Teacher's Guide

Efficiency of Nitinol Wire

Grade Level: High school

Subject area: Physics

Time required: 50 minutes

Learning objectives: Through inquiry, students will learn about memory metal, efficiency of the wire, and determine input and output energies.

Summary: This lab activity focused on nitinol or muscle wires which are shape memory alloys. These wires can be used to lift a weight up a height. Students will explore how the work performed lifting a load with the nitinol wire compares to the energy pumped into the wire by an electrical current. In this lab, the student will calculate the work required to lift the load by measuring the change in potential energy and the energy input into the wire by measuring the voltage across the wire and the current through the wire. The time needed by the device to raise the load is also determined. The activity uses either a Pasco Probeware or a Vernier LabPro.

Lesson Background Information: The activity uses a shape memory alloy called nitinol. The history of nitinol begins in 1932, with Swedish researcher Ame Olander who observed the shape and recovery ability of a gold-cadmium alloy (Au-Cd) and noted that it actually created motion. In 1950, L.C. Chang and T.A. Read at Columbia University observed this unusual motion at the microscopic level by using x-rays to note the changes in crystal structure of Au-Cd. As a result of Chang and Read, other such alloys were discovered including indium-titanium. In 1963, W.J. Buehler and co-workers at the US Naval Ordinance Laboratory observed the shape memory effect in a nickel and titanium alloy, today known as nitinol - **N**ickel **T**itanium **N**aval **O**rdinance **L**ab. Other studies followed and researchers found the shape memory effect in other alloys, including copper-tin, iron-platinum, and nickel-aluminum. However, nickel titanium and copper-zinc-aluminum are the materials of choice because of their low cost, strength, large-shape changing abilities, and ease of fabrication.

Shape memory alloy are a class of materials also referred to as smart materials. These alloys can be deformed when cold but are able to return to the pre-deformed shape when heated to a specific temperature. These alloys possess the ability to change crystal structure or phase at a distinct temperature. If the alloy is below the "transition temperature," it can be stretched and transformed without permanent damage. Once it is heated above the transition temperature, the alloy "recovers" and returns to the un-stretched shape. The shape of the SMA can be set and reset many times. There are two phases of nitinol:

- High temperature – austenite with cubic symmetry, hard and rigid
- Low temperature – martensite, less symmetric, more flexible

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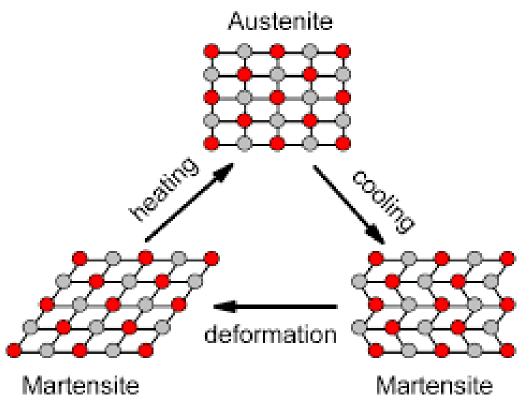

Nitinol structural formations from Wikipedia: https://commons.wikimedia.org/wiki/File:NiTi_structure_transformation.jpg

Why are shape memory alloys considered a part of nanotechnology? These alloys possess the ability to radically change crystal structure or phase at a distinct temperature. The changes that occur with this material is at the atomic level e.g., the nanoscale. When pressure is applied at the lower temperature, the atoms change orientation/position to adjust to the pressure. But when nitinol is heated above its transition temperature, where the phase transformation occurs, then the nitinol returns to its original atomic configuration. This is a solid state phase transition. Varying the amounts of nickel and titanium in the wire will change the transition temperature.

In the past twenty years, SMAs (shape memory alloys) have been incorporated into a variety of products. Coffee makers, eyeglass frames, guide wires for arthroscopic surgery, staples for attaching broken bone fragments, mechanical hands, and a mechanical coupler are just some applications.

Shape Memory Wire – a.k.a. Nitinol or Muscle wires can be used to lift a weight up a height. A lot of energy is wasted as heat. This holds true for muscle wires and motors. This lab allows for students to see that a lot of energy is wasted, as well as introduces them to the idea of a wire that remembers its shape. It also can be used with the concept of phase change and expansion of a wire. Students are taught that when materials heat up, they expand. This lab shows a counter example – the wire shortens upon heating. This is due to a change in phase – a solid state phase transformation. Another counter intuitive example of this is the contraction of water from 0^{o} to 4^{o} Celsius.

Resources:

- Muscle Wires Project Book: (book and sample kit) https://www.jameco.com/shop/ProductDisplay?catalogId=10001&langId=-1&storeId=10001&productId=357659
- Shape Memory Alloys. Wikipedia: https://en.wikipedia.org/wiki/Shape-memory_alloy
- Shape Memory Materials. Explain that Stuff: https://www.explainthatstuff.com/how-shape-memory-works.html
- Smart Materials – Shape Memory Alloys: https://www.nnci.net/node/5320
- Memory Metal: https://education.mrsec.wisc.edu/topic-memory-metal/

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- How Shape Memory Alloys Work: https://depts.washington.edu/matseed/mse_resources/Webpage/Memory%20metals/how_shape_memory_alloys_work.htm

Pre-requisite Knowledge: Familiarity with Pasco Probeware or Vernier LabPro is useful but experiment can be changed to use other modes of measurement. Understanding of a simple circuit.

Materials: (per set up)

- Nitinol wire lever setup (specifications below).
- Nitinol wire (10-15 cm)
- Cardboard
- Dowel (lightweight) or balsa wood
- Voltmeter and Ammeter or a Voltage/Current Probe system (recommended)
- Metric ruler
- 2 AA batteries
- AA battery holder
- Alligator clips
- Crimp, tube or something to hold nitinol to cardboard
- Tack/push pin
- 30 gram mass – washers, nuts, bolts, pennies, dimes etc. in a small plastic bag
- Pasco or Vernier probe ware controller.

Source of nitinol:

- https://www.teachersource.com/category/s?keyword=nitinol
- https://www.amazon.com/s?k=nitinol+wire&ref=nb_sb_noss_1
- https://www.jameco.com/shop/StoreCatalogDrillDownView?langId=-1&storeId=10001&catalogId=10001&search_type=jamecoall&freeText=memory+wire

Advance Preparation: The teacher should have experience with measurement systems such as Pasco Probeware or Vernier LabPro.

You can either make the lab setups or have student groups create them. For the equipment setup, you will need nitinol wire and some sort of backing to hold the wire and lever system in place such as cardboard. Make the lever arm out of lightweight cardboard or a small dowel. You want the lever system to be **very** light.

For this lesson, I used a modified version of the lever setup from *Muscle Wires Project Book* by Robert G. Gilbertson. It describes how to set up a lever system and how to attach the wire. The book (from resource below) also provides wire as part of a kit. However, you may need more wire for an entire class. The book is available at various websites but I used the one listed below in Resources. Not all books come with wire.

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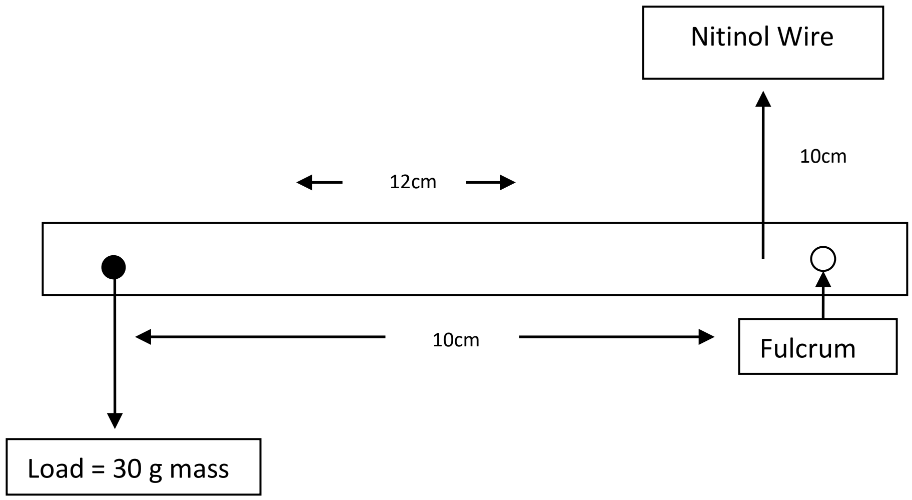
The basic design is to create a type 3 lever so the force the nitinol lifts is reduced on the load, but the distance the load is lifted is increased. This allows for an easier measurement of the height the load is lifted. A ruler placed behind the load being lifted allows for easy measurement of the change in height of the load. The nitinol wire needs to be attached to the cardboard. The Muscle Wires book uses a crimp and staple to hold the wire in place. The nitinol wire is connected a distance from the fulcrum of approximately 1 cm. The load is attached 10 cm from the fulcrum. The lever should be 12 cm long with the fulcrum placed 1 cm from the end of the lever. The load should be a 30 gram mass – use any common objects to obtain the desired weight. Schematic for setup is below:



Connect the power supply to the each end of the nitinol wire with alligator clips. You will want to measure the current in the circuit with an ammeter and the voltage across the wire. Attach the leads of the voltmeter to the ends of the wire. Attach the leads to the alligator clips that are on the ends of the wire, not the wire itself.

Students will measure the time it takes for the load to rise. This can happen quickly, so use a motion detector or video camera and determine the time it is moving. Video analysis is the easiest way to measure this. A frame by frame analysis can be analyzed and the number of frames can be counted to determine the time. A motion detector can also be used. Aim the detector at the load, and measure the time it takes for the system to change from one position to another. You can also use this to measure the change in height.

Safety Information: The wire can become hot, but they are very thin, so should not be unsafe if brushed up against. You can use thicker wires for the nitinol to reducing the fragility and this will lift greater loads. However, the currents required will increase as the wire gets thicker, as more energy is required to heat the wire.

Directions for the Activity: In student guide with answers below.

Assessment: Students should be able to collect the data required in the tables and complete the calculations. In addition, they will correctly answer the questions in the Student Guide.

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Next Generation Science Standards:

- HS-PS2-6.Communicate scientific and technical information about why the molecular-level structure is important in the functioning of designed materials.
- HS-PS2.B.Types of interactions
- HS-PS3.A. Definitions of energy
- HS-ETS1.C. Optimizing the design solution

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Supporting Programs: NNIN RET Program at Georgia Institute of Technology NSF EEC and National Nanotechnology Coordinated Infrastructure NSF ECCS 1626183

Student Guide

(with answers in red)

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Shape Memory Wire – a.k.a. nitinol or muscle wires can be used to lift a weight up a height. How does the work done lifting the load with the nitinol wire compare to the energy pumped into the wire by an electrical current? In this lab, you will calculate the work required to lift the load by measuring the change in potential energy and the energy input into the wire by measuring the voltage across the wire and the current through the wire. The time needed by the device to raise the load is also needed.

Materials: (per set up)

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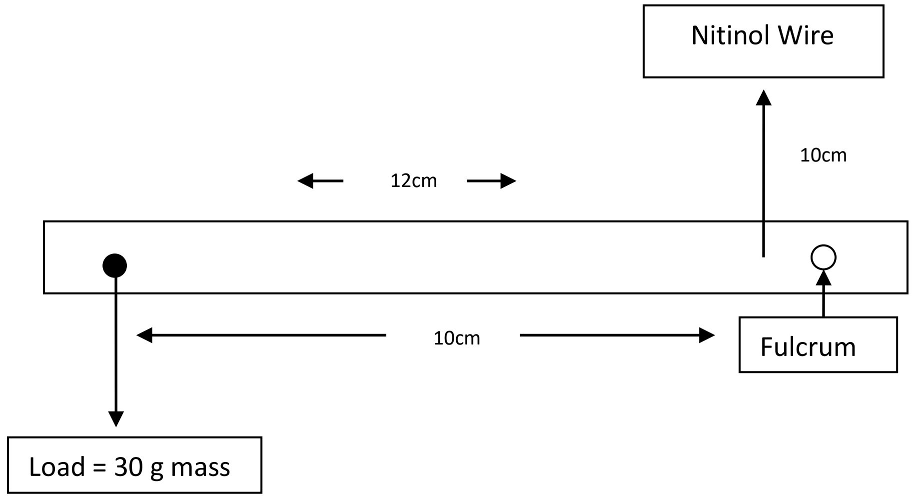
- Pasco or Vernier probe ware controller.

Schematic for set up:



The nitinol wire is connected a distance from the fulcrum of approximately 1 cm. The load is attached 10 cm from the fulcrum. The lever should be 12 cm long with the fulcrum placed 1 cm from the end of the lever. The load should be a 30 gram mass

Procedure:

1. You or your teacher will create the lever system to measure the time it takes for the nitinol wire to lift the load.
2. Once the lever system is constructed, connect the power supply to the each end of the nitinol wire with alligator clips.
3. Attach the leads of the voltmeter to the ends of the wire. Attach the leads to the alligator clips that are on the ends of the wire, not the wire itself.
4. You will want to measure the current in the circuit with an ammeter and the voltage across the wire.
5. Measure the time it takes for the load to rise. This can happen quickly, so use a motion detector or video camera and determine the time it is moving. Aim the detector at the load, and measure the time it takes for the system to change from one position to another. Use a ruler or the detector to measure the change in height.
6. Determine the time it takes for the load to rise.

Data:

Voltage:	
Current:	
Time:	
Mass of Load:	
Change in height:	

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Input Energy = Power x time = Voltage x Current x time

Input Energy:	

Output energy = Mass x (acceleration due to gravity) x (change in height)

Output Energy:	

Efficiency of the machine = (Output energy / Input energy) x 100%

Efficiency	

Analysis and Conclusion:

Answer the following questions:

1. How does a nitinol wire get shorter when heated? Explain why this is unusual for a metal, and the reasons for this unusual behavior.
   A nitinol wire undergoes a phase change as it is heated. It changes from one solid phase to another solid phase. The arrangement of the atoms is different in each phase. The phase at the higher temperature (Austenite) takes less space the lower temperature phase (Martensite). Most metals do not undergo a phase change when heated. They simply expand.

2. How efficient is the lifting process? How do you think this will compare to the efficiency of an electric motor?
   The students should find the efficiencies are fairly low. Much of the energy is wasted as heat.

3. How is the nitinol wire like a muscle? Can you make the wire stronger? Compare your method to how muscles are made stronger.
   As the wire becomes thicker, the strength of the wire increases. You can make braided nitinol wire or just thicker wire. Each will be stronger than a thinner wire. Muscle fibers are built up to strengthen a muscle. The similarity exists that each pull by contracting their length.

4. Where could nitinol wire be used that an electric motor could not be used? Remember that is heat, not the electricity that makes the wire expand.
   Look in the Muscle Wire project book for lots of examples or Google applications of Nitinol. Small spaces sometimes limit the use of a motor. Orthodontists use this type of wire in braces, tightening the wires by heating from the body temperature of the patient to make the braces tighter.

5. How is nitinol related to nanotechnology?
   The rapid phase change occurs at the atomic level or the nanoscale.

6. How would you improve on the design? Answers will vary.

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