FORCE AND MOTION

CHAPTER 3
## Review: Important Equations – Chapter 2

<table>
<thead>
<tr>
<th>Definitions</th>
<th>Average speed:</th>
<th>( \bar{v} = \frac{d}{t} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Final velocity:</td>
<td>( v_f = at + v_0 )</td>
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<tr>
<td></td>
<td>Acceleration:</td>
<td>( a = \frac{\Delta v}{\Delta t} = \frac{v - v_0}{t - t_0} )</td>
</tr>
<tr>
<td></td>
<td>Distance fallen:</td>
<td>( d = \frac{1}{2}gt^2 )</td>
</tr>
<tr>
<td></td>
<td>Centripetal acceleration:</td>
<td>( a_c = \frac{v^2}{r} )</td>
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</table>

- \( a = g \) for the case of gravity
- \( g = 9.80 \text{ m/s}^2 = 32 \text{ ft/s}^2 \) (acceleration, gravity)
Scientific “Thinking”

- Speeding VS Falling Bullet. Could it be true?
- Doubt is the servant of knowledge
- Evaluating Authority
From Measurement to Cause

Kopernikus 1542
Galileo 1564-1642
Newton 1686

Chapter 1  Chapter 2  Chapter 3

Units  Motion  Force
Measurement  Inertia
Reference Point  Gravity
In chapter 2 we studied motion but not its cause.

In this chapter we will look at both force and motion – the cause and effect.

Essentially, we’re discovering a new quantity that seems necessary for a complete model of the cause of motion.

We will consider:

- Newton’s three laws of motion
- Newton’s law of universal gravitation
- Buoyancy and momentum
Like distance, mass, and time, force derives from the physical experience of our senses.

Force – a vector quantity capable of producing motion or a change in motion
  A force is capable of changing an object’s velocity and thereby producing acceleration.

A given force may not actually produce a change in motion because other forces may serve to balance or cancel the effect.
Balanced (equal) forces, therefore no motion.

Equal in magnitude but in opposite directions.
Unbalanced forces result in motion

Net force to the right
Newton’s First Law of Motion

- Aristotle considered the natural state of most matter to be at rest.
- Galileo concluded that objects could naturally remain in motion indefinitely.
- Newton’s 1st Law of Motion – An object will remain at rest or in uniform motion in a straight line unless acted on by an external, unbalanced force.
Objects and Newton’s 1st Law

- An object will remain at rest or in uniform motion in a straight line unless acted on by an external, unbalanced (net) force.

- Balanced forces have equal magnitude in opposite directions

- An external force is a force applied to the entire object or system.

- (We’re ignoring an objects distortion, or change in shape under applied forces.)
Motion and Inertia

- Inertia - the natural tendency of an object to remain in a state of rest or in uniform motion in a straight line (first introduced by Galileo)

- Newton went one step further and related an object’s mass to its inertia.
  - The greater the mass of an object, the greater its inertia.
  - The smaller the mass of an object, the less its inertia.
The large man has more inertia – more force is necessary to start him swinging and also to stop him – due to his greater inertia
Mass and Inertia

Quickly pull the paper and the stack of quarters tend to stay in place due to inertia.
“Law of Inertia”

- Because of the relationship between motion and inertia:
  - Newton’s First Law of Motion is sometimes called the Law of Inertia.
  - Seat-belts help ‘correct’ for this law during sudden changes in speed.
Newton’s Second law of Motion

- Acceleration (change in velocity) produced by a force acting on an object is directly proportional to the magnitude of the force (the greater the force the greater the acceleration.)

- Acceleration of an object is inversely proportional to the mass of the object (the greater the mass of an object the smaller the acceleration.)

- \[ a = \frac{F}{m} \]  or  \[ F = ma \]
Force, Mass, Acceleration

• **Original situation**

\[ a = \frac{F}{m} \]

• If we double the force we double the acceleration.

• If we double the mass we half the acceleration.
\[ F = ma \]

- \( F \) is the net force (unbalanced), which is likely the vector sum of two or more forces.
- \( m \) & \( a \) concern the whole system
- Units?
  - Force = mass x acceleration = kg x m/s\(^2\) = N
  - N = kg x m/s\(^2\) = newton -- this is a derived unit and is the metric system (SI) unit of force
Forces are applied to blocks connected by a string (weightless) resting on a frictionless surface. Mass of each block = 1 kg; $F_1 = 5.0$ N; $F_2 = 8.0$ N

What is the acceleration of the system?
Forces are applied to blocks connected by a string (weightless) resting on a frictionless surface. Mass of each block = 1 kg; $F_1 = 5.0$ N; $F_2 = 8.0$ N. What is the acceleration of the system?

GIVEN:

- $m_1 = 1$ kg; $m_2 = 1$ kg
- $F_1 = -5.0$ N; $F_2 = 8.0$ N
- $a = ?$
Net Force and Total Mass - Example

\[ F_{net} = F_1 + F_2 = -5.0 \text{ N} + 8.0 \text{ N} = 3.0 \text{ N} \]

\[ m_{tot} = m_1 + m_2 = 1.0 \text{ kg} + 1.0 \text{ kg} = 2.0 \text{ kg} \]

\[ a = \frac{F_{net}}{m_{tot}} = \frac{3.0 \text{ N}}{2.0 \text{ kg}} = 1.5 \text{ m/s}^2 \]

Units:

\[ \text{m/s}^2 = \frac{\text{N}}{\text{kg}} = \frac{\text{kg-m/s}^2}{\text{kg}} = \text{ m/s}^2 \]
Mass & Weight

- Mass = amount of matter present
- Weight = related to the force of gravity
- Earth: weight = mass x acc. due to gravity
- \( w = mg \) (special case of \( F = ma \)). Weight is a force due to the pull of gravity.
- Therefore, one’s weight changes due to changing pull of gravity – like between the Earth and Moon.
- Moon’s gravity is only 1/6th that of Earth’s.
Computing Weight – an example

What is the weight of a 2.45 kg mass on (a) Earth, and (b) the Moon?
What is the weight of a 2.45 kg mass on (a) Earth, and (b) the Moon?

Use Equation $w = mg$

Earth: $w = mg = (2.45 \text{ kg}) (9.8 \text{ m/s}^2) = 24.0 \text{ N}$ (or 5.4 lb. Since 1 lb = 4.45 N)

Moon: $w = mg = (2.45 \text{ kg}) [(9.8 \text{ m/s}^2)/6] = 4.0 \text{ N}$ (or 0.9 lb.)
Acceleration due to gravity is independent of the mass.

Both $F$ & $m$ are doubled, resulting in $g$ remaining constant.

\[ g = \frac{F}{m} \]

\[ g = \frac{2F}{2m} \]
Friction

Friction – resistance to relative motion that occurs whenever two materials are in contact with each other.

- Ever-present and found in all states (solids, liquids, and gases) of matter

- In some cases we want to increase friction (sand on ice), in other cases we want to reduce friction (motor oil).

- A Dissipative force in that it always works against you! (loosely speaking)
Newton’s Third Law of Motion

• For every action there is an equal and opposite reaction.

or

• Whenever one object exerts a force on a second object, the second object exerts an equal and opposite force on the first object.

• action = opposite reaction

• $F_1 = -F_2$  or  $m_1a_1 = -m_2a_2$
Newton’s Third Law of Motion

- $F_1 = -F_2$  or  $m_1a_1 = -m_2a_2$

- Jet propulsion – exhaust gases in one direction and the vehicle in the other direction

- Gravity – jump from a table and you will accelerate to Earth. Is the earth accelerating to you in proportion to its mass?
  - You – small mass, huge acceleration ($m_1a_1$)
  - Earth – huge mass, very small acceleration ($-m_2a_2$)

BUT -> $m_1a_1 = -m_2a_2$
Newton’s Laws in Action

- $f = \text{friction force of the road on the tires, provides necessary centripetal acceleration.}$
- What is the force of the tires on the road? (Hint: 3rd law)
- Momentarily, passengers continue straight ahead in original direction, then, as car turns the door comes toward passenger – 1st Law
- As car turns you push against door (seat, etc.) and the door (seat etc.) pushes against you – 3rd Law
Newton’s Law of Gravitation

* Gravity is a fundamental force of nature
  We do not know what causes it
  We can only describe it

* Law of Universal Gravitation – Every particle in the universe attracts every other particle with a force that is **directly proportional to the product of their masses** and **inversely proportional to the square of the distance** between them
Newton’s Law of Gravitation

\[ F_{\text{grav}} = G \frac{m_1 m_2}{r^2} \]

- \( F_{\text{grav}} \) is the magnitude of the force, acting on a line between the particles.

- \( G = 6.67 \times 10^{-11} \text{ N-m}^2/\text{kg}^2 \)

- \( G \):
  - gravity is considered a “weak” force
  - thought to be valid throughout the universe
  - “constant of proportionality” basically makes the units come out right!
Newton’s Law of Gravitation

The forces that attract particles together are equal and opposite

\[ F_1 = -F_2 \quad \text{or} \quad m_1a_1 = -m_2a_2 \]
Newton’s Law of Gravitation

- For a **homogeneous** sphere the gravitational force acts as if all the mass of the sphere were at its center

\[
F = m \left( G \frac{m_E}{r_E^2} \right)
\]

\[
g = G \frac{m_E}{r_E^2}
\]
Two objects with masses of 1.0 kg and 2.0 kg are 1.0 m apart. What is the magnitude of the gravitational force between the masses?
Gravitation – Example

Two objects with masses of 1.0 kg and 2.0 kg are 1.0 m apart. What is the magnitude of the gravitational force between the masses?

\[ F = G \left( \frac{m_1 m_2}{r^2} \right) \]

\[ F = 6.67 \times 10^{-11} \text{ N-m}^2/\text{kg}^2 \left( \frac{1.0 \text{ kg} \times 2.0 \text{ kg}}{1^2 \text{ m}^2} \right) \]

\[ F = 1.3 \times 10^{-10} \text{ N} \]
“Weightlessness” in space is the result of both the astronaut and the spacecraft ‘falling’ to Earth at the same rate.
Gravity Makes Orbit Possible!

http://www.youtube.com/watch?v=DPlbDEl63B4

Buoyancy

- Buoyant force – the upward force resulting from an object being wholly or partially immersed in a fluid.
- The Archimedes’ Principle – An object immersed in a fluid experiences a buoyant force equal to the weight of the volume of fluid displaced.
- Both liquids and gases are considered fluids.
Buoyancy

* The buoyant force depends on the weight of the fluid displaced.
* The weight of the fluid displaced depends on the density of the fluid and the volume displaced.

* Salt water is denser than fresh water.
* Therefore, one floats higher in salt water, since one needs to displace less salt water to equal one’s weight.
Examples of Buoyancy

- Ships float because the average density of the ship is less than the water it would displace.
- Oil floats on water, since oil is less dense than water.
- Cream floats on milk, since cream is less dense than milk.
- By taking in, or pumping out water, submarines can vary their buoyancy.
Momentum

- Linear momentum = mass x velocity
- \( p = mv \)
- If we have a system of masses, the linear momentum is the sum of all individual momentum vectors.
- \( P_f = P_i \) (final = initial)
- \( P = p_1 + p_2 + p_3 + \ldots \) (sum of the individual momentum vectors)
Law of Conservation of Linear Momentum

- Law of Conservation of Linear Momentum - the total linear momentum of an isolated system remains the same if there is no external, unbalanced force acting on the system.

- Linear Momentum is 'conserved' as long as there are no external unbalanced forces.

- It does not change with time.

Section 3.7
Conservation of Linear Momentum

- $P_i = P_f = 0$ (for man and boat)
- When the man jumps out of the boat he has momentum in one direction and, therefore, so does the boat.
- Their momentums must sum to zero

Section 3.7
Applying the Conservation of Linear Momentum

Two masses at rest on a frictionless surface. When the string (weightless) is burned the two masses fly apart due to the release of the compressed spring ($v_1 = 1.8 \text{ m/s}$).
Two masses at rest on a frictionless surface. When the string (weightless) is burned the two masses fly apart due to the release of the compressed spring \((v_1 = 1.8 \text{ m/s})\).

**Given:**
- \(m_1 = 1.0 \text{ kg}\)
- \(m_2 = 2.0 \text{ kg}\)
- \(v_1 = 1.8 \text{ m/s}\)

**Momentum:**
- \(P_f = P_i = 0\)
- \(P_f = p_1 + p_2 = 0\)

**Result:**
- \(v_2 = ?\)
Applying the Conservation of Linear Momentum

\[ m_1 v_1 + m_2 v_2 = 0 \]

\[ (1.0 \text{ kg})(1.8 \text{ m/s}) + (2.0 \text{ kg})v_2 = 0 \]

\[ v_2 = -\frac{(1.0 \text{ kg})(1.8 \text{ m/s})}{(2.0 \text{ kg})} = -0.90 \text{ m/s} \]
Rocket Propulsion

- Rocket Propulsion can be explained in terms of both Newton’s 3rd Law & Linear Momentum

- \[ p_1 + p_2 = 0 \text{ or } m_1v_1 + m_2v_2 = 0 \]

- The exhaust gas molecules have small \( m \) and large \( v \).

- The rocket has large \( m \) and smaller \( v \).

- BUT: \( m_1v_1 + m_2v_2 = 0 \) (momentum is conserved)
Angular Momentum

* \( L = mvr \)

* \( L = \) angular momentum, \( m = \) mass, \( v = \) velocity, and \( r = \) distance to center of motion

* \( L_1 = L_2 \)

* \( m_1v_1r_1 = m_2v_2r_2 \)
Torque

- Torque – the twisting effect caused by one or more forces

- As we have learned, the linear momentum of a system can be changed by the introduction of an external unbalanced force.

- Similarly, angular momentum can be changed by an external unbalanced torque.
Torque

- Torque is a twisting action that produces rotational motion or a change in rotational motion.
Torque and Lever Arm

- Torque varies with the length of the lever arm. As the length of the lever arm is doubled, the torque is doubled, for a given force.
Law of Conservation of Angular Momentum

- Law of Conservation of Angular Momentum - the angular momentum of an object remains constant if there is no external, unbalanced torque (a force about an axis) acting on it.

- Concerns objects that go in paths around a fixed point, for example a comet orbiting the Sun.
Angular Momentum – Example planets in the Solar System

- Mass (m) is constant. Planet orbit paths are slightly elliptical, therefore both r and v will slightly vary during a complete orbit.
- As r changes so must v. When r decreases, v must increase so that \( m_1v_1r_1 = m_2v_2r_2 \)
Conservation of Angular Momentum Example

- A comet at its farthest point from the Sun is 900 million miles, traveling at 6000 mi/h. What is its speed at its closest point of 30 million miles away?
- EQUATION: \( m_1v_1r_1 = m_2v_2r_2 \)
- GIVEN: \( v_2, r_2, r_1, \) and \( m_1 = m_2 \)

\[
v_1 = \frac{mv_2r_2}{mr_1} = \frac{(6000 \text{ mi/h})(900 \times 10^6 \text{ mi})}{30 \times 10^6 \text{ mi}}
\]

\[
v_1 = 1.8 \times 10^5 \text{ mi}
\]
Conservation of Angular Momentum

Rotors on large helicopters rotate in the opposite direction.
Conservation of Angular Momentum

- Figure Skater – she/he starts the spin with arms out at one angular velocity. Simply by pulling the arms in the skater spins faster, since the average radial distance of the mass decreases.

- \[ m_1 v_1 r_1 = m_2 v_2 r_2 \]

- \( m \) is constant; \( r \) decreases;

- Therefore \( v \) increases
Chapter 3 - Important Equations

\[ F = ma \]  Newton’s Second Law \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad 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Chapter 3 Homework

* On pages 76 and 77:

* Exercises:
  3.1-1,
  3.3-6, 3.3-9,
  3.5-11, 3.5-13, 3.5-16,
  3.7-21, 3.7-23