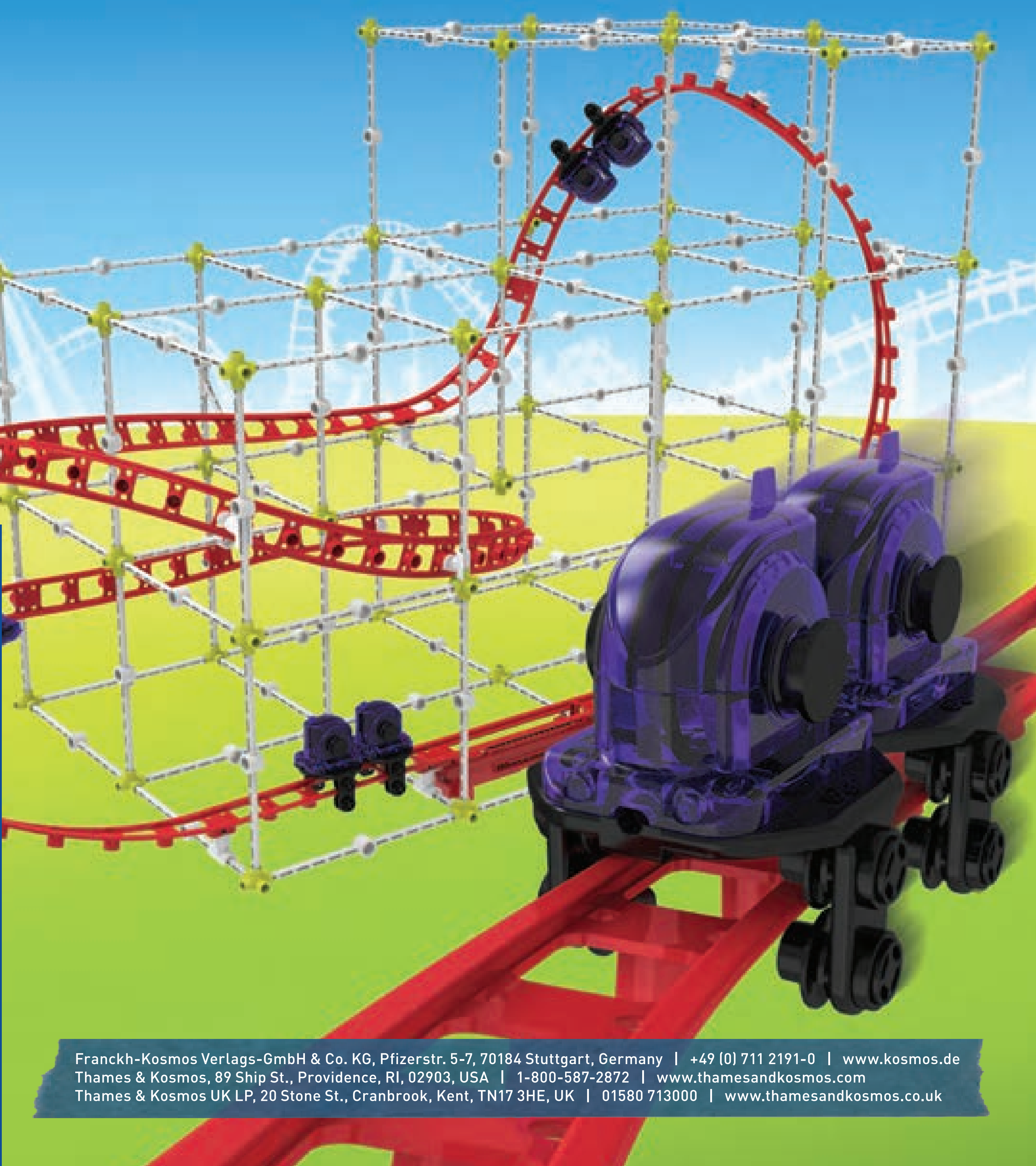
Experiment Manual

Roller Coaster Engineering



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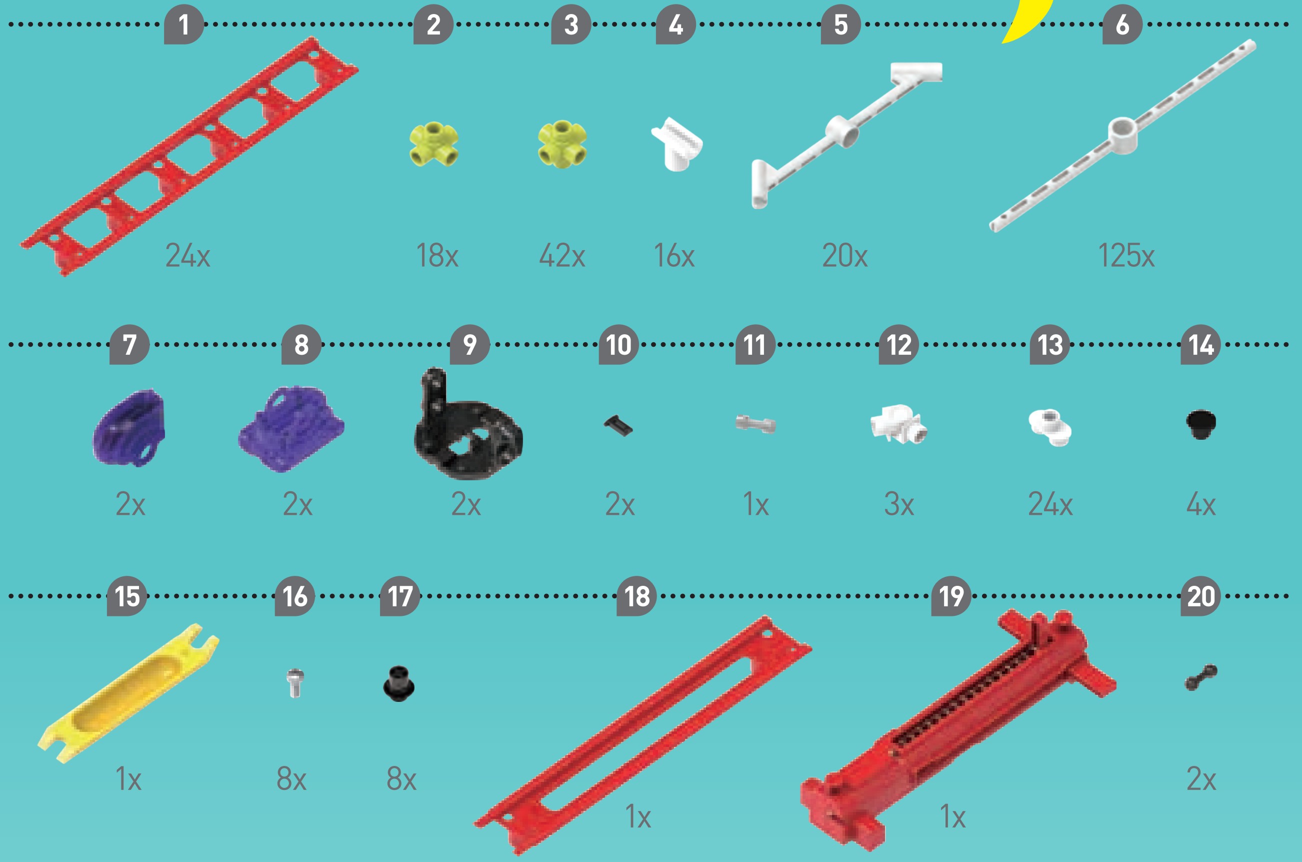
KIT CONTENTS

Good to know!
Do you have any questions or are you missing any parts? Our tech support team will be happy to help you!
USA: support@thamesandkosmos.com
or 1-800-587-2872
UK: support@thamesandkosmos.co.uk
or 01580 713000

What's inside your experiment kit:



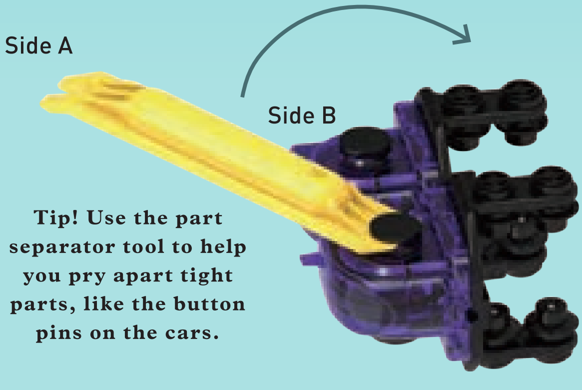
Checklist:

✓	No.	Description	Quantity	Item No.
○	1	Track	24	7071-W10-A1R
○	2	5-way rod connector	18	7071-W10-B1G
○	3	6-way rod connector	42	7071-W10-C1G
○	4	Track support	16	7071-W10-D1W
○	5	Frame strut	20	7071-W10-E1S
○	6	Frame rod	125	7071-W10-F1S
○	7	Car cover	2	7071-W10-G1TP
○	8	Car body	2	7071-W10-G2TP
○	9	Car chassis	2	7071-W10-H1D
○	10	Car launch trigger	2	7071-W10-H4D

✓	No.	Description	Quantity	Item No.
○	11	Car coupler, metal	1	M10#7071
○	12	Hinge	3	7061-W85-F1W
○	13	2-to-1 converter	24	7061-W10-G1W
○	14	Button pin	4	7061-W10-W1D
○	15	Part separator tool	1	7061-W10-B1Y
○	16	Screw	8	M20-44
○	17	Wheel	8	7071-W85-A
○	18	Launcher track	1	7071-W10-I5R
○	19	Launcher	1	7071-W85-B
○	20	Car coupler, plastic	2	7071-W10-H5D

The parts not included in the kit are marked in *italics* in the YOU WILL NEED lists.

YOU WILL ALSO NEED:
Small Phillips-head screwdriver, large coins (e.g., quarters), adhesive tape



Tip! Use the part separator tool to help you pry apart tight parts, like the button pins on the cars.

TABLE OF CONTENTS

TIP

ADDITIONAL INFORMATION CAN BE FOUND IN THE CHECK IT OUT SECTIONS ON PAGES 9, 19, 25, AND THE INSIDE BACK COVER.

Dear parents and adults,

This experiment kit offers your child a fun introduction to physics and engineering through the topic of roller coasters! 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. This manual touches on some fairly advanced physics concepts —help interpret them for your child as best you can, but also know that your child is learning simply by playing with the models and observing how the roller coaster train behaves in each experiment. We hope you and your child have a lot of fun with the experiments!

WARNING!

Not suitable for children under 3 years. Choking hazard — small parts may be swallowed or inhaled. Strangulation hazard — long flexible tracks may become wrapped around the neck.

Keep the packaging and instructions as they contain important information.

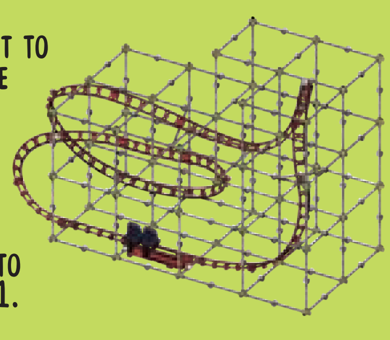
Keep your hands, face, hair, and all other parts of the body out of the way of the moving train.

VIDEOS

SCAN THIS QR CODE TO SEE A VIDEO OF EACH OF THE ROLLER COASTER EXPERIMENTS IN ACTION!

WE SUGGEST YOU START AT THE BEGINNING OF THE MANUAL AND DO THE EXPERIMENTS IN ORDER, FOR MAXIMUM LEARNING!

IF YOU WANT TO JUMP TO THE COMPLETE ROLLER COASTER PICTURED ON THE FRONT OF THE BOX, GO TO PAGE 31.



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Cool!
Let's get rolling!

Roller Coaster Engineering

What do roller coaster engineers need to know in order to design thrilling — and safe — rides? It's all about physics! Roller coasters are designed by teams with a range of expertise, including structural, mechanical, and electrical engineers.

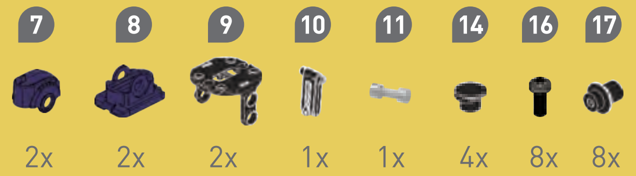
One thing you may not realize when you're zooming around a roller coaster track at high speeds is that the train you're on has no engine. To make riders scream, roller coaster designers rely on one very important force: **gravity.**

On traditional coasters, a train climbs a **lift hill** to gain **gravitational potential energy.** The higher the train climbs, the more energy it stores up for the rest of the ride. When the train begins its descent, potential energy is converted into **kinetic energy** — the energy of motion. The more kinetic energy the car has, the faster its speed. When the train climbs the coaster's next hill, or zooms through a vertical loop, kinetic energy is converted back into potential energy.

Modern roller coasters accelerate trains with mechanisms that create other forms of potential energy, including **electromagnetic** and **elastic potential energy.** These coasters can reach greater speeds than those with a conventional "lift hill." This kit includes a spring-powered launcher to create an initial burst of speed.

In this kit, you will build many different model roller coasters, from simple to complex, and conduct twenty experiments to test the physics principles involved in engineering awesome roller coasters.

TRAIN ASSEMBLY



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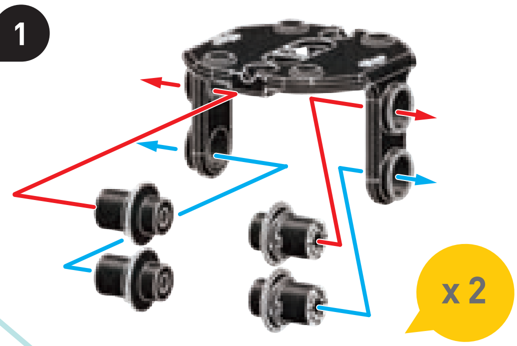

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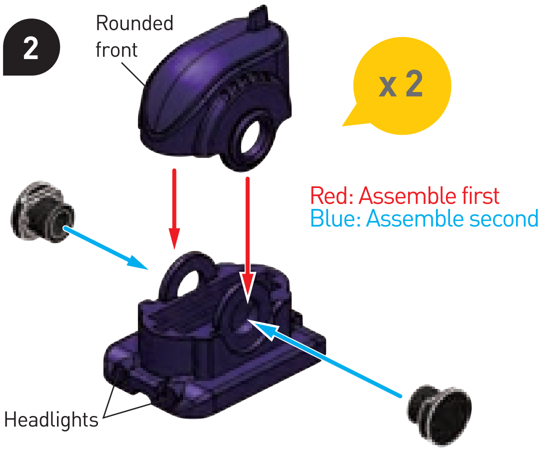
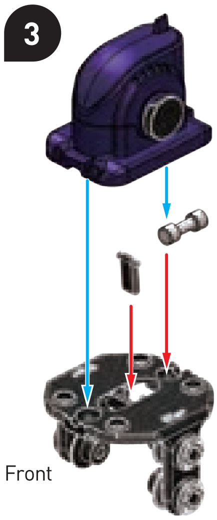


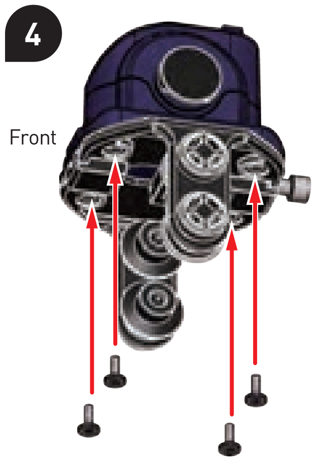
Note: The rounded side of the car cover and the headlights face forward.

3



Pay close attention to the orientation of all the parts here. The trigger hinges toward the coupler.

4



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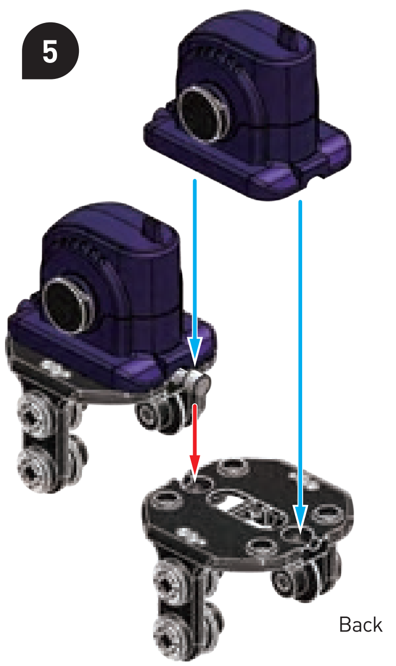

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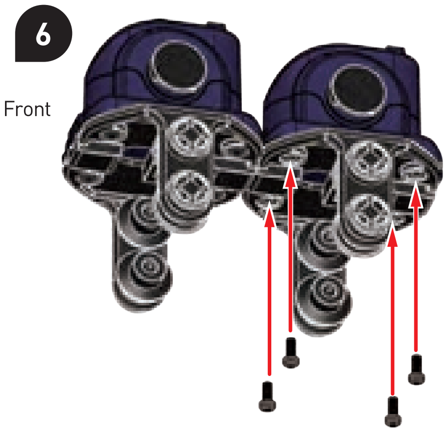

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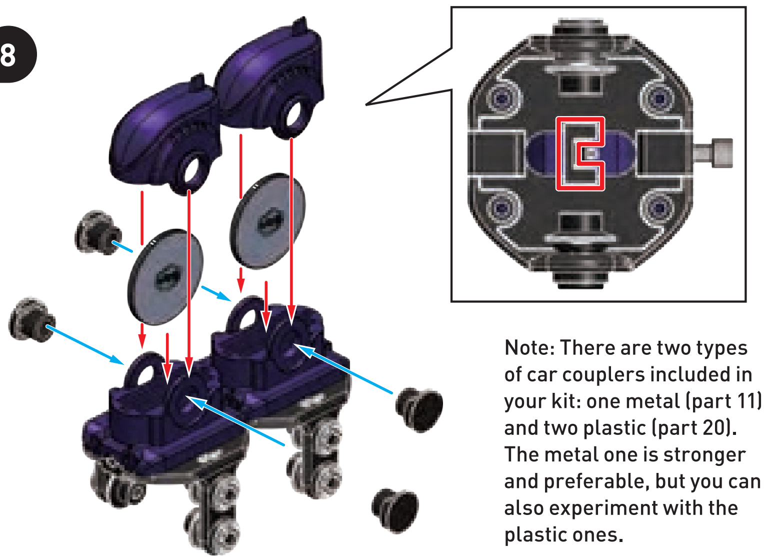
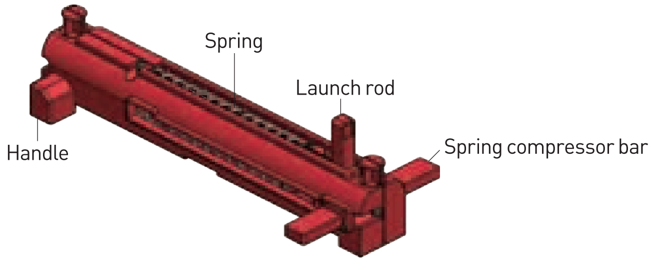


Note: There are two types of car couplers included in your kit: one metal (part 11) and two plastic (part 20). The metal one is stronger and preferable, but you can also experiment with the plastic ones.

! Pay attention to the direction of the train, because the launch trigger on the bottom of the car only hinges in one direction and it must be facing the correct direction in order to trigger the spring launcher.

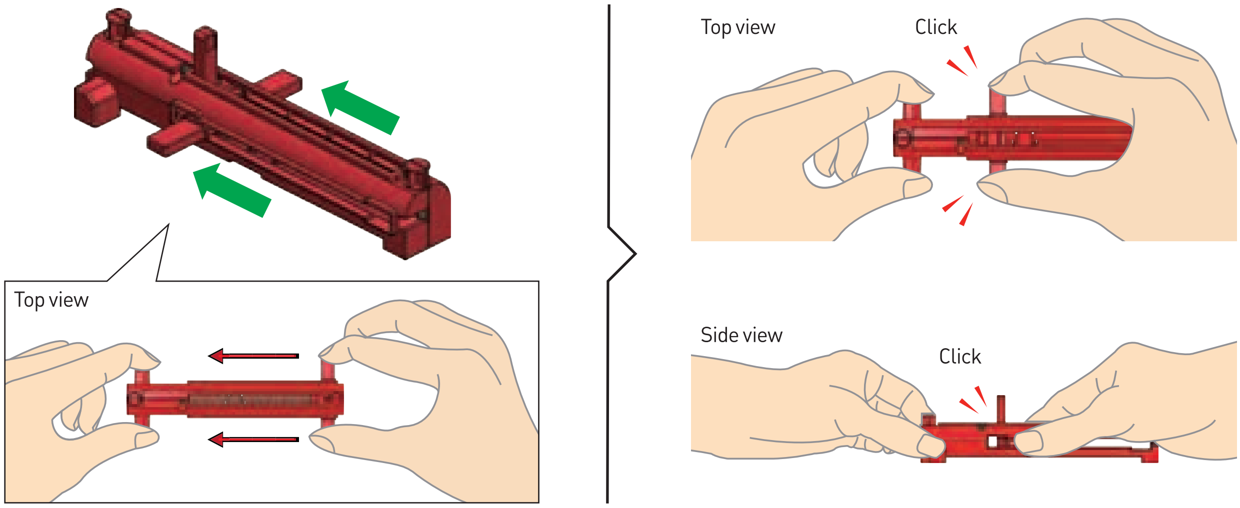
HOW TO USE THE LAUNCHER

1 The launcher starts out with the spring uncompressed.

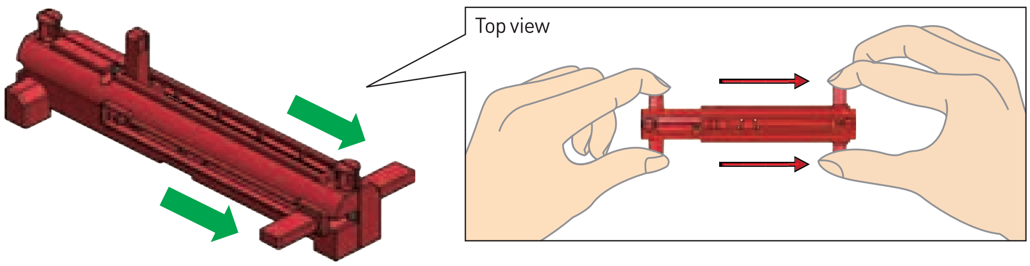


Handle the launcher carefully!
The loaded spring stores a lot of energy and the launch rod and spring compressor bar can move very quickly when the spring is discharged.
When you are not actively using it and during assembly, keep the launcher unloaded with the spring uncompressed.

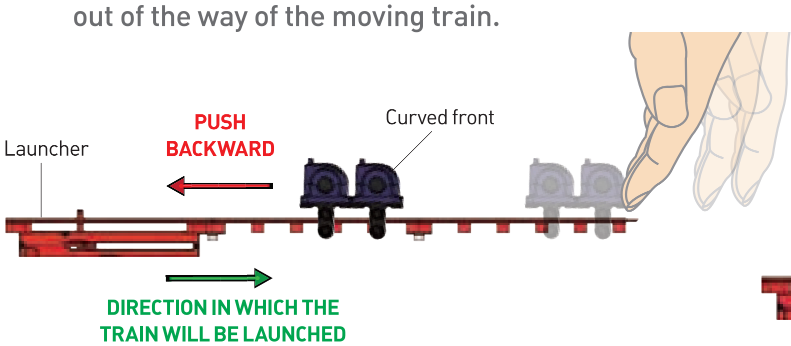
2 Holding the launcher by its handles, push the spring compressor bar in, compressing the spring, until the launch rod snaps into place.

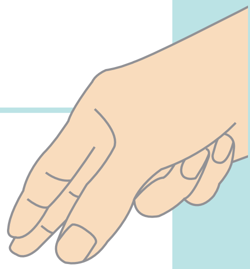


3 Slide the spring compressor bar back out. Now the launcher is ready to launch the train!

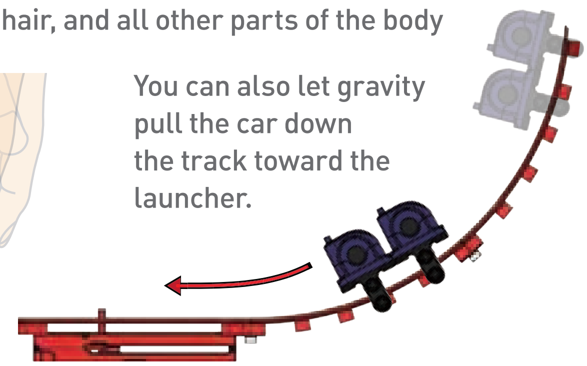


4 To launch the train, first make sure both the launcher and the train are facing the correct direction onto the track. The curved front of the train must be facing the direction in which you want the train to be launched. Give the train a push so it rolls backward toward the launch rod. When it makes contact with the launch rod, the spring will release and propel the car forward. Make sure to keep your hands, face, hair, and all other parts of the body out of the way of the moving train.

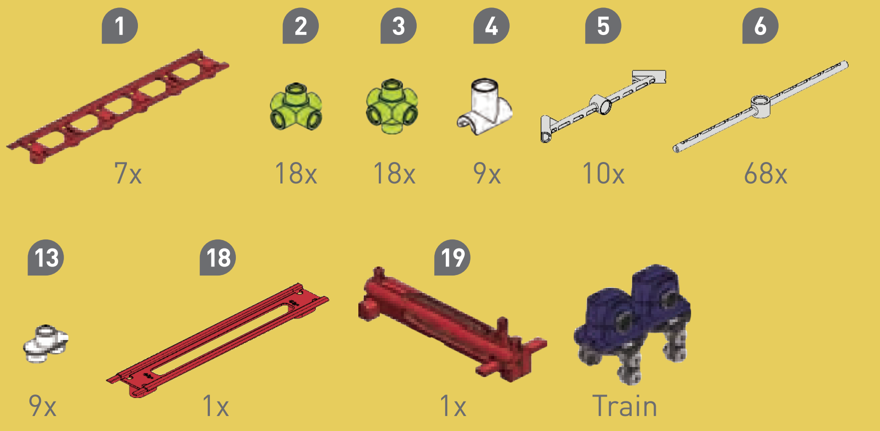




You can also let gravity pull the car down the track toward the launcher.



MODEL FOR EXPERIMENTS 1 AND 2 ⦿○○

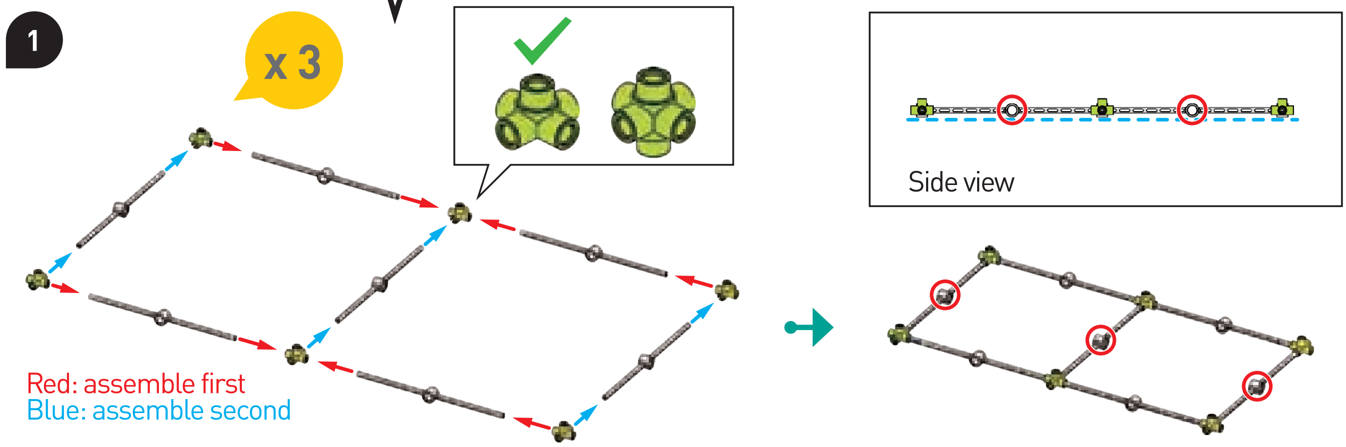


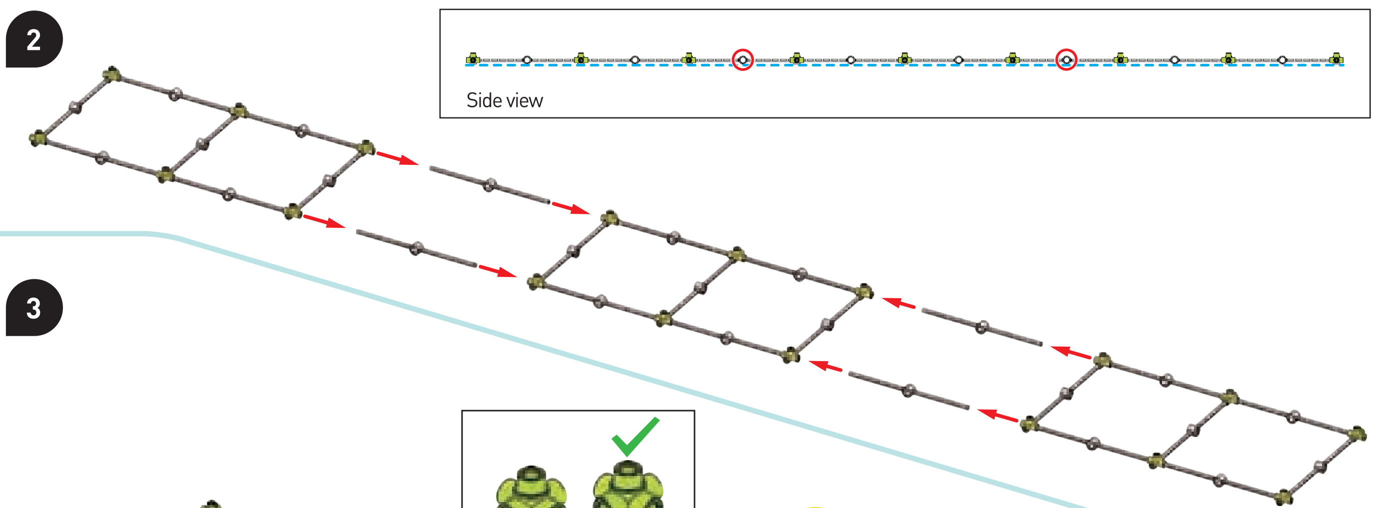
TIP

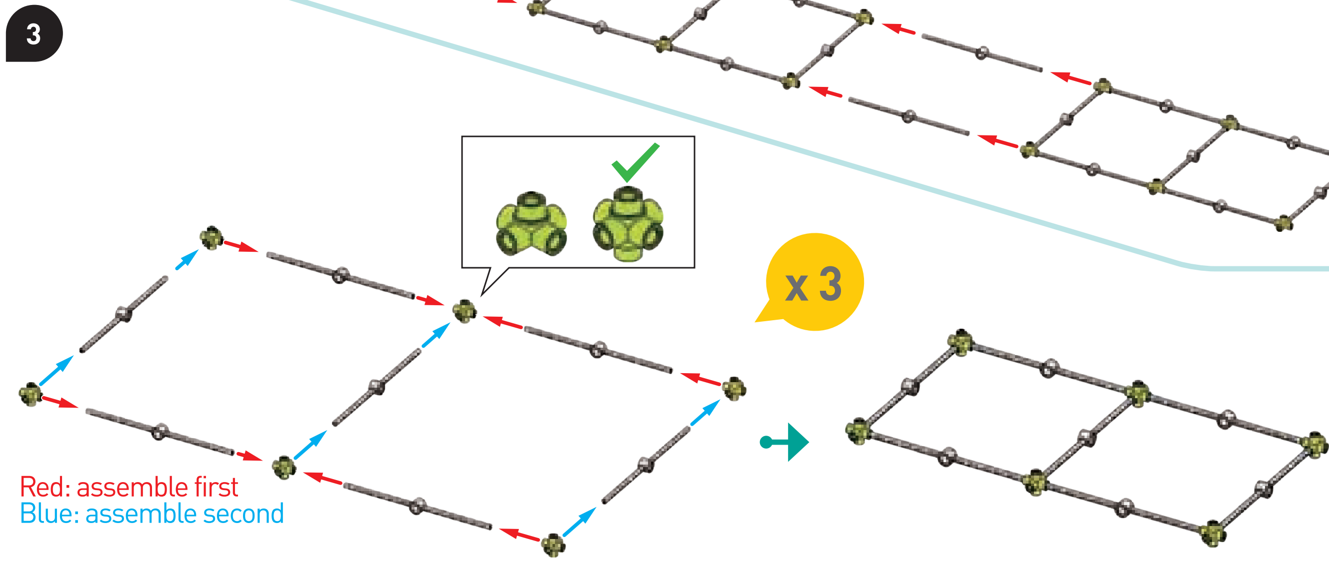
A DIFFICULTY RANKING IS GIVEN FOR EACH MODEL AT THE TOP OF ITS ASSEMBLY INSTRUCTIONS PAGE:

⦿○○ Easy ⦿⦿○ Medium ⦿⦿⦿ Hard

First, build the frame. Then, attach the track to the frame, completing the model. Finally, conduct the experiments using the model you built.







MODEL FOR EXPERIMENTS 1 AND 2

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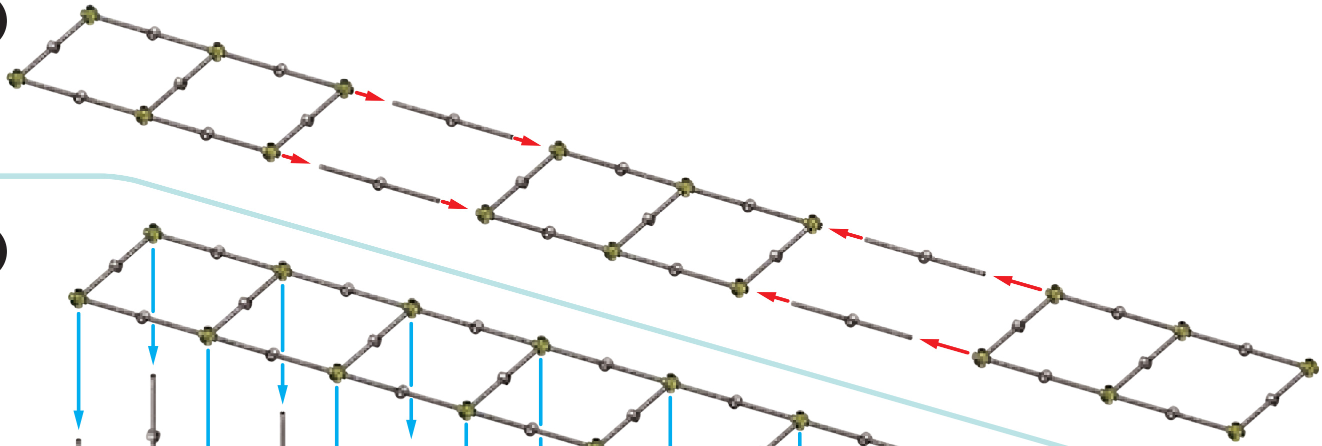

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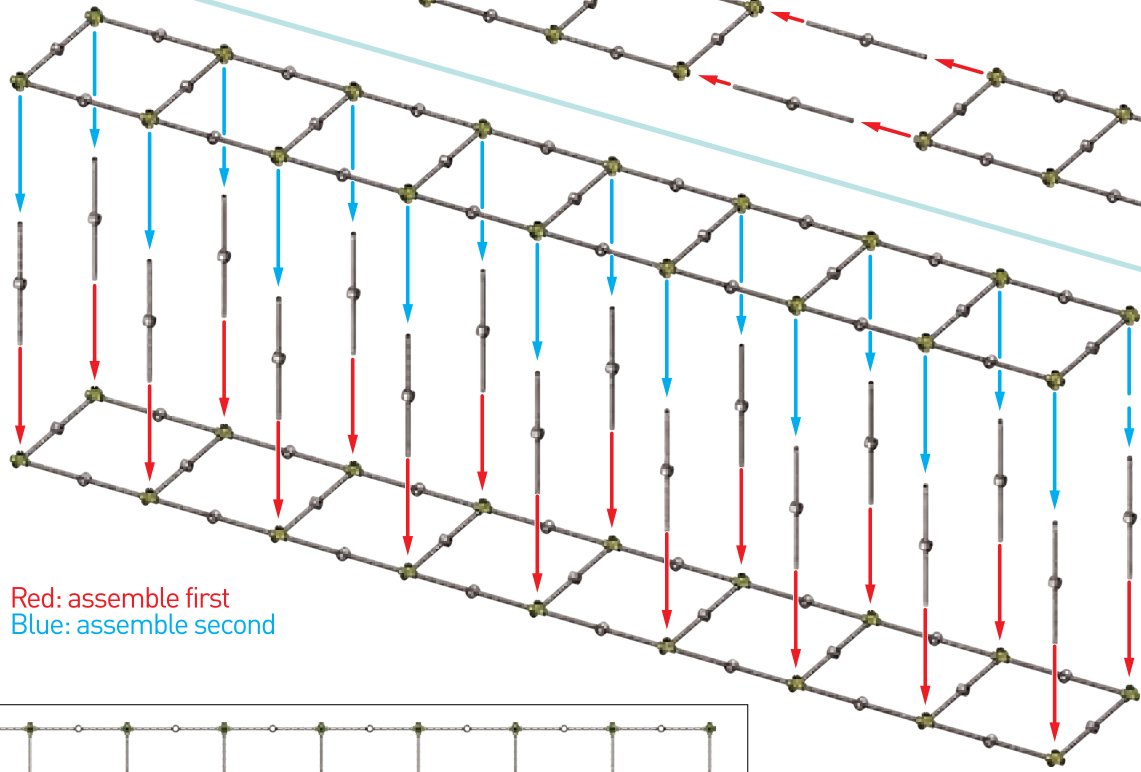
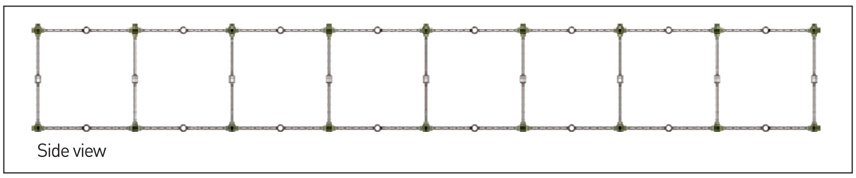


Red: assemble first
Blue: assemble second



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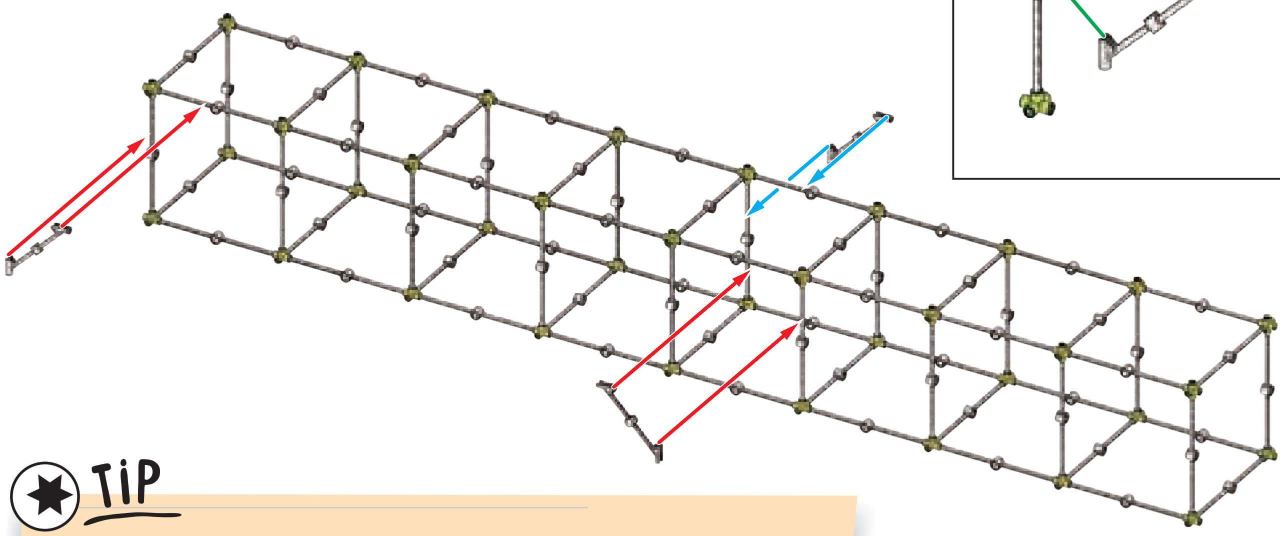

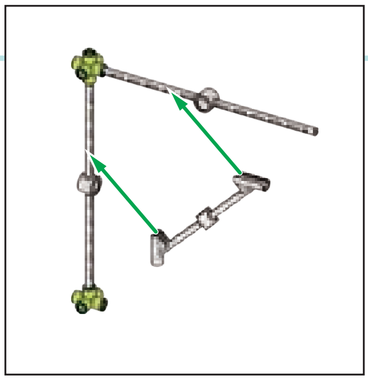

TIP

AS A GENERAL RULE, YOU DON'T HAVE TO FOLLOW THE ASSEMBLY EXACTLY AS SHOWN. IF YOUR MODEL IS CLOSE TO THE MODEL SHOWN, THE EXPERIMENT WILL STILL WORK. IN OTHER WORDS, YOU CAN IMPROVISE A LITTLE WHEN BUILDING THE MODELS.

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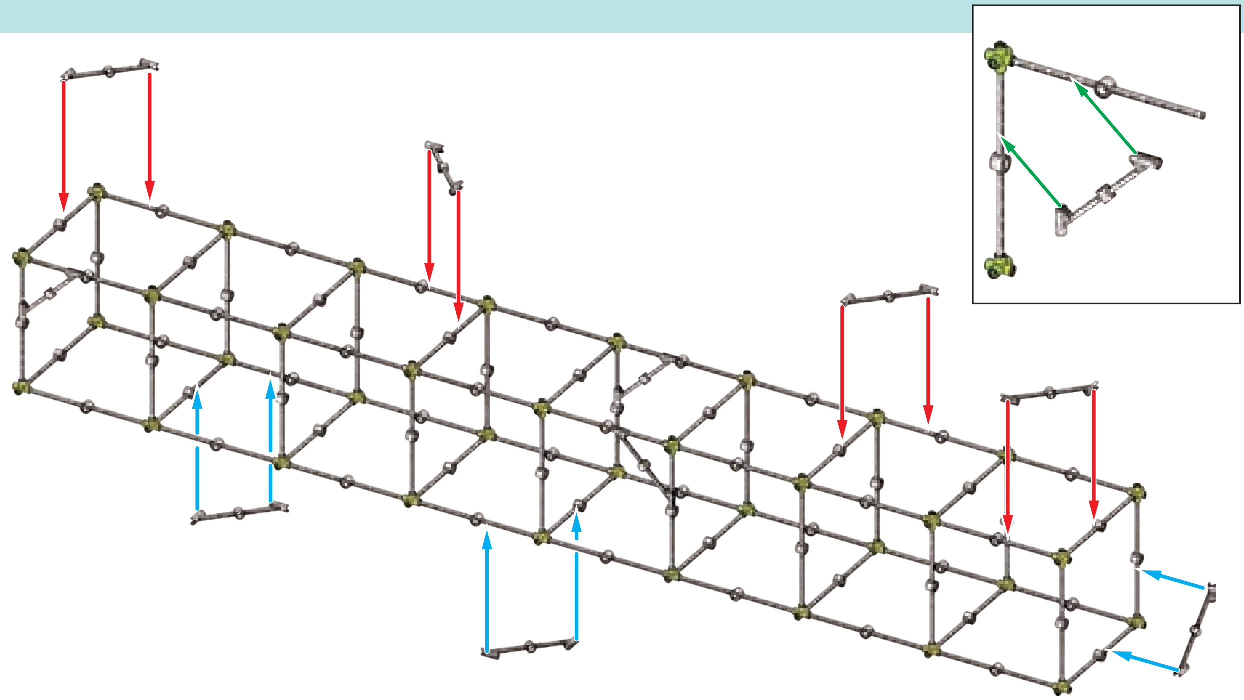

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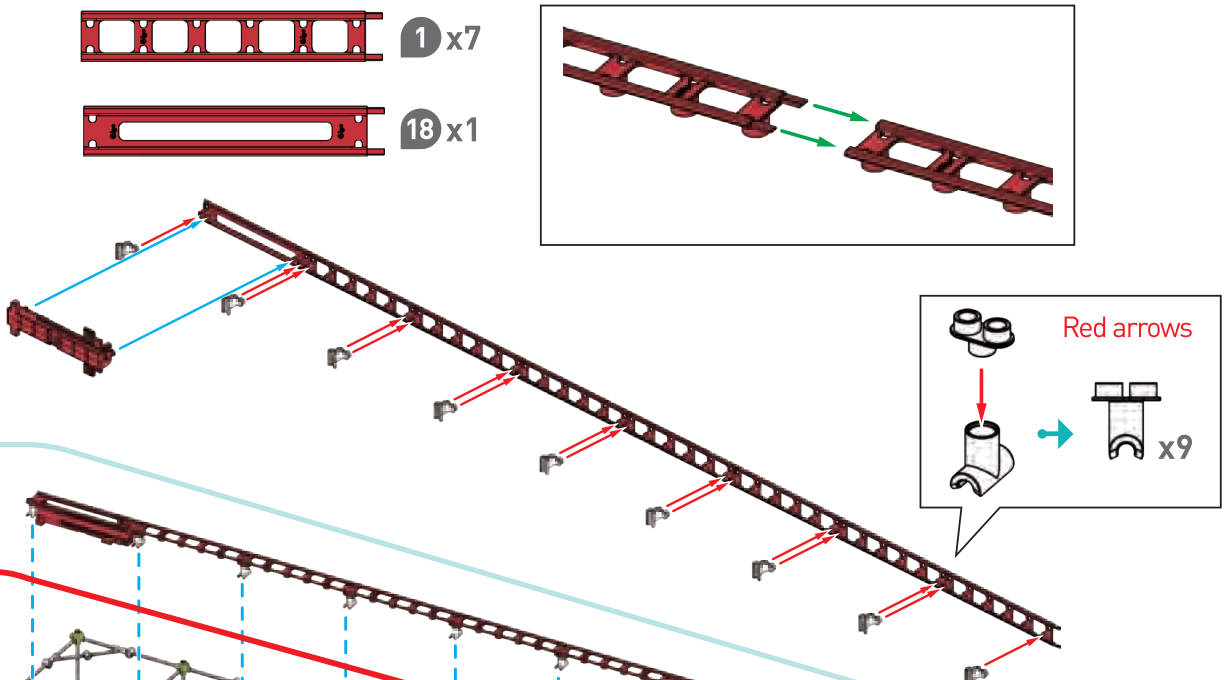

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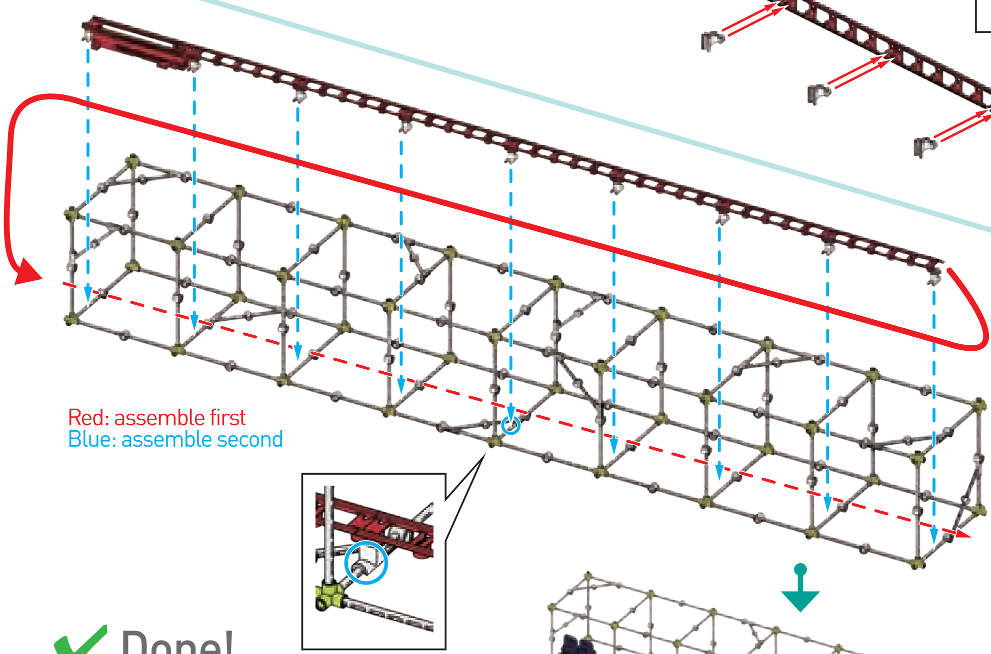
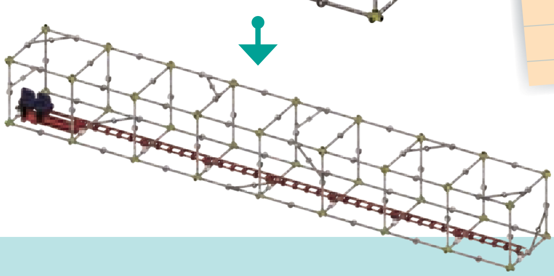




TIP

FOR THE MOST STABILITY DURING YOUR EXPERIMENTS, TAPE THE FRAME TO THE FLOOR!

✔ **Done!**

Now try the experiments on the next page.

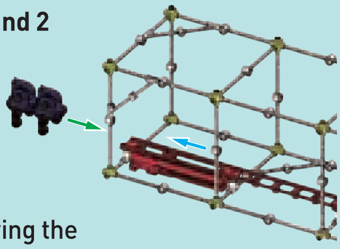
EXPERIMENT 1

Force and distance

How does changing the launch force affect how far a roller coaster train travels?

You will need

- **Model for experiments 1 and 2**
- **Assembled train**



Here's how

1. After you have assembled the model and train following the instructions on the previous pages, place the model on the floor with empty space in front of it into which the train can be launched. Slide the train onto the track, with its front facing forward, so the bottom wheels are below the track and the top wheels are above the track. It will roll smoothly.
2. Roll the train past the launch rod. If the train does not pass the launch rod easily, it is facing the wrong direction. Remove the train from the track, rotate it around and load it onto the track again.
3. With one hand, pull back the spring compressor bar to compress the spring inside the launcher to the midpoint.
4. Still holding the spring compressor bar, roll the train backward until the car launch trigger meets the resistance of the launch rod.
5. Release the spring compressor bar. How far did the train travel?
6. Put the train on the track in front of the launcher again.
7. Now pull the spring compressor bar back until it clicks into the notch in the launcher and locks into place.
8. With your finger, flick the train backward toward the launcher. How far did the train travel this time?

WHAT'S HAPPENING?

Inside your launcher is a spring. When compressed, springs store **elastic potential energy.** The more a spring is **compressed,** or squished, the more elastic potential energy is stored in the spring. When the compressed spring inside the launcher is released, it puts a **force** on the train, causing the train to **accelerate** — in other words, to increase in speed moving forward.

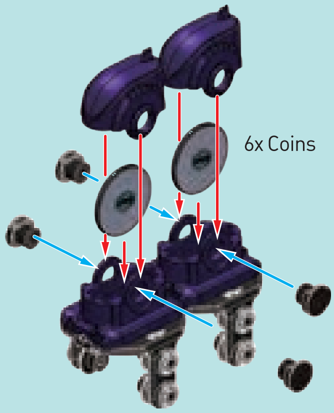
EXPERIMENT 2

Changing the mass

How does changing the mass of the train affect how far it travels?

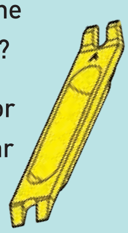
You will need

- **Model for experiments 1 and 2**
- **Assembled train**
- **Part separator tool**
- *6 Large coins (e.g., quarters)*



Here's how

1. Slide the train onto the track.
2. Pull the spring compressor bar back until it clicks into the notch in the launcher.
3. With your finger, flick the train backward, toward the launcher to launch it. How far does the train travel?
4. Take the train off the track. Using the part separator tool, remove the button pins on the sides of both car covers, then remove the car covers.
5. Place three large coins (e.g., quarters) in each car.
6. Replace the car covers and button pins on both cars.
7. Launch the train again. What do you notice?



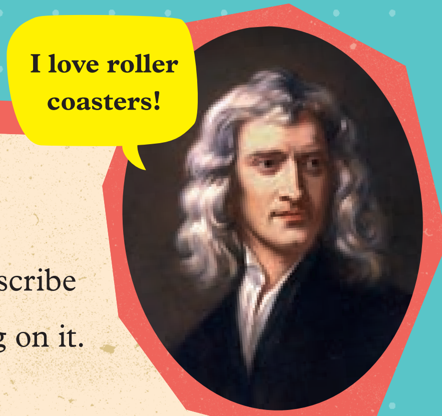
WHAT'S HAPPENING?

You probably observed that the lighter train goes faster and farther than the heavier train. The acceleration of an object depends on two things, force and mass. According to **Newton's second law,** the acceleration of an object is directly proportional to the net force and inversely proportional to its mass. As you saw in experiment 1, when you put a greater force on an object, it has a larger acceleration. Whereas, when you add more mass to an object, as in experiment 2, it has a lower acceleration.

If you conduct these experiments several times, you might see slightly different results. There are many variables here, including the force from the launcher. If you flick the train at the launcher with more force, it will travel further than if you flick the train with a small amount of force.

CHECK IT OUT

Newton's Laws



In 1687, Isaac Newton outlined these three fundamental laws that describe the relationship between the motion of an object and the forces acting on it.

NEWTON'S FIRST LAW

AN OBJECT IN MOTION STAYS IN MOTION, AND AN OBJECT AT REST STAYS AT REST, UNLESS ACTED UPON BY AN UNBALANCED FORCE.

Imagine you are sitting in a roller coaster car waiting for the ride to start. Suddenly, the coaster speeds forward. What do you feel? You might feel like your body is being pushed backward into the seat cushion. But there's no force actually pushing you back. So what is going on? According to Newton's first law, your body has **inertia** — a tendency to resist any change in motion. Because it starts at rest, your body will remain at rest until it is acted upon by a force. The seat behind you pushes your body forward so that you move along with the car. While this feels like you are being pushed backward, it is actually inertia that you are feeling!

NEWTON'S SECOND LAW

THE NET FORCE ON AN OBJECT IS EQUAL TO ITS MASS TIMES ITS ACCELERATION.

You saw in experiments 1 and 2 how Newton's second law applies to roller coasters. Newton's second law is often written as:

$$F_{net} = ma$$

If you divide both sides by mass, so that acceleration is by itself, you get:

$$a = \frac{F_{net}}{m}$$

Acceleration is directly proportional to net force (F_{net} is in the numerator), so if F_{net} increases, acceleration will also increase.

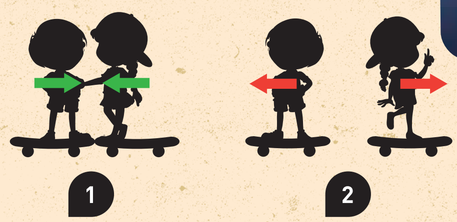
Acceleration is inversely proportional to mass (m is in the denominator), so if mass increases, acceleration will decrease.

NEWTON'S THIRD LAW

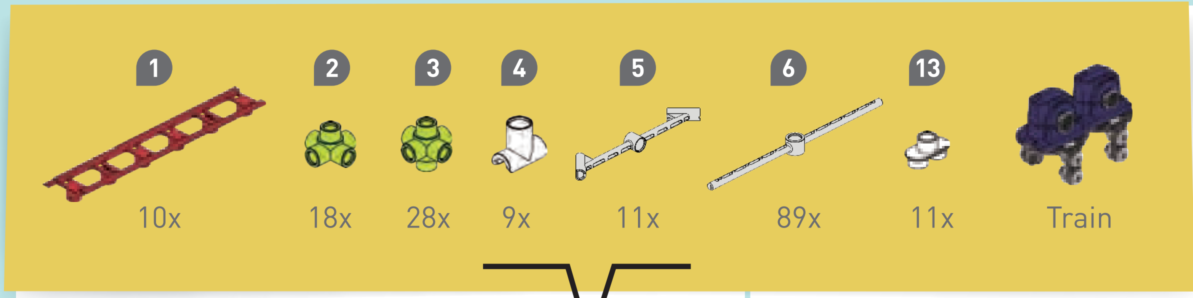
ALL FORCES COME IN PAIRS. FOR EVERY ACTION THERE IS AN EQUAL AND OPPOSITE REACTION.

As you sit in your roller coaster seat, your body applies its force of gravity, or weight, onto the seat. The seat applies an equal and opposite force on your body, which is called the **normal force.**

Engineers rely on this law to send rockets into space. Thrusters burn fuel which creates a downward force on the air below the rocket. The air then provides an upward force on the rocket, pushing it out toward space.



MODEL FOR EXPERIMENTS 3 AND 4



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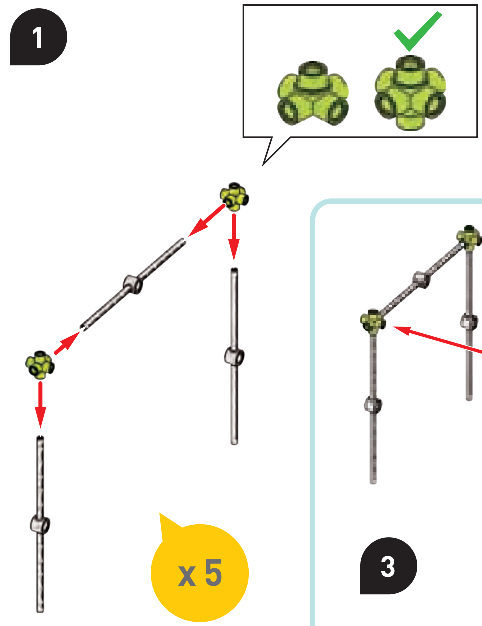

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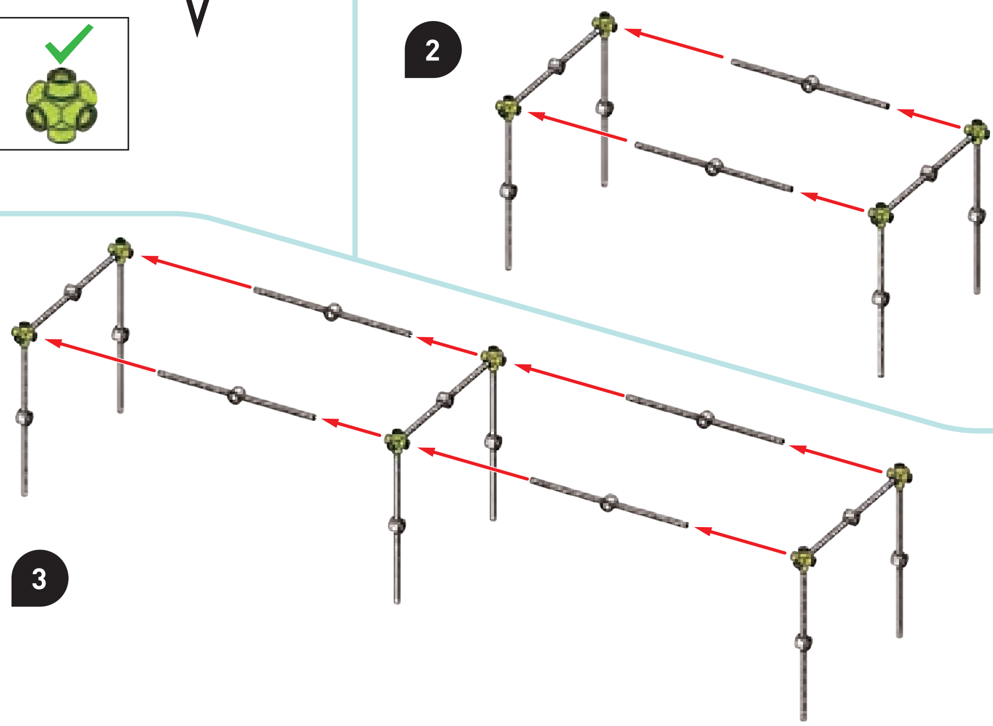

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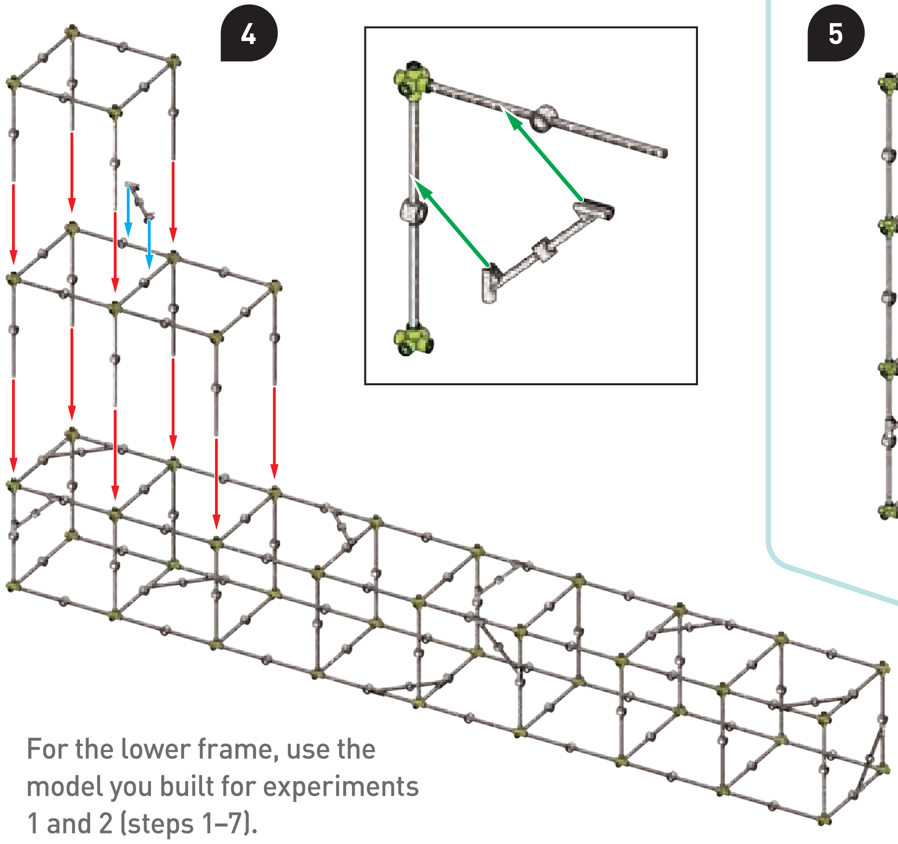

4

For the lower frame, use the model you built for experiments 1 and 2 (steps 1–7).

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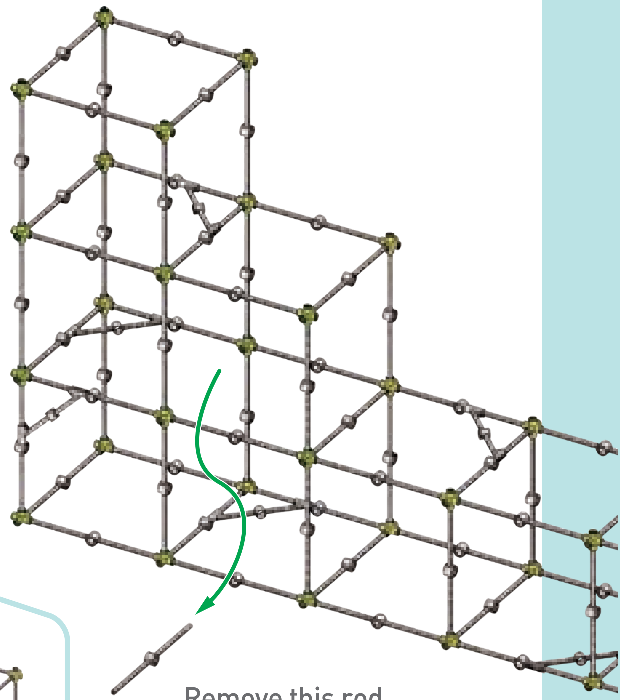
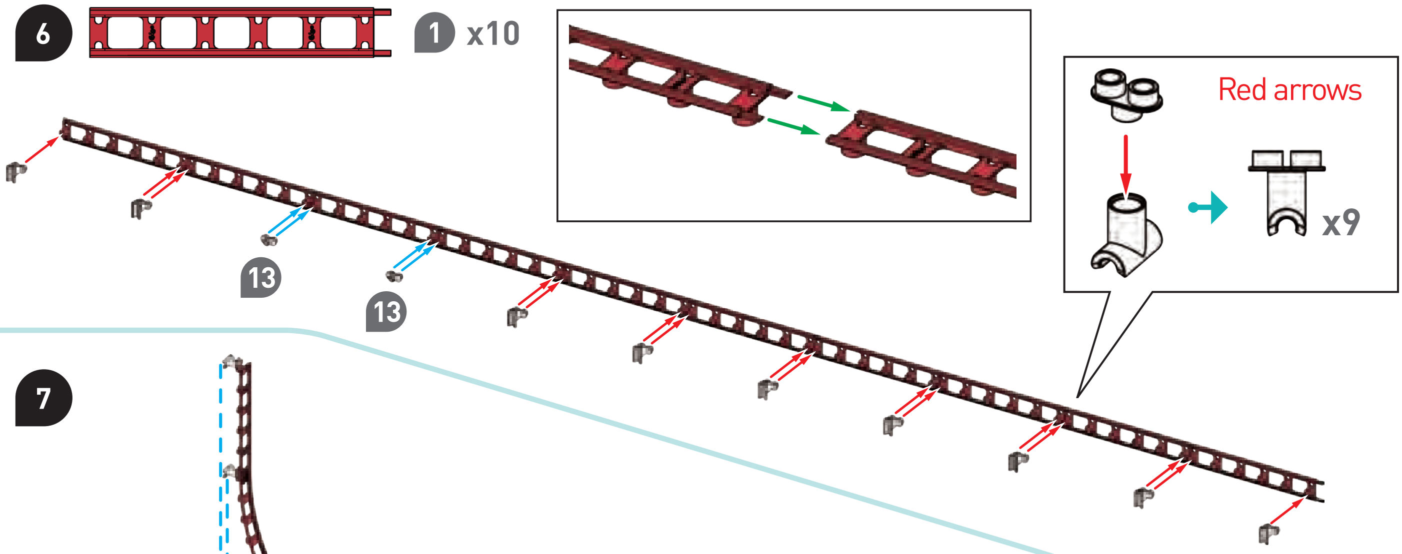


Remove this rod.

6



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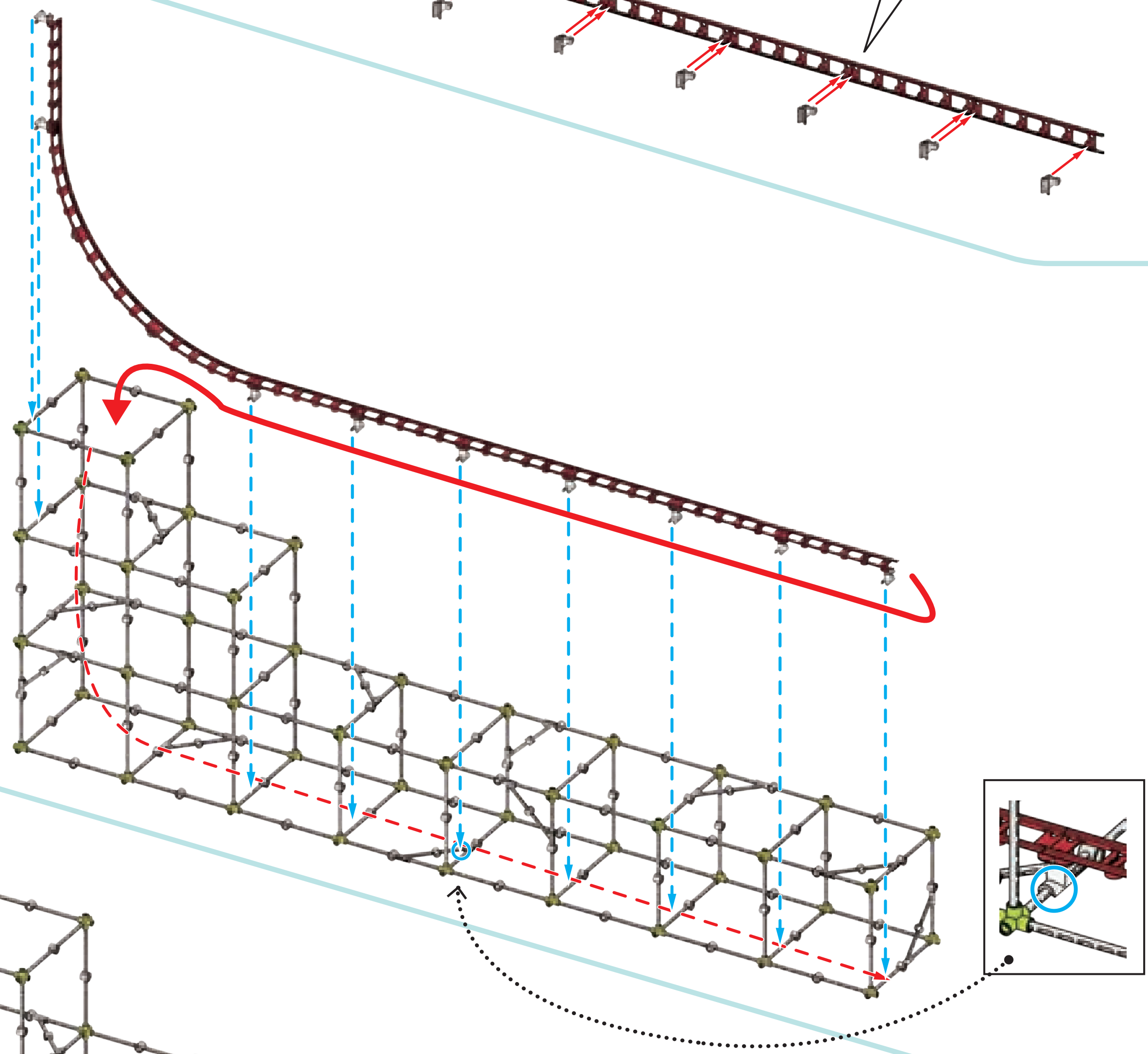

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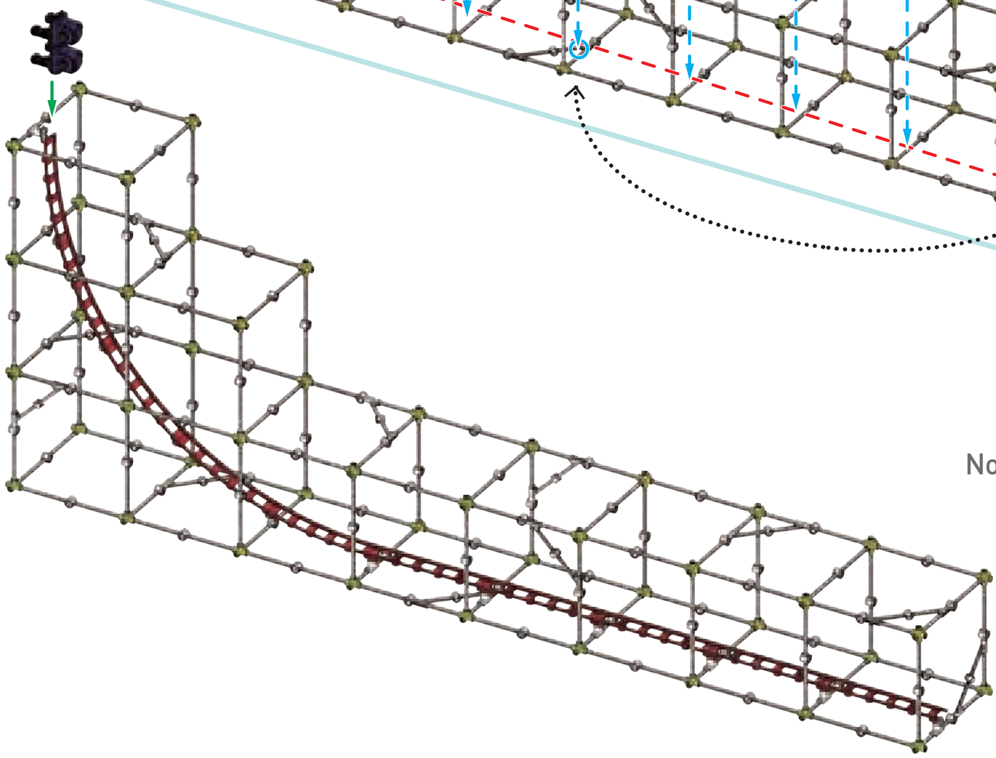


Done!

Now try the experiments on the next page.

EXPERIMENT 3

Changing the height

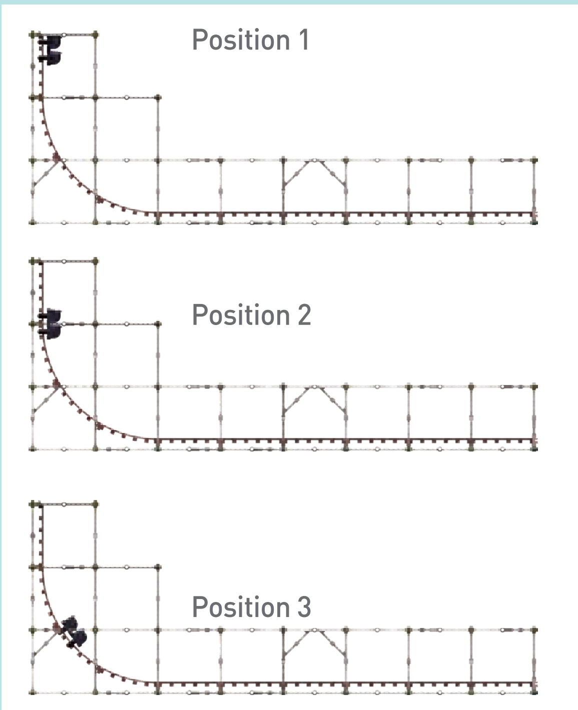
How does changing the starting height affect the speed of the train?

You will need

- **Model for experiments 3 and 4, including train**

Here's how

1. Bring the train to position 1 on the track as shown in the diagram below. Release the train to roll down the track. How far does the train travel?
2. Bring the train to position 2 and release. How far does the train travel compared to when you released it from position 1?
3. Bring the train to position 3 and release. What do you notice about the relationship between the height at which the train is released and the distance it travels across the floor?



WHAT'S HAPPENING?

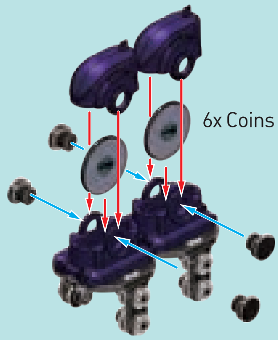
The higher off the ground an object is, the more **gravitational potential energy** it has. According to the **law of conservation of energy,** energy cannot be created or destroyed. As the train moves downhill, the potential energy at the top of the hill is converted into **kinetic energy.** The higher a train starts, the more kinetic energy — and therefore **speed** — the train will have at the bottom of the hill. Trains moving faster at the bottom of the hill have more momentum, meaning they will travel a longer distance before stopping.

EXPERIMENT 4

Mass and speed

How does changing the mass affect the speed of the train?

You will need



- **Model for experiments 3 and 4, including train**
- **Part separator tool**
- *6 Large coins (e.g., quarters)*

Here's how

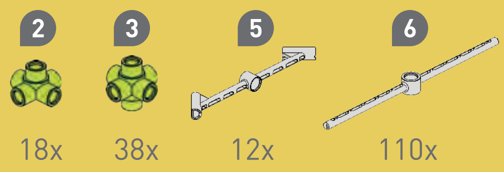
1. Bring the train to the highest position on the track and release it. How far does the train travel?
2. Place three large coins in each car, as you did in Experiment 2.
3. Bring the train to the highest position on the track and release again. How far does the train travel compared to when it was empty?

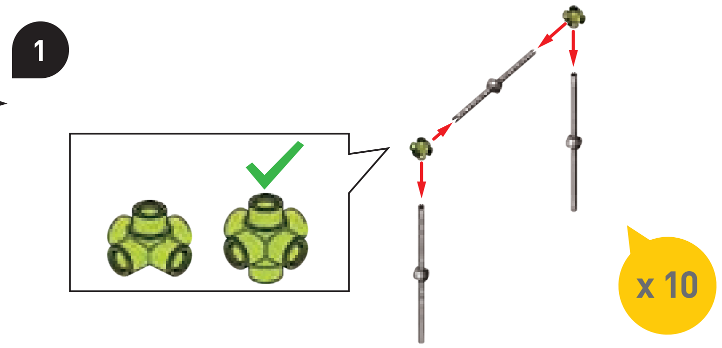
Keep the coins inside the cars for the next experiment.

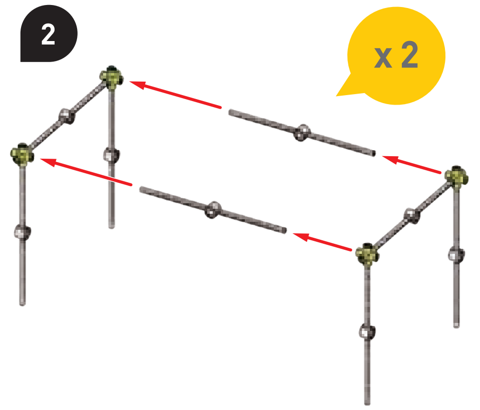
WHAT'S HAPPENING?

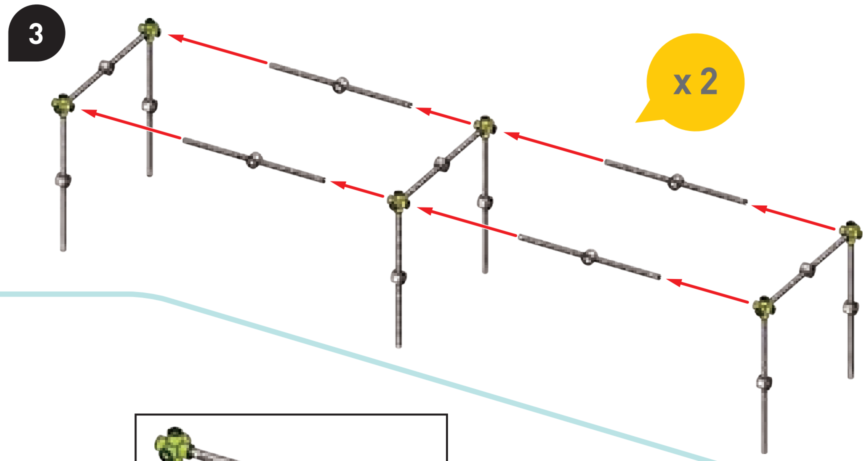
Potential energy is directly proportional to mass, so the heavier train has more potential energy at the top of the hill and therefore more kinetic energy (and speed) at the bottom of the hill. Because of its mass, the heavier train also has more momentum, so it will require more force to stop it. The only forces stopping the train are **friction** between the wheels and the track and **air resistance,** which is another form of friction. Because these stopping forces are similar for all of the trains, it will take more time to stop a heavier train.

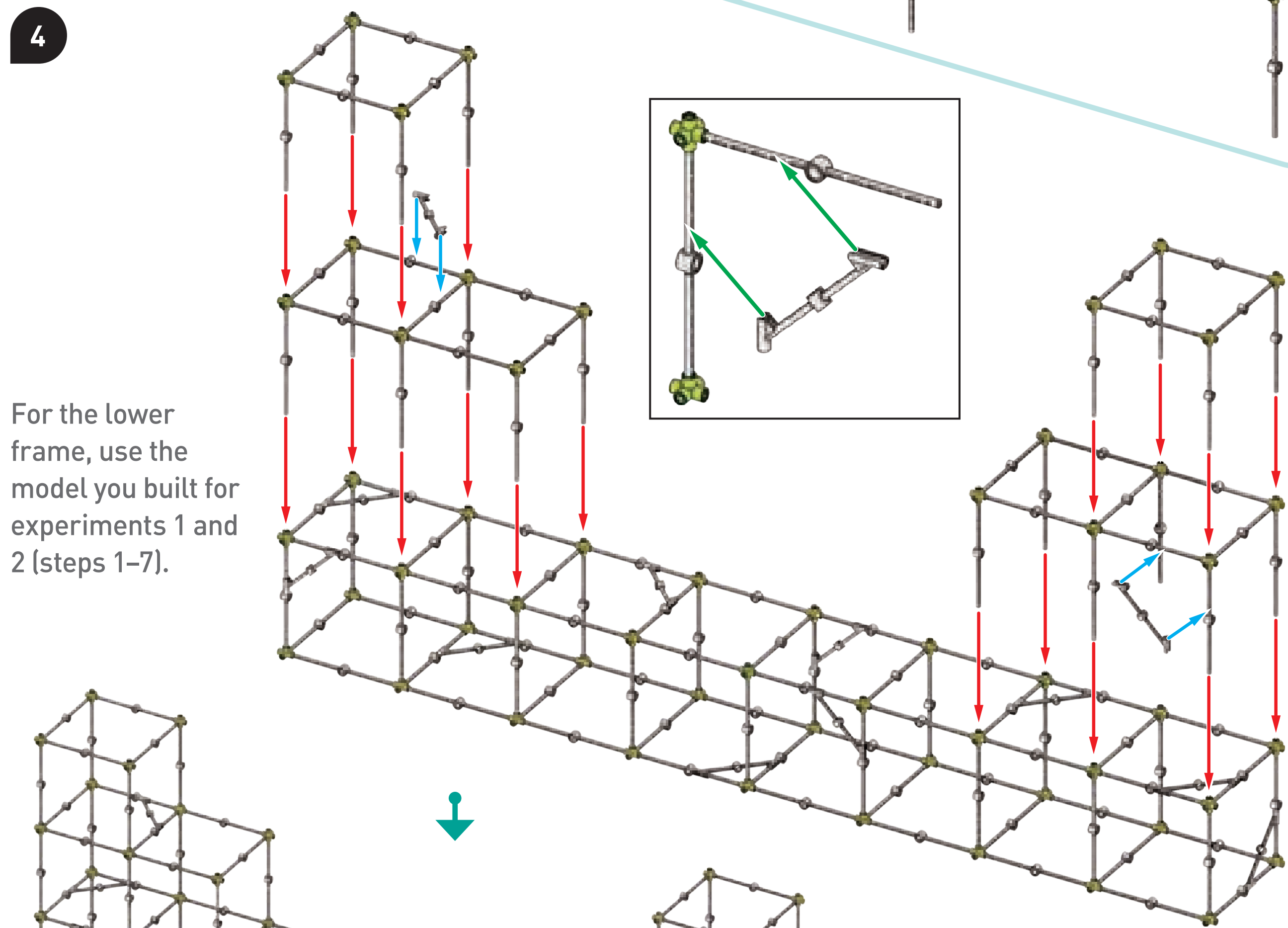
BASE FRAME FOR EXPERIMENTS 5–8



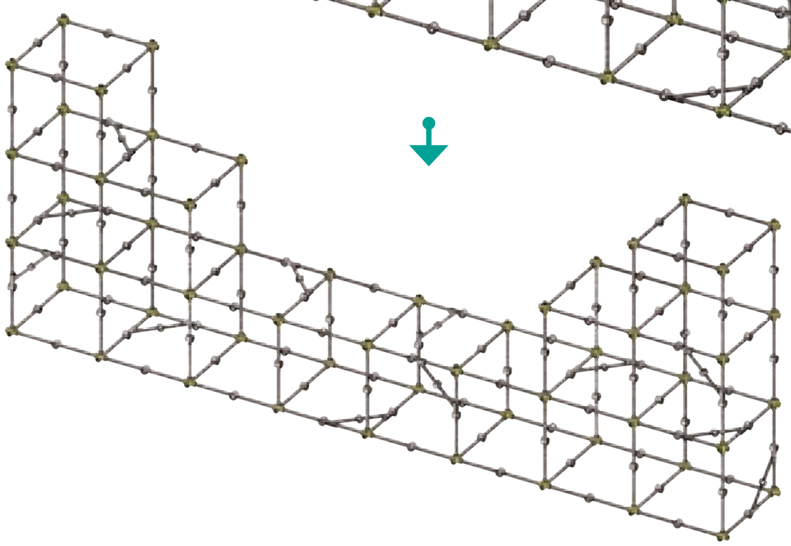








For the lower frame, use the model you built for experiments 1 and 2 (steps 1–7).



Frame done!

Now attach the track and try the experiment on the next page.

EXPERIMENT 5

Momentum and height

Can a train with more momentum climb up to a higher point?

You will need

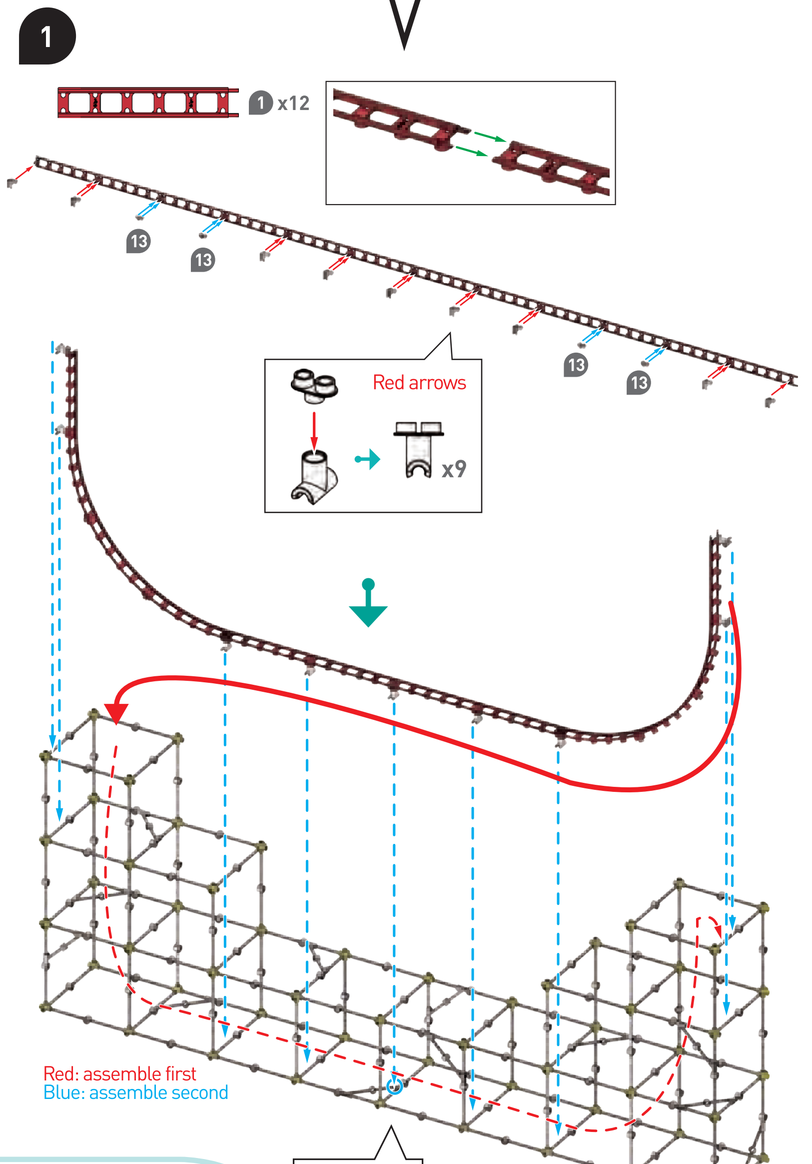
- Parts pictured to the right, including the base frame from the previous page and train filled with coins
- Part separator tool

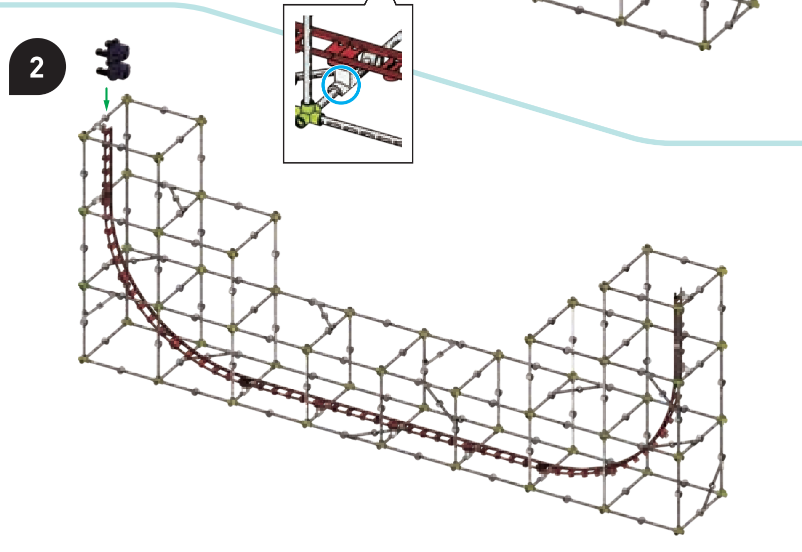
Here's how

1. Complete the model by attaching the track to the frame as shown.
2. Bring the train to the highest position on the track, and then release. What height does the train reach on the other side of the track?
3. Remove all of the coins from the cars.
4. Bring the train to the highest position on the track again and release. What height does the train reach compared to when it was empty? How does this result compare to what you noticed in experiment 4?

WHAT'S HAPPENING?

No matter their mass, all trains reach the same height on the other side of the ramp. You saw in experiment 4 that a heavier train has more potential energy at the top of the ramp than a lighter train, and thus more kinetic energy at the bottom of the ramp. As a train rises up the ramp on the other side, its kinetic energy is converted back into potential energy. It takes more energy to lift trains with more mass. As it turns out, mass doesn't make any difference in this experiment!





EXPERIMENT 6

Varying slopes

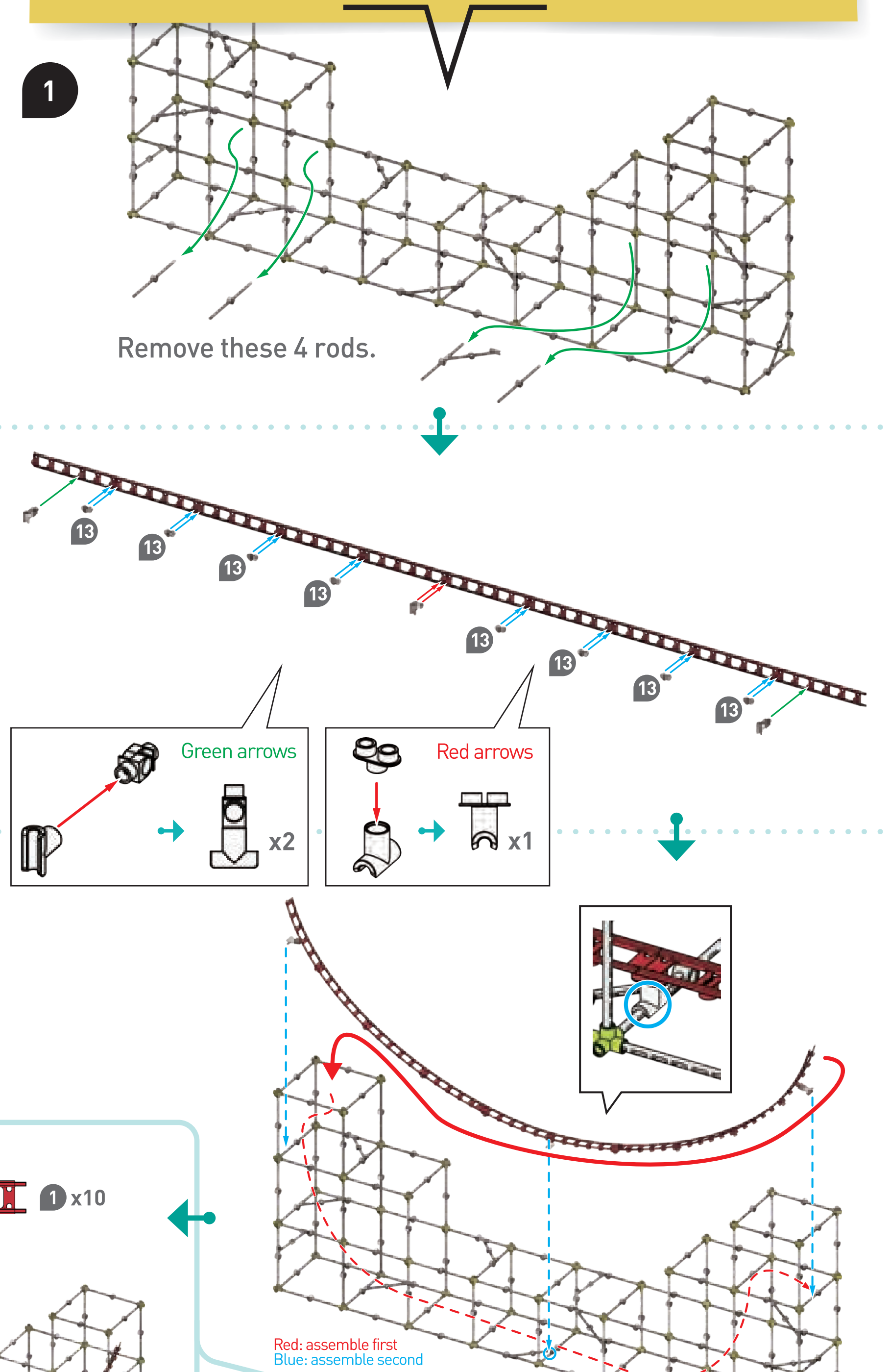
How does changing the slope affect the acceleration of the train?

You will need

– **Parts pictured to the right**

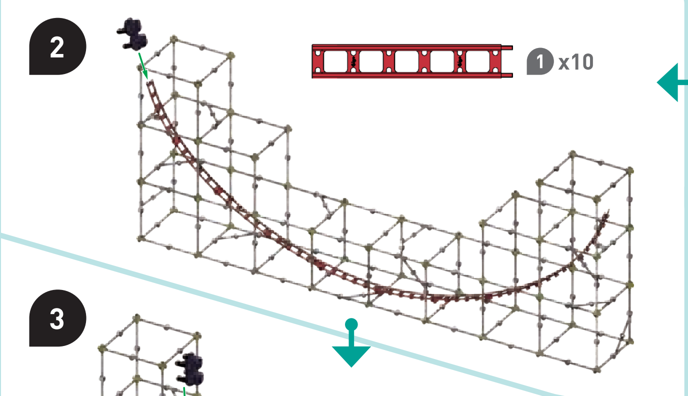
Here's how

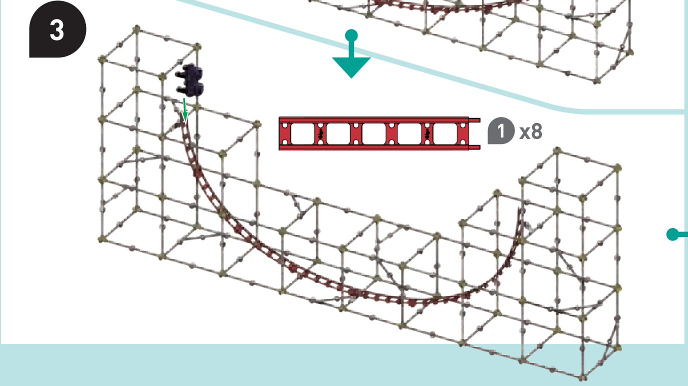
1. Complete the model by attaching the track to the frame as shown.
2. Release the train from the top of the track. What height does the train reach on the other side of the track?
3. Remove two pieces of track and set up the track with a steeper slope, as shown here. Test the train.
4. Remove two more pieces of track and retest. What do you notice about the heights the train reaches each time?

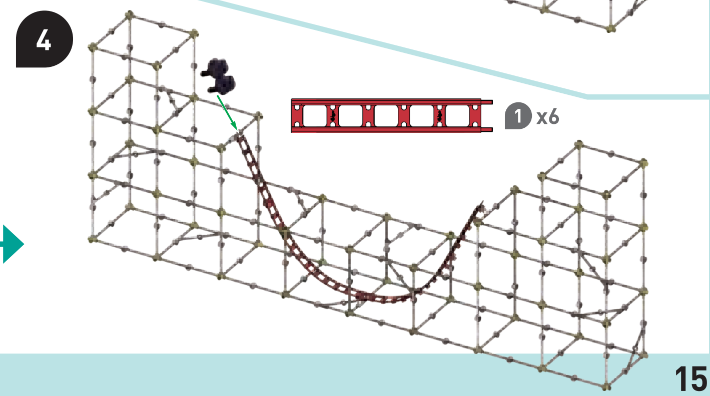


WHAT'S HAPPENING?

The potential energy of trains starting from the same height will be equal no matter the slope of the track. In other words, the slope of the ramp does not affect the train's motion.







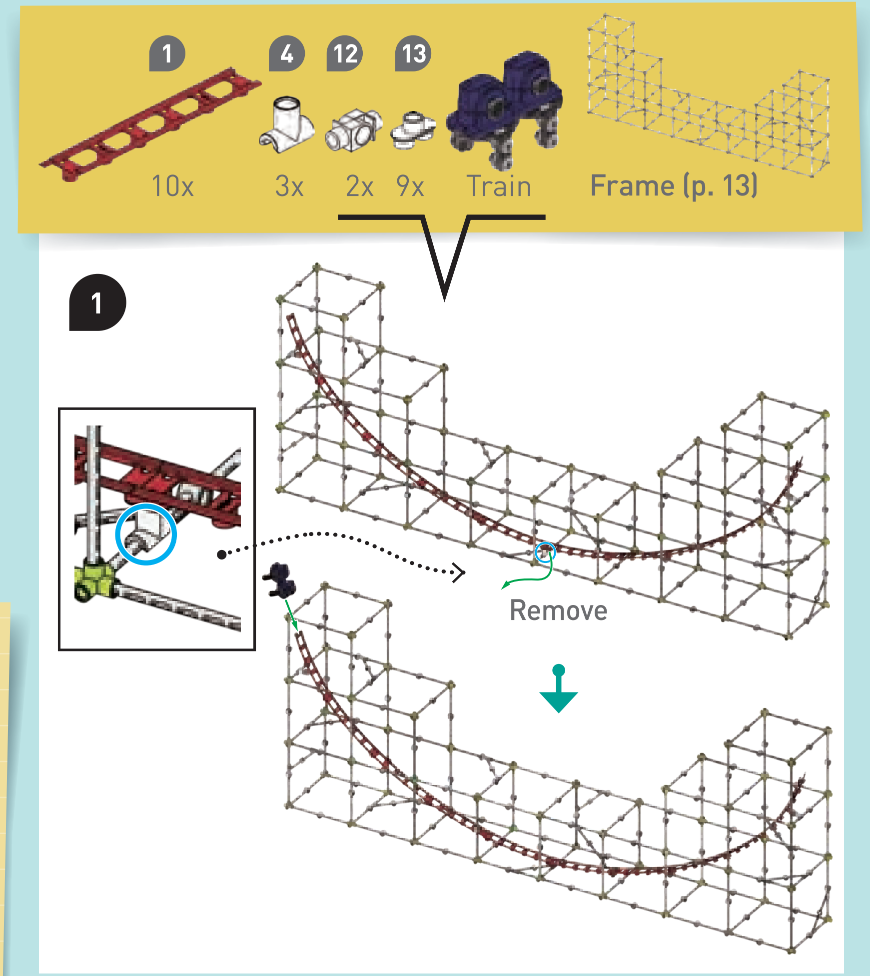
EXPERIMENT 7

Stability

How does securing the track to the frame influence the distance traveled by the car?

Here's how

1. Rebuild the model from experiment 6, step 2 and repeat this experiment step. Now, remove the two track support pieces at the bottom of the track. Bring the train to the top of the track again and release. What do you notice? Did the train make it as high on the ramp as when the track was secured at the bottom?



WHAT'S HAPPENING?

The train on the "floppy" track will give more of its energy to the track itself, causing movement in the track. This robs energy from the train, so it does not have as much energy to make it up the ramp on the other side.

Engineers spend a lot of time thinking about how to connect parts (like the track and the frame). Loose connections are not just annoying, they can be dangerous. Roller coaster tracks that are not properly bolted will vibrate excessively, and cause parts to wear more quickly, and possibly break.

EXPERIMENT 8

Energy conserved

Is all energy actually conserved?

Here's how

1. Use the model from experiment 6, step 2. Bring the train to the top of the track and release the train without pushing it. Does the train make it up to the top of the other hill? Now, bring the train back to the starting position and push the train down the hill. Can you give the train just enough extra energy with your push to make it to the top of the ramp on the other side?

Over the course of a roller coaster ride, energy changes from potential energy (PE) to kinetic energy (KE) and back again several times.

You can use equations to figure out the energy of the train at a given point on the ride.

$PE = mgh$	m: mass g: acceleration due to gravity on Earth (9.8 m/s²)
$KE = \frac{1}{2}mv^2$	h: height above ground v: velocity

If all energy is conserved, and there is no energy lost to friction, then the sum of potential and kinetic energy at any point on the track will remain constant.

$$PE_{start} + KE_{start} = PE_{finish} + KE_{finish}$$

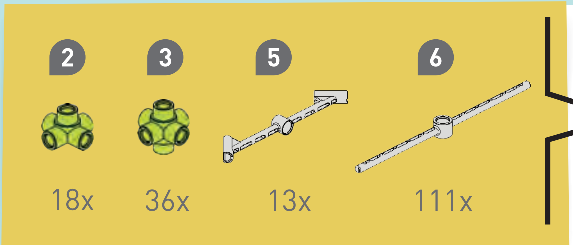
However, as you see in experiment 8, all of the energy is not conserved. Some is dissipated — or spent — because of friction. A more accurate equation would be:

$$PE_{start} + KE_{start} = PE_{finish} + KE_{finish} + E_{dissipated}$$

WHAT'S HAPPENING?

Theoretically, if all energy was actually conserved, all of the train's potential energy would be converted into kinetic energy and then back into potential energy and the train would make it up to the top of the other hill. The train falls short of making it to the top of the other hill because in reality, a little bit of energy is "lost" to friction. If you successfully push the train just enough so that it stops at the top of the other hill, in a sense you've replaced the exact amount of energy that is lost to friction throughout the train's journey.

BASE FRAME FOR EXPERIMENTS 9–13



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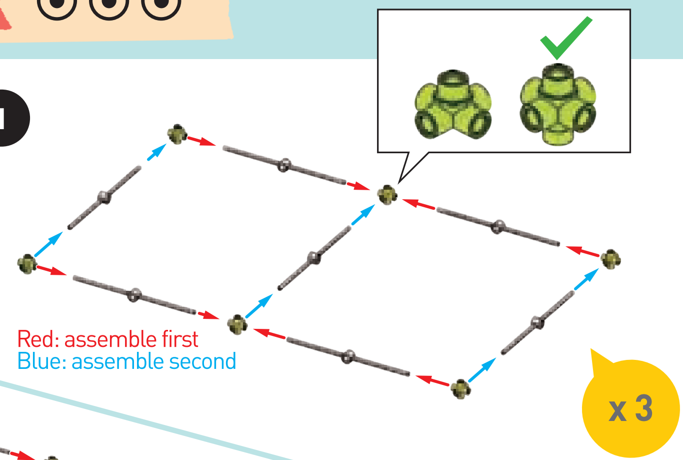

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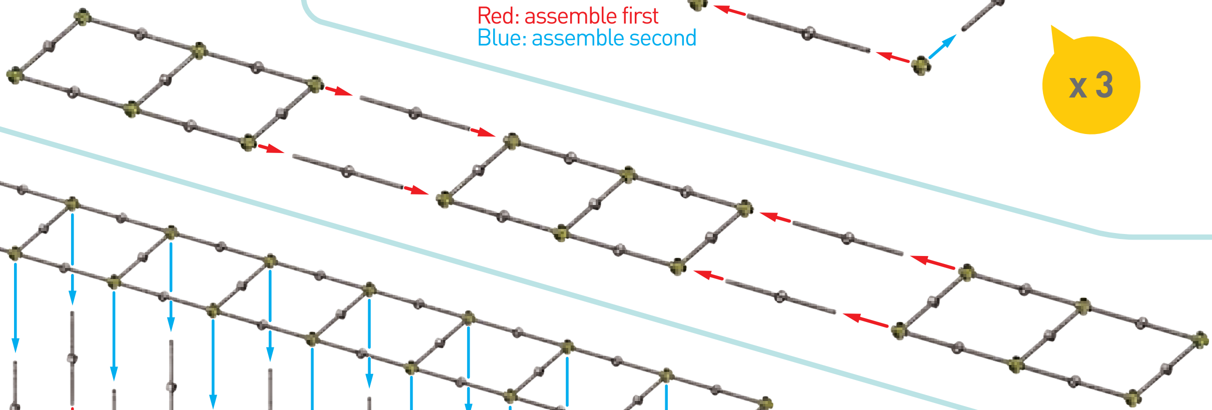

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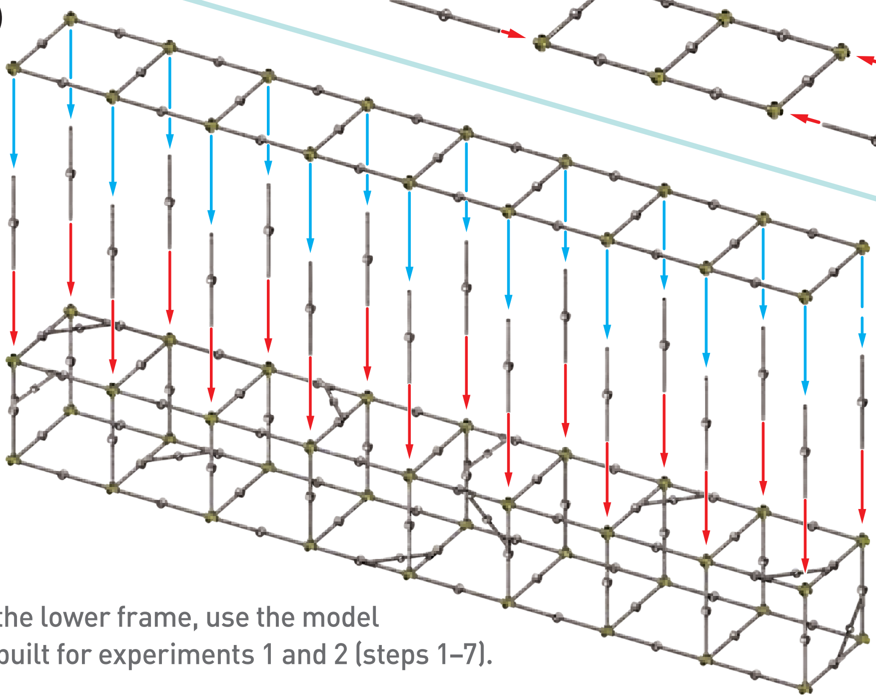
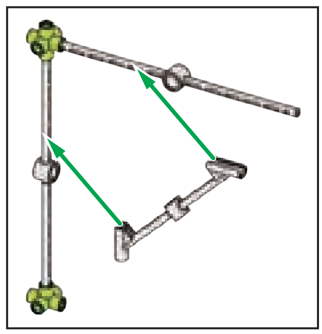


For the lower frame, use the model you built for experiments 1 and 2 (steps 1–7).



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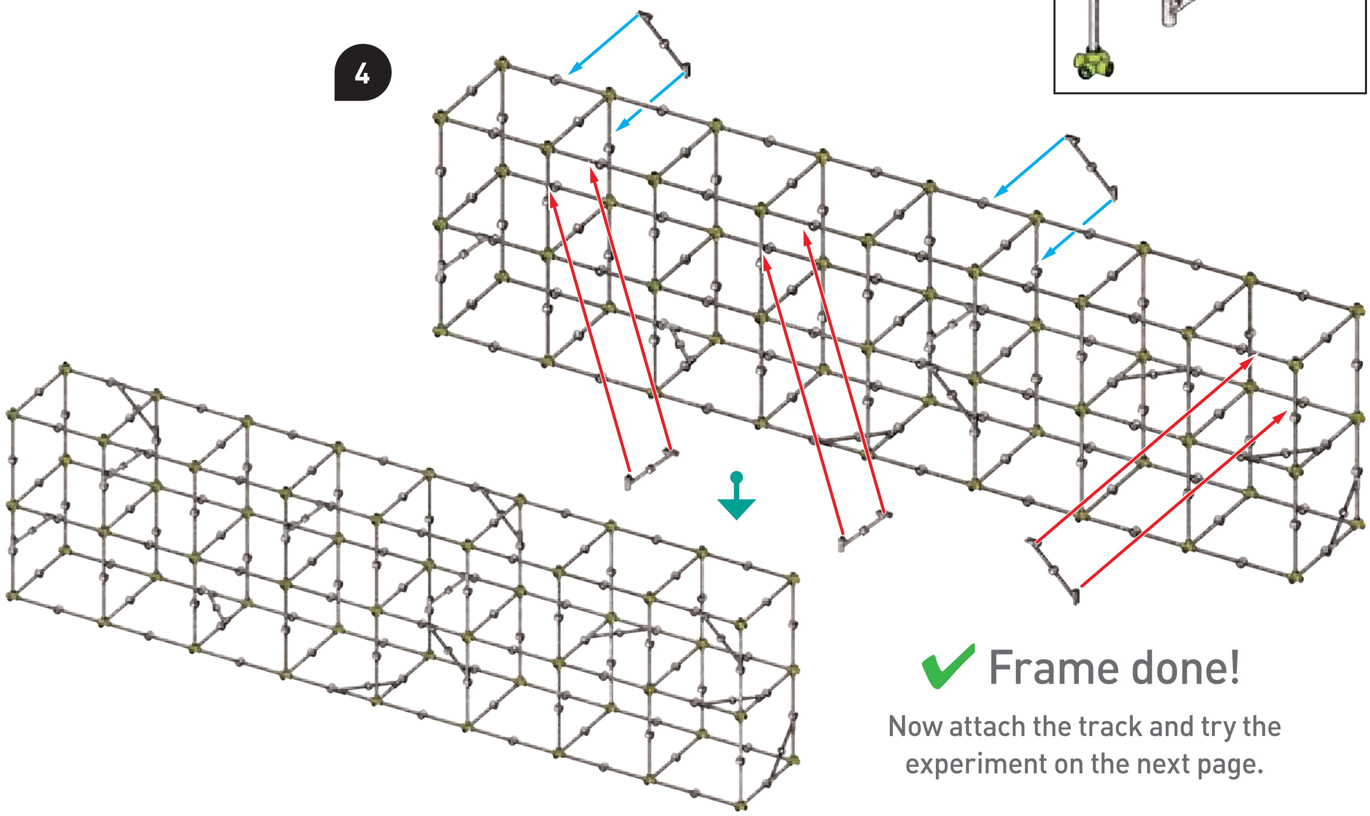


Frame done!

Now attach the track and try the experiment on the next page.

EXPERIMENT 9

Looping the loop

From what height do you need to drop the train so it makes it around the vertical loop?

You will need

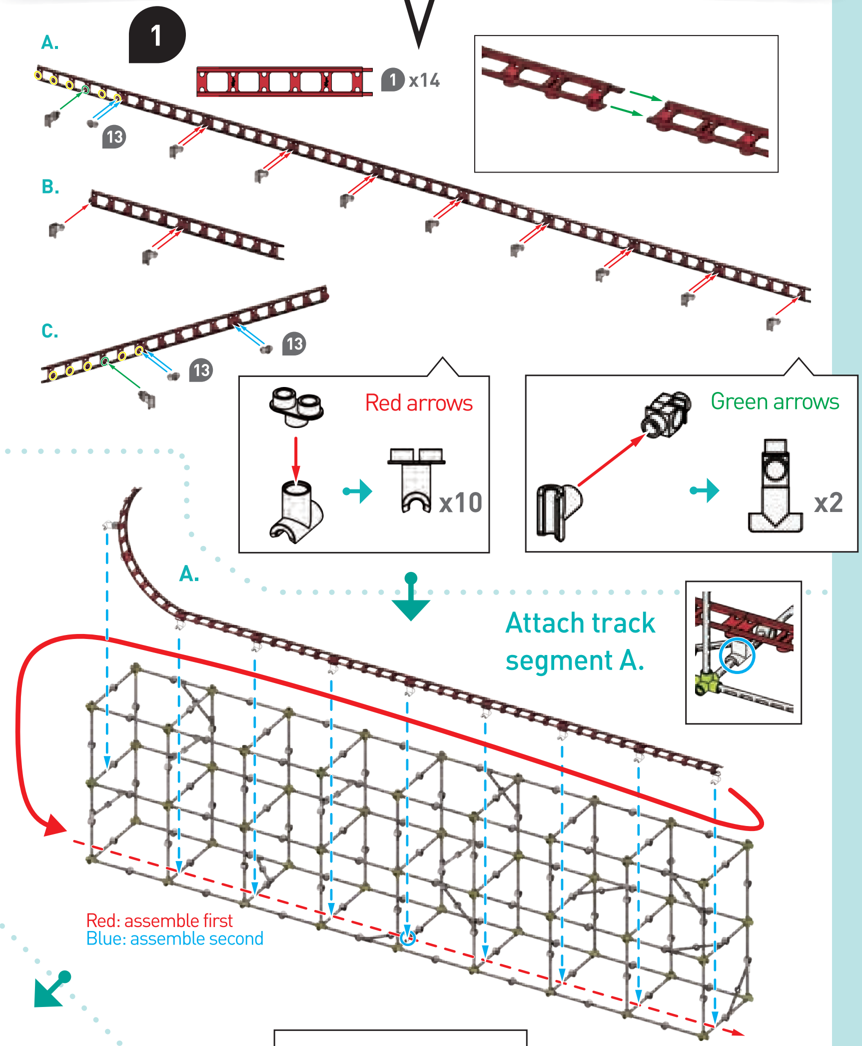
- Parts pictured to the right

Here's how

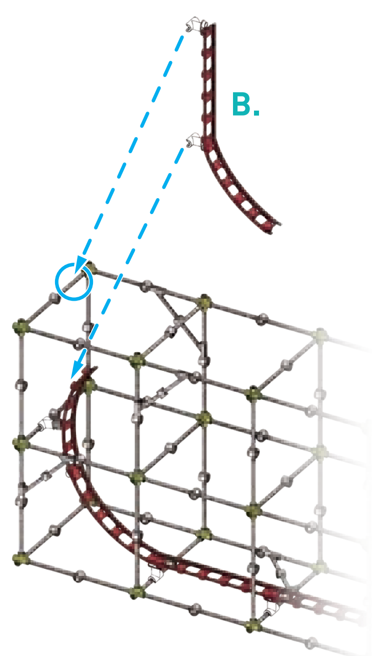
1. Complete the model by attaching the track to the frame as shown and tilting it upright.
2. Release the train from different heights until you find the minimum height from which the train successfully completes the loop.

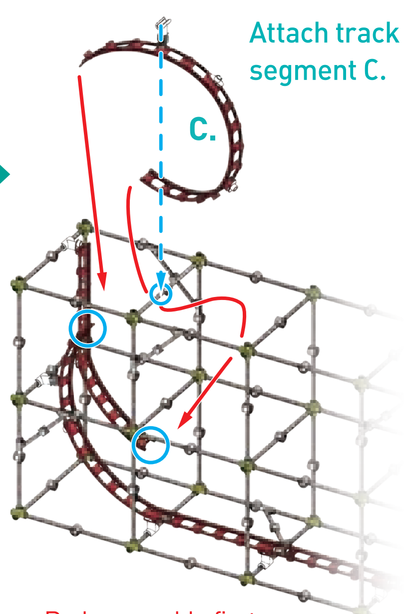
WHAT'S HAPPENING?

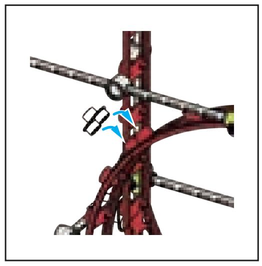
You just found the minimum speed required for the train to complete the **vertical loop.** This is the speed required to make sure the train can keep moving in a circle at the very top of the loop. Go on to the next page for more information on the physics of g-forces in vertical loops.



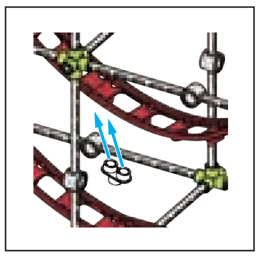
Attach track segment B.



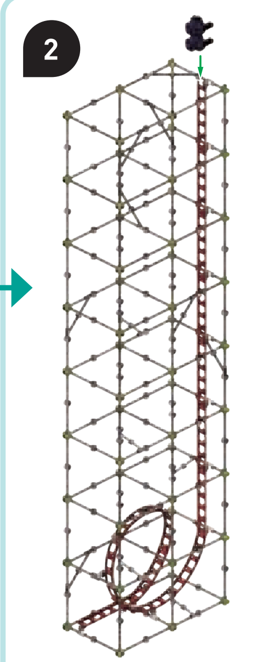




Connect segments A and C with part 13.



Connect segments B and C with part 13.



CHECK IT OUT

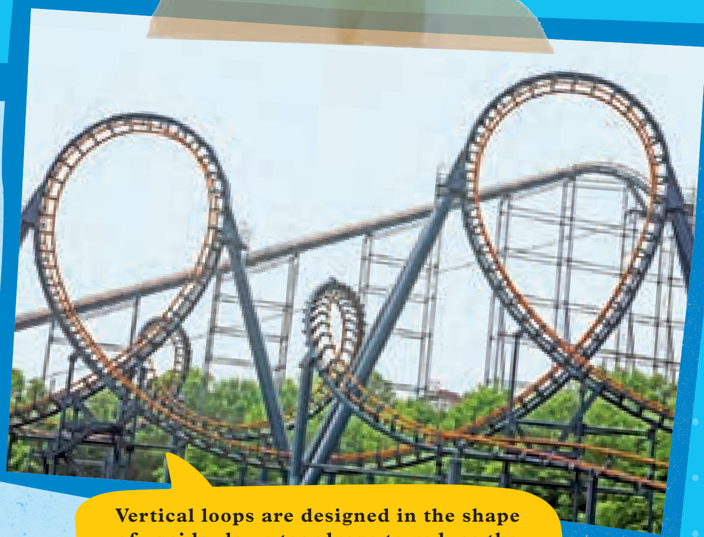
G-Forces

When you fly around a roller coaster and feel like your stomach is floating up toward your throat, or like you're being squished into your seat by a giant weight, you are experiencing **g-forces.** What's going on? You are being thrown around by forces that are even greater than Earth's **gravity.** Engineers talk about forces with measurements called g-forces. **One "g" equals the amount that earth's gravity pulls on the body,** or an acceleration of 9.8 m/s^2. Forces cause accelerations (see Newton's second law on page 9), so you can measure force by measuring acceleration.

Right now, if you are standing still on the ground, you are experiencing a g-force of 1 g. That's because the ground pushes up on you with the exact amount of force with which Earth's gravity pulls you down. Oddly, g-forces measure all the forces *except* gravity acting on an object. So, if you free-fall in a vacuum (meaning there's no air resistance, and only gravity is acting on you), you experience 0 g. When you experience a g-force greater than 1, you feel heavier, like something is pushing you down, whereas, when you experience a g-force closer to 0, you will have the sensation of weightlessness.

EXAMPLES OF G-FORCES

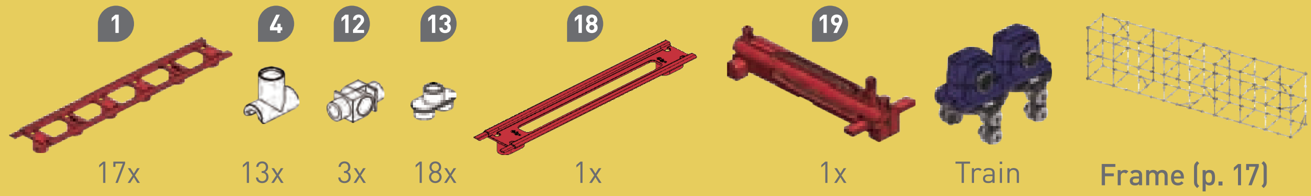
0 G	FREE-FALLING THROUGH SPACE
1 G	STANDING ON THE GROUND
5 G	WHAT AN AVERAGE HUMAN CAN HANDLE
6.3 G	HIGHEST G-FORCE ON ROLLER COASTER TODAY (TOWER OF TERROR IN JOHANNESBURG SOUTH AFRICA)
12 G	G-FORCE ON RIDERS ON VERTICAL LOOP AT CONEY ISLAND'S FLIP FLAP RAILWAY BUILT IN 1898 (CLOSED 1901).



Vertical loops are designed in the shape of upside-down teardrops to reduce the g-forces experienced by riders.

Engineers need to think a lot about g-forces when designing roller coasters, because high g-forces can be dangerous for humans. One of the biggest places riders experience changes in g-forces is in the **vertical loop,** also known as a loop-the-loop or loop-de-loop. For the train to move in a loop, there must be a force pushing toward the center of the circle, called the **centripetal force** — otherwise the train would continue moving in a straight line, (see Newton's first law on page 9). As a roller coaster train rises up into a loop, the track provides the centripetal force, pushing up on the train to get it moving in a circle. As you will see in experiment 12, g-force is at its maximum at the base of the loop.

Engineers can reduce the number of g's experienced by riders at the base of loops by designing **clothoid loops** instead of circular loops. If the radius of the curve is larger at the base, then the required centripetal acceleration — and thus g-forces — will be lower.



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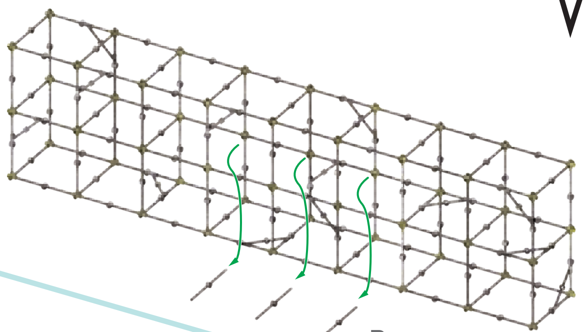

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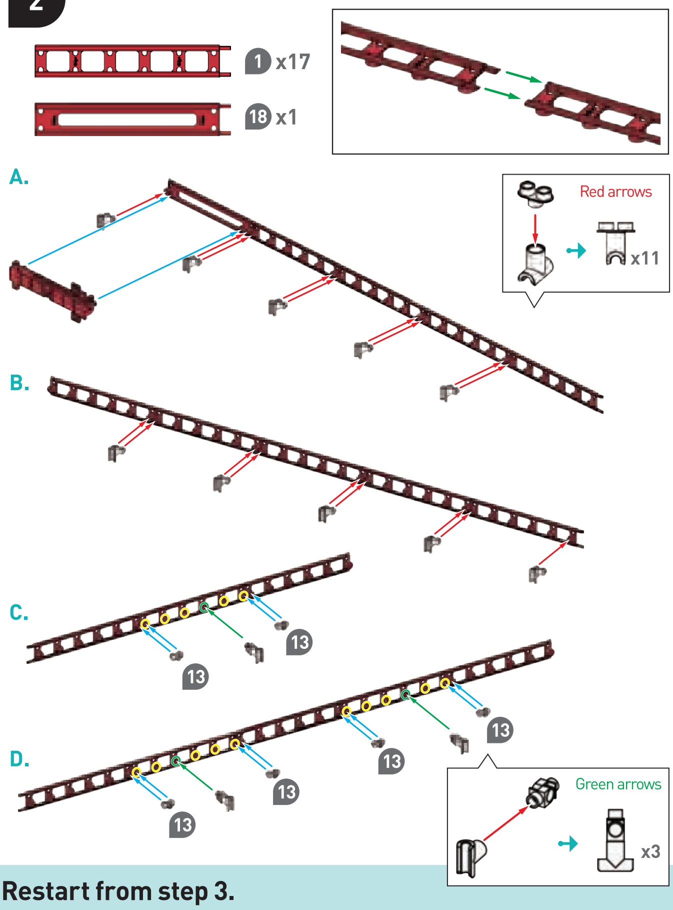

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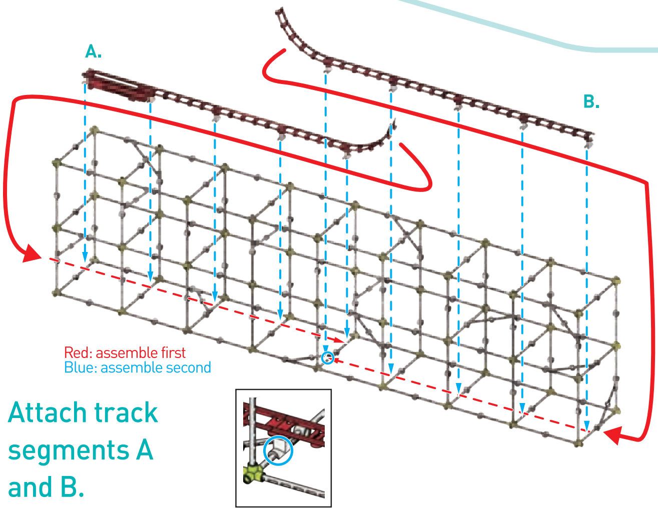
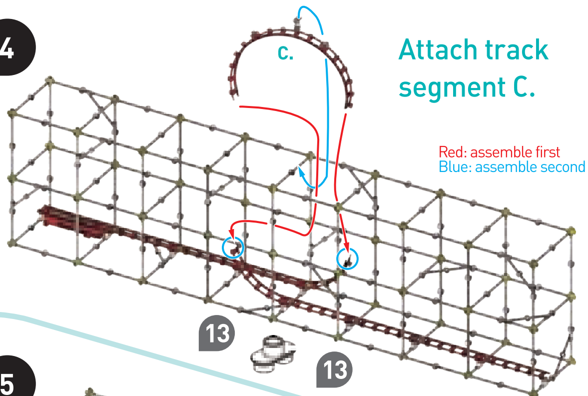


Attach track segments A and B.

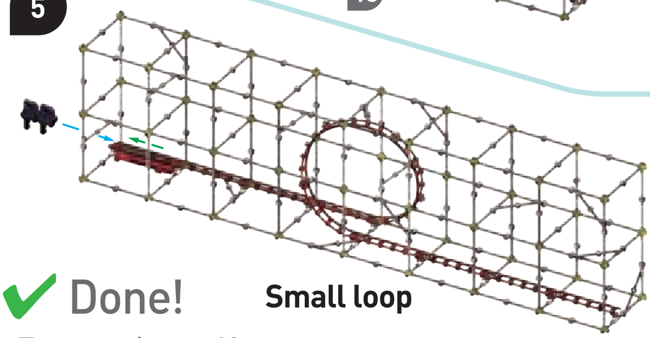
Restart from step 3.

4



Attach track segment C.

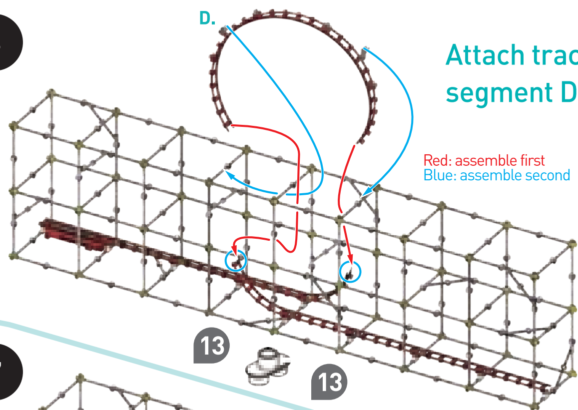
5



✔ Done! **Small loop**

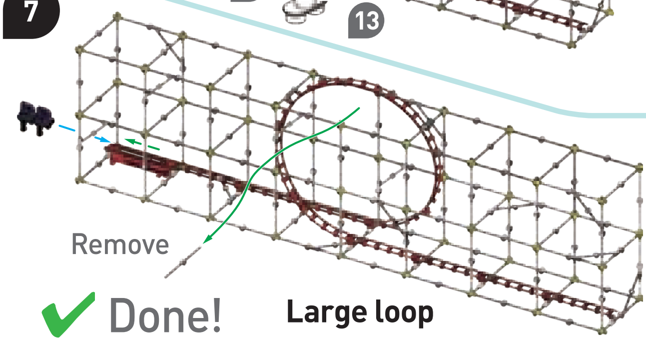
Try experiment 10.

6



Attach track segment D.

7



✔ Done! **Large loop**

Try experiment 11.

EXPERIMENT 10

Speed and the loop

How does changing the train's speed affect whether it makes it around the full loop?

You will need

- **Small loop model from previous page**

Here's how

1. Pull back the spring compressor bar to the midpoint, then roll the train backward until the car launch trigger meets the resistance of the launch rod.
2. Release the spring compressor. Does the train make it around the loop?
3. Put the train on the track in front of the launcher. Pull the spring compressor bar back until it clicks into the notch in the launcher. With your finger, flick the train backward toward the launcher. Does the train make it around the loop this time?

WHAT'S HAPPENING?

Just like in experiment 9, you see that a train needs enough speed to make it around the loop.

EXPERIMENT 11

A larger loop

Does changing the height of the loop affect whether the train makes it around the loop?

You will need

- **Large loop model from previous page**

Here's how

1. Repeat step 3 of experiment 10 above, but using the model with the larger loop. Does the train make it around the loop this time?

WHAT'S HAPPENING?

The train probably didn't make it around the larger loop. As the train rises up into the loop, it gains potential energy and loses kinetic energy. For a train to make it all the way around the loop, it needs enough kinetic energy at the beginning of the launch to at least match the potential energy the train has at its highest point in the loop. The higher the loop, the more kinetic energy, and therefore speed, is required.

EXPERIMENT 12

The shape of the loop

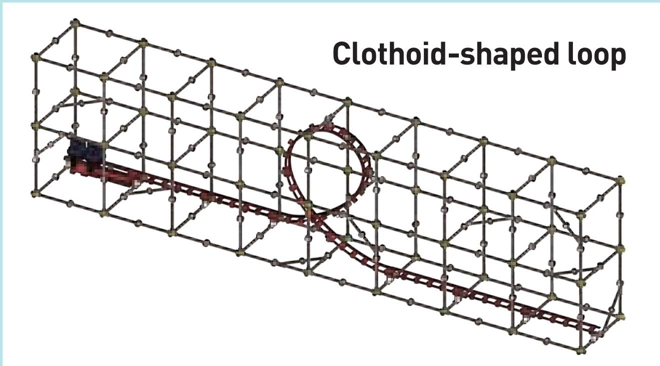
What shape of the loop is most effective?

You will need

- **Various loop models, including the one pictured below**

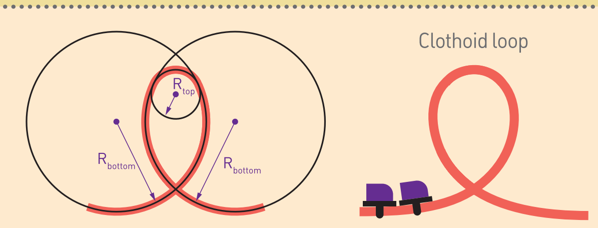
Here's how

1. Compare and contrast the performance of the train in the small loop, large loop, and clothoid-shaped loop (pictured below). You can also try out your own loop designs. What shape of the loop is most effective?



WHAT'S HAPPENING?

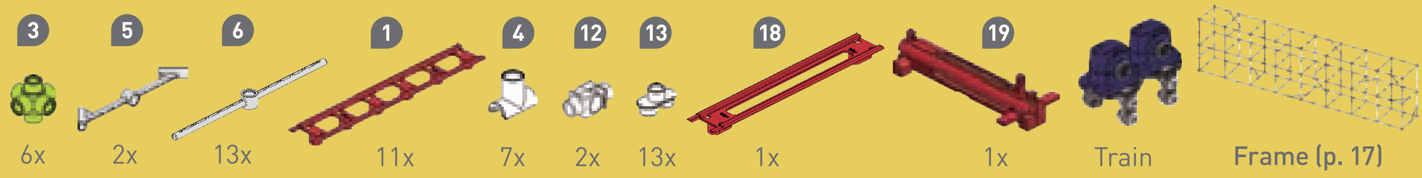
You might have noticed that the train exits the **clothoid-shaped loop** with more speed than the circular-shaped loop. A clothoid shape — which looks like an upside-down teardop — is the most effective shape for a vertical loop. When you change the shape of the loop, you are varying the radius of imaginary circles at the top and bottom of the loop. This changes the amount of centripetal force required to keep the train moving in a loop, because centripetal force is inversely proportional to the radius of a curve ($a_c = v^2/r$).



The radius at the bottom of the clothoid loop (R_{bottom}) is much larger than the radius at the top of the clothoid loop (R_{top}).

When a roller coaster train first enters the loop, gravity pulls down, away from the center of the circle, and thus opposite the direction of centripetal acceleration. The normal force from the track must therefore work twice as hard to keep the coaster moving in a loop. If the radius of the curve is larger, then the centripetal acceleration required will be lower. **Trains do not need to be traveling as fast to make it around a clothoid loop.**

MODEL FOR EXPERIMENT 13



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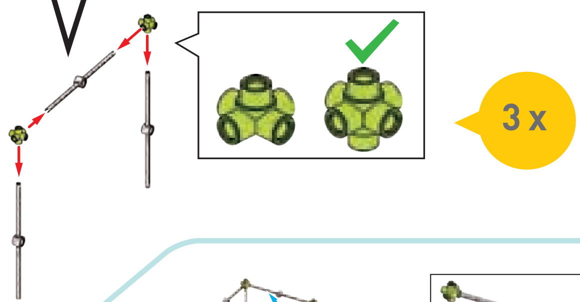

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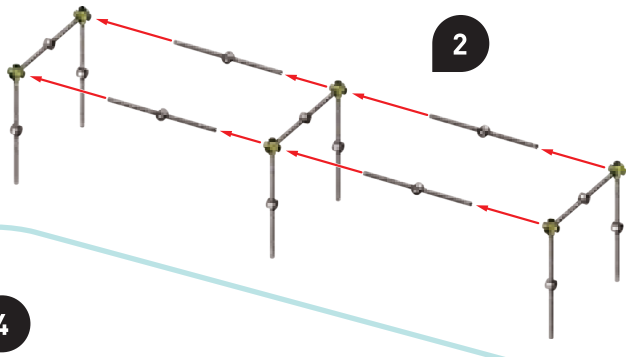

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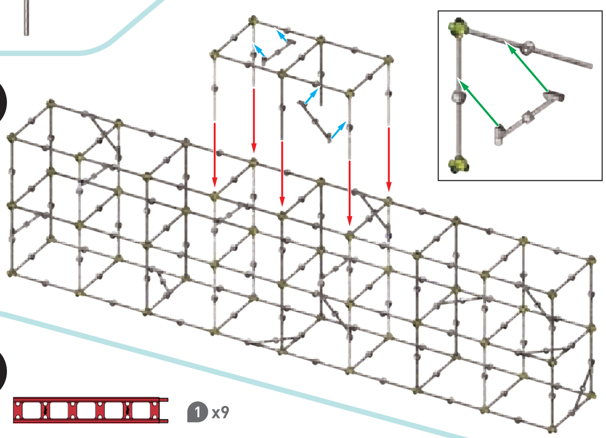

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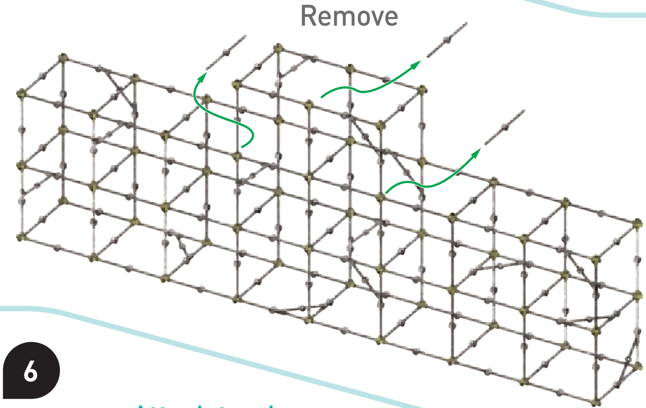

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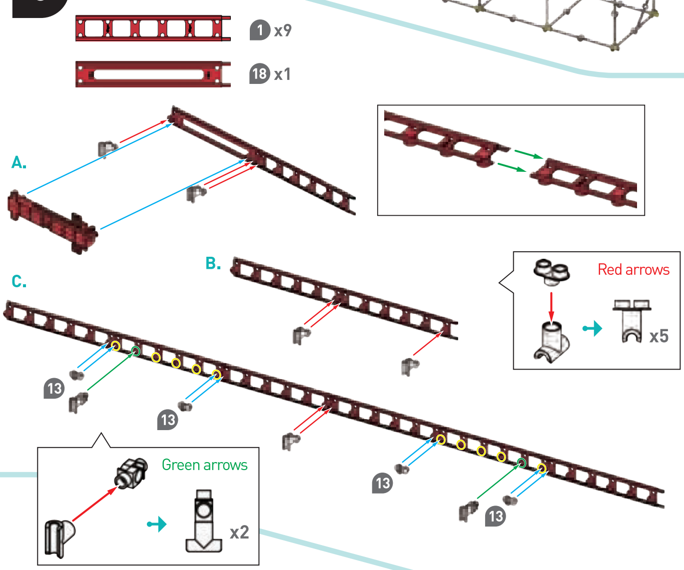

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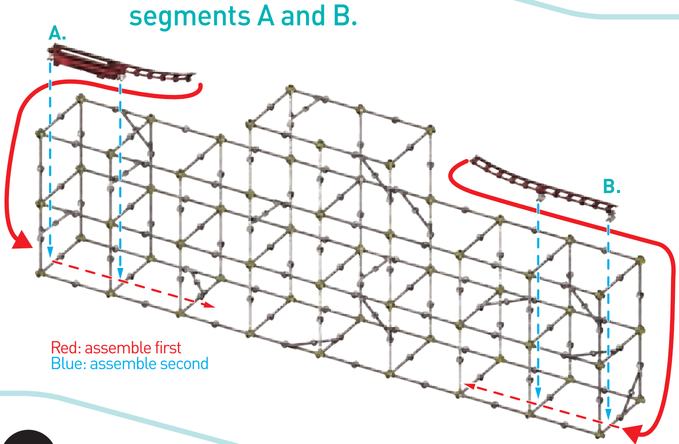
Attach track segments A and B.



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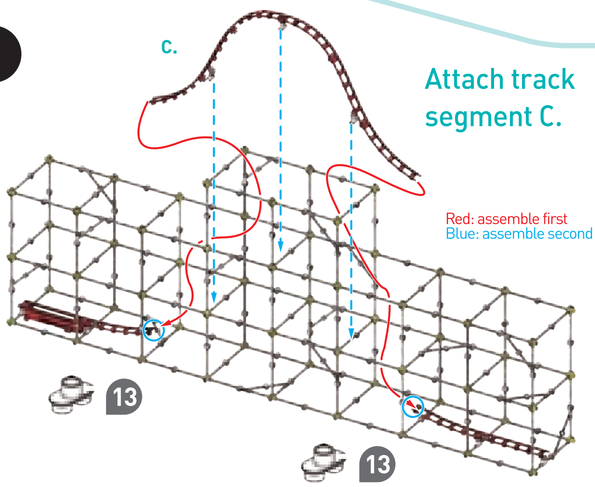
Attach track segment C.



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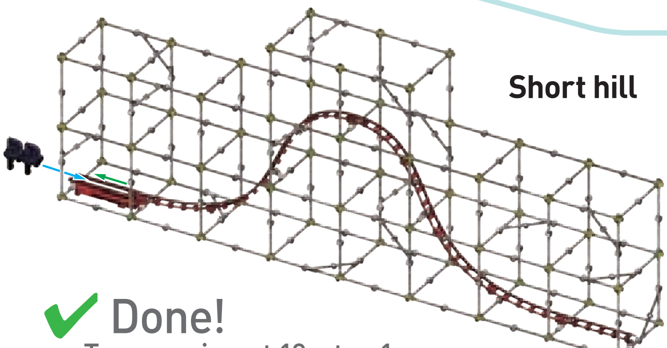


Done!

Try experiment 13, step 1.

EXPERIMENT 13

Climbing the hills

What is the tallest hill the train can make it over?

You will need

- **3 Hill models from previous page and below**

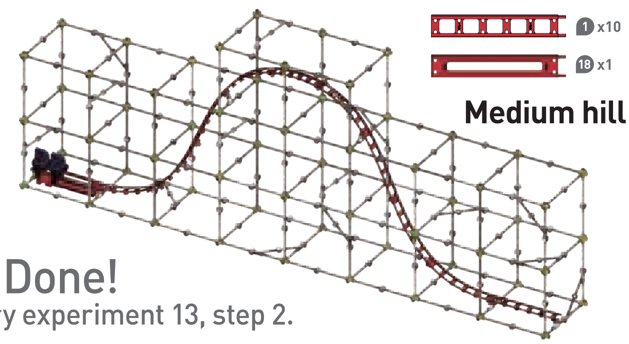
Here's how

1. Launch the train over the small hill. Does the train make it over the hill? How fast is it moving on the other side of the hill?
2. Reconfigure the track with ten track pieces instead of nine. Launch the train again. Does the train make it over the hill this time? And if so, how easily? (Note: You might need to add or remove a few rods from the frame in order to accommodate the new track.)
3. Now build the tallest hill using 11 track pieces. Launch the train again. What happens this time?

WHAT'S HAPPENING?

Unlike in experiments 3–9, in which the train begins with gravitational potential energy, here you start the train from the ground. So where does the train get the energy it needs to make it up the hill? The energy comes from **elastic potential energy** that is stored in the spring of the launcher. When you compress a spring over a certain distance, it gains potential energy. When the launcher is released — and allowed to return to its starting shape — the spring exerts a force on the train.

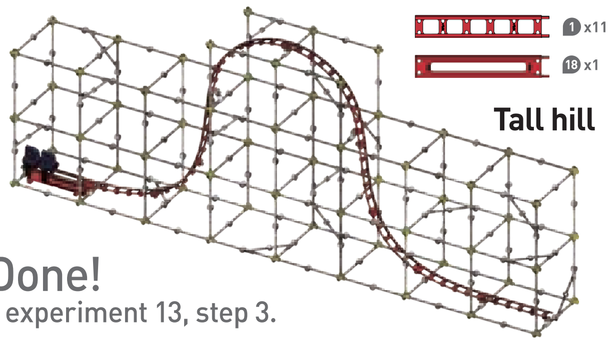
9



Medium hill

Done!
Try experiment 13, step 2.

10



Tall hill

Done!
Try experiment 13, step 3.

EXPERIMENT 14

Calculating speed

Calculate the average speed of the train.

You will need

- **Model pictured below**
- *Measuring tape, calculator, stopwatch*

Here's how

1. Connect 12 pieces of track (including the launcher track), and measure the length of the track with a tape measure. What is the length of the track? (d = ____)
2. Assemble the model pictured below, with the 12 track pieces in an oval and with the train on the track.
3. Start a stopwatch as you flick the train with your finger. Use enough force for the train to make it all the way around the track.
4. Stop the stopwatch when the train returns to its starting position. How many seconds did the train take to make it around the track? (Δt = ____)
5. Calculate the average speed of the train by dividing the length of the track by the time it took the train to complete its journey. (average speed, $v = d/\Delta t$)

WHAT'S HAPPENING?

Speed can be thought of as the rate at which an object covers a certain distance. However, the train's initial position on the track is the same as its final position, so the train's *change* in position — or **displacement** — is zero. While speed is found by dividing distance by time, **velocity** is found by dividing displacement by time. So the train's average velocity during its journey is zero!

EXPERIMENT 15

Friction's effect

What slows the train down?

You will need

- **Model from experiment 14**
- *Calculator, stopwatch, adhesive tape*

Here's how

1. Attach the launcher to the launcher track.
2. Launch the train. Observe.
3. Now create a "brake zone" by placing adhesive tape on the rails of a second of track.
4. Launch the train again. What is the effect of placing tape on the track? What happens if you add even more tape to the track?

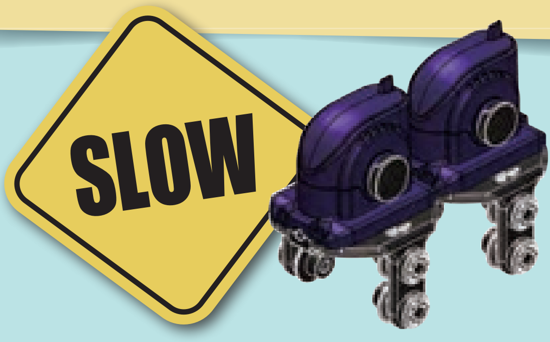
WHAT'S HAPPENING?

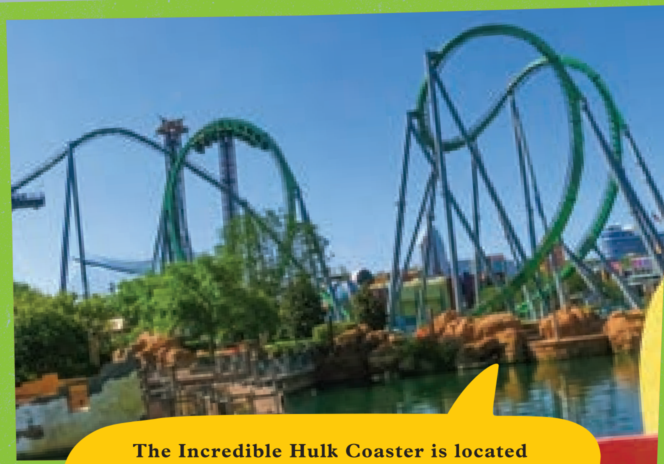
By adding tape you are increasing the amount of **friction** between the surface of the track and the wheels of the train. Think back to Newton's first law. A train in motion will remain in motion, unless an unbalanced force acts upon it. The unbalanced force that brings a roller coaster train to a stop is friction. If there were no friction, then the train would keep going forever!

Friction is the force between surfaces that are sliding, or attempting to slide, across each other. Friction always opposes motion. If you are trying to slide a chair away from you across the floor, friction exists between the bottom of the chair and the floor and points toward you.

The force of friction is determined by the normal force and the **coefficient of friction,** which varies for different materials. This is why it's easier to slide across the floor wearing socks compared to wearing sneakers. (The fabric in most socks has a lower coefficient of friction than the rubbery composite on the bottom of most sneakers).

The surface of the tape has a higher coefficient of friction than the surface of the plastic track. By increasing the force of friction, you slowed the train down more effectively.





The Incredible Hulk Coaster is located at Universal's Islands of Adventure in Orlando, FL. Riders go upside down seven times and reach a maximum speed of 67 miles per hour during the ride.

Donnelly Williams and a team of engineers completed a control system upgrade of the Hulk Coaster in 2016. Here he is on the site in 2016.

Steps to Build a Roller Coaster

STEP	DURATION
Design phase	3–5 months
Buy parts; make and assemble parts in shop (procurement and fabrication)	5–8 months
Factory testing	1–3 months
Roller coaster structure erection on site	8–10 months
Mechanical systems: site build and commissioning	3–5 months
Electrical control systems: site build and commissioning	3–5 months
Final testing	1–2 months

CHECK IT OUT

A Real Roller Coaster Engineer

Donnelly Williams is a professional engineer in British Columbia, Canada, with degrees in mechanical and electrical engineering.

Donnelly Williams thinks of himself as a big kid — a big kid with a dream job. He gets paid to use his **mechanical and electrical engineering** degrees to test and build roller coasters.

When Donnelly was a kid, he loved taking things apart to see how they worked. He spent hours in his parents' basement, his "laboratory," tinkering, sketching and experimenting to build new things, such as a hexapod robot (pictured below).

In college, Donnelly studied mechanical engineering because he wanted to create special effects for movies. This enabled him to work as a mechanical engineer in many different industries. After ten years, he pivoted to working on roller coasters. "In terms of fundamental engineering, if you can design a machine, you can design a roller coaster."

The biggest difference, of course, is safety. Donnelly's main job is to keep riders safe. He uses **finite element analysis** — computer simulations that test the structures of coasters. "We figure out where it's going to break and how it's going to break, and then we figure out how to fix those things [before they ever break]." During the testing phase, Donnelly says, "we basically attempt to break the ride any way we can think of. We need to show that the ride can stop safely, no matter what we do."

"A lot of roller coaster engineering comes down to thinking about: How are we going to take this apart? How are we going to maintain this? What are the pieces that are going to wear down first?" Designers have ideas about how they want things to look, but Donnelly says engineers are the ones who need to figure out how to make the designs a safe reality.

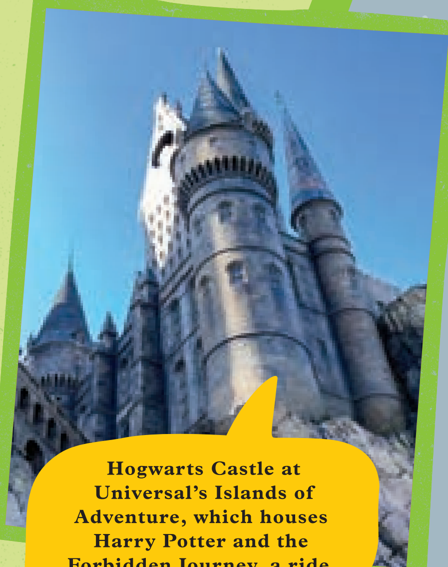
Roller coaster engineers also need to think about the amount of forces their riders experience while on the coaster. There are specific standards that limit the amount of **g-force** the rider can experience in a certain direction (see page 19). But g-forces are also what make rides fun and thrilling! Engineers balance the goal of creating cool rides with the need to eliminate risks.

With the engineering firm he works for, Donnelly has worked on lots of different types of rides, including The Incredible Hulk Coaster and Harry Potter and the Forbidden Journey, both at Universal's Islands of Adventure.

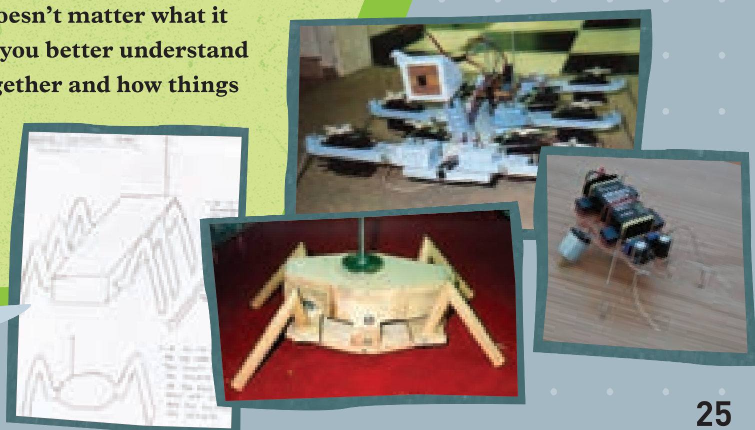
The trains on roller coasters that use launchers or "lift hills" have no engine. "Gravity's got you — gravity and friction, that is." So engineers design **block zones** and **brake zones.** Once the train has been launched, it doesn't stop until it hits the brake zone. The zones are designed with logic, so only one vehicle can occupy a block zone at any point in time. And before each block zone is a brake zone, so if one train gets stuck, the train behind it can be stopped.

Donnelly's best advice to kids who want to design roller coasters someday: **"Build stuff. It doesn't matter what it is. This will help you better understand how things go together and how things work spatially."**

Humans are about 80% water, so in the final testing phase, engineers load the ride with dummies filled with water. "These give you the dynamic movement that a person would have sloshing around on the ride."



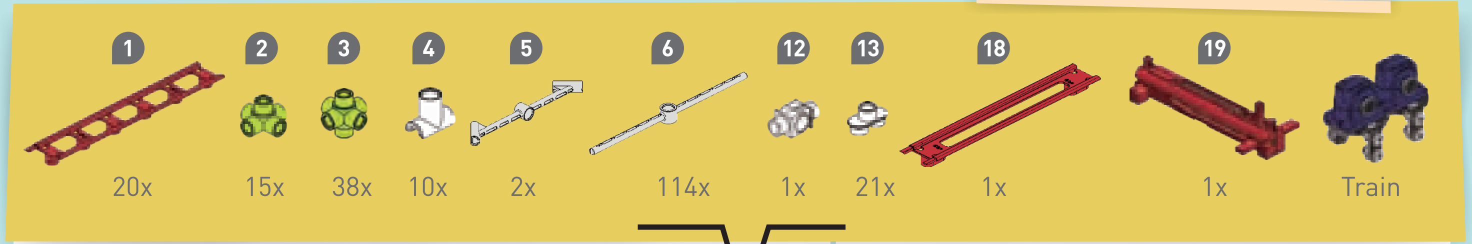
Hogwarts Castle at Universal's Islands of Adventure, which houses Harry Potter and the Forbidden Journey, a ride Donnelly helped design.

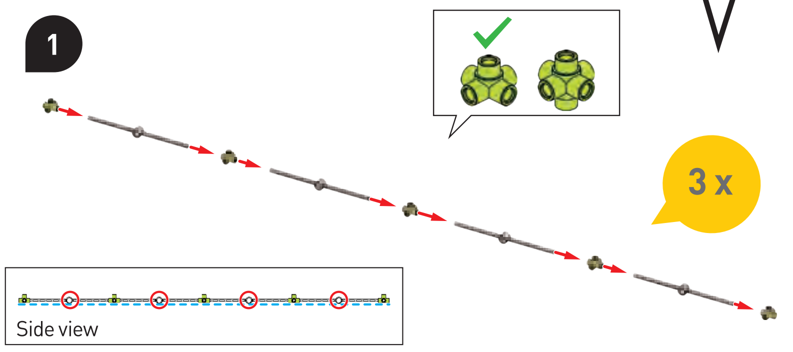


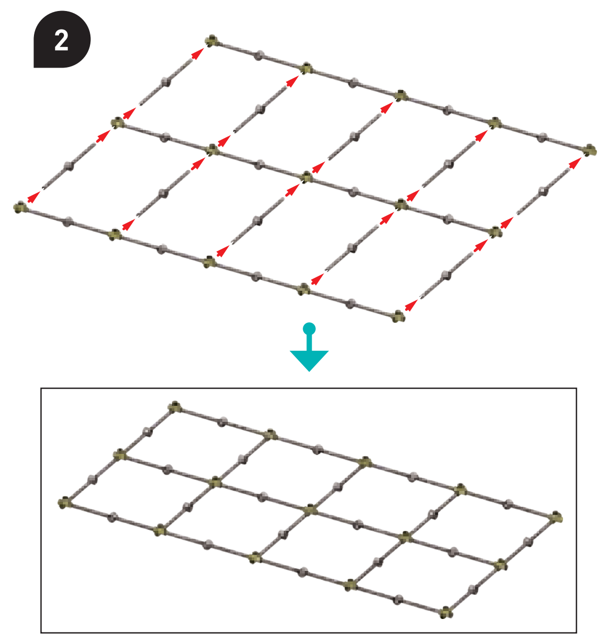
When he was a teenager, Donnelly wanted to make special effects for movies, so he set out to make a robot insect. From left to right: An early sketch of a remote-controlled spider; Donnelly's first attempt at a robot spider; the next iteration, which used motors as legs; Donnelly's final design: a programmable hexapod that could avoid walking into walls.

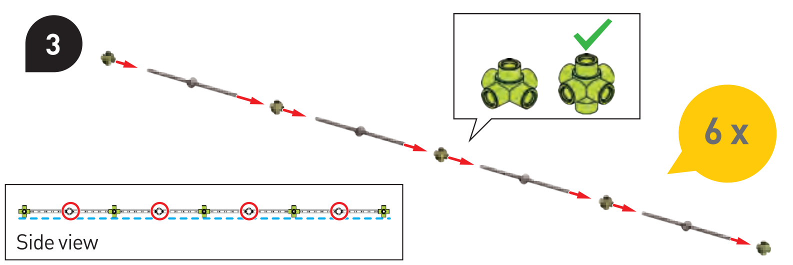
MODEL FOR EXPERIMENTS 16 AND 17

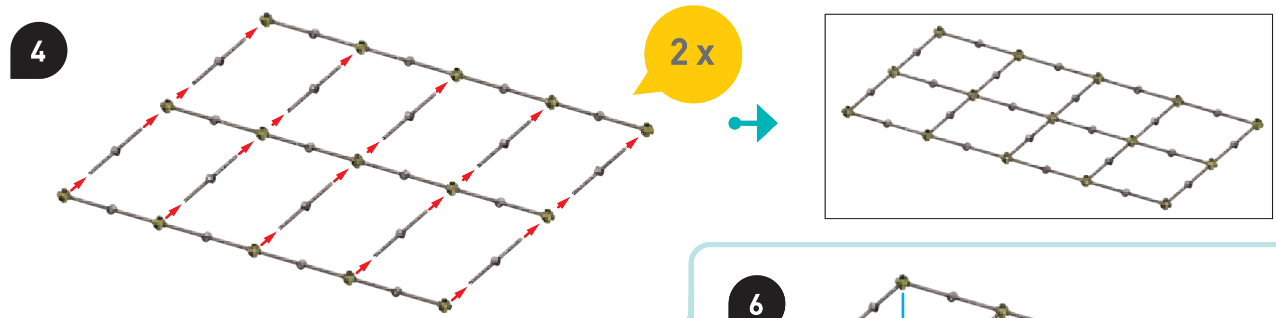
TIP
THIS IS THE BIG ROLLER COASTER MODEL FEATURED ON THE FRONT OF THE BOX!

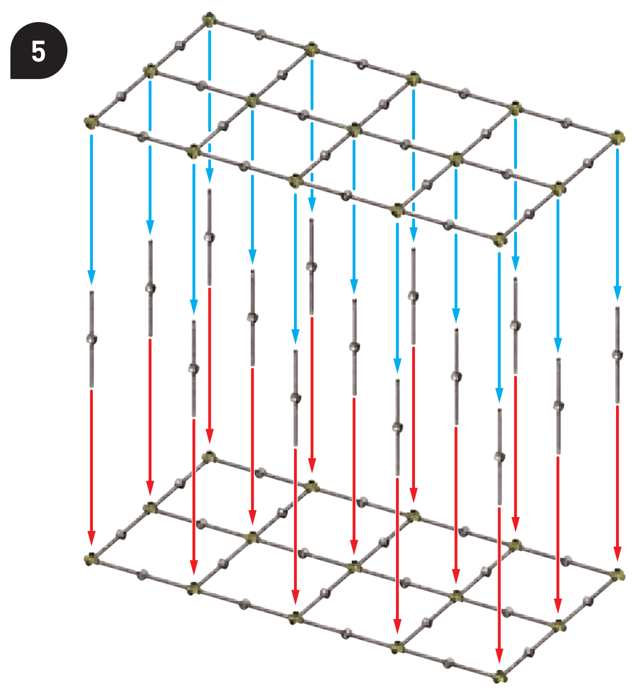


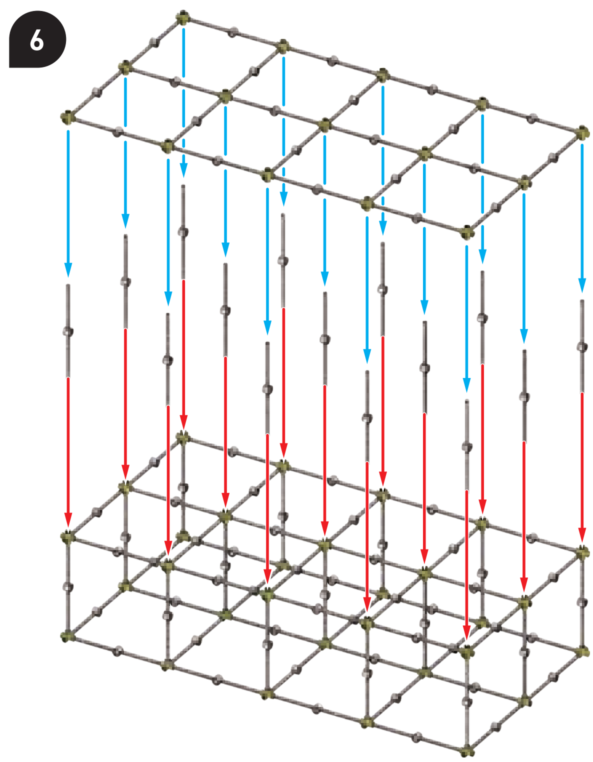












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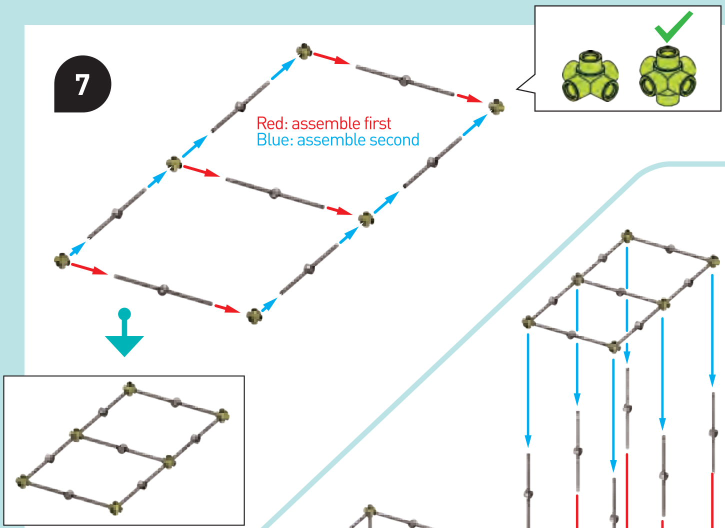
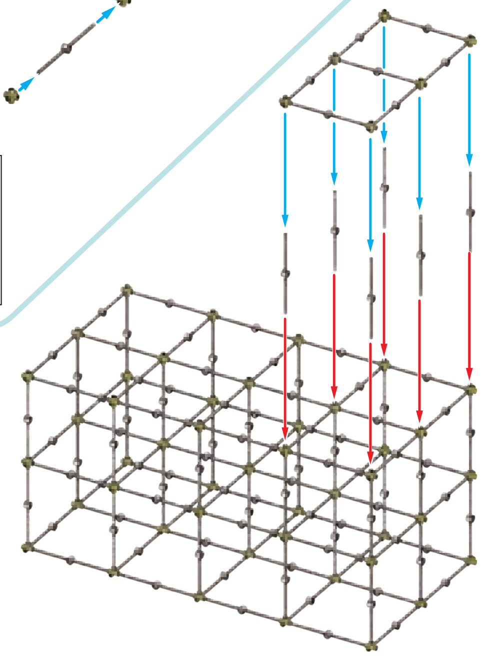

Red: assemble first
Blue: assemble second

8



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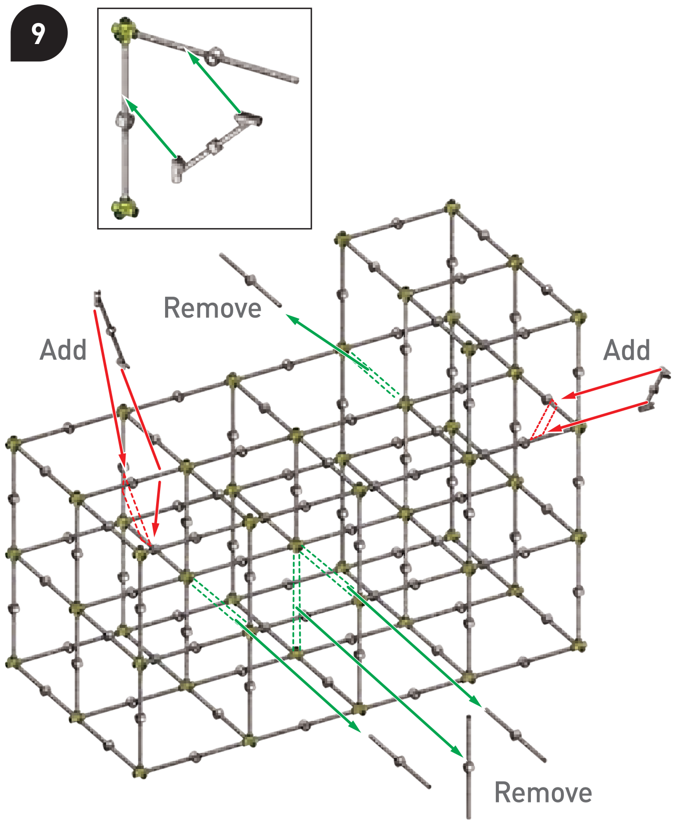
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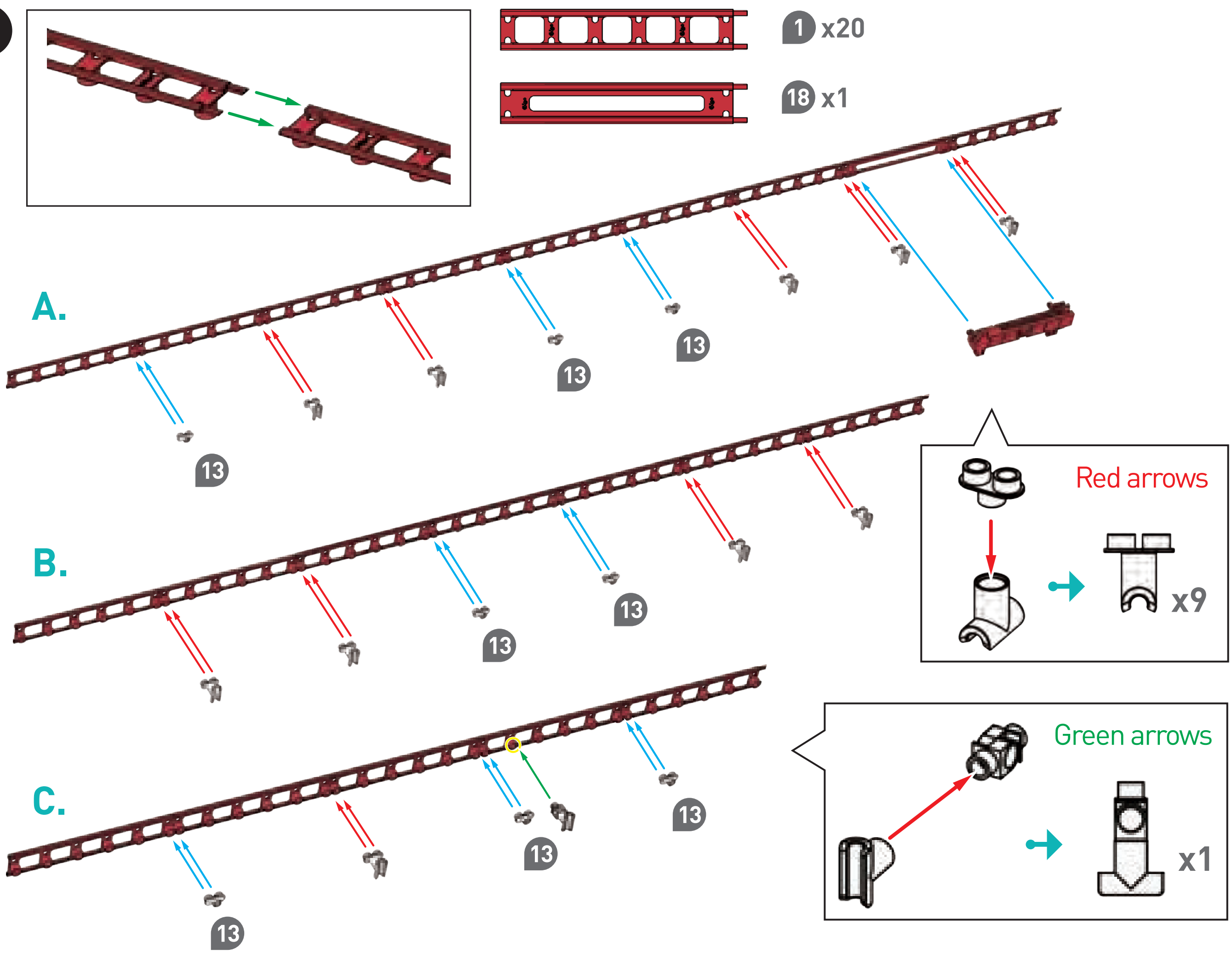
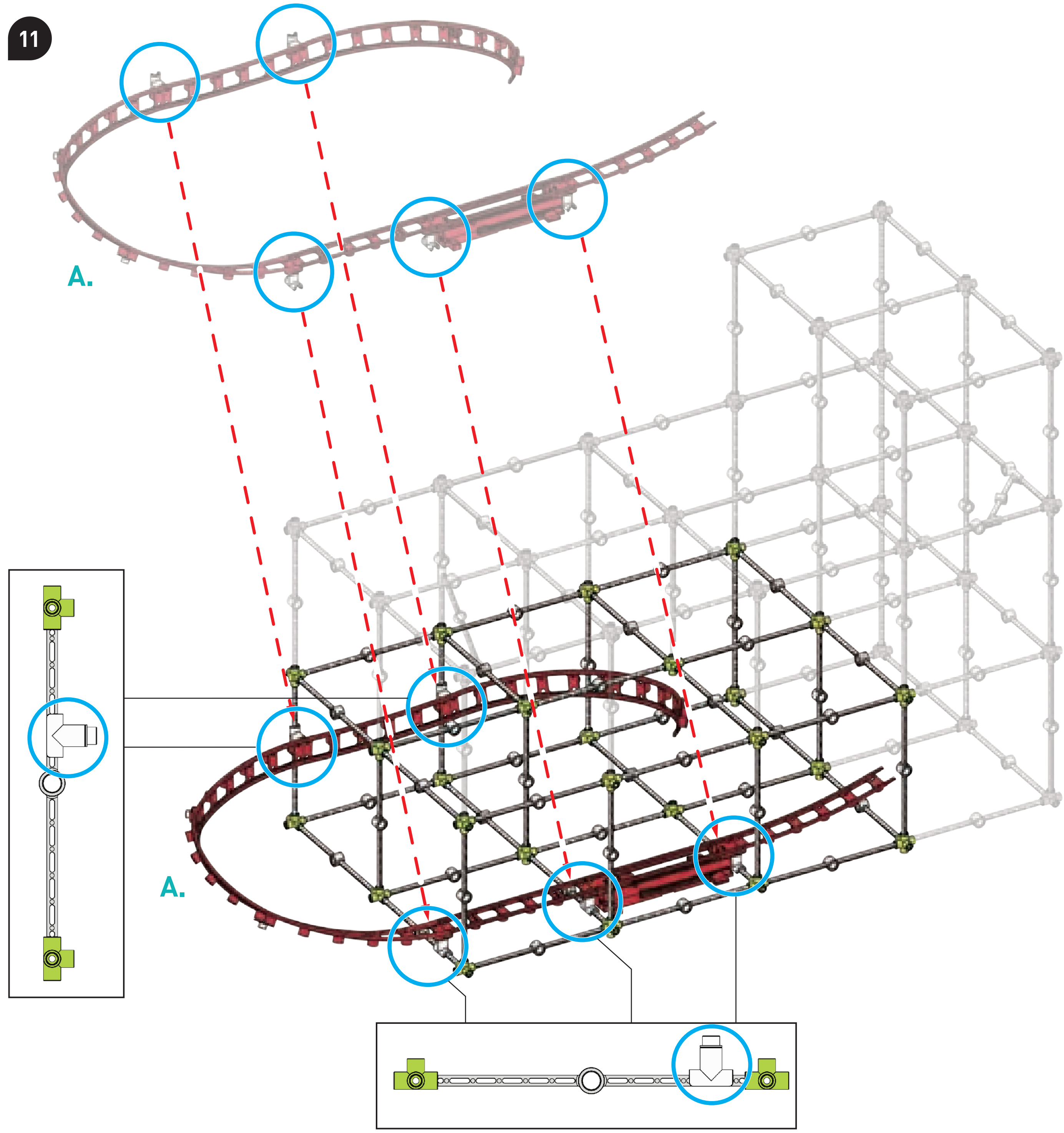
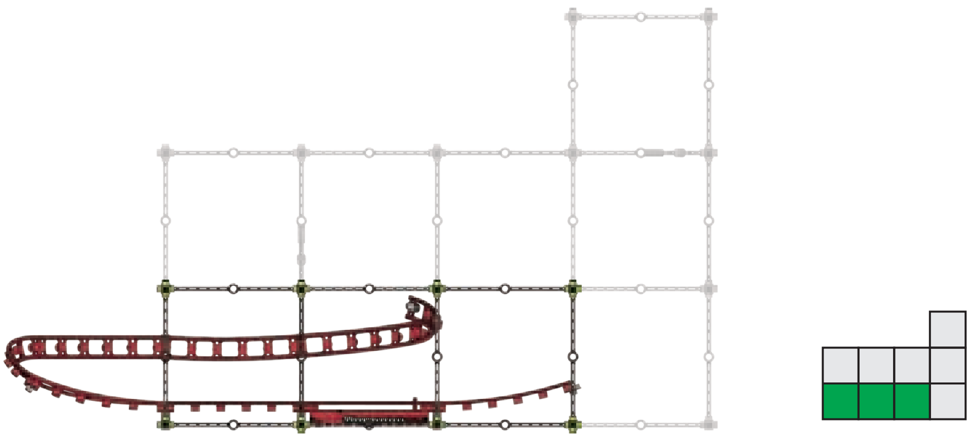

1 x20
18 x1
A.
B.
C.
13
Red arrows
x9
Green arrows
x1



Side view



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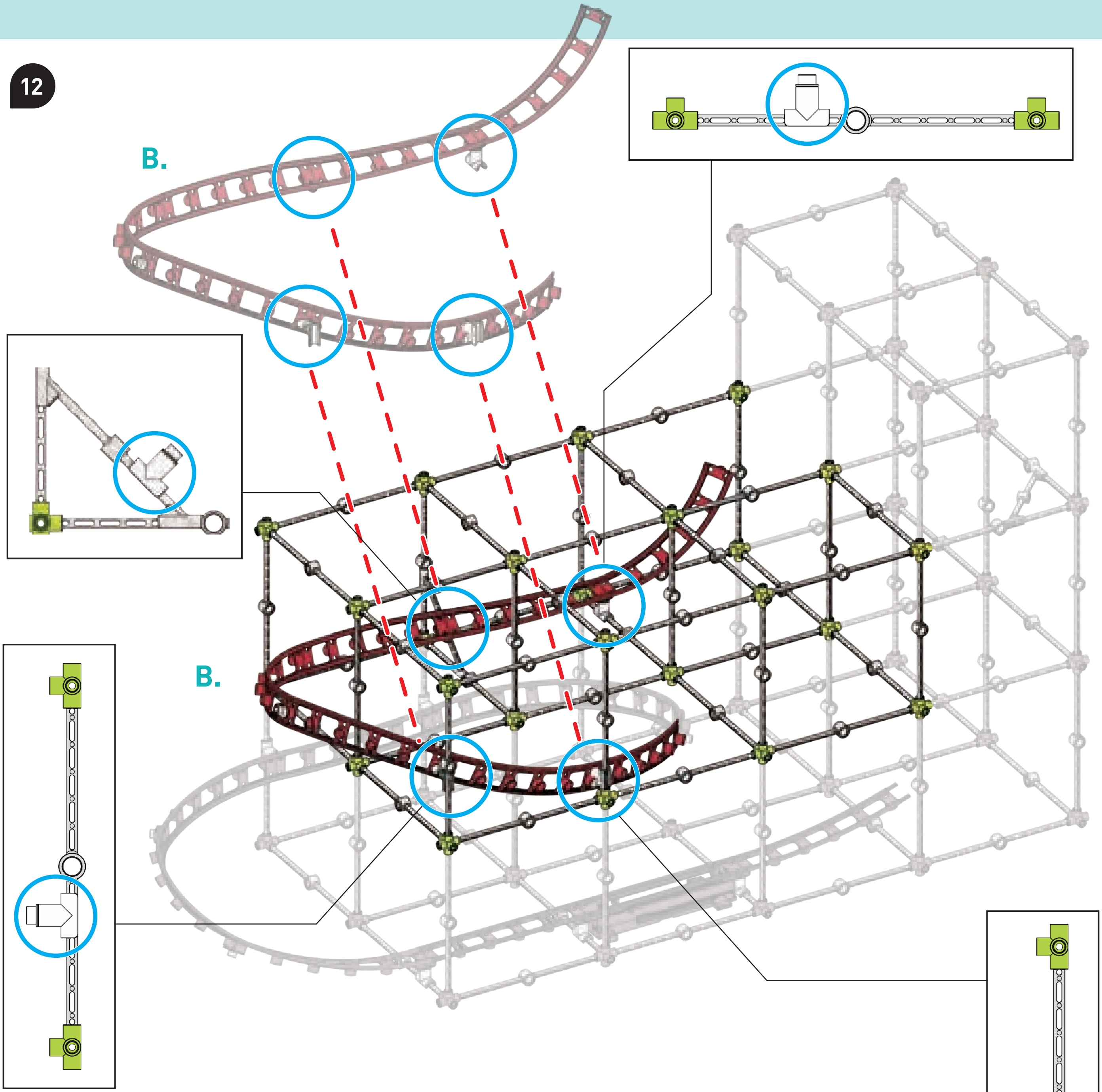
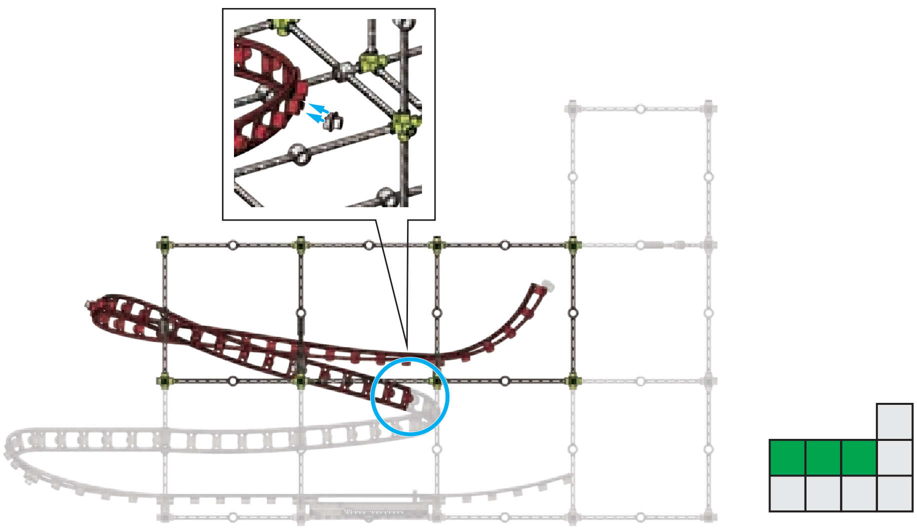


Side view



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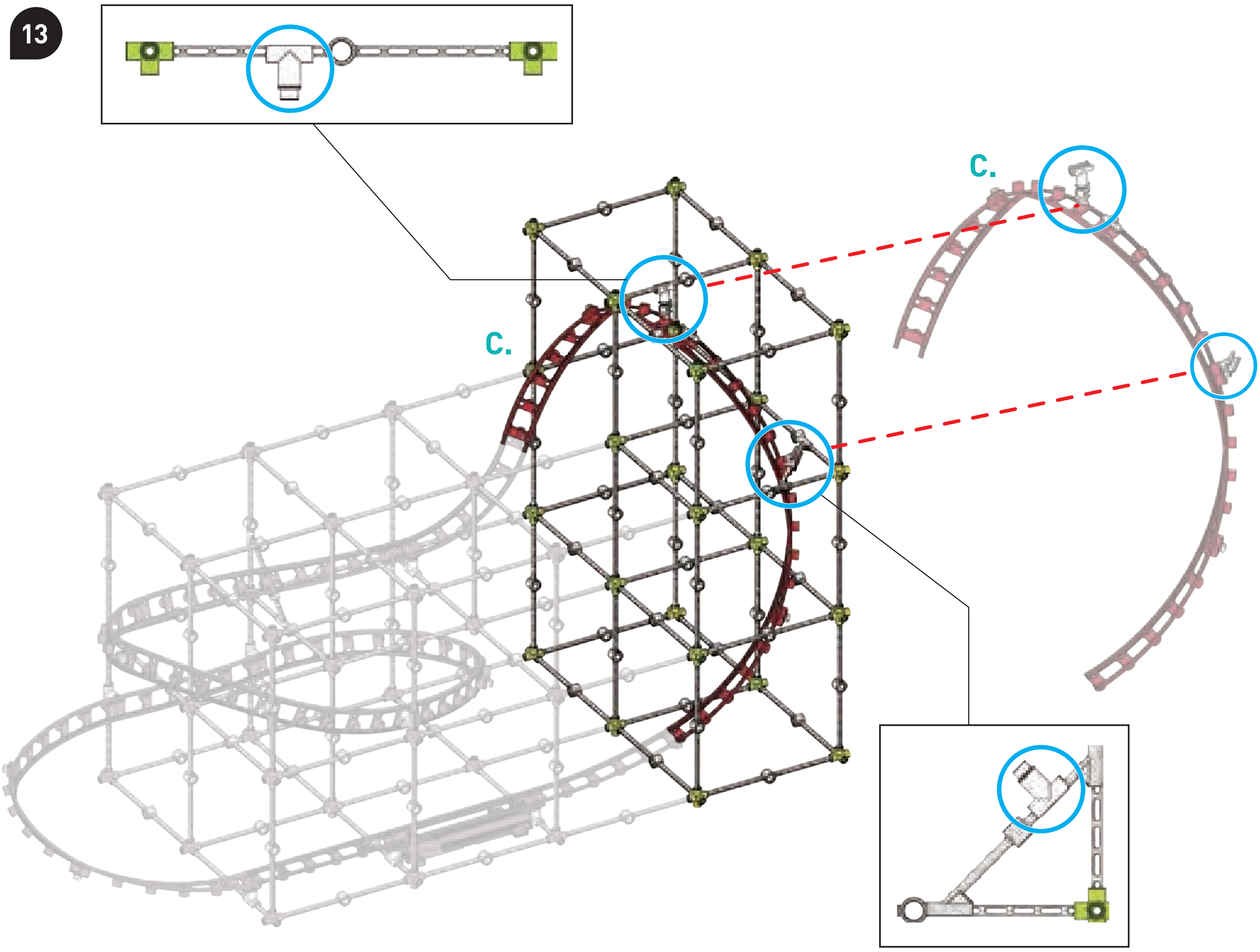
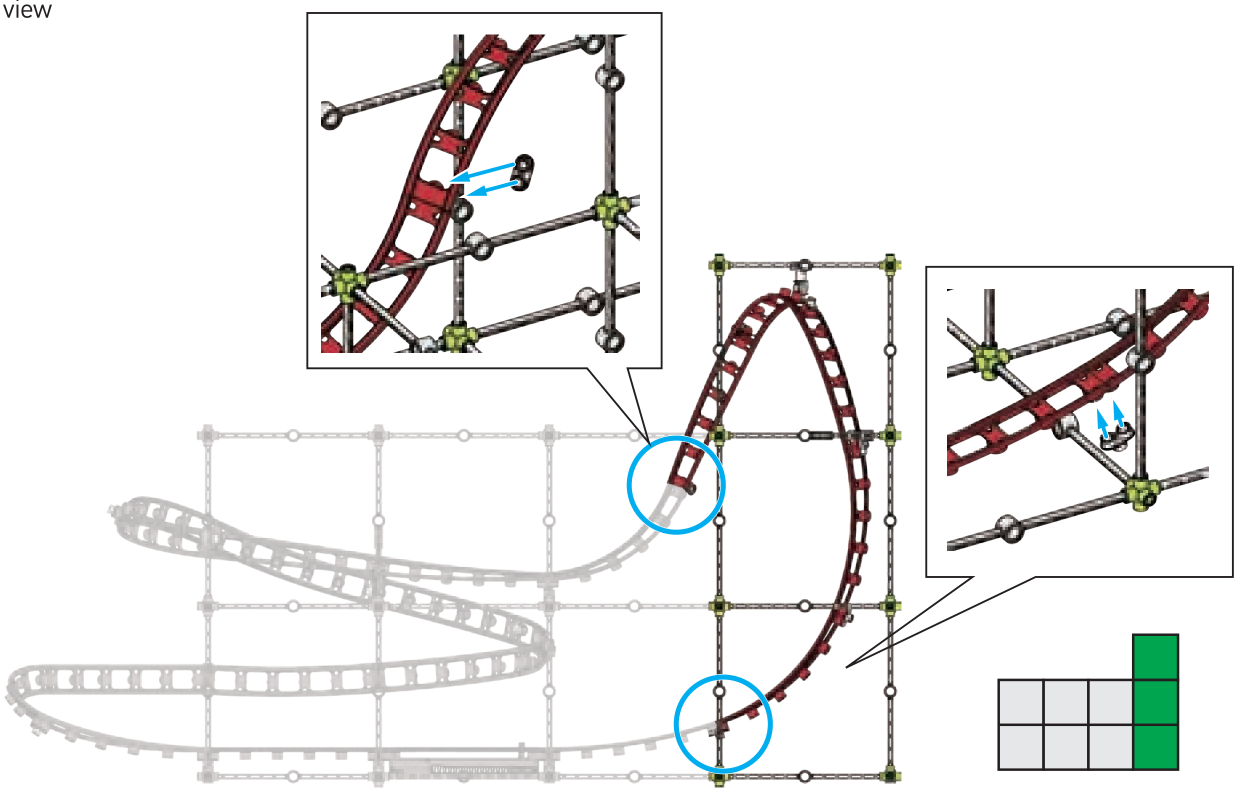


Side view



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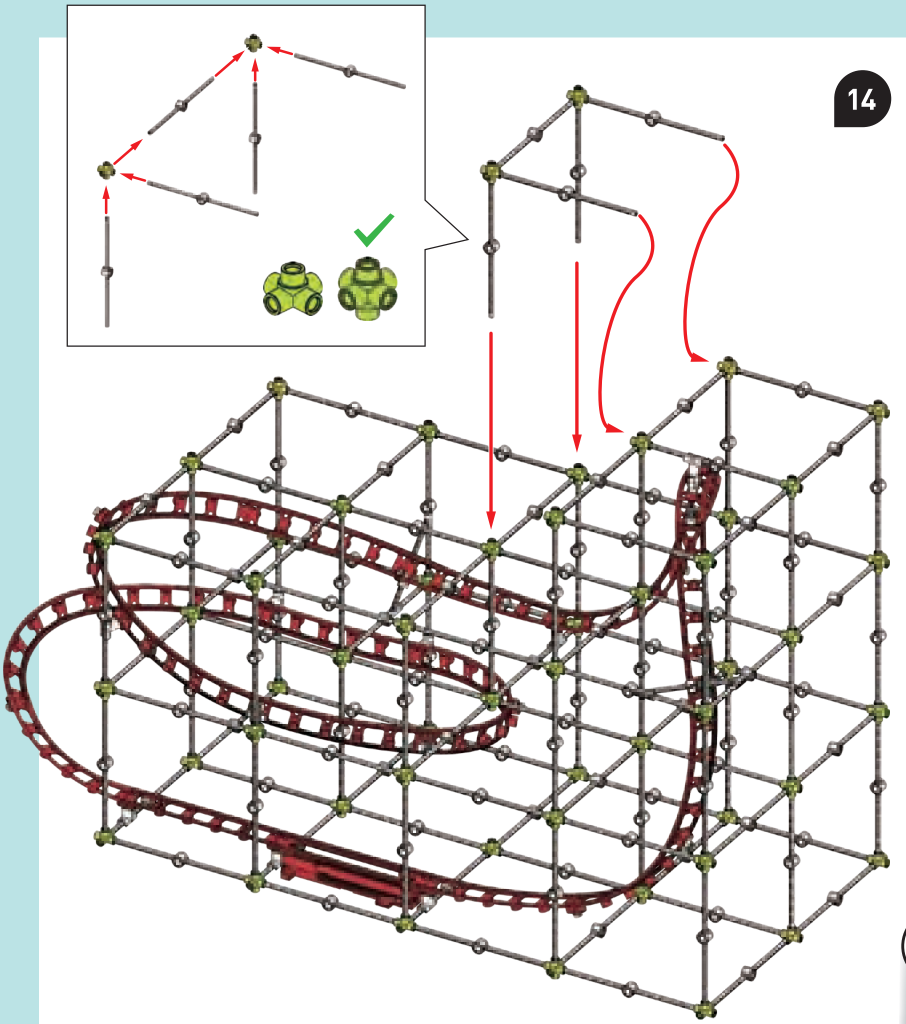

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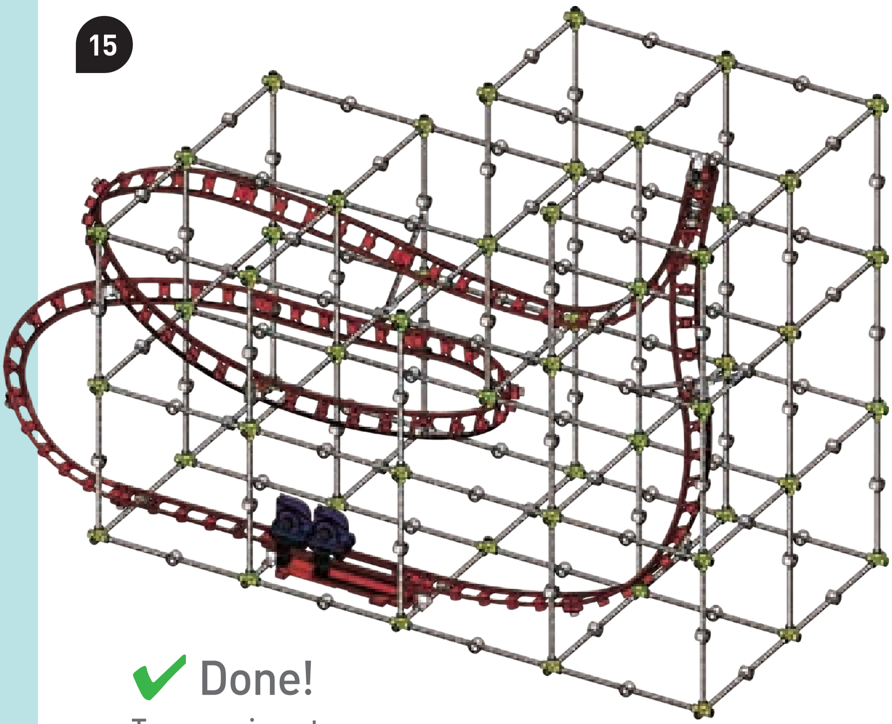


✔ Done!

Try experiments 16 and 17.

EXPERIMENT 16

Ready to roll

Can you get the train to make it all the way around the track?

You will need

- **Model for experiments 16 and 17**

Here's how

1. Roll the train so it is just in front of the launch rod. Make sure it is facing the correct direction, as shown in the model image to the left.
2. Pull the spring compressor bar back until it clicks into the notch in the launcher and locks into place.
3. With your finger, flick the train backward toward the launcher to launch the train. Does it make it up the hill and all the way back to the launcher again?

WHAT'S HAPPENING?

The train should have easily made it up to the top of the hill and then rolled all the way back down to the launcher again. The launcher provided enough kinetic energy to propel the train up the hill. At the top of the hill, the train's potential energy peaks, and then as gravity pulls the train back down again, the potential energy is released back into kinetic energy.

EXPERIMENT 17

Gravity alone

Is the launcher actually necessary?

Here's how

1. Position the train at the very top of the roller coaster hill and release it to roll down the hill. Does it make it all the way back up the hill again?

WHAT'S HAPPENING?

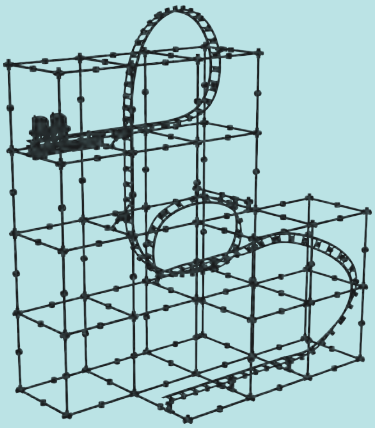
The train cannot make it around the track when simply released from the top of the ride. Because some of the initial gravitational potential energy is lost to friction, energy must be added to the system in order for the train to complete the ride.

For the last three experiments, let's put everything you've learned to the test! See if you can figure out how to build a roller coaster of your own design that satisfies each of the challenges below. Scan the QR code here to view one example solution for each challenge. There are many possible solutions to each.

Challenge 1

Design and build a roller coaster with two vertical loops that the train can travel successfully. The track does not need to be a continuous circuit.

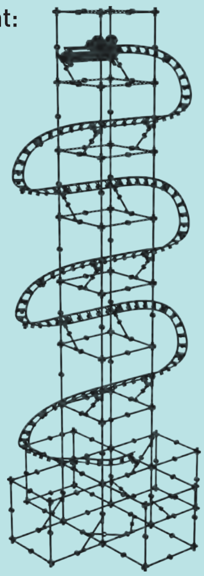
Hint:



Challenge 2

Design and build the tallest roller coaster you can with only the parts in this kit. The track does not need to be a continuous circuit.

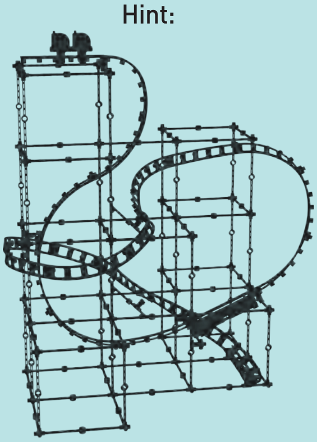
Hint:



Challenge 3

Build a track that uses both the potential energy of the car and the spring-loaded power of the launcher. The track does not need to be a continuous circuit.

Hint:



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Technical product development: Genius Toy Taiwan Co., Ltd., Taichung, Taiwan, R.O.C.
Writing and Editing: Hannah Mintz, Ted McGuire
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Manual design concept: Atelier Bea Klenk, Berlin
Manual illustrations: Genius Toy Taiwan Co., Ltd., Taichung, Taiwan, R.O.C., and Thames & Kosmos

Manual photos: p. 2 (wooden coaster) Micha Klootwijk Photography, p. 2 (background coaster) neillockhart , p. 9 (apple), p. 9 (riders) Jacob Lund, p. 9 (shuttle) Mihail, p. 19 (loops) sonya etchison, p. 24 (coaster) Solarisys, p. 25 (castle) Joni, p. 33 (top) panosk18, p. 33 (middle) Jazon88, CC BY-SA 3.0, p. 33 (bottom) danieldep, all previous ©stock.adobe.com;
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CHECK IT OUT

THE WORLD'S *Coolest* Coasters

World's Tallest: KINGDA KA

Location: Six Flags Great Adventure, New Jersey

Height: 456 feet (139 meters)

Maximum Speed: 90 miles per hour (145 km/h)

Acceleration: 0 to 128 mph in 3.5 seconds

World's Fastest: FORMULA ROSSA

Location: Ferrari World, United Arab Emirates

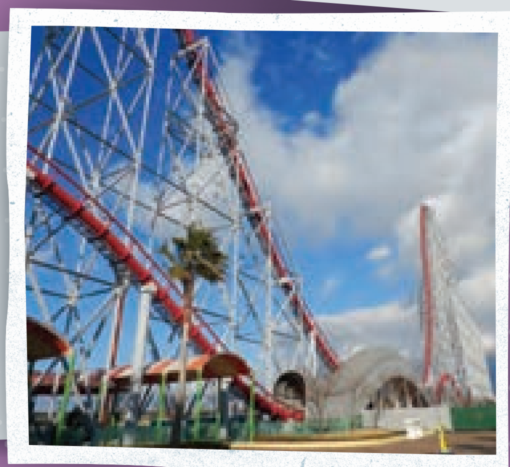
Maximum Speed: 149 miles per hour (240 km/h)

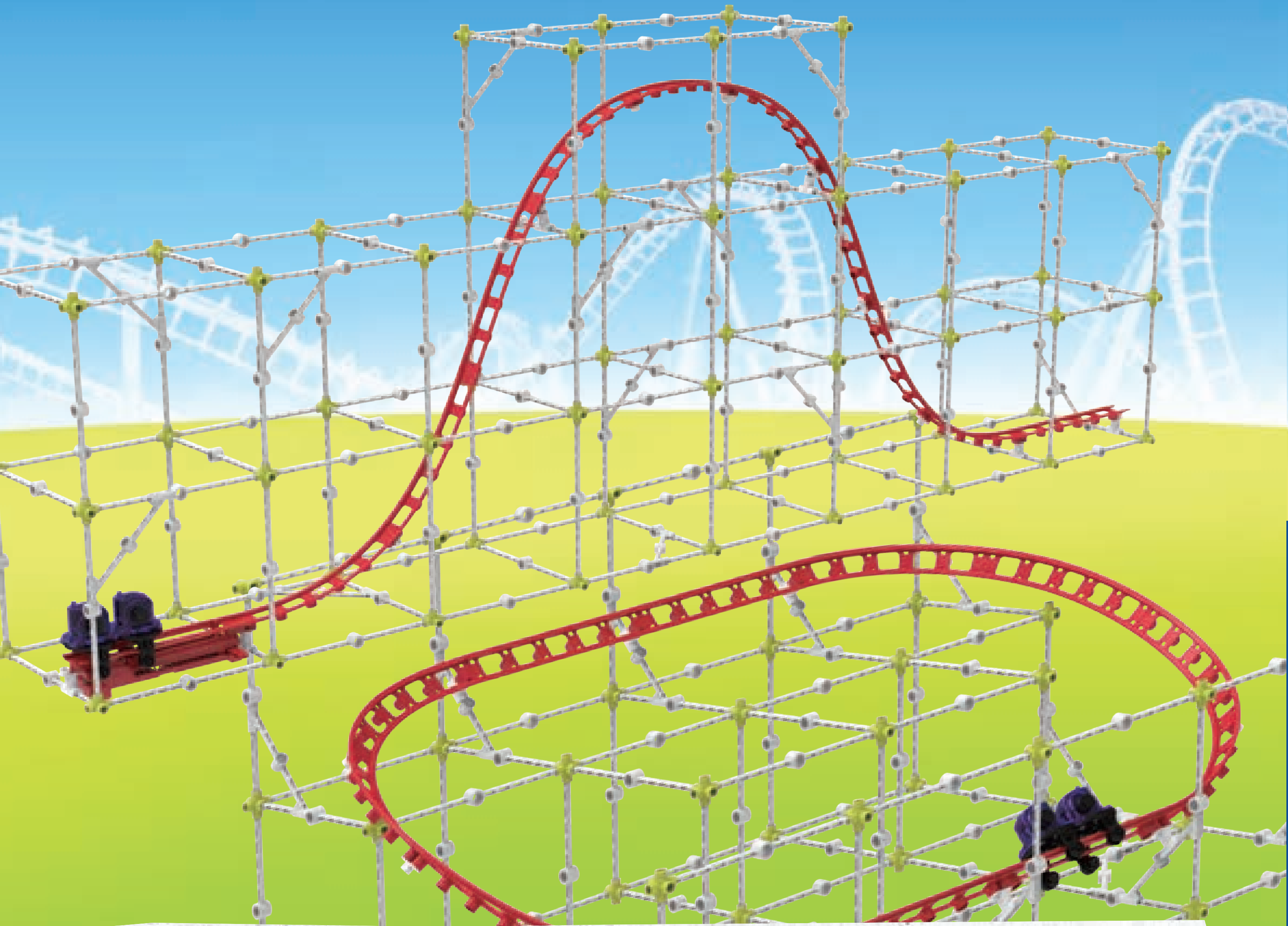
The coaster train accelerates to its top speed in 4.9 seconds using a hydraulic launch system which generates a release velocity similar to that of steam catapults on an aircraft carrier. Riders experience up to 1.7 g-force during acceleration and up to 4.8 g throughout the ride.

World's Longest: STEEL DRAGON 2000

Track length: 8,133 feet (2,479 meters)

With a maximum speed of nearly 95 mph (153 km/h), it is also one of the fastest (and tallest!) that uses a traditional lift hill.





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