THE BIG IDEA

The path of an Earth satellite follows the curvature of the Earth.

14 Satellite Motion
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14.1 Earth Satellites

A stone thrown fast enough to go a horizontal distance of 8 kilometers during the time (1 second) it takes to fall 5 meters, will orbit Earth.

14 Satellite Motion
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14.1 Earth Satellites

If you drop a stone, it will fall in a straight-line path to the ground below. If you move your hand, the stone will land farther away. What would happen if the curvature of the path matched the curvature of Earth?

14 Satellite Motion
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14.1 Earth Satellites

An Earth **satellite** is a projectile moving fast enough to fall continually *around* Earth rather than *into* it.

On an imaginary tiny planet, you would not have to throw the stone very fast to make its curved path match the surface curvature.

Because of the planet's small size and low mass, if you threw the stone just right, it would follow a circular orbit.

14 Satellite Motion
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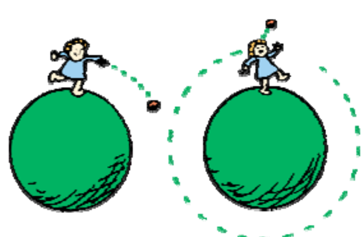
14.1 Earth Satellites

If you toss the stone horizontally with the proper speed, its path will match the surface curvature of the asteroid.



14 Satellite Motion
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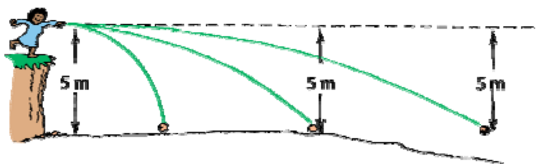
14.1 Earth Satellites

How fast would the stone have to be thrown horizontally for it to orbit Earth?

- A stone dropped from rest accelerates 10 m/s^2 and falls a vertical distance of 5 meters during the first second.
- In the first second, a projectile will fall 5 meters below the straight-line path it would have taken without gravity.

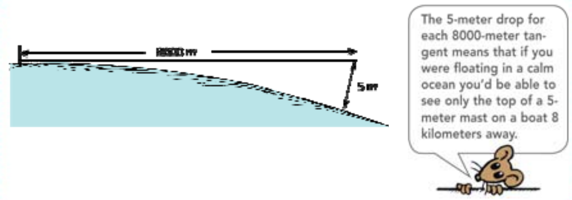
14.1 Earth Satellites

Throw a stone at any speed and one second later it will have fallen 5 m below where it would have been without gravity.



14.1 Earth Satellites

In the curvature of Earth, the surface drops a vertical distance of nearly 5 meters for every 8000 meters tangent to its surface.



14.1 Earth Satellites

The orbital speed for close orbit about Earth is 8 km/s.

- That is an impressive 29,000 km/h (or 18,000 mi/h).
- At that speed, atmospheric friction would burn an object to a crisp.
- A satellite must stay 150 kilometers or more above Earth's surface—to keep from burning due to the friction.

14.1 Earth Satellites

CONCEPT CHECK **How fast does a stone have to be thrown to orbit Earth?**

14.2 Circular Orbits

A satellite in circular orbit around Earth is always moving perpendicular to gravity and parallel to Earth's surface at constant speed.

14.2 Circular Orbits

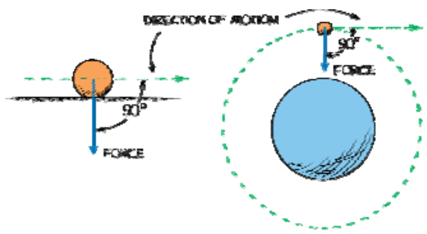
In circular orbit, the speed of a satellite is not changed by gravity.

Compare a satellite in circular orbit to a bowling ball rolling along a bowling alley.

- Gravity acting on the bowling ball does not change its speed.
- Gravity pulls downward, perpendicular to the ball's motion.
- The ball has no component of gravitational force along the direction of the alley.

14.2 Circular Orbits

The speeds of the bowling ball and the satellite are not affected by the force of gravity because there is no horizontal component of gravitational force.



14.2 Circular Orbits

The satellite is always moving at a right angle (perpendicular) to the force of gravity.

- It doesn't move in the direction of gravity, which would increase its speed.
- It doesn't move in a direction against gravity, which would decrease its speed.
- No change in speed occurs—only a change in direction.

14.2 Circular Orbits

For a satellite close to Earth, the time for a complete orbit around Earth, its **period,** is about 90 minutes.

For higher altitudes, the orbital speed is less and the period is longer.

14.2 Circular Orbits

Communications satellites are located in orbit 6.5 Earth radii from Earth's center, so that their period is 24 hours.

This period matches Earth's daily rotation. They orbit in the plane of Earth's equator and they are always above the same place.

The moon is farther away, and has a 27.3-day period.

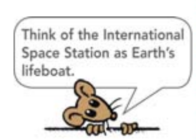
14.2 Circular Orbits

The International Space Station (ISS) orbits at 360 kilometers above Earth's surface.

- Acceleration toward Earth is somewhat less than 1 *g* because of altitude.
- This acceleration, however, is not sensed by the astronauts; relative to the station, they experience zero *g*.

14.2 Circular Orbits

The ISS and its inhabitants circle 360 km above Earth, well above its atmosphere, in a state of continual free fall.



14.2 Circular Orbits

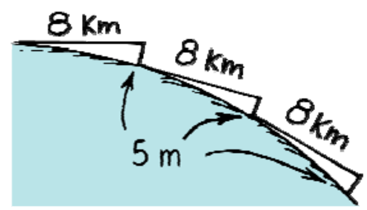
Isaac Newton understood satellite motion from his investigation of the moon's motion.

He reasoned that without air resistance, a cannonball could circle Earth and coast indefinitely if it had sufficient speed.

He calculated this speed to be the same as 8 km/s. Since such speed was impossible then, he was not optimistic about people launching satellites.

14.2 Circular Orbits

A satellite in circular orbit close to Earth moves tangentially at 8 km/s. During each second, it falls 5 m beneath each successive 8-km tangent.



14.2 Circular Orbits

think!

Satellites in close circular orbit fall about 5 m during each second of orbit. How can this be if the satellite does not get closer to Earth?

14.2 Circular Orbits

think!

Satellites in close circular orbit fall about 5 m during each second of orbit. How can this be if the satellite does not get closer to Earth?

Answer:

In each second, the satellite falls about 5 m below the straight-line tangent it would have taken if there were no gravity. Earth's surface curves 5 m below an 8-km straight-line tangent. Since the satellite moves at 8 km/s, it "falls" at the same rate Earth "curves."

14.2 Circular Orbits

CONCEPT CHECK **Describe the motion of a satellite in relation to Earth's surface and gravity.**

14.3 Elliptical Orbits

A satellite in orbit around Earth traces an oval-shaped path called an ellipse.

14.3 Elliptical Orbits

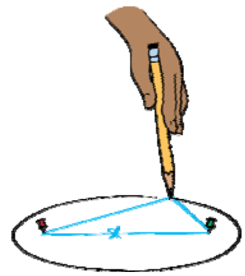
An **ellipse** is the closed path taken by a point that moves in such a way that the sum of its distances from two fixed points is constant.

The two fixed points in an ellipse are called **foci.**

For a satellite orbiting a planet, the center of the planet is at one focus and the other focus could be inside or outside the planet.

14.3 Elliptical Orbits

A simple method of constructing an ellipse is shown here.



14.3 Elliptical Orbits

Satellite speed *varies* in an elliptical orbit.

- When the initial speed is more than 8 km/s, the satellite overshoots a circular path and moves away from Earth.
- It loses speed due to the pull of gravity.
- The satellite slows to a point where it no longer recedes, and begins falling back toward Earth.

14.3 Elliptical Orbits

- The speed lost in receding is regained as it falls back.
- The satellite then rejoins its path with the same speed it had initially.
- The procedure repeats over and over, and an ellipse is traced each cycle.

14.3 Elliptical Orbits

A satellite moves in an elliptical orbit.

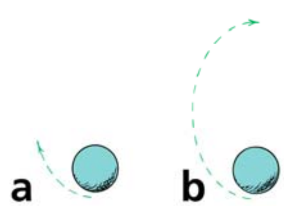
a. When the satellite exceeds 8 km/s, it overshoots a circle.

14.3 Elliptical Orbits

A satellite moves in an elliptical orbit.

a. When the satellite exceeds 8 km/s, it overshoots a circle.

b. At its maximum separation, it starts to come back toward Earth.



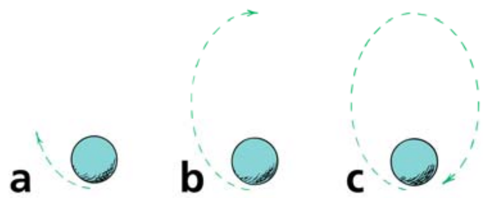
14.3 Elliptical Orbits

A satellite moves in an elliptical orbit.

a. When the satellite exceeds 8 km/s, it overshoots a circle.

b. At its maximum separation, it starts to come back toward Earth.

c. The cycle repeats itself.



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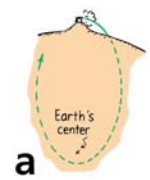
14.3 Elliptical Orbits

The parabolic paths of projectiles, such as cannonballs, are actually segments of ellipses.

a. For relatively low speeds, the center of Earth is the far focus.



14 Satellite Motion
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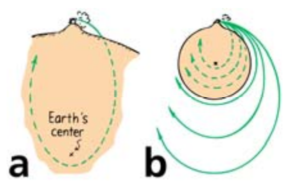
14.3 Elliptical Orbits

The parabolic paths of projectiles, such as cannonballs, are actually segments of ellipses.

a. For relatively low speeds, the center of Earth is the far focus.

b. For greater speeds, the near focus is Earth's center.



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14.3 Elliptical Orbits

When the projectile traces a circular orbit, both foci are together at Earth's center.

For elliptical orbits, the near focus is Earth's center and the location of the far focus varies for different speeds.

14 Satellite Motion
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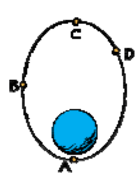
14.3 Elliptical Orbits

think!

The orbit of a satellite is shown in the sketch. In which of the positions *A* through *D* does the satellite have the greatest speed? The least speed?



14 Satellite Motion
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14.3 Elliptical Orbits

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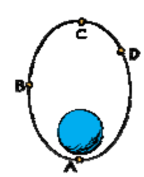


Answer:

The satellite has its greatest speed as it whips around *A.* It has its least speed at *C*. Beyond *C,* it gains speed as it falls back to *A* to repeat its cycle.

14 Satellite Motion

14.3 Elliptical Orbits

CONCEPT CHECK: **What is the shape of the path of a satellite in an orbit around Earth?**

14 Satellite Motion

14.4 Energy Conservation and Satellite Motion

The sum of the KE and PE of a satellite is constant at all points along an orbit.

14 Satellite Motion

14.4 Energy Conservation and Satellite Motion

Moving objects have kinetic energy (KE).

An object above Earth's surface has potential energy (PE) due to its position.

Everywhere in its orbit, a satellite has both KE and PE.

14 Satellite Motion

14.4 Energy Conservation and Satellite Motion

In a circular orbit, the distance between a planet's center and the satellite's center is constant.

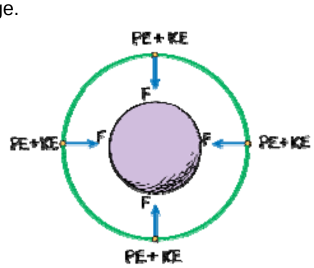
The PE of the satellite is the same everywhere in orbit.

By the law of conservation of energy, the KE is also constant, so the speed is constant in any circular orbit.

14 Satellite Motion

14.4 Energy Conservation and Satellite Motion

For a satellite in circular orbit, no force acts along the direction of motion. The speed, and thus the KE, cannot change.



14 Satellite Motion

14.4 Energy Conservation and Satellite Motion

In an elliptical orbit, both speed and distance vary.

- The **apogee** is the point in a satellite's orbit farthest from the center of Earth.
- The **perigee** is the point in a satellite's orbit closest to the center of Earth.

14 Satellite Motion | Conceptual Physics

14.4 Energy Conservation and Satellite Motion

- The PE is greatest when the satellite is at the apogee and least when the satellite is at the perigee.
- The KE will be least when the PE is most; and the KE will be most when the PE is least.
- At every point in the orbit, the sum of the KE and PE is constant.

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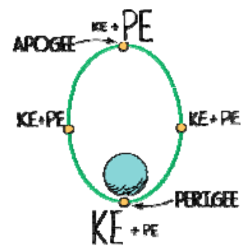
14.4 Energy Conservation and Satellite Motion

The sum of KE and PE for a satellite is a constant at all points along an elliptical orbit.



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14.4 Energy Conservation and Satellite Motion

At all points on the orbit—except at the apogee and perigee—a component of gravitational force is parallel to the direction of satellite motion.

This component changes the speed of the satellite.

(this component of force) × (distance moved) = change in KE.

14 Satellite Motion | Conceptual Physics

14.4 Energy Conservation and Satellite Motion

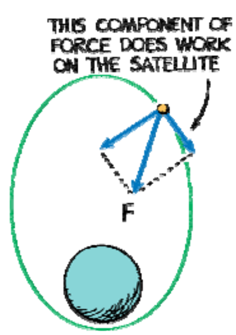
When the satellite gains altitude and moves against this component, its speed and KE decrease. The decrease continues to the apogee.

Once past the apogee, the satellite moves in the same direction as the component, and the speed and KE increase.

14 Satellite Motion | Conceptual Physics

14.4 Energy Conservation and Satellite Motion

In an elliptical orbit, a component of force exists along the direction of the satellite's motion. This component changes the speed and, thus, the KE.



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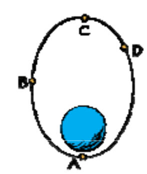
14.4 Energy Conservation and Satellite Motion

think!

The orbital path of a satellite is shown in the sketch. In which of the positions *A* through *D* does the satellite have the most KE? Most PE? Most total energy?



14.4 Energy Conservation and Satellite Motion

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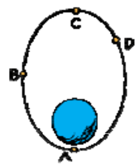


Answer:

The KE is maximum at *A;* the PE is maximum at *C;* the total energy is the same anywhere in the orbit.

14.4 Energy Conservation and Satellite Motion

CONCEPT CHECK

What is the relationship between the KE and PE of a satellite in motion?

14.5 Kepler's Laws of Planetary Motion

- **Kepler's first law states that the path of each planet around the sun is an ellipse with the sun at one focus.**
- **Kepler's second law states that each planet moves so that an imaginary line drawn from the sun to any planet sweeps out equal areas of space in equal time intervals.**
- **Kepler's third law states that the square of the orbital period of a planet is directly proportional to the cube of the average distance of the planet from the sun.**

14.5 Kepler's Laws of Planetary Motion

Newton's law of gravitation was preceded by Kepler's laws of planetary motion.

Kepler's laws of planetary motion are three important discoveries about planetary motion made by the German astronomer Johannes Kepler.

Johannes Kepler (1571–1630)

14.5 Kepler's Laws of Planetary Motion

Kepler started as an assistant to Danish astronomer Tycho Brahe, who headed the world's first great observatory in Denmark, prior to the telescope.

Using instruments called *quadrants*, Brahe measured the positions of planets so accurately that his measurements are still valid today.

After Brahe's death, Kepler devoted many years of his life to the analysis of Brahe's measurements.

Tycho Brahe (1546–1601)

14.5 Kepler's Laws of Planetary Motion

Kepler's First Law

Kepler's expectation that the planets would move in perfect circles around the sun was shattered after years of effort.

He found the paths to be ellipses.

14.5 Kepler's Laws of Planetary Motion

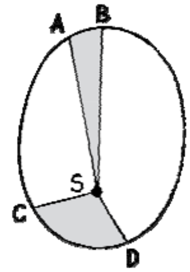
Kepler's Second Law

Kepler also found that the planets do not go around the sun at a uniform speed but move faster when they are nearer the sun and more slowly when they are farther from the sun.

An imaginary line or spoke joining the sun and the planet sweeps out equal areas of space in equal times.

14.5 Kepler's Laws of Planetary Motion

Equal areas are swept out in equal intervals of time.



14.5 Kepler's Laws of Planetary Motion

Kepler was the first to coin the word *satellite*.

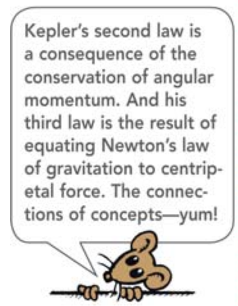
He had no clear idea *why* the planets moved as he discovered. He lacked a conceptual model.

14.5 Kepler's Laws of Planetary Motion

Kepler's Third Law

After ten years of searching for a connection between the time it takes a planet to orbit the sun and its distance from the sun, Kepler discovered a third law.

Kepler found that the square of any planet's period *(T)* is directly proportional to the cube of its average orbital radius *(r)*.

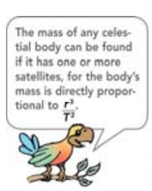


14.5 Kepler's Laws of Planetary Motion

This means that the ratio $\frac{T^2}{r^3}$ is the same for all planets.

If a planet's period is known, its average orbital radial distance is easily calculated.

Kepler's laws apply not only to planets but also to moons or any satellite in orbit around any body.



14.5 Kepler's Laws of Planetary Motion

Kepler was familiar with Galileo's concepts of inertia and accelerated motion, but he failed to apply them to his own work.

Like Aristotle, he thought that the force on a moving body would be in the same direction as the body's motion.

Kepler never appreciated the concept of inertia. Galileo, on the other hand, never appreciated Kepler's work and held to his conviction that the planets move in circles.

14.5 Kepler's Laws of Planetary Motion

CONCEPT CHECK

What are Kepler's three laws of planetary motion?

14.6 Escape Speed

If we give a payload any more energy than 62 MJ/kg at the surface of Earth or, equivalently, any greater speed than 11.2 km/s, then, neglecting air resistance, the payload will escape from Earth never to return.

14.6 Escape Speed

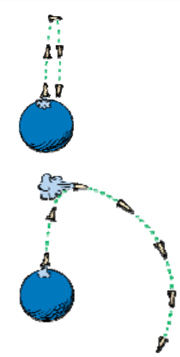
When a payload is put into Earth-orbit by a rocket, the speed and direction of the rocket are very important.

If the rocket were launched vertically and quickly achieved a speed of 8 km/s, it would soon come crashing back at 8 km/s.

To achieve orbit, the payload must be launched *horizontally* at 8 km/s once above air resistance.

14.6 Escape Speed

The initial thrust of the rocket lifts it vertically. Another thrust tips it from its vertical course. When it is moving horizontally, it is boosted to the required speed for orbit.



14.6 Escape Speed

Earth

Neglecting air resistance, fire anything at any speed greater than 11.2 km/s, and it will leave Earth, going more and more slowly, but never stopping.

14.6 Escape Speed

How much work is required to move a payload against the force of Earth's gravity to a distance very, very far ("infinitely far") away?

- Gravity diminishes rapidly with distance due to the inverse-square law.
- Most of the work done in launching a rocket occurs near Earth.

14.6 Escape Speed

- The value of PE for a 1-kilogram mass infinitely far away is 62 million joules (MJ).
- To put a payload infinitely far from Earth's surface requires at least 62 MJ of energy per kilogram of load.
- A KE per unit mass of 62 MJ/kg corresponds to a speed of 11.2 km/s.
- The **escape speed** is the minimum speed necessary for an object to escape permanently from a gravitational field.

14.6 Escape Speed

The Solar System

The escape speed from the sun is 620 km/s at the surface of the sun.

Even at a distance equaling that of Earth's orbit, the escape speed from the sun is 42.2 km/s.

A projectile fired from Earth at 11.2 km/s escapes Earth but not necessarily the moon, and certainly not the sun.

14.6 Escape Speed

Table 14.1 Escape Speeds at the Surface of Bodies in the Solar System

Astronomical Body	Mass (Earth masses)	Radius (Earth radii)	Escape Speed (km/s)
Sun	333,000	109	620
Sun (at a distance of Earth's orbit)	333,000	23,500	42.2
Jupiter	318	11	60.2
Saturn	95.2	9.2	36.0
Neptune	17.3	3.47	24.9
Uranus	14.5	3.7	22.3
Earth	1.00	1.00	11.2
Venus	0.82	0.95	10.4
Mars	0.11	0.53	5.0
Mercury	0.055	0.38	4.3
Moon	0.0123	0.28	2.4

14.6 Escape Speed

The first probe to escape the solar system was launched from Earth in 1972 with a speed of only 15 km/s.

The escape was accomplished by directing the probe into the path of Jupiter.

It was whipped about by Jupiter's great gravitational field, picking up speed in the process.

14.6 Escape Speed

Its speed of departure from Jupiter was increased enough to exceed the sun's escape speed at the distance of Jupiter.

Pioneer 10 passed the orbit of Pluto in 1984.

Unless it collides with another body, it will continue indefinitely through interstellar space.

14.6 Escape Speed

Pioneer 10, launched from Earth in 1972, escaped from the solar system in 1984 and is wandering in interstellar space.

14.6 Escape Speed

The escape speeds refer to the initial speed given by a brief thrust, after which there is no force to assist motion.

But we could escape Earth at any *sustained* speed greater than zero, given enough time.

14 Satellite Motion

14.6 Escape Speed

CONCEPT CHECK

What condition is necessary for a payload to escape Earth's gravity?

14 Satellite Motion

Assessment Questions

1. When you toss a projectile sideways, it curves as it falls. It will be an Earth satellite if the curve it follows
   a. matches the curve of planet Earth.
   b. results in a straight line.
   c. spirals out indefinitely.
   d. is within 150 kilometers of Earth's surface.

14 Satellite Motion

Assessment Questions

1. When you toss a projectile sideways, it curves as it falls. It will be an Earth satellite if the curve it follows
   a. matches the curve of planet Earth.
   b. results in a straight line.
   c. spirals out indefinitely.
   d. is within 150 kilometers of Earth's surface.

Answer: A

14 Satellite Motion

Assessment Questions

2. When a satellite travels at constant speed, its shape is a(n)
   a. circle.
   b. ellipse.
   c. oval that is almost elliptical.
   d. square.

14 Satellite Motion

Assessment Questions

2. When a satellite travels at constant speed, its shape is a(n)
   a. circle.
   b. ellipse.
   c. oval that is almost elliptical.
   d. square.

Answer: A

Assessment Questions

3. A satellite in elliptical orbit about Earth travels
   a. fastest when it moves closer to Earth.
   b. fastest when it moves farther from Earth.
   c. slowest when it moves closer to Earth.
   d. at the same rate for the entire orbit.

Assessment Questions

3. A satellite in elliptical orbit about Earth travels
   a. fastest when it moves closer to Earth.
   b. fastest when it moves farther from Earth.
   c. slowest when it moves closer to Earth.
   d. at the same rate for the entire orbit.

Answer: A

Assessment Questions

4. Energy is conserved when an Earth satellite travels
   a. in either a circular or elliptical orbit.
   b. in only an elliptical orbit.
   c. away from Earth.
   d. toward Earth.

Assessment Questions

4. Energy is conserved when an Earth satellite travels
   a. in either a circular or elliptical orbit.
   b. in only an elliptical orbit.
   c. away from Earth.
   d. toward Earth.

Answer: A

Assessment Questions

5. Kepler is credited as being the first to discover that the paths of planets around the sun are
   a. circles.
   b. ellipses.
   c. straight lines most of the time.
   d. spirals.

Assessment Questions

5. Kepler is credited as being the first to discover that the paths of planets around the sun are
   a. circles.
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   c. straight lines most of the time.
   d. spirals.

Answer: B

Assessment Questions

6. 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, eventually returning to Earth at some future time.
   d. has a potential energy and a kinetic energy that are reduced to zero.

14 Satellite Motion
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Assessment Questions

6. When a projectile achieves escape speed from Earth, it
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   b. outruns the influence of Earth's gravity, but is never beyond it.
   c. comes to an eventual stop, eventually returning to Earth at some future time.
   d. has a potential energy and a kinetic energy that are reduced to zero.

Answer: B