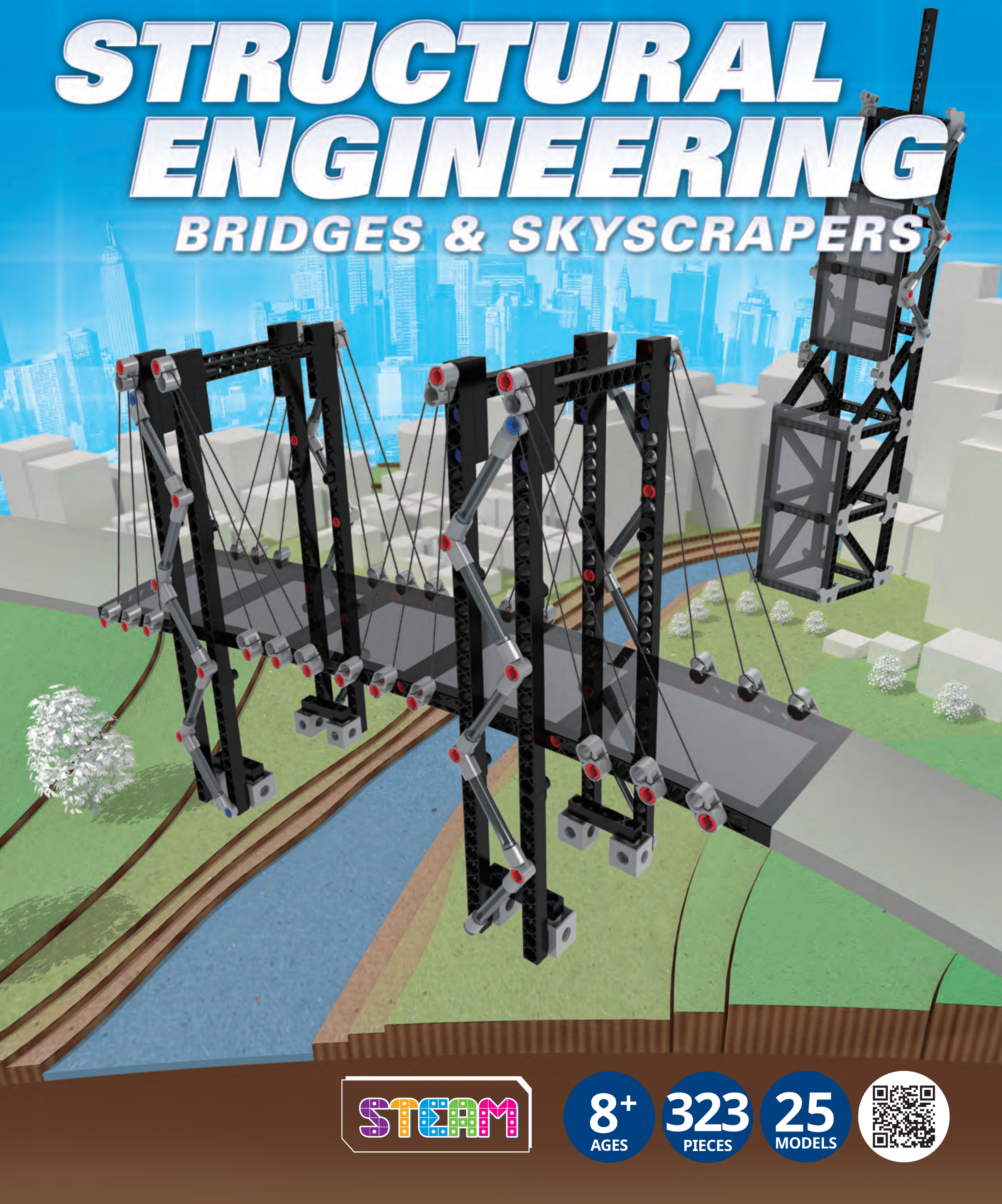
EXPERIMENTS | # 7410

STRUCTURAL ENGINEERING

BRIDGES & SKYSCRAPERS

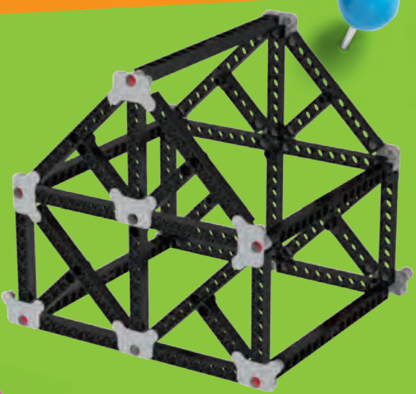


STEAM

8+ AGES

323 PIECES

25 MODELS



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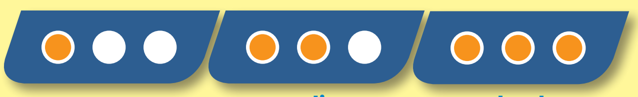
TIP!

At the top of each model assembly page, you will find a blue bar:

››› It shows how difficult the model's assembly will be:

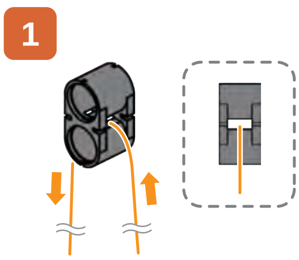


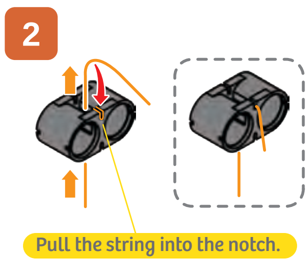
easy medium hard

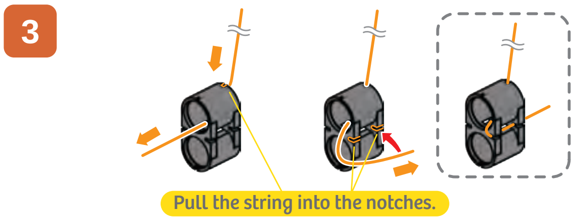
››› ASSEMBLY TIPS

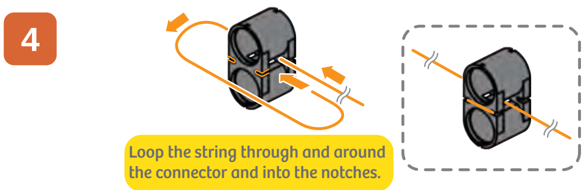
String connectors

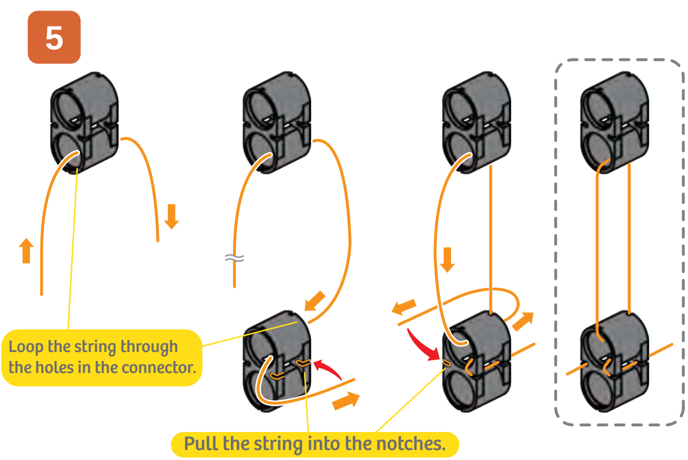
Some of the models in this kit use string connectors to connect the strings to the other parts. These diagrams show you five different ways to insert the strings into the string connectors.











Peg and Axle connector

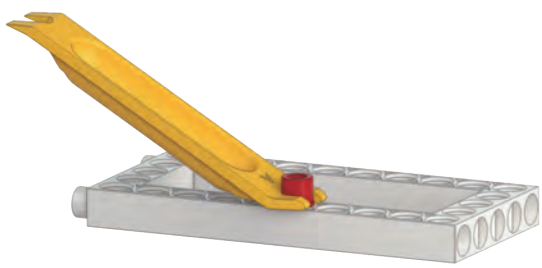
Take a careful look at the different assembly components. Red long peg, blue short peg and axle connector all look pretty similar at first glance. When you assemble the models, it's important to use the right ones. The blue short peg are shorter than the red ones. The axle connector allow the parts to rotate.

Axles

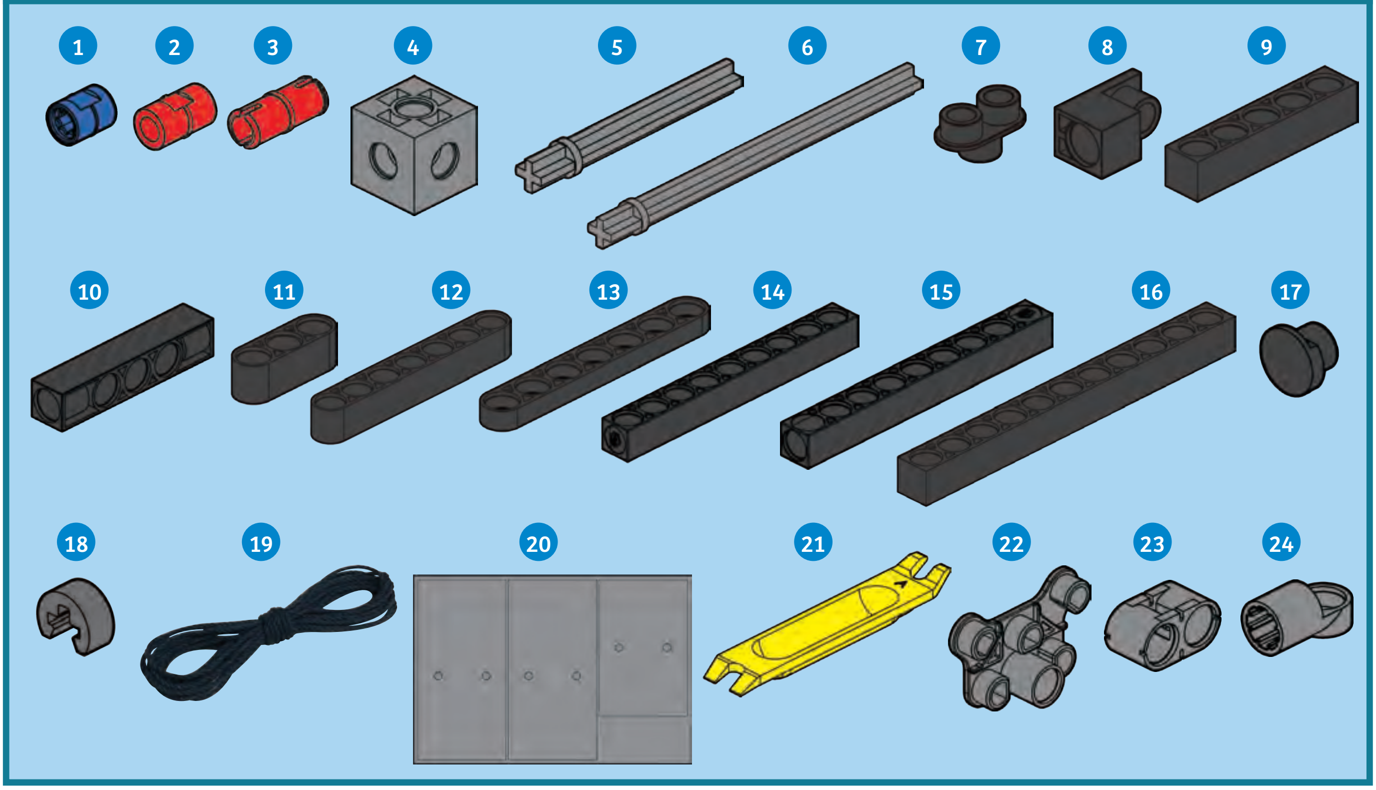
The building system contains axles of various lengths. In this kit, these axles are used as rods. Axles can be connected to the other axles and to each other using the axle rod connectors. When assembling a model, always be sure that you're using the right axle and that the axle rod connector is oriented the correct way on the axle .

Peg Romover

When you want to take your model apart again, you will need the peg remover lever. Use the narrow end of the lever to remove the pegs. You can use the wide end to pry apart other parts.



What's inside your experiment kit:



Checklist: Find – Inspect – Check off

✔	No.	Description	Qty.	Item No.
❍	1	B-SHORT PEG	40	7344-W10-C2B
❍	2	C-LONG PEG	20	7061-W10-C1R
❍	3	C-AXLE CONNECTOR	32	1156-W10-A1R
❍	4	B-6 HOLE CUBE	8	880-W10-N1S1
❍	5	C-60mm AXLE	12	7413-W10-M1S
❍	6	C-100mm AXLE	4	7413-W10-L2S
❍	7	C-TWO-IN-ONE CONVERTER	16	7061-W10-G1D
❍	8	C-FRONT CONVERTER	14	7061-W10-J2D
❍	9	C-5 HOLE ROD	12	7413-W10-K2D
❍	10	C-5 HOLE ROD FRONT CLOSED	10	7413-W10-K3D
❍	11	C-3 HOLE ROUND ROD	2	7404-W10-C1D
❍	12	C-7 HOLE ROUND ROD	2	7404-W10-C2D
❍	13	C-7 HOLE PROLATE ROD	2	7404-W10-C3D
❍	14	C-9 HOLE ROD	24	7407-W10-C1D
❍	15	C-9 HOLE ROD FRONT CLOSED	13	7407-W10-C2D
❍	16	C-11 HOLE ROD	11	7413-W10-P1D
❍	17	C-SHORT BUTTON FIXER	8	7061-W10-W1D
❍	18	C-AXLE FIXING	9	3620-W10-A1D
❍	19	C-4000mm STRING	2	R39#7410
❍	20	P-DIE CUT PLASTIC SHEET	1	K41#7410
❍	21	B-PEG REMOVER	1	7061-W10-B1Y
❍	22	C-6-WAY CONNECTOR	24	7410-W10-A1S
❍	23	C-STRING CONNECTOR	24	7410-W10-B1S
❍	24	C-AXLE ROD CONNECTOR	32	7410-W10-C1S

To build the models, you will also need:
scissors, ruler or measuring tape

Cutting the string to length

You will need to cut the two 400-cm black strings to the following lengths. The specific lengths needed for each model are indicated in the assembly instructions for each model.

20 cm x 4

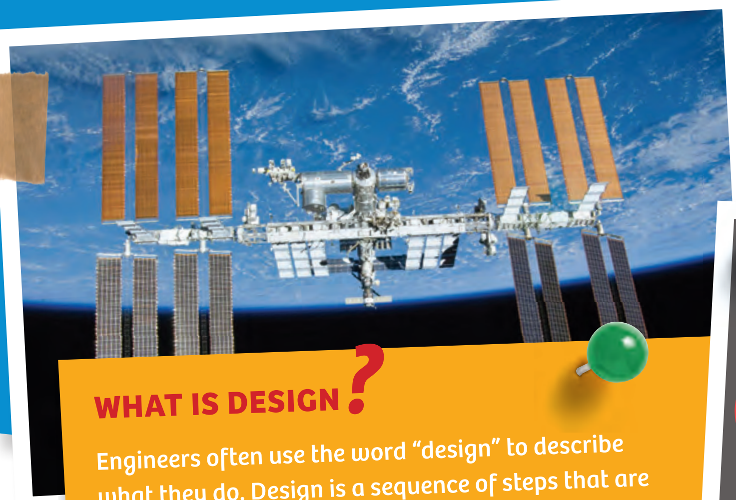
24 cm x 4

38 cm x 8

What Is Structural Engineering?

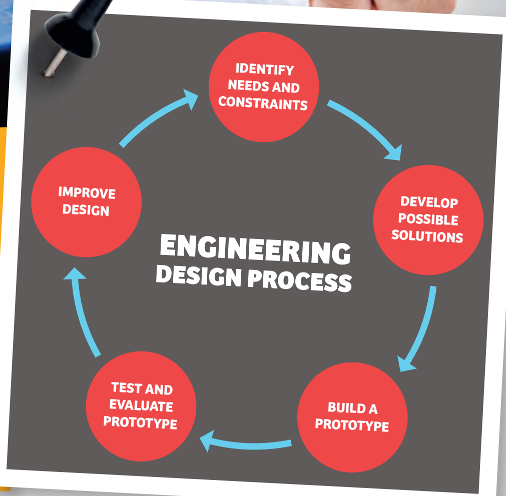
Structural engineers apply **physical laws** and **empirical knowledge** to build complex structural systems. Empirical knowledge is simply information you learn by observing the results of experiments and observing occurrences in the world around you. Engineers build complex structures by combining many simpler parts, called **structural elements,** together. These elements have well-documented physical properties, so engineers can predict how they will work together in the final structure. In this kit, you will learn about some of these structural elements and use them to build your own complex structures.

When people think of structural engineering, most often they imagine the design and construction of buildings, towers, dams, and bridges. But structural engineers are also involved in the design of structures such as satellites, aircraft, ships, and medical devices such as stents. The same physical laws apply to the design of structures of all shapes and sizes.



WHAT IS DESIGN?

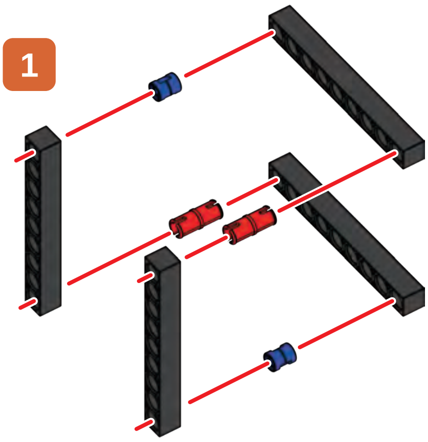
Engineers often use the word "design" to describe what they do. Design is a sequence of steps that are used to take an idea from concept to functioning product or process. The engineering design process is iterative, meaning steps can be repeated multiple times and then improvements can be made each time, until the correct or optimal outcome is achieved.



SQUARE

First, let's build some simple models and conduct simple experiments with them to show how connecting structural elements together in different ways can affect the strength and stability of a structure.

1



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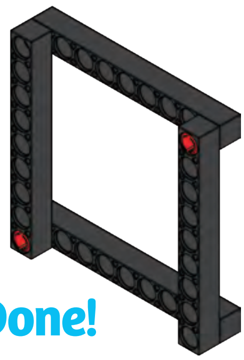
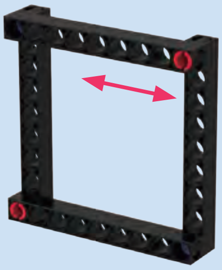


Done!

EXPERIMENT 1

Stability of a shape

HERE'S HOW



Hold one corner of the model in one hand and try to deform the model by moving the opposite corner. Does the model deform?

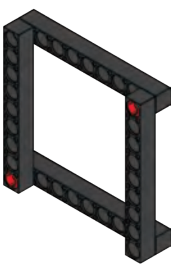
WHAT'S HAPPENING?

When you are pushing on the corner of the square, you are applying a **force**, or **load**, to the structure. A goal of structural engineering is to achieve the **stability** of a structure under different loads. All structures will change shape to some degree when loads act on them. In a **stable** structure, the changes in shape, or **deformations**, are small, and forces within the structure return the structure to its original shape after the load is removed.

In an **unstable** structure, the changes in shape are large and usually increase as long as the forces are applied. An unstable structure does not have the internal forces required to restore the structure to its original shape. Is the square a stable or unstable structure?

BRACED SQUARE

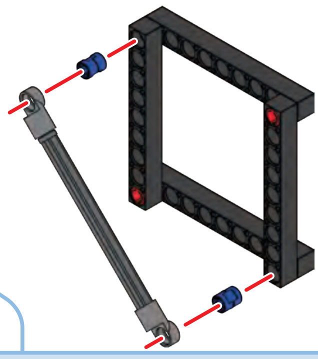
1



Start with the model from Experiment 1.

2

3



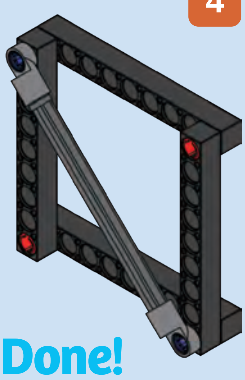
EXPERIMENT 2

Reinforced structures

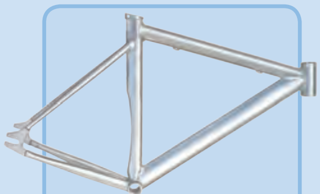
HERE'S HOW

Repeat Experiment 1 with the braced square. How does the braced square react to the load?

4



Done!



The frame of a bicycle uses a similar shape!

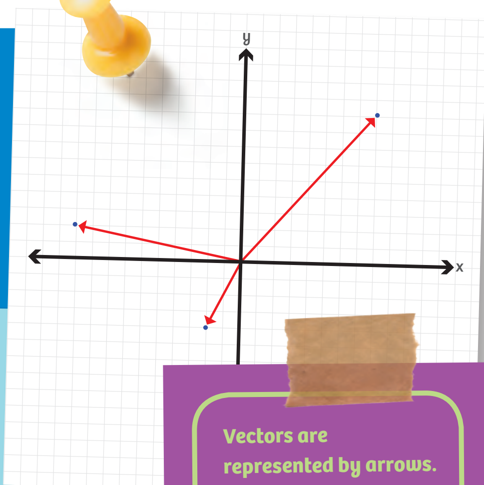
WHAT'S HAPPENING?

You made the square model into a stable structure by adding a rod connecting the two corners. This locked the angle of the other rods. When you push on the corner of the square, you can feel the model move a little bit. As you stop pushing on it, you can feel it return to its original shape.

CHECK IT OUT

Vectors, Forces, and Moments

To understand what makes a structure stable, you must understand vectors, forces, and moments.



Vectors are represented by arrows. The arrow's head points in the direction of the vector and the line's length represents the vector's magnitude. A longer arrow means a larger magnitude.

VECTORS

A quantity that only requires a unit of magnitude to describe it is known as a **scalar.** For example, if you wanted to describe how much an object weighs, you would only need to include a unit of measure such as pounds (lb) or kilograms (kg).

In physics and engineering, another useful concept is a **vector.** A vector is a quantity that has both a **magnitude** and a **direction.**

Two important examples of vectors are **velocity** and **acceleration.** Velocity describes how fast an object is moving and in what direction. If you rode your bike at five miles per hour and went due north, then that would be your velocity. Acceleration is a measure of how the velocity of an object changes. An object, such as a car, is accelerating when it is speeding up, slowing down, or changing direction.

An important part of structural engineering is calculating how forces and moments affect and pass through a structure. A mistake in these calculations could cause the structure to fail, or fall down.

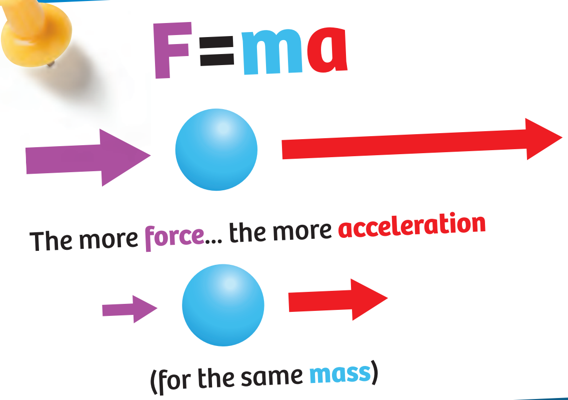
FORCES

A **force** is an interaction between objects. There are three laws that govern the ways that forces behave, called **Newton's laws of motion.**

NEWTON'S FIRST LAW OF MOTION ...

... states that an object remains at rest or in motion at a constant velocity, unless acted upon by a net force. This is often called the law of inertia, and is simplified to: "An object in motion stays in motion, and an object at rest stays at rest."

CHECK IT OUT



NEWTON'S SECOND LAW OF MOTION ...

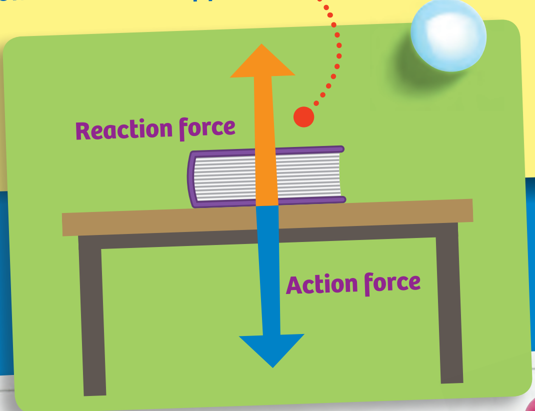
... states that the sum of the forces on an object is equal to the mass (m) of the object multiplied by the acceleration (a) of the object, or

$$F = m \times a$$

Both acceleration and force are vectors, so both can change if either their magnitude or direction changes.

NEWTON'S THIRD LAW OF MOTION ...

... states that when a force is exerted on an object, the object exerts a force equal in magnitude but opposite in direction. In structural engineering, these forces are called **reaction forces**. They typically occur at connections or supports.



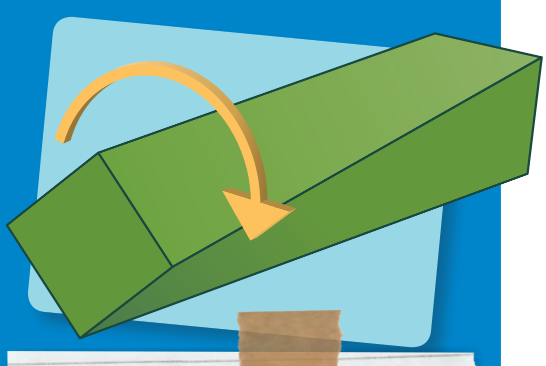
For example, all objects have a weight, which is due to the force of gravity acting on them. If a book is sitting on a table, the book generates a force that pushes down on the table due to its weight. The table pushes back on the book with an equal and opposite force. If there was no reaction force, the book would fall through the table!

MOMENT

A force tends to cause an object to move. But depending on where the force is applied on an object, the force can also cause an object to rotate. For example, if you push on the end of a wrench, the force causes it to turn around the bolt. A **moment** is a measure of a force's tendency to cause an object to rotate around a specific reference point. A moment is calculated by multiplying the force by the distance between the point at which the force is acting on the object and the reference point:

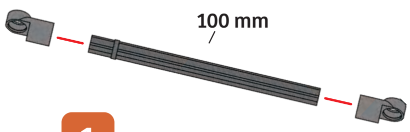
$$M = F \times d$$

You can increase the moment by increasing the force or the distance between the force and the point of rotation.

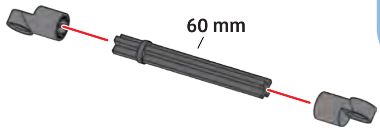


A moment is also a vector, but it is represented by a curved arrow. The direction of the arrow (clockwise or counterclockwise) represents the direction of the moment, and the length represents the magnitude.

TRIANGLE



1



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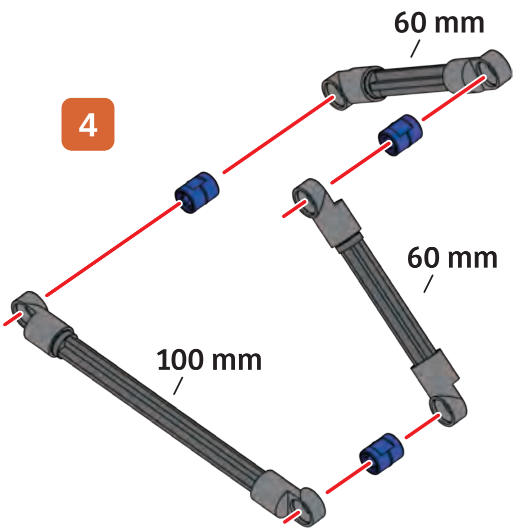


EXPERIMENT 3

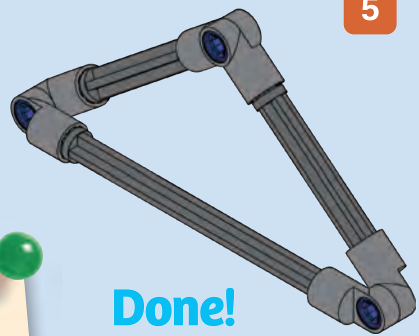
Minimizing materials

HERE'S HOW

Repeat Experiment 1 with the triangle. How does the triangle compare to the square and braced square?

The triangle is the simplest geometric shape that is stable.

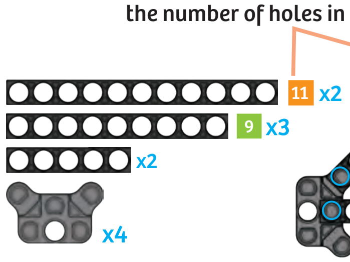
5



Done!

SIMPLE TRUSS

Note: These callouts indicate the number of holes in the rods.



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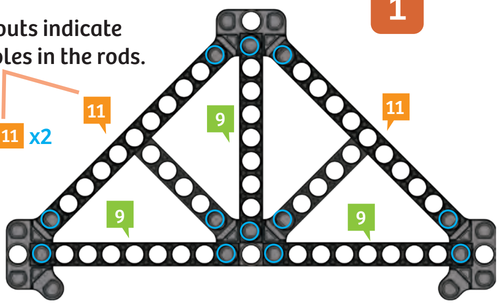

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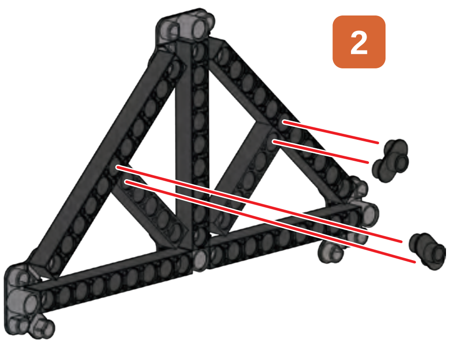


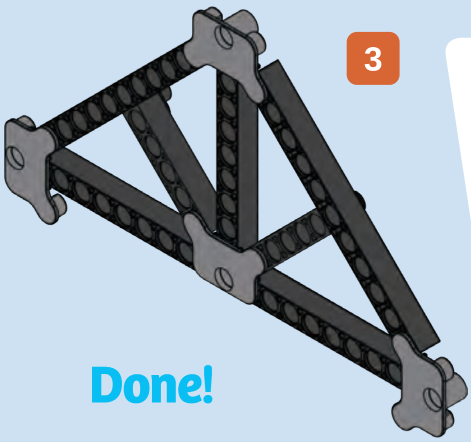
EXPERIMENT 4

Simple truss

HERE'S HOW

Push and pull on the corners of the simple truss. Observe how it responds to these forces. Compare this to the previous experiments.

3



Done!

WHAT'S HAPPENING?

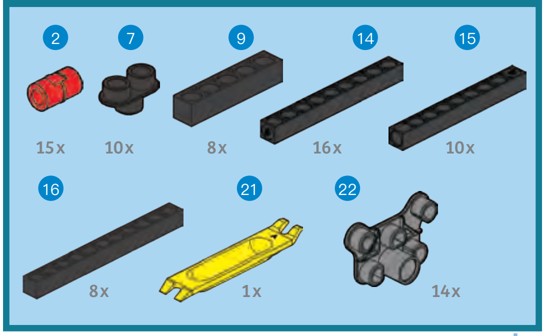
Structural engineers regularly combine simple, well-understood elements together to build more complex structures. In this case, four triangles are combined together to form what is called a **simple truss.** The truss uses a relatively small amount of material to achieve a relatively large amount of stability.

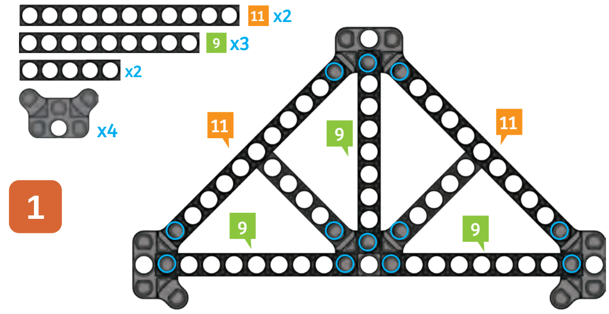
HOUSE FRAME

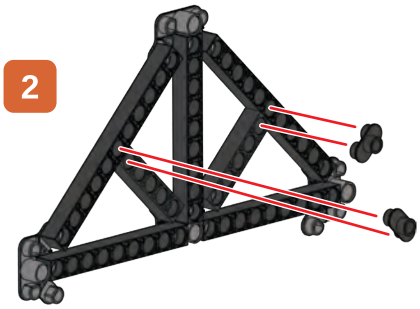
Now, let's build a couple more complex models using some of the simple elements you already built.

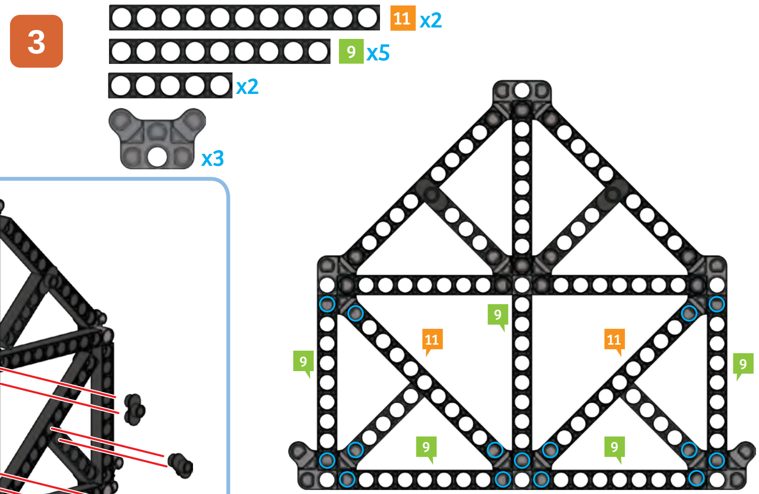
×2
Repeat steps 1–5 two times.

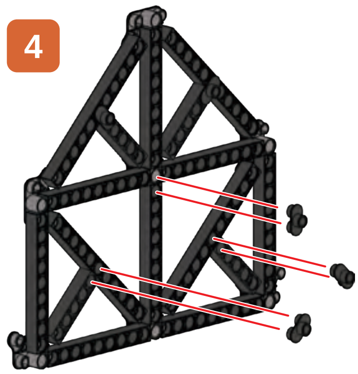
Parts Needed

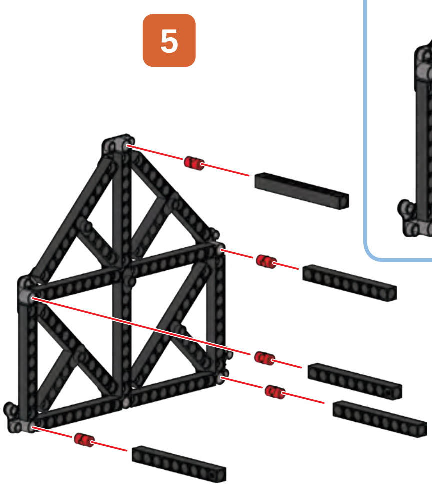


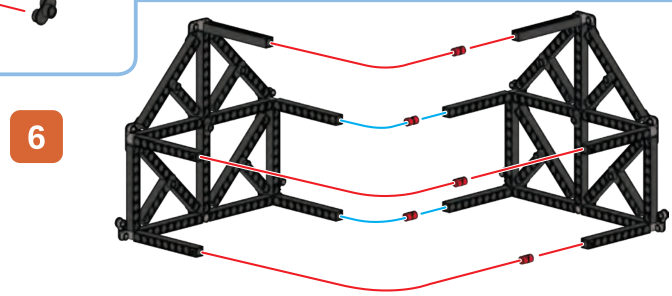












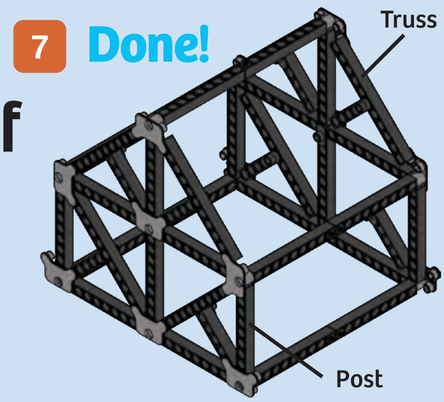
EXPERIMENT 5

Snow on the roof

HERE'S HOW

Open a heavy book in the middle and place it over the top of the house frame. What do you observe happens to the house frame?

7 **Done!**

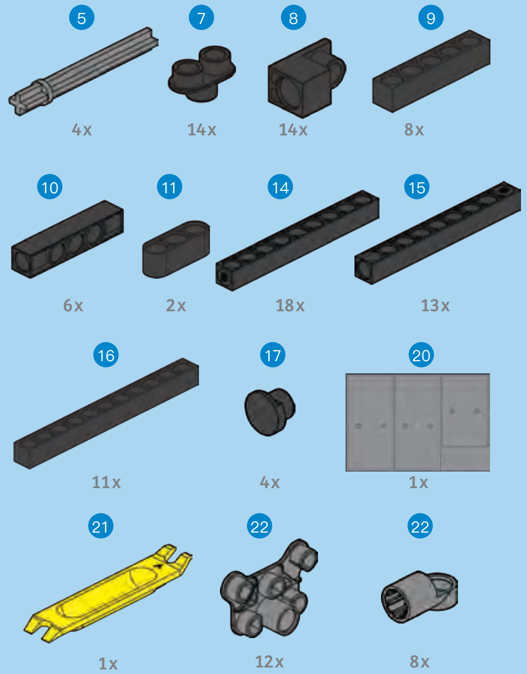


WHAT'S HAPPENING?

Trusses are used to support the roofs of houses. In this experiment, the roof trusses transfer the load from the book to the posts of the house frame. The posts then transfer the load down to the surface on which the house frame model is sitting, which is pushing back up on it.

MODERN HOUSE

Parts Needed



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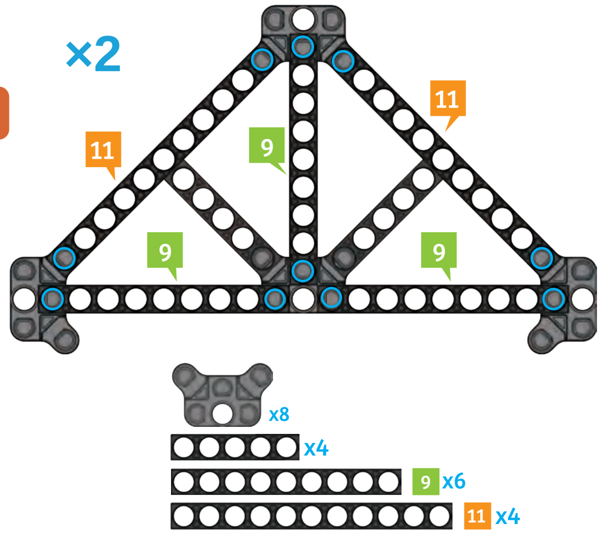
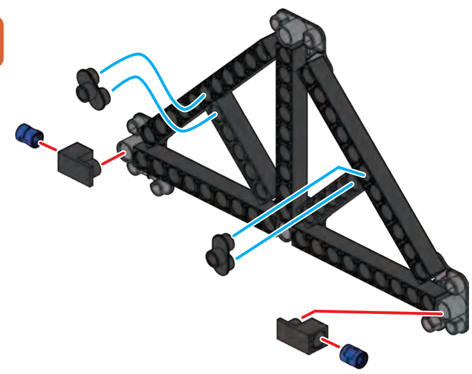
×2



2

×2



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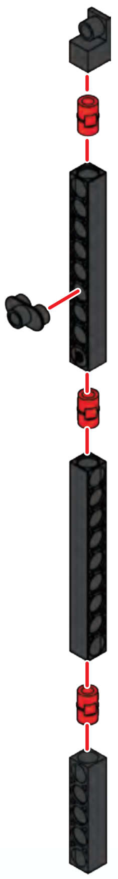

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×2

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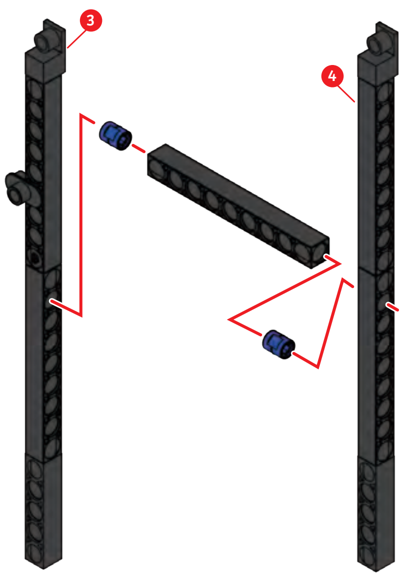

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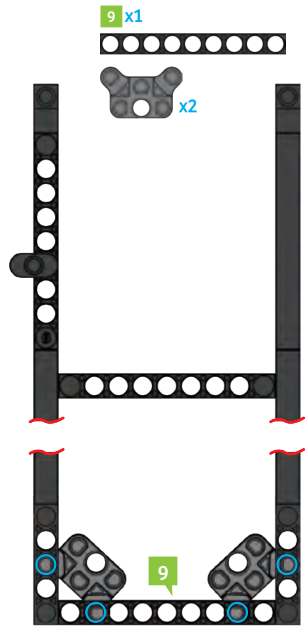

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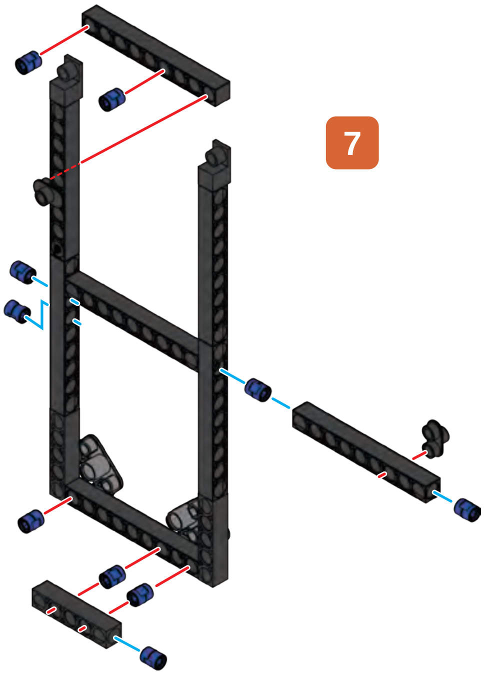

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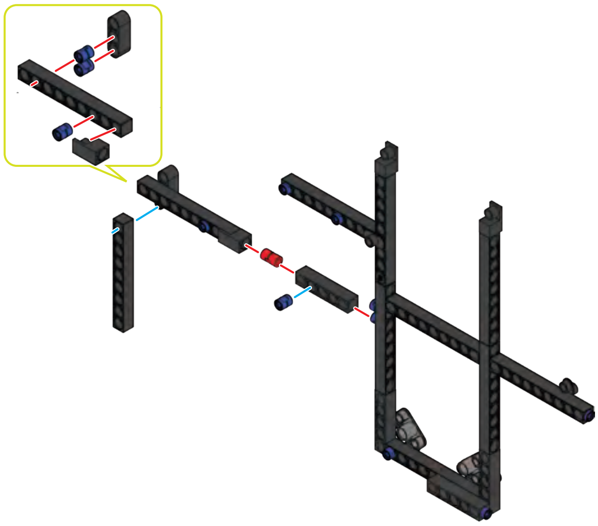

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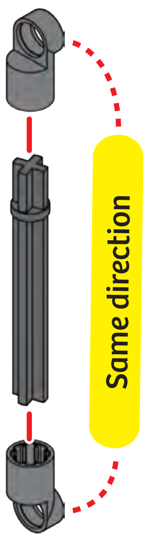
×4



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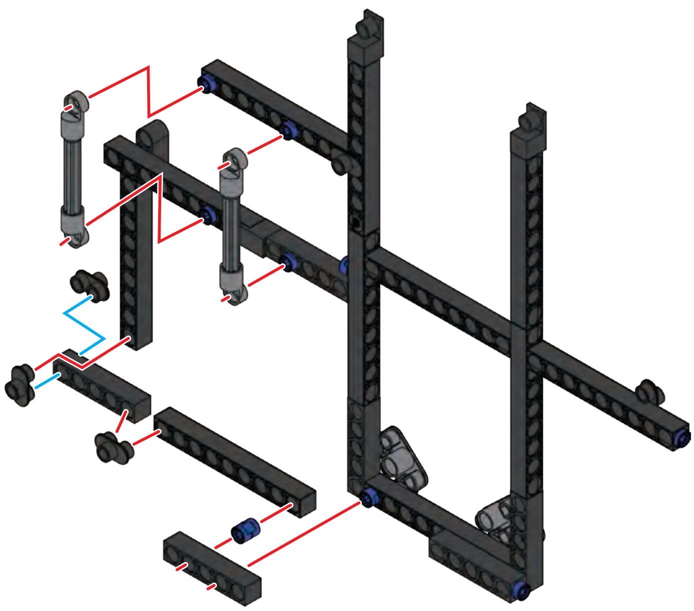

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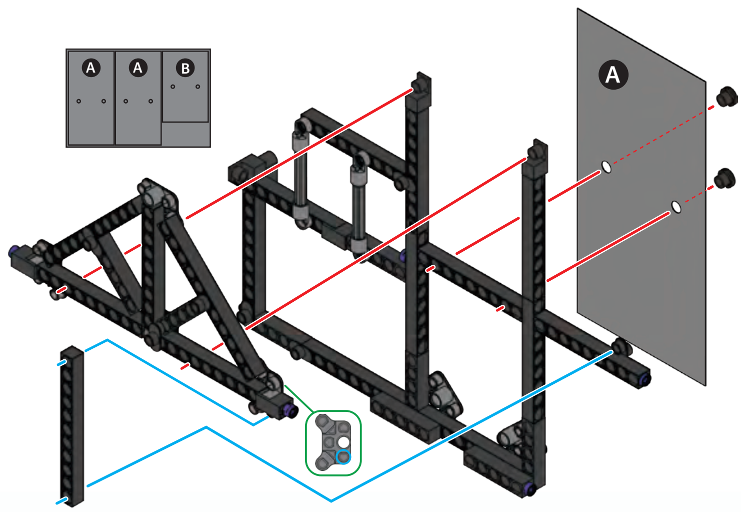

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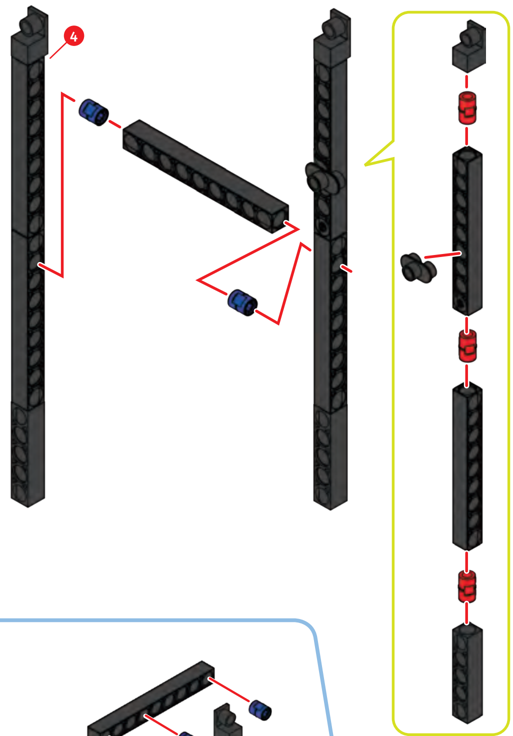

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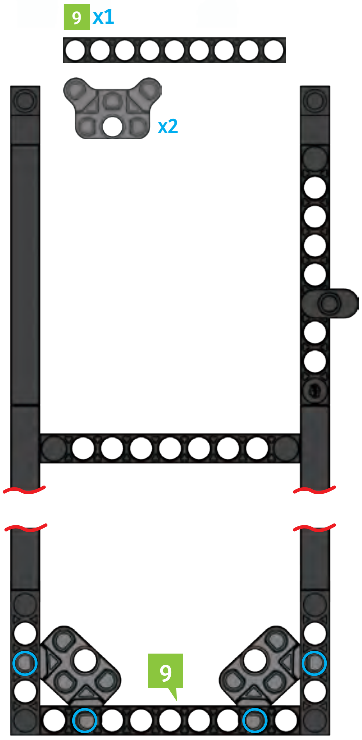

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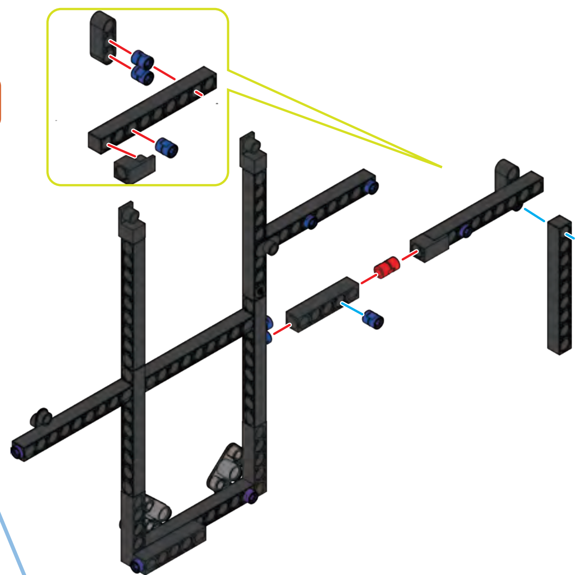

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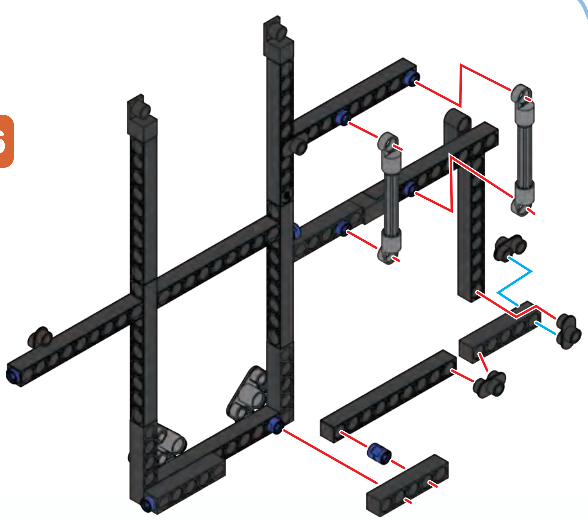

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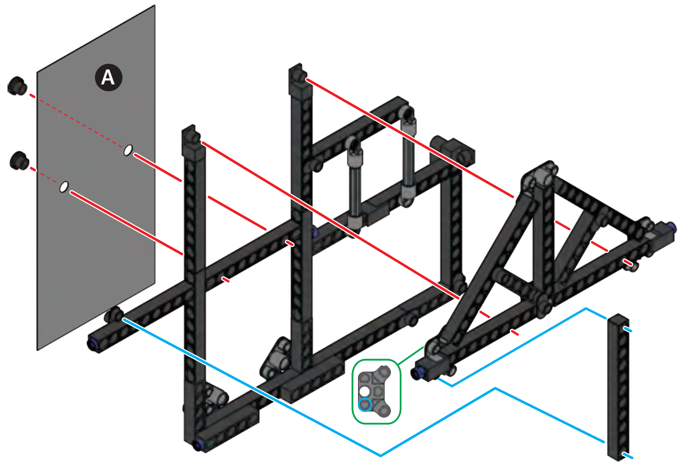

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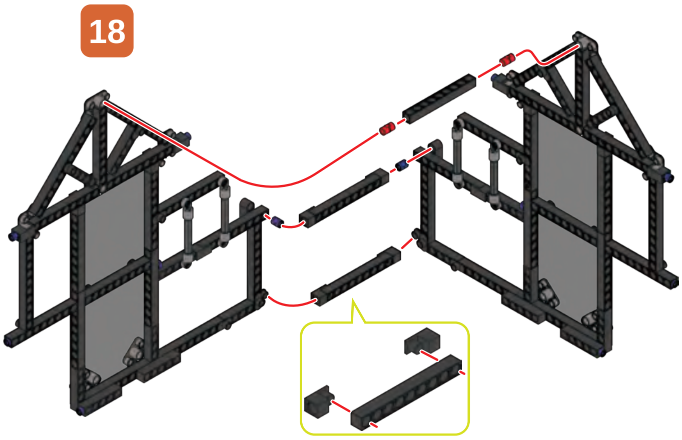

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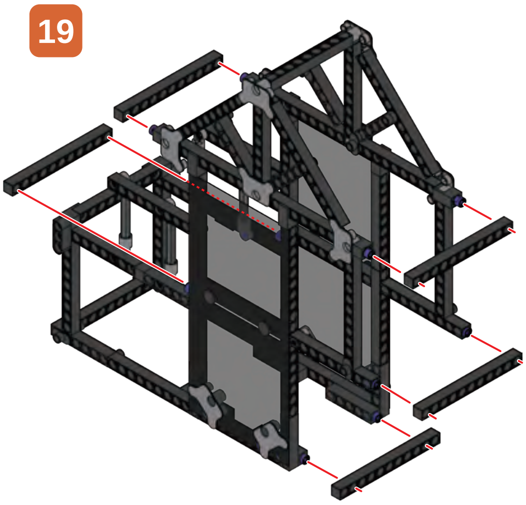


EXPERIMENT 6

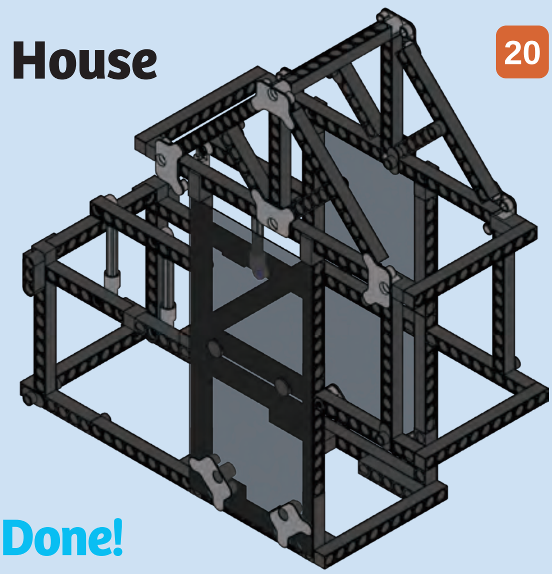
Engineering Design Challenge: House

HERE'S HOW

Using only the materials in this kit, design and build your own house. Think about how the rooms in the house will be used. How many rooms do you need? How are you limited by the amount of space and materials you have? What do you need to do in order to make the house safe and comfortable for its occupants?

These are just some of questions that engineers and architects have to consider when designing and building a house.

20

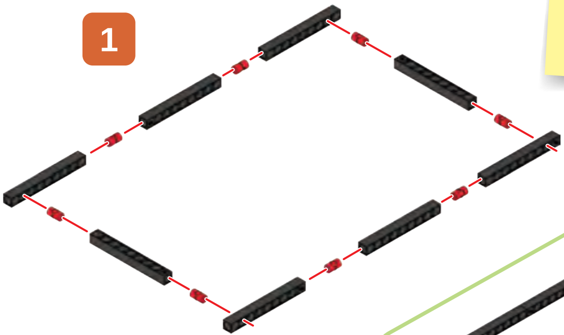


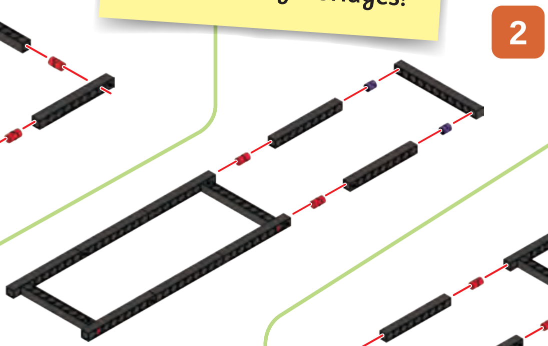
Done!

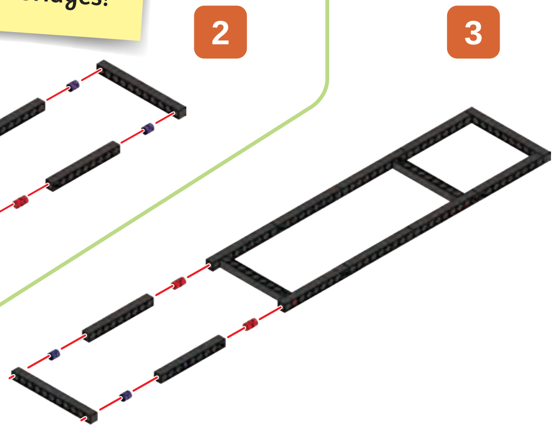
EXPERIMENTS

BEAM BRIDGE

Now, let's apply what you have already learned to another type of structure that many structural engineers design: bridges!





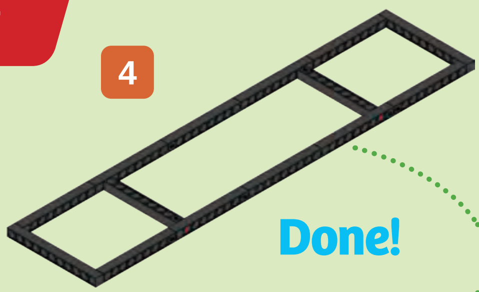


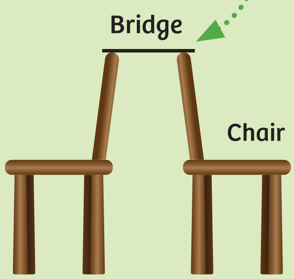
EXPERIMENT 7

Bending

HERE'S HOW

Set up two chairs as shown. Lay the beam bridge so it spans the distance between the backs of the two chairs. Tie a weight to the center of the bridge using a string. Use a ruler to measure the **deflection**, or the degree to which the bridge is displaced under the load, at the middle. Change the weight and measure the deflection again.





WHAT'S HAPPENING?

When you hang the weight on the beam bridge, the force of the weight causes the bridge to **deflect**, or **bend**, because the bridge is only supported by the two chairs at its ends. The middle of the bridge deflects downward because the materials of the bridge are not strong or rigid enough to counteract the load.

Can you think of some ways you could make this bridge stronger and deflect less?

Engineering Design:

Serviceability and Material Properties

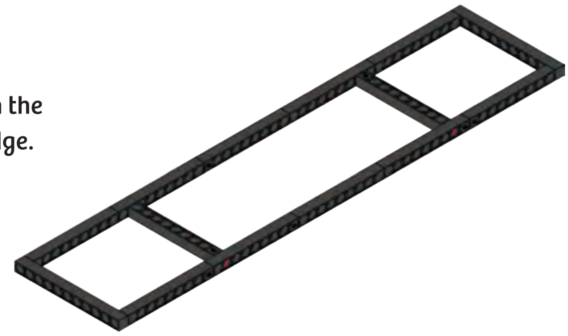
Structural engineers must consider the serviceability of all of the structures they design. **Serviceability** is the ability of a structure to fulfill its function. A structural engineer has to consider not only the ability of a structure to stay standing, but also whether the structure will be able to meet all of the needs of its users or occupants over its entire lifespan. For example, the structure must not vibrate so much that people can't be comfortable inside it.

In addition to understanding forces and moments, a structural engineer has to understand the properties of the materials that they are using. **Material properties** are quantitative measurements of how different materials respond to the application of different kinds of forces and moments. Material properties allow structural engineers to assess the benefits and drawbacks of using different materials.

REINFORCED BEAM BRIDGE

1

Start with the beam bridge.



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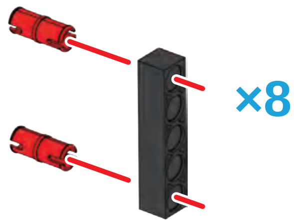

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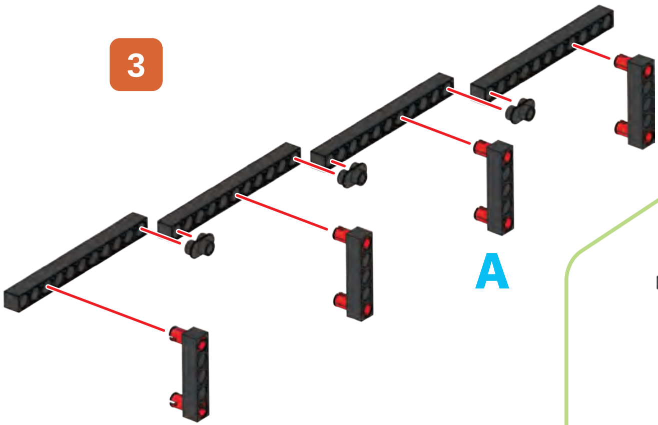

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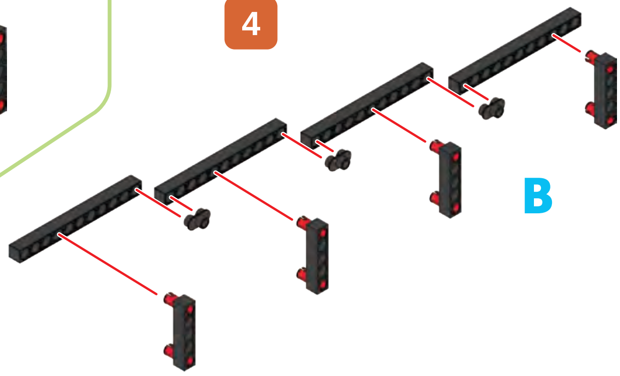

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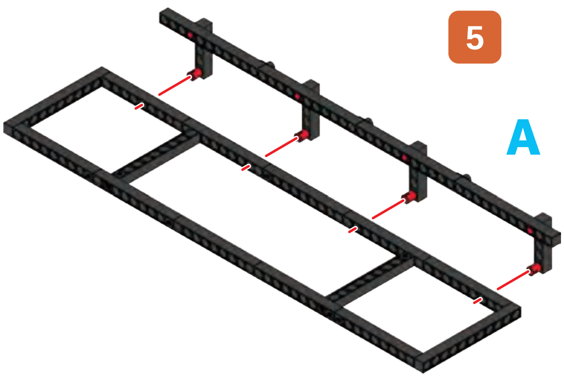

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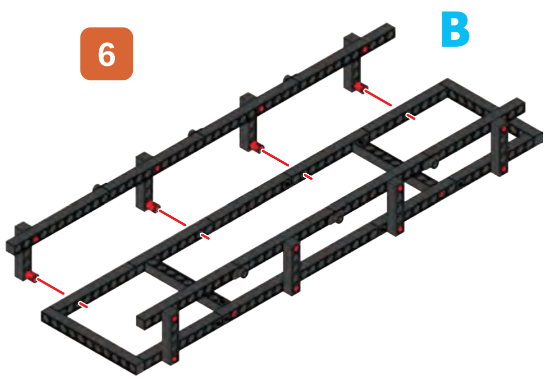

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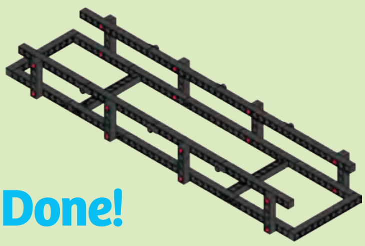


Done!

EXPERIMENT 8

Send in the reinforcements

HERE'S HOW

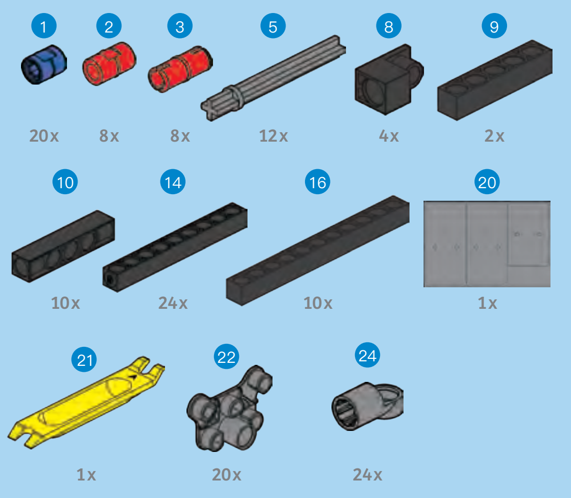
Place the reinforced beam bridge between two chairs as you did in the previous experiment. Tie a weight to the center of the bridge using a string. Use a ruler to measure the deflection of the bridge. Compare the deflection to the results of the previous experiment for the same weight.

WHAT'S HAPPENING?

Because the bridge is reinforced with some additional rails along the side, the amount of deflection is reduced.

TRUSS BRIDGE

Parts Needed



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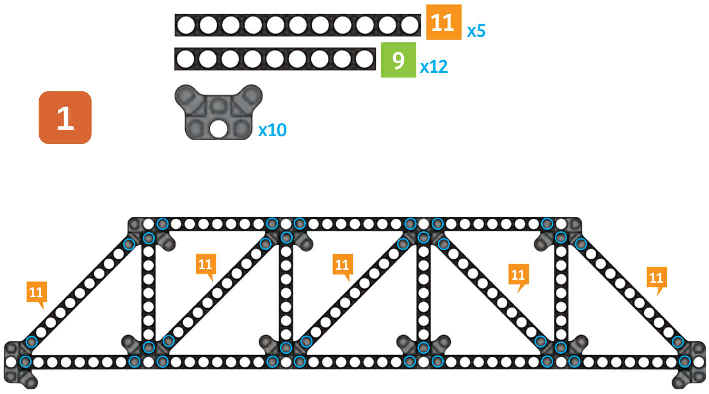

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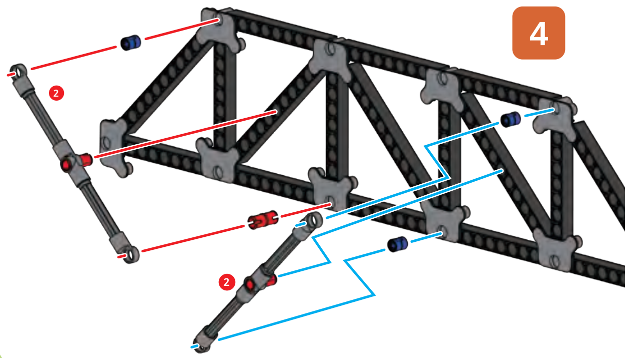

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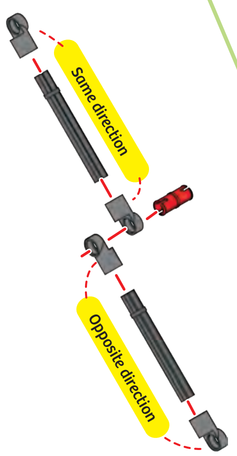

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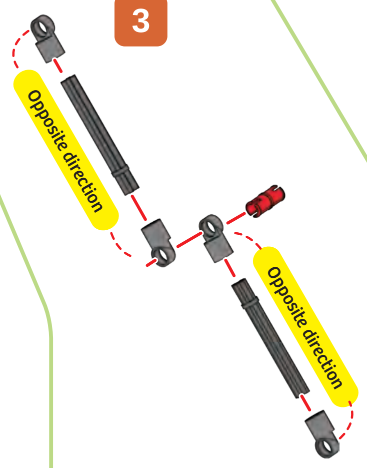

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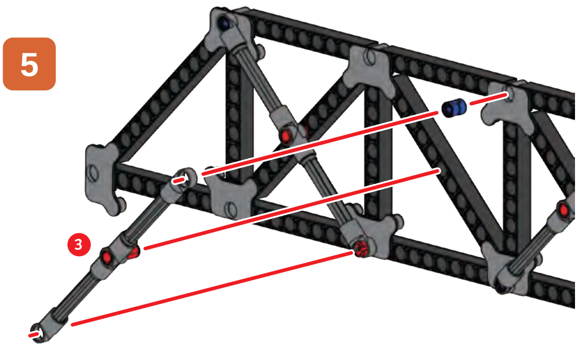

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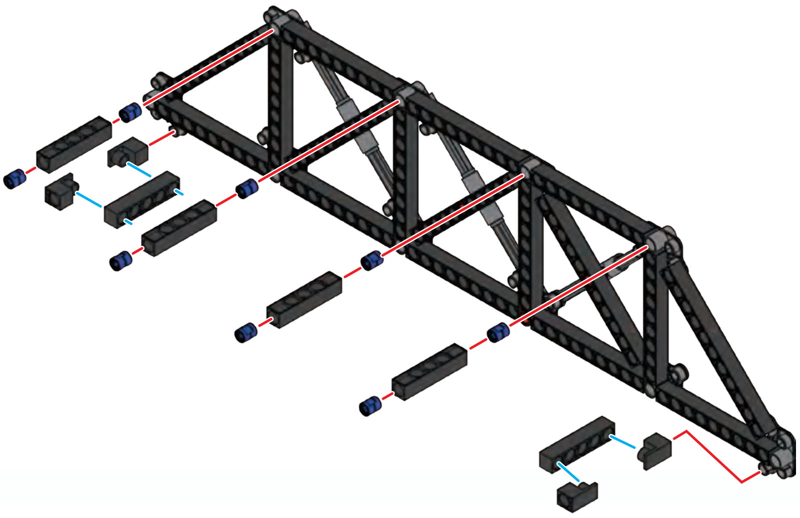

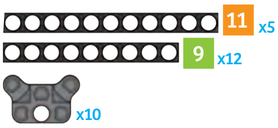

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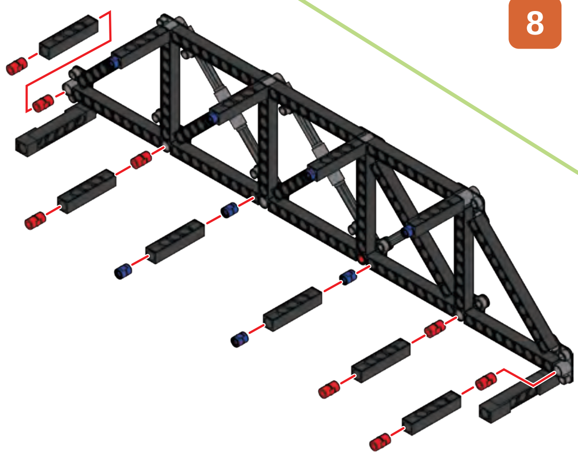

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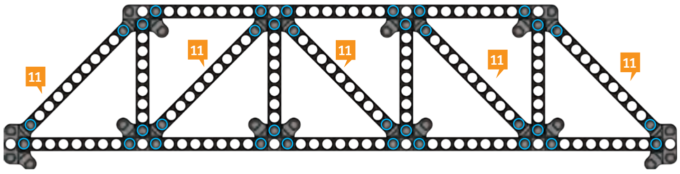

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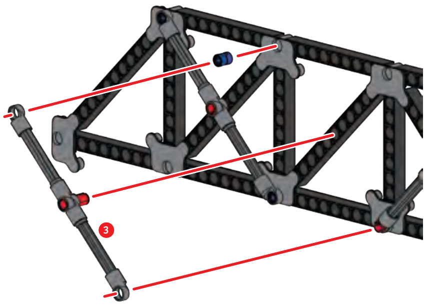

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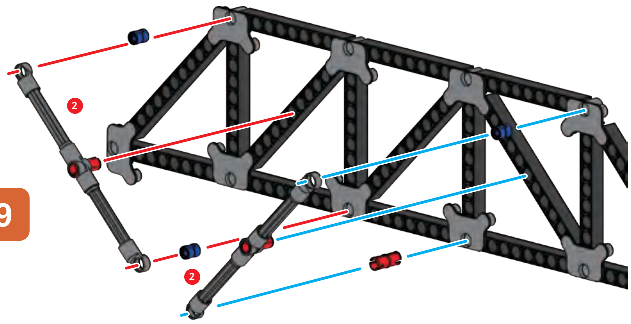

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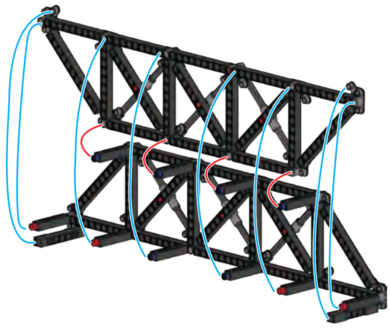

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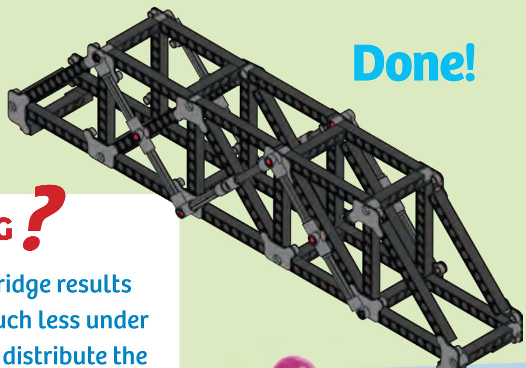


EXPERIMENT 9

Engineering constraints

HERE'S HOW

Repeat Experiment 7. Compare the amount of deflection in the different bridges. Which bridge is the strongest?

A crucial task of an engineer is to identify and understand constraints in order to develop a solution. An engineer has to balance many different trade-offs. Some trade-offs an engineer may face include available resources, cost, productivity, time, quality, and safety.

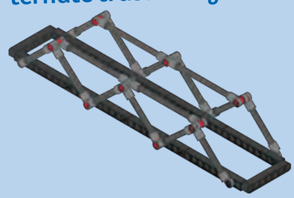
WHAT'S HAPPENING?

Adding the trusses to the bridge results in a bridge that deflects much less under the same load. The trusses distribute the forces through the bridge in such a way that the middle of the bridge deflects less. Some of the rods in the truss are under compression and some are under tension, and each rod and connection point is suitably strong to hold up to the forces acting on it.

Read about tension and compression on the next page.

BONUS EXPERIMENT

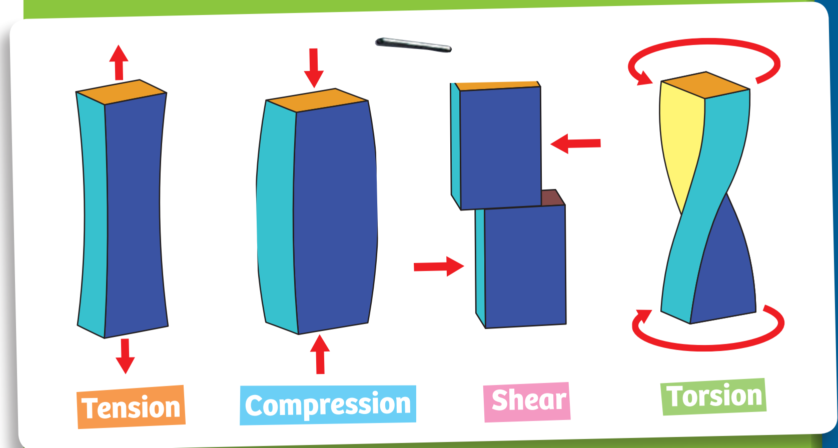
Can you build this alternate truss bridge?



CHECK IT OUT

Load

Another important part of designing a structure is understanding how **loads** affect a structure. Loads are forces, deformations, or accelerations that are applied to a structure or its parts.



Structural engineers often use four terms to describe how a load can affect a structure: tension, compression, shear, and torsion.

Tension is any force that pulls (or stretches) an object apart.

Compression is any force that pushes in on (or squeezes) an object.

Shear is a force that causes parallel internal surfaces within an object to slide past each other. (You will see an example of shear in the next experiment.)

Torsion is a force that causes the twisting of an object due to a moment.

DID YOU KNOW ...

... **toughened glass,** which is the glass used in smartphone screens, is strengthened by treating it with heat and chemicals to induce a state of compression in the outer surface of the glass and a state of tension inside the glass. This increases its ability to withstand external loads without breaking.

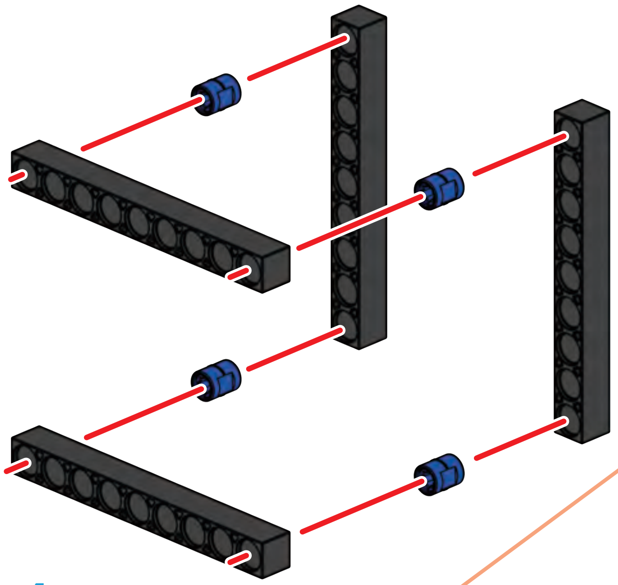
A structure, such as a building, is made up of many different parts such as walls, floors, beams, and ceilings. A structural engineer groups the parts of a building or structure into a small number of categories based on their physical behaviors. In this kit, we focus on understanding how **columns, beams, planes, trusses, catenaries, arches, cables,** and **shells** work in a structure.

Just as important as which structural elements are used in a building are the ways in which those structural elements are connected together. A building is designed to safely transfer its load through its structural elements to the ground. There are three common types of connections used in buildings: **rollers, pins,** and **fixed supports.**

For example, **roller supports** are commonly used at one end of bridges. This allows the bridge to move when it expands and contracts with changes in temperature.

1

Now, let's build some models to investigate how structural elements handle compression forces.



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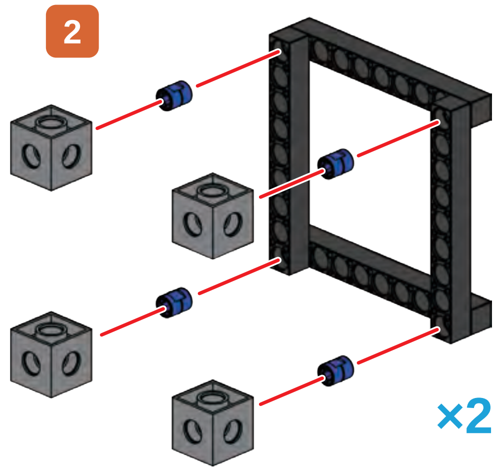
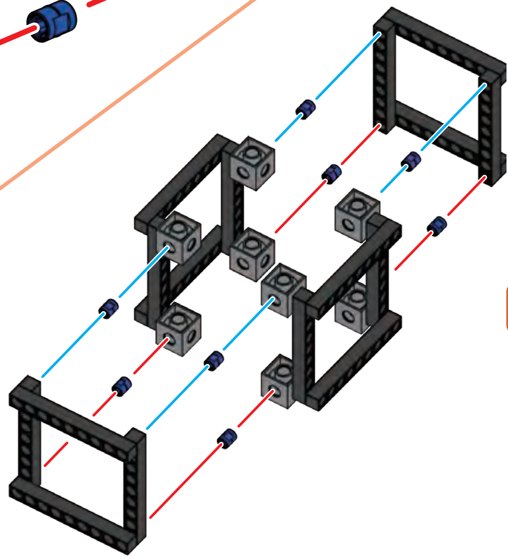
COMPRESSION CUBE

2





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EXPERIMENT 10

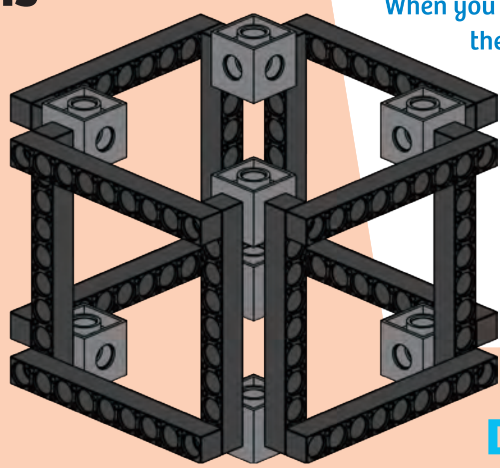
Columns and beams

HERE'S HOW

Place one hand on top of the cube and one on the bottom. Push your hands together, compressing the model. What do you observe happens?

Next, holding the bottom of the cube with one hand, slide the top of the cube around in a lateral motion with your other hand.

4



WHAT'S HAPPENING?

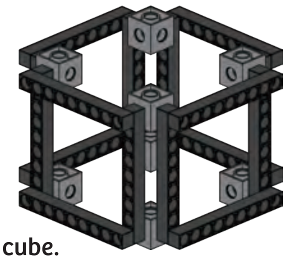
When you try to press down on the cube, the cube is able to withstand the compression without deforming. But when the cube experiences lateral forces, it is unstable.

The cube model consists of two structural elements: columns and beams.

Done!

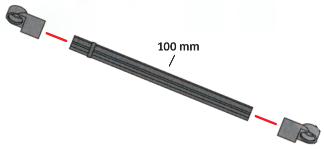
REINFORCED CUBE

1



Start with the cube.

2



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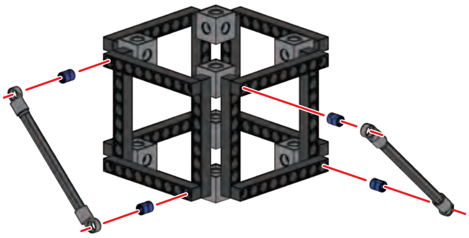

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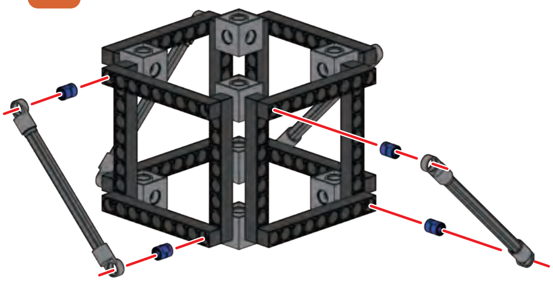
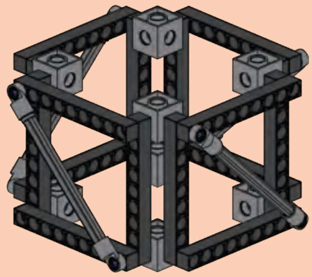


EXPERIMENT 11

5

Done!

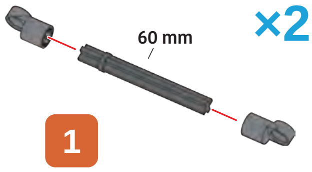


HERE'S HOW

Repeat Experiment 10 with the reinforced cube. What effect do the diagonal braces have on the model?

TETRAHEDRON

1



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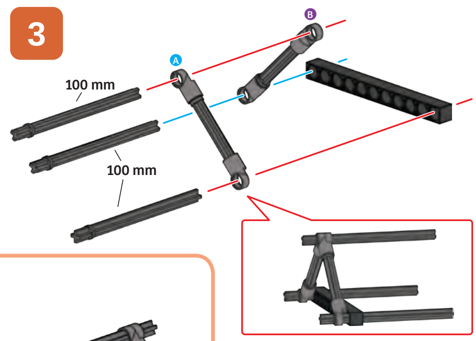

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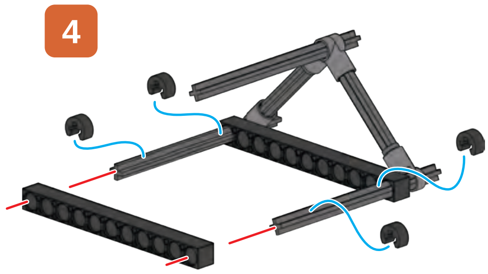

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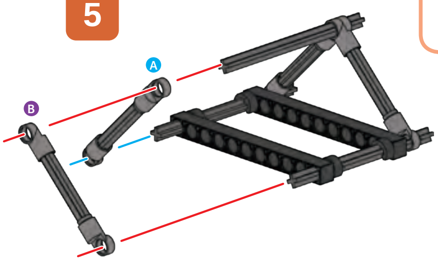

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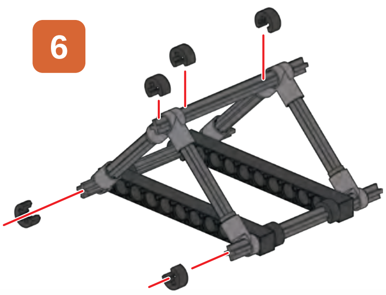


EXPERIMENT 12

7

HERE'S HOW

Use both hands to push, pull, and twist the corners of the tetrahedron. What do you observe happens?

Done!

CHECK IT OUT

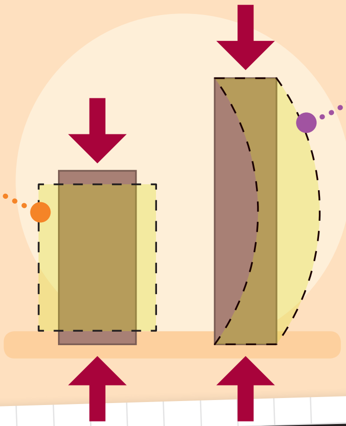
Structural Elements:
Columns, Beams, and Plates

COLUMNS

Columns are structural elements that transmit forces vertically, through compression. As you observed in Experiment 10, columns are strong in resisting vertical forces but weak in resisting horizontal forces. When columns experience compression, they deform to be shorter and wider.

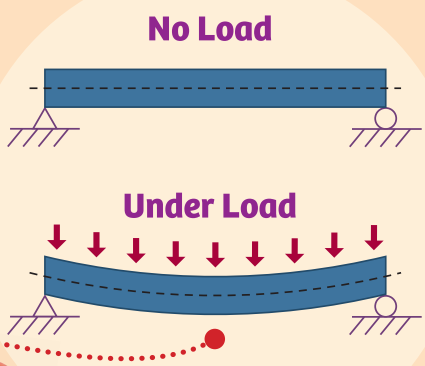
Why don't you see the columns in a building getting shorter and wider? The reason is that these changes are usually very small because building materials are very stiff.

Structural engineers want to prevent columns from failing due to a phenomenon called buckling. Buckling is when a structural element starts to bow sideways due to a high compressive load. This failure can cause the structural element to lose all ability to carry a load.



BEAMS

Beams are structural elements that are able to resist horizontal loads but are weak in resisting vertical loads. As you saw with the beam bridge in Experiment 7, when beams experience vertical forces, they undergo bending.



When a beam experiences bending, the top edge of the rod is in compression, while the lower edge is in tension.

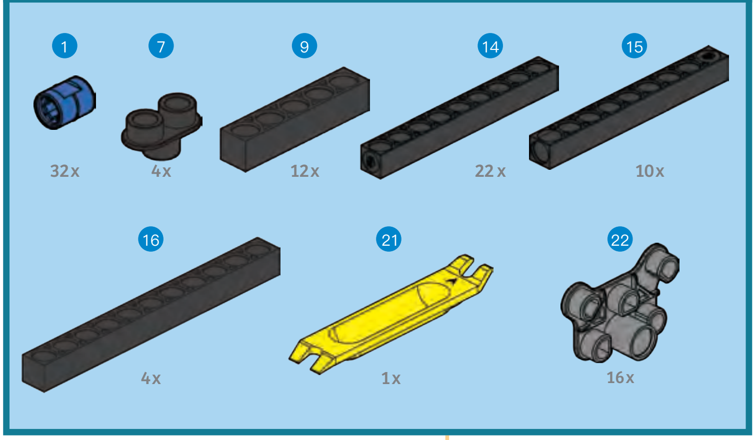
PLATES

A **plate** is a solid structural element with a thickness that is very small compared to its other dimensions. Loads applied to a plate are assumed to be perpendicular to the faces of the plate. The die-cut plastic sheet is an example of a plate.

SKYSCRAPER VERSION 1

Now, let's build some skyscrapers. Can you identify the structural elements used in them?

Parts Needed



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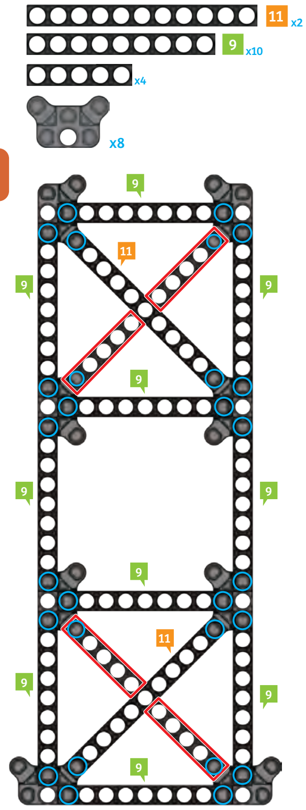

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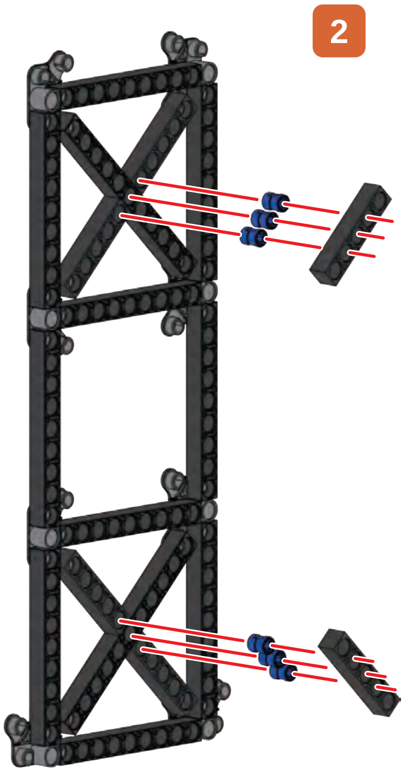

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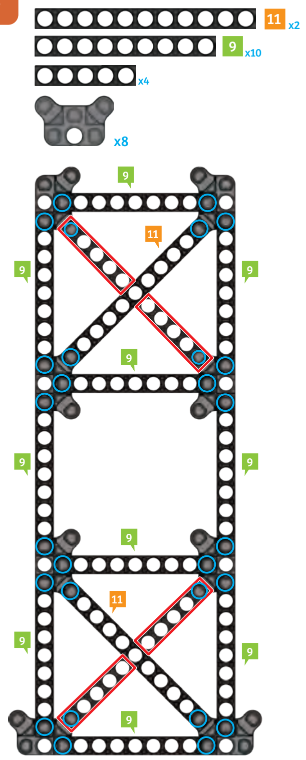

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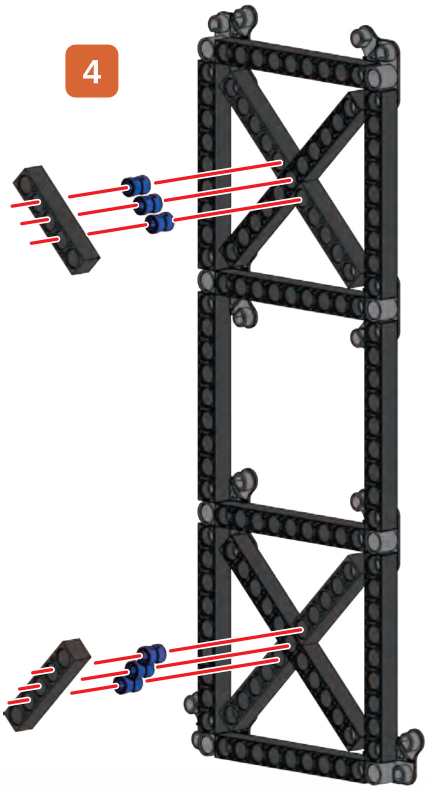

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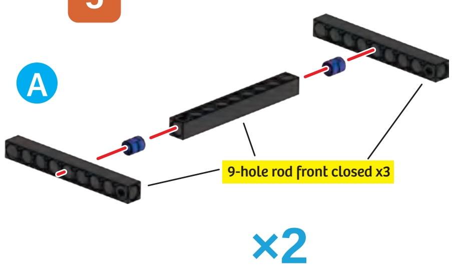

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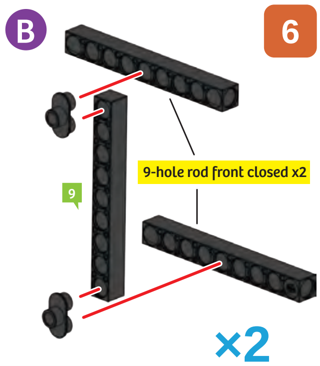

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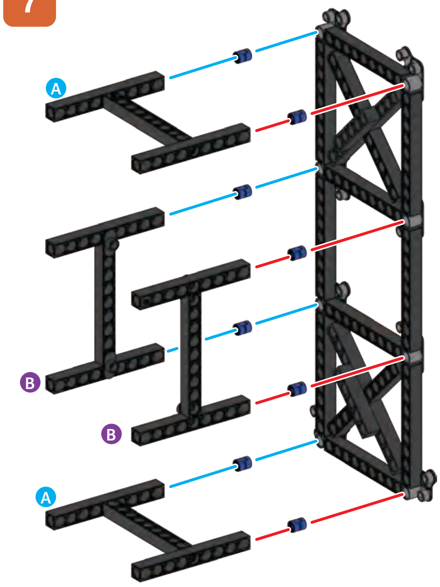

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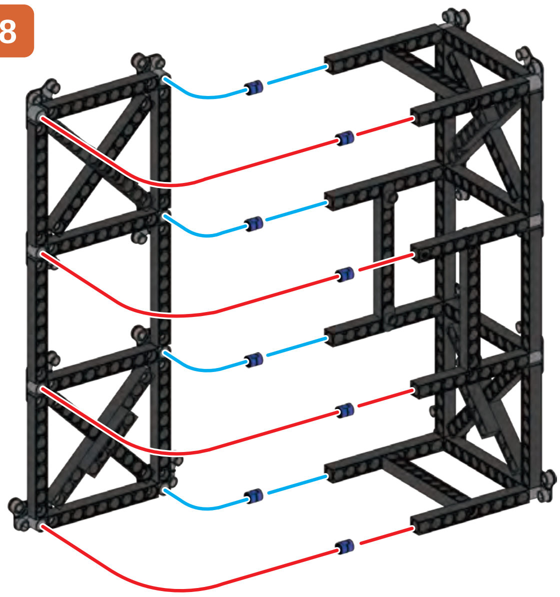


EXPERIMENT 13

Earthquake!

HERE'S HOW

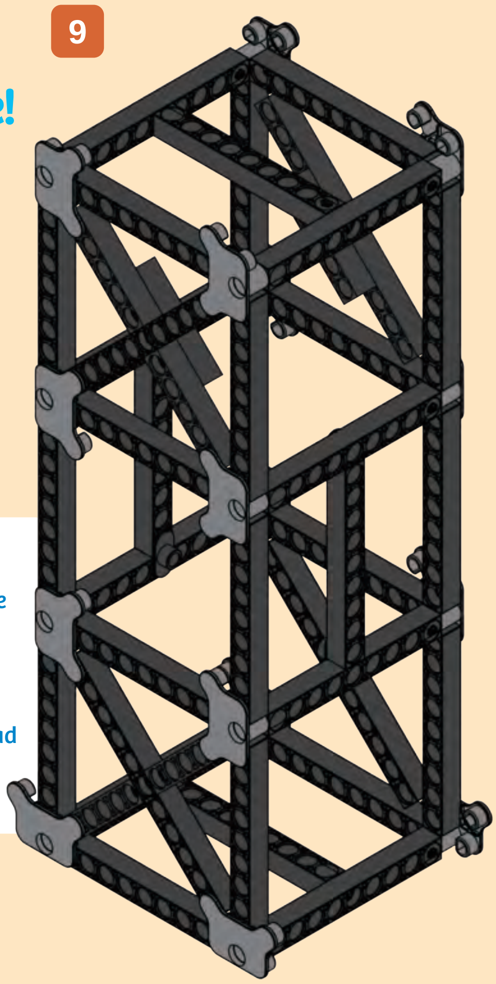
Place the skyscraper on a piece of paper or cardboard. Slide the piece of cardboard back and forth on the table. What do you observe happens to the skyscraper?

WHAT'S HAPPENING?

Earthquakes cause surface soil to move back and forth, like the piece of paper in your experiment. This causes structures to fall over, slide, or twist about their bases. A wide foundation helps prevent a building from falling over, and a flexible structure that can bend a little instead of breaking helps prevent a building from falling apart during an earthquake.

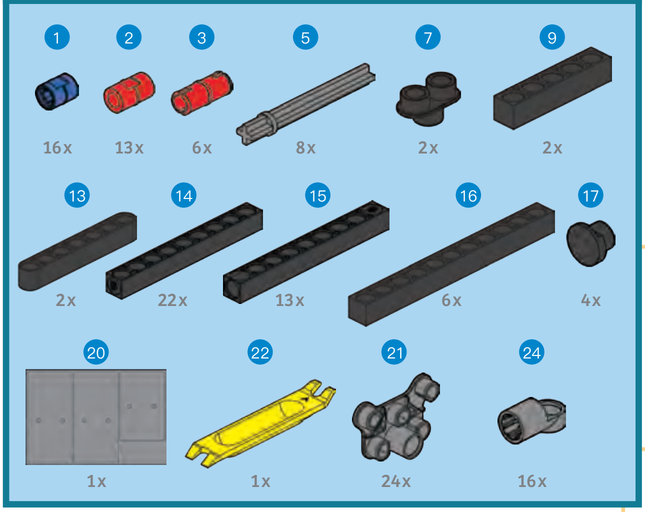
9

Done!



SKYSCRAPER VERSION 2

Parts Needed



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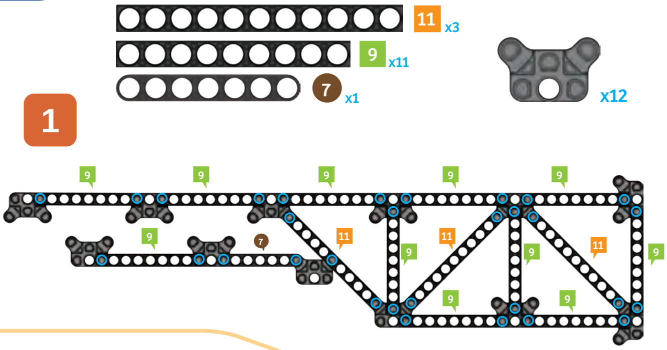

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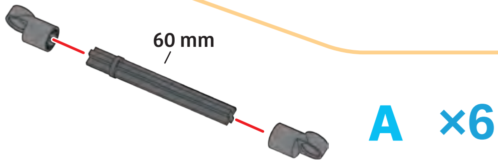

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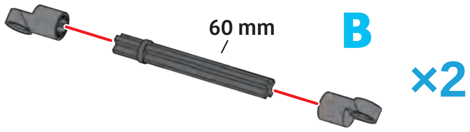

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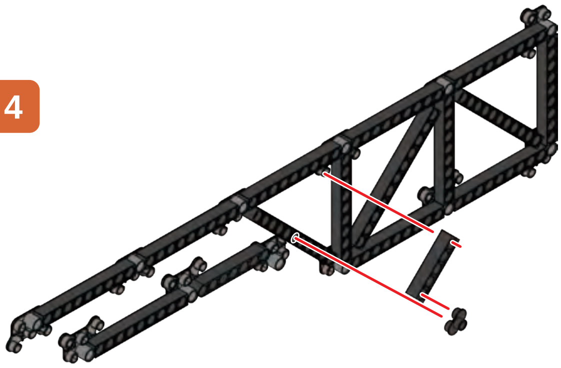

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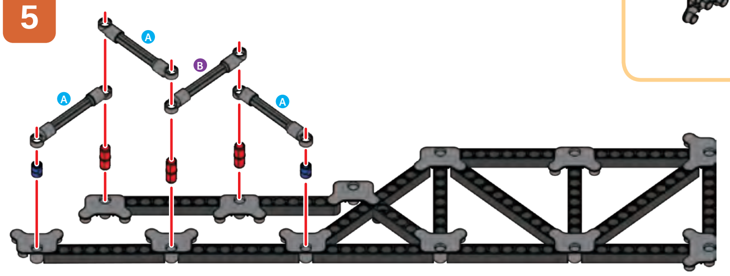

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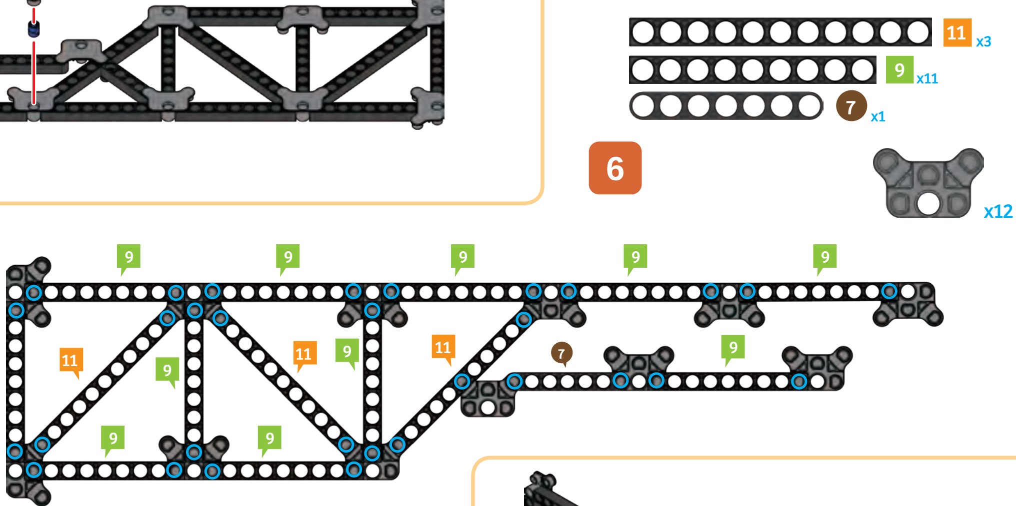

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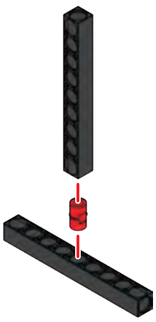

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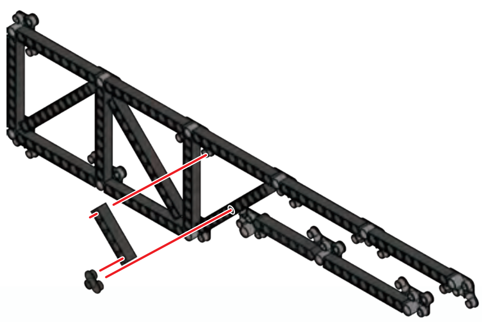

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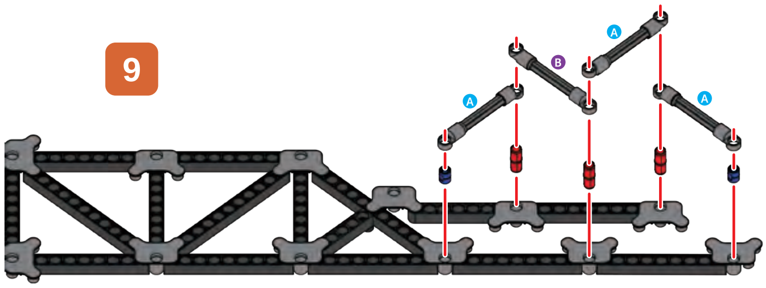

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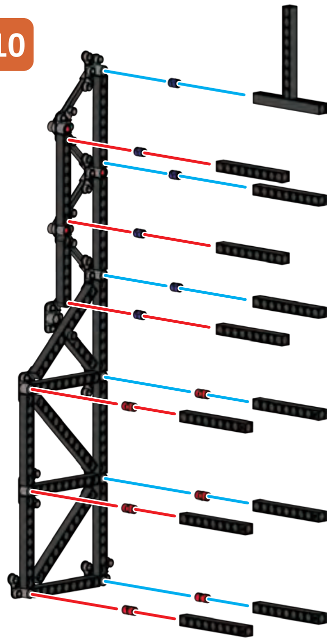

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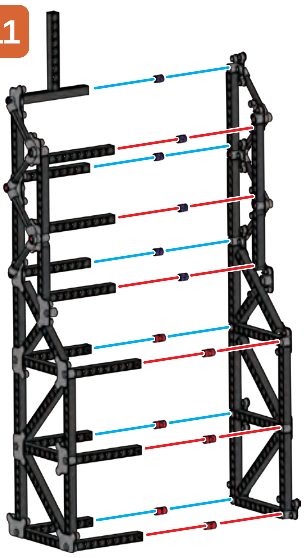

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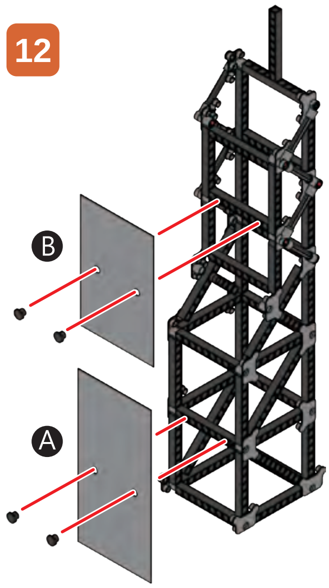
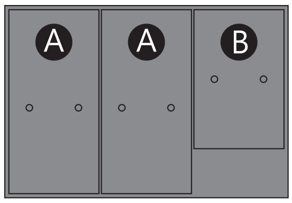




EXPERIMENT 14

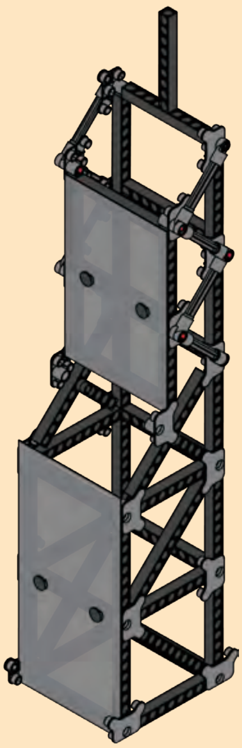
Engineering Design Challenge: Skyscrapers

HERE'S HOW

Using only the materials in this kit, build the tallest skyscraper possible. The skyscraper must be able to remain standing on its own. You can make the challenge more difficult by adding other requirements, such as that the skyscraper must withstand the flow of air from a hair dryer, or the shaking of the table, or must hold a certain amount of weight.

Some engineering constraints relating to skyscrapers that you may need to consider in your design include the materials available, height, weight of the skyscraper and occupants, location, time, cost, and the strength and stability needed to resist loads such as earthquakes and wind.

13

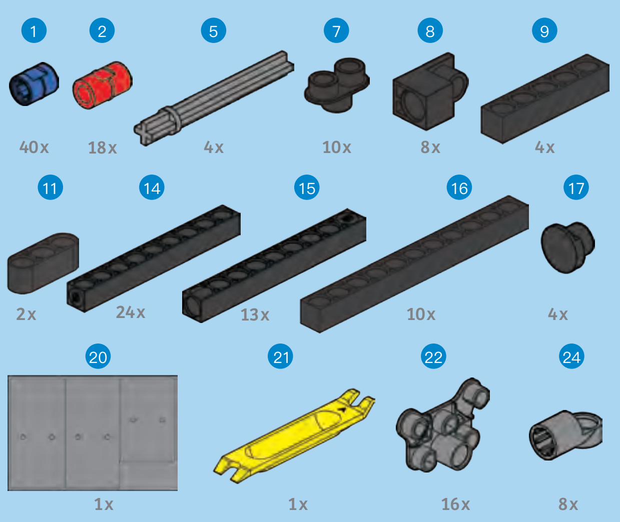


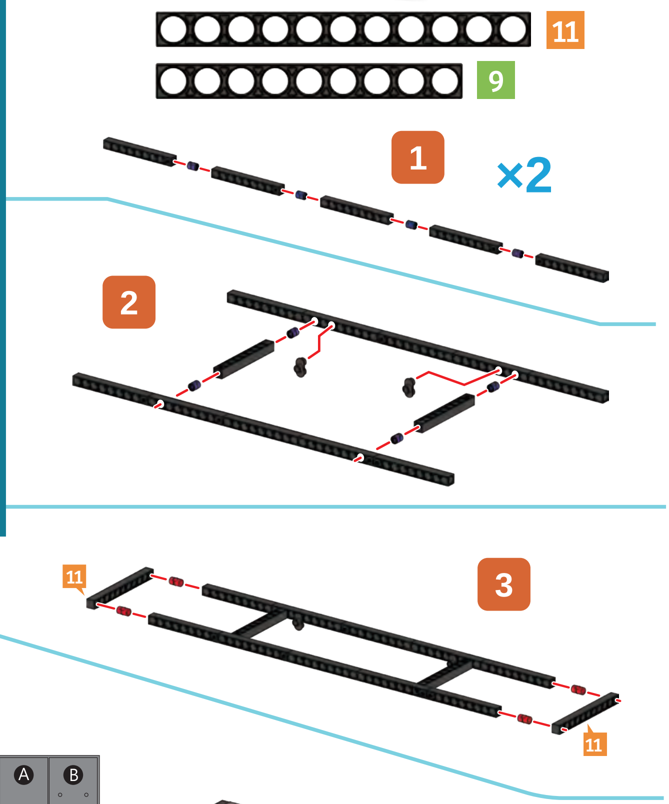
Done!

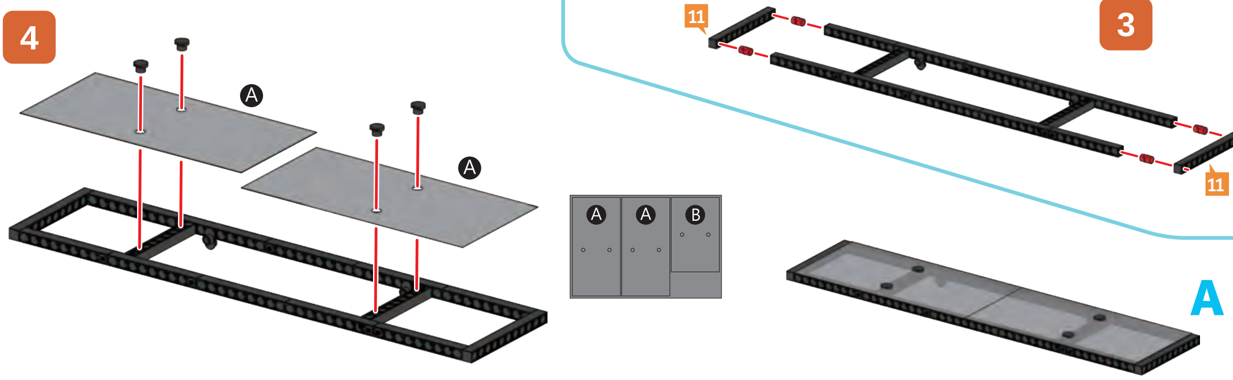
DECK ARCH BRIDGE

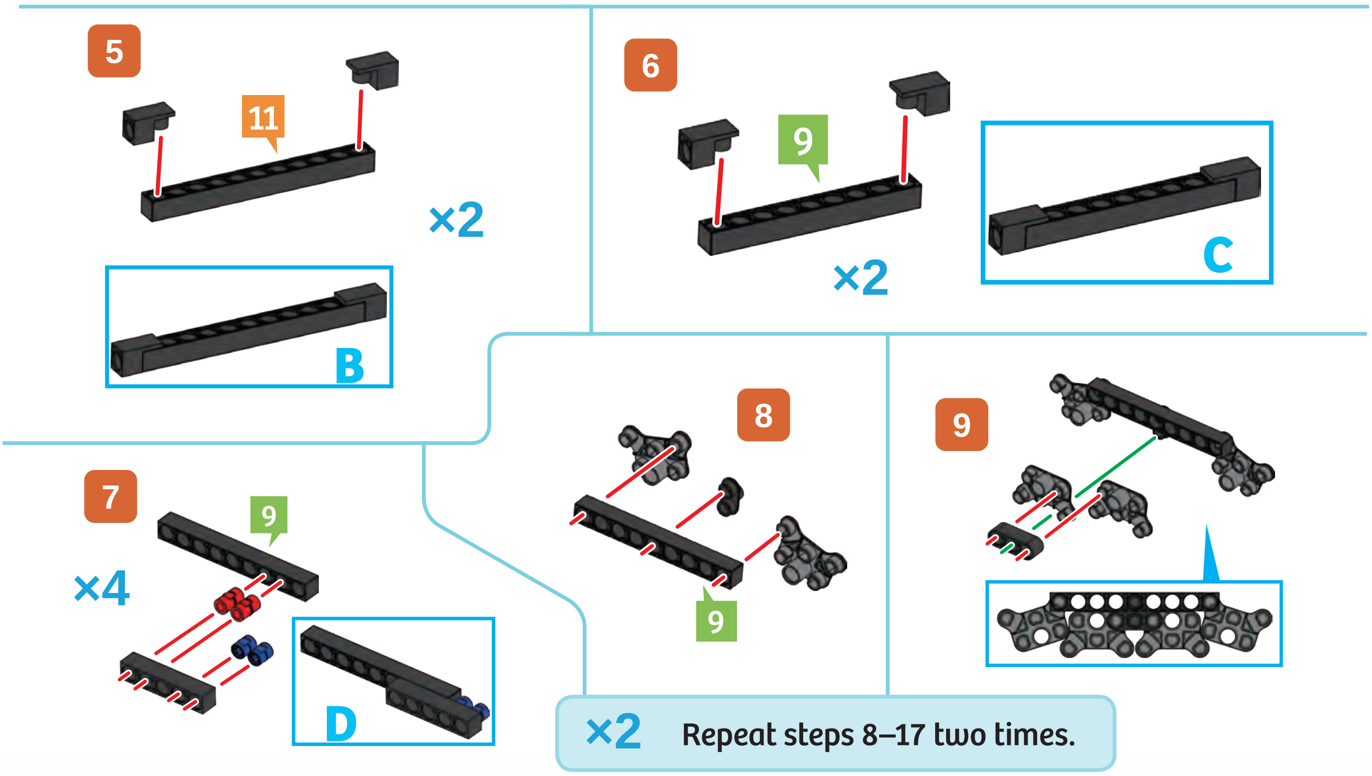
Now, let's build some arch bridges. Where do you think compression might be acting on the bridges?

Parts Needed



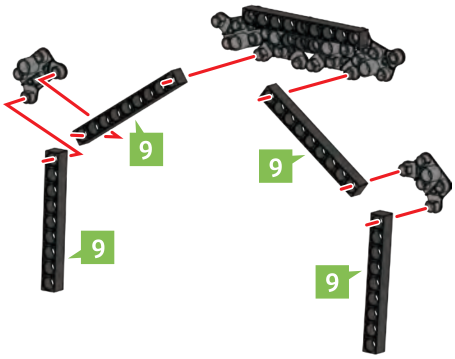






×2 Repeat steps 8–17 two times.

10



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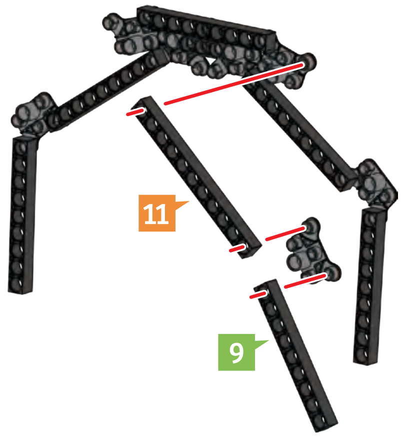

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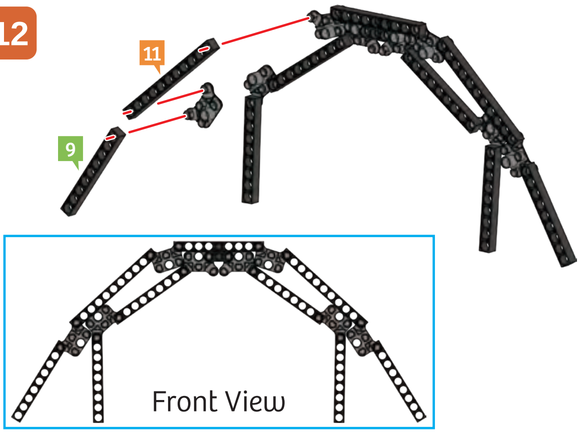

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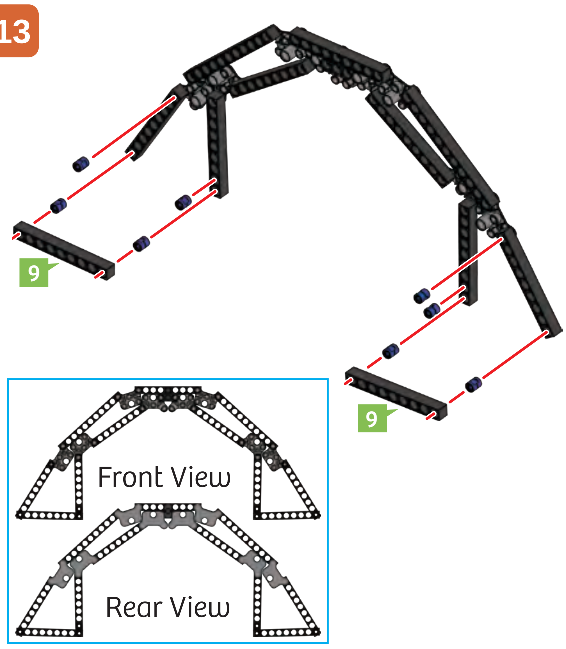

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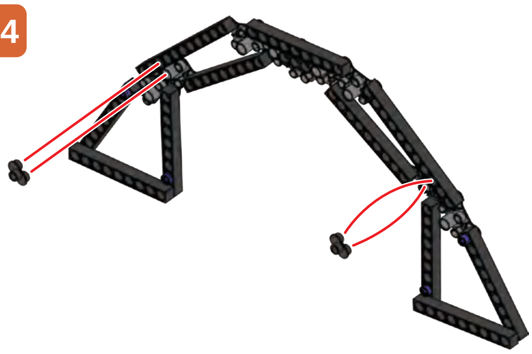

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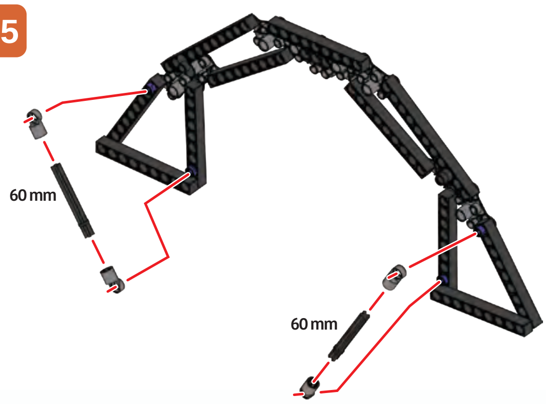

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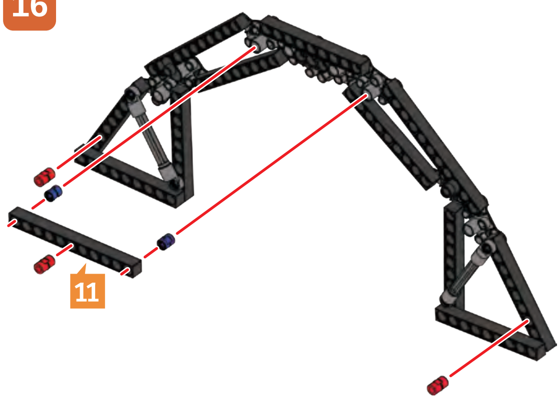

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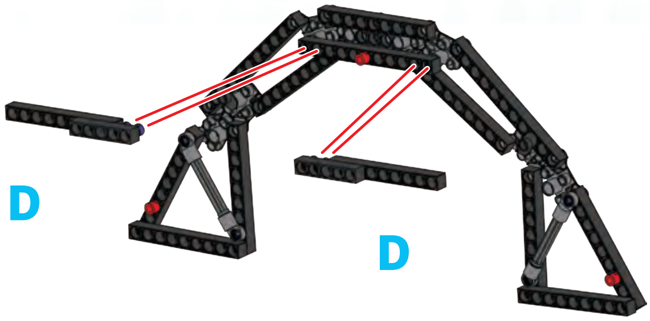

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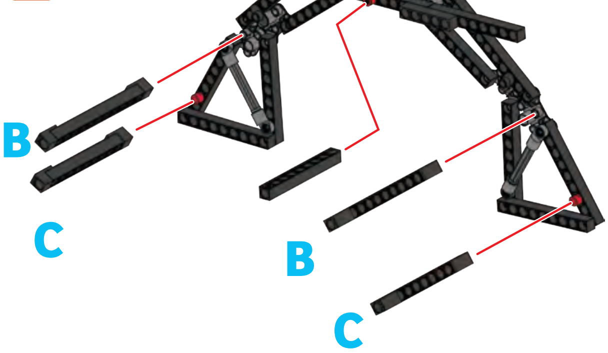

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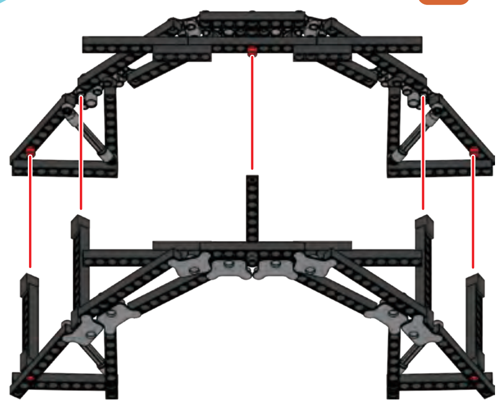

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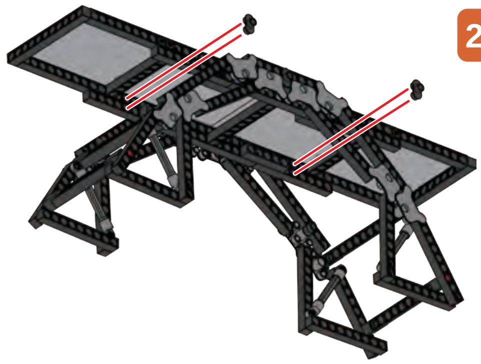


21

EXPERIMENT 15

Arches

HERE'S HOW

Place your hands on the bottom portion of the arch. Have a friend or family member place a book on top of the arch bridge. What do you observe happens to the arch when the book is placed on top?

22

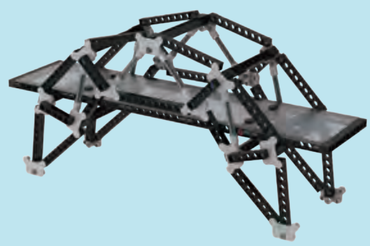
Done!

WHAT'S HAPPENING?

An arch transforms forces that push down on the top of it into forces that push outward at its base. There must be either internal or external structures which counteract the outward forces at the base; otherwise, the arch will collapse.

BONUS EXPERIMENT

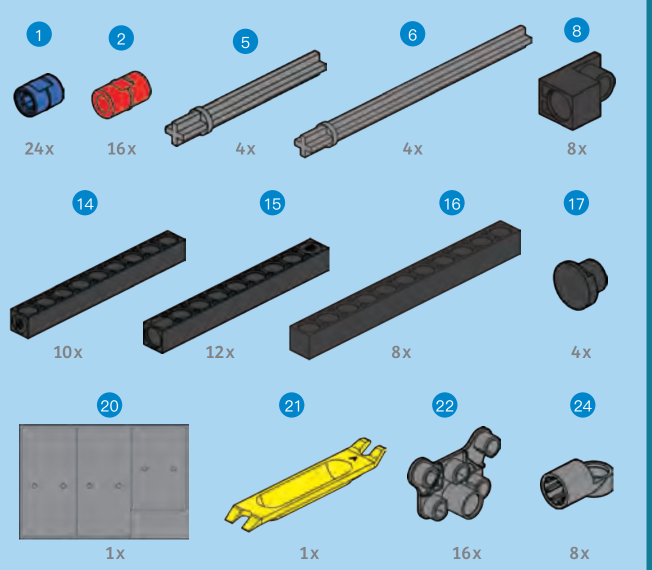
Can you build this through-arch bridge?



EXPERIMENTS

TIED-ARCH BRIDGE

Parts Needed



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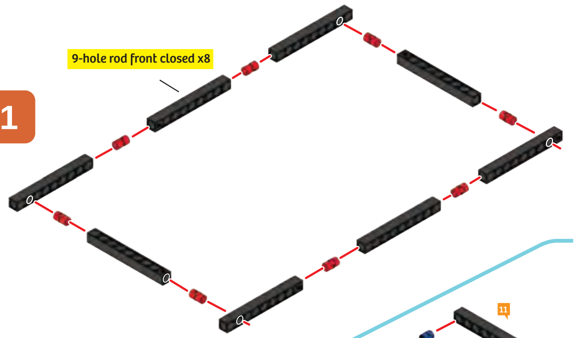

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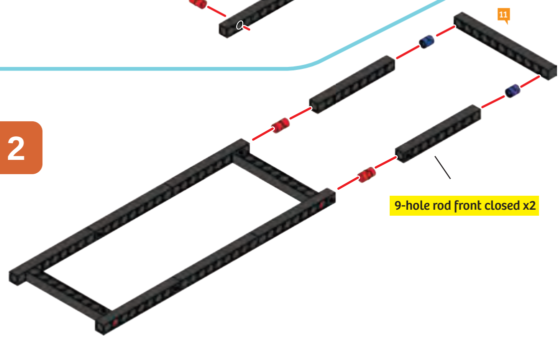

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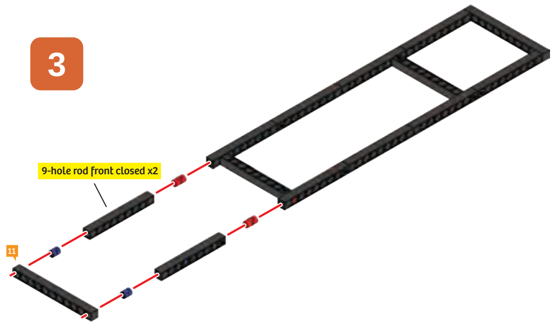

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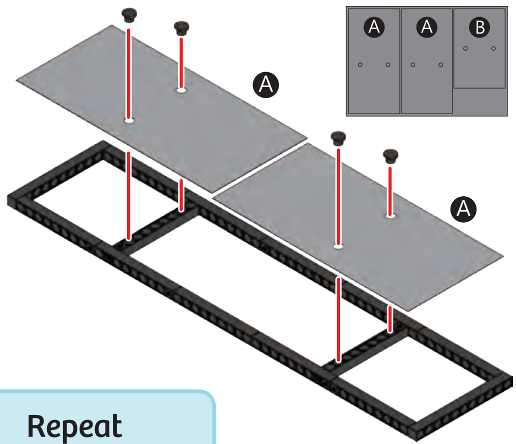

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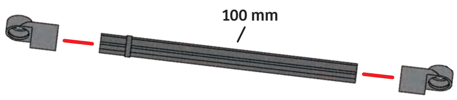
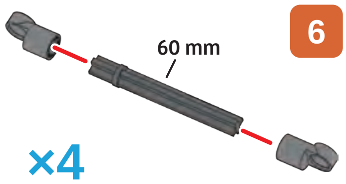


×2 Repeat steps 7 and 8 two times.

6



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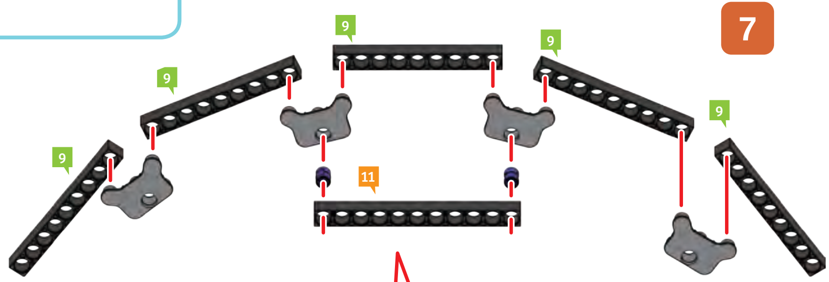

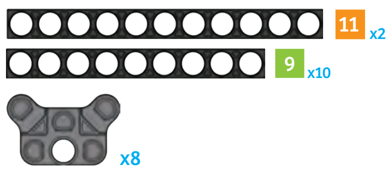

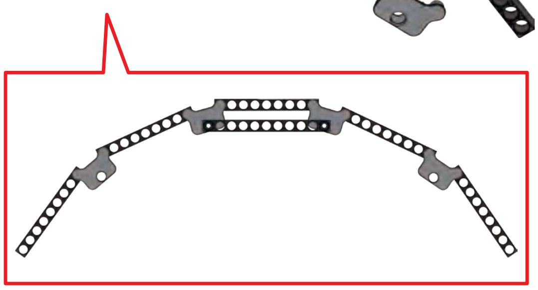

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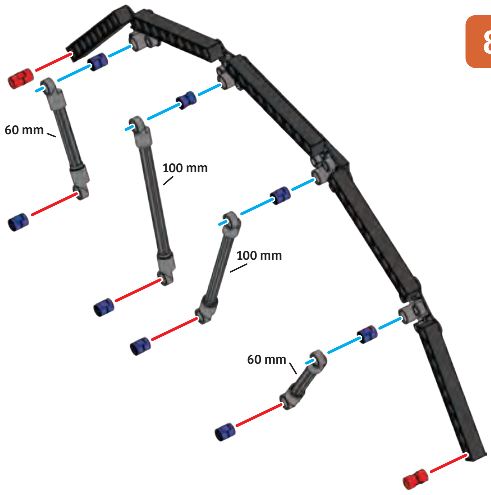

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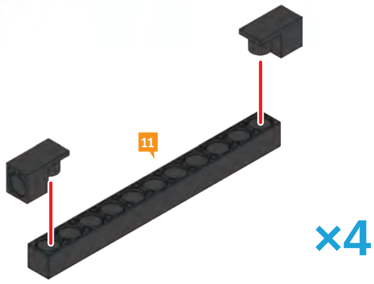

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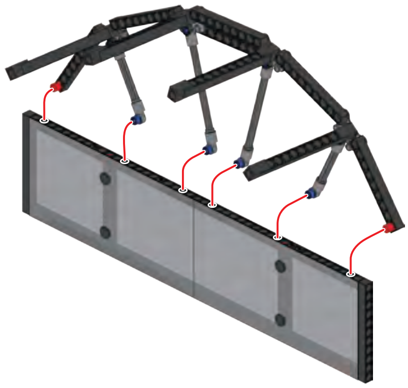

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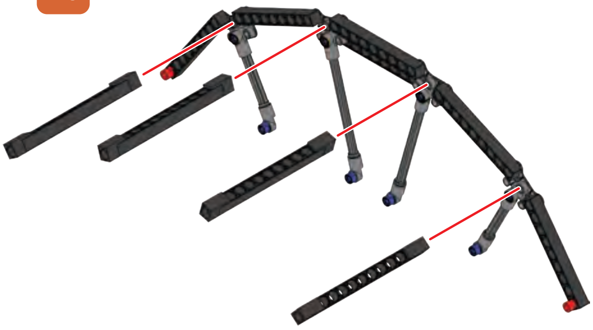

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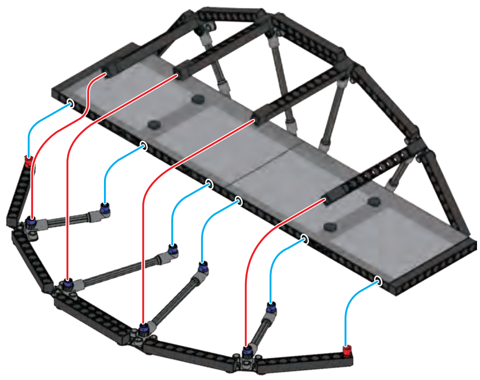

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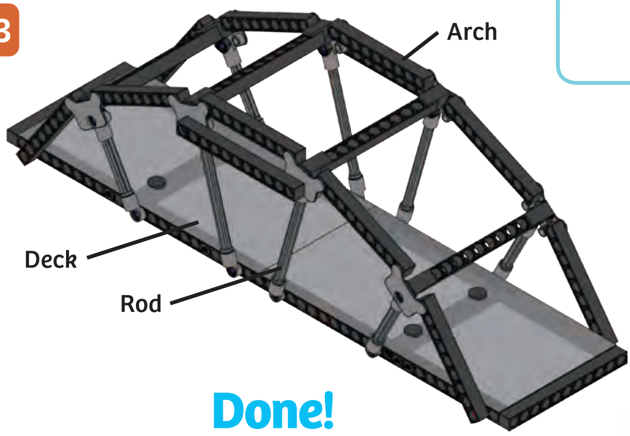
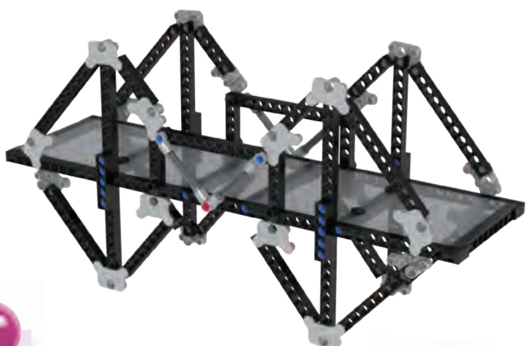


Done!

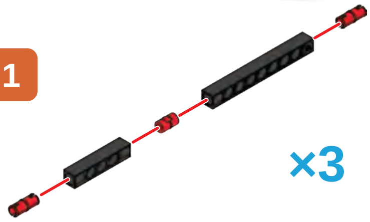
Forces that push downward on the deck of the bridge cause the vertical rods to pull on the arch. This causes the arch to push out at the ends, just like the deck arch bridge. However, in a tied-arch or bowstring bridge, these movements are restrained by the connection of the arch to the deck of the bridge, just like a strung bow.



BONUS EXPERIMENT
Can you build this cantilever bridge?

In the next few models, let's explore how tension works in structures.

1



×3

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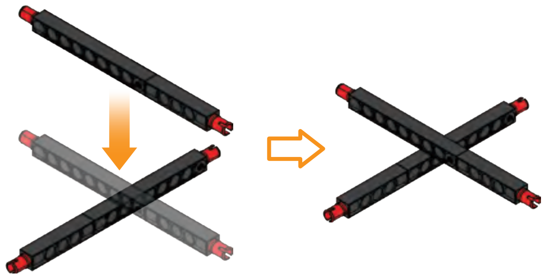

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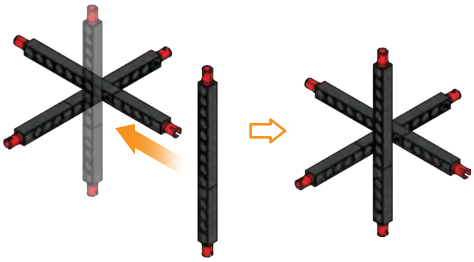

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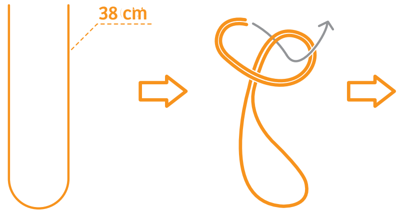

×4

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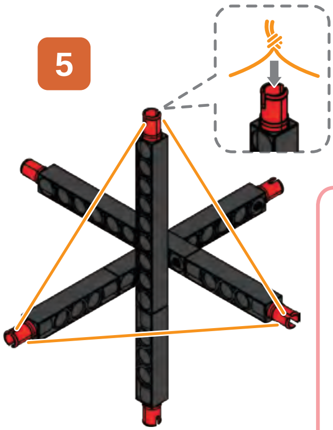

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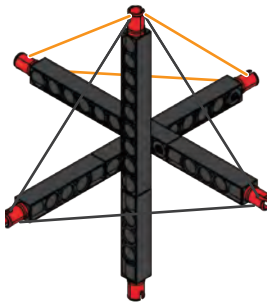

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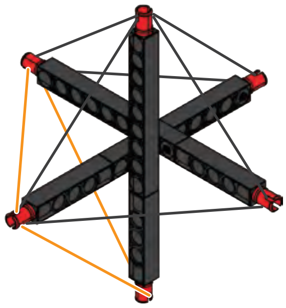

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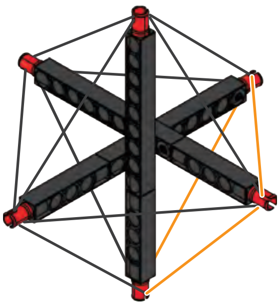


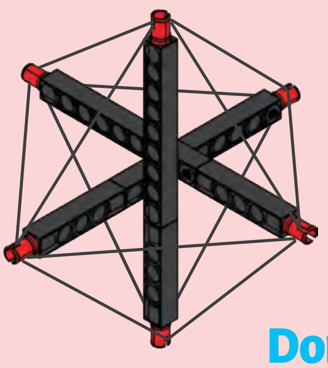
EXPERIMENT 16

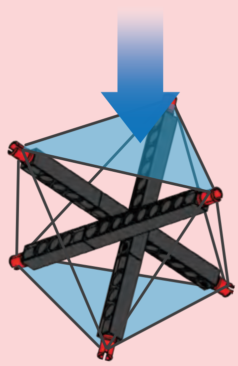
Tension and compression

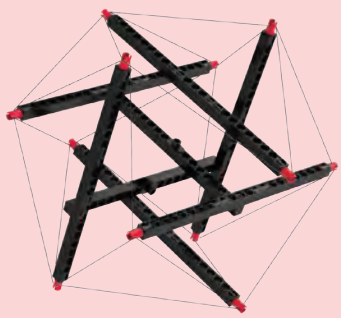
HERE'S HOW

Push down or place a book on top of the tensegrity. Notice how the tensegrity is able to support weight even though the rods are held together only by the strings.

9





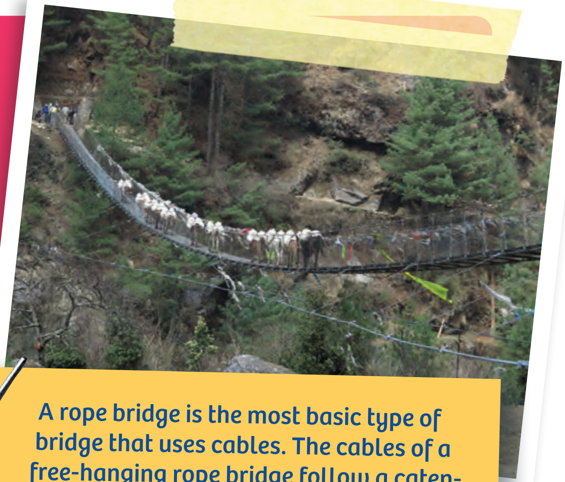


Done!

BONUS EXPERIMENT
Try to build a larger tensegrity.

CHECK IT OUT

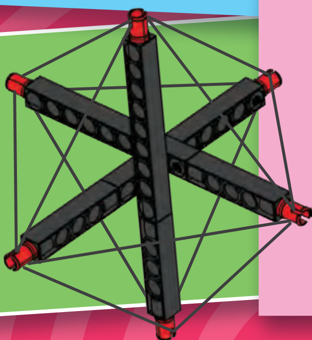
Structural Elements: Catenaries, Cables, Arches, and Shells



A rope bridge is the most basic type of bridge that uses cables. The cables of a free-hanging rope bridge follow a catenary curve.

CATENARIES

Hold both ends of a piece of string and let it hang down freely in the middle. Observe the shape that the string forms naturally under its own weight. This curve is called a **catenary**. Ropes, chains, and cables assume this shape as a result of the way in which gravity pulls down on them.



The tensegrity is a structure that has compression elements (in this case rods) held together by tension elements (in this case strings).

CABLES

Now thread the string through a 5-hole rod. Hold the string at both ends and let it hang down freely in the middle again. Notice that the string now forms two straighter lines and you feel a slight pull from the string on both of your hands. **Chains, ropes,** and **cables** can only provide support by pulling on another structural element through tension.

The Gateway Arch in St. Louis, Missouri is a flattened catenary, because the arch gets narrower near the top.

ARCHES

As you learned in Experiment 15, **arches** transform forces that push down on them into forces that push outward at their bases. This is due to the curved shape of arches.

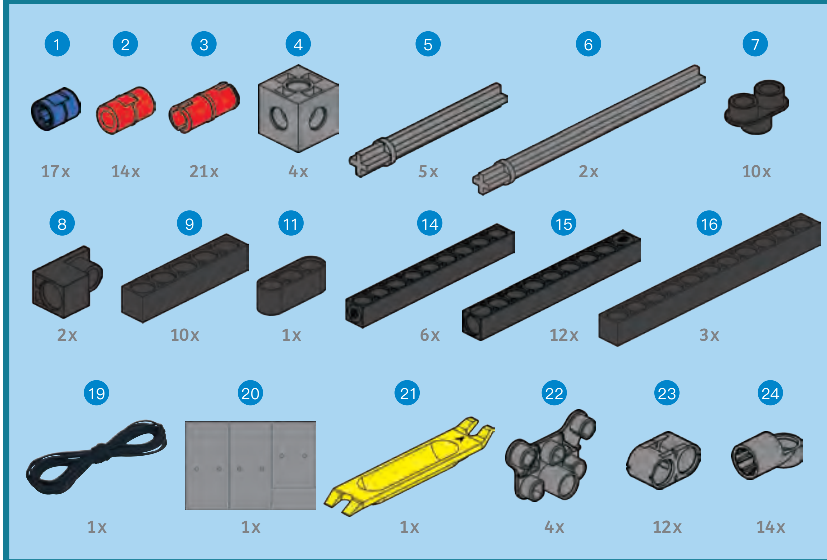
SHELLS

Like plates, **shells** are structural elements with thicknesses that are much smaller compared to their other dimensions. However, shells are curved structures, while plates are flat. Shells can produce both tension and compression.

The optimal shape for an arch of uniform density and thickness that needs to support only its own weight is a catenary that has been flipped upside down. This is because a catenary is the most efficient shape for turning the force of gravity into the compressive forces that are transferred through the arch to the ground.

CABLE TOWER

Parts Needed



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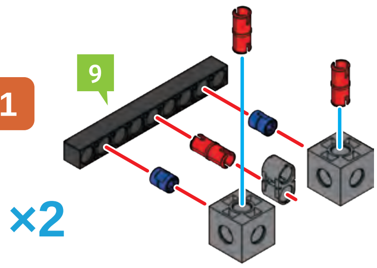

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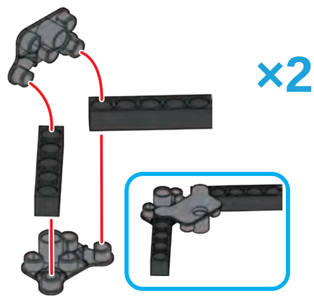

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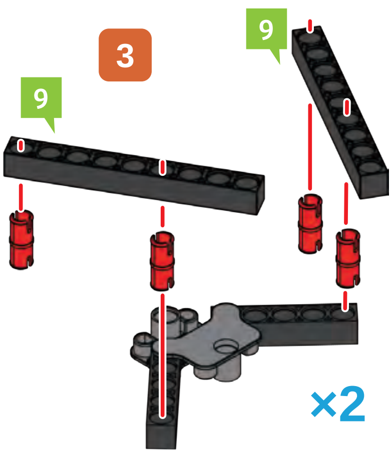

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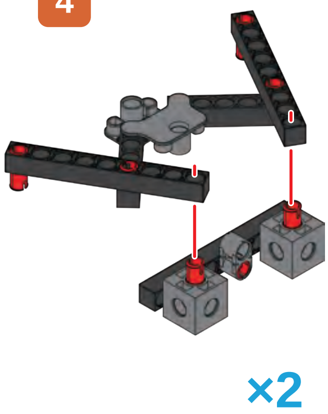

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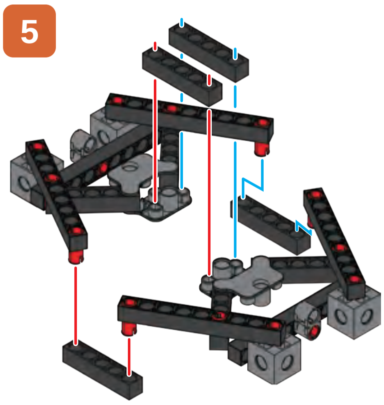

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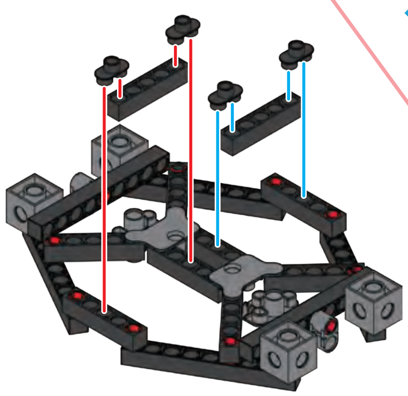

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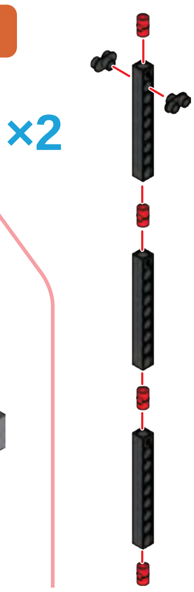

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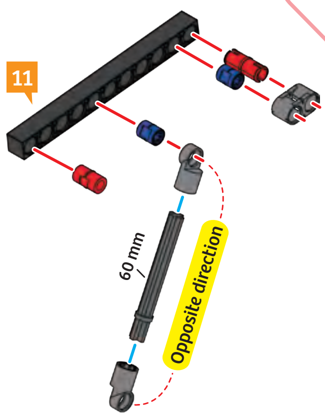

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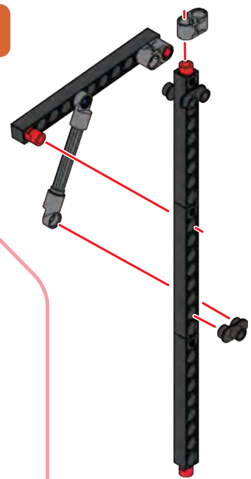

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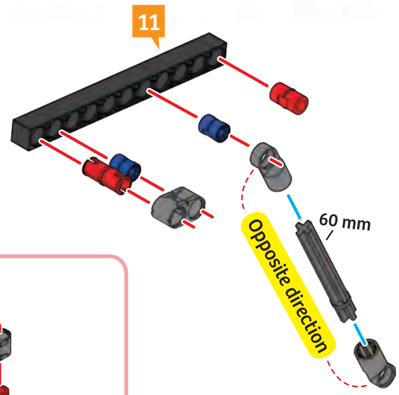

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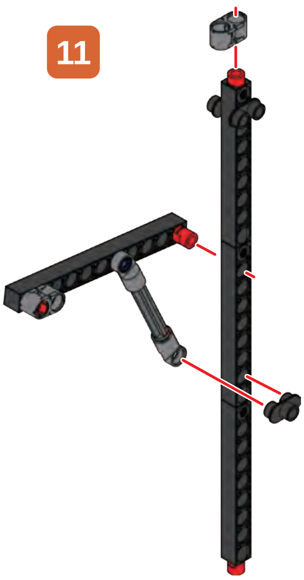

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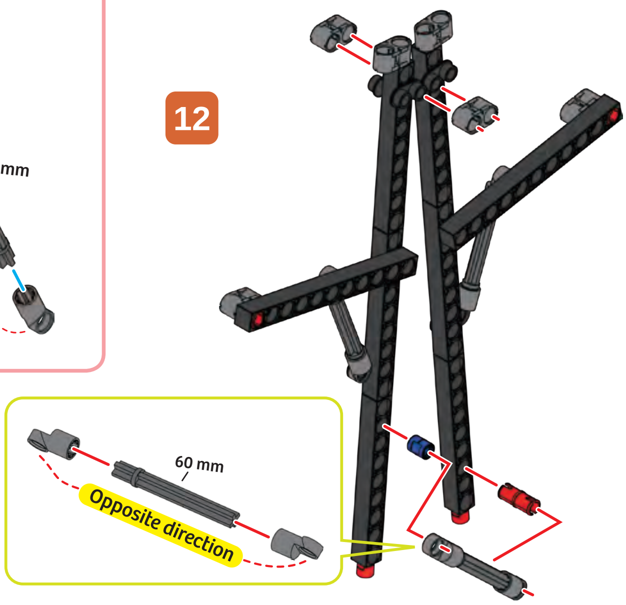

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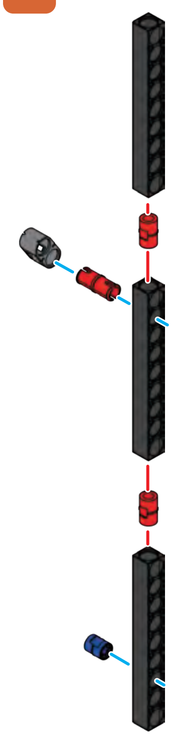

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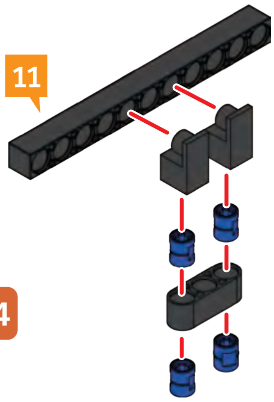

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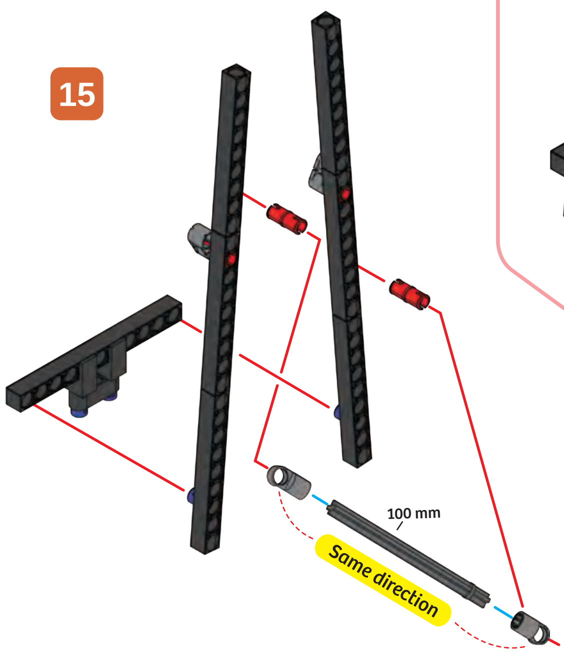

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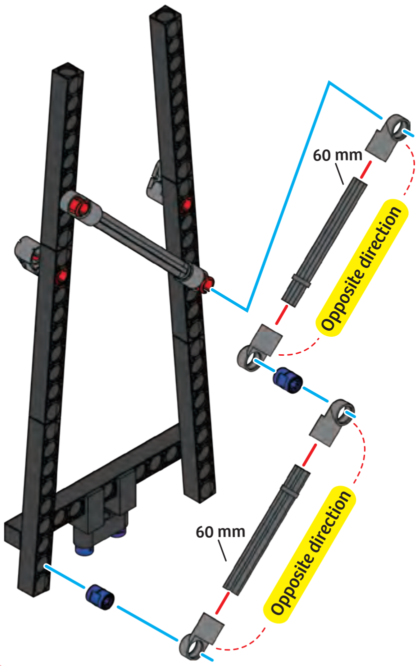

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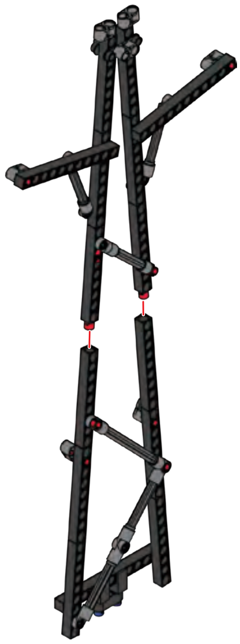

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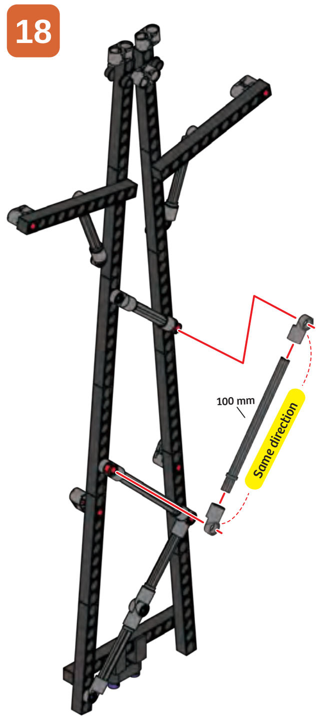

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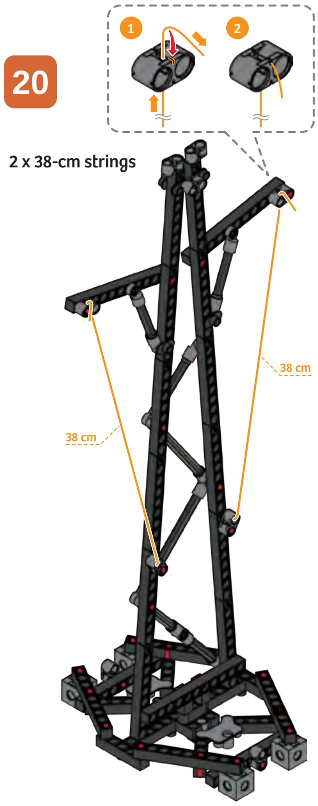


21

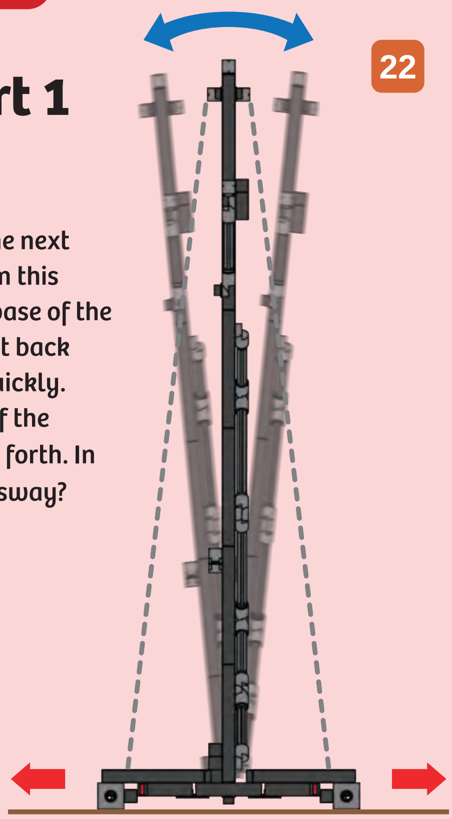
EXPERIMENT 17

Cables: Part 1

HERE'S HOW

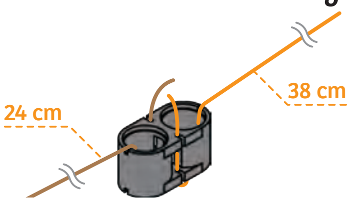
Before moving on to the next assembly step, perform this experiment. Hold the base of the cable tower and slide it back and forth on a table quickly. Observe how the top of the tower sways back and forth. In what direction does it sway?

22



23

2 x 24-cm strings
2 x 38-cm strings



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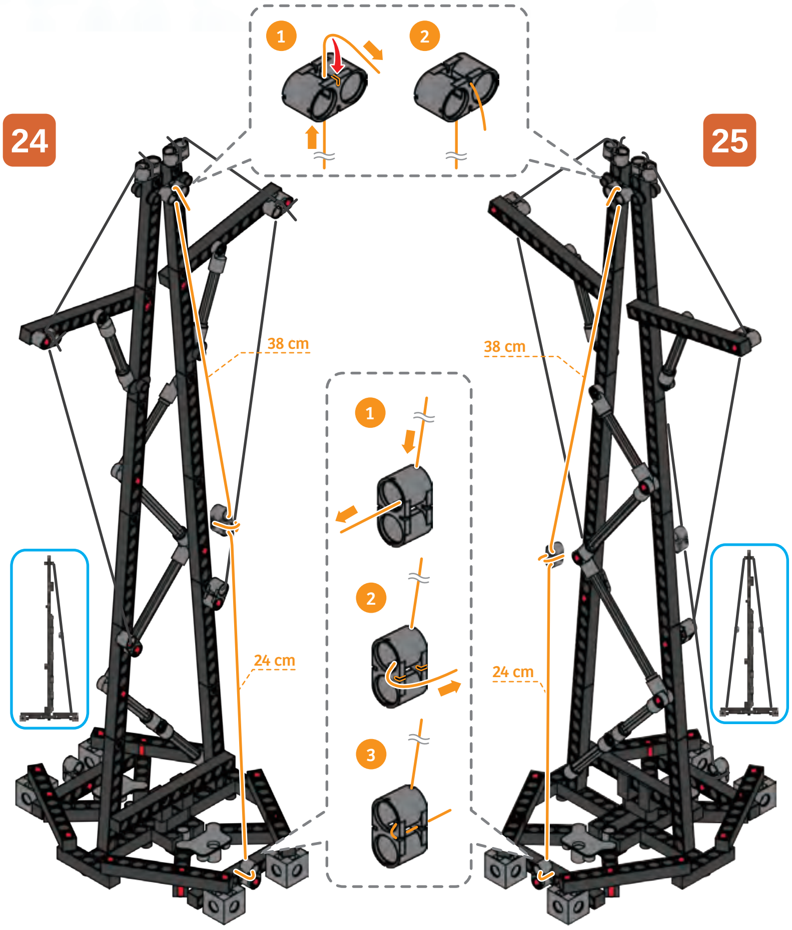

EXPERIMENT 18

Cables: Part 2

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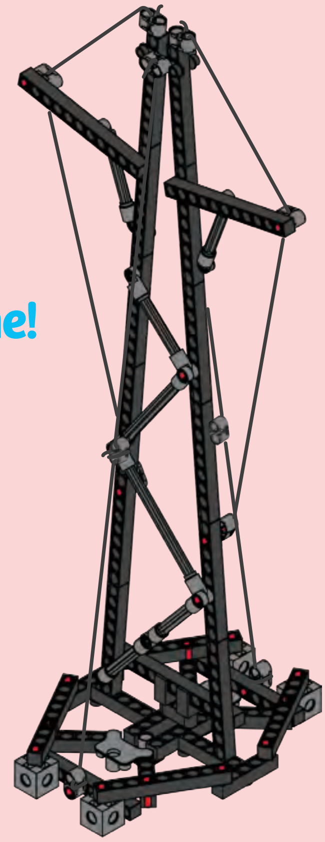
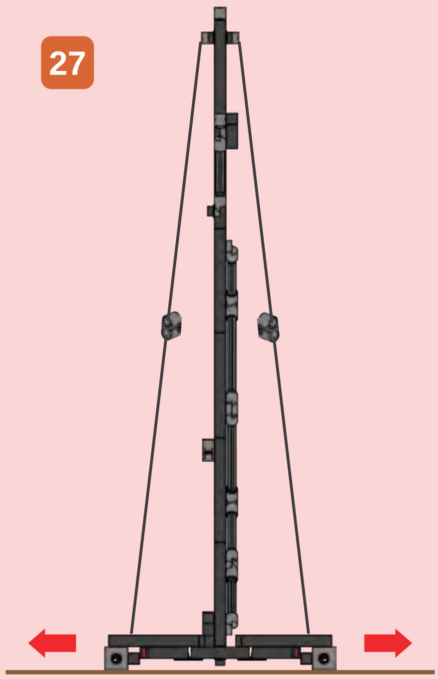
27





HERE'S HOW

Slide the cable tower back and forth again. Now the tower will not sway back and forth because the cables resist the motion of the tower.

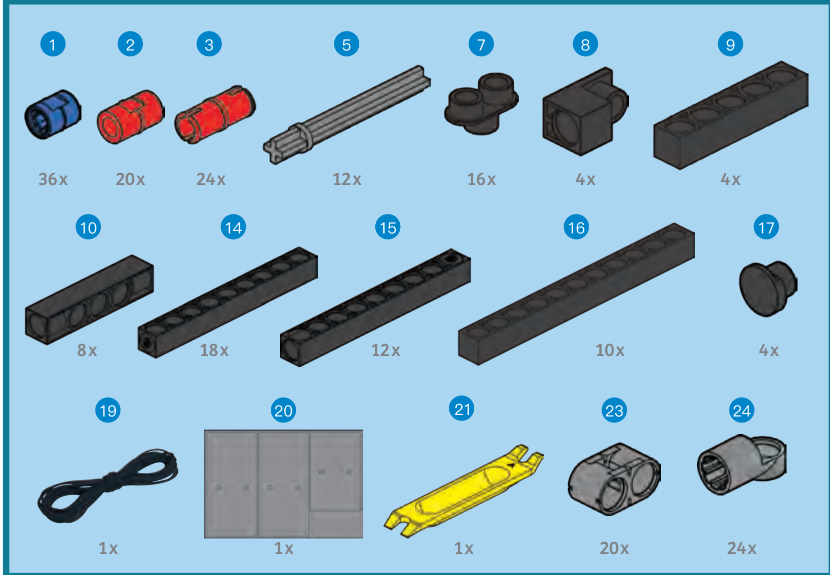
Done!

WHAT'S HAPPENING?

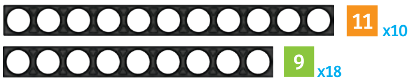
In the first cable tower experiment, the connections at the base of the model are not rigid enough to keep the top of the tower from swaying. In the second experiment, the cables on both sides of the tower are pulling equally on the top of the tower. The cables are under tension. This stabilizes the tower and prevents it from swaying when the base is moved.

SUSPENSION BRIDGE

Parts Needed



In this final section, let's use everything you have learned so far to build two types of bridges that use cables to suspend their decks.



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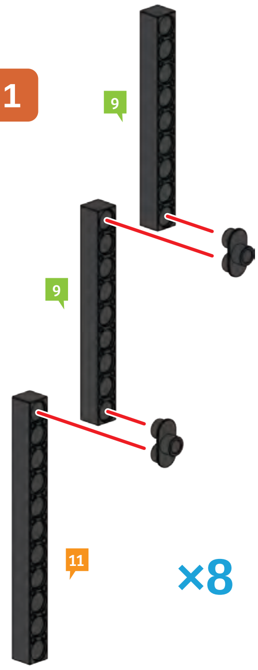

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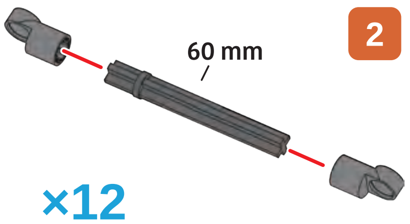

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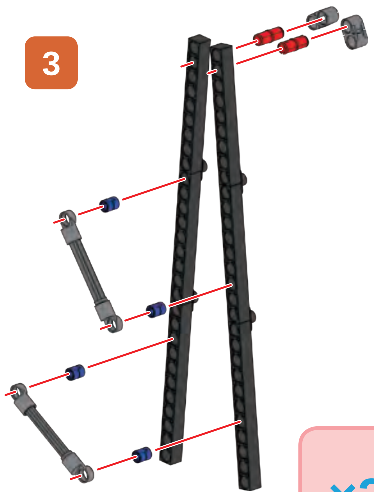
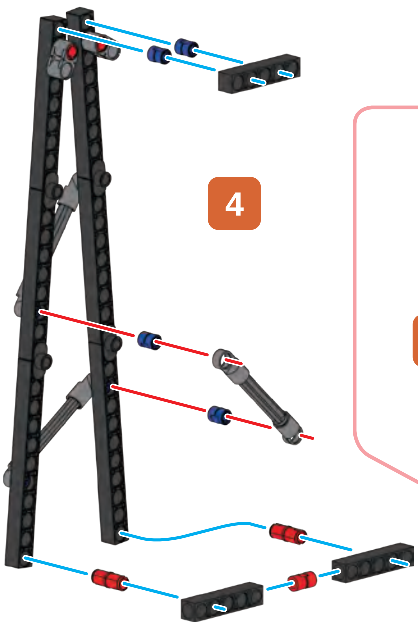


×2 Repeat steps 3–7 two times.

4



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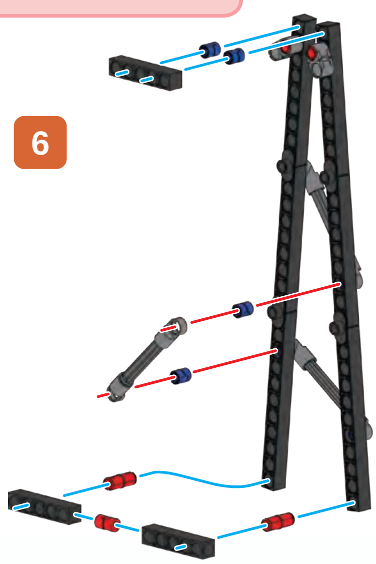

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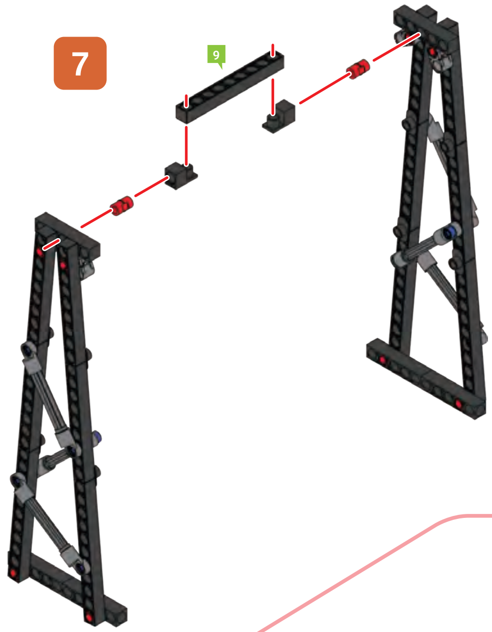

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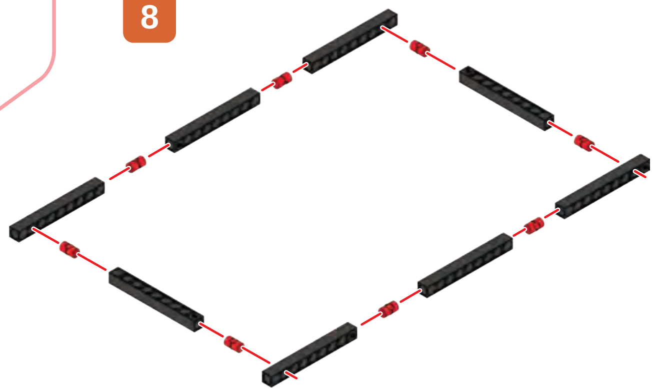

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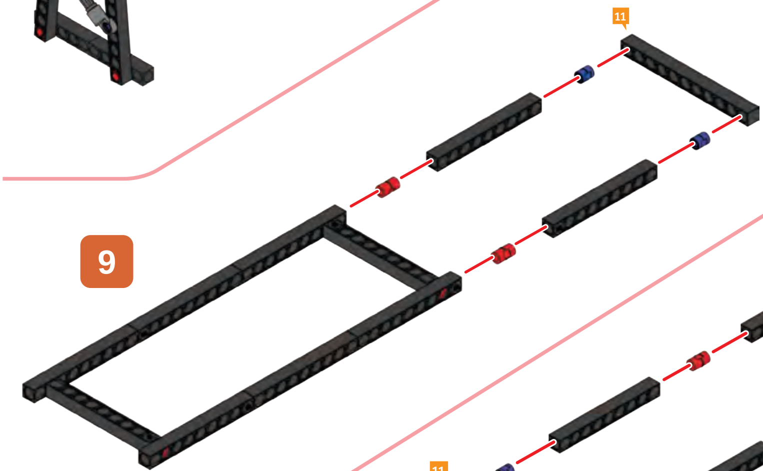

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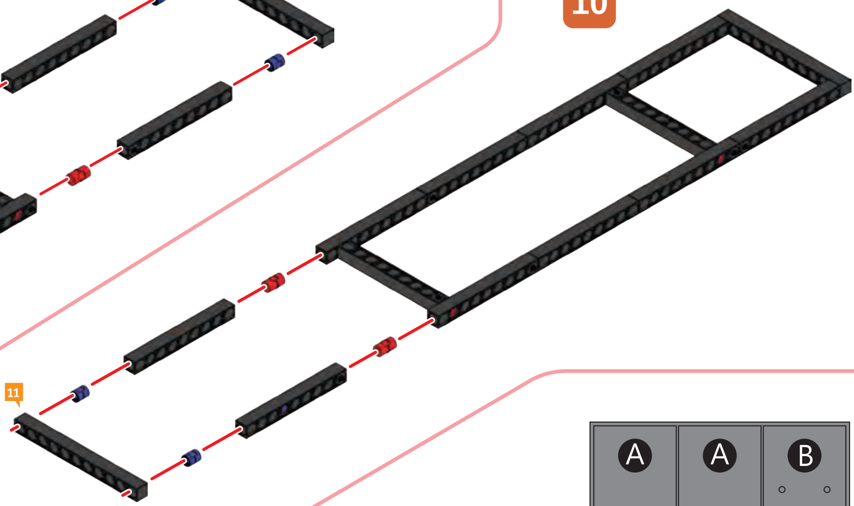

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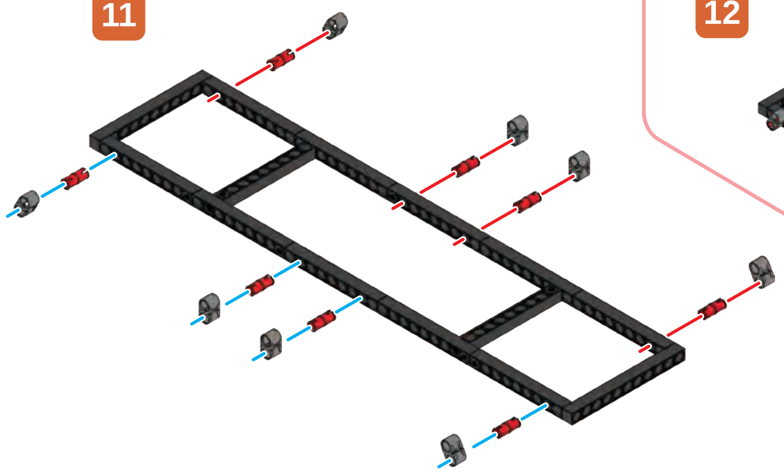

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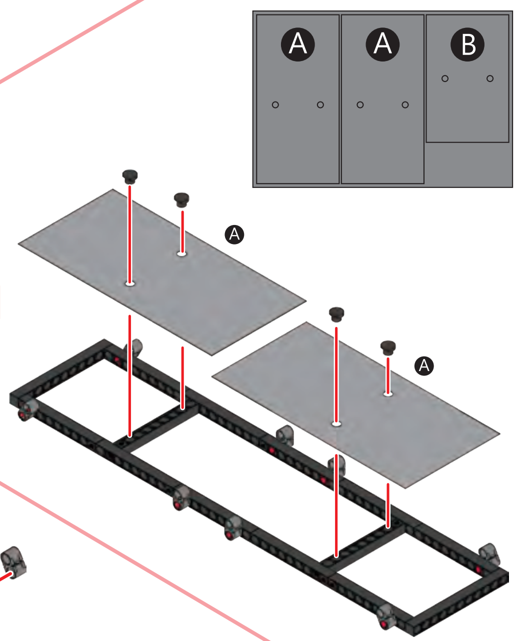

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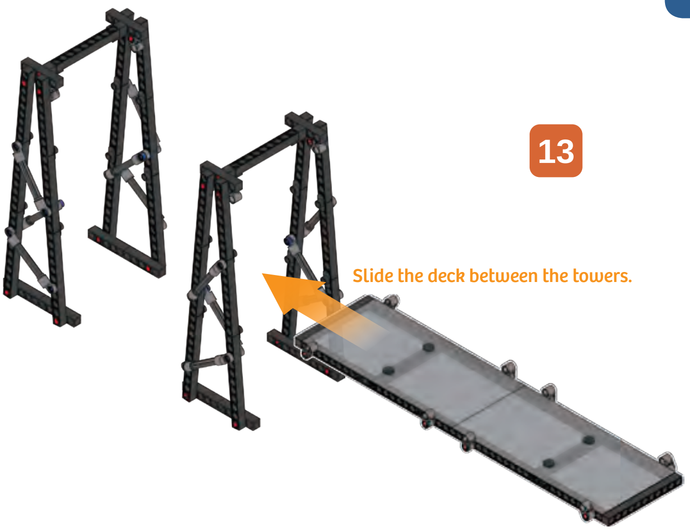
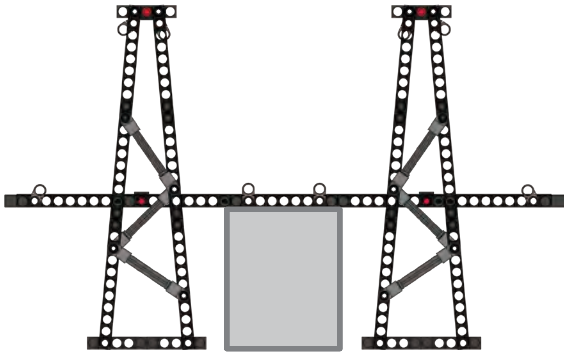
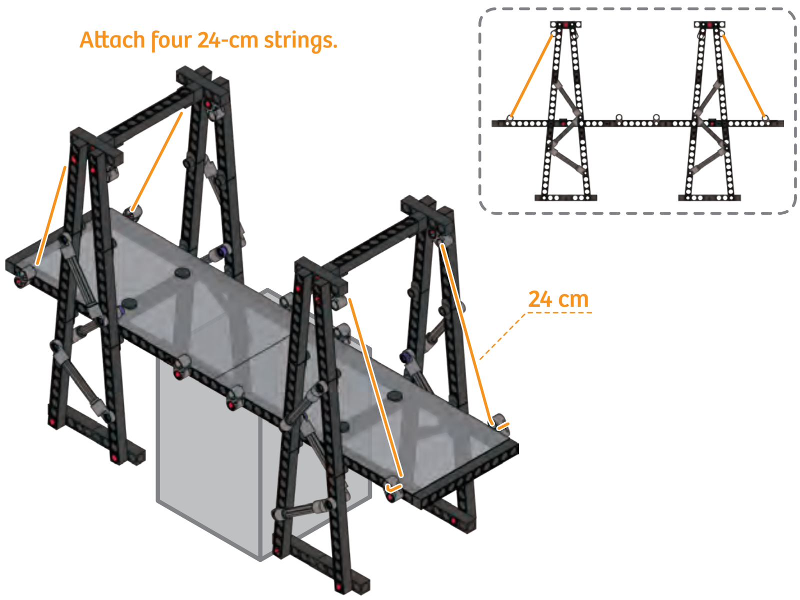




Tip: Find an object that can hold the deck in this position. This will make it easier to attach the cables.

14



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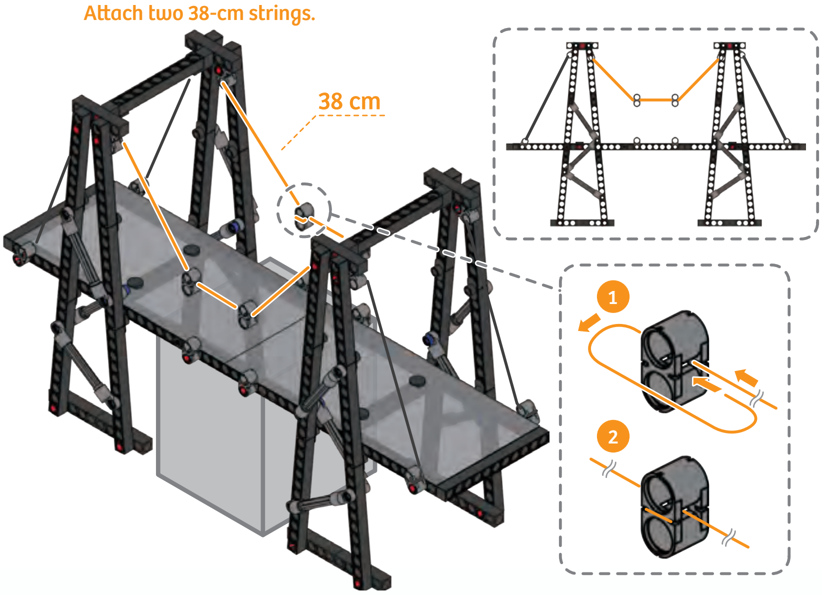
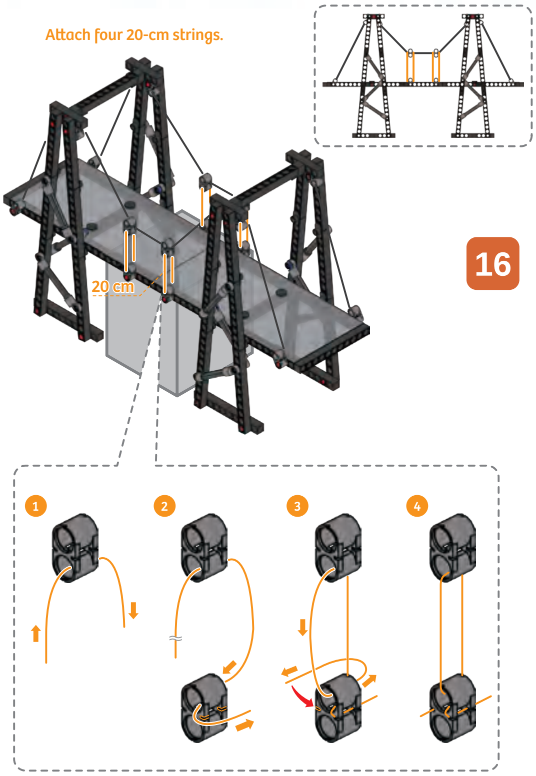
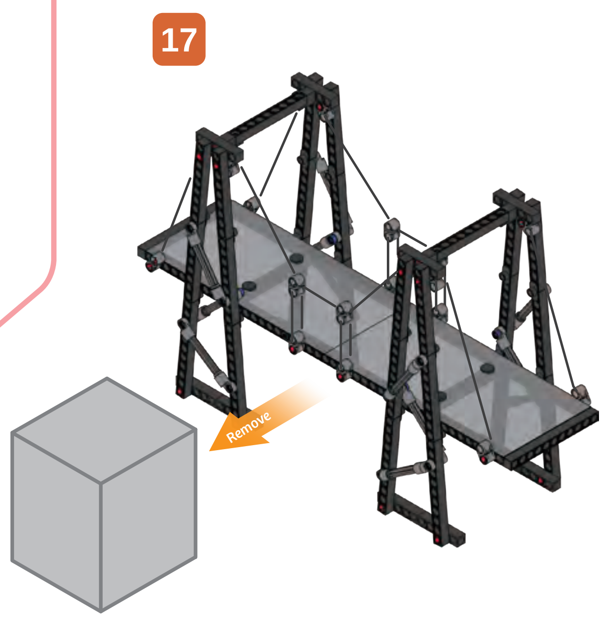




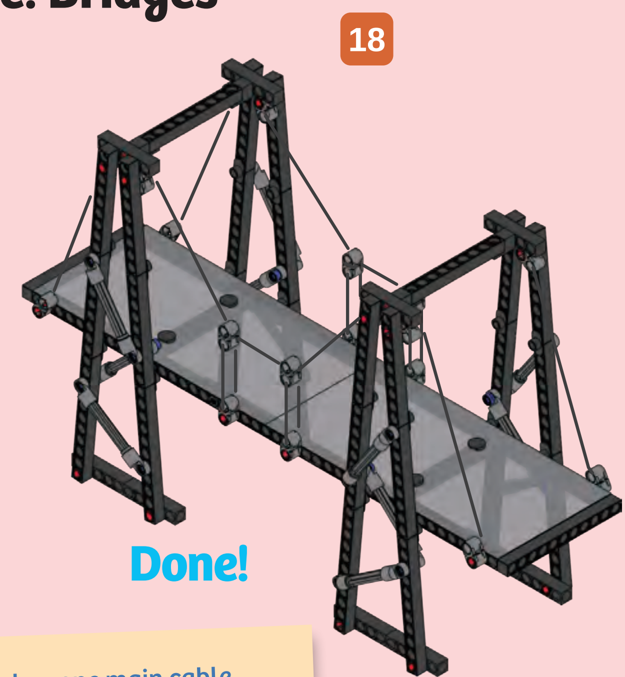


EXPERIMENT 19

Engineering Design Challenge: Bridges

HERE'S HOW

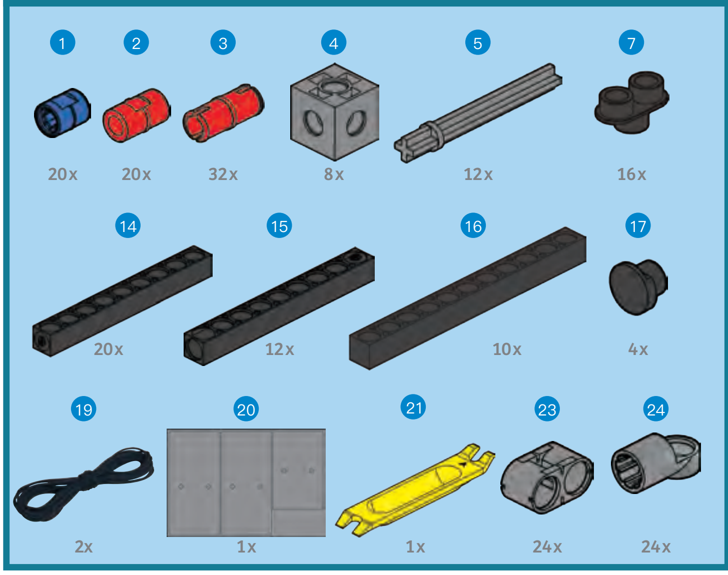
Using only the materials in this kit, design and build a bridge that is able to span a distance of three feet. The bridge should use the least amount of material possible, and you should be able to safely hang a weight of two pounds from its center without it falling down. You can vary the distance and weight to make this challenge easier or harder.



A suspension bridge has one main cable that runs between its towers with vertical cables that connect to its deck. A suspension bridge is better for spanning long distances than a cable-stayed bridge.

CABLE-STAYED BRIDGE

Parts Needed



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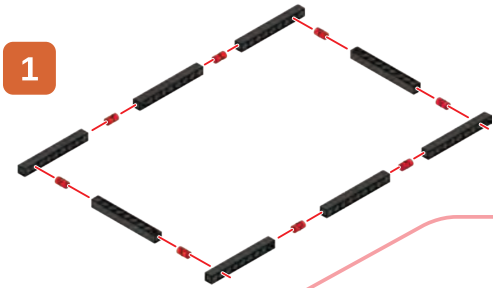

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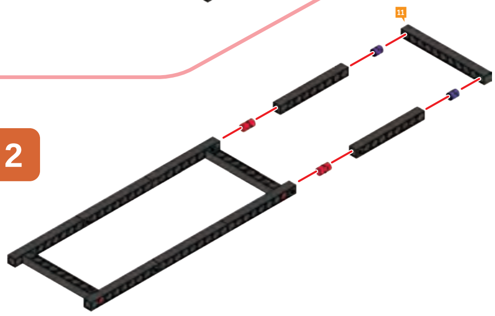

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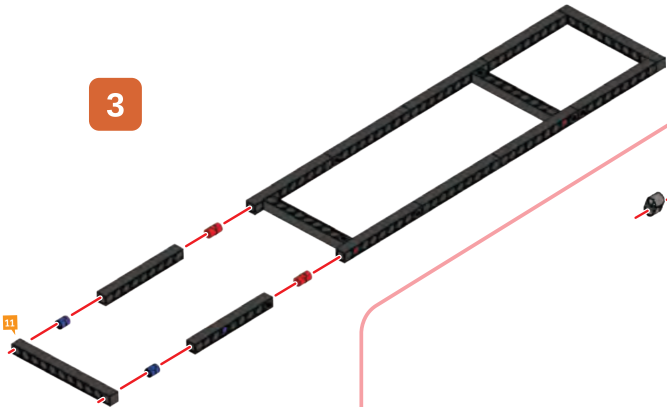

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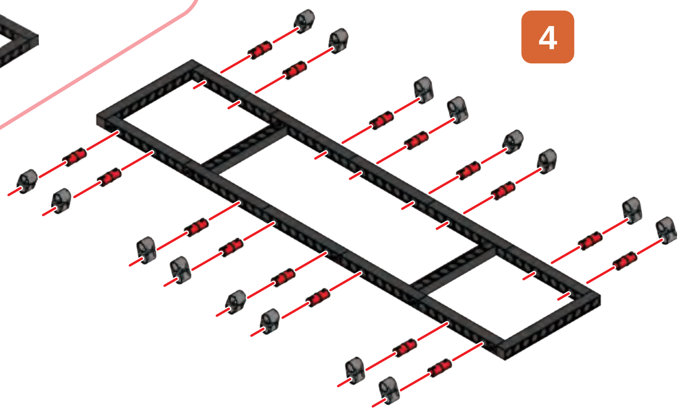

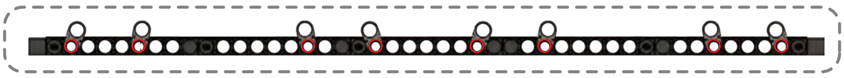

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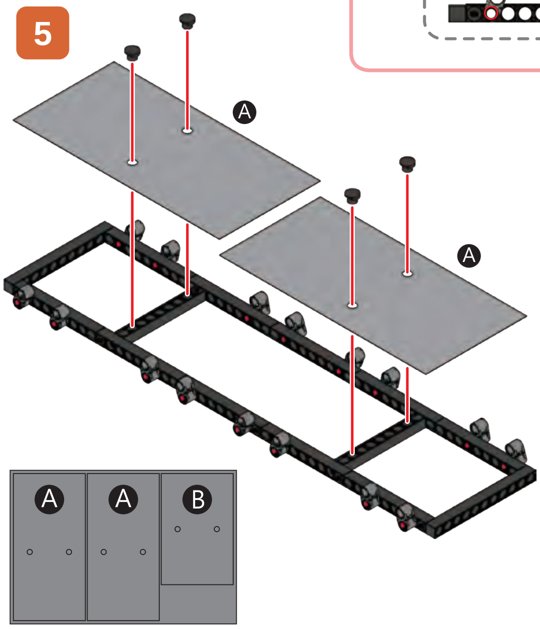

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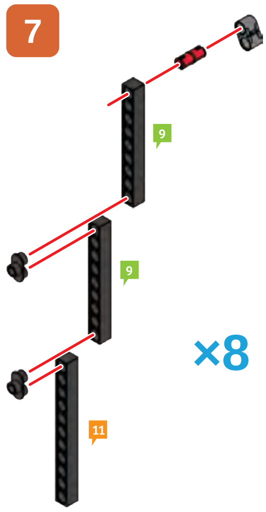

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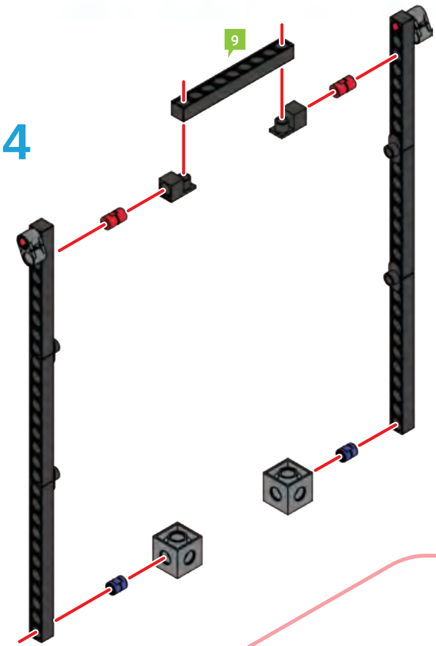

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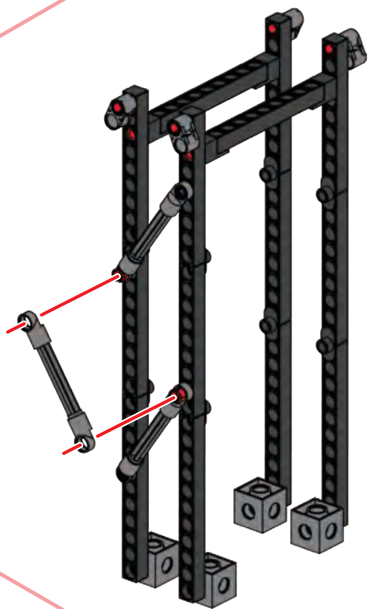

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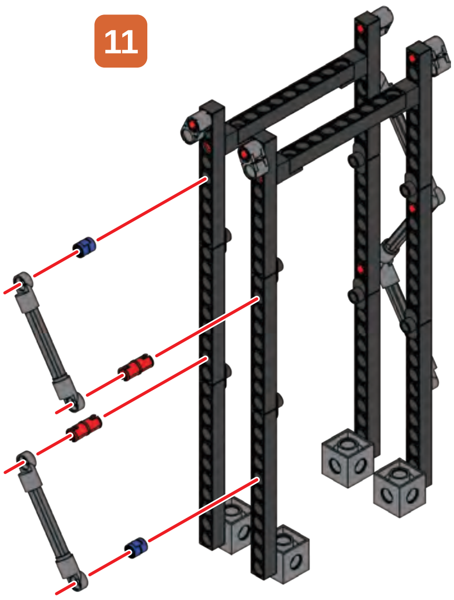

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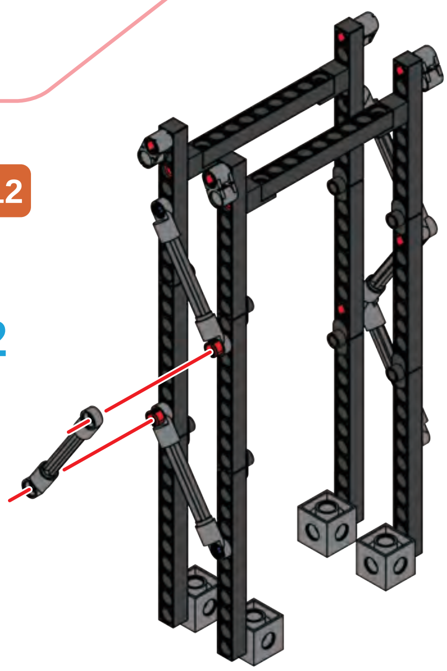
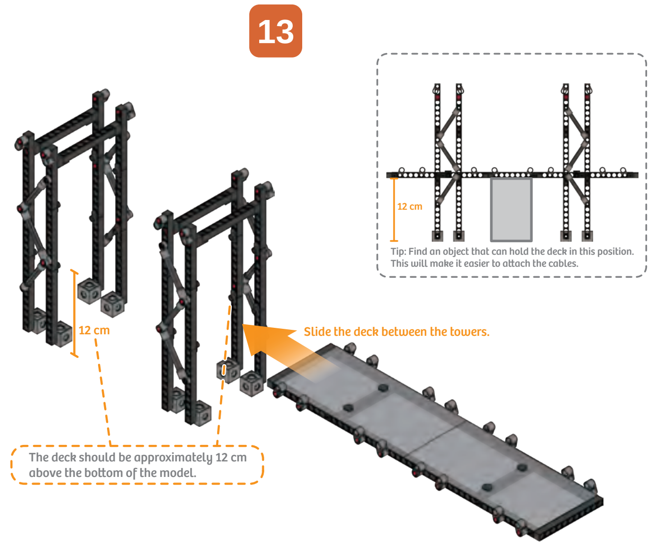
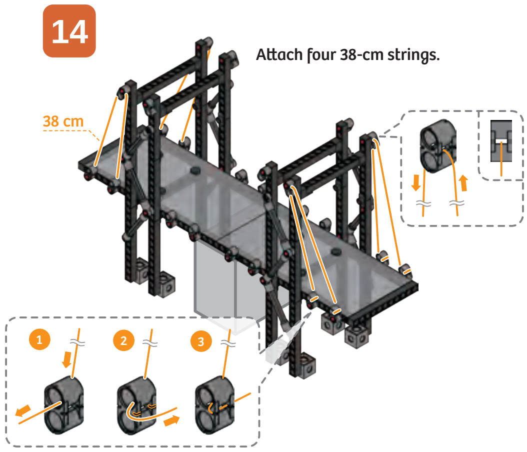
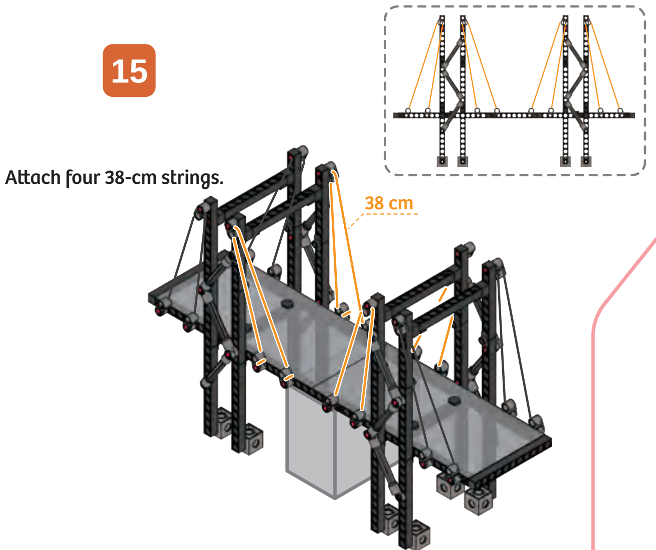
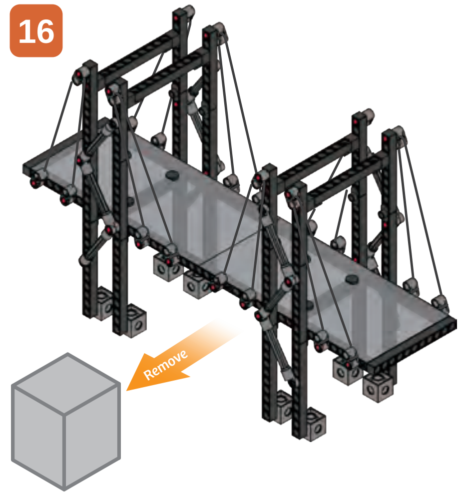










EXPERIMENT 20

Cable-stayed bridge

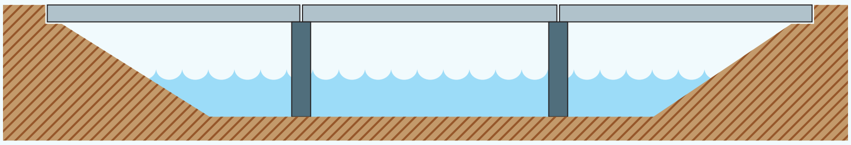
HERE'S HOW

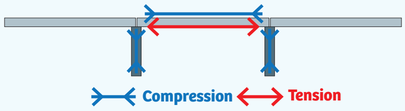
Try loading the bridge with increasing amounts of weight, such as toy blocks. Where does the bridge fail first? Do the towers fall over or do the cables come loose? What can you infer about the forces acting on the different structural elements in the bridge based on the way it fails?

A cable-stayed bridge has one or more towers with cables that run from the tower to the deck. The cables support the deck of the bridge.

Types of Bridges

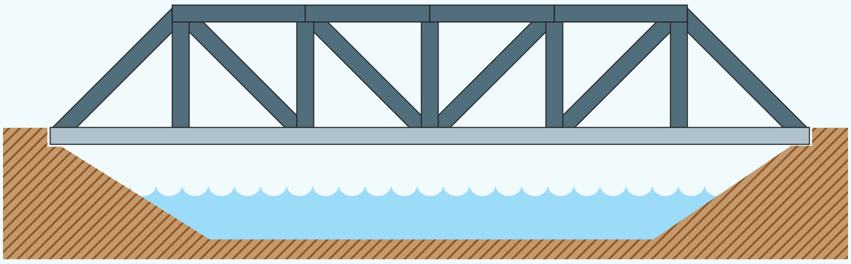
Beam Bridge

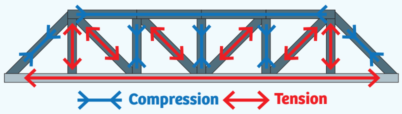




The beam bridge is the simplest type of bridge. It cannot span long distances because it does not transfer moments through its structural supports.

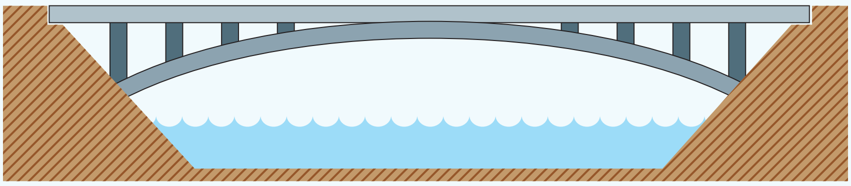
Truss Bridge

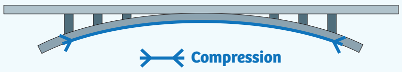




The truss bridge is made of struts connected in triangular units to give strength and support to the deck. The truss can be above or below the deck.

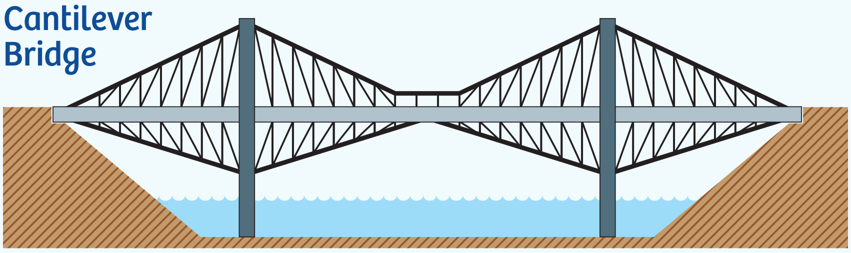
Arch Bridge

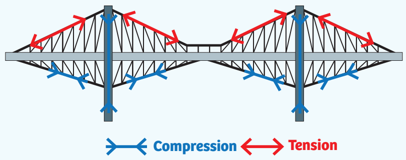




The arch bridge dates back to ancient times, when they were first constructed of stone blocks. Now, modern arch bridges are made of concrete and metal. The deck can be above, below, or even through the middle of the arch.

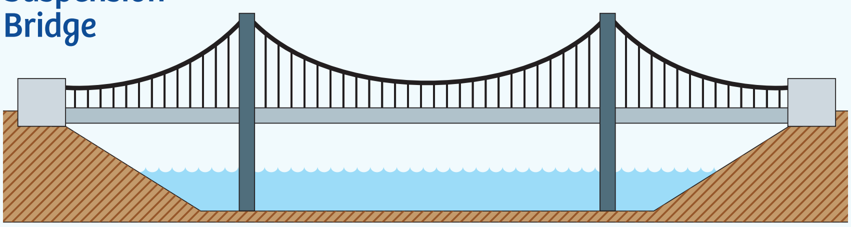
Cantilever Bridge

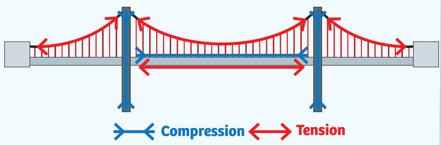




A cantilever bridge uses cantilevers, which are horizontal structures that project out into space and are supported only at one end. These bridges often use trusses to support the cantilevers.

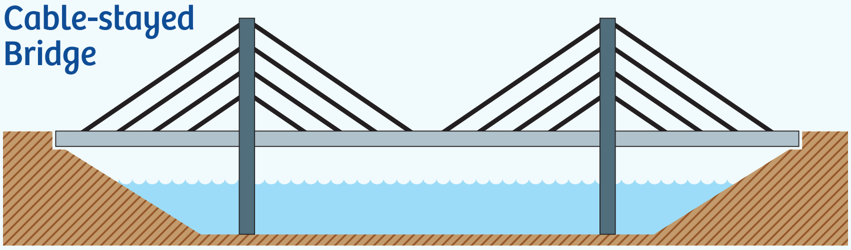
Suspension Bridge

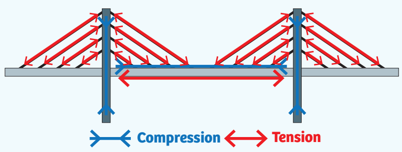




The deck of a suspension bridge is hung from cables. The cables are suspended from towers and anchored in the ground or massive blocks.

Cable-stayed Bridge





Like a suspension bridge, a cable-stayed bridge is supported by cables. The cables are connected directly to a central tower.

Skyscraper Design

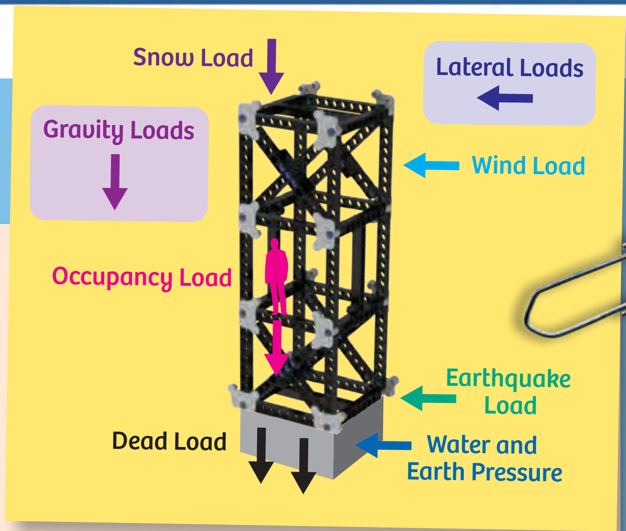
Loads Acting on a Building

Buildings and skyscrapers must withstand many different types of loads that could pull them down or push them over. Loads can be divided into two categories: Dead loads and live loads.

Dead loads include the weight of the building itself and all the permanent things installed in the building. Gravity pulls these loads downward.

Live loads include the weight of the people, furniture, and other objects inside the building. The snow load and rain load — the weight of the snow or water on the roof — are also live loads.

Some live loads act laterally on the building, instead of pulling downward. The wind load is caused by the wind pushing on the side of the building. The groundwater and earth around the building's foundation push laterally on it. And even the load from occasional earthquakes must be considered when designing a strong, stable building.



Skyscraper Structural Systems

This chart shows five types of structural systems used in skyscrapers and the maximum number of floors that can be achieved with each type.

Type 1: Rigid Frame

This is the oldest type of skyscraper structural system. A steel-frame structure of this type can rise to a height of about 30 stories.

Type 2: Frame with Shear Truss

By adding trusses to the frame, the skyscraper can be strengthened to rise to a height of about 60 stories.

Type 3: End Channel Framed Tube

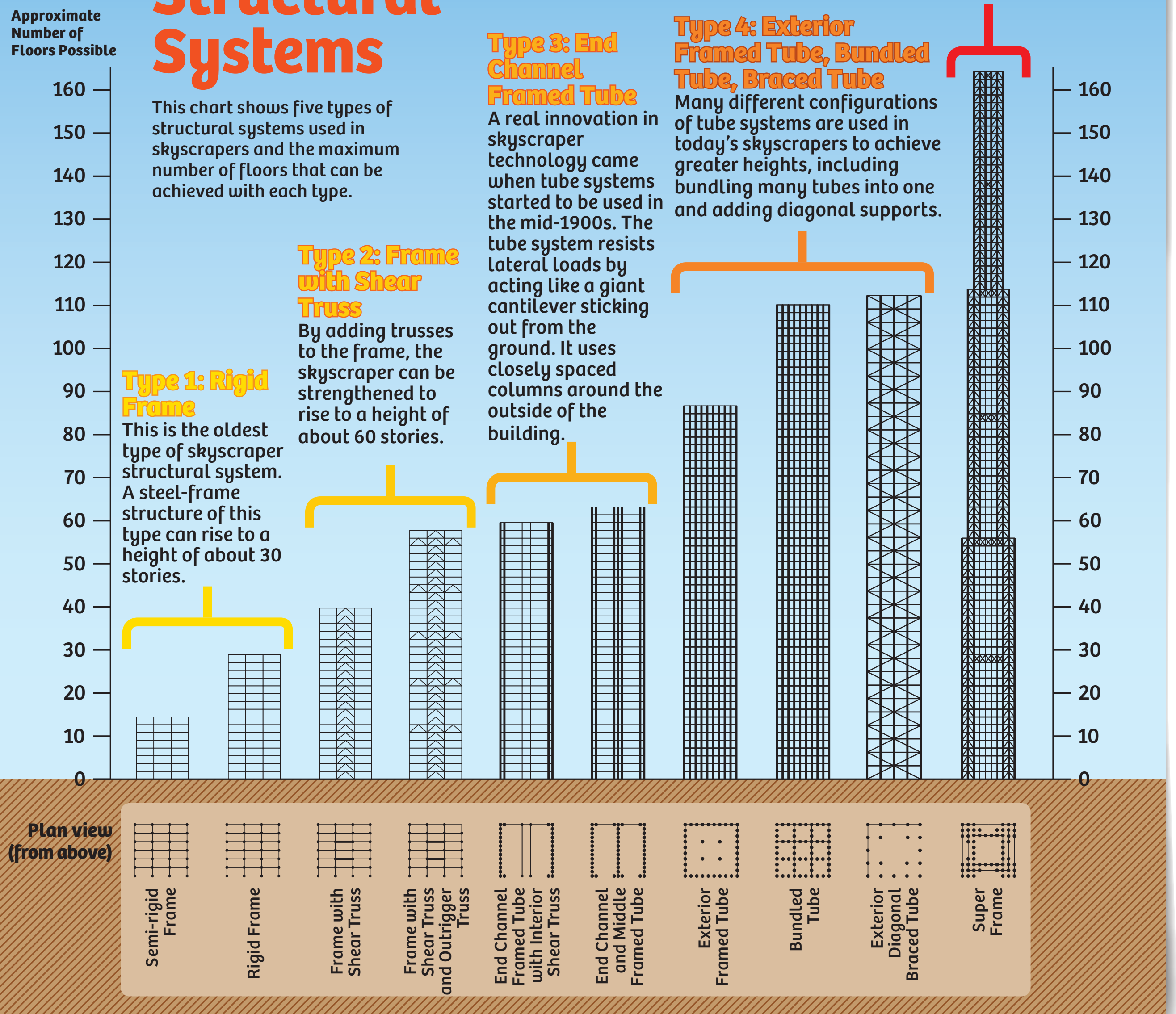
A real innovation in skyscraper technology came when tube systems started to be used in the mid-1900s. The tube system resists lateral loads by acting like a giant cantilever sticking out from the ground. It uses closely spaced columns around the outside of the building.

Type 4: Exterior Framed Tube, Bundled Tube, Braced Tube

Many different configurations of tube systems are used in today's skyscrapers to achieve greater heights, including bundling many tubes into one and adding diagonal supports.

Type 5: Super Frame

By the early 2000s, super-tall buildings of 160 or more floors were possible using super frames, which have braced frames at the corners linked together by horizontal multistory trusses every 10 or 20 floors.



IMPORTANT INFORMATION

Safety Information

Warning! Not suitable for children under 3 years.

Choking hazard— small parts may be swallowed or inhaled. Strangulation hazard — long cords may become wrapped around the neck.

Store the experiment material and assembled models out of the reach of small children.

Keep packaging and instructions as they contain important information.

Dear Parents and Supervising Adults,

Before starting the experiments, read through the instruction manual together with your child and discuss the safety information. Check to make sure the models have been assembled correctly. Assist your child with the experiments, especially with reading the assembly diagrams and putting pieces together that may require more dexterity or hand strength than the child currently possesses.
We hope you and your child have a lot of fun with the experiments!

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