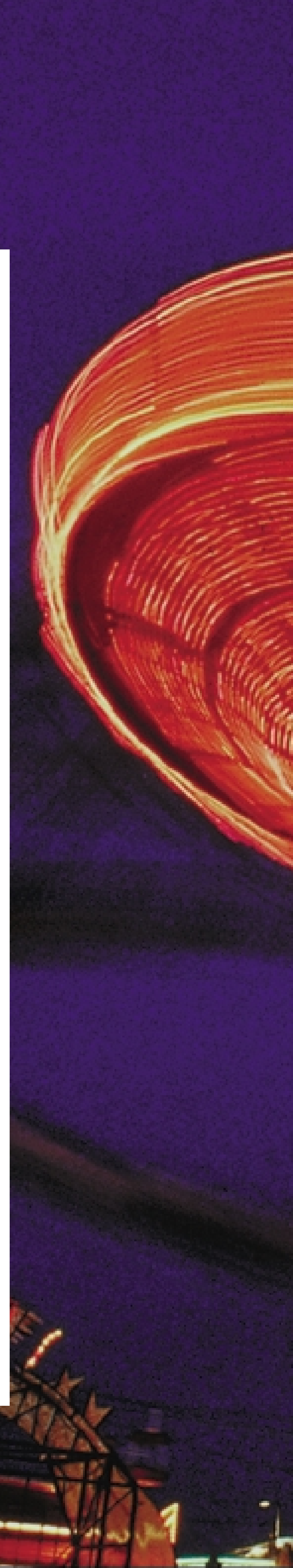
UNIT 4

Structures and Forces



Have you ever been on an amusement park ride that is similar to one shown in this photograph? Did you find yourself wondering about the safety of its various parts — the cables, the towers, or the concrete on which the structure rested?

All of us trust our lives to structures every day. Some structures, such as dams and skyscrapers, contain such enormous amounts of materials that their weight distorts the ground beneath them. Other structures, such as amusement park rides and gymnastics apparatus, have carefully arranged parts that hold them up and support whatever they must carry. All structures, no matter how they are built, must keep their shape and do a particular job.

Small or large, structures are designed using similar principles. Professional architects and designers understand the scientific principles behind the reasons and the ways structures fail. This knowledge allows them to solve design problems so that structures meet specific needs. Some structures need to withstand extreme weather conditions. Some must be beautiful to look at. Others need to be as light and strong as possible. Still others need to be as inexpensive as the manufacturer can make them, while still being strong, beautiful, or light enough to do the structure's other jobs.

By learning the principles that designers use, you can do a better job of designing and building your own projects. As well, you will have a better understanding of how a ski lift or an amusement park ride can be safe, and why you can depend on the apparatus in gym class!

Unit Contents

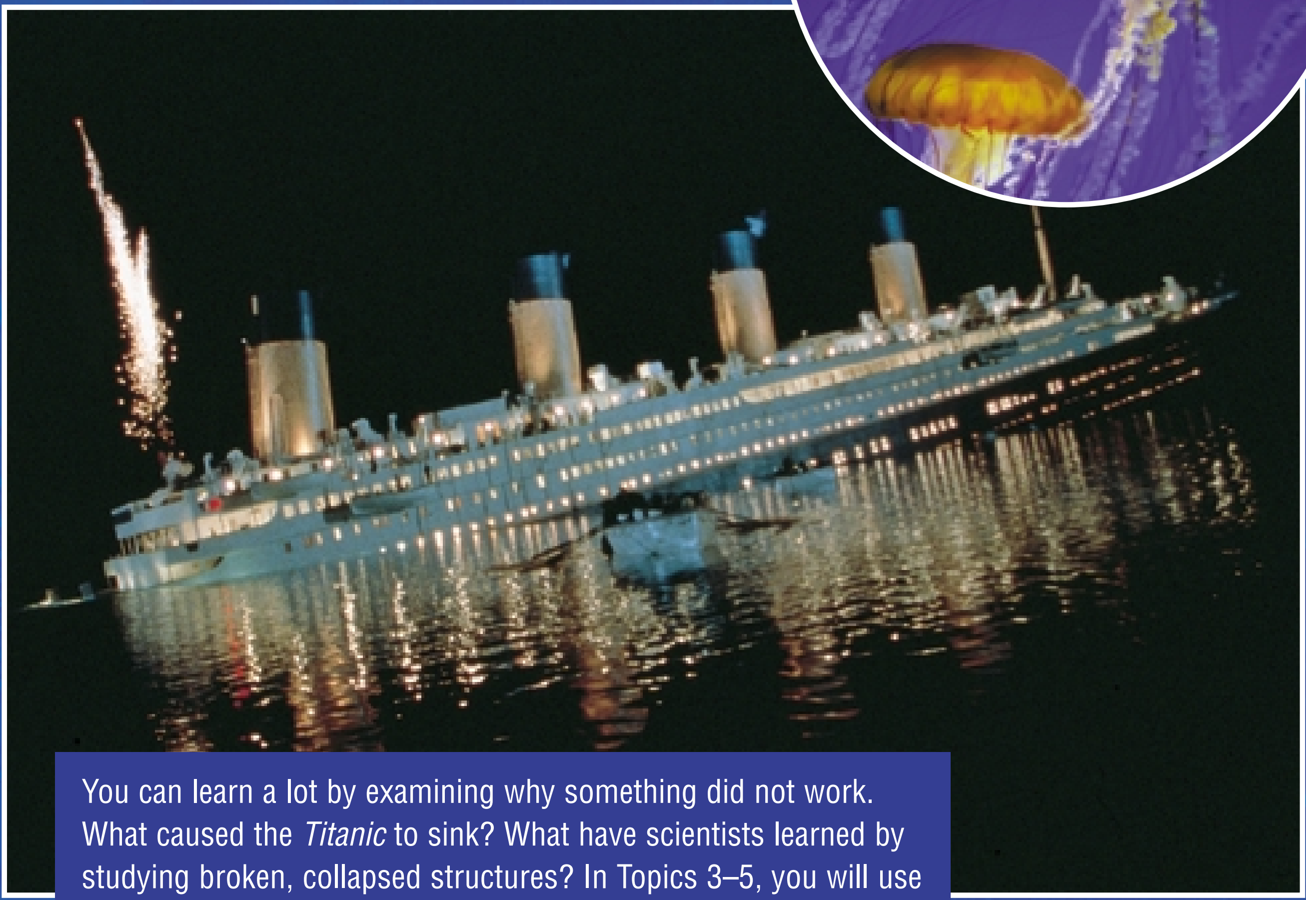
UNIT 4

Preview

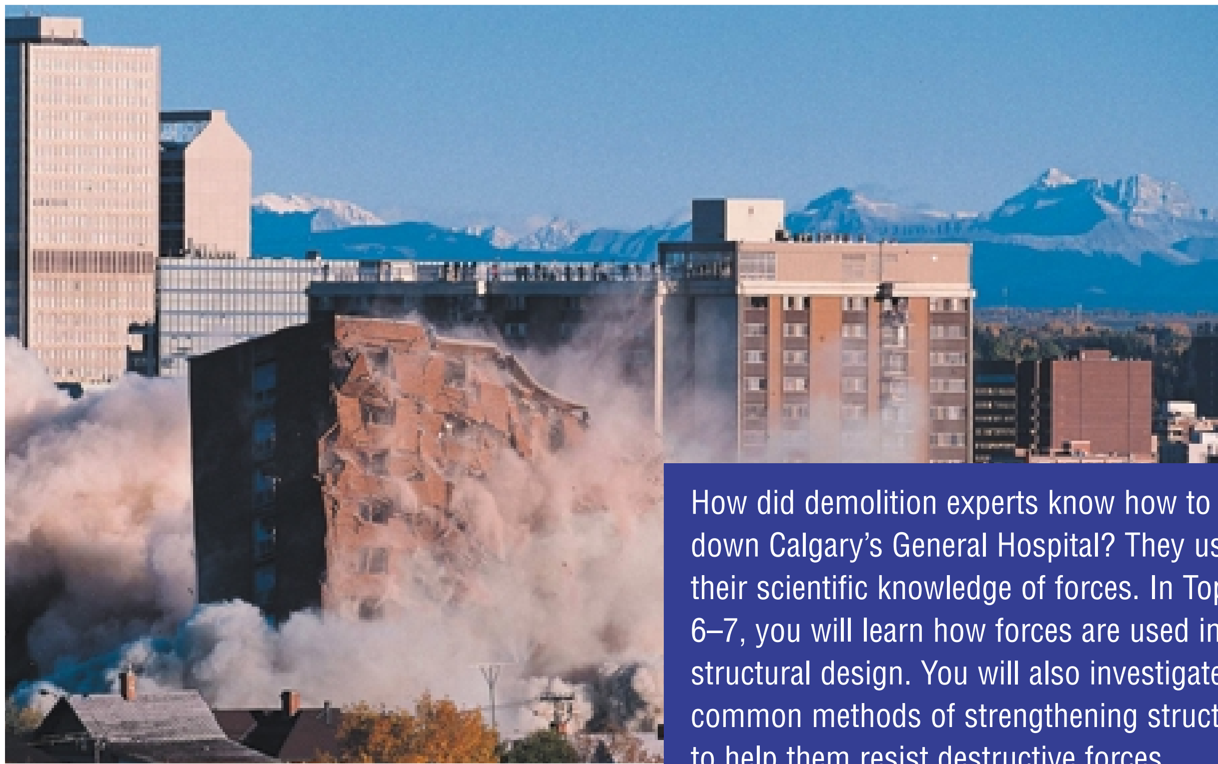
Focussing Questions

- What features do structures have?
- What makes structures fail?
- What design choices make strong and stable structures?

This jellyfish and the amusment park ride on the previous page are very different. As structures, they may have similar properties. In Topics 1–2, you will learn how to classify and describe structures to understand their function and properties.



You can learn a lot by examining why something did not work. What caused the *Titanic* to sink? What have scientists learned by studying broken, collapsed structures? In Topics 3–5, you will use what you know about forces to find out what causes structures to fail—and why some stuctures are designed to do just that!



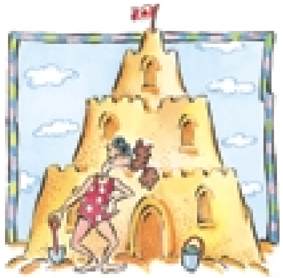
How did demolition experts know how to tear down Calgary's General Hospital? They used their scientific knowledge of forces. In Topics 6–7, you will learn how forces are used in structural design. You will also investigate common methods of strengthening structures to help them resist destructive forces.

Looking Ahead

Read pages 344–345 about your unit project, the Reverse Bungee Drop of Doom. This is your chance to apply your scientific understanding of what makes structures strong. Keep in mind the questions below as you work through the unit.

- How will you make your structure strong and lightweight?
- How can you make sure your ride is stable and safe without anchoring it permanently?
- Besides materials, what other design choices will ensure a strong, stable ride?
- What useful information can you add to your project file?

TOPIC 1 Types of Structures



Have you ever made a sand castle or an ice sculpture? What about building an igloo or assembling a tent? Have you peered through a telescope at another planet, or examined a snowflake under a microscope? All these objects are examples of **structures**: things with a definite size and shape, which serve a definite purpose or **function**. To perform its function, every part of the structure must resist **forces** (stresses such as pushes or pulls) that could change its shape or size. For example, a brick wall must be able to stand up to the force of the wind. The bricks at the bottom must support the weight of the bricks above. If a person climbs on top of the wall, the bricks must support that **load** (the weight carried or supported by a structure) as well.

Many different structures are pictured on these two pages. Look around your classroom for a moment. Pick out other things you think could be called structures. In what ways are they similar to each other? What can you think of that should not be called a structure? Why not? Write answers to these questions before reading further.

Pause & Reflect

You will learn a lot about functions, forces, and loads in this unit. What do these words mean to you now? In your Science Log, write a brief definition of each word, using your own words. Then write a sentence that uses each word correctly.

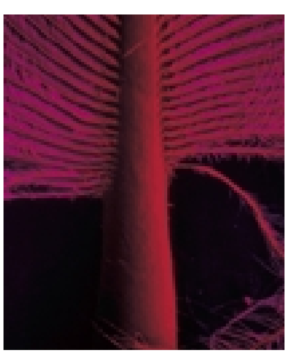
There are so many different structures that it is difficult to form a definition that fits them all. Instead, we will concentrate on describing a structure's origin, its function, its form, its design, the materials and parts it is made of, and the ways it is held together. Before reading further, get together with a partner to develop your own classification system for the structures pictured on pages 270–271.

Classifying Structures

It would be inefficient to learn about structures by studying them one at a time. There are far too many! It is much more efficient to group, or classify, structures by picking out those that share common features.

One common classification divides structures into groups according to their origin. In this system, structures are divided into natural and manufactured objects.

Natural Structures



Natural structures are not made by people. Examine the photo of a bird's feather, for example. It has a definite shape, and it is made of many parts held together in a complex pattern. Feathers serve many purposes: they insulate birds in cold weather, protect them from rain, and allow them to fly. Feathers, like many familiar things in the natural world, are structures.

Non-living parts of the natural world may also have some structural characteristics. Think of sand dunes, for example. They have a characteristic shape and are made of many parts (sand grains) arranged in a particular pattern. They provide a home for small animals and insects and play a role in a desert ecosystem. What other natural, non-living structures can you think of?

Manufactured Structures

Many things built by people are **manufactured structures**. The largest buildings, the tiniest beads, a complicated jigsaw puzzle, and a simple spoon are all manufactured structures. Many manufactured structures are modelled after natural structures. A fishing net, for example, has a design similar to that of a spider web. Suggest natural structures that resemble a parachute, an umbrella, and a Velcro™ fastener.

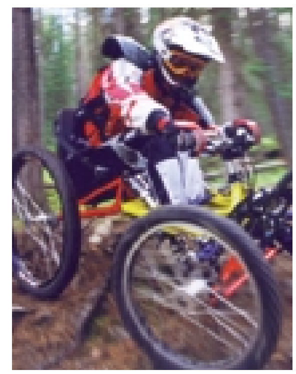


Figure 4.1 Canadian wheelchair athlete Stacy Kohut competes in mountain bike competitions with his four-wheel bike.

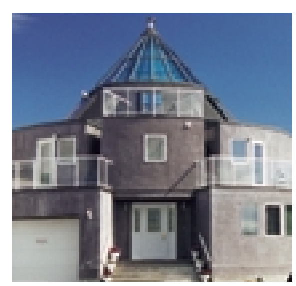


Figure 4.2 Kayhan Nadji, the designer of this tipi house in Yellowknife, combined elements of the traditional Inuit Igloo and Dene tipi with modern technology such as central heating and electric lights.

You can also classify structures by the way they are built. How a structure is put together, how it is shaped, and the materials making up the structure are all part of its **design**. You will study three kinds of designs: mass, frame, and shell structures.

Mass Structures

To build a sand castle, you start by making a big pile of sand. A sand castle is a mass structure, as is a brick. A **mass structure** can be made by piling up or forming similar materials into a particular shape or design. Mountains and coral reefs are natural mass structures. Snow sculptures, dams, and brick walls are manufactured mass structures. So are foods such as omelettes, cakes, and breads.

Figure 4.3 This dam, a mass structure, was built by beavers making a large pile of wood and mud.

Making something from a lot of building materials has advantages. The structure is held firmly in place by its own weight. If small parts are worn away or broken, this usually makes very little difference. Mass structures like Hadrian's Wall in England have been eroding for thousands of years without being destroyed.

A Layered Look

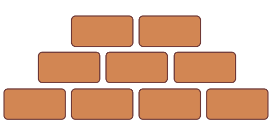


Figure 4.4 The pattern in these bricks is called a "running bond." It is used for strength.

All around you there are mass structures made of carefully arranged pieces. Have you ever noticed the pattern of bricks in a brick wall? The centre of each brick is usually placed over the ends of two bricks in the row below, as Figure 4.4 shows. Bricks and concrete blocks are often arranged in other ways, however. Look at several outside and inside walls made of bricks or blocks and compare the patterns used. Look around doors and windows to see if the arrangement is different there.

DidYouKnow?

What is the largest amount of material ever used in a dam? The dam that was built to create the tailings pond at the Syncrude Oil Sands project in northern Alberta contains over 540 million m^3 of material! Some of the world's largest heavy equipment was used to build the dam.

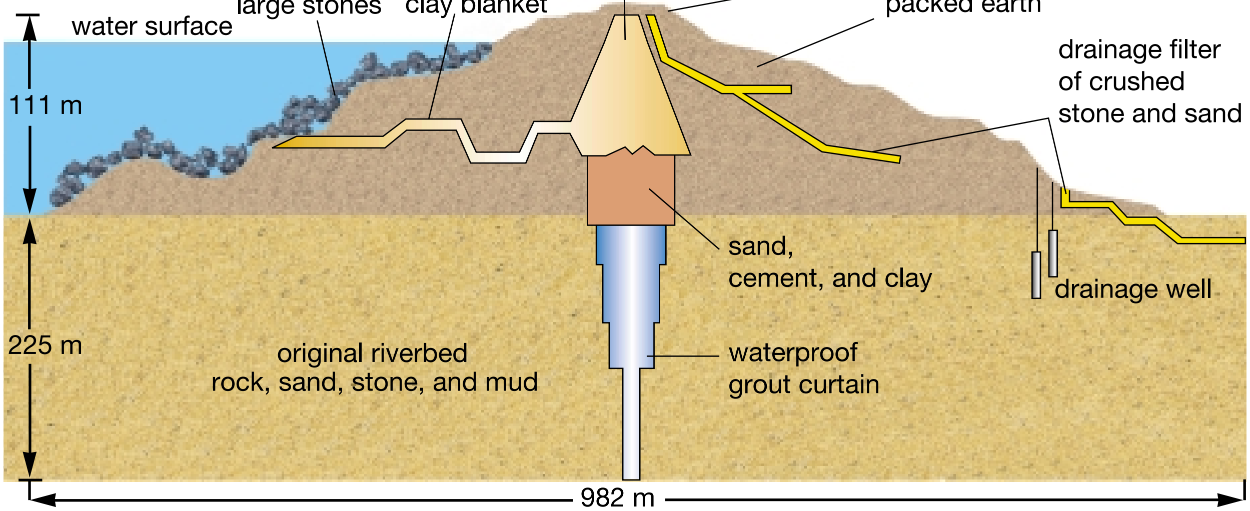


Figure 4.5 A dam is an example of a mass structure.

Take a look at the dam in Figure 4.5. Try to guess the purpose of each type of material.

Mass structures are not always solid. Inside many power dams are enormous rooms that hold electric generators. Bricks and concrete building blocks are often hollowed out so that wires and pipes can pass through them.

Because of their large size and weight, mass structures must be carefully designed. Think of a wall of sandbags holding back a flooding river. There will be big problems if the wall fails! There are four main ways that a sandbag wall structure can fail.

- The wall may not be heavy enough to stay in place. The whole structure is pushed out of place by the force of the water against it.
- The wall may be so heavy that the earth beneath it is pressed down unevenly. The structure becomes unstable and tips over or falls apart.
- The wall may not be thick enough or fastened tightly together, so parts of it are pushed out of place. Then the structure breaks apart.
- The structure may not be anchored firmly to the ground. If very large forces press against the top, the structure may tip over.

Off the Wall

The Great Pyramid in Egypt contains passages and rooms that once held everything that ancient Egyptians believed the dead Pharaoh would need as he journeyed to the spirit world.

Did You Know?

Flying passenger aircraft across the oceans seemed almost impossible in the 1930s. The trip required too much fuel. Canadian inventor Frederick Creed designed and built models of huge floating islands where planes could land and refuel in the middle of the ocean. During the Second World War, another inventor, Geoffrey Pyke, suggested building these artificial islands, or even aircraft-carrying ships, out of ice! A trial project in Alberta found that a frozen mixture of water and wood pulp was strong enough to build a refuelling island or a ship. Building with the new material was as expensive as using steel, however, so the project was dropped.

Frame Structures

Human dwellings and office buildings are not usually mass structures made by hollowing out piles of building materials. **Frame structures**, like the body of most buildings, have a skeleton of very strong materials, which supports the weight of the roof and covering materials. Most of the inside of the building is empty space. Extra partition walls can be built to separate different rooms, but they do not need to be particularly strong because the load-bearing framework supports the structure and everything in it. Can you identify load-bearing walls and partition walls in Figure 4.6?

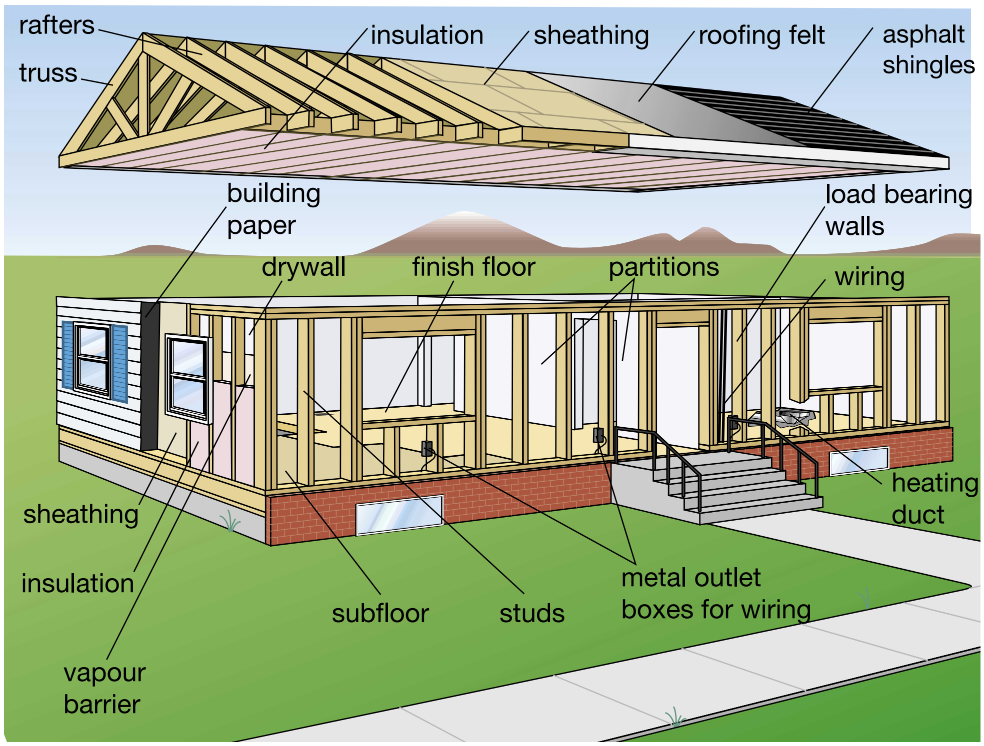


Figure 4.6 Load-bearing walls hold up a frame structure, while partition walls simply divide rooms.

Career CONNECT

Many different people work together to construct a building. Getting the foundation in the photograph built to this stage required the work of an architect, a contractor, a surveyor, an excavation team, and foundation builders. What was the responsibility of each member of the team? Which members of the team were responsible for the house's stability? Brainstorm the types of workers who would be involved in the next stages of construction for the house. Choose one, and find out about the kind of work this worker does.

Some objects, such as ladders, snowshoes, and spider webs, consist of only a frame. More complex objects may have other parts added to the frame, such as the pedals, gears, and brakes of a bicycle. The frame may be hidden beneath covering materials (as in umbrellas, automobiles, and boats) or left exposed (as in drilling rigs and steel bridges). Frame structures are relatively easy to design and build, making them one of the least expensive construction choices. Whether simple or complex, hidden or exposed, all frames must overcome similar problems.

Do you remember building frame structures in other science classes? How did you fasten the parts together? How did you make your frames strong without using too much material? How did you shape or brace them so that they would not bend or collapse?

Certain kinds of frame structures present special design challenges. Tents and other lightweight structures need some type of anchor to fasten them securely to the ground. Very tall frame structures, such as communications towers, can easily become unstable unless they are carefully braced. Large, complicated projects, such as buildings and bridges, have many parts that all have to fit together perfectly when they are finally assembled at the building site. This can happen only if every detail of the design is calculated in advance.

Find Out ACTIVITY

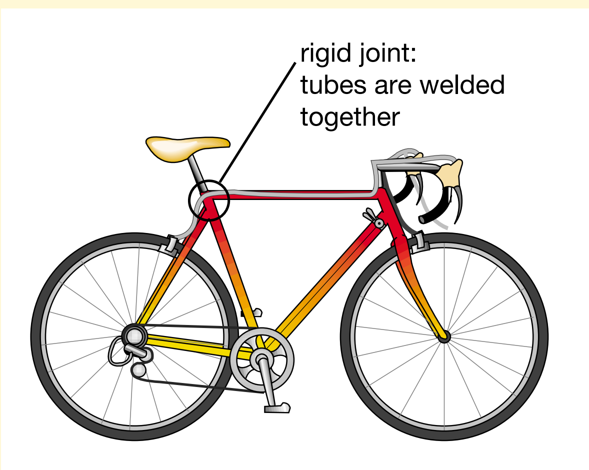
Picture a Frame

Procedure Analyzing and Interpreting

1. The diagrams show a manufactured and a natural example of frame structures. Sketch the two structures, or study the sketches that your teacher gives you.

2. Find at least one place or part on each structure that illustrates
   - **(a)** rigid joint: fastens parts of the frame together so that they cannot move
   - **(b)** mobile joint: holds parts of the frame together but allows them to move or turn
   - **(c)** brace: strengthens a joint or another part that must support a heavy load
   - **(d)** rigid shape: will not collapse or change shape even when large forces push or pull on it
   - **(e)** thin, lightweight material: does not have to be an especially strong part or place
   - **(f)** part that uses extra material for strength

3. Describe the primary purpose or function of each frame and the primary materials from which it is made. Explain why each material is well suited for the function it is intended to carry out.



PROBLEM-SOLVING

INVESTIGATION 4-A

SKILLCHECK

- Initiating and Planning
- Performing and Recording
- Analyzing and Interpreting
- Communication and Teamwork

Golf Ball Bridge

Designers face many challenges when planning a new project. One of the first is that their design must fulfil specific criteria or specifications for the job. For example, the specifications for a bridge might be that it needs to be 20 m long. If the final bridge is only 19 m long, it would be useless. In this activity, you will test your ability to solve a design challenge based on a set of specifications. You will use your skills in solving problems, evaluating and testing prototypes, and applying results to practical problems.

Skill FOCUS

For planning steps to solve problems, see Skill Focus 7.

Challenge

Build a free-standing frame bridge that supports a track capable of supporting a rolling golf ball.

Safety Precautions

Handle sharp objects with care.

Materials

15 to 20 large, thick plastic straws
15 small paper clips
60 cm masking tape
1 golf ball
scissors

Design Specifications

A. The bridge must span an opening between two desks or tables that are 30 cm apart.

B. The bridge must be free standing. It may not be attached to the desks or to anything else.

C. The bridge must support a track at least 5 cm above the surface of the desks.

D. The track must support a golf ball as it rolls from one end of the bridge to the other.

E. One end of the bridge must be higher than the other end so the golf ball will easily roll across the bridge.

F. You may use only the materials provided by or approved by your teacher.

G. You must construct the bridge in 40 min or less.

H. In at least three of five trials, the golf ball must successfully roll from one end of the bridge to the other without falling off.

I. The golf ball must roll on its own without being pushed.

J. The bridge must not fall over during testing.

Plan and Construct

1. With your group, brainstorm ideas for the design of your bridge. Each group member should contribute at least one alternative design. All designs must meet the specifications stated.

2. Based on your group's ideas, choose a plan for the bridge that you intend to build. Each group member should draw and submit a labelled diagram of the bridge to your teacher.

3. When your teacher has approved your group's design, begin to construct the bridge.

4. If, at any time during the construction process, your group agrees that the bridge will not function properly, make adjustments in the design.

5. When you have finished constructing your bridge, set it up at the designated test site. Carry out five trials.

Evaluate

1. Did your bridge pass the golf ball test? If not, explain what happened.

2. Did your bridge meet all of the structural specifications? If not, explain why it did not meet the specifications.

3. Which design specifications did you find the most difficult to meet? Explain why.

4. Describe at least three changes you would make if given the chance to re-construct the bridge. Explain the reason for each change.

Extend Your Knowledge

5. If your bridge was actually being built across a deep river gorge and the track had to support a heavy freight train rather than a golf ball, what additional things would you have to consider? List as many considerations as you can think of. For each consideration, explain why it would be important to the design and construction process.

DidYouKnow?

Alexander Graham Bell, the inventor of the telephone, was also very interested in flying machines. Bell experimented with many different kinds of kite frames, trying to find one that would be strong enough and light enough to lift a person and a gasoline-powered motor. The most promising kites used bamboo or aluminum frames made of many tetrahedral (pyramid-shaped) sections or cells covered in silk. In 1905, at his summer home in Baddeck, Nova Scotia, Bell demonstrated a 1300-cell kite named *Frostking*, which could lift a person into the air in only a light breeze!

Bell was certain that a practical flying machine could be built from his kite designs, but he could not do it alone. He and his wife Mabel Hubbard gathered a small troop of skilled helpers who called themselves the Aerial Experiment Association, shown here. They were one of the first modern research groups.

Figure 4.7 The dome of the Taj Mahal in Agra, India, is one of the most famous shell structures in the world.

Shell Structures

Think igloo. Think egg. Think cardboard box. All of these objects are strong and hollow. They keep their shape and support loads even without a frame or solid mass of material inside. Egg cartons, food cans and bottles, pipes, and clay pots are other examples of **shell structures**: objects that use a thin, carefully shaped outer layer of material to provide their strength and rigidity. Flexible structures, such as parachutes, balloons, and many kinds of clothing, are a different type of shell. Even the bubbles in foams and cream puffs can be thought of as shell structures.

Shell structures have two very useful features. They are completely empty, so they make great containers. Because they have only a thin outside layer, they use very little building material.

You might think that the material in a shell structure would have to be extremely strong, but this is not always the case. The shape of a shell spreads forces through the whole structure. Each part of the structure supports only a small part of the load, and the complete structure can be amazingly strong.

Off the Wall

Canoes are shell structures that are built from birch bark, aluminum, or fibreglass. Did you know they can also be built from concrete? Some engineers believe that concrete shells could be used to build the floating ocean platforms used for offshore oil drilling. They believe that concrete shells would perform better than the steel construction now used.

INTERNET CONNECT

www.mcgrawhill.ca/links/sciencefocus7

Find out more about concrete canoes by going to the web site above. Click on **Web Links** to find out where to go next. Write a short newspaper report telling who builds concrete canoes and why they do it.

Constructing strong shell structures can be tricky. Builders face problems like these:

- Tiny weaknesses like scratches on a glass jar can cause the whole structure to fail. Bubbles pop, balloons burst, and glass seems to explode when forces are not resisted equally by all parts of the shell.
- If a shell is formed from hot or moist materials, such as melted plastic or clay, uneven cooling or drying can cause some areas to push and pull on nearby sections. Strong forces build up inside the shell, as in Figure 4.9. If any extra force, even a small one, acts on the shell, the stressed places may break unexpectedly.
- Flat materials, such as sheets of plywood, are not easily turned into the rounded shape of a shell structure. Imagine building a plywood igloo! Each piece would need to be shaped and fitted into place individually, so construction would be slow and difficult. If you were paying a builder, the cost would be higher than for a frame structure.
- Assembling flexible materials into a shell is also tricky. Garment pieces need to be pinned into position before sewing. Afterward, the fabric edges must be specially finished so that the cloth will not pull apart along the seams.

Figure 4.8 A turtle's shell is a shell structure. It is made from a very strong, natural material called keratin. Your fingernails are made from the same substance.

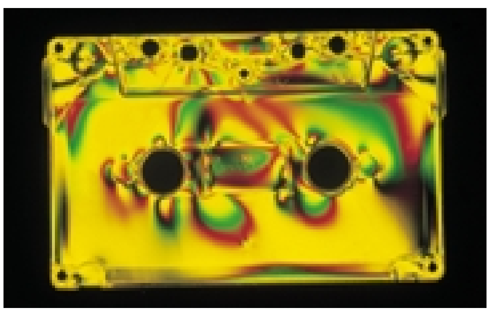


Figure 4.9 When polarized light (light waves of only one direction) passes through transparent materials, such as this cassette tape, the stressed areas appear as coloured fringes.

Across Canada

Dr. Marie-Anne Erki

As a child, Marie-Anne Erki often took apart her toys. Now she is a professor of civil engineering at the Royal Military College of Canada in Kingston, Ontario. These days, she is more concerned with putting structures together than taking them apart!

Dr. Erki works with high-strength fibres embedded in a polymer (plastic). They are called Fibre Reinforced Polymers (FRP). FRPs are as strong as steel but much lighter. "My field is making existing structures like bridges and buildings stronger using carbon tape. It's just like taping up a hockey stick," she says. In Canada and other cold-weather countries, road salt eats away at the steel bars that reinforce concrete bridges. FRP tape can patch and wrap these weak, rusted bridge columns and beams in order to strengthen them. Also, new concrete bridges can be reinforced with FRP bars instead of steel reinforcements so they will never rust.

In her work for the Canadian Forces, she is developing materials to make lightweight bridges that can be transported by airplane. This technology will be helpful when there is a natural disaster, such as a hurricane or a flood. It will enable washed-out bridges to be quickly and inexpensively replaced so that people are not cut off from food or medical aid. When she is not developing improved materials for construction, Dr. Erki helps university students with their research projects.

Mix and Match

Figure 4.10 What makes this building's shape unusual?

Football helmets are shell structures, but the opening in front is covered with a strong frame. The combination of frame and shell construction protects the player while also allowing good visibility and ventilation. The helmet's designers combined different designs to improve the structure. Many structures, such as those below, combine designs.

- Hydro-electric dams are mass structures, but inside they contain enormous rooms filled with electric generators. The walls and ceilings of the generator rooms are built with very strong frames. Otherwise, they would collapse from the enormous pressure of the rock, earth, or concrete that forms the dam.
- Airplanes are built around a metal framework, but the frame is not nearly strong enough to support the weight of the engines, fuel, and cargo. The metal "skin" that covers the framework is stretched tightly and acts like a shell. Stresses are spread through the whole frame, and the finished aircraft is strong, lightweight, and flexible.

Figure 4.11 A flimsy framework of balsa wood, covered with painted tissue paper or plastic film, makes a model aircraft strong enough to take off, do complicated stunts, and land safely.

- Domed buildings usually combine frame and shell construction. The dome forms a shell, which gains strength from its curved shape. The dome itself is often a thin layer of cloth, metal, wood, or concrete stretched over a wood or metal frame. Sometimes only the roof of a domed structure is a shell, placed on top of framed walls.
- Warehouses and other large, single-storey buildings are often built with steel columns that support the roof. The columns form a framework, but there are big spaces between them. The spaces are filled with walls of concrete blocks, which stay in place because of their weight. The walls are mass structures, but they are too tall and thin to be strong by themselves. When the walls are fastened to the steel framework, however, the combination forms a strong, easily constructed structure.

TOPIC 1 Review

1. What type of structure (mass, frame, or shell) is each object listed below?

(a) a backpacking tent

(b) a pop can

(c) a concrete barrier in a parking lot

(d) the "jewel box" in which a CD is packed

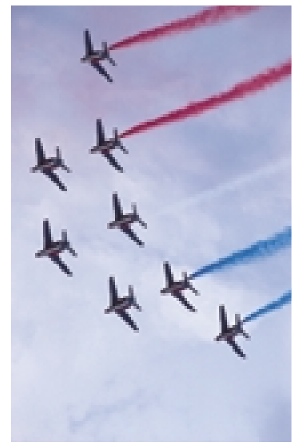
2. Name the type of structure that is most likely to fail because

(a) the material it was built from has small cracks or weaknesses

(b) the weight of the structure caused the ground underneath it to shift

(c) the outside walls were tilted slightly by an earthquake

3. **Apply** Model airplane wings are sometimes built by shaping solid pieces of foam plastic with a hot wire. They can also be made from many pieces of lightweight balsa wood glued together and covered with paper, plastic, or cloth. Full-sized, modern aircraft wings have a metal frame, but the frame is quite weak until a metal covering is stretched over it. Then the wings become strong enough to support the weight of the plane, as well as the weight of its fuel, which is carried in tanks inside the wings.



(a) Name the structure type, or combination of types, represented by

- a foam plastic wing
- a balsa wood wing
- a real airplane wing

(b) Explain which of the two types of model airplanes would be easier to build.

4. **Design Your Own** Choose a small frame structure to test, perhaps one that you have already designed and built. Design an experimental procedure to determine the point at which the structure will fail. For example, how many golf balls can your straw bridge (from Problem-Solving Investigation 4-A) hold at one time? If you find the point at which your bridge will break, you will find what engineers call the *ultimate strength* of the structure. Predict the ultimate strength of your structure. If your teacher agrees that your chosen frame structure is safe to test, carry out your procedure.

STRETCH Your Mind

Designers need to be able to visualize how the parts of a project can be arranged to create the final structure. Imagine that you are designing a small orchard. The owner wants the trees to be arranged in certain patterns.

1. How can ten trees be arranged in five rows, with four trees in each row?
2. If nine trees are arranged in rows of three, what is the largest possible number of rows you can make?

Describing Structures

Imagine discussing the bridge in Figure 4.12 with the engineer who designed it.

You: Wow! That's a fantastic piece of engineering!

Designer: Thank you. When I designed it almost a century ago, trains were much smaller than nowadays. I had no idea how enormous they would become, but my design had a good safety margin. It's still strong enough.

You: It must have cost a lot to build.

Designer: Yes, it was expensive for the time. The company tried to find other places to cross the river valley where it isn't so wide and deep. But when they added up all the costs, this was the still the cheapest. I used a very efficient design. There's no wasted material. Every piece of steel helps carry the load.

You: It doesn't look a century old. In fact, it looks really good.

Designer: Well, the railway company paints the structure frequently. It wouldn't last long without regular maintenance.

You: I was thinking more about the shape. It just looks strong and stable.

Designer: That's probably because of the symmetrical way the towers are designed and arranged. Most people find that very attractive. Did you notice that every tower is divided into triangular sections that make it strong and rigid?

You: That's right. You thought of everything!

Designer: Well, I tried to, but something unexpected always happens on a large project. I had to modify my design when the ground under one of the towers became unstable.

You can work like an architect or engineer. If you plan a project carefully, your final design will be improved. In this Topic you will learn about some things a designer must consider when planning a new project: function, aesthetics, safety, materials, and joints.

Looking Ahead

After reading the conversation on this page, make a list of questions and challenges the designer considered when building this bridge. Think about these challenges in terms of your upcoming unit project that will ask you to build a reverse bungee ride prototype. How many challenges will be similar?

Figure 4.12 This trestle bridge in Lethbridge, Alberta, was the longest structure of its height in the world when it was built in 1909. It carries trains 97 m above the valley of the Oldman River, for a distance of 1.6 km.

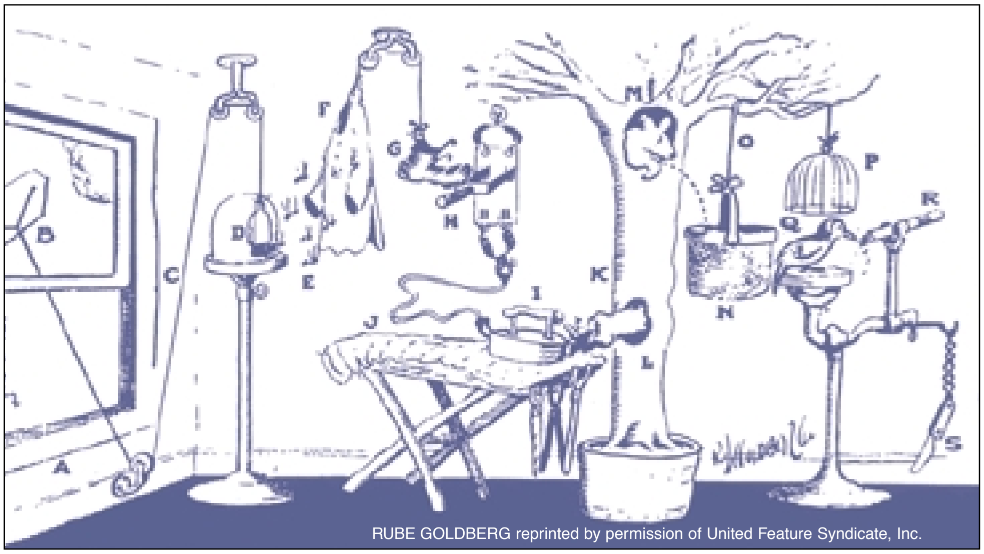


Figure 4.13 Fantastic devices like this were made famous by a cartoonist named Rube Goldberg.

Word CONNECT

Here are a few words that describe common functions of structures:

- containing
- transporting
- sheltering
- supporting
- lifting
- fastening
- separating
- communicating
- breaking
- holding

Examine Figure 4.14 and list as many functions of a running shoe as you can.

INTERNET CONNECT

www.mcgrawhill.ca/links/sciencefocus7

To find out more about Rube Goldberg, go to the web site above. Click on **Web Links** to find out where to go next. Design your own Rube Goldberg™ device, and write a brief description of it.

Function

What is this thing supposed to do? The answer to this question will guide all of your design decisions. Simple? Not really. Most structures have several functions. Think of a bridge. Its job is to support … what? Vehicles and people, of course, but the steel and concrete the bridge is made from can weigh many times more than the cars and trucks travelling across the bridge. Thus one very important function of any structure is to support its own weight.

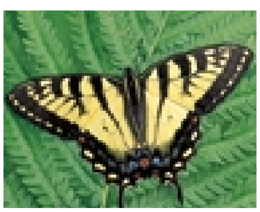
Structures do more than just support loads. For example, a running shoe, such as the one in Figure 4.14, grips the ground or gym floor and cushions your foot bones from the impact of running. But it has many other functions, too. The words in the Word Connect on this page may suggest some of them.

Designers have a hard time creating structures that perform all of their functions equally well. Plastic-covered running shoes certainly keep water *out* when you run through a puddle. But they also keep perspiration *in*, so your feet soon get hot and sweaty. Most runners have rubber and plastic soles and cloth uppers. This compromise does not let much puddle water in but does let most perspiration out.

Figure 4.14 Running shoes have much more to them than meets the eye.

DidYouKnow?

Symmetrical shapes can be turned or folded to fit exactly on top of themselves. Most people's faces are quite symmetrical, as are many other natural and manufactured structures. Because symmetry looks very pleasing, it is a powerful element of good design. Symmetrical parts, braces, and decorations on an object help it look attractive. If you start watching for symmetry in structures you observe every day, you might find ways to use this principle in your next design project. Find the axis of symmetry — the line that divides the butterfly into two parts with almost identical shapes.



How well must a structure perform its functions? Designers work to a set of specifications that give precise, measurable standards their structure must meet. Specifications for a running shoe might be:

- sole must flex 100 000 times without cracking
- materials must not contain chemicals that could irritate the skin

Aesthetics

One very important design specification is seldom written down. The best designs look good. Designers refer to such designs as "aesthetically pleasing." (**Aesthetics** is the study of beauty in art and nature.)

Think of an attractive car, building, or butterfly. It might feature shapes that are repeated or carefully arranged. There might be interesting textures and colours that are carefully chosen to be harmonious or contrasting. Sometimes the choice of materials and the methods used to make a structure can have a huge impact on aesthetics. The marble columns used in classically designed Greek buildings are beautiful, functional, strong … and expensive! The concrete columns under a highway overpass are functional, strong, and relatively inexpensive. Check with your art teacher for other principles of design that can help your projects look attractive.

Above all, architects and engineers try to keep their designs simple. Clean designs look better than over-complicated, busy ones. So remember to keep it simple!

Figure 4.15 The Museum of Civilization in Hull, Québec, echoes a seashell in its design.The building was designed by Métis architect Douglas Cardinal, who is known for his ability to combine aboriginal design aesthetics with modern technology. Many aboriginal structures echo elements of nature in their designs.

Designing for Safety

Have you ever been in an elevator and looked at the safety notice on the wall? What do you suppose would happen if extra people crowded into the elevator, so it was carrying more than the greatest permitted load? The answer is: probably nothing. The elevator is strong enough to be able to carry a much larger load than could ever be squeezed into it. It was designed with a large **margin of safety**. This means it has extra strength that allows it to withstand much larger loads than it would normally need to carry.

Almost all structures are built with a margin of safety. In Canada, for example, building roofs are designed to support enormous weights, so they do not collapse under the weight of snowdrifts that develop in the winter. Bridges are designed to carry much larger loads than would ever occur, even if a traffic jam stalled a convoy of transport trucks on them.

Figure 4.16 Extreme weather conditions can cause both natural and manufactured structures to fail.

Balancing Safety With Cost

Making structures stronger usually makes them more expensive. Bigger, stronger parts use more material. Skilled crafts-people may cost more than inexperienced workers. Good design is a compromise between a reasonable margin of safety and reasonable cost.

Designers plan their structures to withstand conditions they imagine might occur. Totally unexpected conditions, or very rare events, may cause even well-designed structures to fail. Bridges, for example, are always designed to be strong enough to withstand the force of flood waters and the impact of floating debris. But the designers of the Groat Bridge in Edmonton failed to make the temporary forms and braces that were used during construction equally strong. In 1954, the partially completed bridge was seriously damaged by the flooded North Saskatchewan River.

Figure 4.17 Edmonton's Groat Bridge was damaged by flood waters during construction.

DidYouKnow?

Imagine driving a car made of foam. The Karmann company in Germany has developed a layered material with thin sheets of aluminum covering a core of hard metal foam. Car body panels made from the metal "sandwich" are ten times stiffer than steel panels and much lighter, because the foam is filled with empty spaces. The foam is made by forcing gases through hot, liquid metal, making bubbles that harden as they cool.

Materials

Choosing building materials is another important design decision. The **properties** or characteristics of the materials must match the purpose of the structure. Different materials can be combined to give the exact properties needed.

Composite Materials

There are different kinds of strength. Steel rods and cables can support very strong tension (pulling) forces, but they bend and twist if you compress them (push them together). Concrete is just the opposite: it resists large pushing forces, but breaks if it is pulled or twisted. The workers in Figure 4.18 are pouring concrete around steel rods and mesh. This produces reinforced concrete, a **composite** made from more than one kind of material. If reinforced concrete breaks, the steel rods help to support the structure.

Other composites have different properties. Fibreglass cloth embedded in rigid plastic is moulded into boat hulls. Flexible plastic formed around a nylon mesh is used in lightweight garden hose to strengthen it against the pressure of the water.

Figure 4.18 Reinforced concrete can withstand both tension and compression. It is used to make buildings, bridges, and other large, strong structures.

Layered Materials

Use a fingernail to separate the edge of a TetraPak™ beverage container. Can you see the thin sheets of paper, plastic, and aluminum foil that make the container waterproof, airtight, lightweight, easily transported, and inexpensive? Layers of different materials, pressed and glued together, often produce useful combinations of properties. Inside the safety glass of car windshields is a plastic film that helps the glass resist shattering. Drywall panels on the walls of a room, and tiles or linoleum on the floor, contain **laminations** (layers) of different materials. Even layers of one substance can be more useful than a single thick piece. Examine Figure 4.19 and pick out the layers of wood that make up a sheet of plywood. Compare the diagram to a real piece of plywood. What differences can you find?

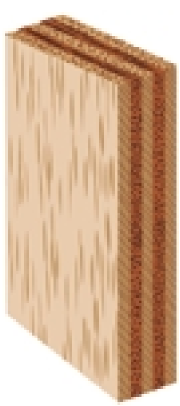


Figure 4.19 How do plywood laminations add strength to the wood?

Woven and Knit Materials

Use a magnifying glass to examine a piece of cloth. Can you see the hair-like fibres that have been spun (twisted together) into long, thin strings called yarn? A loom is used to weave two or more pieces of yarn together in a crisscross pattern to make cloth. Yarn can also be looped and knotted together to make knit materials. Figure 4.20 shows how each section of the knit is interlocked with many other sections. Knit materials stretch in all directions, so they fit well over complex shapes, such as human bodies.

Weaving and knitting are not the only ways to make flexible materials. Paper and felt are made from fibres that have been pressed and matted together. Aluminum foil and plastic wrap are made by melting and dissolving a substance and then letting it harden into thin solid sheets. No matter how they are made, materials that can be folded or rolled are extremely useful for lightweight structures that must be easily transported and stored, such as clothing, tents, and parachutes.

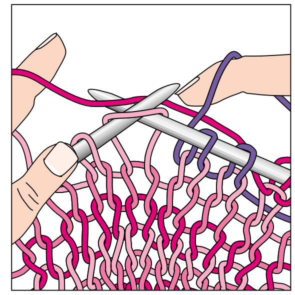


Figure 4.20 Interlocking yarn in a knit material spreads the forces throughout the fabric.

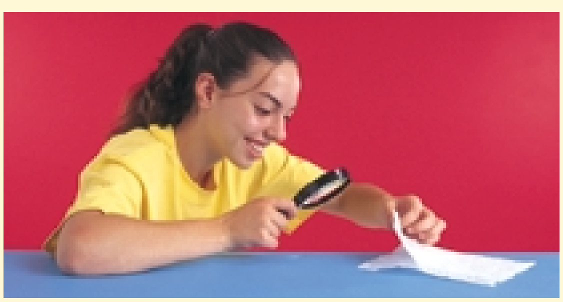
Find Out 

Sneezeproof Strength

Look closely at a facial tissue. Use the information in the previous section to infer why such thin material has enough strength to resist sneezes.

Materials

facial tissue
magnifying glass
pencil



Procedure — Performing and Recording

1. Partly separate a facial tissue into its layers. Look at the fibres through a magnifying glass. Record your observations. Use diagrams if necessary.
2. Put one layer of the tissue flat on a desk. Gently pull the two top corners apart. Record how much force is needed to tear the tissue.
3. Now turn the tissue 90 degrees, and try pulling apart the same layer again. Record your observations.
4. Mark the grain of the layer along the direction that pulls apart more easily.
5. Repeat steps 2 to 4 for the other layer.

What Did You Find Out? — Analyzing and Interpreting

1. Are the layers arranged with their grains pointing in the same direction or in different directions? Which arrangement would be stronger? Which arrangement would be easier to tear apart? Include sketches to make your answers clearer.
2. Are the fibres pressed or woven together?
3. In which direction is the tissue easier to tear? Explain.

Extension

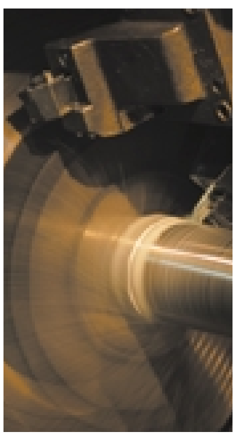
4. Facial tissues are made from wood pulp. So are writing paper, newsprint, paper towels, and paper napkins. Find out if these other products have a grain and, if they are arranged in layers, whether the grains of different layers are aligned or not.

Choosing Materials

Have you ever shopped for clothing, redecorated your bedroom, repaired a broken bike or chair, or patched a torn pair of jeans? All of these tasks, and many others, involve choosing among different materials, most of which could probably do an acceptable job. Choosing one material from many means balancing the advantages and disadvantages of each possible choice. Higher quality, stronger materials are often more expensive than weaker alternatives. Study the scenario below to discover some of the things to consider when making this design decision.

Cool Tools

Solid metal can be cut into complex shapes by milling machines like the one in the photograph. Other materials are formed and finished with different kinds of specialized equipment. You can find out more about the cool tools used with materials like clay, plastics, rubber, leather, rock, or glass by talking to a crafter or materials teacher, or by doing library or Internet research.



Choosing a Shirt

Figure 4.21 Choosing the right shirt

Jacob is shopping for a new shirt. He finds several that fit well and have colours and designs that he likes. To help choose, Jacob checks the labels to see what material each shirt is made from. One, which is very comfortable, is 100 percent cotton, a natural fibre made from the fluffy seeds of cotton plants. The care label says the garment should be washed with cool water, dried at low temperature, and ironed.

Another shirt, which is a bit less expensive, is labelled 100 percent polyester, a synthetic plastic fibre. The care label says to machine wash and dry, and hang up immediately. The third choice is also polyester, but it is labelled "Contains recycled materials." A card tied to the garment explains that the polyester is partly made from recycled pop bottles.

Jacob asks the store's sales clerk what else he should consider. The clerk tells him that cotton garments tend to shrink if they are washed in hot water, and that stains can be difficult to remove. Polyester is easier to care for, and much stronger than cotton, but it is less comfortable in hot or cold weather. Jacob now feels ready to make his choice.

Pause & Reflect

Which shirt would you choose? Why? How would you balance the different properties of the different materials? Write answers to these questions in your Science Log before reading on. Write a list of questions about materials that you will use for your unit project.

To pick the most suitable materials for a structure, architects, engineers, and designers need to organize their information about possible choices. They might consider the following:

- **Cost:** The lowest-cost materials may not be a bargain. If they are of poor quality, making the structure may be difficult and much material may be wasted. Cheaper materials may wear out quickly or require a lot of maintenance. On the other hand, less expensive material may do an acceptable job.
- **Appearance:** Structures like buildings and bridges last a long time. The materials they are made from need to remain attractive and strong without requiring expensive maintenance.

- **Environmental impact:** Using recycled materials, or materials made from renewable resources, helps preserve Earth's resources. You can choose not to use materials that are produced in ways that damage the environment. You can also avoid materials that require construction techniques that use harmful chemicals, or materials that are difficult to dispose of or to recycle.
- **Energy efficiency:** The cost of many structures includes more than just materials and construction. Buildings need to be kept warm in winter and cool in summer. Refrigerators and freezers use electricity to stay cold. Washing machines and clothes dryers use water and air that has been heated by electricity or natural gas. Your choice of materials can reduce the amount of energy a structure requires. This reduces its operating costs, and also preserves Earth's limited supply of energy sources.

Find Out ACTIVITY

Tough Tissue Test

Tissue manufacturers often boast about the strength and quality of their product. In this activity, you will evaluate the properties of different kinds of tissues.

Materials

2 sheets of several brands of facial tissue (both one- and two-ply)
large empty container
600 to 800 pennies (or washers)

Procedure

Performing and Recording

1. Prior to testing the tissues for strength, examine all brands carefully and write down as many properties as you can observe. Write a hypothesis about which brand will be strongest.
2. Put the empty container on a desk. Place a one-ply tissue over the open end of the container. (For thicker tissues, carefully separate the two plies and place one over the container.)
3. One partner holds the tissue firmly over the container, by holding it at the sides of the container. The other partner adds pennies to the centre of the tissue. Be sure that the tissue does not droop in the middle.
4. Continue adding pennies until the tissue tears and the pennies fall into the container.
5. Count the number of pennies the tissue held prior to tearing and record this value, along with your other observations about the tissue. The pennies collected could also be weighed.
6. Repeat the above steps for all of the brands of facial tissue.

What Did You Find Out?

Analyzing and Interpreting

1. Which tissue was strongest?
2. What features do you think make a tissue stronger?
3. Describe other properties of tissues that could affect their function or sales.
4. Which of the tissues tested would you buy? Use your list of properties to explain your choice.

Extension

5. If time permits, the above test could be repeated with damp samples of each brand of tissue. Would testing damp or wet tissues be a fairer test of a tissue's strength? Explain your answer.

Joints

How should we fasten this structure together? That is a critical decision because structures are often weakest where their parts are joined together.

Mobile joints are joints that allow movement. Door hinges, elbows, and the pins in a bicycle chain are examples of mobile joints. They hold parts together while still allowing some movement. Their complicated shapes are tricky to make, and they must be coated with a lubricant (a slippery substance) so that they move smoothly. Without lubrication, door hinges squeak, bicycle chains wear out, and human joints develop arthritis and similar painful diseases.

Compare the functions of the mobile joints in Figure 4.22. Look around your classroom and your home to see how many types of mobile joints you can find. What is the most common material that is used to make mobile joints?

Many structures consist of hundreds, even thousands of parts. Each one of these parts must be securely held together to form a sturdy structure. **Rigid joints** attach these parts together. Most rigid joints fit into five categories: fasteners, ties, interlocking shapes, adhesives, and melted joints. These categories are discussed separately below.

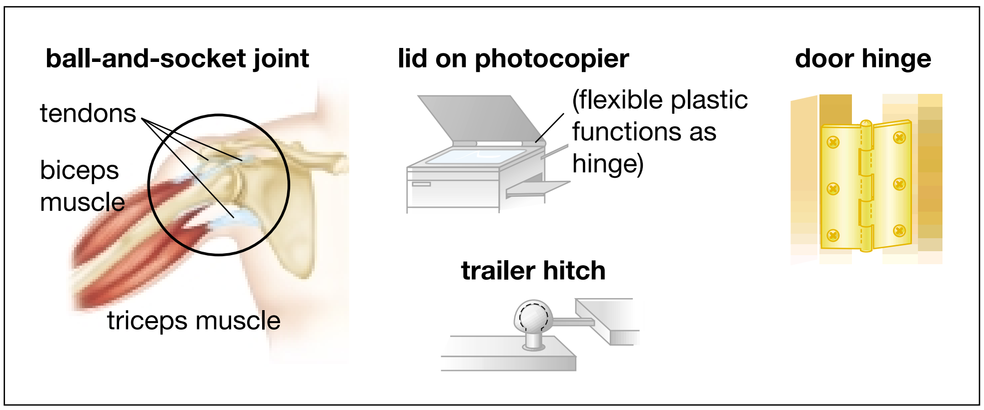


Figure 4.22 Examine each of these mobile joints. What are the requirements of the materials used in making mobile joints?

Fasteners

Nails, staples, bolts, screws, rivets, and dowels (shown in Figure 4.23) are used to hold many structures together. Unfortunately the holes that fasteners make also weaken the materials they fasten. Staples and nails are usually forced into the parts they join, which can crack and separate the material. Drilling holes for bolts, screws, and dowels does not weaken the material as much, but the holes are time-consuming to position and cut.

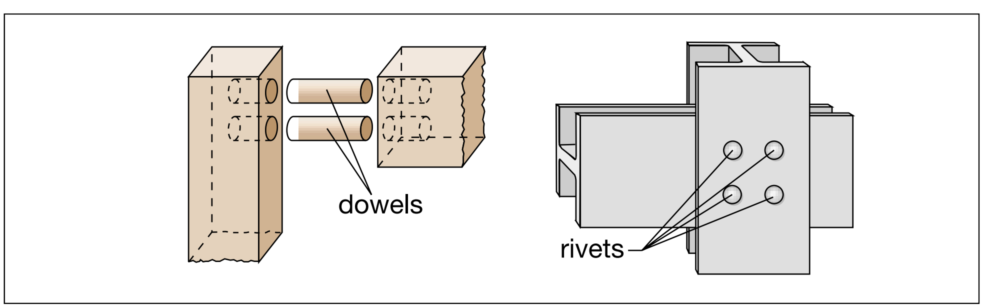


Figure 4.23 Dowelled joints are used by cabinetmakers to hold pieces of furniture together. How are the rivets in the steel beams similar to the dowels? How do they differ?

Attaching parts with just one fastener allows the parts to twist around it when they are pushed or pulled. Several fasteners make a more rigid joint, but the extra holes weaken the material more. So making a strong joint does not mean simply pounding in a bunch of big nails! Both the kind and number of fasteners must be carefully planned.

Interlocking Shapes

Carefully shaped parts can hold themselves together. Lego™ bricks and some paving stones fit together and stay together because of their shape. The fronts of wooden drawers are often locked to the sides with dovetail joints. Dentists shape the holes they drill in teeth to keep the filling material in place.

The joints in flexible materials are also carefully shaped. The sheet metal in the furnace and heating ducts of your home is overlapped or folded to strengthen the places where it is joined. Folded seams protect the cut edges of pieces of cloth and give a neat, finished appearance to the joints in clothing. Figure 4.24 shows some of the different kinds of interlocking joints.

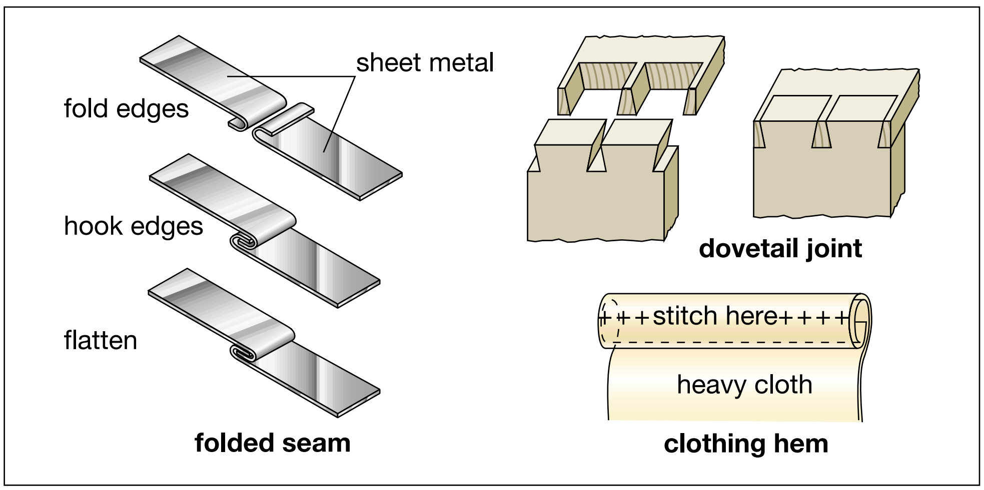


Figure 4.24 Various kinds of interlocking joints can be used to strengthen different types of structures.

Ties

Thread, string, and rope can also fasten things together. Shoes are tied with laces. Jacket hoods are tightened with drawstrings. Seams in clothing are "tied together" with a sewing machine. Figure 4.25 shows how the needle and bobbin thread are intertwined to tie the seam in place. Before sewing machines were invented, people sewed all of their clothing, including their shoes, by hand.

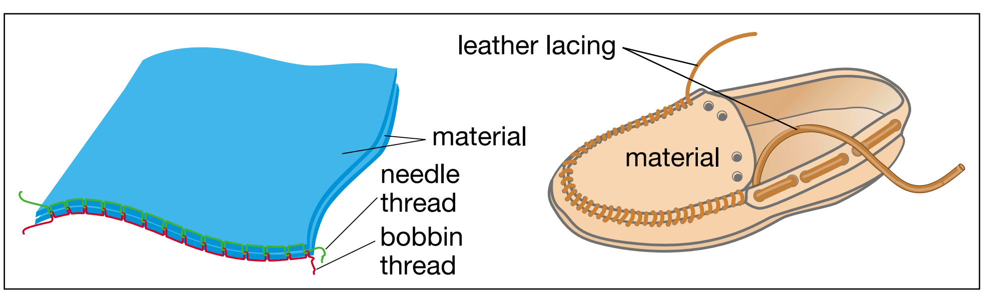


Figure 4.25 Sewing machines tie two threads together as they stitch a seam. Moccasins are sewn by hand with a strip of leather.

Adhesives

Sticky substances, called **adhesives** or glues, can hold things together. Figure 4.26 shows how glue flows into tiny rough areas on the surface of the pieces it joins. When the glue hardens, it locks the pieces together. *Thermosetting glues* like those used in glue guns harden when they cool. *Solvent-based glues* harden as they dry out. The strongest glues also create a special kind of force between the tiniest particles of the pieces being joined. Because of these forces, epoxy resins and super glues are strong enough to hold pieces of car bodies together.

Even the strongest glued joints fail under extreme conditions. Glues may soften in water or under very hot conditions. If a glue is stronger than the substances it joins, the material next to the joint may break.

Adhesives can be a health hazard. Some glues start to harden as soon as they touch moisture. If a drop gets on your fingers or in your eye, it can stick your fingers or eyelids together almost instantly. Other glues, such as those used to make plywood and particleboard, release powerful chemicals into the air as they harden. These gases collect between walls, in basements, and in other places that have poor air circulation. If people with asthma and allergies live or work in these areas, the gases may trigger breathing difficulties, skin problems, headaches, and other health problems.

DidYouKnow?

Chemist Spence Silver was supposed to develop a super powerful glue. He tried many recipes. One recipe made a not-very-sticky substance that definitely did not meet specifications. It held papers together temporarily, but the joint could easily be pulled apart. Silver kept experimenting for almost ten years, sure that his glue could be useful somehow. Finally, in 1974, a co-worker, Arthur Fry, suddenly thought of a use for the temporary adhesive — sticky bookmarks that would not fall out of place! Post-It™ notes were the result, and they were an instant success.

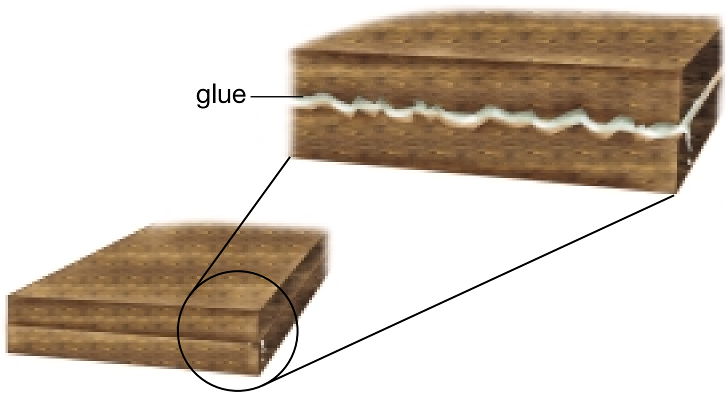


Figure 4.26 Glue creates a bridge between two surfaces and locks them together.

Melting

Pieces of metal or pieces of plastic can be melted together. **Welding** melts the pieces themselves. **Soldering** (or brazing) surrounds pieces with a different melted material, which locks the pieces together as it cools and hardens. To increase strength, the pieces to be joined may be twisted or folded together. The pieces must be carefully cleaned before joining, and the melted material must be cooled slowly and carefully. Otherwise, the joint will be brittle and weak.

There are many ways of melting materials to make welded joints. Torches use a hot flame. Arc welders and spot welders use heat from an electric spark. Plastics can be melted and welded together with strong chemicals and even with sound waves.

Figure 4.27 Welders use a dark mask to protect their eyes and to see white-hot joints clearly.

STRETCH Your Mind

Builders need to avoid waste when cutting large pieces of building materials. How can you make one straight vertical cut and one straight horizontal cut to divide the cross shape below into four pieces that can be reassembled into a square?

Find Out **ACTIVITY**

Design Detective

Procedure Analyzing and Interpreting

1. At home, search for a small device with several parts that you can bring to school. Look for something with a clear function. A device made from unusual materials or fastened together in an interesting way would also be a good choice.
2. Print your name on one side of a small index card. On the other side, list the following details about the device:
   (a) name
   (b) function
   (c) material(s) from which it is made
   (d) how it is fastened together
3. Bring your device to class. Display it with the index card beside the device with your name facing upward.
4. Examine each device on display. Observe what it is made of and how its parts are fastened together. Guess its function and what it is called.
5. At your teacher's signal, compare your ideas with the information on the hidden side of each object's display card. Give yourself one point for every correct answer, so you can earn up to four points per device.

What Did You Find Out?

Choose one device and write a short paragraph analyzing why its particular materials and fastening methods were selected. What advantages do they have over other possible materials and fastening devices? What disadvantages do they have?

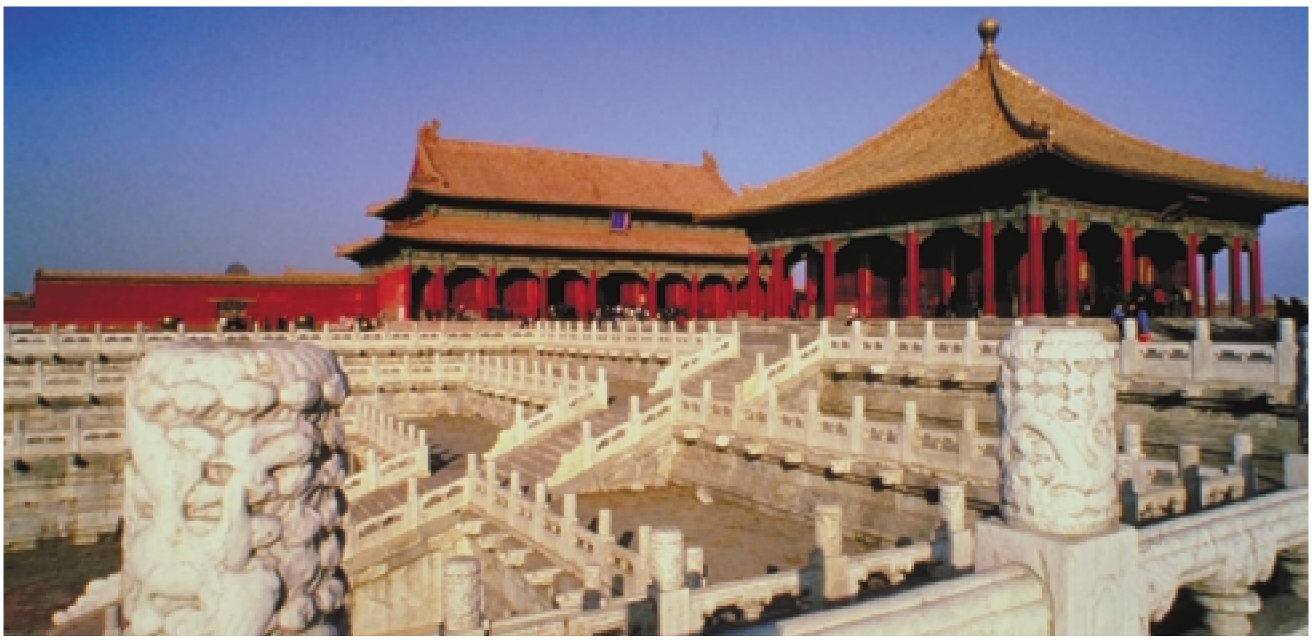
INVESTIGATION 4-B

SKILLCHECK
- Initiating and Planning
- Performing and Recording
- Analyzing and Interpreting
- Communication and Teamwork

Traditional Structures

Think About It

People have been building useful structures for thousands of years. Early builders probably chose their designs out of necessity. For example, they had to use materials that were available in the areas where they lived. Their structures had to be appropriate for the climate or the area. As new technologies became available, builders modified their structures. Often, the design of a structure reveals its purpose. You can sometimes determine whether a structure was determined to protect the people inside from dangerous enemies or from the ravages of winter. What type of structure attracts your attention and makes you want to learn more about it?



Procedure

1. As a group, choose a structure that you would like to research. For example, it could be a famous historical building in your area or a famous building somewhere else. It might be a type of structure used by Aboriginal peoples or European pioneers in Canada. As a guide for your research, read the Analyze questions on the following page. You might also collect information about the original builders. Include any information about their lifestyle that could relate to the structure's design and function.

2. Divide up the questions among your group members. After your group receives teacher approval, research the structure you have chosen. Use resources such as the Internet, encyclopedias, and library books.

3. On the left side of a large piece of poster paper, make a scale drawing of the structure you have chosen to study. Pay as much attention to detail as possible. Label significant structural features.

Skill FOCUS

For tips on using the Internet and other communication technology for research, turn to Skill Focus 9.

Analyze

1. Within your group, discuss the answers to the questions and other information that you found in your research. Prepare a report to go on the right side of your poster. If some information applies directly to a part of your scale drawing, you may wish to put that information beside the label.
   - **(a)** What type of structure is it (mass, frame, shell)? What is it called? Who built it?
   - **(b)** What materials were used in your structure's construction. Why were they chosen?
   - **(c)** Describe the intended function of the structure and why the original builders chose this design. If possible, relate the design and function to the lifestyle and culture of the builders.
   - **(d)** What features of your structure are designed to enhance its appearance (aesthetics)?
   - **(e)** What sales techniques would real estate salespeople of the time use to promote the structure?
   - **(f)** Describe the steps followed by the builders during the structure's construction.
2. Were there questions you could not answer in your research? Explain what they were and why you might have trouble finding the answers.
3. What scientific knowledge did the builders apply in designing and building their structure?

Extend Your Knowledge

4. Display the information compiled by each group for the whole class to see. Study the variety of structures, then construct a chart to compare the structures based on similarities and differences. Try to explain why the differences and similarities exist.

TOPIC 2 Review

1. Imagine that you are stranded on a tropical island with very few supplies. Among your supplies is a roll of heavy plastic sheeting. Describe five possible functions the plastic could have. Be creative!

2. Suggest examples of

(a) a woven material

(b) a laminated material

(c) a composite material

(d) a glued joint

(e) a structure that is tied or sewn together

(f) something that is welded together

3. **Apply** Imagine that you are the architect for a new arts centre in your province's capital city. What kind of information would you need before you could begin your initial design? Write a list of questions you would ask your clients about their needs and expectations for the building.

4. **Apply** Your foot is a wonderful, complex structure. Use what you have learned in this section to analyze the structure of your foot and answer the questions below.

(a) Name three functions of your foot.

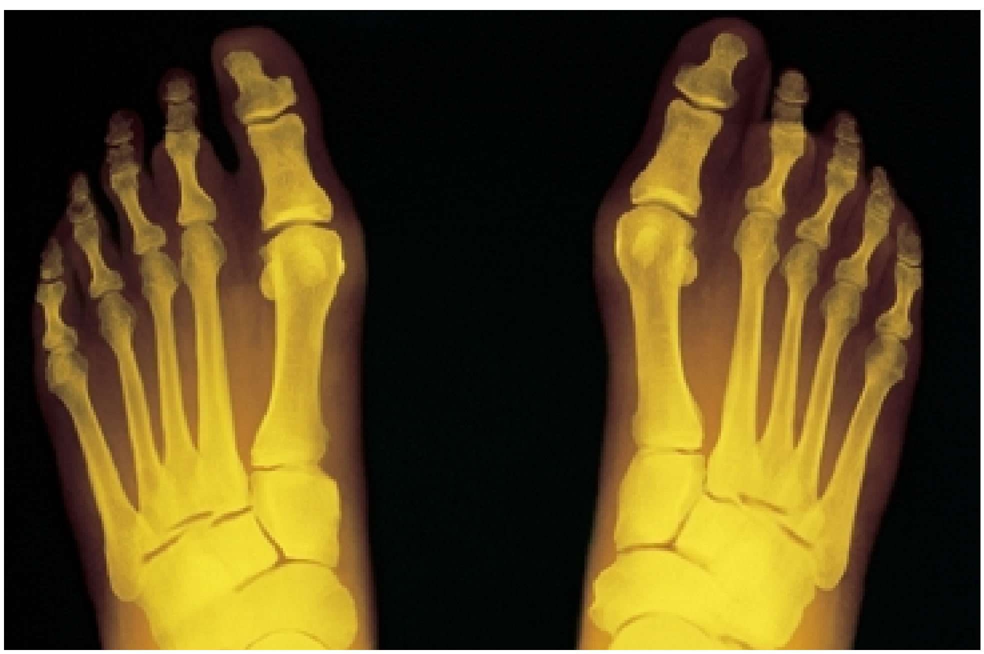
(b) Identify three materials that make up your foot. For each material, describe one particular function that it has and one property that allows it to perform this function.

(c) What type of structure is your foot (mass, frame, or shell)?

(d) What type of fastening method holds the parts of your foot together? How many parts does your foot have? (You may have to do some extra research to answer this!)

Looking Ahead

Write down ideas from Topic 2 that might be useful for your unit project to build a reverse bungee ride prototype. Select your best ideas for the group file or notebook.



Wrap-up TOPICS 1-2

If you need to check an item, Topic numbers are provided in brackets below.

Key Terms

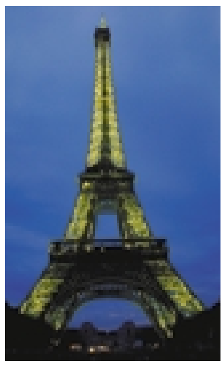
structures
function
forces
load
natural structures
manufactured structures
mass structures
frame structures
shell structures
design
aesthetics
margin of safety
properties
composite
laminations
mobile joints
rigid joints
adhesives
welding
soldering (brazing)

Reviewing Key Terms

1. Write down at least three pairs of natural and manufactured structures that share a similar form or function. Explain how they are similar or different. (1, 2)

2. Think of examples of
   (a) four mass structures (1)
   (b) five frame structures (1)
   (c) five shell structures (1)

3. What is the difference between a welded joint and a joint held together with adhesives? (2)



Understanding Key Concepts

4. Think about a glass filled with orange juice. (1)
   (a) Is the juice a structure? Explain your answer.
   (b) Is the glass a structure? Explain your answer.

5. Describe one property of glass that makes it
   (a) a good material for making beverage containers (1, 2)
   (b) a poor material for making beverage containers (1, 2)

6. People have invented many different types of foot gear. Four examples are wooden shoes, soft leather moccasins, sports sandals, and downhill ski boots moulded from strong, rigid plastic.
   (a) What is the main function of each of these types of foot gear? (2)
   (b) What type of structure is each type of foot gear? (1)
   (c) How is each type of foot gear fastened together? (2)

7. You are stranded on an island covered in vegetation. To escape, you decide to build a raft out of layers of reeds and small branches. (2)
   (a) Would it be better to line up the reeds in each layer and tie them together, or to crisscross them and weave them together? Explain.
   (b) Would it be better to line up the reeds in each layer in the same direction as the layer below, or should the reeds in each layer point in different directions? Explain.

8. Describe how the material in a structure can be weakened when pieces are held together by
   (a) ties, such as shoelaces (2)
   (b) welded joints (2)