Chapter 5
Newton’s Laws of Motion

We will study classical motion:
• No quantum mechanics
• No relativity

We introduce the concept of force and define it in terms of the acceleration of a “standard body”
Intuitively, we know that force is a “push” or “pull”. Forces come in different classes (types):

- **Contact**
  - Macroscopic forces of contact friction, viscosity, the contact force from the floor supporting my feet).

- **Field** (originally described as action-at-a-distance)
  - Examples: Gravity, Electromagnetism

**Force** $\mathbf{F}$ is a vector quantity: You push or pull in a specific direction

$\mathbf{F}$

If force has direction, what is it’s measure?

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**The Empirical ‘Feel’ of Forces**

- We have a direct sensation of the forces that act on our body.
  - As I stand on the floor, I feel my shoes pushing up on my feet. The nerves in the soles of my feet transmit this feeling to my brain.
  - The nerves in our joints also give us a sense of the weight of our bodies.
  - If you hit your toe (or worse) you feel the force against your toe.
What is the connection between Force and Motion? (Dynamics)

• The ancient Greeks, especially Aristotle, had a very elegant philosophy of nature:
  ▪ Four elements: Earth, Air, Fire, Water
  ▪ Two Forces: Gravity, Levity
  ▪ Gravity pulled earth and water down, Levity pushed Fire and Air up.
• To Aristotle (and perhaps to our common sense) *everything tended to its natural state*. For material objects (earth & water) the natural state was at rest.
  ▪ To use modern language, friction was seen as part of the fabric of space time.
• It was Galileo who suggested that friction was not essential, but rather subject to technological manipulation (and ideally elimination).

In 1686, Newton presented The Laws of Motion:

Newton’s First Law
An object at rest remains at rest, and an object in motion continues in motion with constant velocity, unless it experiences a net force.

Velocity = constant (acceleration = 0) if there is no force (or if all forces add to zero).
Remember, Velocity = constant does not mean velocity = 0.
Examples

1. An object that is moving and that continues to move with constant velocity without any force acting on it.
   • A hockey puck sliding (almost without friction) across the ice

2. An object at rest that remains at rest.

3. What about pushing a chair?
   • If the floor pushes just as hard (friction) the net force (vector sum) is zero.

4. What happens when you turn a corner quickly in your car?
   • The car would continue straight ahead unless the friction from the road pushes inwards to guide the car around the circle.

We know from experience that different objects resist a change in motion differently.

Example:
• push a door
• push a semi-trailer

⇒ Not the same response!
Inertia

The tendency of an object to resist a change in its velocity is called inertia.

The measure of inertia is mass.

- SI units measure mass as multiples of the standard kilogram (kg=1000g) stored at the International Bureau of Weights and Measures in Sèvres, France.

Newton’s First Law tells us about motion if $F = 0$

What if $F \neq 0$?

Newton’s Second Law

The acceleration of an object is directly proportional to the resultant force acting on it and inversely proportional to its mass. The direction of the acceleration is the direction of the resultant force.

$$F = ma$$
\[ F_{\text{Net}} = ma \]

Implicit and explicit meaning

- Force is a vector
  - The net force is the vector sum of all forces acting on the object \( m \).
- Mass is a scalar:
  - The value of the mass of an object does not change with the direction of the acceleration.
- Mass is invariant:
  - If two objects are put together (or separated), the mass of the combined object is simply the arithmetic sum of the two masses \( m = m_1 + m_2 \).
  - Chemical combination, welding, cutting does not change mass.
    - Einstein corrected this, but Relativistic effects are small for ordinary matter.
- Force can be quantified by measuring the acceleration it produces on a standard kilogram (or any multiple thereof).

Example

An object of mass 5 kg undergoes an acceleration of \([8 \text{ m/s}^2 \hat{y}] = 8 \text{ m/s}^2 \) in +y direction

What is the force on that object?

\[ F = ma \]
\[ = (5 \text{ kg})(8 \text{ m/s}^2) \hat{y} = 40 \text{ kg} \cdot \text{m/s}^2 \hat{y} \]
\( \hat{y} \) = vector on unit length (no dimensions) in +y direction.

The force is in the same direction as the acceleration.
Units

The SI unit of Force is the Newton defined as:

\[ 1 \text{ N} = 1 \text{ kg} \cdot \text{m/s}^2 \]

Notice pounds and kilograms do not directly convert.
The British unit of mass is the slug (don’t ask).
The force of gravity (near Earth’s surface) acting on a 1 kg mass is 2.2 lb.:

\[ (1.0 \text{ kg}) \cdot (g) = 2.2 \text{ lb.} \]

Do not confuse g=gram with \( g=9.8 \text{m/s}^2 \)=acceleration due to gravity.

Problem 1

A catcher stops a 92 mi/h pitch in his glove, bringing it to rest (with uniform deceleration) in 0.15 m. If the force exerted by the catcher is 803 N, what is the mass of the ball? (1 mi =1609 m)
Newton’s Third Law

If object 1 exerts a force $F$ on object 2, then object 2 exerts a force $-F$ on object 1.

- Forces come in pairs.
- The force pairs act on different objects.
- The forces have the same magnitude but opposite direction.

Example: I push on the wall with a force of 20 N. The wall pushes back on me with a force of 20 N in the opposite direction.

Problem 2

A force of magnitude 7.50 N pushes three boxes with masses $m_1 = 1.30$ kg, $m_2 = 3.20$ kg, and $m_3 = 4.90$ Kg, as shown in the Figure. (crucial assumption omitted in the problem: no friction!) Find the contact force between (a) boxes 1 and 2, and (b) between boxes 2 and 3.

(a) $F_{21} = F_{12} = 6.46$ N
(b) $F_{23} = F_{32} = 3.91$ N
A MAC truck and a Honda Civic have a head-on collision.

Which vehicle experiences the greatest force?
Which vehicle experiences the greater acceleration?

The Vector Nature of Forces

In the formula $F = ma$, $F$ is the total (net) force acting on the object. We must consider the vector sum of all forces acting on an object. We can also consider each dimension separately:

$$\sum F_x = ma_x$$
$$\sum F_y = ma_y$$
$$\sum F_z = ma_z$$
Problem 3
A farm tractor tows a 4400-kg trailer up a 21° incline at a steady speed of 3.0 m/s. What force does the tractor exert on the trailer? (Ignore friction.)

Weight

The weight of any object on the Earth is the gravitational force exerted on it by the Earth:

$$ W = mg $$

Note:

*Weight is a force* (and therefore a vector).
*Weight is not equivalent to mass.*

Can a person’s weight be zero?

When we say we want to “lose weight”, what do we really mean?
Apparent Weight

Our sensation of weight comes from the force of the floor pushing up on us. We can feel light or heavy if the floor is accelerating down or up. The upward force of the floor on our feet is known as apparent weight $W_a$.

*It is your apparent weight that is measured on a scale.*

Problem 4

As part of a physics experiment, you stand on a bathroom scale in an elevator. Though your normal weight is 610 N, the scale at the moment reads 730 N.

(a) Is the acceleration of the elevator upward, downward, or zero?

(b) Calculate the magnitude of the elevator’s acceleration.
Normal Forces

Normal means perpendicular.

The normal force is a contact force and is perpendicular to the surface between the two objects in contact.

The table and the box are compressing each other’s atoms slightly, like springs.

The box pushes down on the table and the table pushes up on the box. These two forces are reaction pairs.

If you lean against the wall, the normal force from the wall is horizontal. When the cart rolls down the incline in your physics lab, the normal force is perpendicular to the incline.

Motion on an Incline

Frictionless

- Cart rolls without friction on incline
- Find the acceleration of the cart (as a function of θ).
- Draw a coordinate system parallel to incline
- x,y-components of gravity
  - $W_x = -mg \sin(\theta)$
  - $W_y = -mg \cos(\theta)$
Problem 5

A shopper pushes a 8.7 kg shopping cart up a 13° incline, as shown in Figure 5-21. Find the horizontal force, $F$, needed to give the cart an acceleration of 1.21 m/s$^2$.

Problem 6

To give a 18 kg child a ride, two teenagers pull on a 3.4 kg sled with ropes, as indicated in Figure 5-23. Both teenagers pull with a force of $F = 53$ N at an angle of 35° relative to the forward direction, which is the direction of motion. In addition, the snow exerts a retarding force on the sled that points opposite to the direction of motion, and has a magnitude of 57 N. Find the acceleration of the sled and child.