Motion: definitions

- Motion of an object is specfied by describing how fast an object is moving (speed), and also what direction it is moving in
- Combination of speed and direction is called the **velocity** of an object
- If the velocity of an object is changing (**either** speed or direction), the object is said to be **accelerating.** **Acceleration** is a change in velocity.

Newton's Laws of Motion (1)

- Law of inertia: the velocity of an object will not change unless a force acts on it
  - An object at rest stays at rest unless something pushes it
  - An object that is moving will continue to move in the same direction at the same speed unless something pushes it

Newton's laws of motion (2)

- Force law: if a force is applied on an object, the object will accelerate
  - Change in velocity can be a change in speed, a change in direction, or both
  - The acceleration is larger if the force is stronger
  - For a given force, the acceleration is larger on a less massive object than on a more massive object

    acceleration = force / mass

Newton's laws of motion (3)

- Action/reaction law
  - For every applied force, a force of equal strength but opposite direction arises
  - Explains how many things on Earth move
  - Has an important consequence called the conservation of momentum
    - Momentum is defined as mass times velocity (p=mv)
    - When there are no other forces, the total momentum of a set of objects is unchanged (conserved)
    - Principle behind rocket/jet propulsion
    - Another familiar application is recoil

Forces in nature

- Newton's laws tell us how objects will move in the presence (or absence) of forces. But where do forces come from?
- To date, only four basic forces have been discovered:
  - Gravity: force between objects that have mass
  - Electromagnetic force: force between objects that have electric charge
  - Strong force : only important within atomic nucleii
  - Weak force: only important within atoms
- Of these forces, only gravity is important for most astronomical objects

Gravity

- Gravity is a force that exists between any objects that have **mass.** All such objects have an attractive force between each other
- Gravity is a **central** force: it acts between the centers of objects**.** So the force of gravity from the Earth comes from the center of the Earth.
- The strength of gravity depends on:
  - the mass of the objects: the greater the mass, the greater the force
  - the distance between the (centers of) the objects: the larger the distance, the weaker the force
  - Mathematically,

    Force = G M m / R^2

    where M and m are the masses of the two objects, and R is the distance between them

Gravity: the origin of our weight

- Gravity holds us down to the ground. If we jump off of something, gravity is the force that causes us to accelerate towards the ground. When we reach the ground, another force holds us up, but gravity continues to pull us so that we exert force on the ground.
- The force we exert on the ground is called our *weight*. It depends on our mass, the mass of Earth, and the distance between us and the center of the Earth
  - The mass of an object doesn't change with location, since it is an intrinsic property of an object
  - The weight of an object can change if the strength of the gravitational force changes

Example: weight on other planets

- Since weight is a measure of the force of gravity, your weight would be different if you went to a different planet, since the force of gravity would be different
- Weight on other planets depends on two things
  - mass of the planet: the more massive the planet, the stronger the force of gravity
  - size (radius) of the planet: the bigger the planet, the farther you will be from the center, so the weaker the force of gravity will be
  - Consider some examples

Orbits

- The same force that holds us to the ground, gravity, keeps objects in orbit around each other
- The difference between an object on Earth and one in orbit is that an orbiting object has *transverse*, or sideways, velocity.
- If an object has transverse velocity, the combination of its inertia and the force of gravity will cause it to orbit
  - If an object has zero transverse velocity it will fall towards the other object
  - If an object has transverse velocity, it will fall *around* the other object; the amount of transverse velocity will determine the shape of the orbit.
- Why do people in orbit appear to be weightless?

Orbits (2)

- The law of gravity and the laws of motion can be combined mathematically to derive the shapes of orbits and determine how fast objects will move at different locations in the orbit. One finds that:
  - Shapes of orbits are elliptical
  - In elliptical orbits, objects travel faster when closer, slower when farther from the body they are orbiting
  - Objects in bigger orbits travel slower than objects in smaller orbits
- These are exactly Kepler's laws! But they are more general: they apply not only to planetary motion, but to all gravitational motion.

Orbits: the origin of transverse velocity

- If objects have transverse velocity, they will fall around other object, i.e., they will orbit around other objects
- To understand why the planets orbit the Sun rather than fall into it, we need to understand how they got their initial transverse velocity.
- Origin of the Solar System
  - Solar system forms from clouds in interstellar medium
  - Clouds collapse by gravity
  - As clouds collapse they start to spin faster because of conservation of angular momentum
  - Increased spinning is source of the transverse velocity
  - Collisions between particles make orbits nearly circular

Measuring masses

- We can use our understanding of gravity and our observations of motion to measure masses of astronomical objects
- Basic idea is simple: gravity causes objects to move, and strength of force depends on mass and distance between objects, so if we measure motion and distance between objects, we can infer masses
- Newton's laws relate the size of the orbit, the period of the orbit, and the masses of the two objects

  $$(M1+M2)*P^2 = a^3$$

  where M are the masses of the objects (in solar masses), P is the period of the orbit (in years), and a is the semimajor axis (in astronomical units)
- If we see objects in orbit around others, and can measure the period and separation, we can derive the masses of the objects

Measuring masses (1): planets

- Planetary masses can be determined by looking at objects that orbit around them
  - Moons
  - Manmade satellites
- Masses of planets cover large range. In units of Earth masses:
  - Mercury (0.06), Venus (0.82), Earth (1.00), Mars(0.11), Jupiter (317.9), Saturn (95.2), Uranus (14.5), Neptune (17.1), Pluto (0.003)
  - Clearly, there are different types of planets

Measuring masses(1) : stars

- Measure masses of stars from binary stars: stars that orbit each other
  - Measure the size and period of orbits, velocities of stars in their orbits --> masses of the stars
  - Stars come in a range of masses
    - Most massive stars about 100 times mass of Sun
    - Least massive stars about 1/10th mass of Sun
    - Many more low mass than high mass stars

Measuring masses: galaxies

- In galaxies, there are lots of stars that orbit, but the periods are very long!
- We can still measure masses because we can measure the speed of stars, using a property of light called the Doppler shift, for edge-on galaxies
- Since there are lots of stars in a galaxy, we can measure the orbital speed at lots of different distances from the center of the galaxy
- Since it looks like most of the light in galaxies is at the center, we expected the orbital speeds of stars to decrease as we go farther from the center

Dark matter in galaxies

- When we measure orbital speeds of stars in galaxies, we find that stars farther out are moving just a fast as stars in the inner regions
- Implication:
  - Either our understanding of gravity is wrong (but it seems to work perfectly everywhere else!)
  - There's a lot of extra matter at large distances from the center of galaxies that provide more pull than we expected based on where we see the light coming from
- Most astronomers feel that the latter is more likely, hence we believe that galaxies are filled with some unknown type of *dark matter*

Other evidence for dark matter

- Other observations also suggest the existence of dark matter:
  - Motions of galaxies in galaxy clusters
  - Gravitational lensing

What is dark matter?

- We don't know what the dark matter is, even though we think it dominates the mass of galaxies!
- Several possibilities
  - “failed stars”, too low mass to shine --> UNLIKELY
  - “dead stars”, faded stars that no longer shine --> UNLIKELY
  - Black holes --> UNLIKELY
  - Some new sort of undiscovered matter --> MOST LIKELY!
- Clearly, we have a lot to learn. Note several current experiments to detect dark matter are ongoing