WHAT IS NANOTECHNOLOGY?

Adapted from Online Materials Available from NNIN:

http://www.nnin.org/nnin_edu.html

Nanotechnology is the science and technology of small things – in particular, things that are less than 100nm in size. One nanometer is 10^{-9} meters or about 3 atoms long. For comparison, a human hair is about 60-80,000 nanometers wide.

Scientists have discovered that materials at small dimensions—small particles, thin films, etc—can have significantly different properties than the same materials at larger scale. There are thus endless possibilities for improved devices, structures, and materials if we can understand these differences, and learn how to control the assembly of small structures.

There are many different views of precisely what is included in nanotechnology. In general, however, most agree that three things are important:

1. Small size, measured in 100s of nanometers or less
2. Unique properties because of the small size
3. Control the structure and composition on the nm scale in order to control the properties.

Nanostructures—objects with nanometer scale features—are not new and they were not first created by man. There are many examples of nanostructures in nature in the way that plants and animals have evolved. Similarly there are many natural nanoscale materials, such as catalysts, porous materials, certain minerals, soot particles, etc., that have unique properties particularly because of the nanoscale features. In the past decade, innovations in our understanding of nanotechnology have enabled us to begin to understand and control these structures and properties in order to make new functional materials and devices. We have entered the era of engineered nanomaterials and devices.

Nano- & Micro-lithography: "Top-Down Nanotechnology"

An area of nanotechnology that has been evolving for the last 40 years is the technique of micro- and nano-lithography and etching. These techniques are the source of the great microelectronics revolution, sometimes called "top-down" nanotechnology. Here, small features are made by starting with larger materials and patterning or "carving down" to make nanoscale structures in precise patterns. Complex structures such as microprocessors containing hundreds of millions of precisely positioned nanostructures can be fabricated. Tthis is the most well-established of all forms of nanotechnology. Production machines for these techniques can cost millions of dollars and a full-scale microprocessor factory can cost a billion dollars or more. In recent years, the same "top down" nanoprocessing techniques have enabled many non-electronic applications, including micromechanical, microptical, and microfluidic devices.

Molecular/Chemical Nanotechnology: "Self-Assembly"

Often called molecular or chemical nanotechnology, this fundamentally different area of nanotechnology results from starting at the atomic scale and building up materials and structures, atom by atom. It is essentially molecular engineering. This is accomplished by utilizing the forces of nature to assemble nanostructures – the term "self assembly" is often used. Here the forces of chemistry are in control and we have, at least to date, somewhat less flexibility in making arbitrary structures. The nanomaterials created this way, however, have resulted in a number of consumer products. Significant advances continue, the more we explore and understand the area of chemical nanotechnology.

In addition, there are many exciting applications that combine both bottom-up and top-down processing. An example of this would be single-molecule transistors that have large (macroscopic) leads fabricated by top-down as well as single molecule (microscopic) assemblies built from the bottom, up.

Unique Properties of Nanomaterials

At the nanoscale, properties of materials behave differently, governed by atomic and molecular rules. Researchers are using the unique properties of materials at this small scale to create new and exciting tools and products in all areas of science and engineering.

Nanotechnology combines solid state physics, chemistry, electrical engineering, chemical engineering, biochemistry, biophysics, and materials science. It is thus a highly interdisciplinary area – integrating ideas and techniques from a wide array of traditional disciplines. Some universities have begun to issue degrees in nanotechnology; others view it as a portion of existing academic areas. Either way many trained scientists, engineers, and technicians in these areas will be required in the next 30 years.

Many are predicting that nanotechnology is the next technical revolution and products resulting from it will affect all areas of our economy and lifestyle. It is estimated that by 2015 this exciting field will need 7 million workers worldwide. The workforce will come from all areas of science and engineering and will include those with two-year technical degrees up to PhD researchers in universities and industry.

Nanotechnology Careers: What is the Workforce Need?

As nanoscale science and technology come to have increasing impacts on many aspects of our daily lives, the opportunities for careers in these fields are expanding rapidly. A major challenge for the field is the education and training of a new generation of skilled workers. Nanotechnology job projections are estimated to be nearly two million workers worldwide by 2015. In what countries will these jobs occur? (In addition to the figures below, nanotechnology will create another five million jobs worldwide in support fields and industries.)
**Source: Mihail Roco Nature Biotechnology vol. 22 No. 20 Oct. 2003*

- 0.8-0.9 million – USA
- 0.5-0.6 million – Japan
- 0.3-0.4 million – Europe
- 0.2 million – Asia Pacific (excluding Japan)

Where are the Career Areas?

Career areas as diverse as designing medical diagnostic devices to building better batteries, creating cosmetics, enhancing energy-efficient windows, auto and plane manufacturing, or researching the nature of matter itself will all depend upon knowledge of nanoscale science and technology. Current applications of nanoscale science and technology, with corresponding career opportunities, exist in areas such as:

Electronics/semiconductor industry	Medical fields	Automobile industry
Pharmaceuticals including drug delivery, cosmetics, among others	Materials science including textiles, polymers, packaging, among other	Environmental monitoring and control
Biotechnology	Sports equipment	Optoelectronics
Forensics	Food science: quality / packaging	Aerospace industry
Military	National security	University and federal lab research

Nanoscale science and technology are fueling a revolution in **manufacturing and production**, creating new materials and novel processes. Not only will the areas listed above continue to grow and benefit from nanotechnology, but the following fields are expected to undergo explosive developments:

- Medicine: diagnostics and therapeutics (e.g., drug delivery)
- Energy: capture, storage, & use; fuel cells, batteries
- Environmental remediation: in conjunction with GM microbes
- Robotics: many uses
- Manufacturing: self-assembly; "bottom-up" fabrication of novel materials
- Commerce: Radio Frequency Identification (RFID) "smart" tags
- Space exploration: space elevator

As these lists of nanoscience-based applications indicate, our world is increasingly dependent on science for food, shelter, energy, etc. For our democratic society to function effectively, citizens must become familiar with at least some basic science and, perhaps even more importantly, with thinking scientifically.

What Type of Education is Needed for a Career in Nanotechnology?

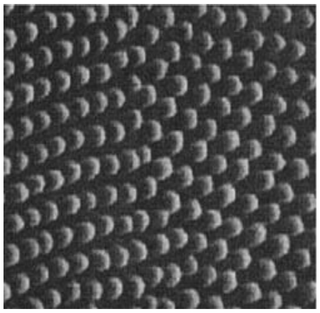
Nanoscale phenomena underlie many of the properties and interactions of matter, and thus the sciences of **physics, chemistry, and biology, as well as mathematics and computer sciences**. Studying these fields, and paying attention to the developments in nanoscience that advance them and the applications in nanotechnology that they support, can provide you with a solid foundation for any of a broad range of careers. Potential fields of study include: Biology, Chemistry, Physics, Environmental Science, Agricultural Science, Engineering, Medicine, Forensic Science, Law, Business, & Ethics.

Not everyone working in the field will require a doctorate degree in one of the fields noted above. A skilled workforce trained at a variety of levels is needed to meet the projected workforce challenge of 7 million workers. The table below indicates level of degree, the estimated time to completion for a full-time student after receiving a high school diploma, and then the expected salaries for work in nanotechnology:

Type of Degree	Years to Completion	Expected Salary Range
Associates degree	2 years	$ 30-50,000
Bachelor's degree	4 years	$ 35-65,000
Masters degree	6 years	$40-80,000
Doctorate	8 years	$75-100,000
***Source**: Pennsylvania State University; Center for Nanotechnology Education and Utilization*		

Some additional sites to explore: http://www.nano.gov/html/edu/careers.htm
http://www.tinytechjobs.com
http://www.workingin-nanotechnology.com
http://www.nanostudent.com
http://www.nnin.org/nnin_careers.html

Nanostructures in Nature



If we look closely, we can notice that many plants and animals around us have developed special features that are at the nanoscale level. Let's examine some of the ways in which nature has used nanostructures.

A moth's eye has very small bumps on its surface. They have a hexagonal shape and are a few hundred nanometers tall and apart. Because these patterns are smaller than the wavelength of visible light (350-800nm), the eye surface has a very low reflectance for the visible light so the moth's eye can absorb more light. The moth can see much better than humans in dim or dark conditions because these nanostructures absorb light very efficiently. In the lab, scientists have used similar man-made nanostructures to enhance the aborption of infra-red light (heat) in a type of power source (a thermo-voltaic cell) to make them more efficient!

On the surface of a butterfly's wings are multilayer nanoscale patterns. These structures filter light and reflect mostly one wavelength, so we see a single bright color. For instance the wings of the male Morpho Rhetenor appear bright blue. But the wing material is not, in fact, blue; it just appears blue because of particular nanostructures on the surface. The nanostructures on the butterfly's wings are about the same size as the wavelength of visible light and because of the multiple layers in these structures optical interferences are created. There is constructive interference for a given wavelength (around 450nm for the Morpho Rhetenor) and destructive interferences for the other wavelengths, so we see a very bright blue color. In the laboratory, many scientific instruments use this same phenomena to analyze the color of light.

The edelweiss (Leontopodium nivale) is an alpine flower which lives at high altitudes, up to 3000m / 10,000 ft, where UV radiation is strong. The flowers are covered with thin hollow filaments that have nanoscale structures (100-200nm) on their periphery. They will absorb ultraviolet light, which wavelength is around the same dimension as the filaments, but reflect all visible light. This explains the white color of the flower. Because the layer of filaments absorbs UV light, it also protects the flower's cells from possible damage due to this high-energy radiation.

Amazing Creatures with Nanoscale Features

Developed by the NNIN site at Pennsylvania State University, this animation is an introduction to microscopy, scale, and applications of nanoscale properties. It introduces some of the tools that are used by scientists to visualize samples that are smaller than what we can see with our eyes. This includes the optical microscope, scanning electron microscope, and the atomic force microscope. In this animation, you will take a closer look at a butterfly wing at different magnifications and see features at the nanoscale that give the butterfly unique properties. Then, you will learn how scientists and engineers are able to mimic these structures through engineering techniques. Look for the addition of more specimens and applications in the future. This activity runs within Flash Player. You can download the latest version of Flash Player from Adobe.

Click on the link here to launch the activity: http://www.cneu.psu.edu/activities/Amy/index.html

How Do We See Nanostructures?

First, it takes some pretty sophisticated instruments to see nanostructures.

Optical (light) Microscopes focus visible light through “lenses” to make a magnified image. They work essentially like a magnifying glass. Some of you may even own a microscope, or have used one in school. Precision optical microscopes used in nanotechnology can cost up to $50,000. But even with the most precision, most sophisticated optical microscope, one problem remains—light waves are “big”, at least on the scale of nanostructures. As the resolution power of these instruments is limited to about half of the wavelength of light, they can only reveal features down to ~250 nm.

When we talk about seeing small structures, it is important to distinguish between “resolution” and “magnification”. We can “blow up” (magnify) an image (e.g. a picture) as much as we want - make it as big as a poster on your wall - but that does not make the image any sharper or increase our ability to resolve small structures – i.e. to have sharp edges and to distinguish separately closely spaced objects. Blowing up a picture too big just gives you a fuzzy big picture; that is called “empty magnification” and it does us little good. What is important is the ability to sharply see structures that are close to each other. This latter is called resolution and is the most important property of any microscope.

Optical microscopes give us a top-down, flat, "airplane" view of the surface. It is difficult to learn much about 3-D objects with a high powered optical microscope because they have very low "depth of field"- i.e only objects at a certain, very narrow height will be in focus. For a high magnification optical microscope, this "depth of field" can be less than 1 micro meter- anything taller than 1 micrometer is out of focus and blurry.

With a super high quality optical microscope, we see and resolve structures down to about 250 nm. That still leaves a lot that we can’t see. For those, we need an electron microscope!

Electron Microscopes use electron beams instead of visible light, enabling resolution of features down to a few nm. Several different types of EMs exist, including Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) . Electron Microscopes use a beam of high energy electrons to probe the sample. Electrons do not suffer the same resolution limits that light does, so we can “see” features as small as 0.1 nm. This is the size of an individual atom. Electronic signal processing is used to create a picture of what the sample would look like if we could see it. While electron microscopy offers finer resolution of features than does optical microscopy, it requires vacuum conditions in order to maintain a focused electron beam. This makes electron microscopy inconvenient for examining many biological samples, which must first be preserved and coated with layers of metal atoms. Another advantage of electron microscopes is that they have both high magnification and high depth of field. We can see objects as in apparent three dimensions. This is again due to the short "wavelength" of electrons. You may have seen some really "monster" like pictures of bugs that highlight the imaging capabilities of the scanning electron microscope. High quality electron microscopes can cost from $250,000 to $1,000,000! They are one of the most useful instruments in our laboratories.

Scanning Probe Microscopes (SPM) of various types trace surface features by movement of a very fine pointed tip mounted on a flexible arm across a surface. SPM enables resolution of features down to ~1 nm in height, allowing imaging of single atoms under ideal conditions. Scanning Tunneling Microscopes (STM) measure current (i.e., electron flow) between the probe tip and sample, essentially acting like a tiny voltmeter. This method requires that the sample be electrically conductive. Atomic Force Microscopes (AFM - sometimes call Scanning Force Microscopes) measure interaction forces between probe tip and sample, providing information on the mechanical properties of surfaces. They can measure forces of 10-9 Newton. (For comparison, the force exerted by an apple is ~1 N.) AFMs are widely used to measure surface topography of many types of sample and do not require special conditions such as conductive surfaces or vacuum.

Scanned probe microscopes and particularly AFMs basically see things by touching. Imagine you have your right hand in a dark box with a mystery object and you are trying to figure out what the object is, without looking. One systematic way to do this would be to touch every point on a grid , say 30 points wide and 30 points deep, covering the entire floor of the box. Imagine that with your left hand, you record the the "height" (or any other physical property) at each grid point on a piece of graph paper. You could then make a 3-d graph surface, or a 2-d plot with colors indicating height. After touching and recording 900 points, you would have a "picture" of the object. That is exactly what an atomic force microscope does, except the AFM uses a very fine point instead of a finger, and is built on a mechanism that can reproducibly move the tip less than 0.1 nm between points. Scanning probe microscopes can actually 'feel" the bumps due to individual atoms and molecules !

About the National Nanotechnology Infrastructure Network (NNIN)

The federal government believes that nanotechnology is one of the most important research endeavors for our country. In 2001 it established the National Nanotechnology Initiative (NNI) as an umbrella organization to promote and organize nanotechnology research across the government. Under NNI, ten federal agencies fund nanotechnology research with a current budget of approximately $1 billion per year. An aggressive set of technology milestones and grand challenges have been set by NNI. In 2004, President Bush signed into law the 21st Century Nanotechnology Research and Development Act which further promoted nanotechnology research. Other countries around the world have followed with significant programs in Nanotechnology. The National Nanotechnology Infrastructure Network (NNIN) consists of specialized nanotechnology laboratories at 13 universities across the nation, and was funded in 2004 by the National Science Foundation as part of the NNI program. The NNIN provides researchers from across the nation with economical access to state-of-the art nanotechnology facilities.

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