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Cornell NanoScale Science & Technology Facility

ISSUE 19 • 2023

NanoOoze

ALL ABOUT
NANO MANUFACTURING

This 3D-printed axolotl has small moving parts!

Some 3D printers can print tiny parts that are even smaller than the width of a human hair.

SMALLER 3D PRINTING

INTERESTING TINY CREATIONS

THE MANY PITFALLS OF TINY MOVING PARTS

BUILDING THE WORLD'S SMALLEST MOTOR

NANOOZE

ALL ABOUT THE THINGS TOO SMALL TO SEE

Welcome to Nanooze!

What is a Nanooze? (Sounds like *nah-news*.) Nanooze is not a thing, Nanooze is a place to hear about the latest exciting stuff in science and technology. What kind of stuff? Mostly discoveries about the part of our world that is too small to see and making tiny things using nanotechnology. Things like computer chips, the latest trends in fashion, and even important stuff like bicycles and tennis rackets. Nanooze was created for kids, so inside you'll find interesting articles about what nanotechnology is and what it might mean to your future. Nanooze is online at **nanooze.org**, or just Google "Nanooze"—you'll find interviews with real scientists, the latest in science news, games and more!

How can I get Nanooze in my classroom?

Copies of Nanooze are **FREE** for classroom teachers. Please visit **nanooze.org** for more information or email a request for copies to: info@nanooze.org.

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Nano-manufacturing and building from the bottom up

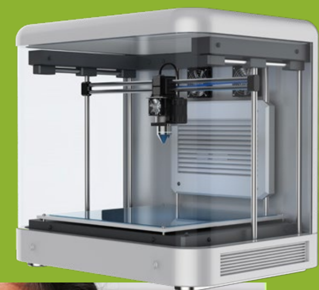
In this issue of Nanooze we will explore **nano-manufacturing** and the ways that new technology has made it possible to create nanometer-sized objects and devices using a whole new set of innovative materials.

A nanometer is one billionth (1/ 1,000,000,000) of a meter. When you get to that kind of small (really, really, unbelievably small), making things isn't easy. It isn't like putting together two tiny pieces of wood with a tiny nail and a tiny hammer (and pretty good aim). Nano-manufacturing requires a whole new set of tools and equally important materials.

Traditional nanofabrication using photolithography is limited to certain types of materials (such as silicon) and a limited number of shapes and sizes. Over the past few years, the notion of what you can make at the nanoscale has expanded. Nano-manufacturing has the potential to create super small things that can move around electrons (that's really tiny) and other complex things like liquids and even cells.

Nano-manufacturing allows engineers to make things from the bottom up instead of from the top down.

In top-down manufacturing, parts of a layered material are selectively removed. In bottom-up manufacturing, material is laid out in a very precise way. The biggest advance in nano-manufacturing is the development of 3D printing, with nanometer-scale precision. 3D printers are continuing to improve and are capable of making things smaller and smaller with innovative materials.



3D printing technology is getting better (and smaller) every year. It is now possible to create nanometer-sized things with 3D printing techniques.

It's a lot more complicated. Nano manufacturing isn't accomplished with tiny hammers. It requires a whole new set of specialized tools.

Images: Adobe Stock

NANO KNOW-HOW

Learning about nano stuff is fun, but it can be complex, so it helps to keep these four important facts in mind:

1. All things are made of atoms.

It's true! Most stuff, like you, your dog, your toothbrush, your computer, is made entirely of atoms. Things like light, sound and electricity are not made of atoms, but the sun, the earth and the moon are all made of atoms. That's a lot of atoms! And they're incredibly small. In fact, you could lay one million atoms across the head of a pin.

2. At the nanometer scale, atoms are in constant motion.

Even when water is frozen into ice, the water molecules are still moving. So how come we can't see them move? It's hard to imagine that each atom vibrates, but they are so tiny that it's impossible to see them move with our eyes.

3. Molecules have size and shape.

Atoms bond together to form molecules that have different sizes and shapes. For instance, water is a small molecule made up of two hydrogen atoms and one oxygen atom, so it is called H_2O. All water molecules have the same shape because the bonds between the hydrogen atoms and the oxygen atom are more or less the same angle.

Single molecules can be made up of thousands and thousands of atoms. Insulin is a molecule in our bodies that helps to control the amount of sugar in our blood. It is made up of more than one thousand atoms! Scientists can map out the shapes of different molecules and can even build most types of molecules in the lab.

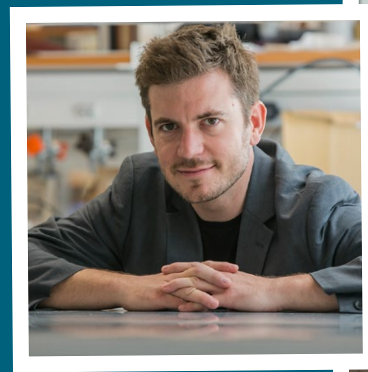
4. Molecules in their nanometer-scale environment have unexpected properties.

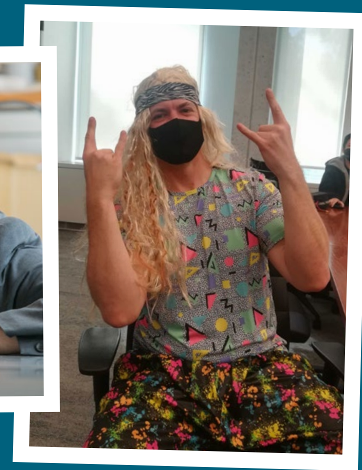
The rules at the nanometer scale are different than what we usually encounter in our human-sized environment. For instance, gravity doesn't count because other forces are more powerful at the molecular level. Static and surface tension become really important. What is cool about nanotechnology is that we can make things that don't behave like we expect. ***Things are really different down there!!***

Q&A

with
Rob Shepherd

Professor and Materials Scientist





Scientists are also known to have a fun side and this is Prof. Shepherd dressed up for a lab meeting on Halloween. Properly masked, because you need to be careful.

Rob Shepherd is a materials scientist who is inventing new ways to make things. His work involves 3D printing and molding to create structures and tiny channels to move liquids.

What is your current job and what do you like about it? Professor and researcher. I love it because I get paid to learn and teach what I learn. Many people have to balance work and learning—we don't!

What is a typical day like for you? There is no typical day! There are papers and grants to write, literature to review and read, coursework to prep, committees to serve, research talks to give, and this mix varies day to day. It is exciting, but stressful at times.

When you were a kid, what did you want to be? And if it wasn't a scientist, what was it and why did you change your mind? I first wanted to be a detective from all the Sherlock Holmes I was reading. Later, in high school, I watched a television show called "Next Step" on the Discovery Channel that featured stereolithography 3D printing—when I saw a plastic skull being pulled out of a liquid resin, I was sold. I wanted to be a materials scientist after that.

What did you do to get your current job? What kind of education did you need? I dug deep into polymer physical chemistry as it pertained to material processing. I felt it required a doctorate degree to innovate at the molecular level for additive manufacturing processes, but have also discovered there is room for important innovation at all education levels.

Tell us something fun about yourself. And it doesn't have to be about science. I've started to fall in love with wood. I live on land where two to three large trees fall down each year, and when I open up slabs with a mill, they reveal unique and beautiful grain. Nature makes the beauty and I just need to reveal it. I'm now learning woodworking tools to turn this natural and beautiful material into useful objects. Though I am using power tools, I try to use manual ones where feasible—it helps me feel more connected to our past. Note: I am still awful at woodworking. I'll report back in a decade on my progress.

Studying Snake Skin

One example of Professor Shepherd's work is designing new devices that are modeled after the structures in the skin of the puff adder snake. He and his student Rachel Miller (who has been studying nano since high school) are trying to figure out how the puff adder is able to mask its scent to help it hide from predators.

The puff adder snake.

A soft negative replica of the surface of puff adder skin.

TINY GIZMOS!

Humans have built some pretty amazing tiny things!

Over the years, lots of cool nanoscale things have been made. Most of these things are not serious tools or functional items, but they are fun and demonstrate how far the fabrication process has come. Scientists do try to have a nano-scale bit of fun now and again. While the claim of "world's smallest [fill in the blank]" is a little hard to prove since you need a big fancy microscope to even see them, here are a few prime examples.

Compare to Shaq's shoe

How many of each nano-scale object would fit the length of Shaquille O'Neal's shoe? He wears a size 22—that's 14.6 inches (370,000,000 nanometers) long.

SIZE 22
14.6 inches long

370,000,000 nanometers

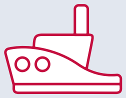
Leiden University

A BOAT!

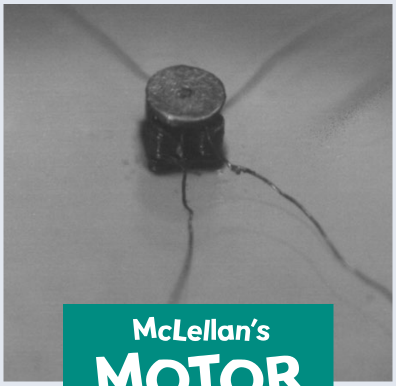
Made in 2020

Ahoy, mates—all aboard! The world's smallest boat was made by engineers in the Netherlands at Leiden University. It was 30,000 nanometers in length, meaning a standard-sized bacteria (typically 1,000 nanometers) could have been its captain. Why a boat? These engineers were interested in researching how to make micro-swimmers and the boat was a way to test some shapes and how they might move through the water. Safe travels to you, nano boat, because if you run into a hair it will be like the Titanic running into an iceberg.

12,333 boats would fit along the length of Shaq's shoe.



30,000 nanometers



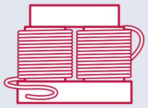
Caltech Archives

McLellan's MOTOR

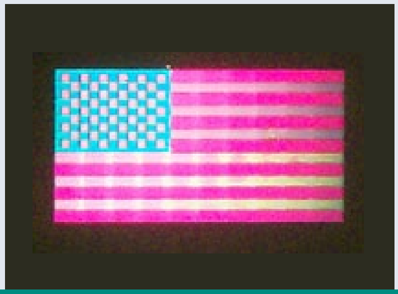
Made in 1959

This motor (that really works!) is an oldie but goodie, made in the days when nanofabrication was just at its beginnings. The original challenge offered by the famous nanotechnologist Richard Feynman was to build an operating motor that was no bigger than 1/64 of an inch on a side (400,000 nanometers). William McLellan, a very skilled machinist, succeeded, although he didn't really use any new nanofabrication methods. But in 1959, this was an amazing accomplishment no matter how it was done.

925 motors would fit along the length of Shaq's shoe.



400,000 nanometers



Cornell University

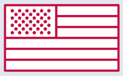
Smallest AMERICAN FLAG

Made in 2004

The smallest American flag was made at Cornell University. It isn't just a nanofabricated object but something that shows its colors. Colors are generated by dyes, but they can also be made by diffraction. Think about a rainbow—it is water droplets suspended in the air that take sunlight and divide it up to produce colors (red, orange, yellow, green, and blue). If you take a piece of silicon and make ridges spaced out at a precise distance, you can produce blue light. Make the spaces a bit bigger and you get green, even bigger and you get red... Engineers made a nano-sized flag that was 500 nanometers across, and even a White House, for the science advisor to the president of the United States.

and the White House!

740,000 flags would fit along the length of Shaq's shoe.



500 nanometers

Cornell University

A SAXOPHONE

Made in 2000

Making nano-trinkets is something of a thing for engineers at Cornell University. The world's smallest saxophone was made using photolithography techniques to etch silicon. Each saxophone was about 8,000 nanometers long and 6,000 nanometers wide, or about the size of a red blood cell. What was extra cool was that 287,900 saxophones were used to make an image of then President Bill Clinton playing a…saxophone. What kind of sound did it make? Well, if you could purse your lips small enough and blow, it wouldn't make a sound because it is too small to vibrate and generate a sound you could actually hear.

46,250 saxophones would fit along the length of Shaq's shoe.

8,000 nanometers

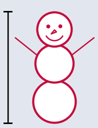
Smallest SNOWMAN

Image credit: Todd Simpson / Western University Nanofabrication Facility

Made in 2016

Most kids try to build the world's biggest snowman. But in 2016, engineers at Western University in Ontario, Canada, built the world's *smallest* snowman. Coming in at less than 3,000 nanometers high, this guy was built from three small spheres stacked one on top of another.

3,000 nanometers



123,333 snowmen would fit along the length of Shaq's shoe.

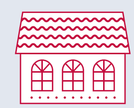
Smallest GINGERBREAD HOUSE

Image credit: Canadian Centre for Electron Microscopy / McMaster University

Made in 2019

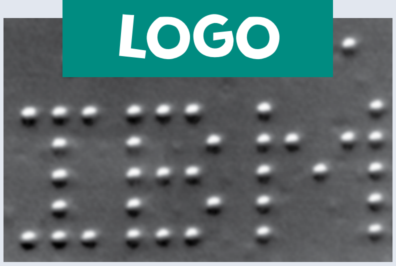
Where should the world's smallest snowman live? How about a gingerbread house that is only 10,000 nanometers long? Like the snowman, this little house was built in Canada, at McMaster University. And instead of gingerbread, it's made from silicon that was etched using a focused ion beam microscope. The house is decorated with a wreath and trees, and for the human's-eye view, they even etched the initials of the center (Canadian Centre for Electron Microscopy) on the roof.

37,000 houses would fit along the length of Shaq's shoe.



10,000 nanometers

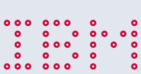
World's smallest LOGO



IBM

Made in 1989

Perhaps the most famous of all the super tiny creations is one of the simplest. In 1989, a group of scientists led by Don Eigler moved a total of 35 xenon atoms to spell out I-B-M. The entire logo was about **3 nanometers across**. This simple demonstration of moving atoms became an icon for nanotechnology. Eigler used a very special instrument called a scanning probe microscope that "sees" with a tiny needle as a probe. This needle is used to "feel" the contours of the surface and, if you're careful, it helps you "see" atoms. Under an extreme vacuum and very cold temperatures, the team at IBM moved those 35 atoms and got them to stay in place long enough to take a picture before they floated away.



3 nanometers

123,000,000 IBM logos would fit along the length of Shaq's shoe.

What nanoscale object would you build?

Additive Manufacturing

Building from the bottom up

TAKING AWAY AND BUILDING UP

For a long time, making small things like transistors involved a top-down process called photolithography. Most computer chip parts are made using photolithography, which is where a material is etched away in some areas leaving a complex pattern. This is a top-down process called *subtractive manufacturing*. The opposite process is called *additive manufacturing*, where material is added to specific places so structures are built by adding layer upon layer.

3D PRINTING

In the last 10 years, 3D printing has made new things possible in the manufacture of nanometer-sized objects. You might have even used a 3D printer—it has a nozzle that spits out molten polymer that quickly cools to form a solid. The key is the ability to control the position of the nozzle in two dimensions (front/back and left/right). Inkjet printers are similar to 3D printers, but they only print a single layer. In 3D printing, after the first layer is put down, the nozzle is raised a little bit and a second layer is put down. And so on, and so on, building up layer upon layer.

3D-printed objects are designed in a computer-assisted design (CAD) program. You can make replacement parts for something that is broken or make entirely new pieces using 3D printing. And since it starts off with a digital file, you can design something on one side of the country (or the planet) and easily make it in an entirely different place.

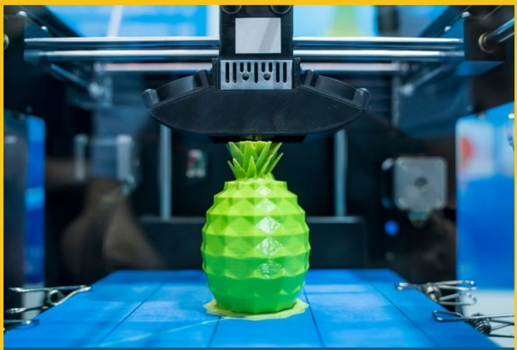
PRINTING WITH NEW MATERIALS

There are a lot of different polymers that can be used with 3D printers. The original polymers were mostly plastics that could be melted and then quickly solidify. There are polymers that are mostly plastics and others that are metallic and can conduct electricity. Even proteins and other biological materials can be "printed."

The first 3D printers were expensive and couldn't print out anything with any kind of fine details. But as the technology advanced, the resolution got a lot better. The best 3D printers can produce objects with features that are smaller than 25 nanometers using a tiny 1.6 nanometer nozzle.

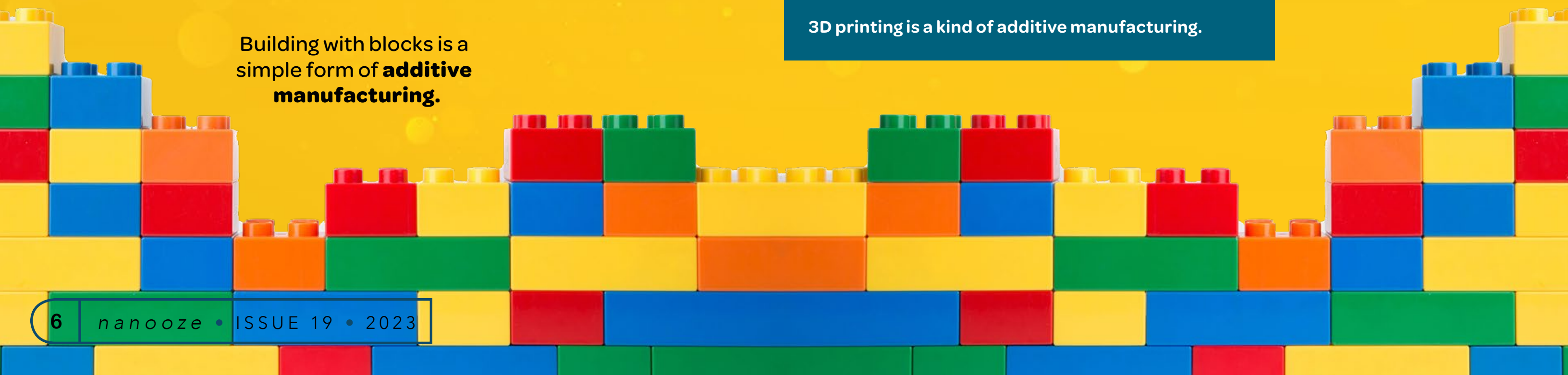
What are some of the crazy things that are being 3D printed? Well, for starters, replacement parts for repairing damaged parts of the human body, like ears and skin. Even food is being 3D printed, from simple things like fancy chocolate candies to really complicated things like fake meats, where the different bits we see in a steak, for instance—like muscle, fat, even bone—are printed using plant-based materials.

3D printing can produce complex objects.



3D printing is a kind of additive manufacturing.

Images: Adobe Stock



Building with blocks is a simple form of **additive manufacturing.**

Making Tiny Moving Parts

There's a lot that gets in the way

STATIC FORCES

It's one thing to build a nanometer-scale object that is solid or has no moving parts. But building something nano-sized that has moving parts, that's really tough.

It isn't easy to make small moving parts, let alone things that can move on their own. One of the problems is just controlling where these little things go because they're so tiny. Think about dust. It floats around and is blown by the wind. You can't really control where it goes. You can catch it by using something like dusting spray, but then it just sticks there. That's because things like static electricity are so powerful at the nanoscale—dust particles are so small that the dust defies gravity.

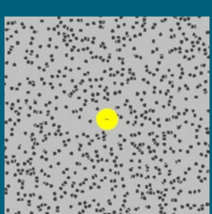
MINI MOVEMENTS

Another problem is something called thermal motion. When things get really small, let's say 1/1,000th the width of a hair, they vibrate almost uncontrollably. You have probably seen this kind of vibration when you look at tiny stuff in water under the microscope. This is called *Brownian motion,* and all of the rattling around makes it hard to keep little machines in one piece, so a tiny device would likely shake itself apart.

POWER CHALLENGES

Then there's powering the device. When something is about 100 nanometers long (1/1,000th the width of a hair), it is really tough to move it, especially in liquids. For something like a tiny submarine, you would probably need a battery that was something like 1,000 times bigger than the object itself! Tiny living things like germs can swim, but nobody is really sure how they power themselves with biological energy. That might be one way to power a tiny device, but we still have a lot of work to do to make it happen.

What is Brownian motion?

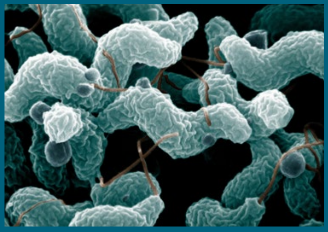


Brownian motion is the random motion of particles suspended in a liquid or a gas. In 1827 botanist Robert Brown observed the motion while examining pollen grains suspended in water under a microscope.

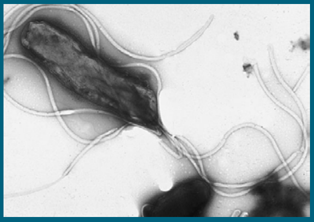
Watch Brownian motion in action!
See a simulation of a dust particle colliding with molecules of a gas.

Taking inspiration from bacteria

Scientists are studying **bacterial flagellums** to gain insight on tiny moving parts. These powerful propellers are only 20 nanometers thick and can stand up to the forces of Brownian motion.



Campylobacter jejuni
The most common cause of bacterial food-related gastrointestinal illness in the United States, it has a single flagellum at one or both ends.



Helicobacter pylori
bacteria have 4–6 flagella and are highly mobile. It is estimated that 50% of the world's population has this in their stomach.

Chlamydomonas
This single-cell algae with two flagella is found worldwide in soil and water.

Images: Wikimedia Commons

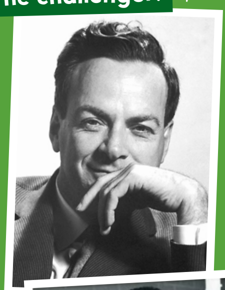
The World's Smallest Motor

Scan QR code to watch the clip from ***I've Got a Secret*** that features McLellan and his tiny motor.

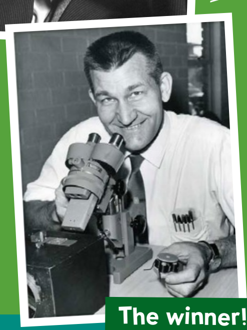
YouTube / Richard Carson

I want to offer a prize of $1,000 to the first guy who makes an operating electric motor that is only a 1/64 inch cube.

The challenger!



Wikipedia



The winner!

Richard Feynman (top) and William McLellan (bottom) with a scale model of his winning motor.

William McLellan: COURTESY OF THE ARCHIVES, PASADENA MUSEUM OF HISTORY

BIG CHALLENGE, SMALL FIELD

Richard Feynman is generally regarded as the father of nanotechnology. Before the word nanotechnology even existed, Feynman put out an outrageous challenge. He was smart and liked to provoke people to think big in a very small field.

THE CHALLENGE

In 1959, he issued a challenge to create a motor that would fit inside a 1/64 inch cube. How big is a 1/64 inch cube? Well, 1/64 of an inch is about 400,000 nanometers. A human hair is about 100,000 nanometers across so this motor needed to be less than 4 hairs wide. Making a small motor is hard; making one that moves and works is very, very hard.

Why is it hard? At the nanometer-scale, atoms are in constant motion, which makes creating very tiny moving parts a real problem. Then there is the additional challenge of powering that motor.

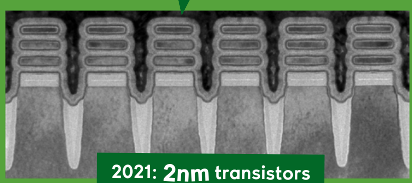
WILLIAM MCLELLAN TAKES ON THE CHALLENGE

One of the people who took on Feynman's challenge was William McLellan, a very talented electrical engineer. McLellan delivered a tiny 250 microgram motor that had 13 parts and required a microscope to see it. His tiny motor was smaller than the periods on this page. Feynman was hoping that the person who took on the challenge would develop some revolutionary technology to make super small things. Alas, McLellan used conventional machining techniques and a very steady hand. One of his tools was a toothpick that was used to move the tiny parts around.

McLellan's motor was driven by electricity and had a set of four coils and a rotating disc, so he did manage to build a tiny motor that actually worked. For this feat, Feynman paid him $1,000, as promised. McLellan also received a certain amount of fame, appearing in the 1960s TV show "I've Got a Secret" (kind of like 20 questions), but the panel failed to guess his secret. McLellan remained at Caltech in the Department of Astronomy for the rest of his life and never stopped tinkering with things, from cars to kid's toys.

1959: 20,000nm transistor

10,000 times smaller



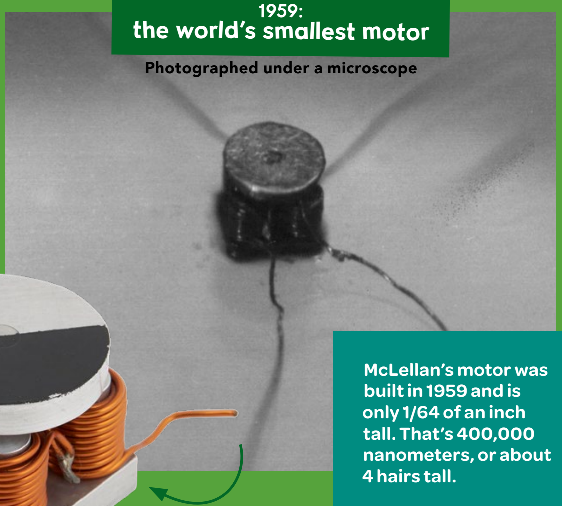
2021: 2nm transistors

IBM

In 1959, a transistor was about 20,000 nanometers across and today transistors are as small as 2 nanometers.

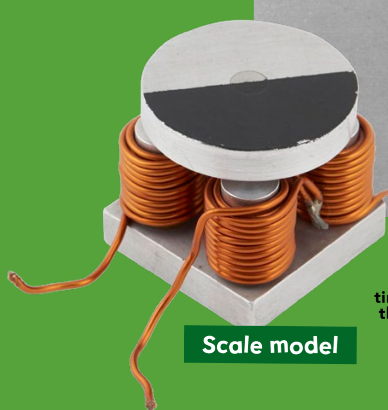
1959: the world's smallest motor

Photographed under a microscope



Caltech Archives

McLellan's motor was built in 1959 and is only 1/64 of an inch tall. That's 400,000 nanometers, or about 4 hairs tall.



100 times bigger than the actual motor

Scale model

20,000nm transistor: Adobe Stock, Scale model: Science Museum Group