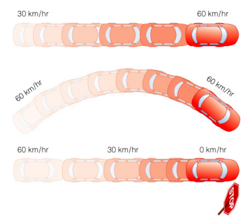
Chapter 4
Making Sense of the Universe:
Understanding Motion, Energy, and Gravity

How do we describe motion?



Precise definitions to describe motion:

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

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

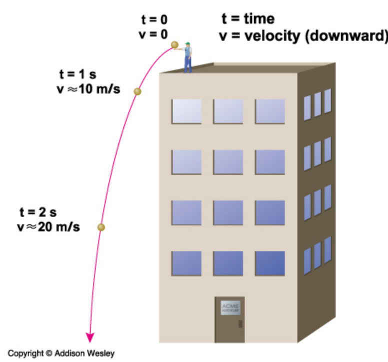
  example: speed of 10 m/s

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

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

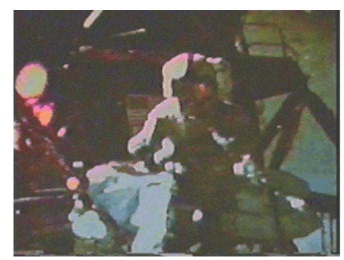
The Acceleration of Gravity

- 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.



The Acceleration of Gravity (*g*)

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



Apollo 15 demonstration

Momentum and Force

- Momentum = mass × velocity
- A **force** changes momentum, which generally means an acceleration (change in velocity)

  Force = mass × acceration
- Rotational momentum of a spinning or orbiting object is known as **angular momentum** = mass × velocity × radius

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

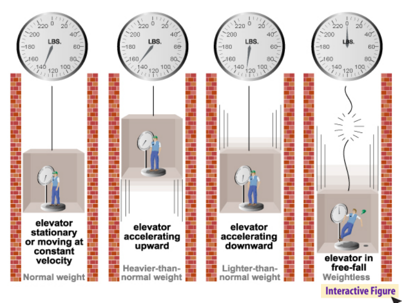
1. A car coming to a stop.
2. A bus speeding up.
3. An elevator moving up at constant speed.
4. A bicycle going around a curve.
5. A moon orbiting Jupiter.

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

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!

Thought Question
On the Moon:

A. My weight is the same, my mass is less.
B. My weight is less, my mass is the same.
C. My weight is more, my mass is the same.
D. My weight is more, my mass is less.

Thought Question
On the Moon:

A. My weight is the same, my mass is less.
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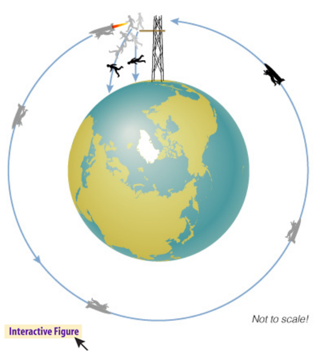
Why are astronauts weightless in space?



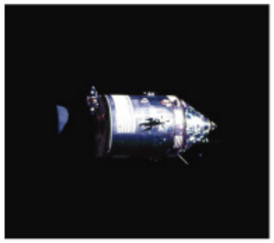
- There *is* gravity in space
- Weightlessness is due to a constant state of free-fall

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…

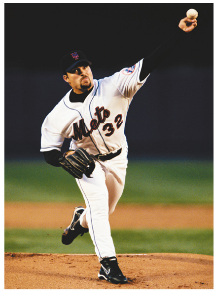
What are Newton's three laws of motion?



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

Newton's second law of motion

Force = mass × acceleration



Newton's third law of motion:

For every force, there is always an *equal and opposite* reaction force.

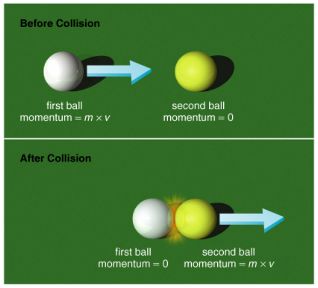
Thought Question:
Is the force the Earth exerts on you larger, smaller, or the same as the force you exert on it?

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

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

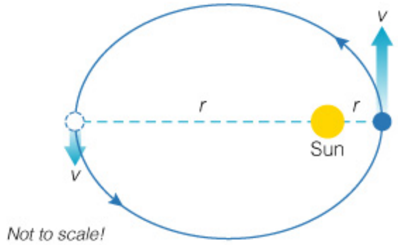
A. Earth exerts a larger force on you.
B. I exert a larger force on Earth.
C. **Earth and I exert equal and opposite forces on each other.**

Conservation of Momentum



- The total momentum of interacting objects cannot change unless an external force is acting on them

What keeps a planet rotating and orbiting the Sun?



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

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

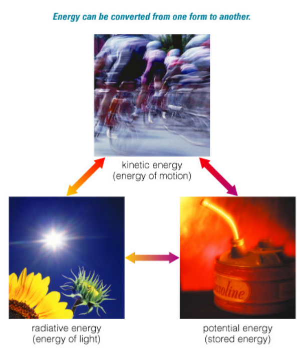
Where do objects get their energy?

- Energy makes matter move.
- Energy is conserved, but it can:
  - Transfer from one object to another
  - Change in form

Basic Types of Energy

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

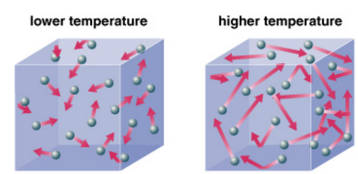
Energy can change type but cannot be destroyed.



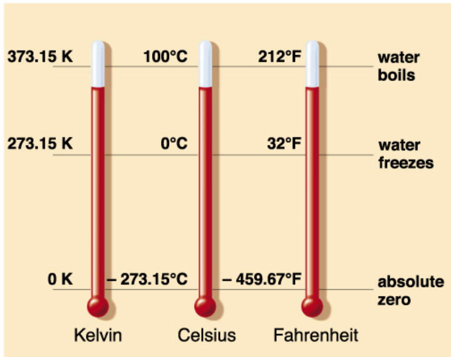
Thermal Energy:

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

Temperature is a measure of the *average* kinetic energy of the many particles in a substance.

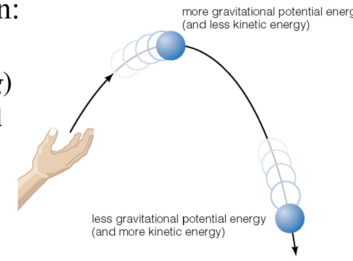


Temperature Scales



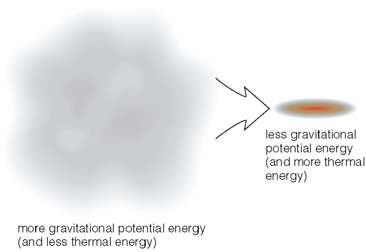
Gravitational Potential Energy

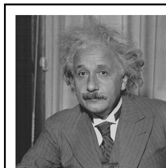
- On Earth, depends on:
  - object's mass (m)
  - strength of gravity (*g*)
  - distance object could potentially fall



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.



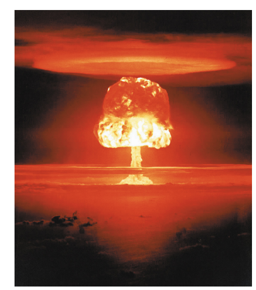


Mass-Energy

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)



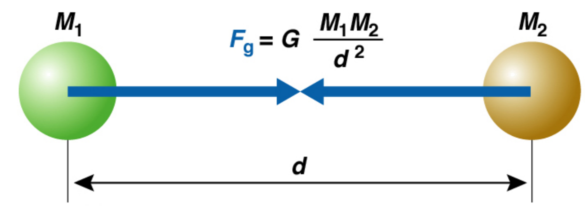
Conservation of Energy

- 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.

What determines the strength of gravity?

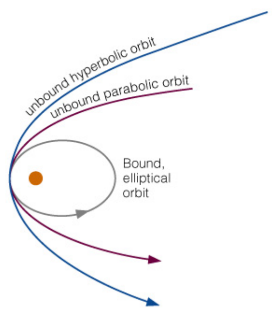
The **Universal Law of Gravitation:**

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.

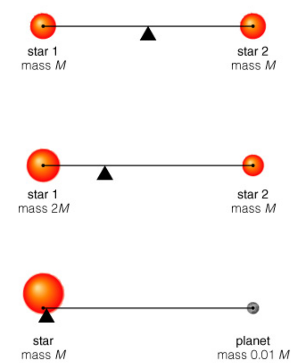


How does Newton's law of gravity extend Kepler's laws?

- 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



Center of Mass



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

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 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

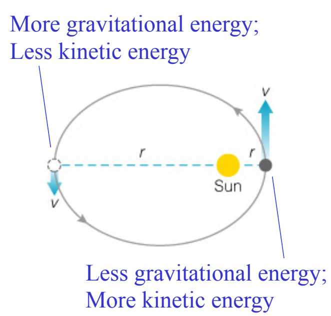
$$p^2 = \frac{a^3}{(M_1 + M_2)} \qquad \text{OR} \qquad M_1 + M_2 = \frac{a^3}{p^2}$$

p = orbital period (years)

a=average orbital distance (AU)

$(M_1 + M_2)$ = sum of object masses (M_{Sun})

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



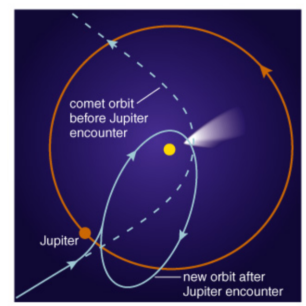
Total orbital energy stays constant

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

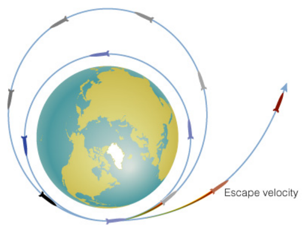
Changing an Orbit

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

- Friction or atmospheric drag
- A gravitational encounter.

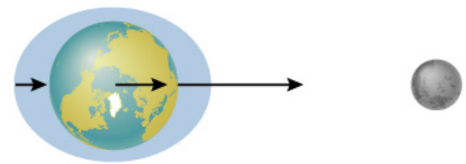


Escape Velocity



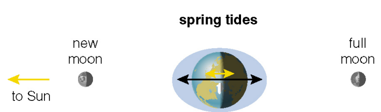
- If an object gains enough orbital energy, it may escape (change from a bound to unbound orbit)
- **Escape velocity** from Earth ≈ 11 km/s from sea level (about 40,000 km/hr)

How does gravity cause tides?

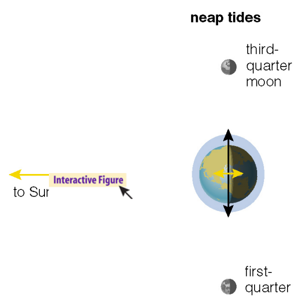


- Moon's gravity pulls harder on near side of Earth than on far side
- Difference in Moon's gravitational pull stretches Earth
- How often do we have tides? **Twice a day**

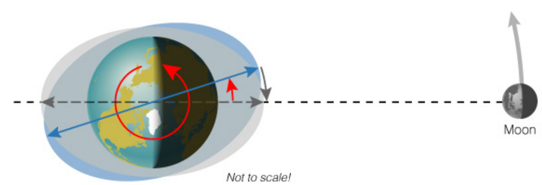
Tides and Phases



Size of tides depends on phase of Moon



Tidal Friction



- Tidal friction gradually slows Earth rotation (and makes Moon get farther from Earth).
- Moon once orbited faster; tidal friction caused it to "lock" in synchronous rotation.
- Eventually, the Earth's rotation will lock into the Moon's orbit/rotation periods.