If I have seen further it is by standing on the shoulders of giants.

– Sir Isaac Newton
What We Will Learn Today

• What are the basic elements of motion?
• What are Newton’s laws of motion?
• What are the three main conservation laws?
• How does gravity work?
• What causes tides on Earth?
• Why is the Moon’s rotational period equal to its orbital period?
Basic Elements of Motion

- **Speed**
  - Distance / Time

- **Velocity**
  - Speed along a specified direction

- **Acceleration**
  - Change in velocity
  - Can be positive (increase in speed) or negative (decrease in speed)
  - Can be a change in direction
  - You can not feel velocity but can feel acceleration
  - Direction of acceleration is opposite the direction we “fall”

*Fig 4.1*
Mass, Momentum, and Force

• Mass
  – Measure of the amount of matter (units kg, pounds etc.)

• Weight
  – The force of attraction applied on a mass due to gravity (units Newton, kg-wt, lb-wt etc.)

• Inertia
  – A property of matter that makes it resist any change to its state of rest or motion

• Momentum
  – Mass x Velocity
  – Unchanging unless external force is applied

• Force
  – External influence applied on a mass to change its momentum or velocity i.e. to accelerate it
  – Remember, “acceleration” could be a decrease in velocity
Acceleration Due To Gravity

Fig 4.2

\[ t = 0 \]
\[ v = 0 \]

\[ t = 1 \text{ s} \]
\[ v \approx 10 \text{ m/s} \]

\[ t = 2 \text{ s} \]
\[ v \approx 20 \text{ m/s} \]

\[ t = \text{time} \]
\[ v = \text{velocity} \]
\[ (\text{downward}) \]
Angular Momentum

• Momentum of objects due to motion along a curve
  – Rotational angular momentum
    • Skater, Earth
  – Orbital angular momentum
    • Racetrack, Earth

• Torque
  – Force applied on object to change angular momentum
  – Lever arm – door handle at other end of hinges
Orbit is a Free-Fall

- What goes up, must come down
  - Not always!
- Why are astronauts weightless?
  - In a constant state of free-fall
Sir Isaac Newton (1642 – 1727)

• Formulated the laws of motion & gravity
  – Explained the “why” behind Kepler’s laws
• Probed the nature of light
• Built the first reflecting telescopes
• Invented calculus
An object moves at constant velocity if there is no net force acting upon it

- Essentially restates Galileo’s discovery
- This is the law of inertia
- Object at rest stays at rest
- Object in motion stays in motion
  - Not intuitive due to friction on Earth
  - Airplane example
- Explains why we feel acceleration but not uniform motion
Newton’s Second Law

\[ \text{Force} = \text{Mass} \times \text{Acceleration} \]

- External force is required to change an object’s state of motion (or rest)
- Quantifies relationship between force applied and the resultant acceleration of the object
- For a given mass, greater force results in greater acceleration
- Same force on unequal masses – smaller mass accelerates more
Newton’s Third Law

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

- Some examples
  - Rockets flying
  - Gun recoiling upon firing
  - Garden hose moves back when water is turned on
  - Filled balloon left loose
  - It hurts when you run into a wall!
Conservation Laws

- The “why” behind Newton’s laws
- Conserved = Unchanged
- Three conservation laws
  - Conservation of Momentum
  - Conservation of Angular Momentum
  - Conservation of Energy
Conservation of Momentum

• In the absence of an external force, the total momentum of interacting objects remains unchanged (conserved)
  – Explains first law i.e. inertia
  – Explains third law i.e. rocket launch
Conservation of Angular Momentum

- In the absence of an external torque (twisting force), the total angular momentum of interacting objects remains unchanged
  - i.e. it is conserved
  - Explains why planets keep spinning & orbiting the Sun
  - Explains Kepler’s second law
    - Planets move faster when closer to the Sun
Conservation of Energy

- The total energy in an isolated system remains unchanged.
- It can change form (kinetic, potential, thermal, radiative etc.).
- It can be transferred from one object to another.

Fig 4.14
Newton’s Law of Gravity

• Every mass attracts every other mass through the force of gravity

• The force of gravity is
  – *Directly proportional* to the product of the two masses
  – *Inversely proportional* to the square of the distance between them

\[
F_g = G \frac{M_1 M_2}{d^2}
\]

  – *Inverse square law*

  – \( M_1, M_2 \) are the masses of the two objects (SI unit: kg)
  – \( d \) is distance between them (SI unit: m)
  – \( G \) is Newton’s gravitational constant
  – In SI units, \( F \) is measured in Newtons (kg m s\(^{-2}\))
  – If distance between two objects is tripled, force of gravity drops to \( \frac{1}{3^2} = \frac{1}{9} \) of original value
• From Newton’s second law: \( F = m \times a \)
• To describe gravity on the surface of the Earth, we write this as \( F = m \times g \), where \( g \) is gravitational acceleration on Earth’s surface
• Using Newton’s gravitational law, we see that

\[
F = \frac{GM_E m}{d^2} = mg
\]

• Which leads to

\[
g = \frac{GM_E}{r_E^2} = 9.8 \text{ m/s}^2
\]
Newton’s Laws Improved Kepler’s

- Explained the basis for the laws
- Extended the laws to all orbits
  - Not just planets around the Sun
  - Asteroids, comets, artificial satellites
  - Other solar systems, multiple star systems

\[ a^3 = \frac{G(M_1 + M_2)}{4\pi^2} p^2 \]

- Sun is not at the focus of planetary orbits
  - The center of mass of the Solar System is at the focus
Moon’s Gravity: Tides on Earth

- Sun’s contribution is about a third of the Moon’s

Spring tides: Sun/Moon aligned

Neap tides: Sun/Moon tidal forces counteract
Tidal Friction

- Earth’s rotation is slowing down
  - 1 extra second for every 50,000 years
  - Day is 20 minutes longer now than it was a million years ago
- Moon is drifting farther away
  - 38 mm per year
  - Conservation of angular momentum
- Explains Moon’s synchronous rotation

Fig 4.26