

Chapter 4

Newton's Laws

Ch. 2 and 3 were about motion itself in one and two dimensions. In Ch. 4 we will study “Why things move?”

Dynamics

The Concepts of Force and Mass

Force A push or a pull

Contact forces

arise from physical contact

Non-contact forces OR

Action-at-a-distance forces

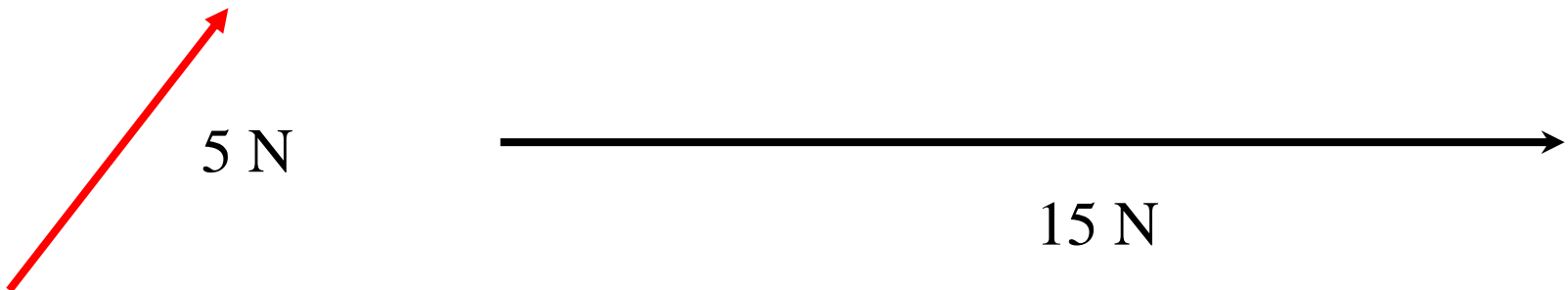
do not require contact

Examples: gravity,
electrical and magnetic
forces

Is force a **Vector** or **Scalar**? **Vector**

SI Units of force? **Newton**

Arrow can be used to represent a force. The length of the arrow is proportional to the magnitude of the force.



The Concepts of Force and Mass

Mass

is a measure of the amount of “stuff” contained in an object.

SI Units of mass?

kg

Is mass a scalar or vector quantity?

Scalar

4.2 Newton's First Law of Motion

Newton's First Law

An object continues in a state of rest or in a state of motion at a **constant speed along a straight line**, unless compelled to change that state by a net force.

constant velocity

Law of Inertia

- You need a net force to change the velocity of an object.
- No force is required to keep things moving with constant velocity.

Net Force? The **net force** is the vector sum of all of the forces acting on an object.

Whenever there is a net force on an object, there must be acceleration in that object.

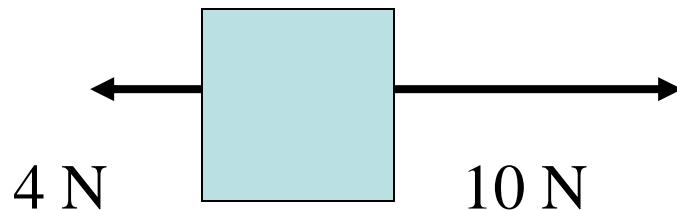
Newton's First Law of Motion

Net Force

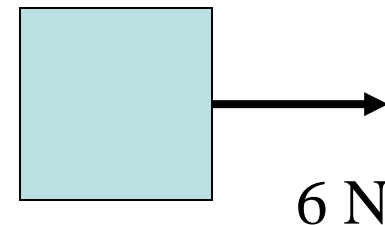
The net force on an object is the vector sum of all forces acting on that object.

The SI unit of force is Newton (N).

Individual Forces

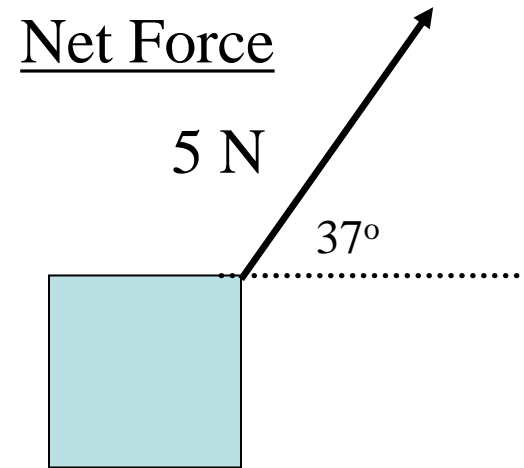
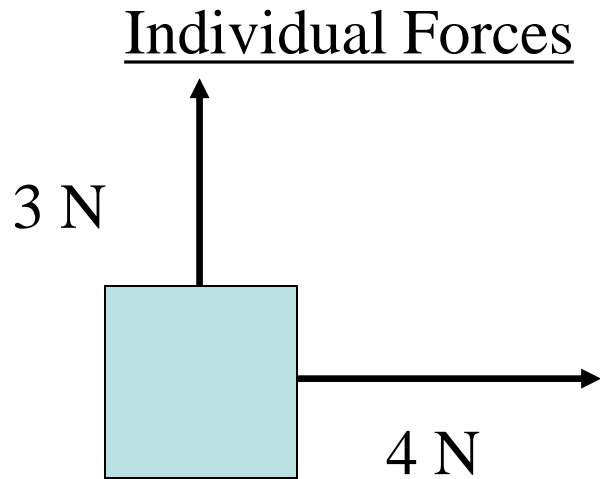


Net Force



Newton's First Law of Motion

More examples:



Mathematically, the net force is written as $\sum \vec{F}$

where the Greek letter sigma denotes the vector sum.

Is it possible that more than one force acting on an object but net force be zero?

YES

Newton's Second Law of Motion

First Law “whenever there is a net force on an object, there must be acceleration in that object”

Newton's Second Law

When a **net external force** acts on an object of mass m , the acceleration that results is directly proportional to the net force and is inversely proportional to the mass. The direction of the acceleration is the same as the direction of the net force.

Mathematically

$$\vec{\mathbf{a}} = \frac{\sum \vec{\mathbf{F}}}{m} \quad \longrightarrow \quad \sum \vec{\mathbf{F}} = m\vec{\mathbf{a}} \quad \vec{\mathbf{F}} = m\vec{\mathbf{a}}$$

Heart of Newtonian Physics

Newton's Second Law of Motion

SI Unit for Force

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

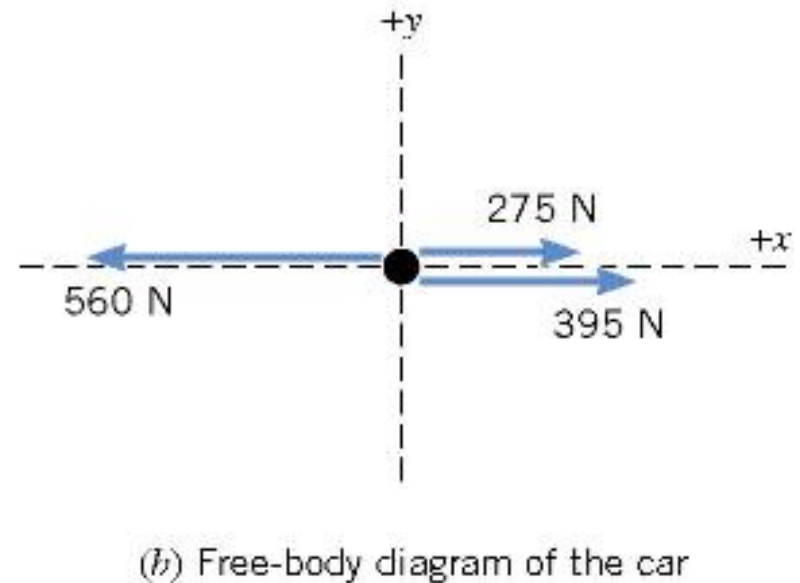
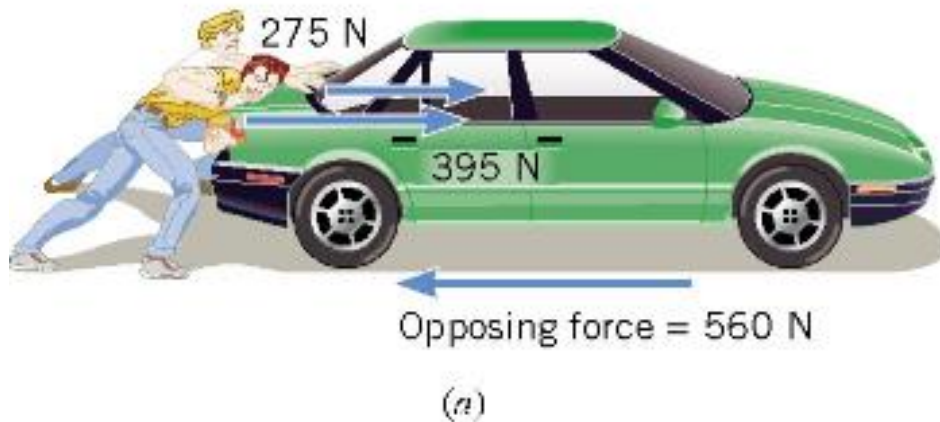
$$(\text{kg})\left(\frac{\text{m}}{\text{s}^2}\right) = \frac{\text{kg} \cdot \text{m}}{\text{s}^2}$$

This combination of units is called a *Newton* (N).

$$1N = 1\frac{\text{kg} \cdot \text{m}}{\text{s}^2}$$

Newton's Second Law of Motion

A *free-body-diagram* is a diagram that represents the object and the forces that act on it.



The net force in this case?

$$275 \text{ N} + 395 \text{ N} - 560 \text{ N} = +110 \text{ N}$$

and is directed along the + x-axis of the coordinate system.

Newton's Second Law of Motion

If the mass of the car is 1850 kg then, by Newton's second law, the acceleration is

$$a = \frac{\sum F}{m} \quad \Rightarrow \quad a = \frac{110N}{1850kg}$$

$$0.059 \text{ m/s}^2$$

Direction of acceleration?

Same as direction
of Net Force

The Vector Nature of Newton's Second Law

The direction of force and acceleration vectors can be taken into account by using x and y components.

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

is equivalent to

$$\sum F_x = ma_x \qquad \sum F_y = ma_y$$

Q. A car rounds a curve while maintaining a constant speed. Is there a net force on the car as it rounds the curve?

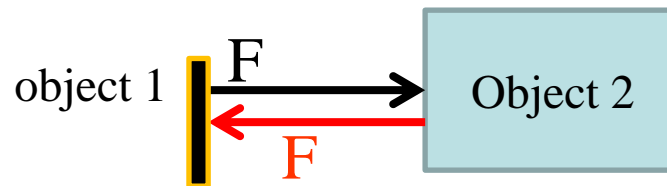
- a. No
- b. Yes
- c. Impossible to tell

Q. Which one of the following situations is **not possible**

- a. A body has zero acceleration and a non zero velocity
- b. A body travels with Northward velocity and a southward acceleration
- c. A body travels with Northward velocity and a Northward acceleration
- d. A body has a constant velocity and non zero acceleration

Newton's Third Law of Motion


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



$$\vec{\mathbf{F}} = -\vec{\mathbf{F}}$$

- Here the net force on object 2 is **F** and is responsible for **acceleration** of object 2.
- While the net force on object 1 is **F** and hence produces **acceleration** in object 1.

Newton's Third Law of Motion

1st Law  A net non zero force is required to change the velocity of an object.

2nd Law  What happens when there is a net non-zero force applied?

The results is acceleration

$$\vec{\mathbf{a}} = \frac{\sum \vec{\mathbf{F}}}{m} \quad \text{OR} \quad \sum \vec{\mathbf{F}} = m\vec{\mathbf{a}}$$

3rd Law  Where the force/s coming from?

Idea of Gravity

Newton saw an apple falling from tree while moon stayed in the sky

- Both moon and apple were more or less round
- Apple is on earth and moon is in the sky
- Apple falls to the ground while moon stays aloft

But Newton saw the similarity

Although velocities of apple and moon are different, forces on two may be similar.

He was interested in Forces

How do the forces compare?

1st Law Force is required in order for moon to deviate from straight line motion

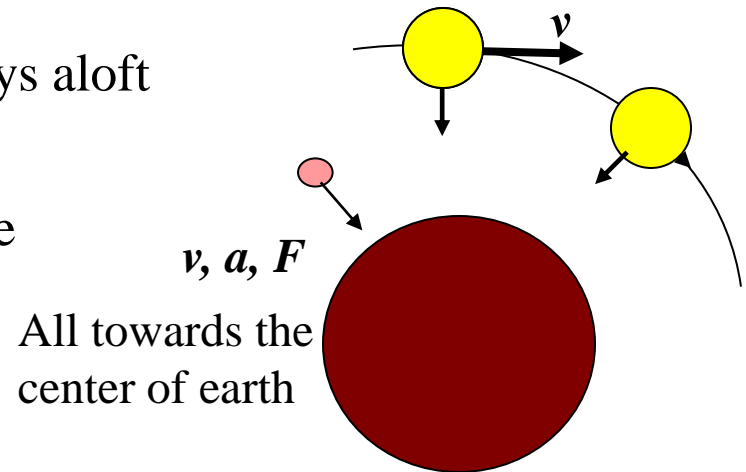
What is the direction of force? If there were no force Moon would move straight

Moon does two things:

- Its inertia keeps it moving forward in straight line
- Simultaneously pulled towards earth: It also falls

Force must be directed towards earth just like the force on apple.

Both forces must have same source -- Gravitational attraction



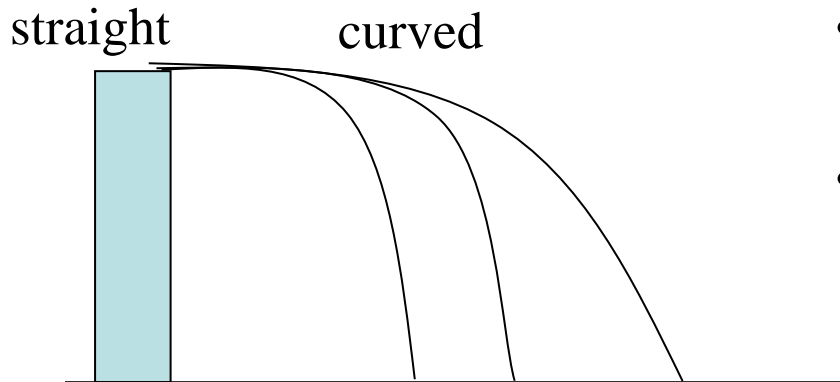
Although the velocity of a falling apple and the moon are quite different, the acceleration of both are directed towards the center.

True for all objects moving in circle

Then why moon or other objects stay up?

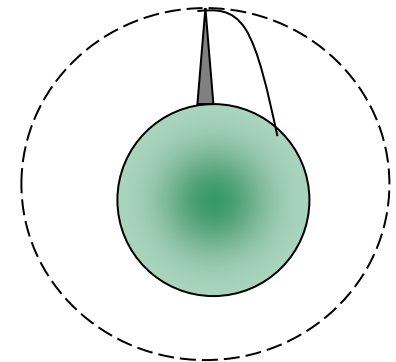
Newton's Law of Universal Gravitation

If you throw a ball horizontally, what will be its path



- Larger the horizontal velocity, farther from the base, the ball will land
- At very large velocities the curvature of earth becomes significant.

If the launch velocity is large enough, the projectile would never reach the surface of the earth. It keeps falling, but earth's curvature falls away too. You need a speed of 8 km/s (29000 MPH).



Newton's view: Moon is actually falling, just as a projectile does. The same force that accounts for the acceleration of object near the surface of earth, explains the orbit of the moon.

- Moon is planet of earth and Earth is planet of sun.
- Planets keep moving forward because of inertia. The sun's gravitational pull bends their orbit into ellipses.
- 3rd Law (of force pairs) → every satellite must also pull back. That is gravitational pulls on both bodies.
- All the satellites must also be pulling each other (Earth and Mars).

Why the gravity be restricted to astronomical bodies.
It should also be between smaller bodies?

Gravitational force is universal

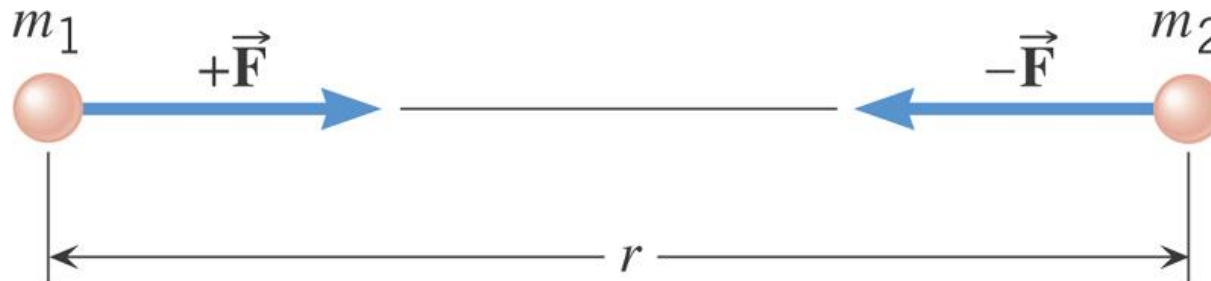
All Laws of Physics are universal

The Gravitational Force

Newton's Law of Universal Gravitation

Every particle in the universe exerts an attractive force on every other particle.

A **particle** is a piece of matter, small enough in size to be regarded as a mathematical point.



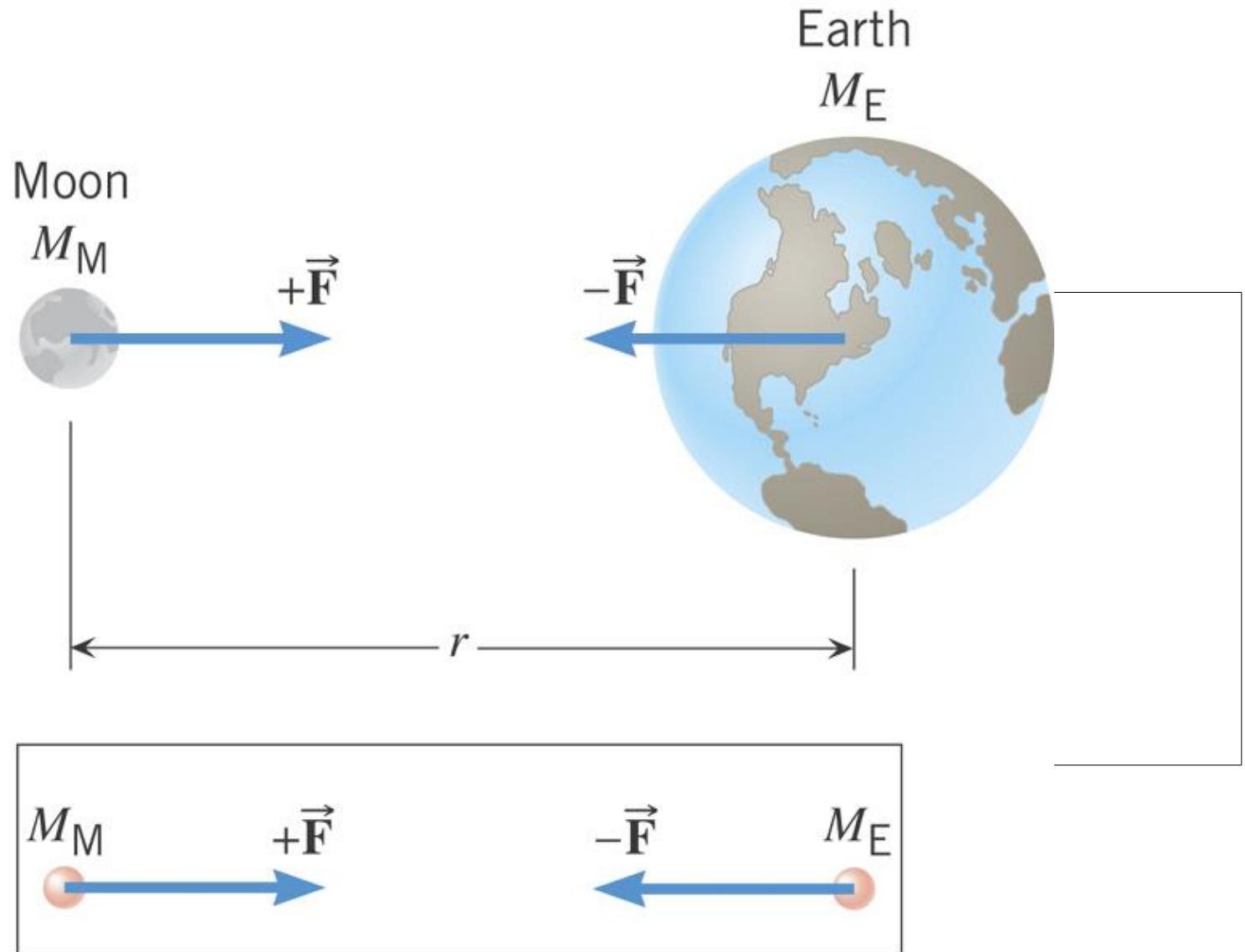
For two particles that have masses m_1 and m_2 and are separated by a distance r , the force has a magnitude given by

$$F = G \frac{m_1 m_2}{r^2}$$

$$G = 6.673 \times 10^{-11} \text{ N} \cdot \text{m}^2 / \text{kg}^2$$

Universal Gravitational Constant

The Gravitational Force



Definition of Weight

The weight of an object on or above the earth is the gravitational force that the earth exerts on the object.

The weight acts toward the center of the earth.

SI Unit of Weight?

Newton (N)

On or above another astronomical body, the weight is the gravitational force exerted on the object by that body towards the center of that astronomical body.

The Gravitational Force

Relation Between Mass and Weight

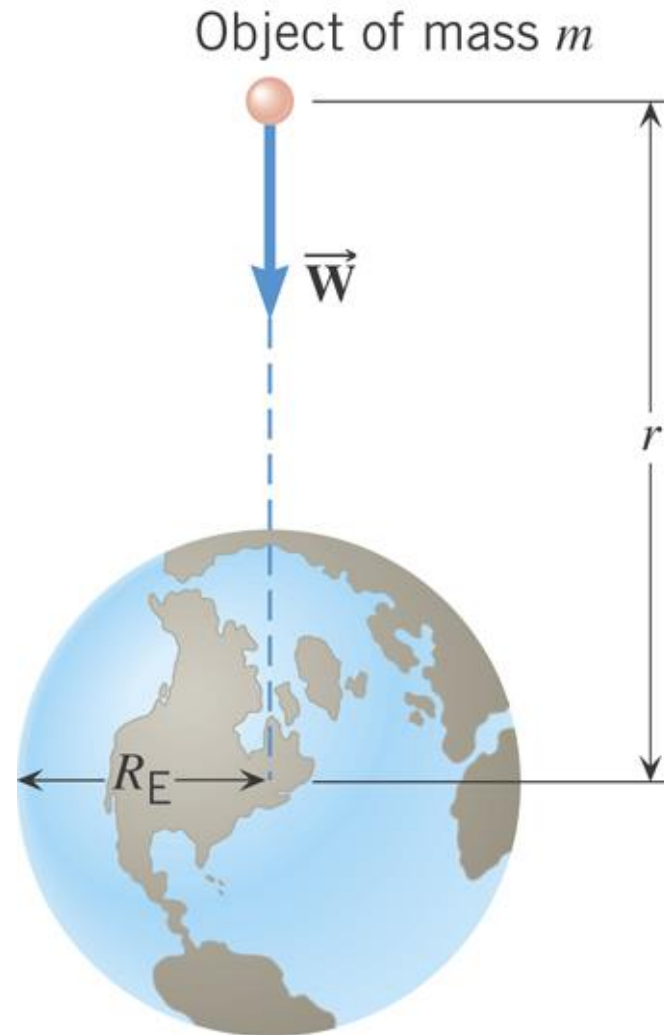
$$W = G \frac{M_E m}{r^2}$$

$$F = ma$$

$$W = mg$$

Both must be equal

$$g = G \frac{M_E}{r^2}$$

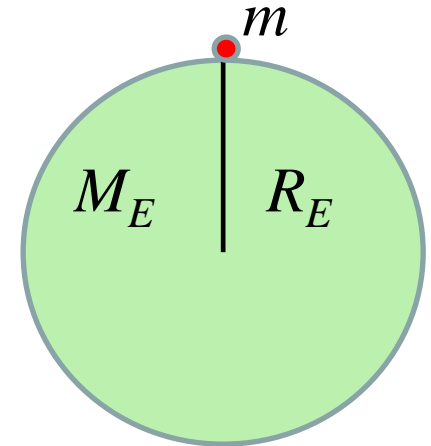


4.7 The Gravitational Force

On the earth's surface:

$$mg = G \frac{mM_E}{R_E^2}$$

$$g = G \frac{M_E}{R_E^2}$$



$$= \left(6.67 \times 10^{-11} \text{ N} \cdot \text{m}^2 / \text{kg}^2\right) \frac{\left(5.98 \times 10^{24} \text{ kg}\right)}{\left(6.38 \times 10^6 \text{ m}\right)^2}$$

$$g = 9.8 \frac{\text{m}}{\text{s}^2}$$

Forces

```
graph TD; Forces[Forces] --> Fundamental[Fundamental]; Forces --> NonFundamental[Non-Fundamental];
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Fundamental

Non-Fundamental

Result of fundamental Forces

1. Gravitational
2. Strong Nuclear
3. Electro-weak

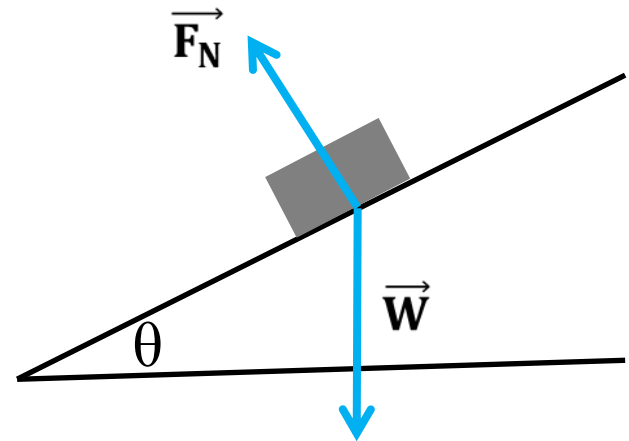
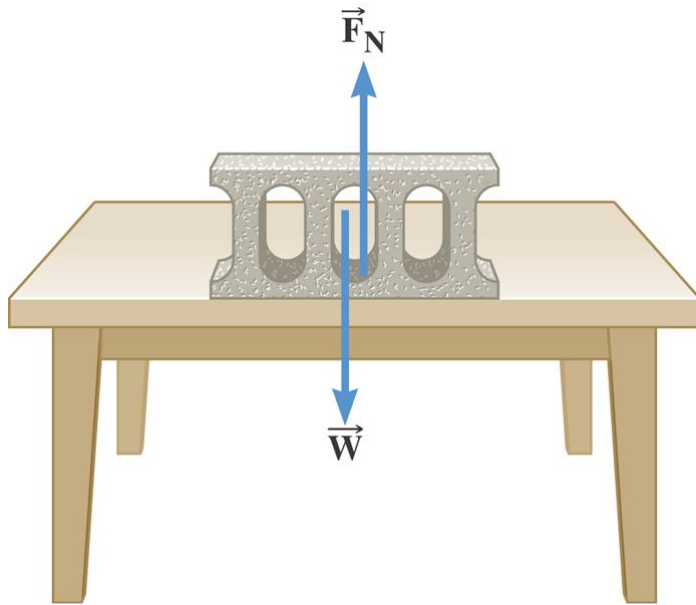
- Electromagnetic
- Nuclear Weak

- Frictional force
- Normal force
- Tension
- Centripetal force, etc

The Normal Force

Normal Force

The normal force is one component of the force that a surface exerts on an object with which it is in contact – namely, the component that is perpendicular to the surface.



The Normal Force

If there is no acceleration in vertical direction

$$\sum F_y = ma_y = 0$$

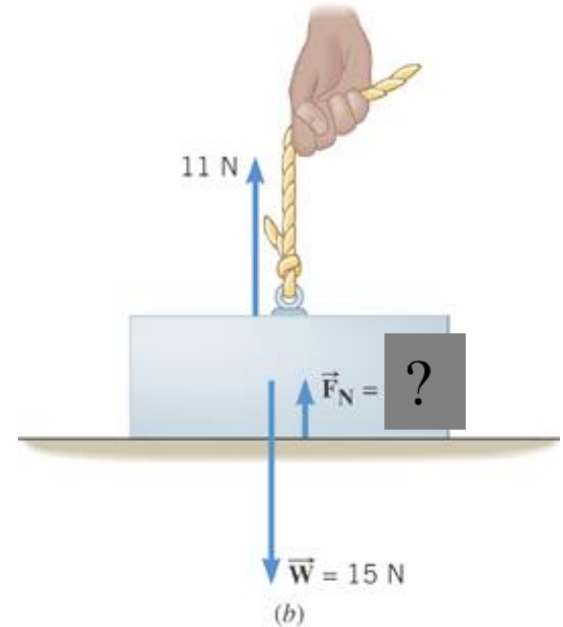
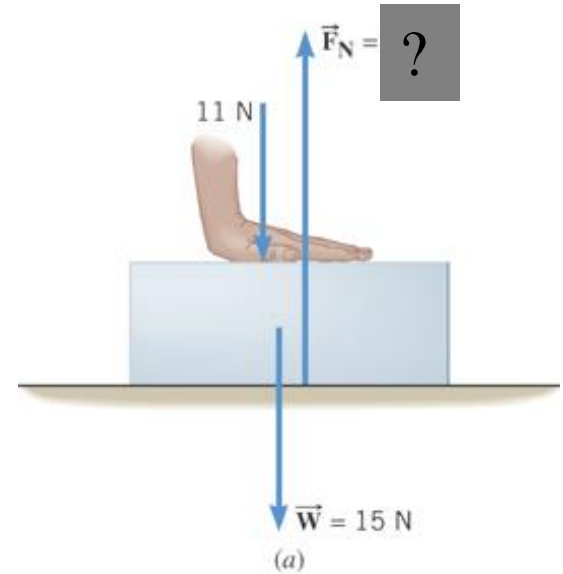
$$F_N - 11 \text{ N} - 15 \text{ N} = 0$$

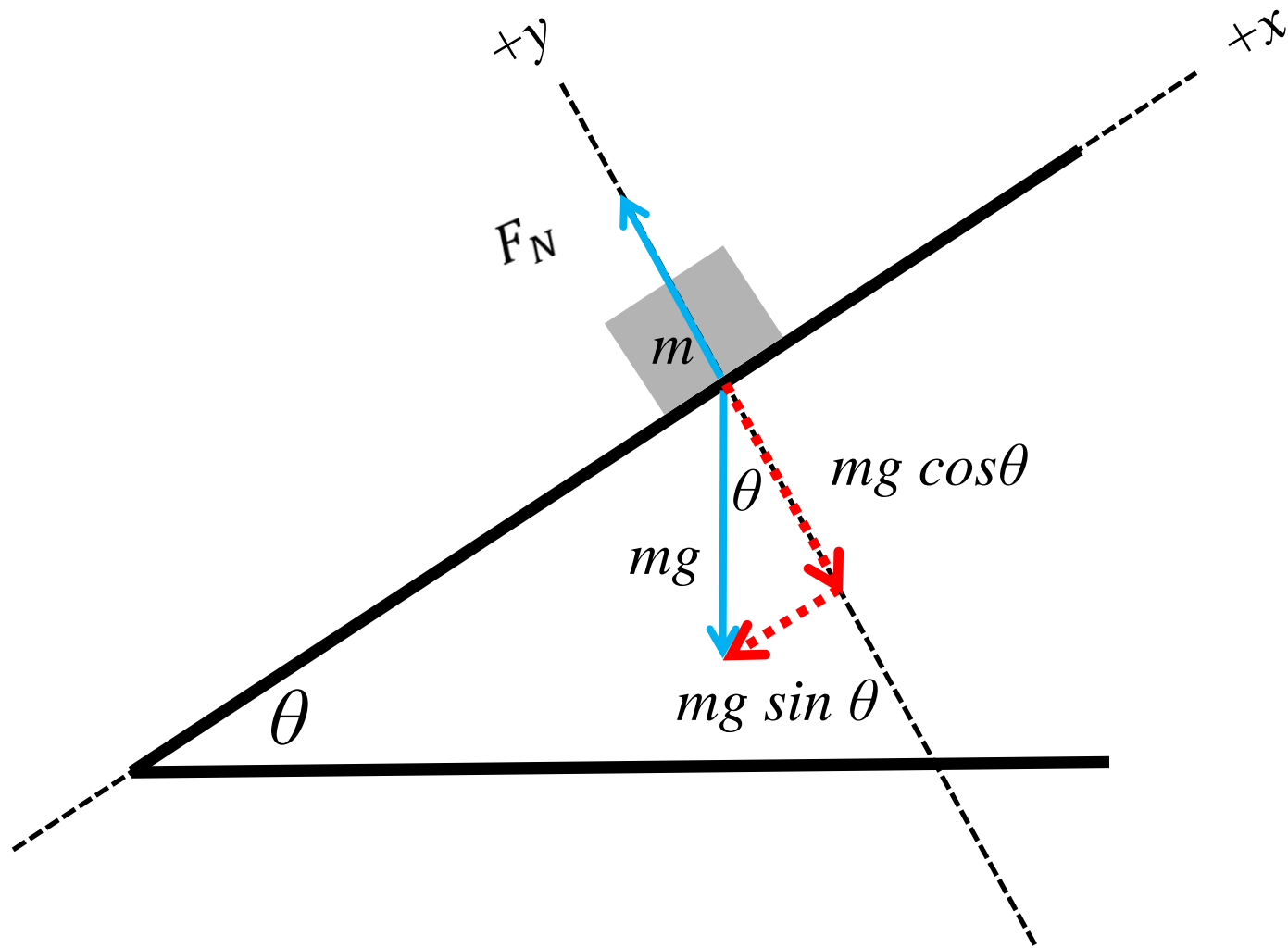
$$F_N = 26 \text{ N}$$

Similarly

$$F_N + 11 \text{ N} - 15 \text{ N} = 0$$

$$F_N = 4 \text{ N}$$





Along y-axis

$$F_N - mg \cos \theta = 0$$

$$F_N = mg \cos \theta$$

Apparent weight

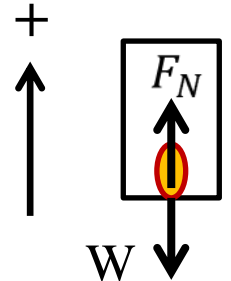
In an elevator

- **accelerated upward** with acceleration of a

$$\sum F = F_N - w \quad \Rightarrow \quad ma = F_N - w$$

$$F_N = w + ma$$

F_N is apperant weight
 w is real weight



Apparent weight is more than real weight

- **accelerated downward** with acceleration of a

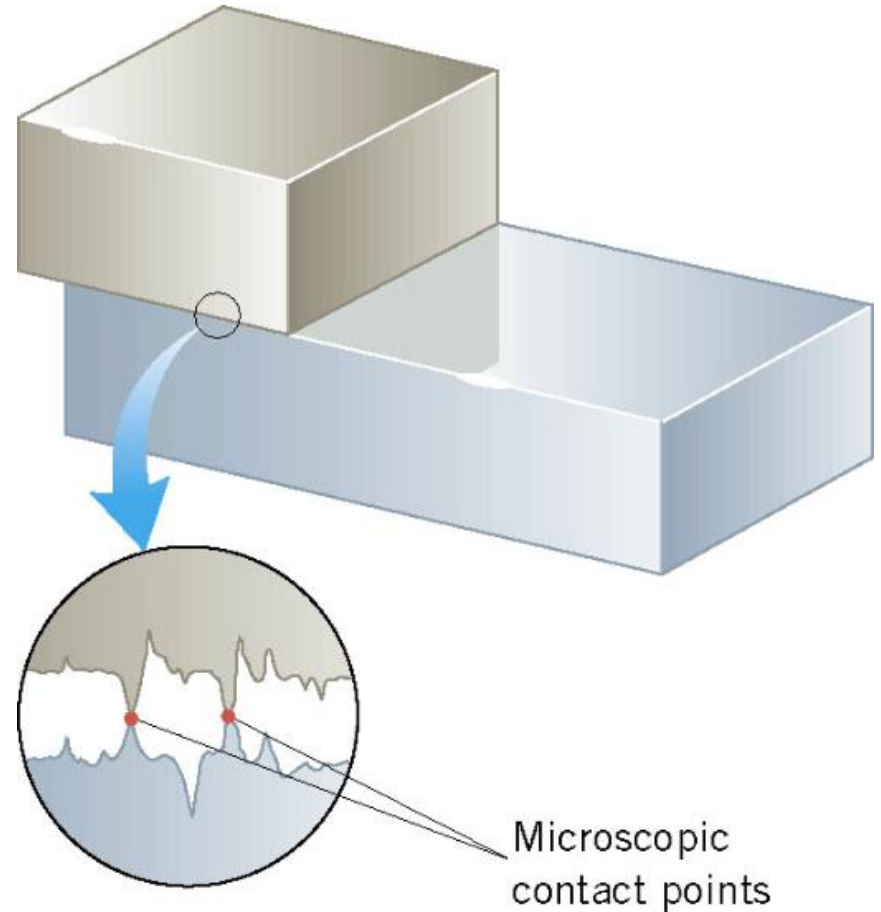
$$\sum F = F_N - w \quad \Rightarrow \quad -ma = F_N - w$$

$$F_N = w - ma$$

Apparent weight is less than real weight

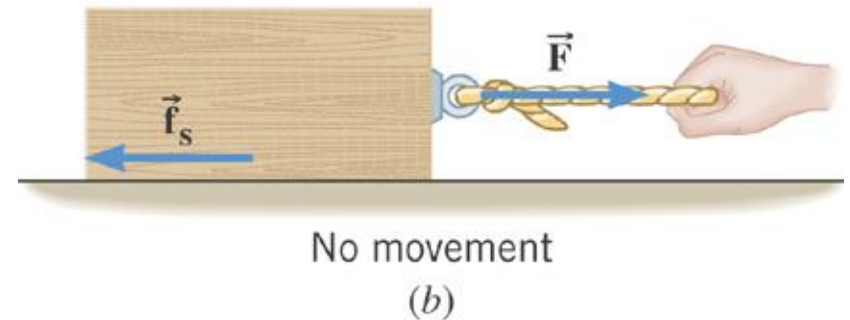
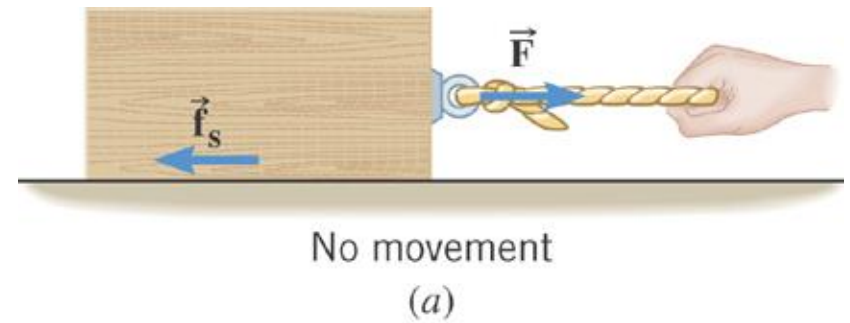
Frictional Force

When an object is in contact with a surface there is a force acting on that object. The component of this force that is parallel to the surface is called the ***frictional force***.

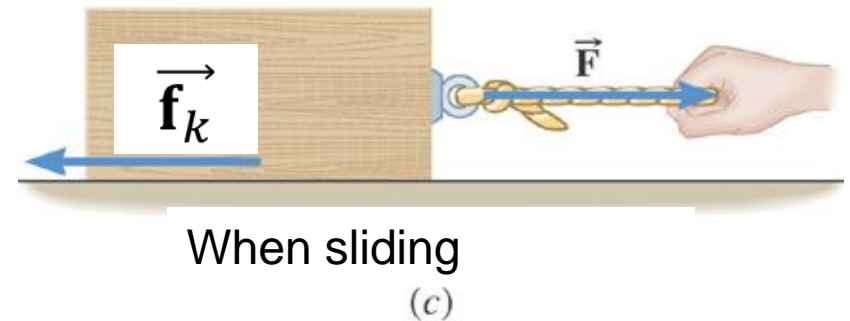


Static and Kinetic Frictional Forces

When the two surfaces are not sliding across one another the friction is called *static friction*.



When the two surfaces are sliding across one another the friction is called *Kinetic friction*, \vec{f}_k



4.9 Static and Kinetic Frictional Forces

The magnitude of the static frictional force can have any value from zero up to a maximum value.

$$f_s \leq f_s^{MAX}$$

$$f_s^{MAX} = \mu_s F_N$$

$\mu_s \geq 0$ is called the coefficient of static friction.

Larger the magnitude of Normal Force, larger the friction

Static and Kinetic Frictional Forces

Static friction opposes the *impending* relative motion between two objects.

$$f_s^{MAX} = \mu_s F_N$$

$\mu_s \geq 0$ is called the **coefficient of static friction**.

Kinetic friction opposes the relative sliding motion motions that actually does occur.

$$f_k = \mu_k F_N$$

$0 \leq \mu_k$ is called the **coefficient of kinetic friction**.

Static and Kinetic Frictional Forces

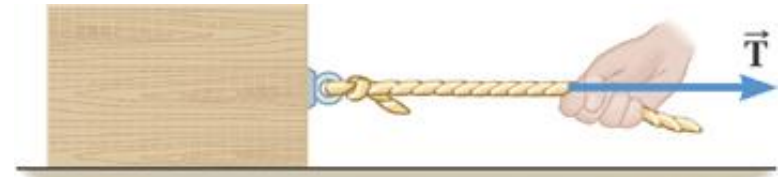
Table 4.2 Approximate Values of the Coefficients of Friction for Various Surfaces*

Materials	Coefficient of Static Friction, μ_s	Coefficient of Kinetic Friction, μ_k
Glass on glass (dry)	0.94	0.4
Ice on ice (clean, 0 °C)	0.1	0.02
Rubber on dry concrete	1.0	0.8
Rubber on wet concrete	0.7	0.5
Steel on ice	0.1	0.05
Steel on steel (dry hard steel)	0.78	0.42
Teflon on Teflon	0.04	0.04
Wood on wood	0.35	0.3

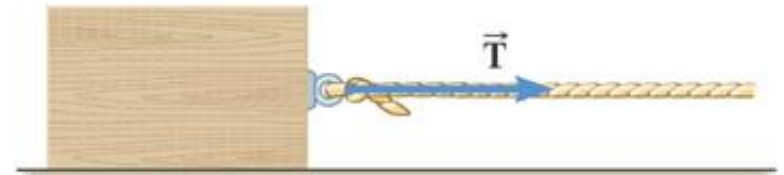
*The last column gives the coefficients of kinetic friction, a concept that will be discussed shortly.

Tension

Cables and ropes transmit forces through *tension*.



(a)



(b)



(c)

Strategy

- Select an object(s) to which the equations are to be applied.

Equilibrium $\sum F = ma = 0$

- Draw a free-body diagram for each object chosen above. Include only forces acting on the object, not forces the object exerts on its environment.
- Choose a set of x , y axes for each object and resolve all forces in the free-body diagram into components that point along these axes.
- Apply the equations and solve for the unknown quantities.

Newtonian Physics

Laws of Motion

First Law or Law of Inertia

In absence of any external force, an object will not be accelerated

2nd Law

acceleration = Net Force / mass

3rd Law

Action and reaction are always equal but opposite in direction

Newton's Law of Universal gravitation

Fundamental forces

Non Fundamental forces

Concepts

Speed

Velocity

Acceleration

Inertia

Mass weight

Force

Equations of motion

For Recitation Practice

Chapter 4: FOC 1, 3, 12 & 16.

Problems 3, 5, 11, 16, 24, 38, 52, 77, 78 & 98.