Nanotechnology: Myth and Reality

- *What* is "nano?"
- *Why* is "nano" important?
- *How* do scientists work at the nanoscale?

What is nano?:
The scale of things in words

Nanos: greek for dwarf

- "Nano" is a standard of measurement of the very small. One nanometer (nm) is one-billionth of a meter and is 10^{-9} Meter - m OR

Millimeter – mm – 1,000 times smaller than a meter

↓

Micrometer – µm – 1,000 times smaller than a millimeter

↓

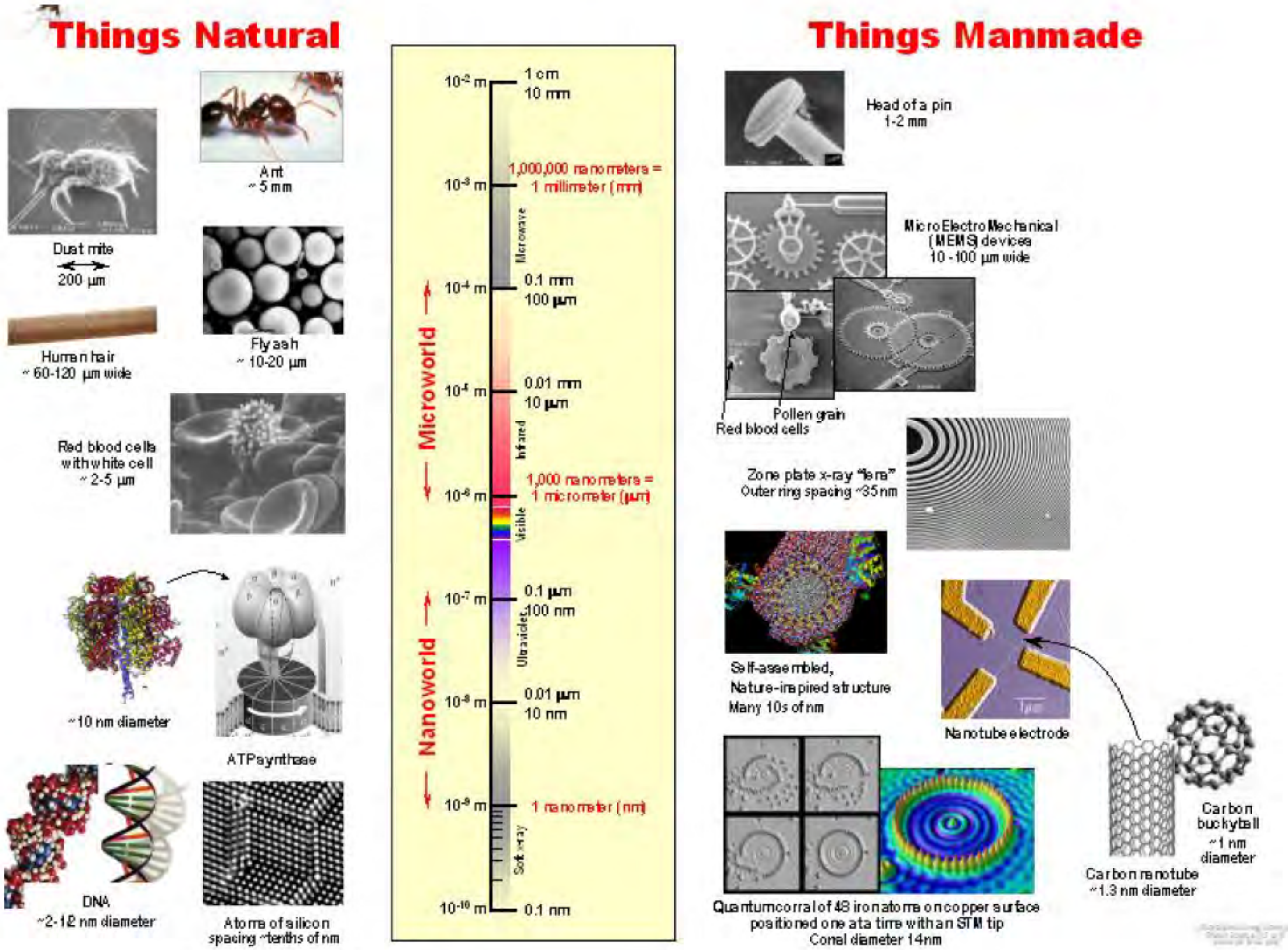
Nanometer – nm – 1,000 times smaller than a micrometer

So: 1,000 X 1,000 X 1,000 = 1,000,000,000—one BILLION—times smaller than a meter!

- The world of everyday objects is described by Newton's laws of motion, while simple molecules, atoms, and sub-atomic particles are ruled by quantum mechanics—the effects of quantum mechanics are typically not observable on macroscopic scales—if Newtonian laws governed the workings of an atom, electrons would rapidly travel towards and collide with the nucleus rather than remain in an orbital path around the nucleus.

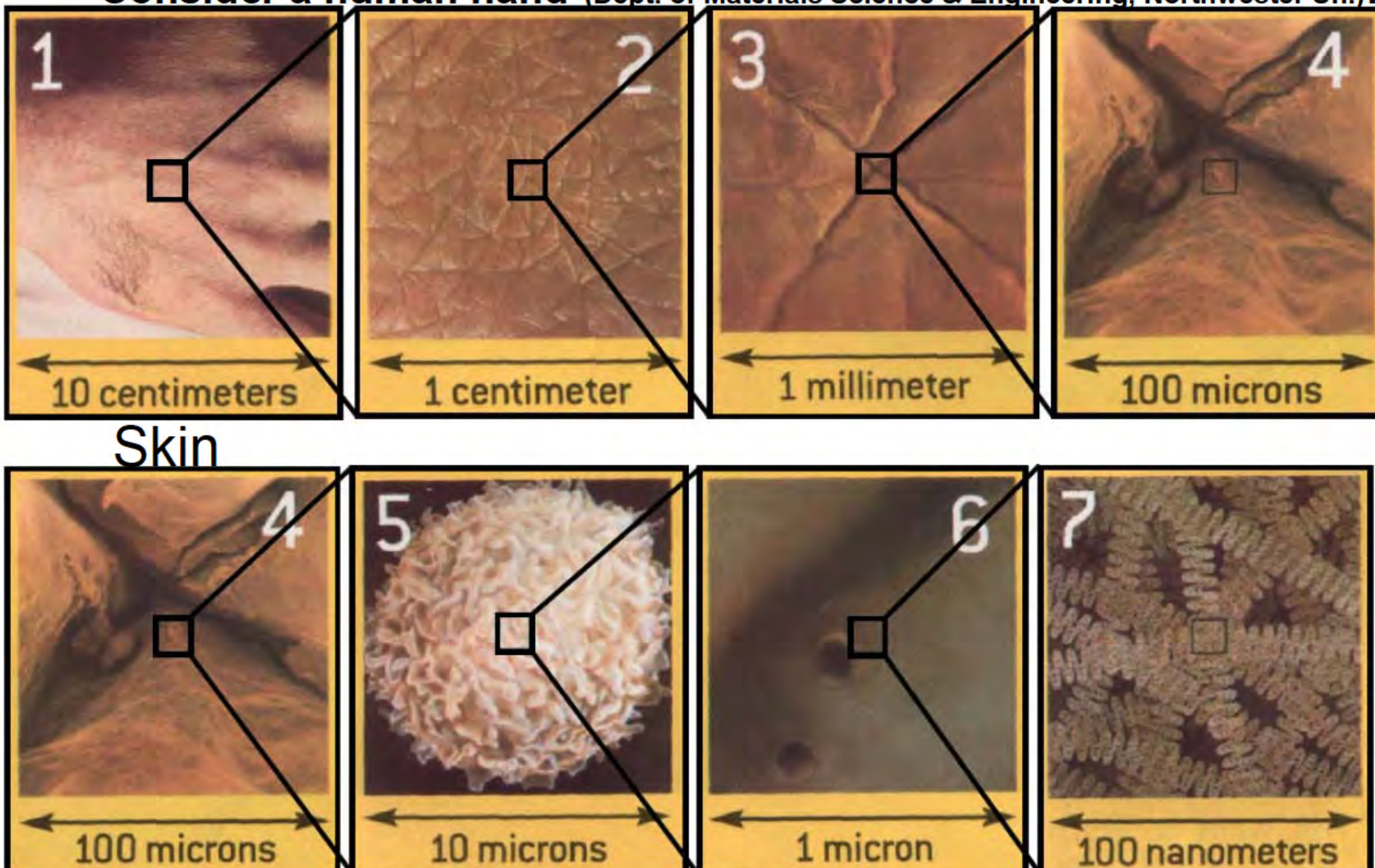
- Nanoscale materials exists in a realm that straddles the quantum and the Newtonian.

What is nano?:
The scale of things in images



What is nano?: The scale of things in human terms

Consider a human hand (Dept. of Materials Science & Engineering, Northwester Un.):



Skin

Skin

White blood cell

DNA

The Myth: 

Eric Drexler's "Grey Goo" (Engines of Creation, 1986):

"Imagine such a replicator floating in a bottle of chemicals, making copies of itself....the first replicator assembles a copy in one thousand seconds, the two replicators then build two more in the next thousand seconds, the four build another four, and the eight build another eight. At the end of ten hours, there are not thirty-six new replicators, but over 68 billion. In less than a day, they would weigh a ton; in less than two days, they would outweigh the Earth; in another four hours, they would exceed the mass of the Sun and all the planets combined - if the bottle of chemicals hadn't run dry long before."

...where "nanobots" devour all carbon-based objects turning our planet to dust.

Why this couldn't happen:

- If nanobots comprised organic molecules, they would be prey—not just preditor
- Nanoscale size simply precludes nanoparticles from moving very fast
- ENERGY!
  - ✓ The energy available for exponential nanobot replication (sun and oxidation of biological matter) is likely insufficient to outcompete existing life
  - ✓ Nanobots would need additional energy for locomotion anyway
  - ✓ If nanobots comprised inorganic compounds (e.g., silicon) not abundantly available from living matter, then even more energy would be required for synthesizing/purifying these building blocks; little chemical energy is available from "rocks" as most are in well-oxidized "low-energy" form

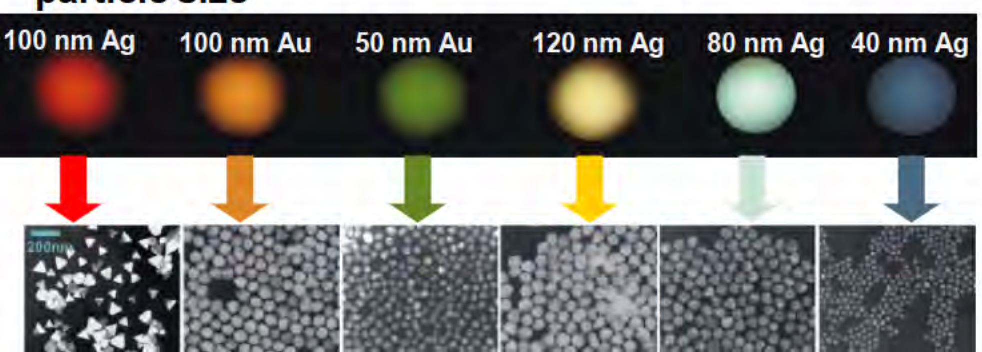
Word of caution:

Nanotechnology may have environmental and health risks associated with the enhanced reactivity and largely unknown toxicity of many nanomaterials

The Reality: Nanoparticles that just "sit there" have remarkable & useful properties

- **Nanoscience and technology defined:** The ability to measure, see, manipulate, and manufacture things between 1 and 100 nanometers in size
- **Things change at the nanoscale: Materials properties are altered**
  - ✓ *Thermal*: melting points are lower
  - ✓ *Mechanical*: adhesion (stickiness) and strength change
  - ✓ *Electrical*: conductivity changes
  - ✓ *Optical*: absorption and scattering of visible light changes – color changes
  - ✓ Magnetic: stronger magnetic fields due to larger surface areas and perfect crystallinity
- **At other scales, size doesn't matter:**
  - ✓ At the quantum level, one gold atom acts like any other gold atom
  - ✓ At the bulk level, a nugget of gold has the same chemical and electrical properties as another nugget.
  - ✓ But two nanoparticles, both made of pure gold, can exhibit markedly different behavior - different melting temperature, different electrical conductivity, different color - if one is larger than the other.

Example: Gold (Au) and silver (Ag) nanoparticles: scatter or reflect different colors depending upon their particle size

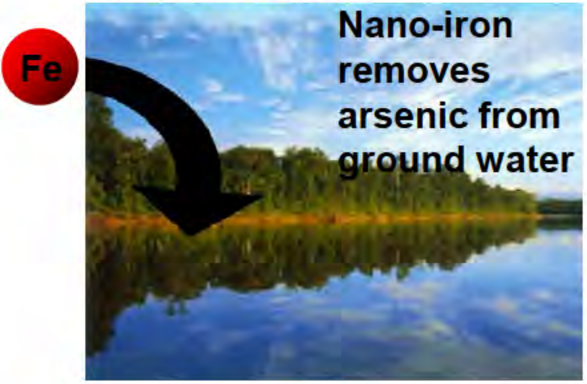


Early nanotechnology: Medievil stained glass used nano-Ag (yellow) and nano-Au (red)

How?: By mixing gold chloride into molten glass, they created nano-Au spheres.

The Reality: "Nano" can make existing technologies better

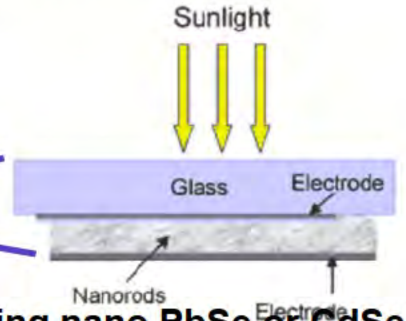
- Remove pollutants/toxins from air and water supplies = better health



Nano-iron removes arsenic from ground water

Buildings as air purifiers: nano-TiO_2 coated = "photocatalysts"

- Energy generation = lower energy costs

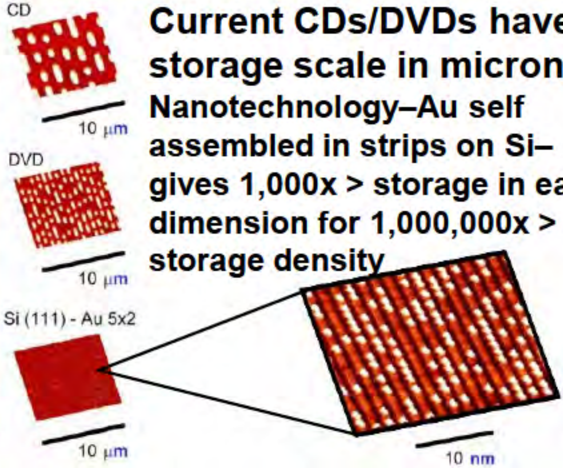


Solar cells made by mixing nano PbSe or CdSe in conductive plastic and sandwiched between electrodes could be coated on rooftops

- Durable products = fewer replacement costs

Stain-resistant clothing: 10 nm carbon whiskers coat cotton fibers

- Ultra-high-density data storage = improved products



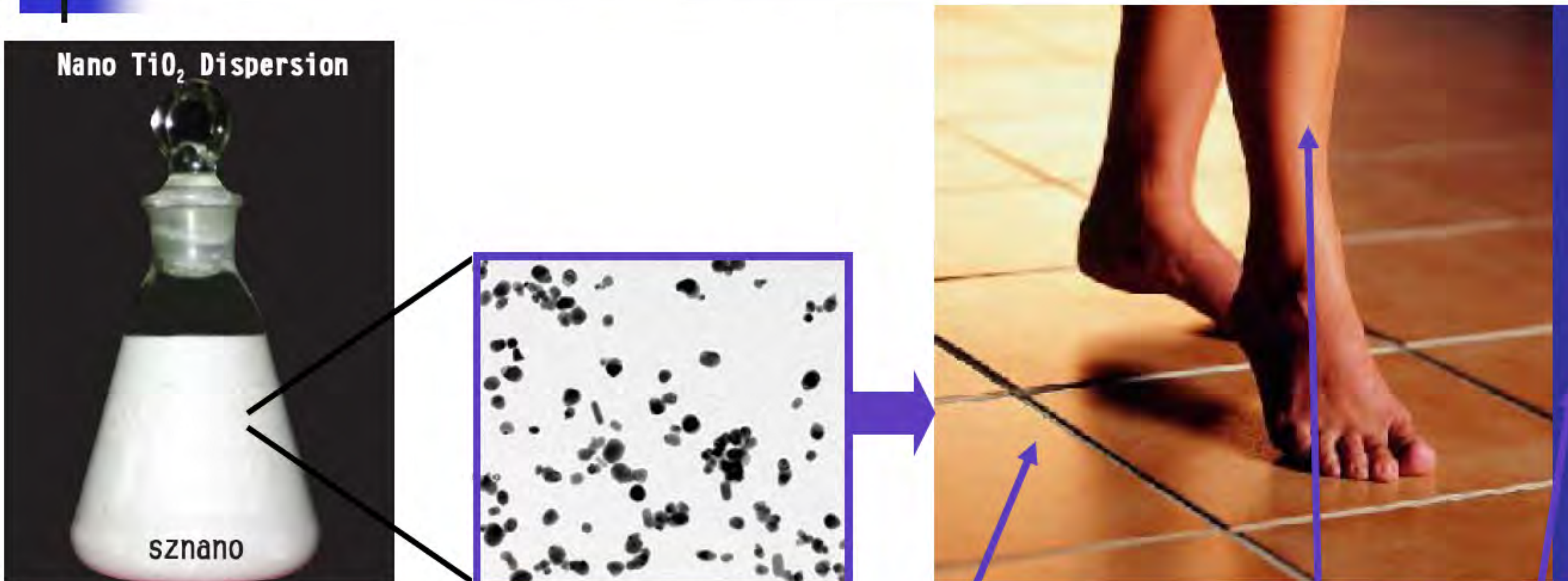
Current CDs/DVDs have storage scale in microns. Nanotechnology–Au self assembled in strips on Si–gives 1,000x > storage in each dimension for 1,000,000x > storage density

- Disease detection and control = increased survival

Au nanoshells absorb light/release heat to destroy tumors

Nano-Ag wound dressing

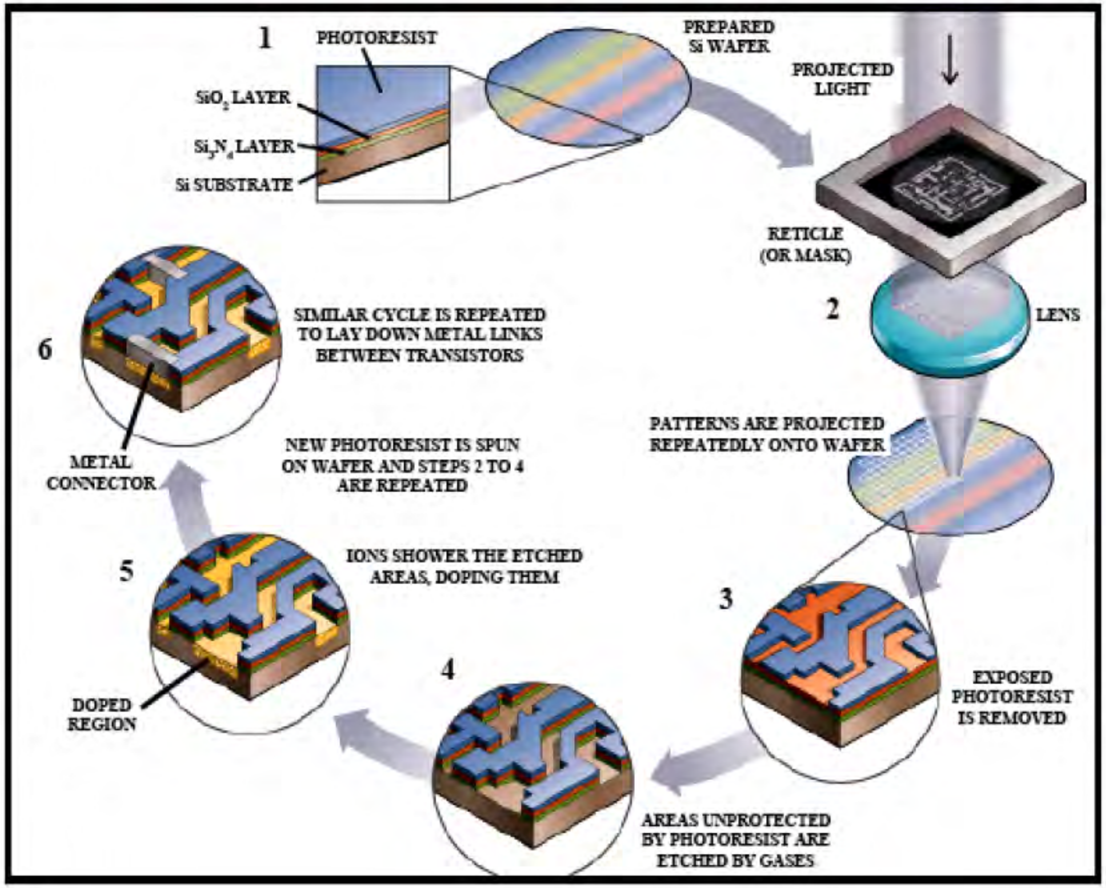
Are you wearing it?



- Anti-microbial floor coating
- "Non-chemical" sunscreen
- UV-resistant paint

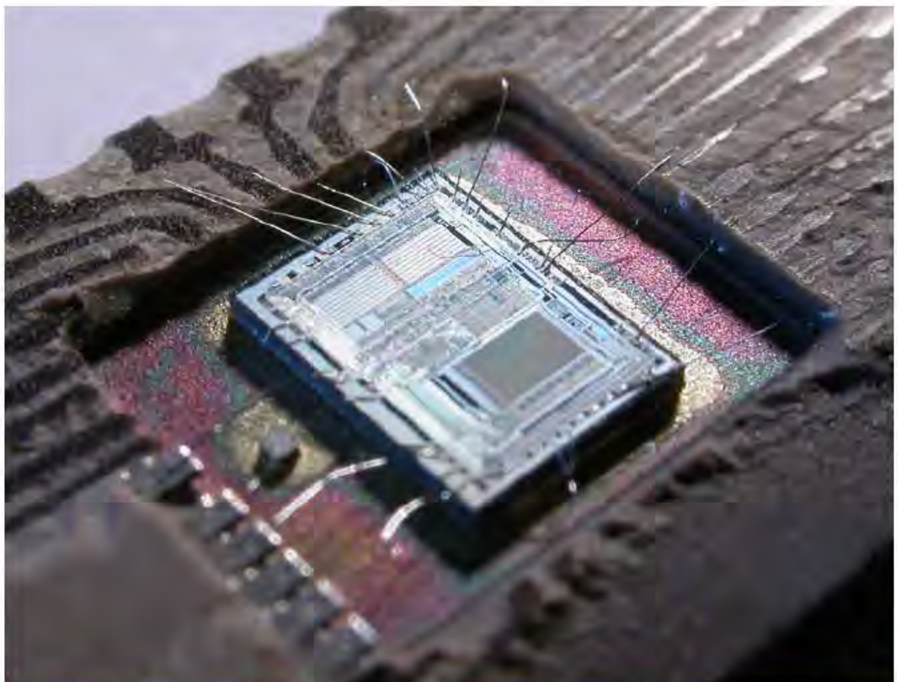
Manipulating matter at the nanoscale: Two basic ways

1. Top-down: "chisel" away material to make nanoscale features
   - ✓ Patterning by microlithography (<10 μm) and nanolithography (<100 nm)
     - ✓ Light or electron beams, for example, are used to create patterns for material deposition and material etching: photo- or e-beam lithography

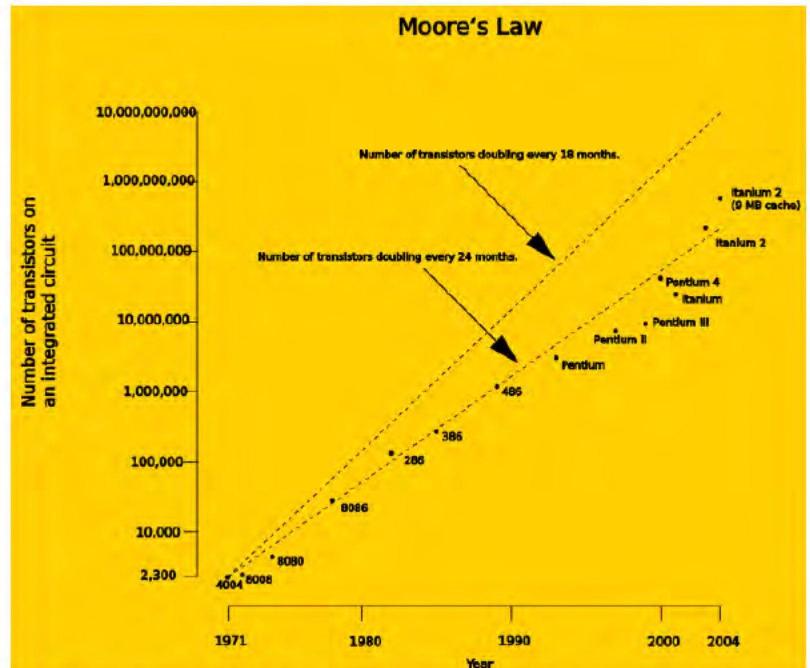


Manipulating matter at the nanoscale: Two basic ways

1. <u>Top-down:</u> "chisel" away material to make nanoscale features
   - ✓ Patterning by microlithography (<10 μm) and nanolithography (<100 nm)
     - ✓ Especially "microfabrication" used for making microprocessors



The integrated circuit from an Intel 8742, an 8-bit microcontroller that includes a CPU running at 12 MHz, 128 bytes of RAM, 2048 bytes of EPROM, and I/O in the same chip.



"Law:" The number of transistors that can be inexpensively placed on an integrated circuit is increasingly exponentially–doubling every 2 years. Trend for >50 years.

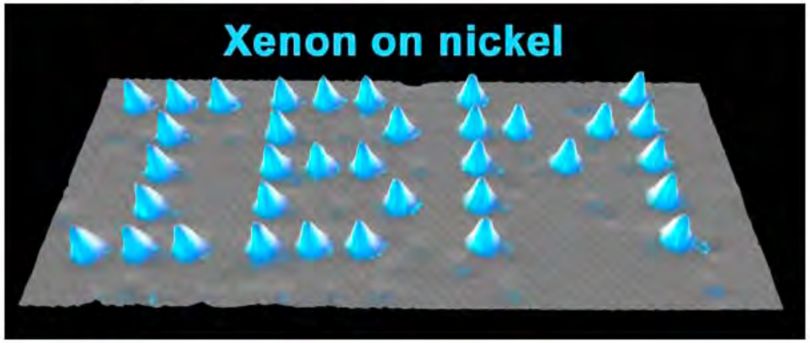
Manipulating matter at the nanoscale: Two basic ways

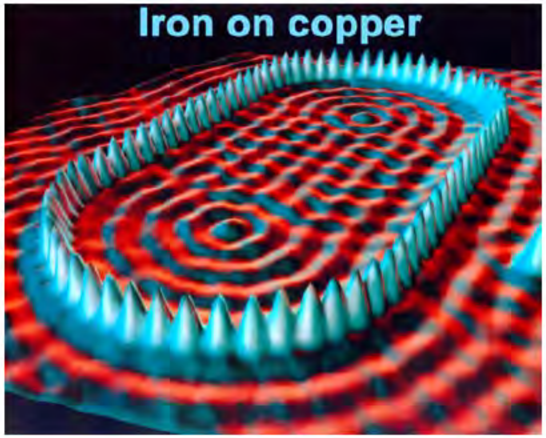
1. Top-down: "chisel" away material to make nanoscale features
   - ✓ Patterning by microlithography (<10 μm) and nanolithography (<100 nm)
     - ✓ May ultimately be limited by physics and cost constraints

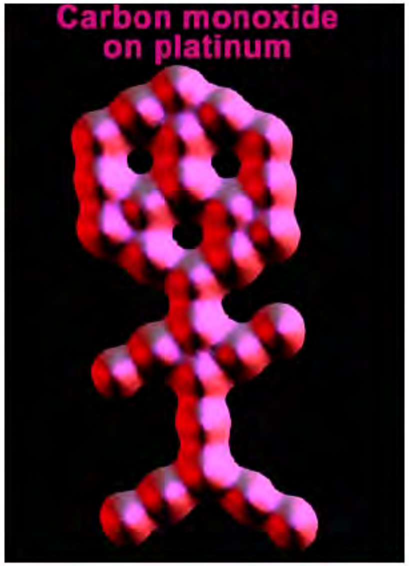
2. Bottom-up:
   - ✓ Pick atoms up and move them into place
   - ✓ "Self-assembly" or crystal growth

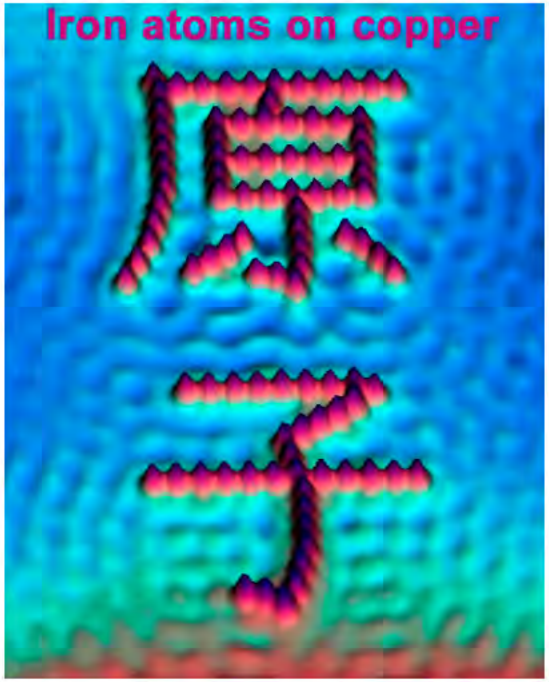
Goal: Design new materials with "dialed-in" properties by building at the scale of nature—the nanoscale)

Fun examples of atom-by-atom bottom-up assembly









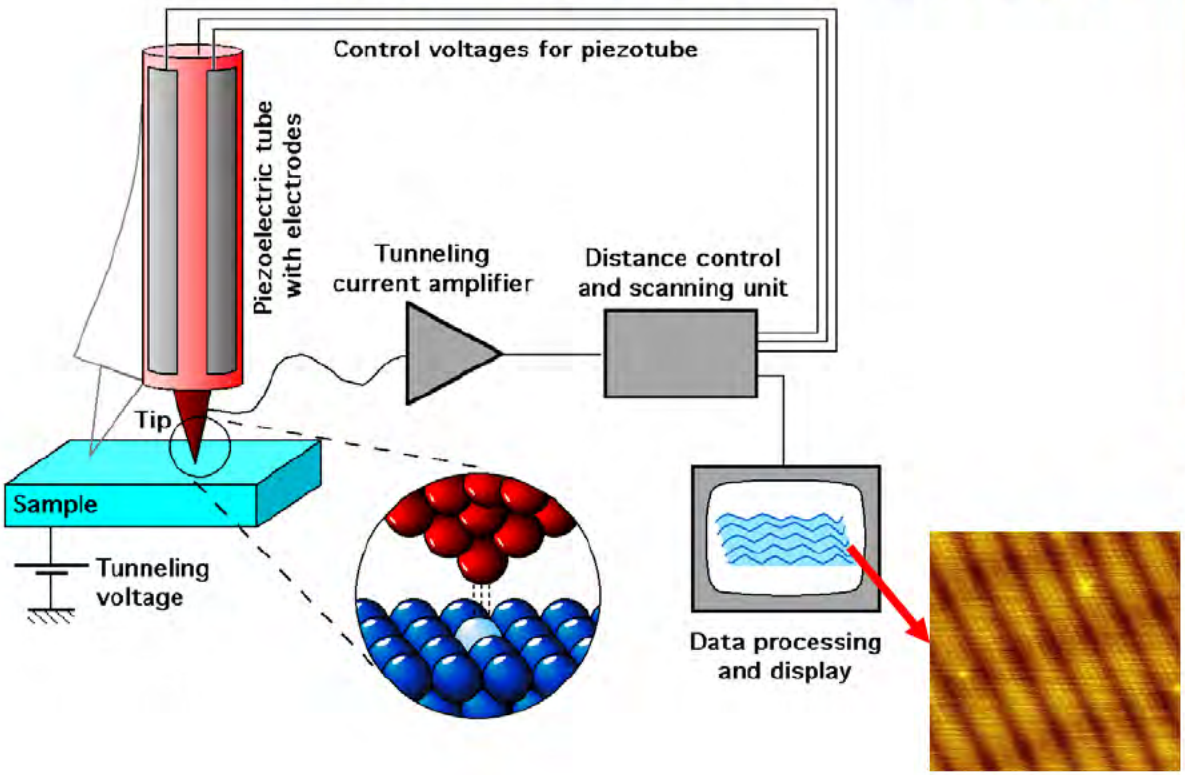
<u>The tools:</u> Scanning tunneling or Atomic force microscopes

- ✓ STM's and AFM's are non-optical microscopes use to look at atomic and nanoscale objects
- ✓ STM's and AFM's can also be used to move atoms to create nanoscale objects

More on the STM

<u>The tools:</u> Scanning tunneling microscope

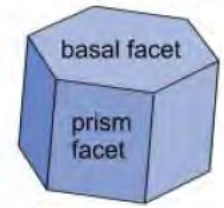
- STM can "see" with a side-to-side resolution of 0.1 nm and up-down resolution of 0.01 nm
- How?
  - ✓ Bring very tiny conducting tip very near to a metallic/semiconducting surface
  - ✓ Apply a voltage to tip
  - ✓ Electrons "tunnel" between tip and surface
  - ✓ Differences in this "tunneling current" as the tip is dragged over the surface equals changes in height and spacing = an STM image



Close-up of STM head with platinum/iridium stylus

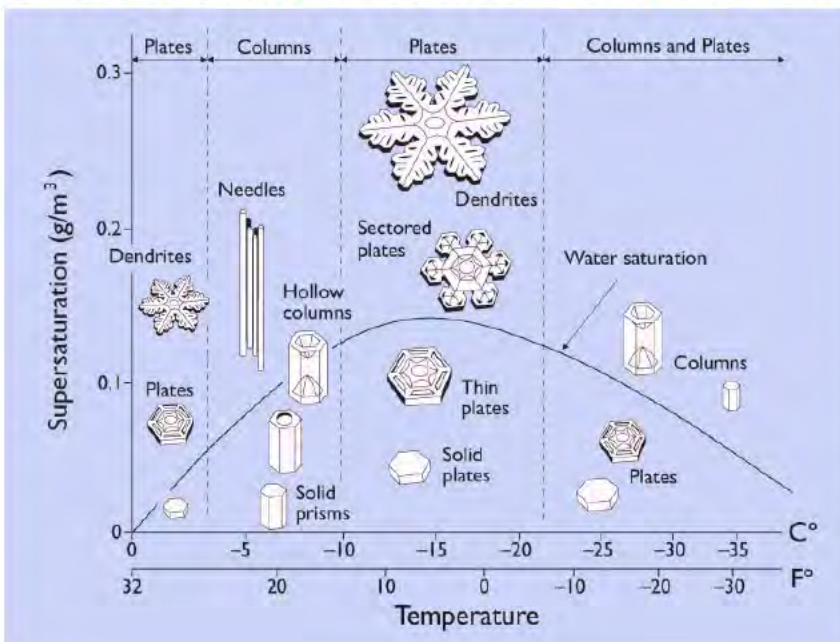
Manipulating matter at the nanoscale: Self assembly and crystal growth

- Molecules self-assemble when the forces between these molecules are sufficient to overcome entropy
- Snow crystal growth is an example of water (H_2O) molecules coming together to form a larger crystal with defined shape
- Snow crystals form when water vapor solidifies directly into ice
- The simplest form of the snow crystal is a hexagonal prism:



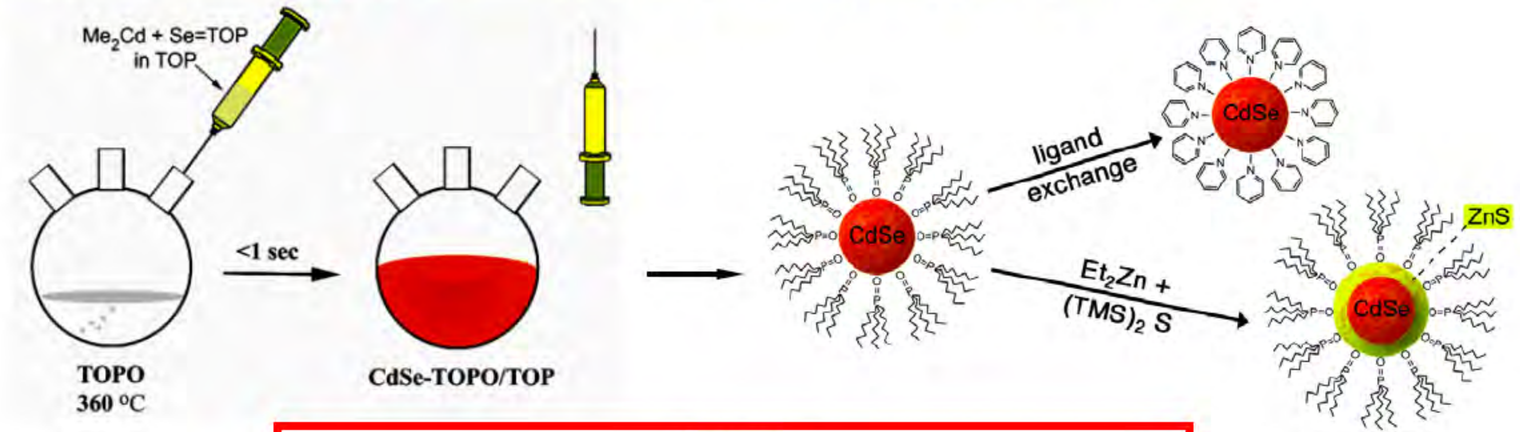
- As snow crystals grow, branches sprout:

- Temperature and humidity determine shape and size:



Manipulating matter at the nanoscale: Self assembly and crystal growth

- Quantum dots! Instead of H_2O, we assemble semiconductor compounds: CdSe, PbSe, InAs, etc.
- Self assembly and crystal growth similar to snow crystal formation
- Difference: We control the ingredients, temperature and **CONTROL** the growth
- Key for nano: **STOP** growth before the crystals get too big!

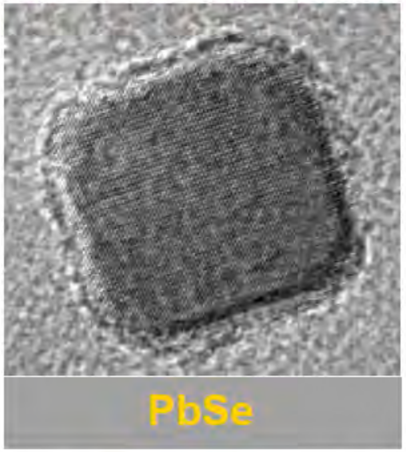


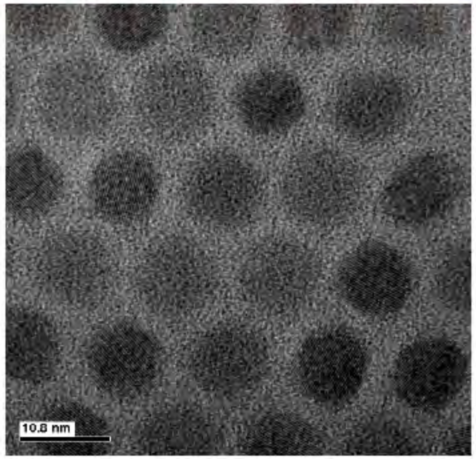
RECIPE

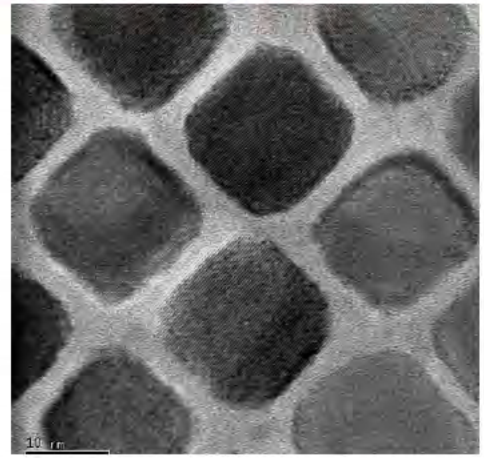
- "Round-bottom flask:" mixing bowl
- "Solvent" that boils at high temperatures: oven
- Ingredients or "precursors" are injected using a syringe
- High temperatures cause precursors to break apart or "decompose" and re-assemble as nanocrystals

Quantum dots: What do they really look like?

Spheres, cubes, rods, dumbbells, wires, stars depending on growth conditions…







In$_2$O$_3$ NWs: TEM

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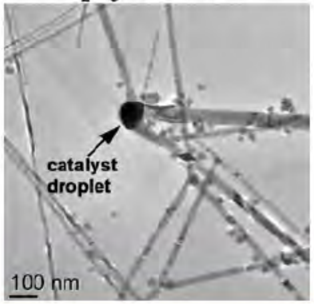
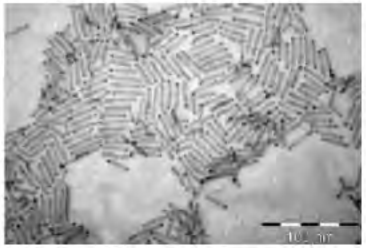
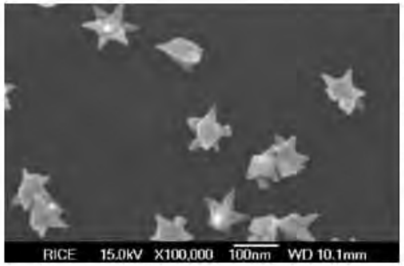
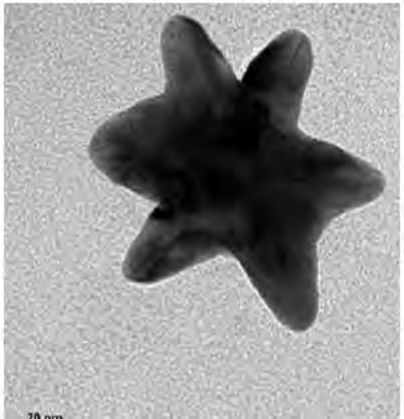






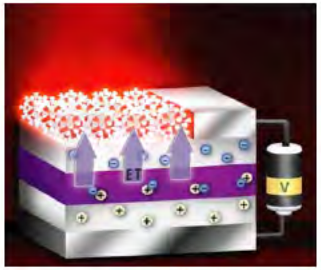


Active light emission! (all CdSe q-dots)

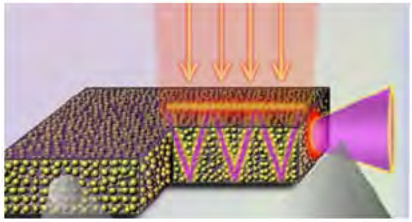
Composition, size and shape control give us control over optical properties

Some important quantum dot applications

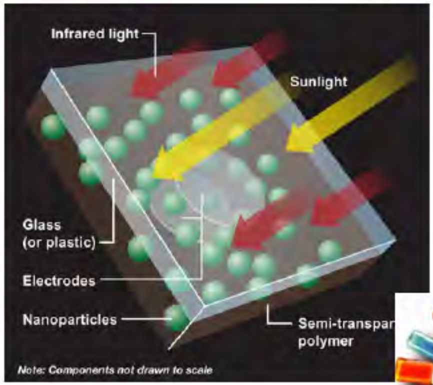
Color-tunable light emitting diodes: efficient lighting



Color tunable lasers: UV through infrared



Solar cells: low cost, high efficienct "generation III"



Biomedicine: Cell and biomolecule labeling/tracking; Diagnosis; treatment