5.3 Forces and Equilibrium

We almost never feel only one force. For example, friction and weight are two forces that both act on us when we're walking. It is the total of *all* forces acting on our bodies that determines how we move. This section is about how forces can be added and subtracted.

VOCABULARY

net force - the sum of all forces acting on an object.

balanced forces - combined forces that result in a zero net force on an object.

Adding forces

An example The sum of all the forces acting on an object is called the **net force**. The word *net* means "total." *Net force* also means that the direction of each force is considered when multiple forces are added. Consider a flying airplane (Figure 5.15). Four forces act on the plane: weight, drag (air friction), the thrust of the engines, and the lift force caused by the flow of air over the wings. For a plane to fly at a constant speed on a level path, the forces must all balance. **Balanced forces** result in a net force of zero.

A pilot must always be aware of these four forces and know how to change them in order to speed up, slow down, lift off, and land. For example, to speed up there must be a net force in the forward direction. The thrust must be greater than the drag. To climb, there must be an upward net force. The lift force must be greater than the weight.

Figure 5.15: *Four forces act on a plane as it flies.*

Adding x-y components To calculate the net force on an object, you must add the forces in each direction separately. Remember to define positive and negative directions for both the x-direction and y-direction. In the diagram above, $+x$ is to the right and $+y$ is up. The net force in the x-direction is zero because the +20,000 N and −20,000 N add up to zero. The net force in the y-direction is +5,000 N (+55,000 N − 50,000 N). The plane climbs because there is a positive (upward) net force.

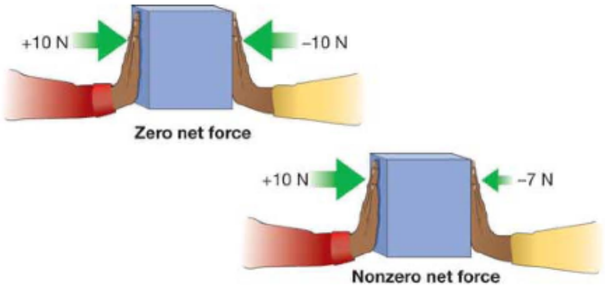
Equilibrium

Net force can be zero or not zero

When many forces act on the same object either:

The net force is zero, or

The net force is NOT zero.



Definition of equilibrium

When the net force on an object is zero, we say the object is in **equilibrium**. Equilibrium does NOT mean there are no forces! Equilibrium means all forces cancel each other out leaving zero net force. For example, when the net force is zero, an object at rest will stay at rest. Interestingly, an object can be in motion at constant speed and still be in equilibrium. This happens when a pushing force and a friction force are equal but opposite in direction so the object does not speed up or slow down (Figure 5.16).

Using equilibrium to find unknown forces

The idea of equilibrium is often used in reverse. Instead of thinking "an object in equilibrium stays at rest," we think "an object at rest must be in equilibrium." If an object is at rest, *the net force on it must be zero*. This fact often allows us to find the strength and direction of forces that must be there even if we don't directly cause them.

When net force is not zero

If the net force is NOT zero, then the motion of an object will change. An object at rest will start moving. An object that is moving may change its velocity. In other words, unbalanced forces cause *acceleration*.

VOCABULARY

equilibrium - the state in which the net force on an object is zero.

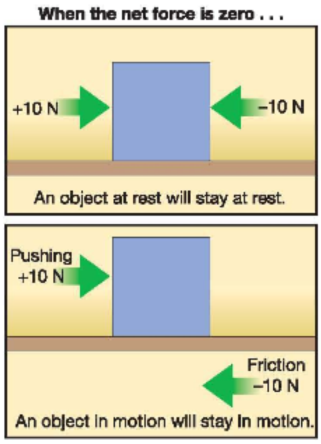


Figure 5.16: *Objects are in equilibrium when the net force is zero.*

Normal forces

Definition of normal force Imagine a book sitting on a table (Figure 5.17). Gravity pulls the book downward with the force of the book's weight. The book is at rest, so the net force must be zero. But what force balances the weight? The table exerts an upward force on the book called the **normal force**. The word *normal* here has a different meaning from what you might expect. In mathematics, *normal* means "perpendicular." The force that the table exerts is perpendicular to the table's surface. The normal force is also sometimes called the *support force*.

When normal force is created A normal force is created whenever an object is in contact with a surface. The normal force has *equal strength* to the force pressing the object into the surface, which is often the object's weight. The normal force has *opposite direction* to the force pressing the object into the surface. For example, the weight of a book presses down on the table's surface. The normal force is equal in strength to the book's weight but acts upward on the book, in the opposite direction from the weight.

What normal force acts on The normal force acts on the object pressing into the surface. That means, in this example, the normal force *acts on the book*. The normal force is created by the book *acting on the table*.

Strength of the normal force What happens to the normal force if you put a brick on top of the book? The brick makes the book press harder into the table. The book does not move, so the normal force must be the same strength as the total weight of the book and the brick (Figure 5.18). The normal force acting on the book increases to keep the book in balance.

How the normal force is created How does a table "know" how much normal force to supply? The answer is that normal force is very similar to the force exerted by a spring. When a book sits on a table, it squeezes the atoms in the table together by a tiny amount. The atoms resist this squeezing and try to return the table to its natural thickness. The greater the table is compressed, the larger the normal force it creates. The matter in the table acts like a bunch of very stiff springs. You don't see the table compress because the amount of compression is very small.

VOCABULARY

normal force - the perpendicular force that a surface exerts on an object that is pressing on it.

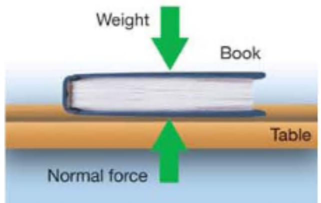


Figure 5.17: *The normal force and the weight are equal in strength and opposite in direction on a horizontal surface.*

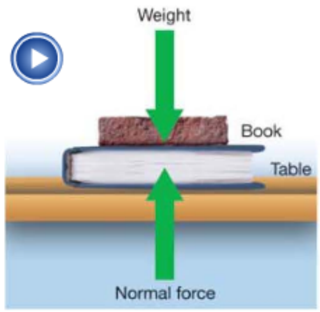


Figure 5.18: *The normal force is greater if a brick is placed on the book.*

The free-body diagram

Forces on a free-body diagram How can you keep track of many forces with different directions? The answer is to draw a **free-body diagram**. A free-body diagram contains only a single object, like a book or a table. All connections or supports are taken away and replaced by the forces they exert on the object. An accurate free-body diagram includes *every* force acting on an object, including weight, friction, and normal forces.

An example As an example of a free-body diagram, consider a stack of books weighing 30 newtons resting on a table that weighs 200 newtons. The books are on one corner of the table so that their entire weight is supported by one table leg. Figure 5.19 shows a free-body diagram of the forces acting on the table.

Finding the forces Because the table is in equilibrium, the net force on it must be zero. The weight of the books acts on the table making a 30 N force. The weight of the table acts on the floor. At every point where the table touches the floor (each leg) a normal force is created. The correct free-body diagram shows six forces. The normal force at each of the four legs is one-quarter the weight of the table (50 newtons). The leg beneath the book also supports the weight of the book (50 N + 30 N = 80 N).

The purpose of a free-body diagram By separating an object from its physical connections, a free-body diagram helps you identify all forces and where they act. A normal force is usually present when an object is in contact with another object or surface. Forces due to weight may be assumed to act directly on an object, often at its center.

Positive and negative forces There are two ways to handle positive and negative directions in a free-body diagram. One way is to make all upward forces positive and all downward forces negative. The second way is to draw all the forces in the direction you believe they act on the object. When you solve the problem, if you have chosen correctly, all the values for each force are positive. If one comes out negative, it means the force points in the opposite direction from what you guessed.

VOCABULARY

free-body diagram - a diagram showing all the forces acting on an object.

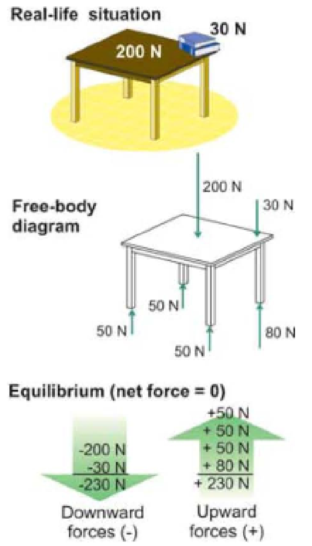


Figure 5.19: *A free-body diagram showing the forces acting on a table that has a stack of books resting on one corner.*

Solving Problems: Equilibrium

Two chains are used to support a small boat weighing 1,500 newtons. One chain has a tension of 600 newtons (Figure 5.20). What is the force exerted by the other chain?

1. Looking for: You are asked for an unknown tension in a chain.

2. Given: You are given the boat's weight in newtons and the tension in one chain in newtons.

3. Relationships: The net force on the boat is zero.

4. Solution: Draw a free-body diagram.
The force of the two chains must balance the boat's weight.
$600\text{ N} + F_{chain2} = 1{,}500\text{ N}$ $F_{chain2} = 900\text{ N}$

Your turn...

a. A person with a weight of 400 N is sitting motionless on a swing (Figure 5.21). For the swing to be in equilibrium, what is the tension force in each rope holding up the swing?

b. A heavy box weighing 1,000 N sits on the floor. You press down on the box with a force of 450 N. What is the normal force on the box?

c. A cat weighing 40 N stands on a chair. If the normal force on each of the cat's back paws is 12 N, what is the normal force on each front paw? (You can assume the force is the same on each front paw.)

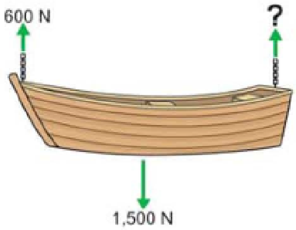


Figure 5.20: *What is the force exerted by the other chain that is supporting the boat?*

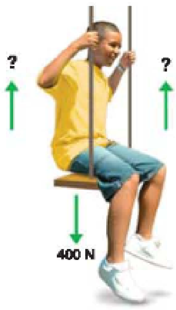


Figure 5.21: *What is the tension force in each rope holding up the swing?*

SOLVE FIRST LOOK LATER

(a) The upward force from both ropes must be 400 N, so the force in each rope is 200 N. (b) 1,450 N; (c) 8 N

Section 5.3 Review

1. What is the relationship between net force and balanced forces?
2. Make two diagrams. The first diagram should show a net force of zero on an object and the other diagram should show a net force that is not zero.
3. If an object is accelerating, can the net force acting on it ever be zero? Explain your answer.
4. If you push down on a table with a force of 5 newtons, what is the normal force pushing back on you?
5. The diagram in Figure 5.22 shows three forces acting on a pencil. What is the net force acting on the pencil?
6. If an object is in equilibrium,
   a. the net force on the object is zero.
   b. the object has zero total mass.
   c. no forces are acting on the object.
   d. only normal forces are acting on the object.
7. A train is climbing a gradual hill. The weight of the train creates a downhill force of 150,000 newtons. Friction creates an additional force of 25,000 newtons acting in the same direction (downhill) (Figure 5.23). How much force does the train's engine need to create so the train is in equilibrium (going uphill at constant speed)?
8. Draw a free body diagram of your own body sitting on a stool. Include all forces acting on your body.
9. If a force has a negative value, such as −100 N, that means the force
   a. is less than 100 N in strength.
   b. acts in the opposite direction from a +100 N force.
   c. is a normal force.
10. A child weighing 200 newtons is sitting in the center of a swing. The swing is supported evenly by two ropes, one on each side. What is the tension force in one of the ropes?

Figure 5.22: *Question 5.*

Figure 5.23: *Question 7.*