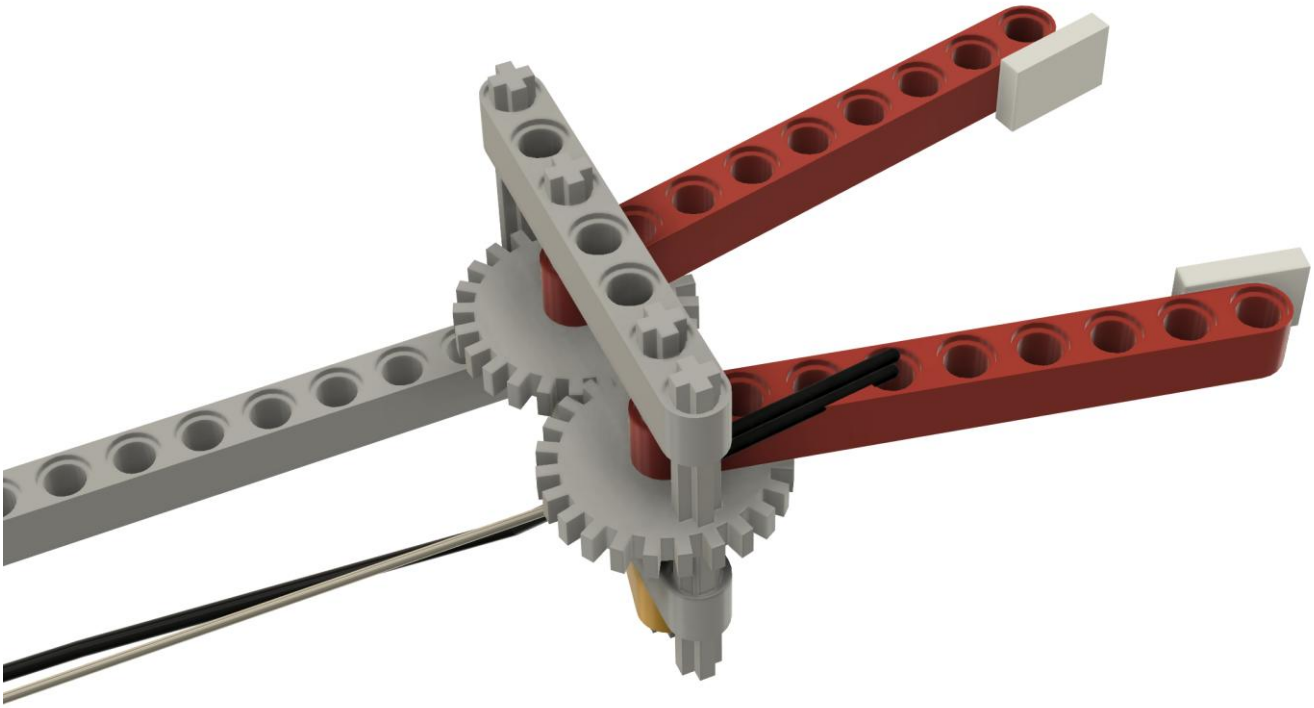
KELLOGG'S RESEARCH LABS

NITINOL

ROBOTICS LAB BOOK

14 hands-on labs with nitinol wire and LEGO® Technic™-compatible parts

For high school physics, engineering and robotics classes



www.KelloggsResearchLabs.com · nitinol@kelloggsresearchlabs.com · 1-855-583-5353

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Welcome

Nitinol is a nickel-titanium alloy that can remember a shape. Bend it cool, warm it up, and it springs back. Run a small electric current through a nitinol wire and it pulls like a muscle, with no motor, no gears and no noise.

This book turns that metal into fourteen classroom labs. Students start by watching a bent wire straighten itself in hot water. They finish by programming a walking robot and a three-wire continuum arm. Along the way they measure stress, strain, resistance, power, energy and heat flow with real data from a real engineering material.

Every robot in this book is built from LEGO® Technic™-compatible beams, pins, axles and gears, plus a few 3D-printed parts. The nitinol, crimps and data cards come in the KRL Educator Kit.

Who this book is for

- High school physics, physical science, engineering and robotics classes (grades 9–12)
- Teachers with no prior nitinol experience
- Students who have used a ruler, a multimeter and a stopwatch

How the book is organized

Part	What students do
Part 1: The Material	Labs 1–3. See shape memory and superelasticity. Find the transformation temperature.
Part 2: Making It Move	Labs 4–8. Heat the wire with electricity. Measure stroke, force, leverage and cooling speed.
Part 3: Robots	Labs 9–14. Build a spring actuator, a bending spine, a gripper, a rotary stepper, an Arduino-controlled walker and a multi-degree-of-freedom continuum arm.
Capstone	An open design challenge with a scoring rubric.
Teacher Pages	Safety, kit contents, Technic parts lists, 3D-printed parts, standards, expected results and answer keys.

Labs 1–3 need no electricity. Labs 4–14 build on each other, so run them in order where possible. Each lab fits one or two 50-minute periods.

What every lab includes

- **Big idea:** one sentence on what the lab shows
- **Materials:** what each team needs
- **Safety:** messages for hazards specific to that lab
- **Background:** just enough theory to make sense of the data
- **Procedure:** numbered steps
- **Data and analysis:** tables to fill in, graphs to draw and questions to answer
- **Go further:** an extension for fast teams

Student pages contain no answers, so they can be photocopied. Expected results and answer keys are in the Teacher Pages at the back.

> LEGO® and Technic™ are trademarks of the LEGO Group, which does not sponsor, authorize or endorse this book. Any Technic-compatible beams, pins, axles and gears will work.

Safety First

Safety messages in this book follow ANSI Z535.6, the US standard for safety information in product manuals. Read this page with the class before Lab 1.

⚠ DANGER	Will cause death or serious injury. No hazard in this book reaches this level.
⚠ WARNING	Could cause death or serious injury.
⚠ CAUTION	Could cause minor or moderate injury.
NOTICE	Could damage equipment or materials, but not people.

⚠ WARNING	**Burn hazard: hot wire and hot water.** A powered nitinol wire passes 100 °C in seconds, and some labs use water up to 90 °C. Either can burn skin. Do not touch a wire while it is powered or for 30 seconds after. Handle hot water, and anything in it, with tongs. Keep hot water at the teacher's station.

⚠ WARNING	**Eye hazard: nitinol is powerful.** Pound for pound, nitinol is one of the strongest actuator materials made. A wire as thin as pencil lead lifts more than 3 kg, and industrial nitinol actuators produce tons of force. A loaded wire that is not properly constrained can snap or slip from its crimp and whip into an eye. Wear safety glasses whenever a wire is loaded, powered or being cut.

NOTICE	**Melting plastic.** LEGO beams soften near 90–100 °C and PLA prints near 60 °C. Keep hot wire off plastic. Wherever wire, crimps or screws meet LEGO parts, isolate them with silicone or nitrile washers: they are cheap and handle far more heat than LEGO. Print parts that touch the wire in PETG or ASA.

Meet Nitinol

Nitinol was discovered at the US Naval Ordnance Laboratory in the early 1960s. The name comes from **Ni**ckel **Ti**tanium **N**aval **O**rdnance **L**aboratory. It is roughly half nickel and half titanium, atom for atom.

Today nitinol opens valves, controls air valves in car seats, holds arteries open, straightens teeth, keeps eyeglass frames from bending, and moves robot fingers. In every case it does one of two tricks: **shape memory** or **superelasticity**.

Two crystal structures

Nitinol can arrange its atoms two ways. The arrangement it takes depends on temperature and stress.

- **Austenite** is the hot, strong, orderly structure. It holds the shape the metal "remembers."
- **Martensite** is the cool, soft structure. Its atoms sit in a zigzag pattern that can shift sideways, letting the metal bend without breaking any bonds.

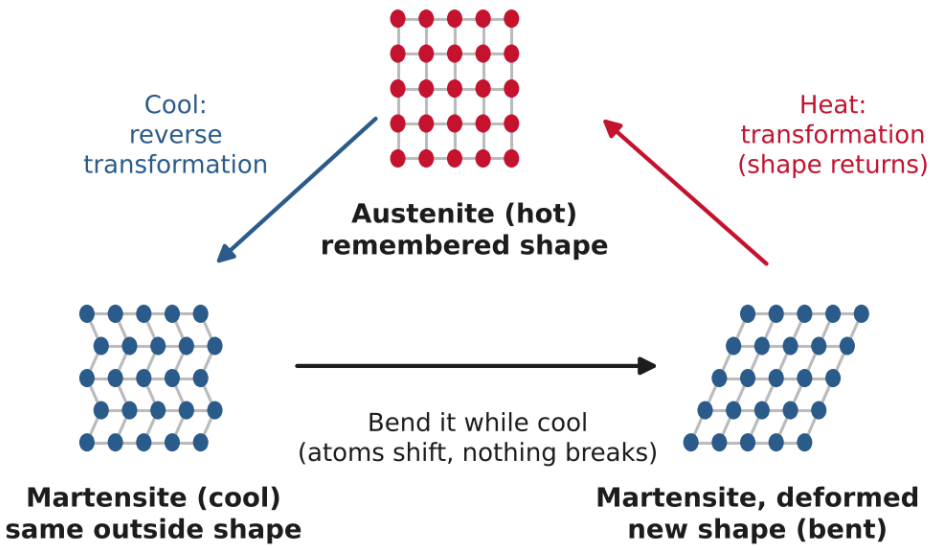


Figure 1. The shape memory cycle. Bending cool martensite only shifts the zigzag. Heating converts it back to austenite, and the remembered shape returns.

Transformation and reverse transformation

In this book, **transformation** means the change from martensite to austenite on heating. That is the moment the wire moves and does work. **Reverse transformation** means the change back to martensite on cooling, which resets the wire for the next cycle.

The two changes happen at different temperatures. A wire that transforms near 70 °C on heating may not reverse until it cools to 40–50 °C. That gap is called **hysteresis**, and Lab 3 measures it.

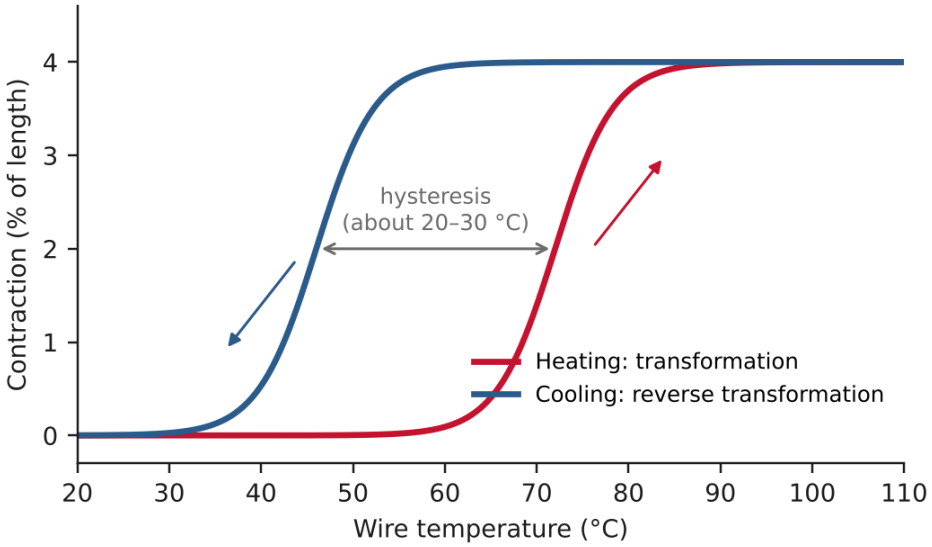


Figure 2. Heating and cooling follow different paths. The gap between them is hysteresis.

Superelasticity

Some nitinol is made so that austenite is stable at room temperature. Bend it, and the stress itself turns austenite into martensite. Let go, and it turns straight back. This wire can stretch 6–8% and still return to its original shape. Ordinary steel takes a permanent bend at about 1%. Lab 2 shows the difference.

Numbers to know for 0.5 mm wire

Every lab uses 0.5 mm wire unless it says otherwise. These typical values are a starting point. Use the data card that ships with your kit when its numbers differ.

Property	Typical value, 0.5 mm wire
Cross-sectional area	0.196 mm²
Resistance	About 4 Ω per meter (0.4 Ω per 10 cm)
Mass	About 1.3 g per meter
Usable contraction	3–5% of length (plan on 4%)
Recommended pull, long life	Up to about 33 N (about 3.4 kg), which is 170 MPa
Heating current	2 A to start, 3 A maximum, in pulses of 5 seconds or less
Time to contract at 2 A	About 2–5 seconds
Time to relax in still air	About 5–15 seconds
Transformation finishes (actuator wire)	About 70 °C (see your data card)

> **Rule of thumb for D cells:** use about one D cell per 10 cm of 0.5 mm wire. Two cells (3 V) on 20 cm of wire gives roughly 2–2.5 A. Always check with an ammeter.

PART 1

The Material

Labs 1–3 need no electricity. Students see shape memory and superelasticity with their own hands, then find the temperature where the change happens.

LAB

1

Meet Nitinol

Big idea: *A bent nitinol wire returns to its original shape when heated.*

Time: One period

You will

- Watch a metal remember its shape
- Find out roughly how hot the wire must get
- Compare nitinol with an ordinary metal wire

Materials (per team)

- Two 10 cm pieces of 0.5 mm nitinol actuator wire (kit)
- One 10 cm piece of 24 AWG bare copper wire (0.51 mm)
- Pencil or 3D-printed mandrel (6–10 mm diameter)
- Three cups of water: room temperature, about 45 °C, and 85–90 °C (teacher supplied)
- Tongs or needle-nose pliers, thermometer, paper towels
- Optional shape-setting step: Bunsen burner, steel rod or 6 mm bolt, pliers, cup of cold water
- Safety glasses

⚠ WARNING	**Burn hazard.** Water at 85–90 °C scalds. Handle the wires only with tongs, and keep hot cups on a tray at the center of the table.

Background

The kit wire was "shape set" straight at the factory by holding it straight at about 500 °C. Straight is now its remembered shape. At room temperature the wire is martensite, so you can bend it easily. Heat it past its transformation temperature and it returns to austenite, and straight.

Procedure

1. Put on safety glasses. Look at and feel both wires. Write down how they look and bend.
2. Wrap one nitinol wire once around the pencil to make a loop. Do the same with the copper wire.
3. Using tongs, dip both looped wires into the room-temperature water for 10 seconds. Record what happens.
4. Move both wires to the 45 °C water for 10 seconds. Record.
5. Move both wires to the 85–90 °C water for 10 seconds. Record.
6. Take the second nitinol wire and bend it into the first letter of your name. Dip it in the hot water. Record.
7. Once it cools, bend that wire into a new letter and repeat. Try it at least five times.

Optional: Set your own shape

Nitinol makers set a wire's memory by holding it in shape at about 500 °C. You can do the same with a Bunsen burner.

⚠ WARNING	**Burn hazard: open flame and red-hot metal.** The flame and the glowing rod can cause serious burns. Do this step only with the teacher present. Hold the rod with pliers, tie back long hair and keep the quench water beside the burner.

1. Wrap a fresh 10 cm nitinol wire tightly around a steel rod, such as a 6 mm bolt or a large nail. Twist the ends around the rod so the wire cannot spring loose.

2. Dim the room lights. Holding the rod with pliers, put the wrapped section in the flame.
3. The moment the wire just barely glows red, pull it out and quench it in cold water.
4. Unwrap the wire, straighten it, and dip it in the 85–90 °C water. Record the shape it returns to.

> Hotter is not better. A wire heated past a dull red glow loses much of its shape memory.

Q1 What shape does your wire remember now? How could you use this to make a nitinol part of your own design?

Data

Wire	Room temp water	45 °C water	85–90 °C water
Nitinol loop			
Copper loop			

Q2 How many times did the letter-shaped wire return to straight? Did it get worse with use?

Analysis

Q3 Which water temperature made the nitinol move? What does that tell you about its transformation temperature?

Q4 The copper wire stayed bent. Using the idea of atoms sliding or shifting, explain the difference between copper and nitinol.

Q5 Your body is about 37 °C. Would this wire work as a self-opening heart stent? What would you change?

Go further

Hold a bent nitinol wire in your closed hand for one minute. Then try a hair dryer on high from 5 cm away. Which works, and why?

LAB

2

Superelasticity

Big idea: *Superelastic nitinol bends many times farther than steel and still springs back straight.*

Time: One period

You will

- Bend three wires by measured amounts
- Calculate bending strain
- Find the strain where each wire takes a permanent bend

Materials (per team)

- 15 cm of 0.5 mm superelastic nitinol wire (kit)
- 15 cm of 0.5 mm steel music wire (hobby store)
- 15 cm of 24 AWG bare copper wire (0.51 mm)
- 3D-printed mandrel set: 25, 15, 10, 8 and 6 mm diameters (see Teacher Pages)
- Protractor template (below), safety glasses

Background

When a wire bends around a round form, its outside surface stretches. The **strain** is how much it stretches, as a fraction of its length:

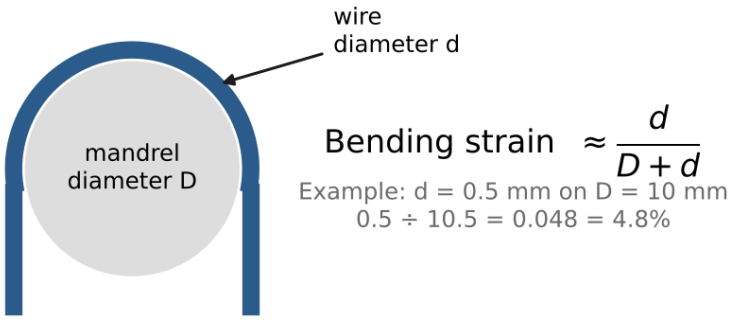


Figure 3. Smaller mandrels bend the wire harder.

Most metals stretch elastically only a fraction of a percent. Past that, atoms slide permanently and the wire stays bent. Superelastic nitinol turns into martensite as it bends, then back into austenite when released. It can return straight from 6–8% strain.

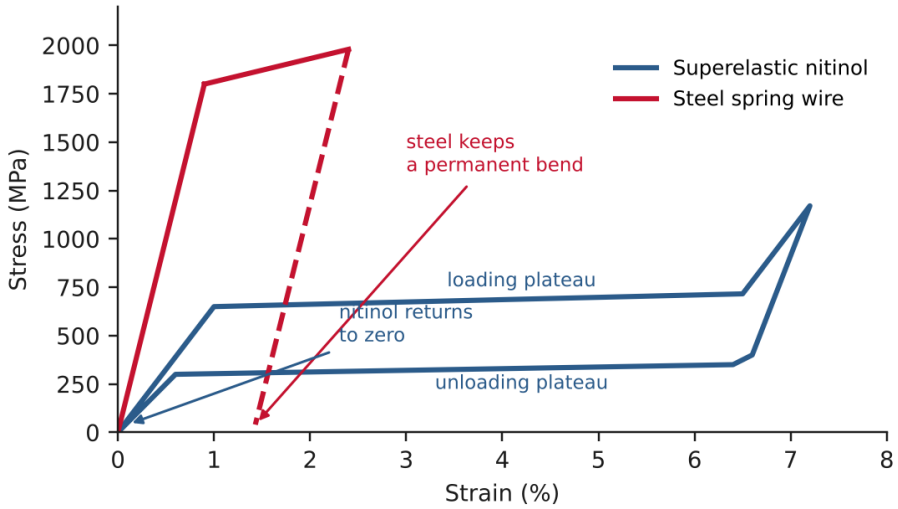
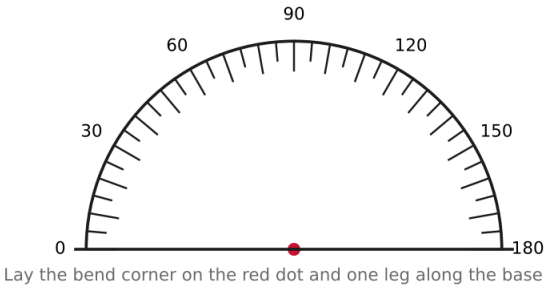


Figure 4. Superelastic nitinol unloads along a lower plateau and returns to zero. Steel keeps a permanent set.

Procedure

1. Calculate the strain for each mandrel and fill in the second column of the table.
2. Start with the largest mandrel. Wrap the nitinol wire halfway around it (180°) and hold for 5 seconds.
3. Release. Lay the wire on the protractor template and measure the angle of any bend that remains. Straight is 0°.
4. Repeat with the steel and copper wires on the same mandrel. Use a fresh section of wire for each mandrel.
5. Move to the next smaller mandrel and repeat.



Protractor template

Data

Mandrel D (mm)	Strain (%)	Nitinol bend left (°)	Steel bend left (°)	Copper bend left (°)
25				
15				
10				
8				
6				

Analysis

Q1 At what strain did each wire first keep a permanent bend? Rank the three wires.

Q2 Eyeglass frames, orthodontic arch wires and cell phone antennas have all used superelastic nitinol. Pick one and explain why superelasticity helps.

Q3 Steel music wire is stronger than nitinol. Why isn't "stronger" the same as "springs back farther"?

Go further

Bend the superelastic wire around the 6 mm mandrel 50 times. Does it still return straight? Now put it in a freezer for 10 minutes and try again. What changed?

LAB

3

Finding the Transformation Temperature

Big idea: *Scientists and nitinol makers measure transformation temperatures with standard test methods. You will run classroom versions of two of them.*

Time: Two periods

You will

- Run a bend and free recovery test, the method of ASTM F2082
- Find As and Af with the tangent method
- Run a constant-force thermal cycle, the method of ASTM E3097, and measure hysteresis width

The language of the standards

ASTM International publishes the test methods used by nitinol producers and medical device makers. Its nitinol terminology standard, ASTM F2005, defines the temperatures you will measure.

Term	Meaning (ASTM F2005)
As	Austenite start temperature: the martensite to austenite transformation begins on heating
Af	Austenite finish temperature: the martensite to austenite transformation is complete on heating
Ms	Martensite start temperature: the austenite to martensite transformation begins on cooling
Mf	Martensite finish temperature: the austenite to martensite transformation is complete on cooling
Active Af	The Af of a finished wire, tube or part, measured after its final heat treatment
Free recovery	Unconstrained motion of a shape memory alloy as it heats and transforms to austenite

In this book, the change at As and Af is the **transformation** and the change at Ms and Mf is the **reverse transformation**.

> When a nitinol data card says "Af = 70 °C," it usually means the active Af measured by bend and free recovery, the test in Part A.

Materials (per team)

- Part A: three 10 cm pieces of 0.5 mm nitinol actuator wire, 20 mm mandrel, 3D-printed recovery fixture (with a built-in angle scale), ice
- Part B: one 25 cm piece of 0.5 mm actuator wire with crimped loops at each end, 1 kg hooked steel mass (a water bottle will not work: under water it weighs almost nothing)
- Tall 2 L beaker or stockpot, hot plate, stirring spoon, thermometer or temperature probe reading to 1 °C or better
- Ruler with millimeter marks, ring stand or test stand, tongs, phone camera
- Safety glasses

⚠ WARNING	**Burn hazard.** A spilled pot of 90 °C water can cause severe burns. Keep the hot plate on the table, never lean over the pot, and let only the teacher move hot containers.

Part A: Bend and free recovery (ASTM F2082)

In the standard test, a specimen is bent around a mandrel while cold, then heated slowly while a sensor records how far it moves back. The plot of motion against temperature shows where recovery starts and where it finishes.

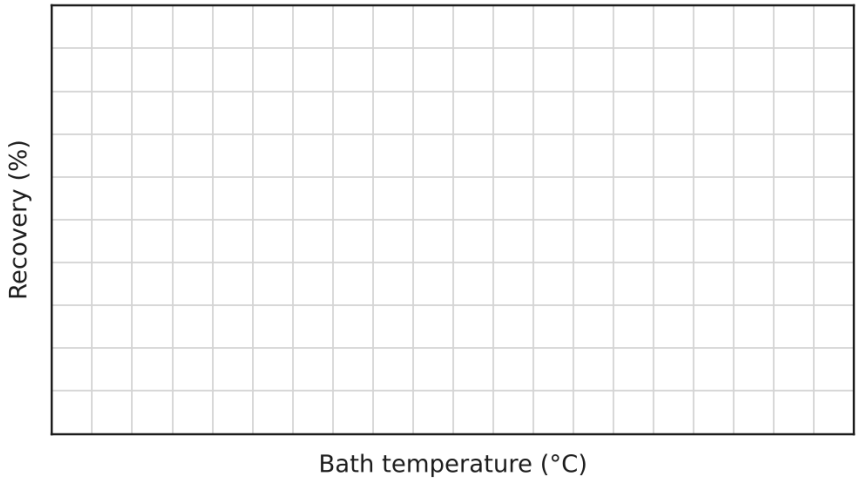
1. Fill the pot with ice water at 10 °C or below. ASTM F2082 requires this for wire that is martensite at room temperature.
2. Pick the mandrel. ASTM F2082 calls for 2 to 2.5% strain on the outside of the bend. Solve the bending strain formula from Lab 2 for the mandrel diameter D:

> **Choosing the mandrel.** Strain = d ÷ (D + d), so D = d ÷ strain − d. For 0.5 mm wire at 2.5% strain (0.025): D = 0.5 ÷ 0.025 − 0.5 = 19.5 mm. At 2% strain (0.020): D = 0.5 ÷ 0.020 − 0.5 = 24.5 mm. Any mandrel from 19.5 to 24.5 mm meets the standard, so use the 20 mm mandrel. Check: 0.5 ÷ (20 + 0.5) = 0.024, or 2.4%.

Under the cold water, wrap one wire 180° around the 20 mm mandrel.

3. Set the bend at the center of the fixture's angle scale. Clamp one leg in the fixture's groove with the M3 screw so the other leg can swing freely over the scale. Leave it in the bath for at least 3 minutes, the standard's equilibration time.
4. Heat the bath slowly, no faster than 4 °C per minute, the standard's limit. The simple way is to film it:
   - Set a phone on a stand above the bath so it sees the free leg, the fixture's angle scale and the thermometer together. Start recording.
   - Turn the hot plate to low. A 2 L bath on low warms about 2–4 °C per minute.
   - Stir gently and read the thermometer once a minute. If it rose more than 4 °C, turn the hot plate down.
   - After the run, play back the video. Pause every 2 °C and record the angle of the free leg.
5. Stop at least 10 °C above the temperature where the leg stops moving.
6. Calculate recovery: Recovery (%) = (180 − angle left) ÷ 180 × 100.

Temp (°C)	Angle left (°)	Temp (°C)	Angle left (°)	Temp (°C)	Angle left (°)	Temp (°C)	Angle left (°)



Graph 3A. Plot recovery against bath temperature.

The tangent method

ASTM F2082 reads transformation temperatures from the recovery curve with straight lines. Draw one line along the flat start, one along the steepest part of the curve and one along the flat finish.

- **As** is where the flat start line meets the steepest line.
- **Af-tan** is where the steepest line meets the flat finish line.
- **Af-95** is the temperature at 95% recovery. The standard accepts either Af.

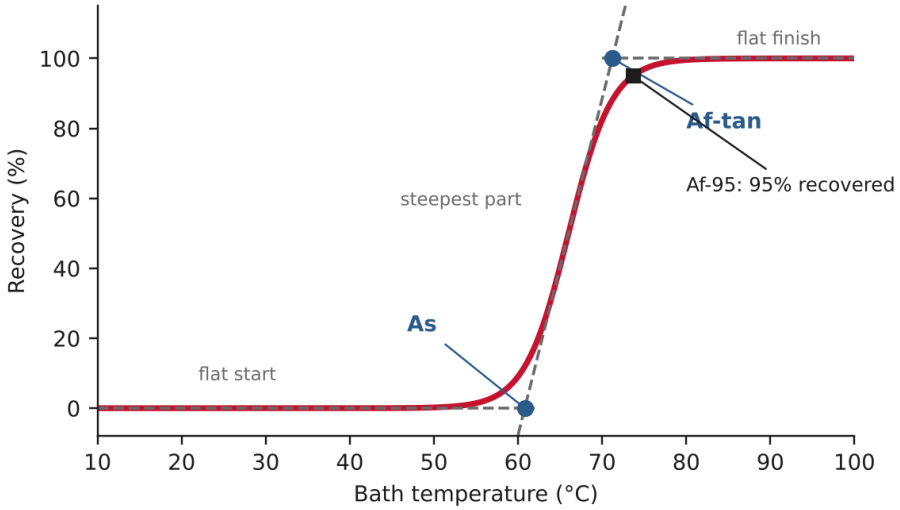


Figure 5. Reading As and Af from a bend and free recovery curve.

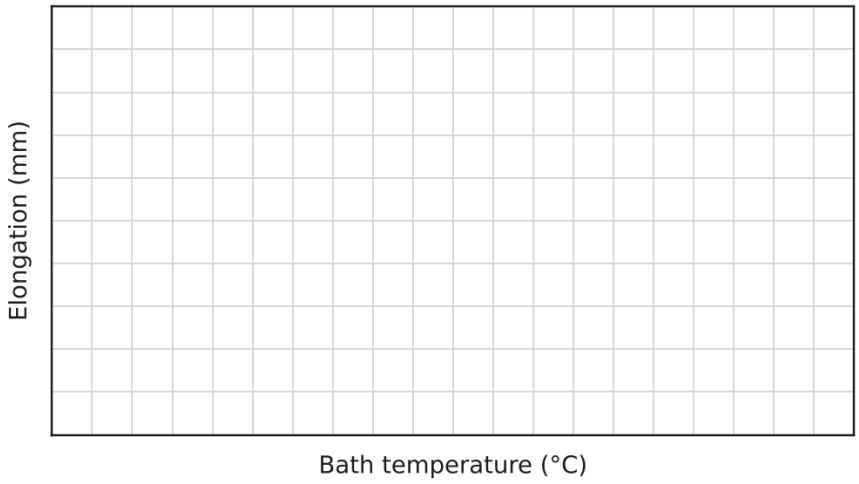
Part B: Constant-force thermal cycling (ASTM E3097)

Actuator engineers use this test. It holds the wire at a constant load while the temperature cycles, just as an actuator works. The standard heats the wire to an upper cycle temperature (UCT) above Af, applies the load, cools to a lower cycle temperature (LCT) below Mf, then heats back to the UCT.

1. Hang the 25 cm wire from the test stand inside the empty pot. The teacher fills the pot with 90 °C water. This is the UCT.
2. Hang the 1 kg mass on the bottom loop. It must not touch the bottom. Mark the mass's position on the ruler as zero.
3. Cool slowly to the LCT, about 15 °C, by adding small amounts of ice and stirring. Every 5 °C, record how far the mass has dropped.

4. Heat back to 90 °C on the hot plate, recording every 5 °C.

Bath (°C)	90	80	75	70	65	60	55	50	45	40	30	15
Cooling (mm)												
Heating (mm)												



Graph 3B. Plot elongation against temperature for cooling and heating, in two colors.

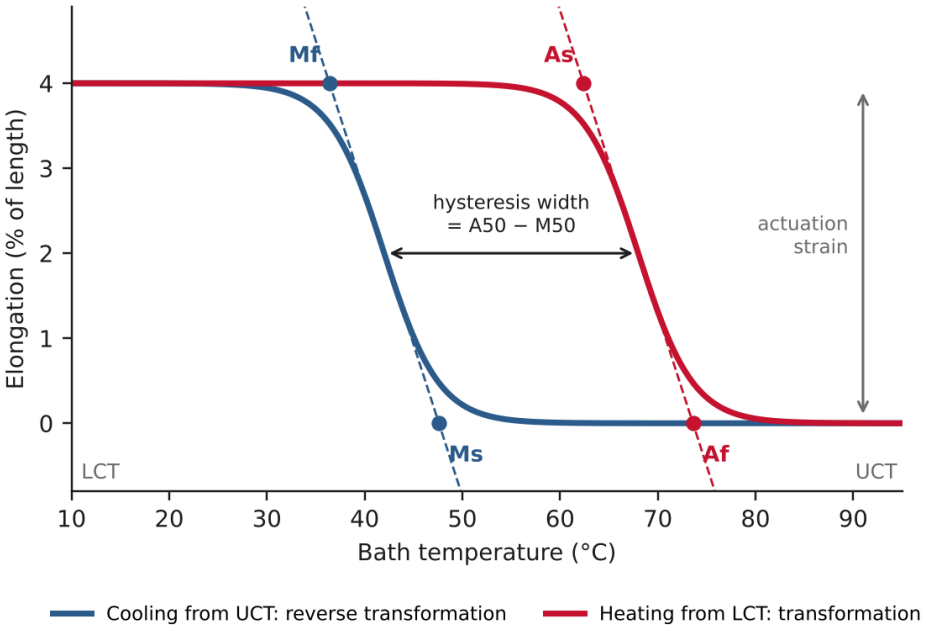


Figure 6. ASTM E3097 terms on a constant-force thermal cycle.

Analysis

Q1 From Graph 3A, use the tangent method to find As and Af-tan. Then find Af-95. How far apart are the two Af values?

Q2 From Graph 3B, use tangent lines to find Ms and Mf on the cooling curve and As and Af on the heating curve.

Q3 Calculate A50 = (As + Af) ÷ 2 and M50 = (Ms + Mf) ÷ 2. The hysteresis width is A50 − M50. What is it for your wire?

Q4 Actuation strain is the total elongation divided by the wire length. Calculate it as a percent.

Q5 Compare Af from Part A (almost no load) with Af from Part B (50 MPa). Which is higher? Stress stabilizes martensite, so a loaded wire must get hotter before it transforms.

Q6 An engineer wants a nitinol vent that opens at 70 °C and closes at 65 °C. Using your hysteresis width, is that possible with this wire? Explain.

> The standards use displacement sensors, thermocouples and controlled heating. Your protractor, ruler and thermometer are slower and less precise, but the method, the terms and the tangent construction are the same.

Go further

Repeat Part B with a 2 kg mass (100 MPa). Measure how far As, Af, Ms and Mf shift. Engineers call this the stress rate of the transformation, in °C per MPa.

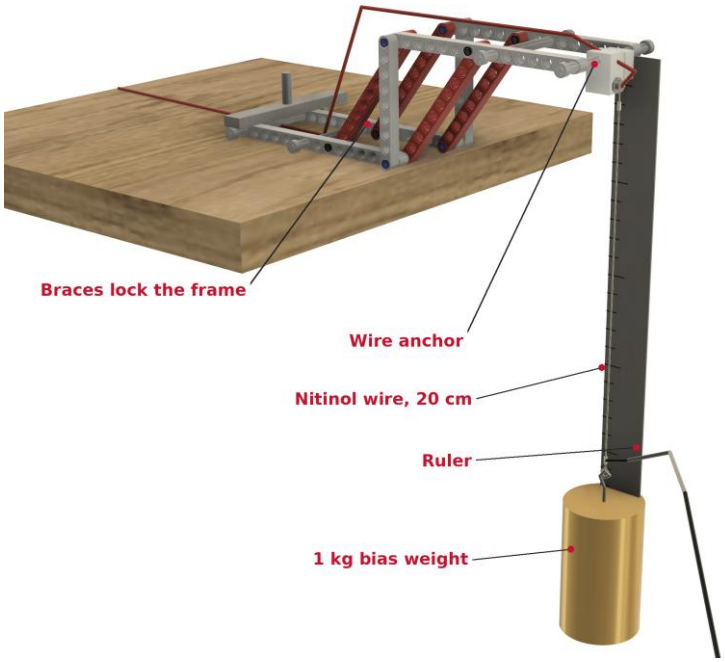
PART 2

Making It Move

Labs 4–8 heat the wire with electricity. Students measure the current, stroke, force, leverage and cooling time that every nitinol actuator designer works with.

Build: The Nitinol Test Stand

Labs 4, 5, 6 and 8 use the same test stand. Build one per team before Lab 4 and keep it for the rest of the book.



Parts

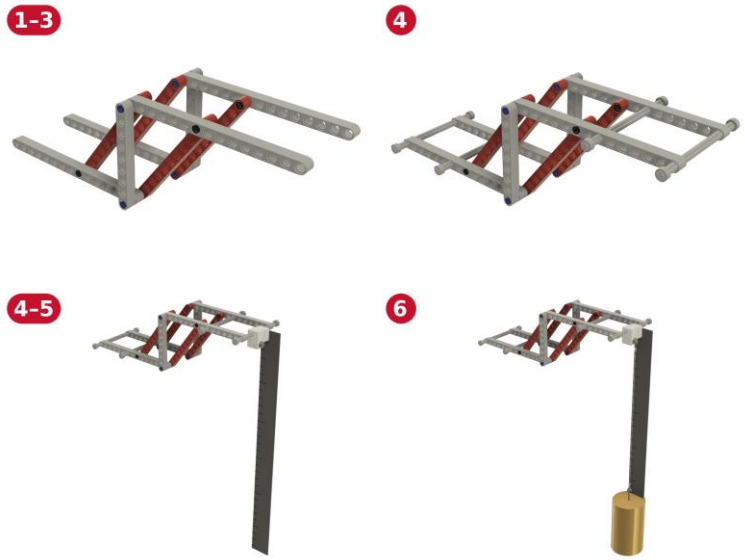
Part	Qty
Technic beam, 15 holes (base and arm)	4
Technic beam, 9 holes (upright)	2
Technic beam, 11 holes (brace)	4
Technic 3-long pin	4
Technic friction pin	4
Technic axle, 10 studs long	4
Technic bushing	8
3D-printed wire anchor with M3 screw and washer (PETG or ASA)	1
3D-printed ruler clip	1
Silicone or nitrile washers, M3	4
30 cm steel ruler	1
C-clamp	1

Assembly

Count holes from the front end of each beam, starting at 0.

1. Build a side frame. Lay a 15-hole base beam and a 15-hole arm beam side by side, one above the other. Join the upright to hole 0 of each with 3-long pins, the upright on the outside.
2. Add two braces on the inside. One runs from base hole 6 to the top 3-long pin. The other runs from the bottom 3-long pin to arm hole 6. Use friction pins at holes 6. The two triangles lock the frame square.

3. Build a second side frame as a mirror image of the first.
4. Join the sides with four axles through base holes 8 and 14 and arm holes 8 and 14. Before pushing in the arm hole 14 axle, slide the wire anchor and ruler clip onto it between the sides. Add a bushing on each axle end.
5. Clip the ruler on so it hangs beside the wire path, zero at the top.
6. Clamp the base to the table edge so the arm reaches past the edge. The wire and weight hang below the tabletop.



Red numbers match the build steps.

Attaching the wire

1. Slide a crimp sleeve onto the wire, loop the wire end back through it, and leave a loop about 5 mm across.
2. Crimp firmly with the crimp tool. Tug hard to test it.
3. Repeat at the other end so the wire measures the required length between loop ends.
4. Put the top loop over the anchor screw with a ring terminal from one test lead, and a silicone or nitrile washer between the loop and any plastic. Tighten the screw.
5. Hook the bias weight to the bottom loop. Clip the second test lead to the bottom crimp. Leave the lead slack so it doesn't carry any weight.

> Nitinol is hard to solder. Use crimps and screws for every connection.

LAB

4

Electric Heating

Big idea: *Current heats the wire from the inside, and the heating power grows with the square of the current.*

Time: Two periods

You will

- Measure the resistance of a nitinol wire
- Predict and measure the current from a battery pack
- Calculate heating power and energy, and compare them with the heat the wire needs

Materials (per team)

- Test stand with 20 cm of 0.5 mm actuator wire and a 1 kg bias weight
- Battery holder for 2 D cells, 2 fresh alkaline D cells
- Momentary push-button, three test leads with alligator clips
- Digital multimeter with a 10 A current jack, stopwatch or phone camera
- Safety glasses

NOTICE	Release the button the moment the wire stops moving, and never hold it longer than 5 seconds. Longer presses overheat the wire and ruin its memory.

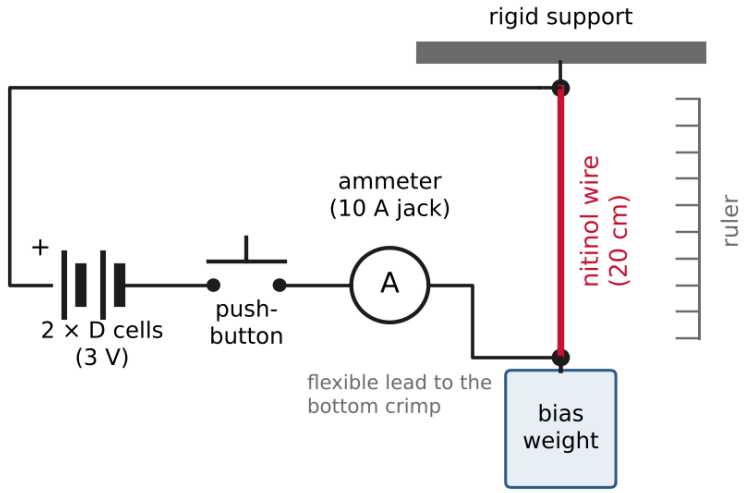


Figure 7. Wire the battery, button, ammeter and nitinol in one loop.

Part A: Resistance

1. Set the meter to its lowest resistance range. Touch the probe tips together and record the reading. This is the lead resistance.
2. Touch the probes to the two crimps. Record the reading. Subtract the lead resistance.
3. Calculate the expected resistance. Nitinol's resistivity is about 0.82 μΩ·m.

Quantity	Value
Lead resistance (Ω)	
Measured wire + leads (Ω)	
Wire resistance (Ω)	
Expected $R = \rho L \div A$ (Ω)	

Part B: Current and contraction

1. Measure the voltage of the battery pack with the meter. Record.
2. Move the red probe to the 10 A jack and set the meter to DC amps. Wire the circuit in Figure 7.
3. Zero the ruler reading at the bottom of the weight.
4. Press the button and start the stopwatch. Release both when the weight stops rising. Record the current, the time and the lift.
5. Wait 30 seconds. Repeat for three trials.
6. Remove one D cell and replace it with a jumper wire. Repeat with one cell (1.5 V). Stop at 10 seconds if the weight hasn't finished rising.

Trial	Cells	Current (A)	Time to lift (s)	Lift (mm)
1	2			
2	2			
3	2			
4	1			
5	1			

Analysis

Q1 Use Ohm's law to predict the current from 2 cells through your wire. Why was the measured current lower? (Hint: the battery has resistance inside it.)

Q2 Calculate the heating power, $P = I^2R$, for 2 cells and for 1 cell. How many times larger is the 2-cell power?

Q3 Calculate the electrical energy delivered, $E = P \times t$, for a 2-cell trial.

Q4 The 20 cm wire has a mass of about 0.25 g. Heating it from 20 °C to 80 °C takes about 7 J, and the transformation itself absorbs about 5 J more. Compare that 12 J with your answer above. Where did the extra energy go?

Q5 If you hold the button down for a full minute, the wire keeps receiving energy but can't shed it as fast. Explain why the 5-second rule exists.

Go further

Try 3 cells on the same 20 cm wire for one quick 1-second press. Measure the time to lift. Is it faster? Why is this risky for the wire?

LAB

5

The 4% Rule

Big idea: *A nitinol wire contracts by about the same fraction of its length, whatever its length.*

Time: One period

You will

- Measure stroke for wires of different lengths
- Find the wire's working strain from a graph
- Discover why every nitinol wire needs a bias force

Materials (per team)

- Test stand, 1 kg bias weight, 3 D cells and holder, push-button, leads, meter
- 0.5 mm actuator wire with crimped loops: one each of 10 cm, 20 cm and 30 cm
- Safety glasses

NOTICE	Match the cells to the wire: 1 cell for 10 cm, 2 cells for 20 cm, 3 cells for 30 cm. Too many cells overheat a short wire in seconds.

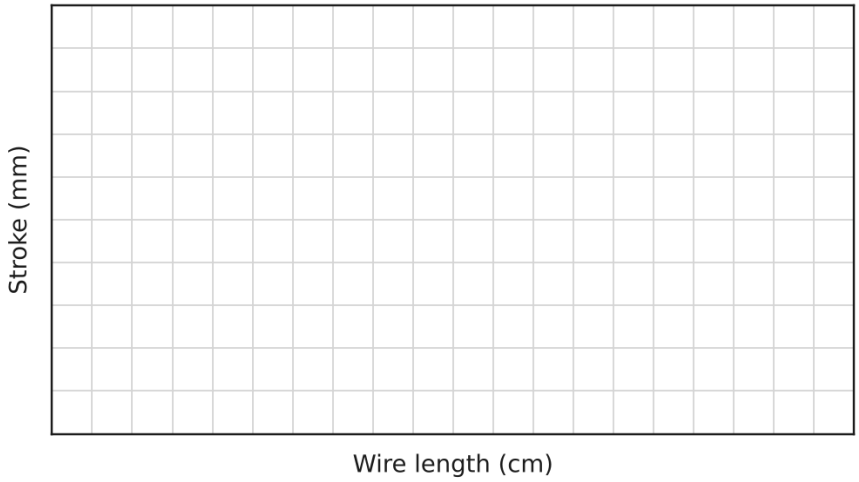
Background

When the wire transforms, every small piece of it shortens by the same fraction. That fraction is the strain. Longer wires give more stroke, but not more force.

Procedure

1. Hang the 10 cm wire with the 1 kg weight. Zero the ruler at the bottom of the weight.
2. Using 1 cell, press the button until the weight stops rising. Record the lift. Release and let the wire cool for 30 seconds. Record whether the weight returned to zero.
3. Repeat for three trials.
4. Repeat steps 1–3 with the 20 cm wire on 2 cells and the 30 cm wire on 3 cells.
5. Remove the weight from the 20 cm wire. Press the button for 3 seconds. Measure the wire length. Let it cool, then measure again.

Length (cm)	Cells	Trial 1 (mm)	Trial 2 (mm)	Trial 3 (mm)	Average (mm)	Strain (%)
10	1					
20	2					
30	3					



Graph 5. Plot average stroke against wire length. Draw the best-fit line through the origin.

Analysis

Q1 What is the slope of your line? Convert it to a percent. This is the working strain of the wire.

Q2 A design needs 12 mm of stroke. How long must the wire be?

Q3 What happened in step 5, when there was no weight? Why does a nitinol actuator need a bias spring or weight to reset?

Q4 Longer wires give more stroke. What do they cost you in speed, power and space?

Go further

Replace the weight with a rubber band stretched from the bottom crimp to the base. Measure the stroke. Does a spring that pulls harder as it stretches change the result?

Extension challenge: how much can one wire lift?

Pound for pound, nitinol is one of the strongest actuator materials made. In graduate school, KRL's founder lifted buckets of sand with a single 0.5 mm wire. How far can your team go?

⚠ CAUTION	**Falling load.** A heavy load that drops can injure feet and break equipment. Hang it from a steel hook or a clamped ring stand, never from the Technic stand, and keep it no more than 2–3 cm above the floor.

1. Fit a fresh 20 cm wire. Crimp each end twice: crimps slip before the wire gives out. This test uses up the wire, so retire it afterward.

2. Hang a small bucket from the wire, just clear of the floor.
3. Add sand 1 kg at a time, weighed on the kitchen scale. After each addition, power the wire with 3 D cells for no more than 3 seconds and record the lift.
4. Stop when the bucket lifts less than 1 mm.

Load (kg)	Force (N)	Stress (MPa)	Lift (mm)	Lifted? (Y/N)
2				
4				
6				
8				
10				
12				
14				

Q5 What was your heaviest lift? Calculate the stress and compare it with the 170 MPa long-life rating.

Q6 Why does the lift shrink as the load grows? Hint: Lab 3 showed that stress raises the transformation temperature.

LAB

6

Force and Stress

Big idea: *The force a nitinol wire can safely pull depends on its cross-sectional area, not its length.*

Time: One period

You will

- Lift loads from 0.25 kg to 2 kg with the same wire
- Calculate stress in megapascals
- Find the load range that gives full stroke

Materials (per team)

- Test stand with 20 cm of 0.5 mm actuator wire, 2 D cells, push-button, leads
- Loads: water bottles filled to 250, 500, 1,000, 1,500 and 2,000 g (1 mL of water ≈ 1 g; weigh the empty bottle too)
- Kitchen scale, safety glasses

⚠ CAUTION	**Falling load.** A load that slips off its hook can injure hands and feet. Keep them out from under the load, and do not exceed 2 kg on 0.5 mm wire.

Background

Stress is force spread over an area:

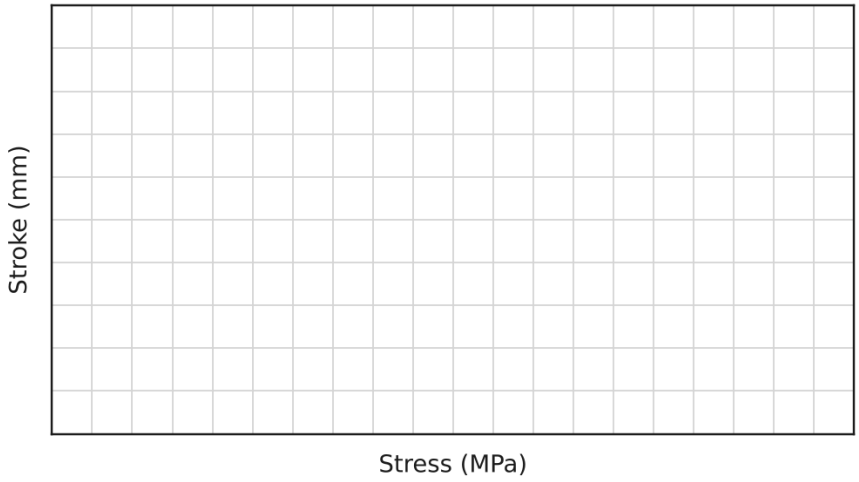
> **Stress (MPa) = Force (N) ÷ Area (mm²).** A 1 kg mass pulls with 9.8 N. On 0.5 mm wire (0.196 mm²) that is 50 MPa.

For long life, nitinol actuator wire is usually run at no more than about 170 MPa. A thicker wire carries more force. Doubling the diameter quadruples the area, and the force.

Procedure

1. Weigh each load on the kitchen scale, including the bottle. Record.
2. Hang the lightest load. Zero the ruler.
3. Press the button until the load stops rising. Record the lift.
4. Release. After 30 seconds, record whether the load returned to zero (the reset).
5. Repeat for every load, light to heavy.

Load (g)	Force (N)	Stress (MPa)	Lift (mm)	Strain (%)	Full reset? (Y/N)
250					
500					
1,000					
1,500					
2,000					



Graph 6. Plot lift against stress.

Analysis

Q1 Which load gave the most stroke? Why did the lightest load give less?

Q2 How much could this wire lift at 170 MPa? Show your work.

Q3 A 0.25 mm wire has one quarter the area. How much could it lift at 170 MPa?

Q4 An engineer needs to lift 10 kg with 8 mm of stroke. Suggest a wire diameter, a number of wires and a length.

Go further

Two 20 cm wires side by side, wired in parallel, share the load. Predict the current each will draw from 2 cells, then test it with 2 kg. What happens to the stroke?

LAB

7

Levers: Trading Force for Stroke

Big idea: *A lever turns the wire's short, strong pull into a long, gentle motion.*

Time: Two periods

You will

- Build a Technic lever tower driven by nitinol
- Measure stroke multiplication at three output points
- Calculate work in and work out

Materials (per team)

- 20 cm of 0.5 mm actuator wire, 2 D cells, push-button, leads, wire anchor, two silicone or nitrile washers
- Technic: 15-hole beams (two for the base, four for the uprights, one yellow for the lever), four 11-hole braces, axles, bushings, 3-long and friction pins
- Small loads: 50, 100, 200 and 300 g (washers in a cup, or a mass set)
- Part B: test stand, two 20 cm and one 40 cm piece of 0.5 mm actuator wire, a 5-hole Technic beam, 1 kg and 2 kg loads, 4 D cells
- Ruler, protractor, safety glasses

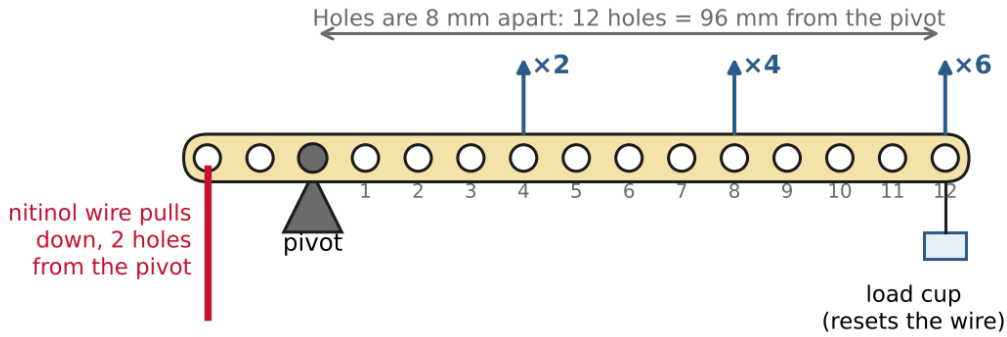
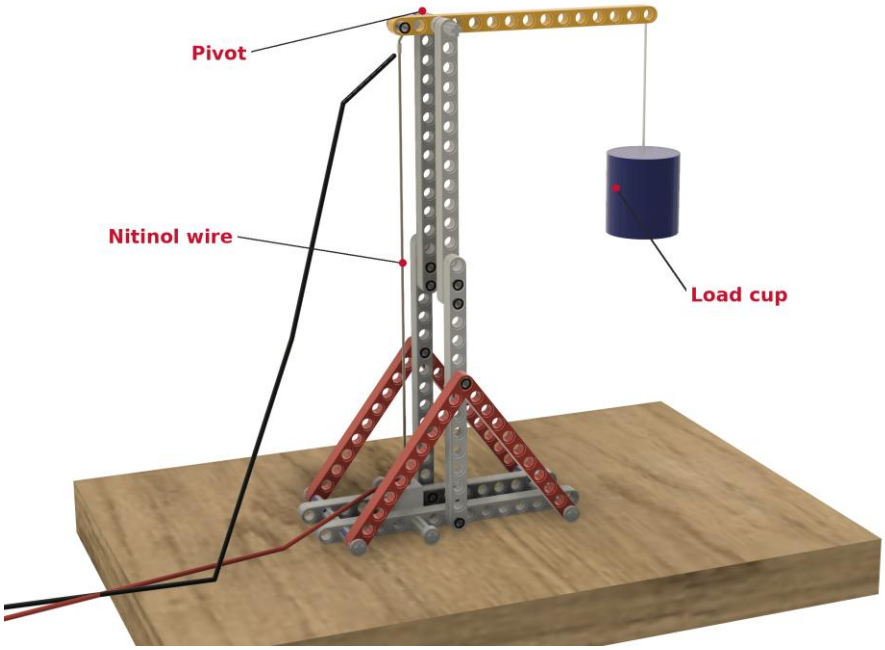


Figure 8. The wire pulls down 2 holes from the pivot. The long side lifts the load. Output motion ÷ input motion = output holes ÷ input holes.

Build



1. Build two towers. Each is a 15-hole base beam with two 15-hole uprights stacked and pinned where they overlap, braced by two red 11-hole beams.
2. Join the towers with axles through the base beams. Put the pivot axle through the top holes of both towers.
3. Slide the yellow lever onto the pivot axle at its hole 2, so 2 holes stick out on the short side and 12 on the long side. Add bushings on both sides of the lever.
4. Fit the wire anchor on the base axle directly under the short end. Crimp the wire to the anchor and to the pin at the lever end, just tight when the lever is level. Put a washer on each side of the crimped loop on the pin so the hot wire never touches the lever.
5. Hang a 100 g load cup 12 holes out on the long side. Its weight stretches the wire back out after each pull.



Red numbers match the build steps.

Part A: Leverage

1. Level the lever. Mark the starting height of the points 2, 4, 8 and 12 holes from the pivot with tape on the ruler.
2. Press the button until motion stops. Record how far each point moved.
3. Repeat with 200 g and 300 g in the cup.

Point	2 holes, wire (mm)	4 holes (mm)	8 holes (mm)	12 holes (mm)
Movement				
Ratio to wire	1			

Load in cup (g)	Lift at 12 holes (mm)	Lifts fully? (Y/N)	Wire force (N)
100			
200			
300			

Part B: Same nitinol, different shape

A lever is one way to trade force for motion. The shape of the nitinol is another. Wires side by side share the load, so together they lift more. A longer wire adds up more 4% shortenings, so it moves farther.

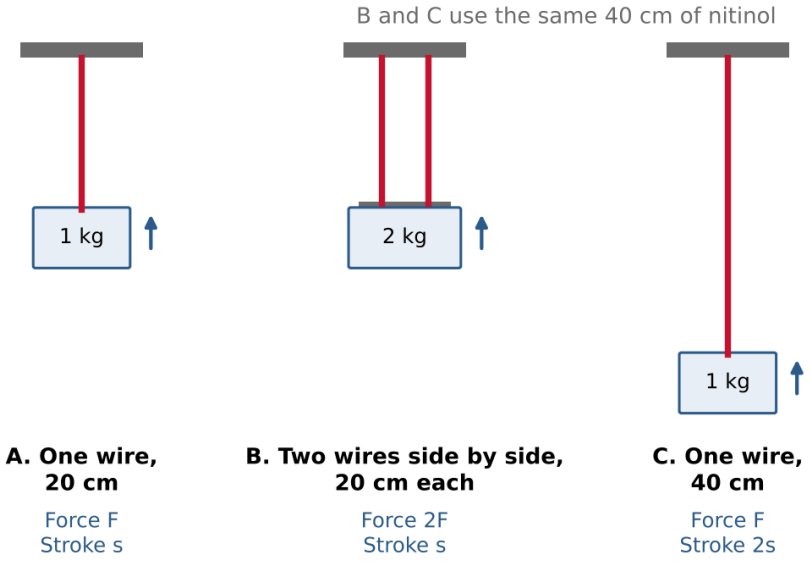


Figure 9. Side by side multiplies force. End to end multiplies stroke.

1. Hang two 20 cm wires side by side from the test stand anchor. Join their bottom loops with a 5-hole Technic beam, a washer on each side of each loop. Hang 2 kg from the middle of the beam.
2. Power both wires together with 2 D cells. Record the lift.
3. Replace them with one 40 cm wire and 1 kg. Power it with 4 D cells. Record the lift.
4. Add your result for one 20 cm wire with 1 kg from Lab 5.

Setup	Nitinol used (cm)	Load (kg)	Lift (mm)	Work = mgd (J)
A. One wire, 20 cm	20	1		
B. Two wires side by side	40	2		
C. One wire, 40 cm	40	1		

Analysis

Q1 How does each movement ratio compare with its hole count divided by 2? Explain any difference.

Q2 Calculate work out for the 300 g load: W = mgd, with d in meters. The wire pulled with about six times that weight. Calculate work in. What is the lever's efficiency?

Q3 Your wire pulls about 20 N. What is the heaviest load the cup could hold and still lift?

Q4 Name three places where nature or machines trade force for distance this way.

Q5 Setups B and C use the same 40 cm of nitinol. Which lifted more? Which moved farther? Compare the work each did.

Q6 A design needs 40 mm of stroke and 5 N of force. Would you use a long wire, a lever or a coil (Lab 9)? Explain.

Go further

Turn the lever into a railroad crossing gate or a flag that rises when a button is pressed. Add a second wire on the long side so the gate is driven both ways, with no load cup.

LAB

8

Cooling and Cycle Speed

Big idea: *Nitinol actuators are fast to heat but slow to cool, and thin wires cool much faster than thick ones.*

Time: One period

You will

- Film the heating and cooling of two wire diameters
- Measure cooling time from video
- Test a rule of thumb that ties cooling time to diameter

Materials (per team)

- Test stand, 2 D cells, push-button, leads, meter
- 20 cm of 0.5 mm actuator wire with a 1 kg load
- 20 cm of 0.25 mm actuator wire with a 250 g load (the same stress: 50 MPa)
- Phone camera with slow-motion or 60 fps video, desk fan
- Safety glasses

Background

The current can pump heat into a wire as fast as you dare. Getting heat out is harder. The wire can only lose heat through its surface into the surrounding air, so cooling usually limits how fast a nitinol actuator can cycle.

A thicker wire stores more heat for each millimeter of surface. Engineers often use this rule of thumb: **doubling the diameter roughly quadruples the cooling time.** You will test it.

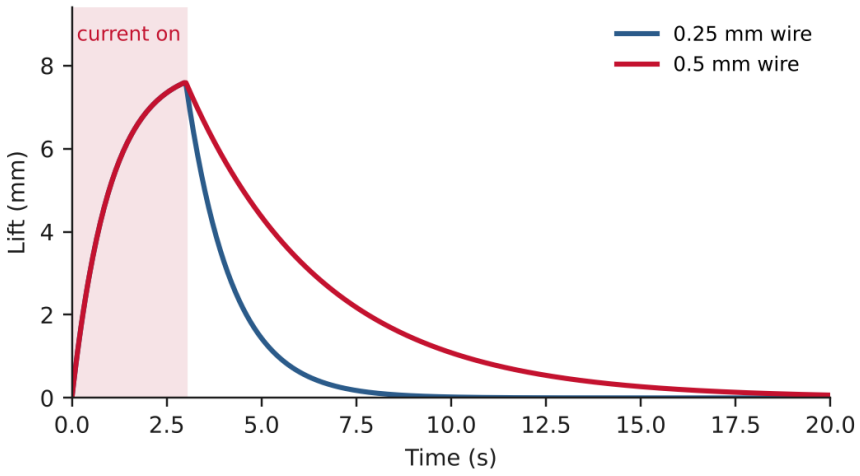


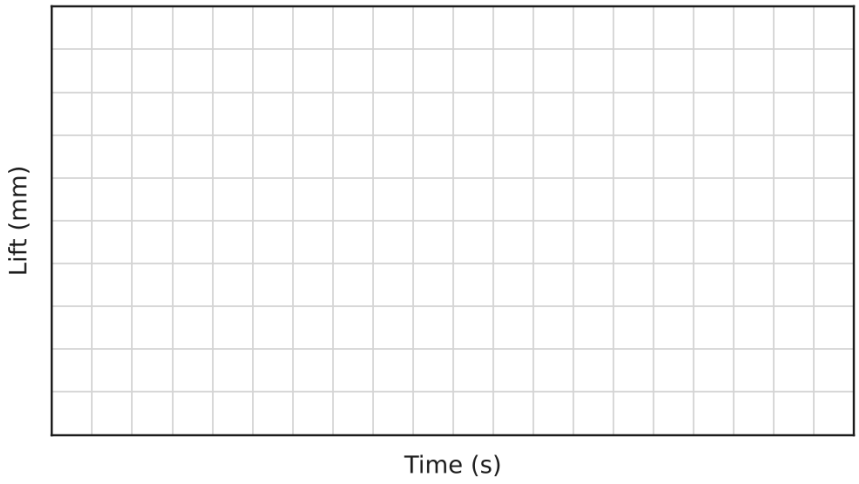
Figure 10. Example lift curves. Heating is quick; cooling sets the cycle time.

Procedure

1. Hang the 0.5 mm wire with 1 kg. Set the phone to film the ruler and the bottom of the load, with a clock or stopwatch in view.
2. Press the button until motion stops, then release. Keep filming for 30 seconds.
3. Repeat for three trials, 30 seconds apart.
4. Replace with the 0.25 mm wire and 250 g load. Repeat steps 1–3.
5. Repeat both wires with a desk fan blowing on the wire from 50 cm away.

6. From the video, find the cooling time: from the release of the button until the load has dropped 90% of the way back.

Wire and air	Trial 1 (s)	Trial 2 (s)	Trial 3 (s)	Average (s)
0.25 mm, still air				
0.5 mm, still air				
0.25 mm, fan				
0.5 mm, fan				



Graph 8. Plot lift against time for one trial of each wire.

Analysis

Q1 Ratio = (0.5 mm cooling time) ÷ (0.25 mm cooling time). The rule of thumb predicts about 4. What did you measure?

Q2 The cooling time scales as diameter to some power, n. Find n = log(ratio) ÷ log(2). How close is it to 2?

Q3 How much did the fan help each wire? Why might it help one more than the other?

Q4 A robot leg must step twice per second. Which wire would you choose, and what else could you do to speed it up?

Go further

Bundle four 0.25 mm wires in parallel to carry the same load as one 0.5 mm wire. Do they cool as fast as a single 0.25 mm wire? What new problem do they bring?

PART 3

Robots

Labs 9–14 put nitinol to work in real mechanisms: a spring actuator, a bending spine, a gripper, a rotary stepper, a walking robot and a three-wire continuum arm.

LAB

9

Spring Actuators

Big idea: *Coiling nitinol into a spring trades force for a much longer stroke.*

Time: One period

You will

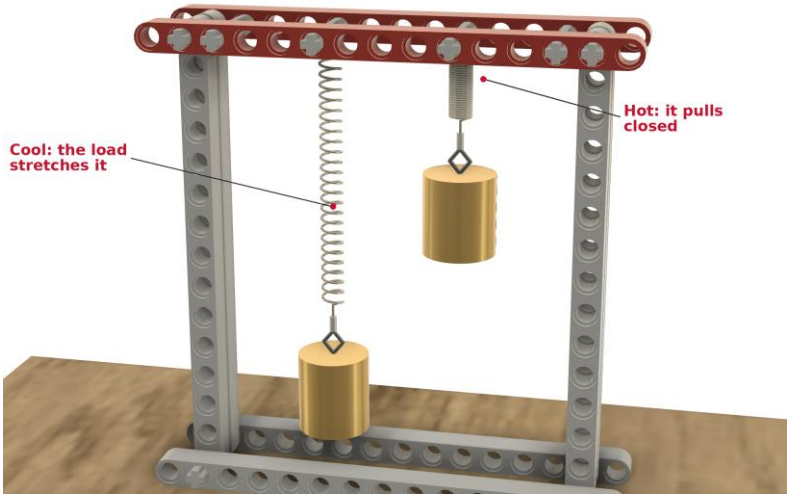
- Compare a nitinol spring with a straight wire
- Measure stroke and force for each
- Calculate work per gram of nitinol

Materials (per team)

- Test stand, push-button, leads, meter, D cells (the number on your kit data card for the spring)
- KRL shape memory spring actuator (kit), with its data card
- 20 cm straight 0.5 mm actuator wire from earlier labs
- Loads: 50, 100, 150 and 200 g, kitchen scale, safety glasses

Background

A straight wire contracts 4% and pulls hard. Coil the same wire into a spring and the spring can shorten by its own length or more, but it pulls far more gently. The spring twists the wire rather than stretching it, and the twist adds up along every coil.



Procedure

1. Weigh the spring. Hang it from the anchor with a 50 g load. Record its length.
2. Power it with the cell count on the data card until motion stops. Record the lift. Let it cool for 60 seconds.
3. Repeat for each load until the spring no longer lifts the load fully.
4. Hang the 20 cm straight wire with 1 kg and record its lift (or use your Lab 5 data). Weigh a 20 cm piece of wire, or use 0.25 g.

Load (g)	Cool length (mm)	Lift (mm)	Lifts fully? (Y/N)
50			
100			
150			
200			

Actuator	Mass (g)	Force (N)	Stroke (mm)	Work (J)	Work per gram (J/g)
Spring					
Straight wire					

Analysis

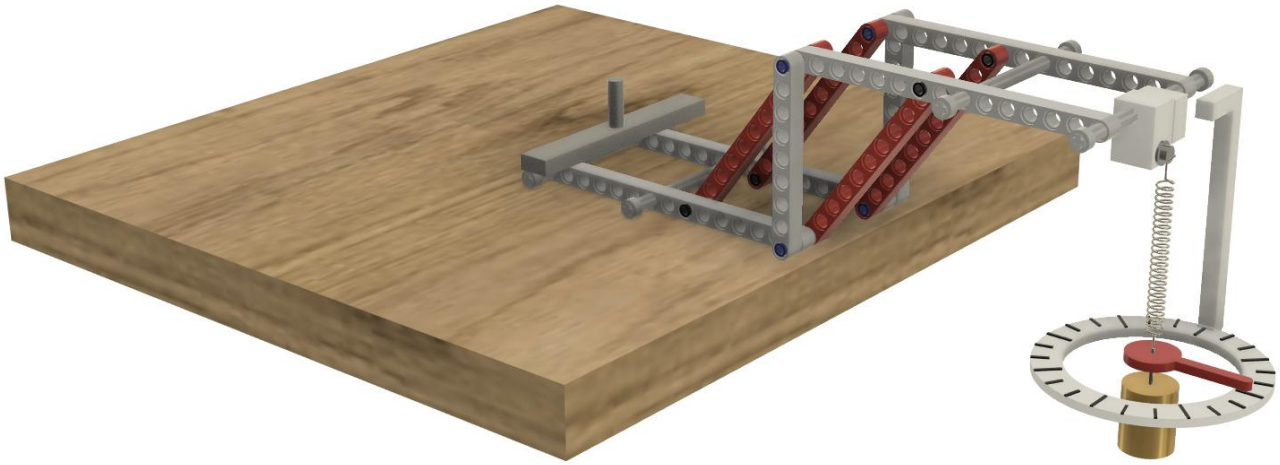
Q1 How many times longer was the spring's stroke? How many times weaker was its pull?

Q2 Which actuator did more work for each gram of nitinol? Why might a designer still choose the other?

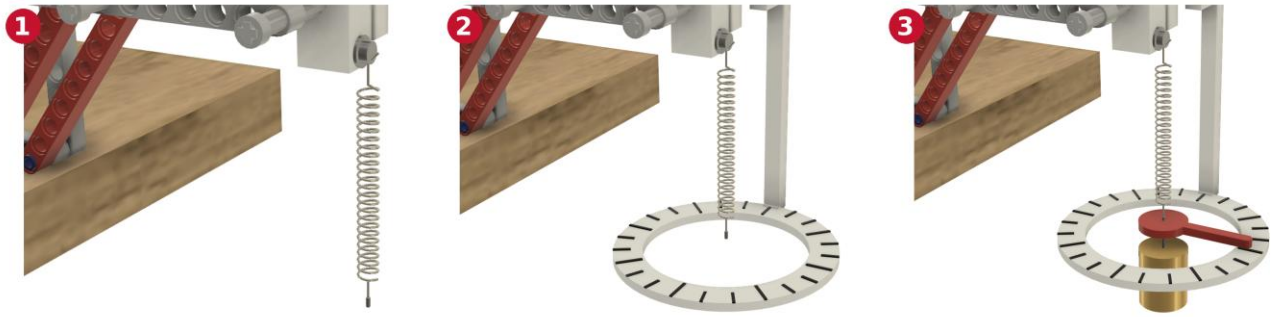
Q3 Give one product that needs a long, gentle stroke and one that needs a short, strong pull.

Extension challenge: two motions from one part

A nitinol coil can lift and turn at the same time. That is rare among actuators. A motor turns and a solenoid pushes, but neither does both: getting two motions from them takes gears, cams or linkages. Nitinol does it with one part and no moving joints. Watch for both motions at once.



1. Hang the spring from the test stand anchor.
2. Slide the printed protractor ring's bracket onto the arm-tip axle so the ring circles the spring's bottom hook.
3. Push the pointer disk onto the bottom hook and hang a 50 g load below it. Record the pointer's starting angle on the ring.



Red numbers match the build steps.

4. Heat the spring. Record the lift and how far the pointer turned, in degrees.
5. Repeat three times. Is the rotation repeatable?

Q4 Sketch a device that uses both the lift and the twist from a single nitinol part, for example a valve that lifts and turns, or a latch that pulls and rotates.

LAB

10

Bending and Curling Actuators

Big idea: *A wire pulling off-center makes a flexible spine curl. The bend angle equals the wire's shortening divided by its offset.*

Time: Two periods

You will

- See a shape-set nitinol strip curl on its own
- Build a bending spine driven by one wire
- Test the bending rule $\theta = \Delta L \div d$

Materials (per team)

- Part A: KRL curl actuator strip (kit), a cup of 85–90 °C water, tongs
- Part B: 3D-printed bending spine (PETG, 160 mm long, guide posts every 20 mm with holes 5, 10 and 15 mm from the spine) and base block
- PTFE tube with 2 mm inside diameter (3D printer Bowden tube), cut into 5 mm liners
- 18 cm of 0.5 mm actuator wire with crimped loops, M3 screw, a silicone or nitrile washer, 2 D cells, push-button, leads
- Technic: two 15-hole beams and two axles for the base
- Protractor template, safety glasses

NOTICE	The wire runs through plastic guide posts. Line every guide hole you use with PTFE tube, which tolerates far more heat than the wire reaches.

Background

Lab 9 coiled the wire for more stroke. Another way is to run the wire beside a flexible spine. When the wire shortens, the spine has to curl toward it, the way a finger curls when the tendon on the palm side pulls.

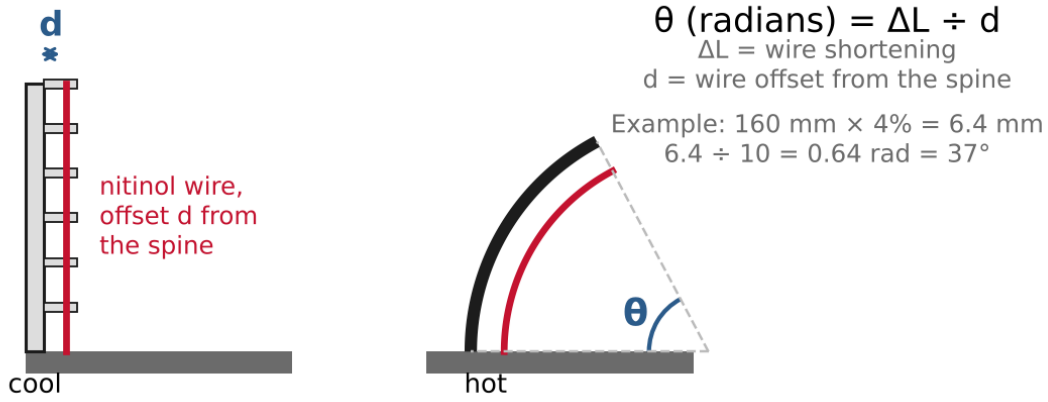


Figure 11. The wire's shortening ΔL and its offset d set the bend angle.

The spine is printed with a built-in curve away from the wire. That curve is the bias spring: it stretches the cool wire back out after every cycle.

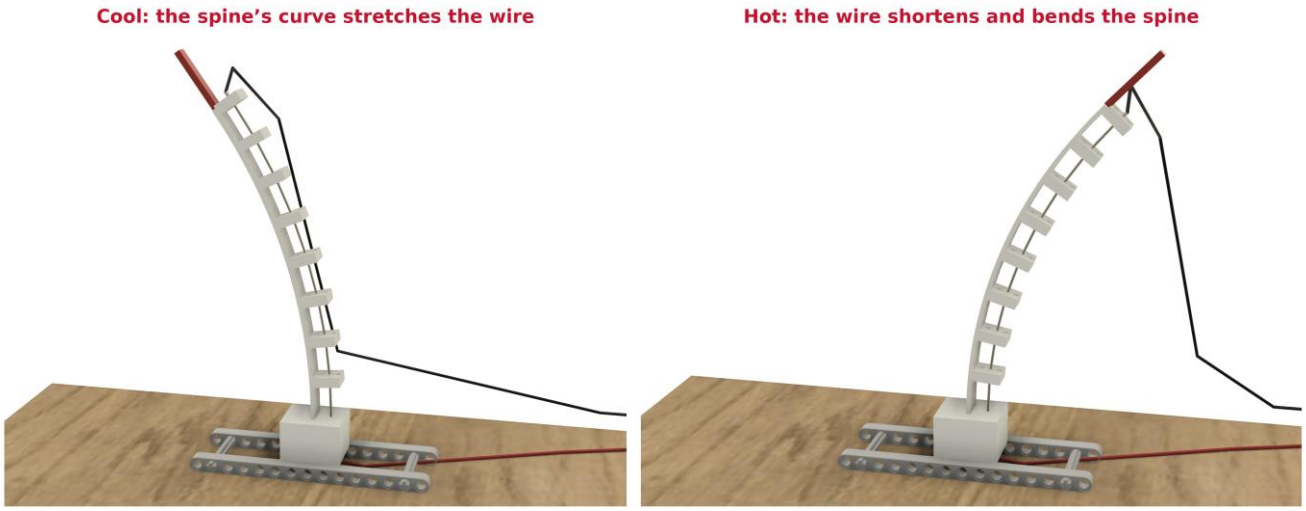
Part A: The curl strip

1. Flatten the curl strip with your fingers at room temperature.
2. With tongs, dip it in the hot water. Record what it does.

3. Flatten it again. Repeat three times and measure the curl diameter each time.

Q1 Does the strip return to the same curl every time? What does it need in order to flatten again?

Part B: Build the bending spine



1. Fix the base block between two 15-hole beams joined by axles.
2. Press the spine into the base block, guide posts on the wire side.
3. Push PTFE liners into the 10 mm guide holes. Thread the wire up through the base block and the liners.
4. Crimp the wire at the tip just tight, with the spine resting in its printed curve. Fix the bottom loop under the base with the M3 screw, a washer between the loop and the base.

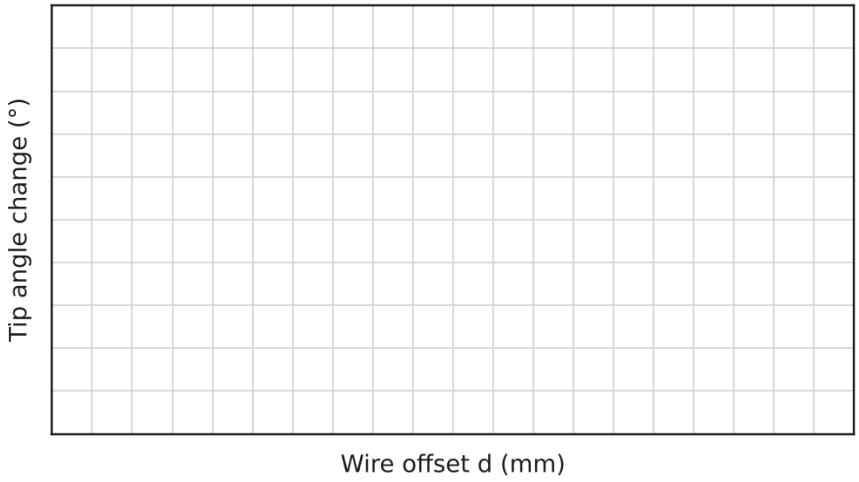


Red numbers match the build steps.

Procedure

1. Stand the protractor template behind the spine. Record the angle of the tip pointer, cool.
2. Press the button until the spine stops moving. Record the hot tip angle. Release and let it cool for 30 seconds.
3. Repeat three times.
4. Move the wire and liners to the 5 mm holes, then the 15 mm holes. Repeat.

Offset d (mm)	Cool angle (°)	Hot angle (°)	Change (°)	Predicted (°)
5				
10				
15				



Graph 10. Plot measured and predicted angle change against offset.

Analysis

Q2 Predict the angle change for each offset. The wire runs 160 mm along the spine and shortens about 4%. Use $\theta = \Delta L \div d$, then multiply radians by 57.3 to get degrees.

Q3 Which offset gave the biggest bend? Which would push hardest at the tip? Explain the trade.

Q4 Your measured bends are probably smaller than predicted, most of all at 5 mm. Where did the stroke go?

Q5 Each post-to-post section bends by about the same amount, so the spine curls into an arc. Engineers call this constant curvature. Why does it make the tip position easy to predict?

Go further

Print a straight spine with guide posts on both sides and run a wire on each side. Each wire now resets the other, and the spine bends both ways. Lab 14 adds a third wire to bend in any direction.

LAB

11

Technic Gripper

Big idea: *A nitinol wire and two meshed gears make a gripper that closes silently on command.*

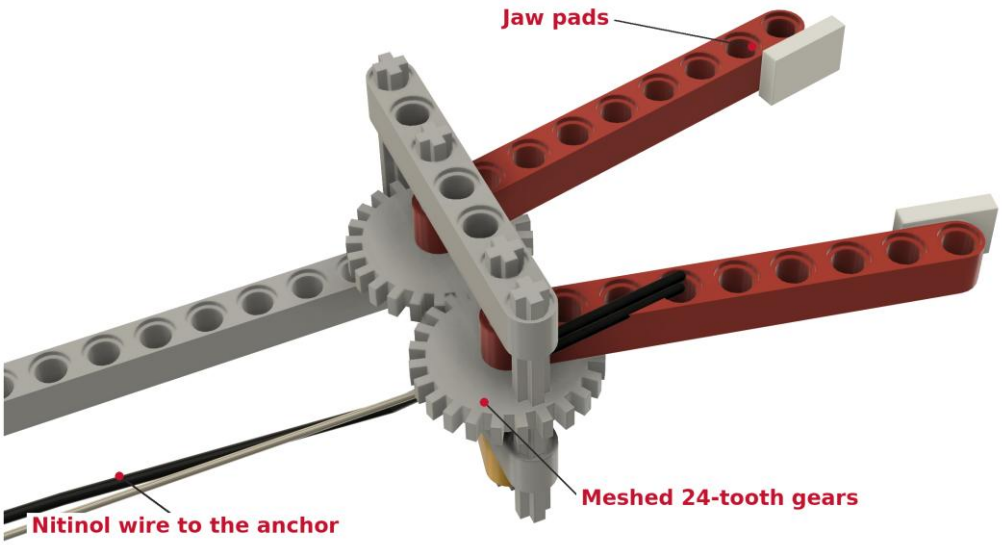
Time: Two periods

You will

- Build a two-jaw Technic gripper driven by nitinol
- Measure jaw travel and grip force
- Test what the gripper can pick up

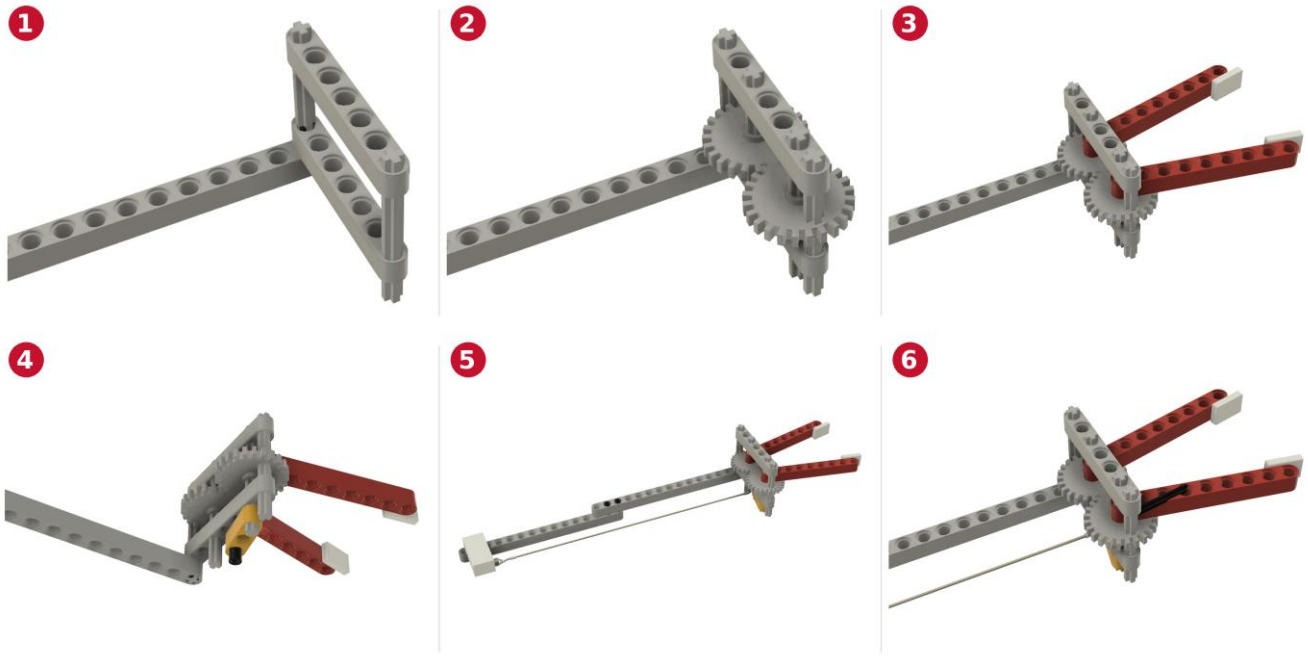
Materials (per team)

- Technic: two 24-tooth gears, two red 9-hole beams (jaws), two 7-hole beams (frame plates), two 15-hole beams (handle), one yellow 3-hole beam (lever), axles, bushings, friction pins
- 20 cm of 0.5 mm actuator wire, wire anchor, two silicone or nitrile washers, rubber band
- 3D-printed jaw pads (TPU or PETG), 2 D cells, push-button, leads
- Spring scale (0–10 N), test objects: foam cube, golf ball, empty can, pencil, safety glasses



Build

1. Make the frame: two 7-hole plates, one above the other, joined by axles through their end holes. Pin the two 15-hole handle beams end to end and fix the handle under the bottom plate.
2. Put axles through the plates 3 holes apart. Slide a 24-tooth gear onto each between the plates so the gears mesh. Meshed gears turn in opposite directions, so the jaws move together.
3. Fix a red jaw beam on top of each gear, on the same axle. Push a jaw pad onto the tip of each jaw.
4. Under the bottom plate, fix the yellow lever on one gear axle, pointing across toward the other gear.
5. Anchor the wire at the far end of the handle and crimp the other end to a pin in lever hole 2, with a washer on each side of the loop. Pulling the wire turns the gears and closes the jaws.
6. Stretch the rubber band from one jaw to the frame so it pulls the jaws open when the wire is cool.



Red numbers match the build steps.

Procedure

1. Measure the gap between jaw tips when open and when closed (powered). Record.
2. Hook the spring scale to one jaw tip. Power the wire and pull the jaw open slowly. Record the force at which the jaw starts to move. That is the grip force at the tip.
3. Try to pick up and hold each test object for 5 seconds. Record success or failure.

Measurement	Trial 1	Trial 2	Trial 3
Open gap (mm)			
Closed gap (mm)			
Tip force (N)			

Object	Held? (Y/N)	Notes
Foam cube		
Golf ball		
Empty can		
Pencil		

Analysis

Q1 The wire pulls about 20 N at 16 mm from the gear center. Calculate the torque. Each jaw tip is about 64 mm from its gear center. Predict the tip force, then compare it with your measurement.

Q2 Where is force lost? Name two places.

Q3 What would you change to grip harder? To open wider?

Go further

Add a second wire that pulls the jaws open, and remove the rubber band. Wire each to its own button. What do you gain, and what do you lose?

LAB

12

Click-Pen Rotary Stepper

Big idea: *A click-pen ratchet turns the wire's straight pull into steps of rotation that hold their position with no power.*

Time: Two periods

You will

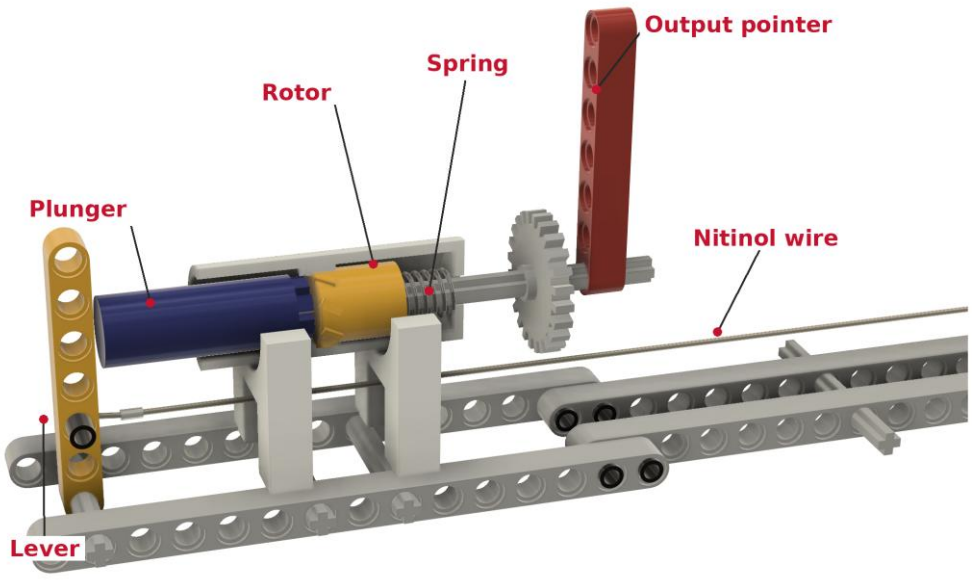
- Build a rotary stepper from a click-pen mechanism and nitinol
- Measure step angle and steps per minute
- Compare it with an electric stepper motor

Materials (per team)

- 3D-printed KRL click-pen stepper set: barrel, cap, plunger, rotor with a Technic axle hole and two barrel saddles (see Teacher Pages)
- Spring from a retractable ballpoint pen, or the printed spring
- Technic: four 15-hole beams (frame rails), a yellow 7-hole beam (lever), axles, friction pins, a 24-tooth gear and a red 7-hole pointer beam
- 20 cm of 0.5 mm actuator wire, wire anchor, two silicone or nitrile washers, 2 D cells, push-button, leads
- Protractor template, stopwatch, safety glasses

Background

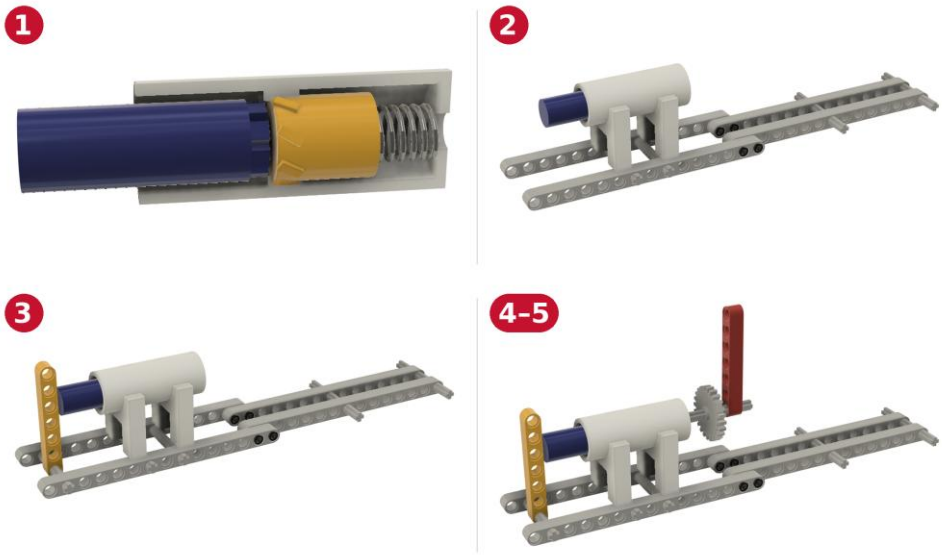
Click a retractable pen and the inside rotor turns by one notch every time. The pen spring pushes it back against a set of angled teeth that force it to turn. The same trick makes a stepper: each pull of the wire clicks the rotor forward one step. When the power is off, the teeth hold the rotor in place.



Build

1. Drop the plunger into the barrel from the top, teeth up, so its keys slide down the channels and rest on the bottom lip. Add the rotor teeth down, then the spring, and press in the cap.

2. Build the frame: two pairs of 15-hole rails pinned end to end, joined by axles. Snap the barrel into the two saddles and fix them on the frame.
3. Mount the yellow lever on the rear frame axle so it stands just behind the plunger. Hole 4 pushes the plunger; the wire pulls at hole 2. The lever doubles the wire's stroke to about 15 mm.
4. Push a Technic axle into the rotor through the front of the barrel. Fit the gear and the red pointer beam on the far end.
5. Run the wire forward under the barrel, from a pin in lever hole 2 to the anchor at the front of the frame. Put a washer on each side of the loop on the lever pin.



Red numbers match the build steps.

Procedure

1. Mark the pointer's position on the protractor template.
2. Press the button until the plunger clicks, then release. Wait for the plunger to reset. Record the new pointer angle.
3. Repeat for 16 steps.
4. Find the fastest rate that still steps reliably. Time 10 steps at that rate.

Step	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Angle (°)																

Analysis

Q1 What is the average step angle? How many steps make one full turn?

Q2 How many steps per minute did you reach? What limits the rate?

Q3 A small electric stepper motor turns 1.8° per step and can make hundreds of steps per second. List two advantages it has over your nitinol stepper, and two advantages your stepper has over it.

Q4 Gear the output down 3:1. What step angle do you get? What else changes?

Go further

Add a fan to cool the wire. How many more steps per minute do you get?

LAB

13

Inchworm Walker

Big idea: *An Arduino times heating and cooling pulses so a nitinol robot walks on its own.*

Time: Three periods

You will

- Build a walking robot powered by one nitinol wire
- Control it with an Arduino and a MOSFET switch
- Tune the timing for the fastest walk

Materials (per team)

- 3D-printed back foot and front foot, each with directional teeth underneath and an anchor post on top (PETG or ASA)
- Technic: two 12-stud axles (the slide), one shock absorber, two 8-hole beams (side rails)
- 20 cm of 0.5 mm actuator wire with crimped loops, two M3 screws, two silicone or nitrile washers
- Arduino Uno and USB cable, logic-level N-channel MOSFET (for example IRLB8721), 220 Ω and 10 kΩ resistors
- Breadboard, jumper wires, 2 D cells and holder, in-line 5 A fuse
- 2 m of light, flexible hookup wire for the tether, meter stick, stopwatch, safety glasses

NOTICE	A coding error can leave the wire switched on and overheat it. Keep the 5-second limit in the code.

Background

An inchworm moves by stretching out and pulling in. Our robot's feet slide easily forward but grip when pushed backward. The nitinol wire pulls the back foot forward. The shock absorber spring then pushes the front foot forward while the wire cools. Each cycle moves the robot one stroke.

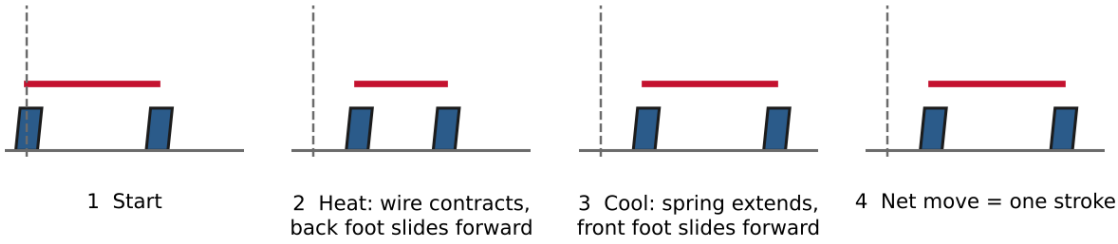
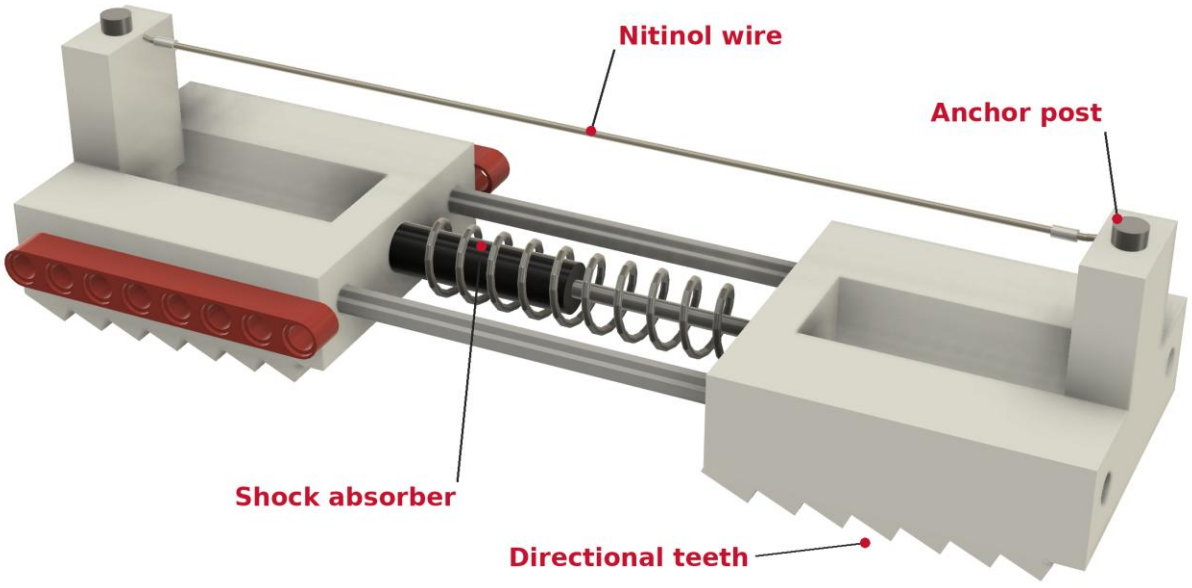
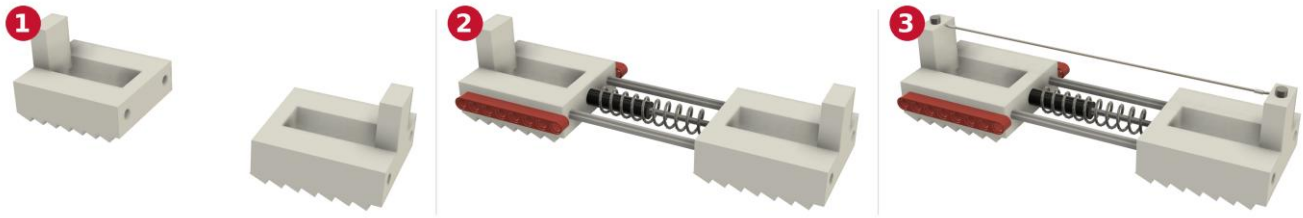


Figure 12. One walking cycle.



Build

1. Push the two slide axles through the back foot so they are held tight. Pin the red side rails to the back foot.
2. Slide the front foot onto the axles so it moves freely. Fit the shock absorber between the feet so it pushes them apart.
3. Stretch the wire between the screws on the two anchor posts, a washer under each loop, just tight when the shock absorber is relaxed. The wire runs above every plastic part.
4. Run the two tether leads from the anchor screws to the breadboard.



Red numbers match the build steps.

Wiring

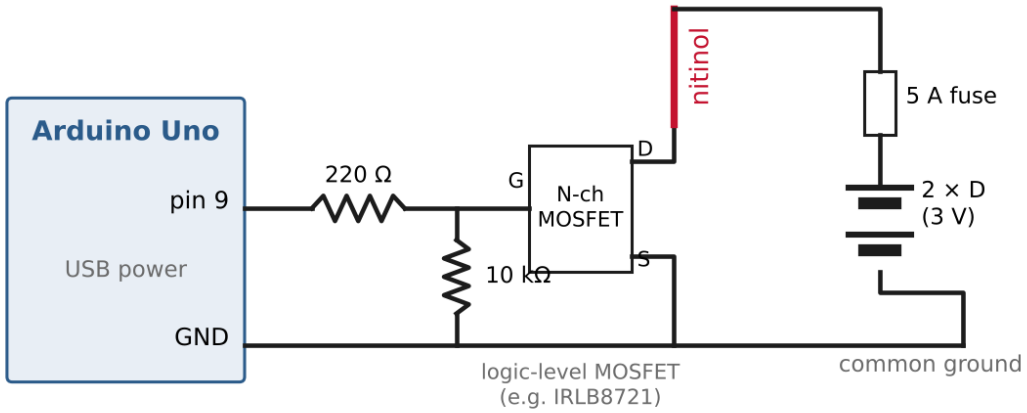


Figure 13. The Arduino switches the MOSFET; the D cells supply the wire current.

1. Connect Arduino pin 9 to the MOSFET gate through the 220 Ω resistor. Connect the 10 kΩ resistor from gate to ground so the wire stays off while the Arduino starts up.
2. Connect the MOSFET source to ground. Connect the Arduino GND to the same ground.
3. Connect battery positive through the fuse to one end of the nitinol wire, and the other end of the wire to the MOSFET drain.

Code

```
// Nitinol inchworm walker
const int WIRE = 9;
const unsigned long HEAT_MS = 3000;  // time the wire is on
const unsigned long COOL_MS = 8000;  // time the wire cools
const unsigned long MAX_HEAT_MS = 5000;  // safety limit

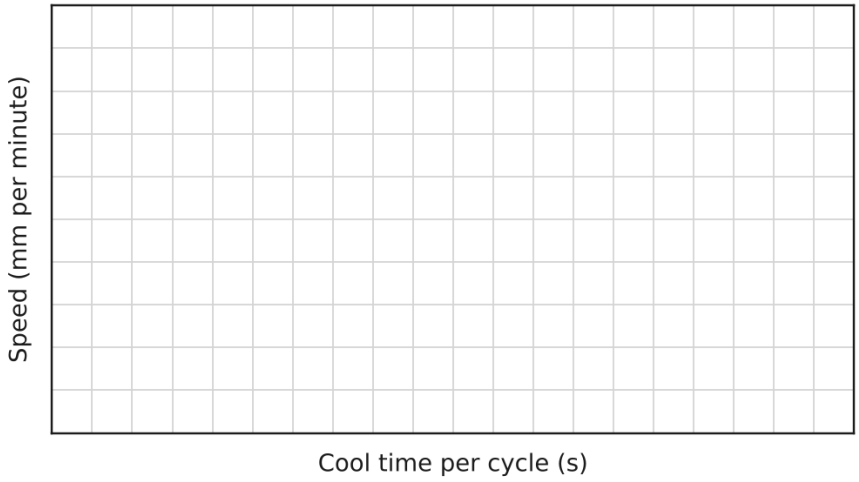
void setup() {
  pinMode(WIRE, OUTPUT);
  digitalWrite(WIRE, LOW);
}

void loop() {
  digitalWrite(WIRE, HIGH);
  delay(min(HEAT_MS, MAX_HEAT_MS));
  digitalWrite(WIRE, LOW);
  delay(COOL_MS);
}
```

Procedure

1. Upload the code with the battery unplugged. Then plug in the battery and set the robot at the start line.
2. Run for 5 cycles. Measure the distance traveled and the step length.
3. Change COOL_MS to 3000, 5000, 8000 and 12000. For each, run for 2 minutes and measure the distance.

Cool time (ms)	Cycles in 2 min	Distance (mm)	Step (mm)	Speed (mm/min)
3,000				
5,000				
8,000				
12,000				



Graph 13. Plot speed against cool time.

Analysis

Q1 Which cool time gave the fastest walk? Why do short cool times give short steps?

Q2 Predict the speed if a fan cut the cooling time in half. Test it.

Q3 The wire draws about 2.4 A for 3 seconds of every cycle. What is the average current? How long would two D cells (about 12 amp-hours at low current, less at high current) last?

Go further

Add a second wire and a pivoting front foot so the walker can steer. Or replace digitalWrite with analogWrite(WIRE, 180) to heat more gently, and find the best combination of power and timing.

LAB

14

Continuum Arm: Multiple Degrees of Freedom

Big idea: *Three wires spaced 120° apart can bend one flexible segment in any direction. Stacking segments adds degrees of freedom.*

Time: Three periods

You will

- Count the degrees of freedom of a continuum robot
- Build a three-wire continuum segment
- Program an Arduino to point the tip in any direction

Materials (per team)

- 20 cm of 1.5 mm superelastic nitinol rod for the backbone (kit)
- Three 20 cm pieces of 0.5 mm actuator wire with crimped loops
- 3D-printed pedestal, six spacer disks and a red top disk (ASA). Each disk has a center hole for the rod and three wire holes 10 mm out, 120° apart.
- PTFE tube liners for every disk hole
- Technic: two 15-hole beams and a friction pin for the base
- Arduino Uno, three logic-level MOSFETs, three 220 Ω and three 10 kΩ resistors, breadboard
- 2 D cells and holder, in-line 5 A slow-blow fuse, polar target sheet (0–360°), safety glasses

Background

A degree of freedom (DOF) is one independent way a mechanism can move. A door hinge has one. Your wrist has three.

A straight wire has one DOF: shorter or longer. The spine in Lab 10 bends in one plane. Spread three wires around a round backbone and one segment can bend by any amount in any direction. That is two DOF: the bend angle and the bend direction. Stack two segments and you have four.

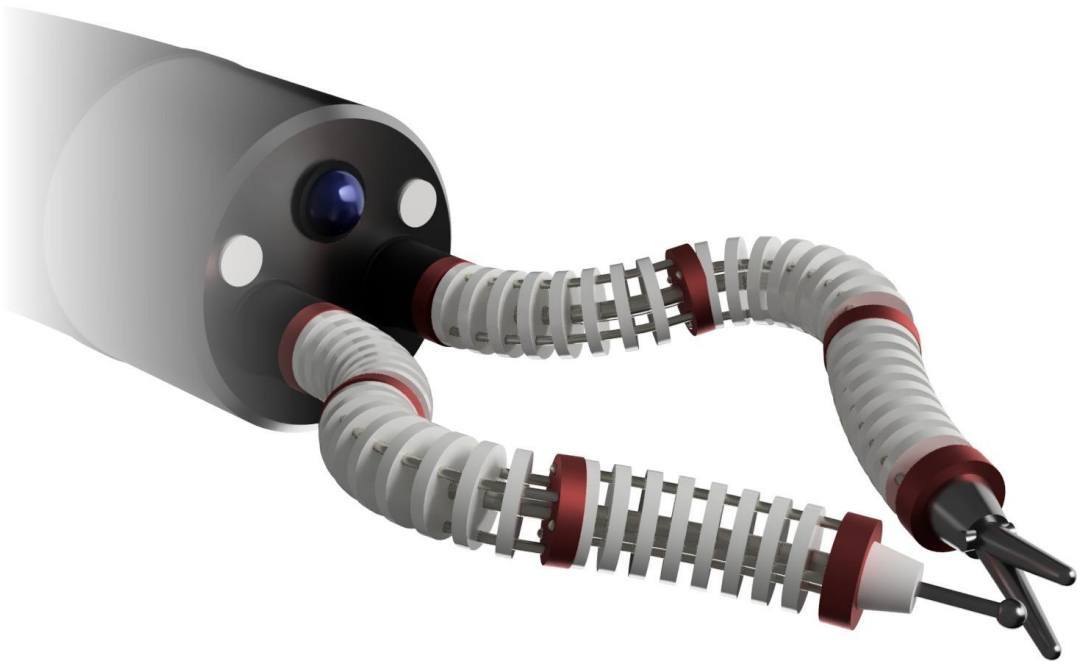


Figure 14. A surgical continuum robot modeled in Fusion. Each arm has three segments with three nitinol wires per segment, and a tool at the tip.

Each wire is also the bias spring for the other two. When one shortens, it bends the backbone and stretches the other two back out.

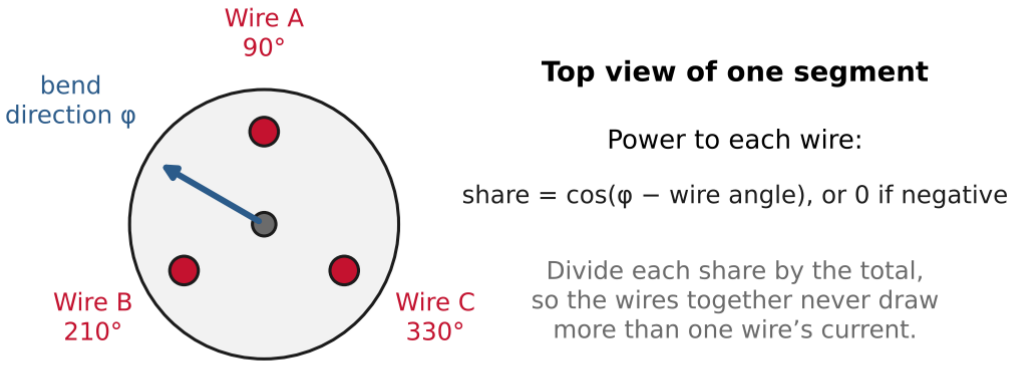
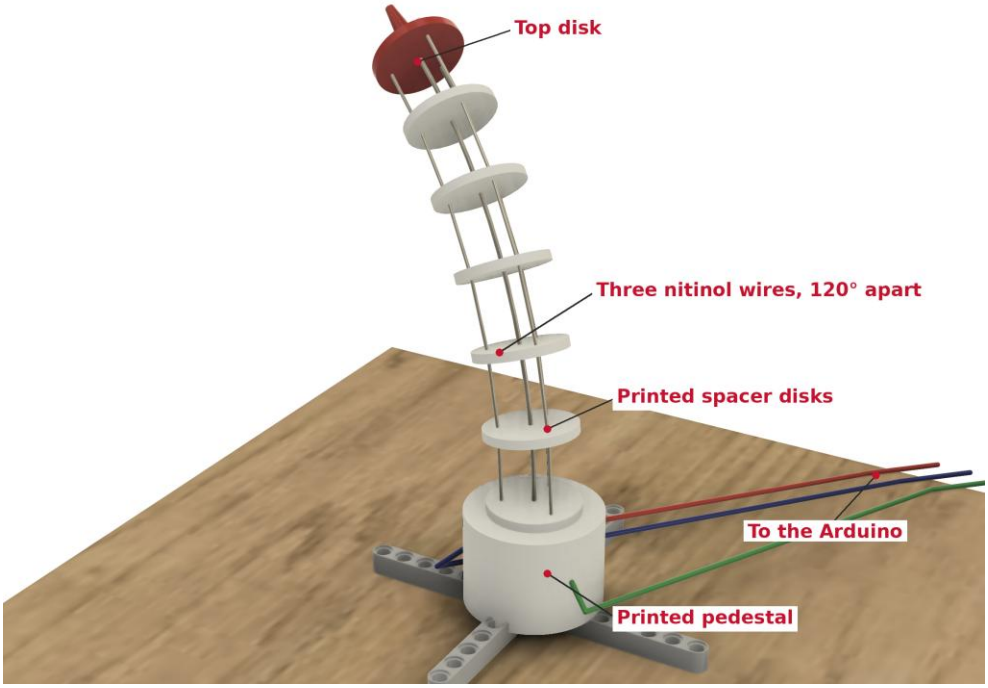


Figure 15. Sharing power between neighboring wires points the bend between them.

Build



1. Pin the pedestal on two crossed 15-hole beams. Push the backbone rod into the pedestal's center hole.
2. Slide the six spacer disks onto the rod 25 mm apart, and the red top disk at 150 mm. Fix each with a drop of glue. Press PTFE liners into every wire hole.
3. Thread each wire down through the matching hole in every disk and in the pedestal. Crimp its bottom end so the crimp sits in the exit slot at the base of the pedestal, then crimp the top end just tight above the top disk.
4. Wire each channel like Figure 13: Wire A to pin 9, Wire B to pin 10, Wire C to pin 11, all sharing one battery and one fuse.



Red numbers match the build steps.

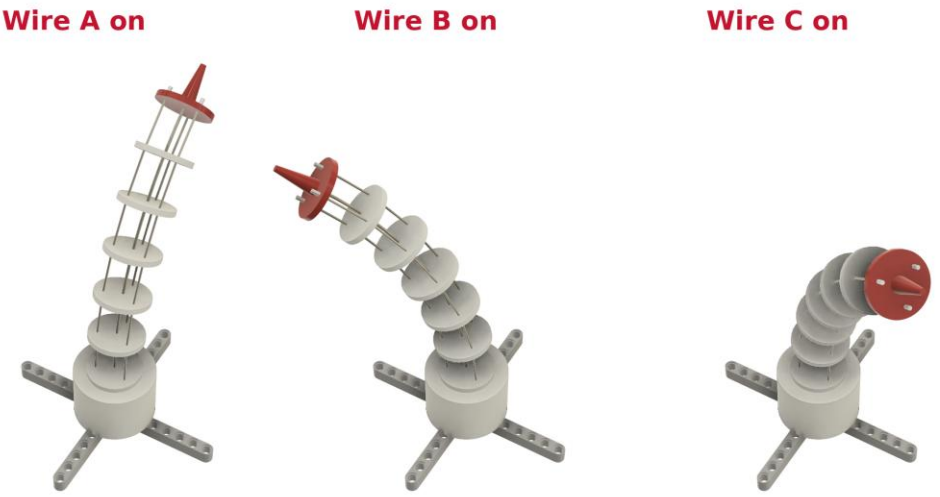


Figure 16. Heating one wire bends the segment toward that wire.

Code

```
// Three-wire continuum arm: type a direction in the Serial Monitor
const int PIN[3] = {9, 10, 11};        // Wire A, B, C
const float ANG[3] = {90, 210, 330};   // wire positions (degrees)
const unsigned long HEAT_MS = 3000;    // never more than 5000
const unsigned long COOL_MS = 10000;

void setup() {
  for (int i = 0; i < 3; i++) { pinMode(PIN[i], OUTPUT); analogWrite(PIN[i], 0); }
  Serial.begin(9600);
  Serial.println("Type a direction in degrees, 0 to 359");
}

void bend(float phi) {
  float share[3], total = 0;
  for (int i = 0; i < 3; i++) {
    share[i] = cos((phi - ANG[i]) * PI / 180.0);
    if (share[i] < 0) share[i] = 0;
    total += share[i];
  }
  for (int i = 0; i < 3; i++) analogWrite(PIN[i], (int)(255 * share[i] / total));
  delay(HEAT_MS);
  for (int i = 0; i < 3; i++) analogWrite(PIN[i], 0);
  delay(COOL_MS);
}

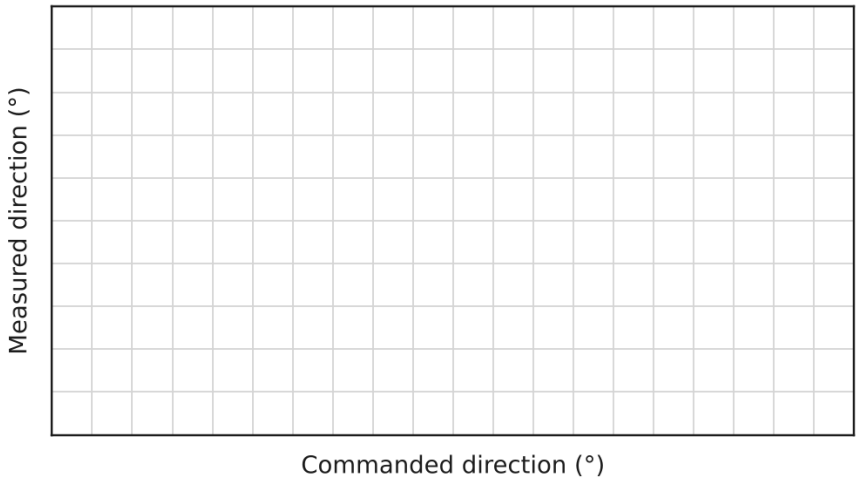
void loop() {
  if (Serial.available()) {
    float phi = Serial.parseFloat();
    Serial.print("Bending toward "); Serial.println(phi);
    bend(phi);
  }
}
```

Procedure

1. Upload the code with the battery unplugged. Then plug in the battery.
2. Lay the polar target sheet under the arm with 0° pointing to the right, so Wire A sits at 90°.

3. Type each direction in the table into the Serial Monitor. Looking straight down, record where the tip points and how far it moved.

Commanded (°)	0	30	60	90	120	150	180	210	240	270	300	330
Measured (°)												
Tip travel (mm)												



Graph 14. Plot measured against commanded direction. A perfect arm falls on a straight 45° line.

Analysis

Q1 How many degrees of freedom does one segment have? Two segments? One arm of the robot in Figure 14?

Q2 Which directions were most accurate? Commands between two wires split the power, so each wire heats more slowly. How did that show up in your tip travel?

Q3 Why don't the three wires need a separate bias spring?

Q4 A second segment needs three more wires and three more channels. The Uno has six PWM pins. What else limits how many segments a nitinol continuum robot can have?

Go further

Add a second segment on top, with its own three wires on pins 3, 5 and 6. Program the arm to trace a circle with its tip, or to point at a target and hold.

Capstone Design Challenge

Teams design, build and test a nitinol-powered machine. Pick one challenge or propose your own.

Challenges

- **Rescue arm:** lift a 100 g object 5 cm off the table and hold it for 30 seconds.
- **Walker race:** cover 50 cm in the shortest time.
- **Self-opening vent:** open a 10 × 10 cm flap with heat alone (a lamp or warm water), with no battery.
- **Sorting gate:** send marbles left or right on command.

Rules

- No more than 60 cm of 0.5 mm wire in total, and no more than 3 D cells.
- Heating pulses of 5 seconds or less, enforced in code or by a push-button.
- Kit nitinol, Technic-compatible parts and no more than three 3D-printed parts of your own design.

Deliver

1. A sketch with the wire's length, stroke, force and stress calculated
2. The working build
3. A data table from at least five test runs
4. A two-minute demonstration and explanation

Scoring rubric

Criterion	4 Excellent	3 Good	2 Developing	1 Beginning
Calculations	Stroke, force and stress correct and used in the design	Mostly correct	Partly complete	Missing
Performance	Meets the goal every run	Meets it most runs	Meets it once	Does not meet it
Data	Five or more runs, graphed and explained	Five runs, partly explained	Fewer than five runs	No data
Communication	Clear, uses correct terms (transformation, stress, strain)	Mostly clear	Hard to follow	Not presented

FOR TEACHERS

Teacher Pages

Kit contents, equipment, printable parts, standards, expected results, answer keys and troubleshooting. Remove these pages before photocopying student labs.

Equipment and Kits

KRL Educator Kit (per team)

Item	Quantity	Labs
0.5 mm nitinol actuator wire, Af near 70 °C	4 m	1, 3–8, 10–14
0.5 mm superelastic nitinol wire	0.5 m	2
0.25 mm nitinol actuator wire	0.5 m	6, 8
KRL shape memory spring actuator	2	9
KRL curl actuator strip	1	10
1.5 mm superelastic nitinol rod (backbone)	20 cm	14
Crimp sleeves for 0.5 mm and 0.25 mm wire	30	All
Ring terminals, M3	10	All
Wire data card and spring data card	1 each	All

School-supplied equipment (per team)

- LEGO® Technic™-compatible beams, frames, pins, axles, bushings, 24-tooth gears and a shock absorber (list below)
- Digital multimeter with a 10 A jack, three alligator-clip test leads, a momentary push-button
- Battery holder for 3 D cells, alkaline D cells, an in-line 5 A fuse
- Crimp tool, flush cutters, needle-nose pliers, tongs
- 30 cm steel ruler, protractor, stopwatch or phone, kitchen scale, 0–10 N spring scale
- Hooked mass set (to 2 kg) or water bottles, a 2 L beaker or stockpot, hot plate, kettle, thermometer, ice
- Arduino Uno, breadboard, three IRLB8721 MOSFETs (or similar logic-level parts), three 220 Ω and three 10 kΩ resistors
- PTFE tube with 2 mm inside diameter (3D printer Bowden tube), for guide liners in Labs 10 and 14
- Silicone or nitrile washers, M3, to isolate hot wire and crimps from LEGO parts. Silicone is rated to about 200 °C and nitrile to about 100–120 °C; both are sold cheaply in bags of 100.
- Safety glasses for every student

Bench power supply option

A current-limited DC bench supply (0–30 V, 0–5 A) can replace the D cells in any lab. Set the voltage to 5 V and the current limit to 2.0 A for 0.5 mm wire, or 0.8 A for 0.25 mm wire. The supply then holds the current steady as the wire heats, which gives cleaner data. Keep the push-button in the circuit.

Technic parts per team

Teams can take each build apart for the next lab. Keep the test stand built through Lab 8.

Part	Qty	Used in
Beam, 15 holes	11	Stand, Labs 7, 10–12, 14
Beam, 11 holes	4	Stand, Lab 7
Beam, 9 holes	2	Stand, Lab 11
Beam, 8 holes	2	Lab 13
Beam, 7 holes	4	Labs 11, 12

Part	Qty	Used in
Beam, 3 holes	1	Lab 11
Gear, 24 teeth	2	Labs 11, 12
Shock absorber	1	Lab 13
3-long pins	8	Stand, Lab 7
Friction pins	30	All builds
Axles, 3–12 studs (assorted)	12	All builds
Bushings	16	All builds

3D-printed parts

Print every part that touches the wire in PETG or ASA. PLA softens near 60 °C, close to the wire's working temperature. File names below drop the KRL-LabBook- prefix.

Part	STL file	Qty	Material	Labs
Wire anchor (M3 screw)	wire-anchor	4	PETG or ASA	Stand, all electric labs
Ruler clip	ruler-clip	1	Any	Test stand
Mandrel set: 25, 20, 15, 10, 8, 6 mm	mandrel-set	1	Any	2, 3
Bend and free recovery fixture	bfr-fixture	1	PETG	3
Spring pointer disk	spring-pointer-disk	1	PETG	9
Protractor ring and bracket	protractor-ring-bracket	1	PETG	9
Bending spine	bending-spine	1	PETG	10
Spine base block	spine-base-block	1	PETG or ASA	10
Gripper jaw pads	jaw-pad	2	TPU or PETG	11
Click-pen barrel and cap	clickpen-barrel, clickpen-cap	1 each	PETG	12
Click-pen plunger and rotor	clickpen-plunger, clickpen-rotor	1 each	PETG	12
Click-pen saddle	clickpen-saddle	2	PETG	12
Walker feet	walker-back-foot, walker-front-foot	1 each	PETG or ASA	13
Continuum arm pedestal	arm-pedestal	1	ASA	14
Spacer disks and top disk	arm-spacer-disk, arm-top-disk	6 and 1	ASA	14

Printing tips

- 0.2 mm layers, 30% infill, three walls. Holes are sized for Technic axles and pins, 4 mm PTFE tube and M3 screws threaded straight into the plastic.
- Print the bending spine and the walker feet on their sides. Print the rotor teeth up and the plunger teeth up. Print everything else as it opens in the slicer.
- The click-pen set is a prototype. Print one set and test it before printing for the class. If it binds, sand the ribs and teeth lightly.

> STL files for every printed part are available from KRL. Email nitinol@kelloggsresearchlabs.com.

Standards Alignment

Standard	Performance expectation	Labs
HS-PS2-6	Communicate why molecular-level structure is important in the functioning of designed materials	1, 2, 3, 9, 10
HS-PS3-1	Create a computational model to calculate the change in energy of one component in a system	4, 8
HS-PS3-3	Design, build and refine a device that converts one form of energy into another	4, 7, 10–14, Capstone
HS-PS3-4	Investigate how thermal energy transfers between components at different temperatures	3, 8
HS-ETS1-2	Break a complex real-world problem into smaller, manageable problems	11–14, Capstone
HS-ETS1-3	Evaluate a solution against criteria and trade-offs	9, 10, 12, 14, Capstone

Science and engineering practices used throughout: planning and carrying out investigations, analyzing and interpreting data, using mathematics and computational thinking, and constructing explanations.

Expected Results and Answer Keys

Results depend on the wire lot, room temperature, battery freshness and student technique. Ranges below are typical for the kit wire. Check the data card for your lot's transformation temperature.

Lab 1: Meet Nitinol

- No change at room temperature or 45 °C. Full return to straight at 85–90 °C, in about a second. Copper never changes.
- The letter returns many times. A sharp kink bent with fingers can over-strain the wire beyond about 8%, and that spot will not fully recover.
- Answers: the transformation temperature lies between 45 °C and 85 °C. Copper bends by atoms slipping past each other permanently; nitinol martensite bends by its zigzag shifting, which heating undoes. This wire would not work as a stent: body temperature is too low. A stent needs wire whose transformation finishes below 37 °C (superelastic wire).
- Go further: a hand will not move it. A hair dryer may, if held close.
- Optional shape setting: a dull red glow is roughly 500–550 °C, close to industrial shape-setting temperatures. The wire remembers the coil. Wires heated to orange lose most of their memory; let students see one fail on purpose.

Lab 2: Superelasticity

- Strains: 2.0%, 3.2%, 4.8%, 5.9%, 7.7% for the 25, 15, 10, 8 and 6 mm mandrels.
- Nitinol: 0° left on all mandrels, possibly a few degrees at 6 mm. Steel: a small set even at 25 mm (2.0%), growing with each smaller mandrel. Copper: a large set on every mandrel.
- Ranking (most recovery to least): superelastic nitinol, steel, copper.
- Strength is the stress needed to bend a wire permanently. Recovery depends on how much strain the wire tolerates elastically. Steel resists more force, but tolerates only about 1% strain.
- Go further: cold makes the superelastic wire martensite, so it stays bent until it warms up.

Lab 3: Transformation Temperature

- Part A (bend and free recovery): As near 55–65 °C, Af-tan near 68–78 °C. Af-95 usually lands within a few degrees of Af-tan, a little higher.
- Classroom readings scatter more than an instrumented ASTM F2082 test. Agreement with the data card within about 5 °C is a good result.
- Part B (constant force, 50 MPa): Ms, Mf, As and Af all read a few degrees hotter than unloaded values. Hysteresis width (A50 − M50) of 20–30 °C. Elongation of 7–10 mm on 25 cm, an actuation strain of about 3–4%.
- Af under load is higher than Af in Part A, since stress stabilizes martensite.
- A vent that opens at 70 °C and closes at 65 °C needs a hysteresis width of about 5 °C. This wire's 20–30 °C makes that impossible; it would need a low-hysteresis alloy or a control system.
- Go further: transformation temperatures typically rise roughly 1 °C for every 6–8 MPa, so doubling the load to 100 MPa shifts them about 6–8 °C.

Lab 4: Electric Heating

- Measured R: 0.75–0.90 Ω for 20 cm. Expected: 0.82 μΩ·m × 0.20 m ÷ 0.196 × 10^{-6} m^2 = 0.84 Ω.
- Two fresh D cells: 2.0–2.6 A, lift in 2–5 s. One cell: 1.1–1.5 A, lift in 8–15 s or incomplete.
- Ohm's law with 3.0 V and 0.84 Ω predicts 3.6 A. The difference comes from battery internal resistance (about 0.3 Ω for two cells) and the leads.

- Power ratio is roughly 3–4× for twice the current, since $P = I^2R$.
- Energy delivered is typically 15–30 J, more than the 12 J the wire needs. The rest heats the air during heating.
- In a minute, the wire would far exceed its safe temperature. Nitinol overheated above about 250–300 °C loses some of its memory, and it can burn skin or melt plastic.

Lab 5: The 4% Rule

- Typical stroke: 4 mm, 8 mm and 12 mm for 10, 20 and 30 cm wire. Slope about 0.4 mm per cm, or 4% (range 3–5%).
- 12 mm of stroke needs about 30 cm of wire.
- With no weight, the wire contracts and stays short when cool. Martensite only stretches back out if something pulls it. Every nitinol actuator needs a bias force: a weight, spring or second wire.
- Longer wires need more voltage for the same current, more nitinol and more space. Cooling time stays about the same, since it depends on diameter, not length.
- Extension: most 0.5 mm wires still lift 1 mm or more somewhere between 8 and 15 kg (400–750 MPa). Lift shrinks with load, since stress raises the transformation temperatures by about 1 °C per 6–8 MPa and the wire needs more heat. Crimp slip usually ends the test before the wire breaks. Wires pushed this hard lose stroke; retire them.

Lab 6: Force and Stress

- Stress per load: 12.5, 25, 50, 75 and 100 MPa for 250, 500, 1,000, 1,500 and 2,000 g.
- Stroke at 250 g is small with incomplete reset; it reaches 3.5–4.5% from about 50 MPa upward.
- Light loads can't stretch the martensite back out, so the next stroke starts short.
- At 170 MPa: 170 × 0.196 = 33 N, about 3.4 kg. A 0.25 mm wire: 8.3 N, about 0.85 kg.
- 10 kg is 98 N. Three 0.5 mm wires (99 N at 170 MPa), each 20 cm long for 8 mm of stroke. A single 1 mm wire also works.
- Go further: about 1.6–1.9 A per wire from two cells; the same stroke at half the stress.

Lab 7: Levers

- Movement ratios close to 2, 4 and 6 (hole count ÷ 2). Slightly lower ratios come from pivot play and from the lever swinging through an arc.
- Example: 300 g lifted 45 mm is 0.13 J out. The wire pulls about 17.6 N through 7.5 mm, or 0.13 J in. Efficiency 70–95%.
- About 20 N ÷ 6 = 3.3 N at 12 holes, roughly 340 g including the cup.
- Examples: crowbar, bicycle gearing, a human forearm (muscle near the elbow), a pliers handle.
- Part B: about 8 mm with 2 kg for two wires side by side, about 16 mm with 1 kg for one 40 cm wire. Both do about 0.16 J of work: the same nitinol does the same work, and the shape decides whether it comes out as force or stroke.
- 40 mm at 5 N needs 5 × 0.04 = 0.2 J, more than one 20 cm wire delivers (about 0.16 J). A 25 cm wire (about 10 mm at 20 N) on a 4:1 lever gives 40 mm at 5 N. A 1 m straight wire also works but takes far more space; a coil gives long stroke in little space.

Lab 8: Cooling and Cycle Speed

- Still air: 0.25 mm cools in about 1.5–4 s; 0.5 mm in about 5–12 s.
- Measured ratios usually fall between 2 and 4, giving n between 1 and 2. Thin wires lose heat faster per unit of surface, which pulls the ratio below the rule of thumb. Discuss why a rule of thumb is a starting point, not a law.
- The fan cuts both times by 30–60%.

- Two steps per second calls for thin wire, forced air or liquid cooling, and short strokes. Bundles of thin wire cool fast but need more crimps and careful load sharing.

Lab 9: Spring Actuators

- The spring's stroke is typically 5–10 times the straight wire's, at roughly one tenth of the force.
- The straight wire does more work per gram. Designers choose springs when they need long travel in a small space.

Lab 10: Bending and Curling Actuators

- Part A: the strip curls to the same diameter every dip, but only flattens again when pushed. It is a one-way actuator and needs a bias.
- Predicted changes: $\Delta L = 160 \times 0.04 = 6.4$ mm. At 5 mm offset, 1.28 rad or 73°; at 10 mm, 0.64 rad or 37°; at 15 mm, 0.43 rad or 24°.
- Measured values typically reach 60–90% of prediction. The 5 mm offset falls furthest short: the wire must pull hardest to bend the spine, so it contracts less. Guide friction and slack also eat stroke.
- Small offsets give big bends with weak tip force; large offsets give small bends with more force. It is the lever trade from Lab 7 again.
- Constant curvature means the tip position follows from one number, the bend angle, which makes the motion easy to predict and control.

Lab 11: Gripper

- Torque: $20\ \text{N} \times 0.016\ \text{m} = 0.32\ \text{N·m}$. Predicted tip force: $0.32 \div 0.064 = 5$ N per jaw, less the rubber band. Measured 2–4 N is typical.
- Losses: rubber band, gear friction, axle bending, jaw flex.

Lab 12: Click-Pen Stepper

- The printed rotor advances 45° per click, 8 steps per turn. Students should see 40–50°.
- Rates of 4–8 steps per minute in still air; cooling limits the rate.
- Electric stepper advantages: speed, precision, easy reversing. Nitinol stepper advantages: silent, holds position with zero power, very light, very few parts.
- 3:1 gearing gives 15° steps, three times the torque, and one third the speed.

Lab 13: Inchworm Walker

- Step length 5–8 mm. With 3 s heat and 8 s cool, about 5.5 cycles per minute, or 30–45 mm per minute.
- Too short a cool time leaves the wire partly contracted, so the spring can't push the front foot fully forward.
- Average current: $2.4\ \text{A} \times 3 \div 11 = 0.65$ A. Fresh D cells last several hours at this rate.

Lab 14: Continuum Arm

- One segment has 2 DOF (bend angle and bend direction). Two segments have 4. One arm of the endoscope robot has 6, plus its tool.
- Directions aimed straight at a wire (90°, 210°, 330°) are most accurate and travel farthest. Directions between two wires split the power, so each wire heats more slowly and the tip travels less in the same 3 seconds. Students can lengthen HEAT_MS for those, up to the 5-second limit.
- Each wire stretches the other two back out when it contracts, so the set needs no separate bias spring.
- Limits on segments: wire count and routing through lower segments, heat building up in a tight bundle, slow cooling, power supply current, and the control effort of coordinating many wires.

Troubleshooting

Problem	Fix
Wire doesn't move	Check the crimps and the battery. Measure the current: below 1.5 A on 0.5 mm wire is too low.
Wire moves once, then won't reset	Add bias force. The wire needs at least 50 MPa (1 kg on 0.5 mm) to stretch back out.
Stroke smaller than expected	The bias load is too light, or slack in the build is eating the stroke. Tighten the anchors.
Wire slips from crimp	Use the correct crimp size and a real crimp tool, and loop the wire back through the sleeve.
Plastic part softened	The wire touched it, or the part is PLA. Add silicone or nitrile washers where the wire meets plastic, reprint in PETG or ASA, and keep the wire clear.
Battery gets warm	Normal after many cycles. Hot means a short circuit: disconnect immediately.
Wire stopped working after a long press	It overheated. Replace it, and enforce the 5-second rule.
Arduino walker won't stop	Unplug the battery. Check the 10 kΩ pull-down and that the MOSFET is logic-level.

Glossary

Term	Meaning
Actuation strain	The strain a loaded wire recovers between the lower and upper cycle temperatures (ASTM E3097).
As, Af	Austenite start and finish temperatures: where the transformation begins and ends on heating (ASTM F2005).
Austenite	The hot, strong crystal structure of nitinol. It holds the remembered shape.
Bias force	The weight, spring or second wire that stretches nitinol back out after each stroke.
Constant curvature	A bend in which every section curves the same amount, so the shape is an arc.
Continuum robot	A robot that moves by bending a flexible backbone instead of turning joints.
Degree of freedom	One independent way a mechanism can move.
Free recovery	Unconstrained return of a bent specimen to its shape as it heats (ASTM F2005).
Hysteresis width	A50 − M50: the gap between the heating and cooling midpoints of a thermal cycle.
Hysteresis	The temperature gap between transformation on heating and reverse transformation on cooling.
Martensite	The cool, soft crystal structure of nitinol that bends without breaking bonds.
Ms, Mf	Martensite start and finish temperatures: where the reverse transformation begins and ends on cooling.
Reverse transformation	The change from austenite back to martensite on cooling. It resets the actuator.
Shape memory	Returning to a remembered shape when heated through the transformation.
Shape setting	Holding nitinol in a shape at about 500 °C so it remembers that shape.
Strain	Change in length divided by original length, often given as a percent.
Stress	Force divided by cross-sectional area, in megapascals (N/mm^2).
Stroke	How far an actuator moves.
Superelasticity	Large, fully recoverable bending at room temperature, caused by stress-induced martensite.
Tangent method	Reading transformation temperatures where straight lines drawn on a recovery curve intersect.
Transformation	The change from martensite to austenite on heating. This is when the wire moves and does work.

KELLOGG'S RESEARCH LABS

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