MAKING STUFF WITH DAVID POGUE

DEMONSTRATION

Breaking Point: Testing Tensile Strength

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MAKING STUFF STRONGER Demonstration

Overview

TITLE
Breaking Point: Testing Tensile Strength

SHOW
Making Stuff: Stronger

DESCRIPTION
The audience will participate to test and compare the tensile strength and elasticity of Kevlar®, Nylon, and cotton thread by lifting weighted buckets with wooden dowels. Visitors will then compare the tensile strength of Kevlar® to steel wire. In both rounds, Kevlar® wins handily.

OBJECTIVE
Visitors will learn:

- that materials can be strong in different ways; for example, some possess high tensile strength while others are more elastic
- that materials scientists test the strength of materials by stressing them to their breaking point

OTHER KEY TALKING POINTS

- materials scientists have invented synthetic polymers, such as Kevlar®, that are stronger than natural polymers (and in this case, steel).
- the strength of a material is determined by its molecular structure.

AUDIENCE
General public, ages 10 and up

TIME
Set-up: 10 minutes
Presentation: 20 minutes

"Strong as steel" is a familiar saying, and it's an apt one. Steel, an iron alloy, is one of the strongest and most versatile materials around. But, as host David Pogue discovers in NOVA's *Making Stuff: Stronger*, scientists are creating new materials that push the idea of *strong* to extraordinary new limits.

In *Making Stuff: Stronger,* materials scientists demonstrate the latest breakthroughs in strengthening old materials and developing new, stronger ones. Some of these include:

- Kevlar® (a registered trademark of DuPont)—a unique polymer fiber tough enough to stop the impact force of a bullet with a few layers of fabric, each only millimeters thick
- Spider silk—a natural protein polymer similar to Nylon that, pound for pound, has more tensile strength than either Kevlar® or steel. Scientists have genetically engineered goats to produce this protein in their milk
- Carbon nanotubes—hollow pipelines just a few atoms thick that may be the strongest material yet discovered and could one day be used to build many things, including a 200-mile-long cable to lift things into orbit

Materials scientists are asking:

- How can we make materials stronger?
- How can stronger materials be lighter, cheaper, or better in other ways?
- How can we develop new strong materials for specific applications?

Science Background

TENSILE STRENGTH AND ELASTICITY

The word *strong* actually refers to a range of properties, each defined by the ability to stand up to a different type of force. **Strength** is a measure of how well a material can resist a force (or load) before failing. The load is distributed over an area and is more accurately defined as **stress** (force per unit area). There are different kinds of stresses, including tension (pulling), compression (squeezing), impact (a sharp blow), torsion (twisting), and shearing (surfaces sliding past one another). We apply these stresses in our daily lives when we pull open a door, push a cart, or twist the cap off a bottle.

Materials scientists test the strength of materials by stressing them to the breaking point, called **failure**, at which point the material ruptures and cannot rebound to its original condition or shape.

Tensile strength is how much stress a material can withstand while being pulled in opposite directions. This stress causes the material to temporarily lengthen. If the stress is low enough, when you release the force, the material will return to its original length—this ability for the thread to stretch and rebound is a property called **elasticity.** The amount the material lengthens is called the **elongation**. (If you divide the elongation by the original length you get what is called **strain.**)

If you continue to pull, the bonds between atoms in the material will start to break, eventually reaching the point at which the material will not rebound when the stress is released; the deformation is permanent, or **plastic.** When enough bonds break, the material snaps apart. The amount of stress the material can endure at the time of failure is the strength of a material.

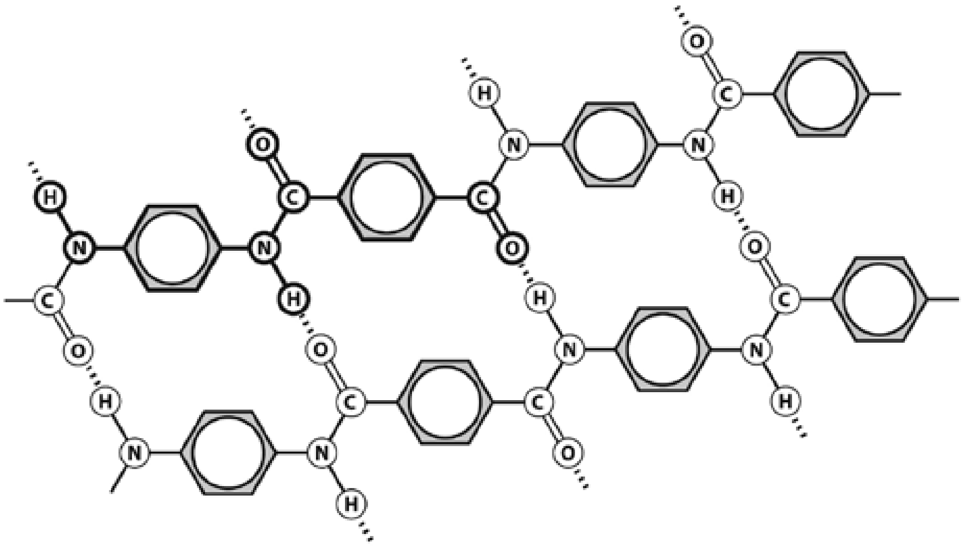
COTTON, NYLON, KEVLAR®, AND STEEL

This demonstration investigates and compares the tensile strength of cotton, Nylon, Kevlar®, and steel, and shows that different materials can be strong in different ways.

Cotton is a natural polymer, or plastic, composed of long chains of cellulose molecules. These small units of cellulose are formed through side-by-side hydrogen bonding. However, because its molecules are randomly arranged, it has low tensile strength, which means it will break under relatively low stress. Cotton will stretch 8–10 percent before breaking. Size 35 cotton thread (an equivalent gauge to size 46 Nylon and Kevlar® thread) has a tensile strength of approximately 2 pounds (0.9 kilograms).

Nylon is a lightweight synthetic polymer that also has long strands and hydrogen bonds, but it has a more ordered molecular structure than the cellulose in cotton, which gives it higher tensile strength. Like rungs of a ladder, the hydrogen bonds lock the rigid molecules into a tight formation. In addition, Nylon will stretch 30–40 percent of its length before breaking, which makes it an ideal material for parachute cords, for example. Size 46 Nylon thread has a tensile strength of approximately 8 pounds (3.6 kilograms).

Kevlar® is a lightweight synthetic polymer with a highly ordered molecular structure that gives it the highest tensile strength of the four materials. Like Nylon and cotton, it also has hydrogen bonds between strands. And like Nylon, it has ordered polymer strands, which increase the strength. On top of that, however, Kevlar® has rigid ring structures within the polymer strands, which further increases the strength. Polymers with ring structures have high tensile strengths.



Molecular Structure of Kevlar®

Kevlar® molecules are composed of long chains of repeating units (in bold at right). These chains of rigid rings run parallel to the fibers and are bonded to each other by strong hydrogen bonds. Like rungs of a ladder, the hydrogen bonds lock the rigid rings into a tight formation giving Kevlar® its superior tensile strength.

Size 46 Kevlar® thread has a tensile strength of approximately 18 pounds (8 kilograms). However, larger sizes of Kevlar® thread will hold 400 pounds or more. Also, Kevlar® fibers will only stretch 3–5 percent before breaking. So it is much less elastic than Nylon of the same gauge, but possesses much higher tensile strength. **That is, Kevlar® doesn't stretch much before breaking, but it can withstand a much greater force before it breaks.**

Steel is an alloy of iron and carbon that, like all metals, has a crystalline structure, which means the atoms are arranged in an ordered pattern. The addition of carbon hardens the iron by locking the layers of iron atoms into a strong, rigid structure. In general, metals have higher tensile strengths than polymers. In the case of Kevlar® the rigid ring structures give it superior strength for a polymer, especially such a lightweight one. Pound for pound, Kevlar® is five times stronger than steel.

Material	Tensile Strength (What's the maximum stress it can withstand before breaking?)	Elasticity (How much does it stretch before breaking?)
Cotton Thread size 35	2 lbs (0.9 kg)	8–10%
Nylon Thread size 46	8 lbs (3.6 kg)	30–40%
Steel Wire size 28	10 lbs (4.5 kg)	8–15%
Kevlar® Thread size 46	18 lbs (8 kg)	3–5%

A bulletproof plastic? Give me a break! Kevlar® has a rigid structure and does not stretch much. When a bullet strikes a vest, it hits the layers of Kevlar® and acts to pull them apart. The Kevlar® fabric in a bulletproof vest is made of several very thin layers of fibers. The fibers are woven perpendicular to each other to help distribute the force of an impact. When Kevlar® is struck, it responds by stretching individual fibers a small amount. This serves to dissipate the energy of the bullet. Some of the fibers break and also absorb the energy. The total amount of energy a material can absorb is its **toughness,** and Kevlar® fabric is one of the toughest materials ever created.

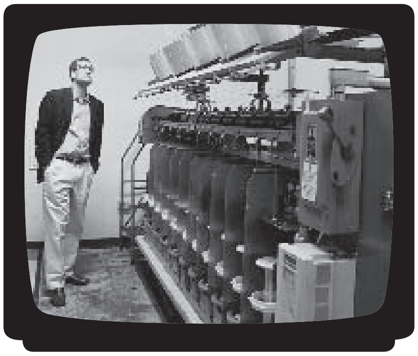
Materials List

- 1 case of 24 plastic bottles of water, 16.9 oz/0.5 L each, *unopened* (to use as uniform weights, 1 bottle = 1.16 lbs/0.525 kg)
- 4 identical 5-gallon buckets with firmly attached handles
- 5 metal S-hooks large enough to latch onto the bucket handles
- 5 wooden dowels, 7/8" x 48"
- 10 pairs of safety glasses (clean after each use)
- cotton thread, size 35 (equivalent diameter to size 46 Nylon and Kevlar®)
- Kevlar® filament thread, size 46
- Kevlar® fabric swatches
- Nylon thread, size 46
- steel picture-hanging wire, 28-gauge (twice the diameter of the threads)
- tape (vinyl electrical tape works well for securing the thread to the dowels and hooks)
- wipes, to clean safety glasses
- wire cutters
- bucket labels (see Resources)
- Demonstration Title Sign and applications collage (see Resources) –mount on foam core or insert into a clear plastic display rack
- (optional) Nylon sample (e.g., pantyhose)
- (optional) NOVA *Making Stuff: Stronger* video clip (see Resources) and video display equipment
- (optional) photo of Kevlar® bulletproof vest or real vest if possible

For Resources, visit **pbs.org/nova/education/makingstuff**

Materials and supplies for this demonstration can be found at most hardware and home improvement stores. The specific thread types and gauges are available online at **thethreadexchange.com**. Kevlar® fabric samples or tape can be obtained from several online vendors including **fibreglast.com**, **jamestowndistributors.com**, and **fiberglasssupply.com**.

Showing Video Clips from MAKING STUFF: STRONGER



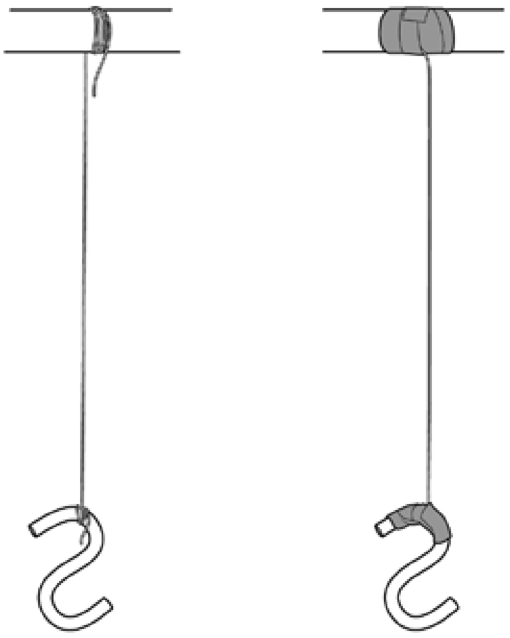
▶ If you are able to show video at the demonstration site, the video clip from NOVA's *Making Stuff: Stronger* can be used either as an introduction or as a follow-up to your demonstration. The clip can also be played on a continuous loop nearby to draw visitors into the demonstration area.

Advance Preparation

1. **Test the demonstration before presenting it to an audience.**

2. **Assemble three dowels,** each with a different type of thread (cotton, Nylon, Kevlar®). For each dowel, cut a piece of thread 48 inches long (the same as the length of the dowel).

   Wrap one end of the thread **around the center** of the dowel 10 times and tape it firmly in place with several layers of electrical tape. Wrap the other end of the thread around the top of an S-hook 10 times and tape it firmly in place with several layers of electrical tape. Do not knot the thread, as a knot forms a point of weakness in the thread. This should leave about 12 inches of thread exposed.



How to Attach the Thread and Wire to the Dowel and S-Hook
Wrap the ends of the thread and wire around the center of the dowel and the top of the S-hook and tape firmly in place.

3. **Assemble two more dowels,** another dowel with Kevlar® thread set up as above, and one set up with the steel wire. Cut a piece of wire about 24 inches in length (half the length of the dowel). Wrap one end around the center of the dowel and the other end around the top of an S-hook, five times each, and secure it with electrical tape. Be careful not to bend the wire more than necessary, as bends, like knots, can create points of weakness. This should leave about 12 inches of wire exposed.

4. **Place the labels on the four buckets.** A standard plastic 5-gallon bucket, available at most hardware or home improvement stores, weighs a little over 1.5 pounds. The weight of the bucket alone may be enough to break the cotton thread.

5. **Set the stage.** Just before the demonstration:
   - Set out the Nylon and Kevlar® samples.
   - Place the first three labeled buckets (*cotton*, *Nylon*, and *Kevlar®*) and three threaded dowels side-by-side on the floor with eight water bottles next to each one.
   - Set the other two dowels (Kevlar® and steel) and the bucket labeled *steel* out of view for the first part of the demonstration.
   - Cue up the NOVA video clip, if you are using it.
   - Keep the threads, scissors, wire, and tape on hand to re-thread the dowels in between demonstrations. Or, if the demonstration is to be repeated, consider two sets of dowels and hooks to limit set-up time in between demonstrations.
   - Put on your safety glasses and the bulletproof vest, if available. (Or ask a volunteer to wear it.)
   - Post the Demonstration Title Sign on the cart/table.

SAFETY NOTES

- Have your volunteers put on safety goggles.
- Buckets can be lifted by single volunteers or a pair of volunteers (see photo, left). Assign two lifters per bucket, one on each end of the dowel. Assign children to the cotton thread first, then the Nylon as they will be lighter loads to lift. Steer adult volunteers first toward the Kevlar®.
- Ensure that volunteers hold the dowels and buckets at a safe distance from their faces and other visitors to avoid rebound or dropping the bucket on toes.

6. **Note:** Due to the very low tensile strength of the cotton, the line may break immediately, under just the weight of the bucket. After each line breaks, the water bottles from that bucket can be used to continue the test. The likely outcome of the test is shown at right.

Thread Type	Water Bottles
Cotton	0–1
Nylon	4–5
Kevlar®	11–12

Demonstration Script

1. **Welcome visitors** to the demonstration and briefly introduce the show. *"Welcome to this* Making Stuff *demonstration.* Making Stuff: Stronger, Smaller, Cleaner, Smarter *is a four-part NOVA series on materials science that will air on PBS in January 2011. This demonstration accompanies the* Making Stuff: Stronger *episode."*

2. **Engage your visitors.** *"What are some strong materials?* (steel, concrete, etc. Accept all answers.) *Those are good examples, but what does it really mean for a material to be 'strong'?" (Accept all answers.)*

3. **Introduce materials science.** *"Well, it turns out there is an entire field of science dedicated to answering that question. These scientists are called materials scientists and some of them develop and test materials by breaking them to see how strong they are. Wouldn't that be a fun job, to break things for a living? You may be familiar with some of the tests already."*
   - *Perhaps you've seen video of car crash tests where a car is hooked onto a cable and slammed into a wall—that's an **impact test** to see how much force the materials can withstand before breaking.*
   - *There are also machines that pull materials apart with more and more force until they stretch out and break—that kind of test tells materials scientists how much **tensile strength**, which is **how much stress**, or **pulling**, the materials can withstand before breaking.*

4. **Introduce the challenge.** *"Well, we don't have a machine like that here but we can do a simple test to investigate **tensile strength** and **elasticity**, which is how much **something can stretch before breaking**."*

5. **Get volunteers.** Solicit three to six volunteers to lift the dowels and one to three other volunteers to load the buckets. Distribute the safety glasses and instruct the volunteers to put them on.

6. **Describe the procedure.** While the volunteers hook the S-hooks to the bucket handles, say: *"We're going to test the tensile strength and elasticity of three different materials. All three materials are polymers, which are materials whose molecules are made up of long chains of repeating atoms."*
   - ***Cotton**: a lightweight natural fiber that some of you might be wearing right now*
   - ***Nylon**: the very first synthetic, or human-made, fiber, which was invented by materials scientists in 1935*
   - ***Kevlar®**: a lightweight synthetic fiber that was invented by materials scientists in 1965 and is used in bulletproof vests, tires, and firefighting gear*

7. **Ask for predictions.** *"All three of these threads are the same diameter so it is a fair test of the strength of the thread. Which material do you think will be the strongest? How many think it will be the cotton?...the Nylon?... the Kevlar®?"*

8. **Load the buckets.** With the buckets on the floor, ask the loader(s) to add one water bottle to each bucket and step back. Then ask the lifters to *gradually*

Presentation tips

- Encourage participation by having the audience members count in unison as the water bottles are added to the buckets.
- Use hand signals to help volunteers raise the buckets at a steady pace. Slowly raise your hand, palm up to signal lifting and a flat outward palm to signal stop.
- Have volunteers set the bucket down on the floor before adding each water bottle.

hoist the three buckets at the same time. **Caution** the lifters not to jerk or yank the dowels as that could snap a line and is a different kind of stress than the one being tested.

9. **Continue the test** lowering the buckets, adding water bottles and lifting the buckets, until each thread breaks.
    - When the cotton breaks, say: *"Okay, so we just saw that the tensile strength of cotton is very low, just a few pounds. And how much did it stretch?"* (A little bit. Cotton stretches, or elongates, 8–10 percent.) *But what about the other two?*
    - When the Nylon breaks, say: *"Okay, so now we see that Nylon has greater tensile strength than cotton. And how much did it stretch?"* (A lot more. Nylon stretches 30–40 percent.)
    - When the Kevlar® breaks, review the final bottle counts and say: *"Okay, so we've just seen that this material has more* ***than twice the tensile strength of Nylon and almost 10 times as much as cotton****. And how much did it stretch?"* (Not very much. Kevlar® stretches only 3–5 percent.)
10. **Compare Kevlar® to steel.** "*But how do you think* ***Kevlar®*** *would stand up to steel?"* Bring out the steel and Kevlar® dowels and say: *"Here we have a steel wire that is* ***twice the diameter*** *of the Kevlar® thread. Which do you think will have the greater tensile strength?"* (Accept all answers. Many in the audience will expect the steel to be stronger.)
11. **Repeat** the test, testing Kevlar® versus steel, using two bottles of water per lift. The steel should break first, at about 6–8 bottles. If time permits, keep going until the Kevlar® again breaks at about 10–12 bottles.
12. **Summarize.** *"So we've seen that Kevlar® has* ***greater tensile strength*** *than the other materials, including steel, but is* ***less elastic****."*
13. **Pass around the Kevlar® fabric samples** and ask: *"Can anyone guess why those properties make Kevlar® good for bulletproof vests?"* (Kevlar® fibers can absorb a lot of force while stretching very little, which stops the bullet. If it were more elastic, like Nylon [hold up the Nylon pantyhose and stretch them] it would allow the bullet's force to impact the wearer. Also, the fibers are woven perpendicular to each other to create a net that further dissipates the force of the bullet. This protects the wearer from receiving its full impact.)
14. **Wrap up.** *"So what does the word* strong *really mean?"* (Accept all answers.) Then reiterate: *"As this demonstration shows, a material can be strong in one respect (tensile strength) and weak in another (elasticity). However, materials scientists can turn those different properties into advantages when designing new materials and products. For example, Nylon, which has greater elasticity than Kevlar® is used more often for parachute cords, where the stretchy fibers decrease the jerking motion when the chute is deployed."*
15. **Conclude the demo.** Ask if anyone has any questions, and share some other applications of Kevlar® (see page 42).

How to Gauge Elasticity

- Ask audience members to pay attention to how much each line stretches before the bucket lifts off the floor. For example, the Nylon thread will stretch for some time before the bucket finally lifts off the floor, but the Kevlar® bucket will rise almost immediately after the volunteer begins lifting.
- Ask the lifters how much they feel the lines stretching when they lift the buckets.
- Visually compare the lengths of the line while the buckets are raised in the air.

Q Why is the Kevlar® thread so strong?

A Failure happens when the stress overcomes the force of the atomic bonds that hold the material together. The stronger the bonds, the more force it takes to make the material fail. Also, bonds are stronger when the molecules form a rigid, regular pattern. All three of the polymers have hydrogen bonds, but cotton molecules are randomly arranged, while Nylon molecules have a more ordered structure making it stronger. Steel has a highly ordered crystalline structure that makes it very strong. Kevlar® molecules are also highly ordered, but they have additional rigid ring structures that give Kevlar® superior tensile strength.

Applications

Materials scientists often combine materials to produce composites that have unique properties (flexibility, stiffness, elasticity, etc.). These are a few applications of Kevlar® and composites containing Kevlar®:

Applications of Kevlar®

- bicycle helmets
- protective suits for motorcyclists
- the hulls of sailboats, yachts, canoes, and kayaks
- the strings of tennis rackets
- snowboards and skis
- baseball bats and hockey sticks
- industrial gloves for workers who handle glass, sharp metals, etc.
- hoses and pipes on deep-ocean oil rigs
- protective shields for satellites and spacecraft
- strong, fire-resistant mattresses
- firefighting clothing and gear
- inside-the-home storm rooms that can stand up to tornados.

Glossary

- **elastic deformation**–change that is non-permanent; when the stress is released the material returns to its previous shape
- **elasticity**–the ability for a material to lengthen under stress and then return to its original shape when the stress is removed
- **elongation**–the amount the material lengthens while undergoing elastic deformation
- **failure**–the rupture or breaking of a material, with no chance of returning to the way it was
- **plastic deformation**–deformation, or change, that is permanent; when the stress is released the material does not return to its previous shape
- **polymer**–large molecules made of long chains of repeating atoms; can be synthetic or natural
- **strain**–the elongation divided by the original length
- **strength**–a measure of how well a material can resist a force (or load) before failing
- **stress**–force per unit area; types of stress include tension (pulling), compression (squeezing), impact (a sharp blow), torsion (twisting), and shearing (surfaces sliding past one another).
- **tensile strength**–how much stress a material can withstand while being pulled apart
- **toughness**–the total amount of energy a material can absorb at fracture or failure

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