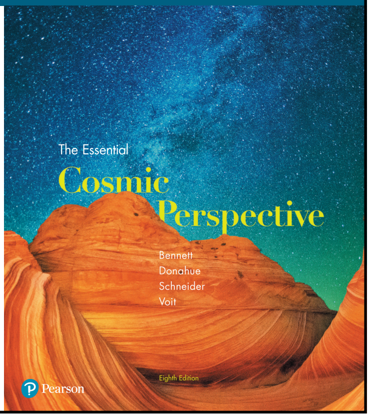
Lecture Outline

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



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4.1 Describing Motion: Examples from Everyday Life

Our goals for learning:

- How do we describe motion?
- How is mass different from weight?

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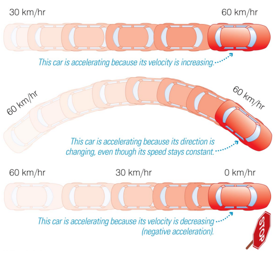
How do we describe motion?



Precise definitions to describe motion:

- **Speed**: Rate at which object moves

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

Example: speed of 10 m/s

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

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

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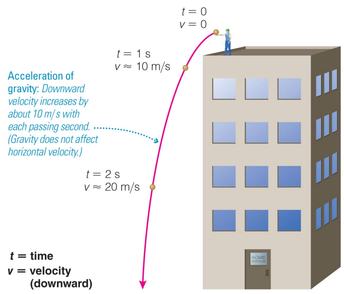
Acceleration of Gravity

- All falling objects accelerate at the same rate (ignoring air resistance).
- On Earth, $g \approx 10\ \text{m/s}^2$: speed increases 10 m/s with each second of falling.



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Acceleration of Gravity (g)

- Galileo showed that g is the *same* for all falling objects, regardless of their mass.

Apollo 15 demonstration

PLAY Feather and Hammer Drop

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Momentum and Force

- **Momentum** = mass x velocity.
- A **net force** changes momentum, which generally means an acceleration (change in velocity).
- **Net force** means the sum of all the forces acting on a body.

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Thought Question

Is a net force acting on each of the following? (Answer yes or no.)

- A car coming to a stop
- A bus speeding up
- An elevator moving up at constant speed
- A bicycle going around a curve
- A moon orbiting Jupiter

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Thought Question

Is a net force acting on each of the following? (Answer yes or no.)

- A car coming to a stop: **Yes**
- A bus speeding up: **Yes**
- An elevator moving up at constant speed: **No**
- A bicycle going around a curve: **Yes**
- A moon orbiting Jupiter: **Yes**

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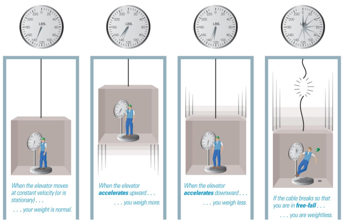
How is mass different from weight?

- **Mass**—the amount of matter in an object
- **Weight**—the *force* that a scale measures



You are weightless in free-fall!

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Thought Question

On the Moon,

A. your weight is the same; your mass is less.
B. your weight is less; your mass is the same.
C. your weight is more; your mass is the same.
D. your weight is more; your mass is less.

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Thought Question

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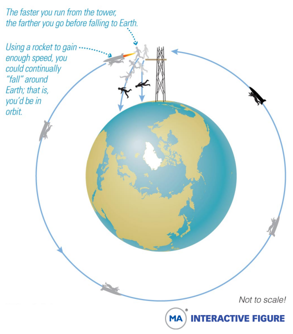
Why are astronauts weightless in space?



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

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4.2 Newton's Laws of Motion

Our goals for learning:

- How did Newton change our view of the universe?
- What are Newton's three laws of motion?

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How did Newton change our view of the universe?

Sir Isaac Newton (1642–1727)

- He realized the same physical laws that operate on Earth also operate in the heavens:
  - ⇒ one *universe*
- He discovered laws of motion and gravity.
- Much more: Experiments with light; first reflecting telescope, calculus…

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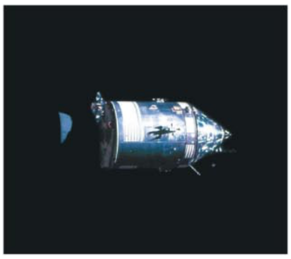
What are Newton's three laws of motion?



Newton's first law of motion: An object moves at constant velocity unless a net force acts to change its speed or direction.

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Newton's second law of motion:
Force = mass x acceleration.

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Newton's third law of motion: For every force, there is always an *equal and opposite* reaction force.

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Thought Question

Is the force that Earth exerts on you larger, smaller, or the same as the force you exert on it?

A. Earth exerts a larger force on you.
B. You exert a larger force on Earth.
C. Earth and you exert equal and opposite forces on each other.

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Thought Question

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Thought Question

A compact car and a large truck have a head-on collision. Are the following **true** or **false**?

- The *force* of the car on the truck is equal and opposite to the force of the truck on the car.
- The *momentum* transferred from the truck to the car is equal and opposite to the momentum transferred from the car to the truck.
- The *change of velocity* of the car is the same as the change of velocity of the truck.

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Thought Question

A compact car and a large truck have a head-on collision. Are the following **true** or **false**?

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- The *momentum* transferred from the truck to the car is equal and opposite to the momentum transferred from the car to the truck. **T**
- The *change of velocity* of the car is the same as the change of velocity of the truck. **F**

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4.3 Conservation Laws in Astronomy

Our goals for learning:

- What keeps a planet rotating and orbiting the Sun?
- Where do objects get their energy?

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Conservation of Momentum

- The total momentum of interacting objects cannot change unless an external force is acting on them.
- Interacting objects exchange momentum through equal and opposite forces.

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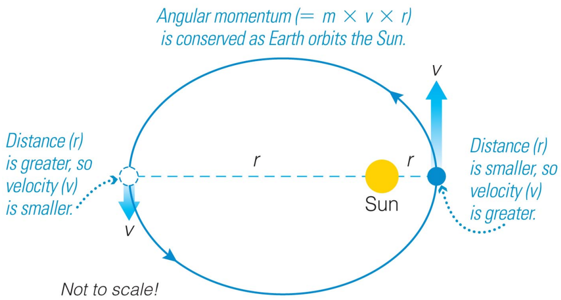
What keeps a planet rotating and orbiting the Sun?



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Conservation of Angular Momentum

angular momentum = mass x velocity x radius

- The angular momentum of an object cannot change unless an external twisting force (torque) is acting on it.
- Earth experiences no twisting force as it orbits the Sun, so its rotation and orbit will continue indefinitely.

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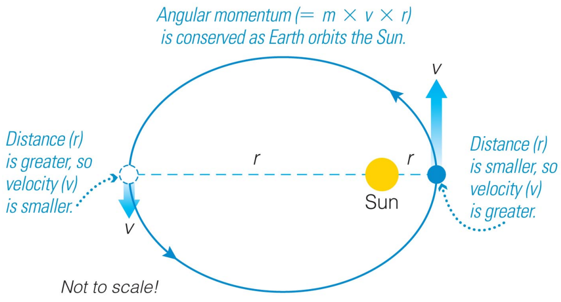
Orbital Angular Momentum



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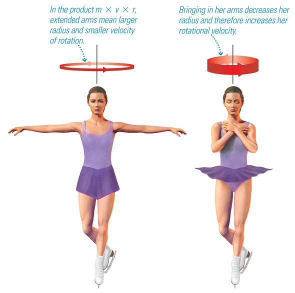
Angular momentum conservation also explains why objects rotate faster as they shrink in radius – rotational angular momentum.



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Where do objects get their energy?

- Energy makes matter move.
- Energy is conserved, but it can…
  - transfer from one object to another.
  - change in form.

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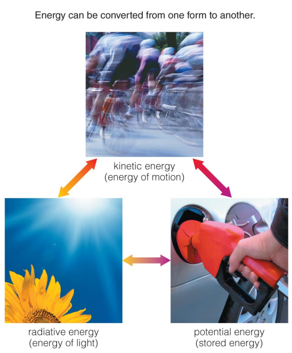
Basic Types of Energy

- Kinetic (motion)
- Radiative (light)
- Stored or potential

Energy can change type but cannot be destroyed.



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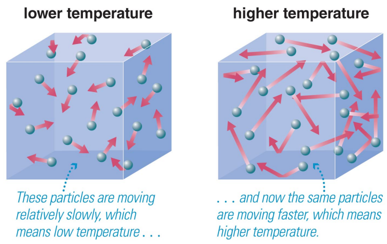
Thermal Energy

The collective kinetic energy of many particles (for example, in a rock, in air, in water)

Thermal energy is related to temperature but it is NOT the same. **Temperature** is the *average* kinetic energy of the many particles in a substance.



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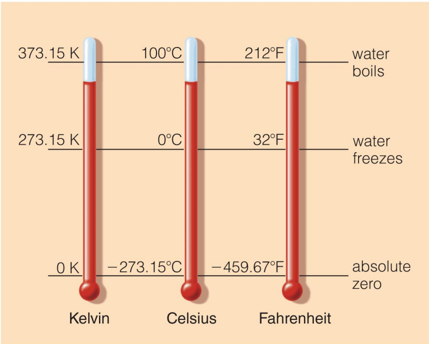
Temperature Scales



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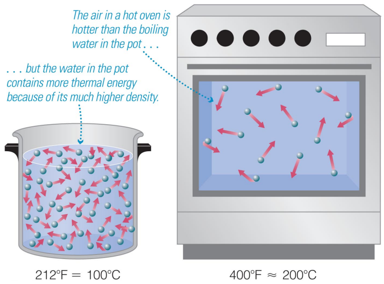
Thermal energy is a measure of the total kinetic energy of all the particles in a substance. It therefore depends on both *temperature* AND *density*.

Example:



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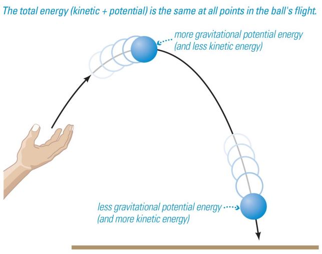
Gravitational Potential Energy

- On Earth, it depends on…
  - an object's mass (m).
  - the strength of gravity (g).
  - the distance an object could potentially fall.



a The ball has more gravitational potential energy when it is high up than when it is near the ground.

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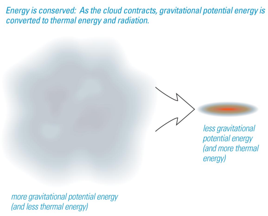
Gravitational Potential Energy

- In space, an object or gas cloud has more gravitational energy when it is spread out than when it contracts.

⇒ A contracting cloud converts gravitational potential energy to thermal energy.



b A cloud of interstellar gas can contract because of its own gravity. It has more gravitational potential energy when it is spread out than when it shrinks in size.

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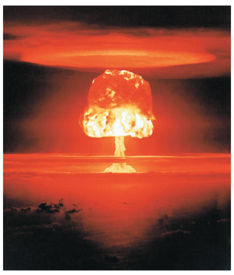
Mass-Energy

Mass itself is a form of potential energy.

$$E = mc^2$$

- A small amount of mass can release a great deal of energy.
- Concentrated energy can spontaneously turn into particles (for example, in particle accelerators).



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Conservation of Energy

- Energy can be neither created nor destroyed.
- It can change form or be exchanged between objects.
- The total energy content of any isolated system must always stay the same.

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4.4 The Force of Gravity

Our goals for learning:

- What determines the strength of gravity?
- How does Newton's law of gravity extend Kepler's laws?
- How do gravity and energy together allow us to understand orbits?
- How does gravity cause tides?

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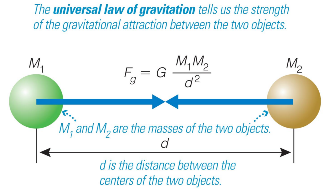
What determines the strength of gravity?

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.



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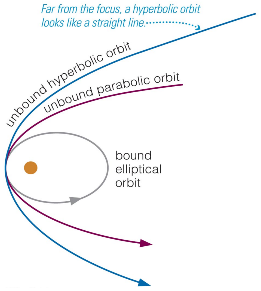
How does Newton's law of gravity extend Kepler's laws?

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



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- Newton generalized Kepler's third law:

Newton's version of Kepler's third law:

IF a small object orbits a larger one and you measure the orbiting object's *orbital period* AND *average orbital distance*

THEN you can calculate the mass of the larger object.

Examples:

- Calculate the mass of the Sun from Earth's orbital period (1 year) and average distance (1 AU).
- Calculate the mass of Earth from orbital period and distance of a satellite.
- Calculate the mass of Jupiter from orbital period and distance of one of its moons.

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Newton's version of Kepler's third law

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

p = orbital period

a = average orbital distance (between centers)

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

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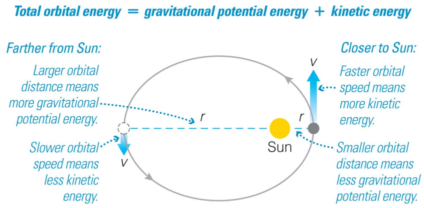
How do gravity and energy together allow us to understand orbits?

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



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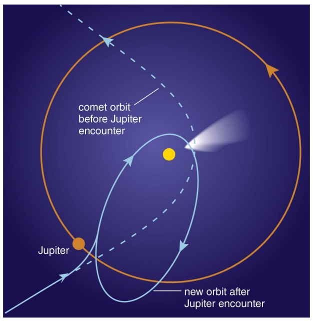
Changing an Orbit

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

- Friction or atmospheric drag
- A gravitational encounter



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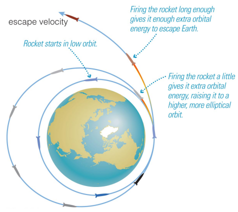
Escape Velocity

- 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).



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PLAY Relationship Between Cannonball's Mass and Orbital Trajectory

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Escape and orbital velocities don't depend on the mass of the cannonball.

PLAY Relationship Between Cannonball's Mass and Orbital Trajectory

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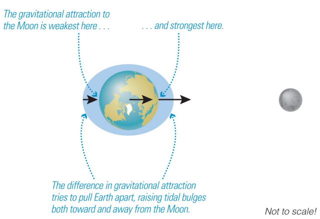
How does gravity cause tides?



- 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.

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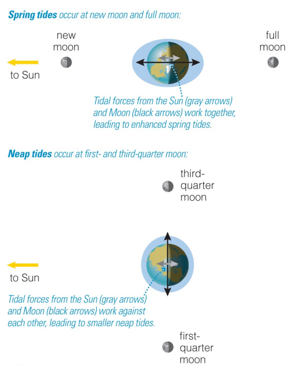
Tides and Phases

Size of tides depends on the phase of the Moon.



PLAY Tides

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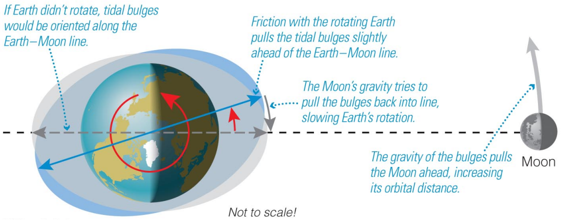
Why does the moon always show us the same face?



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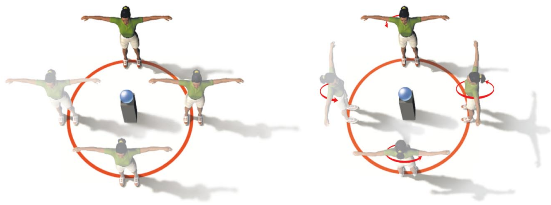
Tidal Friction



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

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