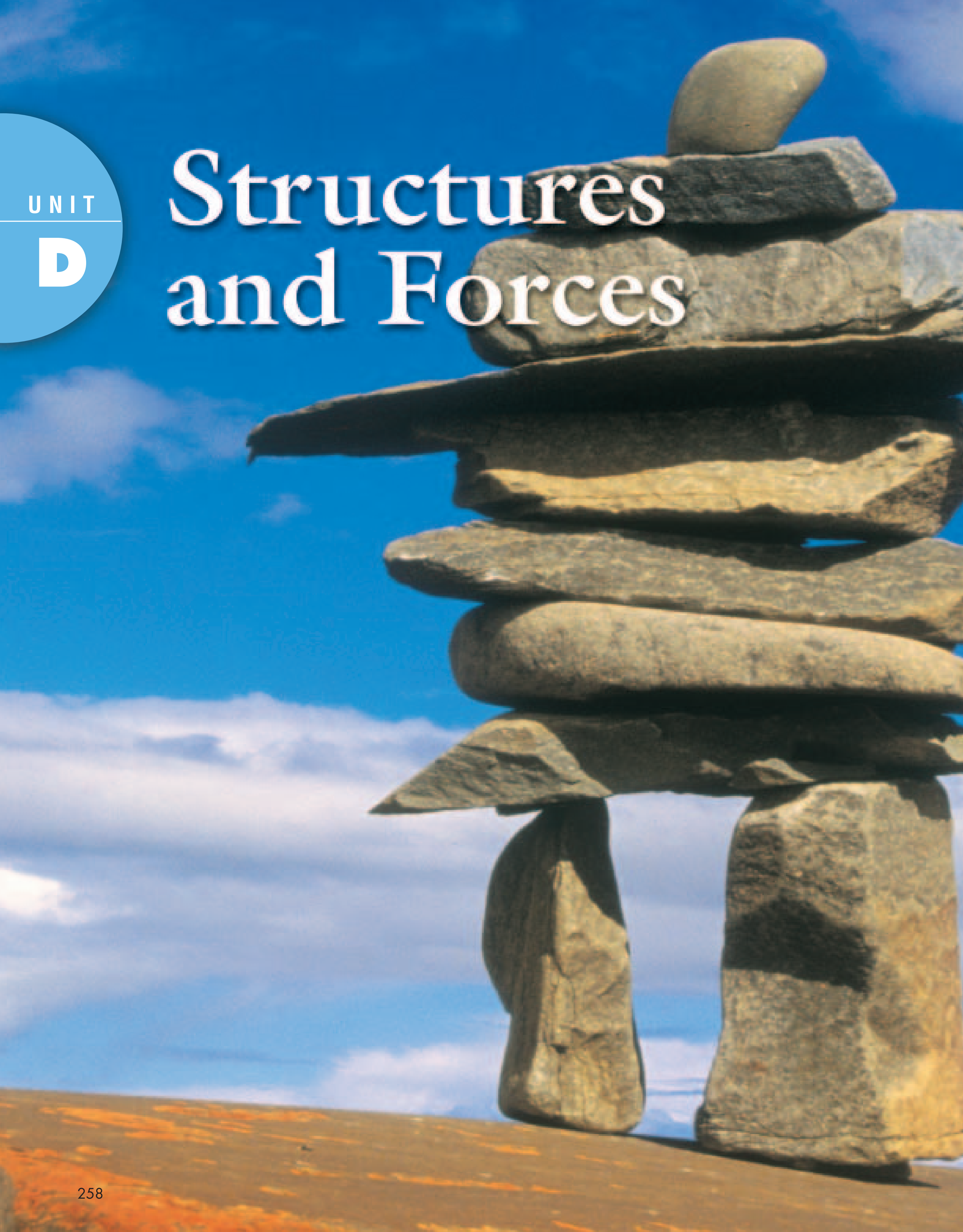
UNIT D

Structures and Forces



In this unit, you will cover the following sections:

1.0

Structures are found in natural and human-made environments.

- **1.1** Classifying Structural Forms
- **1.2** The Function of Structures
- **1.3** Human-Built Structures around the World

2.0

External and internal forces act on structures.

- **2.1** Measuring Forces
- **2.2** External Forces Acting on Structures
- **2.3** Internal Forces within Structures
- **2.4** Designing Structures to Resist Forces and Maintain Stability

3.0

Structural strength and stability depend on the properties of different materials and how they are joined together.

- **3.1** Materials and Their Properties
- **3.2** Joining Structural Components
- **3.3** Properties of Materials in Plant and Animal Structures

4.0

Structures are designed, evaluated, and improved in order to meet human needs.

- **4.1** Building Safe Structures in All Environments
- **4.2** Strengthening Materials to Improve Function and Safety
- **4.3** Evaluating Designs from an Overall Perspective

Exploring

Structures have a job to do. A roof must stay in place even under the weight of heavy snow, sheltering whatever it covers. A bridge must support hundreds of vehicles, as well as be able to withstand the forces of weather and, in some cases, even earthquakes. The case around a television must protect its internal parts—just as your rib cage must protect your internal parts from the wear and tear of daily life.

In this unit, you will learn about a wide variety of structures in both the natural and human-built environments, examining the many different purposes they serve and the forms they can take. Investigating and analyzing the forces that act within and on structures will help you explore how different materials, components, and ways of joining can affect structural strength and stability. As you build and test your own structures, you will also learn about the relationship between design and function. This will help you evaluate how structures built in the past, as well as those you use every day, can be developed and improved to meet human needs in a safe and efficient manner.

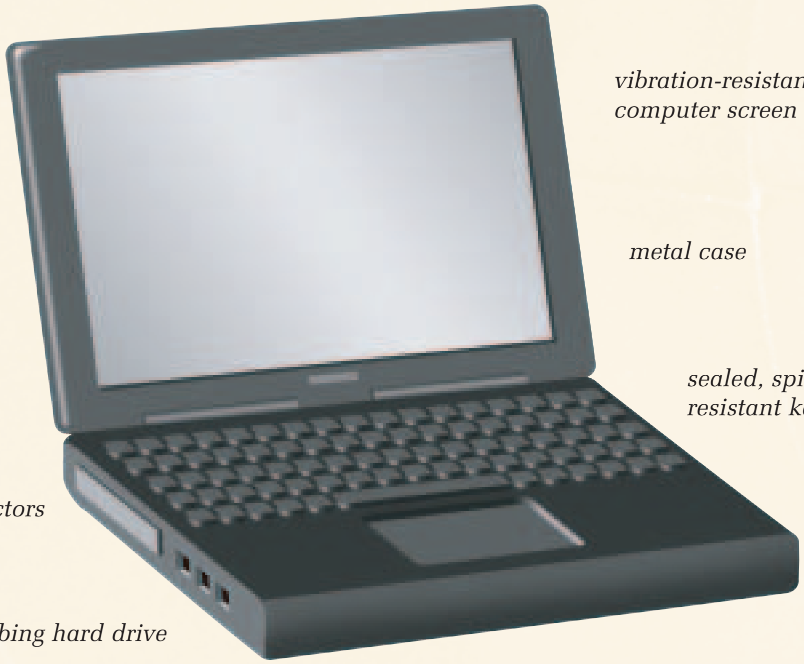
Rugged Computers for a Rugged Life

A recent survey by a leading maker of computers in the world reported that businesses in North America are spending millions of dollars each year to repair and replace damaged laptop computers. Laptops, the survey found, are most often damaged as a result of being dropped, crushed, or spilled on. This is likely to become a greater problem as people rely more and more on being able to take their laptop computers wherever they go: the office, school, the mountains, the beach—even into space.

A laptop computer has many delicate parts that can break. It must therefore be designed to withstand being bumped around every day. Still, it must also be light enough to carry. Early laptops were heavier than today's models because of the materials and components used to make them. As computer technology has improved, laptops have become increasingly lighter. At the same time, designers and computer technicians have come up with clever ways of making the devices more rugged. The illustration on the next page shows several of the standard features on new laptops today.

Many laptop computers are used far from classrooms and offices. In this photograph, a satellite communicator is also being used.

Laptops are not meant to be mistreated, but when accidents happen, today's portable computers can often survive with good results.



Give it a TRY ACTIVITY

SAVE THIS EGG!

How well could you design a structure to protect a very delicate object like a laptop computer? Rather than finding out using a real computer, you're going to test your design abilities on another delicate object—an egg.

- Brainstorm what design and materials might be used to protect an egg from cracking when it is dropped.
- Using the least amount you can of the materials listed here, design an egg protection case that will enable the egg to survive the force of impact when it is dropped from a height of 3 m.
- When everyone in the class has had a chance to test their egg protectors, discuss the results. Which means of protection worked the best? What materials provided the best protection? Was there a particular arrangement of materials that did the most effective job? Which successful protection case was the lightest (that is, used the least material)?

Materials & Equipment

Options:
- straws
- newspaper
- cardboard
- paper
- Popsicle sticks
- masking tape
- glue
- string
- paper clips
- elastic bands

Focus On SCIENCE AND TECHNOLOGY

As you learn about structures and forces in this unit, you will be given many opportunities to solve practical problems using your knowledge of both science and technology.

Science provides an ordered way of learning and explaining the nature of things. Technology is concerned with finding solutions to practical problems that arise from human needs. As you'll discover, there are often several possible solutions to the same technological problem, each involving different designs, materials, and processes. In approaching a problem, it is helpful to

- define your need clearly
- develop an appropriate plan and design
- test and evaluate your design

To guide your reading as you learn about the nature of structures and forces, keep the following questions in mind.

1. **How do structures stand up under a load?**
2. **What forces act on structures?**
3. **What materials and design characteristics contribute to a structure's strength and stability?**

The answers to these questions will help you understand the roles that both science and technology have in the designing and building of a wide variety of structures.

1.0 Structures are found in natural and human-made environments.

Key Concepts

In this section, you will learn about the following key concepts:

- structural forms
- function and design
- structural stability

Learning Outcomes

When you have completed this section, you will be able to:

- recognize and classify structural forms and materials
- interpret and evaluate variation in the design of structures that share a common function
- compare example structures developed by different cultures and at different times
- interpret differences in structural functions, materials, and aesthetics
- describe and interpret structures found in the natural environment

Every object that provides support is a **structure**. A structure may be made up of one or more parts, and it may be large or small.

Think for a moment of all the structures that are around you in your everyday life. Some you can see in the natural environment, and some are built by people. Some are made of delicate material, and others of very rugged, hard material. Some structures have lasted a long time because they can bend without breaking. Others have lasted a long time because they are rigid.

You will probably also notice that the structures around you vary in their strength and stability. **Structural strength** refers to a structure's capacity to hold itself up, as well as any weight added to it. **Structural stability** is a structure's ability to maintain its position even when it is being acted on by a **force**.

If there are so many types of structures, how can we even begin organizing them into a meaningful classification that helps us understand them better? In this section, you will find out.

For Web links relating to 1.0, visit **www.pearsoned.ca/scienceinaction**

1.1 Classifying Structural Forms

Usually, the first thing you notice about a structure is its shape, or form. You can learn a great deal about a structure by comparing its overall form with that of other structures. How would you do this?

There are three basic structural forms. You can see these for yourself by copying the actions in Figure 1.1. First, use your hand to make a fist. This is an example of a *solid structure*. Feel what it is like. Now, open your hand and put both hands together so your fingertips are touching. This is an example of a *frame structure*. Would this form be as strong and stable as your fist if you added a mass on top of it? Next, make one hand into a cup shape, as though you wanted to carry water in it. This is an example of a *shell structure*. Suppose you added a mass on top of this form. What do you predict about its strength and stability?

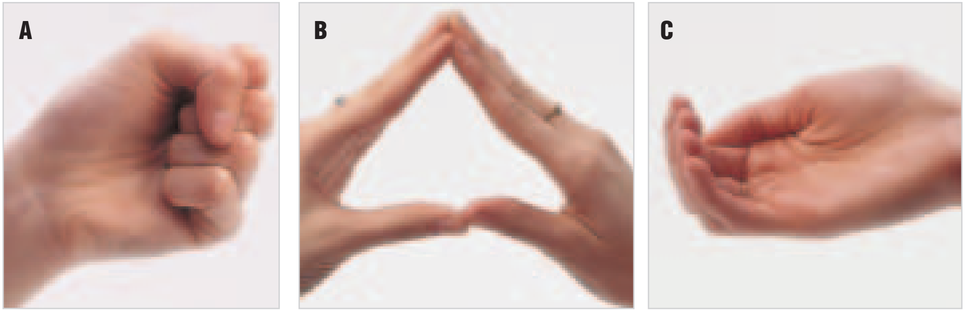


Figure 1.1 Your hand in the shape of a fist is a solid structure (A). Placing your hands in a tent-like position creates a frame structure (B). Cupping your hand creates a shell structure (C).

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Portable Shelters

The earliest human-built structures were dwellings made with ice, sod, or wood. They were strong and weather-resistant, but too heavy to be easily moved. Today, synthetic building materials (materials made from chemicals) mean that many dwellings can be strong but also light and portable. Examples are nylon tents and prefabricated trailers.

Give it a TRY — ACTIVITY

TAKE THE POP BRIDGE CHALLENGE

If someone told you it was possible for a full can of pop to be supported by a sheet of paper, would you believe it? Try this activity and find out. Your teacher has a can of pop and two stacks of books 15 cm apart at the front of the class.

- Using only a sheet of paper (about 26 cm × 20 cm, roughly the size of a page from your notebook), design a structure that will rest between the two stacks of books and support the can of pop. You have 5 min to work on your design at your desk. You will then get a chance to put your structure to the test on the set-up at the front of the class.

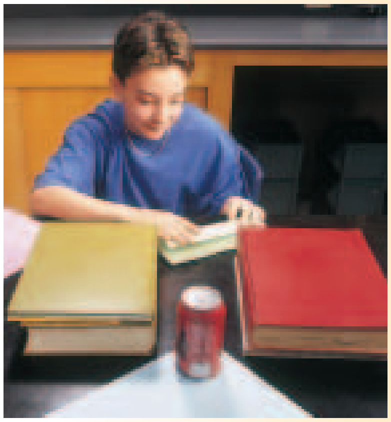

Figure 1.2 How could you create a paper bridge strong enough to support a full can of pop?

Solid Structures

A **solid structure** is formed from a solid piece (or solid combination of pieces) of some strong material. A concrete parking barrier is a solid structure. So is a brick wall and a hockey puck. A solid structure has little or no space inside, and relies on its own mass to resist the forces that act on it. (You will find out more about *mass,* meaning the amount of matter in an object, in section 2.0.) Solid structures are usually stronger than either frame or shell structures, but they are also more massive and therefore harder to move. Other examples of solid structures are shown in Figure 1.3.

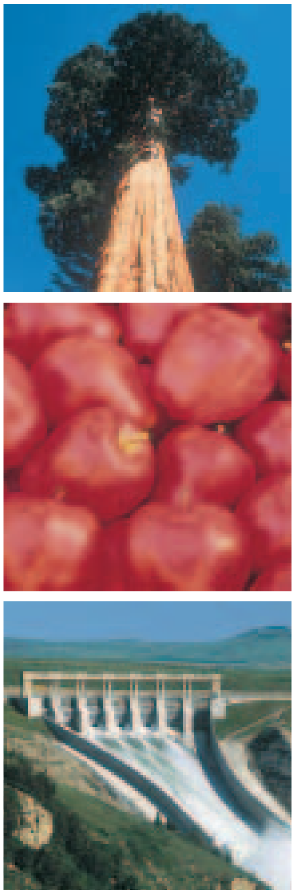

Figure 1.3 Examples of natural and human-made solid structures

Frame Structures

A **frame structure** is made up of a rigid arrangement of parts, or structural components, fastened together. An example is your skeleton, which is made up of bones, ligaments, and joints. The strength of a frame structure comes from the way the components are joined. Individually, no one component of a frame structure is as strong as the components combined.

A frame structure can be arranged in two dimensions, the way a door frame or fence is. It can also be arranged in three dimensions, as a music stand or house is. Compared to solid structures, frame structures are lighter because they use less material. Figure 1.4 shows additional examples of frame structures.

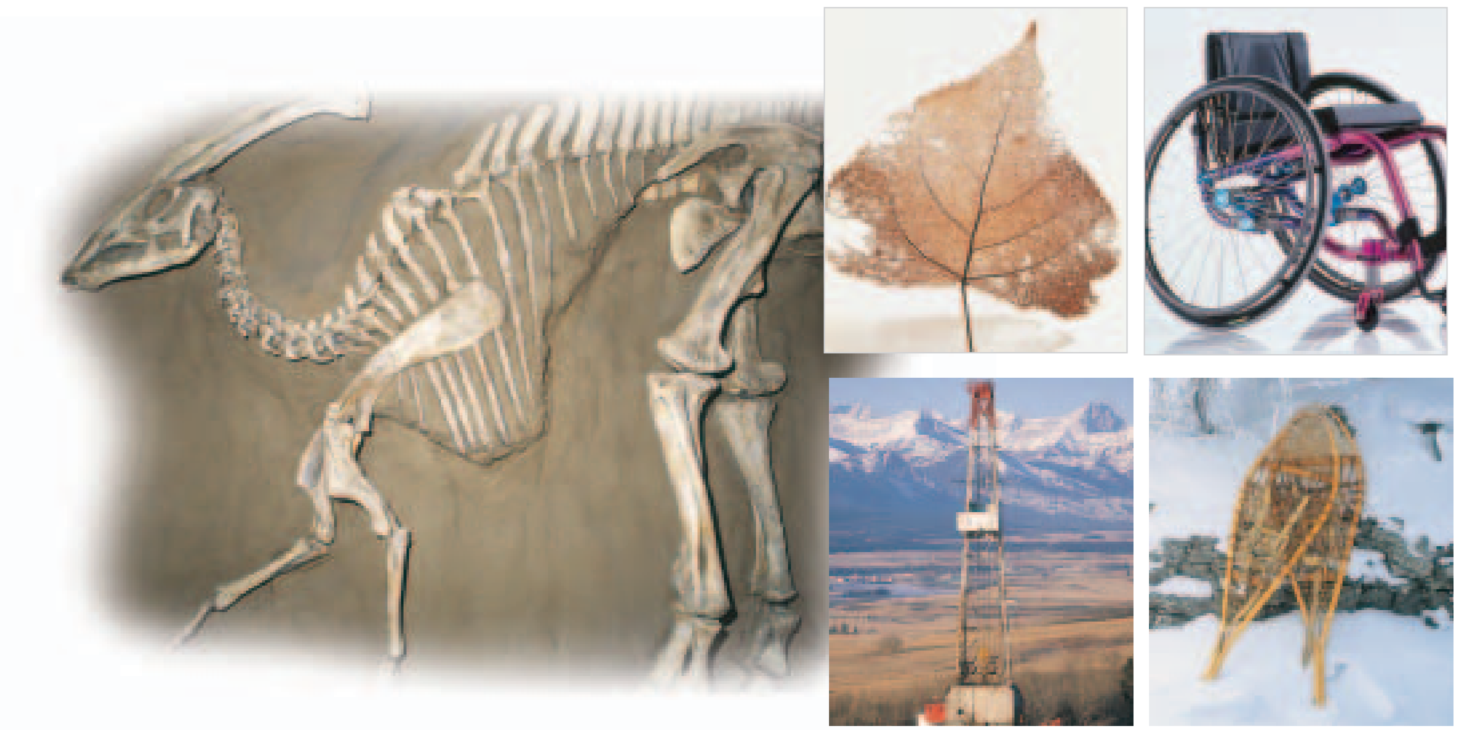

Figure 1.4 Examples of natural and human-made frame structures

Shell Structures

A **shell structure** has a solid outer surface, which may be rounded or flat in shape, and a hollow inner area. Shell structures with a rounded outer surface are usually stronger than those with a flat outer surface, because the curved areas distribute the load around the whole surface. A bean pod, a tennis ball, and a car body are all examples of shell structures. So are a flowerpot, a lunch kit, and a CD case.

Having a hollow interior means that shell structures are lighter than solid structures. They are also often stronger than frame structures and are therefore commonly used to provide protection. (Think of helmets, for instance.) Other examples of shell structures are shown in Figure 1.5.

math Link

The spider's web at the beginning of this section can hold up to 4000 times the weight of the spider that made it. If you were a spider, how much weight would your web hold?

Figure 1.5 Examples of natural and human-made shell structures

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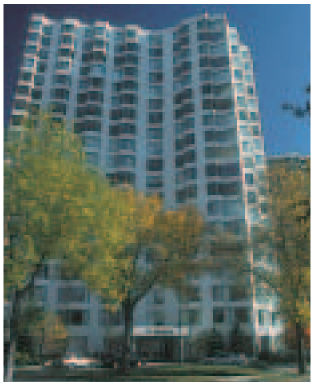
Combination Structures

You may have noticed that most structures in the built environment are actually a combination of structural forms. Combination structures use the best of the three basic forms to advantage. Study the structures to the right and decide which structural forms they combine.



Calgary's Saddledome shows how innovative architects can be when it comes to designing buildings.

Examples of combination structures

Check and Reflect

1. Name the three main structural forms. In your notebook, make a simple sketch of the basic design of each.
2. Copy the chart below into your notebook. Write the names of the three structural forms in the left-hand column. Then, for each structural form, write in two examples from the natural environment and two from the human-made environment. Try to make all your examples for (b) ones that have not been shown or mentioned in the text.

Structural form	Examples from the natural environment	Examples from the human-made environment
1.	a) b)	a) b)
2.	a) b)	a) b)

Figure 1.6 Make a chart like this for Question 2.

3. Large human-built solid structures are often made from brick, concrete, mud, or stone. Why do you think these materials are used to construct solid structures?
4. Consider these facts: a) a bird's wing bones are hollow, not solid; and b) the supporting skeleton of some invertebrates (such as sea stars and lobsters) is outside, not inside, their bodies. What advantages do these structural designs have?

1.2 The Function of Structures

Imagine the following situation:

You are a landscape designer who has been hired by the local parks commission to design a style of park bench that will last a long time and can't be easily moved. Knowing what you do about structural forms, you decide that a solid bench is the best choice. From your design, 10 block-like concrete benches are built. Several months after they are installed, a member of the parks commission calls you with a concern. Few people ever use the benches because they are so unappealing and uncomfortable.

What important point was overlooked in the design task? It was that the main **function** of the benches (that is, their use or purpose) was not properly considered. Too much attention was given to designing a bench that would be durable and secure. Not enough attention was given to designing a bench whose function was to provide comfortable, inviting seating.

Figure 1.7 The Muttart Conservatory in Edmonton is noted for its five glass pyramids. Housed within these pyramids are indoor gardens that include tropical and desert plants.

Multiple Functions

Many structures are designed to serve more than one function. An airplane, for example, provides both movement and shelter. So does a train. Sometimes these two types of structures are built to move and shelter cargo. Other times they are built to move and shelter people.

When a designer knows what all the functions of a planned structure are to be, he or she will be better able to design a structure that will be used.

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Inukshuit

What human need does an *inukshuk* (pronounced "in-OOK-shook") meet? This structure, found across the Canadian North, is a unique symbol of Inuit culture. It expresses "joy and much happiness" to anyone who encounters it. More than a greeting, however, many types of *inukshuit* also serve as signs, providing valuable information for travellers. For this reason, they must be clearly visible, stable, and strong.

Some *inukshuit* point in the direction where, traditionally, caribou herds have been hunted.

Function and Effective Design

Technological problems can often be solved in a variety of ways, using many different structural designs, materials, and processes. What all successful solutions have in common, however, is that they pay close attention to function. For example, consider Canadian inventor Norman Breakey. In 1940, he grappled with the following technological problem: how do you paint a large wall quickly and inexpensively? People had been using paint brushes, but it was a slow process and sometimes wasted a lot of paint.

Breakey thought of designing a device that would allow the paint to be rolled on quickly and smoothly. Wisely, he also remembered to think about how the device would be used. It had to be light enough for people to handle, easy to use in large or small spaces, and inexpensive to make. After making many modifications to his prototype, he developed the hand-held paint roller. Today, the roller is used by professional and do-it-yourself painters all over the world.

Figure 1.8 Predict what might have happened if Norman Breakey had thought only about the science of how his new device applied paint, and not about the practical problems of using the device.

To get ideas for structures that will meet particular functions, many designers, architects, and inventors look at the natural world. For example, Prairie rancher Michael Kelly invented barbed wire in 1868 when he realized he needed something that would function the same as a thorny bush to keep his livestock in one place. Over time, Kelly's invention has been refined, but the basic design has stayed the same.

Problem Solving Activity

Design the Perfect Desk

Recognize a Need

Right now you're probably sitting at a desk. Think about what your desk has to do. What are its main functions? How does its design help the desk perform those functions? Is there something you would add to make your desk more useful? Here's your chance to improve on an old design.

Materials & Equipment

- ruler
- metre-stick
- graph paper (optional)

Functions (*Ways I want to use my desk*)	**Design** (*What special features my desk will have so I can use it that way*)
Writing	A flat surface large enough to hold a workbook and textbook

The Problem

Design the "perfect" desk, one that serves all the functions you need it to do during the school day.

Criteria for Success

For your design to be considered successful, it must

- represent a completed desk that would fit an area no larger than 60 cm × 90 cm on the floor and 120 cm high
- show at least six unique features not used in current desks

Brainstorm Ideas

1 Working on your own, make a list of (a) your desk's essential functions and (b) the extra functions you think it could serve. For example, do you need more work space? Do you want a place to keep your lunch cold?

2 Beside each function you've listed, write down possible design solutions. Maybe you need a built-in pencil sharpener, or a hook for hanging your backpack off the floor? Be creative, but practical!

Make a Drawing

TOOLBOX

3 Decide what scale you will use in making a diagram of your design. For example, 6 cm in actual size could be represented by 1 cm in your drawing (see Toolbox 8).

4 Draw your design ideas on paper, using the scale you have set. If you need to, make two or three drawings to show your desk from various views, such as side, front, and back.

5 Label the design features shown in your drawings. Also, label the measurements of the overall desk as they would be in actual size.

Test and Evaluate

6 Post your completed drawings on the wall.

7 As a class, assess whether the various designs look as though they would be strong and stable enough to serve their intended functions.

Communicate

8 Share with the class any additional design ideas you had but were unable to use because of the size limitations or another reason. Invite your classmates to make suggestions for possible design solutions you hadn't thought of.

Common Function, Different Design

Some structures, although they look very different from one another in their design, actually share a common function.

For instance, look at the roofed structures pictured in Figure 1.9. In simple terms, all roofs serve the same purpose. They provide a top covering for a building and protect the contents inside. Yet, as the pictures show, there is great variation in the way roofs are designed and built. All of the roofs shown here are effective in their own way because they suit the local climatic conditions and they meet the needs of the people using them.

Over time, people have discovered through trial and error what works and what doesn't work in roof design. How effective do you think a flat roof on a house would be if the house were located high in the mountains? After one season of heavy snow, how would you modify the roof design?

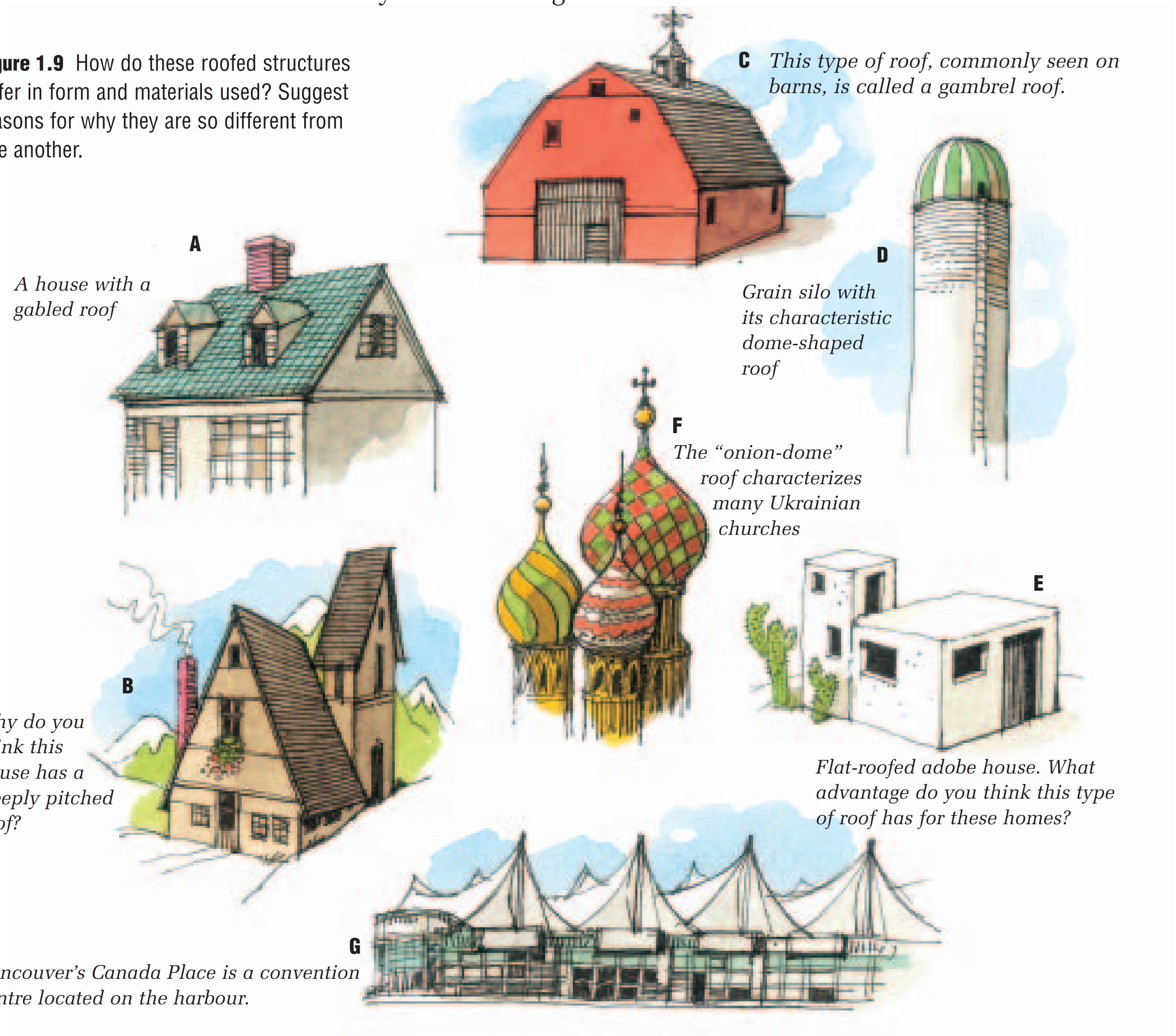

Figure 1.9 How do these roofed structures differ in form and materials used? Suggest reasons for why they are so different from one another.

A *A house with a gabled roof*

B *Why do you think this house has a steeply pitched roof?*

C *This type of roof, commonly seen on barns, is called a gambrel roof.*

D *Grain silo with its characteristic dome-shaped roof*

E *Flat-roofed adobe house. What advantage do you think this type of roof has for these homes?*

F *The "onion-dome" roof characterizes many Ukrainian churches*

G *Vancouver's Canada Place is a convention centre located on the harbour.*

Other Characteristics of Structures

In addition to form and function, structures can be interpreted and classified according to the materials and components they are made of. You will learn more about these in section 3.0, but for now, look at the structures in Figure 1.10 and analyze their characteristics.

Match one of the natural structures with one of the human-built structures that is similar in shape. Compare the two structures. How else are they similar besides the design? How are they different? For example, a bat's wing and an airplane wing are similar in shape. They are also similar in function since both provide a means to fly. However, they are different in the materials they are made of, and they are different in how they work.

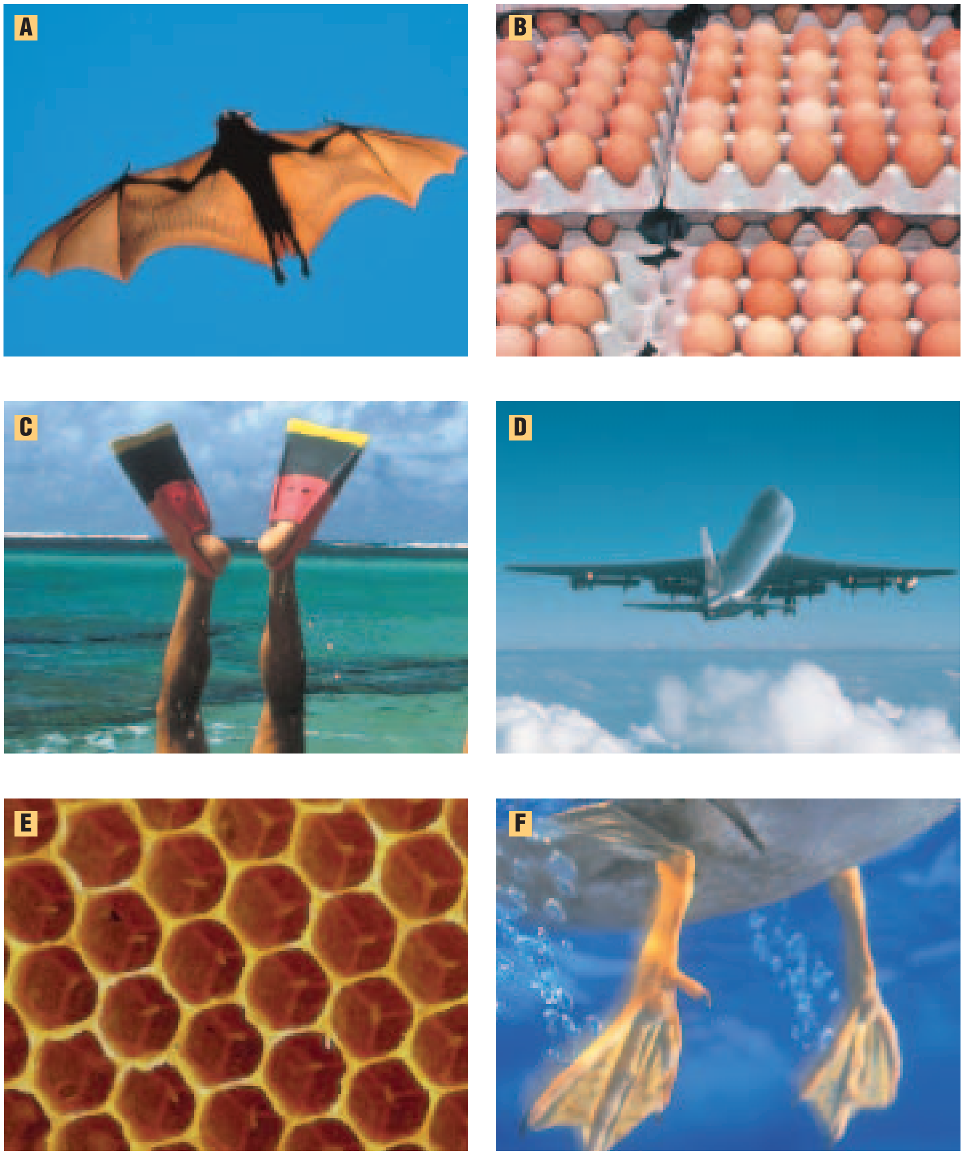

Figure 1.10 In terms of structural characteristics, which objects from the natural environment and which from the human-built environment can be paired up?

Aesthetics

One other way that structures can be interpreted and classified is in terms of their aesthetic quality. **Aesthetics** refers to the pleasing appearance or effect that an object has because of its design. Not all structures need to be aesthetically pleasing. For example, the framework supporting a train trestle does not have to be beautiful in design, colour, or finish, but it does have to be strong and stable. A park band shell, on the other hand, should be pleasing to look at and use.

Figure 1.11 Honouring its Ukrainian heritage, the town of Vegreville built this monument to the *pysanka* (Ukrainian Easter egg). The aluminum egg, weighing 2270 kg and measuring 7 m by 6 m, stands on a steel and concrete base. Why might a concrete block with a plaque have been a less aesthetically pleasing structure?

Humans throughout time and across cultures have shared a need for beauty in their surroundings. Indigenous peoples around the world have traditionally decorated their dwellings on both the outside and the inside with painted designs and other artistic features. Today, people still make a conscious effort to design and embellish their dwellings and other buildings so that they are attractive.

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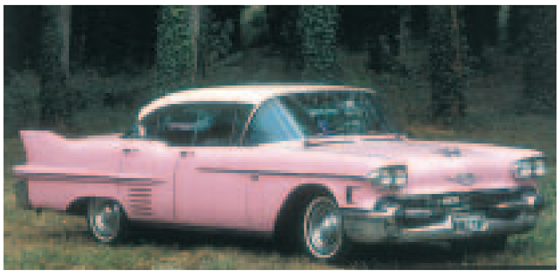
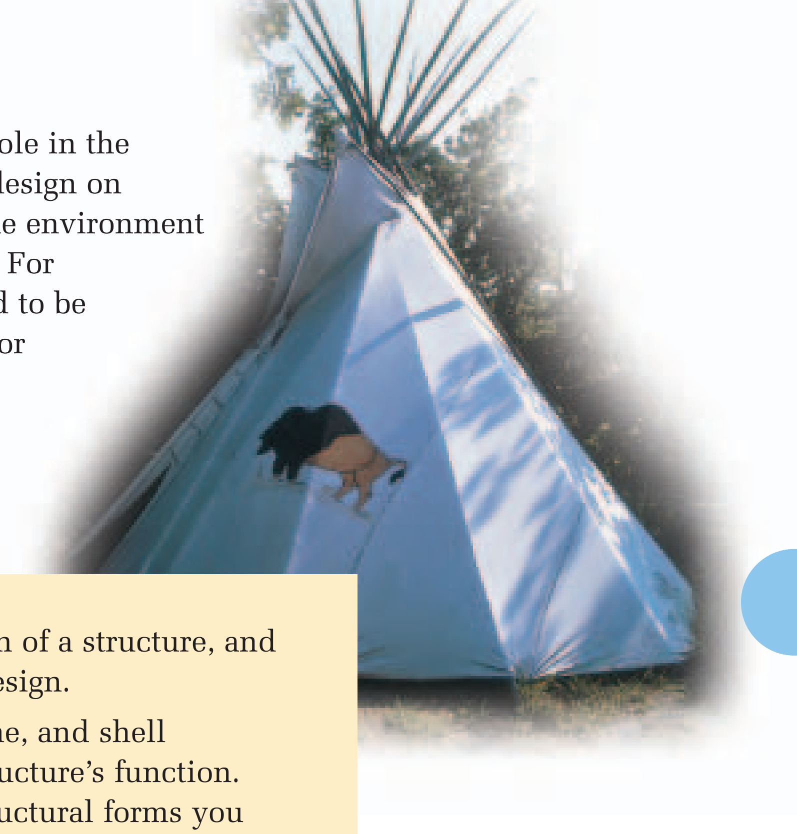
Nice Fins ...

Just as with clothing, trends and styles in structural design come and go. What was considered aesthetically pleasing at one time may not be many years later. Cars built with large "fins" were popular in the 1950s and early 1960s, but that feature gave way to more rounded vehicle forms. Choose another type of structure that interests you and research how changing tastes in aesthetics have affected the structural design of that object over the years.



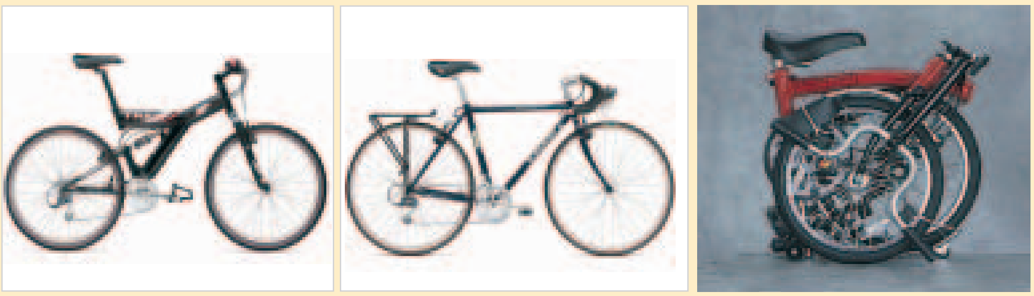
Aesthetics plays a big part in structural design. Aesthetics, of course, is "in the eye of the beholder."

Aesthetics has always played an important role in the structural designs of First Nations people. The design on teepees used by Plains First Nations reflected the environment as well as the owner's personal spiritual beliefs. For example, the animals portrayed were considered to be sacred and were thought to provide protection for the family living within.



Check and Reflect

1. Briefly explain what is meant by the function of a structure, and why function is such an important part of design.
2. Think about the characteristics of solid, frame, and shell structures, and about the importance of a structure's function. With these points in mind, decide which structural forms you would use to make each of the following and explain why:
   a) a bridge to carry trains over a deep valley
   b) a rain shelter in a public garden
   c) a stand to hold a guitar
   d) a stand to hold a large plant
   e) a child's playhouse
3. Study the three bicycles in Figure 1.12.
   a) Even though they all share a common function, what does the variation in their design show?
   b) Evaluate the effectiveness of each design. Does each bicycle serve the function it was designed to? Explain your answers.



A B C

Figure 1.12 (A) a mountain bike, (B) a racing bike, and (C) a folding bike

4. What is aesthetics? List three structures that you consider beautiful. Explain why this beauty is important to their function.

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Stonehenge

Stonehenge is an ancient monument on the Salisbury Plain in England. Built more than 3000 years ago, the structure consists of more than 36 megaliths (large stones) arranged in a circle and surrounded by a ditch 91 m in diameter. Although there are many theories about how Stonehenge came to be, what its function was when it was built is not completely understood.

1.3 Human-Built Structures around the World

Figure 1.13 Taj Mahal, Agra, India

Throughout this unit, you've already seen or thought about many different types of structures. Some of these are modern and some are from ancient times; some are from Canada and some are from elsewhere in the world. As the examples of various roof structures in Figure 1.9 showed, even those structures with a common purpose can have very different designs. Climate, culture, tradition, technology, and economics are among the main reasons that structures are so varied.

The Human Home

Homes developed by different cultures and at different times are just one example of how widely humans have adapted a basic form.

Many people around the world built homes that, while providing protection, were also portable. Similar to the North American teepee, for example, were the yurts used in Siberia and the tents used in the deserts of the Middle East.

Houses built of sod (clumps of earth) were long used by early peoples in Europe. This was also a common structure built by pioneers in the Prairies. The material was easy to get and didn't cost anything. It also created a relatively protected enclosure that could be heated by a fire.

In countries with hot climates, houses have traditionally been constructed of sun-baked brick (adobe), clay, or mud. These materials, combined with a shell form having few windows or door openings, create interiors that can be kept cool even under intense sun. Dwellings made of grasses and bamboo have been built for hundreds of years in many warm, wet countries. In some locations, these homes are constructed high on stilts to raise the dwelling above wet ground.

Look at Figure 1.14 to see examples of these and other types of homes. As different as they are from one another, they still share two essential characteristics of effective structures: 1) they are all basically stable; and 2) they all provide shelter for the people who live in them.

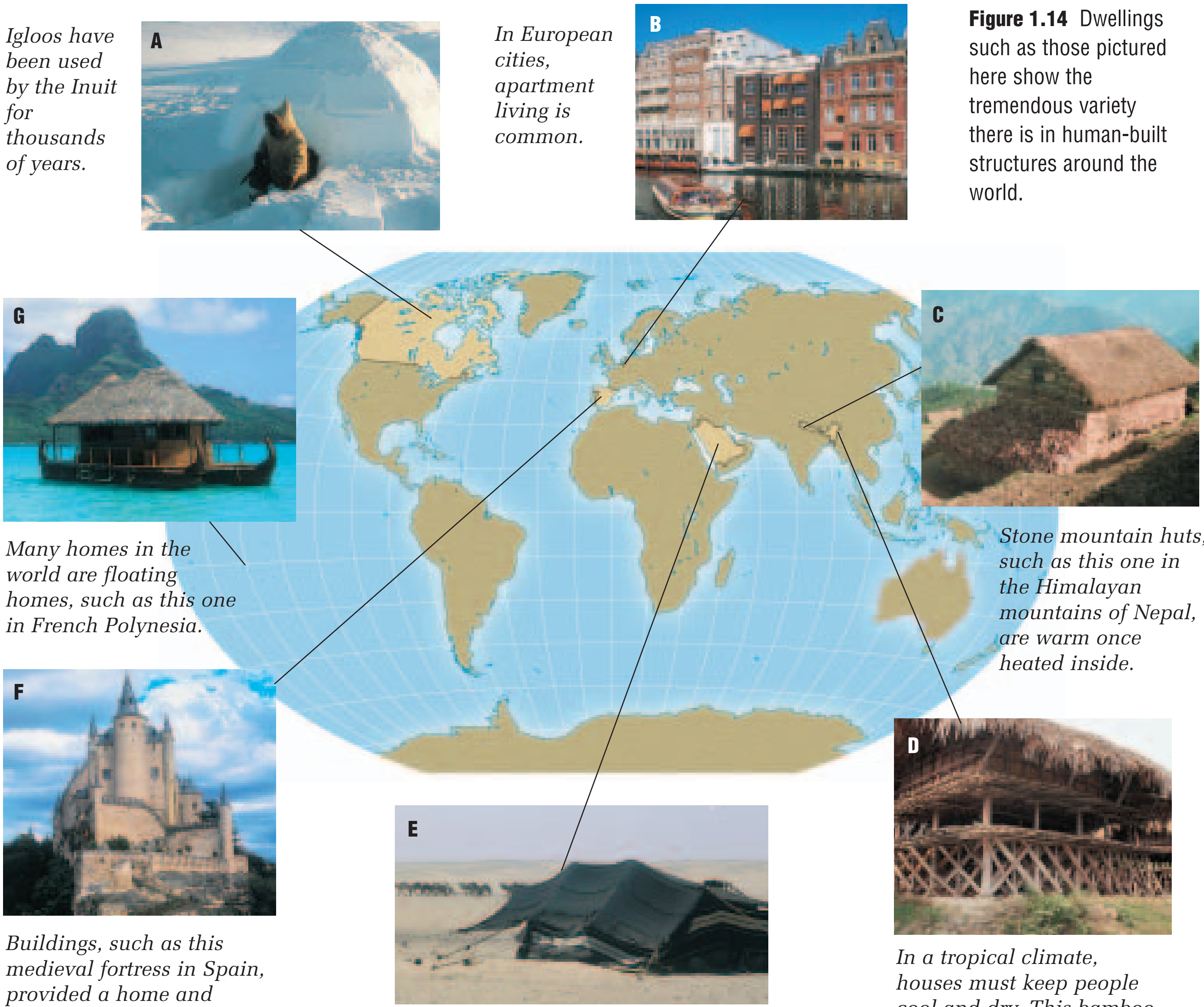


Figure 1.14 Dwellings such as those pictured here show the tremendous variety there is in human-built structures around the world.

Igloos have been used by the Inuit for thousands of years.

In European cities, apartment living is common.

Stone mountain huts, such as this one in the Himalayan mountains of Nepal, are warm once heated inside.

In a tropical climate, houses must keep people cool and dry. This bamboo house is in Assam state, India.

Tents offer desert dwellers protection from sun, wind, and cool night temperatures. This photograph was taken in Saudi Arabia.

Buildings, such as this medieval fortress in Spain, provided a home and protection against invasion.

Many homes in the world are floating homes, such as this one in French Polynesia.

Give it a TRY ACTIVITY

CURRENT OR CLASSICAL? ANALYZE A STRUCTURAL DESIGN

You work for a company called "Build It Yourself: Current or Classical Boats." It's an unusual business that specializes in selling kits to people who want to build their own life-size sailing vessel. All the kit designs are of authentic sailing vessels, from all cultures and eras. You have been hired for your skills in interpreting different types of boat structures. This week's assignment? The sales staff want you to assess three vessels and write notes that they can use to help their customers in choosing a kit.

- Study the three sailing vessels shown in Figure 1.15. Analyze each vessel's general design and the materials from which it appears to be made.
- In a small group, brainstorm as many advantages and disadvantages as you can think of for each vessel. Record these on a large sheet of paper. Share your ideas with the class.

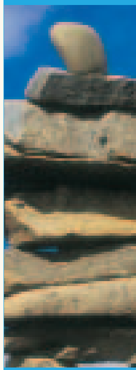
Figure 1.15 Human-built structures vary widely, even those that share a basic function and design.

CHECK AND REFLECT

1. What are some of the main reasons for the great variation in even the same type of human-built structure?
2. Look at the two modern suburban houses in Figure 1.16. In what kind of climate do you think each of these houses is located? In what ways do you think the designs of these houses would differ because of the climates?

A B

Figure 1.16 Question 2.



Assess Your Learning

1. Choose a structure in your classroom.
   a) Identify its basic structural form, and then describe its function.
   b) What special features of the structure allow it to be used the way it is? Are there any features you would change if you were redesigning this structure?
   c) Given the materials and design characteristics of the structure, briefly describe how long you think the structure will last.
2. Name three examples of human-made structures that are copies of natural structures in design and function.
3. In design terms, is it fair to say that an umbrella is stronger than a mushroom, or that a jet is more efficient at movement than a hummingbird? Why or why not? Express your views in a class discussion.
4. Think of examples in your own neighbourhood where aesthetically pleasing features are part of various structures. Compare your examples with those of your classmates. Do you all have the same opinions about what is aesthetically pleasing and what isn't? Discuss why defining an object in terms of aesthetics can vary from individual to individual.

Focus On Science and Technology

When a technology is used to solve a problem, it must be appropriate for the situation. If it is not, it hasn't really solved the problem. Reflect on what you learned about structures in this section.

1. What were some of the solutions to technological problems you read about?
2. What factors must you consider when assessing the appropriateness of a technological solution?
3. How could you apply what you have learned about structural form and function in solving a technological problem such as how to build a summer outdoor shelter for your pet?

2.0 External and internal forces act on structures.

Key Concepts

In this section, you will learn about the following key concepts:

- material strength and flexibility
- forces on and within structures
- direction of forces
- structural stability
- modes of failure
- performance requirements

Learning Outcomes

When you have completed this section, you will be able to:

- use units of force and mass, and measure forces and loads
- identify tension, compression, shearing, and bending forces within a structure
- describe how forces can cause failure in natural and built structures
- infer how the stability of a model structure will be affected by changes in mass distribution and the foundation design

Tall, taller, tallest. Office towers allow large numbers of people to work and live in the same city block. Communication towers must stand high above their surroundings so that signals can be broadcast and received without interference from other structures or features on the landscape. It seems there's no end to how tall these types of towers can be. Or is there?

Imagine you've been asked to design the tallest possible tower that will withstand the force of a wind. What determines the ability of a structure—especially a tall one—to keep standing despite the push of air? What other forces affect structures? You will need the answers to these and other questions to be able to meet the design challenge at the end of this section.

For Web links relating to 2.0, visit **www.pearsoned.ca/scienceinaction**

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.

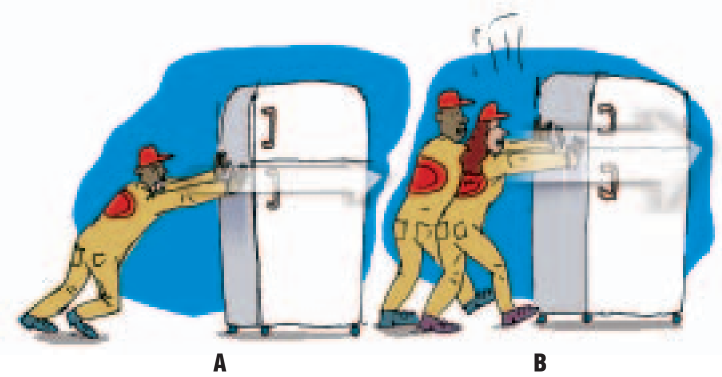


Figure 2.4 Two people pushing on a large object exert more force than one person. What forces are trying to keep the fridge from moving?

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.

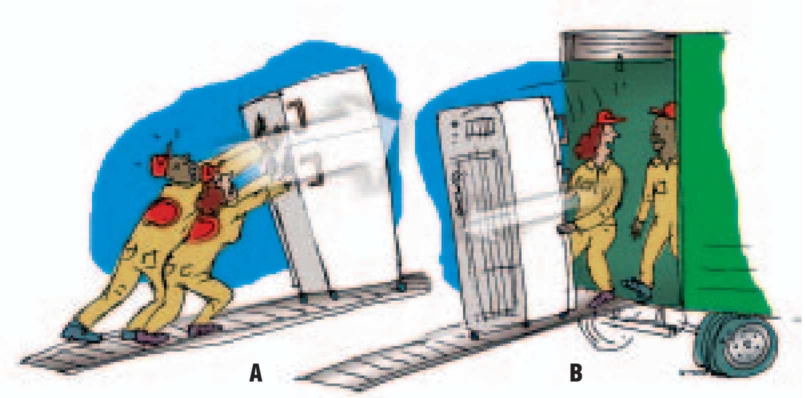


Figure 2.5 Why is pushing the fridge in one direction (A) more difficult than pushing it in the other direction (B)?

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).

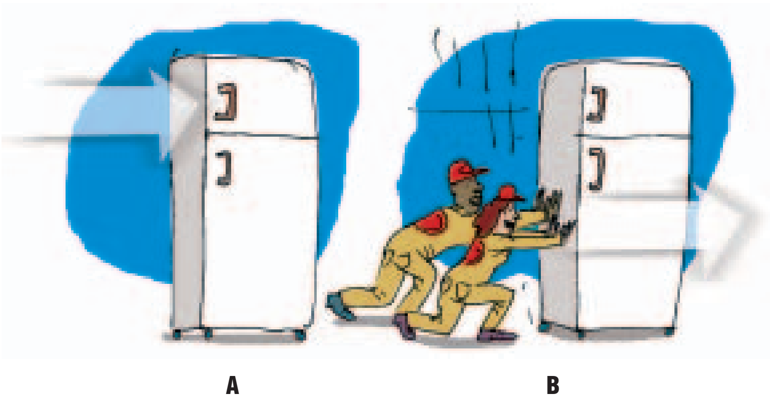


Figure 2.6 What happens when force is applied too high up on the fridge?

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?

Materials & Equipment

- straws
- masking tape
- spring scale

Procedure

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.

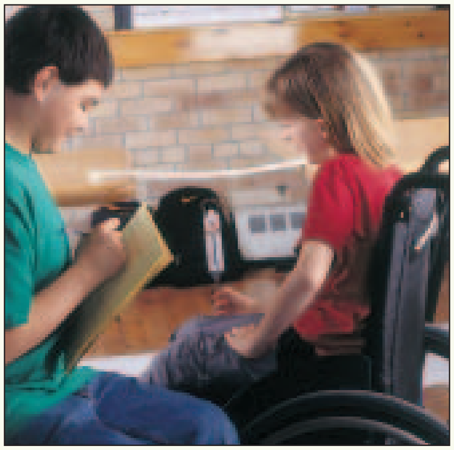
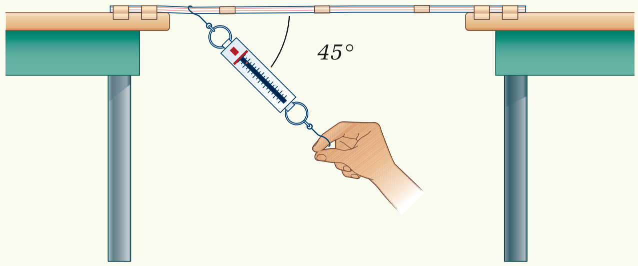


Figure 2.7 Step 2



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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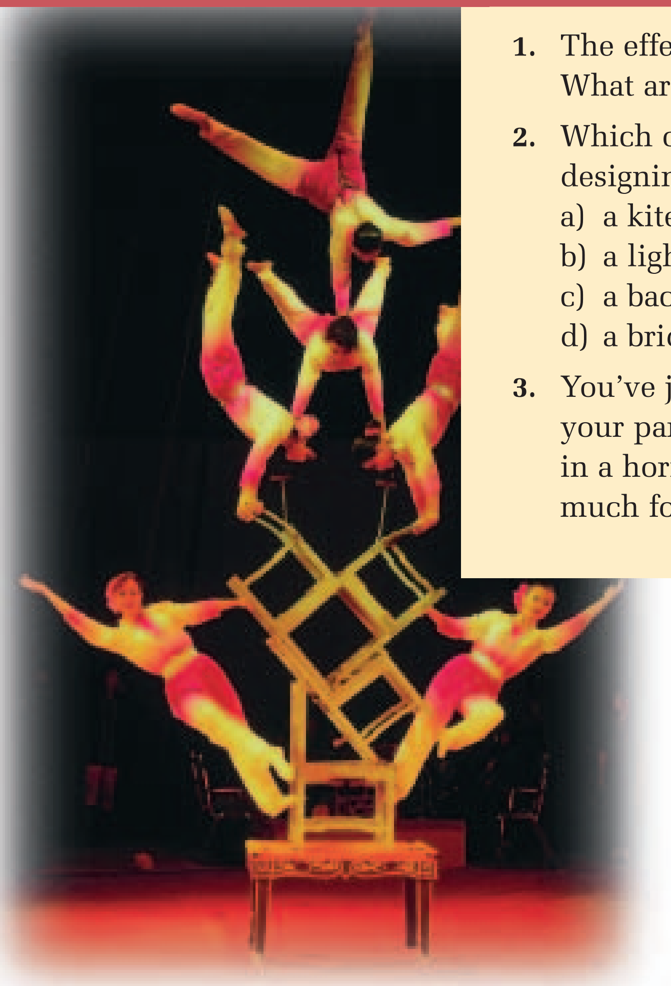
Sir Isaac Newton

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

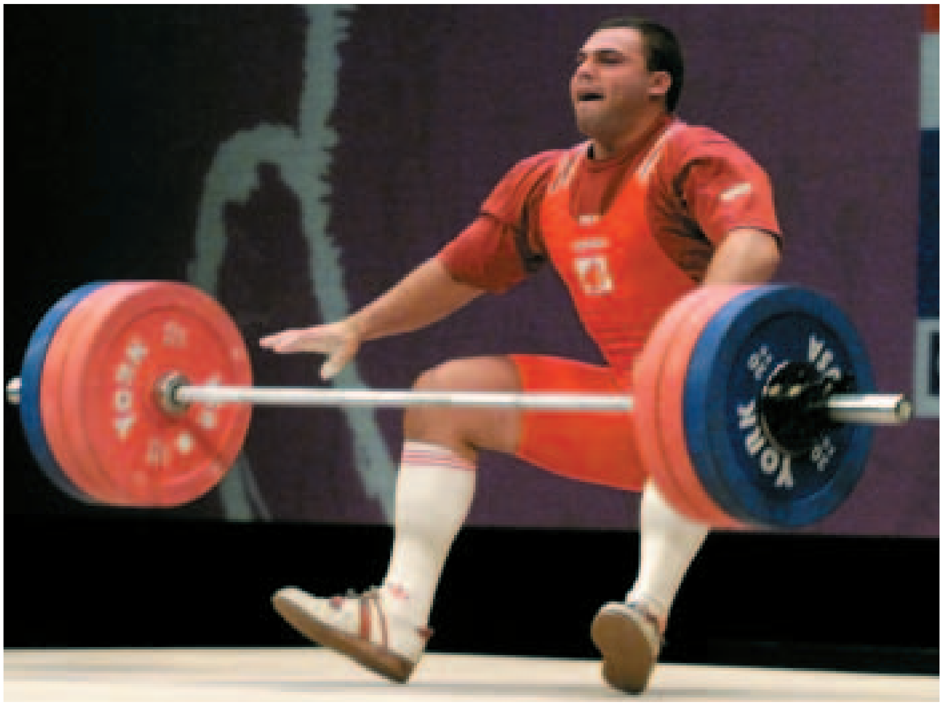


Figure 2.8 The external force of gravity is pulling the weights to the ground.

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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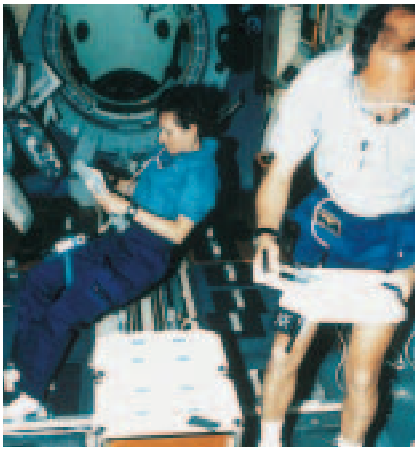
Height Gains in Space

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.

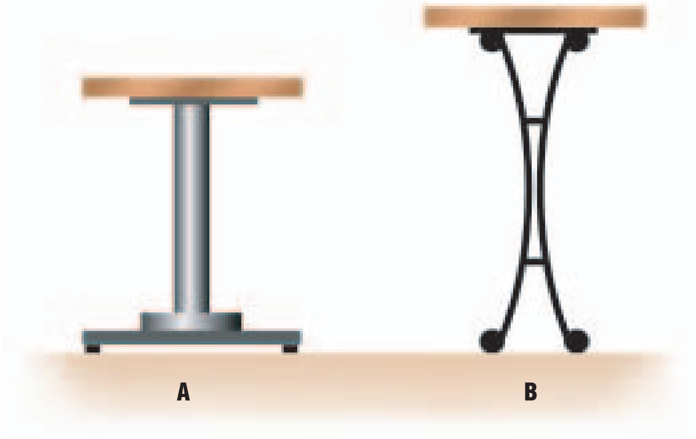


Figure 2.9 In most cases, structures with a low centre of gravity and wide base are stable. Which of these tables do you predict is the more stable of the two? Why do you think that?

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.

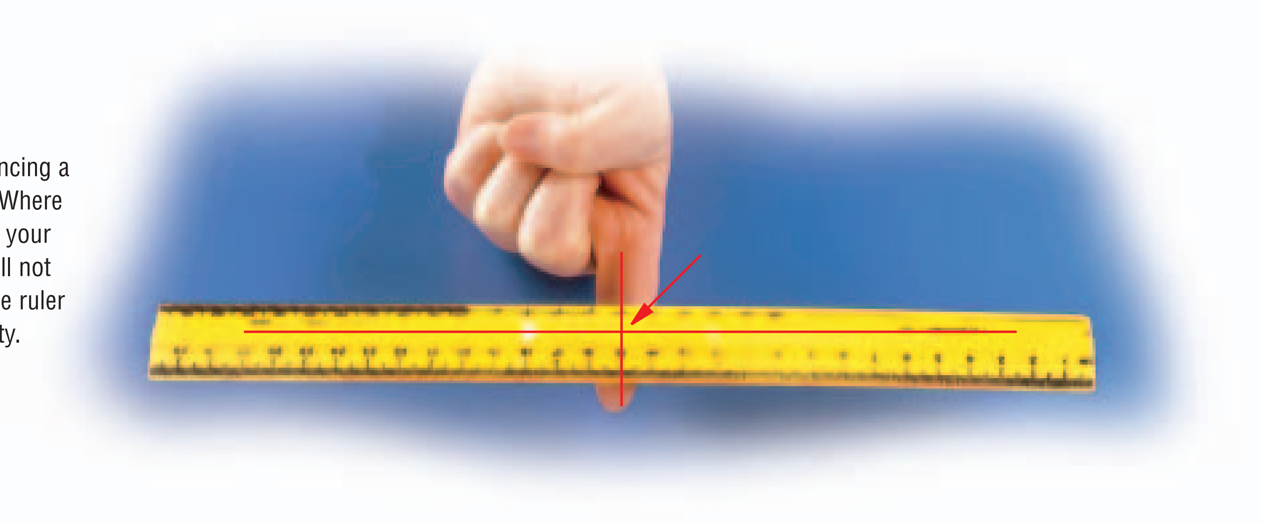


Figure 2.10 Try balancing a ruler on your finger. Where do you have to place your finger so the ruler will not fall? That point on the ruler is the centre of gravity.

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.

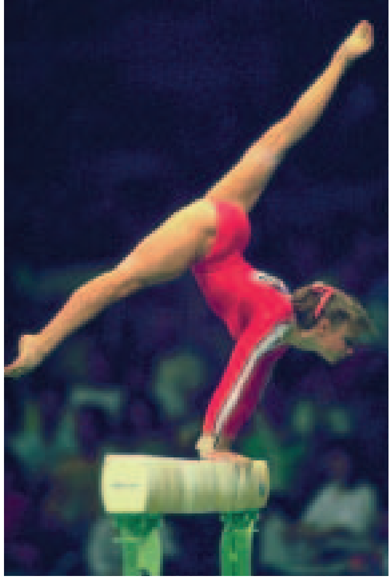


Figure 2.11 For this gymnast to hold a stable position on the balance beam, the forces of gravity on all parts of her body in the air must be balanced around her hands on the beam.

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

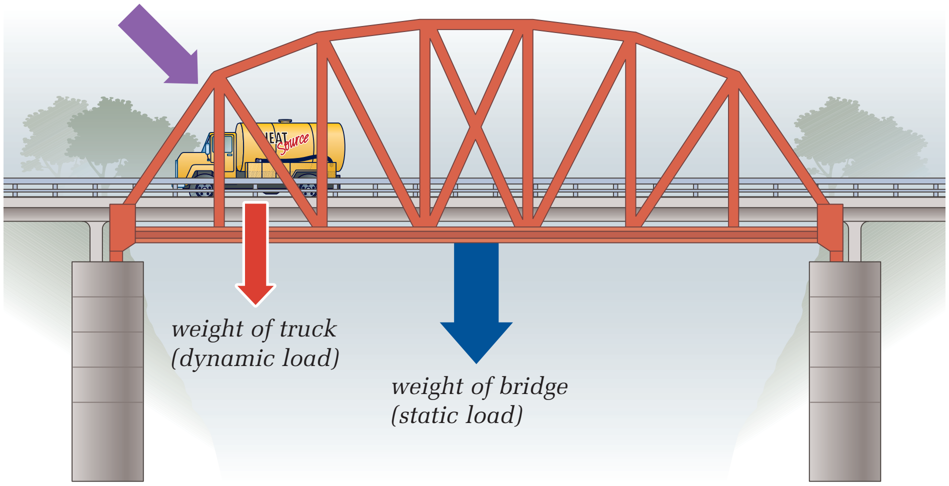


Figure 2.13 Forces acting on this bridge include the weight of the bridge (static load), the weight of the truck (dynamic load), and the wind (dynamic load).

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).

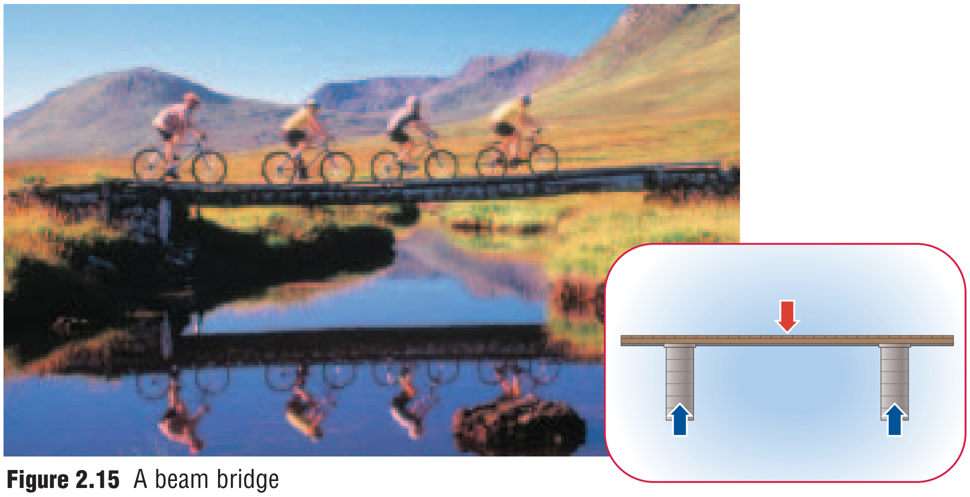


Figure 2.15 A beam bridge

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

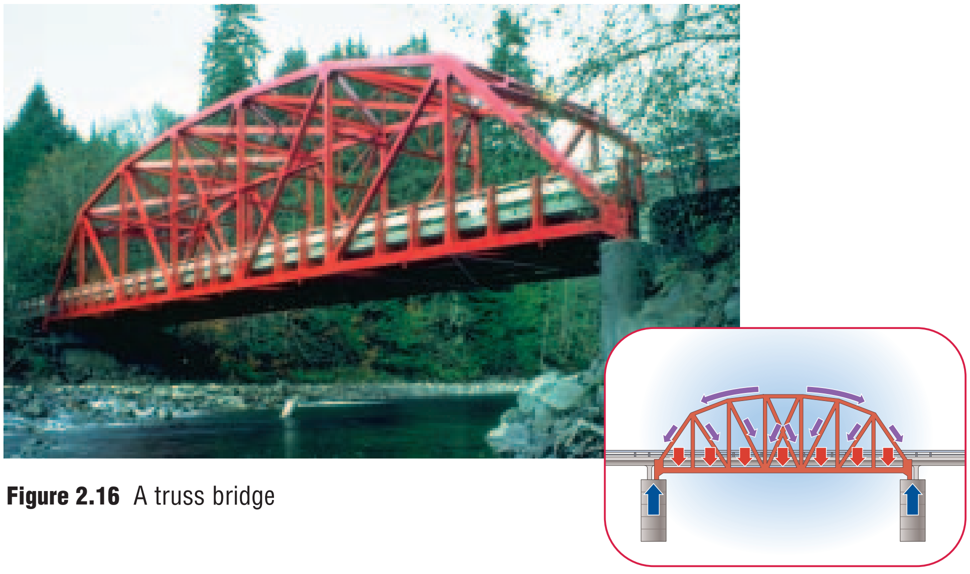


Figure 2.16 A truss bridge

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.

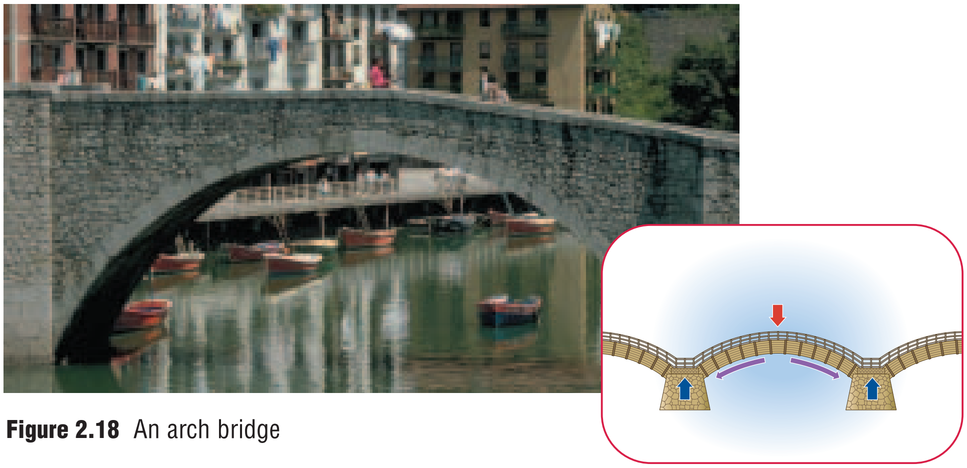


Figure 2.18 An arch bridge

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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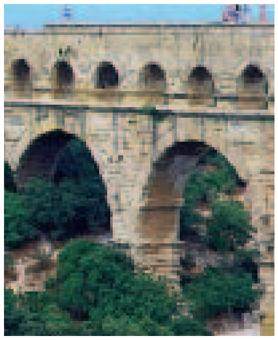
Arch Support

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.



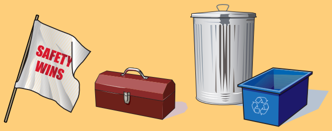
Aqueducts are a type of bridge used to carry a large quantity of flowing water between places. Many Roman aqueducts are still standing today.

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.

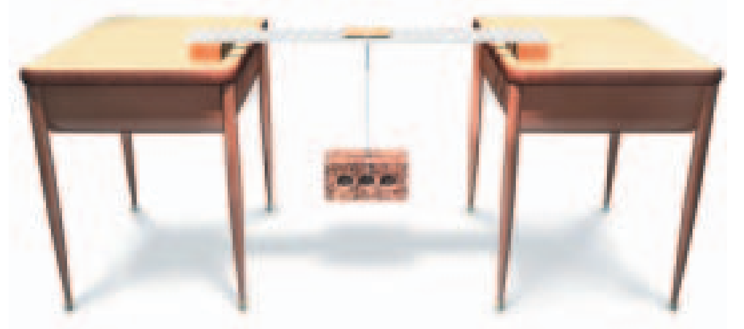


Figure 2.19 Step 4. This is one way to test a static load on a bridge.

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

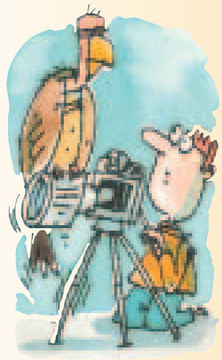
The performance of one structure can also be compared with that of another. Consider the following example. Bridge A has a total mass of 10 000 kg. It is designed to support cars and trucks with a total mass, at any one time, of 100 000 kg. Bridge B has a total mass of 1000 kg and is designed to support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

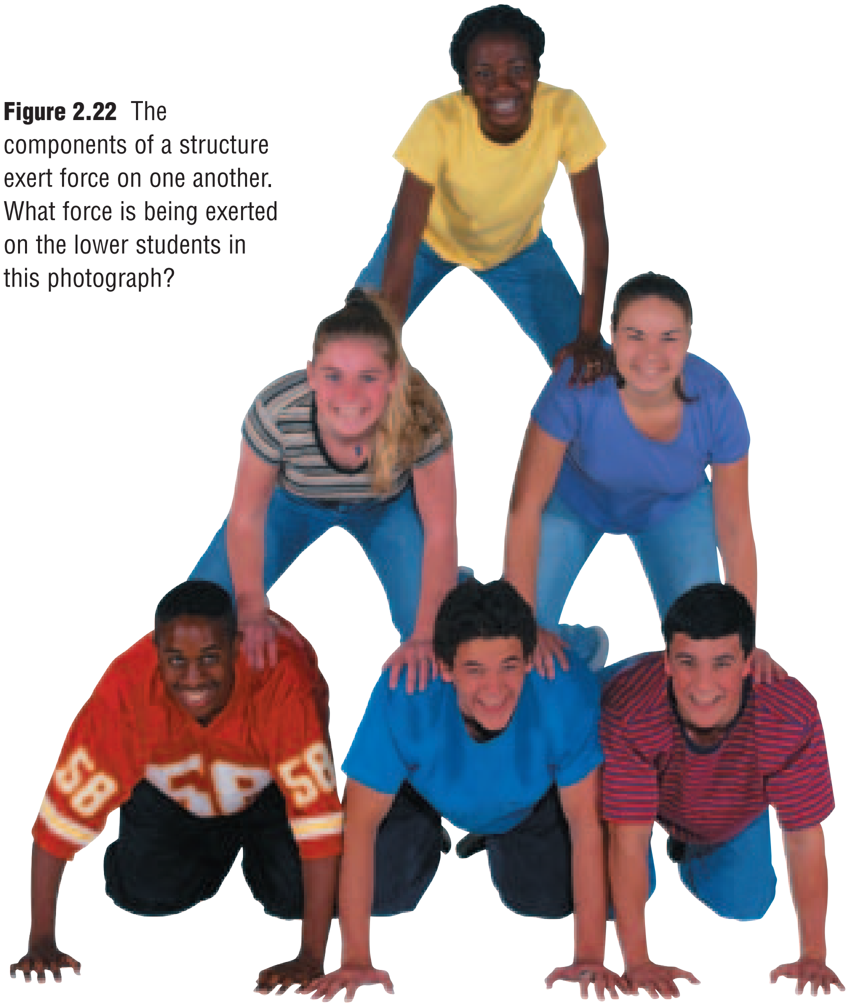


Figure 2.22 The components of a structure exert force on one another. What force is being exerted on the lower students in this photograph?

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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.

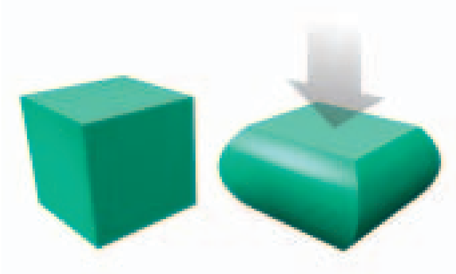


Figure 2.23 Compression

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.

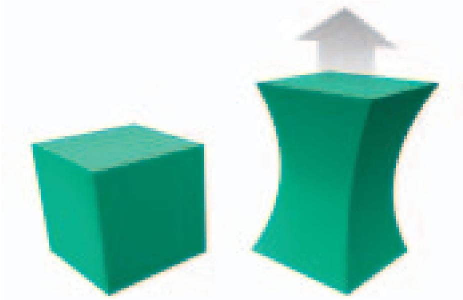


Figure 2.24 Tension

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.

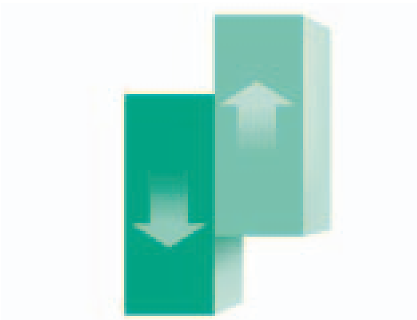


Figure 2.25 Shear

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.

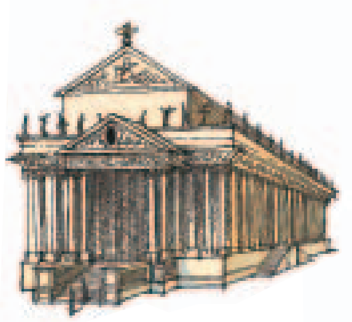
Figure 2.27 Make shallow cuts in the Styrofoam.

CHECK AND REFLECT

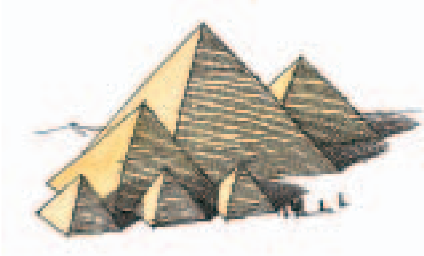
1. Copy the following sentences into your notebook. Fill in the blanks with one of the following terms: compression force, tension force, shear force.
   a) When you stretch an elastic band, you are applying ________.
   b) When you tear a piece of cardboard in half, you are applying ________.
   c) 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

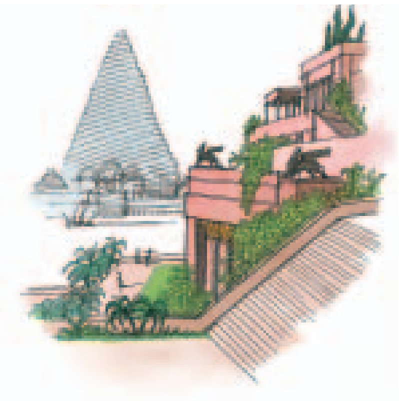


2500 B.C.—The Pyramids of Giza, Egypt

297 B.C.—The Pharos of Alexandria

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

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.



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

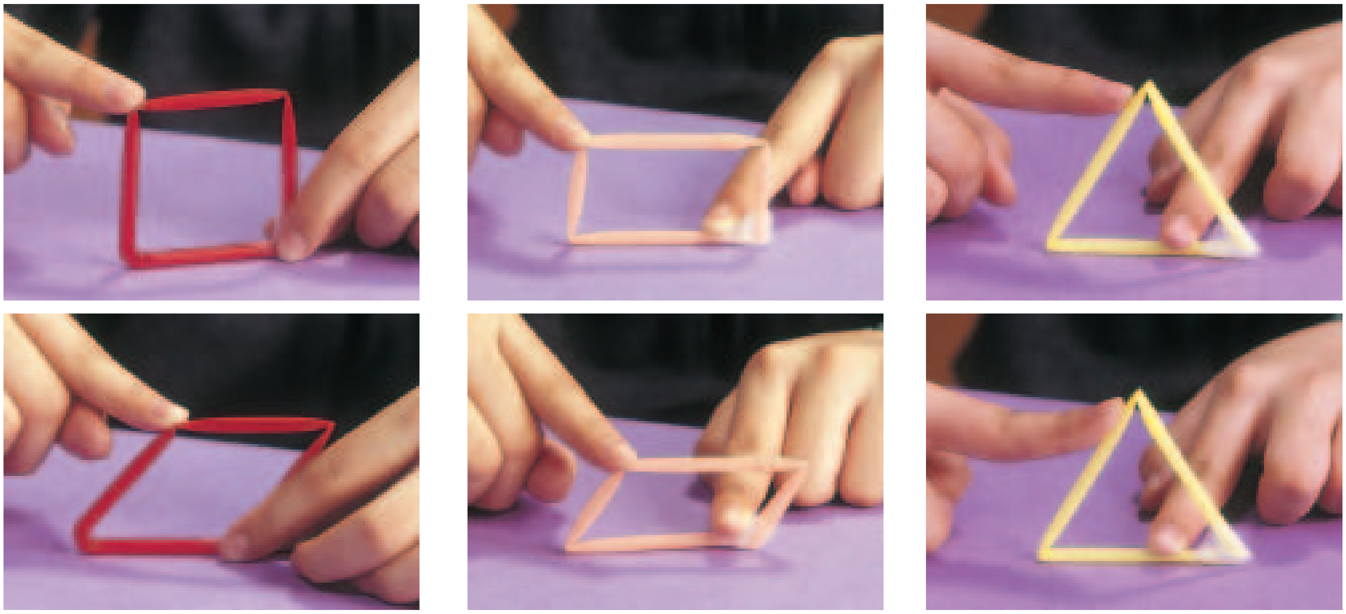
Figure 2.28 The Seven Wonders of the Ancient World. Some took many years to complete, so the dates of when they were built are approximate.

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.

Strong Structural Shapes

You've had several opportunities in this unit to think about how a structure's shape might affect how strong it is. From that knowledge, what do you think the strongest two-dimensional shape is: a triangle, a square, or a rectangle? What is the strongest three-dimensional shape: a triangular prism or a rectangular prism?

If you're not sure about the answer to these two questions, use some straws to try the simple exercise shown in Figure 2.29. What you should notice is that while the square and rectangle will shift their shape slightly, the triangle will not. A triangle is a very strong and rigid shape that cannot be bent easily. In the same way, a triangular prism is stronger than a rectangular prism, a pentagonal prism, or any other multi-sided three-dimensional shape.



A B C

Figure 2.29 Bend one straw into a square (A), one into a rectangle (B), and one into a triangle (C). Tape the ends of each shape together. Lying each structure flat on a table or resting it upright on a table, gently push on an upper corner of the structure (in the same plane as the structure itself).

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Standing the Test of Time

Part of the foundation of the Mausoleum of Halicarnassus can still be seen where it was built in what is now Turkey. Some of its statues are in the British Museum in London. One of the original 127 columns in the Temple of Artemis (located in Ephesus, not far from where Halicarnassus was) also still exists. Longest lasting, however, have been the Pyramids at Giza, near Cairo, Egypt. They still stand much as they were when they were built 4500 years ago.

Structural Components

Have you ever tried to cross a small river or stream by walking on a flat wooden plank laid across it? If the plank was weak, you probably noticed it bending. If you tried bouncing up and down, you probably knew there was a chance you could end up getting wet.

Figures 2.30 to 2.36 show several components that make up structures. Also shown are some of the ways these components can be combined to create strong structures.

Arches

An **arch** is a common shape in structures such as bridges (Figure 2.30). The arch can support a large load because the force of the load is carried down through the arch to the foundation. This spreads out the load.

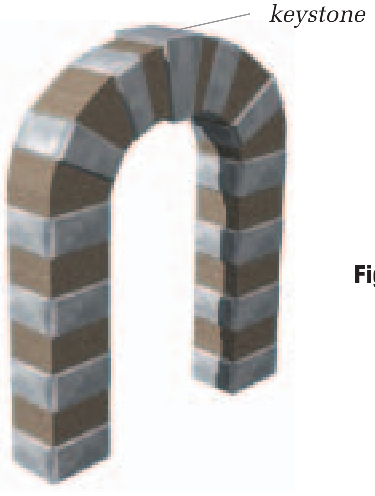


Figure 2.30 Arch

Beams

Beams are common components in a wide range of structures. A simple **beam** is a flat structure that is supported at each end (Figure 2.31). If too much weight is put on a beam in the middle, it will bend in a U-shape and may even break. Changing the shape of a beam, however, can increase its strength.

The shape of an **I-beam** gives it strength (Figure 2.32). I-beams have less mass than solid beams. **Girders**, or box beams, are long beams in the shape of hollow rectangular prisms (Figure 2.33).

Figure 2.31 Simple beam

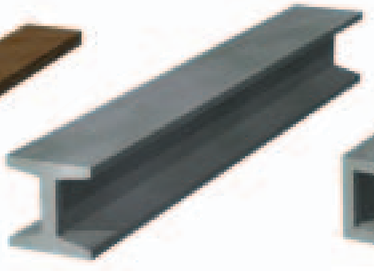


Figure 2.32 I-beam

Figure 2.33 Girder, or box beam

A **truss** is a framework of beams joined together (Figure 2.34). Trusses are usually in the form of interlocking triangles. A **cantilever** is a beam that is supported only at one end (Figure 2.35). When weight is placed on the beam, the beam bends in an N-shape to resist the load.

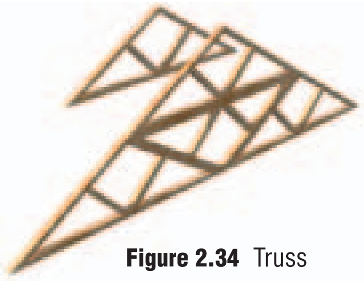


Figure 2.34 Truss

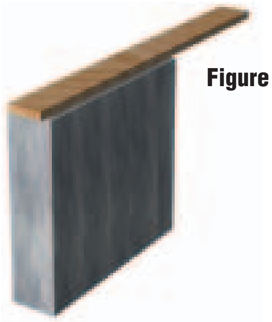


Figure 2.35 Cantilever

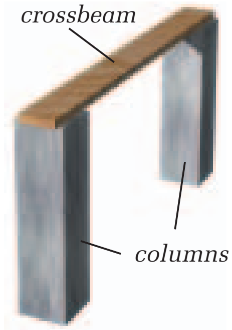


Figure 2.36 Column

Columns

A **column** is a solid structure that can stand by itself (Figure 2.36). Columns can be used to support beams.

Structural Stress, Fatigue, or Failure

Sometimes too great a combination of external and internal forces acting on a structure can weaken it. The result can be **structural stress**.

A strong, stable structure is designed and built to be able to resist stress without any damage happening. However, repeated abnormal use of the structure could cause **structural fatigue**. This is a permanent change in a structure caused by internal forces such as compression, tension, and shear. Cracks, for example, might start appearing in the material. **Structural failure**, such as the collapse of a bridge, occurs when a structure can no longer stand up to the forces acting on it. Failure can also take the form of buckling, shearing, separating of components and deformation, as illustrated in Figure 2.37.

A structure needs strength and stiffness to avoid failure:

- The *strength of a structure* is defined by the load at which it fails. For example, if it takes a load of 100 kg to cause a skateboard to collapse, the strength of the skateboard would be 100 kg.
- The *stiffness of a structure* is its ability to withstand changing its shape under a load. For example, the skateboard must be stiff enough to prevent failure for any load up to about 100 kg.

reSEARCH

Geodesic Domes

Do you know what a geodesic dome is? Find out about these noteworthy structures, how they are built, and what gives them their strength and stability. Use library resources and the Internet in researching these structures.

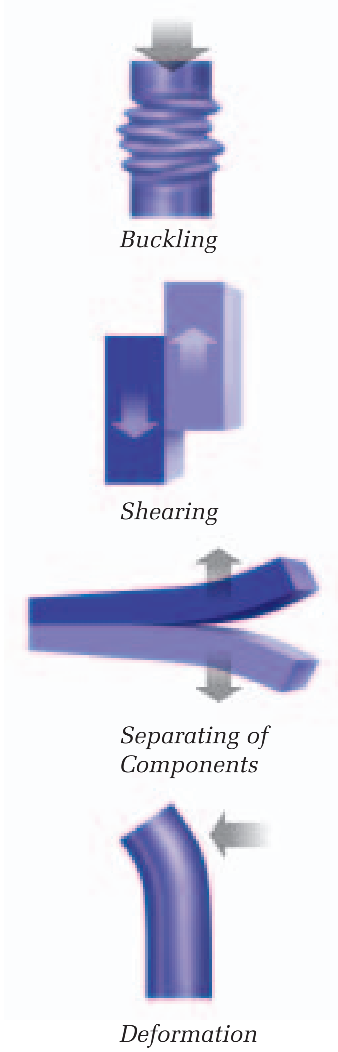


Figure 2.37 Some forms of structural failure

Problem Solving Activity

THE TALLEST TOWER

Recognize a Need

Several companies are hoping their design will be chosen for the new communications tower. This tower must be the tallest structure in the city so that signals for telephone, television, and radio will be able to pass above all other buildings. The communications company would also like to build a restaurant and observation deck near the top of the tower, so the structure must be able to carry this additional load safely.

The Problem

You and your group have been hired by one of the companies who want to build the new tower. As part of your preliminary work, you must design and build a tall, stable free-standing model of the proposed tower with the materials provided. You will have 20 min to design and build your tower before it is tested. Your teacher will set a timer.

Criteria for Success

- Your structure must be built from at least three of the materials listed.
- Your structure must be the tallest possible free-standing structure that can support an egg or golf ball without structural failure.
- Your structure must be able to withstand the wind from a fan for 60 s.
- You must complete the activity within the time given.

Brainstorm Ideas

1 Discuss and sketch out design ideas for your tower. Keep in mind the function of the tower, the design criteria, and the time limitations. What factors about external and internal forces and loads must your design consider?

2 Consider the materials you have to work with. This may give you some design ideas and options. (Also, in real-life situations, the materials available for a project may be limited. Learning to work with what you've got is all part of the design process!)

3 Predict which of your design ideas will best meet the Criteria for Success. Use this design.

Build a Prototype

4 Assemble the materials you will need to build your structure.

5 Construct the tower as quickly as possible. As a group, you may wish to assign different members to construct certain components of the structure. These can be assembled when they are ready.

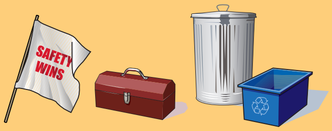
Figure 2.38 Steps 4 and 5

Materials & Equipment

- newspaper
- uncooked spaghetti
- bamboo skewers
- plastic straws
- plastic interlocking blocks
- masking tape
- cellophane tape
- marshmallows
- a balance
- a ruler
- egg or golf ball
- a fan

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 should you store any tools after using them?
3. How should you dispose of any waste or unused materials?



Test and Evaluate

6 When your tower is complete, test that it can be free-standing. Place the egg or golf ball on top of the model to test the strength of the structure. Make design or construction modifications if there is time.

7 Place the fan about 1 m away from the model and let it blow onto the model for 60 s. Observe how well the model maintains its stability. Again, make design or construction modifications if time allows.

8 Measure the mass of your completed structure and record it.

9 Does your structure meet the design criteria? Explain why it does and/or why it does not.

10 Evaluate your structure along with those of the other groups.

a) What is the overall range of structure heights? Which structure is the tallest? the shortest?

b) Why are some structures better able to resist the wind? That is, why are they more stable than others?

c) How does the mass of your structure compare to that of the other groups' structures? How does the quantity of material you used compare?

11 Compare the area of the bottom of your structure with the area of the top of your structure. Did this ratio prove to be an advantage or a disadvantage in making your structure strong and stable? Explain.

Communicate

12 Compile the results of the activity in a short report:

a) State the problem you were trying to solve and list the performance requirements of the model.

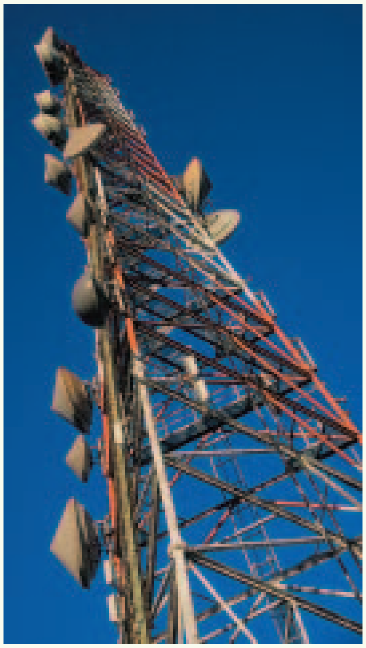
b) Sketch the design you chose for your prototype and label it with the forces acting on it.

c) Note the quantity of materials you required to build your structure and what two- and three-dimensional shapes you used most often and least often. Describe any construction difficulties you had.

d) Summarize your test and evaluation results under the following headings: Strength, Stability, Height (compared to all the designs in the class). Explain whether you think you could have used more or less material than you did to achieve the same strength and stability.

e) Explain whether your prediction in step 3 was right. Suggest improvements that you would make to your structure.

f) Write a concluding statement that answers the following questions: To build a structure taller and taller, what must be done to maintain its stability? Is there a limit to how tall a structure can reach and still be free-standing, strong, and stable? Explain.



Communications tower

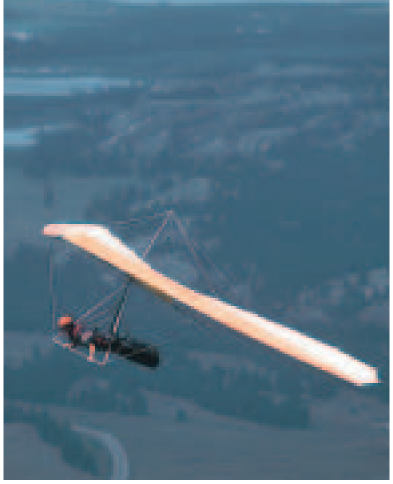


Figure 2.39 What external forces are acting on this hang-glider? what internal forces? What type of design features and materials have been used to make it structurally stable?

Building for Structural Stability

Designing a hang-glider that is stable in the air requires careful analysis of the forces that will be acting on it. It is important that the hang-glider be designed so that it is symmetrical and so that the mass within the structure gets evenly distributed. Distributing the load in that way helps reduce internal forces such as tension, compression, and shear.

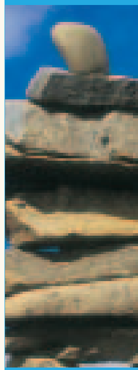
The properties of the materials used for the individual parts of a structure also determine how well the structure will hold together under different loads and forces. Look at the hang-glider in Figure 2.39. The components of the structure are not all made of the same material. Rather, a variety of materials has been used, each for its effectiveness in resisting the applied forces.

Check and Reflect

1. Make a labelled drawing of the three main types of structural components. Answer the following questions:
   a) For each, give an example of a structure in which you would use this component.
   b) For each, what is the advantage of including this component in a structure?
   c) If an arch and a beam were of the same mass, which one would be the strongest? Why?

2. Make a flowchart to connect the following events, beginning with the one that happens first. You can connect more than one event to another. You can use an event in more than one place. (Hint: First, put these events in the correct order.)
   - The bridge structure experiences structural stress.
   - A freight train loaded with iron ore passes over the bridge.
   - The bridge collapses.
   - The beams of the rail bridge bend slowly.
   - The rail bridge carries 10 trains a day over the valley.
   - The beams of the rail bridge give way.
   - The bridge is experiencing structural fatigue.
   - A rail bridge was built here 30 years ago.
   - The bridge is experiencing structural failure.

SECTION REVIEW



Assess Your Learning

1. Think of a symmetrical solid structure and determine its centre of gravity and lines of symmetry. How do you know that your findings make sense?

2. Describe and provide examples of the following structural forces:
   a) compression
   b) tension
   c) shear

3. Explain how compression and tension act together by describing what happens when a diver jumps up and down on a diving board.

4. How can a structure remain standing for several years, then suddenly collapse?

5. What makes many free-standing coat racks so unstable? What design characteristics should you consider when making a coat "tree"?

6. A local marina wants to suspend a sign from a bridge. There are two choices for doing this: it could be hung straight down from cables, or it could be hung between two cables at 45° angles from the bridge. Which arrangement do you recommend? Why?

Focus On SCIENCE AND TECHNOLOGY

Scientific knowledge may lead to the development of new technologies, and new technologies may lead to scientific discovery.

Reflect on what you learned about forces in this section.

1. What forces act on and within structures, and how can they be measured?

2. How can these forces cause structures to fail?

3. Some skiers lost in a snowstorm face the necessity of spending the night on a mountain. They decide to construct an emergency structure out of branches and snow. How could you apply what you have learned about forces to make their structure stable?

3.0 Structural strength and stability depend on the properties of different materials and how they are joined together.

Key Concepts

In this section, you will learn about the following key concepts:

- deformation
- joints
- material strength and flexibility
- structural stability

Learning Outcomes

When you have completed this section, you will be able to:

- compare properties of structural materials, including natural materials and synthetics
- use methods of testing the strength and flexibility of structural materials
- identify examples of frictional forces and their use in structures
- analyze methods of joining used in structures and evaluate their appropriateness for a given structure
- investigate the role of different materials found in plant and animal structures

Figure 3.1 What materials are within your reach? within your sight?

What materials can you see around you? What is holding them together?

With your teacher timing you for one minute, work with a partner to make a list of all the materials you can spot in your classroom. When a minute is up, repeat the exercise, but this time identify examples of fasteners (that is, things that join materials together). Again, you've got one minute. At the end of the allotted time, compare your two lists with those of the other groups.

When everyone has finished the exercise, the class will compile one large list of materials and fasteners. You will use these lists later in this section.

3.1 Materials and Their Properties

In the past, people constructed shelters out of material they could find, including animal skins, mud, and sticks. Some of these shelters were large and elaborate. Over the years, many more materials were discovered or invented. Today, designers can choose from a wide variety of materials.

Even though there's now so much choice in materials compared to before, how do we know *which* material will be best to use for a particular purpose? Think for a moment about jumping on a skateboard made of nylon or trying to carry a tent made of bricks. You know these materials are poor choices for each of those structures, because you already know a lot about materials. But what else is there to know about their properties?

Classifying Material Properties

The materials used in structures can be evaluated according to many properties. How well the designer, engineer, or builder analyzes those properties determines how well the resulting structures will do what they're supposed to. It also determines how long the structures will last before giving in to the forces acting on them.

Some of the most important properties of materials are listed in Figure 3.2.

Some Properties of Materials	Other Considerations
• **brittleness** (How easily does the material break?) • **ductility** (How easily can the material be made into wire?) • **hardness** • **plasticity** (How easy is the material to shape?) • **resistance to heat** • **resistance to water** • **compression** • **tensile strength**	• **aesthetics** (appearance, texture, etc.) • **consumer demand** • **availability** • **cost** • **effect on the environment** (Can the material be used safely?) • **disposal of waste** (Can the material be recycled or reused? Is there a cost to dispose of it?)

Figure 3.2 Properties of materials and other considerations.

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Letting the Sun Shine In

New materials today allow builders to use the sun to advantage. For example, the windows on the top floors of this home are made of tinted glass that lets light in but keeps ultraviolet radiation out. The solar panels produce electricity, making the home more energy efficient.

Testing Deformation and Flexibility of Materials in Structures

Deformation

Focus for a moment on the property of strength. Any time you have to design and build a structure, you need materials that will have enough strength to resist the forces acting on the structure. You also need materials that won't deform easily. **Deformation** is a change of shape in a structure or any structural component, because the material is unable to resist the load acting on it. When too much deformation occurs, a component or the entire structure might fail.

Figure 3.3 When you apply a very small force to an aluminum can, its sides start to dent, but will return to the original shape when the small force is released. If you apply a greater force, the dent may become permanent, and the can is deformed permanently.

Flexibility

Flexibility is the ability of a material to be bent under force without breaking. How much an object can change shape under a given load without breaking is an indication of how flexible it is.

Structures such as tall buildings must be able to resist the force of the wind. However, being very strong and rigid is not necessarily the best way for a tall building to be designed. Think of a tall tree in the wind. The tree bends a little as the wind pushes against it, and when the wind stops, the tree straightens up again, unharmed. Copying nature, structural engineers have found ways of using materials and combining structural components to make buildings in "high hazard" wind or earthquake zones more flexible.

Figure 3.4 It is their flexibility that allows trees to resist being deformed under strong forces like that applied by the wind.

Inquiry Activity

Material Strength and Stability

The Question

Is it possible to predict what material would be suitable for providing strength and stability to a structure?

Materials & Equipment

- uncooked spaghetti
- newspaper
- plastic straws
- bamboo skewers
- masking tape
- blocks or other small heavy objects
- ruler

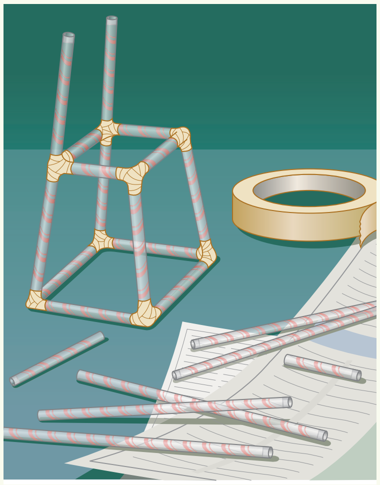

Figure 3.5 Example of a straw model, Step 1

Procedure

1. Organize into groups of three or four. Each group will be assigned a different material to build a model tower as illustrated in Figure 3.5. Predict the suitability of the material for building the tower.
2. Before any building begins, decide as a class how you will test all the materials for strength and stability. Agree on what observations you will record before, during, and after the test to determine the effect of the forces acting on the structures. Include:
   - Qualitative observations: These are changes you observe taking place in the structure as you proceed with your test.
   - Quantitative observations: These are changes you are able to measure in the structure as you proceed with your test.
3. Work with your group to build your model.

Collecting Data

4 After all towers have been completed, each should be tested in front of the class using the test methods agreed to in step 2.

> Note: If a computer and software are available, you may enter your data into a spreadsheet. This will allow you to produce graphs to show your results and compare them with those for other materials.

Analyzing and Interpreting

5 Which material most resisted the forces acting on the structure? Why do you think that is? Which properties gave the structure that strength and stability? Which material least resisted the forces acting on the structure?

Forming Conclusions

6 Do you agree or disagree that by knowing the properties of given materials, you can accurately choose a material that will provide strength and stability to a structure? Explain, using the results of this investigation.

7 What material properties do you think are the most important in real life for building tall, free-standing structures that can support the greatest mass? Why?

Give it a TRY — ACTIVITY

MEASURING DEFORMATION

Deformation of a structure can be measured.

- Weigh the masses and record the amounts.
- Measure the height of your foam cube and record the height in a table.
- Add the smallest mass to the top of the cube.
- Measure the height of the foam and record it.
- Repeat the procedure using each of the different masses.

Observations and Analysis

TOOLBOX

- What internal force is acting in this activity?
- Plot a line graph of your results. (Refer to Toolbox 7 if you need help drawing a graph.)

Materials & Equipment

- polyester foam cube
- ruler
- 3–4 small heavy masses

CHECK AND REFLECT

1. Explain why it is important to match structural material and structural function.
2. Do you agree or disagree with the statement, "Almost any material can be used to build any structure"? In a paragraph, explain your answer.
3. The hydro-electric dam in your area is beginning to need expensive repairs. The building of a new dam is being proposed. Several people have been asked to provide advice to the designers of the new dam, including
   - the manager of the marina upstream from the dam
   - a freshwater ecologist
   - a drinking water expert from the city downstream
   - a person representing the hydro-electric power company
   - a person representing a local group wishing to open a biking trail and to use the new dam as a bridge

   a) In your notebook, list the people above. In turn, put yourself in the position of each person. Note what structural characteristics of a dam would be important to you, and how those characteristics would affect the choice of building materials you would recommend.
   b) Choose to be one of the individuals above. Compare your ideas for material choice with those of a classmate who is being a different individual. How could both of your needs be met in the new design?

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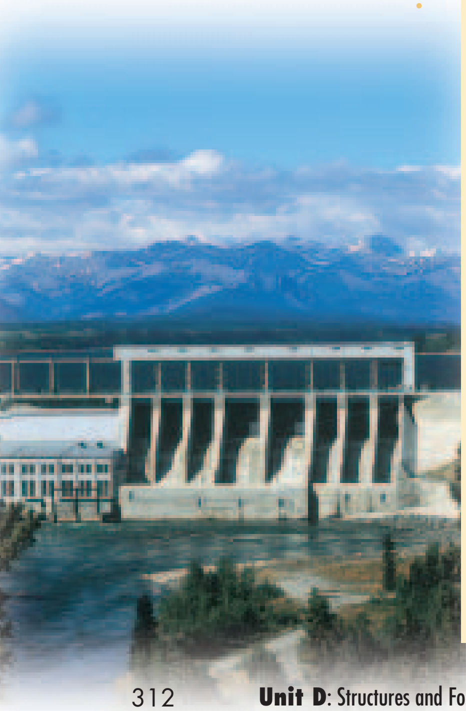
Wasp Nests

Research how wasps build their nests. What materials do they use to make their nests? What is the advantage of these materials?



3.2 Joining Structural Components

Figure 3.6 What is happening when the design and materials of a structure are just right, but the structural components don't stay connected?

Have you ever taped the broken frame of a pair of glasses together only to have the pieces work their way apart again? Have you ever struggled with a locker or cupboard door when one of the hinges has broken off?

The problem is that the components are not properly joined. Just as design and materials are important to a structure's strength and stability, so is how the parts of the structure are fastened together. The place at which structural parts are joined is called the **joint**. Some joints need to be rigid, or fixed, for the structure to work as intended. Others need to be flexible, or movable.

Joints That Rely on Friction

Think of pulling your desk across the floor. The drag or resistance you feel is the result of the **friction** that is occurring between the floor and the legs of the desk. Friction is the force that results when the surface of one object moves against the surface of another object. You may be able to overcome the force of friction easily when you are moving just the desk by itself. But what if a friend sat on the desk while you were pulling? You would have to work harder to move it. Can you explain why, using the terms *gravity*, *mass*, and *force*?

The strength of the force of friction also depends on the roughness or smoothness of the two surfaces in contact with each other. It is easier to move a desk across a freshly waxed linoleum floor than across a rough concrete floor. Why do you think that is?

To create strong joints between parts of a structure, the force of friction can be used to prevent the individual components from slipping apart.

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Expansion Joints

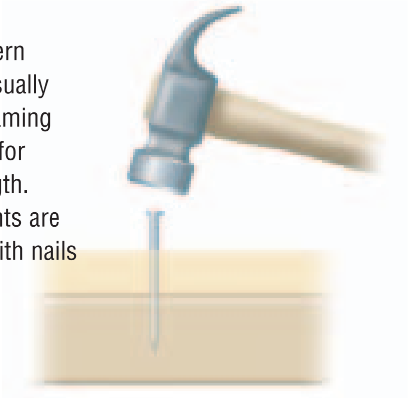
Outdoor structures such as bridges get very cold in winter and very hot in summer. Because their components contract and expand at different rates with these temperature changes, the joints connecting them must be able to move a little bit, too. Next time you're crossing a large bridge, watch for these "expansion joints."

Figure 3.7 What force is helping this rock climber's foot stay joined to the rock? Is this the same force that is keeping the pitons (metal spikes) firmly in the cracks where they were hammered?

Nails, Screws, Rivets, Tacks, Staples

When a nail, screw, rivet, tack, or staple is used to hold components together, it is the friction between the metal and the material surrounding it that does the job. This is the most common type of joining used in modern construction (Figure 3.8). One advantage of screws, tacks, and staples is that they can be easily removed to dismantle a structure if necessary.

Figure 3.8 Modern structures are usually made of steel framing riveted together for maximum strength. Wood components are often fastened with nails and screws.



Interlocking Pieces

Since friction is the force as two surfaces rub against one another, you can increase the amount of friction by increasing the area in contact. As Figure 3.9 shows, this method is used, for example, to join wood together in interlocking pieces (without screws or nails).

Figure 3.9 The notches cut into these logs ensure that the parts in this structure will remain tightly interlocked. Furniture uses notches for strong joints.

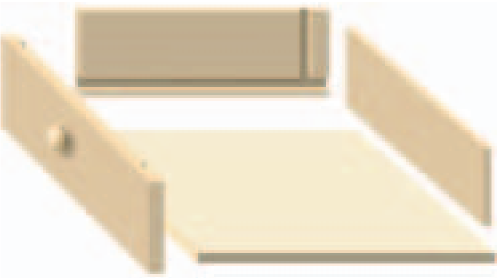
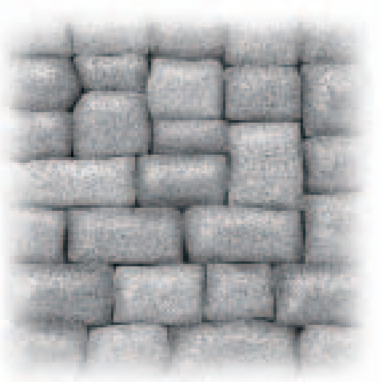


Figure 3.10 Landscape architects often use this “mass” method of joining to design stone retaining walls and split-rail fences.

Mass

The friction between the base of the block shown in Figure 3.10 and the surface underneath is enough to keep the block in place. The blocks forming the Pyramids of Giza are joined together only by the force of friction.



Joints That Rely on Bonding

Another form of joining actually changes the two surfaces being joined so that they are connected by a common material—whatever bonding substance is spread on them.

Glue, Tape, Cement, Welds

Adhesive glue and tape (which has glue on one side), cement, and welds act to bond the surfaces of two materials. Some types of glue, for example, dissolve the surfaces on which they're spread, creating a chemical change. The two new surfaces mix and harden together into one solid mass. Figure 3.11 shows an example of glue being used as a means of joining.

Figure 3.11 The joints in wooden furniture can be strengthened using glue.

Fixed or Movable? Which Joint for Which Structure?

All of the methods of joining just described can be combined in different ways to create fixed joints or movable joints.

Fixed joints are rigid to prevent any movement. They result, for example, from welding, cementing, gluing, or nailing parts firmly together. Which of these methods works best in any given structure depends on the material of the components, how the structure is to be used, and where it is to be located. Why would gluing to hold a fence together or welding to assemble a kite not be appropriate?

Movable joints are flexible or mobile so that parts of the structure can move as required. Hinges, pin joints, and flexible rubber tubing are examples of movable joints. So are your knees, elbows, and shoulders. Even though they are mobile, movable joints must still be able to withstand a load and the stress of repeated movements.

Figure 3.12 No matter how good a structure's design is on the drawing board, the ultimate strength and stability of that structure depend on the right materials and method of joining being used.

Problem Solving Activity

A Home for Time

Recognize a Need

Your school has decided to do a unique project to mark its upcoming anniversary. Each class will put together a message for students of the future, as well as small objects that may have special meaning in 100 years. The messages and objects will be put into a metal time capsule. The school is asking students to submit designs for a small structure to protect the box until a century has passed. The structure will be built by a local contractor who has volunteered time and materials.

Materials & Equipment

Suggested modelling materials. Use other materials if you prefer.

- Plasticine or modelling clay
- cardboard or foam board
- Popsicle sticks
- tape
- glue

The Problem

You and a small group of fellow students have decided to submit a design to the contractor. Your group will come up with an overall shape for the structure, as well as make suggestions for the materials and how they should be fastened. You will present your design as a combination of a scale model and a written list of materials for the real structure.

Figure 3.13 How would you build a structure to protect a time capsule?

Criteria for Success

The contractor who has volunteered to build the structure to hold the time capsule has set the following criteria for the student designs:

- There must be a door in the structure that can be opened when the time comes (in 100 years), but which would be locked until then.
- The material for the real structure must be able to withstand the climate found at your school over time.
- The material must be easily obtained.
- Preference will be given to a design that uses a material that is easily obtained, not expensive, and attractive looking.
- There has to be some way people in the future will be able to identify the function of the structure, so they know there is a time capsule inside.

Brainstorm Ideas

1 Brainstorm how you want the structure to look. Make sketches to show possible structures from different views, such as from the top and from the side. Keep in mind the structure will be outside and visible to the public.

2 When you're ready, make a scale drawing of your design. Include any features such as doors or other moving parts, as well as any signs or ornamentation you wish to use.

3 Brainstorm possible materials and their pros and cons. Once your group has decided on the materials you want for the structure, modify your design if necessary. Make note of any properties of your materials that will be especially valuable for this structure.

4 Build a model of your structure using any modelling material you wish. Your model should include a scale model of the time capsule so you can demonstrate how the capsule fits inside. Make any modifications you need to during the building process.

Test and Evaluate

5 Your teacher will, if possible, invite a local contractor to help assess the various designs. Alternatively, a class selection committee can be formed to choose the design that best fits all of the criteria.

Communicate

6 In a short assessment report, summarize:
   a) the most difficult aspect of this challenge that you had to overcome in your design
   b) how you overcame that difficulty
   c) how you might have tested your design for strength and stability

7 Which features of the chosen design were considered most important by the contractor or selection committee? Discuss how the other designs could be improved using some or all of these features. Often one design will be just as good as another, and a final choice is made based on personal opinions about appearance. If this was the case in your class, hold a vote to see which design would receive the most support.

8 This could be a project that your school or a community group would be interested in doing. Discuss how you might get such a project started.

St. Paul, Alberta, is home to the world's first UFO landing pad. Built in 1967 (the year this picture was taken), this imaginative structure also contains a time capsule.

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When Friction Is a Problem

When structural parts are joined together, friction can cause wear in one or both of the surfaces rubbing together. Friction also generates heat where the two surfaces rub. Neither of these is a good thing when it comes to keeping structures strong and stable. Think of an example in which wear and heat generation between structural parts pose a problem. Research how the problem is being dealt with.

DESIGNING JOINTS TO LAST

If a structure is to last any reasonable length of time, it must be designed to withstand the forces acting on it year after year.

For some structures, such as a monument, the main forces acting on them are extremes in weather (such as extreme heat or cold).

For structures with moving parts, "building for time" is also a challenge. The joints used in them must be able to survive the force of repeated movement. Consider your refrigerator at home. How many times a day does its door get open and shut? How many times a week is that? How many times a year? An inappropriate type of joint for the job will eventually experience fatigue and then breakage, even though other parts of the structure remain strong.

Figure 3.14 A structure's basic shape may be stable and its materials strong, but if its joints are not suited to how and where it is used, it won't be useful for long.

CHECK AND REFLECT

1. Remember the list of fasteners, or joints, you made at the start of subsection 3.1? Which ones function based on friction? How does friction help those joints do the job they are supposed to do—that is, not slip apart?
2. Given what you now know about friction, read the statements below and correct the three that are incorrect (one is right!):
   - A camper spreads rubber tarp on slightly sloping ground, then puts a backpack on top of the tarp. When the camper returns a moment later, the backpack has slid several centimetres down the slope.
   - It is easier to open a jar lid if your hands are dry than if they are wet.
   - A hockey skater reduces speed by digging in the tip of each skate when striding forward.
   - A very thin film of water on a road is less slippery to a moving car or truck than a dry road.
3. Identify four structures found in the natural environment that have fixed joints and four that have movable joints.

3.3 Properties of Materials in Plant and Animal Structures

As you have studied, structure and function go together. The living world is no exception. Have you ever seen a Venus flytrap catch an insect? If you have, you would have been amazed at how fast the leaves that have been modified to form a trap can move. The unsuspecting insect triggers this reaction when it touches the small hairs located on the inside of the trap. The human body is built to move quickly as well.

Figure 3.15 The Venus flytrap has an unusual structural design for trapping its food.

Materials in the Human Structure

Think about your body as a structure. Each of the components in the human body is a unique material with special properties suited to the function of that part.

Bones, Ligaments, and Cartilage of the Frame Structure

Bones in the human adult are hard and rigid. They form a structural frame that is strong enough to support and protect other parts of the body. The thigh bone is connected to the shin bone by ligaments. These are bands of strong, flexible connective tissue. Cartilage that is found at the ends of some bones reduces friction and provides a smooth surface for movement. When you fall off your bicycle, the cartilage helps to absorb the shock of your bones being bumped together.

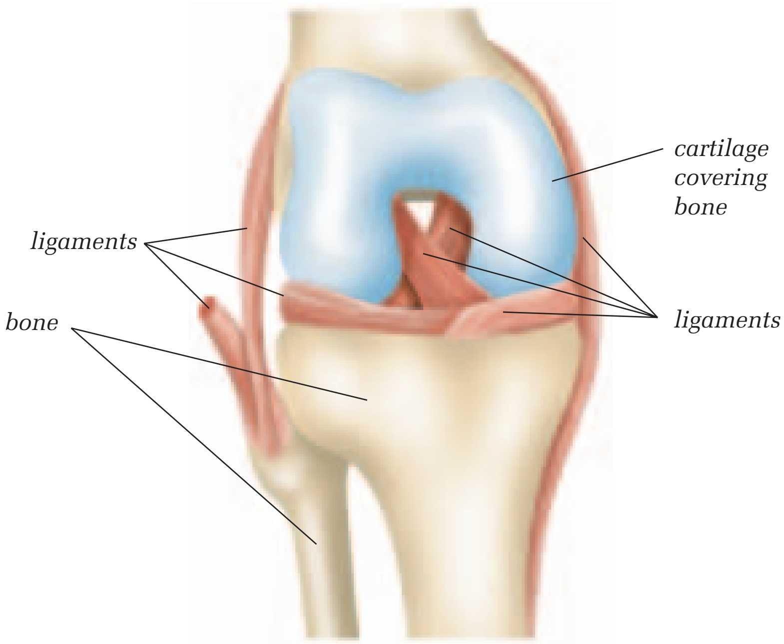

Figure 3.16 The seven ligaments that hold your leg bones together meet at your knee.

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Synthetic Muscles

Scientists have discovered that a glue commonly used for such jobs as holding road signs up over highways may create the perfect "muscles" for robots and artificial limbs. The glue, an *acrylic elastomer*, can take strain better than human muscle can. It also creates as much force as human muscle does. Other advantages are its light weight and the fact that it goes back to its original shape even after it has been stretched.

Muscles and Tendons

The muscles of your body, 656 of them, allow your skeletal frame to move. Muscles are made of semi-solid fibrous tissue that functions by contracting (shortening) and relaxing. They are attached to bones by tendons. Like ligaments, tendons are strong and flexible. A tendon will often hold together even when the bone to which it is connected breaks. When a skeletal muscle contracts, a bone moves. Muscles also are located in your internal organs. Heart muscle contracts and pumps blood. Digestive tract muscles contract and move food along.

Joints

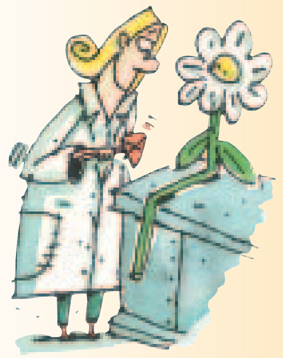
The joints in your body are specialized for various functions. Ball-and-socket joints in your shoulders and hips permit movement in many directions. Elbows and knees function with hinge joints. There are pivot joints in your spinal column and gliding joints in your wrists. All of these allow movement. However, there are joints in the body that don't allow movement at all. They are found between the bones of your skull. What do you think the function of the skull is? Do immovable joints make it suited for that function?

Give it a TRY ACTIVITY

MATERIALS IN PLANTS AND ANIMALS

You've just learned a little about the role of different materials found in the human body. You've also seen how the functions of the body's various components are made possible by a range of methods of joining. The role of different materials in plant and animal structures is just as fascinating.

- Using the library or Internet, research the material composition of a plant or animal of your choice. Find out what properties the main materials have and what advantages these give the structure in terms of how it functions. Also note how the parts of the structure in your chosen plant or animal are joined.
- Write a summary of your findings, and include drawings to illustrate the materials and joints.



Skin, the Human Shell

Skin, along with the bones, joints and connective tissue, form a shell and frame structure. Skin is a tough, flexible material. It provides the ultimate structural shelter. It waterproofs your body and protects it from harmful bacteria. As well, it helps to regulate your body's temperature through such actions as perspiration and shivering.

Materials in a Tree's Structure

A tree trunk may seem to be made of just one material ("wood"), but in fact, it is a structure composed of several layers of different materials. As Figure 3.17 shows, each layer of material has a specific job to do to maintain the strength and stability of the tree.

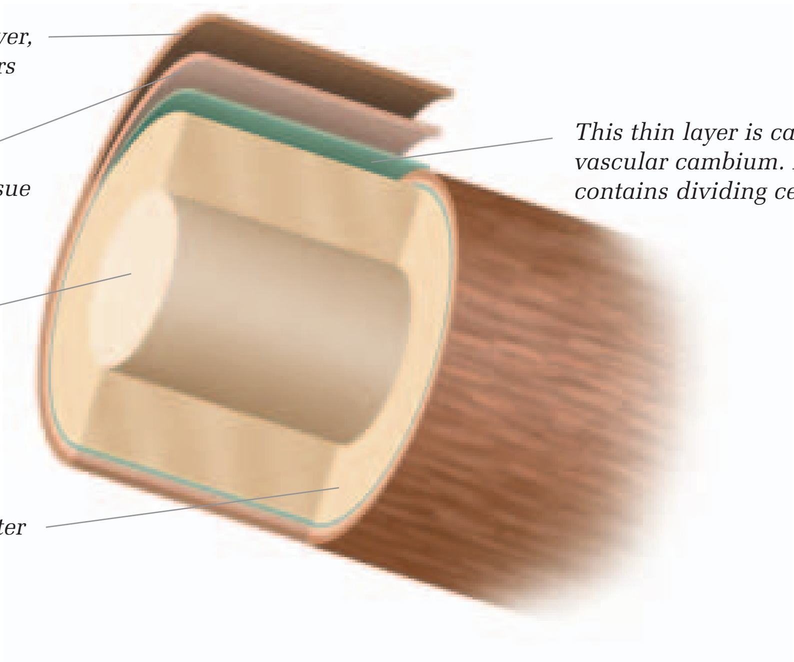


Figure 3.17 Each layer of material in this tree plays a role in keeping the tree strong, stable, and healthy.

Check and Reflect

1. What would happen if ligament material in the human body were replaced by bone material?
2. Most sports injuries involve damage to joints such as ankles, knees, and wrists. Why do you think this is so?
3. True or false? The different layers of materials found in plants are needed only to make the plants strong. Explain your answer.

Careers and Profiles

Designing for the Environment

Figure 3.18 Jenny Tse was trained in Hong Kong and moved to Canada in 1969.

Jenny Tse is an architect in Alberta. It's important that Jenny understands the natural forces in the environment. Buildings in Canada have to last through the heat of summer, the cold of winter, wind, snow, rain, and even earthquakes!

"In Hong Kong, the weather is always warm and there is not much space for building. It was a fun and interesting adjustment to adapt myself to cold climate design," Jenny says. "For example, in the Arctic region, buildings are put on stilts. This stops the building's heat from escaping into the ground, which will melt the permafrost and cause the building to collapse."

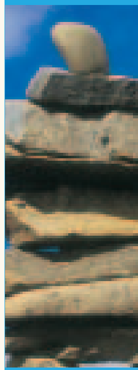
How does Jenny plan a house? First, she starts drawing designs. These drawings show her ideas about the shape of the house and the arrangement of the rooms. If Jenny's clients like her design, she makes working drawings of the house. These are very detailed drawings that tell the builder how to construct the house. When construction starts, Jenny has to check the construction site often to make sure the builder is following her design and instructions. Then, finally, she hands the new house over to its new owners.

Figure 3.19 Jenny was a design architect of this building, Mineral Springs Hospital in Banff, Alberta.

Figure 3.20 Edmonton Buddhist Research Institute, Edmonton, Alberta, is another one of Jenny's designs.

Jenny's job changes all the time and gives her lots of challenges. Still, she says she loves it. "Students who want to be architects should be creative and love to work with people," says Jenny. "An architect's life is exciting, and you will learn a lot, too!"

1. Why must architects have a good understanding of the natural environment for which they are designing structures?
2. If you were an architect, which part of planning and overseeing the building of a house do you think would be most challenging? Why?



Assess Your Learning

1. As part of a community parks restoration project, students in a grade 7 class have volunteered to design and build a bridge across a 5-m-wide stream. They can use only non-living, natural materials found in the forest and a hand saw.
   a) Based on your knowledge of structural components, what suggestions would you make to the students for designing and constructing the bridge?
   b) What problems do you foresee happening as the bridge is used over time and under a variety of weather conditions?

2. Look at the typical brick wall shown in Figure 3.21. Why are the bricks in the wall not stacked directly on top of each other?

Figure 3.21 Question 2

3. Explain how each of the following methods can help improve the joining between two components:
   - sanding the surface of a smooth material to make it rougher
   - adding more weight (load) to an object sitting on a base

4. A weight lifter puts a powder on his hands before picking up a pair of heavy weights. Why?

5. Make a concept map that puts together what you have learned about designing a strong and stable structure. Compare your map with that of other students until you have included as many concepts and terms as possible. Put a question mark beside any concepts that you need to review or would like to learn more about.

Focus On SCIENCE AND TECHNOLOGY

Technological problems often have many solutions, involving different designs, materials, and processes.

Reflect on what you learned about materials in this section.

1. What were some of the properties of materials you read about?

2. Why is it important to evaluate the appropriateness of methods of joining for individual structures?

3. How could you apply what you have learned about materials and methods of joining to solve a technological problem such as how to build an emergency winter shelter?

4.0 Structures are designed, evaluated, and improved in order to meet human needs.

Key Concepts

In this section, you will learn about the following key concepts:

- margin of safety
- structural stability

Learning Outcomes

When you have completed this section, you will be able to:

- describe methods to increase the strength of materials and improve designs
- identify environmental factors that can affect the stability and safety of a structure
- analyze a technological design or process according to costs, benefits, safety, and impact on the environment

If you could travel back in time to talk with the cyclist in the black-and-white photograph above, what do you imagine he would say about his new bike? Would you expect him to feel that the bike was strong, efficient, and safe to ride? Would he feel his needs were being met by technology? What might he say about how the design of this bike was an improvement over earlier models?

Now imagine having the same conversation with the cyclist in the colour photograph. Do you think she, too, would feel that her bicycle was strong, efficient, and safe to ride? What improvements in her "state-of-the-art" bike might she identify compared to the bike of her counterpart in the black-and-white photograph?

Few structures remain unchanged in design once they are created. In this final section of the unit, you will learn about the processes used to develop, evaluate, and improve human-made structures so that they do the job we want them to in a safe, reliable, and cost-efficient way.

4.1 Building Safe Structures in All Environments

All structures are created to satisfy human needs. These needs may vary widely, but the one common to all structures is safety. Since so many environmental factors can affect the stability of a structure, designing for safety is a constant challenge.

Margin of Safety

Safety is important to all designers. However, since it is impossible to make anything perfectly safe, designers work with a **margin of safety**. This refers to the limits within which a structure's safety performance is felt to be acceptable.

Think of speed limits on roads and highways. Cars and trucks are designed and built to move safely within these limits. While vehicles are intended to be driven at these speeds, designers still need to make cars and trucks that are safe to drive at slightly higher speeds. The margin of safety in this case might be 30 km/h or 40 km/h faster than the common speed limit.

Tire pressures are determined with a margin of safety also. The manufacturer will have assessed aspects such as size of tire, vehicle load and increased temperature due to use, weather or speed. If someone over-inflates the tires of a vehicle in order for it to carry a heavier than normal load, the margin of safety has been decreased. If a tire hits a pothole, there is a greater chance it will have a blow-out.

Building components are designed in the same way. For example, the steel beams in a bridge must be able to withstand three or four times their maximum intended load.

Figure 4.1 Although all structures are created to satisfy a human need, none would be completely successful if their designer did not take environmental factors into account.

Figure 4.2 Road signs show drivers the safety limits that have been calculated by highway engineers.

Testing for Structural Safety

One way of finding out how safe a structure is before it is in full operation or available on the market is to test how well it can withstand the forces acting on it. Many such tests are extreme.

New hockey helmets are hammered against a steel anvil at almost 15 km/h, or test cars are driven into brick walls at 25 km/h. Helmets must be strong enough to protect a player's head against all types of collisions. Car bumpers must protect the front of cars against damage during impact. Testing occurs at all stages of a product's development, from choosing its components and testing them, to testing the design (e.g., by computer modelling) and testing the final product before approval for consumer use. In the activity where you will build a model of a drawbridge, you will test a component as well as the final product. You will also determine a margin of safety.

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Brought Down by Ice

Six days of freezing rain damaged this hydro tower in Quebec. What forces caused it to collapse? Would a coating of ice be a static or a dynamic load? Suggest ways that a tower like this could be protected from this load.

A downed hydro tower and power line, damaged by the 1998 ice storm in Quebec and Ontario.

Monitoring Structural Safety

Another method of evaluating the safety of a structure is to look at how frequently that type of structure fails and why. This can be done through a process called monitoring, in which experts keep track of how well the structure performs. Information can also be gathered through surveys that ask the users of particular structures what their opinions of the structures are.

Accounting for Environmental Factors

Climatic Conditions

In many parts of the world, buildings, bridges, vehicles, and other outdoor structures must regularly withstand the forces of heavy snow, rain, and wind. Other climate-related factors are intense heat, intense cold, very high humidity, and extreme dryness.

Building on permafrost is a particular challenge in frigid regions around the world, such as Canada's North. Permafrost is a permanently frozen layer in the ground. Although frozen solid in the winter, the upper portions of permafrost melt in the summer, making the ground spongy. Without solid foundations, structures built on these areas undergo structural stress that usually leads to failure. Technology is helping to solve these problems.

Terrain Conditions

Unstable soils and steep terrain make building stable structures difficult. In areas where soils are soft or shifting, special construction techniques must be used. This problem wasn't taken into account when the Empress Hotel in Victoria, B.C., was built in 1905 on landfill over what used to be mudflats. A few decades ago, engineers found that the hotel had sunk about 75 cm over the years. The large stone building has since been "shored up" beneath with concrete supports and pilings.

Areas that are low lying often suffer flooding or pounding from storm waters. While it is debatable whether people should live in those areas at all, some structures, such as lighthouses, must be there. Building them to withstand the forces of water and wind is always a challenge.

On steep mountainsides, hill slopes, and cliffs, mass movement of snow, rock, and mud is a common hazard. Avalanche and rockfall tunnels are often built over highways where this danger exists. They must be able to support massive loads.

Figure 4.3 In Malibu, California, heavy winter rains during 1983 caused landslides on steep, unstable slopes. As a result, several homes suffered serious structural damage.

Earthquake Risk

When an earthquake shakes and heaves the ground, some structures fail and may even topple to the ground, while others remain standing. The stable structures protect people and property. Not all areas are subject to the risk of severe earthquakes, but in those that are, the structures must be designed and built to resist the external and internal forces acting on them.

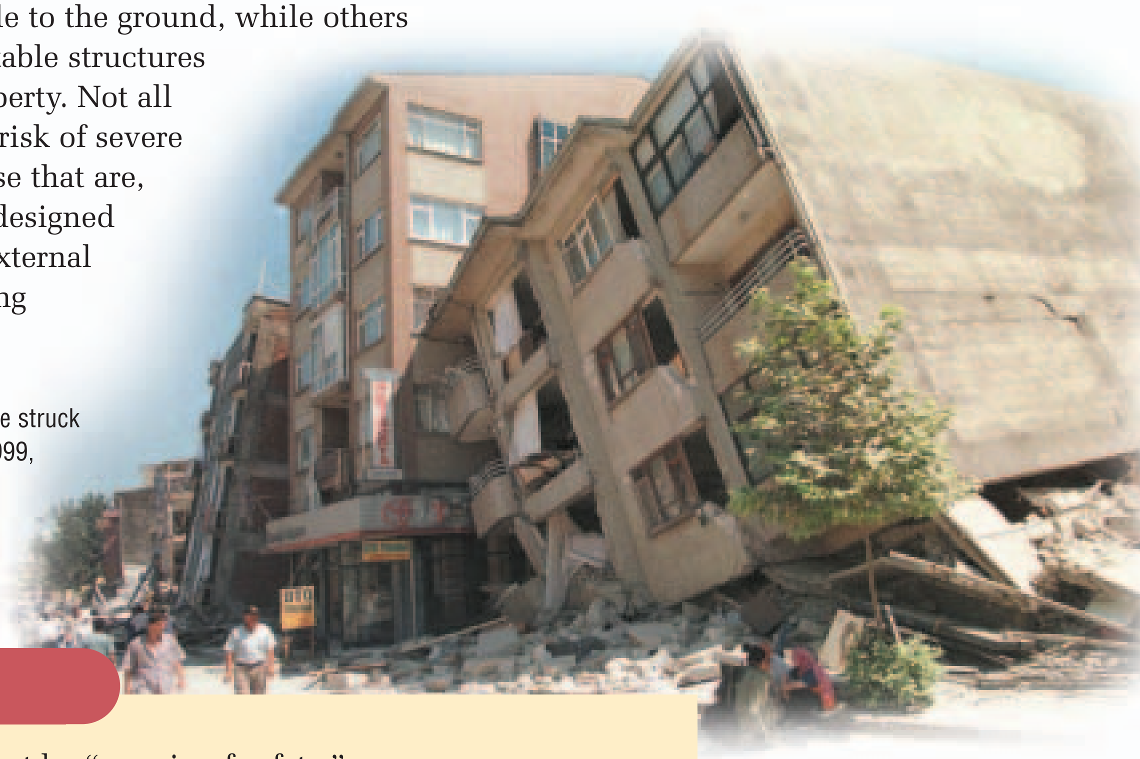


Figure 4.4 A powerful earthquake struck western Turkey on August 18, 1999, killing more than 2000 people. Many victims were trapped in collapsed buildings such as the ones shown here.

Check and Reflect

1. Explain what is meant by "margin of safety."
2. List five environmental factors that structural designers and builders might have to take into account, depending on where they locate their structures.

Experiment ON YOUR OWN

BUILD A WORKING MODEL OF A DRAWBRIDGE

Before You Start ...

You are now familiar with the different types of structural forces, the characteristics of structural stability, and the nature of structural stress, fatigue, and failure. You've also learned a little about how designers test for structural safety. Here's an opportunity for you to use your knowledge to design, construct, and test a bridge that has moving parts.

The Question

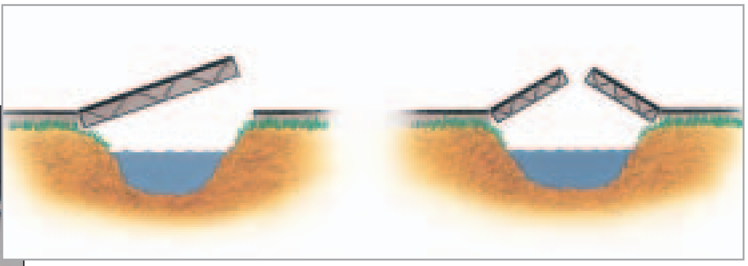
How can a structure with movable parts be built so that it is functional, but strong and safe?

Design and Conduct Your Experiment

1 Working by yourself or with a partner, plan how you could design a model drawbridge that has either one or two movable sections.

2 Discuss what materials and equipment you will need to build and test your model. For example:
   a) What kind of building materials will you use?
   b) Set criteria for one of the building materials. Test the material to see that it meets your criteria and has a 25% margin of safety.
   c) How will you lift and lower the movable sections?
   d) How will you test the structure's strength and stability?

3 Draw up a plan. Include in it a detailed sketch of your design, a list of the materials you propose to use, and a brief description of how you will test the completed structure. Show this plan to your teacher before you proceed.



4 Build your model and test it. Modify the structure, if necessary, to correct practical problems or improve overall strength or stability. Be prepared to demonstrate to your class how the drawbridge works.

5 Present your experimental design and findings to the class. State what limits you would recommend for live load and what your margin of safety is. Describe how well your model meets those criteria.

Figure 4.5 Step 4

4.2 Strengthening Materials to Improve Function and Safety

As you've seen throughout this unit, a goal of science and technology is to provide solutions to practical problems.

A structure such as a bicycle is designed and built to meet a human need. Gradually, through use and formal and informal processes, it is evaluated and tested. From the results of these tests, new designs and materials may be applied. Sometimes, it is trial and error in technological problem-solving that brings about the changes. Other times, it is advances in scientific knowledge that lead to change, as when methods to increase the strength of materials are discovered or new materials are developed.

Altering Materials for Strength

One way that many structural problems can be solved is to combine materials and components in new arrangements. This lets you take advantage of the best characteristics of each.

*info*BIT

Body Fusion

At birth, a baby's skeleton contains 350 bones. As the baby grows through childhood and into an adult, many of the bones fuse together, until the total number of bones is 206. This fusing is nature's way of strengthening and reinforcing the frame of a human for adulthood.

Give it a **TRY** ACTIVITY

Designing a Better Backpack

No structural design, not even that of a backpack, stays the same over time. Humans are always working to adapt and improve designs to meet people's needs better. Here's your chance to do that yourself. The approach you use in this activity to evaluate and improve the backpack is the same basic process you would use to analyze and improve any technological design.

- Prepare a short questionnaire and survey a sample of students. Your survey should find out what the students use backpacks for, under what conditions they use them, and how long, on average, they find a backpack lasts. You should also ask whether your respondents have ever experienced backpack failures and, if so, what parts of their backpacks failed.
- When you have your survey results, work with a small group to brainstorm how the components, materials, and fasteners in backpacks could be improved and strengthened. How could backpacks be made so that they provide more efficient service for a longer time?
- Summarize your ideas and present them to the class. With all the groups, debate the advantages and disadvantages of the various suggestions.

Corrugation

Imagine you wanted to design a way of packing two layers of small glasses in a box. All you have on hand as packing material is some heavy paper. The divider between the two layers must be strong enough to resist bending under the load of the top layer of glasses. It must also be smooth enough to keep the glasses upright. You've learned that triangles and arches are strong shapes. If you folded a flat piece of paper into a series of triangles or arches, that would make a strong support. The only problem is, the folded surface would cause the top glasses to fall over.

What's the solution? If you combined the folded piece of paper with two smooth ones, the result would be a sandwich with a strong interior and a smooth exterior—perfect for making a sturdy, yet lightweight, divider (Figure 4.6).

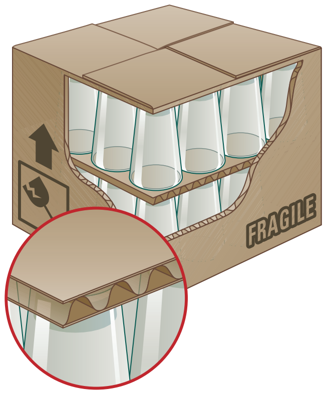


Figure 4.6 Corrugation provided the solution to this packing problem.

Corrugation is the process of forming a material into wave-like ridges or folds. Corrugated cardboard and corrugated metal are common examples.

Lamination

Gluing layers of a material together to create a strong bond is called **lamination**. Laminated materials are stronger than a single piece of the same material of the same thickness. Some laminated beams, for example, are made of short pieces of wood. Overlapping, interlocking, and gluing the members into single beams makes them better than solid beams for supporting heavy loads.

Have you ever looked carefully at plywood? Did you see the five or seven layers? It is laminated. Kitchen counter tops have a waterproof layer laminated onto wood. Another example of a laminated product is automobile safety glass. It consists of two pieces of glass with a layer of plastic in the middle. If the glass is hit by a flying object, the outside layer of glass may break but the plastic layer is elastic and it will hold the broken pieces of glass together.

Strengthening Component Arrangements

If stronger materials to build stronger components are not available or affordable, using different arrangements of components is often a good solution. Making greater use of trusses and arches, for example, can provide the strength that is missing. Even adding small supports for reinforcement (see Figure 4.7) can make structural components stronger.

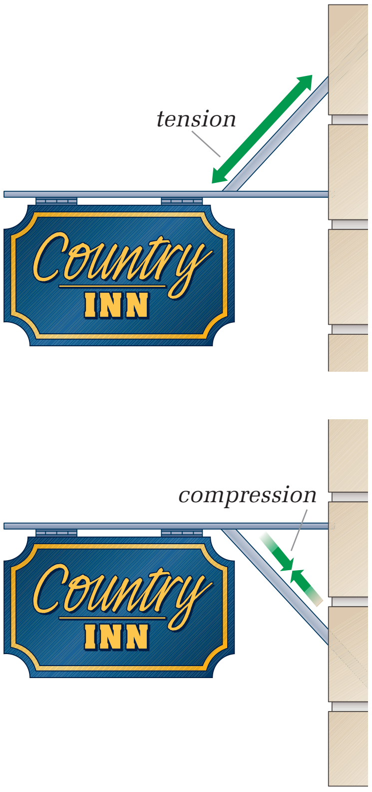


Figure 4.7 The component that provides support for the sign in (A) is called a "tie." It works by resisting tension in the structure. The component that provides support for the sign in (B) is called a "strut." It works by resisting compression in the structure.

Problem Solving Activity

Building Strong

Materials & Equipment

Materials will vary, but may include the following items. Check your choices with your teacher before starting to build.

- cans
- cardboard boxes
- cardboard tubing
- plastic containers
- rope
- plastic cord
- glue
- adhesive tape
- staples
- paint
- papier-mâché

Equipment will vary, but may include the following items. Check your choices with your teacher before starting to build.

- scissors
- scalpel or small sharp knife
- tape measure

Caution!

- Wear goggles when using a knife.
- Wear gloves when using paint.

Recognize a Need

One of the most popular annual events in your school is "The Year's Greatest Designers" competition. The theme this year is "New Idea, Old Materials." You and some friends decide to enter the competition.

The Problem

Your challenge is to design, build, and test a chair using recycled materials.

Criteria for Success

The chair must be made of recycled, "non-traditional chair" materials and be able to withstand an agreed-upon amount of stress. You may use up to four different kinds of material and as many methods of joining or fastening as you want.

Brainstorm Ideas

TOOLBOX

1 Working in a group of two or three, brainstorm ideas for a chair design, the materials you could use, and the method you will use to test your chair. Evaluate all the ideas discussed and reach a decision amongst yourselves about which idea your group will use. (Refer to Toolbox 3.)

Build a Prototype

2 Assemble your materials and any tools or equipment you will need to build your chair prototype.

3 Build your chair, testing all components as well as the final chair. Modify the design if necessary as you go.

4 Troubleshoot problems as they are identified. For example, are there some weaknesses in the original design? If so, how could you resolve them?

Test and Evaluate

5 With your group, present your completed chair to the class. Answer questions about the design. Be prepared to support your design decisions.

6 After all groups have displayed their chairs and given a presentation, the teacher will test how well each chair functions (i.e., how much weight it can support, how stable it is, and determine if the size is appropriate).

7 For all the chairs, the class will vote to select the one that is best in each of four categories: Most Original Use of Materials, Strongest and Most Stable, Most Aesthetically Pleasing, and Overall Best Chair.

Communicate

8 As a class, review the multiple solutions that were found for the practical problem posed by this activity. Why was there not just one solution?

9 Describe what you feel were the biggest challenges in meeting the criteria set for the problem. How did these limitations affect the process you went through in developing your design and then building a prototype?

reSEARCH

Titanium

Titanium is a durable but light metal. It is a material of choice in the automobile and aircraft industries. You may also know of titanium's use in sports equipment such as tennis rackets, bicycles, and golf clubs. Another important property of this metal is that it is non-toxic. This makes it a good material for producing artificial body parts. Research more about the use of titanium to build a wide variety of structures.

Changing Methods of Fastening

The purpose of most backpacks is to carry a load and keep the contents inside protected from weather. Some backpacks maintain their strength and usefulness better than others, but most often the parts that fail are the fasteners: the seams, zippers, and buckles that hold the various materials and components together.

Failed fastenings in structures such as backpacks are usually just an inconvenience rather than a safety concern. Think what would happen if the welds joining the steel plates of a ship's hull failed, or if the cables supporting a gondola snapped. Clearly, the consequences of poor fastenings in these cases could be disastrous.

Changing methods of fastening to strengthen even a simple structure can mean switching to screws from nails, or using cement rather than relying on mass to hold structural parts together.

New Materials

Science and technology are creating new materials all the time. Many of these are providing solutions to challenges of building stronger, lighter, and more stable structures.

Composites of carbon fibres, for example, have properties that are superior to steel and other metals. Their light weight allows them to be used in aircraft structures. Technological advancements have led to other composites such as Kevlar to be used in such diverse products as tires, fibre optic cables, and sporting goods. E-glass fibre (fibreglass) is widely used for energy efficient windows.

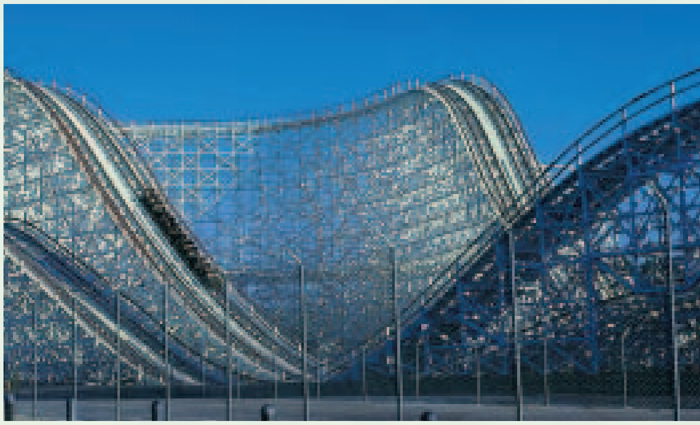
New plastics are being developed. How many objects can you see around you that are made of some type of plastic?

Check and Reflect

1. Define corrugation and lamination, and describe how they add strength to a material.
2. Explain why a builder might choose to reinforce the arrangement of components as a means of strengthening a structure rather than just buying stronger material.
3. True or false? A new material made from combining other materials can never be as strong as the originals. Explain your answer.

Careers and Profiles

Roller-Coaster Designer

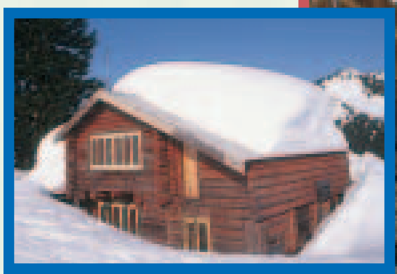


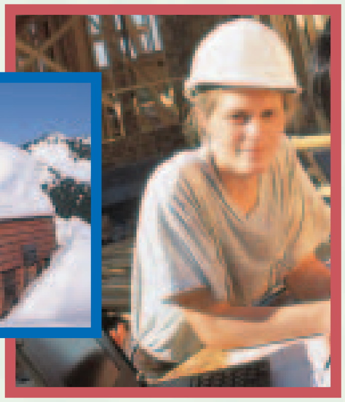
Roller-coaster designers use computer programs to design coasters. These programs help them change factors like the height and steepness of the coaster to get the fastest and safest ride possible.

Once the design is ready, a small-scale model of the coaster is built, probably around one-eighth of the actual size. The designers test this model to make sure it is safe and works well. Next, a full-sized model is built and tested. Finally, the roller coaster is completed. It is set up in an amusement park and ready to go!

What forces do you think are acting on the roller coaster shown at the right?

Building Inspector





People buying a new home often hire a building inspector to examine it. The inspector will check that the structure, heating, plumbing, and electricity in the dwelling are all safe and working well.

Building inspectors need to understand how structures work. They also need to understand how forces such as wind and gravity act on a building. In Canada, for example, roofs have to be strong enough to hold up the weight of snow that builds up during the winter.

Building inspectors make sure buildings are safe for people to live and work in. When a building is under construction, a city building officer will come to check that the builders are following proper safety rules.

- The structure and foundation of the building have to be strong enough to hold up the weight it will be carrying.
- Tall buildings have to be stiff enough to resist the force of strong winds.
- Buildings in earthquake zones have to be sturdy enough to withstand the shaking and movement of the ground.

1. What roles do a roller-coaster designer and a building inspector play in ensuring that amusement park rides and houses meet human needs within a margin of safety?
2. For each of these two careers, list three important skills a person would need to have to be successful.
3. Which aspects of these two careers do you think would be most interesting?

4.3 Evaluating Designs from an Overall Perspective

*info***BIT**

Holiday Lights—Safely

In 1917, a large fire in New York City was found to have been started by open candles placed on a Christmas tree. At the time, the Sadacca family had a novelty business selling imitation birds that lit up. Albert Sadacca, then 15, suggested that his family begin making electric lights for Christmas trees. The lights were not popular, however, until after Albert thought of painting the bulbs different colours.

Any structure, whether it is a backpack or a hydro-electric dam, must meet a range of human needs. "Will it do the job I want it to?" is not the only question that must be answered if you want to evaluate the "whole story" about how effective a structure is. Figure 4.8 lists several other important questions that must be answered.

Cost	Benefits	Safety	Impact on the Environment
• How much will the structure cost to build, operate, and maintain? • Can we afford to build it?	• What are the benefits of having this structure? • Who will enjoy those benefits?	• Is there a safety hazard? • Who and what could be affected by these risks?	• What steps might be taken to prevent environmental harm? • How will waste materials related to the structure be disposed of?

Figure 4.8 Any design should be evaluated from many perspectives.

A Case Study in Improving Designs

In 1978, two men in a Vancouver bike store modified a Nishiki road bike by adding wide tires, straight handlebars, and thumb shifters. This was the first "mountain bike" for the future founders of Rocky Mountain Bicycles. In 1982, the "Sherpa," their first Rocky Mountain bike, was produced.

Read about how Rocky Mountain Bicycles makes its bikes, and then answer the following questions in your notebook.

1. Give an example of a design change the company made based on what customers liked. How did the company get this information?
2. Why are triangles used in the frame of a bicycle?
3. What efforts does this company make to help create a sustainable environment? Why is this important?
4. A designer sometimes has to choose between the material with the best properties and a more economical material. Why? Give an example of how Rocky Mountain Bicycles does this. What would you predict might happen if a new, recycled plastic material, light but as strong as steel, were developed?
5. Why does this company invite trade magazines to test and evaluate its bicycles?

*math***Link**

The frame of a popular bicycle costs $139 to assemble in the factory. A proposed design change would save the manufacturer $4.50 per frame. If 2500 bicycles are built per month, how much money would the manufacturer save over 1 year by making this design change?

How Rocky Mountain Bicycles Makes Bikes

Figure 4.9 Before you make a new bicycle, you have to know what kind of bike people want. By doing market research, the company determines which bicycles are popular and which features, such as straight or curved handlebars, are favoured by customers.

Figure 4.10 At Rocky Mountain Bicycles, the most important criteria for materials are strength, weight, and cost. Some of the materials that have the best strength-to-weight ratios are expensive and limited to only high-end (meaning high cost) bikes. Aluminum, which costs less, also has excellent strength-to-weight properties and is used to make mid- to high-end frames. Steel is generally used for mid- to low-end frames because of its low cost.

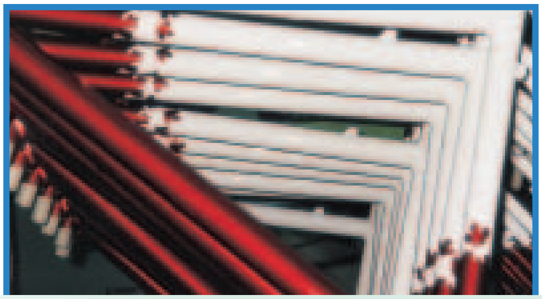


Figure 4.11 The traditional shape for a bicycle is essentially two triangles. Hollow tubes tend to be used because they provide the best strength and stiffness against forces for a given weight.

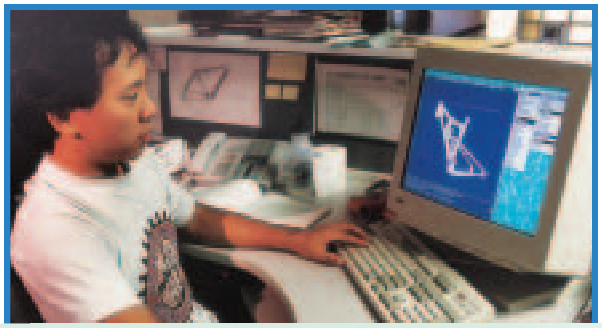


Figure 4.12 Rocky Mountain Bicycles uses computer-aided systems for all of its bike designing and manufacturing. This allows other departments in the company, such as marketing, to approve the design before an actual bike is built.

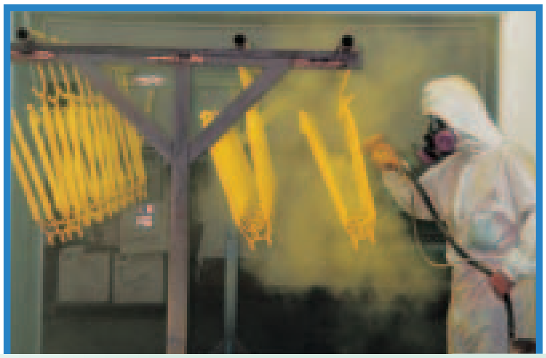


Figure 4.13 New techniques in painting use non-toxic chemicals that produce little waste. Extra material and rejected frames are cut up and recycled. Even the cardboard used for packaging is made from recycled material.

Figure 4.14 Rocky Mountain Bicycles uses a combination of trade shows, advertising in bike magazines, promotions, Web sites, and sponsorships to promote its products. It also encourages trade magazines to test and evaluate its product. However, word of mouth is the best advertisement.

Give it a **TRY** ACTIVITY

STRUCTURAL REPORT CARD

You've had a chance to learn about the technological process that goes into designing, building, and improving the product at Rocky Mountain Bicycles. You've also considered a number of criteria that are important in an overall evaluation of a structure. Now it's your turn.

Choose another structure of interest to you and evaluate the technological design and development process that has gone into creating it. Use the following criteria to guide your evaluation:

- cost of building the structure
- benefits provided by the structure
- safety of the structure
- impact of the structure on the environment

reSEARCH

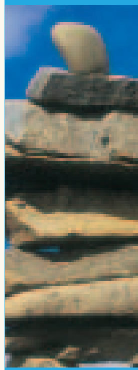
Wind Me Up

The radio shown here doesn't use batteries. Neither does it have a plug for electricity. Instead, a few turns of a crank in the back provide enough power for about 30 min of operation. Find out more about this type of radio and how it works.

Why would a structure such as this wind-up radio be popular? What human needs is it serving?

CHECK AND REFLECT

1. When a bicycle gets old and falls apart, who is responsible for disposing of the bicycle in an environmentally friendly way—the store that sells the bicycle or the buyer?
2. Make a flowchart to show the major steps in designing, making, and selling a new kind of bicycle. For each step, indicate which of the following factors should be considered and explain why: cost, benefits, safety, and impact on the environment.



Assess Your Learning

1. Do you agree or disagree with the statement "It is impossible to make everything perfectly safe"? Explain your reasoning.
2. Identify three environmental factors that can affect the strength and stability of structures in the area where you live. What structural designs help resist those environmental forces?
3. Waste is produced by many technological processes, as well as by the everyday operation of large facilities such as schools and hospitals. Study your own class's waste disposal habits as follows:
   - Make a three-column chart like the one shown in Figure 4.15.

Type of waste	Ideal way to dispose of it	What actually happens

Figure 4.15 Question 3

   - In the first column, list each type of waste item you see in your classroom.
   - In the middle column, state the ideal way to dispose of each type of waste: recycle, reuse, or dispose.
   - Investigate your school's recycling and waste-handling procedures. In the right-hand column, record what you find out actually happens to each type of waste.
   - Make suggestions about how your school could improve its methods of disposing of waste.

Focus On — Science and Technology

All technologies must be assessed to determine whether they are appropriate for the context in which they are to be used.

Reflect on what you learned in this section about designing, evaluating, and improving structures.

1. What environmental factors can affect the stability of structures?
2. How can materials be strengthened to improve safety and service?
3. Besides function, what considerations about a structure should be evaluated?
4. How could you apply what you have learned about designing safe and effective structures to planning a walking aid (walker) for elderly people who cannot walk on their own?

Preserve or Replace?

The Issue

Today, there are thousands of abandoned structures in North America, including homes, stores, and railroad stations. Some people think derelict structures are eyesores that should be torn down and replaced. Other people think older buildings are objects of beauty and heritage that should be preserved. What do you think? Read the two views below for and against preserving old buildings.

View 1: Old Buildings Should Be Preserved	View 2: Old Buildings Should Be Demolished and Replaced
Many old buildings have historical value. They are an important part of an area's heritage.	**Old buildings are unsightly.** This can reduce property values in the neighbourhood.
Many old buildings are beautiful and have architectural value. Demolishing them diminishes the character of an area.	**Old buildings that sit abandoned for a long time are a safety hazard.** They become in danger of collapsing.
Demolishing old buildings to replace them with new ones is a waste of materials and resources. It reflects the bad habits of a consumer society. Many structures can still be modified for new uses.	**Many old buildings don't meet modern building codes or the needs of modern tenants.** They fail to meet standards for electrical wiring, plumbing, and structural stability. Few meet fire code regulations.
	Renovating is often more expensive than demolishing and rebuilding from scratch. Any renovation job, no matter how carefully done, will destroy some of the building's original character.

A

B

The abandoned home shown in (A) was built in the 1890s. The same building has been carefully renovated into a two-family residence (B).

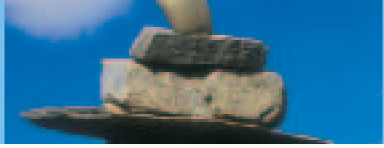
Go Further

Now it's your turn. Look into the following resources for information to help you form an opinion.

- Look on the Web: Check out the Web sites of heritage protection societies and associations.
- Ask the Experts: Talk to experts about the issue. Builders, architects, building inspectors, historians, and specialists in heritage restoration can provide you with important facts and background information.
- Check Newspapers and Magazines: Follow current stories about the issue in local, national, and international newspapers and magazines.

In Your Opinion

Think of an abandoned structure in your area. What would you do with this structure: preserve and renovate it or demolish and replace it? Summarize your opinion on the issue in a letter to the local newspaper, clearly explaining the reasons for your choice.



Unit Summary: Structures and Forces

Key Concepts / Section Summaries

1.0

Key Concepts

- structural forms
- function and design of structures

1.0 Structures are found in natural and human-made environments.

- Structural forms can be classified as solids, frames, or shells. Each offers structural stability under different forces. Examples of the three forms are found in both the natural and the human-built environment.
- For any structure to be effective, it must serve the function for which it was designed. Structures that have a common function may vary widely in design. Many structures serve multiple functions.
- Climate, culture, tradition, technology, and economics all influence the design of human-built structures and reflect the great variation that exists across time and around the world.

2.0

Key Concepts

- material strength and flexibility
- forces on and within structures
- direction of forces
- structural stability
- modes of failure
- performance requirements

2.0 External and internal forces act on structures.

- The effect of a force on a structure depends on the magnitude, direction, and location of the force. These aspects can be identified and measured.
- An external force is one that is applied to an object from the outside. Stability can be affected by changes in the distribution of mass within the structure, and by changes in the design of its foundation. A structure's ability to withstand a load depends on its overall strength and stability. Performance requirements ensure that structures are performing to certain standards.
- Three main types of internal forces at work within structures are compression, tension, and shear. The shape and properties of materials and structural components determine how well they can resist internal forces. When structures cannot withstand the forces acting on them, they undergo structural stress, fatigue, and failure.

3.0

Key Concepts

- deformation
- joints
- material strength and flexibility
- structural stability

3.0 Structural strength and stability depend on the properties of different materials and how they are joined together.

- Structural material, including both natural and synthetic types, can be classified according to a range of properties.
- The strength and flexibility of materials in a structure can be tested. One way is to measure the amount of deformation that occurs when a material is under a load.
- The appropriateness of a type of joint in a structure depends on how and where it will be used in the structure.
- Each of the many different materials found in the structure of a plant or animal plays a special role in maintaining the strength, stability, and functioning of that structure.

4.0

Key Concepts

- margin of safety
- structural stability

4.0 Structures are designed, evaluated, and improved in order to meet human needs.

- Environmental factors can affect the stability and safety of a structure.
- Materials and components can be strengthened in several ways to increase structural safety. Corrugation and lamination are two examples.
- All structural designs and processes can be evaluated on the basis of identified criteria such as costs, benefits, safety, and potential environmental impact.

PROJECT

SURVIVE!!

Getting Started

In this climate, most people have experienced what it feels like to be outside in a winter storm. The wind seems to reach everywhere and makes it hard to keep warm. As the snow builds, it becomes more difficult to move around. If you can get indoors, you know you will be fine. But what if you're not near a warm place? What kind of shelter could you use in an emergency?

In this unit, you have learned how to design structures to withstand forces of various types. You have also learned about considering human factors as you turn ideas into designs. How could you use this information to design and build a temporary shelter to protect yourself until help arrived or the storm was over?

Your Goal

Your goal is to design a shelter that can be set up quickly by two people and that will help them survive a sudden winter storm.

What You Need to Know

Your shelter is to be presented to the class as a drawing and as a model. The model will be tested for its ability to meet the criteria below:

- The shelter must be portable, both when it is set up and when it is packed.
- You must be able to carry the shelter yourself or in a vehicle such as a car.
  - If the shelter is to be carried by a person, it must be small enough to fit inside a backpack (or be tied to the outside of a backpack). It must have a mass of less than 4.5 kg.
  - If the shelter is to be carried in a vehicle, it must be shorter than 0.5 m in any direction. Mass can vary.
- The shelter must be easy for two people to set up quickly in a wind.
- The shelter must be safe to use and must protect two people against wind chill and snow for at least two hours.
- You must dispose of waste materials from its construction properly.

Steps to Success

1 Work with your group to design a plan for solving this technological challenge. For example, think about how you will choose a design and materials, whether you need to build a prototype, how you will test your shelter, and how you will make modifications. (See Toolbox 3 if you need help with this.)

2 When you have a plan, show it to your teacher for approval. Make sure you have a diagram illustrating what your shelter will look like.

3 Proceed with the plan.

> **Caution!**
> - Use equipment with care.
> - Do not test your shelter unless your teacher is present.

4 Make changes to the plan as necessary. Document reasons for your change.

5 Be prepared to demonstrate your model to the class.

How Did It Go?

6 In a short report, answer the following questions:
- Describe how well your shelter met the criteria of the project. How do you know?
- What part of this challenge did you find most difficult? Why? How did you overcome or deal with this problem?
- What part of this challenge did you find most successful? Why?
- Compare your final product with your original idea. Explain any changes you made.
- Describe the skills you needed to learn in order to design and build your shelter. How did you identify those skills? Where did you go to learn them?
- How would you change your shelter so that a person could safely use a candle inside for warmth and light?

UNIT REVIEW: STRUCTURES AND FORCES

Unit Vocabulary

1. Create a concept map of the following terms. Remember to use a couple of words or a short sentence between the terms to show how you connected these terms.

    centre of gravity
    complementary forces
    dynamic and static load
    solid, frame, and shell structures
    structural stability
    structural strength
    structural fatigue
    structure
    materials

Check Your Knowledge

1.0

2. Define the term *structure*.
3. What is the difference between solid, frame, and shell structures?
4. Give an example of a combination structure in the human-built environment and in the natural environment. For each, say what structural forms are combined.
5. Why do structures that serve the same function often have such different designs?

2.0

6. Explain how the direction in which a force is applied can determine the effect that force has.
7. Give an example of a dynamic and a static load. How are these two examples the same and how are they different?
8. What four different types of bridges can be used to support a load? Use a labelled diagram to illustrate the similarities and differences between them.
9. Describe, using a diagram, three different types of internal forces.
10. Name six common structural components (or combination of components) and sketch them in your notebook.
11. What is the difference between structural stress and structural failure?

3.0

12. True or false? A material that is very rigid is always better in a structure than a material that is very flexible. Explain.
13. How can the deformation of a material under a load be measured?
14. What role does friction play in some methods of joining?
15. How would you evaluate whether a particular joint should be made using nails or glue?

4.0

16. How might heavy snow affect the strength and stability of a structure? Use the terms *force* and *structural fatigue* in your answer.
17. What is corrugation and how is it used in structures?
18. What criteria other than strength and stability might you use to evaluate a structure?

Connect Your Understanding

19. An archaeologist finds the remains of three types of structures in an area, all built during the same period of time by the same ancient people. The shell-like structures were made of light materials such as animal hide. The frame-like structures seem to have been permanent, but evidence indicates they were only used in warm weather. The solid structures were formed from piles of stone. Inside each pile were dried grains and other foods. What would you infer was the most likely function of each type of structure for these people? How did the designs of these structures suit their function?
20. A container is needed to hold 50 CDs. It should provide easy access to all discs and be able to withstand being dropped. What shape would you use? Why?
21. If you were to design a picnic table, would you pay more attention to the function or the aesthetics? Explain.
22. Look at the truck below and answer the following questions.
    a) What external forces are acting on the structure of the truck?
    b) Which types of internal forces are acting on the truck?

Question 22

23. From your knowledge and experiences in this unit, what do you think is the best type of structure to hold up a large mass? What evidence can you provide to support your opinion?
24. In what way does your body respond to a compressive force being applied to it? For example, what happens when you jump down from a bench?
25. A broken beam in a frame structure was found to crack along the lower surface first. How could you redesign the beam to account for this problem?
26. Do all methods of joining or fastening need to be strong? Think of two cases where the strongest means of fastening would not be a suitable choice.

27. a) You've been asked to design a hand-pulled wagon for a child. How would you decide what materials and methods of joining to use?

b) What changes to your selections in (a) would you make if you had to design a second wagon for an adult? Why?

28. Suggest improvements to the following structures that might make them useful to more people. Try to make the least change possible.

a) A narrow revolving gate is used to control the number of people entering the fairground at once. It works well for an average-sized person who is not carrying any objects.

b) Two of the three shelves in a set of kitchen cupboards are too high for any member of the family to reach without climbing on a stool.

Practise Your Skills

29. You have been asked to judge a competition in which students were challenged to design the strongest and most stable structure possible using Popsicle sticks and tape. In your role as judge, you will be discussing each structure with the students who designed it. To help you remember and explain the many factors involved in the design of structures, make yourself a concept map using the terms listed below:

- arch
- beam
- centre of gravity
- external forces
- internal forces
- load
- mass
- shape
- structural component
- weight

30. You have been asked to design a short footbridge across a muddy section of the schoolyard. Develop the plans needed to build this structure. You should have a diagram of the structure, a list of materials, and a brief description of how to assemble the bridge.

31. What structural shapes and materials would you use to build an observation tower in a bird sanctuary?

32. You have the choice of building a bicycle storage shed with either concrete blocks or wood. Create a chart that demonstrates the benefits and costs of using each type of material. Once you have completed your chart, select a material and describe why you chose it using the information you collected.

Self Assessment

33. Think about the three questions first posed in the introduction to this unit:

A How do structures stand up under a load?

B What forces act on structures?

C What materials and design characteristics contribute to a structure's strength and stability?

Go back through your notes and write A, B, or C beside main ideas to show how each aspect of your learning in this unit can help you answer those questions.

34. Think back on everything you did during this unit. Use your thoughts to answer the following questions:

- The most surprising part of this unit for me was:
- During my study of structures, the toughest part I found was:
- I solved this by:
- I would like to learn more about:
- My advice to someone starting this unit would be:
- What I liked most about structures was:

35. What types of careers could you pursue that are related to structures? Which one seems the most interesting to you? Why is this?

Focus On SCIENCE AND TECHNOLOGY

In this unit, you have investigated science and technology related to structures and forces. Consider the following questions.

36. Reread the three questions on page 263 about the nature of structures and forces. Use a creative way to demonstrate your answer to one of the questions.

37. What aspects about structures and forces did you investigate that demonstrated how technology could be used to develop solutions to practical structural problems?

38. Describe the process involved in designing a structure to perform a specific task. Was this a straightforward, step-by-step process, or did it require modifications as you developed and evaluated the design?

39. Describe the situation where an understanding of the local conditions was important for a technology to be used appropriately.