Chapter 4: Making Sense of the Universe: Understanding Motion, Energy, and Gravity

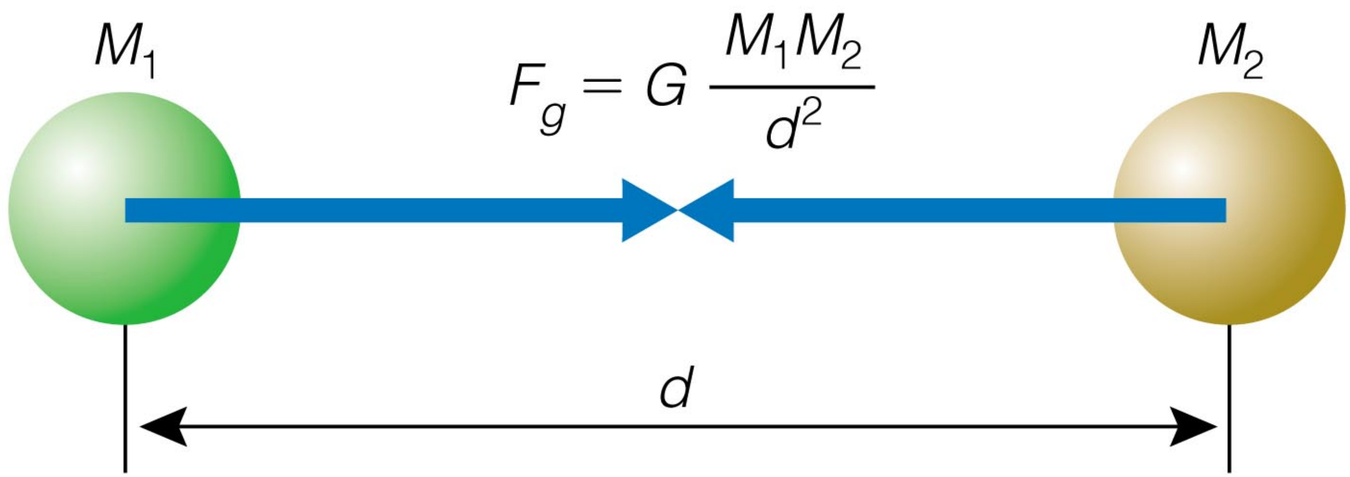
4.4 The Universal Law of Gravitation

- Our goals for learning:
  - **What determines the strength of gravity?**
  - **How does Newton's law of gravity extend Kepler's laws?**

What determines the strength of gravity?

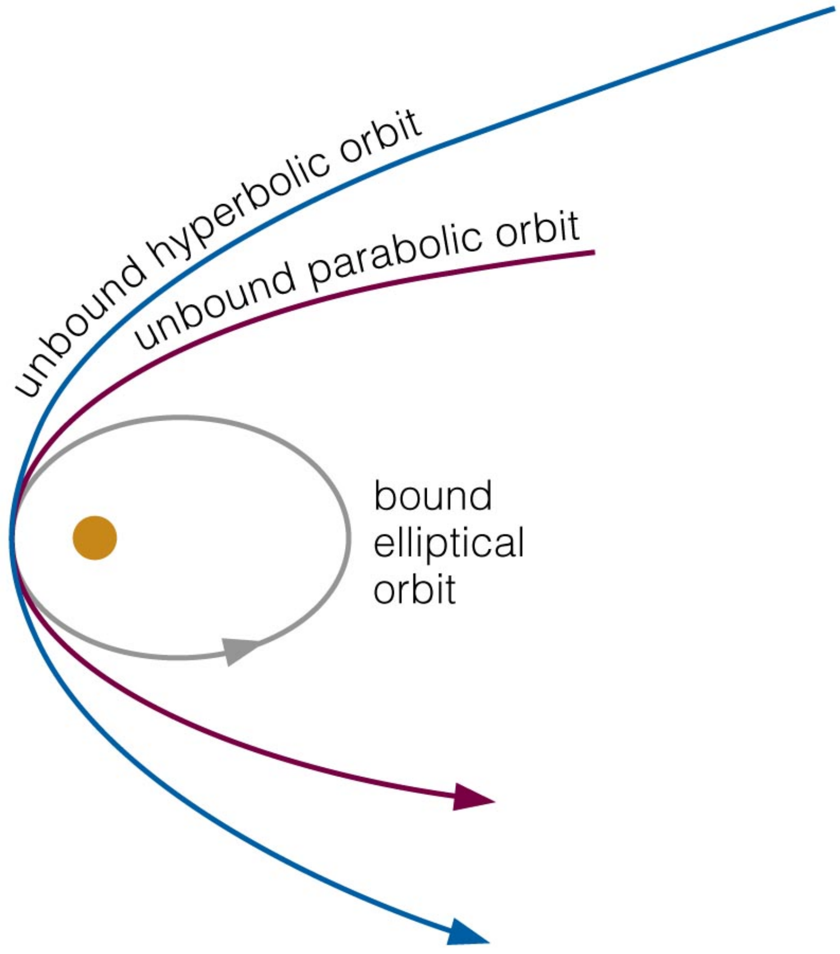
The **universal law of gravitation:**

1. Every mass attracts every other mass – gravitational forces are <u>only</u> attractive
2. Attraction is *directly* proportional to the product of the interacting masses.
3. Attraction is *inversely* proportional to the *square* of the distance between their centers.



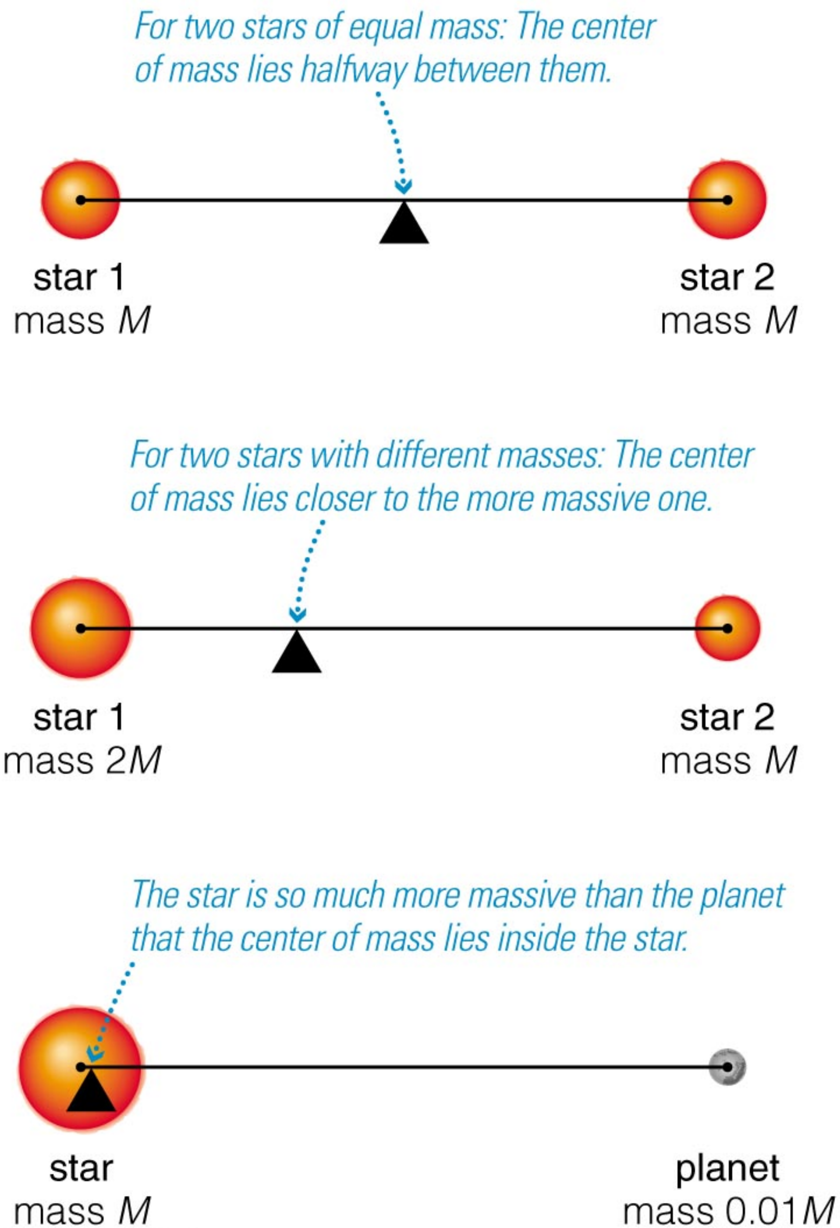
How does Newton's law of gravity extend Kepler's laws?

- Kepler's laws apply to all orbiting objects, not just planets.
- Ellipses are not the only orbital paths. Orbits can be:
  - bounded (ellipses)
  - unbounded
    - parabola
    - hyperbola



a Orbits allowed by the law of gravity.

Center of Mass



- Because of momentum conservation, orbiting objects orbit around their center of mass.

Newton and Kepler's Third Law

- Newton's laws of gravity and motion showed that the relationship between the *orbital period* and *average orbital distance* of a system tells us the *total mass* of the system.

- Examples:
  - Earth's orbital period (1 year) and average distance (1 AU) tell us the Sun's mass.
  - Orbital period and distance of a satellite from Earth tell us Earth's mass.
  - Orbital period and distance of a moon of Jupiter tell us Jupiter's mass.

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
- α = average orbital distance (between centers)
- $(M_1 + M_2)$ = sum of object masses

What have we learned?

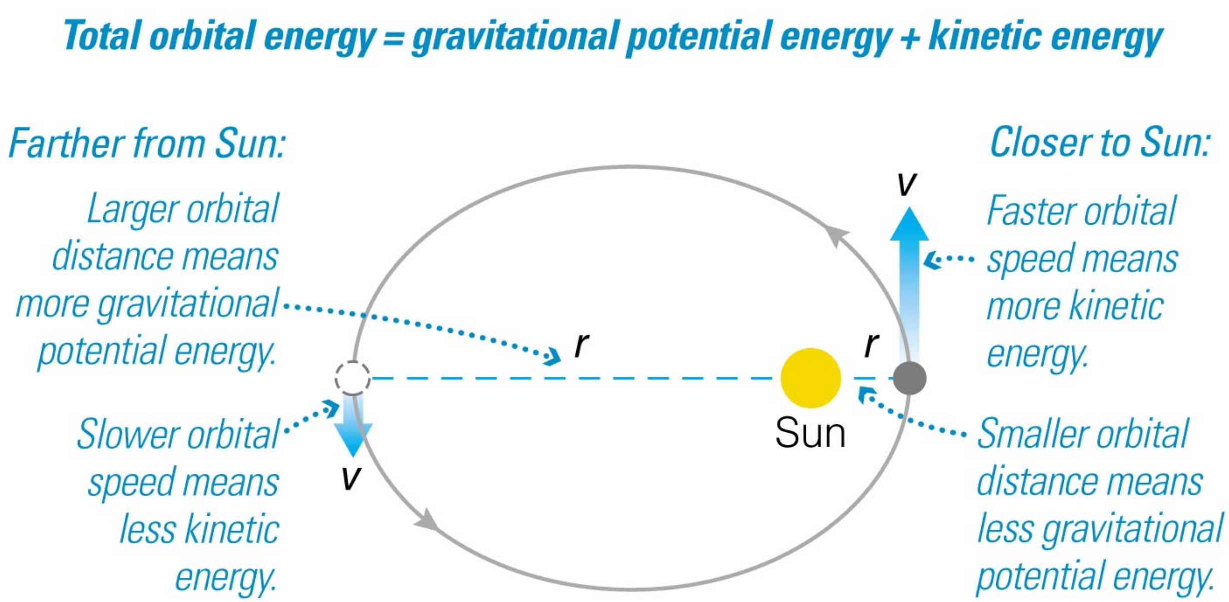
- **What determines the strength of gravity force?**
  - Directly proportional to the *product* of the masses *(M × m)*
  - *Inversely* proportional to the *square* of the separation
- **How does Newton's law of gravity allow us to extend Kepler's laws?**
  - Applies to other objects, not just planets
  - Includes unbound orbit shapes: parabola, hyperbola
  - Can be used to measure mass of orbiting systems

4.5 Orbits, Tides, and the Acceleration of Gravity

- Our goals for learning:
  - **How do gravity and energy together allow us to understand orbits?**
  - **How does gravity cause tides?**
  - **Why do all objects fall at the same rate?**

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

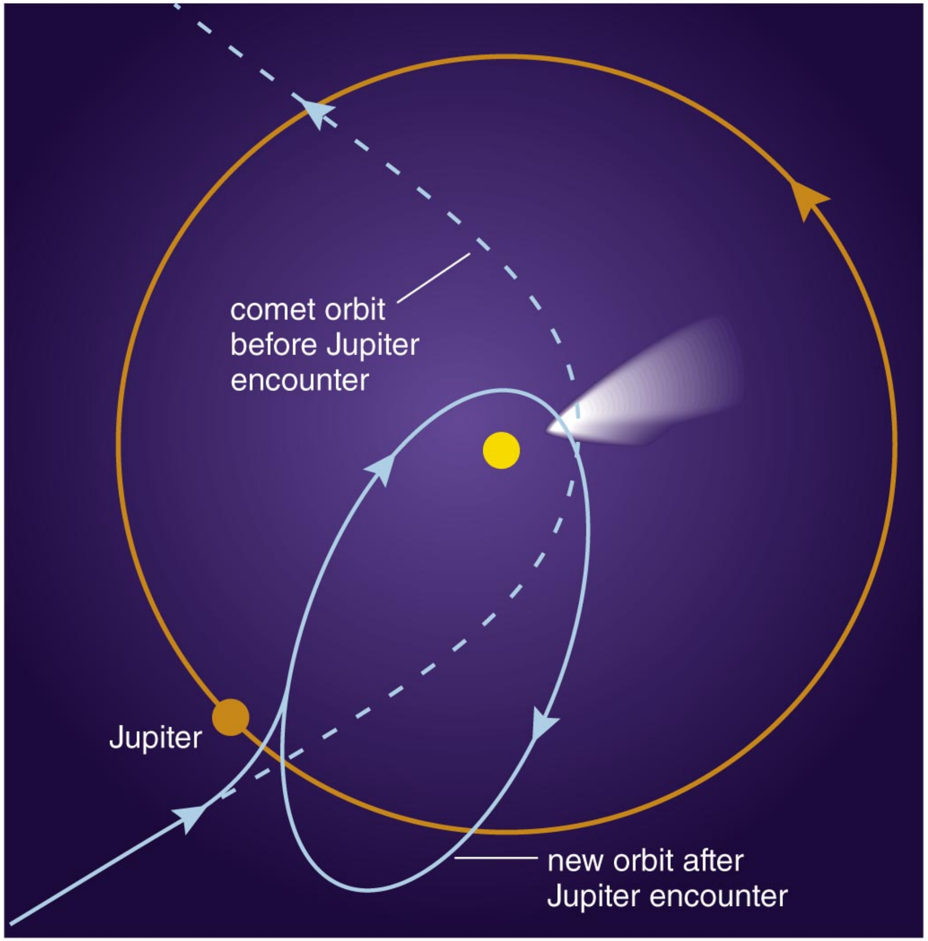
- Total orbital energy (gravitational + kinetic) stays constant if there is no external force.
- Orbits cannot change spontaneously.



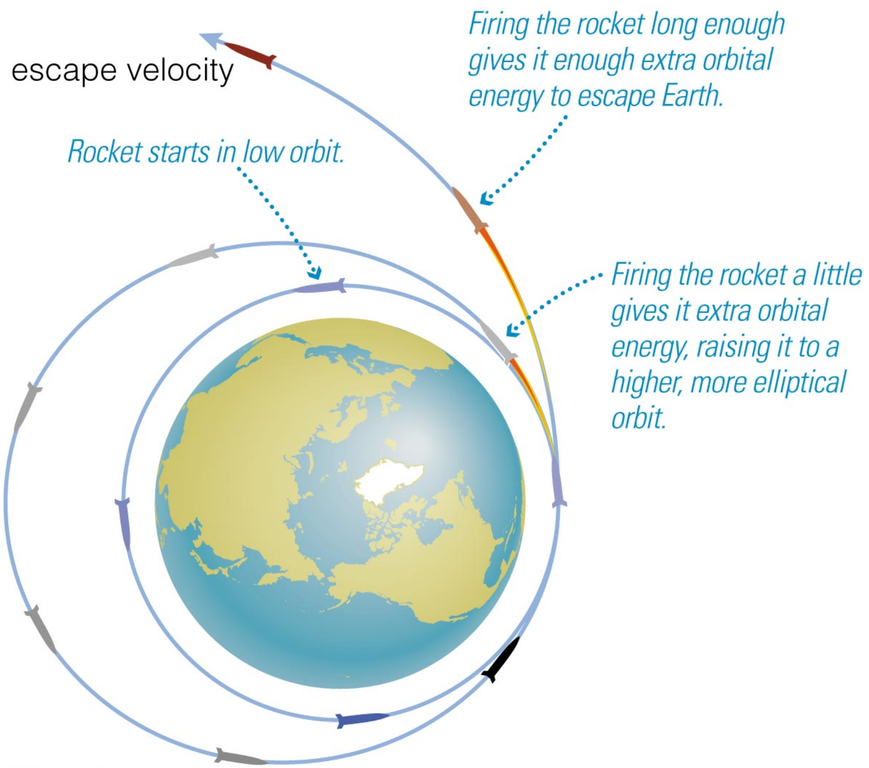
Total orbital energy stays constant.

Changing an Orbit

- So what can make an object gain or lose orbital energy?
- Friction or atmospheric drag
- A gravitational encounter

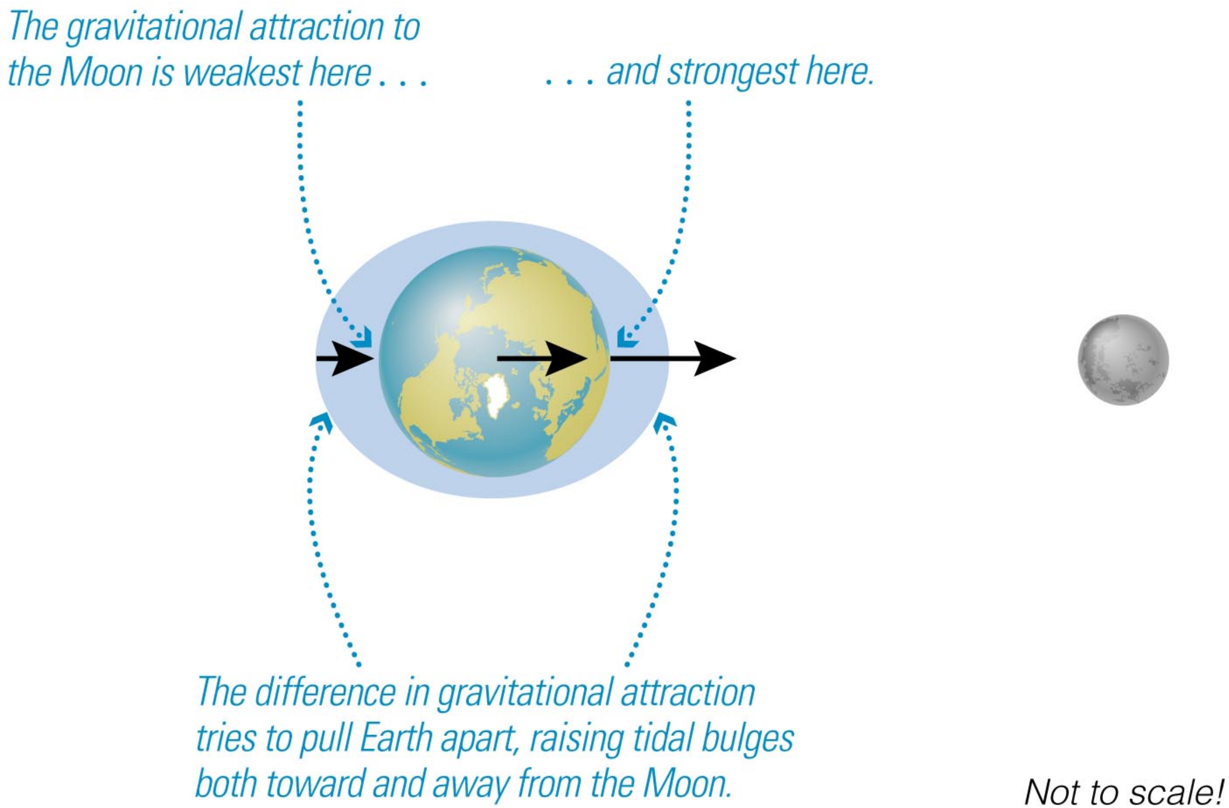


Escape Velocity



- 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 [~25,000 miles per hour])

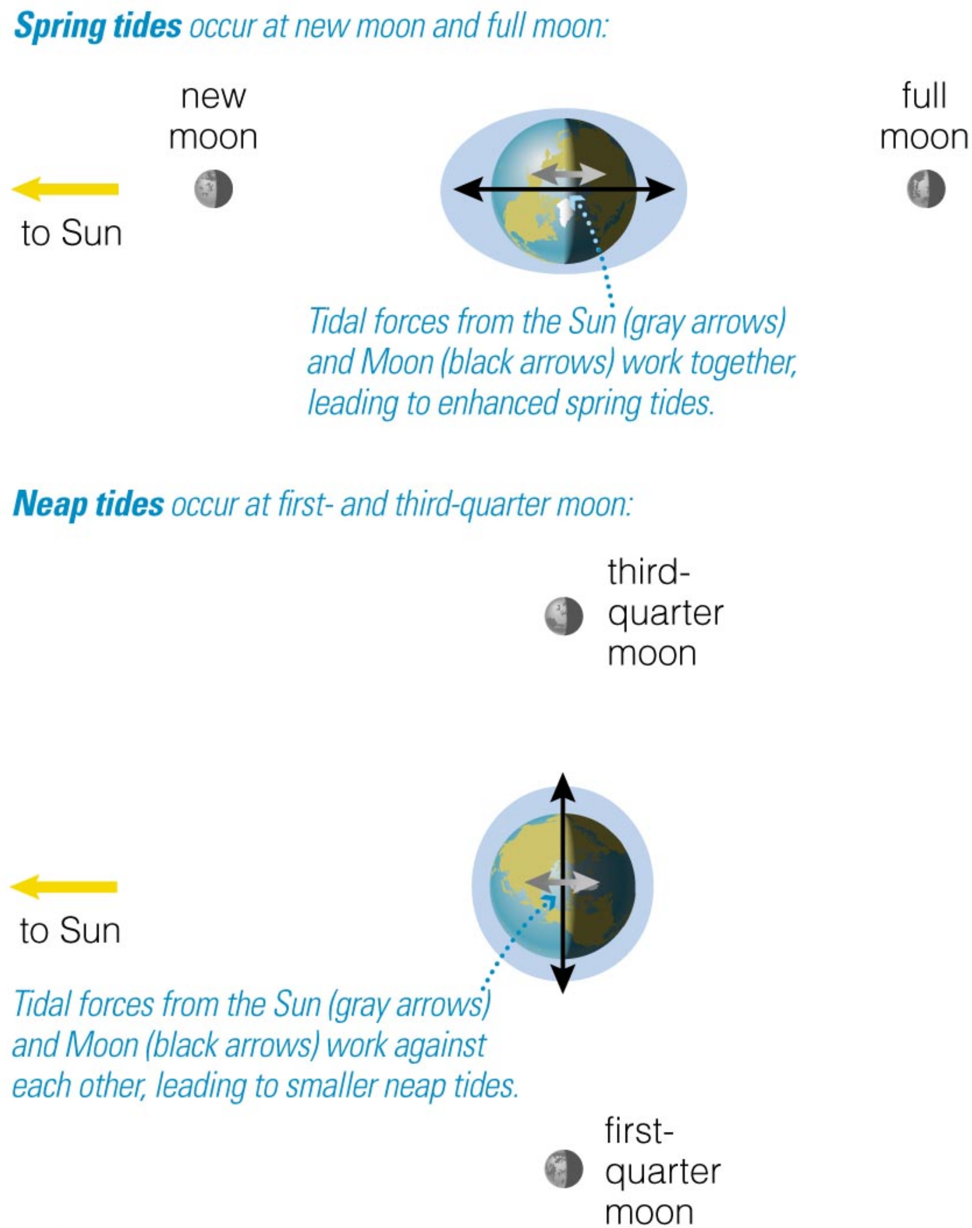
How does gravity cause tides?



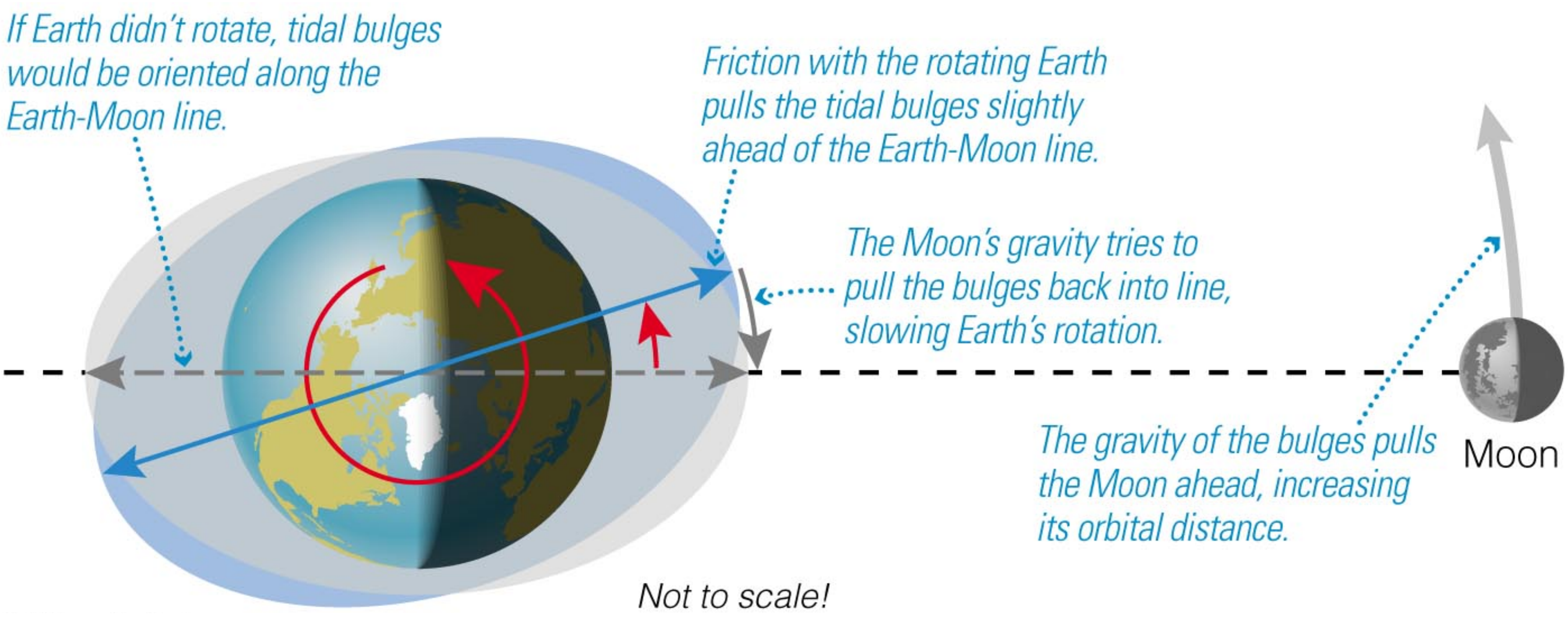
- Moon's gravity pulls harder on near side of Earth than on far side.
- Difference in Moon's gravitational pull stretches Earth.

Tides and Phases

- The Sun also has a small tidal effect on Earth.
- Size of tides thus depends on phase of Moon.



Tidal Friction



- Tidal friction gradually slows Earth's rotation (and makes the Moon get farther from Earth).
- The Moon once orbited faster (or slower); tidal friction caused it to "lock" in synchronous rotation.

Why do all objects fall at the same rate?

$$a_{\text{rock}} = \frac{F_g}{M_{\text{rock}}} \qquad F_g = G\frac{M_{\text{Earth}} M_{\text{rock}}}{R^2_{\text{Earth}}}$$

$$a_{\text{rock}} = G\frac{M_{\text{Earth}} \cancel{M_{\text{rock}}}}{R^2_{\text{Earth}} \cancel{M_{\text{rock}}}} = G\frac{M_{\text{Earth}}}{R^2_{\text{Earth}}}$$

- The gravitational acceleration of an object like a rock does not depend on its mass because M_{rock} in the equation for acceleration cancels M_{rock} in the equation for gravitational force.
- This initially surprising result was fully explained by Einstein, in his general relativity theory.

Proof-of-concept experiment

Credit: TeralabUK @Youtube

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.
- **Why do all objects fall at the same rate?**
  - Mass of object in Newton's second law exactly cancels mass in law of gravitation.