2.1 Measuring Forces

A **force** is a push or pull that tends to cause an object to change its movement or shape. Working with a partner, copy the actions pictured in Figures 2.1 to 2.3 and answer the questions below.

Figure 2.1 Does the size of a force have an effect on your ability to resist it? Caution! Do not overload your hands. Allow time for your arms to recover before performing another test.

Figure 2.2 Does the direction of a force have an effect on your ability to resist it? Record your prediction before testing. Hold your arm in this position while your partner applies a gentle but firm pressure against your hand in different directions. Record any differences. Caution! Use only a gentle pressure during this experiment.

Figure 2.3 Does the location of a force have an effect on your ability to resist it? Record your prediction before testing. Caution! Use only a gentle pressure during this experiment.

Magnitude, Direction, and Location

The actual effect of a force on a structure depends on three things:
- the magnitude, or size, of the force
- the direction of the force
- the location where the force is applied

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Showing Force

In drawings, forces can be represented by arrows. This makes it easier to envision how and where forces act on a structure. The direction in which an arrow points shows the direction in which the force is acting. The length or size of an arrow shows how strong it is.

The bigger a force's magnitude, the stronger it is and the more effect it will have on a structure (Figure 2.4). However, the effect of even a strong force depends on how massive the structure is.

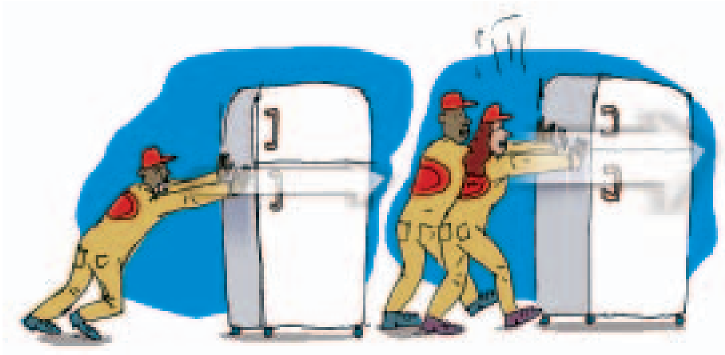


Figure 2.4 Two people pushing on a large object exert more force than one person. What forces are trying to keep the fridge from moving?

The direction in which a force acts on a structure also determines what effect that force will have. In the two situations shown in Figure 2.5, the magnitude of the force is the same, but the direction is different.

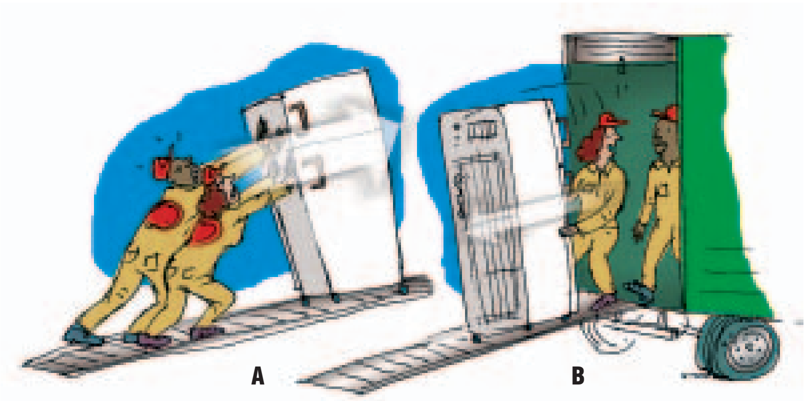


Figure 2.5 Why is pushing the fridge in one direction (A) more difficult than pushing it in the other direction (B)?

The location on a structure where a force is applied affects the outcome. Applying a force at a point high up on an object that you are trying to slide along the floor may cause it to topple over (Figure 2.6).

Figure 2.6 What happens when force is applied too high up on the fridge?

Inquiry Activity

Direction and Location of a Force

The Question

Does the direction and location of a force have any effect on how that force will act on a structure?

Procedure

TOOLBOX

1. Using just enough straws and tape to do the job, construct a simple bridge that will cross a gap of 50 cm between two tables or other supports. Tape the bridge to the tables or supports to hold it in place.
2. Using the spring scale, pull down on the bridge as directed in each of the four cases below. Pull just until the bridge begins to kink and then release the scale. In each case, before you measure the force, predict the results. Observe what happens in each case and record the force on the scale when the bridge begins to kink each time. (See Toolbox 5 on spring scale use.)
   - Pull straight down at the centre of the bridge.
   - Pull straight down at the end of the bridge, close to the support.
   - At the centre, pull down at a 45° angle to the bridge.
   - Pull down at a 45° angle from one end of the bridge close to the support.

Materials & Equipment

- straws
- masking tape
- spring scale

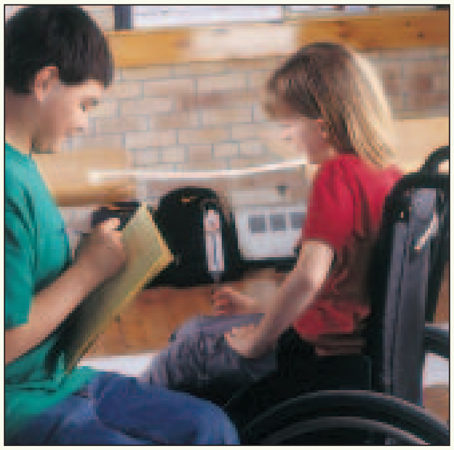
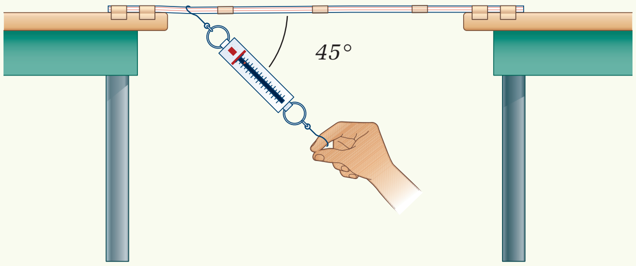


Figure 2.7 Step 2



Collecting Data

3 Organize your data in a table.

Analyzing and Interpreting

4 What was the difference between pulling straight down from the centre of the bridge and pulling straight down from one end of the bridge?

5 What was the difference between pulling straight down from the centre and pulling at a 45° angle? Was this result the same as pulling down at a 45° angle from the end of the bridge?

6 What do you conclude about the importance of knowing where a force will act on a structure?

Forming Conclusions

7 From your results, determine the weakest point on your bridge. What does this suggest about where a bridge should be tested for the largest load it can support?

The Newton

The standard unit for measuring force is called the **newton** (N). One newton is the amount of force needed to hold up a mass of 100 g. That's similar to the force required to hold an apple in your hand. Holding a 1-kg book in your hand would take about 10 N.

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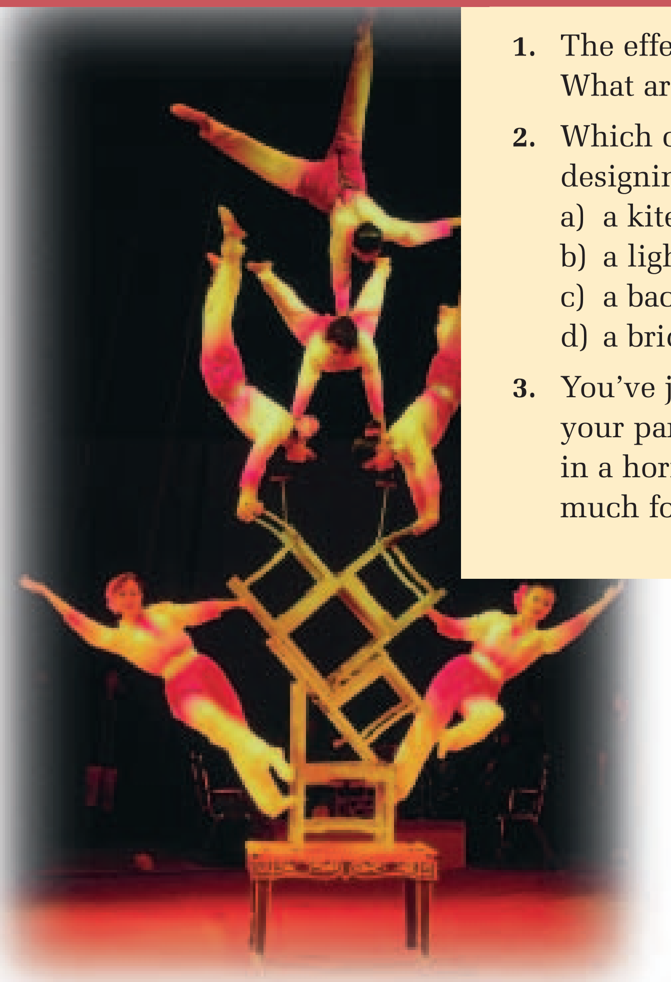
Sir Isaac Newton

The newton is named after Sir Isaac Newton, an English scientist. In 1687, he became the first person to describe the "law of gravitation." Find out the role that mass and distance play in this famous law.

Check and Reflect



1. The effect of a force on a structure depends on three factors. What are they?
2. Which of the factors above are very important to consider in designing each of the following structures? Explain.
   a) a kite
   b) a lighthouse
   c) a backpack
   d) a bridge
3. You've joined the circus as an acrobat. In one act, you must hold your partner, who will try to be stiff as a board, over your head in a horizontal position. He has a body mass of 50 kg. How much force will you need to exert to hold him aloft?

2.2 External Forces Acting on Structures

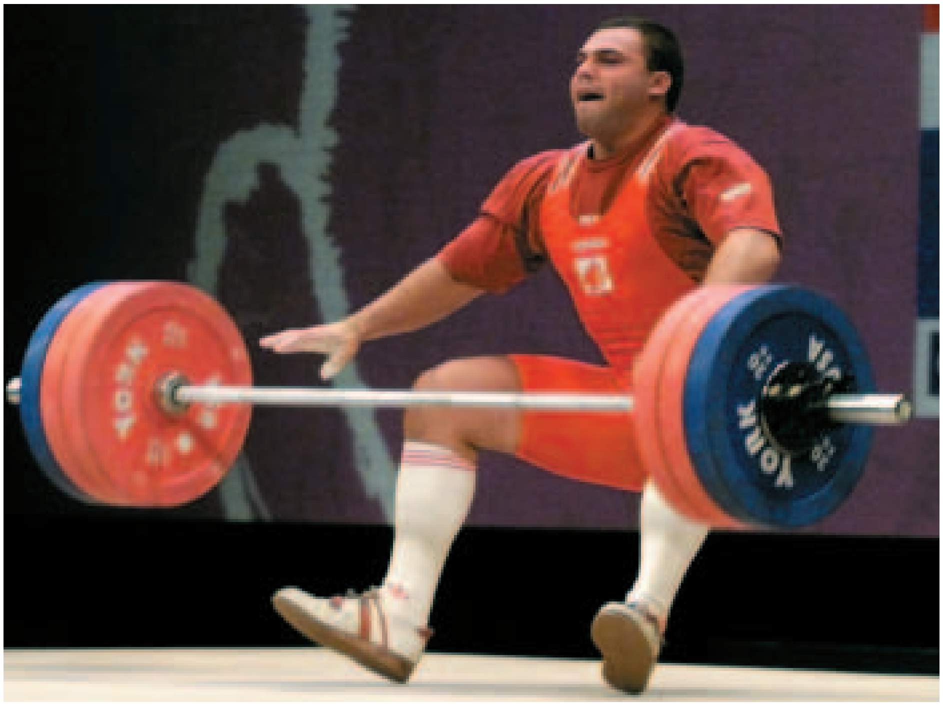


Figure 2.8 The external force of gravity is pulling the weights to the ground.

An **external force** is a force that is applied on a structure by something else. When you walk into a wind or stand in waves, the force you feel acting on your body is an external force. To remain standing, all structures on Earth must be able to resist the force of gravity pulling on them. Since gravity is the pull of Earth, gravity is an external force. It acts constantly on you and everything else on Earth. **Mass** is the amount of matter in an object. The more mass an object has, the greater the gravitational force.

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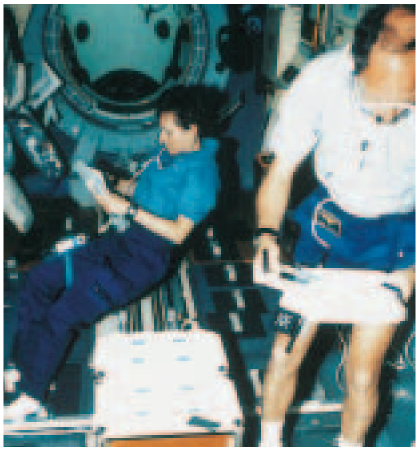
Height Gains in Space

When the space shuttle orbits Earth, astronauts experience weightlessness. With weightlessness, the structure of the human skeleton no longer has to carry a load. This results in the human spine stretching.



Dr. Roberta Bondar, Canada's first female astronaut, became 4 cm taller during her first space mission.

Centre of Gravity

Where does gravity act on a structure? If you hold your arms out straight for a few minutes, you can tell that gravity is acting on both of your arms. What happens if you stand on one foot for a while? To keep balanced, you might have to move your arms about or lean to one side. That is because gravity is having an effect on the stability of your body.

How can you predict the effect of gravity on a structure? Scientists have discovered that even though gravity acts on all parts of a structure, there is a point where we can think of the downward force of gravity acting on a structure. That imaginary point is called the **centre of gravity**. When a structure is supported at its centre of gravity, it will stay balanced. Therefore, the location of the centre of gravity of a structure determines the structure's stability.

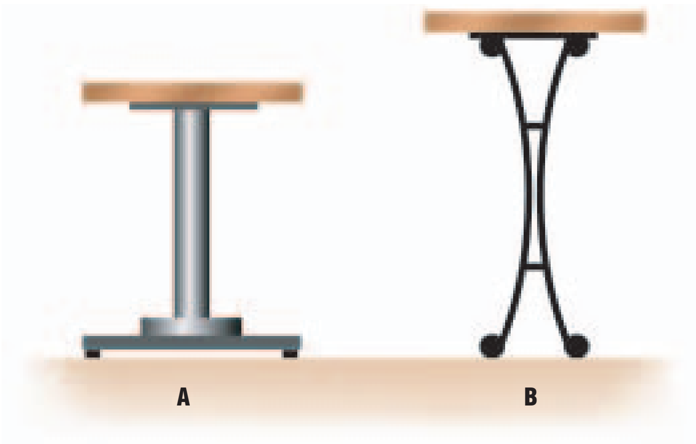


Figure 2.9 In most cases, structures with a low centre of gravity and wide base are stable. Which of these tables do you predict is the more stable of the two? Why do you think that?

The main method of increasing a structure's stability is to increase the width of its base relative to its height. One way to do this is to place most of the mass of the structure close to the ground. This lowers the centre of gravity.

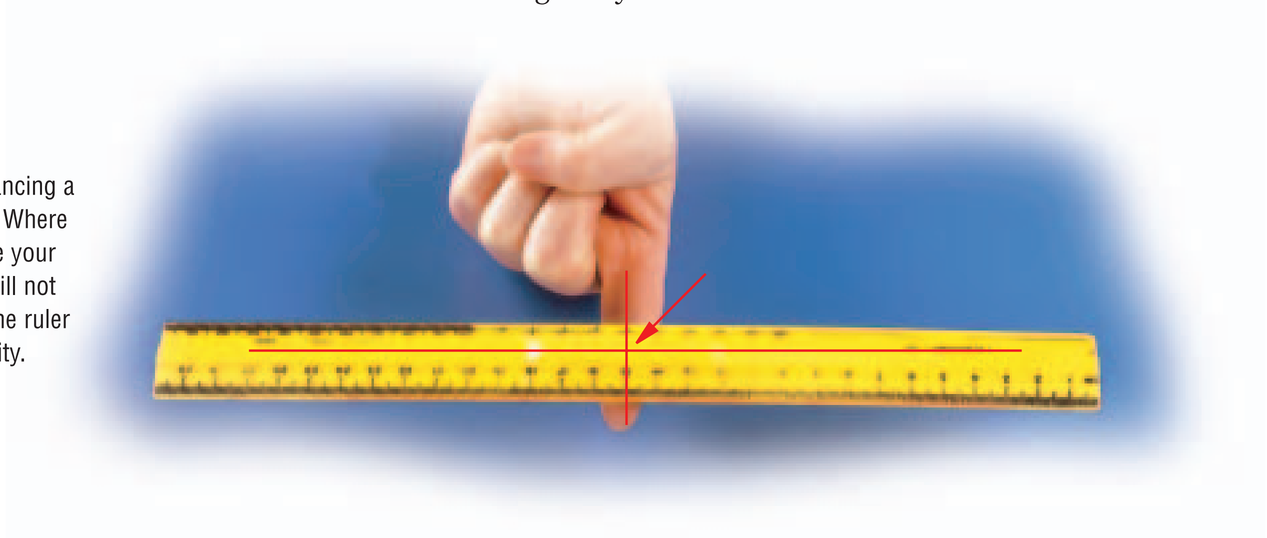


Figure 2.10 Try balancing a ruler on your finger. Where do you have to place your finger so the ruler will not fall? That point on the ruler is the centre of gravity.

Symmetry

Notice in Figure 2.10 that the finger under the balanced ruler divides the ruler into two parts of the same mass. This means that the ruler has **symmetry**, a balanced arrangement of mass that occurs on opposite sides of a line or plane, or around a centre or axis. The force of gravity on either side of the centre point of the ruler (where the finger is supporting it) is the same.

In this symmetrical arrangement, the ruler is stable. What would happen if you moved your finger away from the centre of the ruler, even 1 cm to either side? The mass on one side of the ruler would become greater than on the other, and therefore, the force of gravity would be greater on the side with the greater mass. The ruler would become unbalanced.

For a symmetrical structure to be stable, its mass must be distributed equally around the centre of the structure's base. This means that the force of gravity around the centre is also equal, making the structure stable.

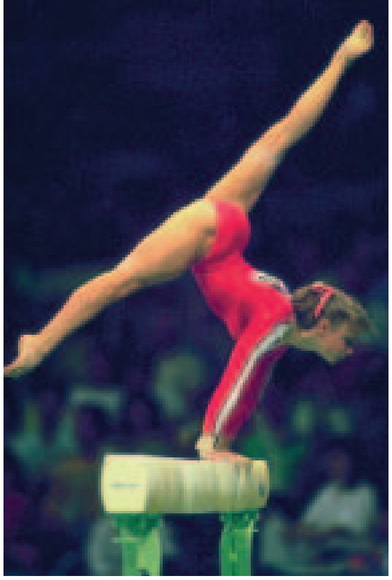


Figure 2.11 For this gymnast to hold a stable position on the balance beam, the forces of gravity on all parts of her body in the air must be balanced around her hands on the beam.

TRY This at Home

ACTIVITY

Testing Teepees

Do you think you could build a teepee that would stay standing even in a strong wind? Build these two models, test them, and find out.

Teepee A:

- Tie 4 of the long skewers together about 2–3 cm from the end of each skewer. Splay them out in 4 directions to make a base and stand the structure on a non-skid mat. Cover the frame with plastic wrap.
- Place the fan about 50–60 cm away from the teepee at the NW position. Turn the fan on high. How does the teepee respond to the force?

Teepee B:

- Tie the 2 short skewers and the 2 remaining long skewers together, again about 2–3 cm from the end of each skewer. Splay the skewers out and set the structure on the second non-skid mat so that the 2 short poles are at the NW and SW positions. Cover the frame with plastic wrap.
- Use the fan as above to test how Teepee B responds to the wind force.

Which teepee design is the strongest?

Materials & Equipment

- 8 bamboo skewers, 2 of 23 cm and 6 of 30 cm
- plastic wrap
- 2 large non-skid mats
- fan
- ruler
- string
- scissors

Caution!

- Take care around the fan when it is on.
- If you have long hair, tie it back.
- Keep water or wet hands away from electrical outlets.

Activity adapted with permission from Science Alberta Foundation

Figure 2.12 The force of gravity pulls down on the bookcase and the books. This is the load the bookcase must bear. This bookcase appears to be overloaded.

Load

When engineers and architects design a structure, they consider the load that the structure will have to resist. For example, a bookcase must be so designed that it will support its own weight and the weight of the books it is going to hold. For a bridge, the load might be the force of gravity on a car crossing the bridge, plus the force of a strong wind blowing against the bridge structure, and of course, the weight of the materials that make up the bridge.

Static and Dynamic Loads

The term "load" has a specific meaning when you are considering structures and their function. A **load** is an external force on a structure. The weight of the books in a bookcase is a load on the bookcase. The force of gravity pulls down on the books and they, in turn, pull down on the bookcase. The weight of the bookcase itself is also a load. It is the force of gravity acting on the mass of the bookcase. A load can be a weight, such as a car crossing a bridge, or the push of a force, such as the wind blowing on a tower. Two types of loads can affect structures: *static* and *dynamic*.

The weight of a structure—and the non-moving load it supports—is called the **static load**. These are forces that stay the same for a long period of time. (Static means not moving or changing.) Some examples of static loads are the wood, nails, and screws used to make a bookcase as well as the books, or the steel beams, cables, rivets, and steel plates used to construct a bridge. Even though these parts make up a structure, the static load they

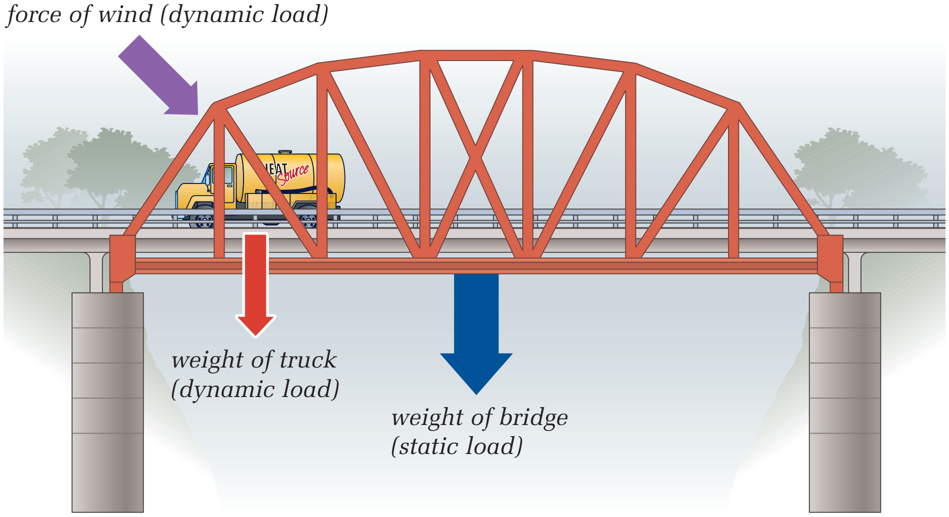


Figure 2.13 Forces acting on this bridge include the weight of the bridge (static load), the weight of the truck (dynamic load), and the wind (dynamic load).

create is an external force. Why? Because it is the force of gravity acting on all the parts of the structure. Static load is also called *dead load*.

A **dynamic load** is an external force that moves or changes with time. These loads can change very quickly, as occurs with a sudden gust of powerful wind or an earthquake. The weight of the moving students on the staircase in Figure 2.14 is a dynamic load. Dynamic load is also called *live load*. Designers must plan their structures to be capable of resisting both dynamic loads and static loads.

Figure 2.14 What is the static load on this staircase? How would you measure it? What is the dynamic load? How would you measure that?

Supporting the Load

Different structures are designed to withstand different loads and forces. Think about a bridge. A number of different types of bridges can be built. Engineers use two conditions to decide which type of bridge will best suit a situation:

- what the bridge is crossing (for example, water or land)
- what kinds of loads the bridge will be supporting

The **beam bridge** (Figure 2.15) is the most common bridge used. A simple beam bridge is flat and is supported at its two ends. A longer beam bridge may be supported by additional piers (vertical supports).

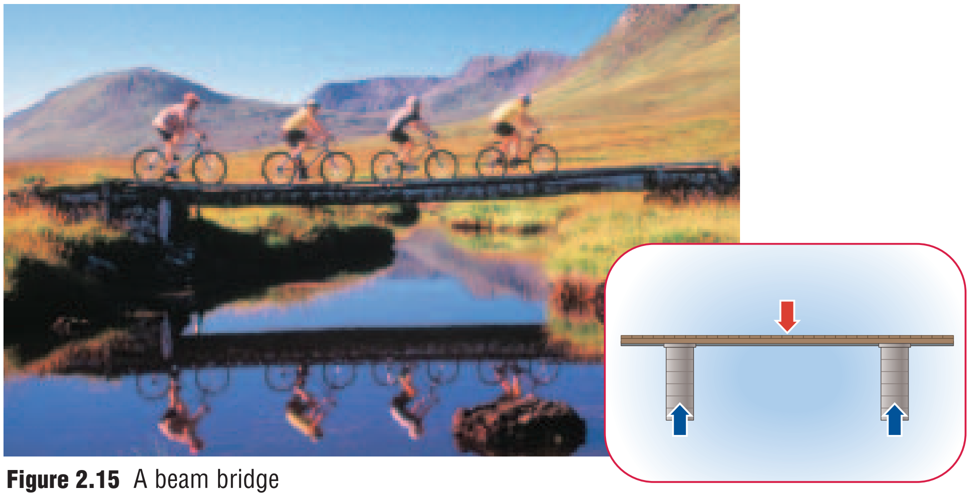


Figure 2.15 A beam bridge

A **truss bridge** (Figure 2.16) is a lightweight but strong bridge, made of trusses (triangle-shaped frames) along its sides.

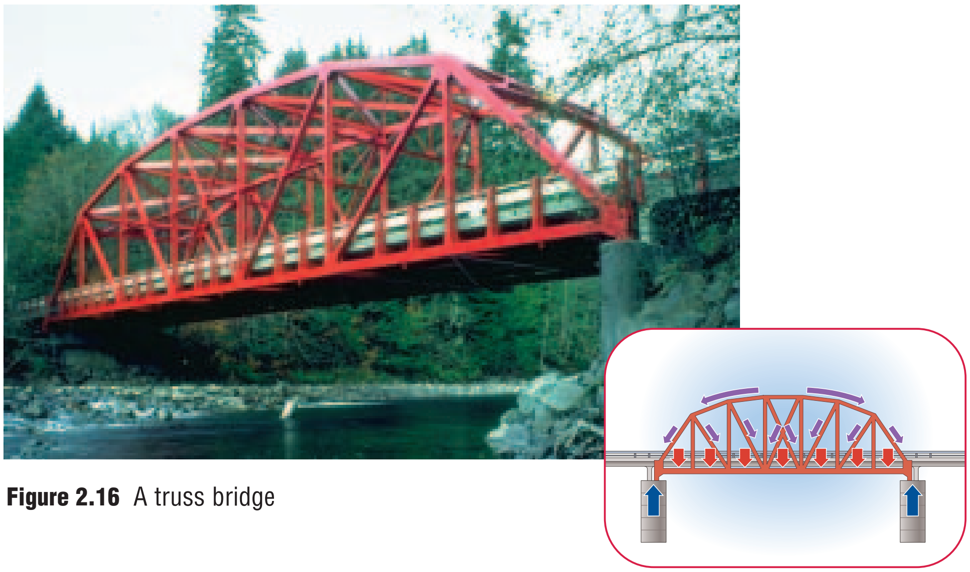


Figure 2.16 A truss bridge

A simple **suspension bridge** (Figure 2.17) hangs between two ends (they may be trees!) that hold it up. A modern suspension bridge has tall towers on either end that support the main cables holding up the bridge. The main cables are anchored in concrete at each end of the bridge. Smaller cables, which support the roadway, are suspended from the main cables.

Figure 2.17 A suspension bridge

An **arch bridge** (Figure 2.18) is designed to withstand heavy loads. The dynamic load of people and other traffic causes each piece of wood or stone in the arch to push against the piece next to it. This push is eventually transferred to the end supports, which are embedded in the ground. The ground pushes back (resists), and this resistance is passed back through all the pieces creating the arch.

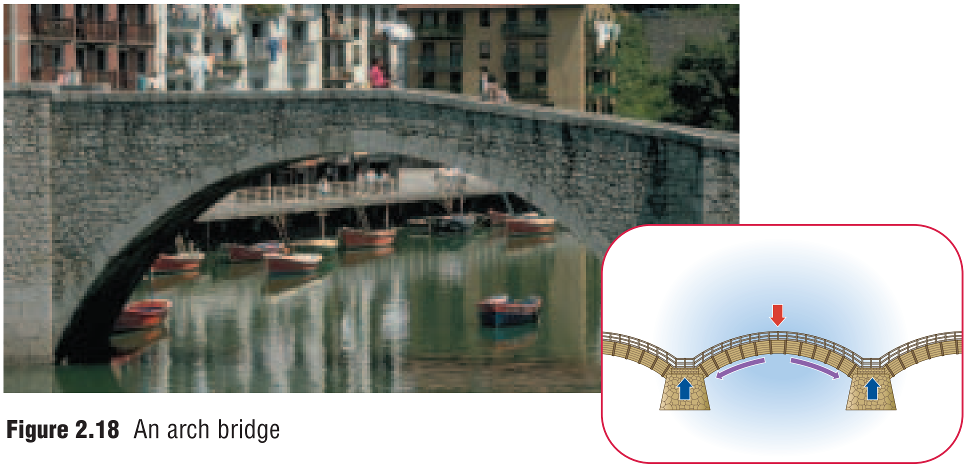


Figure 2.18 An arch bridge

Which of the bridges shown do you think must support the greatest static load? Which must support the greatest dynamic load? Look carefully at the design of each type of bridge. Make note of any components that help add strength and stability to the structure.

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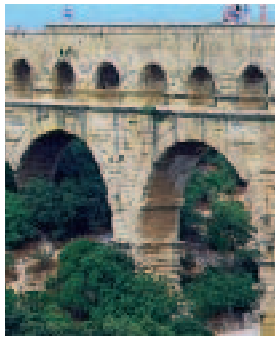
Arch Support

The ancient Egyptians and Greeks first recognized the structural advantages of the arch. However, it was the Romans who made the arch a regular building feature. Use library resources and the Internet to find examples of how arches were used in Roman architecture.



Aqueducts are a type of bridge used to carry a large quantity of flowing water between places. Many Roman aqueducts are still standing today.

Problem Solving Activity

My Bridge Is Stronger Than Yours

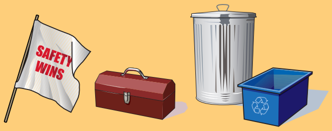
Materials & Equipment

- cardboard
- wire
- aluminum foil
- Plasticine or modelling clay
- straws
- blocks or other small heavy objects
- balance

Caution!

Before starting any construction project, be sure you know the answers to these questions:

1. What special safety precautions should you take?
2. Where do you store any tools when you have finished using them?
3. How should you dispose of any waste or unused materials?



Recognize a Need

A local walking path must cross a stream. The stream is dry during the summer, but in the spring, it fills up with water until it is too wide to jump. A neighbourhood committee has decided to build a small, inexpensive bridge that can hold several people at a time. You've been asked to work with a group to prepare a model of your design. The committee has set certain standards for testing all of the submitted models.

The Problem

To design and build a simple beam bridge model that will support the greatest possible dynamic load under the following conditions:

- The bridge must be 60 cm long.
- The bridge must be no more than 5 cm wide and no more than 5 cm tall.
- The bridge must span a distance of 50 cm (between two desks).
- There must be a means of fastening the test load to the centre of the bridge.

Criteria for Success

The bridge, designed to the specifications outlined above, must support the greatest possible dynamic load without breaking.

Brainstorm Ideas

1 Working with your group, brainstorm designs that meet the conditions set. Keep in mind that the committee wants an inexpensive bridge. Can you produce a design that uses as few materials as possible to support the load required?

2 Choose the combination of suggestions you think will create the best overall design.

3 Decide which materials from those provided you will use.

4 Decide how you will measure the ability of your bridge to support static and dynamic loads. You might, for example, add blocks in progressively heavy amounts to the bridge and see at what weight the bridge kinks.

Figure 2.19 Step 4. This is one way to test a static load on a bridge.

Build a Prototype

5 Build your bridge. If necessary, make modifications to the design as you build.

Test and Evaluate

6 Measure the dimensions of your completed model. Does it meet the conditions set by the committee? Adjust the structure as required.

7 Measure the mass of the bridge.

8 Test the strength of the bridge using the method you decided on in your brainstorm. Record your results according to the headings shown in Figure 2.20.

Bridge Number	Mass of Bridge (g) (Static Load)	Maximum Dynamic Load (kg)

Figure 2.20 Step 8

9 Collect the results from your classmates and add them to your table.

10 Evaluate the materials you used. Are you satisfied that they were the best choice for the design? Why or why not?

Communicate

11 Combine your findings with those of the other groups.

a) From the class results, graph the relationship between bridge mass and the mass of the maximum load the bridge can support without kinking.

b) Copy each sentence below into your notebook and fill in the blank using the information from your graph.

- The smaller the mass of a bridge, the __________ mass it can support.
- The larger the mass of a bridge, the __________ mass it can support.
- The relationship between bridge mass and mass supported is best described as a __________ line.

12 In a class discussion, explain what you think is the best way to make a beam bridge stronger.

13 Consider the different materials that were used to make the bridges. Which materials seemed to be the best choice? Share your ideas in class.

Measuring a Structure's Load Performance

How well a structure holds up under the load it was designed to carry is important for safety, cost, and efficiency reasons. Engineers therefore set conditions that a structure must meet after it is built to show it is performing to certain standards. All these conditions together are referred to as **performance requirements**. Load performance is often expressed as a maximum weight.

A new waterslide, for example, might have to meet the following performance requirements:

- The structure must be able to support the weight of 200 people at one time, plus the weight of the water.
- The structure must be able to withstand high winds and heavy snows in winter without becoming unstable.

Performance requirements also apply to many other aspects of a structure. These include the safety of the structure and its effectiveness in meeting the purpose for which it was designed.

Figure 2.21 Why is it important that load performance requirements be expressed as a maximum weight rather than an average weight?

Comparing Performance

The performance of one structure can also be compared with that of another. Consider the following example. Bridge A has a total mass of 10 000 kg. It is designed to support cars and trucks with a total mass, at any one time, of 100 000 kg. Bridge B has a total mass of 1000 kg and is designed to support people and bicycles with a total mass of 1500 kg. How would you compare Bridge A's performance with Bridge B's?

First, you would calculate that Bridge A is supporting 10 times its own mass (100 000 ÷ 10 000 = 10). Then you would calculate that Bridge B is supporting 1.5 times its own mass (1500 ÷ 1000 = 1.5). This tells you that Bridge A is supporting a greater load per unit of its own mass than Bridge B.

Give it a **TRY** ACTIVITY

FIGURING TRIPOD PERFORMANCE

You work at a camera shop. In a brochure about new tripods, you learn that the "Ace" tripod has a mass of 10 kg and is designed to support a camera and assorted lens sizes up to a total mass of 20 kg. The "Top Choice" tripod has a mass of 6 kg and is designed to support camera equipment with a total mass of 24 kg.

- How does the performance of these tripods compare?
- How might this kind of information be of use to a customer who is looking for a tripod to carry in the mountains for wildlife photography?

CHECK AND REFLECT

1. Copy the following sentences into your notebook. Fill in the blanks using the words below. (Hint: You can use the same word more than once.)

centre   gravity   external   symmetry   stable

a) An ________ force is one that acts on a structure. An example of this kind of force is ________.
b) A structure that can be divided into two equal portions that look the same has __________.
c) If a structure can resist the forces acting on it, it is ________.
d) The ________ of ________ is the point on a structure where the force of gravity appears to pull a structure downward.

2. How do you find out where a structure's centre of gravity is? Describe how a structure's centre of gravity affects its stability.

3. Many structures can be built to great height, but if they are not also symmetrical around their centre of gravity, what will be the result?

4. a) Explain how you can identify the static and dynamic loads that act on structures.
b) Describe the relationship between a structure's stability and its ability to support the load acting on it.

2.3 Internal Forces within Structures

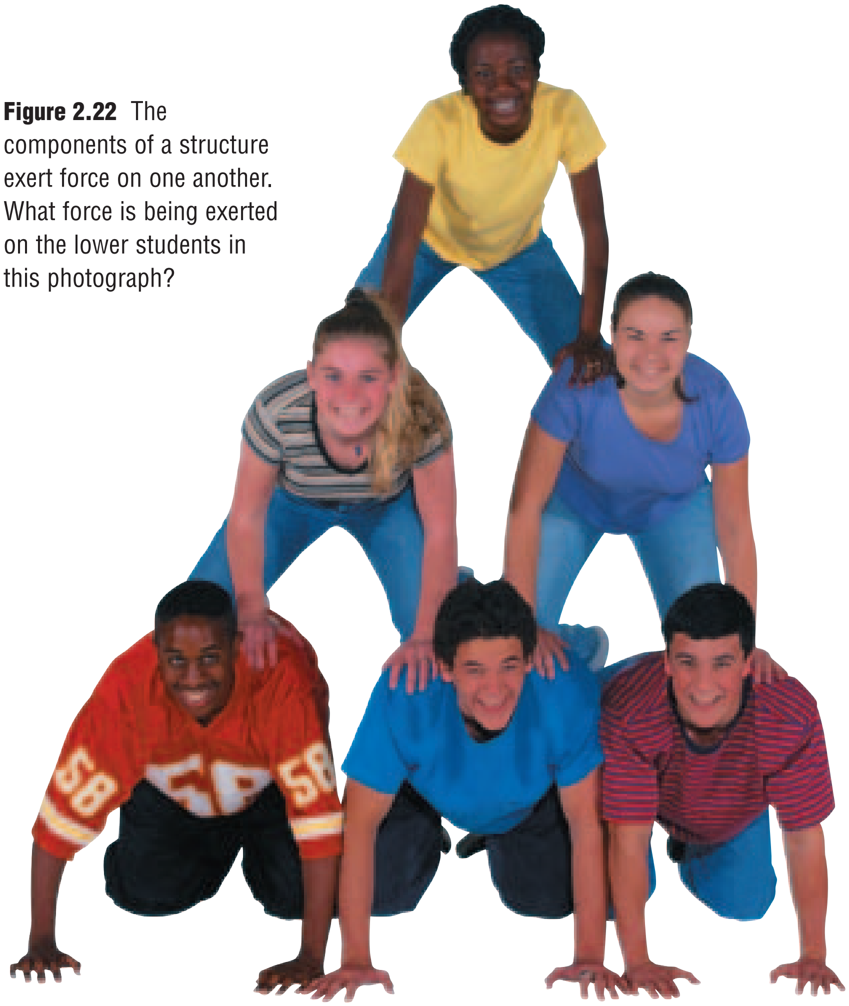


Figure 2.22 The components of a structure exert force on one another. What force is being exerted on the lower students in this photograph?

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Materials under Force

Concrete is strong under compression, but weak under tension. Steel frames are strong under tension, but weak under compression. Some builders combine concrete and steel to make very strong structures.

Modern construction requires good knowledge of how forces act and materials respond.

Think about what you have learned so far about structures and force, and then try to answer the three questions below.

- You crumple a piece of cellophane into a ball and put it on the table. Slowly, the cellophane opens up again. Why?
- You've used an elastic band to hold a collection of cards together. Suddenly, the elastic snaps. Why?
- To remove excess water from a sponge, you squeeze the sponge. To remove excess water from a towel, you could also squeeze the towel, but wringing it works better. Can you explain why?

In all of these cases, some type of **internal force** is at work. An internal force is a force that one part of a structure exerts on other parts of the same structure. In other words, internal forces are forces that act within a structure. Press the palms of your hands together firmly. Can you feel the internal force your muscles are exerting?

Compression, Tension, and Shear

Internal forces can be classified by the direction in which they act within an object. Three internal forces are compression, tension, and shear.

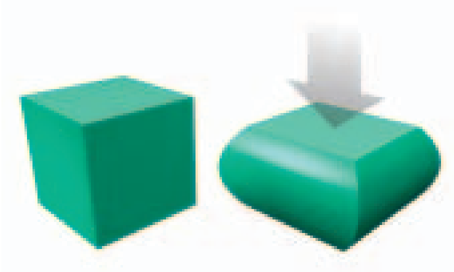


Figure 2.23 Compression

Compression is a force that acts to squeeze an object or push parts within an object together (Figure 2.23). Structures with parts that must resist compression include the human body, chairs, shelves, and architectural columns. Which parts of those structures do you think are resisting compression? Solid structures can usually resist the force of compression because of the strong materials they are made of.

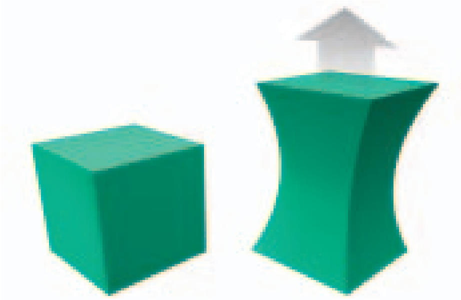


Figure 2.24 Tension

Tension is a force that acts to stretch and pull apart something (Figure 2.24). It can cause lengthening and possibly snapping of a component. Structures with parts that must resist tension include ski lifts, hydro towers, and running shoes. Which components of those structures do you think are resisting tension? Tension can also be used to advantage, as in the case of the cables used to hold up a suspension bridge.

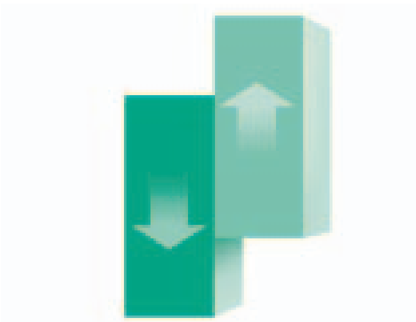


Figure 2.25 Shear

Shear is a force that acts to push parts that are in contact with each other in opposite directions (Figure 2.25). Structures with parts that must resist shear include doors, airplanes, and scissors.

TRY This at Home

ACTIVITY

MODELLING INTERNAL FORCES

One of the best ways to be sure you understand a concept is to see if you can find an example or model of that concept. A good way to model the forces of compression, tension, and shear is to use a piece of Plasticine (or modelling clay).

- Look at the illustrations in Figures 2.23 to 2.25 and note the direction in which the forces are working.
- Using a piece of Plasticine at least 4 cm by 4 cm, copy the force shown in the figures. Observe what happens to the Plasticine.
- Look around you at home. Can you identify different objects in which these forces are being exerted? Can you visualize these forces at work? Is there evidence of their effect?

COMPLEMENTARY FORCES

When different kinds of internal forces act on a structure at the same time, they are called **complementary forces**.

Bending is an example of complementary forces at work. When the beam in Figure 2.26 is bent into a U-shape, compression is produced on the top and tension on the bottom. If the load is too great, the beam will break. This break would be the result of the beam's failure to resist either compression or tension.

By examining where a break happens on a beam, engineers can find out how to improve the structure. For example, if a beam broke (failed) first along the upper surface, the new beam should be designed so that the upper surface is strong enough to resist compression. If the beam failed first along the lower surface, what design change would you recommend? Why?

Figure 2.26 Complementary forces—The weight of the girl results in compression and tension in the beam.

Give it a **TRY** ACTIVITY

MODELLING COMPLEMENTARY FORCES

If you could see inside a structure that is supporting a load, you would be able to observe compression and tension acting together on that same structural part. Here's one way to see these forces at work.

- Make several, equally spaced cuts (about 0.5 cm deep) on both the top and bottom of a Styrofoam strip.
- Place the Styrofoam on two supports of the same size, such as wood blocks or textbooks. Press your finger in the middle of the Styrofoam, enough to make it bend.
- What happens to the top and bottom of the Styrofoam? Can you see two different forces acting on the Styrofoam? Where is the compression force acting? Where is the tension force acting? Record your results in a drawing.

Materials & Equipment

- a strip of Styrofoam, 2 cm by 3 cm by 10 cm
- ruler
- scalpel or small sharp knife

Caution!

- Always handle sharp objects with care.
- Wear goggles in case the scalpel or knife blade breaks.

Figure 2.27 Make shallow cuts in the Styrofoam.

CHECK AND REFLECT

1. Copy the following sentences into your notebook. Fill in the blanks with one of the following terms: compression force, tension force, shear force.

a) When you stretch an elastic band, you are applying ________.

b) When you tear a piece of cardboard in half, you are applying ________.

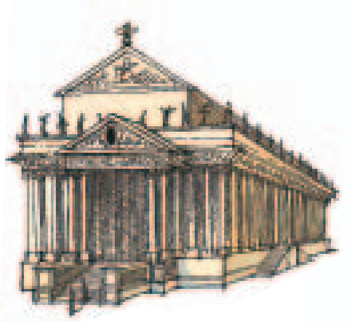
c) When you sit on an air mattress, you are applying ________. As the air pressure inside the mattress increases, the structure of the air mattress experiences an increase in ________.

2. Identify the internal and external forces that act on a tree under a heavy load of snow. Draw a sketch and use arrows to show these forces.

3. Return to the three questions at the beginning of this subsection (page 296). Modify your answers, if necessary, based on what you have discovered about internal forces.

2.4 Designing Structures to Resist Forces and Maintain Stability

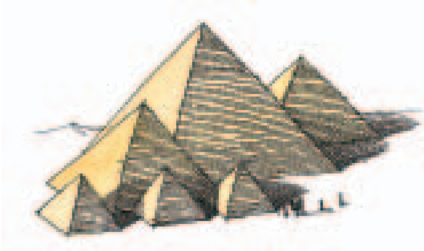
350 B.C.—The marble Temple of Artemis at Ephesus



350 B.C.—The marble Mausoleum of Halicarnassus

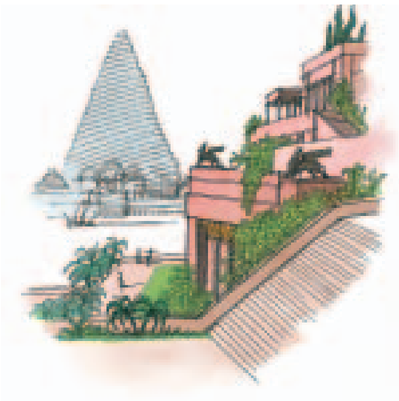
297 B.C.—The Pharos of Alexandria

290 B.C.—The Colossus of Rhodes. This was a huge bronze statue of the sun god, Helios. It stood more than 35 m high, overlooking Rhodes Harbour in Greece.



2500 B.C.—The Pyramids of Giza, Egypt

430 B.C.—The Statue of Zeus at Olympia. It was made of ivory and gold and stood 12 m high.



560 B.C.—The Hanging Gardens of Babylon. These beautiful gardens were created in the middle of the desert.

Figure 2.28 The Seven Wonders of the Ancient World. Some took many years to complete, so the dates of when they were built are approximate.

Have you heard of the Seven Wonders of the Ancient World? All of the structures are shown in Figure 2.28. Some of them lasted a very long time. Look closely at the illustrations. List the structures by name in your notebook and then, for each one, record anything about the shape that you think helped it withstand the forces acting on it. Next, add your ideas about the materials used to make each structure and how those materials may have contributed to the structure's durability.