

## 4.3 Forces and Equilibrium

We almost never feel only one force at a time. Friction and weight are two forces that might act on you at the same time. To figure out how (or if) things move, we need to add up all of the forces that are acting on them. This section is about how forces add up.

### Adding forces

**An example** The sum of all the forces on an object is called the **net force**. The word *net* means total. *Net force* also means the direction of the forces has been taken into account. Consider a flying airplane (Figure 4.14). 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 in a level path, the forces must all balance. **Balanced forces** result in a net force of zero.

**When net force isn't zero**



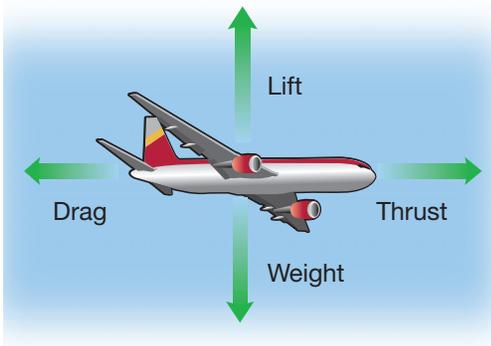
A pilot must always be aware of these four forces and know how to change them in order to speed up, slow down, lift off, and land. For example, to speed up there must be a net force in the forward direction. The thrust must be greater than the drag. To climb, there must be an upward net force. The lift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

**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  $+20,000\text{ N}$  and  $-20,000\text{ N}$  add up to zero. The net force in the  $y$ -direction is  $+5,000\text{ N}$  ( $+55,000\text{ N} - 50,000\text{ N}$ ). The plane climbs because there is a positive (upward) net force.

### 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.



**Figure 4.14:** Four forces act on a plane as it flies.



## Equilibrium

### Net force can be zero or not zero

Two things can be true when many forces act on the same object. One or the other is always true (Figure 4.15).

1. The net force is zero, or
2. The net force is NOT zero.

### Definition of equilibrium

When the net force is zero an object at rest will stay at rest.\* When the net force is zero, we say an object is in **equilibrium**. Equilibrium does NOT mean there are no forces! Equilibrium means all forces cancel each other out leaving zero net force.

### Using equilibrium to find unknown forces

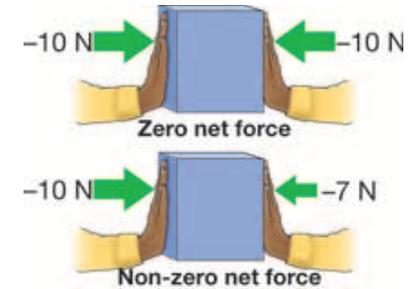
The idea of equilibrium is often used in reverse. Instead of thinking “an object in equilibrium stays at rest” we think “an object at rest must be in equilibrium.” If an object is at rest, *the net force on it must be zero*. This fact often allows us to find the strength and direction of forces that 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 will change its velocity. In Chapter 5, we will learn about how unbalanced forces cause *acceleration*.

## VOCABULARY

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



**Figure 4.15:** The two possibilities for the net force.

### \* The exception!

An object moving at a constant speed in a straight line is also in equilibrium! See Newton’s First Law in the next chapter.



### Finding an unknown force

A person with a weight of 150 N is sitting motionless in a swing. What is the tension force in each rope holding up the swing?

1. Looking for: You are asked for an unknown tension force.
2. Given: You are given the weight in newtons and you know the swing is at rest (equilibrium).
3. Relationships: The net force on the swing is zero.
4. Solution: The upward force from the ropes must exactly cancel the downward force of weight. That means the upward force from both ropes must be 150 N, so the force in each rope is 75 N.



## Normal forces

**Definition of normal force** Imagine a book sitting on a table (Figure 4.16). 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*.

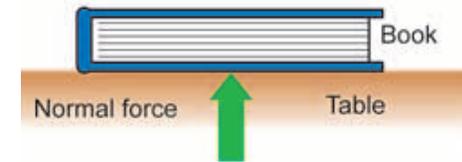
**When normal force is created** A normal force is created whenever an object is in contact with a surface. The normal force has *equal strength* to the force pressing the object into the surface, which is often the object's weight. The normal force has *opposite direction* to the force pressing the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

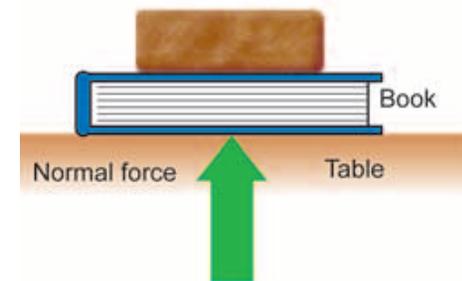
**Strength of the normal force** What happens to the normal force if you put a brick on top of the book? The brick makes the book press harder into the table. The book does not move, so the normal force must be the same strength as the total weight of the book and the brick (Figure 4.17). The normal force 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.

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



**Figure 4.16:** The normal force and the weight are equal in strength and opposite in direction.



**Figure 4.17:** 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 4.18 shows a free-body diagram of the forces acting on the table.

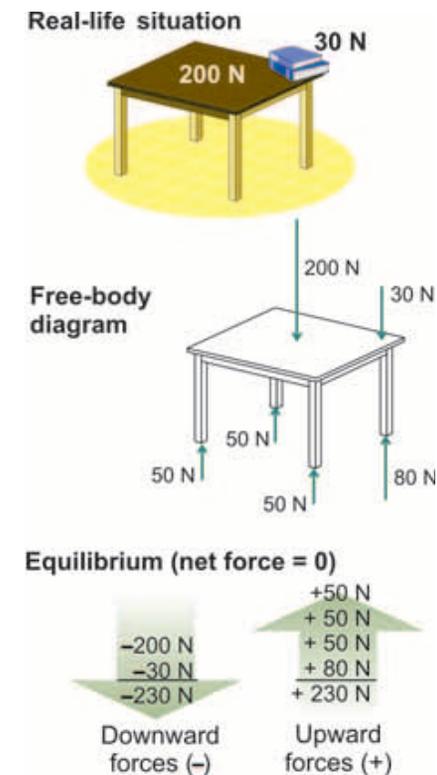
**Finding the forces** Because the table is in equilibrium, the net force on it must be zero. The weight of the books acts on the table making the 30 N force. The weight of the table acts on the floor. At every point where the table touches the floor (each leg) a normal force is created. The correct free-body diagram shows six forces. The normal force at each of three 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 at any point 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.

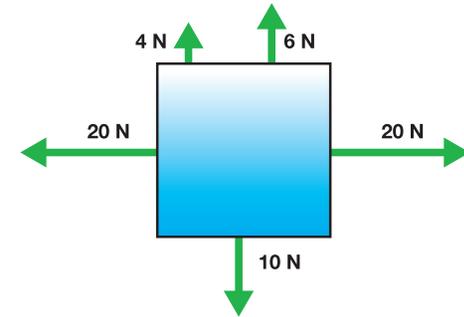


**Figure 4.18:** A free-body diagram showing the forces acting on a table that has a stack of books resting on one corner.

## Solving equilibrium problems

**Finding the net force** For an object to be in equilibrium, all the forces acting *on the object* must add up to zero (Figure 4.19). The net force *in each direction* must be zero. That means the total force in the horizontal ( $x$ ) direction must be zero and total force in the vertical ( $y$ ) direction also must be zero. You cannot mix forces in the horizontal direction with forces in the vertical direction.

**Balancing forces** If you are trying to find an unknown force on an object in equilibrium, the first step is always to draw a free-body diagram. Then, use the fact that the net force is zero to find the unknown force. To be in equilibrium, forces must balance both horizontally and vertically. Forces to the right must balance forces to the left, and upward forces must balance downward forces.



**Figure 4.19:** An object is in equilibrium if the vertical forces balance and the horizontal forces balance.



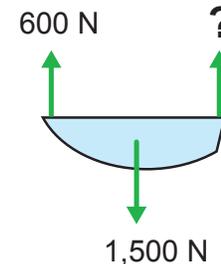
### Equilibrium

Two chains are used to support a small boat weighing 1,500 newtons. One chain has a tension of 600 newtons. 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.  
 $600 \text{ N} + F_{\text{chain2}} = 1,500 \text{ N}$       $F_{\text{chain2}} = 900 \text{ N}$

#### Your turn...

- a. A heavy box weighing 1,000 newtons sits on the floor. You press down on the box with a force of 450 newtons. What is the normal force on the box? **Answer:** 1,450 newtons
- b. A cat weighing 40 newtons stands on a chair. If the normal force on each of the cat's back feet is 12 newtons, what is the normal force on each front foot? (You can assume it is the same on each.) **Answer:** 8 newtons





## 4.3 Section Review

- A vector is an example of a physical quantity that
  - includes information about force and mass.
  - includes information about temperature.
  - includes information about quantity and direction.
  - includes information about forces only.
- The diagram in Figure 4.20 shows three forces acting on a pencil. What is the net force acting on the pencil?
- If an object is in equilibrium, it means
  - the net force on the object is zero.
  - the object has zero total mass.
  - no forces are acting on the object.
  - only normal forces are acting on the object.
- 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 4.21). How much force does the train's engine need to produce so the train is in equilibrium?
- Draw a free-body diagram of your own body sitting on a chair. Include all forces acting on your body.
- If a force has a negative value, such as  $-100\text{ N}$ , that means the force
  - is less than  $100\text{ N}$  in strength.
  - acts in the opposite direction from a  $+100\text{ N}$  force.
  - is a normal force.
- A child weighing 200 newtons is sitting on a swing. The swing is supported by two ropes, one on each side. What is the tension in one of the ropes?

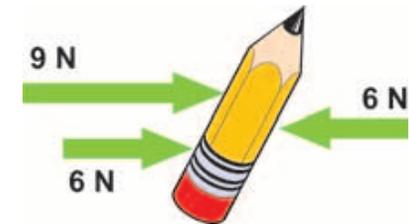


Figure 4.20: Question 2.

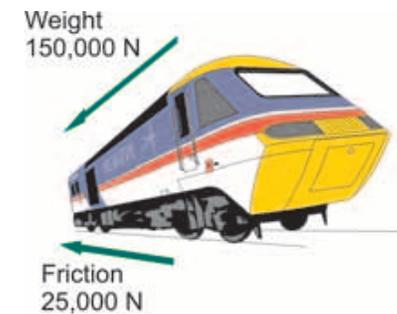


Figure 4.21: Question 4.