Gravity and Forces

Sept 9, 2002

1) Review
2) Kepler’s Laws
3) Newton’s Laws
4) Gravity
5) Examples
Review

- Lots of motion
- The Moon revolves around the Earth
- Eclipses
  - Solar
  - Lunar
  - the Sun, Earth and Moon must all be in a line
- Did you know that all this motion and tilting was happening?
Nicholas Copernicus

- Early people believed the Earth was the center of the Universe and that the Sun, Moon, stars and other celestial bodies revolved around the Earth.
- Nicholas Copernicus (1473-1543) was the first recorded person to suggest the Earth revolved around the Sun.
  - He suggested the planets went around in circles.
  - Didn’t publish this until the year he died.
- Not readily accepted.
Brahe and Kepler

- **Tycho Brahe (1546-1601)**
  - Brahe spent decades observing and recording the positions of the planets in the sky

- **Johannes Kepler (1571-1630)**
  - Compared the data from Brahe to Copernicus’ theory of planets revolving around the Sun in circular orbits
  - The data did NOT support this theory
    - What does the scientific method say we should do?
Kepler began by assuming orbits were circles, but that didn’t work so he tried ellipses.

An ellipses is a flattened out circle.

- **eccentricity** is a measure of how flat it is.

For a circle, the distance from the center is constant, eccentricity = 0.

For an ellipse, the distance from one focal point to the edge to the other focal point is constant.

An ellipse can be defined by its semimajor axis and its eccentricity.
Kepler’s First Law

- Kepler’s First Law of planetary motion

Planets move in orbits which are ellipses with the Sun at one of the focal points

- This is an empirical theory
  - it doesn’t explain why
  - but, it matched the data
- Earth has a fairly circular orbit
  - Earth’s eccentricity = 0.017
- Pluto has a more elliptical orbit
  - Pluto’s eccentricity = 0.224
Kepler’s Second Law

Planets sweep out equal areas in equal times

- Planets move fastest when they are closest to the Sun
- They move slowest when they are farthest from the Sun
Kepler’s Third Law

The square of a planet’s orbital period equals the cube of the orbit’s semi-major axis.

\[(P_{\text{years}})^2 = (A_{\text{AU}})^3\]

- **Orbital period** = time the planet takes to go around the Sun once
  - measured in years
- **Length of semi-major axis of orbital ellipse**
  - measured in astronomical units (AU)
Kepler’s Laws
- do an excellent job of describing the motion of the planets
- but they don’t tell us why the planets do this
Science tries to learn how and why
Two great scientists helped answer these questions
- Galileo Galilei (1564-1642)
- Sir Isaac Newton (1642-1723)
Newton’s Laws of Motion
Newton’s First Law

An object at rest will stay at rest, an object in motion will remain in motion

- ...unless an unbalanced force acts upon it
- The first part seems obvious
  - you stay in your seat unless you make yourself get up or someone/something pushes you
  - you do not go mysteriously flying out of your seat
- The second part seems less obvious
  - you are used to an object sliding across the floor and slowing down
  - but it really does want to keep moving
- Now we need some definitions...
Definitions

- Distance (m) and Time (s)
- Speed (m/s)
  - how fast you are moving
- Velocity (m/s)
  - speed + direction
- Acceleration (m/s\(^2\))
  - how quickly your velocity is changing
- Mass (kg)
  - a measure of how much matter an object has
    - different than weight, but related
- Inertia
  - the amount an object resists changes in motion
Newton’s Second Law

An unbalanced force will change an object’s motion

- The change in motion (acceleration) will be proportional to the amount of force
  - the harder you push the more the motion will change
  - the harder you push the greater the acceleration

\[ F = ma \]
\[ a = \frac{F}{m} \]
Newton’s Third Law

For every action there is an equal and opposite reaction

- Not intuitively obvious
- Examples,
  - two carts
  - baseball hitting a bat or tennis ball hitting a racket
  - Earth pulls on the Moon, Moon pulls on the Earth
  - Space Shuttle launch
    - gas goes one way, Shuttle the other
Does a ball traveling around a circle with constant speed feel an acceleration?
YES, a ball moving in a circle is always accelerating

Consider,
- at the top of the circle the ball is moving to the right
- at the bottom of the circle the ball is moving to the left
- in a short time, the ball completely switches direction, there must be an acceleration

The speed may not be changing, but the direction is
- remember, velocity is speed and direction

The acceleration is inward (towards the center of the circle) at all points on the circle

This is the way planets move around the Sun
Gravity

- All objects with mass feel an attraction to each other due to gravity
  - So if you’ve been strangely attracted to someone sitting next to you, this may be why
- Gravity is the force which...
  - holds us to the Earth
  - causes a rock to fall towards the ground
  - causes the Earth to go around the Sun
  - causes the Sun to be pulled towards the center of the Milky Way galaxy, and much more
- Gravity acts without the objects needing to touch
  - “action at a distance”
Gravity (cont)

- Gravity acts between 2 objects
- The amount of force depends on
  - the mass of the 2 objects
    - the heavier the masses, the greater the force
  - the distance between the 2 objects
    - the closer together, the greater the force
  - a constant of Nature
- Important – BOTH objects feel this force and are attracted to each other
  - the Moon is pulled towards the Earth and the Earth is pulled towards the Moon

\[ F = G \frac{M_1 M_2}{r^2} \]
Gravity and Orbits

- Gravity provides the force which causes the planets to orbit the Sun
- The planets want to fly off into space (Newton’s First Law)
- But gravity pulls them towards the Sun and changes their direction

- It’s even more complicated because the planets pull on each other which causes variations in the orbits
Why doesn’t the Earth Fall Into the Sun?

- In fact, it does fall into the Sun every moment of every day
  - in order for the Earth to revolve around the Sun, it needs the Sun to pull it inward
  - if the Sun didn’t pull the Earth inward, it would go flying off into space
- remember an object in motion wants to continue in motion along the same straight path it is going
Measuring the Mass of the Earth

- From Newton, we know \( F = ma \) and
- We also know
  - All objects are accelerated towards the Earth at the same rate \( (a = 9.80 \text{ m/s}^2) \), from Galileo
  - \( G = 6.67 \times 10^{-11} \text{ Nm}^2/\text{kg}^2 \) from laboratory measurements
  - The radius of the Earth is \( r = 6.38 \times 10^6 \text{ m} \), from measuring the curvature of the Earth
  - \( m = M_1 = \text{mass of an object on the Earth} \)
  - \( M_2 = M_e = \text{mass of the Earth} \)
- From this we measure the mass of the Earth to be \( 5.98 \times 10^{24} \text{ kg} \)
  - Pretty heavy, imagine how big of a bathroom scale you would need!
Weight

- Weight is a measure of how much an object is attracted to the Earth
  - it is really a measure of the gravitational force
- But if you travel to the Moon, your weight will decrease
  - this is because the Moon has less mass than the Earth and exerts a smaller force on you
  - the same is true if you go to another planet, although if the planet has more mass you will weigh more
- But in these cases your mass stays the same
“Weightlessness” in Orbit

- Astronauts in the Space Shuttle or International Space Station (ISS) appear to be weightless
  - but they are still within the Earth’s gravitational pull
- They appear weightless because they (along with the shuttle or ISS) are in orbit
- They are “falling” to the Earth all the time, but this is just keeping them in orbit
Summary

- Kepler discovered empirical laws which described the motion of the planets, but didn’t explain them.
- Newton developed 3 laws of Nature which describe how the planets behave as well as how things on Earth act.
- Gravity is the attraction of 2 objects with mass. It is responsible for the “ballet” of motion throughout the Universe.