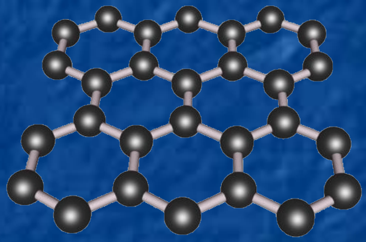
What IS Nanoscience?

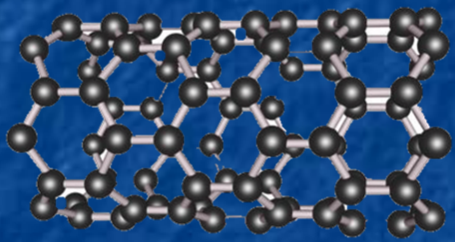
When people talk about Nanoscience, many start by describing **things**

Physicists and Material Scientists point to **things** like new nanocarbon materials:

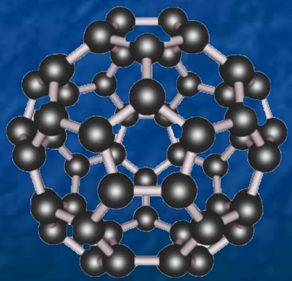
They effuse about nanocarbon's strength and electrical properties



Graphene



Carbon Nanotube

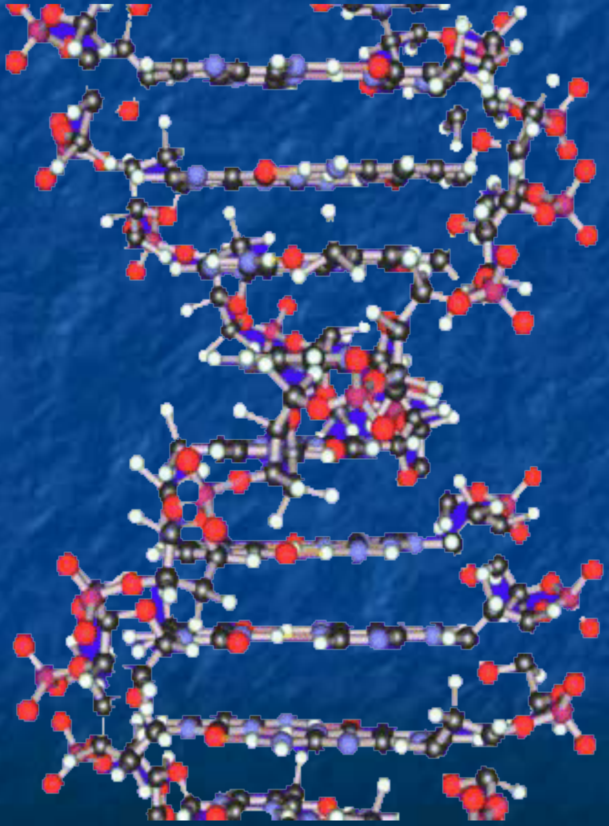


C60 Buckminster Fullerene

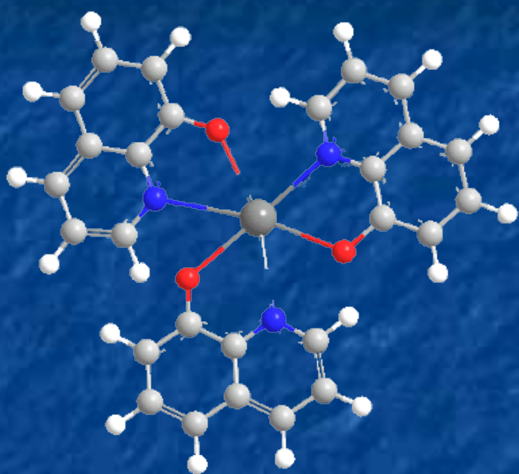
Biologists counter that nanocarbon is a recent discovery

THEY'VE been studying DNA and RNA for much longer

(And are already using it to transform our world)

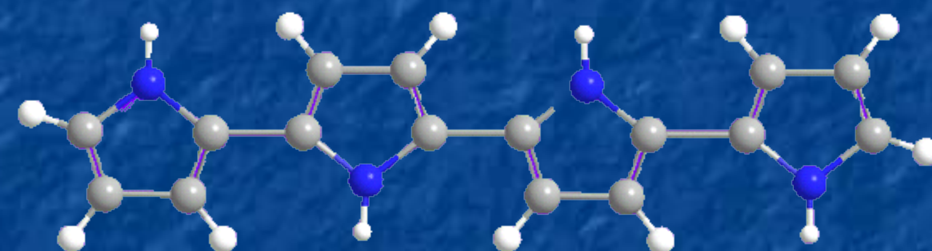


And Chemists note THEY'VE synthesized molecules for over a century

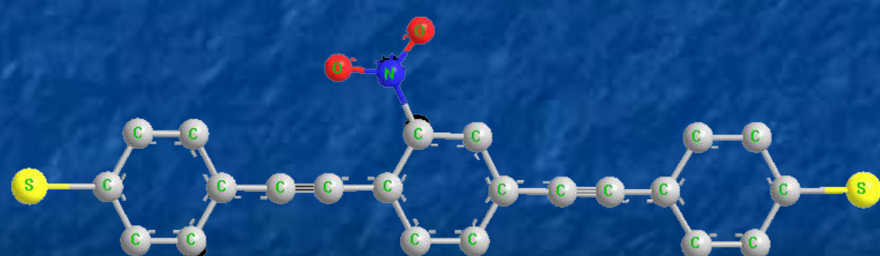


<= First OLED material: tris 8-hydroxyquinoline aluminum

(OLED = organic light emitting diode)



Commercial OLED material: Polypyrrole



Most heavily investigated molecular electronic switch: Nitro oligo phenylene ethynylene

All of these **things** ARE very small

Indeed, they are all about the size of a nanometer:

Nano = 10^{-9} = 1/ 1,000,000,000 = 1 / Billion

A nanometer is about the size of ten atoms in a row

This leads to ONE commonly used definition of nanoscience:

Nanoscience is study of nanometer size **things** (?)

Why the question mark? Because what is so special about a nanometer?

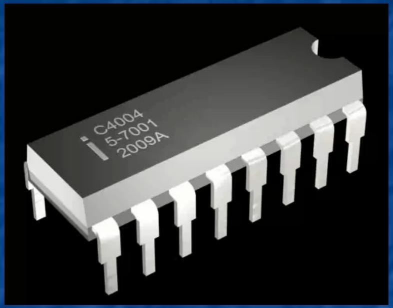
A micrometer is ALSO awfully small:

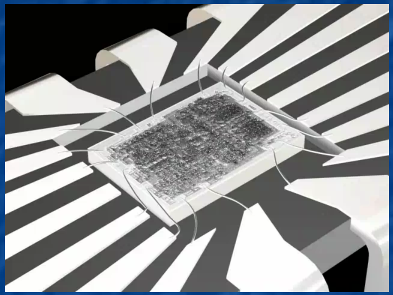
Micro = 10^{-6} - 1/1,000,000 = 1 / Million

A micrometer (or "micron") is ~ size of light's wavelength

And microtechnology has been rolling along for half a century!

Microelectronics = Integrated circuits, PC's, iPods, iPhones . . .

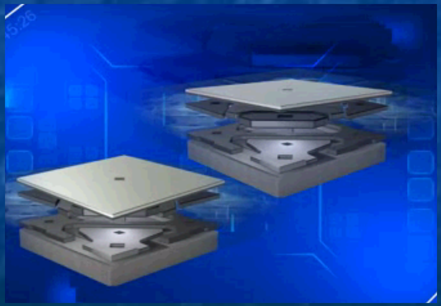




Intel 4004: The original "computer on a chip" - 1971 (Source: UVA Virtual Lab)

Also = MEMS (Micro-electro-mechanical-systems):

Air bag accelerometers, micro-mirror TVs & projectors . . .



(Source: Texas Instruments DLP demo - www.dlp.com/tech/what.aspx)

Indeed, microtechnology has gotten smaller EVERY year

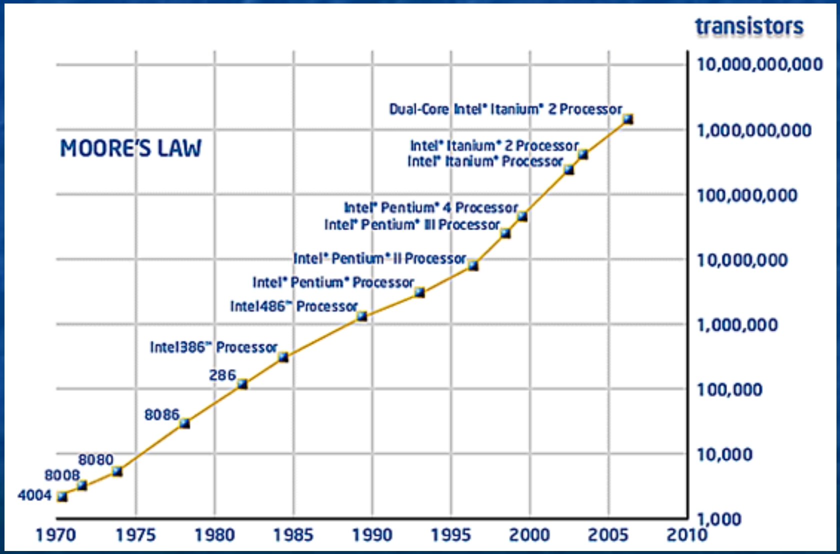
MOORE'S LAW:

The (then almost whimsical) 1965 observation by Intel co-founder Gordon Moore that the transistor count for integrated circuits seemed to be doubling every 18-24 months

He was really sticking his neck out: IC's had only been invented 7 years before!

(by Moore, his Fairchild/Intel colleagues, and Texas Instrument's Jack Kilby)

But his "law" has since been followed for forty five years:



(Source: www.intel.com/technology/mooreslaw/index.htm)

So is Nanoscience/technology really new & unique?

Micro is also VERY small

Micro has been around for a long time

Micro has steadily shrunk to the point that it is now almost NANO anyway !

Leading to a LOT of confusion about the distinction between Micro & Nano

Even among scientists!!

And likelihood that Nanotechnology will be built UPON Microtechnology

Either by using certain Microfabrication techniques

Or, literally, by being assembled ATOP Microstructures

Meaning that the NANO "revolution" is just a lot of hype?

Just about making things **incrementally** smaller?

Just about a simple shift in the most **convenient** unit of measure?

No, as a Nano scientist/teacher, I DO see something very unique about Nano:

Nano is about boundaries where BEHAVIOR radically changes:

When the **BEHAVIOR OF THE OBJECTS SUDDENLY CHANGES**

Or when **OUR BEHAVIOR MUST CHANGE** to make those things

Boundary #1:

ELECTRON WAVES Separate NanoSCIENCE from MicroSCIENCE

The discovery that electrons = waves led to QUANTUM MECHANICS

A weird, new, counter intuitive, non-Newtonian way of looking at the nano world

With a particular impact upon our understanding of electrons: Electrons => Waves

How do you figure out an electron's wavelength?

$\lambda_{electron} = h / p$ "De Broglie's Relationship"

(λ = electron wavelength, h = Planck's Constant, p = electron's momentum)

This relationship was based on series of experiments late 1800's / early 1900's

To put the size of an electron's wavelength in perspective:

Size of **Things** (orange = man-made **things**)

	Millimeters	Microns	Nanometers
Ball of a ball point pen	0.5		
Thickness of paper	0.1	100	
Human hair	0.02 - 0.2	20 – 200	
Talcum Powder		40	
Fiberglass fibers		10	
Carbon fiber		5	
Human red blood cell		4 – 6	
E-coli bacterium		1	
Size of a modern transistor		0.25	250
Size of Smallpox virus		0.2 – 0.3	200 – 300

Electron wavelength: ~10 nm or less

	Millimeters	Microns	Nanometers
Diameter of Carbon Nanotube			3
Diameter of DNA spiral			2
Diameter of C60 Buckyball			0.7
Diameter of Benzene ring			0.28
Size of one Atom			~0.1

Below that line = Nanoscience!

It's NOT just about the metric units we prefer to use when measuring **things**

Things above that line are still often measured using nanometers

It IS about the SCIENCE (QM) => Electrons are mushy clouds of size ~ $\lambda_{\text{De Broglie}}$

Above that line, clouds seem small: Electrons ~ hard B-B like dots

Below that line, mushy cloudiness of electrons becomes very important

Controls electrical, optical, mechanical and other properties

Controls bonding and nanostructure

The Behavior Changes! Microscience ≠ Nanoscience

Or putting it into more human terms

Above that boundary:

Things still **behave** as Sir Isaac Newton would expect

It is still the world WE commonly experience

Even though we DO need microscopes to see its smaller things

And even if those smaller things seem unduly influenced by:

Water tension, static charge . . . (things we largely ignore)

Below that boundary:

The rules of Quantum Mechanics => Mushy electron waves take over

And our (Newtonian) instincts and assumptions are frequently dead wrong!

Boundary #2:

LIGHT WAVES Separate NanoTECHNOLOGY form MicroTECHNOLOGY

Technology = The things we make and how we make them

As opposed to the underlying science dictating how they act

Where does light's wavelength enter into technology?

Micro technology is based on the use of light

How? Light is used for PHOTOENGRAVING:

Use of light images to pattern metal parts =>

Micro projection of light images = Way we make the billions of transistors in the integrated circuits of our PCs, iPods . . .

(a.k.a. "Microfabrication")

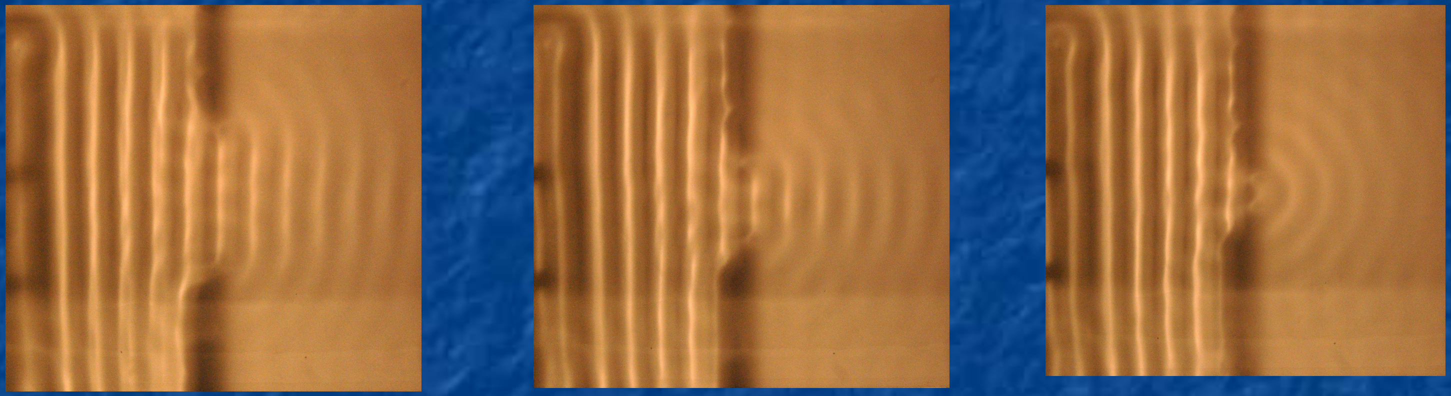
But HOW does Light Wavelength affect Technology?

Micro-photoengraving (photolithography) confines projected light to small beams

Can "confine" by focusing light with a lens

Can "confine" by passing light through holes / shadow masks

But you cannot confine a wave into a beam narrower than its wavelength



Shadow images of water waves, from left, passing thru gap in barrier

Explore fully in lecture 2 - For now, point is can't photo-process below wavelength

OK, but what is light's wavelength?

Size of **Things** (orange = man-made **things**)

	Millimeters	Microns	Nanometers
Ball of a ball point pen	0.5		
Thickness of paper	0.1	100	
Human hair	0.02 - 0.2	20 – 200	
Talcum Powder		40	
Fiberglass fibers		10	
Carbon fiber		5	
Human red blood cell		4 – 6	
E-coli bacterium		1	1000
Visible Light Wavelength:		0.40 – 0.75 microns	400 – 750 nm
Size of a modern transistor (fabricated using UV light)		0.25	250
Size of Smallpox virus		0.2 – 0.3	200 – 300

Electron wavelength: Upper upper limit ~ 10 nm

	Nanometers
Diameter of Carbon Nanotube	3
Diameter of DNA spiral	2
Diameter of C60 Buckyball	0.7
Diameter of Benzene ring	0.28
Size of one Atom	~0.1

At new (upper) visible/UV light boundary and above:

We can still use light-based “Microfabrication” techniques

And even though they were developed for electronics,

they are now also applied to making all sorts of micro things!

Below that new boundary:

NO longer able to use Microfabrication – OUR behavior must change!

Replacement is called “Nanofabrication” or “Nanotechnology”

Dirty little secret: We are still rather poor at Nanofabrication/Nanotechnology

We can do it in very small quantities, at very great expense

But we haven't figured out how to do it well enough to = technology

(I'll return to this point later)

To recap:

There are big changes in OBJECT BEHAVIOR below ~ 10 nanometers:

Newton is out the window. Quantum Mechanics is in.

Hard sensible objects are replaced by squishy electron waves / clouds

Intuition, based on our life experience => fundamentally flawed

And to make things < 100 nanometers WE MUST BEHAVE differently:

Light will not focus this small

Light image based fabrication ceases to work

Need something new ("Nanotechnology") - Still being defined!!!

Further extending definitions of NANO:

BIOMEDICINE: Organisms create critical barriers to penetration

- Skin
- Blood – Brain barrier
- Cell Membranes

Barriers are breached as objects shrink from microns to nanometers

=> Radical impact on organisms

These changes in BEHAVIOR can also be taken as onset of NANO:

Boundary #3: Radically increased penetration of organisms

Extending definitions of NANO (cont'd):

CIVIL ENGINEERING / ENVIRONMENTAL SCIENCE: Dispersion

Normal dust particles rapidly fall out of the air

But as shrink to nanometers, winds carry them around the world!

Larger pollutants can be trapped in waste sites by clay basins

But nanometer pollutants may escape to flow into ground water

These changes in BEHAVIOR can also be taken as onset of NANO

Boundary #4: Radically increased environmental dispersion . . .

So in THIS nano class:

We will NOT focus narrowly on only certain types of objects

We will NOT get hung up on just one unit of measurement

We will instead search for radical changes in behavior:

Behavior of the objects themselves

Behavior of the objects interacting with organisms & ecosystems

The changes in our behavior required for their fabrication

(Why this class is subtitled "We're not in Kansas Anymore!)

Also want to explore how nano might become practical

Light-based processing will NOT work

Other present day techniques are HOPELESSLY slow and/or expensive

So attractive alternative is **SELF-ASSEMBLY**

Setting things up so that Mother Nature does the fine scale work

But to ferret out where Mother Nature may give us a hand, must span:

Physics, Chemistry, Biology, Materials Science . . .

So I will also put major effort into providing insights into those fields

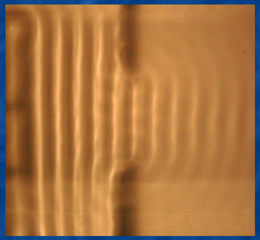
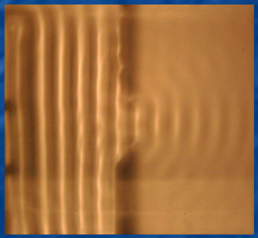
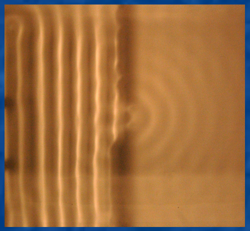
i.e., "**Opening Doors**" into those subjects for you

Specifics about how the class will go?

A recurring theme is wavelength, so:

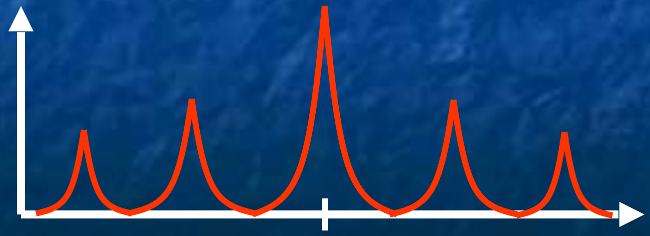
Class 2) We will start by studying waves

Of ALL types - including nice friendly water waves and light waves:

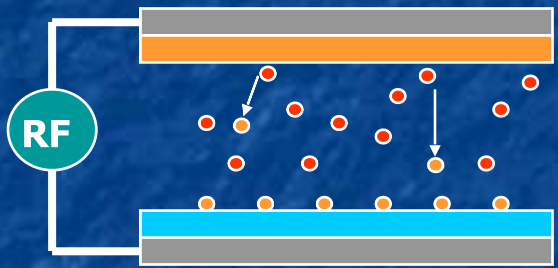
Class 3) We'll then tackle our squirreliest topic: Electron waves & quantum mechanics

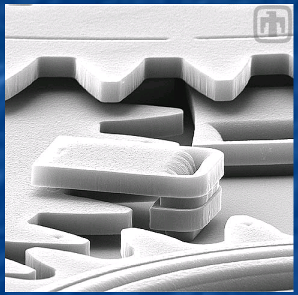
But we'll do this mostly based on what we learned about water waves + some history of why scientists became convinced electrons were truly wavelike



We'll then talk about technology

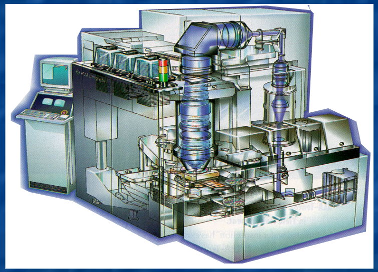
Class 4) We'll learn a bit about microfabrication & microelectronics





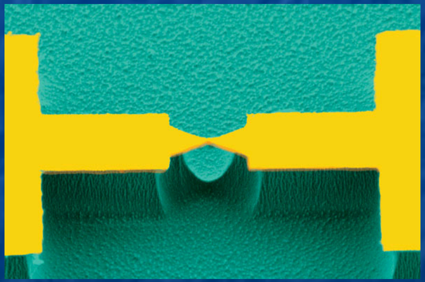
But the lesson will be why, despite MOORE'S LAW, these cannot be extrapolated to nano sizes

Class 5) With that knowledge, we'll distinguish nano <u>science</u> from nano <u>technology</u>



<= Technology

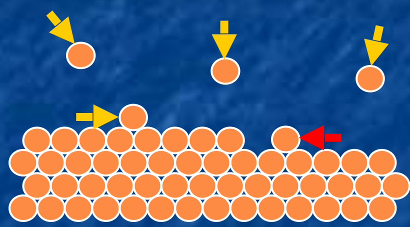
Science =>

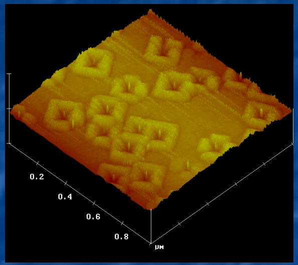


There is a LOT of good Nanoscience, but not yet much in the way of viable Nanotechnology!

We'll then discuss Microfabrication's likely replacement: Nanoscale Self-Assembly

Class 6) Early forms of self-assembly that man tamed (such as crystal growth)

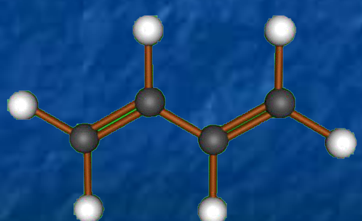


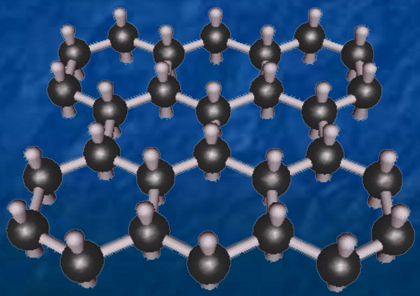


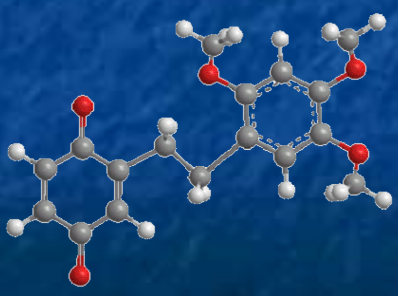
Leading us to the master of self-assembly: Mother Nature

Or what a billion years of random experimentation produced, including:

Class 7) Self-assembly of organic molecules

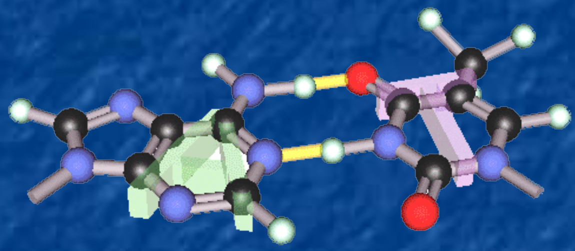




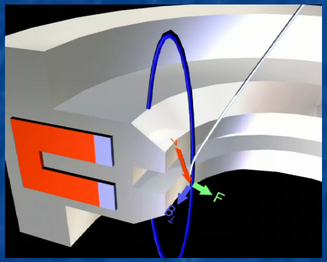


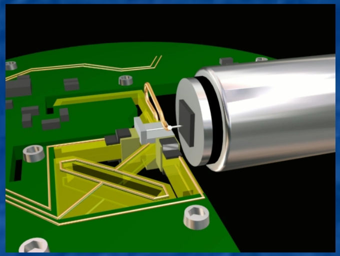
Taking us to the ultimate known form of Self-Assembly: DNA

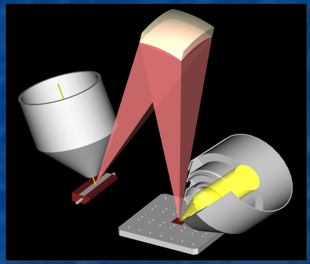
Class 8) The incredible processes of DNA programmed assembly of proteins



Class 9) Leading to a discussion of how we actually "see" and measure at the nanoscale

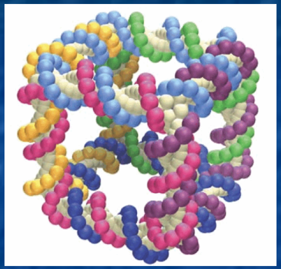


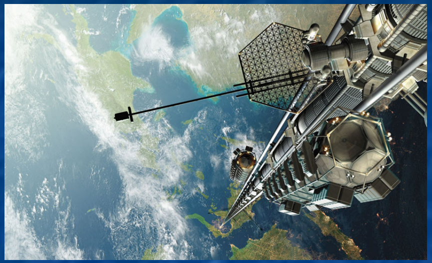




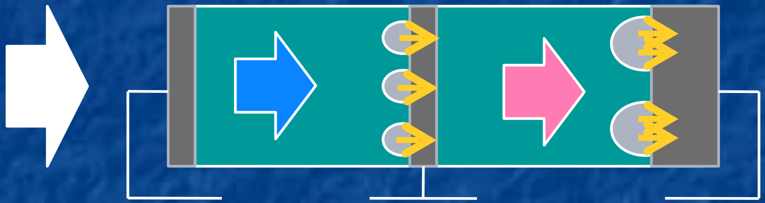
To the "Bleeding Edge:" Where nanoscience **might** be taking us:

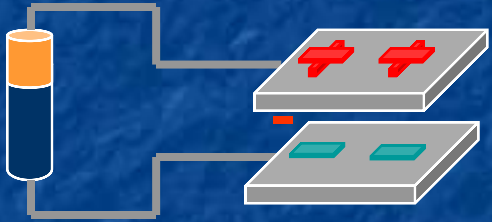
Class 10) Emerging nano-mechanical technologies



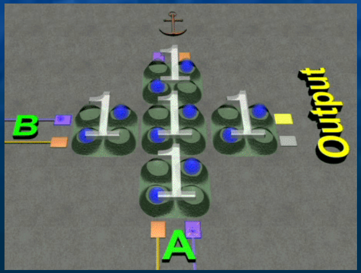


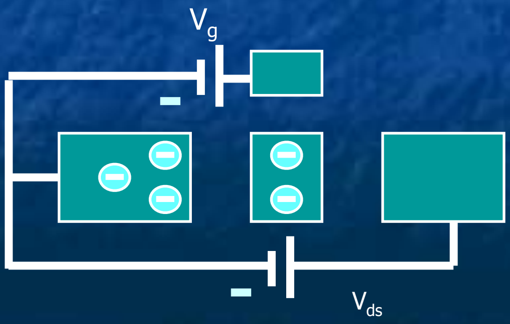
Class 11) Emerging nano-energy technologies





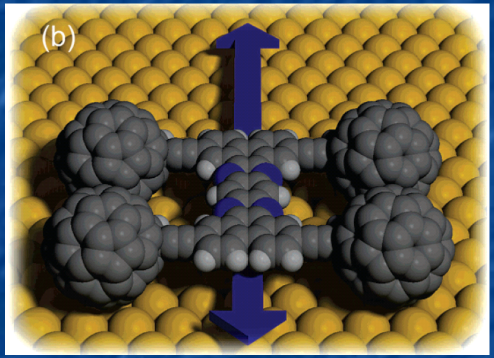
Class 12) Emerging nano-electronic technologies





Then back down to earth for some reality checks:

Class 13) Nano molecular machines: Nanobots in our future?



Class 14) Legitimate fears and challenges of nanoscience & nanotechnology

Labs?

- Waves ("slinky" and "snakey" springs) – to sharpen your observation of waves

- Water Waves – to show why light-based processing is limited,
  why sunblocks use nanoparticles, AND why quantum mechanics is quantized

- Integrated Circuit Microfabrication Cleanroom Demonstration/Tour

- Scanning Electron Microscope

- Self-Assembly (of magnetized atom analogs)

- Using AFM to examine the structure of state-of-the-art integrated circuits

- An introduction to the scanning tunneling microscope

- Using STM to see individual atoms on the surface of graphite

- Super hydrophobic surfaces

- Charlottesville CSI (DNA Fingerprinting)

Homework?

- Weekly personal analyses of nano news reports

- Do-it-yourself models of graphene, nanotubes and Buckyballs

- Do-it-yourself models of DNA

- Study of "UVA Virtual Lab" virtual reality recreations of our

  Scanning electron microscope

  Scanning tunneling microscope

  Atomic force microscope

- Chapters from "textbook"

- Other readings

Credits / Acknowledgements

Funding for this class was obtained from the National Science Foundation (under their Nanoscience Undergraduate Education program).

This set of notes was authored by John C. Bean who also created all figures not explicitly credited above (with the exception of lecture preview figures which are credited in their home set of lecture notes).