What Smart Metal!

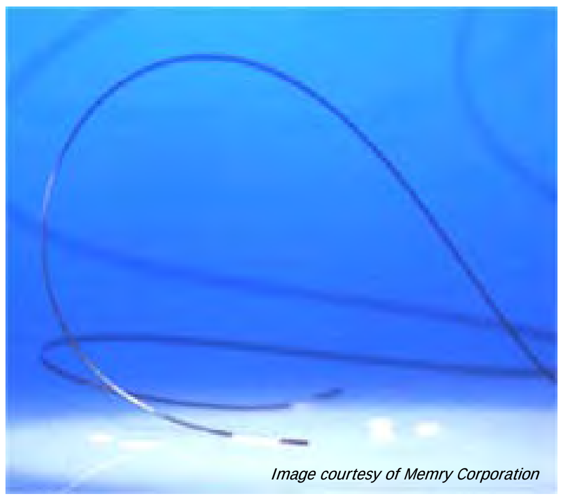

Image courtesy of Memry Corporation

Nitinol: Memory Metal
Explore the properties of this very smart material.

An activity set designed by:
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Cornell Center for Materials Research
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Contents

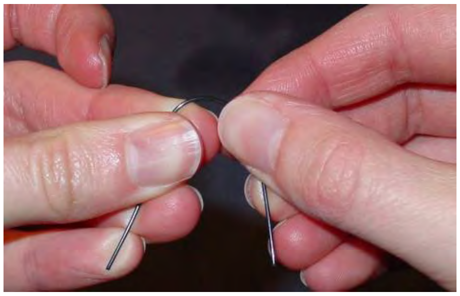
What Smart Metal!

Smart materials respond to things that happen around them. This set of activities explores the properties of one smart material: **Nitinol**. Nitinol is a mixture, or **alloy**, of two different metals: nickel and titanium. Nitinol stands for **Ni** (nickel), **Ti** (titanium), and **N**aval **O**rdnance **L**aboratory, the place where it was discovered in 1965. What makes Nitinol so smart? Find out!

In this activity, you will demonstrate the shape memory properties of Nitinol by shaping and heating samples.

This activity takes about 15 minutes. Parents, please supervise children.

Materials



- Piece of Nitinol wire[1]
- Hairdryer
- Bowl
- Paper clip or other wire (optional)

Pre-activity

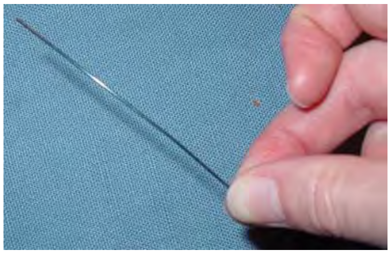
Use your senses to observe the Nitinol wire. Is it soft? Hard? Stretchy? What materials does it remind you of? How would it be different if it were thinner? Thicker?

Activity

- Bend the wire into a shape.
- Try to straighten the wire back out. Give up?
- Put the wire in the bowl, and blow the hairdryer on it. What happens? If nothing happens, move the hairdryer closer to the wire. *Nitinol can get very hot, so please don't hold the wire while heating it.*

Question: If you bend a coat hanger, a paper clip, or other wire out of shape, and then heat it up by blowing on it with a hairdryer, what happens? Try it! How does Nitinol behave differently from other wires? What are the differences between Nitinol and other wires?

What's going on?



Everything around us is made of little building blocks called atoms. Nitinol is made up of two kinds of atoms: Nickel atoms and Titanium atoms. They are arranged in an organized pattern called a ***crystal structure.*** Most solids have a crystal structure, but Nitinol is special because it has two different crystal structures, also called solid ***phases.*** At colder temperatures, Nitinol's atoms are in one arrangement, called ***martensite.*** At higher temperatures, Nitinol's atoms are in a slightly different crystal structure, called ***austenite.***

[1] Nitinol wire may be purchased at the following websites, as well as other sources:
Educational Innovations: www.teachersource.com
Images SI, Inc.: www.imagesco.com
Livewire: www.tinialloy.com/livewire.html

When you heat Nitinol, you give the atoms energy to move from the martensite structure to the austenite structure, and as it cools back down, they move back. The atoms in the Nitinol move just a little bit, but this makes a huge difference in how the metal feels and behaves. At lower temperatures, Nitinol is soft and easy to bend. At hotter temperatures, it is stiff and springy.

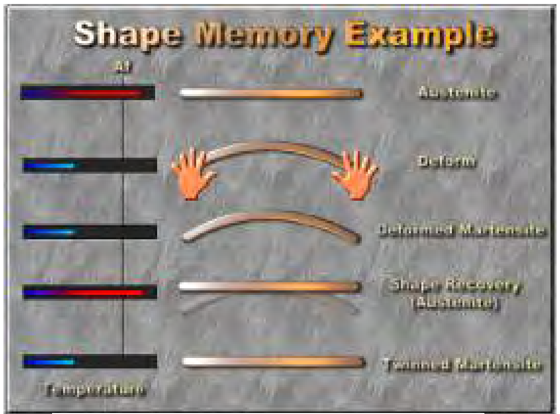
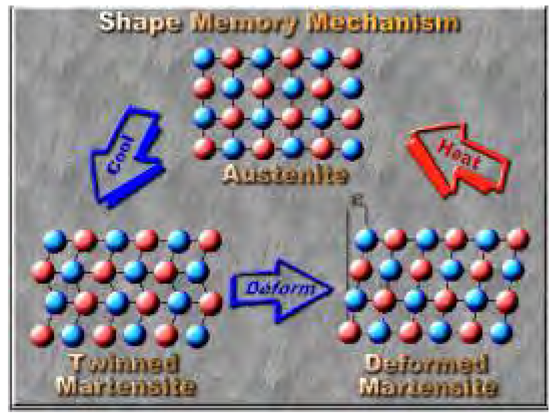


Image Courtesy of Memry Corporation (www.memry.com)

How does that make Nitinol a smart material? When it's in its low-temperature structure, when you heat it up, it will change to its high-temperature structure, and will bounce back to its original shape when that change happens. When you heated the wire up using the hair dryer, you caused the Nitinol to change from one phase to the other, and it went back to the shape it was in before you bent it. The fact that Nitinol remembers its shape gives it its other name, ***memory metal***.



Extension Activity 1

You can use electricity to heat the wire, just like electricity heats the coils in your toaster. Electricity is used to change Nitinol's shape when it is used as the legs of robots, or in toys, statues or machinery.

Materials

- Piece of Nitinol wire
- 6 Volt lantern battery
- 2 leads with alligator clips on both ends

Activity

Parents, please supervise children.

- Bend the wire.
- Clip one end of an alligator clip lead onto the positive terminal of the battery. *Be careful not to pinch fingers in clips.*
- Attach the other end of the lead to one end of your bent piece of Nitinol.
- Attach one end of the other lead to the other end of the Nitinol.
- *Nitinol can get very hot when using electricity. Don't touch the wire as it is heating. Hold the alligator clips by the insulated covers.* Gently touch the other end of that alligator clip to the negative battery terminal. What happens to the wire? Compare it to when you blow a hairdryer on a piece of Nitinol.

Extension Activity 2

What other materials in your house have memory? A rubber band will go back to its original size when you stretch it and then let go. What happens if you stretch a rubber band around a large object and leave it for awhile? Does it go back to its original size?

Can you think of any other materials in your house that have memory?

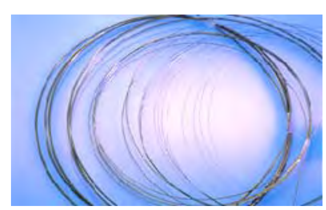
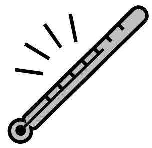


Image Courtesy of Memry Corporation

Taking Its Temperature 

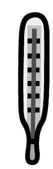
Nitinol, otherwise known as *memory metal,* will spring back to its original shape when it is heated above a certain temperature, called its ***transition temperature.*** The transition temperature can vary between about –140°C (-220°F; as cold as winter on Mars' poles) and 75°C (167°F; as hot as a cooked chicken out of the oven).

In this activity, you will design your own experiment to determine the transition temperature of a specific piece of Nitinol wire.

This activity takes about 20-30 minutes. Parents, please supervise children.

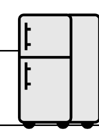
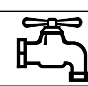
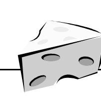
Materials

- Piece of Nitinol wire
- Bowls or containers
- Cold Water and Hot water (you may need to heat this water above the temperature at which it comes out of the tap)
- Thermometer that measures temperatures from 0°C to 100°C



Pre-activity

Make a prediction. At what temperature do you think the Nitinol bounces back to its original shape? This chart shows some temperatures you might know.

Temperature		Description
Celsius (°C)	Fahrenheit (°F)	
0 °C	32 °F	Ice cubes
3 °C	37 °F	The inside of your refrigerator 
22 °C	72 °F	Room temperature
37 °C	99 °F	Normal body temperature
39 °C	102°F	A hot tub 
49 °C	120 °F	Hot water from the tap 
59 °C	138 °F	Swiss cheese melts
75 °C	167 °F	Roast chicken coming out of the oven
100°C	212 °F	Boiling water 

Activity

- Bend the wire.
- Put it in hot water. Does it change shape?
  Be careful with very hot water.
- Measure the hot water's temperature. Record your data on the chart on the other side.
- Add some cold water. Does the wire change shape now? Record your data.
- Repeat, adding cold or hot water to change the temperature, until you have determined the transition temperature to within a few degrees.

  Question: How close was your prediction to your result?

Water Temperature	Did the wire change shape?

What's going on?

Nitinol is a mixture of two different metals, Nickel and Titanium. At a certain temperature, its ***transition temperature,*** it changes from one solid ***phase*** to another. Below this temperature, Nitinol is soft, bendable, and if you bend it, it will keep its bent shape. Above this temperature, Nitinol is stiff, and if you try to bend it, it will spring back. When the change from one phase to another happens, Nitinol bounces back to the original shape it was made in.

Scientists can set the transition temperature varies of Nitinol by changing the ratio of Nickel to Titanium in the alloy. It can vary from about 47% Nickel, 53% Titanium to about 51% Nickel, 49% Titanium.

Question: Nitinol is often used in orthodontic archwires. These are the wires that connect the brackets in braces. The orthodontist bends the wire into the current shape of a patient's teeth, and connects it to the braces. Once in the patient's mouth, the wire warms up, tries to change shape, and pushes on the teeth. What do you think the transition temperature is of a Nitinol archwire?

Question: If Nitinol were used in a coffee pot or a teakettle so it would turn off at just the right temperature, what do you think its transition temperature would have to be? (The answer is at the bottom of the page.)

Question: Flexon® eyeglasses frames are made out of Nitinol. They are in their high-temperature form, which is springy, at room temperature. This is why you can bend them around your finger without breaking them. How low do you think their transition temperature is?

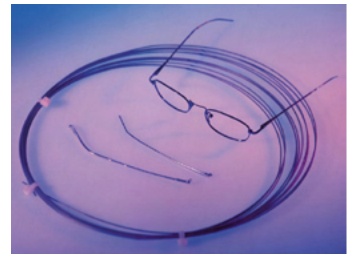


Image Courtesy of Memry Corporation (www.memry.com)

(Answers at bottom of page)

Question answers:

- The transition temperature of orthodontic archwires is usually about 80-90 °F (27-32 °C). This is a little lower than the temperature of the inside of your mouth (about 95 °F, or 35 °C).
- Coffee and tea brews best just below boiling temperature, at about 200 °F, or 93 °C.
- Nitinol eyeglass frames have a transition temperature much below freezing, so the transition doesn't happen in cold weather.

Shape Up!

Nitinol is memory metal. It will spring back to its original shape when heated. To permanently change the shape of Nitinol, you heat the wire to about 500 °C (932 °F). This will change the arrangement of the metal's atoms.

In this activity, you will train a piece of Nitinol wire to a new shape.

This activity takes about 15 minutes. Parents, please supervise children.

Materials

- Piece of Nitinol wire
- Hairdryer
- Candle
- Matches
- 2 pairs of pliers
- Hot mat

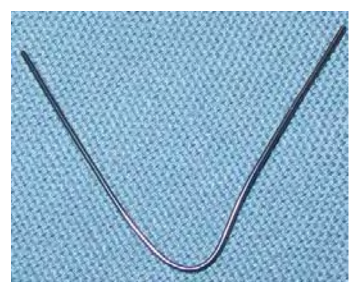
Don't use your fingers!

Use pliers!

Activity

- Ask an adult to help you with the next steps. *Be very careful with the flame and hot wire.*
- Light the candle. Hold the ends of your wire with pliers, and place the middle in the candle flame. Try to bend the wire into a V-shape. When it becomes hot enough, you will feel the pressure on your pliers release, and it will bend into the V-shape.
- Remove it from the flame immediately, and set it on hot mat to cool.
- Wait a minute or two to touch the wire. Bend it into a new shape.
- Blow on the wire with a hair dryer. What happened?

What's going on?

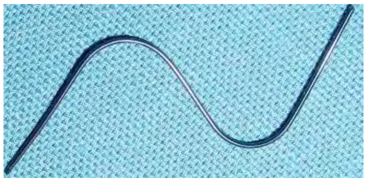


Nitinol wire will bounce back to its original shape when it is heated above its ***transition temperature***. This is why you felt the wire pushing on your pliers as you held it in the V-shape. When enough energy was added to the wire by heating it in the flame, its atoms moved around enough to "reset" its memory. This is why the pressure was released on your pliers. Now the wire has a permanent V-shape, and will return to that shape when bent and heated.

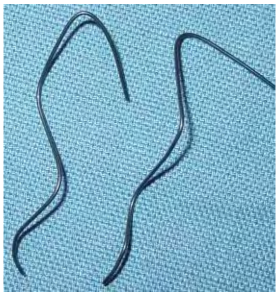
The Nickel and Titanium ***atoms*** in the Nitinol wire are in an ordered arrangement, or ***crystal structure***. But nothing's perfect. There are mistakes in the way the atoms are arranged, and these mistakes are called **defects**. These mistakes could be missing atoms, or extra atoms that are trapped in there. When this kind of Nitinol wire is at room temperature, it is very easy to bend. Heating it causes it to change to a rigid ***phase*** with a different crystal structure. When it cools back down, the atoms go back to exactly their original positions, including defects. Imagine a drawing where, no matter how many times you erase it and draw it again, it comes out the same, including mistakes!

But these mistakes are actually a good thing! It's the position of the defects in this wire that makes it come back to the same shape every time it is cooled and heated. So how did holding the wire in the candle flame change the wire's shape? It gave the metal enough energy that the defects in the crystal structure moved around. When the wire got cooled in this shape, the defects got frozen in their arrangement, and now they make the wire spring back to the V-shape every time it is cooled and reheated.

Extension Activities



- You just made a "V" shape with your wire. What other letters of the alphabet could you make? *Can you make curves and angles?*
- What can you make with your "V" shaped wire?
  - How about antennae or legs for a toy bug? You can bend them in any shape you want, and they will come back every time!
  - What about jewelry?



- Artists have used Nitinol to make statues that move. Make a Nitinol statue by permanently changing a wire's shape and adding things, like paper, cloth, tape... Be creative!

Nitinol Inventions

Summary

Nitinol, otherwise known as memory metal, is used in many products. These products were made better by using Nitinol instead of other materials.

One reason Nitinol is useful is that it has ***shape memory***. Nitinol has two solid phases. The lower temperature phase is soft bendable. If you heat it above a certain temperature, it will transition into a higher-temperature phase and bounce back into its original shape. This can be used to move things, or work as a switch to turn something on or off.

Another useful property of Nitinol is that it is **superelastic**. The higher-temperature phase is stiff. But if you try to bend a Nitinol wire or rod in this phase, the pressure you exert on the metal by bending it will cause it to temporarily change back into the softer phase. Once you release your push on the Nitinol metal, it turns back into austenite again. This makes it incredibly springy.

Activity

Design an invention that uses Nitinol for either its shape memory properties, or its superelastic properties. How does this invention take advantage of Nitinol's properties? Why would Nitinol be better than another material?

Examples

Here are many examples products that Nitinol is used in. Have you seen any of these products before? How has Nitinol improved the product?

Challenge: *For each product, figure out whether it uses Nitinol's shape memory properties, or its superelastic properties.*

Safety Shower Head

A nitinol spring can reduce hot water flow when water gets hot enough to hurt you.
http://vesuvius.jsc.nasa.gov/er/seh/pg80s95.html

Lure Savers

These keep fishers from losing their lures when they get snagged on a rock. Fishing rod guides are also often made from Nitinol.
http://www.ultimateluresaver.com/how.cfm

Image Courtesy of Ultimate NiTi Technologies, Bristol, CT – USA, 1-800-999-NiTi

Smart Wings

Hingeless wings using Nitinol allows for smoother, more aerodynamic flight.
http://www.aero-space.nasa.gov/events/news/vol2_iss6/bird.htm

Golf Clubs

Putters and wedges that include Nitinol allow for better control and spin on the ball.
http://www.sti.nasa.gov/tto/spinoff1997/ch8.html

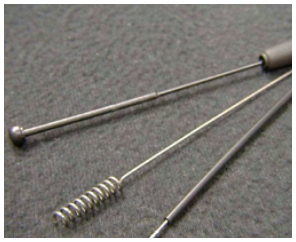


Image Courtesy of Memry Corporation (www.memry.com)

Coffee Maker

A Nitinol spring turns the water heater off when it reaches the right temperature to make coffee.

Cell Phone Antennae

These are flexible and kink resistant.

Orthodontic Archwires

Using memory metal causes less pain for patients, and increases the amount of time between needed visits. And if your braces make your teeth ache, just drink a glass of ice-cold water!

http://www.ultimatewireforms.com/search.html

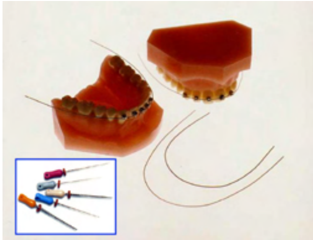


Image Courtesy of Memry Corporation (www.memry.com)

Trick Spoons

These spoons twist when you try to stir your coffee or tea.

http://www.ianrowland.com/WowCards/WowCardsPPOShape%20Shifting%20Spoon.html

Surgical instruments

These can open and close without hinges, and often move using shape memory or superelastic springiness.

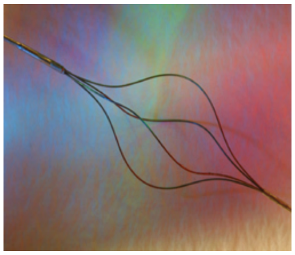


Image Courtesy of Memry Corporation (www.memry.com)

Mars Rover Equipment

Nitinol helped measure dust accumulation on the Mars Rover Sojourner's solar panels in 1997.

http://powerweb.grc.nasa.gov/pvsee/publications/mars/techn.html.

Car Parts

Some cars use a Nitinol spring valve to control transmission fluid, because it is better to have more transmission fluid when the engine is hotter.

<u>Shape Memory Actuators Improve Car Performance</u>, by Dieter Stoeckel.
http://www.nitinol.info/pdf_files/052.pdf

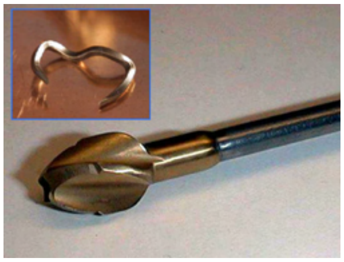


Image Courtesy of Memry Corporation (www.memry.com)

Bone Staples

Nitinol holds broken bones together until they have healed.

Stents

These hold blood vessels open so they don't collapse or get clogged.

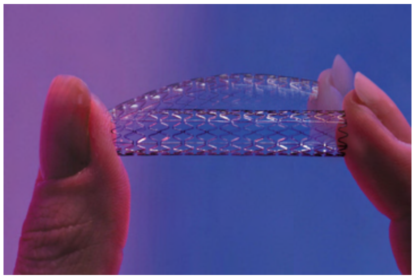


Image Courtesy of Memry Corporation (www.memry.com)

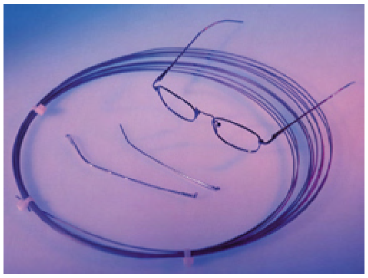


Image Courtesy of Memry Corporation (www.memry.com)

Eyeglass Frames

Flexon™ frames are flexible, comfortable, and won't get out of shape.

http://www.flexon.com

Toys

Nitinol is used in butterflies whose wings flap, as the legs in robots, and as parts in other toys.

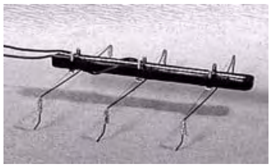


Image Courtesy of Stiquito (www.stiquito.com)

Image Courtesy of Memry Corporation (www.memry.com)

Connectors

Connectors made for use in aircraft and cars shrink when heated, forming a tight seal between pipes and hoses.

Sculptures

Many artists use memory metal in art that changes shape, or reacts to changes in the environment. An example is *Onibaba*, by Etienne Krähenbühl and Dr. Rolf Gotthardt, which features reeds that move as you approach.

http://dpwww.epfl.ch/Gotthardt/ART/Onibaba.html

Image copyright François Busson.
Courtesy of Krähenbühl and Gotthardt.

Clothing

The Corpo Nove fashion company has made a shirt whose sleeves roll up when it gets just warm enough. The other good news? You can iron it with a blow dryer.

http://www.newscientist.com/article.ns?id=dn1073

Buildings

Nitinol anchors may help buildings withstand earthquakes.

http://www.nidi.org/nickel/0300/9-0300n.shtml

Nitinol is a valuable technology whose shape memory and superelastic properties have allowed scientists and engineers to solve problems and improve many products, including those listed above. What do you think Nitinol will be used for next?

How many pennies?

Summary

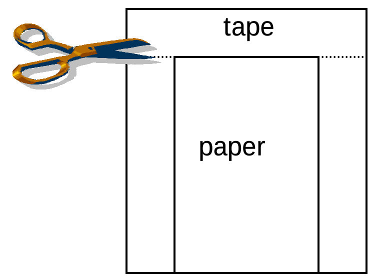
Nitinol, otherwise known as *memory metal,* changes with temperature. Artists have used Nitinol to make sculptures that change shape. One of these sculptures, by French artist Olivier Deschamps, is called “Espoir-Desespoir.” This translates into English as “Hope-Despair.” It features a woman holding a baby. When it is cold out, she is laid out on the ground with the baby in front of her. When it is warm out, she is kneeling holding the baby up to the sky. How does this work? Find out by making a model of the statue.

In this activity, you will use the Nitinol’s shape memory properties and the properties of Nitinol’s two phases to make a sculpture that can lift weight (pennies).

This activity takes about 20 minutes. Parents, please supervise children.

Materials

- Piece of Nitinol wire
- Hairdryer
- Bowl
- Pennies
- Duct tape or package tape
- Piece of paper
- Ruler
- Scissors
- Clothespin



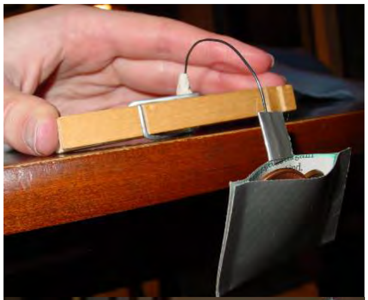
Activity

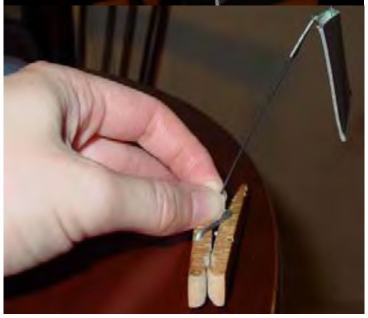
- First, make a penny holder. Cut 2 ½ in. x 1 ½ in piece of paper and a 3 in. x 2 in. piece of duct tape.
- Place the paper on the sticky side of the tape as shown.
- Cut slits in the tape about ¾ of an inch in from each side, as shown.
- Place one end of the Nitinol wire in the center of the tape edge, between the two flaps you’ve just made, and wrap the flaps around the wire. Squeeze to stick it together.

- Fold the whole thing in half to make a pocket for pennies to go in.
- Now we need to secure the other end of the wire. Wrap this end of the wire with masking tape.
- Pinch the tape-wrapped end of the wire in the clothespin in the small hollow near the spring.
- Now it’s time to see how many pennies your sculpture can lift! Hold your sculpture on the edge of a table so the pocket hangs down. Blow on the wire with the hairdryer to straighten it.
  Each time you heat the wire with the hairdryer, observe what happens while it cools. Wait a minute or so before touching it.
- Place a few pennies in the penny holder. What happens to the wire?
- Blow on the wire with the hair dryer. What happens?
- Add a few many pennies, and repeat. How many pennies can your sculpture lift?

What’s going on?

Nitinol is in its soft, bendable phase at lower temperatures. That is why, when the wire is cool, the weight of the pennies bends the wire down towards the ground. When you heat the wire up, it changes to its high-temperature phase, and goes back to its original shape. The force of this





change of shape is enough to lift the pennies. In its high-temperature phase, Nitinol is rigid. That is why it can hold the pennies up while it is heated by the hair dryer.

Similarly, when it is warm outside, the sculpture "Espoir-Desespoir" is in its rigid high-temperature phase, and stands up. When it is cool out, the metal is in its soft phase and sags to the ground.

Question: What happens as the wire cools down after being heated by the hairdryer? Why does this happen?

Extension Activity

The activity, "Shape Up" in this activity set shows how to permanently change the shape of a Nitinol wire. Using that information, and what you have learned in this activity, design your own moving Nitinol sculpture. Use other materials you have around the house – paper, tape, paper clips, cloth.... Be creative!

Sculptures With Memory

Many artists have used Nitinol to make sculptures that move. Some of these sculptures move when the temperature changes, like "Espoir-Desespoir." Other sculptures use electricity to change the shape of the Nitinol wire. Some move constantly, looking like muscles. Some move only when someone enters the room, catching them by surprise. These sculptures are really wild!

Image copyright François Busson.
Courtesy of Krähenbühl and Gotthardt.

Find out more! Here are other examples of Shape Memory sculptures:

- Onibaba: The Magic Reeds
  This sculpture, by Etienne Krähenbühl and Dr. Rolf Gotthardt, features reeds that move as you approach.
  http://dpwww.epfl.ch/Gotthardt/ART/Onibaba.html
  The same artists also worked together on a sculpture, now on display in the Science Museum of Barcelona, called *L'Insoutenable légèreté du cube* (which means "Unbearable lightness of the cube" in French).
  http://sb.epfl.ch/Jahia/site/sb_en/cache/offonce/pid/53064
- *Octofungi*, an 8-armed robotic sculpture, by sculptor Y. Klein.
  http://www.livingsculpture.com/LivingSculptureSite/Sculptures/Octofungi/octofungi.htm
- Artist Jean-Marc Philippe of France is coordinating a satellite time capsule called "KEO" whose wings will flap using memory metal hinges that change shape with temperature.
  Ark De Triomphe, by Robert Kunzig. Discover**,** June, 1999. Pages 62-66.
  A model of the spacecraft's design:
  http://espaeuro.homestead.com/files/1997/oevres/oiseau1000.jpg
  The same artist has created shape-memory sculptures that change form with daily and seasonal changes in temperature.
- *Office Plant #1*, by Marc Böhlen and Michael Mateas, is a "desktop sculpture" that uses shape memory switches to move.
  Intimate Space and Contemplative Entertainment
  http://www.fundacion.telefonica.com/at/vida/paginas/v2/ebohlen.html

For More Information

General Information about Nitinol:

- Nitinol Information, from the Images SI, Inc. website:
  http://www.imagesco.com/articles/nitinol/01.html
- Nitinol Technical Data, from Johnson Matthey's website:
  http://www.jmmedical.com/html/ nitinol_technical_information.html
- Nitinol: The Metal With a Mind, from the Memory-Metalle website:
  http://www.memory-metalle.de/html/01_start/index_outer_frame.htm
- Shape Memory Alloys and Their Applications, by Richard Lin:
  http://www.stanford.edu/~richlin1/sma/sma.html
- Nitinol Movies! From NDC (Nitinol Devices and Components)
  http://www.nitinol.info/flash/index.html
- The Basics of Shape Memory, from the UltimateNiTi website:
  http://www.ultimateniti.com/documents.cfm?cid=12
- Nitinol Manufacturing, From the Memory-Metalle website:
  http://www.memory-metalle.de/html/07_manufact/01_manufacturing.htm
- Nitinol FAQ from Memry Corporation's website:
  http://www.memry.com/nitinolfaq/nitinolfaq.html
- Memory Metal, From UW-Madison MRSEC's Interdisciplinary Education Group:
  http://mrsec.wisc.edu/edetc/memmetal/index.html

These robotics projects use Nitinol:

- Stiquito, a small, 6-legged robot you can build:
  http://www.stiquito.com/
- This book contains several robotics projects using Nitinol:
  Muscle Wires Project Book: A Hands on Guide to Amazing Robotic Muscles That Shorten When Electrically Powered,
  by Roger G. Gilbertson and Celene De Miranda

Shape Up Information: Crystalline Defects

- http://www.cartage.org.lb/en/themes/Sciences/Physics/SolidStatePhysics/AtomicBonding/CrystalStructure/Crystalline/Crystalline.htm

Information on Nitinol Applications

- Nitinol Applications, by Nitinol Devices and Components:
  http://www.nitinol.com/4applications.htm
- Applications of Shape Memory, by T.W. Duerig
  http://www.nitinol.info/pdf_files/061.pdf
- Medical Uses of Nitinol, by A.R. Pelton, D. Stoeckel, and T.W. Duerig
  http://www.nitinol.info/pdf_files/024.pdf
- Industrial Applications for Shape Memory Alloys, by Ming H. Wu and L. McD. Schetky
  http://www.memry.com/technology/pdfs/SMST00_IndApplic.pdf

Vocabulary

Alloy: An alloy is a mixture of two or more metals. For example, brass is an alloy of copper and zinc.

Atom: The smallest piece of matter that has all the properties of a certain element. An atom consists of a nucleus with protons and usually neutrons, orbited by a cloud of electrons.

Austenite: The rigid, springy, high-temperature phase of Nitinol.

Crystal Structure: The organized arrangement of the atoms within a material

Defect: An imperfection. In materials science this means an imperfection in the crystal structure of a material.

Martensite: The soft, bendable, low-temperature phase of Nitinol.

Nitinol: An alloy of Nickel and Titanium that returns to its previous shape when you heat it up.

Phase: A specific form of matter that exists within a certain range of temperature and pressure. This includes gas, liquid, solid and plasma. A material may have several solid phases that exist at different temperatures and pressures.

Superelasticity: The property (springiness) that results from Nitinol changing from its rigid austenite phase to soft martensite phase when deformed.

Transition temperature: The specific temperature at which Nitinol changes phases

References

All sources included in the "For More Information" heading were used, as well as:

Dr. Robert W. Baker, DDS. Orthodontics Associates, Ithaca, NY. Personal communication.

Teaching General Chemistry: A Materials Science Companion. Arthur B. Ellis, Margret J. Gesselbracht, Brian J. Johnson, George C. Lisensky and William R. Robinson. Published by the American Chemical Society, 1993.

Crystal Structures and Shape-Memory Behaviour of NiTi. Xiangyang Huang, Graeme J.Ackland, and Karin M. Rabe. Nature Materials 2, 307-310 (2003).

Introduction to Shape Memory & Superelasticity, Johnson Matthey www.sma-inc.com/html/introduction.html

Art and Shape-Memory Alloys. J.M. Phillippe. Leonardo 22(1), 117-120 (1989).

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