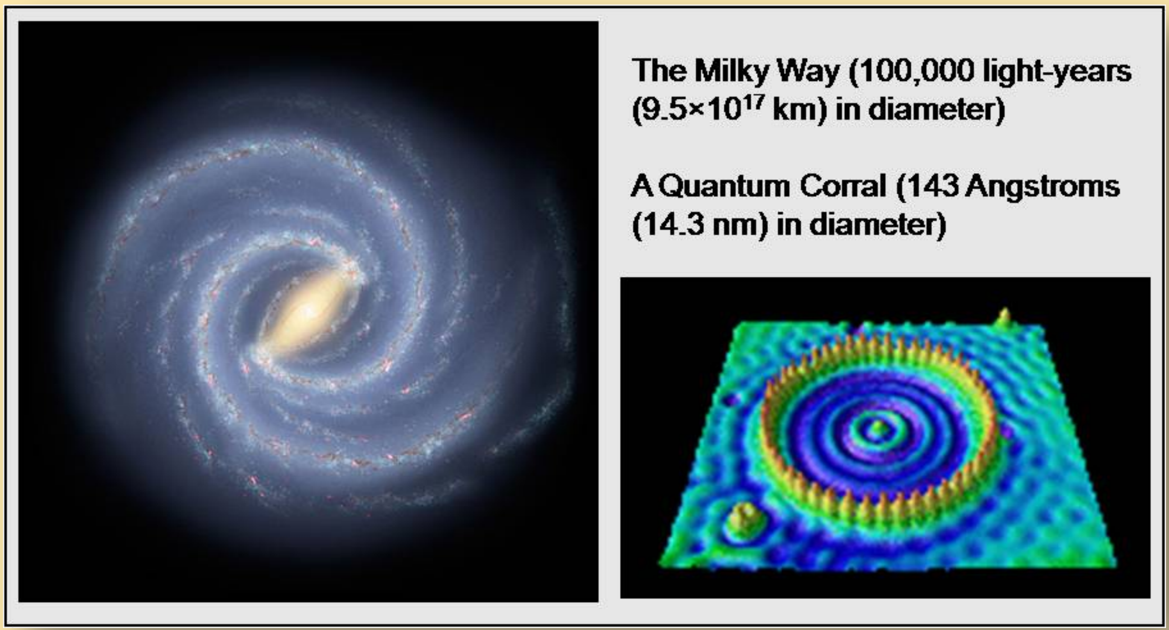
# A COMPARISON OF SCALE: MACRO, MICRO, NANO



# Unit Overview

In order to grasp many of the concepts associated with MEMS and NEMS devices and components, you need to understand scale and the size of objects associated with different scales.

This unit introduces you to concepts associated with scale, and a comparison of the macro, micro and nano-scales.

*MEMS – MicroElectroMechanical Systems*

*NEMS – NanoElectroMechanical Systems*

# Objectives

- Explain the differences in the macro, micro and nano scales in terms of size, applications, and properties.
- Define microtechnology and nanotechnology.
- Discuss what has precipitated an overlap of micro and nano-technologies.

# Introduction

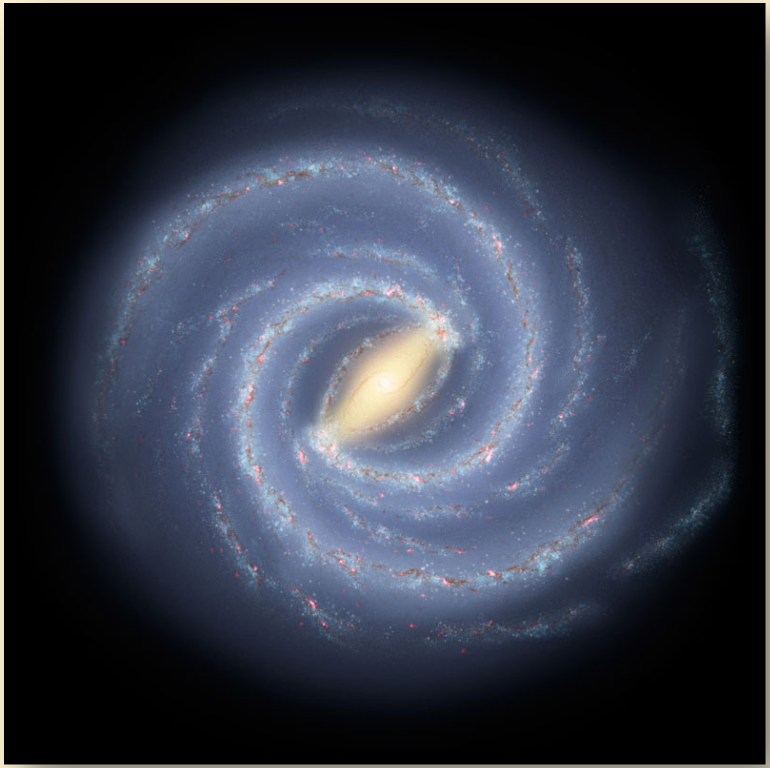
"How big is the universe?"

The Milky Way *(image right)* is one of billions of galaxies.

Our sun is one of several 100 billion stars within The Milky Way.

Our sun is a middle-sized star, 10 times smaller than giant stars.

Our sun is approximately 109 times larger in diameter (1.3 million earths could fit inside the sun)!



***The Milky Way***
***[Image credit: NASA/JPL-Caltech[2]]***

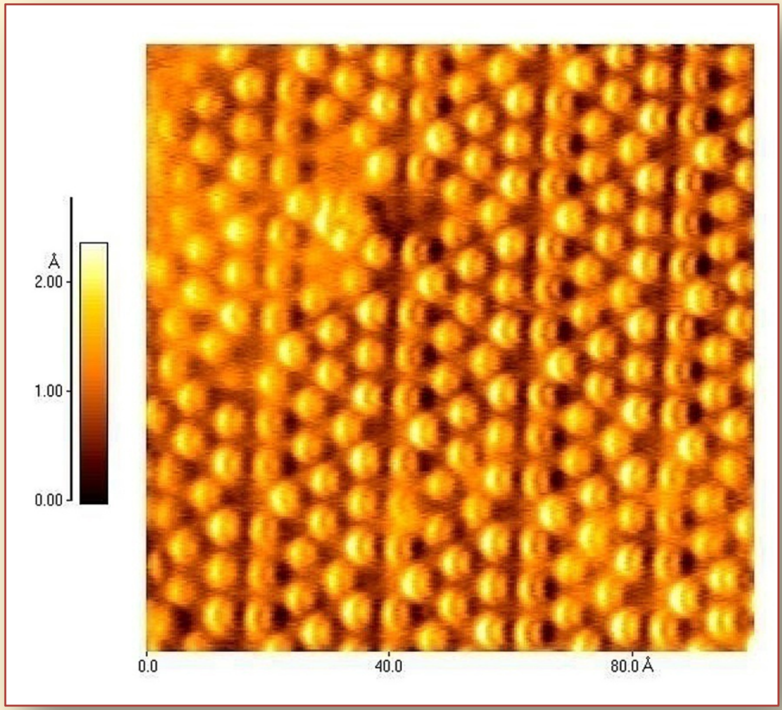
# A Smaller Universe

For years astronomers have explored the universe looking for hints as to how big it really is.

Other scientists have been exploring how small things are.

In these explorations, another whole universe has been discovered, but on a much smaller scale.

Instead of objects measured in kilometers and light-years, objects are measured in micrometers, angstroms, and nanometers, and even the number of atoms *(see image right)*.




***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)]*

# What You Will Learn

This unit explores the concept of scale:

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

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

# Size is Relative

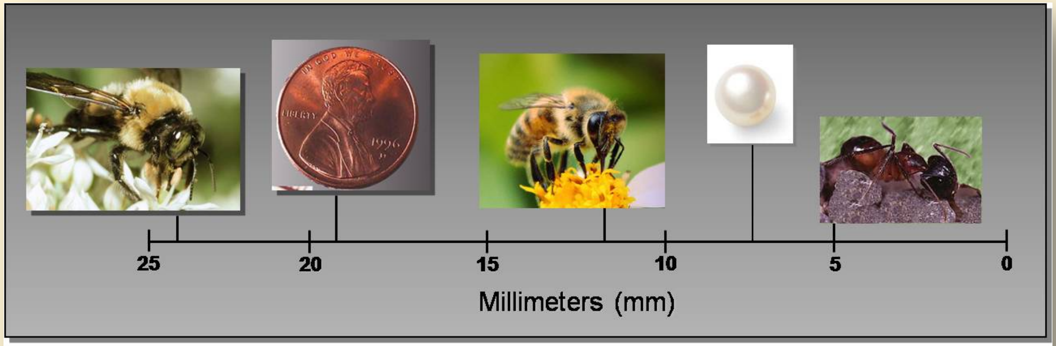
"An ant is small" is a relative statement. Relative to what?

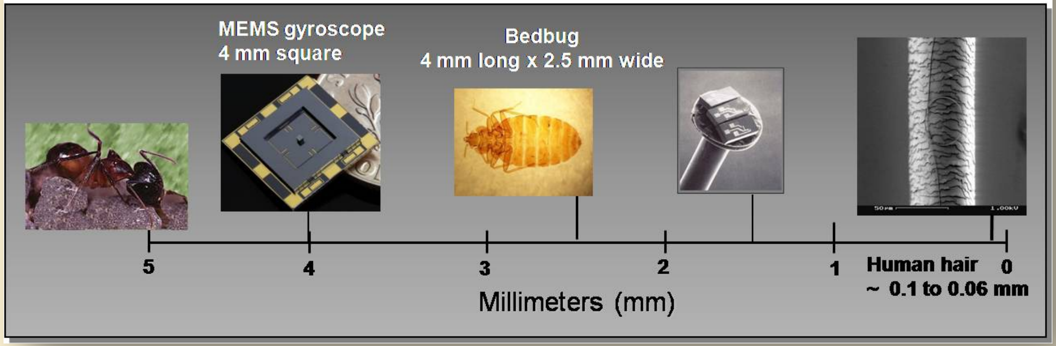
The comparative size of objects can be illustrated in a scale.

In the top scale, the ant is the smallest object. Based on the scale, the ant is almost 5 times smaller than the bumble bee.

In the bottom scale the ant is the largest object.

How much bigger is the ant than the human hair?



# Scale is a Relationship

Scale is the relationship between what is being compared and how that relationship is represented numerically or visually.

Two objects can look the same size, but on a scale, the difference becomes obvious.

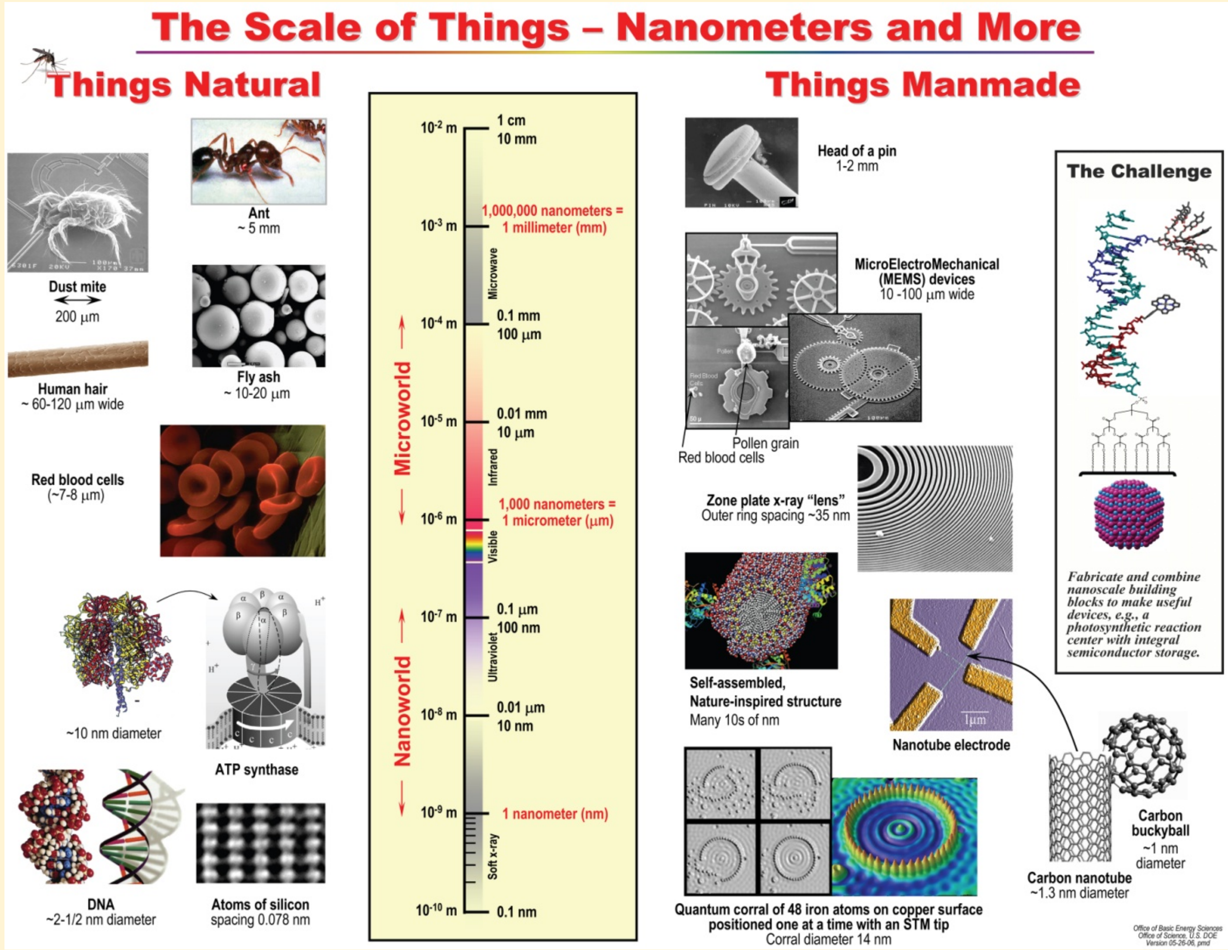
Take a look at the two objects in the figure.

*Would you put them in the same scale?*

*The ant is 7 mm. The red blood cells – 7 µm or 1000 times smaller!*

# How Big is Small?

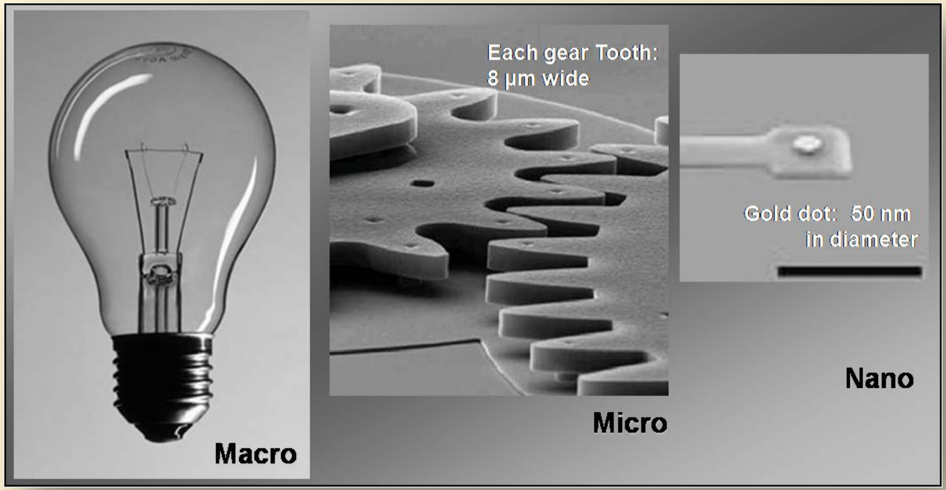
- One light-year is 9,460,730,472,580.8 km.
- One kilometer (km) is 1000 meters.
- One micrometer is $10^{-6}$ (a millionth) of a meter.
- One nanometer is $10^{-9}$ (a billionth) of a meter.
- An attogram is $10^{-18}$ of a gram.




# The Scale of Things – Nanometers and More

From this chart, 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.

# Macro, Micro, Nano

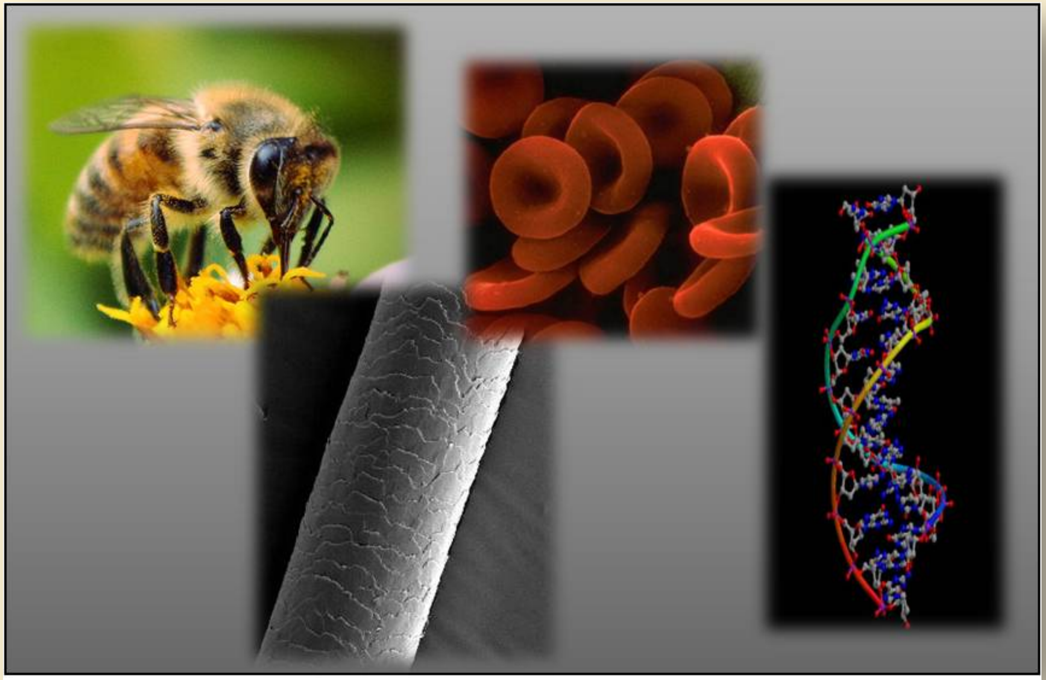



The figure shows a standard light bulb (~80mm), microgears with gear teeth 8 micrometers wide, and a microcantilever with a 50 nanometer gold dot.

- Macro –anything greater than ~100 micrometer.
- Micro – 100 micrometers to 100 nanometers
- Nano – 100 nanometers to 1 nanometer

# Macro, Micro, or Nano?

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



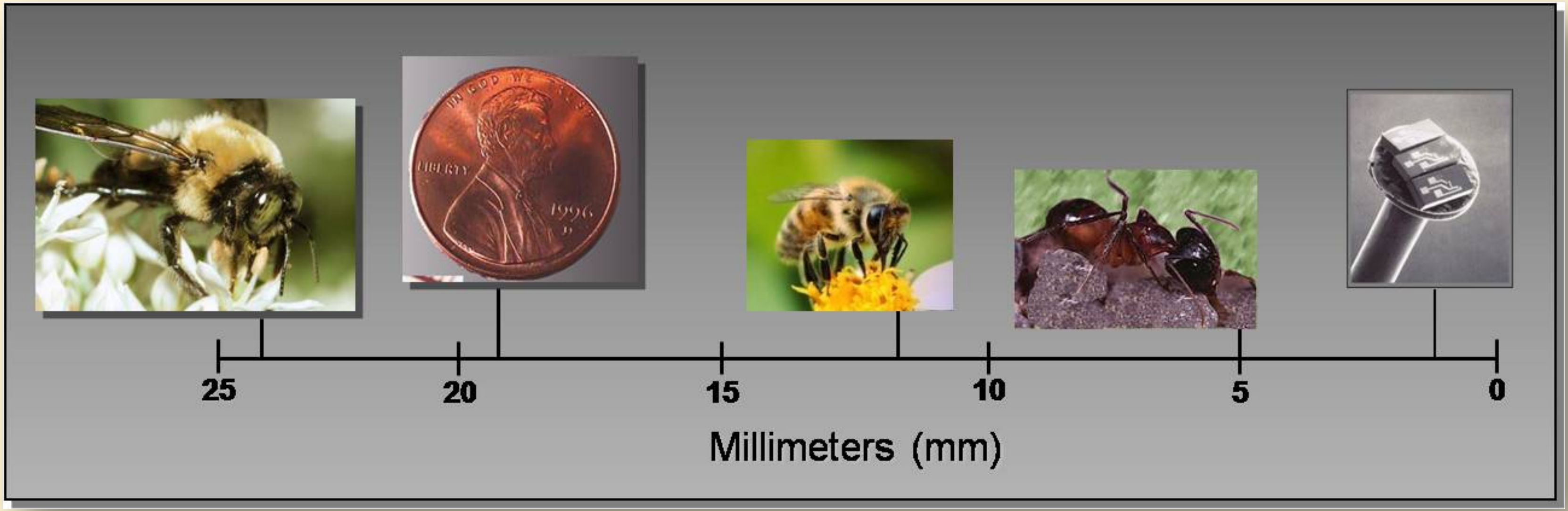
# Scales

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:

- linear scale
- logarithmic scale

Following is a brief discussion and illustration of both types of scales.

# Linear Scale



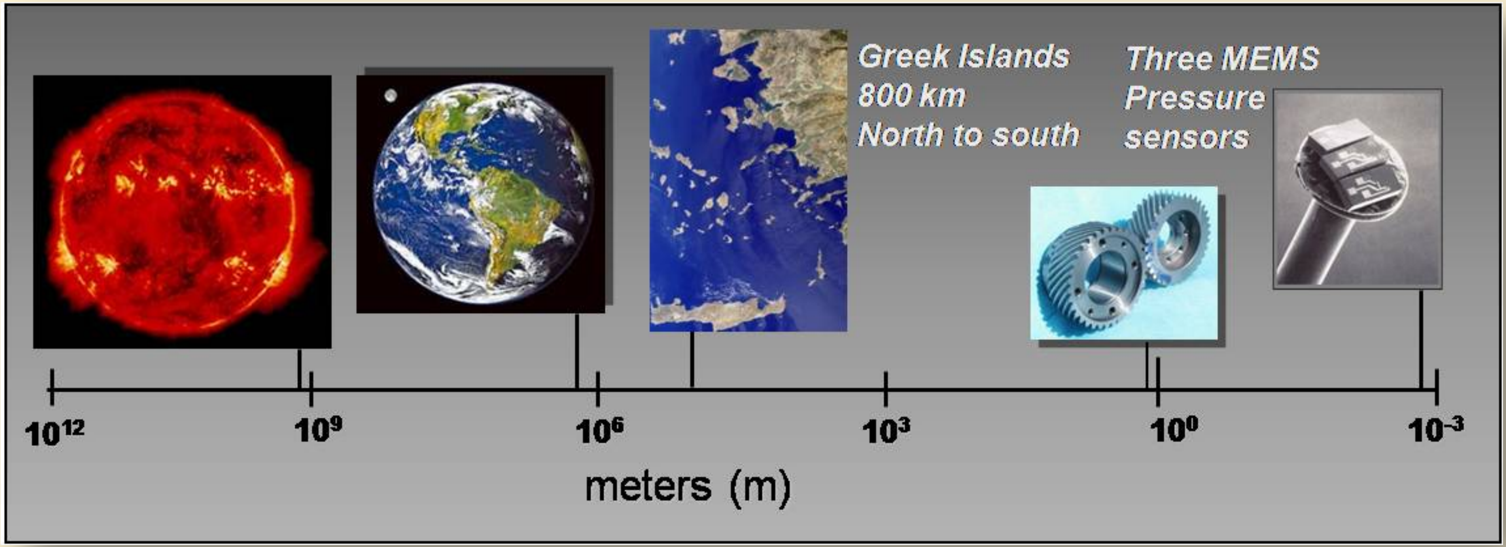

In a linear scale each increment is equal to the one before.

For example, a linear scale from 0 millimeters to 25 millimeters could have 5 increments, each representing 5 millimeters.

A good scale when the total range in the objects' size is small, such as those illustrated in the scale.

*Can you estimate the size of each object?*

# Logarithmic Scale



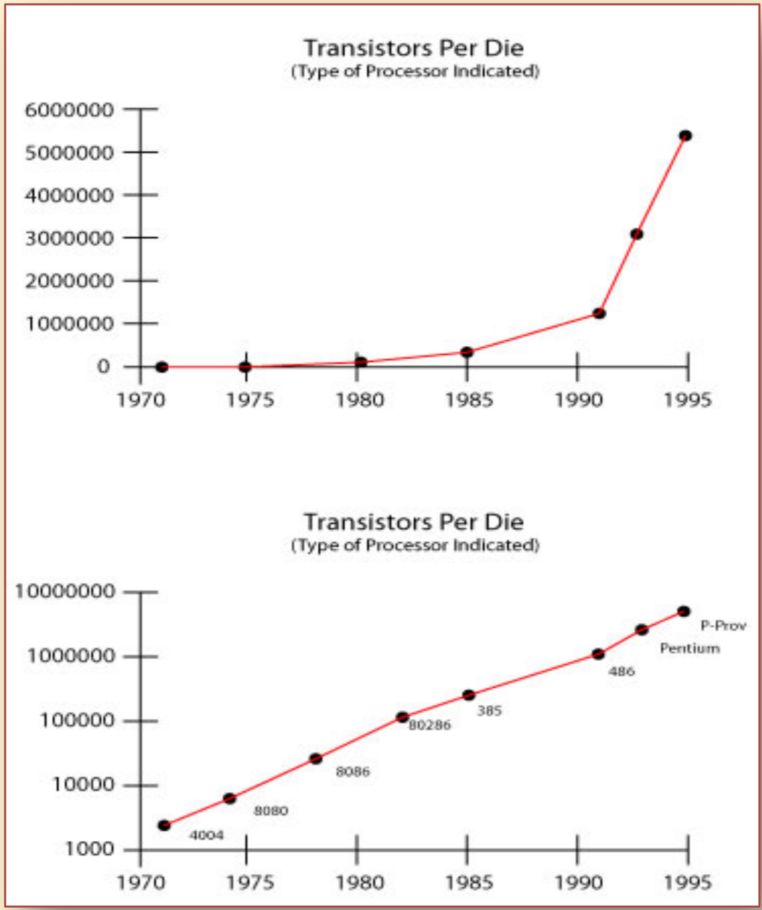

What happens when the range becomes bigger (i.e. from Terameter to millimeter)?

The linear scale is no longer practical; therefore, a logarithmic scale is used

A logarithmic scale uses the powers of 10 to compare the relative size of objects.  This graph covers a huge range from the diameter of the sun (1.39 Gm) to the size of a pin head (1.5 mm).

# Linear vs. Logarithmic

- These two graphs illustrate the same information, but look how different they are.
- They both show the increase in the number of transistors per die from 1970 to 1995.
- So what do these graphs tell us?
- How do they tell it?




*Linear vs. Logarithmic (Number of Transistors per Die from 1970 to 1995)*

# Macro vs. Micro-size Devices

Compared to macroscopic devices micro-size devices are

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

In equivalent applications, micro exceed macro devices in

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

# 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, computerized, chemical, mechanical and optical elements as well as various other materials."* [Federal School of Polytechnics]

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).*

In the U.S., these devices are called microelectromechanical systems (MEMS).

In Europe such devices are called microsystems (MST).

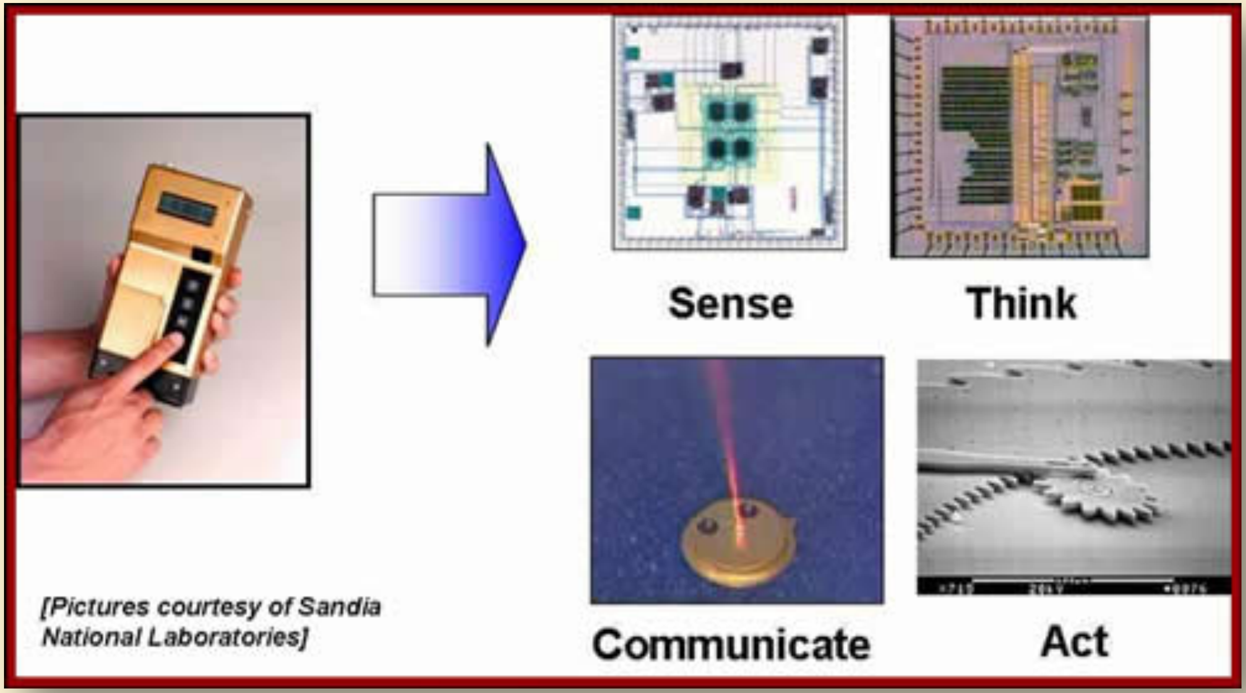
MEMS and MST are normally used interchangeably.

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

# What are Microsystems?

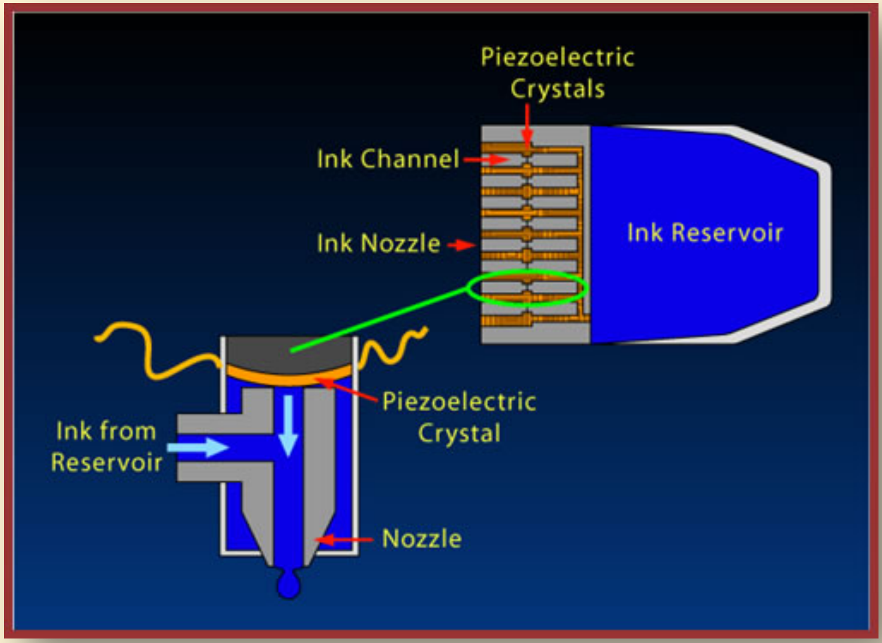
Microsystems are microscopic, integrated, self-aware, stand-alone products that can

- sense,
- think,
- communicate and
- act.



# MEMS Applications

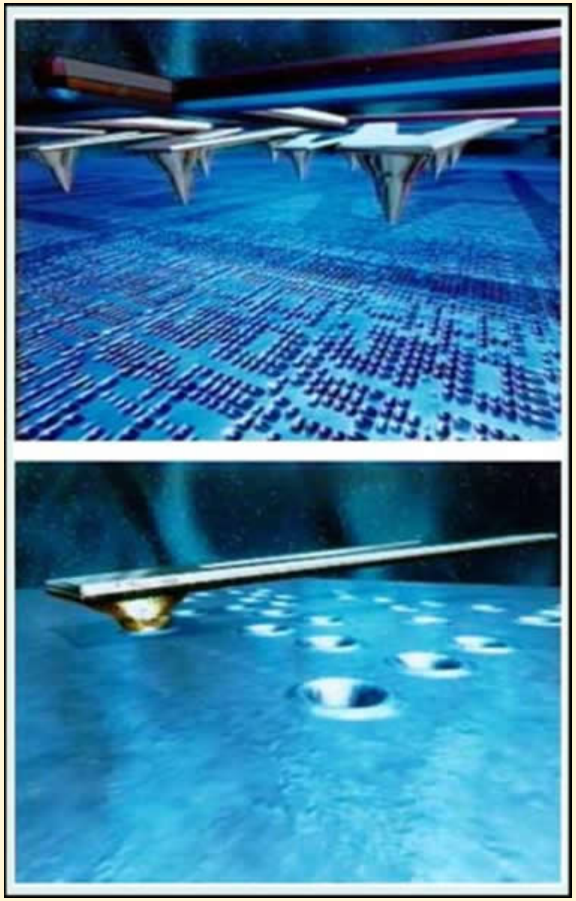
- Accelerometers
- Micro Fluidic Pumps
- Pressure Sensor
- Spatial Light Modulators
- Lab on a Chip
- RF (Radio Frequency) MEMS
- Mass Storage Devices




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

# Nano Meets Micro

- The smaller microsystems become the smaller their components become.
- IBM has a prototype of a read/ write storage device that can fit 1 Terabit of data on a surface the size of a standard postage stamp.
- It uses a cantilever (~2 microns wide) with a "bit-making" component about 10 nm at its apex *(see figure).*



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

# What is Nanotechnology?

*"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)*

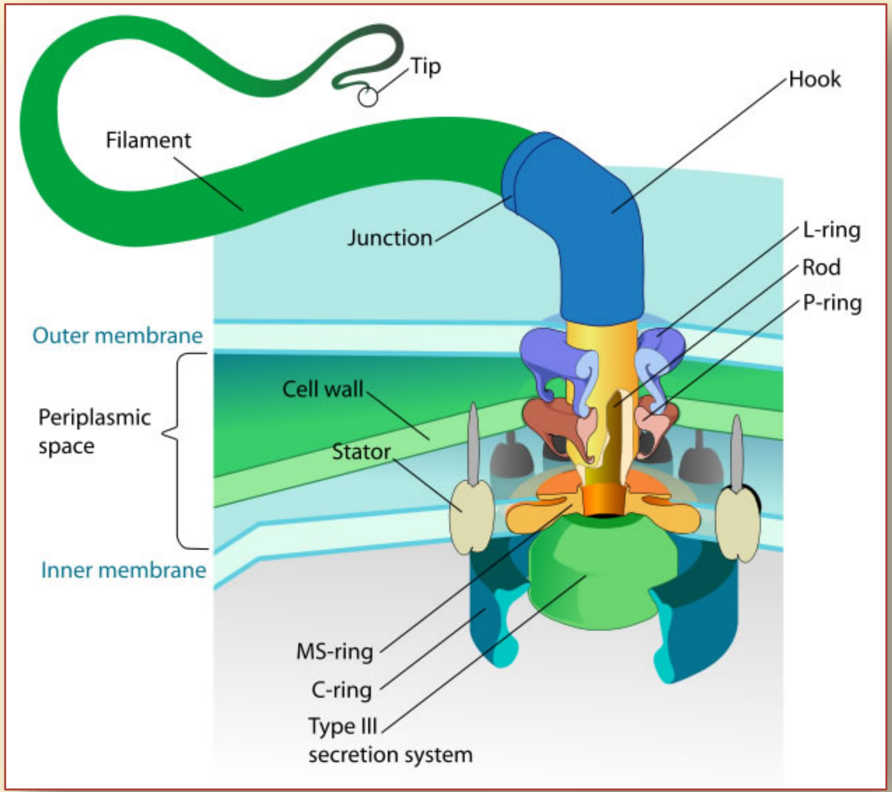
# Nanoscience

The study of novel phenomena and properties of materials that occur at extremely small length scales.

Physicists and biologists have been studying nanodevices for centuries.

In the 18th century, John Dalton, a British chemist and physicist, made the earliest steps toward recognizing that matter was composed of atoms.

Nanotechnology is the application of nanoscale science.




***Structure of a bacterial flagellar motor. The stator is anchored to the cell membrane and encloses the rotor (diameter 50 nm), which turns at a rate of up to 1700 revolutions per second.***

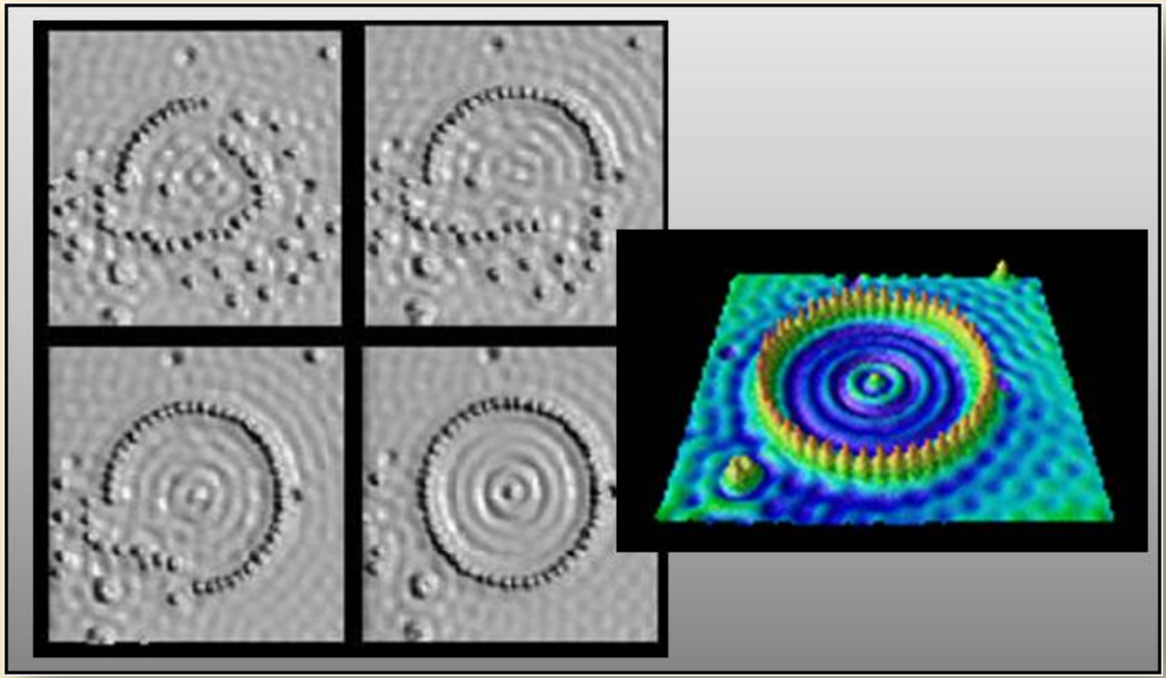
# What is Nano?

- 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
- Anything with unique properties because of its small size

# Micro vs. Nanotechnology

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

# Bottom Up Fabrication



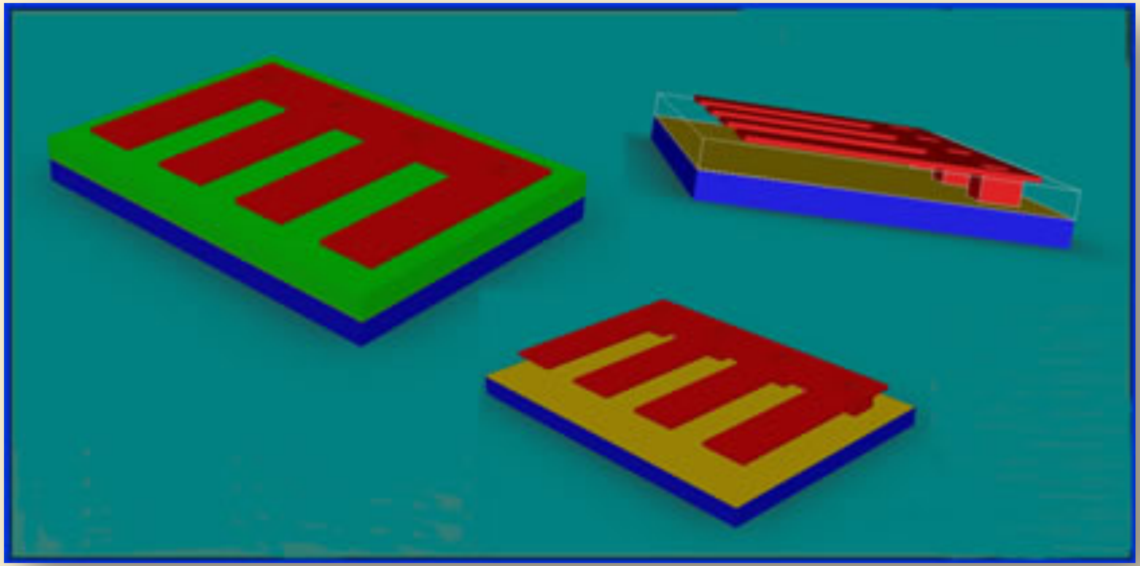
*Four stages in the assembly a quantum corral (left) Final assembly made by placing 48 iron atoms in a circle, one at a time, onto the surface of gold (right) [IBM STM Photo Gallery]*

- The bottom up approach means a structure is made by building it atom by atom or molecule by molecule.
- Each individual atom or molecule is manipulated or controlled for correct placement. (*see figure)*

# What Does Bottom Up Fabrication 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 Fabrication



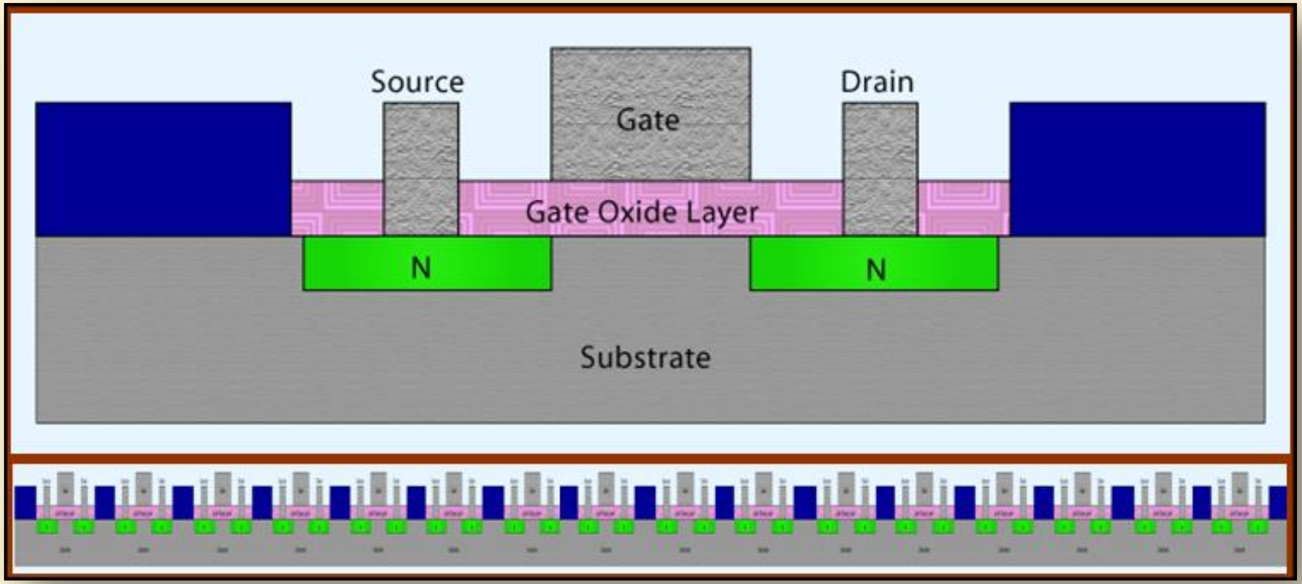
*Creating suspended cantilevers (red) by selective removal of a layer (green)*

- Top down selectively removes material to achieve the desired structure. *(See figure)*
- A pattern is applied (cantilevers in red)
- Exposed material is selectively etched away (green layer)
- A circuit or component is formed  (Cantilevers suspended over substrate)

# What Does Top Down Fabrication Sound Like?

- A sculptor or carpenter 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.

# Shrinking Technologies

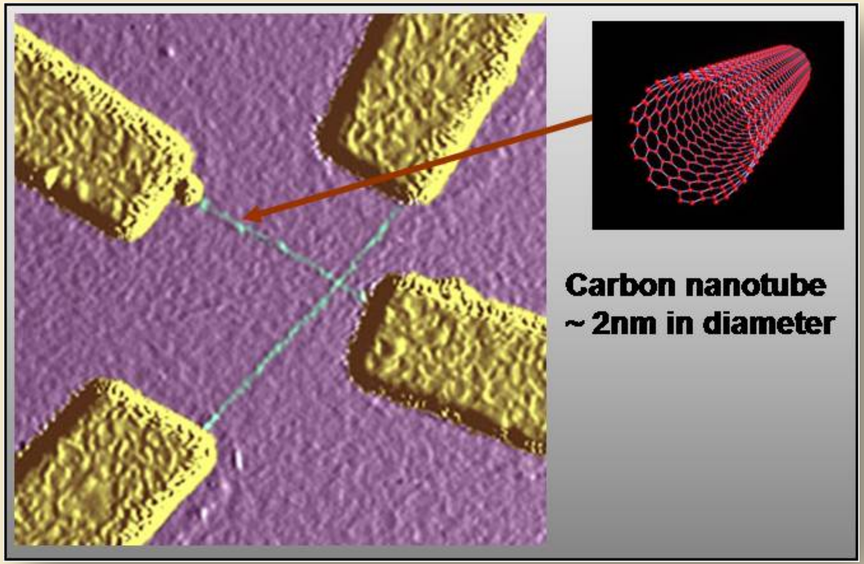



*The space of one transistor, now holds hundreds of transistors (graphic not to scale)*

- Transistors have shrunk due to technological advancements in the deposition of materials and the selective removal of materials through the photolithography and etch processes.
- A deposited gate oxide layer of 20 microns is now 1 nm!
- Gate widths of more than 1 micron are now less that 50 nm!
- This is Nanotechnology.

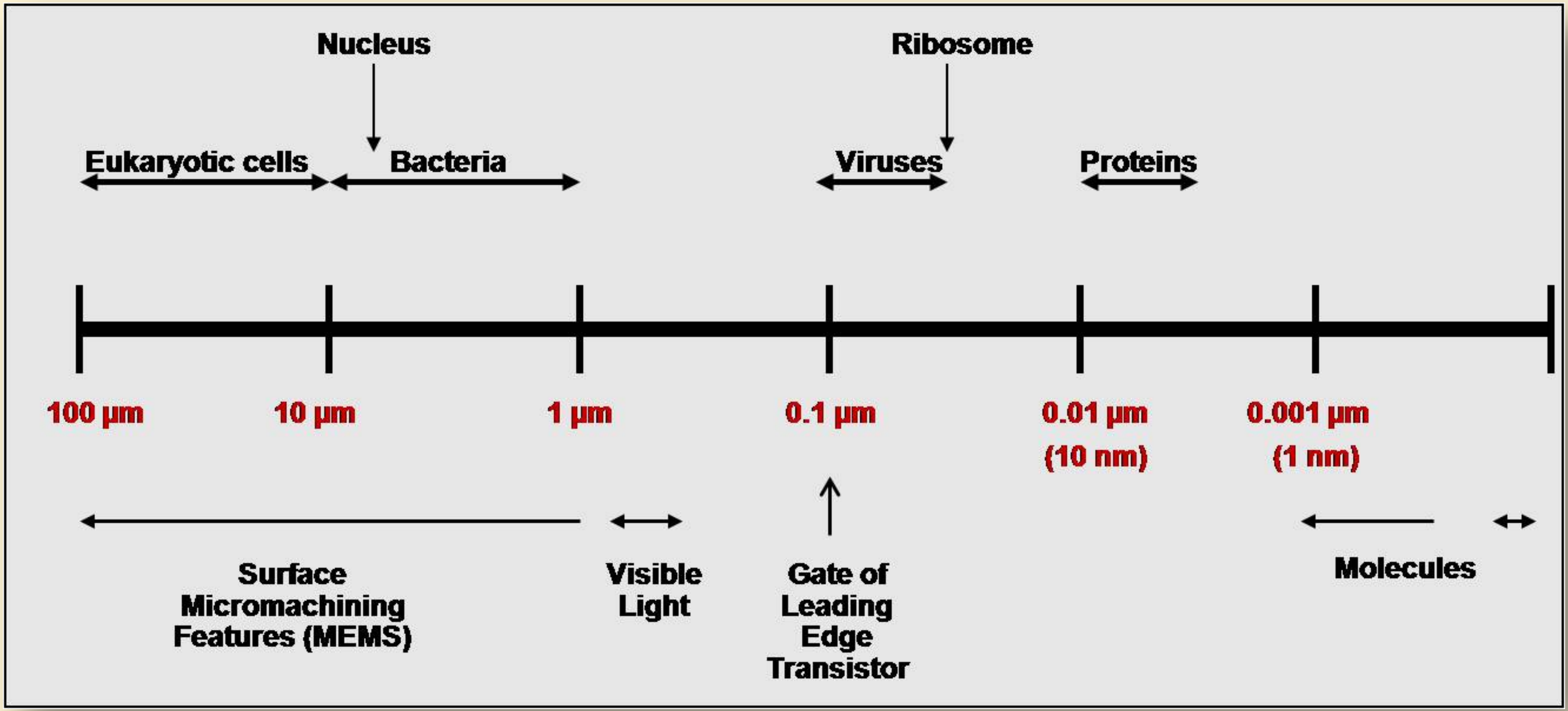
# Nano meets Micro

- As devices shrink, their components shrink.
- Four electronic leads (gold) shown in the figure are connected with carbon nanotubes (green).
- The leads were made using standard semiconductor technology.
- The nanotubes were deposited onto the chip from solution and located using an Atomic Force Microscope. Attaching the nanotubes to the leads required the "find 'em and wire 'em" technique.




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

# BioMEMS

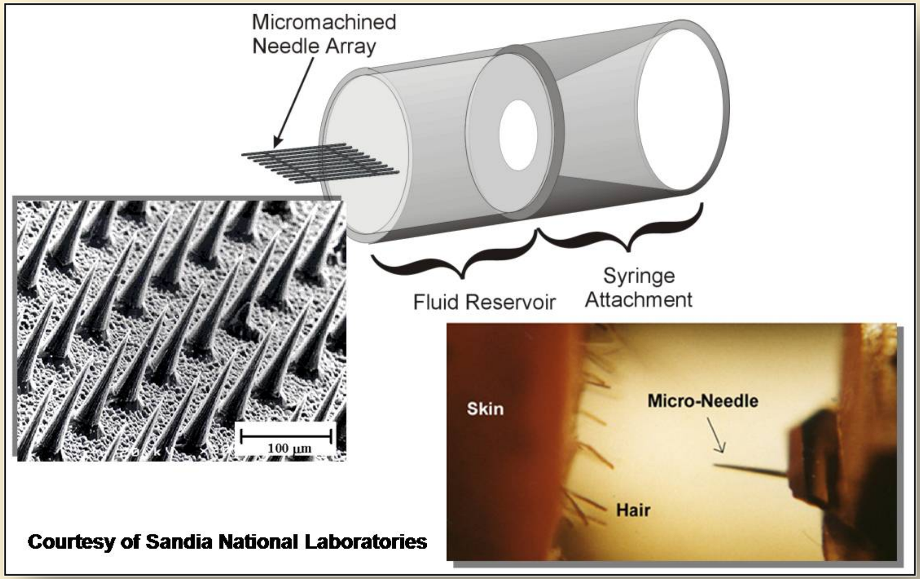



One of the greatest applications for micro / nano devices is in the biomedical field. The overlap between microbiology and microsystem feature sizes makes integration between the two possible. Devices fabricated for the medical field are referred to as BioMEMS.

# Examples of BioMEMS

Examples of BioMEMS

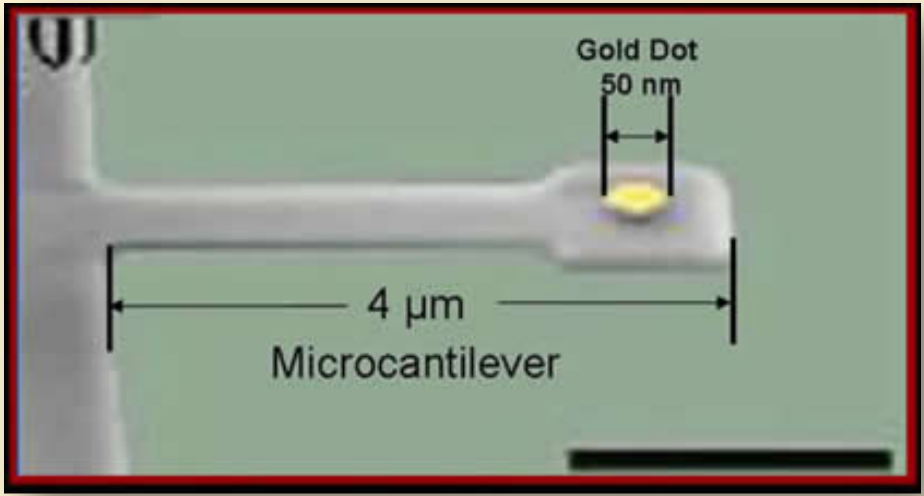
- Drug delivery systems with nano-size needles and micro-size pumps
- Diagnostics arrays that use microcantilevers and nano coatings (monolayers) to capture nano-size particles.




*Drug delivery system using a micropump and nano-size needles*

# A BioSensor

- The biosensor in the figure consists of a gold dot (50 nm diameter), fused to the end of a cantilever oscillator (4 μm long).
- A monolayer of a sulfur-containing chemical is deposited on the gold.




*A gold dot, about 50 nanometers in diameter, fused to the end of a cantilevered oscillator about 4 micrometers long. [Printed with permission by Craighead Group/Cornell University and Cornell University]*

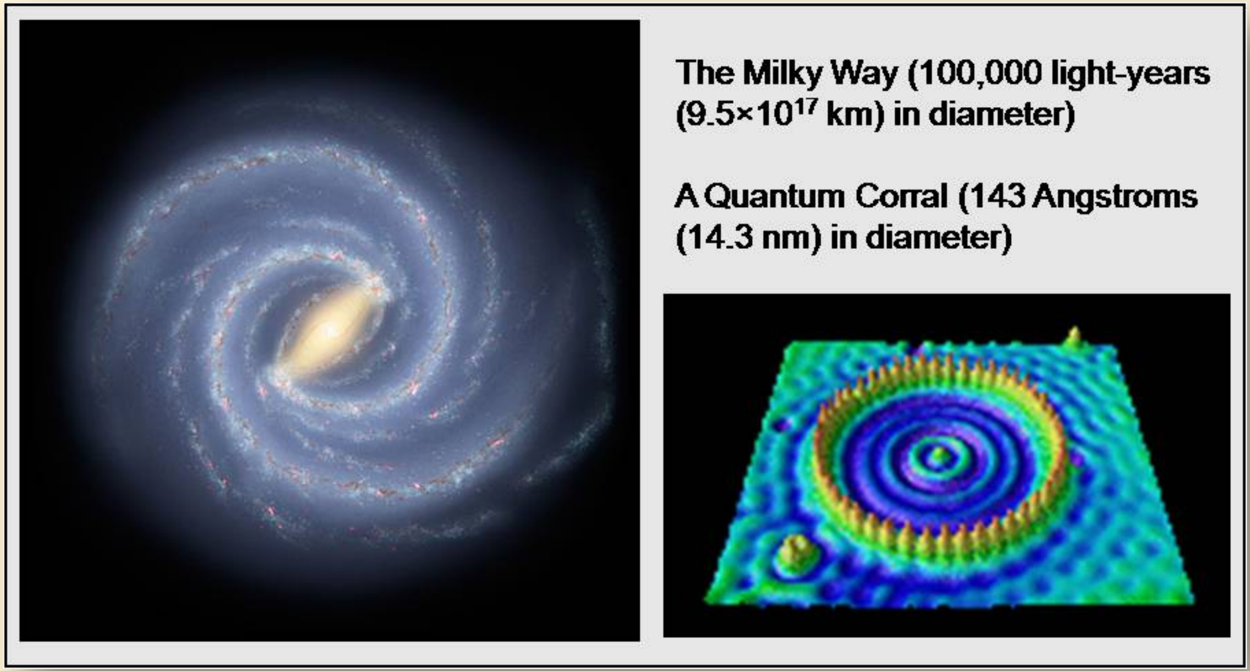
- Target cells stick to the chemically treated layer adding a few attograms of mass to the cantilever. This is enough to affect a measurable change in the oscillations indicating the concentration of target cells in the sample.

# What are they?

Macro, Micro, or Nano?

- Strain of hair
- Molecule
- 75 nm
- 233 mm
- 48 microns
- Pollen

# Light years to Nanometers




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.

# Let's Think About It

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

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

- In today's world, what is small?

# Summary

A macroscale can be a million times bigger than a microscale. A microscale is a thousand times bigger than a nanoscale.

The discovery of nano particles has made an already big universe even bigger.

Distances are now measured in lengths from light years to nanometers.

Modern technologies are taking advantage of the wide range of sizes in order to improve existing processes and develop new ones.

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