If I have seen further it is by standing on the shoulders of giants.

– Sir Isaac Newton

What We Will Learn Today

- What are the basic elements of motion?
- What are Newton's laws of motion?
- What are the three main conservation laws?
- How does gravity work?
- What causes tides on Earth?
- Why is the Moon's rotational period equal to its orbital period?

Basic Elements of Motion

- Speed
  - Distance / Time
- Velocity
  - Speed along a specified direction
- Acceleration
  - Change in velocity
  - Can be positive (increase in speed) or negative (decrease in speed)
  - Can be a change in direction
  - You can not feel velocity but can feel acceleration
  - Direction of acceleration is opposite the direction we “fall”

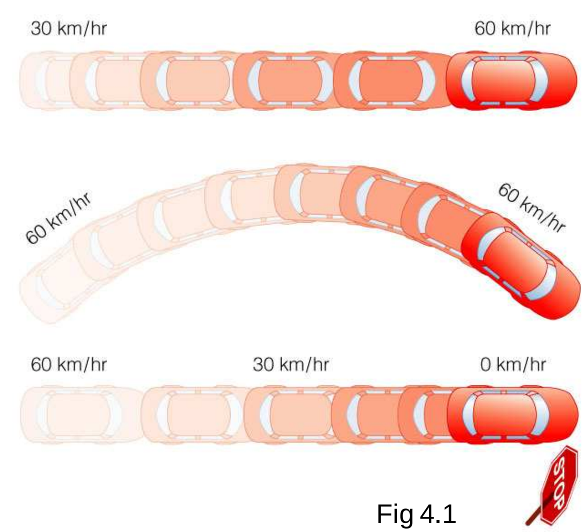


Fig 4.1

Mass, Momentum, and Force

- Mass
  - Measure of the amount of matter (units kg, pounds etc.)
- Weight
  - The force of attraction applied on a mass due to gravity (units Newton, kg-wt, lb-wt etc.)
- Inertia
  - A property of matter that makes it resist any change to its state of rest or motion
- Momentum
  - Mass x Velocity
  - Unchanging unless external force is applied
- Force
  - External influence applied on a mass to change its momentum or velocity i.e. to accelerate it
  - Remember, “acceleration” could be a decrease in velocity

Acceleration Due To Gravity

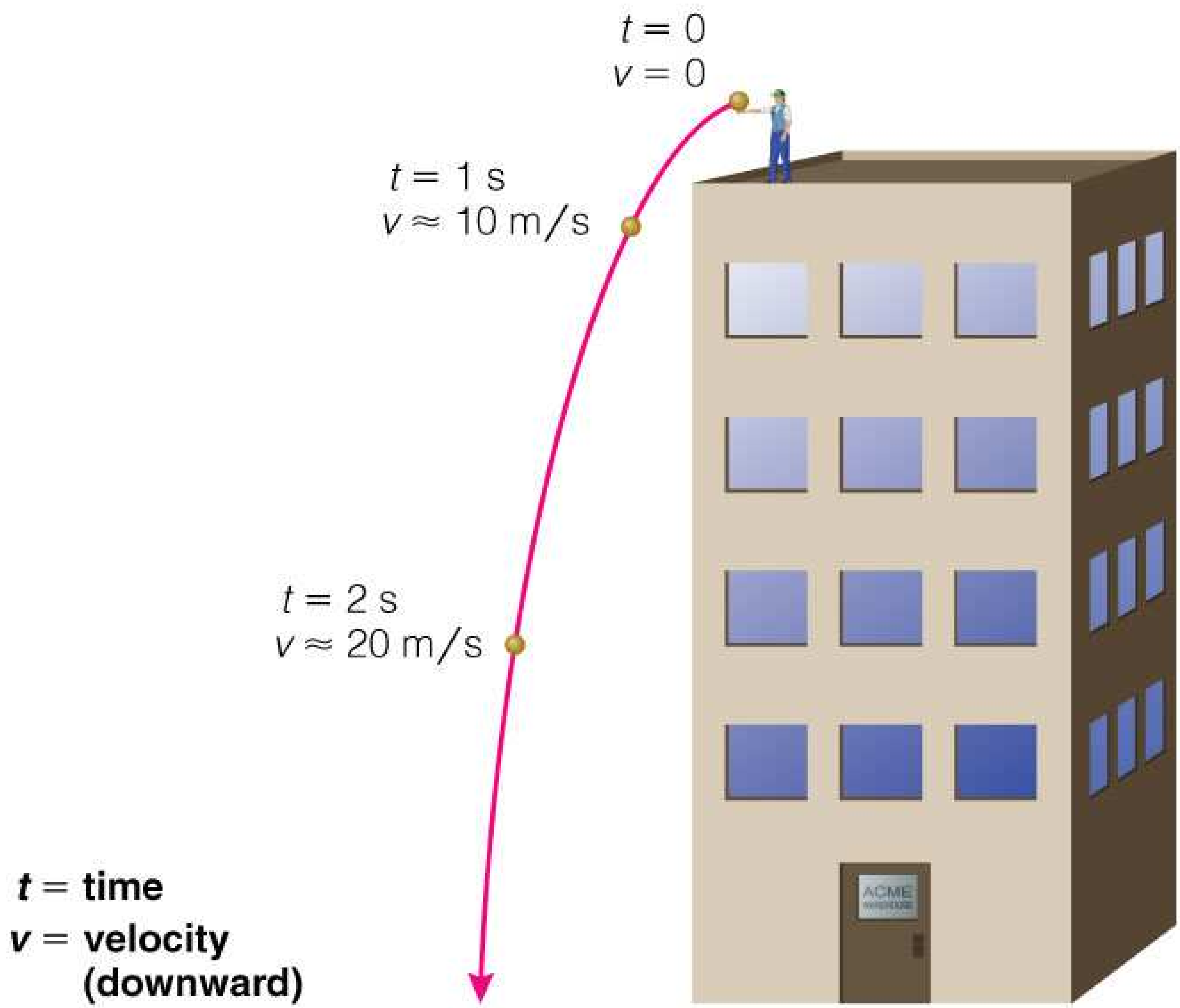


Fig 4.2

Angular Momentum

- Momentum of objects due to motion along a curve
  - Rotational angular momentum
    - Skater, Earth
  - Orbital angular momentum
    - Racetrack, Earth
- Torque
  - Force applied on object to change angular momentum
  - Lever arm – door handle at other end of hinges

Orbit is a Free-Fall

- What goes up, must come down
  - Not always!
- Why are astronauts weightless?
  - In a constant state of free-fall

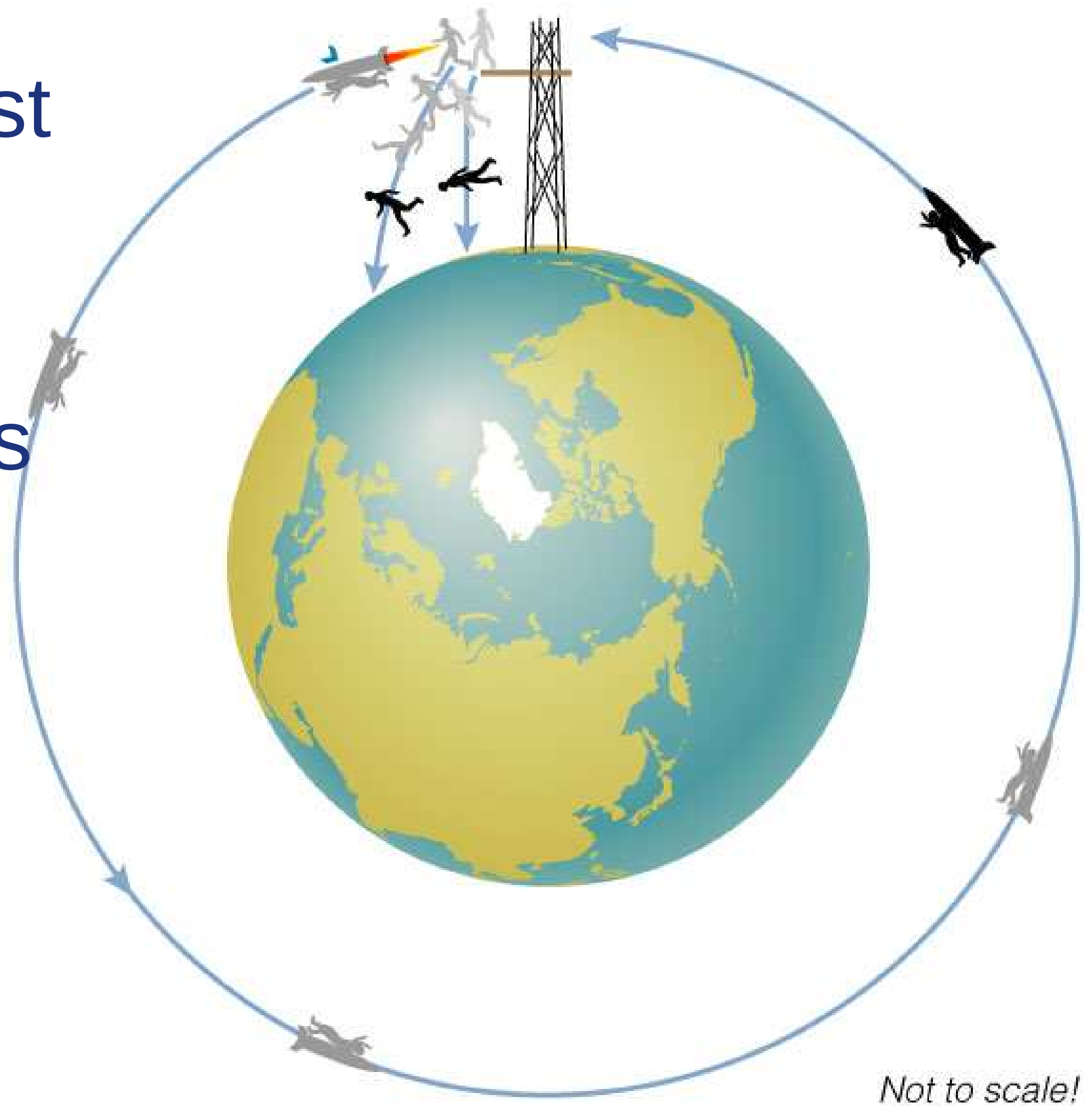
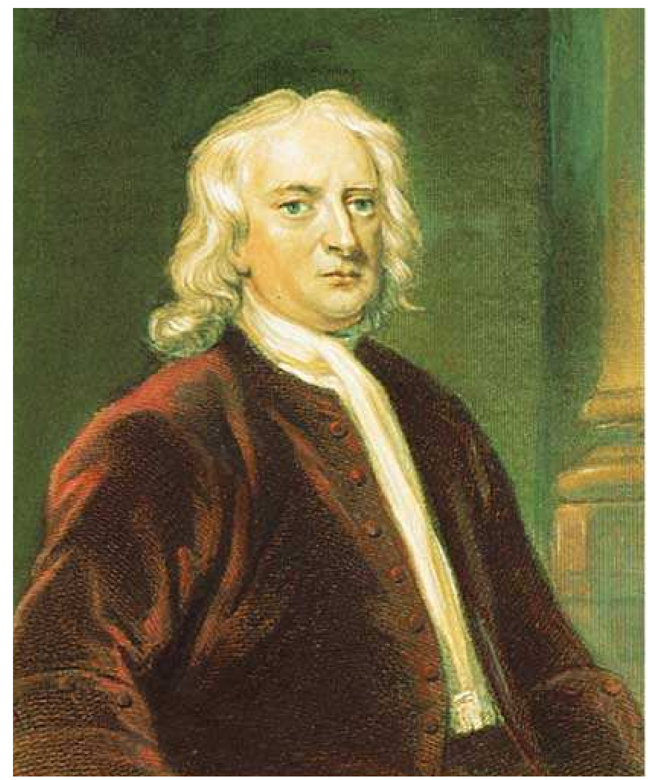


Fig 4.4

Sir Isaac Newton (1642 – 1727)

- Formulated the laws of motion & gravity
  - Explained the “why” behind Kepler’s laws
- Probed the nature of light
- Built the first reflecting telescopes
- Invented calculus



Newton's First Law

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

- Essentially restates Galileo's discovery
- This is the law of inertia
- Object at rest stays at rest
- Object in motion stays in motion
  - Not intuitive due to friction on Earth
  - Airplane example
- Explains why we feel acceleration but not uniform motion

Newton's Second Law

Force = Mass x Acceleration

- External force is required to change an object's state of motion (or rest)
- Quantifies relationship between force applied and the resultant acceleration of the object
- For a given mass, greater force results in greater acceleration
- Same force on unequal masses – smaller mass accelerates more

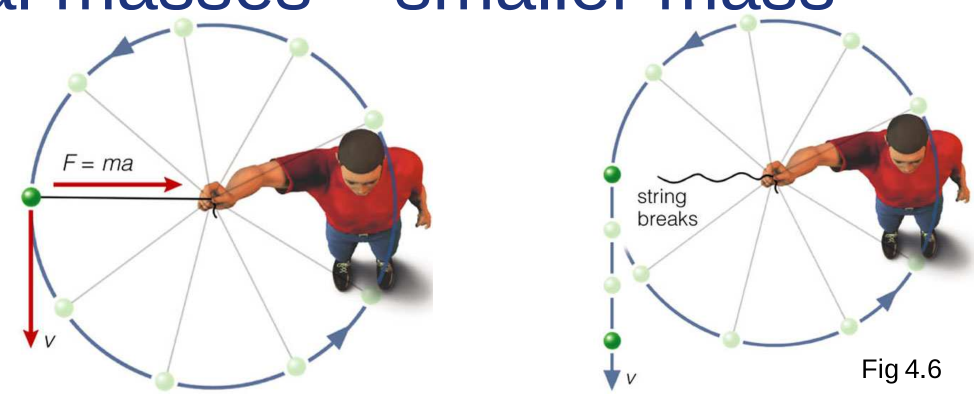
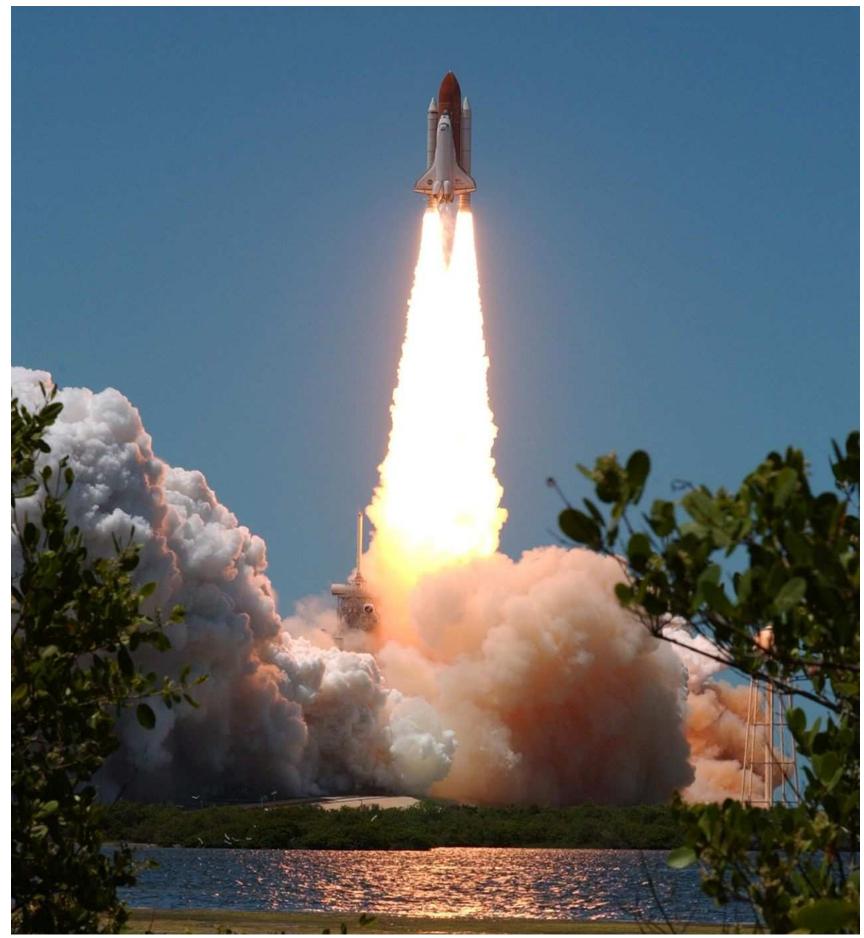


Fig 4.6

Newton's Third Law

For any force, there is always an equal and opposite reaction force

- Some examples
  - Rockets flying
  - Gun recoiling upon firing
  - Garden hose moves back when water is turned on
  - Filled balloon left loose
  - It hurts when you run into a wall!



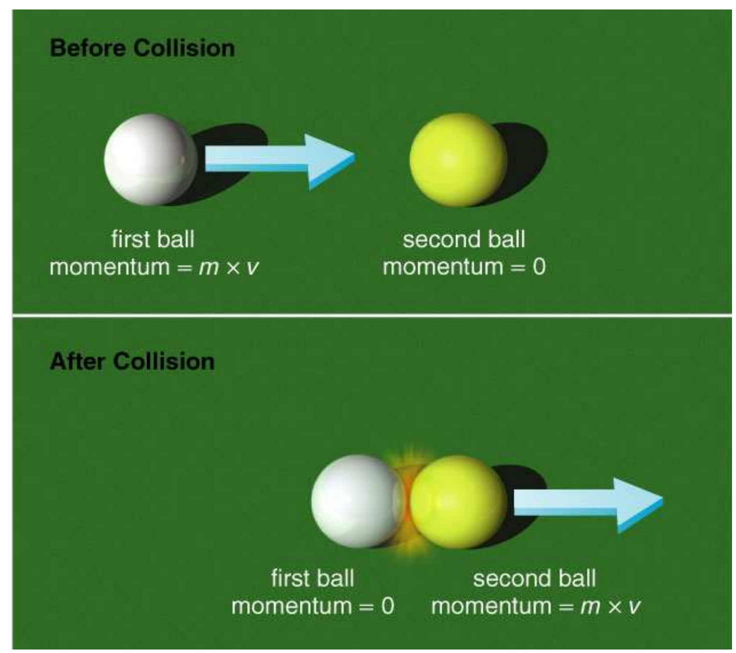
Conservation Laws

- The “why” behind Newton’s laws
- Conserved = Unchanged
- Three conservation laws
  - Conservation of Momentum
  - Conservation of Angular Momentum
  - Conservation of Energy

Conservation of Momentum

- In the absence of an external force, the total momentum of interacting objects remains unchanged (conserved)
  - – Explains first law i.e. inertia
  - – Explains third law i.e. rocket launch

Fig 4.7



Conservation of Angular Momentum

- In the absence of an external torque (twisting force), the total angular momentum of interacting objects remains unchanged
  - i.e. it is *conserved*
  - Explains why planets keep spinning & orbiting the Sun
  - Explains Kepler's second law
    - Planets move faster when closer to the Sun

Fig 4.9

Conservation of Energy

- The total energy in an isolated system remains unchanged
  - It can change form (kinetic, potential, thermal, radiative etc.)
  - It can be transferred from one object to another

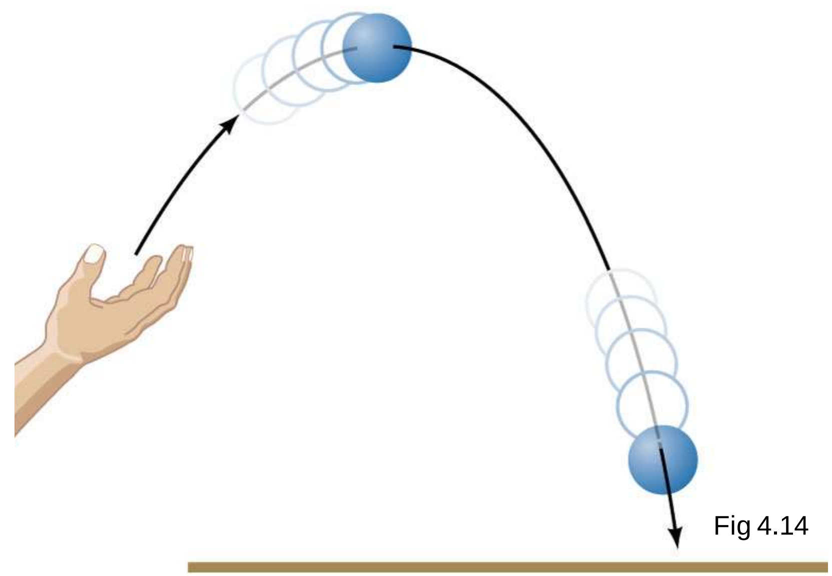


Fig 4.14

Newton’s Law of Gravity

- Every mass attracts every other mass through the force of gravity
- The force of gravity is
  - *Directly proportional* to the product of the two masses
  - *Inversely proportional* to the *square* of the distance between them

$$F_g = G\frac{M_1 M_2}{d^2}$$

inverse square law

  - M_1, M_2 are the masses of the two objects (SI unit: kg)
  - d is distance between them (SI unit: m)
  - G is Newton’s gravitational constant
  - In SI units, F is measured in Newtons (kg m s^{-2})
  - If distance between two objects is tripled, force of gravity drops to $1/3^2 = 1/9$ of original value

Acceleration due to Gravity

- From Newton's second law: F = m x a
- To describe gravity on the surface of the Earth, we write this as F = m x g, where g is gravitational acceleration on Earth's surface
- Using Newton's gravitational law, we see that

$$F = \frac{\mathrm{G\,M_E}\,m}{d^2} = mg$$

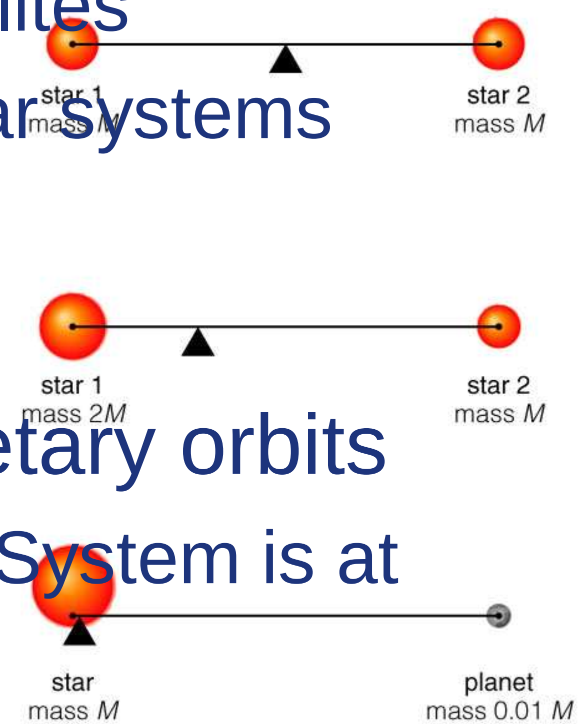
- Which leads to

$$g = \frac{\mathrm{G\,M_E}}{r_E^{\,2}} = 9.8\,m/s^2$$

Newton's Laws Improved Kepler's

- Explained the basis for the laws
- Extended the laws to all orbits
  - Not just planets around the Sun
  - Asteroids, comets, artificial satellites
  - Other solar systems, multiple star systems

$$a^3 = \frac{G(M_1 + M_2)}{4\pi^2} p^2$$



- Sun is not at the focus of planetary orbits
  - The center of mass of the Solar System is at the focus

Moon’s Gravity: Tides on Earth

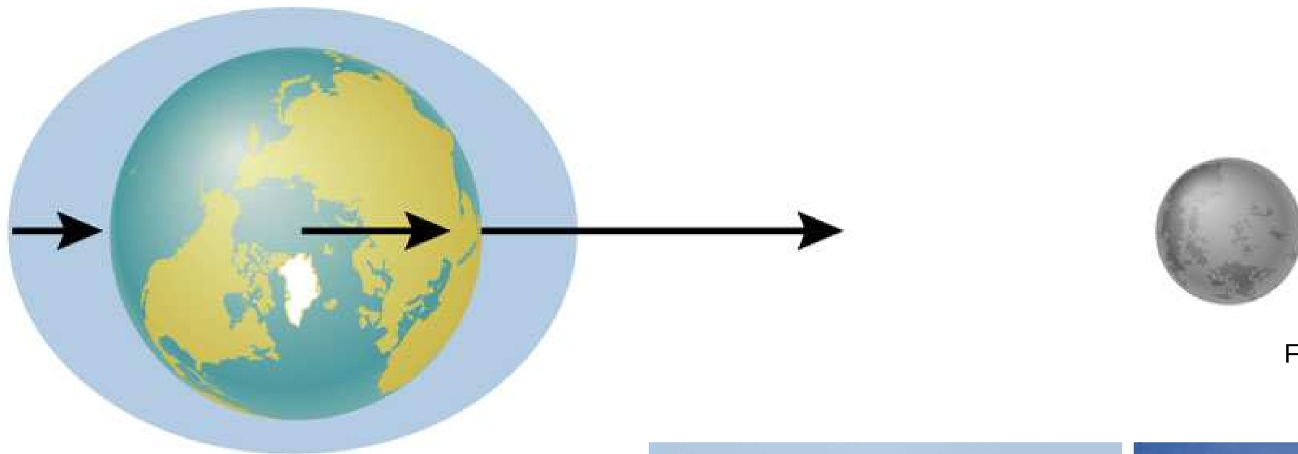


Fig 4.13

- Sun’s contribution is about a third of the Moon’s

Spring tides: Sun/Moon aligned

Neap tides: Sun/Moon tidal forces counteract

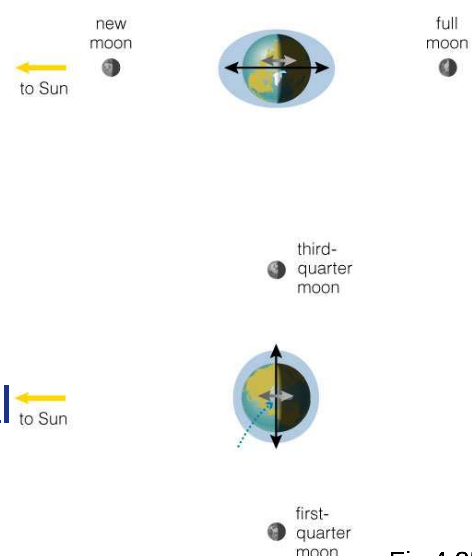
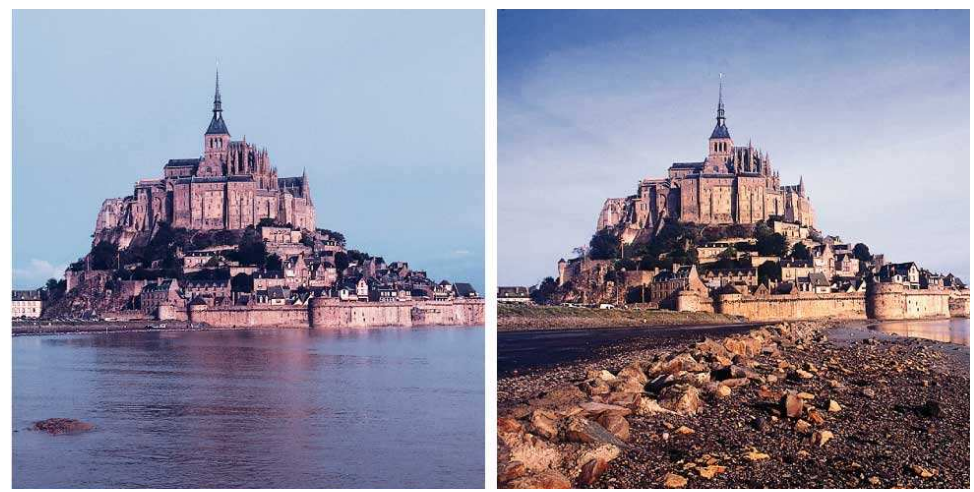


Fig 4.25



Mont-Saint-Michel

Fig 4.24

Tidal Friction

- Earth’s rotation is slowing down
  - 1 extra second for every 50,000 years
  - Day is 20 minutes longer now than it was a million years ago
- Moon is drifting farther away
  - 38 mm per year
  - Conservation of angular momentum
- Explains Moon’s synchronous rotation

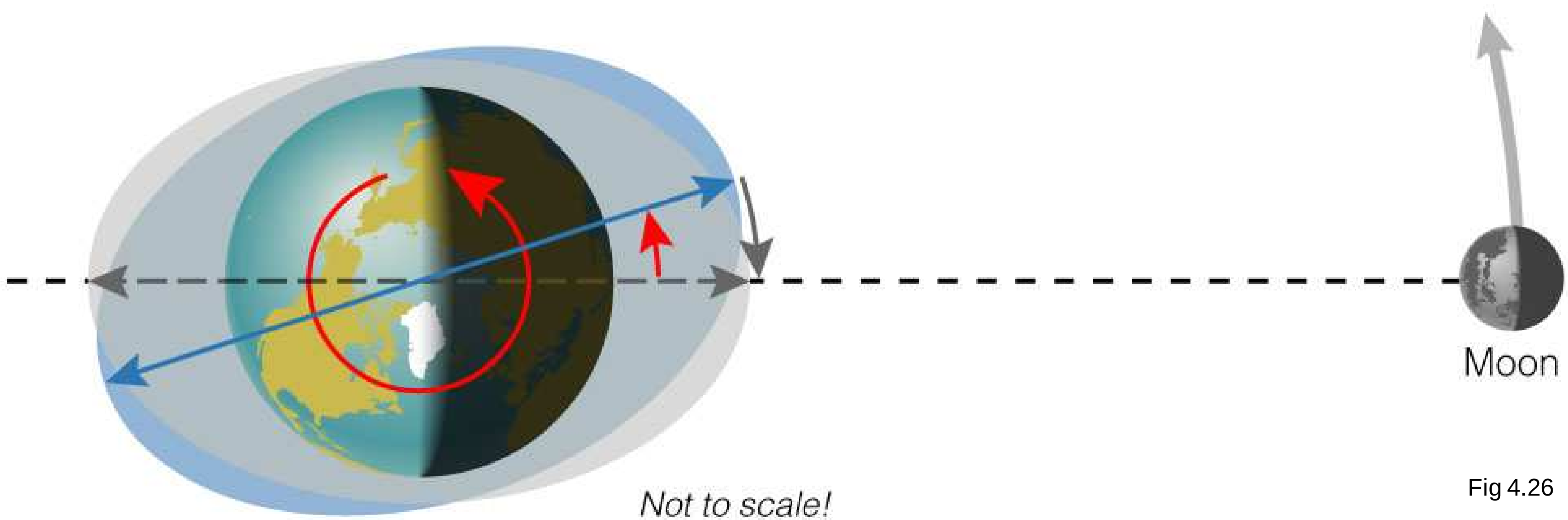


Fig 4.26