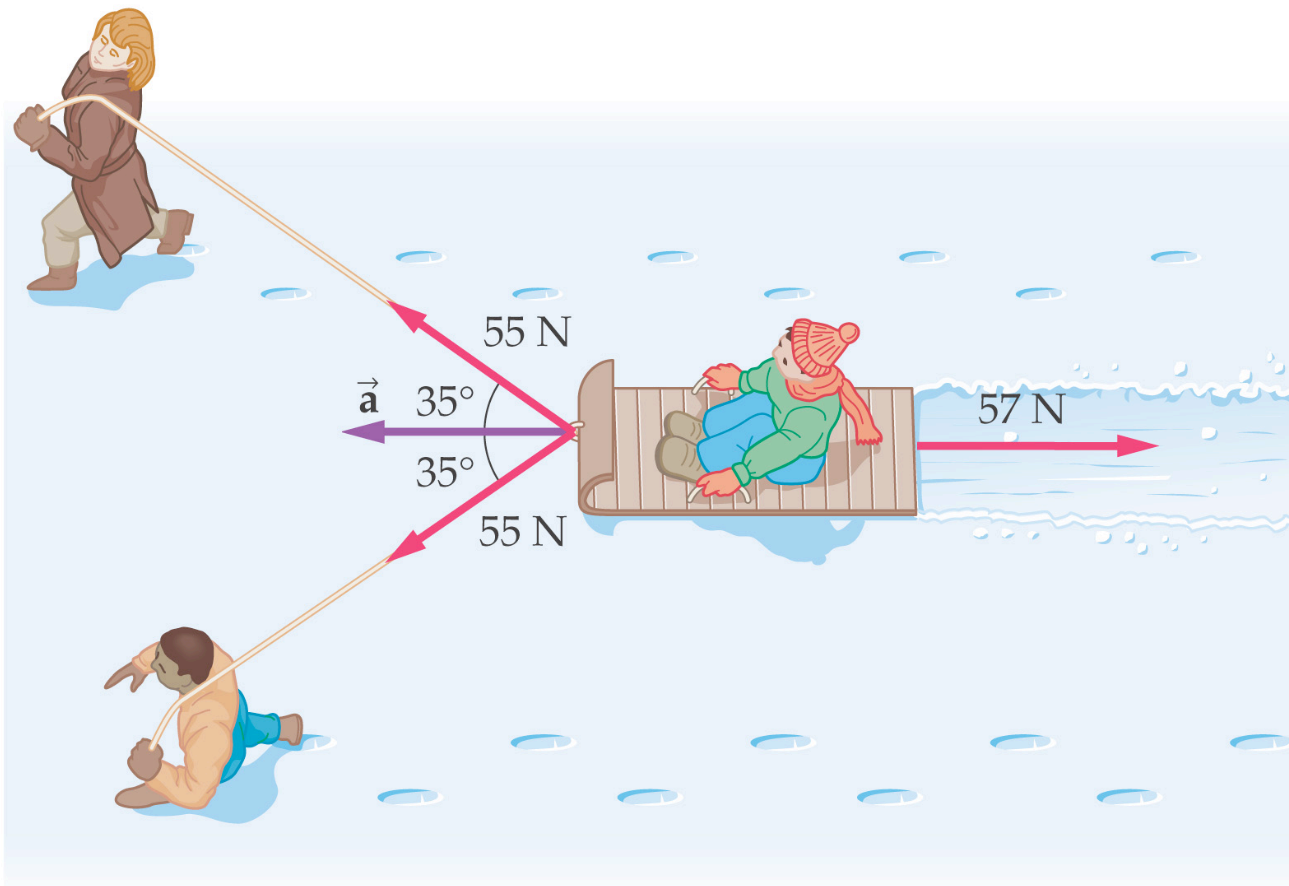
Chapter 5

Newton’s Laws of Motion



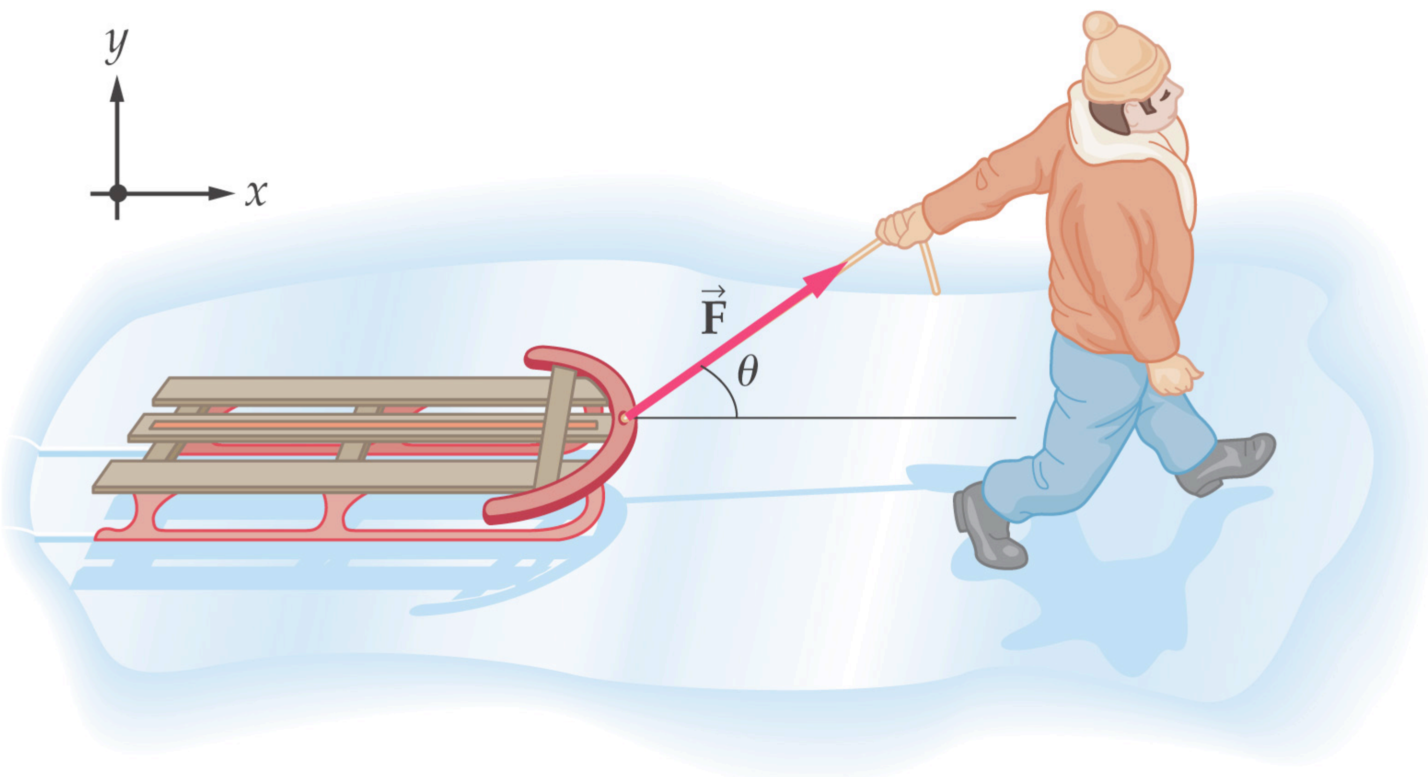
Units of Chapter 5

- Force and Mass
- Newton’s First Law of Motion
- Newton’s Second Law of Motion
- Newton’s Third Law of Motion
- The Vector Nature of Forces: Forces in Two Dimensions
- Weight
- Normal Forces

5-1 Force and Mass

Force: push or pull

Force is a vector – it has magnitude and direction



5-1 Force and Mass

Mass is the measure of how hard it is to change an object's velocity.

Mass can also be thought of as a measure of the quantity of matter in an object.

TABLE 5–1
Typical Masses in Kilograms (kg)

Earth	5.97×10^{24}
Space Shuttle	2,000,000
Blue whale (largest animal on Earth)	178,000
Whale shark (largest fish)	18,000
Elephant (largest land animal)	5400
Automobile	1200
Human (adult)	70
Gallon of milk	3.6
Quart of milk	0.9
Baseball	0.145
Honeybee	0.00015
Bacterium	10^{-15}

5-2 Newton’s First Law of Motion

If you stop pushing an object, does it stop moving?

Only if there is friction! In the absence of any net external force, an object will keep moving at a constant speed in a straight line, or remain at rest.

This is also known as the law of inertia.

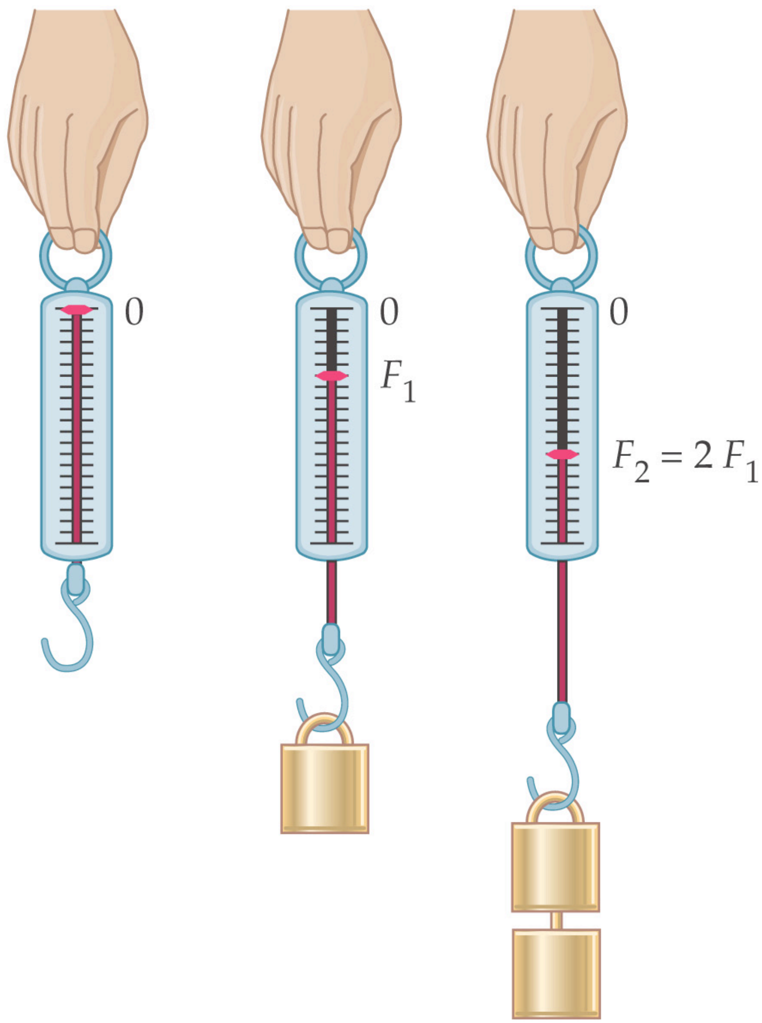
5-2 Newton's First Law of Motion

In order to change the velocity of an object – magnitude or direction – a net force is required.

An inertial reference frame is one in which the first law is true. Accelerating reference frames are not inertial.

5-3 Newton's Second Law of Motion

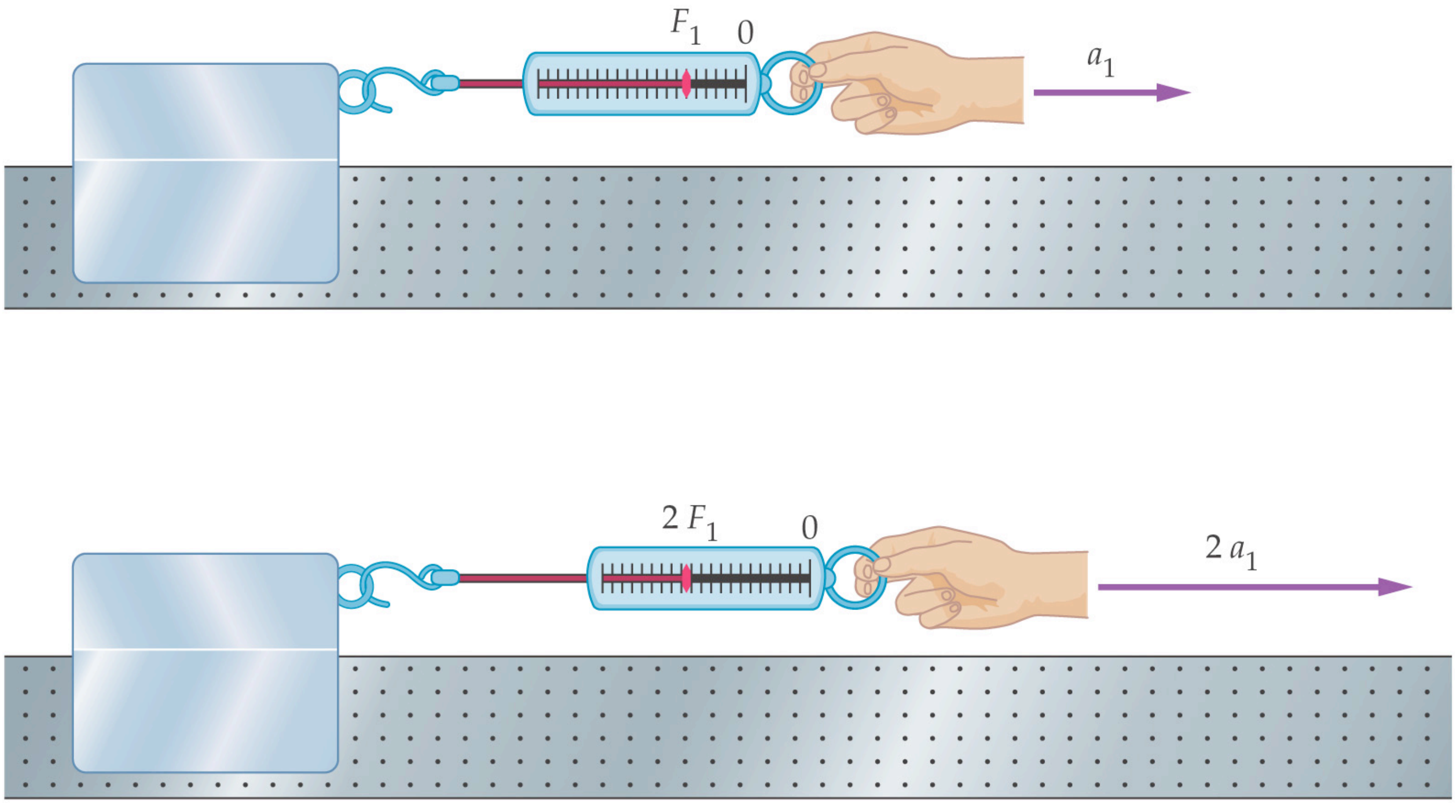
Two equal weights exert twice the force of one; this can be used for calibration of a spring:



5-3 Newton's Second Law of Motion

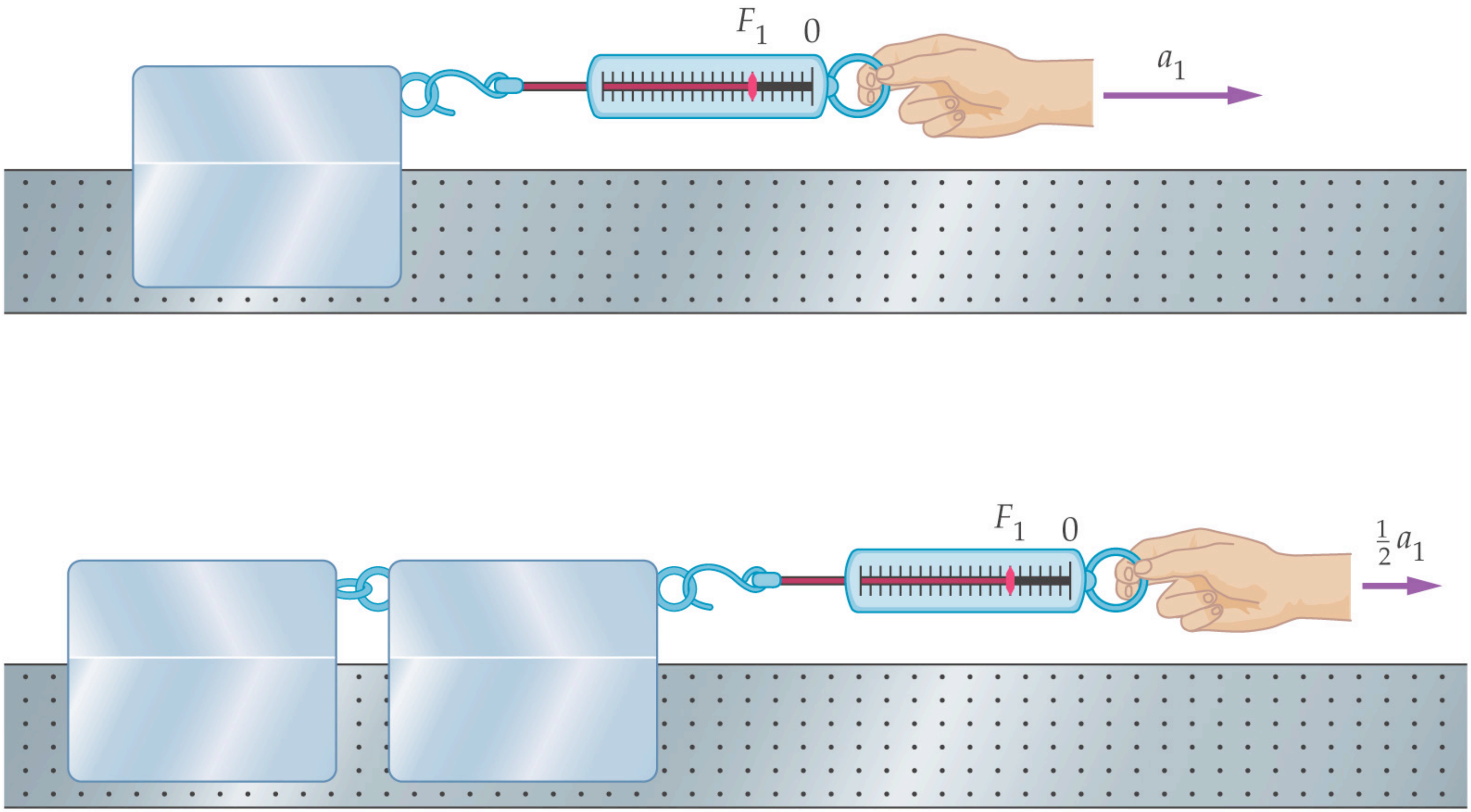
Now that we have a calibrated spring, we can do more experiments.

Acceleration is proportional to force:



5-3 Newton's Second Law of Motion

Acceleration is inversely proportional to mass:



5-3 Newton's Second Law of Motion

Combining these two observations gives

$$a = \frac{F}{m}$$

Or, more familiarly,

$$F = ma$$

5-3 Newton's Second Law of Motion

An object may have several forces acting on it; the acceleration is due to the net force:

$$\sum \vec{F} = m\vec{a} \qquad (5\text{-}1)$$

TABLE 5–2 Units of Mass, Acceleration, and Force

System of units	Mass	Acceleration	Force
SI	kilogram (kg)	m/s^2	newton (N)
cgs	gram (g)	cm/s^2	dyne (dyn)
British	slug	ft/s^2	pound (lb)

(*Note:* $1\ N = 10^5$ dyne $= 0.225$ lb.)

5-3 Newton's Second Law of Motion

TABLE 5–3 Typical Forces in Newtons (N)

Main engines of space shuttle	31,000,000
Pulling force of locomotive	250,000
Thrust of jet engine	75,000
Force to accelerate a car	7000
Weight of adult human	700
Weight of an apple	1
Weight of a rose	0.1
Weight of an ant	0.001

5-6 Weight

The weight of an object on the Earth's surface is the gravitational force exerted on it by the Earth.

Definition: Weight, *W*

$$W = mg$$

SI unit: newton, N

5-3 Newton's Second Law of Motion

Free-body diagrams:

A free-body diagram shows every force acting on an object.

- Sketch the forces
- Isolate the object of interest
- Choose a convenient coordinate system
- Resolve the forces into components
- Apply Newton's second law to each coordinate direction

Free Body Diagrams:

•Must be drawn for problems when forces are involved.

•Must be large so that they are readable.

•Draw an idealization of the body in question (a dot, a box,…). You will need one free body diagram for each body in the problem that will provide useful information for you to solve the given problem.

•Indicate only the forces acting on the body. Label the forces appropriately. Do not include the forces that this body exerts on any other body.

Free Body Diagrams (continued):

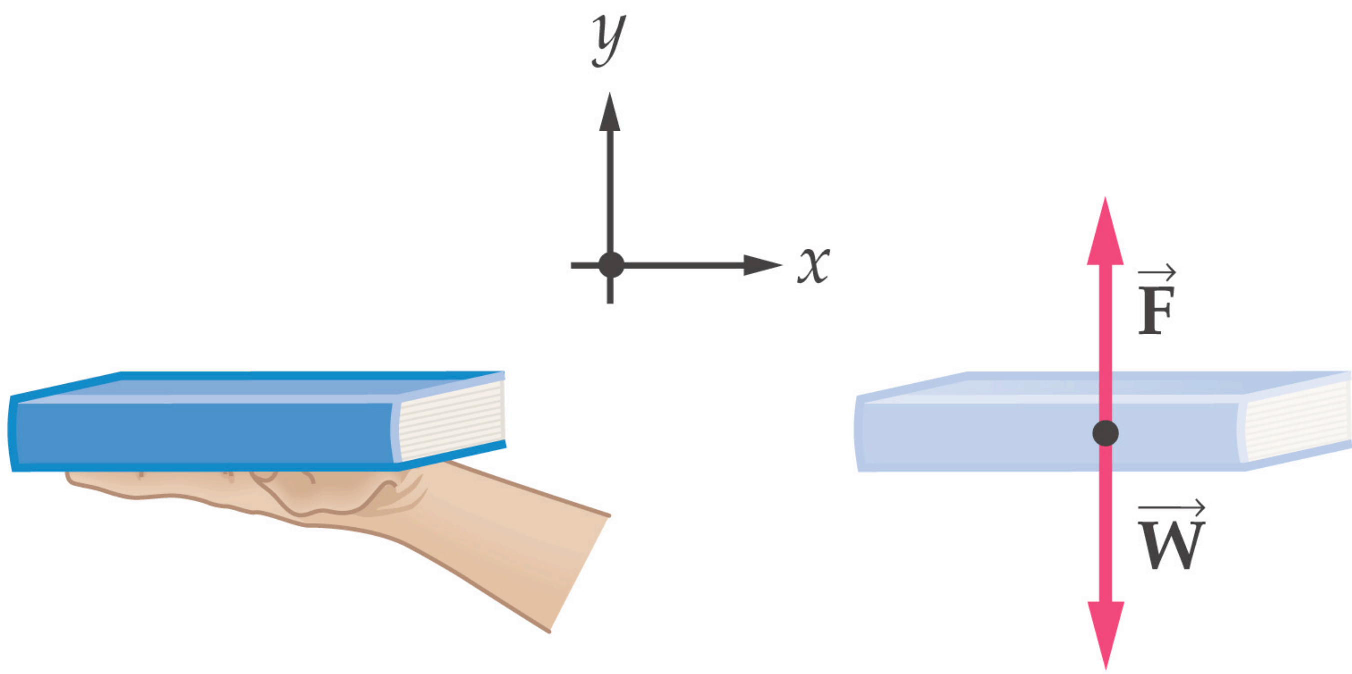
- A coordinate system is a must.

- Do not include fictitious forces. Remember that *m**a*** is itself not a force!

- You may indicate the direction of the body's acceleration or direction of motion if you wish, but it must be done well off to the side of the free body diagram.

5-3 Newton's Second Law of Motion

Example of a free-body diagram:



(a) Physical picture

(b) Free-body diagram

5-4 Newton's Third Law of Motion

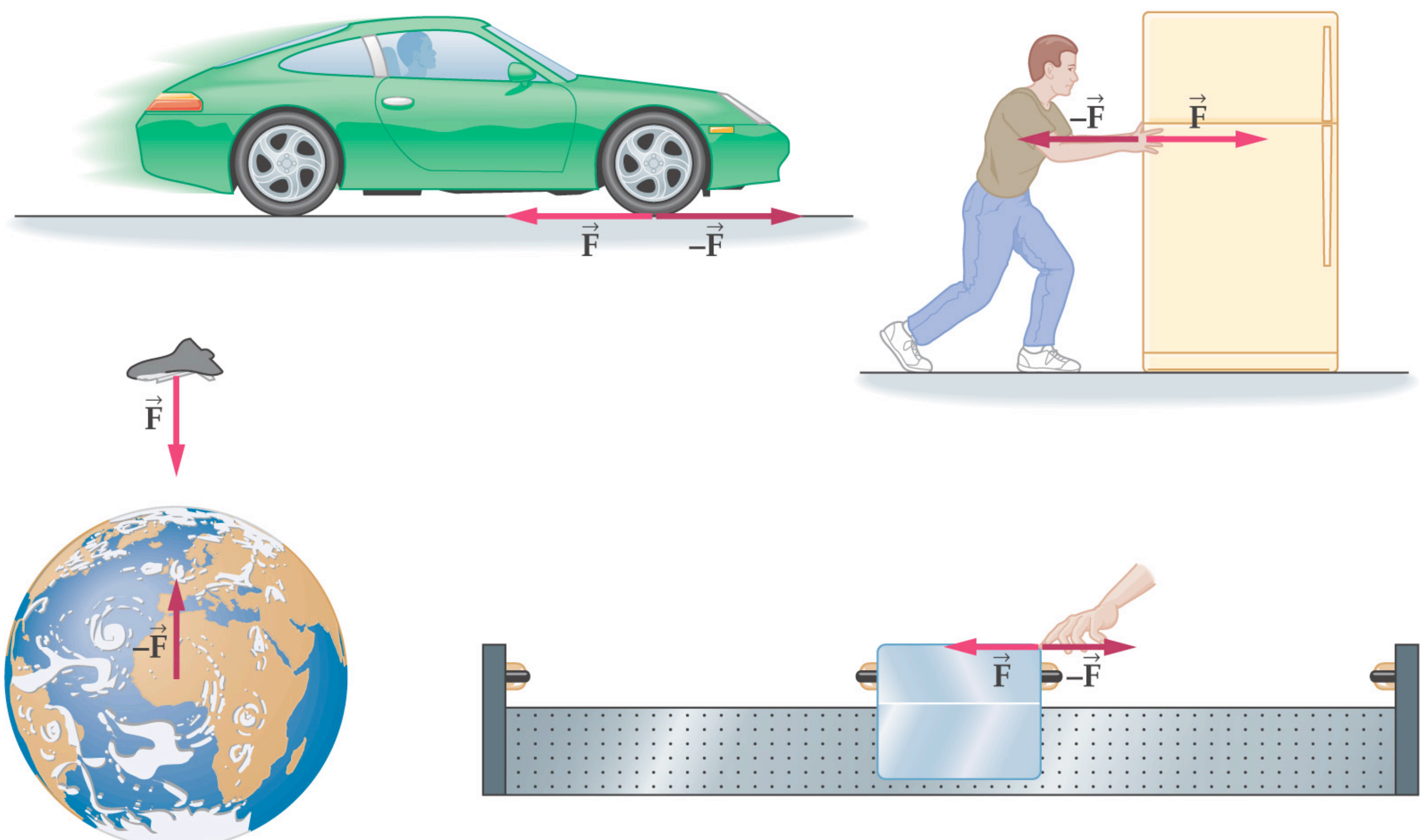
Forces always come in pairs, acting on different objects:

If object 1 exerts a force $\vec{F}$ on object 2, then object 2 exerts a force $-\vec{F}$ on object 1.

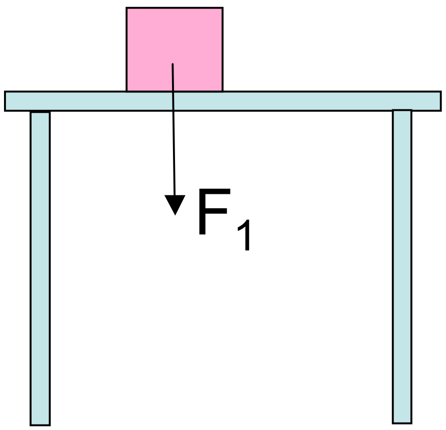
These forces are called action-reaction pairs.

5-4 Newton's Third Law of Motion

Some action-reaction pairs:

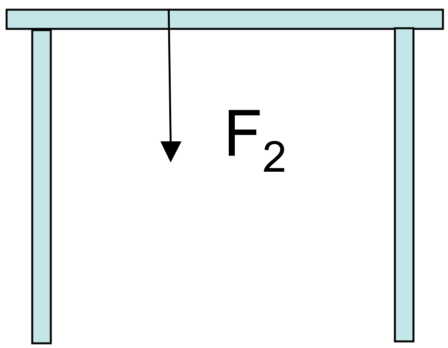


Example: Consider a box resting on a table.



(a) F_1 is the force of the Earth on the box, what is the interaction partner of this force?

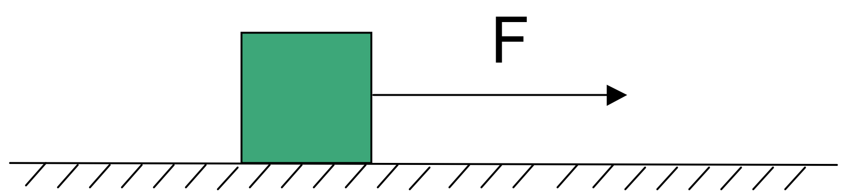
Example continued:



(b) F_2 is the force of the box on the table, what is the interaction partner of this force?

External forces:

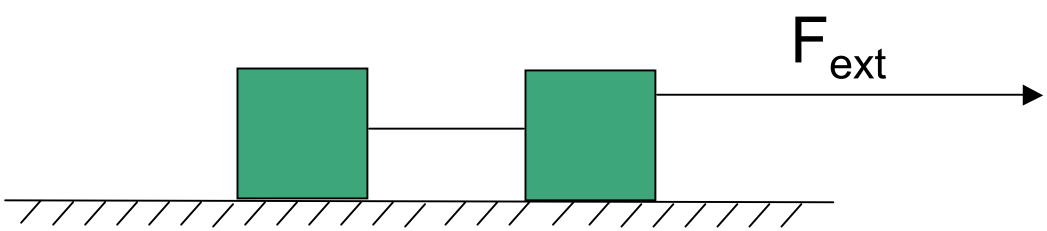
Any force on a system from a body outside of the system.



Pulling a box across the floor

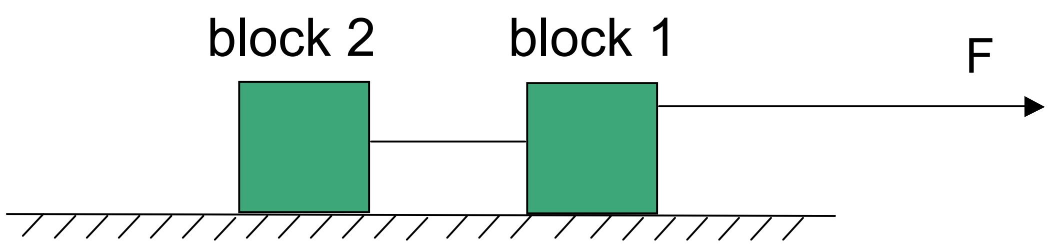
Internal forces:

Force between bodies of a system.



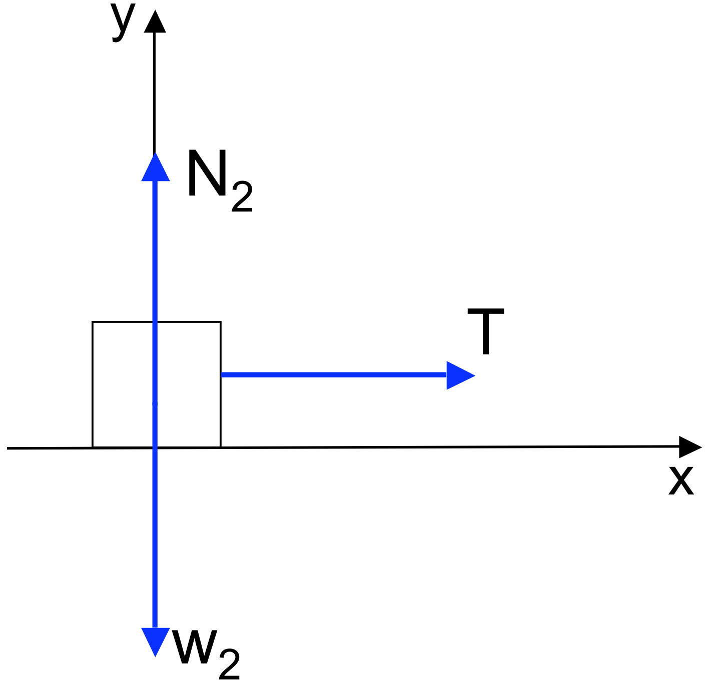
Pulling 2 boxes across the floor where the two boxes are attached to each other by a rope.

Example: Find the tension in the cord connecting the two blocks as shown. A force of 10.0 N is applied to the right on block 1. Assume a frictionless surface. The masses are m_1 = 3.00 kg and m_2 = 1.00 kg.

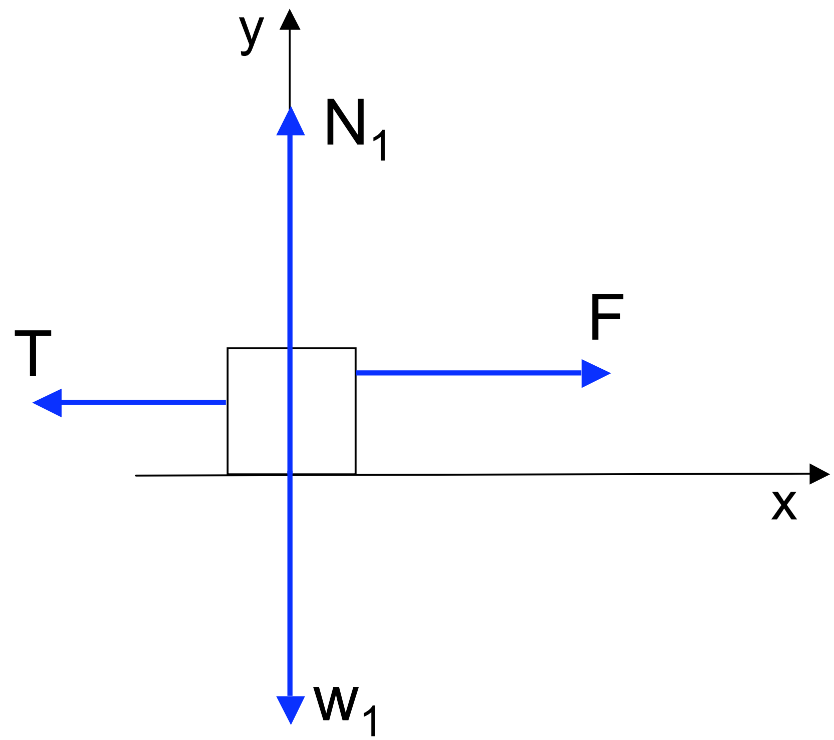


Assume that the rope stays taut so that both blocks have the same acceleration.

FBD for block 2:



FBD for block 1:



Apply Newton's 2nd Law to each block:

$$\sum F_x = T = m_2 a$$
$$\sum F_y = N_2 - w_2 = 0$$

$$\sum F_x = F - T = m_1 a$$
$$\sum F_y = N_1 - w_1 = 0$$

Example continued:

$$F - T = m_1 a \quad (1)$$

$$T = m_2 a \quad (2)$$

These two equations contain the unknowns: *a* and *T*.

To solve for T, a must be eliminated. Solve for a in (2) and substitute in (1).

$$F - T = m_1 a = m_1 \left(\frac{T}{m_2} \right)$$

$$F = m_1 \left(\frac{T}{m_2} \right) + T = \left(1 + \frac{m_1}{m_2} \right) T$$

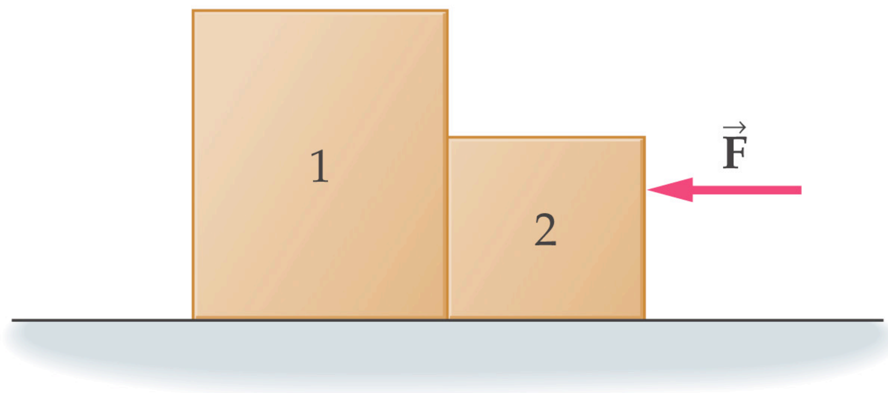
$$T = \frac{F}{\left(1 + \frac{m_1}{m_2} \right)} = \frac{10\ \text{N}}{\left(1 + \frac{3\ \text{kg}}{1\ \text{kg}} \right)} = 2.5\ \text{N}$$

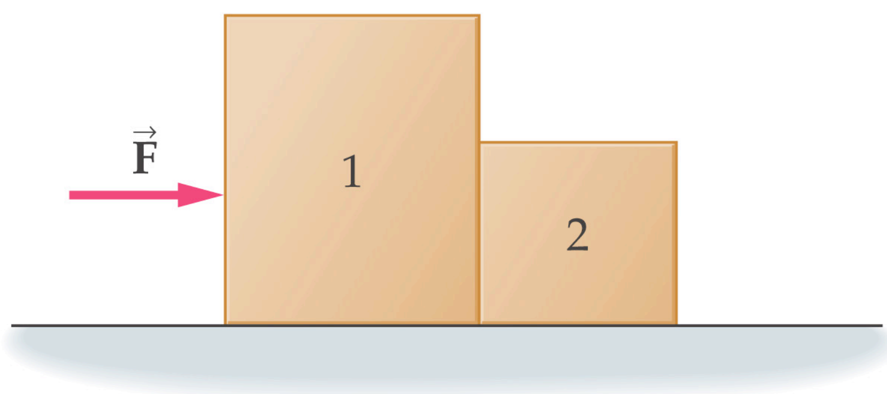
5-4 Newton's Third Law of Motion

Although the forces are the same, the accelerations will not be unless the objects have the same mass.

Contact forces:

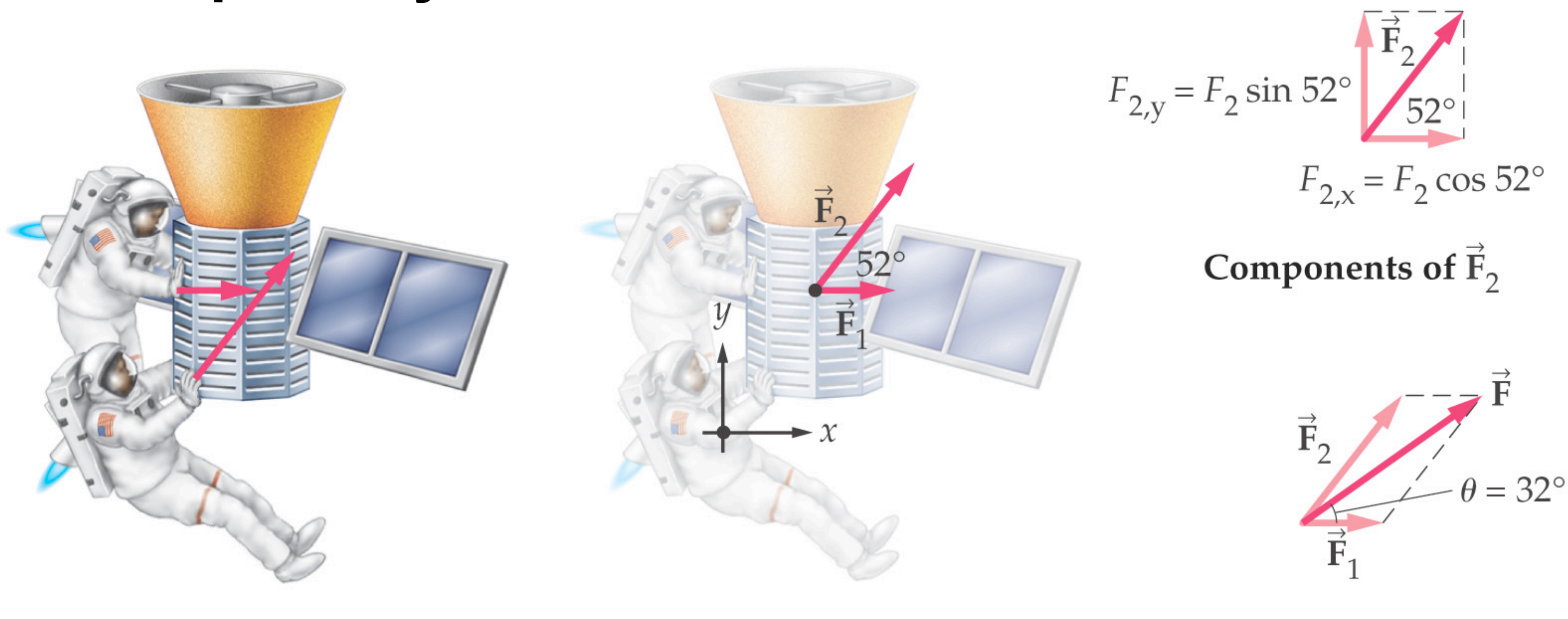
The force exerted by one box on the other is different depending on which one you push.





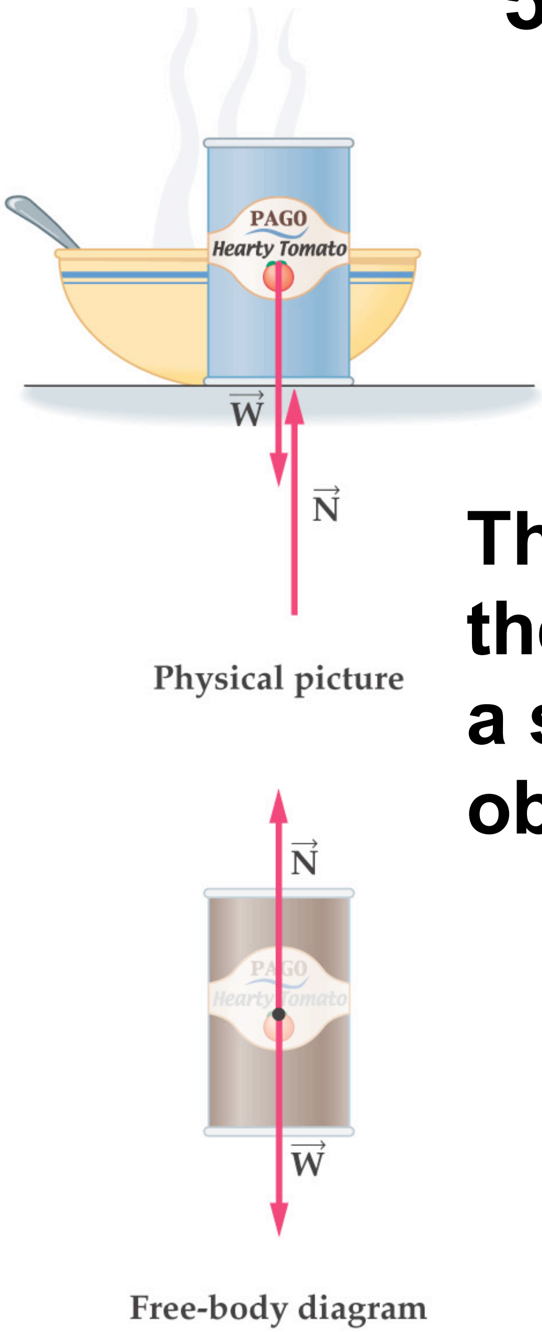
5-5 The Vector Nature of Forces: Forces in Two Dimensions

The easiest way to handle forces in two dimensions is to treat each dimension separately, as we did for kinematics.

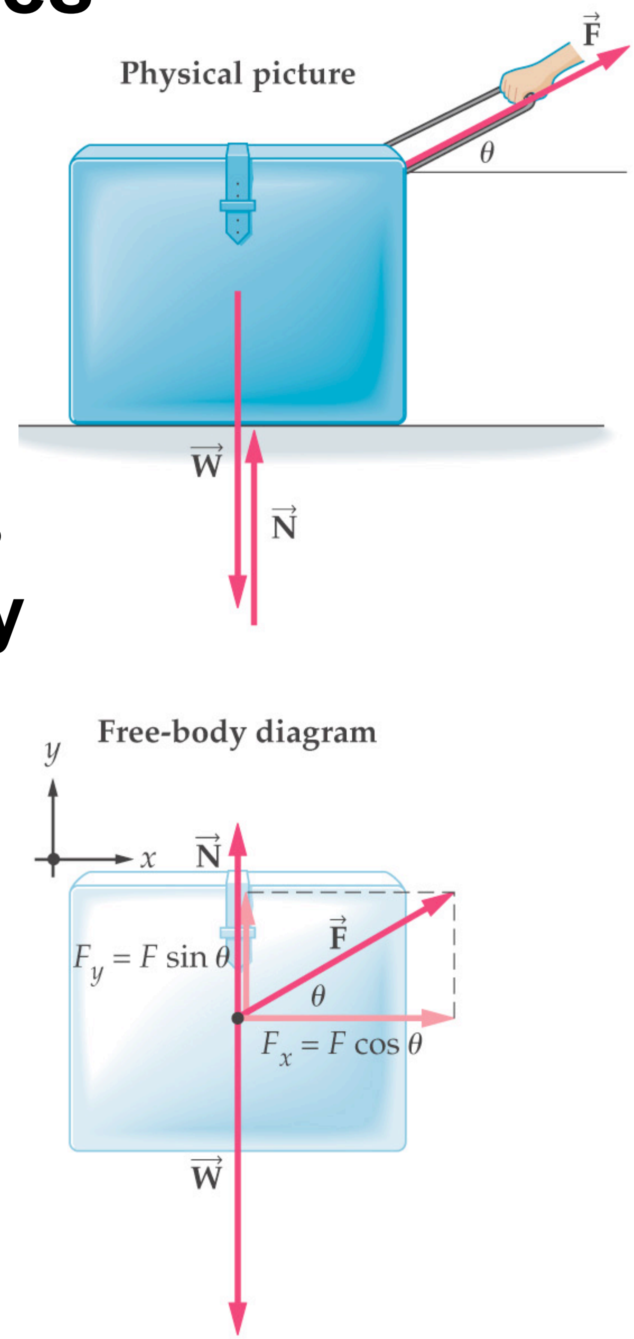


(a) Physical picture (b) Free-body diagram Total force

5-7 Normal Forces

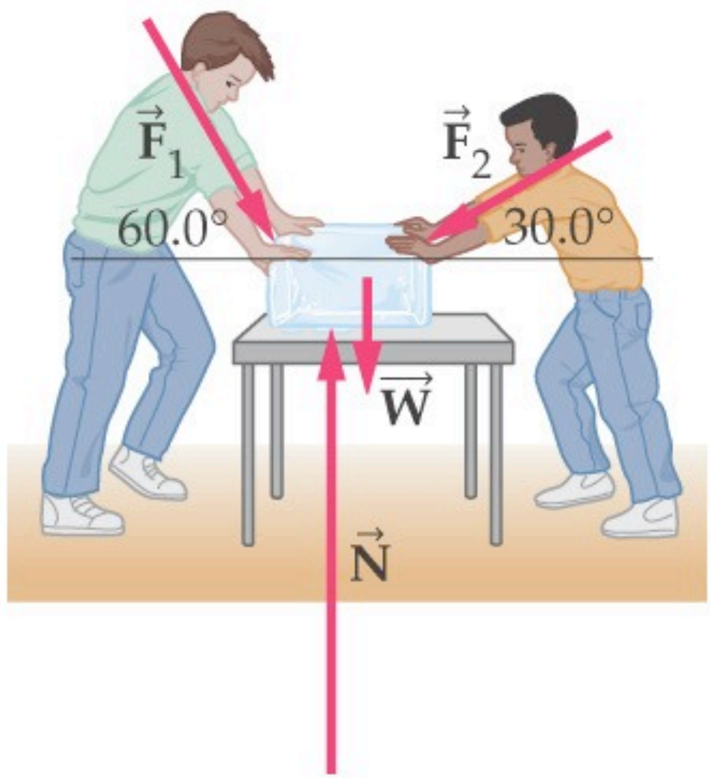


The normal force is the force exerted by a surface on an object.

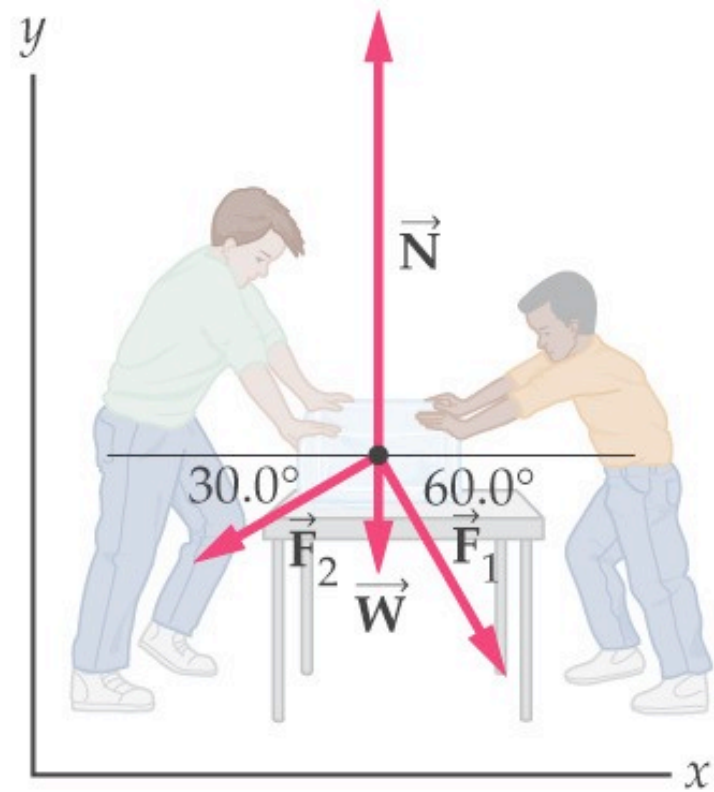


5-7 Normal Forces

The normal force may be equal to, greater than, or less than the weight.



Physical picture



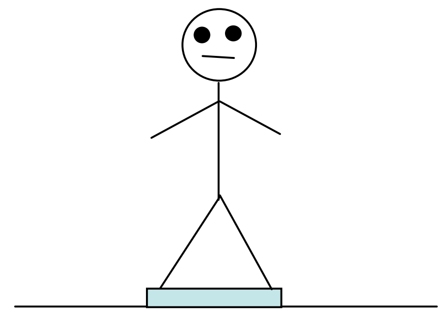
Free-body diagram

5-7 Normal Forces

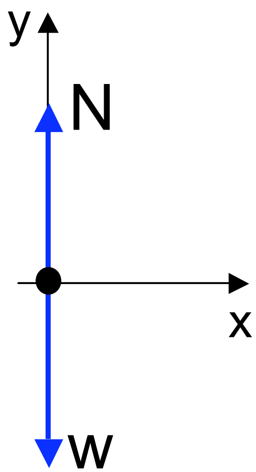
The normal force is always perpendicular to the surface.

Apparent Weight

Stand on a bathroom scale.



FBD for the person:



Apply Newton's 2[nd] Law:

$$\sum F_y = N - w = ma_y$$

$$N - mg = ma_y$$

The normal force is the force the scale exerts on you. By Newton's 3rd Law this is also the force (magnitude only) you exert on the scale. A scale will read the normal force.

$N = m(g + a_y)$ is what the scale reads.

When $a_y = 0$, $N = mg$. The scale reads your true weight.

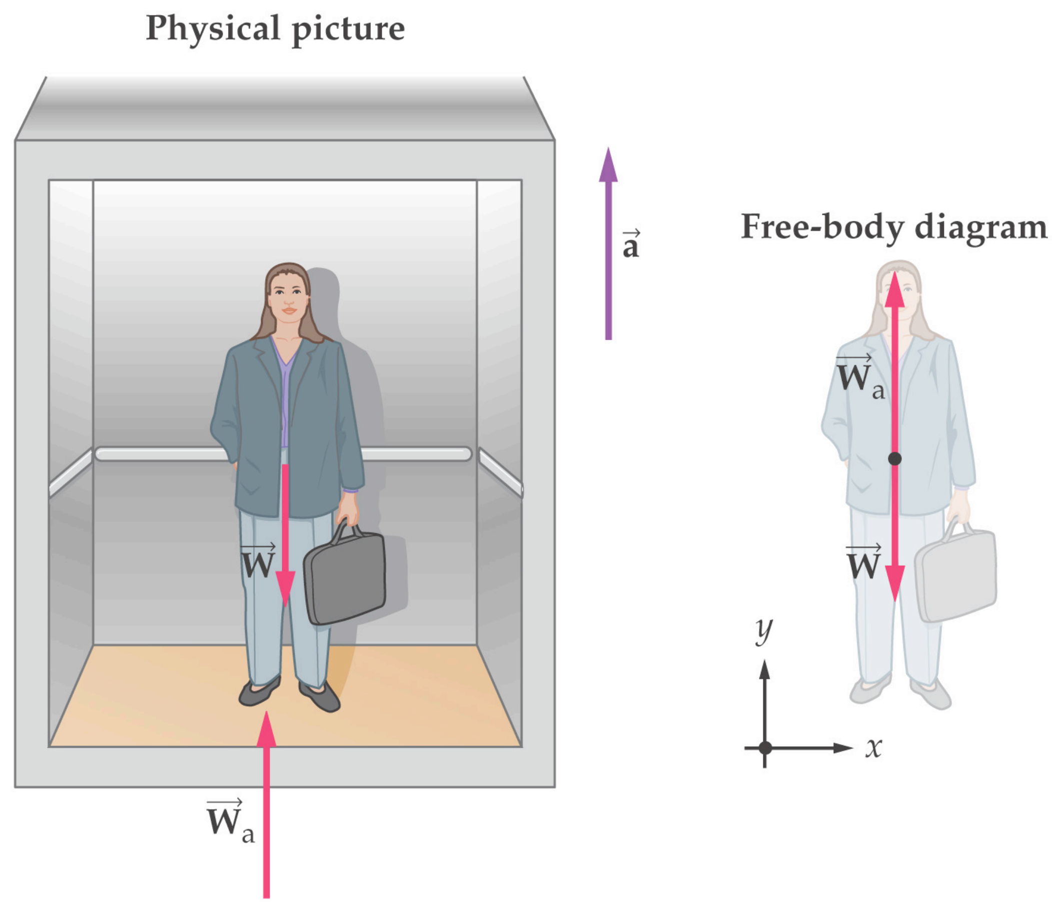
When $a_y \neq 0$, $N > mg$ or $N < mg$.

5-6 Weight

Apparent weight:

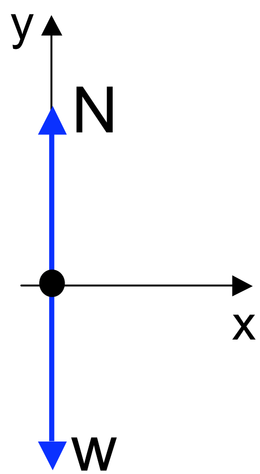
Your perception of your weight is based on the contact forces between your body and your surroundings.

If your surroundings are accelerating, your apparent weight may be more or less than your actual weight.



Example: A woman of mass 51 kg is standing in an elevator. If the elevator pushes up on her feet with 408 newtons of force, what is the acceleration of the elevator?

FBD for woman:



Apply Newton's 2nd Law:

$$\sum F_y = N - w = ma_y$$

$$N - mg = ma_y \qquad (1)$$

Example continued:

Given: N = 408 newtons, m = 51 kg, g = 9.8 m/s^2

Unknown: a_y

Solving (1) for a_y: $$a_y = \frac{N - mg}{m} = -1.8\ \mathrm{m/s^2}$$

The elevator could be (1) traveling upward with decreasing speed, or (2) traveling downward with increasing speed.

Summary of Chapter 5

- **Force: a push or pull**
- **Mass: measures the difficulty in accelerating an object**
- **Newton's first law: if the net force on an object is zero, its velocity is constant**
- **Inertial frame of reference: one in which the first law holds**
- **Newton's second law:** $\sum \vec{\mathbf{F}} = m\vec{\mathbf{a}}$
- **Free-body diagram: a sketch showing all the forces on an object**

Summary of Chapter 5

- **Newton's third law: If object 1 exerts a force $\vec{F}$ on object 2, then object 2 exerts a force $-\vec{F}$ on object 1.**
- **Contact forces: an action-reaction pair of forces produced by two objects in physical contact**
- **Forces are vectors**
- **Newton's laws can be applied to each component of the forces independently**
- **Weight: gravitational force exerted by the Earth on an object**

Summary of Chapter 5

- **On the surface of the Earth, $W = mg$**
- **Apparent weight: force felt from contact with a floor or scale**
- **Normal force: force exerted perpendicular to a surface by that surface**
- **Normal force may be equal to, lesser than, or greater than the object's weight**