
A Comparison of Scale: Macro, Micro, Nano

Primary Knowledge

Participant Guide

Description and Estimated Time to Complete

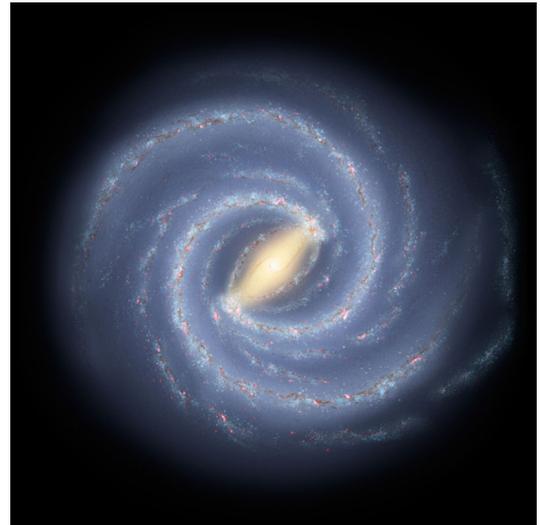
In order to grasp many of the concepts associated with MEMS and MEMS devices and components, you need to understand scale and the size of objects associated with different scales. This unit introduces you to various concepts associated with scale, and a comparison of the macro, micro and nano-scales.

Estimated Time to Complete

Allow approximately 30 minutes to complete.

Introduction

At one time or another everyone has asked the question "How big is the universe?" Trying to develop the answer can be overwhelming because there is no answer. The size of the universe is unknown; however, the size of objects within the universe is known. These objects are constantly being studied, measured, and compared. These comparisons are a means of evoking some sense of scale as to how big the universe could be. For example, the Milky Way (*pictured above*) is one of billions of galaxies. Our sun is one of several 100 billion stars within The Milky Way. There are over 50,000 billion, billion stars. There are more stars in the universe than there are grains of sand on our planet.¹



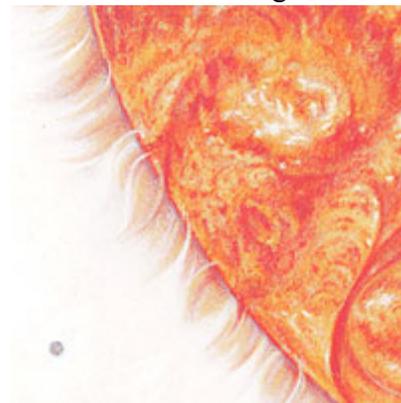
The Milky Way
[Image credit: NASA/JPL-Caltech²]

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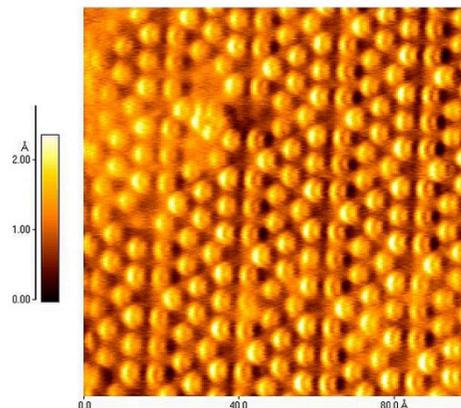
Our sun is considered a middle-sized star. Giant stars are as much as 10 times larger. However, when compared to Earth, the sun is approximately 109 times larger in diameter meaning that 1.3 million earths could fit inside the sun! Do the math!

The sun is much larger than Earth. From the sun's center to its surface, it is about 109 times the radius of Earth. Some of the streams of gas rising from the solar surface are larger than Earth.

[Image source: NASA - Image credit: World Book illustration by Roberta Polfus]



For years astronomers have explored the universe looking for hints as to how big it really is. At the same time, other scientists have been exploring how small things are and how small something has to be before it goes beyond the reach of manipulation or measurement. In these explorations, another whole universe has been discovered, but on a much smaller scale. Instead of objects being measured in kilometers and light-years, objects are measured in micrometers and nanometers, and even the number of atoms (*see image right*).



This unit will explore the concept of scale:

- what is big,
- what is small, and
- how do these objects compare in size?

When working with micro and nanotechnologies it is important to have an understanding of size and of scale. This will lead to a better understanding of the processes and applications used in these technologies.

This atomic force microscope image by German physicist Franz Giessibl shows dozens of silicon atoms. Scientists have debated whether the light and dark crescents - or wing-shaped features seen on the atoms represent orbitals - the paths of electrons orbiting the atoms. [Printed with permission. See F. J. Giessibl et al., Science 289, 422 (2000)]

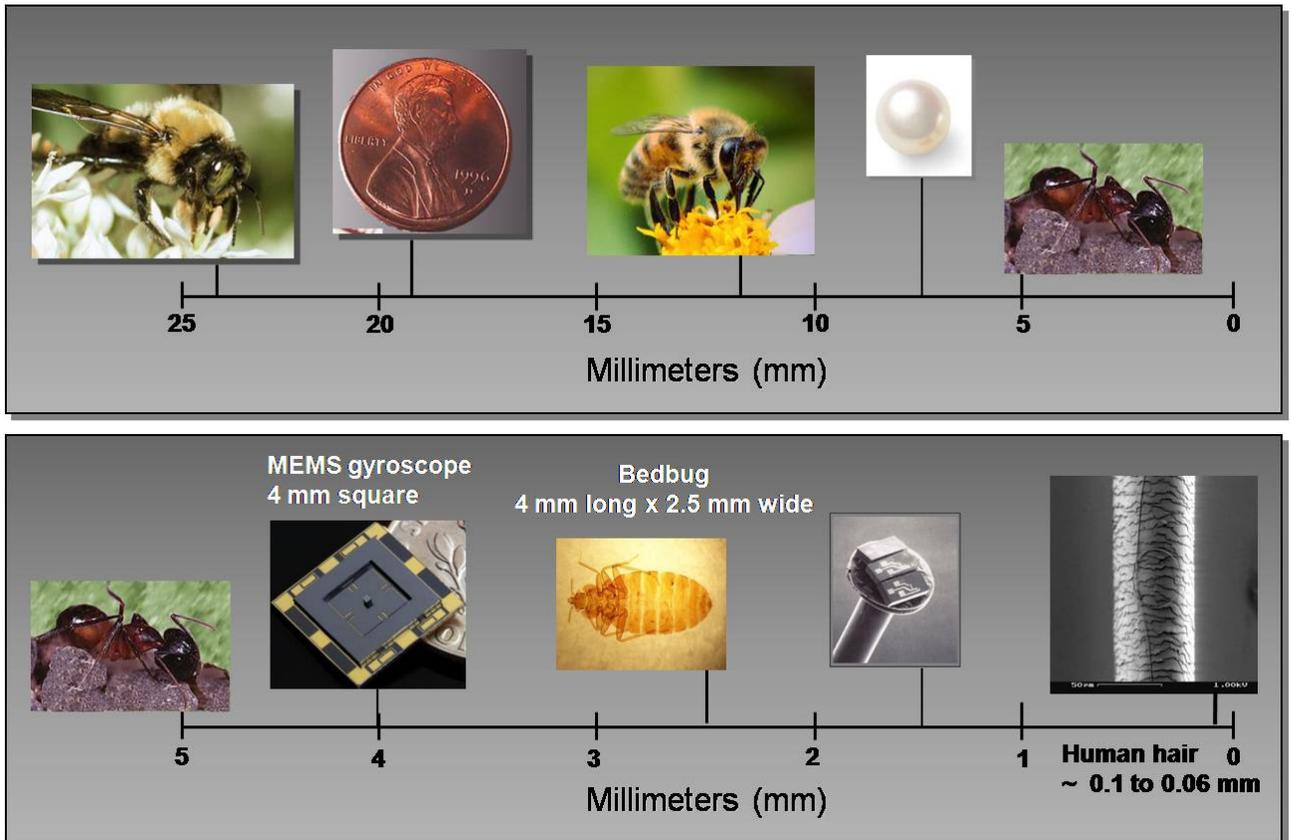
Objectives

- Explain the differences in the macro, micro and nano scales in terms of size, applications, and properties.
- Define microtechnology and nanotechnology.
- Identify objects and applications in the micro-scale and the nano-scale.

Key Terms (Key terms defined in Glossary at the end of this unit)

Linear Scale
Logarithmic Scale
Macroscopic
MEMS
Micro
Micrometer
Micron
Nano
Nanometer
Nanotechnology
Scale

Size is Relative



Size is Relative

"The sun is big" is a relative statement. Big relative to what? "An ant is small." Again, another relative statement. Relative to the size of a human being, yes, an ant is small (anywhere from 2mm long to 25 mm long); however, relative to a human hair (0.1 to 0.06 mm), an ant is huge.

The comparative size of an object in relative terms (big, small, huge) can be illustrated in a scale. In the top scale of "Size is Relative", the ant is the smallest object. However, in the bottom scale the ant is the largest object. Additional comparison scales could be created at both ends of these two scales illustrating even smaller and largest objects.

Question: *In the top scale, the ant is the smallest object. What are three additional objects that could be added to this scale that are bigger than the ant, but smaller than the bumblebee?*

Scale is a Relationship

Scale is the relationship between what is being compared and how that relationship is represented numerically or visually. Two scales can look very similar, but be completely different in the range represented. Two objects can look the same size, but when put in the correct scale, the difference becomes obvious. Take a look at the two objects in the figure. They look close to the same size, don't they? In reality, the ant is approximately 5 mm in length and red blood cells are approximately 5 μm in diameter or 1,000 times smaller!



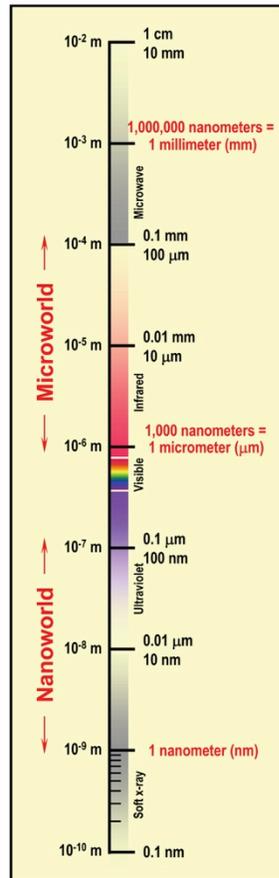
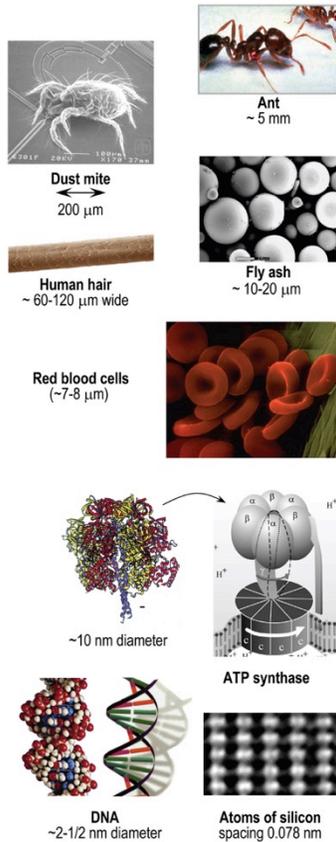
How Big is Small?

- One light-year is 9,460,730,472,580.8 km or about 9.5×10^{15} meters!
- One kilometer (km) is 1000 meters or 1×10^3 meters.
- One micrometer is 10^{-6} (a millionth) of a meter.
- One nanometer is 10^{-9} (a billionth) of a meter.
- One kilogram (kg) is 1000 grams or 1×10^3 grams.
- One milligram (mg) is 10^{-3} (a thousandth) of a gram.
- An attogram is 10^{-18} of a gram.

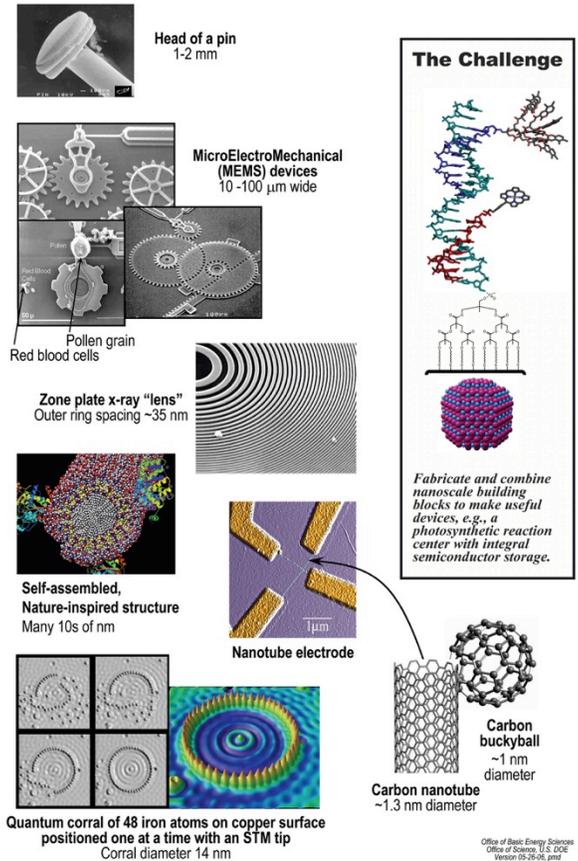
The Scale of Things

The Scale of Things – Nanometers and More

Things Natural



Things Manmade



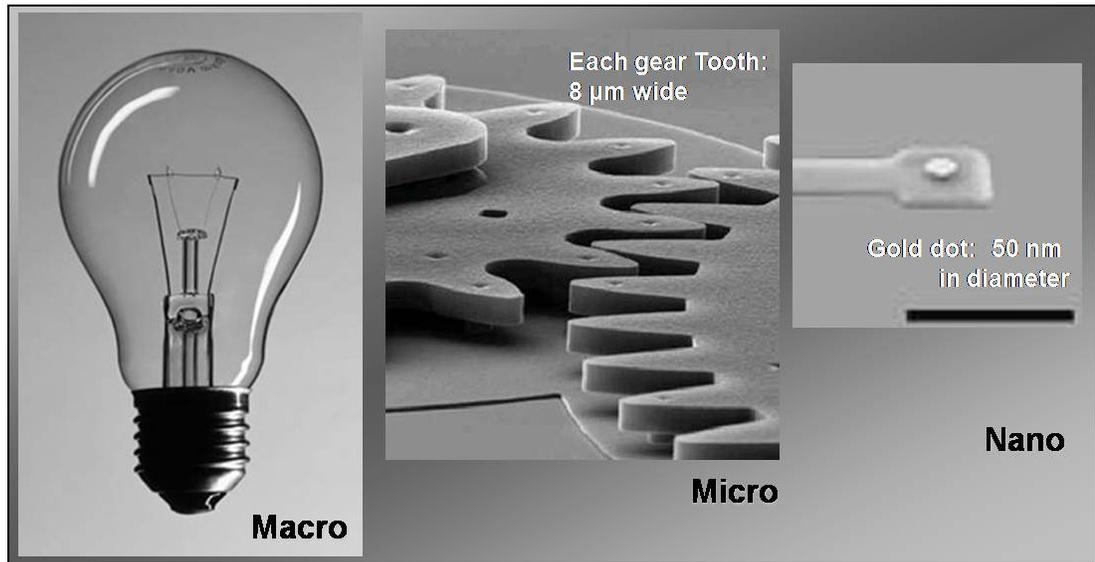
The Challenge

Fabricate and combine nanoscale building blocks to make useful devices, e.g., a photosynthetic reaction center with integral semiconductor storage.

[Graphic courtesy of the Office of Basic Energy Sciences, U.S. DOE]

In the above chart "The Scale of Things – Nanometers and More", you can get a feeling of how things can look the same size, but when placed next to a scale, the real size becomes more apparent. Take a few minutes to study the objects on this chart. Which would you consider macro (large than micro)? Which objects would you place in the micro-scale and which objects in the nano-scale?

Macro, Micro and Nano – What's the difference?



Macro, Micro, Nano

[Micro image of microgears courtesy of Sandia National Laboratories]

[Nano image Printed with permission Craighead Group/Cornell University and © Cornell University]

Macro – anything that can be seen with the naked eye or anything greater than ~100 micrometer.

Micro – 100 micrometers to 100 nanometers

Nano – 100 nanometers to 1 nanometer

Electrical and mechanical devices, components and systems are being manufactured in a variety of sizes from macro to nano. The figure shows such components:

- Standard light bulb with a diameter of ~8 millimeters (mm) or 3.2 inches
- Microgears with individual gear teeth ~8 micrometers (μm) wide
- Microcantilever with a gold nano-dot 50 nanometers (nm) in diameter.

In commercial and residential electrical applications, components such as switches, light bulbs and fans are macro-size objects (greater than 100 micrometers). Airbag actuation sensors, shock sensors for computers and implantable drug delivery systems are micro-sized objects. Biomolecular sensors for proteins and antigens, carbon nanotubes as connectors, and gene analysis devices are nano-sized objects.

Can you add objects to the following table?

| Macro | Micro | Nano |
|--------------|------------------|----------------------|
| Switches | Microswitches | Carbon Nanotubes |
| Light bulbs | Inertial sensors | Biomolecular sensors |
| Fans | Chemical sensors | Biomolecular motors |
| Pumps | Micropumps | |

Table 1: Macro, Micro and Nano Objects

A Sense of Size

A honey bee is approximately 12 mm long
A human hair is 60 to 100 micrometers in diameter
A red blood cell averages about 7 micrometers in diameter
The DNA helix is 0.002 micrometers wide or 2 nm wide.

Something for you to do: Estimate the size of other objects that you are familiar with.

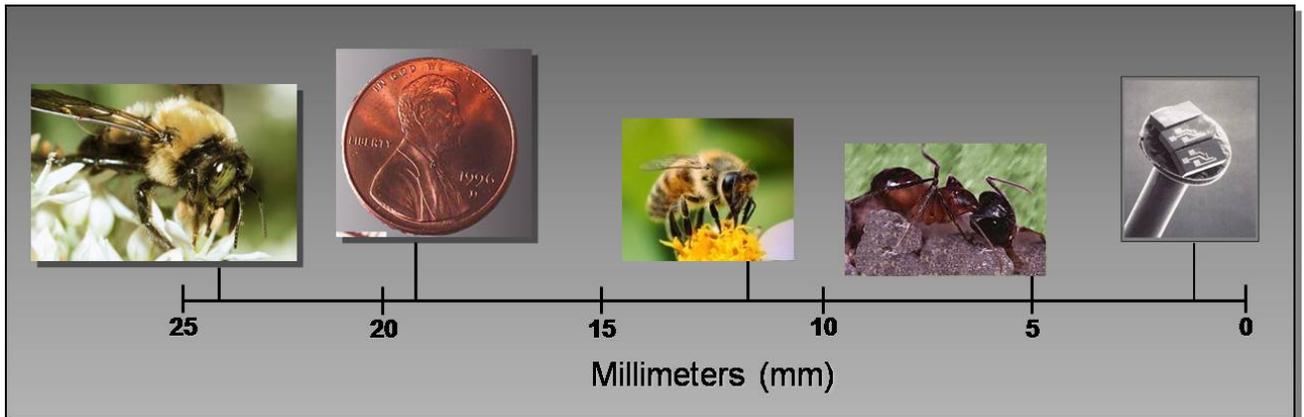


This is a good time to take a break and do one of the activities in this Scale Learning Module. A **good activity to do is "Cut To Size."**

Scales

As seen in previous graphics, a good way to compare the size of different objects is to place the objects on a scale. There are two basic scales that are used: the linear scale and the logarithmic scale. Following is a brief discussion and illustration of both types of scales.

Linear Scales

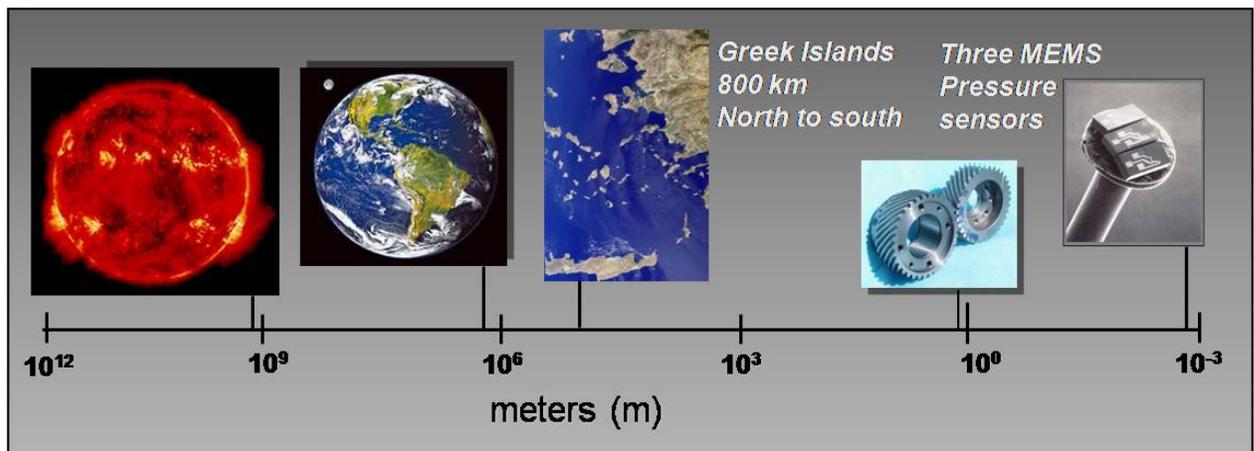


Linear Scale

In a linear scale each increment and incremental increase is equal to the one before (in other words – equal divisions for equal values). For example, the linear scale above goes from 0 millimeters to 25 millimeters in 5 mm increments. This scale works fine when the total range in the size of objects is small, such as illustrating the sizes of five objects from the size of a bumble bee (~24 mm long) to the size of a pinhead (~1 mm in diameter).

Can you estimate the size of each object in the scale?

Logarithmic Scales

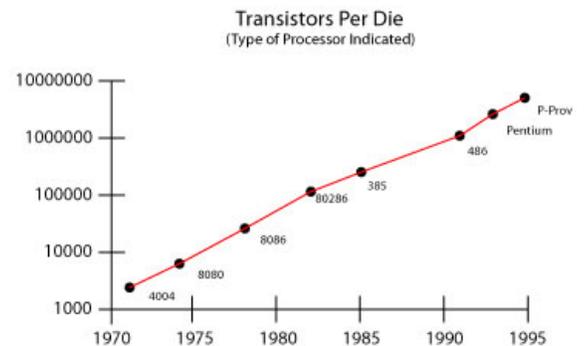
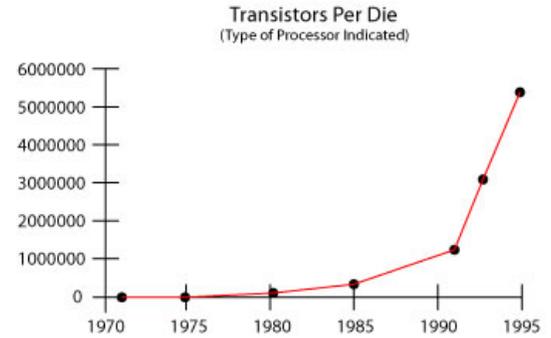


Logarithmic Scale

But what happens when the range becomes bigger (e.g. from 1.5 Gm to $5 \mu\text{m}$)? In such a comparison, a linear scale is not practical, nor as effective; therefore, a logarithmic scale could be used (*above*). A logarithmic scale uses the logarithm of a physical quantity rather than the quantity itself. It is effective for comparing the relative size of objects when the actual range in size is huge. The above graph covers a range from the diameter of the sun (1.39 Gm) to the size of a pin head (1.5 mm). Imagine how long a linear graph would be that compared these objects.

Linear vs. Logarithmic

These two graphs above illustrate the exact same information, but look how different they look. They both show the increase in the number of transistors per die from 1970 to 1995. The graph on the top is a linear scale and the one on the bottom is a logarithmic scale. Notice in the linear scale, the growth is easily seen as being exponential. In the log scale, it almost looks linear; however, since it is logarithmic, you can easily see that the growth between 1970 and 1975 went from over 1000 to just under 10,000 transistors per die. Between 1990 and 1995, the growth was from 1,000,000 to almost 10,000,000 per die! That's a significantly larger increase. By 2008 transistors per die has increased to over 200 million!



Macro vs. Microdevices

When comparing macroscopic devices to their micro equivalents, the micro devices are

- much smaller,
- much lighter,
- more energy efficient, and
- constructed with fewer materials.

In equivalent applications, such as sensors or transducers, microdevices exceed their macroscopic equivalents in

- reliability,
- efficiency,
- selectivity,
- response time, and
- energy consumption.

Micro-sized objects allow us to go places where no objects have gone before.

Microtechnology

"Microtechnology is the art of creating, manufacturing or using miniature components, equipment and systems that have been mass produced. The first and foremost feature in this field is its multidisciplinary nature, as microtechnology systems use electronic, computerised, chemical, mechanical and optical elements as well as various other materials." [Federal School of Polytechnics]⁵

The products of Microtechnology are microsystems and microsystem components.

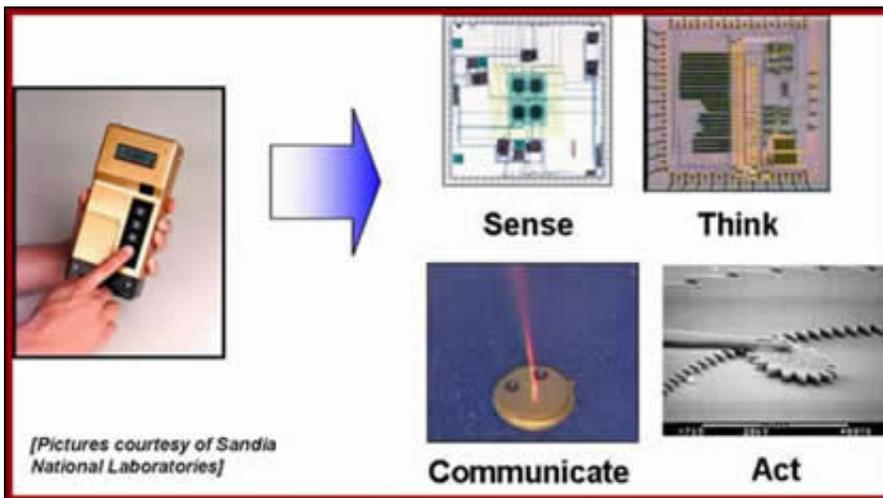
What are Microsystems?

Microsystems are miniaturized integrated systems in a small package or more specifically, micro-sized components working together as a system and assembled into a package that fits on a pinhead (*see figure above*). In the United States, these devices are referred to as microelectromechanical systems or MEMS. European countries referred to such devices as microsystems or MST. These two terms – MEMS and MST – are often used interchangeably.

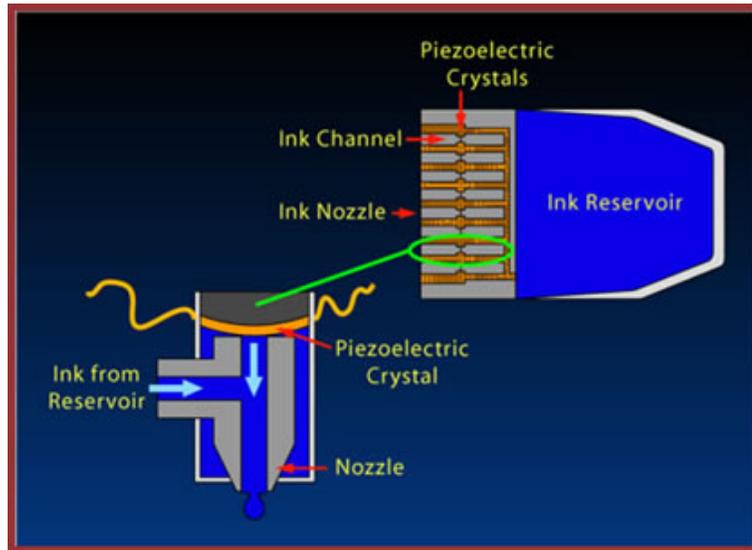


*Three MEMS blood pressure sensors on a pin head
[Photo courtesy of Lucas NovaSensor, Fremont, CA]*

Microsystems are microscopic, integrated, self-aware, stand-alone products that can sense, think, communicate and act. Some systems can do all of these things, plus scavenge for power.



Microsystems Applications

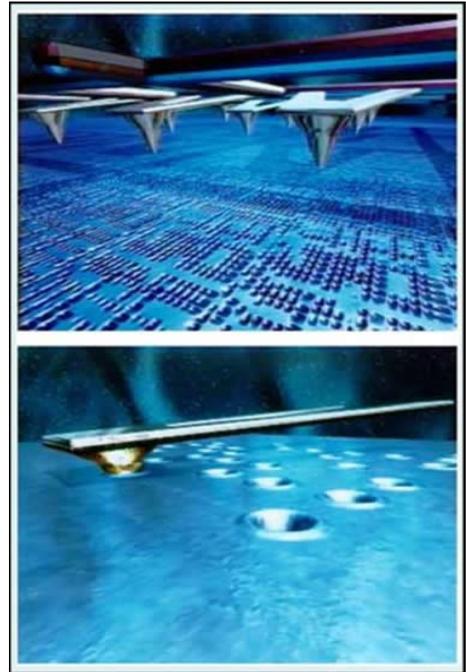


MicroFluidic pump used for inkjet printheads (The piezoelectric crystal expands and contracts to move fluid from the reservoir through the nozzle)

- ❖ Ink Jet Print Heads (*see figure*)
- ❖ Automobile applications (flowrates, tire and oil pressures, crash sensors, airbag deployment)
- ❖ Biomedical applications (drug delivery, diagnostics, therapeutics)
- ❖ Optical applications (digital light processing, microoptoelectromechanical systems, digital mirror devices)
- ❖ Homeland security (gas detections, motion detectors)
- ❖ Environmental applications (earthquake, volcano and tsunami sensors, atmospheric sensors)
- ❖ RF (Radio Frequency) MEMS (digital communications, switching)
- ❖ Mass Storage Devices
- ❖ Aerospace (leak detection, vibration sensors, positioning, navigation, monitoring space personnel health)

Nano meets Micro

The smaller microsystems become the smaller their components become. For example, IBM has been working on a read/write storage device that can fit 1 Terabit of data on a surface the size of a standard postage stamp.⁶ In order to do this, the "bit-making" component needs to be nano-size, not micro-size. Hence the overlap occurs of micro and nano devices. In the IBM read/write storage devices, the cantilevers are approximately 2 microns wide while the read/write tip is approximately 10 nm wide at the apex (see figure right).



MEMS Read/Write Storage Device (IBM Millipede – prototype) [Photo courtesy of IBM]

Nanotechnology

The term Nanotechnology is so new, that how it is defined, depends on who you ask. Below are some definitions of Nanotechnology:

"Nanotechnology is the understanding and control of matter at dimensions of roughly 1 to 100 nanometers, where unique phenomena enable novel applications. Encompassing nanoscale science, engineering and technology, nanotechnology involves imaging, measuring, modeling, and manipulating matter at this length scale." National Nanotechnology Initiative (NNI)

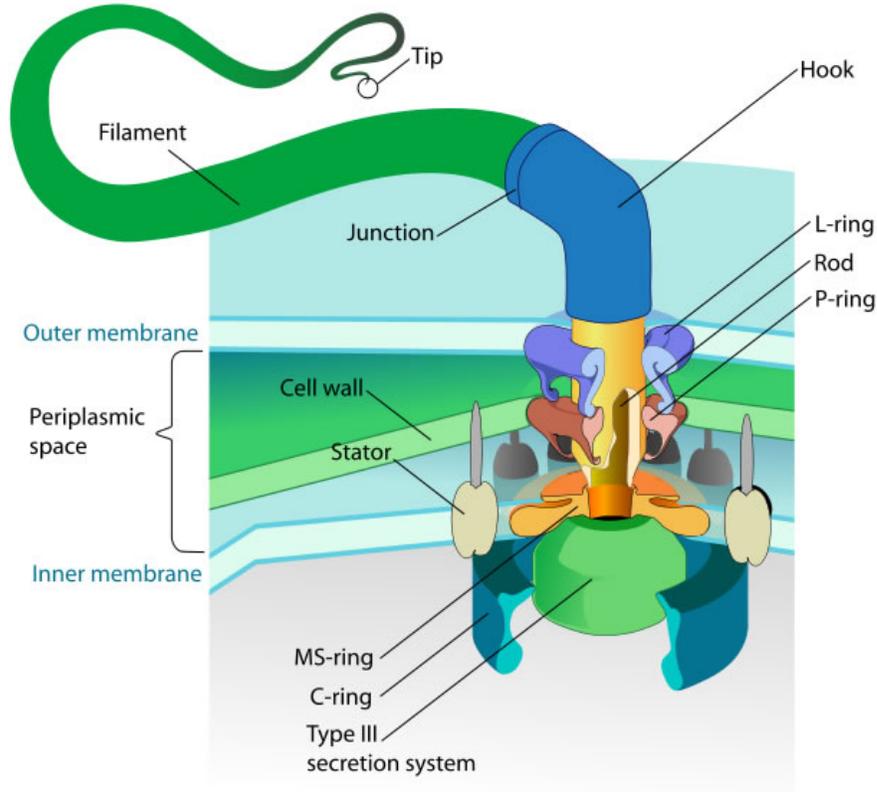
- *"Research and technology development at the atomic, molecular or macromolecular levels, in the length scale of approximately 1-100nm range.*
- *Creation and use of structures, devices and systems that have novel properties and functions because of their small and/or intermediate size.*
- *An ability to control or manipulate on the atomic scale."*

MANCEF Roadmap 2nd Edition, p.161 (based on NNI)

"The name nanotechnology originates from [the] nanometer. In the processing of materials, the smallest bit size of stock removal, accretion or flow of materials is probably of one atom or one molecule namely 0.1-0.2nm in length. Therefore, the expected limit size of fineness would be of the order of 1nm. Accordingly, nanotechnology mainly consists of the processing of separation, consolidation and deformation of materials by one atom or one molecule."

N. Taniguchi, "on the Basic Concept of Nanotechnology," Proc. Intl. Conf. Prod. Eng. Tokyo, Part II – Japan Society of Precision Engineering, 1974

Nanoscience



Structure of a bacterial flagellar motor.

The flagellum is used to move the bacterium through the system. The flagellum is powered by the rotary engine anchor to the cell wall and powered by proton motive force. The rotor can rotate at speeds as high as 17,000 revolutions per minute, moving the flagellar filament at speeds as high as 1000 rpms. Microtechnology is studying this biomolecular devices to see if it can be manufactured and use to move cargo such as medicine to specific parts of the body..⁷

[Image courtesy of LadyofHats]

Nanotechnology, or more specifically, nanoscience has been around for quite a long time. Nanoscience is concerned with the study of novel phenomena and properties of materials that occur at extremely small length scales.

Physicists and biologists have been studying nanodevices such as cells, molecules, and atoms for years, and in some cases, centuries. In the 18th century, John Dalton, a British chemist and physicist, made the earliest steps toward recognizing that matter was composed of atoms. In 1952, a series of experiments by Alfred Hershey and Martha Chase, known as the "Hershey-Chase Blender Experiments", supported the role of DNA as the carrier of genetic information.

Nanotechnology is the application of nanoscale science, engineering and technology to produce novel materials and devices.

So what is Nano?

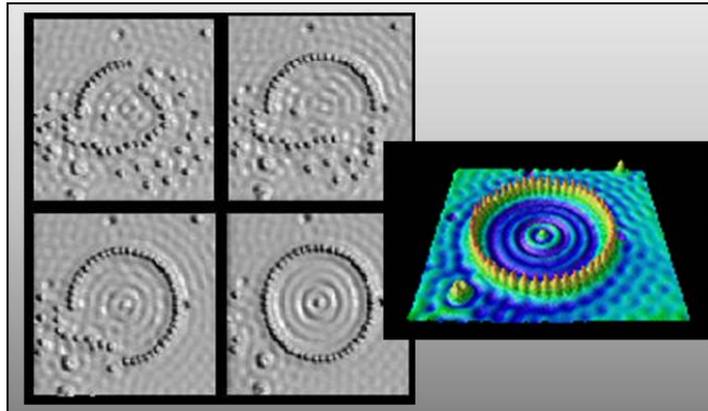
Nano is a lot of things:

- Anything less than 100 nm in any dimension regardless of how it was made.
- Anything made by specifically placing materials atom by atom or molecule by molecule.
- Anything made from the bottom up (one atom at a time).
- Anything with unique properties because of its small size (Some of the laws of physics that apply to macroscopic objects, do not apply to nano-size objects).

Micro vs. Nanotechnology

In addition to the actual size of the objects, fabrication is another primary difference between micro and nanotechnology. Nanotechnology normally uses what is referred to as the "bottom up" approach to fabrication. Microtechnology normally uses the "top down" approach.

Bottom up



*Assembling a quantum corral
[Images courtesy of IBM STM Image Gallery]*

The bottom up approach means a structure is made by building it atom by atom or molecule by molecule from the bottom up. Each individual atom or molecule is manipulated or controlled for correct placement.

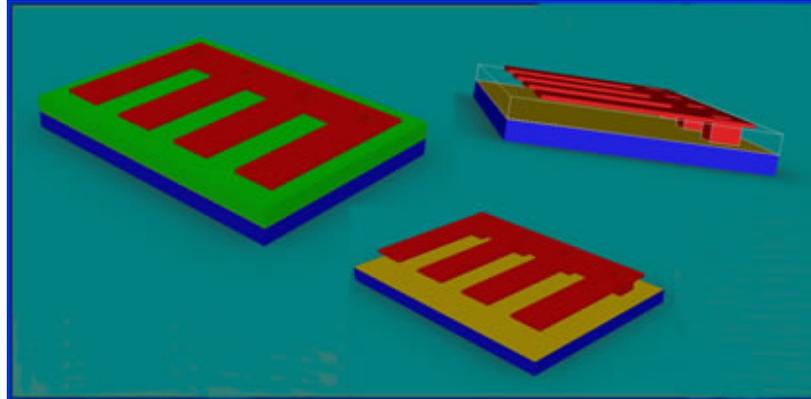
The figure on the left (*above*) shows four stages in the assembly of a quantum corral. The figure on the right (*above*) shows the final assembly of a corral that has been made by placing 48 iron atoms in a circle, one at a time, onto the surface of gold.

So what does the bottom up approach sound like?

Nature or the building of a living object.

- The cells of a seed multiply to become a full blown tree.
- The tree continues to grow by taking individual atoms and molecules and assembling its leaves.

Top down



Creating suspended cantilevers using the top down approach

The top down approach selectively removes material until the desired structure is achieved. In semiconductor and some MEMS processes, one

- applies a pattern,
- selectively etches away exposed material and
- ends up with a circuit or component (*as illustrated above*).

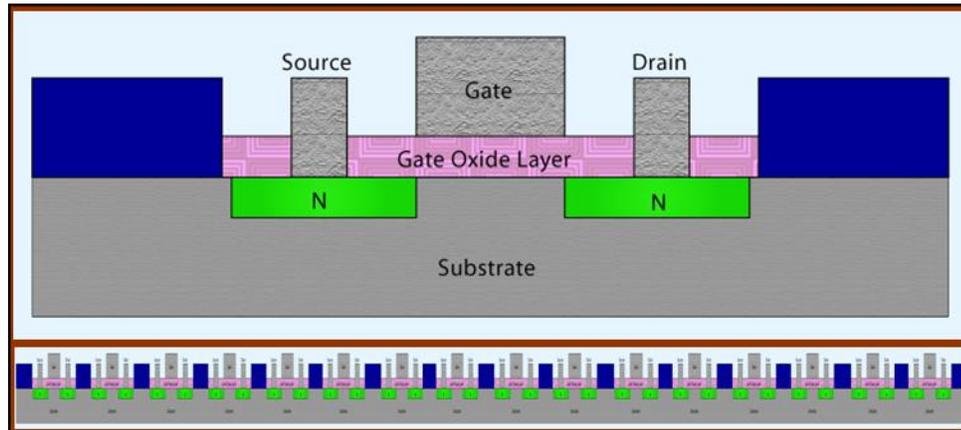
The above graphic shows how microcantilevers (red) are initially incorporated into a block of layered material. By removing the layer below (green), the microcantilevers are released and suspended over the substrate (blue).

What does the top down approach sound like?

Sculpturing

A sculptor can start with a tree trunk and by removing select pieces of the tree, end up with a totem pole, bird, desk, or any desired object. What about Mount Rushmore? How was that made? Start with a cliff, and remove everything that doesn't look like a president!

Shrinking Technology



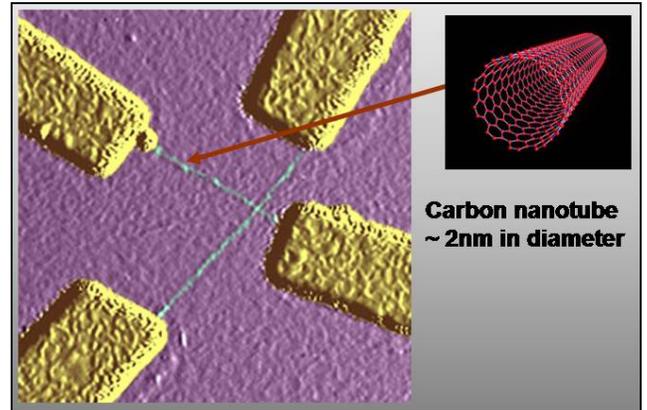
The space of one transistor, now holds hundreds of transistors (graphic not to scale)

Semiconductors have evolved over the years with technological advancements in the deposition of materials and the selective removal of materials through the photolithography and etch processes. Deposition layers have become thinner and etched widths have become smaller (*see figure*).

A deposited gate oxide layer used to be 20 microns or larger. Now it can be as thin as 1 nm! Gate widths, patterned and subsequently etched have shrunk from more than 1 micron dimensions to less than 50 nm! Since today's semiconductor manufacturing processes are creating structures less than 100 nm, this technology can be considered Nanotechnology.

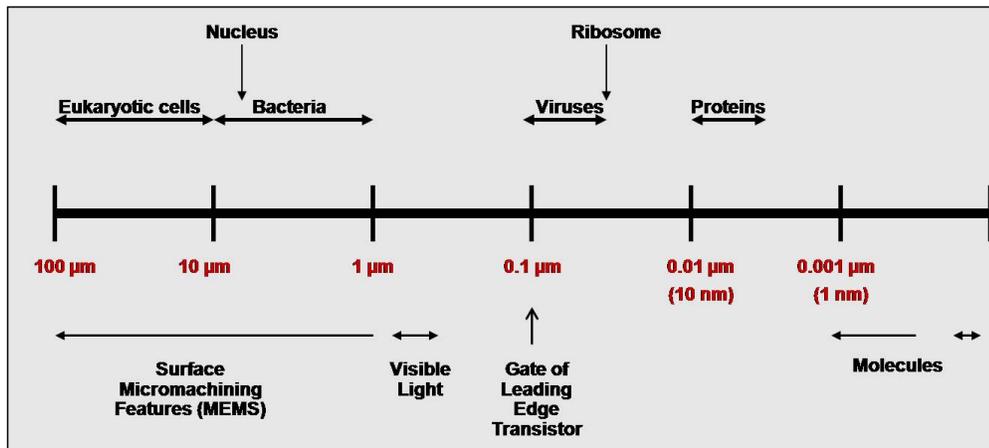
Nano meets Micro

As devices shrink, the necessity to use nano-sized objects when constructing micro-sized devices increases. Take for instance the electronic electrodes shown in the figure to the right. The image on the left shows carbon nanotubes (green) linked to four electronic leads (gold). The leads were made using a standard semiconductor technology deposition of metal by evaporation, followed by lithography and etch for the electrode pattern. The carbon nanotubes were deposited onto the chip from solution and located using an Atomic Force Microscope (AFM). Attaching the nanotubes to the leads required the "find 'em and wire 'em" technique. [University of California – Berkeley]⁸ This technique does not lend itself to high volume production! [The right graphic is an illustration of a carbon nanotube from the Southwest Center for Microsystems Education.]



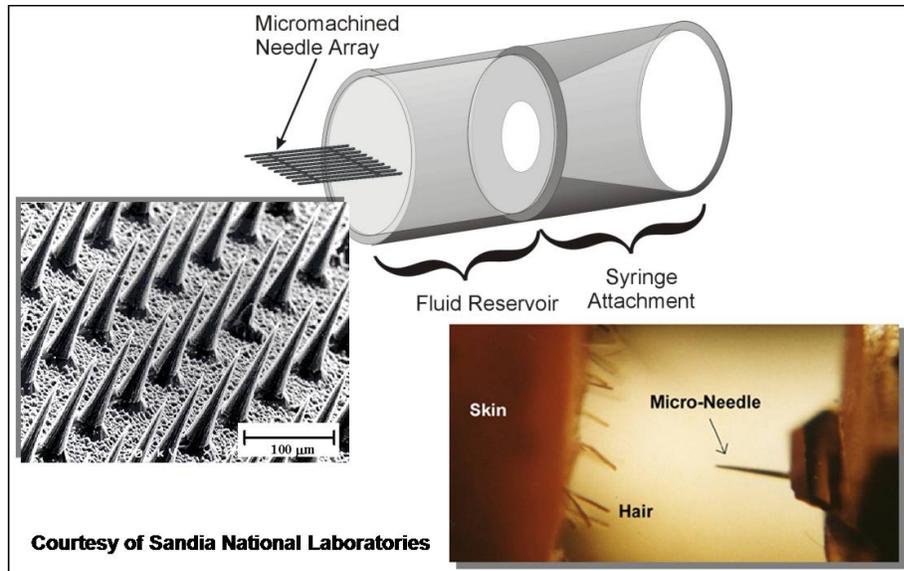
Nanotube connectors for microelectronics
 [University of California – Berkeley,
 Image source: Office of Basic Energy Sciences, U.S. DOE]

BioMEMS



One of the greatest applications for micro / nano devices is in the biomedical field. The overlap between microbiology and microsystem feature sizes makes integration between the two possible. Devices fabricated for the medical field are referred to as bioMEMS.

Examples of BioMEMS

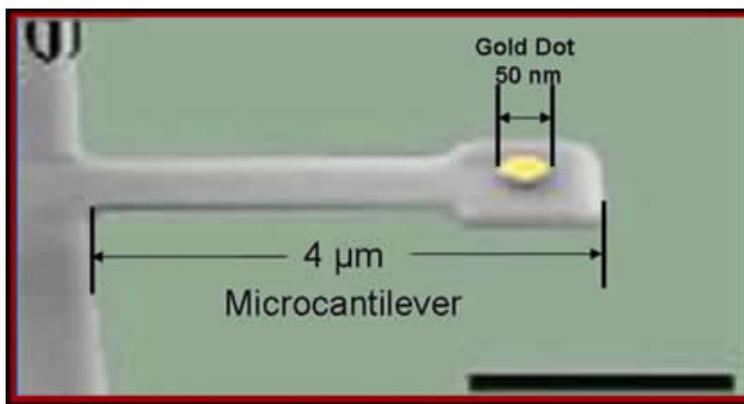


Drug delivery system using a micropump and nanosized needles

Examples of BioMEMS are

- Drug delivery systems with nanosize needles and microsize pumps
- Diagnostics arrays that use microcantilevers and nano coatings (monolayers) to capture nanosize particles.
- Artificial Retina Prostheses that use an electrode microarray implanted on the retina.
- Micro-sized laboratories for analyzing liquid samples such as blood, urine and sputum.
- Numerous devices used for diagnostic and therapeutic applications

A Biosensor



*A gold dot, about 50 nanometers in diameter, fused to the end of a cantilevered oscillator about 4 micrometers long. A one-molecule-thick layer of a sulfur-containing chemical deposited on the gold adds a mass of about 6 attograms, which is more than enough to measure.¹⁰
[Printed with permission Craighead Group/Cornell University and © Cornell University]*

A biosensor is a device used to detect, capture and analyze analytes (i.e. antibodies, antigens, proteins) within a sample solution. The biosensor in the figure consists of a gold dot, about 50 nanometers in diameter, fused to the end of a cantilever oscillator about 4 micrometers long. A one-molecule-thick layer (monolayer) of a sulfur-containing chemical is deposited on the gold. An external excitation causes the cantilever to oscillate.

This biosensor cantilever could be used to detect and collect e-coli cells in a sample. The cells would stick to the chemically treated layer on the gold dot adding a few attograms of mass to the cantilever. Even though a few attograms is very small, it is enough to affect a measurable change in the oscillations of the cantilever. This allows the concentration of e. coli cells in the sample to be measured.

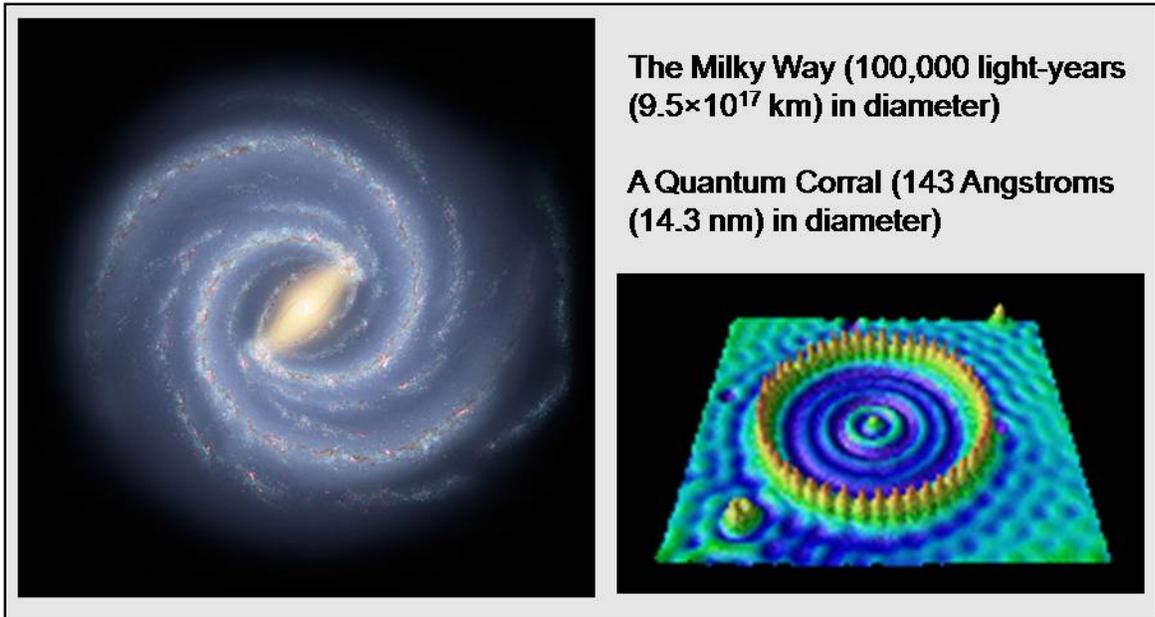
Matching Activity

Match the following components with their scale

| | | Component | | Scale |
|--|---|----------------|---|-------|
| | 1 | Strain of hair | A | Macro |
| | 2 | A molecule | B | Micro |
| | 3 | 75 nm | C | Nano |
| | 4 | 233 mm | | |
| | 5 | 48 microns | | |
| | 6 | Pollen | | |

Table 2: Components and Their Scale

Summary



*Milky Way (left) [Image courtesy of NASA/JPL-Caltech]
Quantum Corral of 48 iron atoms [Courtesy of IBM STM Gallery]*

How big is big? How small is small? It depends on the scale. A macro-scale can be millions of times bigger than a microscale. The microscale is a thousand times bigger than the nanoscale. In the macro-scale, the earth is small when compared to the sun, but huge compared to a baseball. In the micro / nano-scales, an 8 micron wide red blood cell is huge compared to a 2 nm diameter carbon nanotube.

The discovery of nano-sized particles has made an already *big* universe even *bigger*. Distances are now measured in lengths from light years to nanometers (*see pictures above*). Modern technologies are taking advantage of the wide range of sizes in order to improve existing processes and develop new ones.

Food For Thought

How have discoveries in the microscale affected the study of the universe?

How have discoveries in the micro and nano-scales affected our daily lives?

In today's world, what is small?

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9. Quantum Corral Images. IBM STM Image Gallery. (Gallery page no longer available)
10. Silicon Atoms Image. "Observing the Wings of Atoms". Feng Lui. University of Utah News and Public Relations. June 2, 2003.
11. Image of micro-sized gears (Macro, micro, nano) – Courtesy of Sandia National Laboratories. www.mems.sandia.gov
12. Micro to Nano – An Introduction. Mathius Pleil, SCME, CNM
13. Microtechnology Education Resource Center (MERC)

Related SCME Units (can be downloaded from scme-nm.org)

- Units of Weights and Measures PK
- Units of Weights and Measures Activity
- Conversion of Weights and Measures Activity
- Scale Activity: Cut to Size
- Scale Activity: The Scale of Biomolecules
- Scale Activity: Zoom In / Zoom Out

Glossary

Linear Scale: A scale each increment and incremental increase is equal to the one before.

Logarithmic Scale: A scale that uses increments in powers of 10

Macroscopic: Objects greater than 100 microns or visible to the naked eye

MEMS: Microelectromechanical Systems

Micro: A scale between 0.1 μm and 100 μm

Micrometer: One thousandths of a meter (10^{-6} meter)

Micron: A unit of measurement equal to 1 milli Torr or 1 millionth of a meter.

Nano: A scale between 0.1 nm and 100 nm

Nanometer: One billionth of a meter (10^{-9} meter)

Nanotechnology: Technology involved with design and fabrication of devices and thin films with dimensions in the nanometer range ($1\text{E}-9$ m).

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