Lecture 3: The Laws of Motion and Universal Gravitation

Astronomy 2020, Prof. Tom Megeath

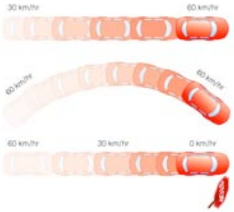
To be ignorant of motion is to be ignorant of nature

-Aristotle

Overview of Today's Lecture

1. Newton's three laws of motions
2. Newton's Universal Law of Gravity
3. Conservation laws:
   I. Conservation of momentum
   II. Conservation of angular momentum
   III. Conservation of energy

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

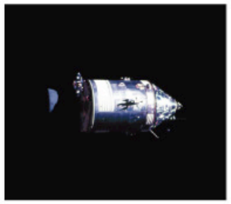
• **Acceleration**: Any change in velocity
units of speed/time (m/s^2)

How did Newton change our view of the universe?

Sir Isaac Newton (1642-1727)

- Realized the same physical laws that operate on Earth extended to the Moon and beyond.
- Discovered laws of motion and gravity - published in Principia in 1687 at the urging of Edmond Halley.
- Much more: Experiments with light; first reflecting telescope, calculus…
- Held Lucasian Chair of Mathematics at Cambridge University, the Chair now occupied by Stephen Hawking

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.

This is also called the ***law of inertia***

Imagine a spacecraft moving through space.

What happens to its speed, velocity and acceleration if the rocket engine is off?

How do you slow down a rocket ship?

How can you explain the expansion of the universe?

Newton's second law of motion

Force = mass × acceleration

No force means no acceleration, and an object continues on with the same speed.

What is mass?

If the force is 1 g, what is the acceleration?

How do you measure mass?

Newton's third law of motion:

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

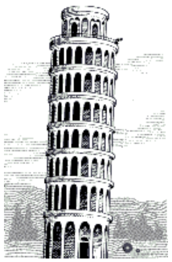
What happens when shooting a gun on roller skates?

What happens to the Earth when something falls?

How does this apply to the space shuttle?

If a SUV collides with a small compact car, which exerts the greatest force on the other?

Acceleration by Gravity



Leaning tower of Pisa

Distance falling by an object is:

$D = 1/2\ g\ t^2$

Where $g = 9.8$ meter/second^2

Thus if you drop any object:

In one second it will fall 4.9 meters

In two seconds it will fall 19.6 meters

Independent of Mass

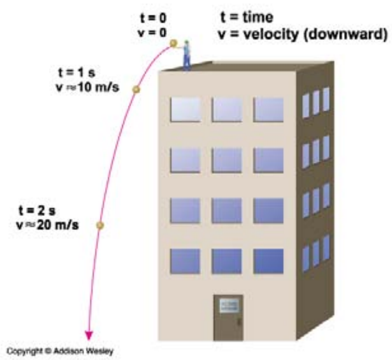
Attributed to Galileo (17th century), but early forms of this law go back to the 14th century.

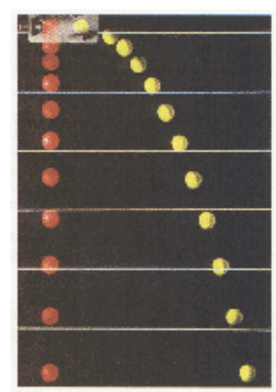
Hammer and Feather on the Moon
Apollo 15, Astronaut David Scott

http://www.hq.nasa.gov/alsj/a15/video15.html#landing

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's Intuition

Motion can be separated into two components, a horizontal component and a vertical component.

The vertical component is accelerated by gravity at the same rate, independent of the horizonal motion.

http://faraday.physics.utoronto.ca/GeneralInterest/Harrison/Flash/ClassMechanics/TwoBallsGravity/TwoBallsGravity.html

http://faraday.physics.utoronto.ca/PVB/Harrison/Flash/ClassMechanics/Relativity/Relativity.html

http://faraday.physics.utoronto.ca/GeneralInterest/Harrison/Flash/ClassMechanics/Projectile/Projectile.html

http://faraday.physics.utoronto.ca/GeneralInterest/Harrison/Flash/ClassMechanics/MonkeyHunter/MonkeyHunter.html

Newton's Insight

A big question in the 18th century is what physics governs the orbits of the planets around the Sun.

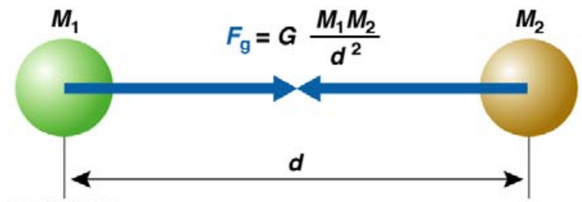
Newton's insight is that the gravity on Earth should continue to extend into space.

Came up with a Universal Law of Gravitation which could explain gravity on Earth and the motions of the planets.

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.



Question: does this predict that acceleration is independent of mass?

Mass and Weight

Mass is constant, but weight depends on the force applied.

$F = G\, m_{student} M_{earth} / R_{earth}^2$

F^{earth} = m (kg) x 6.67 x 10^{-11} x 5.97 x 10^{24} kg / (6378000 meter)^2

F^{moon} = m (kg) x 6.67 x 10^{-11} x 7.36 x 10^{22} kg / (1738000 meter)^2

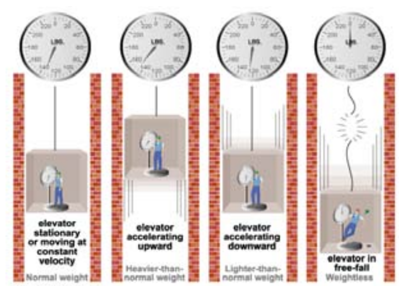
$F^{itokawa}$ = m (kg) x 6.68 x 10^{-11} x 3.51 x 10^{10} kg / (357 meter)^2

Asteroid Itikawa

weight of a 68 kg mass
150 lb weight on earth
24 lb weight on the Moon
0.0003 lb weight on Itokawa

How is mass different from weight?

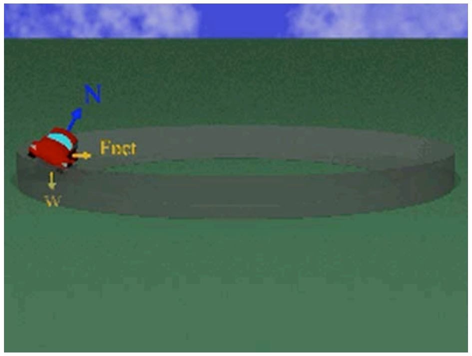
- **Mass** – the amount of matter in an object
- **Weight** – the *force* that acts upon an object



Does your mass depend on whether the elevator is moving up or down?

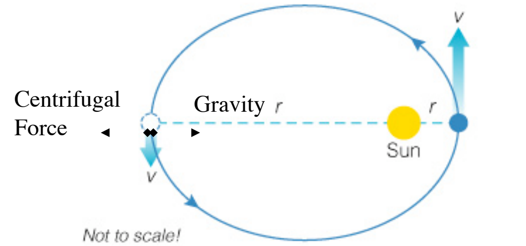
You are weightless in free-fall!

Centrifugal Force: F = Mass x Velocity^2 / radius



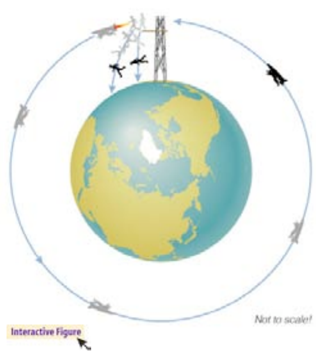
http://rt210.sl.psu.edu/phys_anim/PA.html

What keeps a planet rotating and orbiting the Sun?



Balance between Centrifugal Force and Gravity

Why are astronauts weightless in space?



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

Action at a Distance

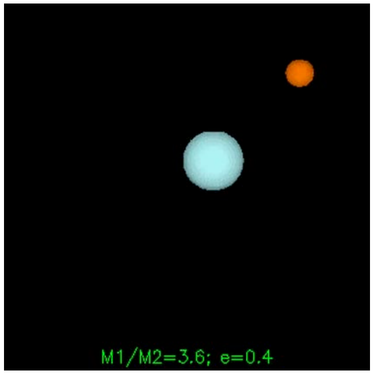
Every body with mass exerts a gravitational force on every other body with mass.

The reach of gravity is infinite, although the strength of gravity diminishes rapidly with distance.

Binary Stars: Two Stars Bound by Gravity

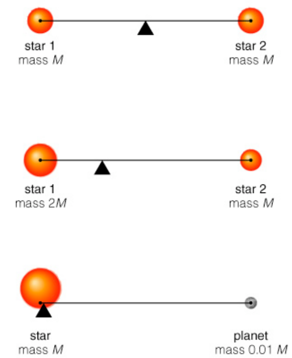
One third of the stars in the sky are double.

Simulation of a F0V and M0V star with a mass ratio of 3.6



http://www.astronomy.ohio-state.edu/~pogge/Ast162/Movies/

Center of Mass

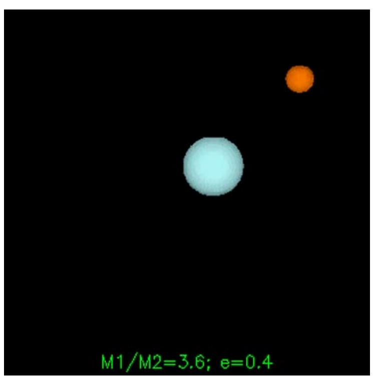


- Because of momentum conservation, orbiting objects orbit around their center of mass

Double Stars:

One third of the stars in the sky are double.

Simulation of a FOV and MOV stars with a mass ratio of 3.6

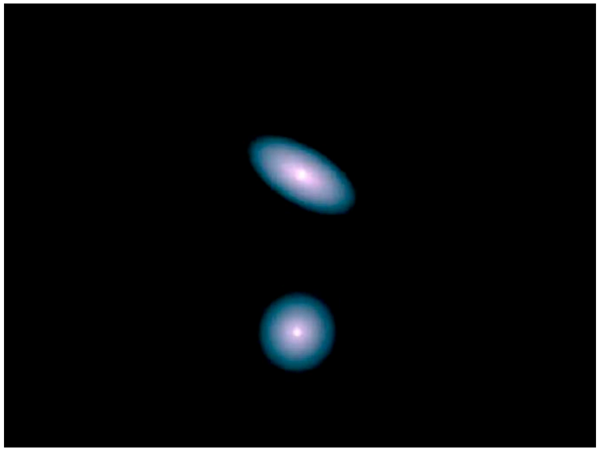


http://www.astronomy.ohio-state.edu/~pogge/Ast162/Movies/

The Laws of Motion and Gravity are Universal

- The same laws are valid throughout the universe
- The laws of motions are an essential part of our technological society. The design of spaceships, airplanes, and even cars and skyscrapers, based on Newton's laws.
- Using these laws, Astronomers can understand how structures evolve in space using calculations and computer simulations.
- Newton's laws are only an approximation, and break down in areas with strong gravitational fields or very high velocities near the speed of light (Einstein's Theory of Relativity needed)

Interacting Galaxies



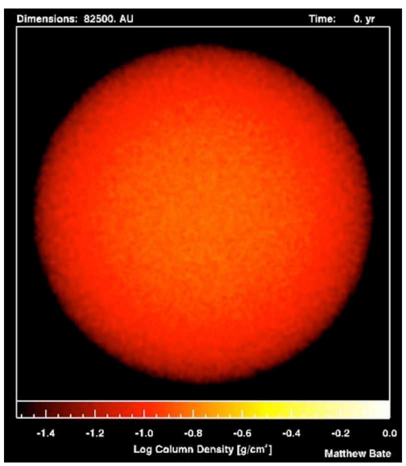
http://www.cita.utoronto.ca/~dubinski/tflops/

Gravitational Collapse of Interstellar Dark Clouds

Stars form in dark, cold clouds many light years across. Although the clouds are massive, with many times the mass of our Sun, the density of gas is very, very low.

Yet the individual gas particles will exert forces on each other.

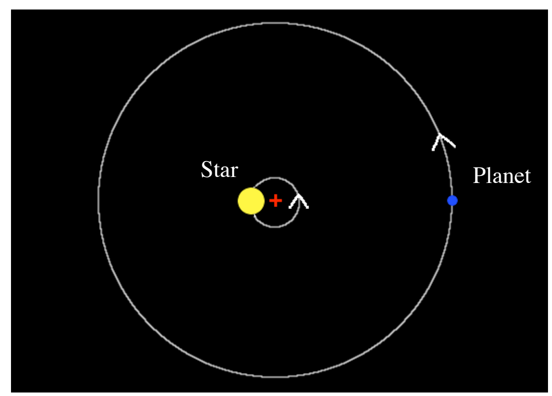
Gravity and Star Formation in Interstellar Clouds



Computer model of how stars may form in a turbulent dark cloud (dark cloud made to glow orange with computer "magic").

Newtonian laws of motion and Gravity ultimately lead to the collapse of the cloud into stars.

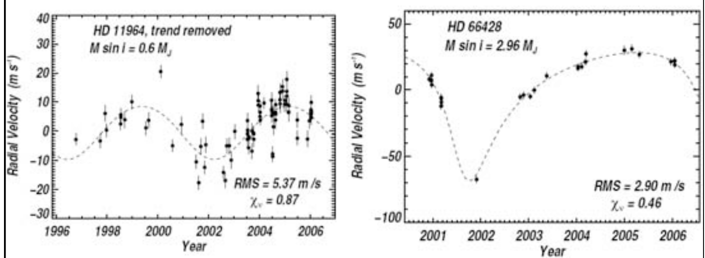
Reflex Motion and the Search for Extrasolar Planets



Every Actionhas an Equal and Opposite Reaction

Wikipedia

Newtonian Gravity Gives us the Masses of Planets in Distant Solar Systems



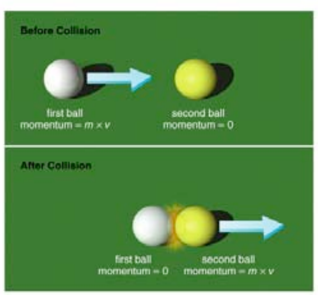
The planets are not directly detected. There presence is inferred from their gravitational tug on the central star.

Conservation Laws

The motions of objects can also be understood through the conservation of momentum and energy.

These are tools that physicist and astronomers use to understand the motion of objects in the Universe.

Conservation of Momentum



- The total momentum of interacting objects cannot change unless an external force is acting on them (same as Newton's first law)
- Interacting objects exchange momentum through equal and opposite forces (same as Newton's second law)

Momentum

Momentum = Mass x Velocity (p = mv)

Change in momentum with time = Force (dp/dt = F)

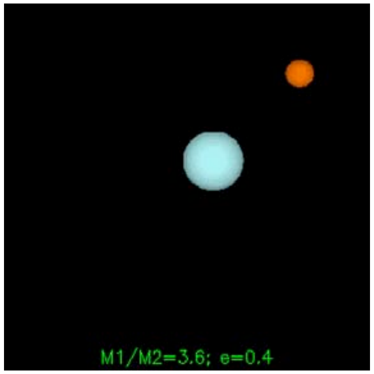
(dp/dt = acceleration - this is Newton's 2nd law).

However, the total momentum must be conserved, an object must exert an equal and opposite force.

Double Stars:

One third of the stars in the sky are double.

Simulation of a FOV and MOV stars with a mass ratio of 3.6



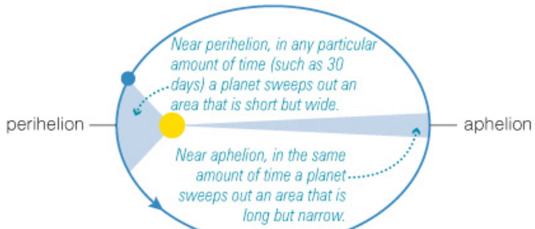
http://www.astronomy.ohio-state.edu/~pogge/Ast162/Movies/

Angular Momentum

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

Angular Momentum = mass x velocity x radius

Orbital Motion and the Conservation of Angular Momentum



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.

Basic Types of Energy

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

Energy can change type but cannot be destroyed.

Kinetic Energy

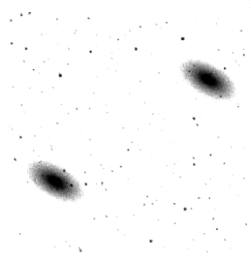
Kinetic energy depends on the mass and velocity of the object.

K.E. = ½ X mass X velocity^2 = 1/2 m v^2

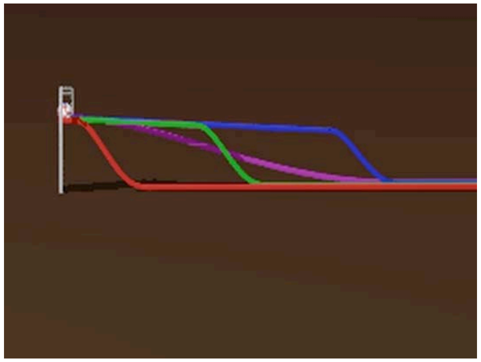
Gravitational Potential Energy

- 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 kinetic energy.



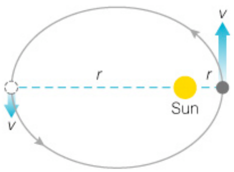
Gravitational Potential Energy



Conversion of gravitational potential energy to kinetic energy

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

More gravitational energy;
Less kinetic energy

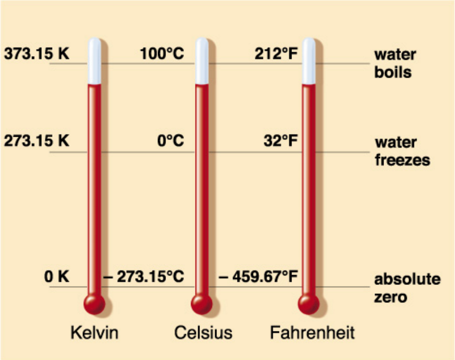


Less gravitational energy;
More kinetic energy

Total orbital energy stays constant

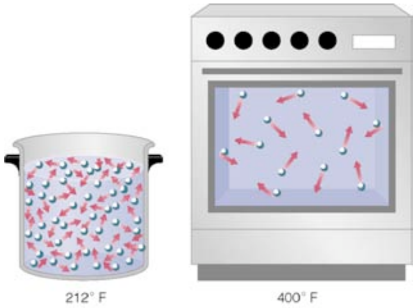
- Total orbital energy (gravitational + kinetic) stays constant if there is no external force
- Orbits cannot change spontaneously.

Thermal Energy: Temperature Scales

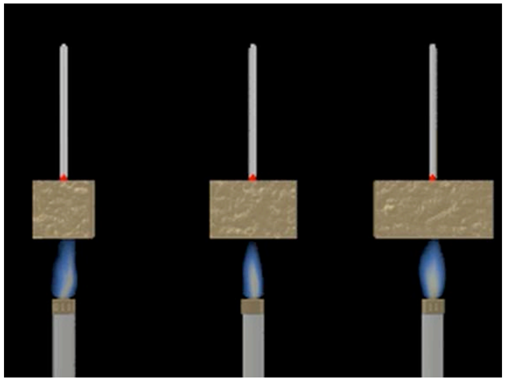


Thermal Energy

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



Thermal Energy



Which one has more energy?

Chemical Potential Energy

One calorie of food has the energy to raise one kilogram of water 1 degree Celsius.

In our bodies this gets converted into thermal energy and kinetic energy.

Electrical Energy

Opposites attract, positive charges attracted to negative charges.

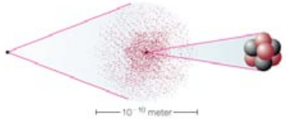
Normally electrons (negative charge) are bound to the nuclei of atoms (positive charge) by electrical forces.

The number of protons and electrons are equal.

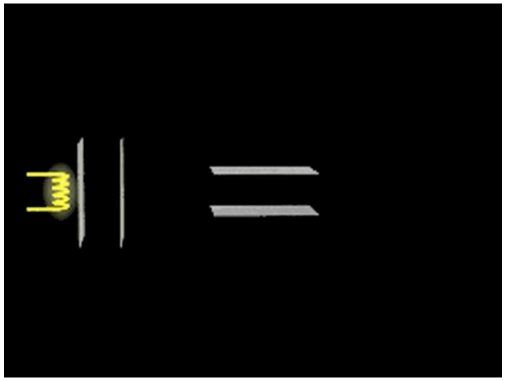
Electricity is the flow of electrons (which are not bound to a particular atom).

A volt give a measure of the amount of energy an electron gains when it goes around a circuit from the negative to the positive end.

Batteries convert potential chemical energy to the kinetic energy of electrons.

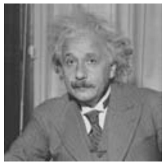


Electrical Energy



The electron guns are used in TVs.

Mass-Energy

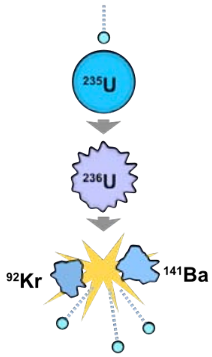


Mass itself is a form of potential energy

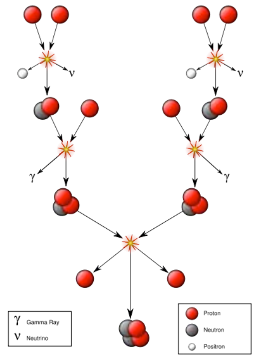
$$E = mc^2$$

- A small amount of mass can release a great deal of energy
- Concentrated energy can spontaneously turn into particles (for example, in particle accelerators)
- If your bodies mass was converted to energy - explosion would have energy of 1500 megatons (1 million times more energy than the atomic bomb that destroyed Hiroshima)

Nuclear Energy: Converts small amounts of Mass into Energy



Nuclear Fission



Nuclear Fusion

Antimatter

Every particle has an antiparticle with an opposite charge:

An anti-proton is negatively charged particle

An anti-electron or positron is positively charged particle

An anti-neutron is neutrally charged particle.

If matter and anti-matter collide, the particles are converted into energy.

Anti hydrogen atoms have been created in the laboratory.

Does antimatter has a positive mass? Is it acted upon by gravity in the same way as normal matter? Yes!!

Things to know (i.e. things that may be on exams)

1. Newton's three laws of Motion
2. The law of Universal Gravitation
3. Conservation of momentum, angular momentum and energy
4. What are the different types of Energy

There are different ways of approaching a problem in physics:

Newton's laws are consistent with conservation laws, but sometimes it is more useful to use Newton's laws and sometimes it is more useful to use conservation laws.