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

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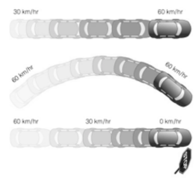
How do we describe motion?



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 (m/s^2)

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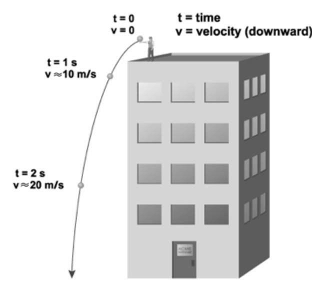
The Acceleration of Gravity

- All falling objects accelerate at the same rate (not counting friction of air resistance).
- On Earth, $g \approx 10$ m/s^2: speed increases 10 m/s with each second of falling.
- Galileo showed that g is the *same* for all falling objects, regardless of their mass.



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Momentum and Force

- Momentum = mass × velocity
- A **net force** changes momentum, which generally means an acceleration
- Rotational momentum of a spinning or orbiting object is known as **angular momentum**

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Thought Question: Is there a net force? Y/N

1. A car coming to a stop.
2. A bus speeding up.
3. An elevator moving up at constant speed.
4. A bicycle going around a curve.
5. A moon orbiting Jupiter.

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Thought Question: Is there a net force? Y/N

1. A car coming to a stop. Y
2. A bus speeding up. Y
3. An elevator moving at constant speed. N
4. A bicycle going around a curve. Y
5. A moon orbiting Jupiter. Y

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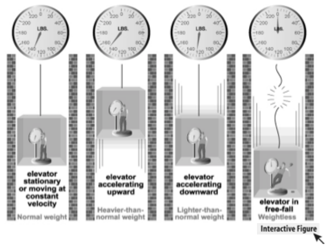
How is mass different from weight?

- **Mass** – the amount of matter in an object
- **Weight** – the *force* that acts upon an object



You are weightless in free-fall!

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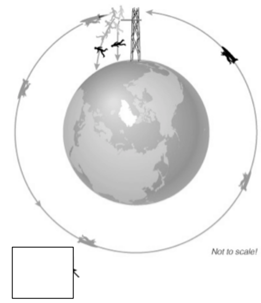
Why are astronauts weightless in space?



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

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How did Newton change our view of the universe?

Sir Isaac Newton (1642-1727)

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

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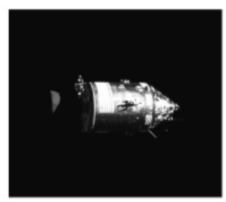
What are Newton's three laws of motion?



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 × 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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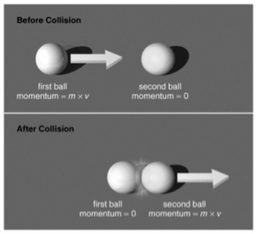
Conservation of Momentum



- 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 … example: pool balls

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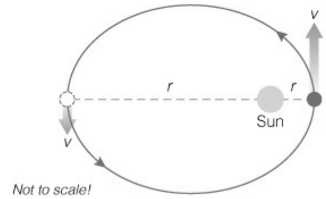
What keeps a planet rotating and orbiting the Sun?



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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 torque as it orbits the Sun, so its rotation and orbit will continue indefinitely

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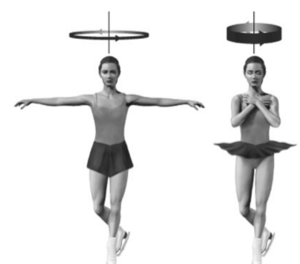
Angular momentum conservation also explains why objects rotate faster as they shrink in radius:



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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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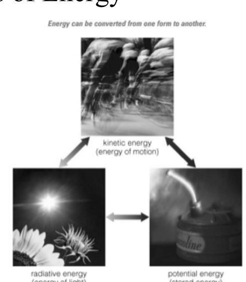
Basic Types of Energy

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

Energy can change type but cannot be destroyed.



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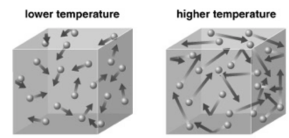
Conservation of Energy

- Energy can be neither created nor destroyed.
- It can change form or be exchanged between objects.
- The total energy content of the Universe was determined in the Big Bang and remains the same today.

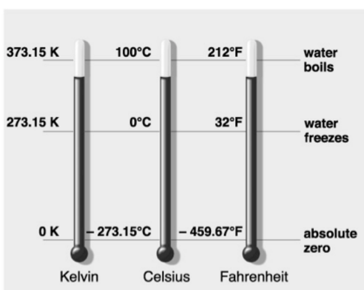
Thermal Energy:

the collective kinetic energy of many particles

- Thermal energy is a measure of the total kinetic energy of all the particles in a substance.
- It depends on *temperature* AND *density*
- **Temperature** is the *average* kinetic energy of the many particles in a substance.



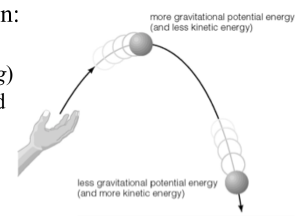
Temperature Scales



No thermal motion

Gravitational Potential Energy

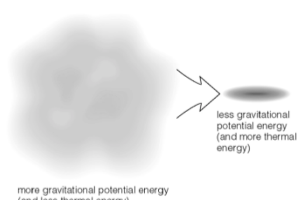
- On Earth, depends on:
  - object's mass (m)
  - strength of gravity (*g*)
  - distance object could potentially fall



Gravitational Potential Energy

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

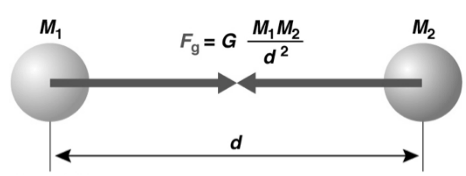
⇒A contracting cloud converts gravitational potential energy to thermal energy.



What determines the strength of gravity?

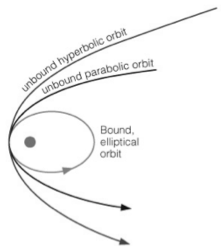
The **Universal Law of Gravitation:**

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.



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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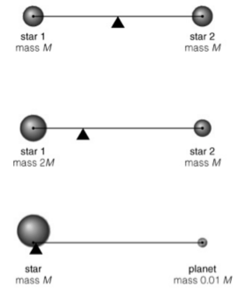
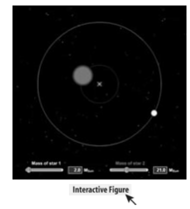
Center of Mass



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



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Newton and Kepler's Third Law

His 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 moon of Jupiter tell us Jupiter's mass.

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Newton's Version of Kepler's Third Law

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

p = orbital period

a = average orbital distance (between centers)

$M_1 + M_2$ = sum of object masses

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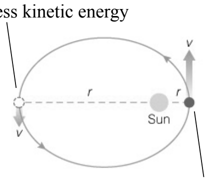
How do gravity and energy together allow us to understand orbits?

More gravitational energy;
Less kinetic energy



Less gravitational energy;
More kinetic energy

Total orbital energy stays constant

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

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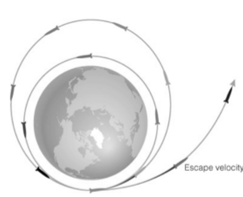
Escape Velocity



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

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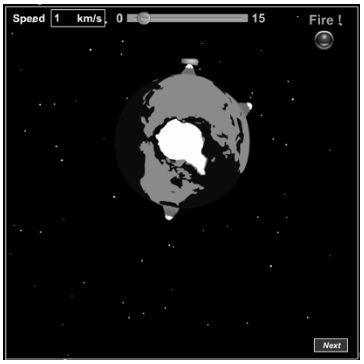

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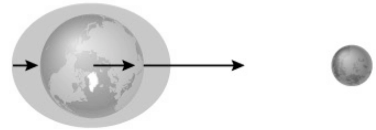
How does gravity cause tides?



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

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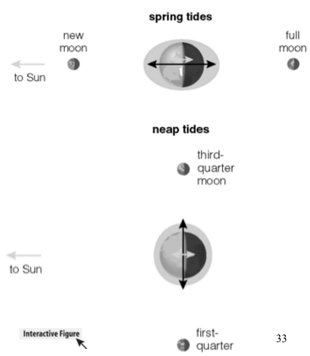
Tides and Phases

Size of tides depends on phase of Moon, due to tides from Moon and Sun



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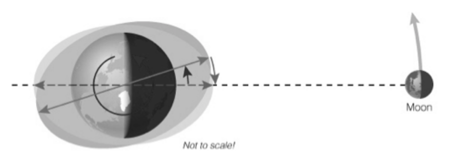
Tidal Friction



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

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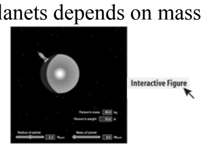
Why do all objects fall at the same rate?

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

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

- The gravitational acceleration of mass M_{rock} does not depend on its mass because M_{rock} cancels out
- Weight on other planets depends on mass and radius of the planet



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Next time:

- Chapter 5:
  Light, spectroscopy
  please read pages 140 – 160 in text.