Note that the following lectures include animations and PowerPoint effects such as fly ins and transitions that require you to be in PowerPoint’s Slide Show mode (presentation mode).

Chapter 5
Newton, Einstein, and Gravity

Outline

I. Galileo and Newton
   A. Galileo and Motion
   B. Newton and the Laws of Motion
   C. Mutual Gravitation
II. Orbital Motion
   A. Orbits
   B. Orbital Velocity
   C. Calculating Escape Velocity
   D. Kepler’s Laws Re-examined
   E. Newton’s Version of Kepler’s Third Law
   F. Astronomy After Newton
III. Einstein and Relativity
   A. Special Relativity
   B. The General Theory of Relativity
   C. Confirmation of the Curvature of Space-Time
A New Era of Science

Mathematics as a tool for understanding physics

Isaac Newton (1643 - 1727)

- Building on the results of Galileo and Kepler
- Adding physics interpretations to the mathematical descriptions of astronomy by Copernicus, Galileo and Kepler

Major achievements:

1. Invented Calculus as a necessary tool to solve mathematical problems related to motion
2. Discovered the three laws of motion
3. Discovered the universal law of mutual gravitation

Velocity and Acceleration

Acceleration ($a$) is the change of a body’s velocity ($v$) with time ($t$):

$$ a = \frac{\Delta v}{\Delta t} $$

Velocity and acceleration are directed quantities (vectors)!

Different cases of acceleration:

1. Acceleration in the conventional sense (i.e. increasing speed)
2. Deceleration (i.e. decreasing speed)
3. Change of the direction of motion (e.g., in circular motion)
Acceleration of Gravity

Acceleration of gravity is independent of the mass (weight) of the falling object!

Iron ball
Wood ball

Newton’s Laws of Motion (1)

1. A body continues at rest or in uniform motion in a straight line unless acted upon by some net force.

An astronaut floating in space will continue to float forever in a straight line unless some external force is accelerating him/her.

Newton’s Laws of Motion (2)

2. The acceleration $a$ of a body is inversely proportional to its mass $m$, directly proportional to the net force $F$, and in the same direction as the net force.

$$a = \frac{F}{m} \Leftrightarrow F = ma$$
Newton’s Laws of Motion (3)

3. To every action, there is an equal and opposite reaction.

The same force that is accelerating the boy forward, is accelerating the skateboard backward.

\[ F = - \frac{GMm}{r^2} \]

(\(G\) is the Universal constant of gravity.)

The Universal Law of Gravity

- Any two bodies are attracting each other through gravitation, with a force proportional to the product of their masses and inversely proportional to the square of their distance:

Understanding Orbital Motion

The universal law of gravity allows us to understand orbital motion of planets and moons:

\[ \Delta v = \frac{F}{m} \]

- Earth and moon attract each other through gravitation.
- Since Earth is much more massive than the moon, the moon’s effect on Earth is small.
- Earth’s gravitational force constantly accelerates the moon towards Earth.
- This acceleration is constantly changing the moon’s direction of motion, holding it on its almost circular orbit.
Orbital Motion (2)

In order to stay on a closed orbit, an object has to be within a certain range of velocities:

Too slow => Object falls back down to Earth

Too fast => Object escapes Earth's gravity
Orbital Motion (3)

Geosynchronous Orbits

Geosynchronous Orbit

Kepler’s Third Law Explained by Newton

Balancing the force (called “centripetal force”) necessary to keep an object in circular motion with the gravitational force → expression equivalent to Kepler’s third law,

\[ P_y^2 = a_{AU}^3 \]