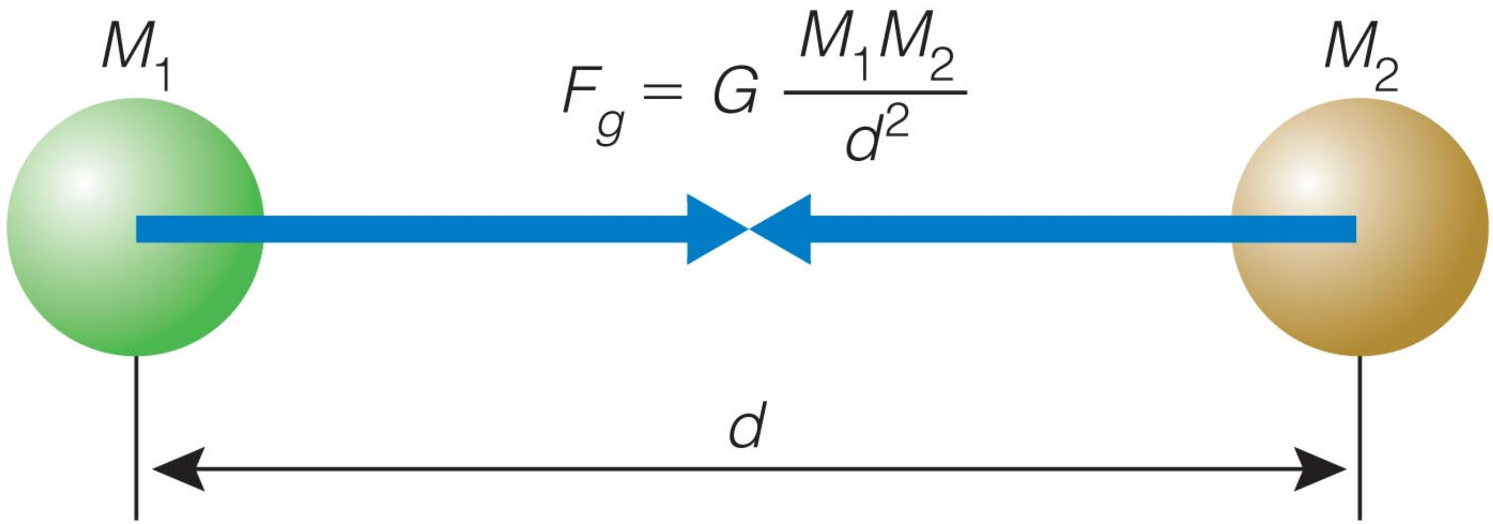
Lectures 6&7 - How the Universe Works

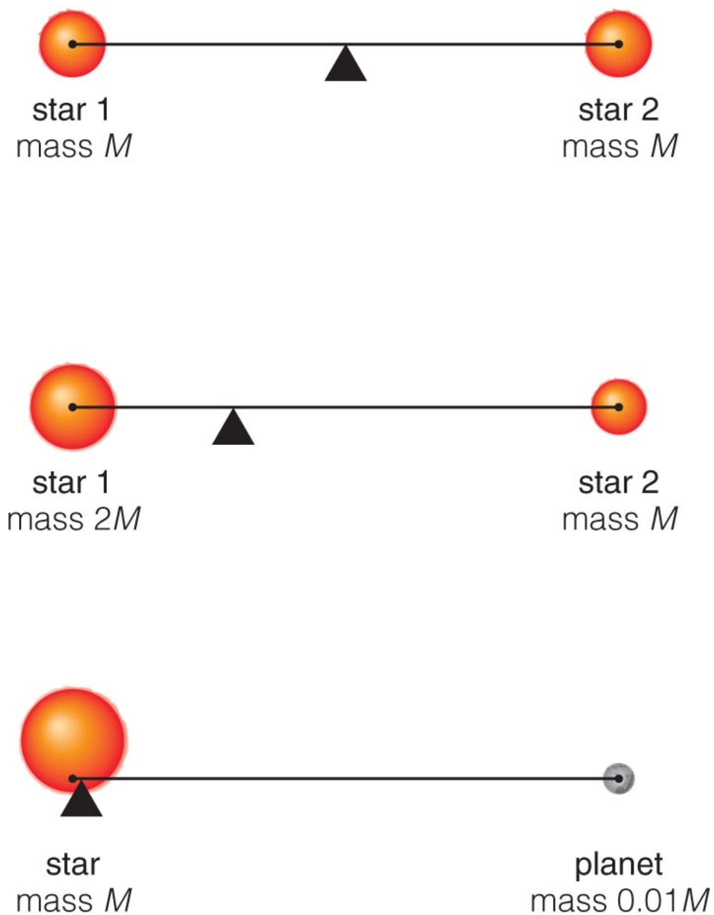
*Understanding **Motion**, **Energy**, and **Gravity***

The **Universal Law** of **Gravitation:**

1. Every mass attracts every other mass.
2. Attraction is *directly* proportional to the product of their masses.
3. Attraction is *inversely* proportional to the *square* of the distance between their centers (doubling distance weakens force by 4x).



Center of Mass



- Objects of different mass balance on center of mass
- *Orbiting* objects orbit around their center of mass.
- *We can use gravity to measure mass!*

Interactive Figure

Gravity and Kepler's Third Law

• Newton's law of gravity combined with Kepler's 3^{rd} Law: <u>the *orbital period* and *orbital distance* of a satellite tells us the *total mass* of the system.</u>
• We measure the orbiting object's *orbital period* and *orbital distance* to calculate the mass of the larger object.

Examples:

- Earth's orbital period (1 yr) and average distance (1 AU) tell us Sun's mass.
- Orbital period and distance of Moon from Earth tell us Earth's mass.
- (See text, p 131 for sample calculation)

Newton's version of Kepler's Third Law

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

p = orbital period

a = average orbital distance (semimajor axis)

$(M_1 + M_2)$ = sum of object masses

If $M_1 >> M_2$ then $M_{Total} = M_1 + M_2 = M_1$

$$M_1 = (M_1 + M_2) \frac{(R_2)}{R_1 + R_2} \qquad M_2 = (M_1 + M_2) \frac{(R_1)}{R_1 + R_2}$$

Newton's version of Kepler's Third Law

For the Earth orbiting the Sun: a = 150,000,000 kilometers and
p = 31,500,000 seconds (1 yr)

$$M_{Sun} + M_{Earth} = \frac{4\pi^2 \text{ x } (1.5 \text{ x } 10^{11} \text{ m})^3}{6.67 \text{ x } 10^{-11} \; \frac{\text{m}^3}{\text{kg s}^3} \; (3.15 \text{ x } 10^7 \text{ s})^2}$$

$$= \mathbf{2 \text{ x } 10^{30} \text{ kg}}$$

(but 99.99% of this is Sun's mass)

Think/Pair/Share

How can astronomers determine the mass of Jupiter?

A. Measure its size, distance and gravitational pull on Earth
B. Track Jupiter's orbital motion around the Sun and determine the strength of its gravity
C. Measure the period and distances of moons orbiting Jupiter
D. All of the above

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What have we learned?

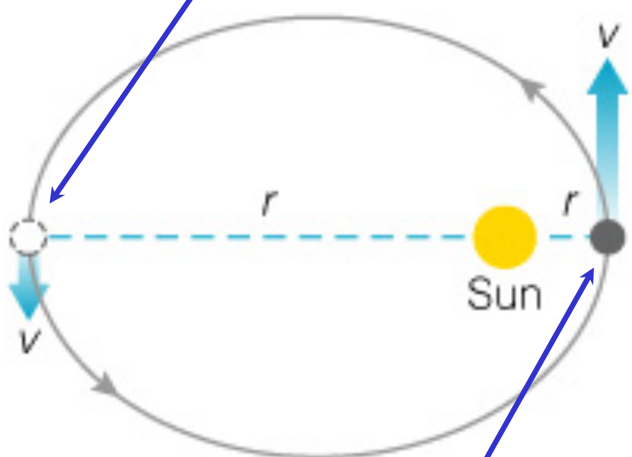
Begin 3 minute review

What have we learned?

- What determines the strength of gravity?
  - Directly proportional to the *product* of the masses ($M \times m$)
  - *Inversely* proportional to the *square* of the separation
- How does Newton's law of gravity allow us to extend Kepler's laws?
  - Applies to other objects, not just planets
  - Can be used to **measure mass of orbiting systems**

How do gravity and energy together allow us to understand orbits?

More gravitational potential energy;
Less kinetic energy



Less gravitational potential energy;
More kinetic energy

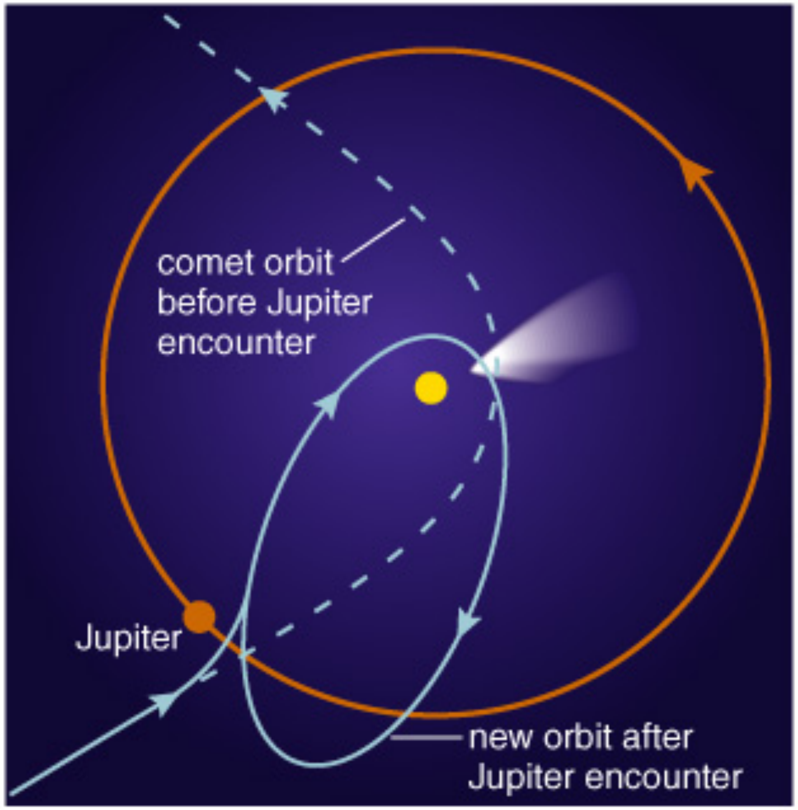
- Total orbital energy (gravitational + kinetic) stays constant if there is no external force.
- Orbits cannot change spontaneously.

Total orbital energy stays constant.

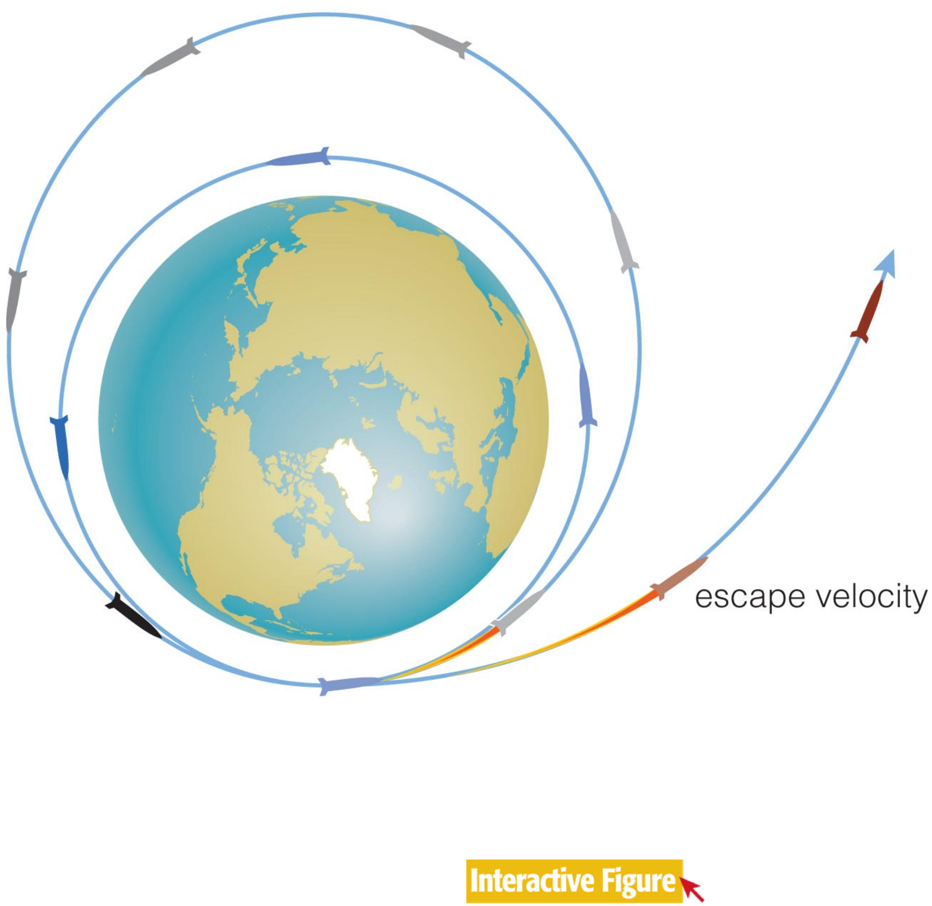
Changing an Orbit

So what can make an object gain or lose orbital energy?

- Friction or atmospheric drag
- A gravitational encounter
- A spacecraft firing its engines

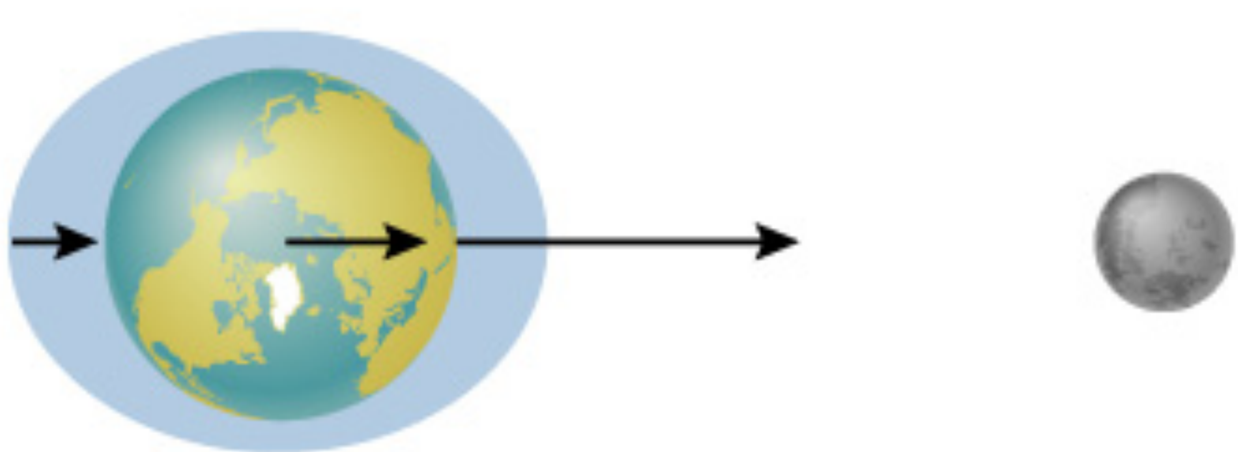


Escape Velocity



- With enough orbital energy, an object may escape
- **Escape velocity** from Earth ≈ 12 km/s from sea level (about 40,000 km/hr)
- Escape and orbital velocities don't depend on the mass (but more energy is needed to launch a heavier object).

How does gravity cause tides?



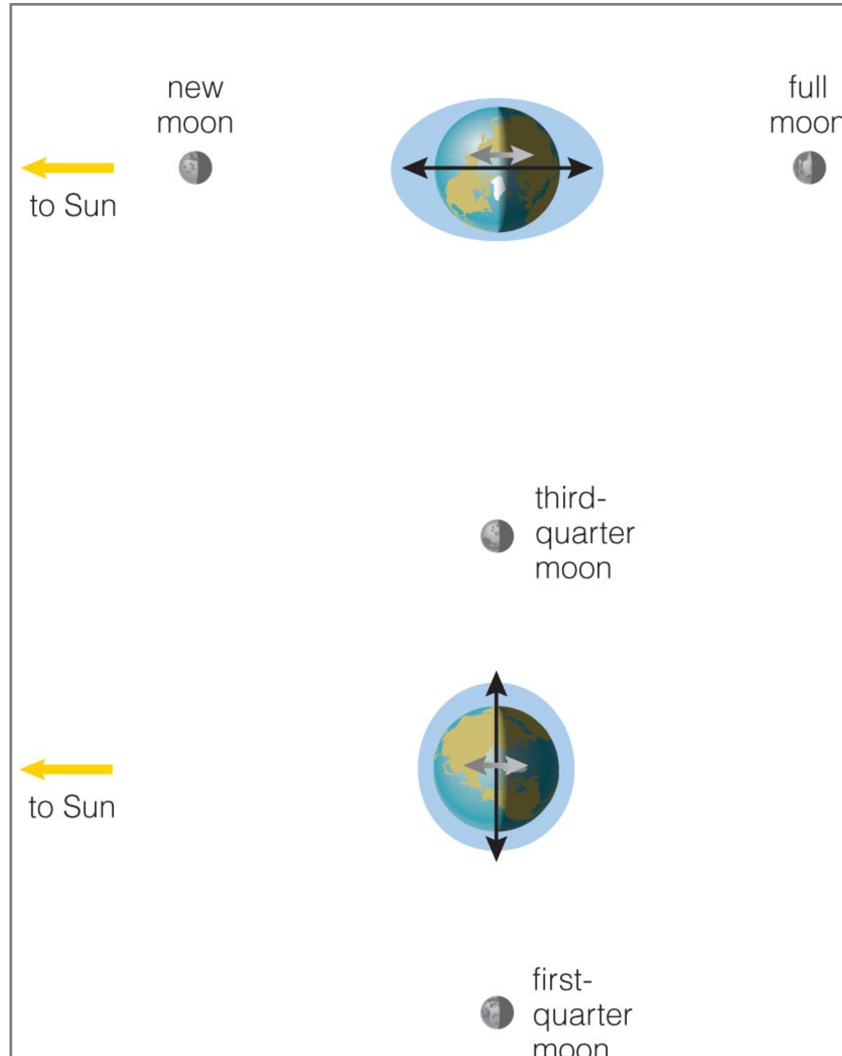
- The Moon's gravity pulls harder on near side of Earth than on far side.
- The *difference* in the Moon's gravitational pull stretches Earth, especially the oceans.

Tides and Phases

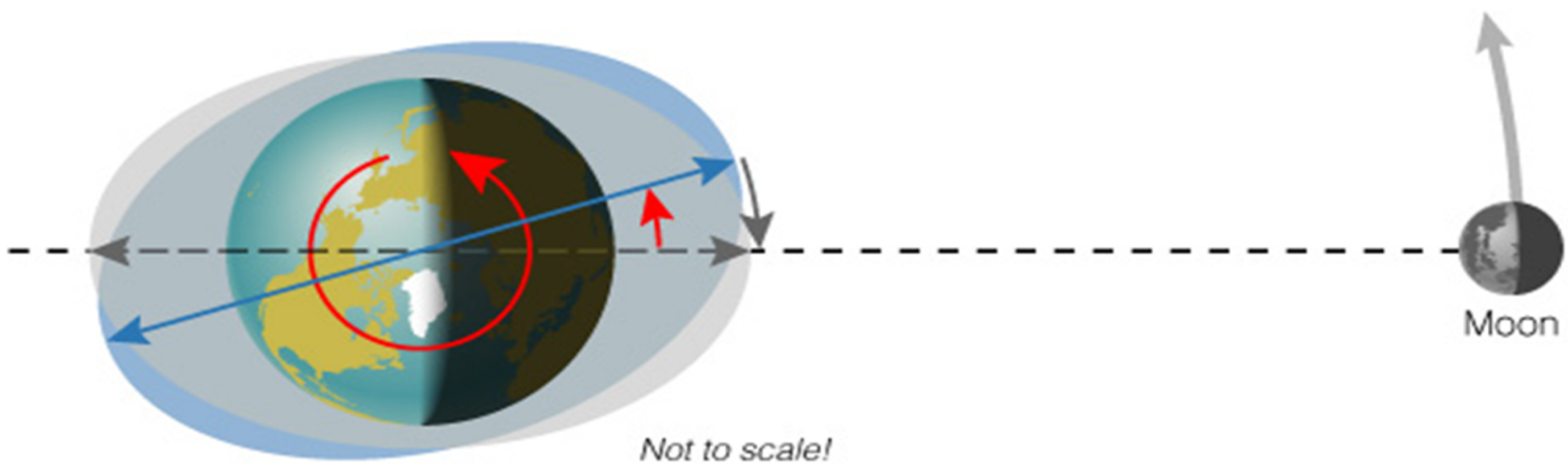
Size of tides depends on phase of Moon – does its gravity add to or cancel the Sun's gravity?

- Tides highest at new and full moon
- Tides lowest at first and third quarter

Interactive Figure



Tidal Friction



- Earth's rotation drags tides along (red); moon tries to keep them in line
- Moon pulls back on bulges; friction gradually slows Earth rotation
- Gravity of bulges pulls Moon ahead or farther - Moon get farther
- Moon once rotated faster; tidal friction from Earth caused *lunar* tidal bulges to "lock" in line with Earth, showing us only one side (synchronous rotation)!

What have we learned?

Begin 3 minute review

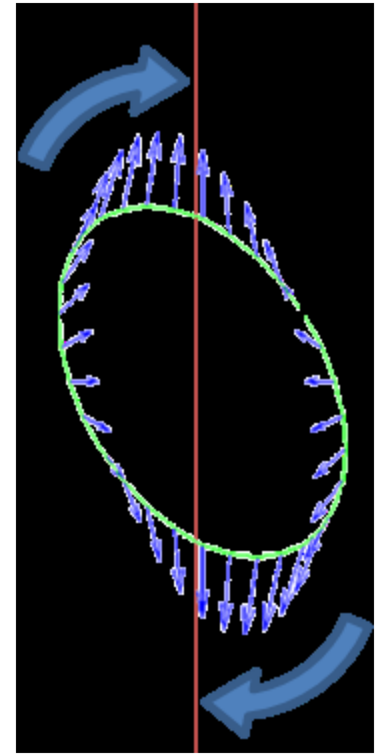
What have we learned?

- How do gravity and energy together allow us to understand orbits?
  - Change in total energy is needed to change orbit
  - Add enough energy (escape velocity) and object leaves.
- How does gravity cause tides?
  - The Moon's gravity stretches Earth and its oceans.
  - Highest tides occur at new and full moon.
  - Tidal friction causes Earth's rotation to slow, moon to drift farther away, lock into synchronous rotation

Tidal forces -1

- The gravity of body A produces a tidal force on B that distorts its shape slightly so that it becomes elongated along the axis oriented toward A, known as tidal bulges. When B is not yet tidally locked, *the bulges travel over its surface*, with one of the two "high" tidal bulges traveling close to the point where body A is overhead, producing a slightly prolate spheroid elongated along its major axis.
- The material of B exerts resistance to this periodic reshaping caused by the tidal force. Some time is required to reshape B to the gravitational equilibrium shape, by which time the forming bulges have already been carried some distance away from the A–B axis by B's rotation. The points of maximum bulge extension *are displaced from the axis* oriented towards A. If B's rotation period is shorter than its orbital period, the bulges are carried forward of the axis oriented towards A in the direction of rotation, whereas if B's rotation period is longer the bulges lag behind instead. If the tidal bulges of a body are misaligned with the major axis, the tidal forces exert a net torque on that body that twists the body towards the direction of realignment.
- Because the bulges are now displaced from the A–B axis, A's gravitational pull on the mass in them exerts a torque on B. The torque on the A-facing bulge acts to bring B's rotation in line with its orbital period, whereas the "back" bulge, which faces away from A, acts in the opposite sense. However, the bulge on the A-facing side *is closer* to A than the back bulge and so experiences a slightly stronger gravitational force and torque. The net resulting torque from both bulges, then, is always in the direction that acts to synchronize B's rotation with its orbital period, leading eventually to tidal locking.

Tidal forces -2



- If rotational frequency is larger than orbital frequency, a small torque counteracting the rotation arises, eventually locking the frequencies (situation depicted in green)
- The angular momentum of the whole A–B system is conserved so when B slows down and loses rotational angular momentum, its orbital angular momentum is boosted by a similar amount. This results in a raising of B's orbit about A in tandem with its rotational slowdown. For the other case where B starts off rotating too slowly, tidal locking both speeds up its rotation, and lowers its orbit.
- If rotational speed is larger than orbital speed, a small torque counteracting the rotation arises, eventually locking the frequencies (shown in green)
- The tidal locking effect is also experienced by the larger body A, but at a slower rate because B's gravitational effect is weaker due to B's smaller size. For example, Earth's rotation is gradually slowing down because of the Moon, by an amount that becomes noticeable over geological time in some fossils.[1] The process has significantly slowed down the rotation of Earth over time from about 6 hours to the current 24 hours or that Earth's day lengthens by about 15 microseconds every year.[2] For bodies of similar size the effect may be of comparable size for both, and both may become tidally locked to each other on a much shorter timescale. Pluto and its satellite Charon have already reached a state where Charon is only visible from one hemisphere of Pluto and vice versa.