5.1: what is physics

- In previous chapters, we have studied the change in velocity as a result of acceleration,
- What cause acceleration and hence velocity change?
  - It is the Force
- A force is a push or pull upon an object resulting from the object's interaction with another object. When the interaction ceases, the objects no longer experience the force

5.2: Newtonian mechanics

- The study of the relation between a force and acceleration, first studied by Isaac Newton 1642-1727, is called Newtonian mechanics. It is applied to relatively slow objects (much less than the speed of light) and large objects (much more than atom size)
5.3: Newton's First Law

- In the absence of an external net force …
  - an object in motion remains in motion with constant velocity in a straight line.
  - an object at rest remains at rest
- This means if net force $\vec{F}_{\text{net}} = 0 \Rightarrow$ acceleration is zero ($\vec{a} = 0$)
- Object is said to be at equilibrium

**Newton's First Law:** If no net force acts on a body, the body’s velocity cannot change; that is, the body cannot accelerate.

5.4: Force

- Only a force can cause a change in velocity $\rightarrow$ acceleration
- Ex: Push, pull, throw an object; gravity; magnetic attraction

- The force exerted on a standard mass of 1 kg to produce an acceleration of 1 m/s$^2$ has a magnitude of 1 Newton (N)

A force $\vec{F}$ on the standard kilogram gives that body an acceleration $\vec{a}$. 
5.4: Force: types

<table>
<thead>
<tr>
<th>Contact forces</th>
<th>Field forces</th>
</tr>
</thead>
<tbody>
<tr>
<td>act through physical contact</td>
<td>act through empty space</td>
</tr>
</tbody>
</table>

- Force is a vector quantity
- Force is measured as the elongation of the spring.
- The total (net) force is the vector sum of all forces acting on the spring.

5.5: Mass

- Mass is an *intrinsic* characteristic of a body; a characteristic that automatically comes with the existence of the body.
- mass is a scalar quantity.
- Relates the force on the body to the resulting acceleration
5.6: Newton’s Second Law

- The acceleration of an object is directly proportional to the net force acting upon it and inversely proportional to its mass.

- **Newton’s Second Law**: The net force on a body is equal to the product of the body’s mass and its acceleration.

\[ \sum \vec{F} = \vec{F}_{\text{net}} = m\vec{a} \]

\[ \sum F_x = ma_x \quad \sum F_y = ma_y \quad \sum F_z = ma_z \]

5.6: Newton’s Second Law

- The SI unit of force is Newton (N) → 1 N = (1 kg)(1 m/s²) = 1 kgm/s².

- Some force units in other systems of units are given in Table shown.

<table>
<thead>
<tr>
<th>System</th>
<th>Force</th>
<th>Mass</th>
<th>Acceleration</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI</td>
<td>newton (N)</td>
<td>kilogram (kg)</td>
<td>m/s²</td>
</tr>
<tr>
<td>CGS</td>
<td>dyne</td>
<td>gram (g)</td>
<td>cm/s²</td>
</tr>
<tr>
<td>British</td>
<td>pound (lb)</td>
<td>slug</td>
<td>ft/s²</td>
</tr>
</tbody>
</table>

- When solving with problems with Newton’s laws, we usually draw Free-body diagram (FBD); Draw the forces vectors act on each mass and its acceleration vector.
5.6: Newton’s Second Law: Example
Two hokey players hits a puck as shown. What is the acceleration of the puck?

\[ \sum F_x = F_{1x} + F_{2x} = F_1 \cos 20^\circ + F_2 \cos 60^\circ \]
\[ \sum F_x = 4.7 + 8 = 8.7 \text{N} \]
\[ \sum F_x = m a_x = 8.7 \text{N} \Rightarrow a_x = \frac{8.7}{0.3} = 29 \text{m/s}^2 \]

\[ \sum F_y = F_{1y} + F_{2y} = -F_1 \sin 20^\circ + F_2 \sin 60^\circ \]
\[ \sum F_y = -1.71 + 6.93 = 5.22 \text{N} \]
\[ \sum F_y = m a_y = 5.22 \text{N} \Rightarrow a_y = \frac{5.22}{0.3} = 17.4 \text{m/s}^2 \]

\[ \Rightarrow \vec{a} = a_x \hat{i} + a_y \hat{j} = 29 \hat{i} + 17.4 \hat{j} \]
\[ |\vec{a}| = \sqrt{29^2 + 17.4^2} = 33.8 \text{m/s}^2 \]
\[ \theta = \tan^{-1} \frac{17.4}{29} = 31^\circ \]

5.6: Newton’s Second Law: Example
In the Fig. the acceleration, \( \vec{a} \), shown is caused by the three forces \( \vec{F}_1, \vec{F}_2 \), and \( \vec{F}_3 \). Find the magnitude and direction of the not shown force \( \vec{F}_3 \).

\[ \vec{F}_{\text{net}} = m \vec{a} \]
\[ \vec{F}_1 + \vec{F}_2 + \vec{F}_3 = m \vec{a} \]
\[ \vec{F}_3 = m \vec{a} - \vec{F}_1 - \vec{F}_2 \]

\( F_{3, x} = m a_x - F_{1, x} - F_{2, x} \)  \hspace{1cm} \text{(x-components)}
\( = m(a \cos 50^\circ) - (-F_1 \cos(30^\circ)) - F_2 \cos 90^\circ \)
\( F_{3, x} = (2)(3) \cos 50^\circ + (10) \cos(30^\circ) - 0 \)
\( = 12.5 \text{ N.} \)

\( F_{3, y} = m a_y - F_{1, y} - F_{2, y} \)  \hspace{1cm} \text{(y-components)}
\( = m(a \sin 50^\circ) - (-F_1 \sin(30^\circ)) - F_2 \sin 90^\circ \)
\( = (2)(3) \sin 50^\circ - (10) \sin(30^\circ) - (20)(1) \)
\( = -10.4 \text{ N.} \)

\[ \vec{F}_3 = F_{3, x} \hat{i} + F_{3, y} \hat{j} = (12.5 \text{ N}) \hat{i} - (10.4 \text{ N}) \hat{j} \]

\[ F_3 = \sqrt{F_{3, x}^2 + F_{3, y}^2} = 16 \text{ N} \]
\[ \theta = \tan^{-1} \frac{F_{3, y}}{F_{3, x}} = -40^\circ \]
Gravity is the attractive force every object feels towards Earth.

\[ \vec{F}_{\text{net}} = m\vec{a} \rightarrow \vec{F}_g = mg \]  

Gravitational Force

\[ -F_g = -mg \Rightarrow F_g = mg \]  

Magnitude of gravitational force

The magnitude of the gravitational force is the called the **weight (W)**; which is minimum force needed to lift a mass \( m \)

\[ W = mg \]

Weight can change from planet to planet depending on gravity acceleration but mass is constant.

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5.7: Some Particular Forces: The Normal Force

When a body presses on a surface, the surface pushes on the body with a normal force \( F_N \) that is perpendicular to the surface.

Ex: Block of mass \( m \) at rest on a table \( \rightarrow \) (mass at rest \( \vec{a} = 0 \))

\[ \Rightarrow \sum \vec{F} = m\vec{a} = 0 \]

\[ \vec{F}_{\text{net}} = \sum F_y = ma_y \]

\[ = F_N - F_g = 0 \]

\[ = F_N - mg = 0 \]

\[ \Rightarrow F_N = mg \]
5.7: Some Particular Forces: Tension

When a cord (or a rope, cable) is attached to a body and pulled taut, the cord pulls on the body with a **tension force** \( \overrightarrow{T} \) directed away from the body and along the cord.

Note that, when two objects connected by a cord in a moving system, at a given instant, both objects will have the same acceleration and velocity.

\[
\sum F_y = F_N + T - mg = 0 \quad (a = 0 \Rightarrow ma = 0 \quad - \text{object at rest})
\]
\[
\Rightarrow F_N = mg - T \quad \text{Normal force get smaller}
\]
\[
T = mg - F_N
\]
5.7: Some Particular Forces: Tension

If mass is lifted by the cord and accelerated \( (T > mg) \), the block is no more pressing on table → Normal force disappear

\[
\sum F_y = T - mg = ma_y \\
\Rightarrow T = ma + mg
\]

To have acceleration, \( T \) must be larger the weight

For example, if \( m = 12 \text{kg} \) and \( a = 0.2 \text{ m/s}^2 \)

\[
\Rightarrow \sum F_y = T - mg = ma \\
\Rightarrow T = ma + mg = m(a + g) \\
= 12(0.2 + 9.8) = 120N
\]

5.7: Some Particular Forces: Tension

An elevator moving up and comes to rest (slowing down)

\[
\vec{F}_{net} = m\vec{a} \\
\sum F_y = T - Mg = Ma_y
\]

only forces in \( y \)-direction

\[
\Rightarrow T - Mg = -Ma \Rightarrow T = Mg - Ma
\]

⇒ the tension is less than the weight
5.8: Newton’s Third Law

- If two objects interact, the force $\vec{F}_{12}$ exerted by object 2 on object 1 is equal in magnitude and opposite in direction to the force $\vec{F}_{21}$ exerted by object 1 on object 2.

5.9: Applying Newton’s Laws: Hints for solving problems using Newton’s laws

- Sketch the situation
- Categorize the problem (moving or at rest)
- Isolate an object and identify the forces acting upon it (draw free body diagram-FBD).
- Establish a convenient coordinate system (x-y) so that one of the axis is parallel to the acceleration
- Apply Newton’s second law to each diagram
- Solve for desired quantities
- Check your answer
5.9: Applying Newton’s Laws: Example

- Box pulled by a force $F$ at an angle $\theta$. The box has a horizontal acceleration $a$. Find
  a) The acceleration b) The normal force

Solution:

1- draw the situation as shown

2- draw free body diagram (FBD)

3- add coordinate system (x-y)

FBD

5.9: Applying Newton’s Laws: Example – continued from previous slide

Solution:

4- analyse forces in directions of x and y

$F_x = F \cos \theta$, $F_y = F \sin \theta$

5- apply newton's laws

$$\sum \vec{F} = m \vec{a}$$

For x-direction

$$\sum F_x = ma_x$$

$F \cos \theta = ma \Rightarrow a = \frac{F \cos \theta}{m}$

For y-direction

$$\sum F_y = ma_y$$

$n + F \sin \theta - mg = 0 \ (a_y = 0)$

$\Rightarrow n = mg - F \sin \theta$
5.9: Applying Newton’s Laws: Example – Atwood machine

Atwood machine

For \( m_1 \)
\[
\sum F_y = ma_y
\]
\[
T - m_1 g = m_1 a \quad \text{.................(1)}
\]

For \( m_2 \)
\[
\sum F_y = ma_y
\]
\[
T - m_2 g = -m_2 a \quad \text{.................(2)}
\]

From (2)
\[
T = m_2 g - m_2 a \quad \text{....(2')}\]

Sub. (2') in (1)
\[
T = 2m_1 m_2 g
\]
\[
\frac{m_2 g - m_1 g}{m_1 + m_2} = m_1 a + m_2 a
\]
\[
\implies a = \frac{m_2 g - m_1 g}{m_1 + m_2}
\]

Sub. a in (1)
\[
T = \frac{2m_1 m_2 g}{m_1 + m_2}
\]
5.9: Applying Newton’s Laws: Example – traffic at rest

Traffic weight 122N, find $T_1$, $T_2$, and $T_3$

For the traffic light

$$\sum F_y = 0 \rightarrow T_3 - F_g = 0$$

$$T_3 = F_g = 122 \text{ N}$$

For the cables joint points

(1) $\sum F_x = -T_1 \cos 37.0^\circ + T_2 \cos 53.0^\circ = 0$

(2) $\sum F_z = T_1 \sin 37.0^\circ + T_3 \sin 53.0^\circ + (-122 \text{ N}) = 0$

From (1) $T_2 = T_1 \left( \frac{\cos 37.0^\circ}{\cos 53.0^\circ} \right) = 1.33T_1$

$T_2$ is substituted into (2)

$T_1 = 73.4 \text{ N}$

$T_2 = 1.33T_1 = 97.4 \text{ N}$
Two blocks A and B are placed in contact with each other on a frictionless, horizontal surface, as shown. A horizontal force $F_{\text{app}}$ is applied to A as shown. Find (a) the magnitude of the acceleration of the system (b) the force exerted by A on B.

Solution:

(a) We can consider the two masses as a single mass $m_A + m_B$.

Apply Newton’s law:

$$F_{\text{app}} = (m_A + m_B) a$$

$$a = \frac{F_{\text{app}}}{m_A + m_B} = \frac{20 \text{ N}}{4.0 \text{ kg} + 6.0 \text{ kg}} = 2.0 \text{ m/s}^2$$

(b) The force exerted by A on B $\Rightarrow F_{BA}$ due to action-reaction between the two blocks (Newton’s 3rd law) shown in the figure.

For block B, we have force from block A

$$F_{BA} = m_B a$$

$$F_{BA} = (6.0 \text{ kg})(2.0 \text{ m/s}^2) = 12 \text{ N}$$

Hence due to Newton’s third law

$$F_{BA} = F_{AB} = 12 \text{ N}$$

But they are opposite in direction.
Assume object of mass \( m \) on an incline plane of incline angle \( \theta \). We can calculate the acceleration and normal force as follows:

1. Good to place our \( x \)-axis parallel to the acceleration \( \Rightarrow \) parallel to the incline
2. The gravity force components are:
   - parallel to the plane: \( mg \sin \theta \)
   - perpendicular to the plane: \( mg \cos \theta \)
3. Object will slide with acceleration along the plane (\( x \)-axis) by the effect of \( mg \sin \theta \)

\[
\sum F_x = ma_x \\
mg \sin \theta = ma_x \\
\Rightarrow a_x = g \sin \theta
\]

\[
\sum F_y = ma_y = 0 \quad (a_y = 0) \\
\Rightarrow n - mg \cos \theta = 0 \quad \Rightarrow n = mg \cos \theta
\]

---

**5.9: Applying Newton’s Laws: motion on an incline plane - Example**

A cord pulls on a box up along a frictionless plane inclined at \( \theta = 30^\circ \). The box has mass \( m = 5 \) kg, and the force from the cord has magnitude \( T = 25 \) N. What is the box’s acceleration component \( a \) along the inclined plane?

\[
\sum F_x = ma_x \\
T - mg \sin \theta = ma \\
\Rightarrow a = \frac{T - mg \sin \theta}{m} = 0.1 \, m/s^2
\]
Example: Two blocks connected as shown. Find (a) the acceleration of block \( S \), (b) the acceleration of block \( H \), and (c) the tension in the cord.

\[ \begin{align*}
\text{For block } M & \rightarrow F_{\text{net},x} = Ma_x \\
& \quad \quad \rightarrow T = Ma 
\end{align*} \quad (1)
\]

\[ \begin{align*}
\text{For block } m & \rightarrow F_{\text{net},y} = Ma_y \\
& \quad \quad \rightarrow T - mg = -ma 
\end{align*} \quad (2)
\]

Sub. (1) in (2) \[ Ma - mg = -ma \]

\[ \begin{align*}
Ma + ma &= mg \\
a &= \frac{m}{M + m} g \\
&= 3.8 \text{ m/s}^2 \\
T &= \frac{Mm}{M + m} g \\
&= 13 \text{ N.}
\end{align*} \]

or \[ \sum F_x(\text{system}) = (\sum m) a_x \]

\[ \begin{align*}
mg - T + T &= (M + m)a \\
\Rightarrow a &= \frac{m}{M + m} g
\end{align*} \]

Note that direction of motion is taken to be +ve.
5.9: Applying Newton’s Laws: two blocks connected by a cord

Example: Two objects of masses \( m_1 \) and \( m_2 \) are attached by a lightweight cord that passes over a frictionless pulley of negligible mass as shown. Find the
a) magnitude of the acceleration of the two objects and
b) the tension in the cord.

From \( m_1 \)

\[
\sum F_y = T - m_1 g = m_1 a_y = m_1 a \quad (1)
\]

Ex: Two Objects Connected by a Cord

From \( m_2 \)

\[
\sum F_x = m_2 g \sin \theta - T = m_2 a_x = m_2 a \quad (2)
\]

From (1) \( T = m_1 (g + a) \) Sub in (2)

\[
m_2 g \sin \theta - m_1 (g + a) = m_2 a
\]

\[
a = \frac{m_2 g \sin \theta - m_1 g}{m_1 + m_2}
\]

Sub. In (2) \( T = \frac{m_1 m_2 g (\sin \theta + 1)}{m_1 + m_2} \)