Roger Freedman • Robert Geller • William Kaufmann III

Universe

Tenth Edition

Chapter 4

Gravitation and the Waltz of Planets

Exam 1 Reminder

Exam 1 will be next Thursday, Feb. 5th.

Bring a #2 pencil (and eraser)

4-1: Ancient astronomers invented geocentric models to explain planetary motion

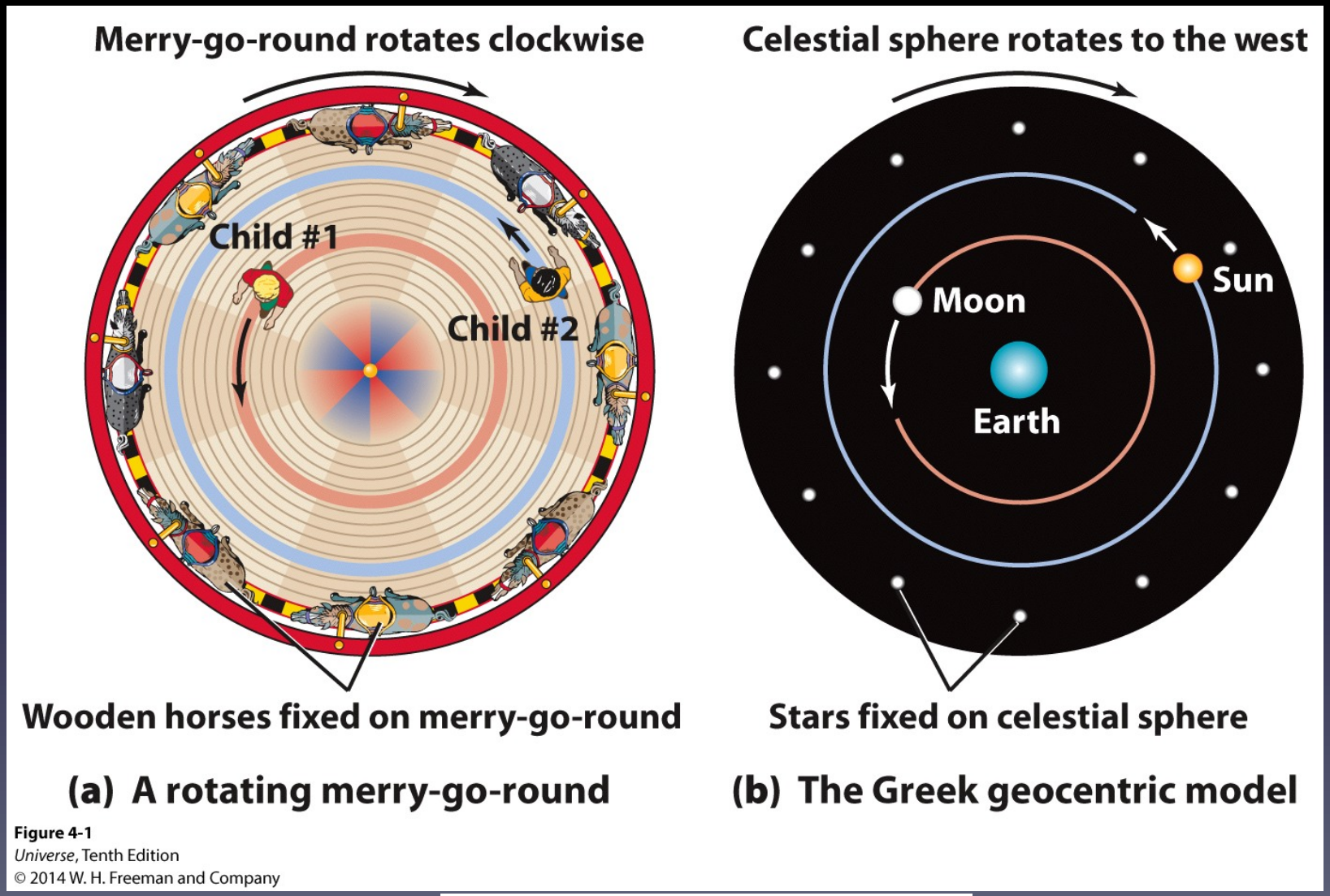

Figure 4-1
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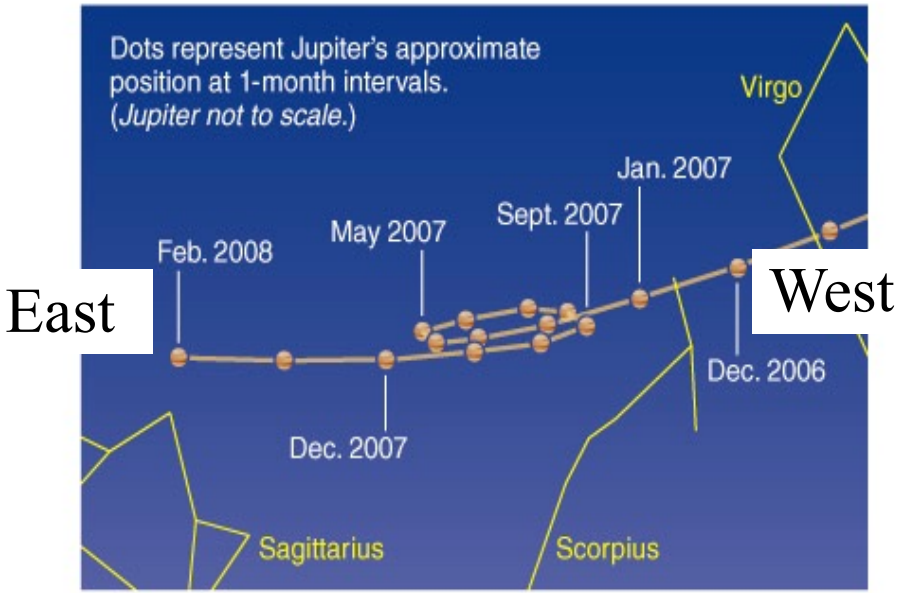
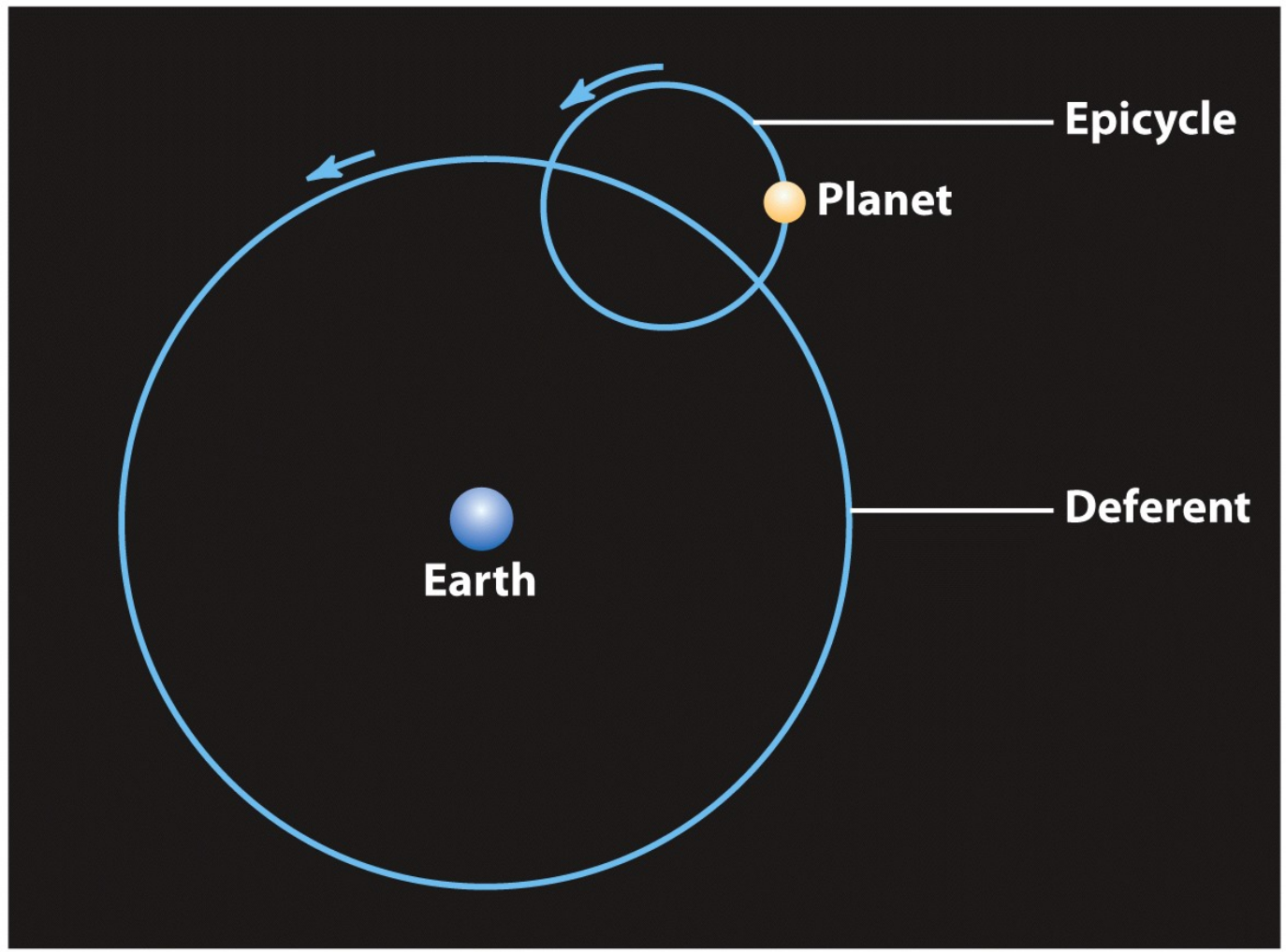
A Merry-Go-Round Analogy


Retrograde motion of Jupiter and Saturn (gif)
E
W

Apparent Retrograde Motion

- Planets usually move slightly *eastward (west to east)* from night to night relative to the stars.
- But sometimes they go *westward (east to west)* relative to the stars for a few weeks: **apparent retrograde motion**





Planetary motion modeled as a combination of circular motions

Figure 4-3a
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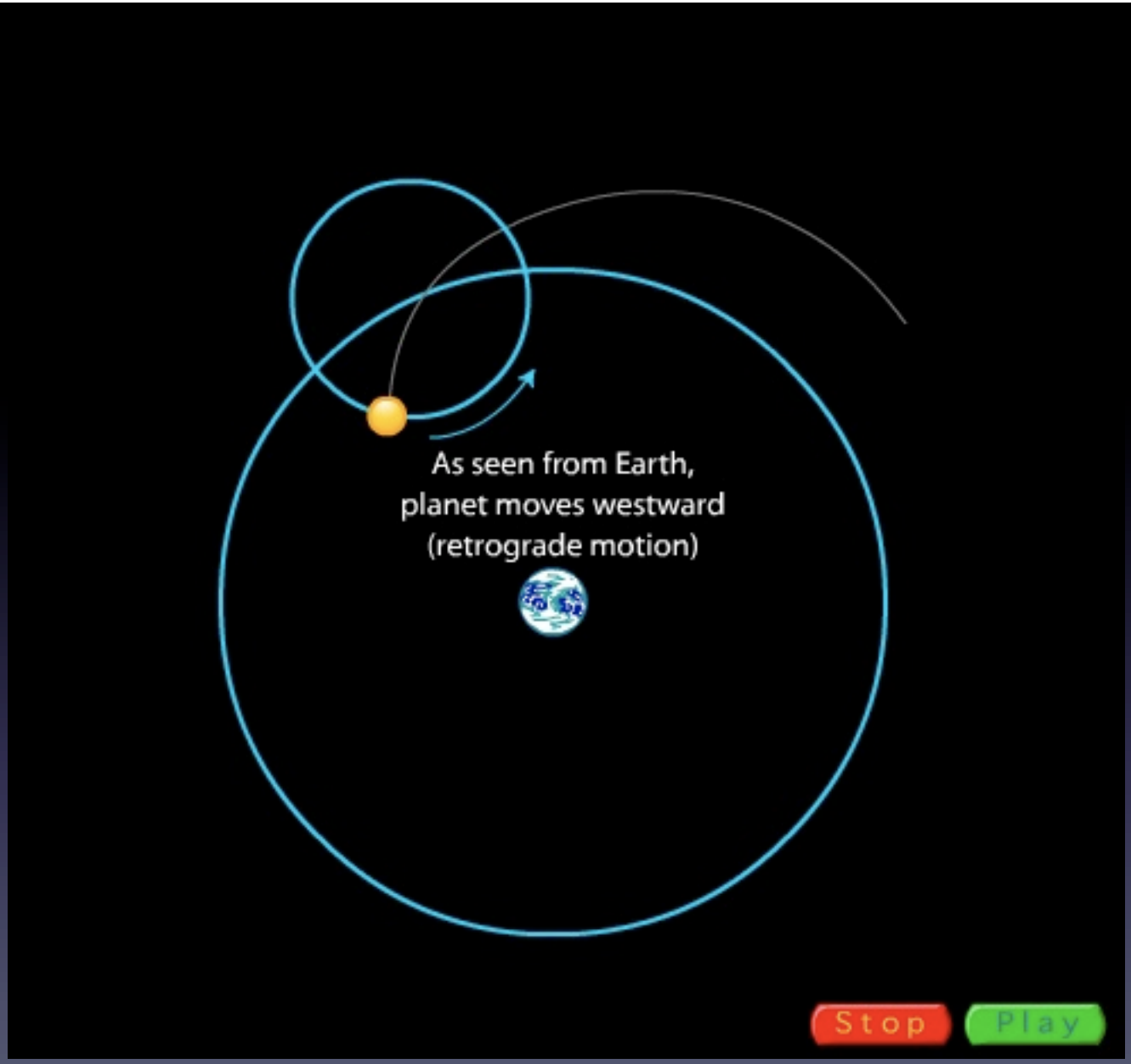
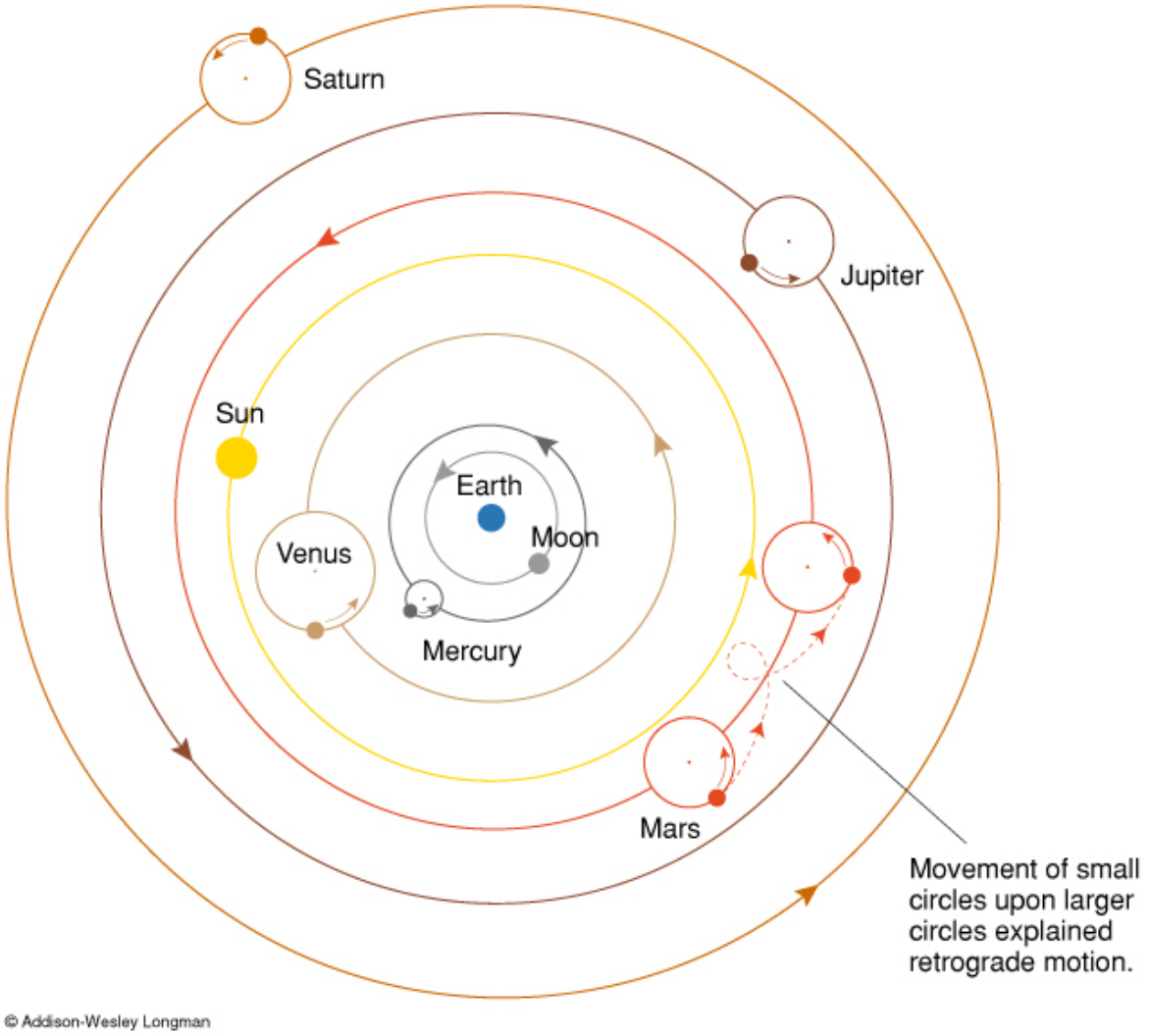
A Geocentric Explanation of Retrograde Motion


As seen from Earth,
planet moves westward
(retrograde motion)
Stop
Play

Ptolemy's Geocentric Model



4-2: Nickolaus Copernicus devised the first comprehensive heliocentric model.

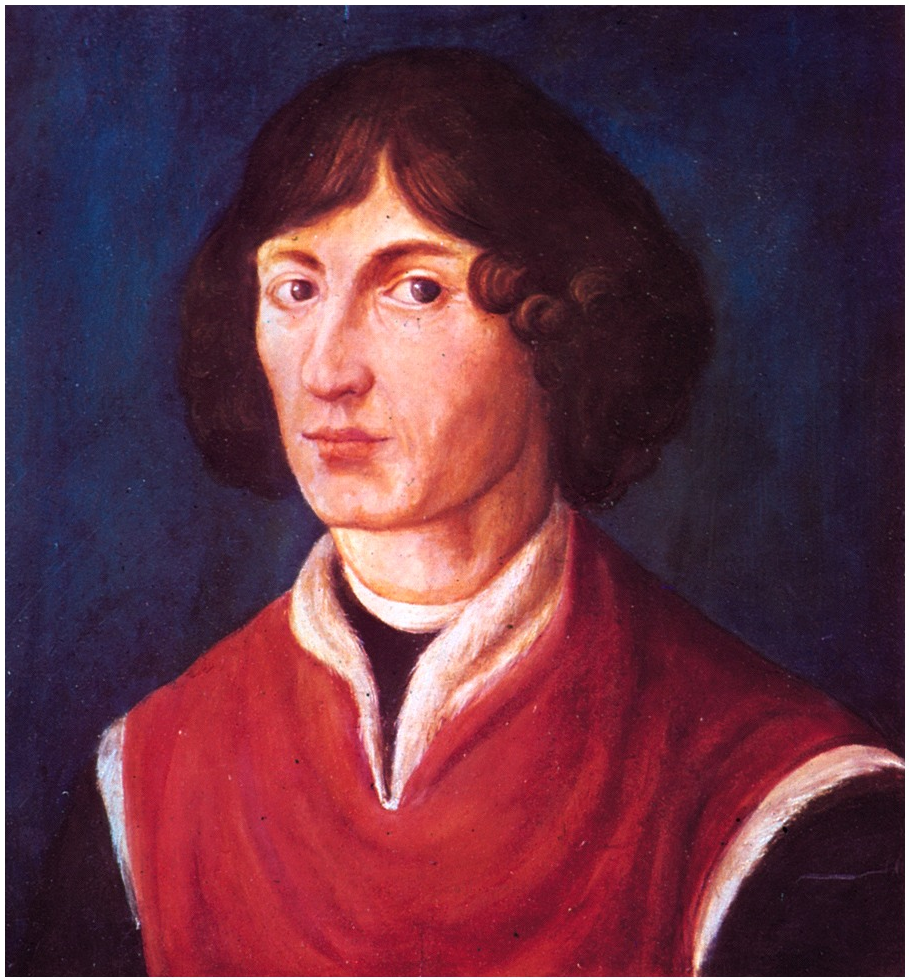


Figure 4-4
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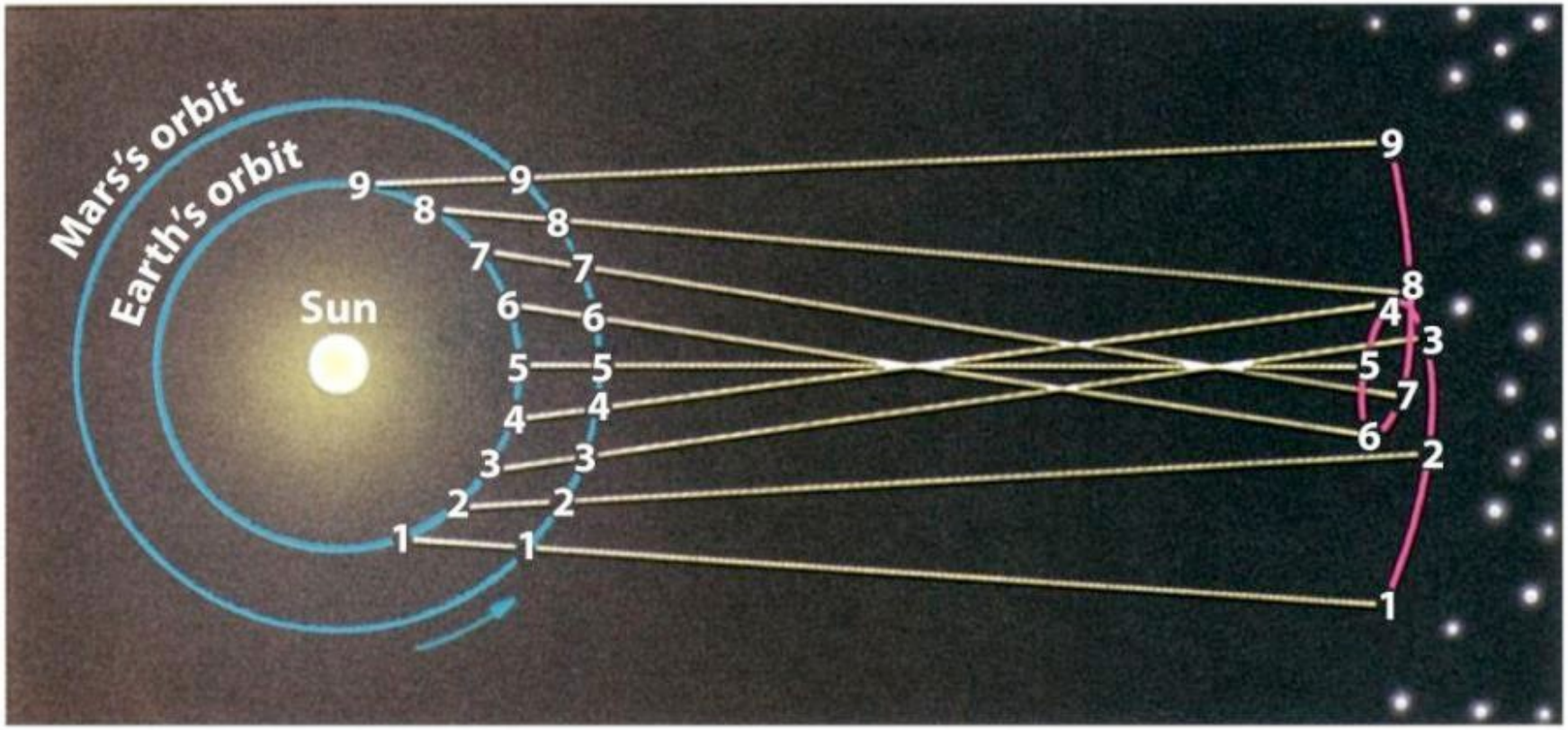
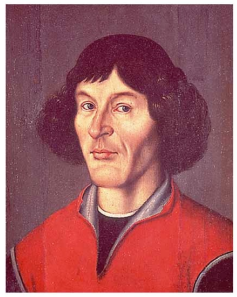
E. Lessing/Magnum

Nicolaus Copernicus (1473-1543)

Correct heliocentric explanation



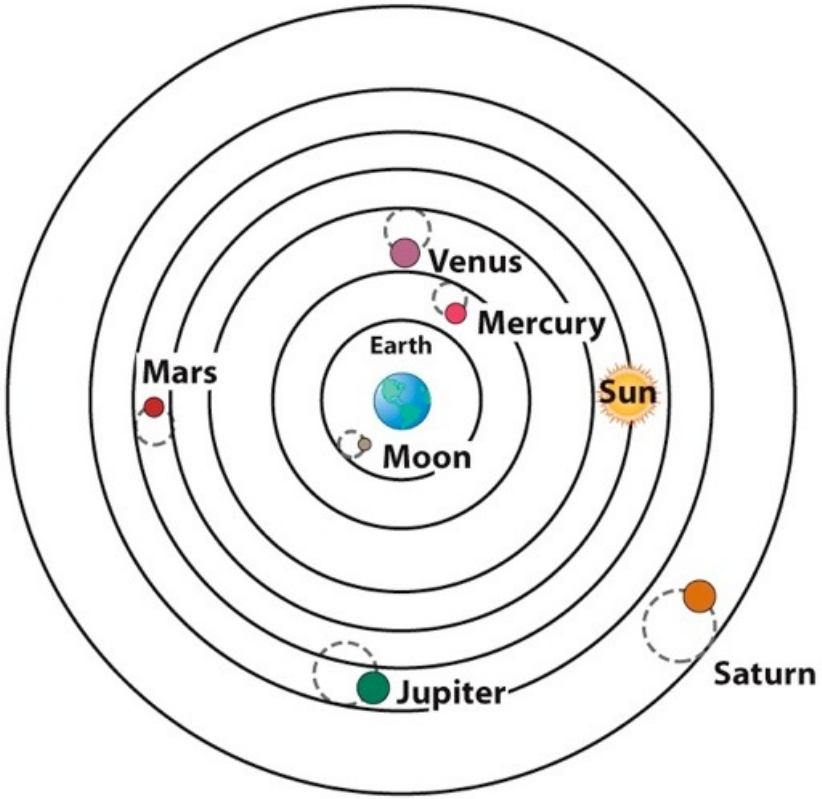
Copernicus (1473 - 1543)

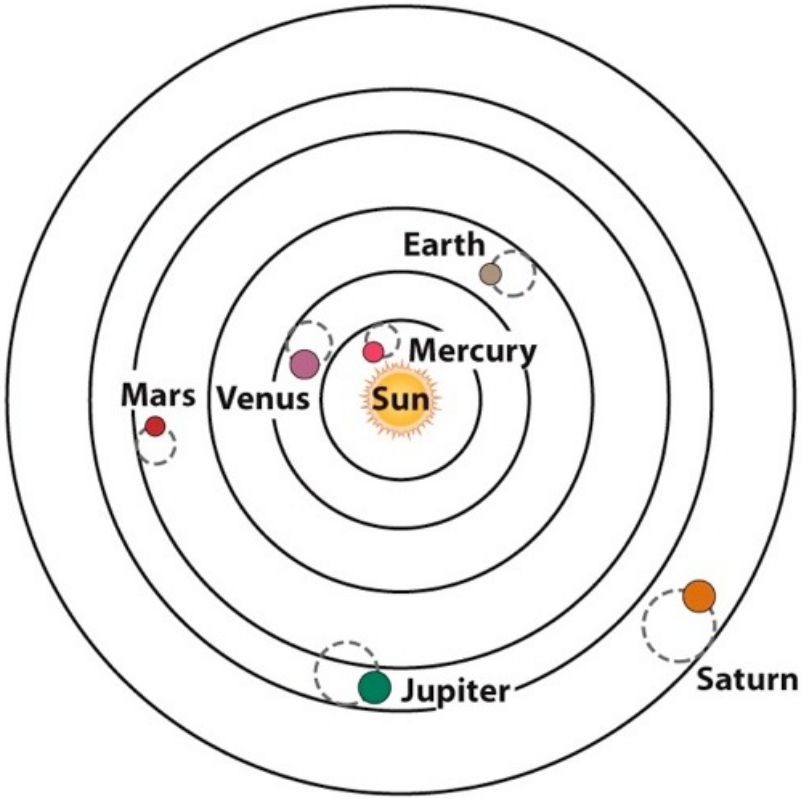


- Model was no more accurate than Ptolemaic model in predicting planetary positions, because it still used perfect circles.
- He had to include epicycles...!

Ptolemy

Copernicus





Both equally accurate; how to tell which was best?

4-3: Tycho Brahe's astronomical observations disproved ancient ideas about the heavens.

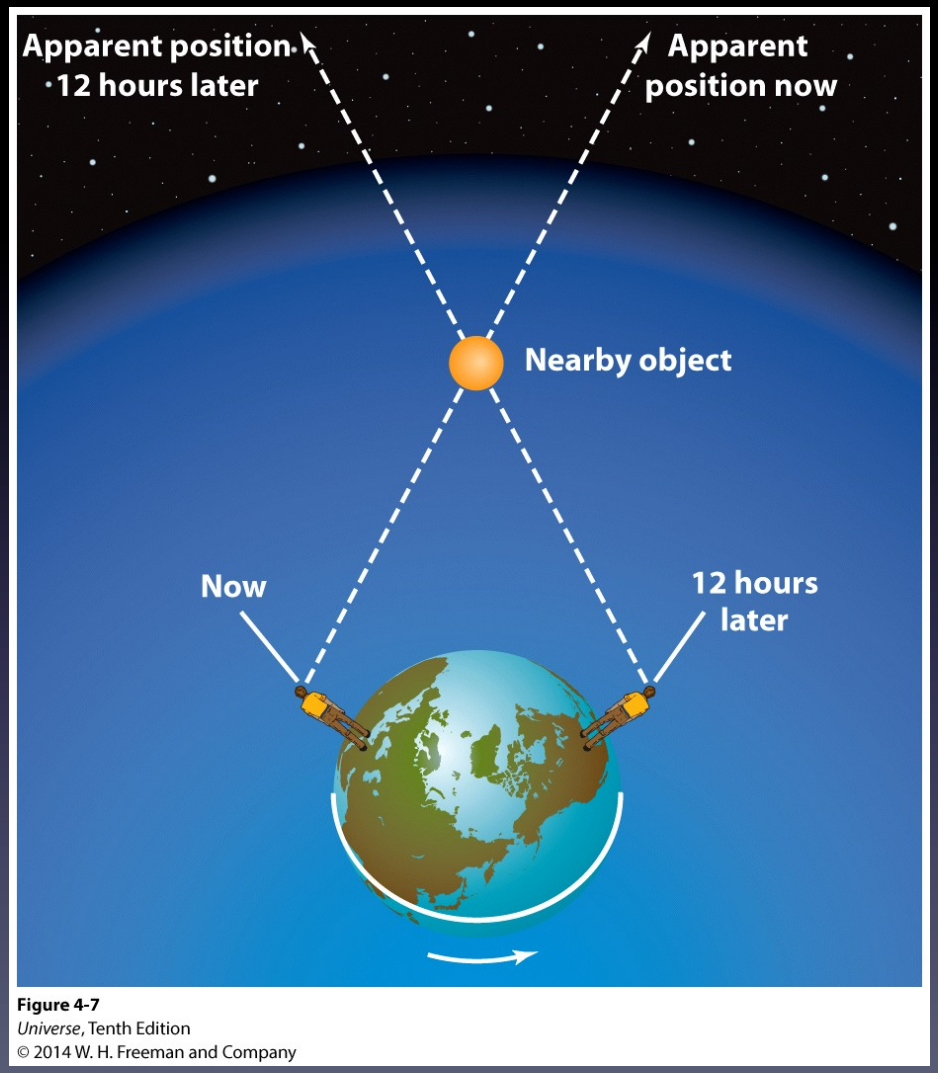


Figure 4-7
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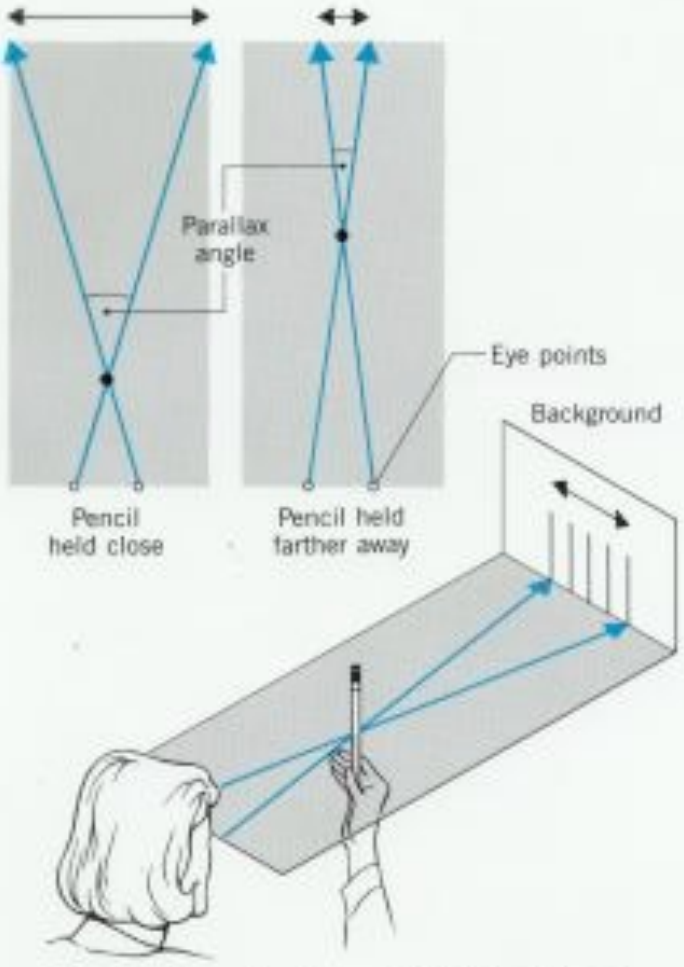
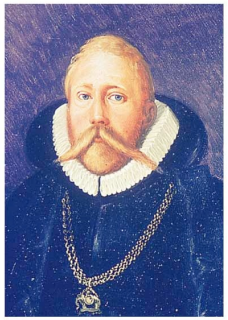
A Nearby Object Shows a Parallax Shift



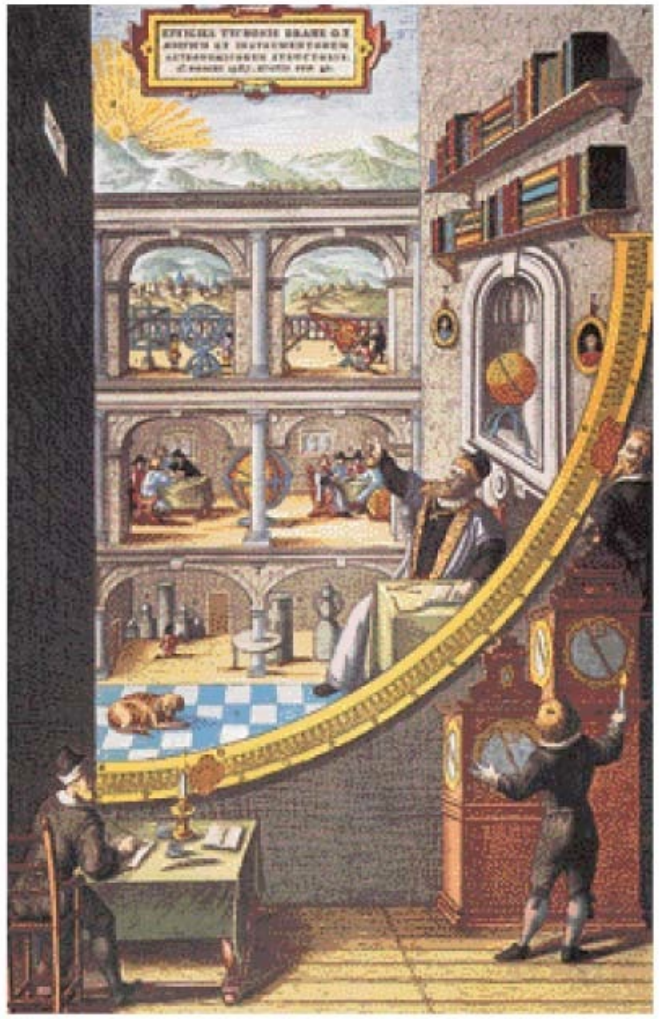
Observing the parallax of a pencil held at arm's length.

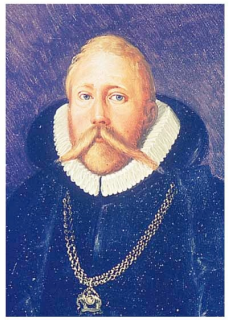
 Zeilik/Astronomy 6E Fig 14-6 101



Tycho Brahe (1546-1601)

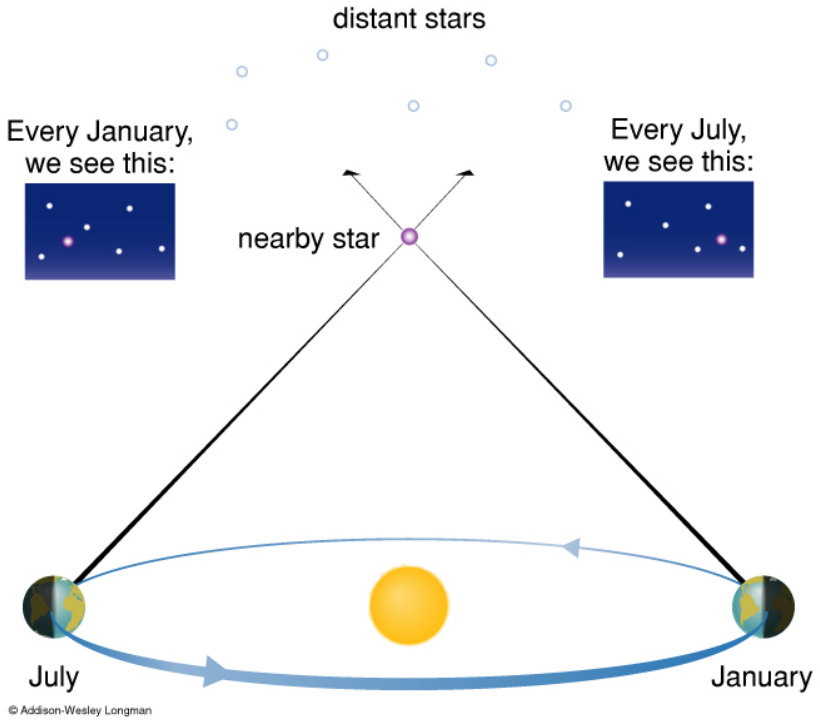
- Built great naked-eye observatory -- no telescopes!
- Compiled the most accurate (one arcminute) naked eye measurements ever made of planetary positions.
- Comprehensive and consistent: 21 years of data





Tycho Brahe (1546-1601)

- Could not detect stellar parallax
  - thought Earth must be at center of solar system
  - other planets orbit Sun
- Hired Kepler, who used Tycho's observations to discover the truth about planetary motion.



4-4: Johannes Kepler proposed elliptical paths for the planets around the sun.

Figure 4-9
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Erich Lessing/Art Resource

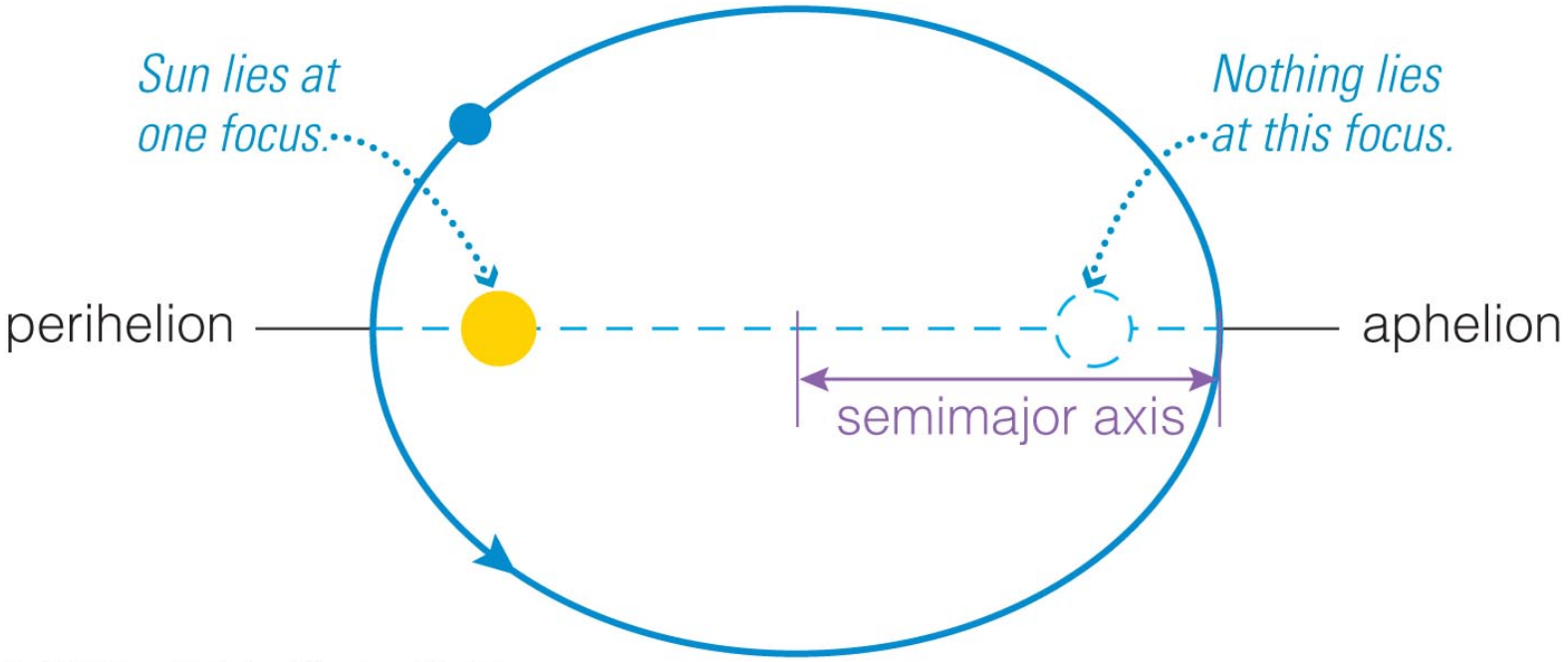
Johannes Kepler (1571-1630)

Johannes Kepler (1571-1630)

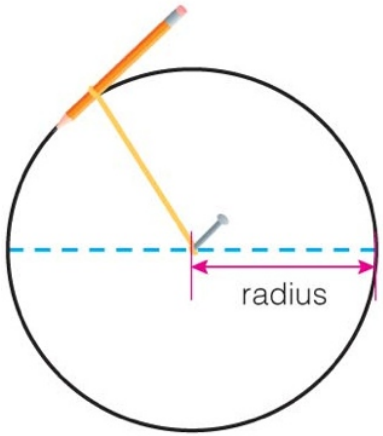
- Kepler first tried to match Tycho's observations with circular orbits
- But an 8-arcminute discrepancy led him eventually to ellipses…

"If I had believed that we could ignore these eight minutes [of arc], I would have patched up my hypothesis accordingly. But, since it was not permissible to ignore, those eight minutes pointed the road to a complete reformation in astronomy."

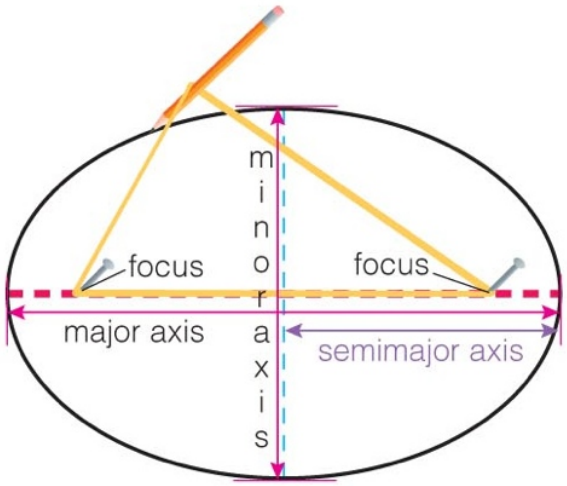
Kepler's First Law: The orbit of each planet around the Sun is an ***ellipse*** with the Sun at one focus.



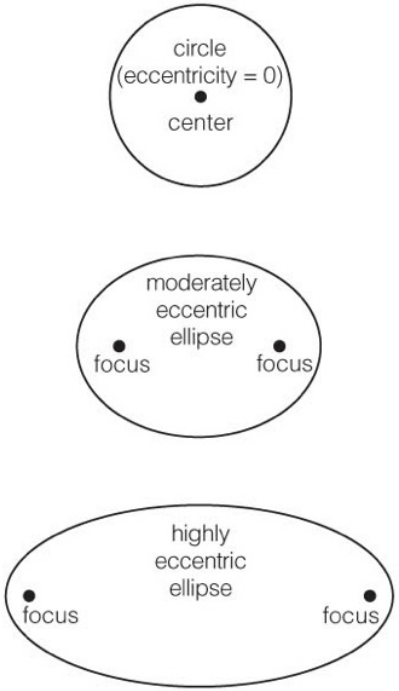
Ellipses



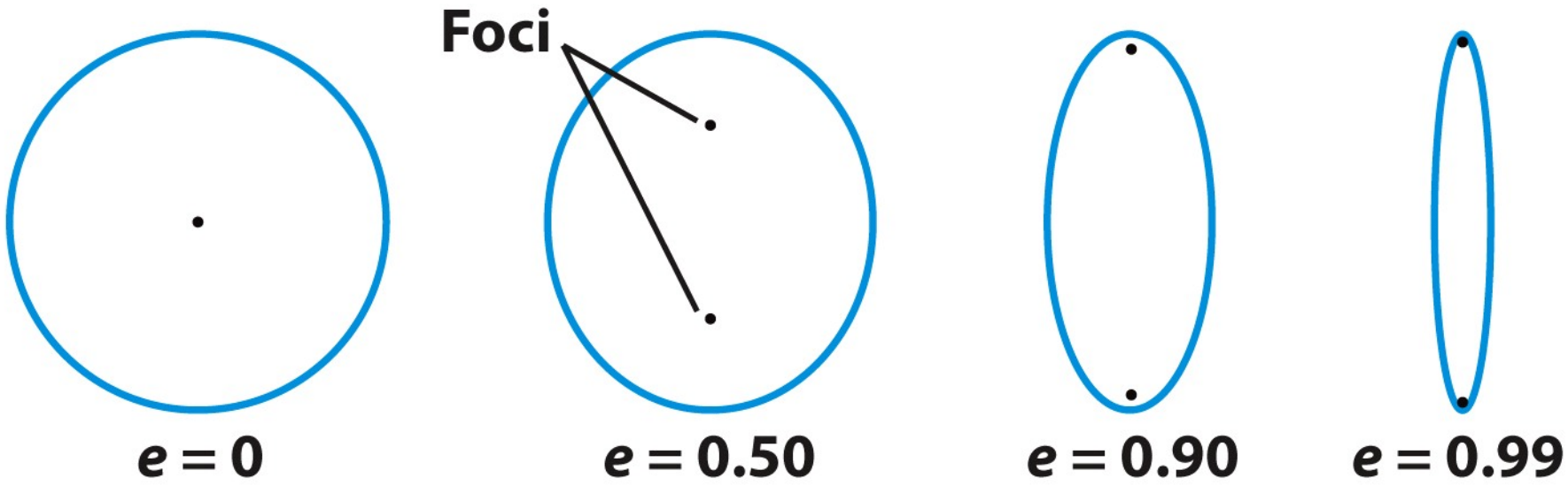
a Drawing a circle with a string of fixed length.



b Drawing an ellipse with a string of fixed length.



c *Eccentricity* describes how much an ellipse deviates from a perfect circle.



Ellipses with different eccentricities

Figure 4-10b
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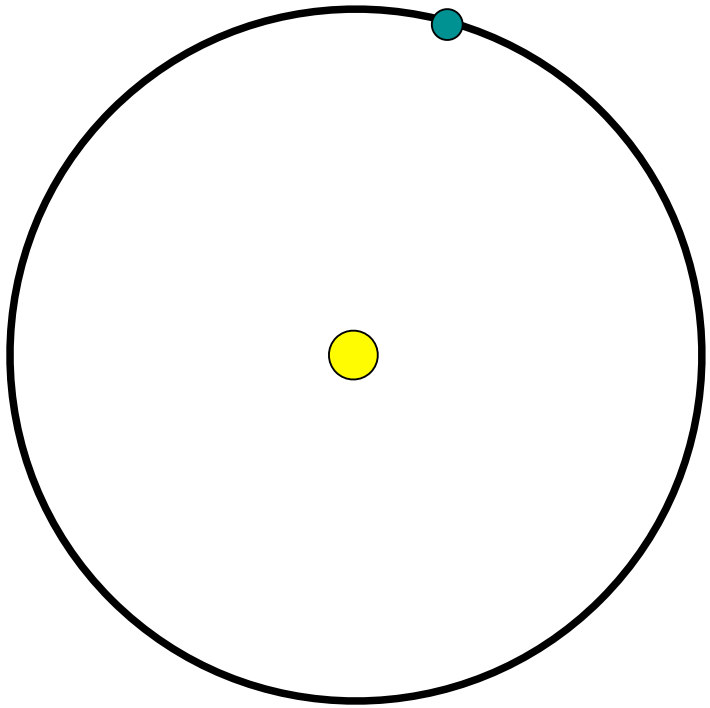
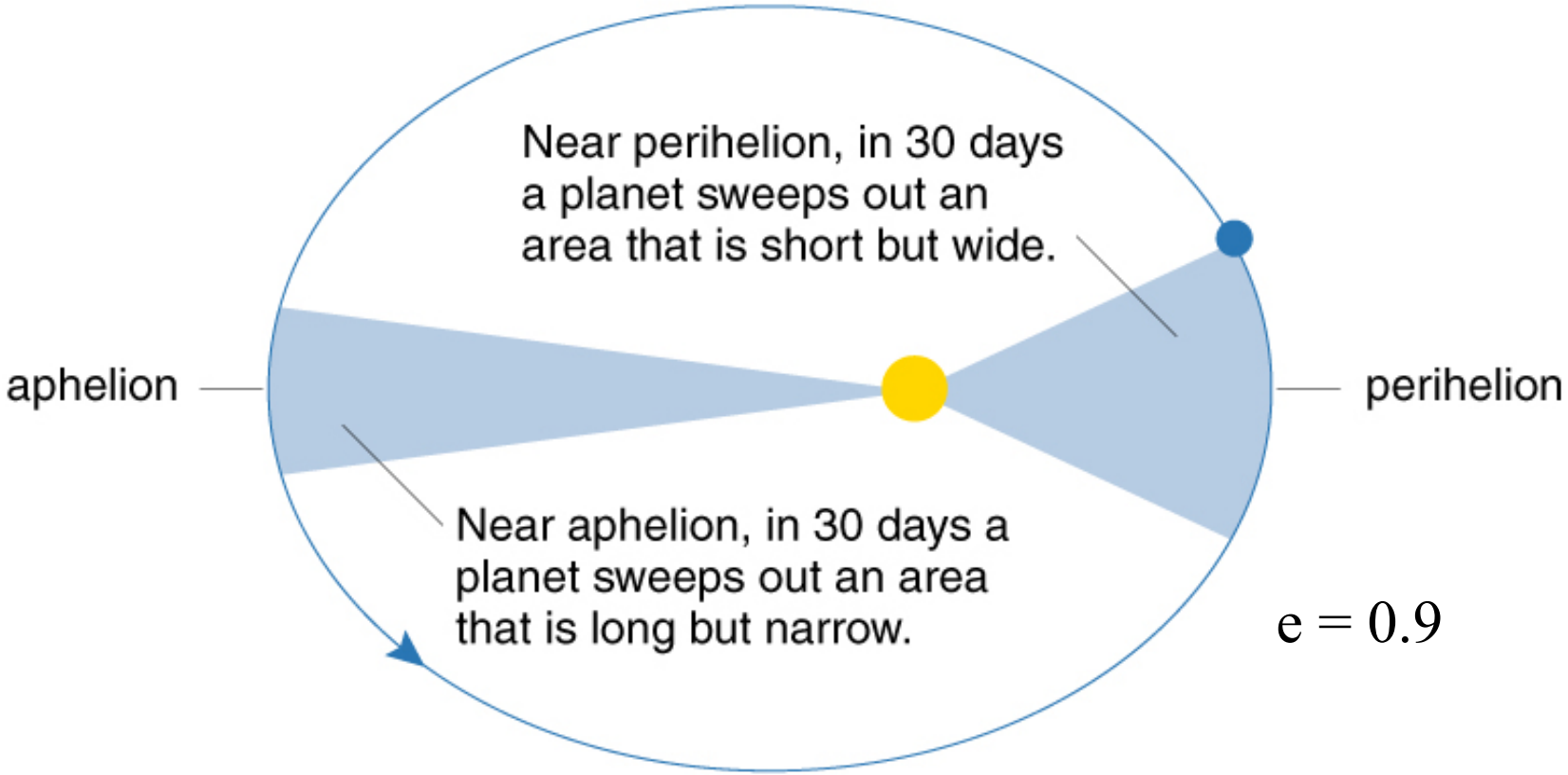
What is the shape of Earth's orbit around the Sun?

- e = 0.016

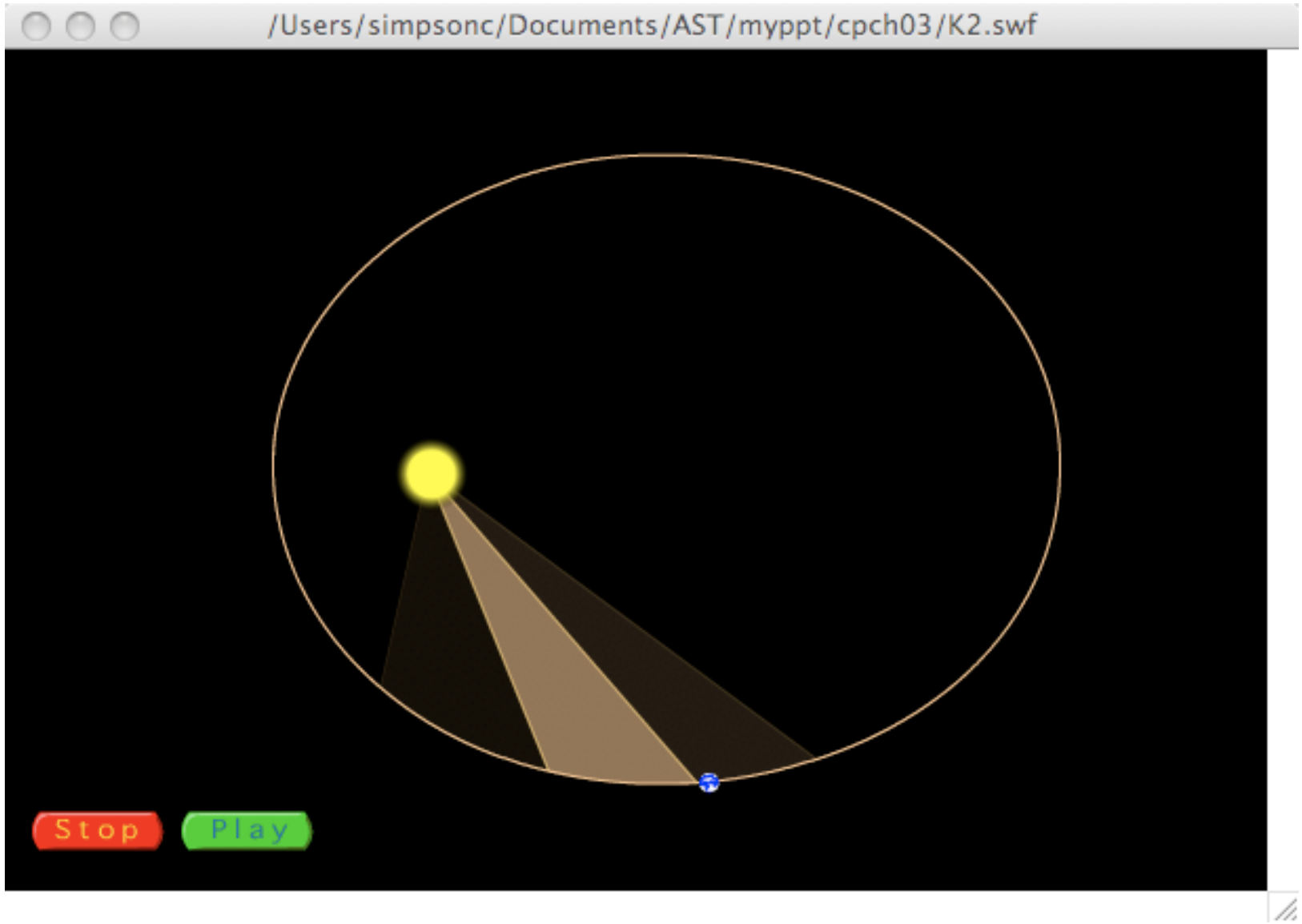


Not to scale!

Kepler's Second Law: As a planet moves around its orbit, it sweeps out equal areas in equal times.



Kepler's Second Law:



Kepler's Third Law

Kepler's Third Law: More distant planets orbit the Sun at slower average speeds, obeying the relationship

$$P^2 = a^3$$

P = orbital period in years
a = avg. distance from Sun in AU

TABLE 4-3 A Demonstration of Kepler's Third Law ($P^2 = a^3$)

Planet	Sidereal period P (years)	Semimajor axis a (AU)	P^2	a^3
Mercury	0.24	0.39	0.06	0.06
Venus	0.61	0.72	0.37	0.37
Earth	1.00	1.00	1.00	1.00
Mars	1.88	1.52	3.53	3.51
Jupiter	11.86	5.20	140.7	140.6
Saturn	29.46	9.55	867.9	871.0
Uranus	84.10	19.19	7,072	7,067
Neptune	164.86	30.07	27,180	27,190

Kepler's third law states that $P^2 = a^3$ for each of the planets. The last two columns of this table demonstrate that this relationship holds true to a very high level of accuracy.

Table 4-3
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4-5: Galileo's discoveries with a telescope strongly supported a heliocentric model

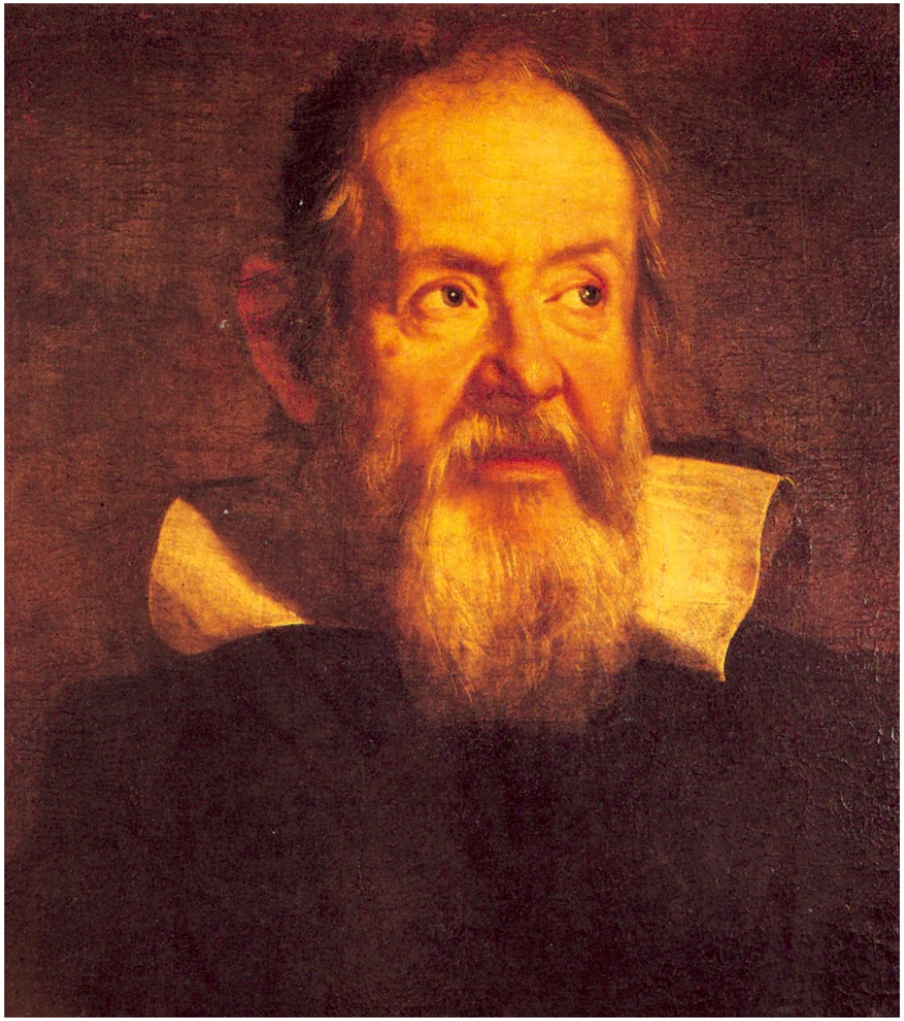


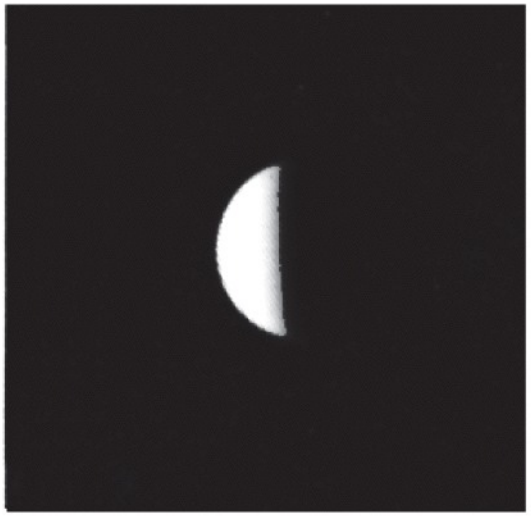
Figure 4-12
Universe, Tenth Edition
Erich Lessing/Art Resource

Galileo Galilei (1564-1642)

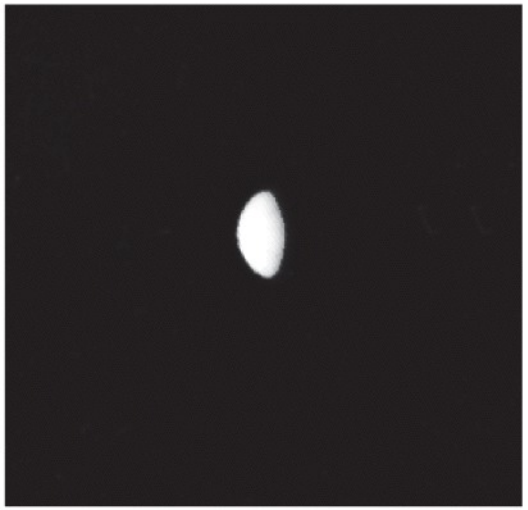
$\alpha = 58°$

$\alpha = 42°$

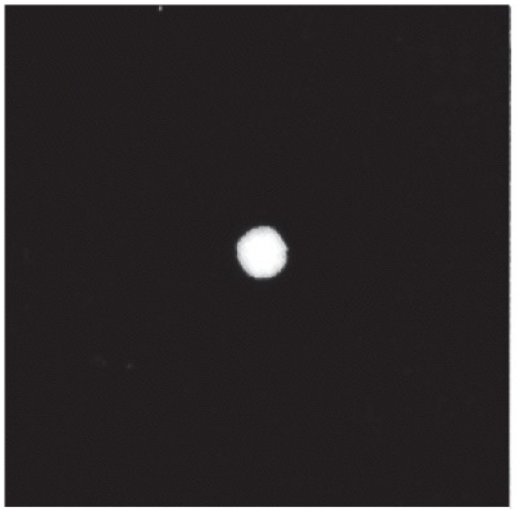
Phases of Venus and apparent size



$\alpha = 24°$

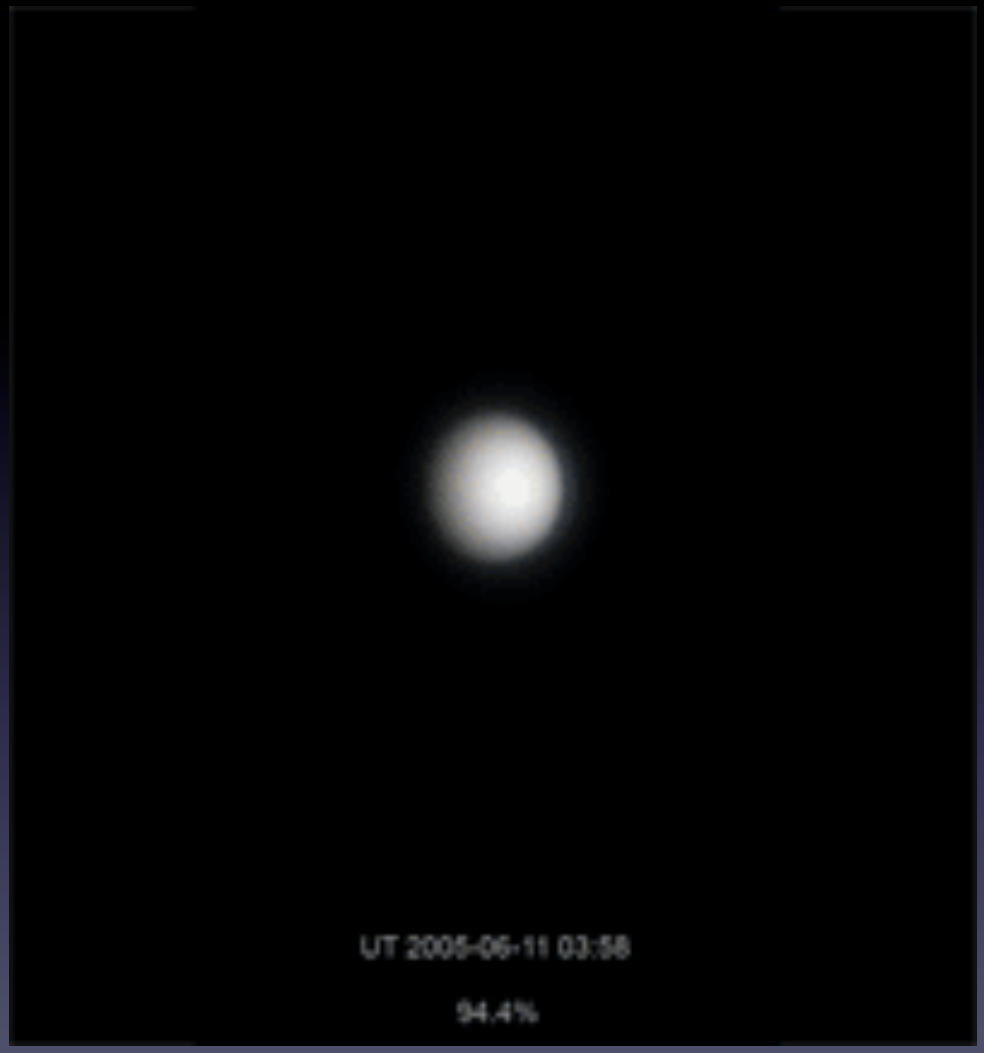


$\alpha = 15°$

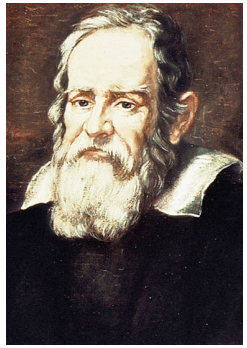


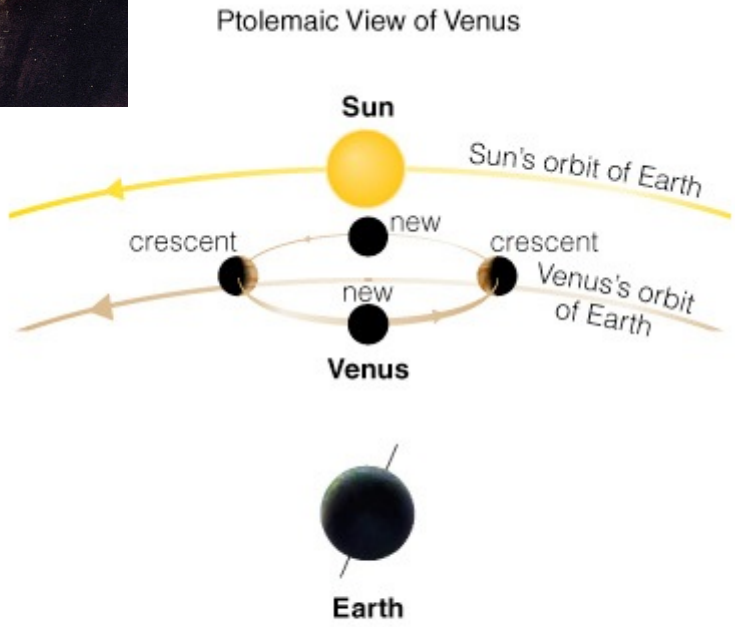
$\alpha = 10°$

Figure 4-13
Universe, Tenth Edition
New Mexico State University Observatory


UT 2005-06-11 03:58
94.4%

Galileo's observations of phases of Venus proved that it orbits the Sun and not Earth.





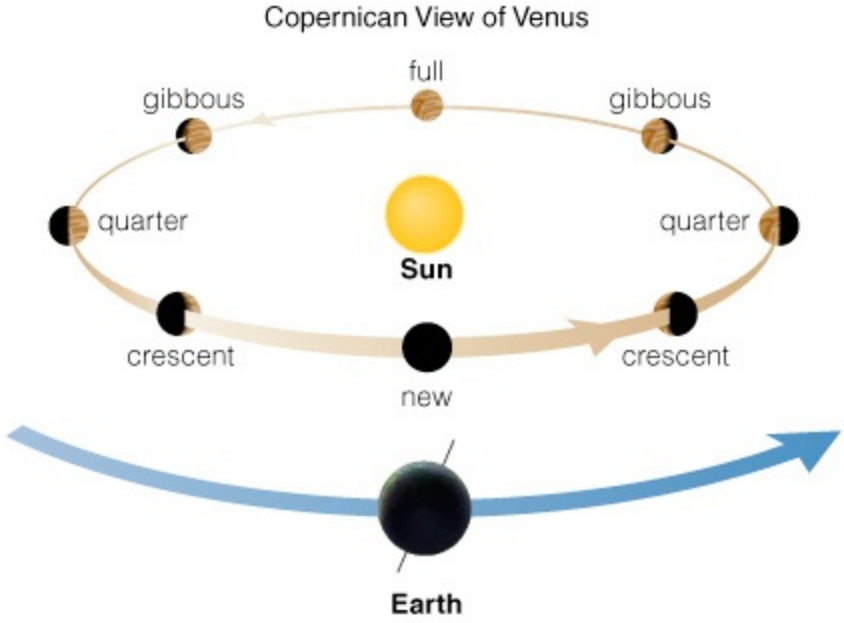


Figure 4-16
Universe, Tenth Edition
Rev. Ronald Royer/Science Source

Jupiter and its Largest Moons

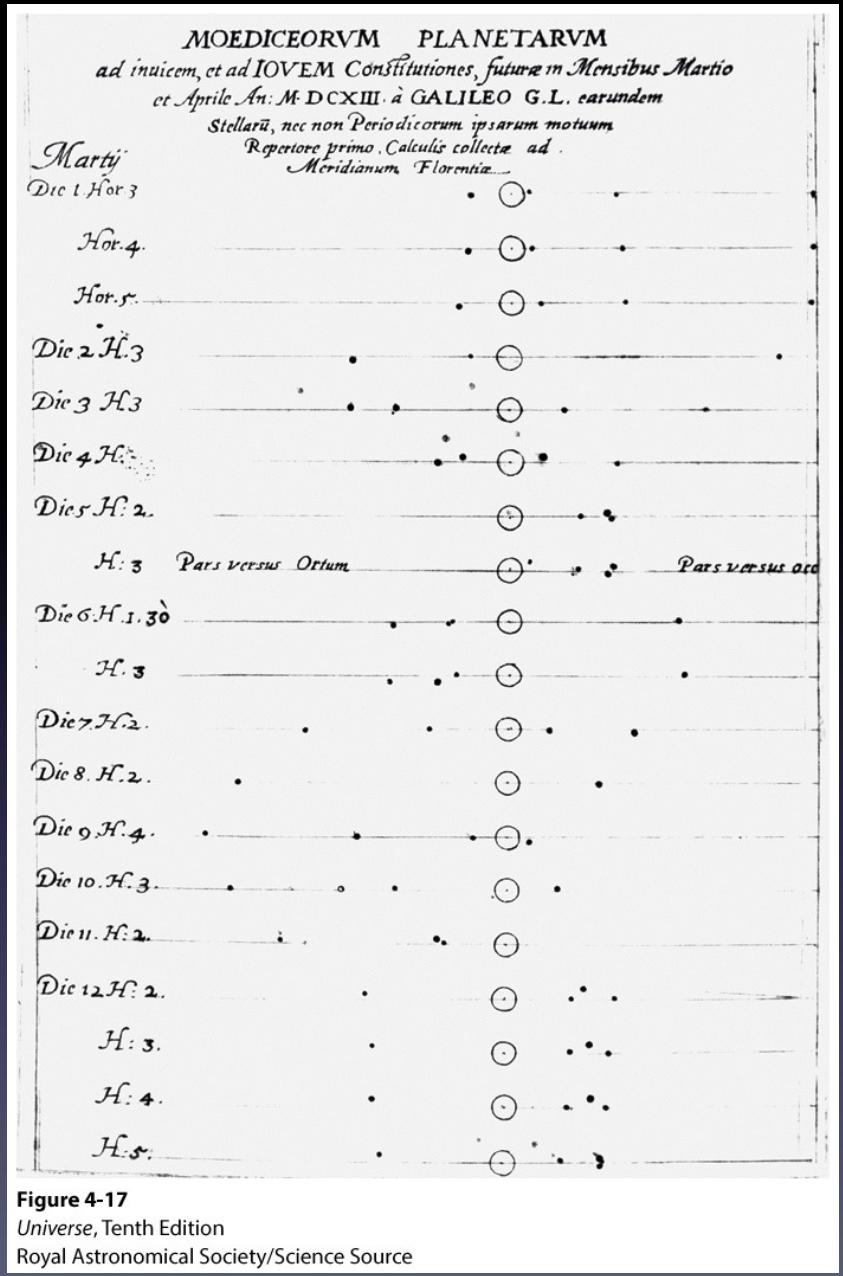
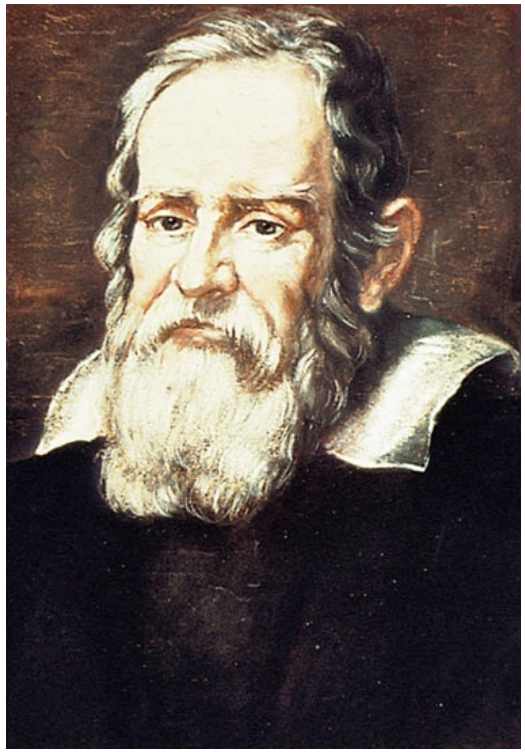


Figure 4-17
Universe, Tenth Edition
Royal Astronomical Society/Science Source

Early Observations of Jupiter's Moons

Galileo Galilei (1564 - 1642)



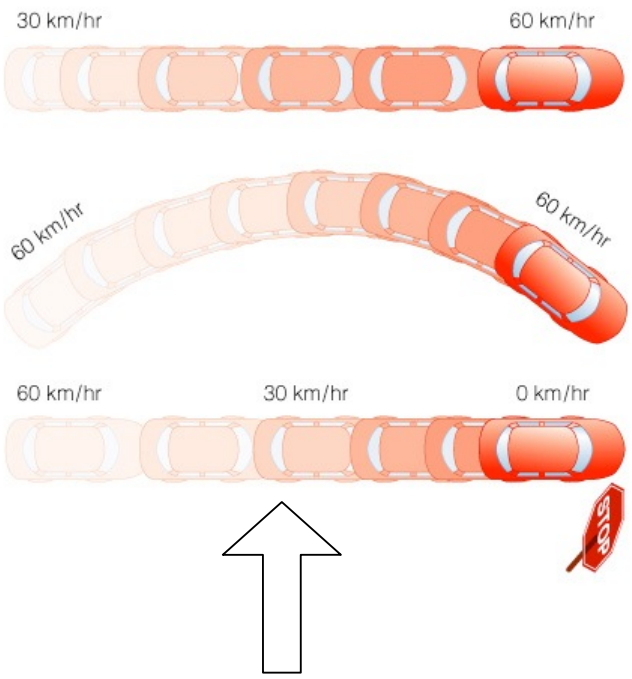
- The Catholic Church ordered Galileo to recant his claim that Earth orbits the Sun in 1633
- His book on the subject was removed from the Church's index of banned books in 1824
- Galileo was formally vindicated by the Church in 1992

4-6: Newton formulated laws of motion and gravity that describe fundamental properties of physical reality.

Figure 4-18
Universe, Tenth Edition
Corbis Images

Isaac Newton (1642-1727)

How do we describe motion?



These are all accelerations

Precise definitions to describe motion:

- **Speed**: Rate at which object moves: distance travelled in a given time

$$\text{speed} = \frac{\text{distance}}{\text{time}} \quad \left(\text{units of } \frac{\text{m}}{\text{s}}\right)$$

example: speed of 10 m/s

- **Velocity**: Speed **and** direction
  example: 10 m/s, due east

- **Acceleration**: Any change in velocity: change in *speed* and/or *direction*
  units of (speed/time)/time (m/s^2)

Newton's First Law

- A body remains at rest or moves in a straight line at a constant speed unless acted upon by an outside (net) force.
  - A rocket will coast in space along a straight line at constant speed.
  - A hockey puck glides across the ice at constant speed until it hits something

Newton's Second Law of Motion

- (net)Force = mass x acceleration

$$F_{net} = m \times a$$

- Acceleration is the rate of change in velocity – how quickly your motion is changing.

How many accelerators are in your car?

Newton's First & Second Laws

The only way to change

- direction and/or
- speed

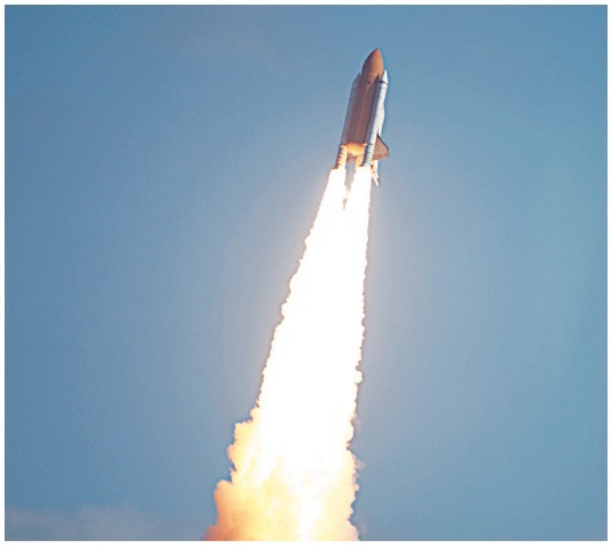
is to apply a (net) force.

Therefore...

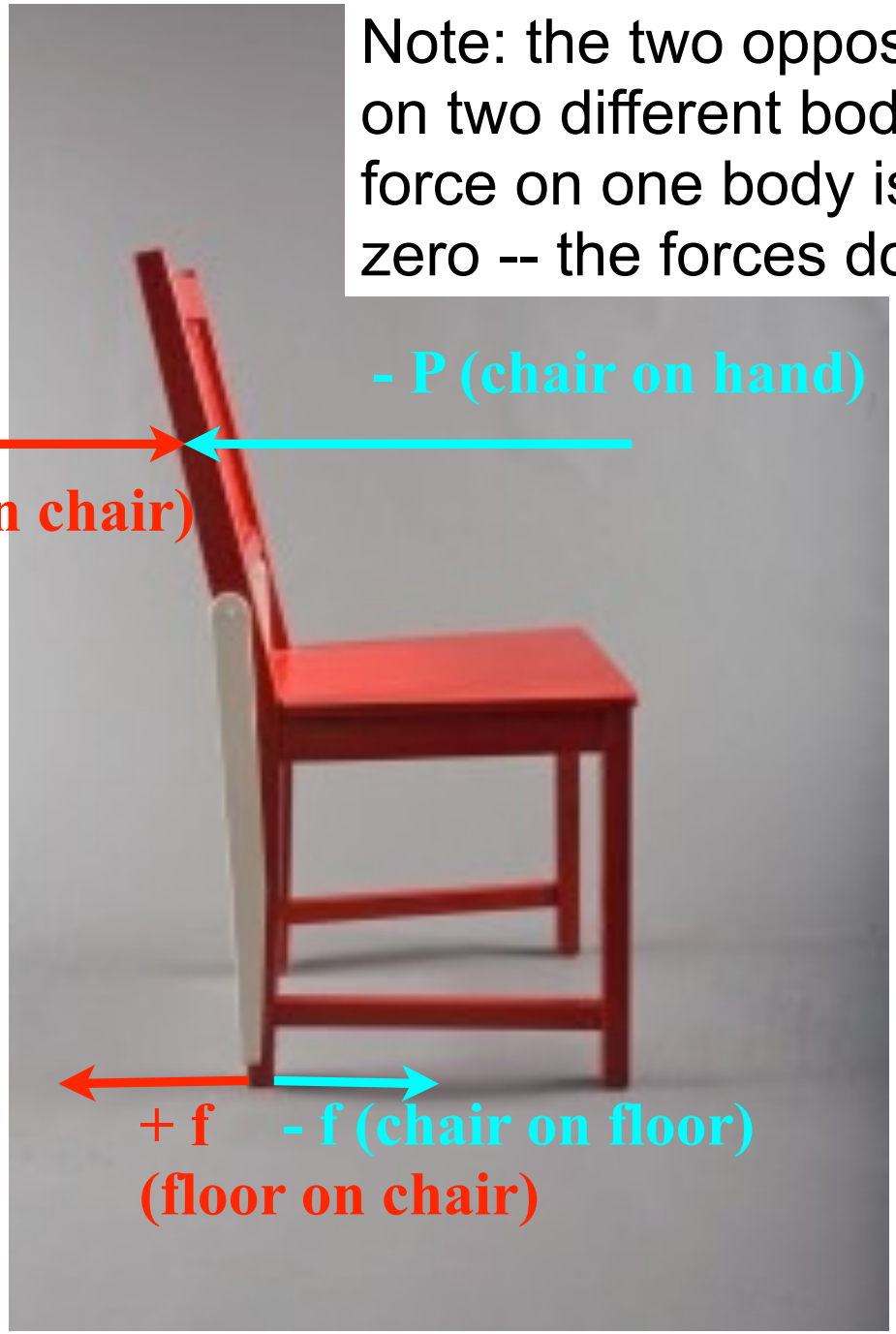
An object moves at constant velocity if there is no net force acting upon it.

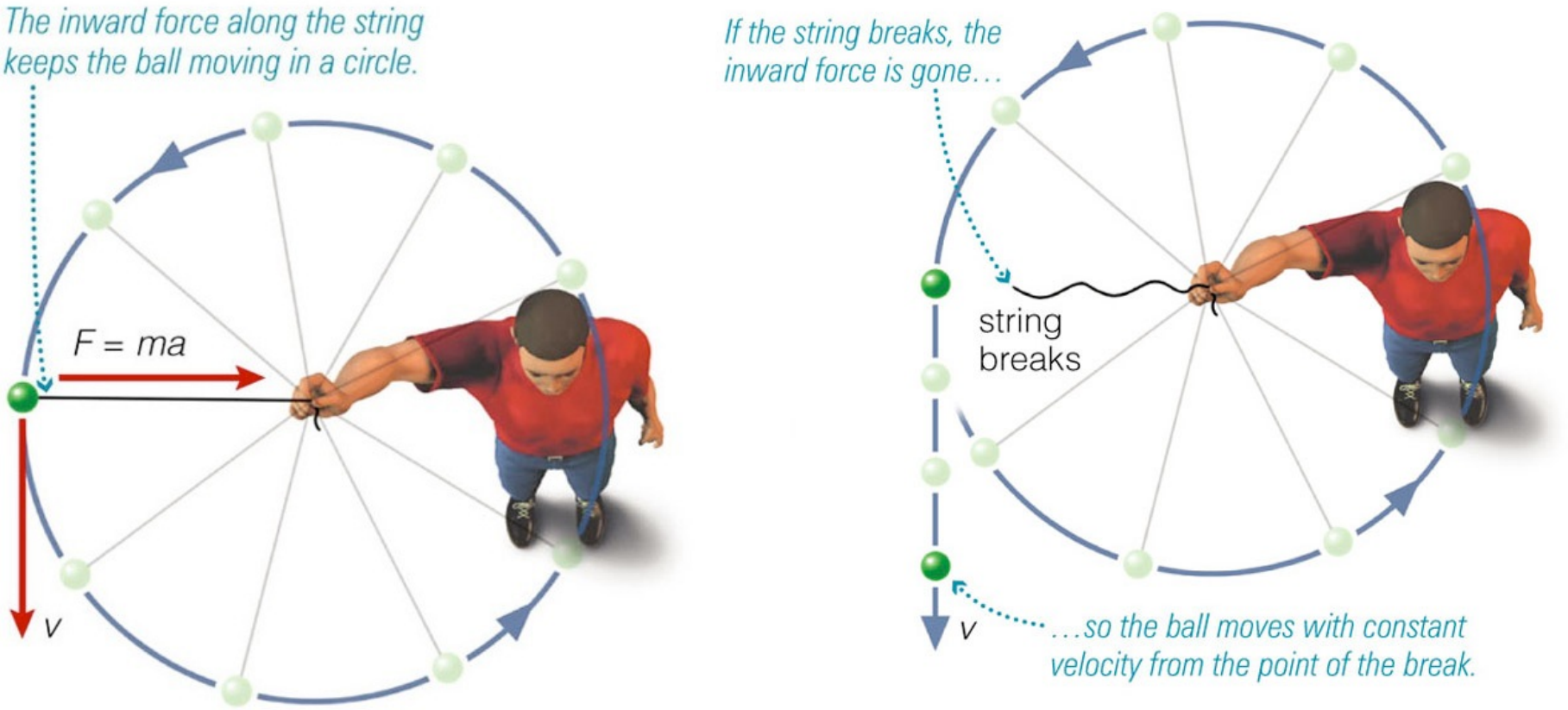
Newton's Third Law of Motion

- Whenever one body exerts a force on a second body, the second body exerts an equal and opposite force on the first body.
  - Don't need a rocket launch pad!
  - The Bug and the Windshield – who is having the worse day?
    - Change in motion (acceleration) depends on masses though...
      - $a_{bug} = F/m_{bug}$
      - $a_{car} = F/m_{car}$



Note: the two opposing forces act on two different bodies, so the net force on one body is not (usually) zero -- the forces don't "cancel" out





A *force* is needed to keep planets orbiting

Newton's Law of Gravitation

- Newton's law of gravitation states: Two bodies attract each other with a force that is directly proportional the product of their masses and is inversely proportional to the square of the distance between them.

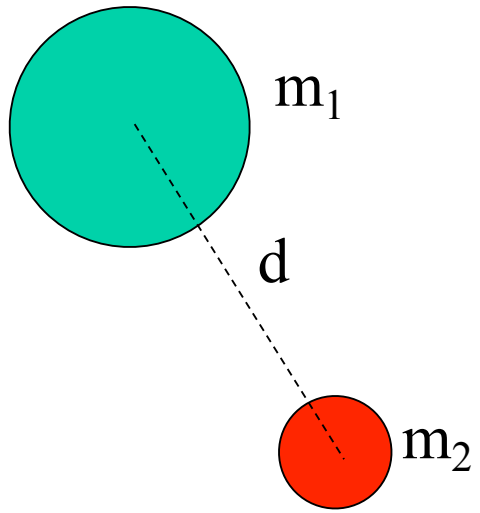
$$F_{grav} = \frac{Gm_1m_2}{d^2}$$

What the ….? I thought I understood gravity?

Newton's Law of Gravitation

- To figure out the gravitational force just multiply the mass of the two things together then divide by the distance they are apart (squared).

$$F_{grav} = \frac{Gm_1m_2}{d^2}$$



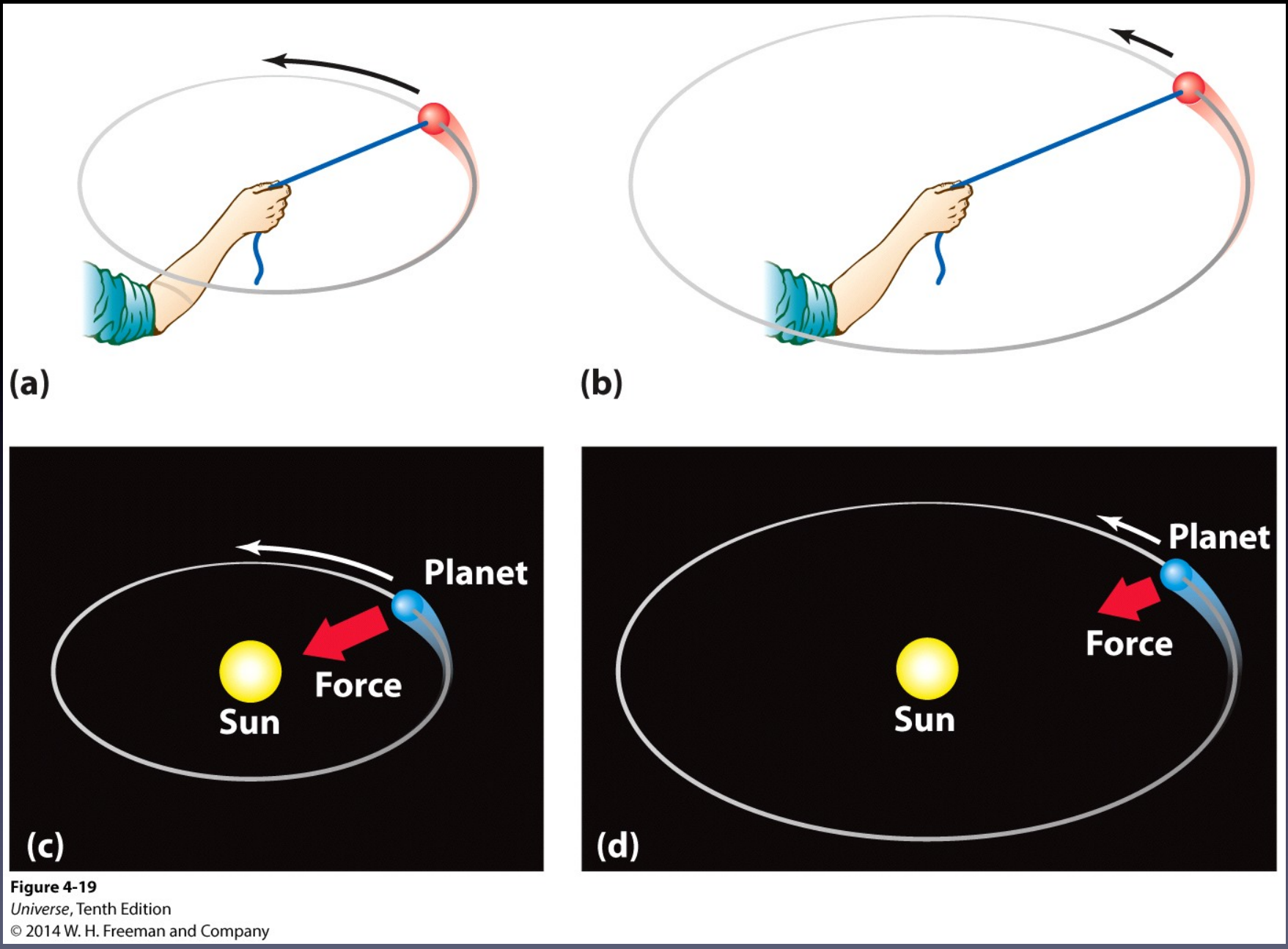


Figure 4-19
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An Orbit Analogy

Orbits and Energy

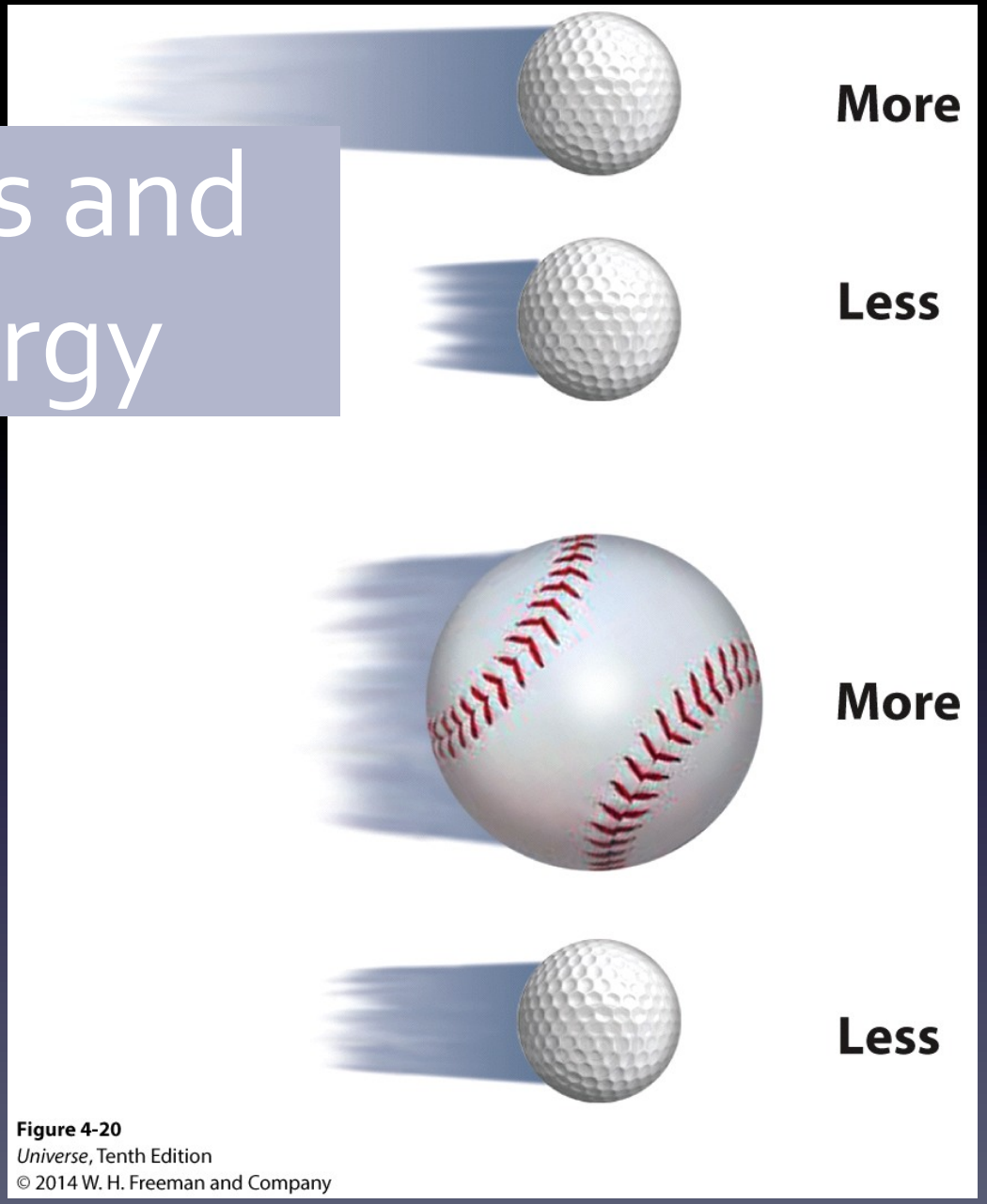

Figure 4-20
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Kinetic Energy

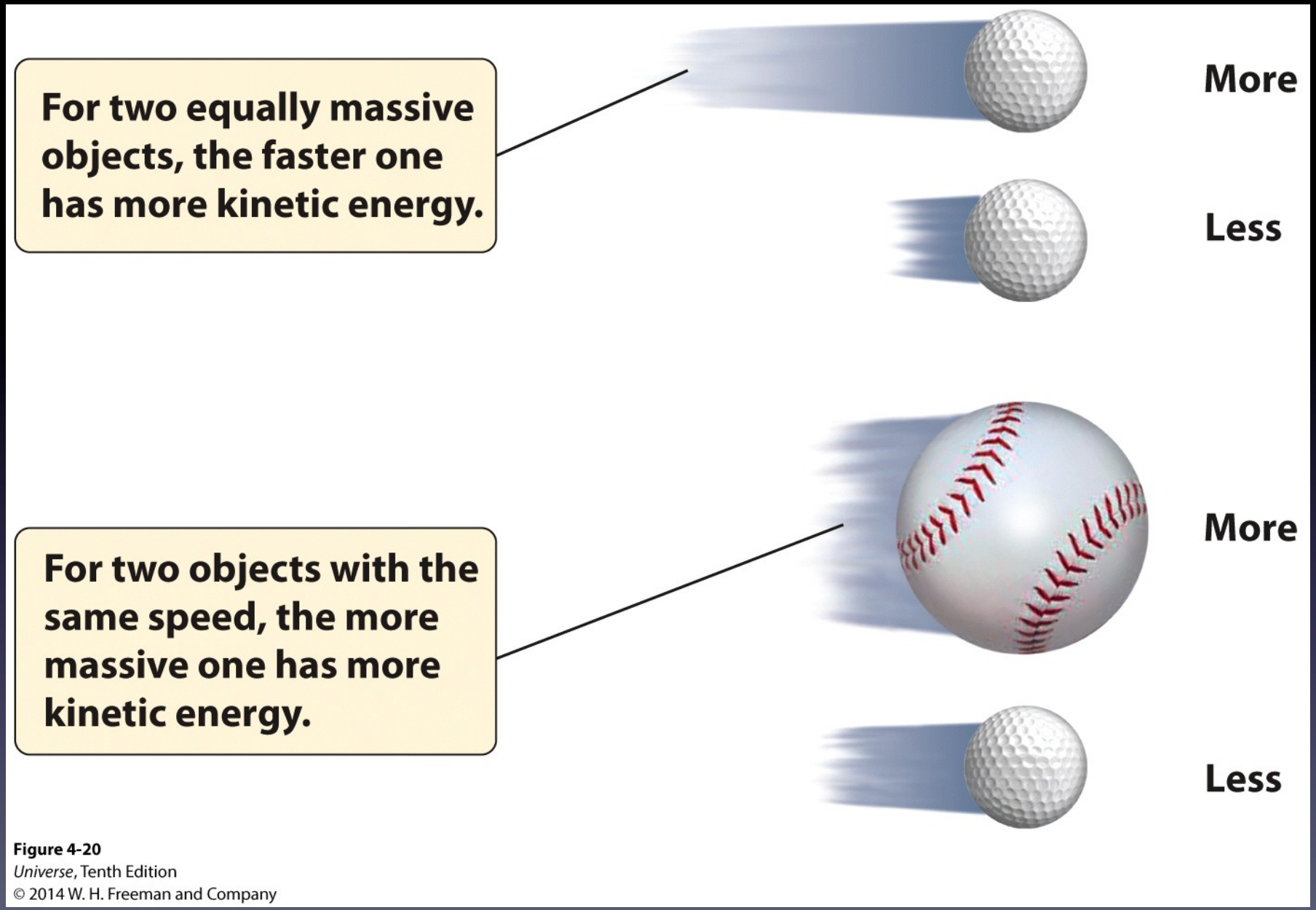

Figure 4-20
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Kinetic Energy

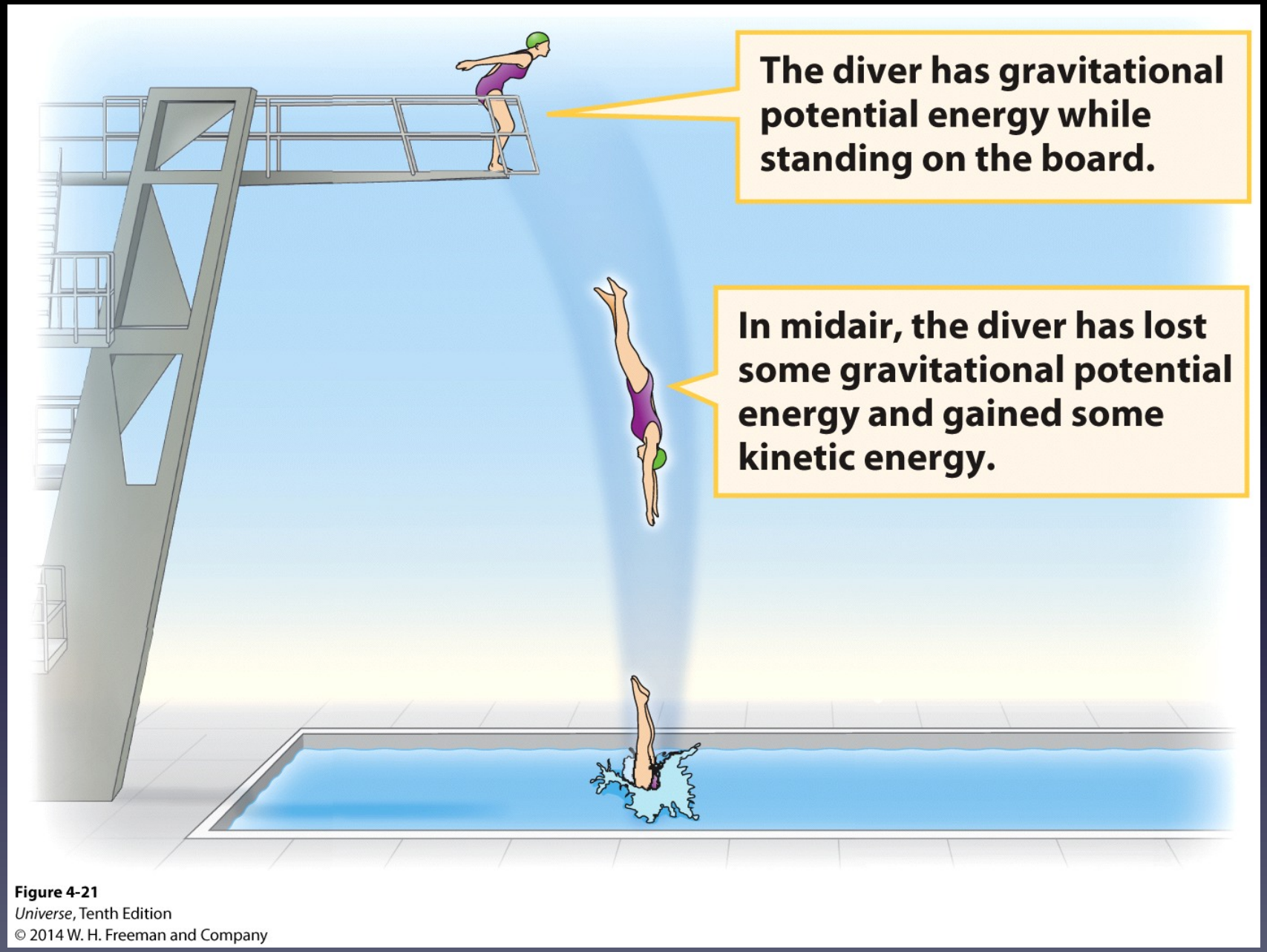

Figure 4-21
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Gravitational Potential Energy

4-7: Describing orbits with energy and gravity

Figure 4-22
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Orbits and the Escape Speed

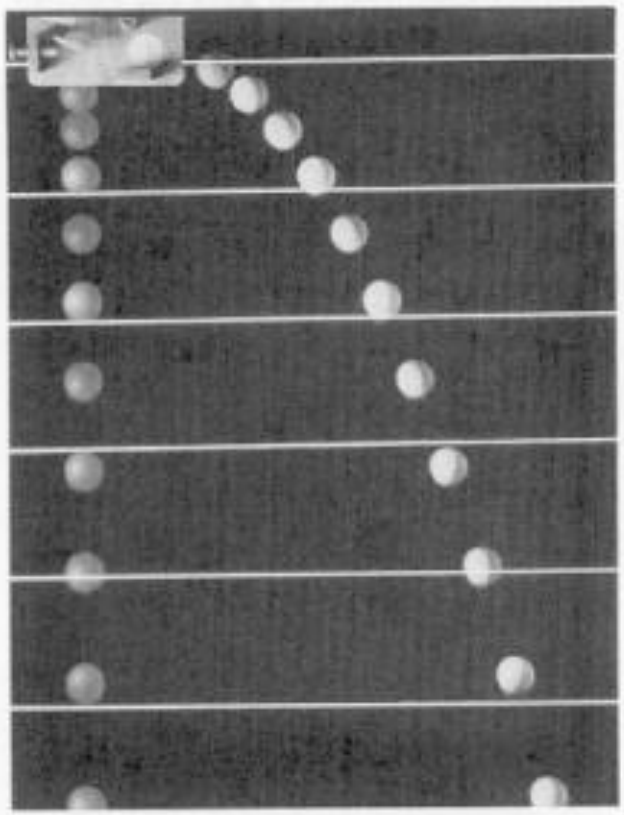
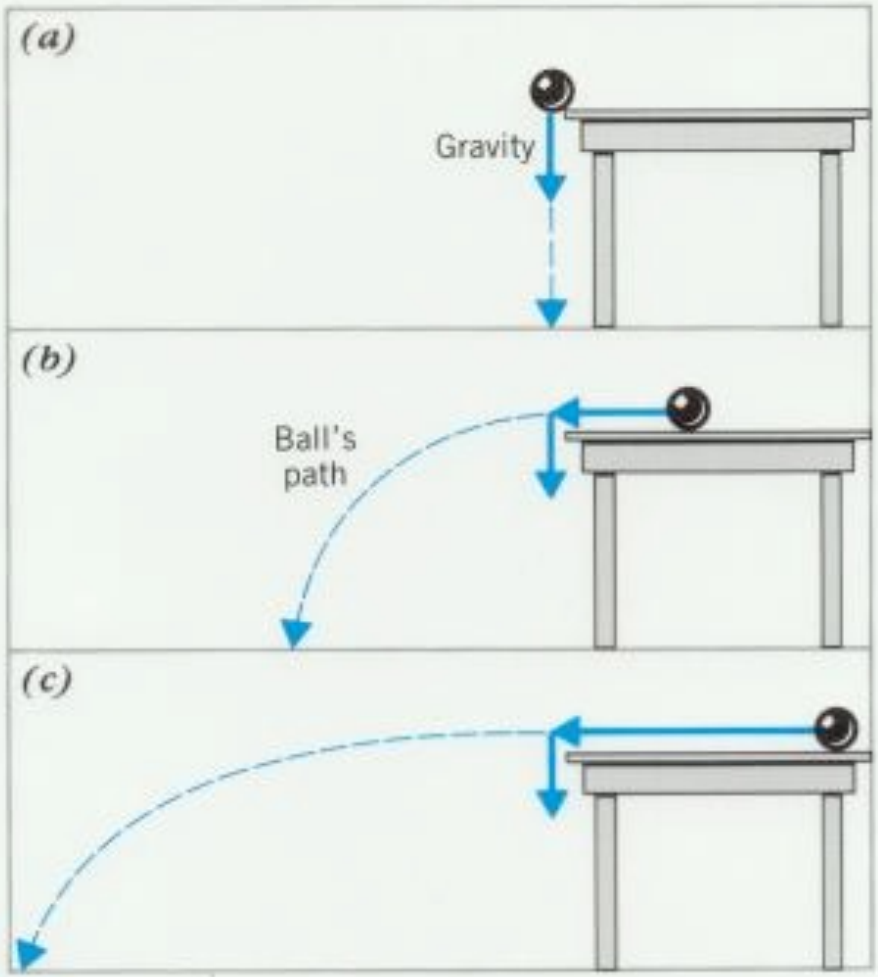
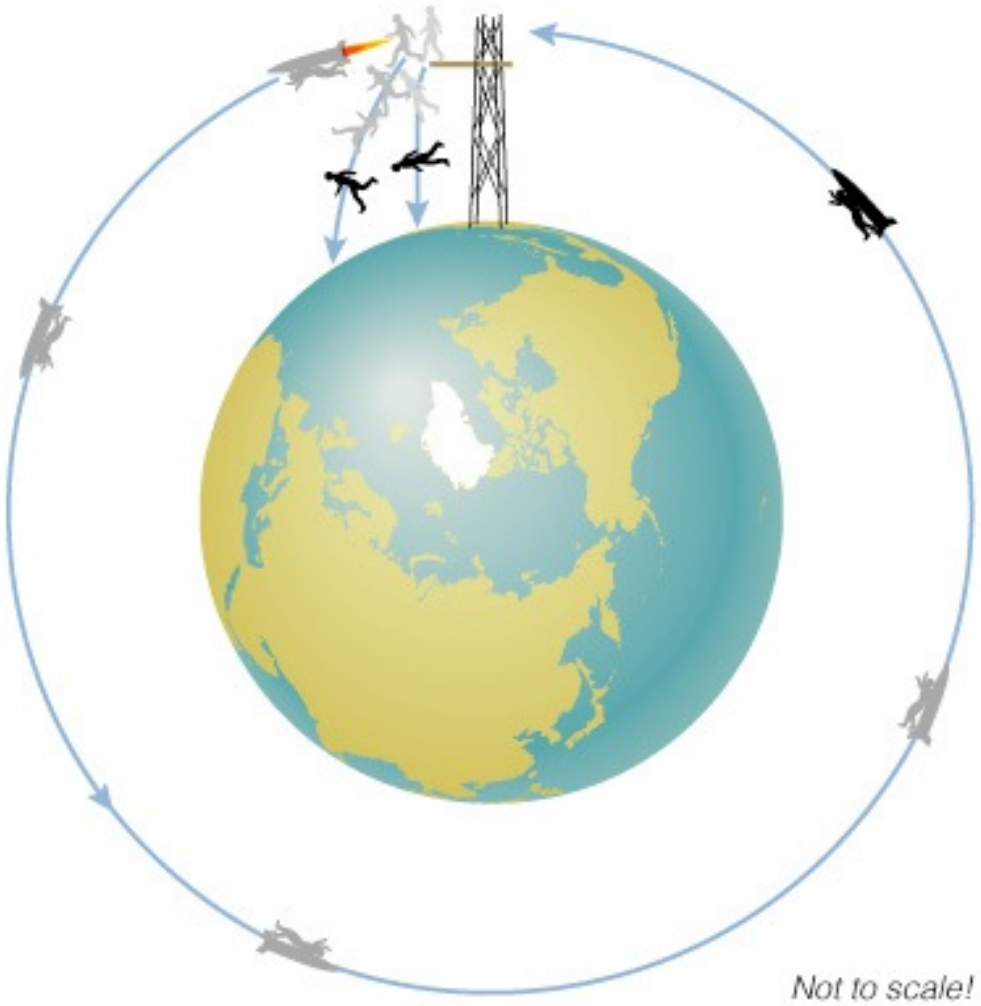


Fig. 1.1.10 - When these two balls were dropped, they accelerated downward at the constant rate of 9.8 m/s^2 and their velocities increased steadily in the downward direction. Even though one of them was initially moving to the right, they descended together.

in 1 second, the ball falls 5 m

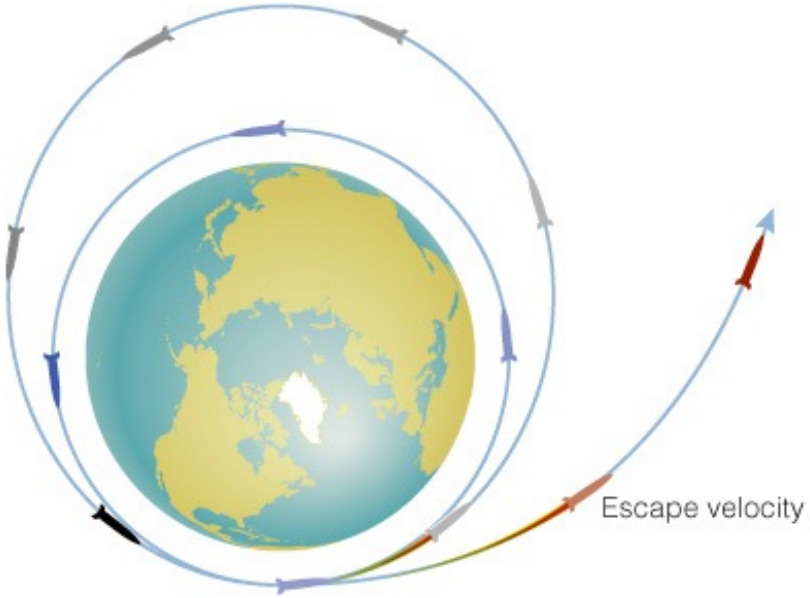


Motion of a ball near the surface of the earth.



- There *is* gravity in space
- Weightlessness is due to a constant state of free-fall

Escape Velocity

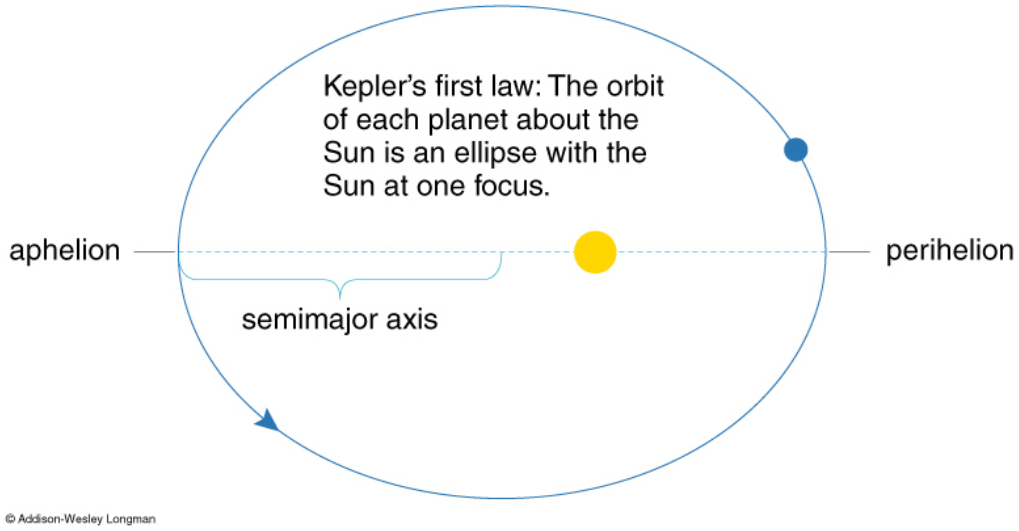


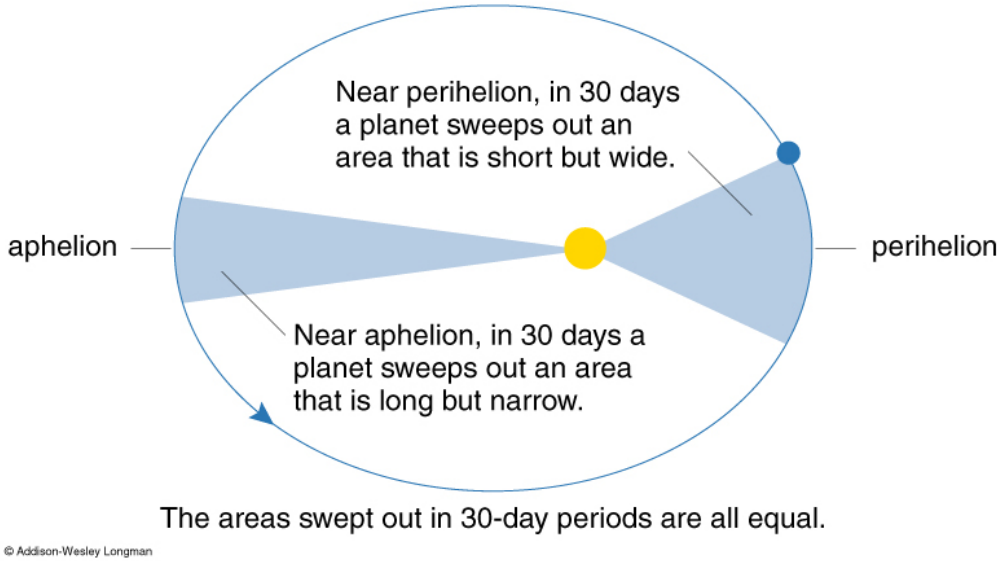
- If an object gains enough orbital energy, it may escape (change from a bound to unbound orbit)
- **Escape velocity** from Earth ≈ 11 km/s from sea level (about 40,000 km/hr)
- Escape (and orbital) velocity is independent of mass of object!

Newton’s Laws and Kepler's Laws

- Newton’s law of gravitation and his three laws of motion prove all of Kepler’s laws

All orbiting objects obey Kepler's first 2 laws





Orbits can be any conic section

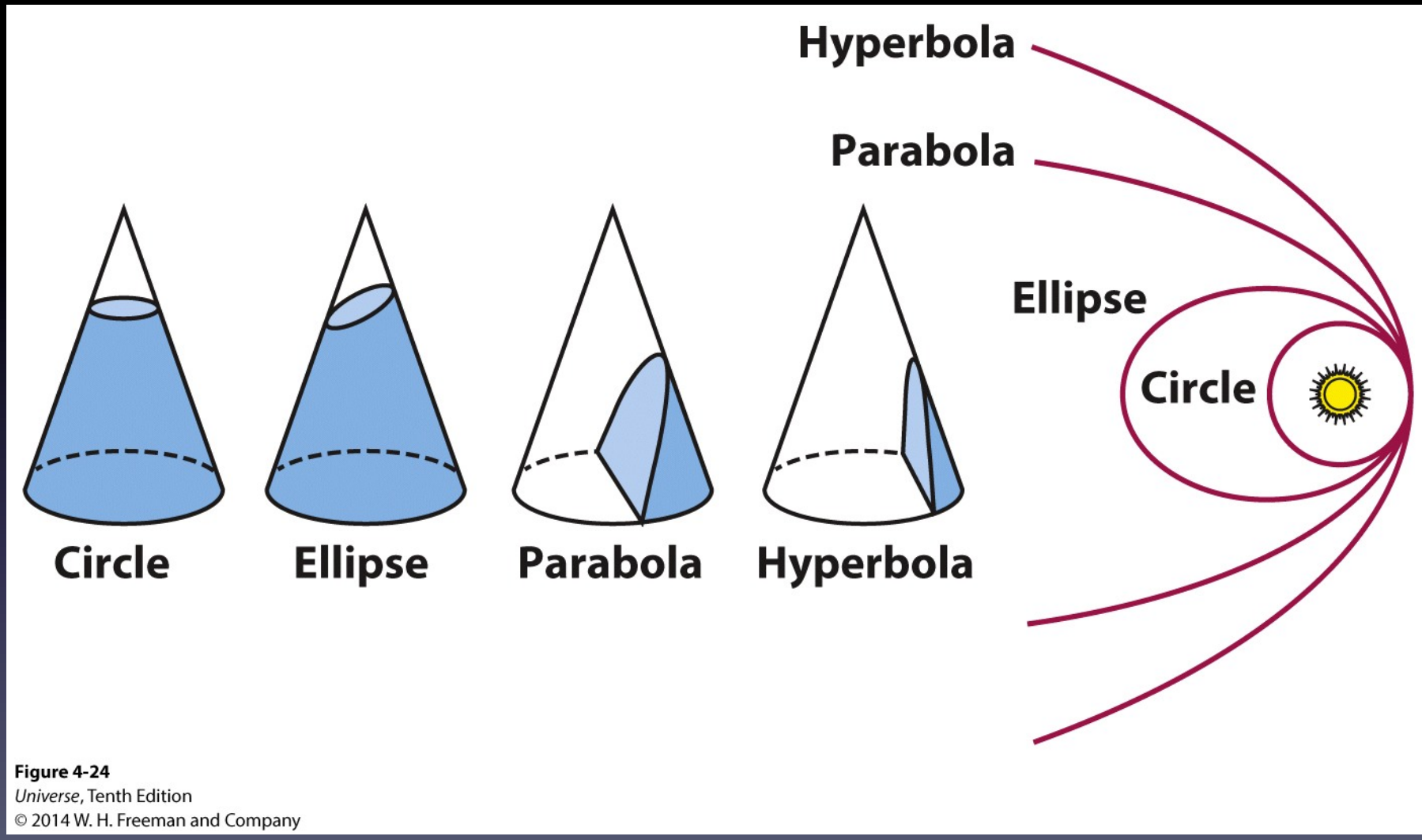


Figure 4-24
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Conic Sections