitation

- everything attracts everything else

  example: Earth is round because of gravitation—all parts of Earth have been pulled in, making the surface equidistant from the center

- The universe is expanding and accelerating outward.

Projectile Motion

- Without gravity, a tossed object follows a straight-line path.
- With gravity, the same object tossed at an angle follows a curved path.

Projectile

- any object that moves through the air or space under the influence of gravity, continuing in motion by its own inertia

Projectile Motion

Projectile motion is a combination of

- a horizontal component

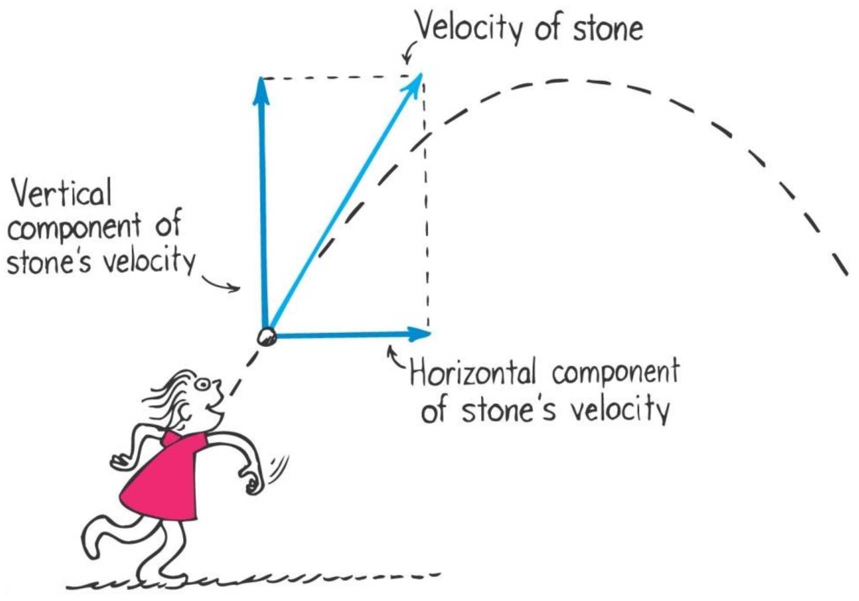
- a vertical component

Projectile Motion

Projectiles launched horizontally

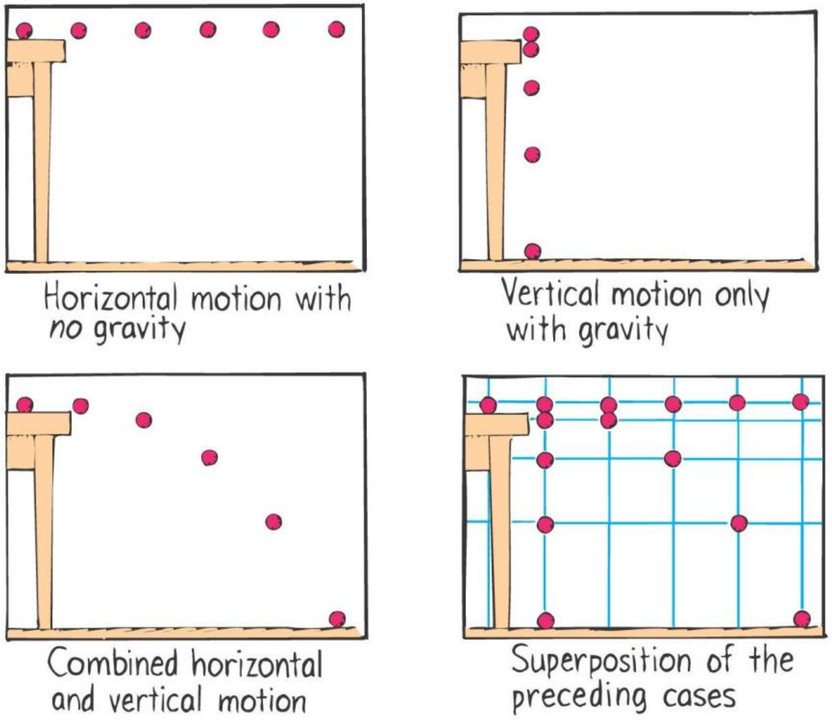
Important points:

- horizontal component of velocity doesn't change (when air drag is negligible)
  - ball travels the same horizontal distance in equal times (no component of gravitational force acting horizontally)
  - remains constant



Projectile Motion

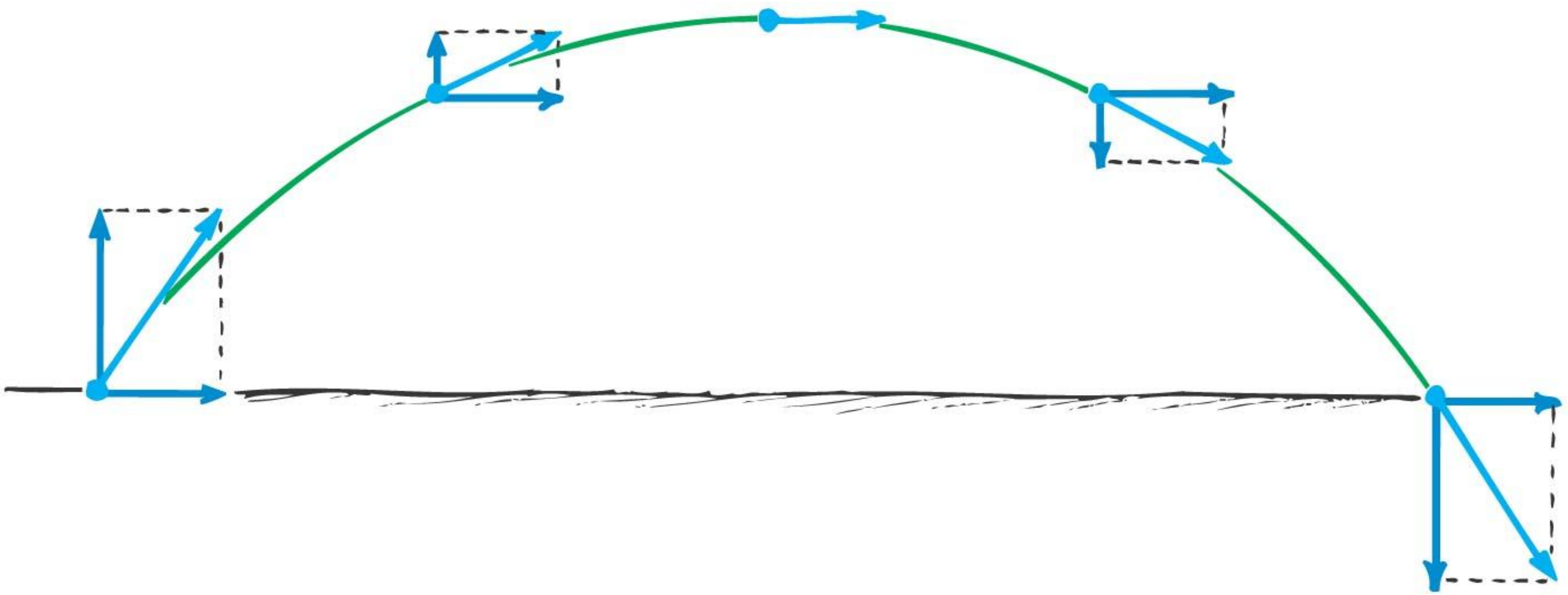
- vertical positions become farther apart with time
  - gravity acts downward, so ball accelerates downward
- curvature of path is the combination of horizontal and vertical components of motion



Projectile Motion

Parabola

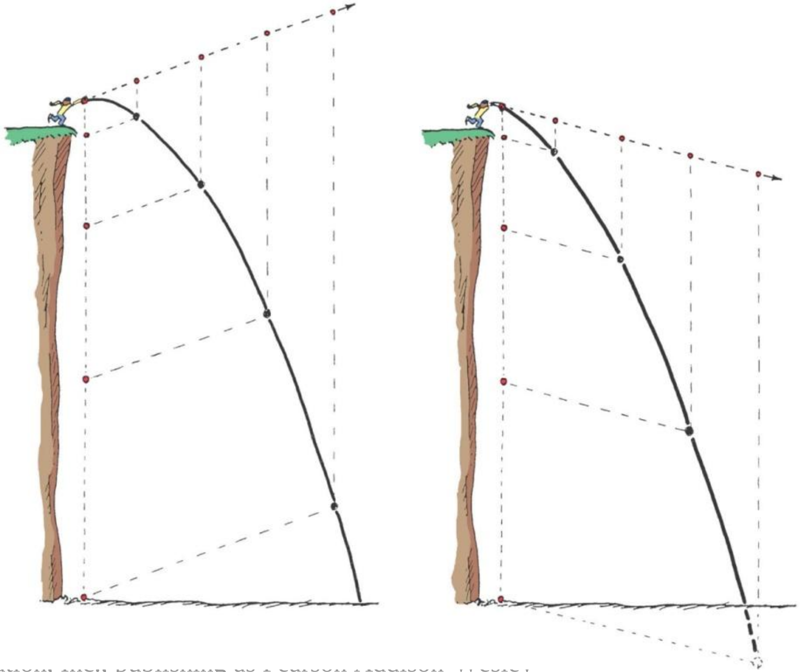
- curved path of a projectile that undergoes acceleration only in the vertical direction, while moving horizontally at a constant speed



Projectile Motion

Projectiles launched at an angle

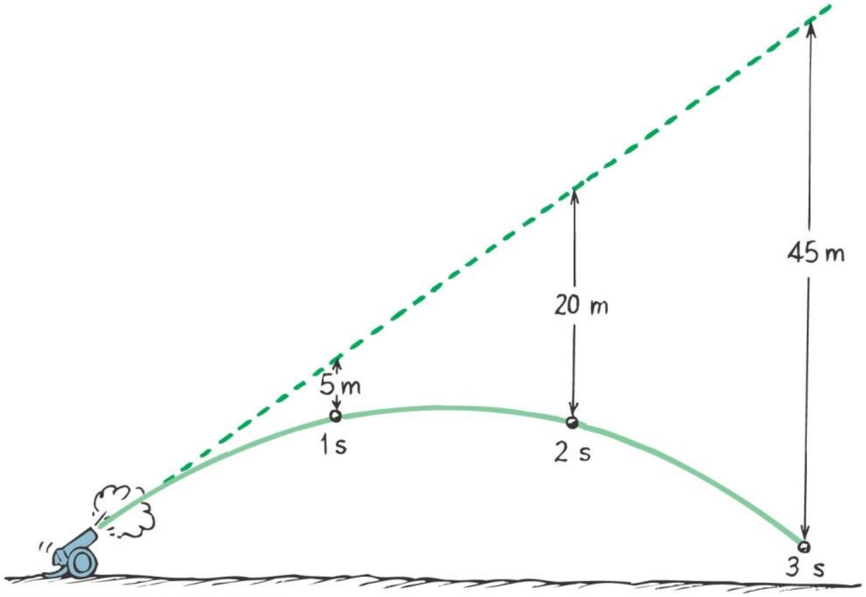
- paths of stone thrown at an angle upward and downward
  - vertical and horizontal components are independent of each other



Smashing Pumpkins

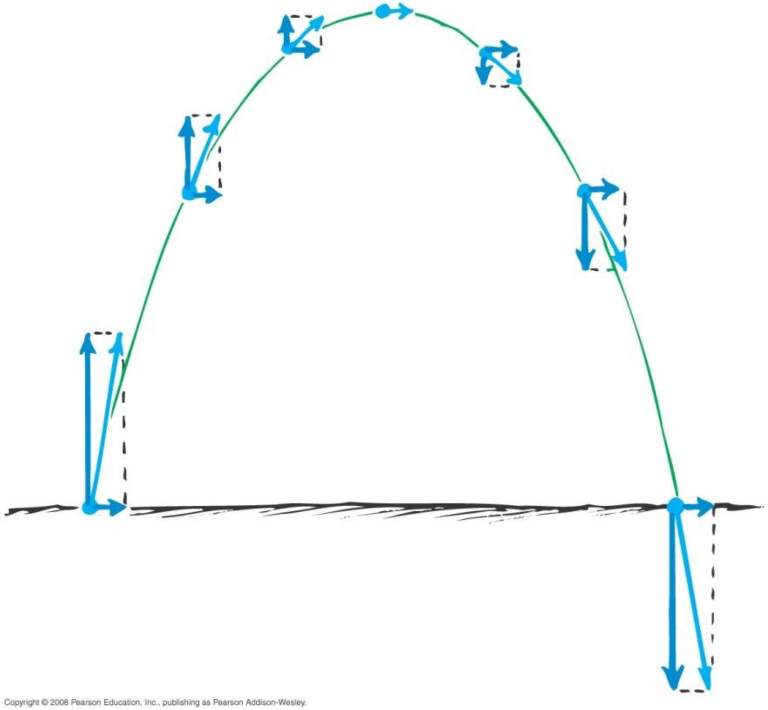
Projectile Motion

- paths of a cannonball shot at an upward angle
  - vertical distance that a stone falls is the same vertical distance it would have fallen if it had been dropped from rest and been falling for the same amount of time ($5t^2$)



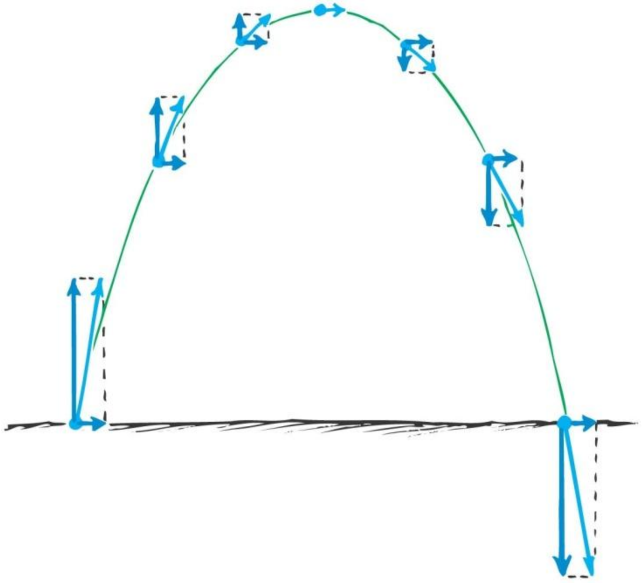
Projectile Motion

- paths of projectile following a parabolic trajectory
  - horizontal component along trajectory remains unchanged
  - only vertical component changes
  - velocity at any point is computed with the Pythagorean theorem (diagonal of rectangle)



Projectile Motion

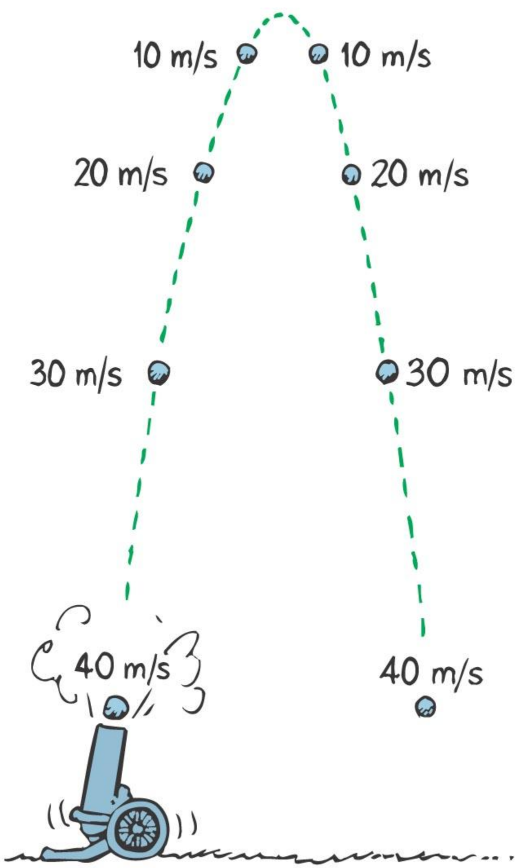
- different horizontal distances
  - same range is obtained from two different launching angles when the angles add up to 90
    - object thrown at an angle of 60° has the same range as if it were thrown at an angle of 30°



Projectile trajectories

Projectile Motion

- different horizontal distances (continued)
  - maximum range occurs for ideal launch at 45°
  - with air resistance, the maximum range occurs for a baseball batted at less than 45° above the horizontal
  - with air resistance the maximum range occurs when a golf ball that is hit at an angle less than 38°
- Without air resistance, the time for a projectile to reach maximum height is the same as the time for it to return to its initial level.



Projectile Motion
CHECK YOUR NEIGHBOR

The velocity of a typical projectile can be represented by horizontal and vertical components. Assuming negligible air resistance, the horizontal component along the path of the projectile

A. increases.
B. decreases.
C. remains the same.
D. not enough information

Projectile Motion
CHECK YOUR ANSWER

The velocity of a typical projectile can be represented by horizontal and vertical components. Assuming negligible air resistance, the horizontal component along the path of the projectile

A. increases.

B. decreases.

C. remains the same.

D. not enough information

Explanation:

Since there is no force horizontally, no horizontal acceleration occurs.

Projectile Motion
CHECK YOUR NEIGHBOR

When no air resistance acts on a fast-moving baseball, its acceleration is

A. downward, *g*.
B. because of a combination of constant horizontal motion and accelerated downward motion.
C. opposite to the force of gravity.
D. centripetal.

Projectile Motion
CHECK YOUR ANSWER

When no air resistance acts on a fast-moving baseball, its acceleration is

A. downward, *g*.
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Projectile Motion
CHECK YOUR NEIGHBOR

A ball tossed at an angle of 30° with the horizontal will go as far downrange as one that is tossed at the same speed at an angle of

A. 45°.
B. 60°.
C. 75°.
D. none of the above

Projectile Motion
CHECK YOUR ANSWER

A ball tossed at an angle of 30° with the horizontal will go as far downrange as one that is tossed at the same speed at an angle of

A. 45°.
B. 60°.
C. 75°.
D. none of the above

Explanation:

Same initial-speed projectiles have the same range when their launching angles add up to 90°. Why this is true involves a bit of trigonometry—which, in the interest of time, we'll not pursue here.

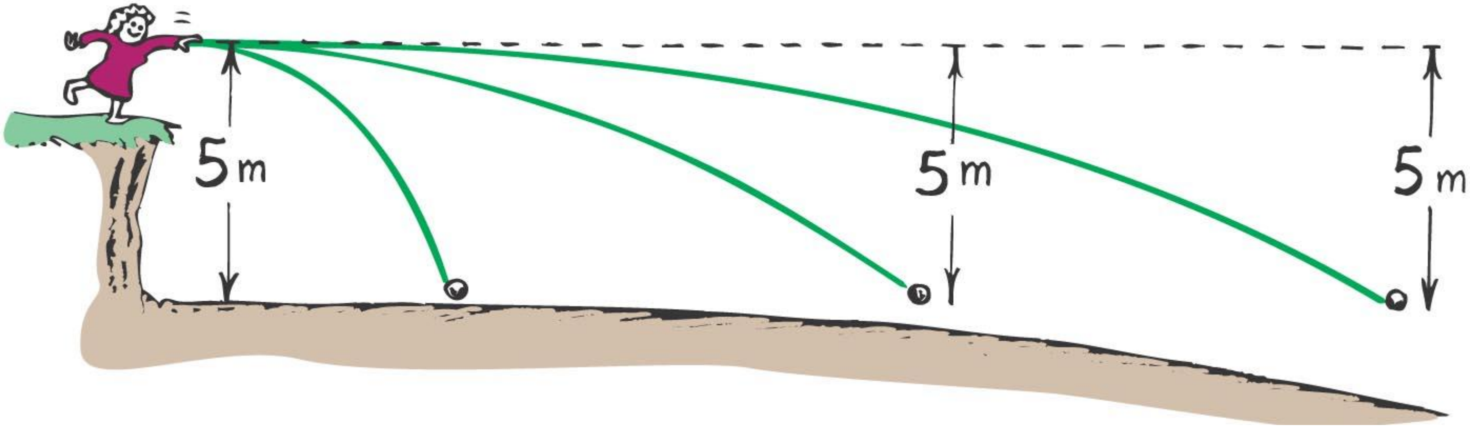
Fast-Moving Projectiles—Satellites

- satellite motion is an example of a high-speed projectile
- a satellite is simply a projectile that falls around Earth rather than into it
  - sufficient tangential velocity needed for orbit
  - with no resistance to reduce speed, a satellite goes around Earth indefinitely.

Fast-Moving Projectiles—Satellites
CHECK YOUR NEIGHBOR

As the ball leaves the girl's hand, one second later it will have fallen

A. 10 meters.
B. 5 meters below the dashed line.
C. less than 5 meters below the straight-line path.
D. none of the above



Fast-Moving Projectiles—Satellites
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As the ball leaves the girl's hand, one second later it will have fallen

A. 10 meters.

B. 5 meters below the dashed line.

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D. none of the above

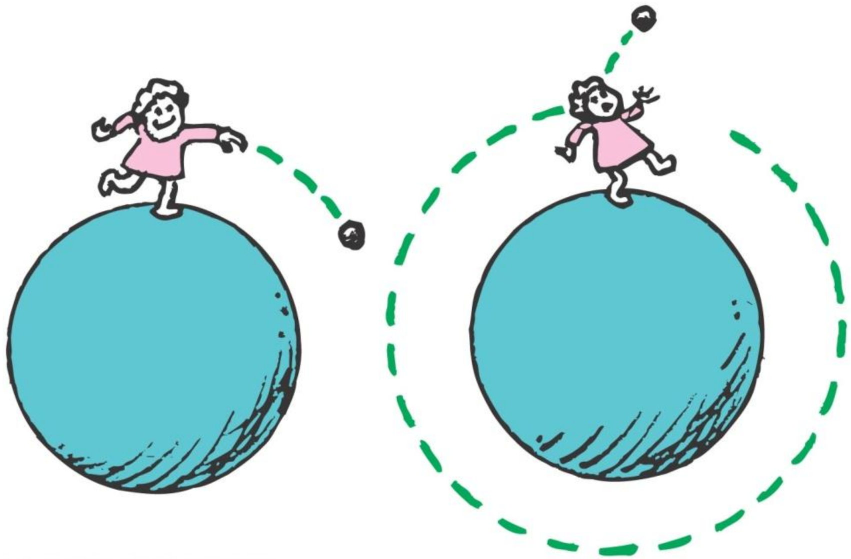
Comment:

Whatever the speed, the ball will fall a vertical distance of 5 meters below the dashed line.

Circular Satellite Orbits

Satellite in circular orbit

- speed
  - must be great enough to ensure that its falling distance matches Earth's curvature
  - is constant—only direction changes
  - unchanged by gravity



Circular Satellite Orbits

- positioning

  beyond Earth's atmosphere, where air resistance is almost totally absent

example: space shuttles are launched to altitudes of 150 kilometers or more, to be above air drag

Circular Satellite Orbits

- motion

  moves in a direction perpendicular to the force of gravity acting on it

- period for complete orbit

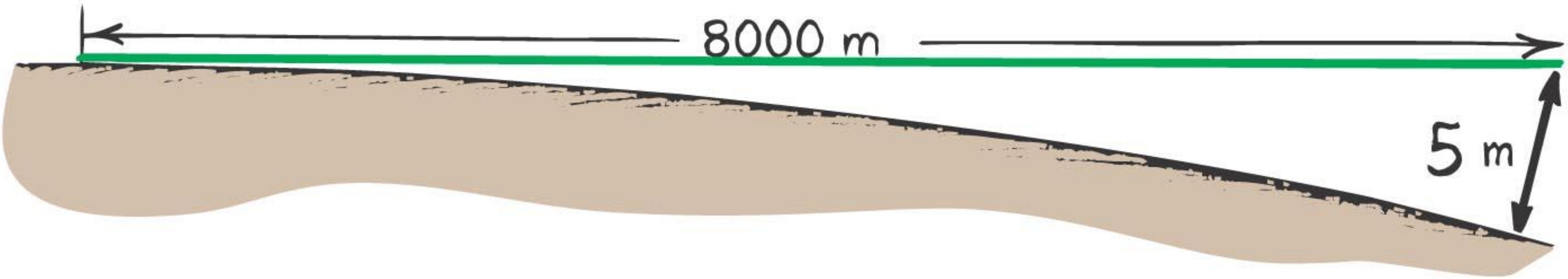
  –about Earth

  - for satellites close to Earth—about 90 minutes
  - for satellites at higher altitudes—longer periods

Circular Satellite Orbits

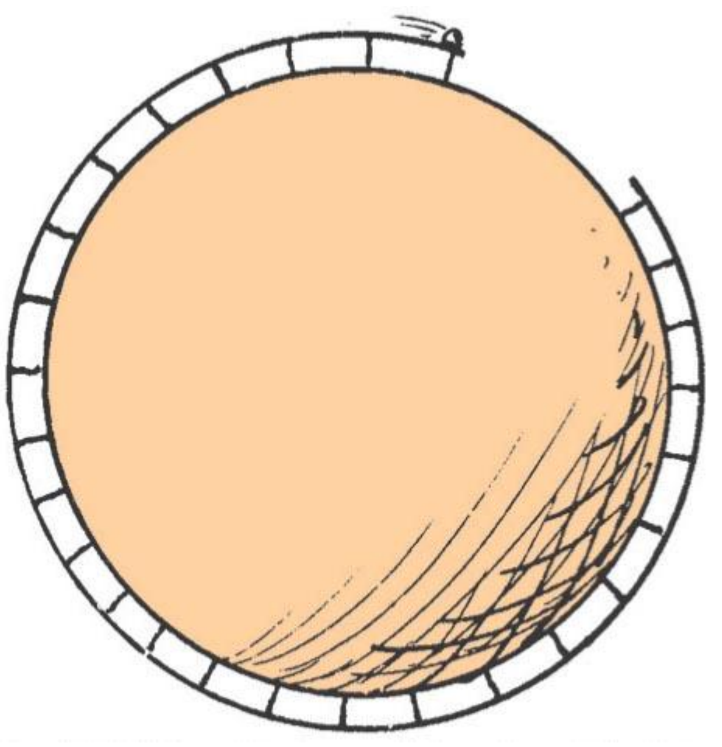
Curvature of the Earth

- Earth surface drops a vertical distance of 5 meters for every 8000 meters tangent to the surface



Camera on balloon at 100,000 feet

Circular Satellite Orbits



What speed will allow the ball to clear the gap?

Circular Satellite Orbits
CHECK YOUR NEIGHBOR

When you toss a projectile sideways, it curves as it falls. It will be an Earth satellite if the curve it makes

A. matches the curved surface of Earth.
B. results in a straight line.
C. spirals out indefinitely.
D. none of the above

Circular Satellite Orbits
CHECK YOUR ANSWER

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Explanation:

For an 8-km tangent, Earth curves downward 5 m. Therefore, a projectile traveling horizontally at 8 km/s will fall 5 m in that time, and follow the curve of Earth.

Circular Satellite Orbits
CHECK YOUR NEIGHBOR

When a satellite travels at a constant speed, the shape of its path is

A. a circle.
B. an ellipse.
C. an oval that is almost elliptical.
D. a circle with a square corner, as seen throughout your book.

Circular Satellite Orbits
CHECK YOUR ANSWER

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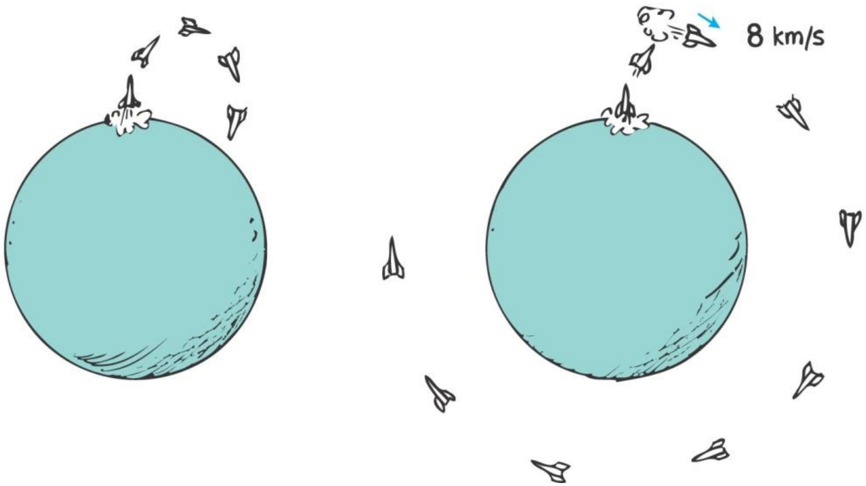
Circular Satellite Orbits

A payload into orbit requires control over

- direction of rocket
  - initially, rocket is fired vertically, then tipped
  - once above the atmosphere, the rocket is aimed horizontally
- speed of rocket
  - payload is given a final thrust to orbital speed of 8 km/s to fall around Earth and become an Earth satellite



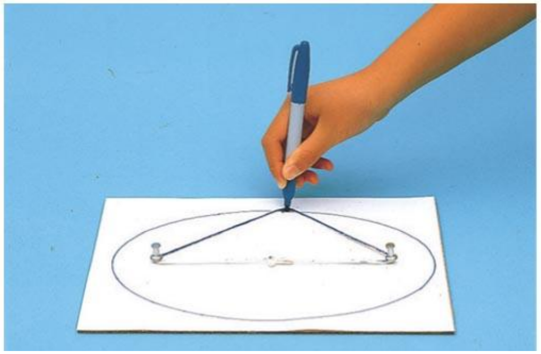
Elliptical Orbits

- A projectile just above the atmosphere will follow an elliptical path if given a horizontal speed greater than 8 km/s.

Ellipse

- specific curve, an oval path

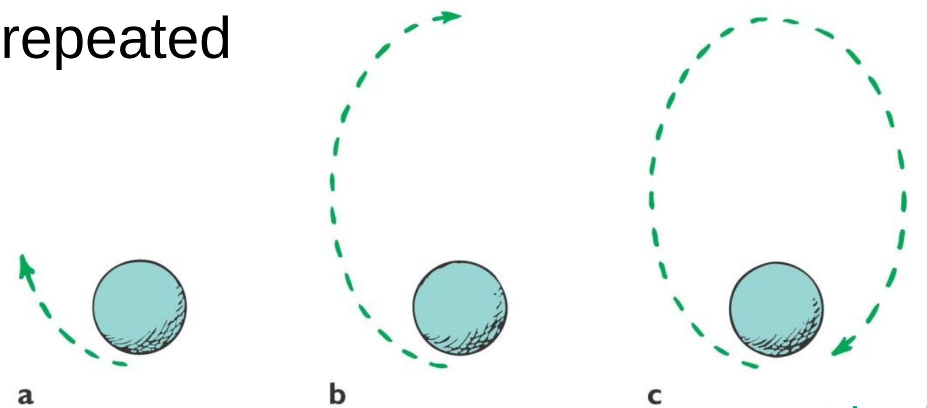
  example: circle is a special case of an ellipse when its two foci coincide



Elliptical Orbits

Elliptical orbit

- speed of satellite varies
  - initially, if speed is greater than needed for circular orbit, satellite overshoots a circular path and moves away from Earth
  - satellite loses speed and then regains it as it falls back toward Earth
  - it rejoins its original path with the same speed it had initially
  - procedure is repeated



Physics Classroom

Elliptical Orbits
CHECK YOUR NEIGHBOR

The speed of a satellite in an elliptical orbit

A. varies.
B. remains constant.
C. acts at right angles to its motion.
D. all of the above

Elliptical Orbits
CHECK YOUR ANSWER

The speed of a satellite in an elliptical orbit

A. varies.
B. remains constant.
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D. all of the above

Energy Conservation and Satellite Motion

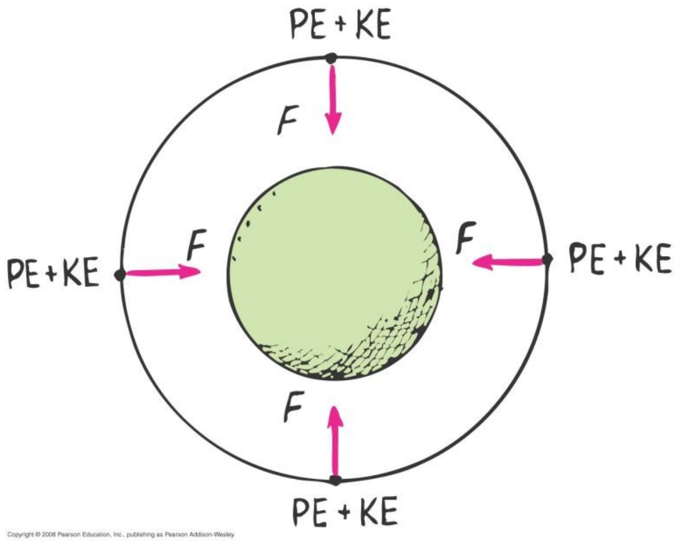
Recall the following

- object in motion possesses *KE* due to its motion
- object above Earth's surface possesses *PE* by virtue of its position
- satellite in orbit possesses *KE* and *PE*
  - sum of *KE* and *PE* is constant at all points in the orbit

Energy Conservation and Satellite Motion

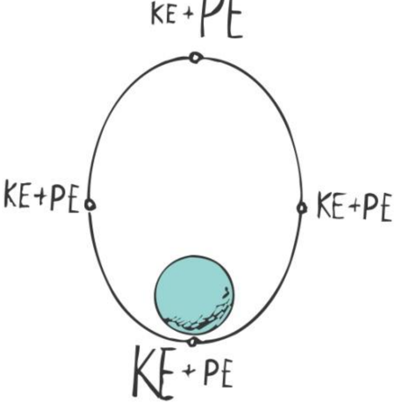
PE, *KE*, and speed in

- circular orbit
  - unchanged
  - distance between the satellite and center of the attracting body does not change—*PE* is the same everywhere
  - no component of force acts along the direction of motion—no change in speed and *KE*



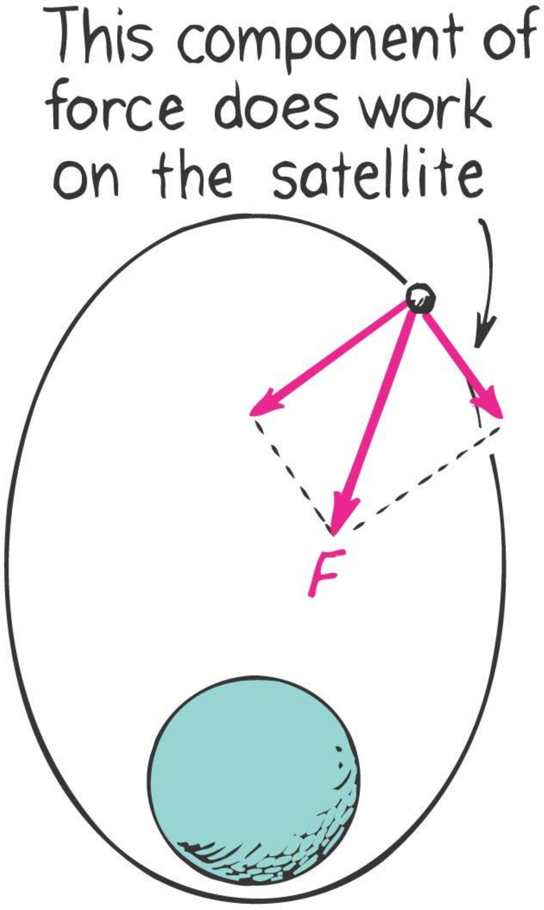
Energy Conservation and Satellite Motion

- elliptical orbit
  - varies
    - *PE* is greatest when the satellite is farthest away (apogee)
    - *PE* is least when the satellite is closest (perigee)
    - *KE* is least when *PE* is the most and vice versa
    - at every point in the orbit, sum of *KE* and *PE* is the same



Energy Conservation and Satellite Motion

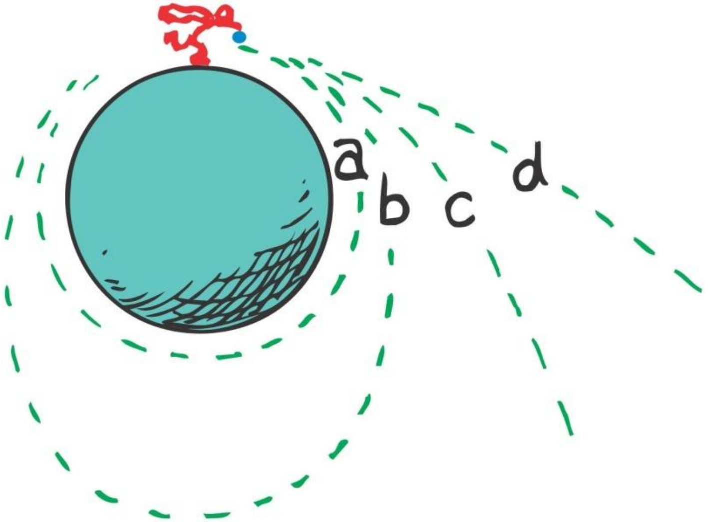
When satellite gains altitude and moves against gravitational force, its speed and *KE* decrease and continues to the apogee. Past the apogee, satellite moves in the same direction as the force component and speed and *KE* increases. Increase continues until past the perigee and cycle repeats.



Escape Speed

Escape speed

- the initial speed that an object must reach to escape gravitational influence of Earth
- 11.2 kilometers per second from Earth's surface



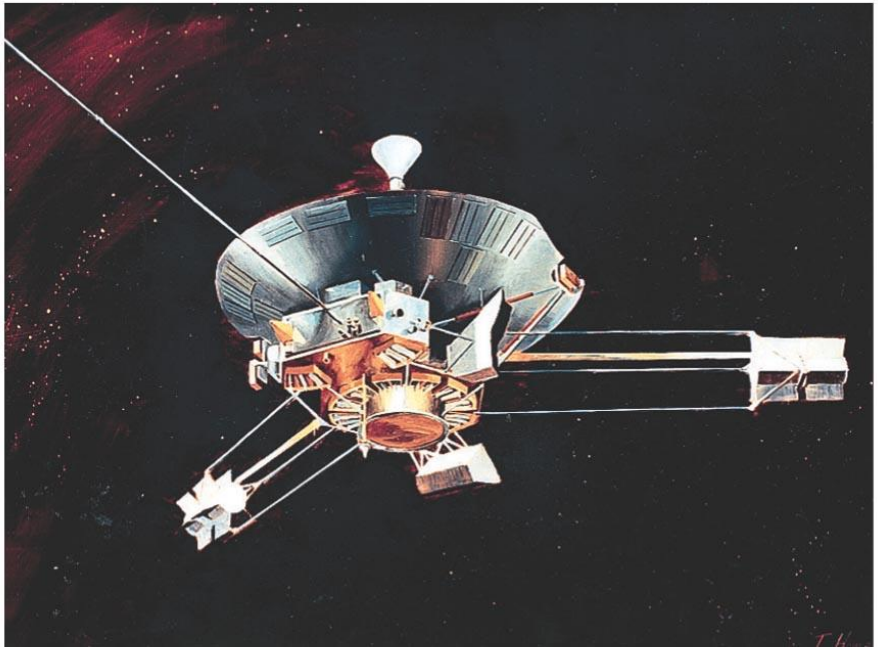
Escape velocity

- is escape speed when direction is involved

Escape Speed

First probe to escape the solar system is *Pioneer 10*, launched from Earth in 1972.

- accomplished by directing the probe into the path of oncoming Jupiter



Escape Speed
CHECK YOUR NEIGHBOR

When a projectile achieves escape speed from Earth, it

A. forever leaves Earth's gravitational field.
B. outruns the influence of Earth's gravity, but is never beyond it.
C. comes to an eventual stop, returning to Earth at some future time.
D. all of the above

Escape Speed
CHECK YOUR ANSWER

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Gravity from Newton to Einstein