TOPIC 6 Designing with Forces

In Topic 4, you learned about the types of forces that act on structures. Then in Topic 5, you saw the ways that forces could make a structure fail. With this type of information, engineers create designs that are most likely to prevent the structures from failing. First they study the general features of the structure. Then they analyze the types of forces that are likely to be the greatest. Finally they choose details for the design that will counteract those forces. Designers often rely on one of three key methods to help structures withstand forces.

- Distribute the load throughout the structure so that no single part is carrying most of the load.
- Direct the forces along angled components so that the forces hold pieces together instead of pulling them apart.
- Shape the parts to withstand the specific type of force they are likely to experience.

Some structural problems, along with potential solutions, are described below. As you read, notice how the solutions fit into one or more of the key methods above.

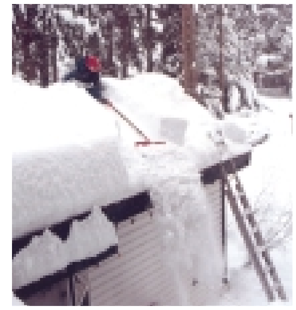


Figure 4.49 What stresses is the weight of the snow exerting on the roof and the frame of this cottage? How could its owner ensure that the snow will not cause the roof to collapse?

PROBLEM 1

Rectangular frames are probably the easiest to build. However, load forces can easily push or pull them out of shape. Examine Figure 4.50 for some possible solutions.

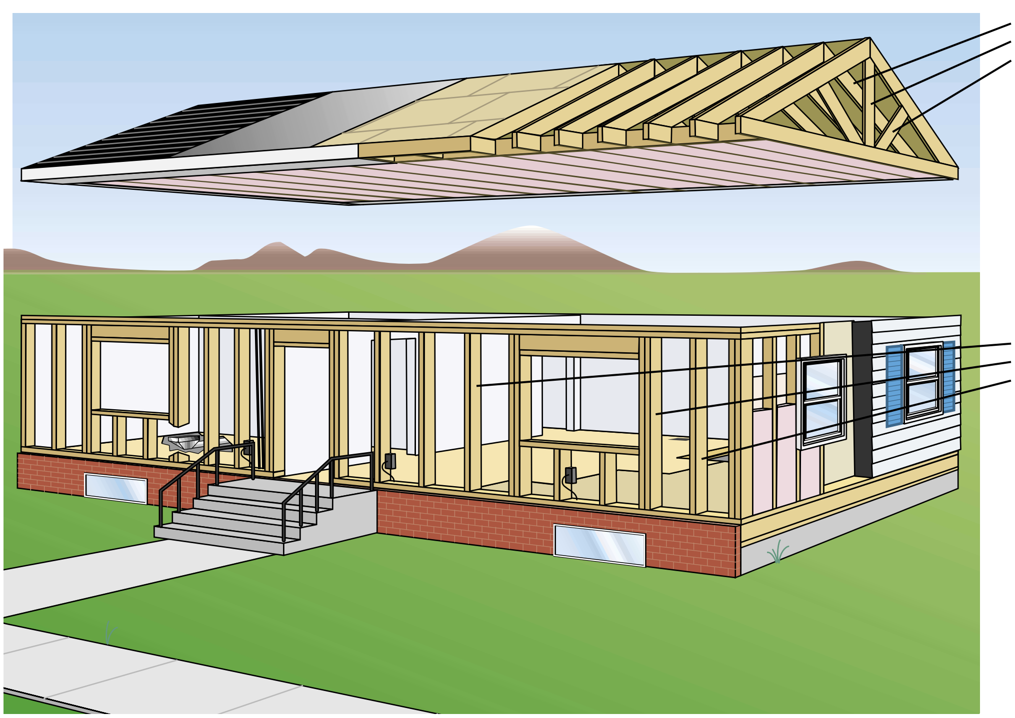


Figure 4.50 Triangles form a sturdy shape Triangular shapes are much stronger than rectangles. A rectangle can collapse but a triangle cannot. Notice the number of triangular shapes in each truss.

Share the Load Frame structures contain many vertical supporting posts. The weight is shared by all of them. Therefore, no single part of the structure carries a large load.

PROBLEM 2

As you can see in Figure 4.51, any structure with a load-bearing, horizontal beam supported only at the ends, may bend in the centre. This bending directs forces outward on the vertical beams. Sometimes it is not practical to put more supporting columns in the centre. Examine Figure 4.52 to find some solutions.

Figure 4.51 When a horizontal structure carries a heavy load, it may begin to sag in the middle.

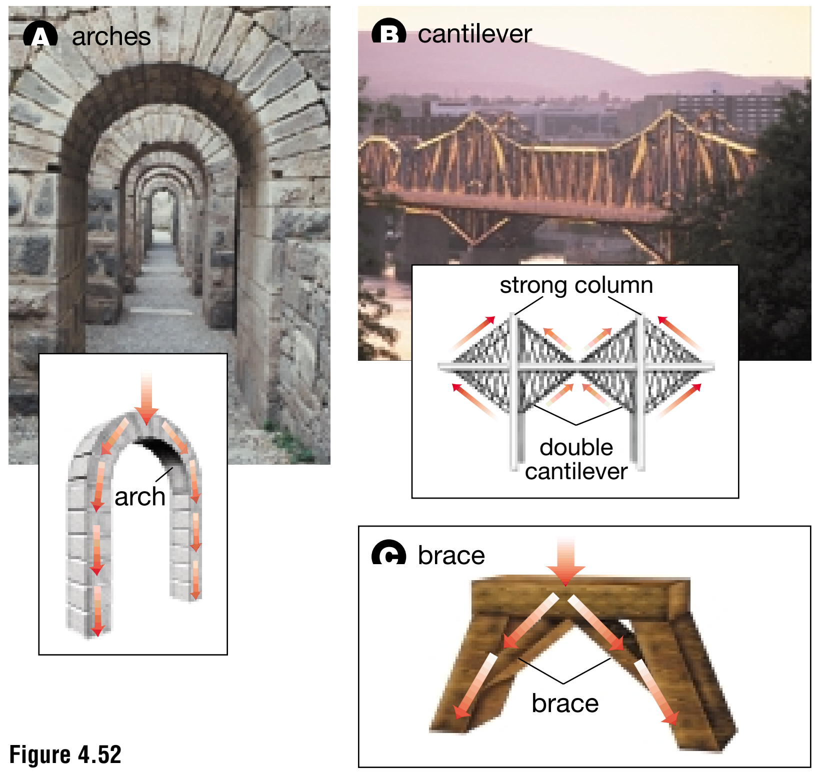


Figure 4.52

A Arches can be rounded and the stones shaped to fit. The central stone is called the keystone. It is shaped like a wedge. As it slips further down between the next two stones, the keystone presses harder against the two beside it. This shape directs the forces along the stones and down to the ground as shown by the arrows. Domes and shell structures are based on the same concept.

B A cantilever is a horizontal board or span, supported by a very strong column at one end. Double cantilever bridges are very strong structures and support heavy vehicles. Beams from the top of the columns pull upward on the ends of the cantilevers. Beams from the columns below the span to the ends of the cantilevers push upward on the ends of the cantilevers.

C Braces can be added and materials angled to direct the forces through the solid part of the structure to the ground as shown by the arrows.

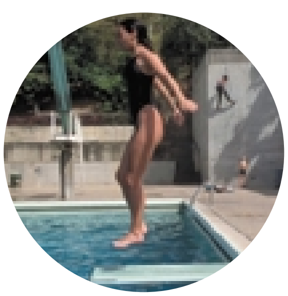


Figure 4.53 (diving board) A cantilever must be able to withstand tension forces on top and compression forces underneath. Engineers must choose materials carefully, when designing a cantilever.

PROBLEM 3

Large, solid beams are very strong. However, they are extremely heavy and hard to handle. As well, they use a lot of building material. Figure 4.54 shows several ways to make strong beams that are not too heavy. Nature uses some of the same tricks.

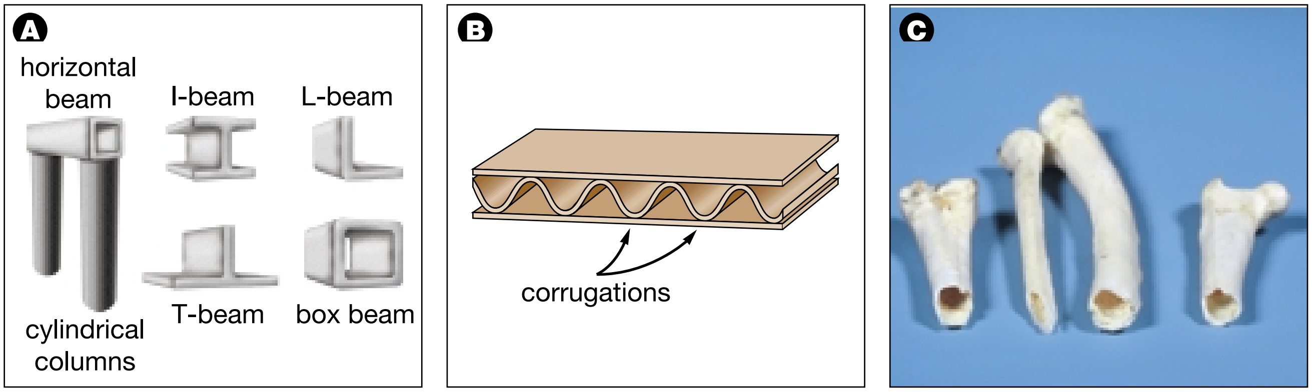


Figure 4.54 Cylindrical columns are very strong but use a little less material than square beams. Beams in the form of an I, L, T, or a box are very strong but use much less material than solid beams.

The wavelike shape in corrugated cardboard gives the cardboard strength. As well, it is lighter and uses less material than solid cardboard.

Animal bones are often hollow. In the living animal, the bones are filled with a very lightweight, spongy material.

How did architects and builders of hundreds of years ago make majestic cathedrals so sturdy that we still enjoy their beauty today? One technique that they used is shown in Figure 4.55A. The construction of the cathedral of Notre-Dame was started in 1162. It took nearly 200 years to complete. The extremely tall sides of the cathedral are supported by columns on the outsides that connect to the building near the top. These columns are called flying buttresses. They support the outer walls in much the same way that the two sides of an arch support each other. With modern materials and techniques, these flying buttresses are no longer needed. However, nature still uses a similar structure (see Figure 4.55B).

Figure 4.55A Flying buttresses were used to support buildings hundreds of years ago.

Figure 4.55B The roots of these mangrove trees function much like the flying buttresses of the cathedral of Notre-Dame.

Career CONNECT

With the help of an adult, contact an architect or building contractor in your area. Interview her or him to find out how architects are trained and what their work is like. Ask the architect to think of a particular building that was challenging to build. What were the functions and specifications for this building, and how did they influence its design?

Vancouver Public Library

Strengthening Structures

In science fiction stories, you can read about wonderful imaginary materials that stand up to almost any force. Real materials are more limited. Concrete and mortar have very high compressive strength if they are made according to the correct recipe. Concrete is quite weak if it is pulled or sheared, however. Similarly, most other materials have one kind of strength but not another. That is why engineers must analyze structures in great detail to find out what types of internal forces are stressing each part. They can then choose materials and shapes with the strength to withstand each force. Even a simple swing needs to be designed in this way (see Figure 4.57).

Shear forces were a big problem for early railways. Tiny cracks inside the rails often weakened them enough that the weight of a loaded train would shear a rail in half, causing a serious accident. But the cracks could be detected only after the rails broke. In 1932 a Canadian metallurgist, J. Cameron Mackie, discovered that the cracks formed when the rails cooled too quickly during the manufacturing process. Mackie tried putting red-hot rails in a covered steel box where they could cool more slowly. He found that this eliminated the cracks completely. Within ten years, Mackie's process was being used by steel companies all over the world to produce strong, crack-free rails.

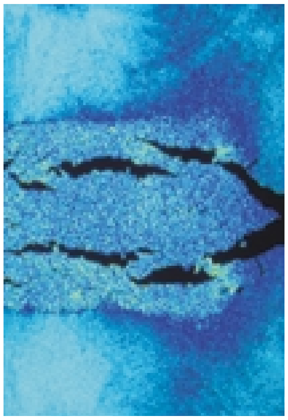


Figure 4.56 Stress cracks in metal can lead to structural failure. Rust can also lead to metal failure.

DidYouKnow?

Bamboo scaffolding is the external scaffolding system commonly used in the construction industry in southeast Asia. This type of scaffolding is often the only type of support used by workers building very tall buildings. Bamboo is such a flexible construction material that there have been cases where scaffolding has survived heavy winds or storms, while the building under construction behind the scaffolding has been damaged!

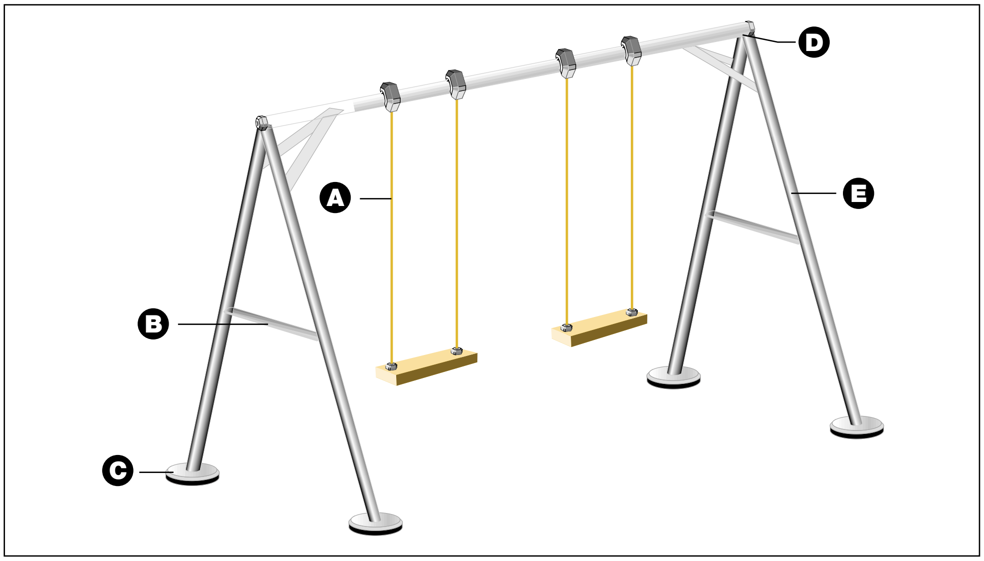


Figure 4.57

A The rope holding the person undergoes a lot of tension. Use rope or chain for high tensile strength.

B The cross bar forms a triangle that strengthens the frame. Use steel.

C The anchor beneath the posts undergoes compression due to the weight of the swings and people using them. Concrete is good and will not rot when the ground is wet.

D The joint gets twisted every time the person swings back and forth. Use a material that has high torsion strength and is not brittle.

E The frame is slanted for stability. Each time the swing moves forward, the front bar experiences compression and the back bar experiences tension. When the swing moves back, the opposite forces apply. Use steel for both compressive and tensile strength.

PROBLEM-SOLVING

INVESTIGATION 4-E

SKILLCHECK

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

The Paper Olympics

Architects and designers are sometimes quite limited as to the materials they can use, but they still need to design the sturdiest structure possible.

Challenge

How can you use your knowledge of shape and strength to turn flimsy paper index cards into load-bearing columns, beams, and flat panels?

Safety Precautions

- Use sharp objects such as scissors with care.
- A glue gun is hot and the glue remains hot for several minutes.
- Wash your hands thoroughly after completing this investigation.

Materials

scissors
templates for beams (optional)
assorted masses of known weight
force meter (or plastic bucket and masses)
5 index cards (20 cm × 13 cm)
glue gun, white glue, or glue stick
flat plywood (20 cm × 20 cm)
string

Design Specifications

A. Use one card to build a column that is the full height of the card (20 cm).

B. Cut and fold a second card into a strong beam that will span a 15 cm gap. Use the diagrams in Figure 4.45 to decide what type of beam to make.

C. Use the last three cards to make a strong flat panel, larger than 10 cm × 12 cm. The panel must have at least three layers that are glued together, and it must be at least 1 cm thick.

D. Let the glue harden overnight.

E. Disqualify any structures that are too small or do not match the specifications.

F. Each group member should draw a diagram of the structures that have been built prior to testing.

G. In each category, the strongest structure receives 100 points, the next strongest gets 90 points, and so on. Your teacher might award extra points for aesthetics and careful construction.

Plan and Construct

1. Stand the column upright on the floor or a desk. Place the piece of plywood squarely on the top of the column. Place masses on the board, distributing them evenly. Add masses until the column fails. Record the maximum amount of weight held by the column (in newtons).

2. Place the beam across a 15 cm gap between two desks. Put a loop of string around the middle and attach the string to a force meter or a plastic bucket. Pull down on the force meter, or add masses to the bucket, until the beam breaks, twists out of shape, or bends more than 1 cm. Record (in newtons) the largest force that the beam can support.

3. Stand the flat panel on a desk or the floor. Lay the piece of plywood on top of the panel. Add masses to the panel until it collapses. Record the maximum weight held by the panel.

Evaluate

Based on your results, suggest ways in which you could improve the design of each of your structures. Draw sketches of your improved designs and explain your reasons for making the changes.

Using Frictional Forces

Figure 4.58 Frictional force holds the bricks in this wall together.

Press your open hand straight down hard on your desk. Keep pressing down while you slide your hand sideways. Unless your desk or hand is greasy, this is probably hard work! You are feeling the force of **friction**, which resists (works against) movement between two surfaces that rub together. That is why friction is so important in assembling structures: it can help keep pieces of the structure from moving apart.

In a brick wall, for example, each layer of bricks rests on the layer below. A thin layer of mortar between rows of bricks keeps them level and evenly spaced. No glue, fasteners, nails, or screws help to hold the bricks together, but the wall is still strong. If you push against one brick, friction between it and neighbouring bricks prevents any movement. The wall is held together by friction.

Friction is especially important in wooden frame structures. Houses and garages, for example, are often built around wooden frames (see Figure 4.6 on page 274). The pieces of the frame are usually nailed together. Friction between each nail and the wood around it keeps the nail in place and the joint rigid. Study Figure 4.59 to learn how different types of fasteners are designed to increase the amount of friction with the wood and produce tighter joints.

DidYouKnow?

Friction also opposes the movement of nails *into* wood. Framing carpenters use especially heavy hammers to help drive nails into joints. When a frame structure must be demolished, workers often must use sledge hammers and long wrecking bars to separate the frame pieces.

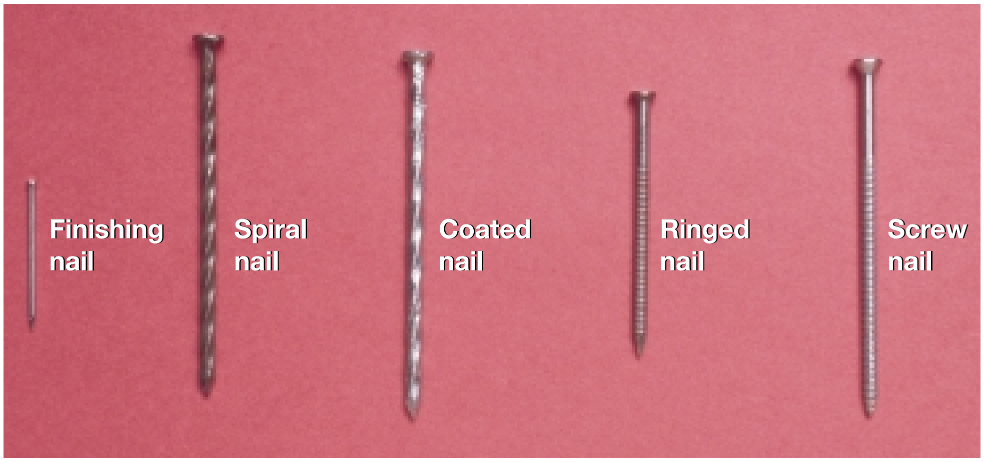


Figure 4.59 Frictional forces are greater between rough surfaces. Which of the fasteners would have the least friction with the wood around it? Which would have the most?

If there is a squeaky place in the floor or stairs of your home, you know one effect of too little friction in a frame structure. Nails holding the plywood subfloor to the house frame have loosened. When you step on the loose spot, the plywood moves up and down a tiny bit, rubbing on the loose nail and causing the squeak. Pounding the nails down seldom helps. They just slip loose again. To really fix the noise, you would have to pull the subfloor tightly against the frame with new fasteners.

PROBLEM-SOLVING

INVESTIGATION 4-F

SKILLCHECK

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

The Windproof Wonder

Some structures have moving parts that must resist friction. Can you design a structure that uses the power of the wind but is not blown over by it?

Challenge

Build a free-standing frame tower to support a working windmill propeller.

Safety Precautions

Handle electrical equipment and sharp objects with care.

Materials

scissors
2-speed hair dryer or fan
paper plates (or index cards)
wooden dowel
30 cm masking tape
2 balls modelling clay (200 g each)
fasteners/connectors (paper clips or pins)
20 plastic drinking straws
2 small sandbags (plastic sandwich bags filled with 200 g of sand)

Design Specifications

A. The windmill frame tower must be at least 50 cm tall.

B. The tower must include a propeller with at least three blades that turn when exposed to wind (from the hair dryer).

C. The masking tape cannot be used to connect the straws to each other. It can only be used in the construction and attachment of the propeller.

D. The sandbags and/or modelling clay can be used as masses to weigh the tower down, but the modelling clay cannot be used to "stick" the tower to the table.

E. After creating your initial design, you have 35 min to build, test, and modify your structure.

Plan and Construct

1. With your group, brainstorm ideas for your design. Make sure your design meets all of the specifications. Plan how to prevent your structure from blowing over and how to ensure that the propeller turns.

2. Use the most practical design ideas as the basis for a neat labelled sketch of your design. Then list the materials you need. After getting your teacher's approval, gather the materials and start building.

3. You may test your frame tower once before judging, but only with the fan or hair dryer set to low power. If you modify your original design, sketch how your structure actually looks when it is complete.

Evaluate

1. With your group, evaluate your structure. Record how well your structure met the specifications. How might you modify its design to eliminate weaknesses and improve its performance?

2. Describe the fixed and mobile joints in your structure. Explain why you chose the materials you did to connect these joints.

3. Describe the live and dead loads that were acting on your structure. How did you try to make your structure strong enough to handle these loads?

4. **(a)** Where is friction a force in your structure?
   (b) For each point listed in (a), describe whether friction helped your structure or lessened its effectiveness.
   (c) Where and how might you try to increase friction?
   (d) Where and how might you try to decrease friction?

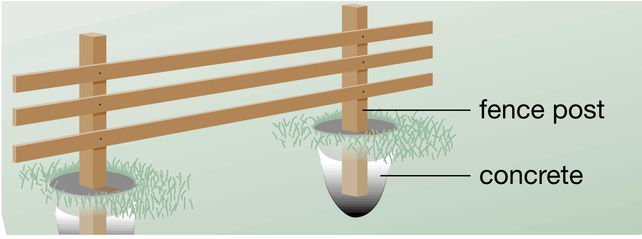


Figure 4.60 Friction between the fence posts and concrete hold the posts in place.

As you may have noticed in Problem-Solving Investigation 4-F, friction between the ground and the bottom of a structure is an important design consideration. Friction helps hold the structure in place when the wind or other forces try to lift or tip it. The bases of fences, flagpoles, communications towers, and playground swings are often made of strong metal pipes or rods driven into the ground. Can you remember playing on a "bumpy" swing set with legs that slid up and down in the ground as your weight twisted the swing frame? Frictional forces between the smooth metal and the ground were too small to hold the swing safely in place. If the swing had been set in larger holes filled with concrete, friction between the rough concrete and the ground would have been much greater, and the swing would have been more stable.

Too little or too much friction can cause problems in other types of structures, too. Chairs stick or grind across the floor if there is too much friction between their legs and the floor. Putting a smooth cloth, metal, or plastic glider on the bottom of the chair legs can help solve the problem.

Did You Know?

Guitars, violins, pianos, and other stringed instruments go out of tune when there is too little friction in their tuning pegs. When the pegs slip, the strings loosen and the instrument goes out of tune.

TOPIC 6 Review

1. Sketch a diagram of each structure listed below:
   (a) an arch
   (b) a column and beam gateway
   (c) a double cantilever bridge
2. Name two ways that friction can be used in a structure.
3. Make a labelled sketch of a sturdy chair. Include two features that increase its strength and two features that increase its stability. Describe how these features are effective.

4. **Apply** Examine the photograph of the suspension bridge.
   (a) Which parts of the bridge are under compression? Which parts are under tension?
   (b) Describe two ways in which the bridge is being supported.
   (c) Identify two ways in which the stability of the bridge has been increased.
5. Think of one structure that has been designed to withstand
   (a) compression **(b)** torsion **(c)** shear force

TOPIC 7 Stable Structures

There is more than one way to collapse a structure. For the figure skaters in Figure 4.61, just a tiny mistake in the distribution of their mass would make them unstable. The force of gravity would pull them down if they lost their balance. However, almost all structures can lean a bit without falling down. A bicycle rider who is moving fast enough can even lean a lot without losing balance. Athletes make adjustments to their body position intuitively, but architects and engineers need to analyze structures to predict how or when a structure will become unbalanced. To design **stable** (less likely to tip) structures, engineers need to know what features of a leaning object determine whether it will tip over or stay balanced.

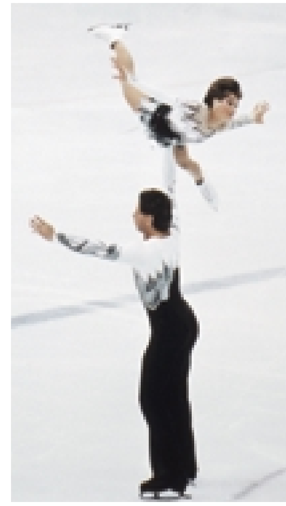


Figure 4.61 How is distribution of mass important to these figure skaters?

Figure 4.62 Why do these structures not fall over?

Off the Wall

The Empire State Building in New York City is a steel frame building, 102 storeys tall. It has a mass of 365 000 t. After it was built, many people worried about the building's safety because strong winds made the top storeys sway back and forth slightly. On a foggy day in July 1945, a U.S. Air Force bomber hit the Empire State Building between the 78th and 79th floors. Fourteen people in the airplane were killed, but the building was not seriously damaged. Doubts about its safety disappeared.

INVESTIGATION 4-G

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

Tip It!

Think About It

If you can stand or walk, your body has learned a lot about balance. Examine the pictures and answer the questions to put your experience into words.

Procedure

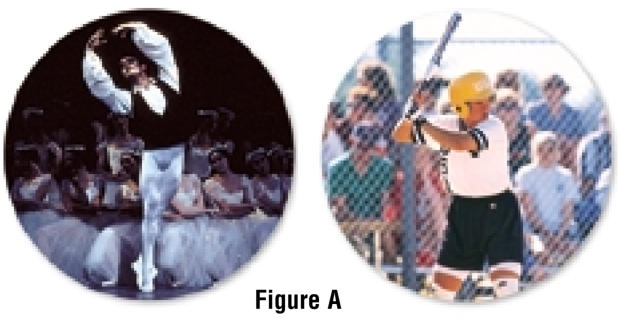


Figure A

1. To find one key to stability, examine the photographs in Figure A.
   - **(a)** Which person is in a more stable position?
   - **(b)** What difference in their positions creates the difference in stability?
   - **(c)** Based on your observations, suggest a hypothesis to explain why an opened stepladder is more stable than the same stepladder with its two legs folded together.

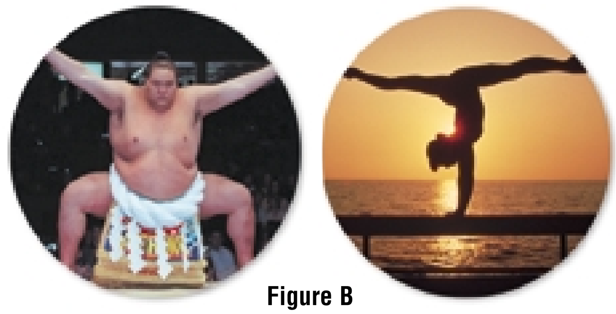


Figure B

2. To find a second key to stability, examine the photographs in Figure B.
   - **(a)** Which athlete is in a more stable position?
   - **(b)** A large part of your body mass is in the area around your hips. What difference in the position of body mass puts one athlete in a more stable position than the other?
   - **(c)** Explain how the same principle makes balancing on stilts much harder than balancing on your feet.

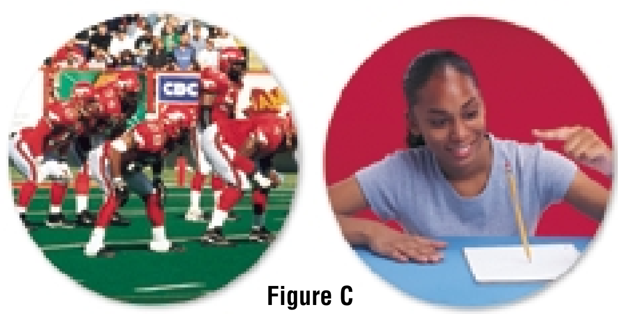


Figure C

3. Football players are coached to keep their stance “wide and low” (Figure C).
   - **(a)** Explain how this advice uses both keys to stability that you have discovered.
   - **(b)** Why is it so hard to balance a pencil on its point (Figure C)? Use the ideas from steps 1 and 2 in your answer.

Balancing Act

In the last investigation, did you conclude that objects are more stable if they rest on a large area and have most of their mass close to the ground? These are useful general principles, but they are not precise enough to ensure that a particular structure, such as a bridge or a building, will be stable. Engineers need to calculate exactly how large a foundation is necessary or the best place to put heavy heating and air conditioning machinery. They also need to design structures, such as aircraft and rockets, that have to be stable even when they are not resting on the ground. To make these precise calculations, engineers must find a special point within the structure called the centre of gravity.

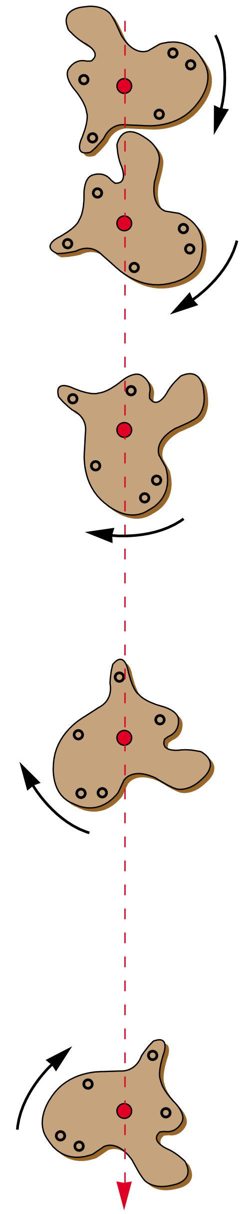


Figure 4.63 Observe the position of the central point of the rotating object while it falls.

Find Out ACTIVITY

The Centre of Gravity

What are some characteristics of the centre of gravity?

Materials

heavy cardboard scissors nail String mass pencil

Procedure

1. Draw an irregular shape on the cardboard, and cut it out. **CAUTION** Be careful when using sharp objects such as scissors or nails.
2. Select four or five points on the cardboard object. Use a nail to make holes at these points large enough for the object to rotate freely around the nail.
3. Put a nail through one of the holes. Tie a piece of string on the nail. Tie the mass to the other end of the string.
4. While you are holding the object up with the nail, have your partner mark the path of the string on the card board.
5. Repeat steps 3 through 5 for every hole in the cardboard object.
6. Remove the nail and string. Try to balance the object on your fingertip. Carefully adjust the position of the cardboard by moving it extremely small distances while trying to balance it.
7. Examine Figure 4.63 in which the cardboard object is rotating while it falls. Notice the path of the central point (centre of gravity.) Choose one other point on the cardboard. In your mind, picture its path as the object rotates and falls. (Do not write in this book.)

What Did You Find Out?

1. How does the point where the object balanced on your finger relate to the lines you drew on the object in Step 4.
2. Write a statement that explains what you think is unique about the point where you balanced the cardboard. Infer the meaning of "centre of gravity."

In the activity, did you relate the point where you balanced your cardboard object with the central point that fell in a straight line in Figure 4.63? These points have the same property. In both cases, the force of gravity appeared to act directly on these points. Any point with this characteristic is called the **centre of gravity**. All objects have a centre of gravity. When an object falls, the centre of gravity falls in a straight line. All other points rotate around the centre of gravity while the object falls. Study Figure 4.65 to better understand why the centre of gravity is the balance point.

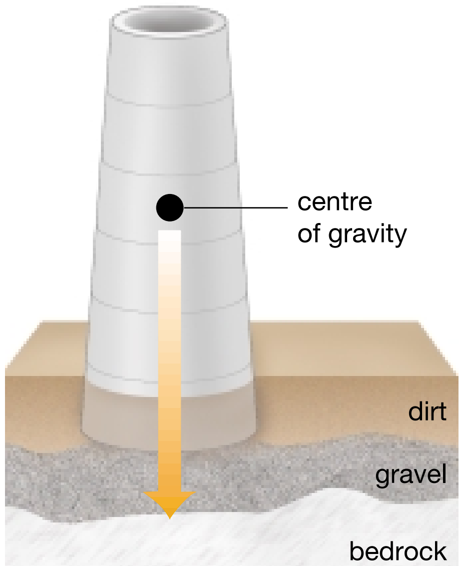


Figure 4.64A In this position, the chimney is stable. The thrust line is inside the foundation.

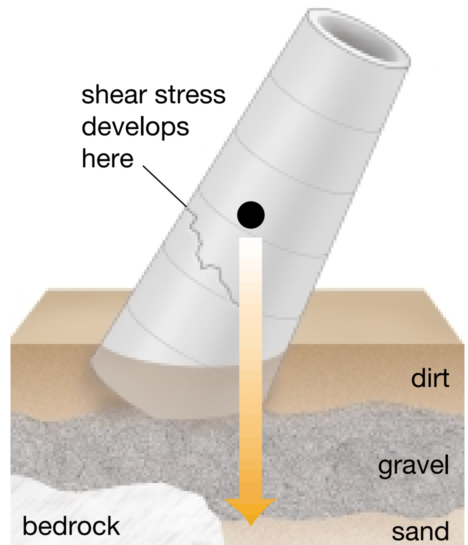


Figure 4.64B In this position, the chimney is unstable. It will tip or break apart as a result of the large shear forces near the arrow.

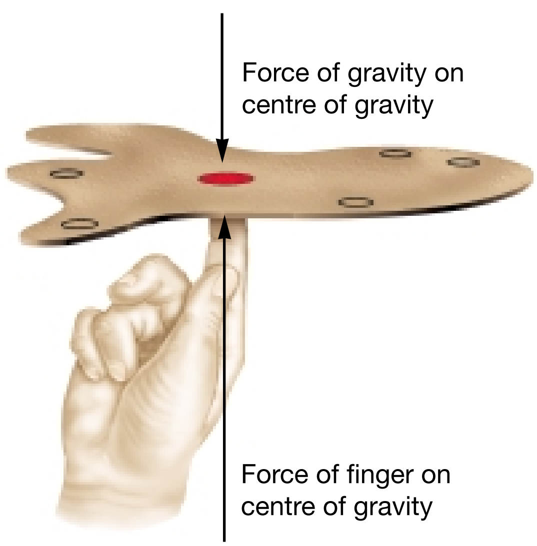


Figure 4.65A When the force exerted by the finger is lined up with the force of gravity acting on the centre of gravity, the object is balanced.

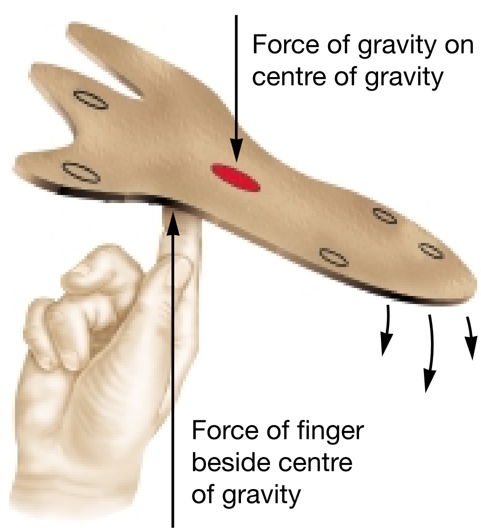


Figure 4.65B When the finger is not supporting the centre of gravity, the object begins to fall.

Unbalanced Structures

Figure 4.66 With your knowledge of the motion of the centre of gravity, explain why this chimney is falling.

Pause& Reflect

Each photograph in Figure 4.67 shows a stable structure. In your Science Log, describe

- forces which, left unbalanced, might cause instability
- how forces are balanced

To determine whether a structure is balanced or is likely to fall, locate its centre of gravity and draw a line directly down toward Earth. If the arrow points to a solid foundation, the structure is balanced as shown in Figure 4.64A. If the arrow falls beside the foundation, the structure is not stable as shown in 4.64B. If the ground beneath a structure is uneven and unstable, the structure may tip. When the imaginary arrow pointing down from the centre of gravity moves to a point beside the base of the structure, the structure will become very unstable.

Inspect each of the photographs below. Estimate the location of the centre of gravity in each structure. Figure out why each structure is stable.

Figure 4.67A A heavy mass acts as a counter-weight to keep the crane stable.

Figure 4.67B The cables on this boat keep the masts stable.

Figure 4.67C Sailors can act as a counter-weight to balance a small boat.

Figure 4.67D Symmetrical structures can also balance gravitational forces around the centre of gravity.

PROBLEM-SOLVING

INVESTIGATION 4-H

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

Building a Balanced Balcony

Whenever engineers or architects have to design a structure that is supported from only one side, such as a balcony, they are faced with a real challenge. With only one side supported, how can they make sure that the structure does not fall over when it experiences stress? As you studied earlier in this topic, centre of gravity and a balance of forces all play an important role in determining a structure's stability.

Challenge

Using your knowledge of centre of gravity and balanced forces, build a tower with a cantilevered balcony capable of supporting a load.

Materials

15 plastic straws (each at least 20 cm long)
5 (10 x 15 cm) recipe cards
30 cm masking tape
pins
paper clips
250 mL styrofoam cup
sand
250 g modelling clay
thread
30 cm ruler
scissors

Specifications

A. Only the materials supplied may be used during construction. The materials may be cut or shaped into whatever size your team thinks is necessary.

B. The tower must be free standing and at least 20 cm tall.

C. The balcony must extend at least 10 cm from the edge of the tower and must be supported only at one end.

D. Your team will be allowed a maximum of 30 min to build the structure.

E. Upon completion, the balcony must support a styrofoam cup half filled with sand for at least 30 s.

Plan and Construct

1. Write a sentence or two to describe your structure's main stability problem. List what you know about stable structures that might help you resolve this problem.
2. Each member of your design and construction team should sketch a rough blueprint of a possible design for your structure.
3. Evaluate the different designs produced by your team members and then as a group choose the best design that will best achieve the goals of this activity.
4. Draw a diagram of the design you have chosen to build and show it to your teacher for approval.
5. After your structure has been approved, begin construction using the materials provided.
6. Test and measure the structure throughout the construction process to see whether it is meeting the stated specifications.
7. Note any changes that your group makes to your initial design.
8. When your structure is complete or the building time is up, bring your structure to the testing desk for evaluation.
9. Each team member should draw a labelled diagram of the final structure prior to testing.
10. Measure the structure to determine whether it meets all specifications. Place the cup (half filled with sand) on the structure's balcony and time for 30 s. Record the performance of your structure.

Evaluate

1. Label the following on your diagram of the structure your group built:
   - all forces acting on the structure (include arrows to show the direction and if possible, the strength of the forces)
   - the centre of gravity of your structure
   - an arrow to indicate the line pointing down from the centre of gravity
2. How did you distribute the mass throughout your structure? How did this affect your structure's stability?
3. What would happen to your structure if you substantially increased the amount of sand in the cup or perhaps added a much larger cup filled with sand? What changes would have to be made to your structure in order to support this greater load?

Extend Your Skills

4. Increase the amount of sand the structure supports until the structure fails. Describe how and where the structure fails. Was the prediction you made in question 3 correct?

Skill FOCUS

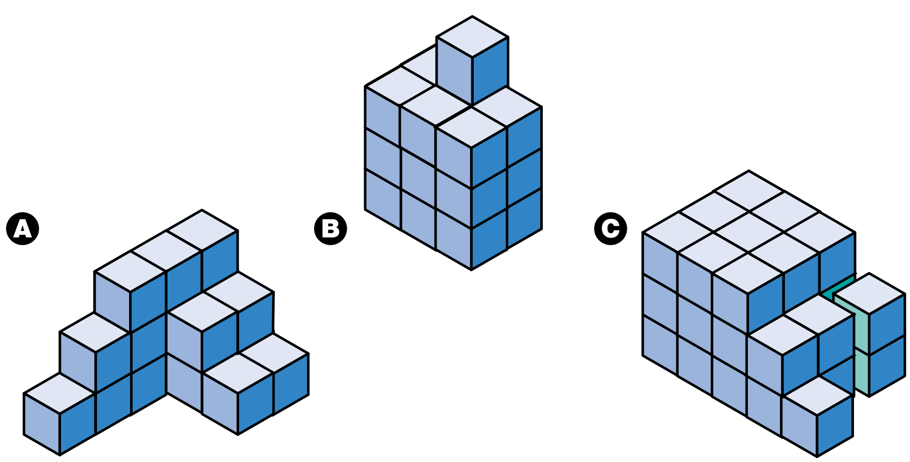
For support with the steps of the problem-solving process, see Skill Focus 7.

RETCH Your Mind

Builders and designers must become very skilled at using flat drawings to represent three-dimensional solid objects. Try to solve the problem shown below by studying the drawings. Then test your answer by making a paper or block model.

Problem

How many cubes would be needed to make each stack below? Assume that all the blocks rest on another block when there is more than one layer.



Pause & Reflect

Imagine that you have been chosen to be interviewed by the education reporter for a local newspaper or radio station. The reporter wants an explanation, in your own words, of what your class has been studying in science for the past few weeks, and why this knowledge is useful in everyday life. There is space for a paragraph of about 150 words. In your Science Log, write what you would say.

Firm Foundation

Skill FOCUS

For tips on doing research and presenting your findings using communications technology, see Skill Focus 9.

Solid ground is not always firm and stable, especially if it is moist. Water near the surface can freeze and expand (swell) in the winter, lifting the ground. In warmer weather, the melted ice water drains away, shifting tiny soil particles and leaving spaces that collapse under pressure. The soil compacts, and potholes appear. Some clay soils act in the same way when they absorb water and then dry out. Larger sections of soil can slip sideways over moist layers underground, causing sinkholes and landslides. Worse yet, very moist soil sometimes flows like a thick liquid when it is shaken or vibrated. If builders do not obtain thorough studies of the ground under a planned subdivision, many homeowners could have cracks in their walls and foundations.

Find Out ACTIVITY

Looking Below

The house shown in the photograph to the right collapsed into the North Saskatchewan River because the ground underneath the house was unstable. Many homeowners in the same area are worried about the stability of their homes. Other people in places such as Richmond, a community in Vancouver, worry about their homes in case of an earthquake. The ground under their homes is full of water and could be unstable in an earthquake.

Procedure

1. Using library, Internet, and community resources, research a structure that has collapsed or may collapse.
2. Present your findings as a poster diagram showing the structure and describing the problems it faces. Show in your diagram the causes of the problem. Include details about the failure or potential failure of the structure you have chosen to study.

What Did You Find Out?

As a class, discuss the kinds of forces causing or threatening structural failure.

How do builders construct a stable structure on shifty ground? They start by creating a firm **foundation**, using one of these strategies.

Find Something Solid

Below the soil lies solid bedrock. If the loose surface soil is not too deep, builders can dig it out completely and build a stable foundation directly on the bedrock. If the loose soil is too deep, they can sink **pilings** (large metal, concrete, or wood cylinders) through the loose soil until the pilings rest on bedrock. Then the structure can be built so that its weight is carried by the pilings to the rock beneath. To support a structure such as a garage, which is not really heavy, builders might not need to dig to bedrock. In many parts of Canada, foundation walls about 1.5 m deep reach firm layers of soil that give enough support and never freeze.

Make a Solid Layer

Road builders always pack loose surface soil before paving to create a solid base for the asphalt or concrete. Later on, if the pavement cracks badly, repair crews dig out the soil and replace it with a solidly packed layer of gravel. They then repave on top of the more solid material. Packed gravel foundations are also used for dams and other mass structures.

Spread the Load

If the weight of a structure is spread over a large area, any particular part of the ground supports only a small part of the weight. This is why buildings are often constructed on many shallow pilings rather than on a few. Even if the pilings do not reach bedrock, the soil beneath each one is strong enough to carry its part of the load. This is also why the **footings**, the concrete foundation beneath house basement walls, are wider than the walls themselves. Spreading the weight of the walls over a larger area reduces the stress on every part of the soil beneath them.

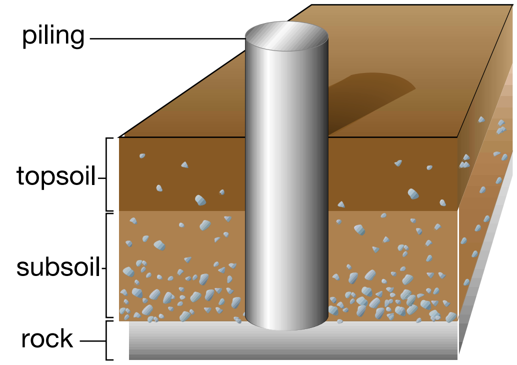


Figure 4.68A Pilings support the weight of many buildings and bridges.

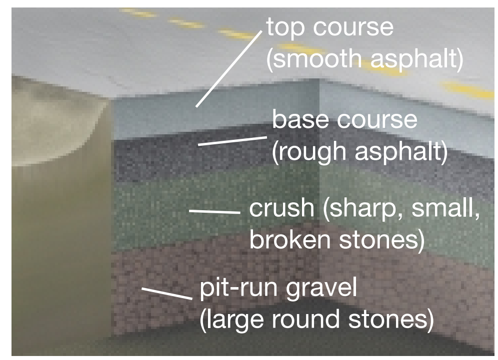


Figure 4.68B Each layer in the road base has a specific function.

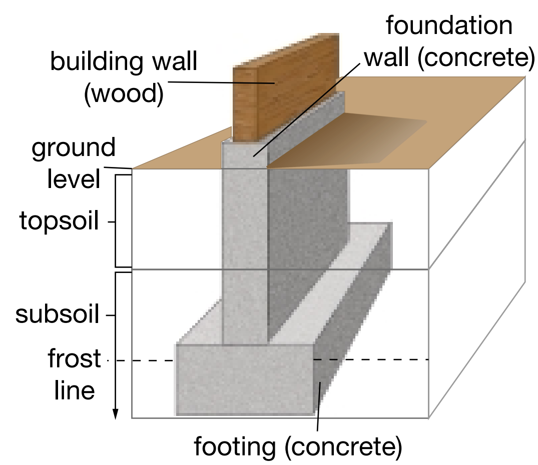


Figure 4.68C Footings beneath a foundation wall reduce stress on the soil.

INQUIRY

INVESTIGATION 4-1

SKILLCHECK

Initiating and Planning

Performing and Recording

Analyzing and Interpreting

Communication and Teamwork

Sink the Stick

Soil testing is an early step in designing any large structure. Knowing how the soil reacts to forces helps an architect or engineer decide what type of foundation will be necessary.

Question

How does loose sand react to impact forces over different areas?

Hypothesis

Read through the procedure before you begin. Form a hypothesis about which dowel will have the greatest impact and which will have the least impact.

Skill FOCUS

For tips on making data tables by hand, see Skill Focus 10.

To develop a data table with spreadsheet functions, see Skill Focus 9.

Safety Precautions

- Do this experiment on newspaper, and have a broom handy to sweep up scattered sand.
- Handle all sharp objects with care.
- Handle the mass with care, following your teacher's instructions.

Apparatus

small tray or plastic container

200 g mass tied to 30 cm string

at least 4 wooden dowels of different diameters

table fork (for loosening the sand)

sharp pencil

ruler

Materials

500 mL of sand

1 cm graph paper

Procedure

1. **Make a data table** with four columns, headed "Object," "Base area (cm^2)," "Depth in loose sand (mm)," and "Depth in packed sand (mm)." Give your table a title.
2. **Sort** your dowels according to the size of their base. **Calculate** the size of each base, and record it in your table. Test the smallest one first.
3. Fill your tray with sand so that it is at least 8 cm deep. Loosen the sand with the fork. Then level the surface.

Math CONNECT

To find the area of the base of the first dowel, use one (or both) of these methods.

1. Stand the dowel on the graph paper and trace around its base. Count the number of centimetre squares it covers. Group any half or quarter squares into whole squares, and include them in the count.
2. If you know the mathematical formula for finding the area of a circle, make the necessary measurements and calculate the area. Round your answer to one decimal place.

4. Hold the dowel gently on the sand so that it is upright but can slide through your fingers. Hold the mass about 20 cm above the top of the dowel. While holding the string, let the mass fall by its own weight and hit the dowel.

5 Mark the dowel at the level of the sand surface.

6 **Measure and record** how far the dowel is pushed into the sand.

7 Repeat steps 3 to 6 with each dowel.

8 Repeat steps 3 to 7, but this time pack the sand firmly before each test.

(a) **Record** the results in the proper column of your data table.

(b) If you have time, moisten the sand and repeat steps 3 to 7.

Skill FOCUS

To find out when to use each type of graph, turn to Skill Focus 10.

Analyze

1. What type of graph (line, bar, or circle) would be most useful for predicting what would happen if you experimented with other dowels of different sizes?
2. **Draw a graph** to show the results of your tests. Use different colours, or solid and dotted lines, to show what happened in the loose and packed sand. Make a key that explains the meaning of each colour or style of line.
3. Was the blow from the falling mass an external force or an internal force on the sand?
4. Did the sand have to support a live load, a dead load, or both? Explain your answer.
5. What type of stress did your falling mass create in the sand?
6. Did you observe any signs of shearing in the sand beside the dowel? If so, describe them.

Conclude and Apply

7. Do your tests support your hypothesis? **Explain** why or why not.
8. If a load is applied to a smaller surface, what happens to the effect of the force under the surface?
9. Why are nails, drill bits, and sometimes fence posts sharpened on the bottom? In your answer, use the ideas and words you have learned in Topic 7.
10. When might a builder need the sort of soil information that you found out in this investigation?
11. Even if every group used the same dowels, sand, and mass, the results would probably not be exactly the same. What are some reasons for this?
12. How do frictional forces affect the stability of the dowels inserted into the sand?

DidYouKnow?

Navigation equipment can use the features of a gyroscope to detect when a ship or an airplane is wandering off course and to correct its heading (direction).

Rapid Rotation

Every bicycle rider knows that it is harder to balance while moving slowly. The faster the wheels spin, the more the bicycle resists being tipped (see Figure 4.69A). If most of the mass of a wheel is located far from the centre, the stability is even greater. **Gyroscopes** (see Figure 4.69B), devices with heavy outer rims, can be built to spin tens of thousands of times per minute. When balanced on its axle, a gyroscope keeps pointing in the same direction, even if the structure on which it is spinning moves or turns.

Spin stabilization, the principle demonstrated by the gyroscope, is especially useful for objects that do not rest on a solid foundation. Space satellites need to keep their antennas pointed back to Earth and their instruments facing the proper location in space. Football players want the ball to travel in a stable, predictable path, so they practise for hours to throw or kick perfect spirals. If you have ever spun a toy top, a yo-yo, or a Frisbee™, you have used spin stabilization.

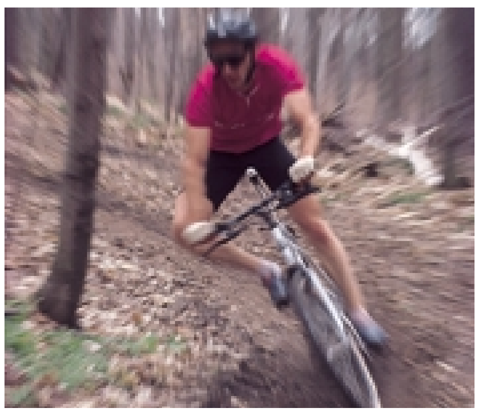


Figure 4.69A Rapidly spinning wheels stabilize a bicycle.

Figure 4.69B Spin stabilization keeps a gyroscope pointing in the same direction.

TOPIC 7 Review

1. For each pair of words below, select one item that is likely to be more stable than the other.
   (a) wet soil/dry soil
   (b) bedrock/loose soil
   (c) unbalanced forces/balanced forces
   (d) arch without a tie beam/arch with a tie beam
   (e) rapidly spinning wheel/slowly spinning wheel
2. Identify one possible cause of each event.
   (a) soil heaving up and tilting a sidewalk
   (b) soil sinking down and collapsing a driveway
3. **Apply** Early settlers built corduroy roads over muskeg by placing logs side by side over the swampy ground. Why would this provide a stable foundation for the road?

Wrap-up TOPICS 6-7

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

Key Terms

stable structure
friction
centre of gravity
foundation
pilings
footings
gyroscopes
spin stabilization

Reviewing Key Terms

1. In your notebook, write a sentence about structures and forces using the paired terms below.

(a) pilings, footings (7)
(b) stability, balance (7)
(c) friction, resistance (6)
(d) footings, load (7)
(e) gyroscopes, spin stabilization (7)
(f) brace, beam (6)
(g) stable structure, foundation (7)

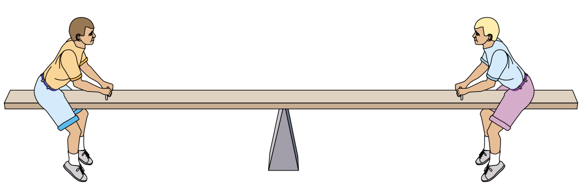
2. Draw diagrams that show how to stabilize structures using (a) pilings, and (b) footings.

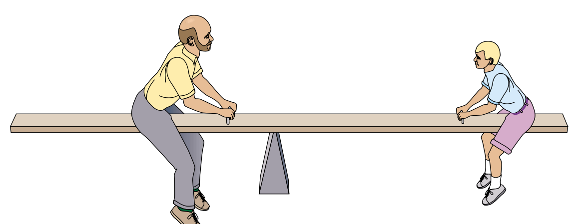
Understanding Key Concepts

3. Draw a diagram that shows how part of the base of a structure is pushed up when the structure itself tips over. (7)

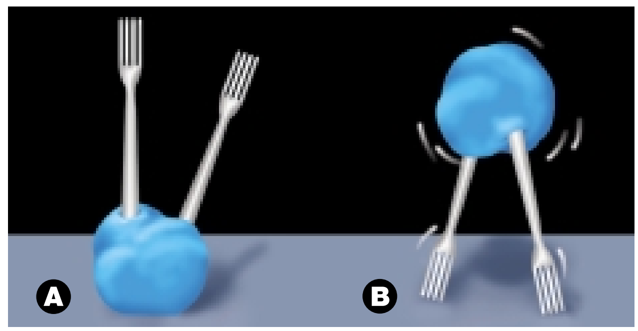
4. Metal or wooden fasteners can be used to hold together parts of a structure made from different materials. Explain how friction affects how well different fasteners work. (6)

5. If people balance a playground teeter-totter as shown, where is the centre of gravity in each situation? (7)


A


B

6. Describe three differences between the two structures below that make structure A more stable than structure B. (7)



7. List five principles of stable structures that a designer might consider when planning a project. (7)

Ask an Expert

There are many people in the world who make things for a living. Not Alan McColman. He's a specialist in taking things apart. Specifically, he takes apart buildings and other structures. Alan is a director of McColman and Sons Demolition in Calgary, Alberta.

Q How did you get into the demolition industry?

A When I was growing up, my father was a crane operator who demolished buildings. Then in 1979, he and my mother and brother started this business. I joined them about two years later.

Q What do you do for the company?

A When someone in the area has a demolition job to be done, I put together a bid from our company. I decide what type of demolition method is right for the project and work with my brother, Dan, to plan how that demolition would be performed. We work out the details of what equipment and how many crew members we would need, what safety issues to take into account, and that sort of thing. Then I outline our plan and include a price quote for the potential customer. If they like our bid better than ones they receive from other demolition companies, they'll hire us to do the job.

Q Are there very many different demolition methods?

A There are a few different types. For most projects we use machinery such as excavators, a wrecking ball on a crane, or bulldozers. What we use depends on the size of the structure, what it is made of, its foundation type, and its location.

Q Why does location have anything to do with it?

A Knocking down a building in the middle of nowhere is very different from knocking down a building that has an office tower on either side of it. In cases where neighbouring buildings are a concern, we often have to employ many crew members with hand tools to take the building down slowly, so we avoid damaging the other structures.

Q Let's say there is a three-storey building with no nearby structures to worry about. How would you demolish it?

A That depends on what it is made of and what type of foundation it has. Each type of building has its own cautions. If it is brick, we may do a lot of work by hand to keep the job from getting out of control. Brick buildings are very unstable when they are coming down. Concrete buildings can sometimes snap off in large sections. Steel frame buildings have more give to them and will sag and bend instead of snapping off. And each building's foundation type will help us determine which sections of the building should be brought down first.

Q Do you ever use dynamite to implode a building?

A In some cases it is necessary to implode a structure. Exploding would scatter debris. We implode so that the debris falls inward and is contained within a defined area. We don't use implosions very often, though, so when we get a job such as the demolition of the Calgary General Hospital, which we completed in 1999, we usually hire implosion experts to set the charges.

Q **How long did the demolition of the hospital take?**

A The implosions themselves brought down the upper storeys of all the hospital buildings in just under 20 seconds. The whole job took much longer, however.

Q **What other stages were involved?**

A First we had to go in and clean out all hazardous materials: asbestos, mercury, lead, biological waste, contaminated soils — that sort of thing. For the hospital project, that was the most time-consuming stage. After the implosion, we had to dispose of the debris from the upper storeys and demolish the foundations as well. The disposal stage took around five months.

Q **What part of this job do you enjoy most?**

A I love the variety. No two projects are exactly the same because every structure is unique in some way. I might be planning the demolition of a high-rise one week and be out on the job site of a bridge demolition the next. Every project has its own safety concerns and its own challenges. I enjoy applying my knowledge to find the solution that's just right for each one.

EXPLORING Further

Alan has explained that each demolition job is different from the next. To see more examples of demolition jobs and how they are completed, visit the web site of a demolition company. Go to **www.school.mcgrawhill.ca/resources/**, go to Science Resources, then to **SCIENCEFOCUS 7** to find out where to go next.

Imagine that you work with McColman and Sons Demolition. Choose a structure in your community and prepare a bid to demolish it. As part of your bid, you will need to explain how long you think the job will take, the special safety concerns and challenges the job poses, the methods you will use in your demolition, how many people will need to be involved and, of course, costs. You can estimate costs based on how many people you think you will need to employ for the job and how long it will take.

UNIT 4 PROJECT

SKILLCHECK

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

Reverse Bungee Drop of Doom

Over the last decade, thousands of people have been thrilled by the exciting sport of bungee jumping, in which a person jumps from a height while attached to a highly elastic “bungee cord.” The stresses placed on the bungee cord and the tower the person jumps from are of great concern to the people who design the equipment for this activity. In recent years, people at carnivals and fairs have enjoyed a “reverse bungee” experience. In the reverse bungee, participants are seated in a chair attached to a bungee cord that is stretched to the ground and then released.

Safety Precautions

- Take care when working with saws, hammers, and glue guns.
- Wear eye protection and aprons when working with tools.

Challenge

You are part of a team that needs to design, build, and test a prototype for a reverse bungee ride. Your team will compete against other teams in your class to build the safest and strongest ride for a travelling carnival. The team with the best prototype will be awarded the contract to build the ride. Your teacher will judge designs very strictly according to the specifications. The prototype, like the final ride, must have a high margin of safety since human lives will depend upon it. You want the ride to be as exciting as possible, while keeping your passengers completely safe from harm. Your structure’s final mass will also be considered in the competition. The mass will reflect how much it will cost for the carnival to move the ride from city to city.

Specifications

A. The structure must be free standing. (It cannot be attached to the desk or anything else.)

B. The structure must be at least 50 cm in height at its highest point.

C. A golf ball will represent a typical two passenger load.

D. You should try make your prototype as lightweight as possible, while maintaining its stability and safety.

E. The load must be suspended at least 30 cm above the test table or desk.

F. The elastic attached to the load must be at least 10 cm long.

G. The golf ball must remain in the basket/chair during testing.

H. The golf ball cannot make contact with the structure during testing.

I. All forms and types of building materials are allowed, with the exception of materials from commercial construction kits.

J. The structure must survive having the load pulled to the surface of the test table and released at least three times in a row.

Plan and Construct

1. Each team member should independently draw a blueprint for their structure. Plans should reflect the specifications for the project.
2. At a team meeting, all members will present their plans. After discussion, the team should choose a single plan (possibly a hybrid of all of the plans).
3. A final blueprint accompanied by a list of materials and tools needed should be submitted to the teacher for approval.
4. Once a plan is approved, construction can begin.
5. Throughout the construction process, teams should test the structure to see if it is capable of meeting the specifications.
6. Teams should adjust their plan if unforeseen problems arise.
7. Once the structure is complete and meets all specifications, it is ready for testing. Give your ride an exciting name and carry it to the testing desk.
8. Draw a diagram of your prototype. Your diagram should be labelled with the following:
   (a) all parts and materials used in construction
   (b) strong shapes integrated into the structure's design
   (c) areas of the structure placed under compression, tension, or bending during its operation
   (d) the centre of gravity and thrust line of your structure
   (e) a description of the live and dead loads the prototype must carry

Evaluate

1. Measure your prototype's mass, total height, load height, and elastic length to ensure that it meets all specifications. Record the measurements on your diagram.
2. Pull the golf ball down to the table and release it. Repeat the test three times. Examine the structure for signs of structural failure after each test. Record any problems on your diagram.
3. Upon completion of the tests, your teacher will score your structure based on the following evaluation scheme.

Reverse Bungee Scoring Guide

Criteria	Comments	Score (Circle one score)
Meets or exceeds all specifications		Poor 0 1 2 3 4 5 Excellent
Mass of structure compared to other successful entries		Poor 0 1 2 3 4 5 Excellent
Passing bungee test		Poor 0 1 2 3 4 5 Excellent
General appearance or aesthetic value		Poor 0 1 2 3 4 5 Excellent
Total Score		/20

4. Describe any changes your team made during the construction process. Explain why the changes were made.
5. If you were to build the structure again, would you make any changes? Explain why or why not. If your structure did not meet some of the specifications, explain how you might address these problems.

UNIT
4 Review

Unit at a Glance

- Structures can be classified according to their origin (natural or manufactured) and according to how they are built (mass, frame, shell).
- Many manufactured structures are similar in form or function to natural structures.
- Structural designers consider such factors as shape, function, appearance, safety requirements, environment, cost, materials, and joints in their design choices.
- Mass is the amount of matter in an object. It is measured with a balance, using kilograms.
- Weight is a measure of the gravitational force between objects. It is measured with a force meter, in newtons.
- External forces acting on structures include live loads (changing or non-permanent loads) and dead loads (the weight of the structure itself).
- Internal forces include tension, compression, shearing, buckling, and bending.
- Certain design shapes help prevent deformation in structures by strengthening them against particular kinds of forces.
- Friction can be used in structures to keep parts of the structure from moving apart.
- Materials have varying abilities to withstand internal forces. Materials can fail under pressure from forces by snapping, buckling, bending, stretching, shearing, and twisting.
- Choices in design and materials can strengthen a structure against particular kinds of forces.
- A structure's stability (ability not to tip over) depends on its centre of gravity, symmetry, and the stability of the ground upon which it sits.

Understanding Key Concepts

1. What are the key features of a mass, a frame, and a shell structure? Give one natural and one manufactured example of each type.

2. Using as many concepts as possible, write a paragraph describing key structural features of a windmill.

3. How is each of the following types of material made: composite, layered, woven, knit?

4. What are the five basic ways of fastening structures together? Give an example and a typical use of each one.

5. How are design specifications used in the construction of a structure? Give examples in your answer.

6. Give an example of something that you think is not a structure and explain why.

7. Describe the changes you might make to a bridge to increase its margin of safety. What factors might limit your ability to make these changes?

8. Name a live load and a dead load on your desk when you are doing homework on it.

9. Write directions for creating each of these internal forces in a marshmallow: compression, tension, torsion, bending.

10. Identify one external force and one internal force that act on a chair when you are sitting on it.

11. What is the difference between mass and weight?

12. Identify the shape of frame that is the most rigid. Sketch two ways of using this frame to strengthen a stepladder.

13. Draw a diagram of a shelf bending under the weight of heavy books. On your diagram, label the live load, dead load, tension, and compression.

14. Explain how you might test the flexibility of materials used in a structure. Give at least two examples of structures where flexibility is important.

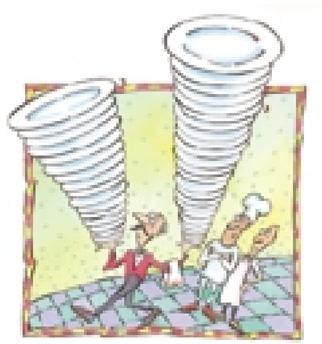
15. Give at least two examples of structures that are designed to withstand compression, and two that are designed to withstand tension.

16. Why does using more nails in a joint often weaken it?

17. Explain how friction can be useful in a structure.

18. Identify the key parts of a lever and the type of structure most likely to be damaged by lever action.

19. What principle does the waiter use to carry this load successfully?



20. Describe
    - **(a)** one way that tension forces cause deformation
    - **(b)** two ways that compressive forces cause deformation
    - **(c)** two ways that torsion forces cause deformation

21. Identify three ways in which builders create firm foundations for their structures.

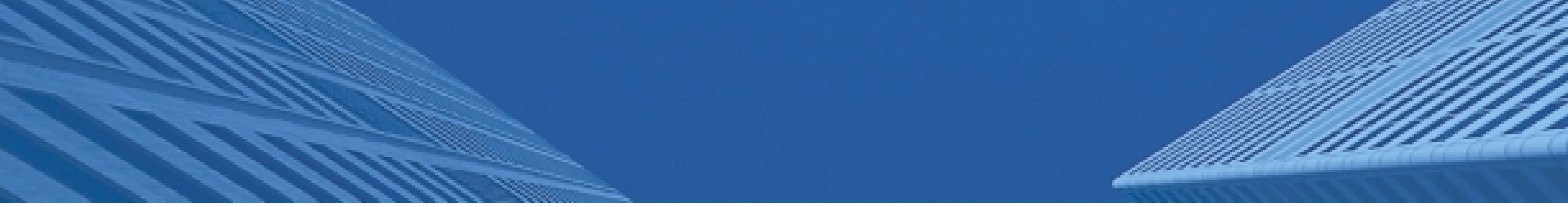
22. Explain, using diagrams, the main factors that affect the stability of structures. Include the following terms as labels on your diagrams: mass, balance, tension, compression, gravitational force, symmetry, centre of gravity.

Developing Skills

23. Draw a concept map to summarize Topic 1. Make sure that it has a section each for mass, shell, and frame structures. Include examples, advantages, and problems for each type of structure.

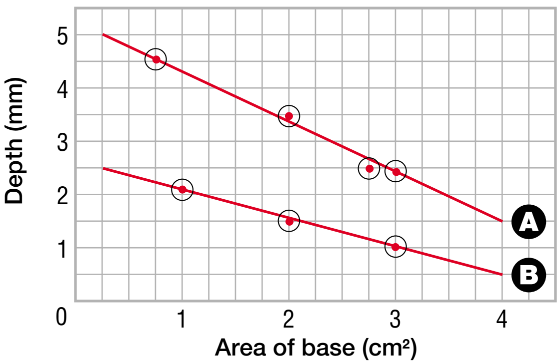
24. Make a concept map to summarize Topic 2. Make sure that it has five sections, one for each of the four design features and one for other important ideas.

25. Write instructions for using each of the pieces of equipment shown in the photographs below. Explain why you would use each.



26. Study the graph below.

Depth an Object Can Be Driven Versus Area of Base



(a) Which soil sample was packed more tightly, sample A or sample B?

(b) How far would a wood block with an area of 2.0 cm² sink in the loose soil?

(c) A nail was driven 1.5 cm deep into the packed soil. What was its base area?

27. The graph above was produced as a result of an investigation.

(a) State the problem that the investigation was trying to solve.

(b) Identify the manipulating and responding variables in the investigation.

(c) Describe at least two variables that would need to be controlled in the investigation.

(d) Based on the data presented in the graph, write a conclusion that answers the problem.

Problem Solving/Applying

28. Suggest three specifications that need to be met by a successful design for

(a) an emergency flashlight

(b) a toothpaste tube

29. You need to store winter clothes to stay clean, dry, and free from insects in summer.

(a) Describe a simple structure to perform this function.

(b) Describe a more complicated structure for this function.

30. Polyester is a type of plastic that can be made into fibres and woven into cloth. Polyester clothing is strong, but it traps perspiration and is not very warm. To overcome these problems, clothing is often made with a blend of wool and polyester fibres. Pure wool is very warm and attractive but it is not strong, especially when it is wet. Wool shrinks unless it is washed very gently in cold water. Some people find that woollen clothing is itchy and irritates their skin.

(a) Check the labels on some of your clothing to find a garment that is mostly wool or polyester. Which of the properties described above does it have?

(b) To make warm winter clothing, would you use a cloth that was mostly polyester or mostly wool? Why?

(c) To make comfortable indoor clothing that could be machine washed, would you use a lot of wool in the blend or a little? Why?

31. Examine the table top hockey game above.

(a) List ways in which the following forces could be exerted while playing the game: compression, tension, bending, torsion, shear, friction.

(b) Could the user of the game decrease any of the above forces during its use? Explain how.

32. What type of foundation would you recommend for each structure listed below? Give a reason for each choice.
   (a) a brick garden wall
   (b) a boat dock
   (c) a roof over the patio behind a house
   (d) the concrete patio under the roof in part (c)

33. Cassette tapes and CDs are sold in brittle plastic cases that often crack and break.
   (a) What type of material failure is happening when you step on a CD case and it cracks?
   (b) Name three ways that you could strengthen the case while still making it out of the same plastic. Why do manufacturers not make these plastic structures stronger?

Critical Thinking

34. Some chairs are built from pieces of metal or wood covered with softer material. Some are made from solid pieces of foam plastic, and some are made of single pieces of moulded plastic.
   (a) Classify each type of chair according to its type of structure.
   (b) Give one advantage and one design problem for each type of design.

35. Very large structures can use a lot of materials and affect a large area. Suggest two environmental problems that designers had to overcome when planning each project described below.
   (a) The "Chunnel" is a 50 km tunnel under the sea between England and France. Three tubes, each large enough for railway trains to pass through, had to be dug through soft, water-filled rock.
   (b) The Confederation Bridge between Prince Edward Island and New Brunswick is a 12.9 km reinforced concrete structure. Icebergs and high winds are common in the area, especially in the winter. Important fishing grounds are nearby.
   (c) The Hibernia drilling platform is the largest object made by humans that was ever moved on Earth. It is the height of the Calgary tower and uses enough steel to build 15 Eiffel Towers. It took six years to build. A lake had to be drained to make room at the construction site to build it. The platform sits in iceberg-filled waters off the coast of Newfoundland.

36. Laboratory balances will not work in "weightless" conditions far from Earth. Why? A diagram might help explain your answer.

37. Copy the four situations below in order of increasing gravitational force.
   (a) two small objects close together
   (b) the same two small objects far apart
   (c) a large object close to a small object
   (d) the same large object equally close to another large object

38. A tree branch can support your weight when you stand on it near the trunk of the tree. When you move farther toward its tip, however, it bends and breaks.
   (a) Explain why your weight has such different effects on the branch.
   (b) Sketch the bending branch. Mark the part that is in compression and the part that is in tension.
   (c) Will the top of the branch snap or buckle when it breaks? Why? What happens to the bottom of the branch? Sketch the break in the branch to illustrate your answer.

39. What problem could arise in a cold climate if house foundations were not dug down deep enough to reach soil that never freezes?