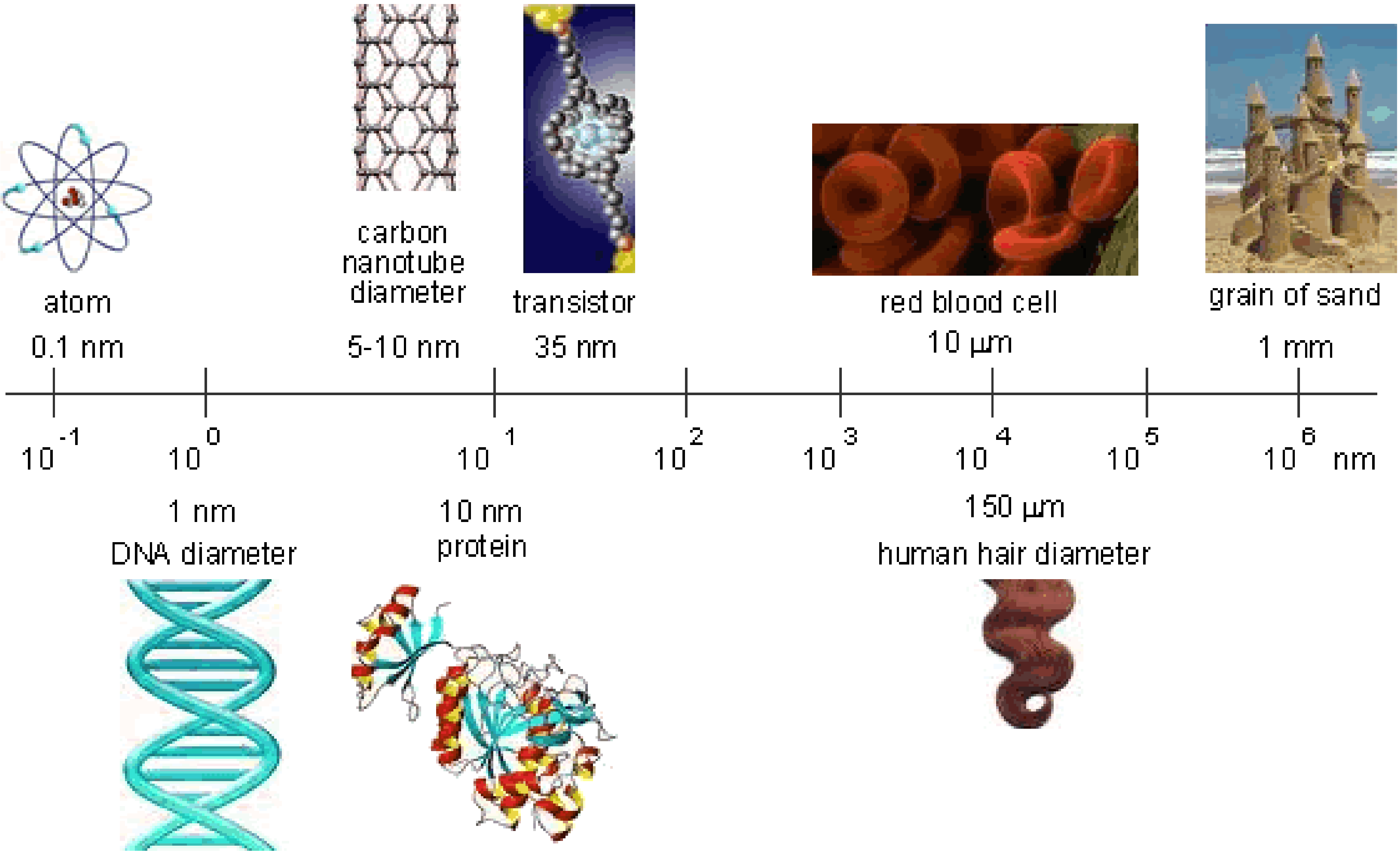
Nanoscale Probing and Imaging

Big Things from the small World

1 inch = 25,400,000 nanometer

1 human hair = 150,000 nanometer

Nano-scale: *how small is 1 nanometer?*



Size Matters for both morphology and composition

Morphology Size →

Composition ↓

bulk	powders	microns	nanometers	angstroms
phase	√	√		
cluster		√	√	
molecules			√	√
atoms				√

Nanoscience: shaping science at nanometer. Examples? Chemical reactions, bonding formation, ...

Nanotechnology: improve technology through nanometer scale manipulation, optimization. Examples? Nanoparticles, Single-molecule transistor, single-cell imaging/operation, ...

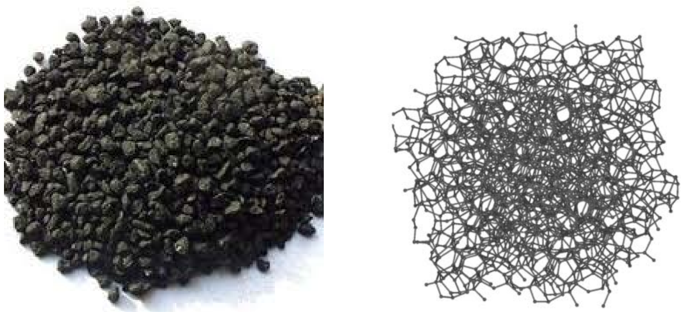
1 nm ~ a few atoms → molecule ←→ building-blocks of materials

→Nanoscale research leads to atomic/molecular scale optimization of materials (e.g. single-crystals) --- bottom up approach, for which the central, and most critical technique is nanoscale imaging and probing, thus developed for characterizing the size, structure, morphology of nanomaterials and their relationship with the optical, electrical and magnetic properties.

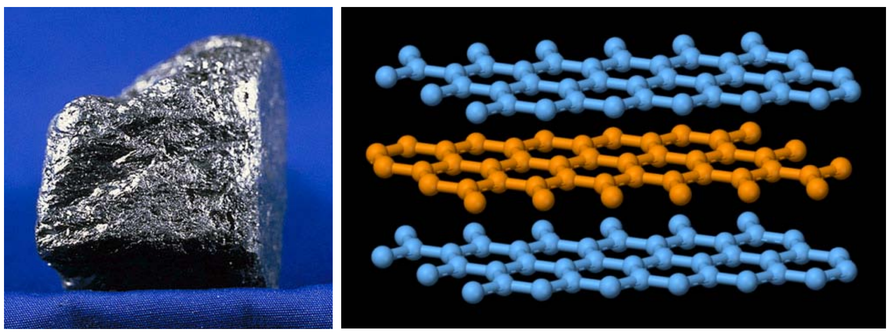
One such example is the structure manipulation of carbon materials. See next slide.

Atomic Manipulation of Carbons

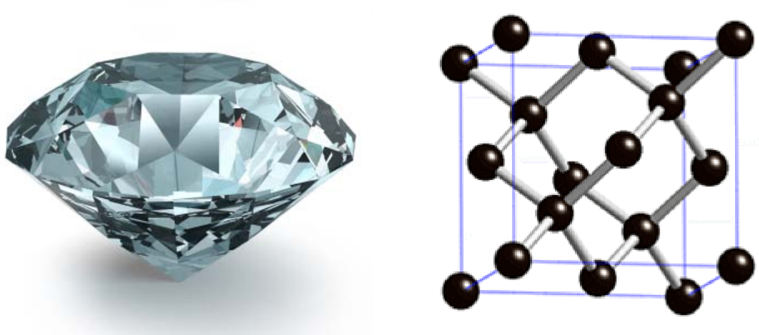
Three major allotropes of carbon: graphite, diamond, and amorphous carbon.



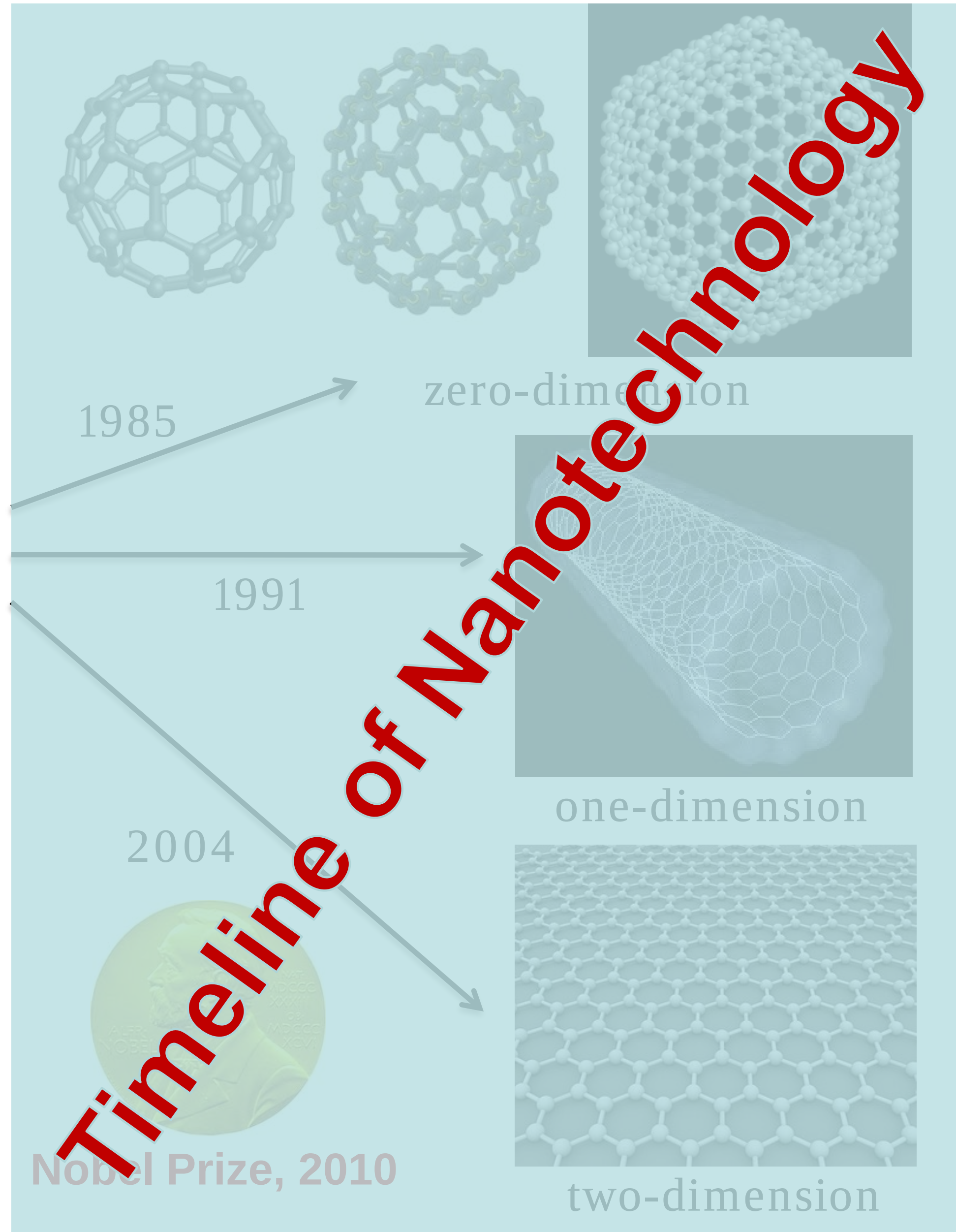
Amorphous carbon: glassy materials



Graphite: Black, conductor or semimetal



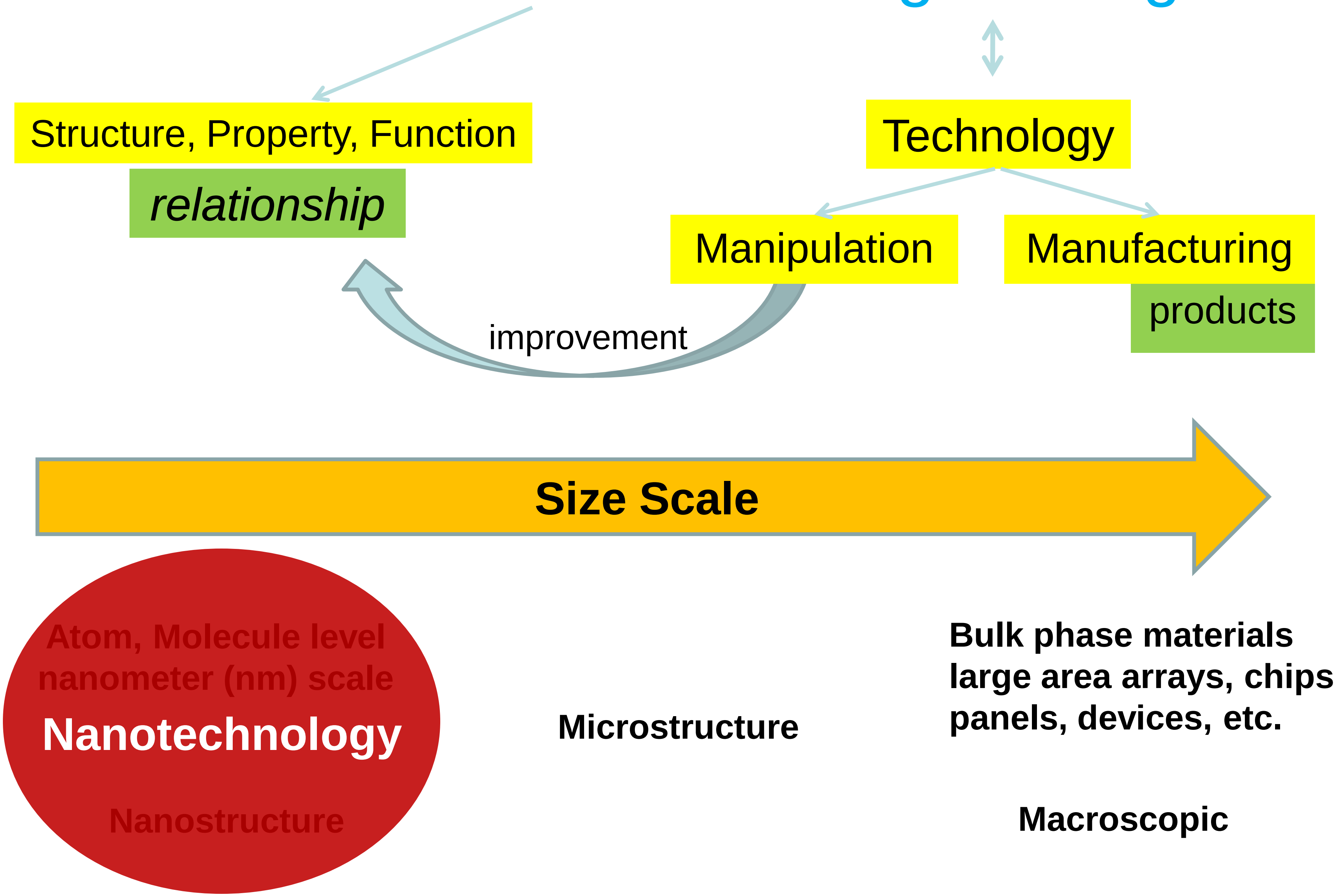
Diamond: transparent, insulator



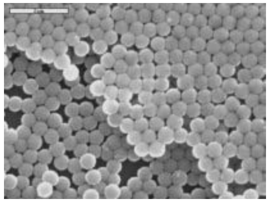
Nano-Quote:

- **$32 billion** in nanotechnology sale, 2008.
- **$2.6 trillion**, by 2014.
- **$1.85 billion**, federal budget for Nanotechnology R&D, 2011, 2012.

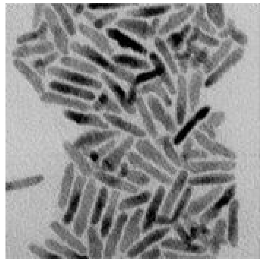
Materials Science and Engineering



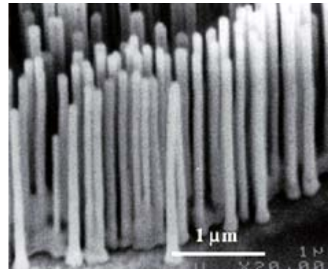
All kinds of ‘Nano’



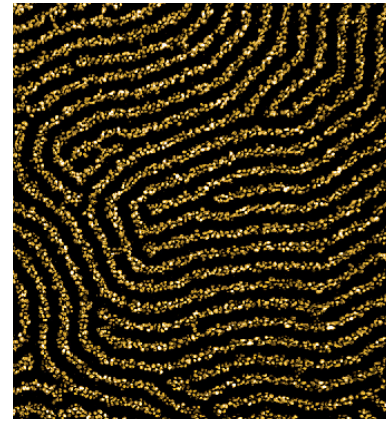
Nanosphere
Nanoparticle
Quantumdot



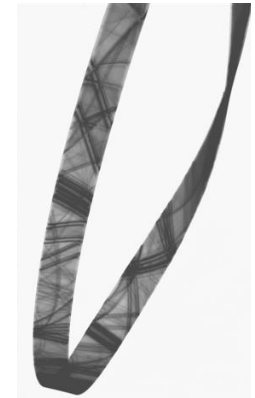
Nanorod



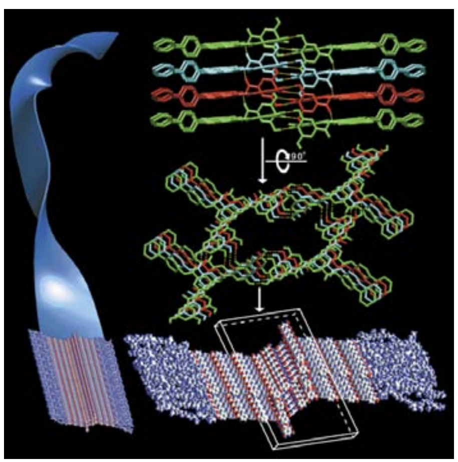
Nanowire



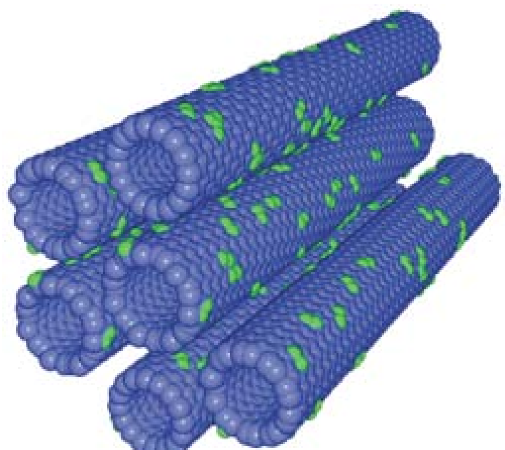
Nanochain



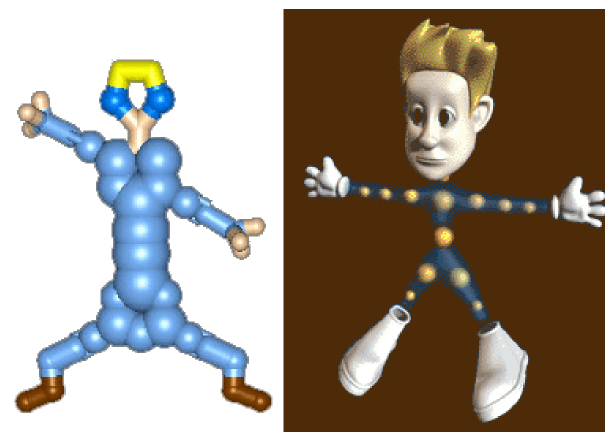
Nanobelt



Nanoribbon



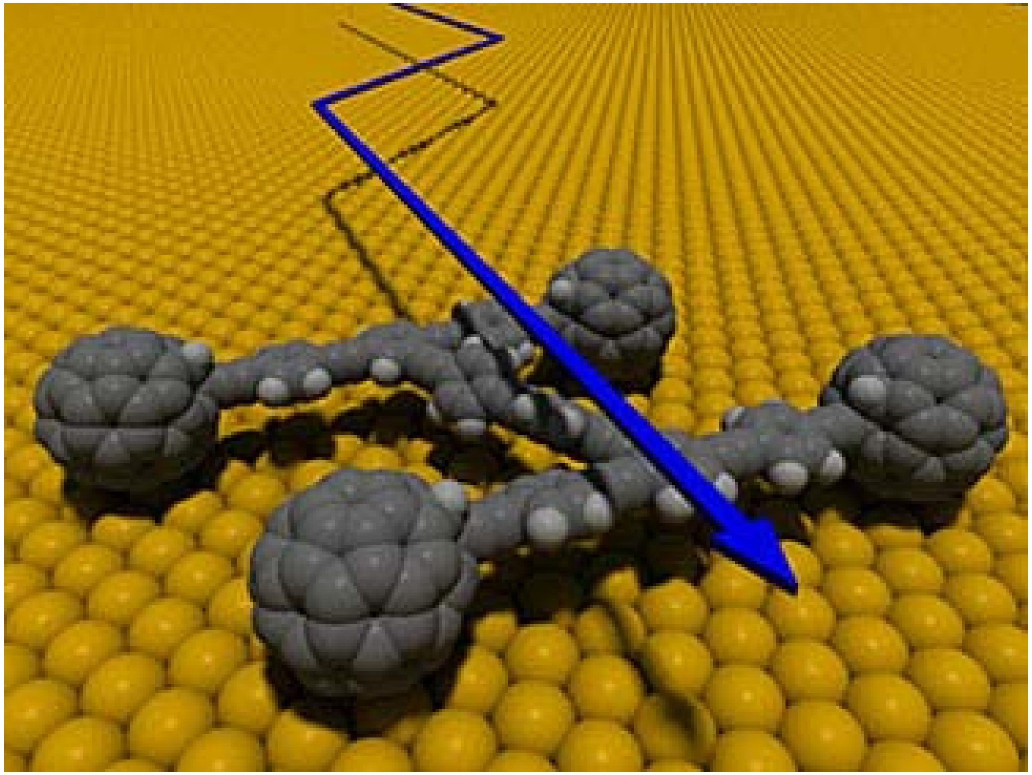
Nanotube



Nanokids

Nanocar Rolls Into Action

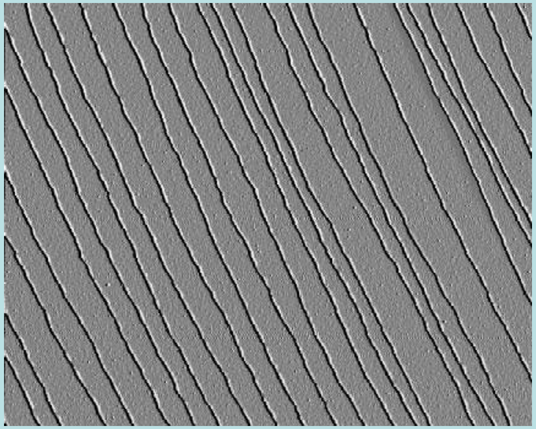
World's first molecular car zips about on fullerene wheels



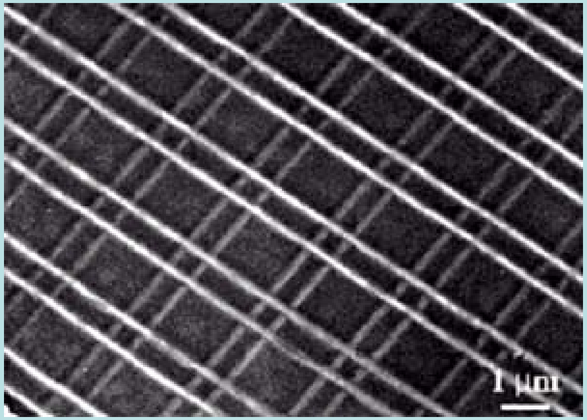
A single-molecule car was developed by Kelly, Tour, and coworkers.

Nano Lett. **2005,** *5*, 2330

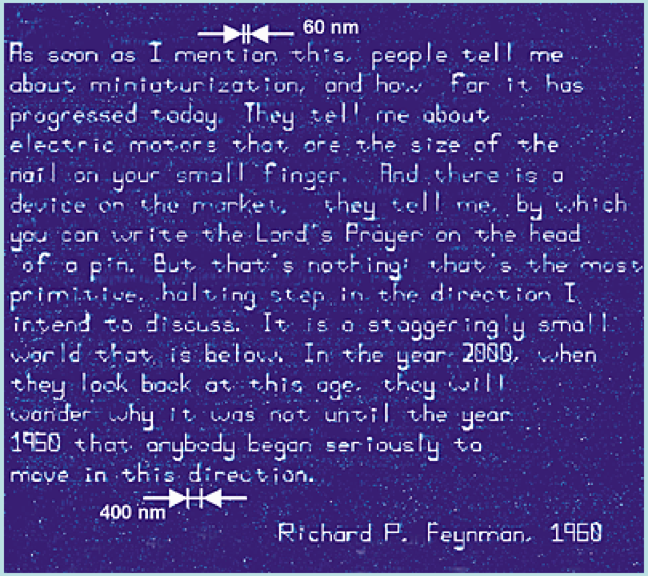
Playing at Nanoscale



Nanoalignment



Nanocross



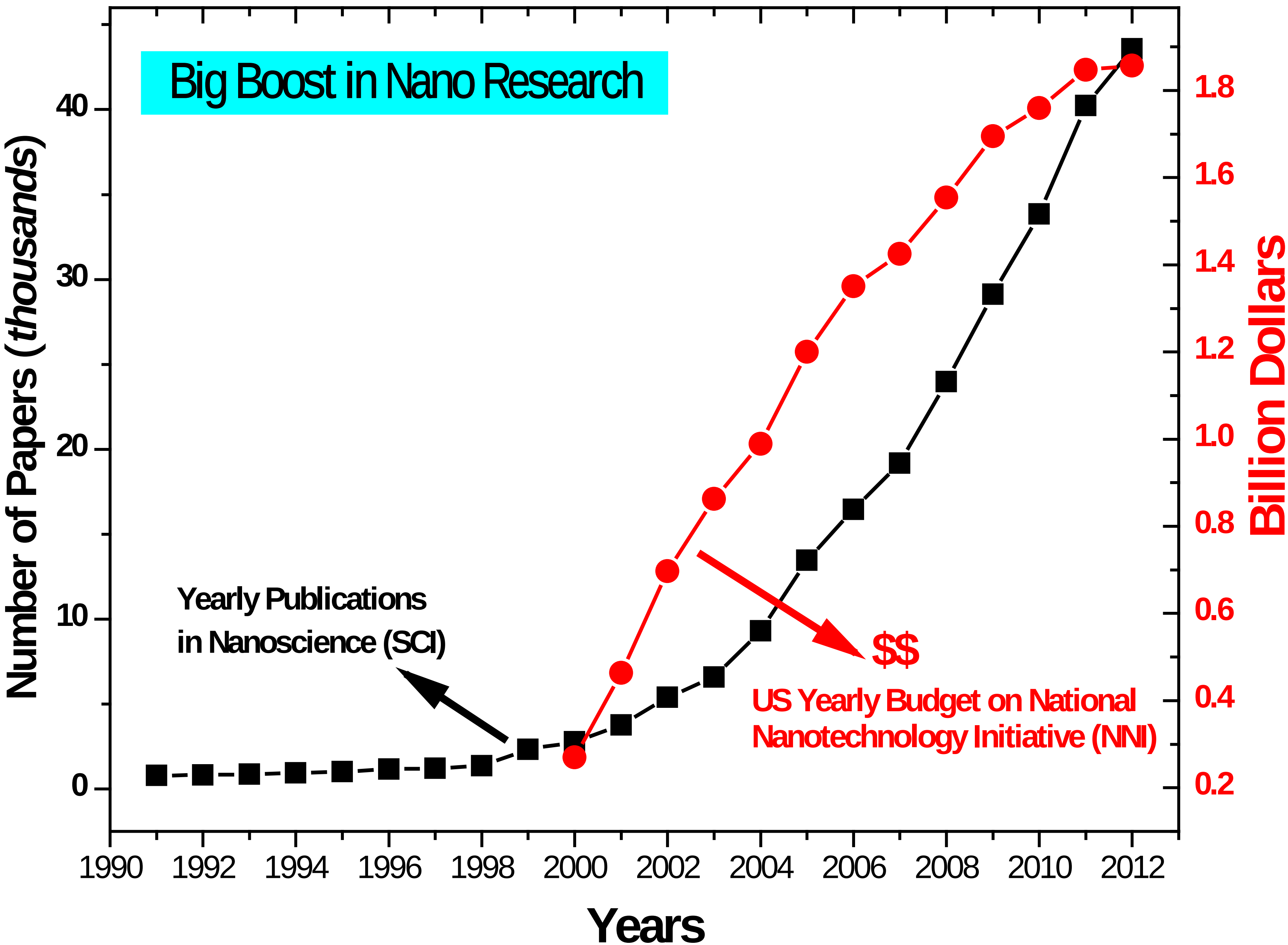
Nanowriting

Nano-Research: *not just emerging, but expanding*

Few terms in the chemical and physical sciences have seen more use (and abuse) in recent years than "nanoscience" or even worse "nanotechnology"

--- James Heath

Acct. Chem. Res. 1999, vol. 32, page 3888



Big Boost in Nano Research
Number of Papers (thousands)
Billion Dollars
Yearly Publications
in Nanoscience (SCI)
$$
US Yearly Budget on National
Nanotechnology Initiative (NNI)
Years
0
10
20
30
40
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012

The National Nanotechnology Initiative (NNI)

--- a program established in fiscal year 2001 to coordinate Federal nanotechnology research and development. The NNI provides a vision of the long-term opportunities and benefits of nanotechnology.
http://www.nano.gov/

other website for updated nanotech news:
http://pubs.acs.org/cen/nanofocus/

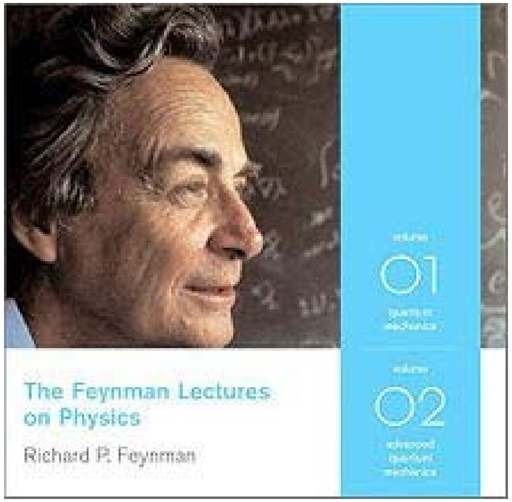
National Nanotechnology Initiative
http://www.nano.gov/

“Imagine the possibilities: materials with ten times the strength of steel and only a small fraction of the weight --- shrinking all the information housed at the Library of Congress into a device the size of a sugar cube --- detecting cancerous tumors when they are only a few cells in size.

President William J. Clinton
January 21, 2000
California Institute of Technology

<u>Where was Nanotechnology originated?</u>

By **Richard Feynman**,
Nobel Prize in Physics in 1965



in a 1959 talk on top-down nanotechnology called **"There's Plenty of Room at the Bottom".**
--- American Physical Society meeting at Caltech on December 29, 1959

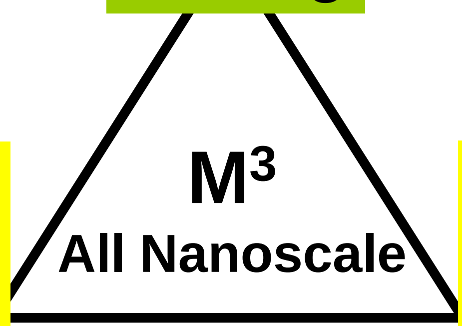
Feynman considered a number of interesting ramifications of a general ability to manipulate matter on an atomic scale. He was particularly interested in the possibilities of denser computer circuitry, and microscopes which could see things much smaller than is possible with electron microscopes. These ideas were later realized by the use of the <u>scanning tunneling microscope (STM),</u> the <u>atomic force microscope (AFM)</u> and other examples of <u>scanning probe microscopy (SPM)</u>.

What is *Nanotechnology*?

Traditional bio-med research with proteins or other nanosized biological units is not considered as nanotechnology.

Synthesis of Nano-sized molecules (Tour, Muellen)
Nanowires, nanotubes (Yang, Lieber, Wang, Dai)
Nanocrystals (Alivisatos, Bawendi)
…

Making



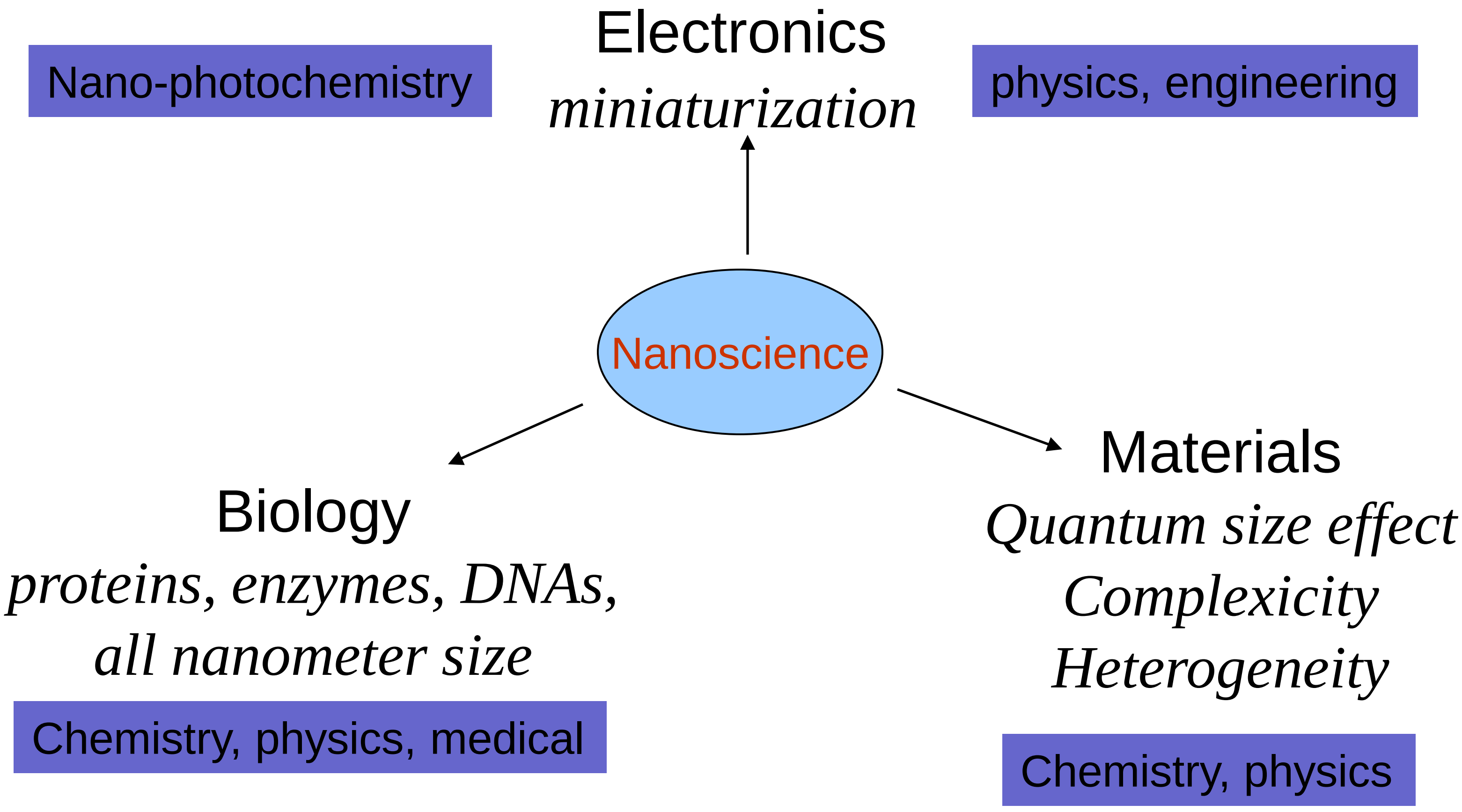
Nanoscale imaging/probing (Weiss, Brus)
Single-molecule measurement (Moener, Nie, Xie, Chu, Barbara)
AFM, STM (Weiss, Bawendi)
Molecule I/V measurement (Reed)
…

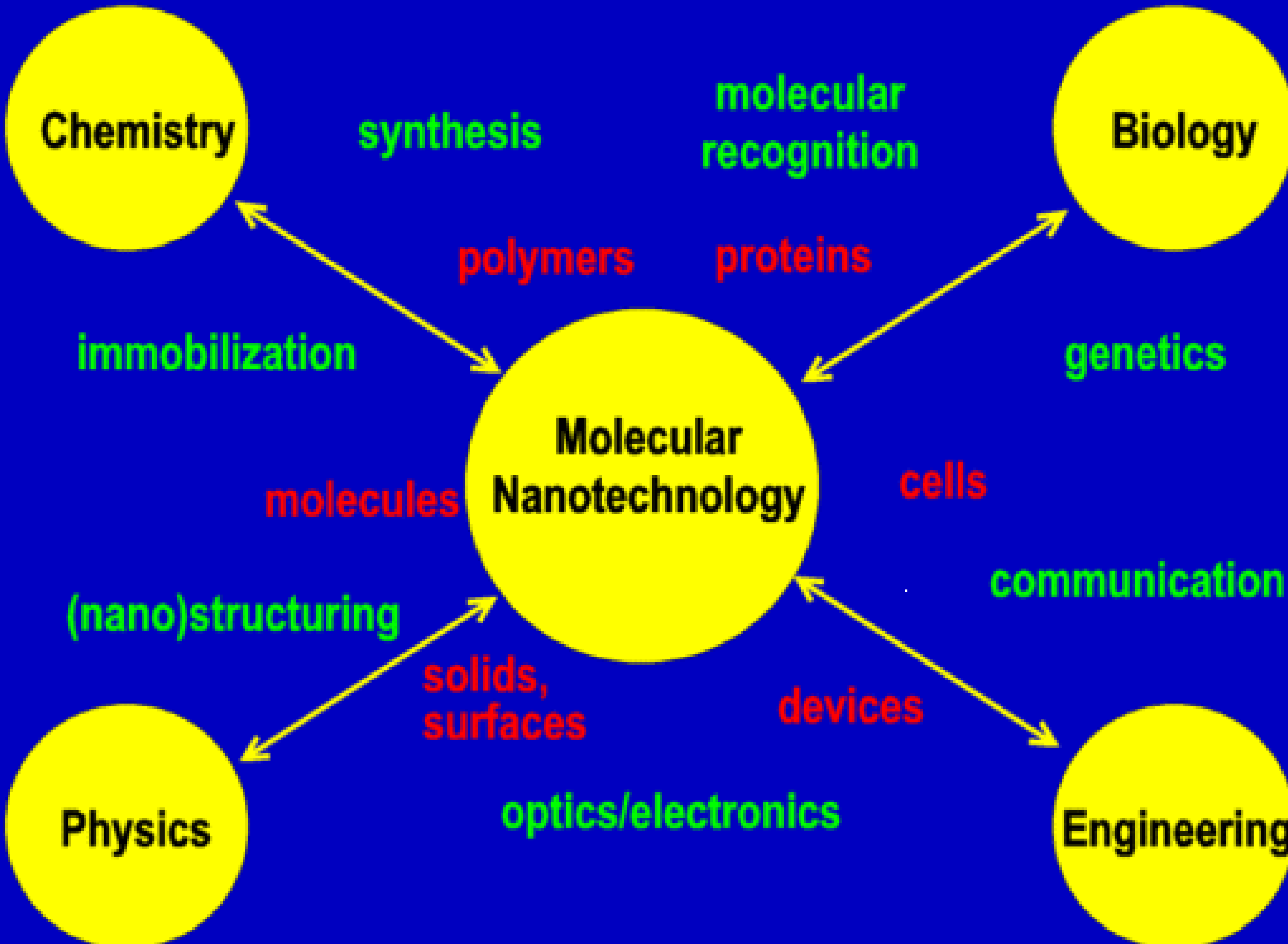
Measuring

Surface nanopatterning (Whitesides, Chou)
Fabrication of nanowires (Lieber, Heath)
DNA assembly (Mirkin, Seeman)
Nano-electronic device (Reed, Heath) …

Manipulating

Why at Nanoscale?





Molecular Nanotechnology: an interdisciplinary field of research

Broad interests in Nano-Research

NANOTECHNOLOGY: THE NEXT BIG THING

U.S. National Nanotechnology Initiative aims to create another Industrial Revolution

William Schulz
C&EN, Washington

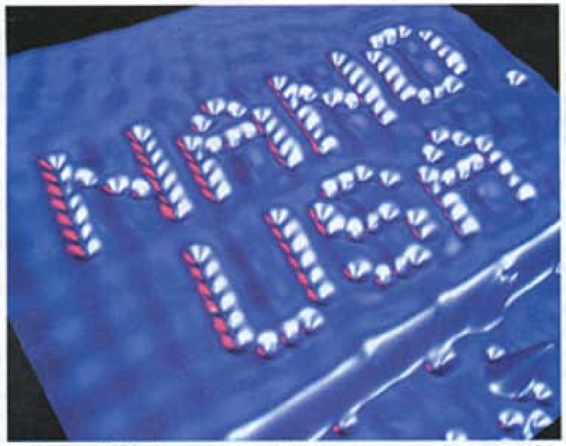
By anyone's measure, nanotechnology is the next big thing. In fact, according to government R&D planners, nanotechnology is nothing short of the next Industrial Revolution.

But to keep the ball rolling, government planners will also have to keep alive the drumbeat of promise about the fruits of nanotechnology research. By their own estimate, government R&D analysts say, payoffs from significant investments in nanotechnology are at least 20 years away.

"We are constantly faced with 'How do we keep this going through the system?'" says Duncan T. Moore, the Administration's point man for nanotechnology in the White House Office of Science & Technology Policy (OSTP). As with any cross-agency government program, he says, the President's recently announced National Nanotechnology Initiative (NNI) will likely face many challenges over the next decade that it is scheduled to be in operation.

"A lot of the old barriers [between R&D agencies] have been broken down," Moore says, to jump-start the nanotechnology initiative. Six of the nation's largest R&D agencies—the National Science Foundation; the Commerce Department's National Institute of Standards & Technology (NIST); the National Institutes of Health; the Department of Defense; the Department of Energy; and the National Aeronautics & Space Administration—will have significant involvement in the initiative, he says. What's more, the Administration has requested an extra $495 million in funding for those agencies' NNI programs in fiscal 2001. Details of how each agency involved with NNI will carry out its portion of the initiative can be found at http://www.nano.gov.

The initiative got its official start in August 1999 when the National Science & Technology Council's (NSTC) Interagency Working Group on Nanoscience, Engineering & Technology released its first report, "Nanostructure Science & Technology." It is, the authors say, a blueprint for the federal government to assess how to make strategic R&D investments in nanotechnology.



This image of 112 carbon monoxide molecules on a copper surface was made at IBM's Almaden Research Center using a scanning tunneling microscope. Each letter is 4 nm high by 3 nm wide. About 250 million nanoletters of this size could be written on a cross section of a human hair; this corresponds to 300 300-page books. President Clinton used the image to unveil NNI.

One of the immediate challenges, Moore points out, is dealing with Congress. Because the initiative is spread out across federal agencies, the Administration must "sell" NNI to different appropriations committees—each with a different set of priorities. But Moore and others feel confident that legislators will support the initiative. With varying degrees of success, he says, OSTP took the same approach with its cross-agency initiative for information technology research.

When NNI was officially unveiled last year by NSTC—a subunit of OSTP that coordinates cross-agency research initiatives—it was accompanied by a strategic public relations plan. NSTC, for example, hired science writer Ivan Amato to pen a glossy brochure entitled "Nanotechnology: Shaping the World Atom by Atom."

In the brochure, Amato sets forth a basic definition of nanotechnology—generally, the world as it works on the nanometer or "billionths" scale—and it lays out the following vision: "What could we humans do if we could assemble the basic ingredients of the material world with even a glint of nature's virtuosity? What if we could build things the way nature does—atom by atom and molecule by molecule?"

Because nanotechnology involves the control of matter at the atomic or molecular level where quantum effects must be taken into account, it is often a difficult subject even for fellow scientists to grasp, Moore says. The brochure and other outreach methods, he continues, are "much like NIH saying, 'This is basic research, and it is to be applied to X, Y, and Z disease categories.' And that's an easier thing to sell to my neighbor."

That strategy has garnered outside support, and it appears to be having an impact. The initiative, for example, was the focus of an American Chemical Society "Science and the Congress" luncheon briefing on Capitol Hill to help acquaint members and congressional staffers with the field of nanotechnology and its promise.

Entitled "Tiny Dynamite: The Nanotechnology Revolution," the briefing reviewed some of the scientific issues concerning nanotechnology and the ways that nanotechnology will affect R&D efforts in everything from drug delivery to aerospace materials. Speakers included Harvard University chemistry professor George M. Whitesides and Motorola's

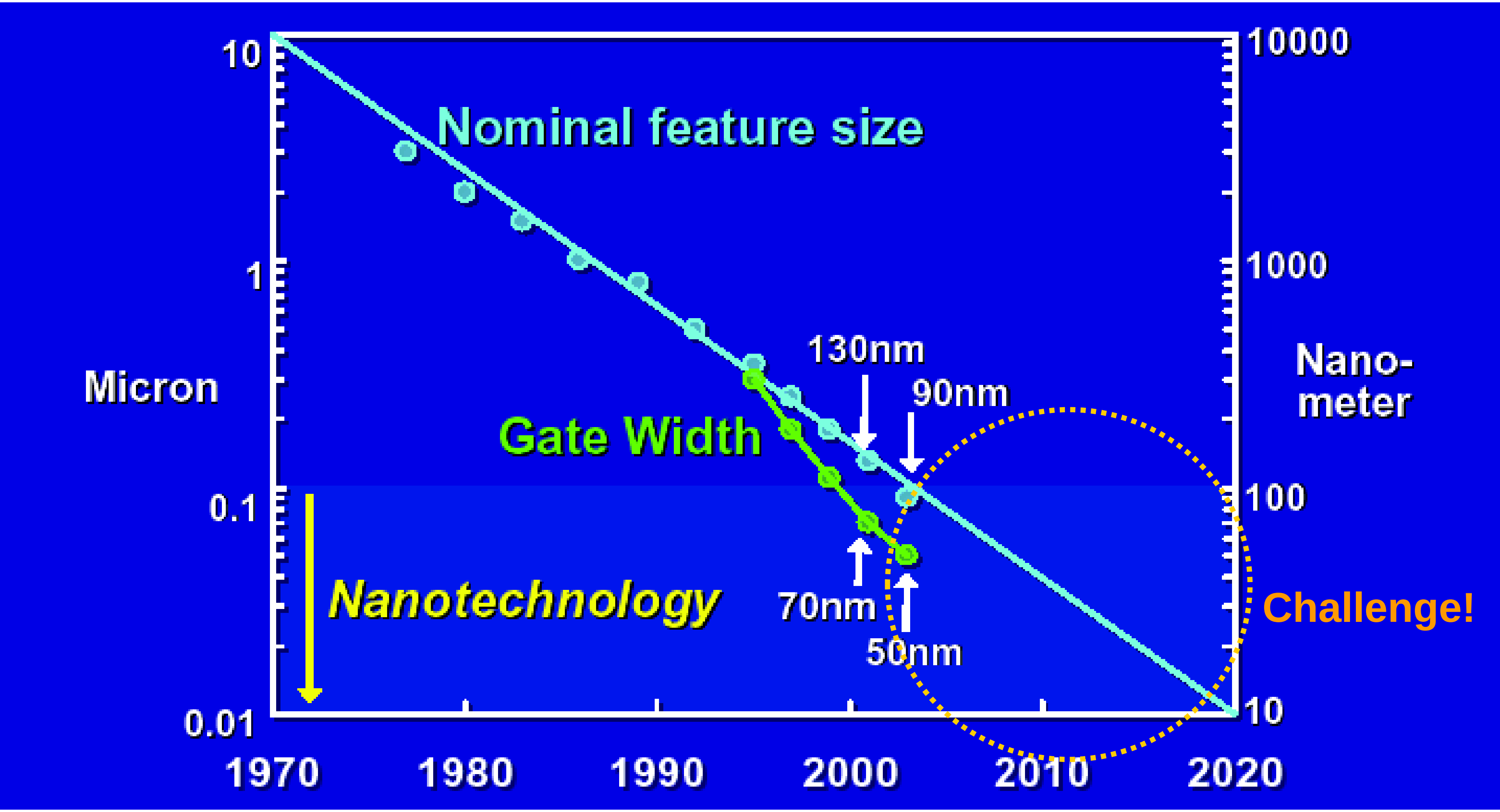
Nanoscale Research is beyond Academia

- IBM
- Lucent, Bell Labs
- Intel
- GE
- Numerous *Nano*-companies: *beyond your imagination*

  (Zyvex, Nanosys, Nanoproducts, Nanologic, Nano Ink, Nanolayers, NanoGram, Nanodevices, Nanomaterials, Nanosphere, …)
- National Labs:

  Argonne, Brookhaven, Oak Ridge…

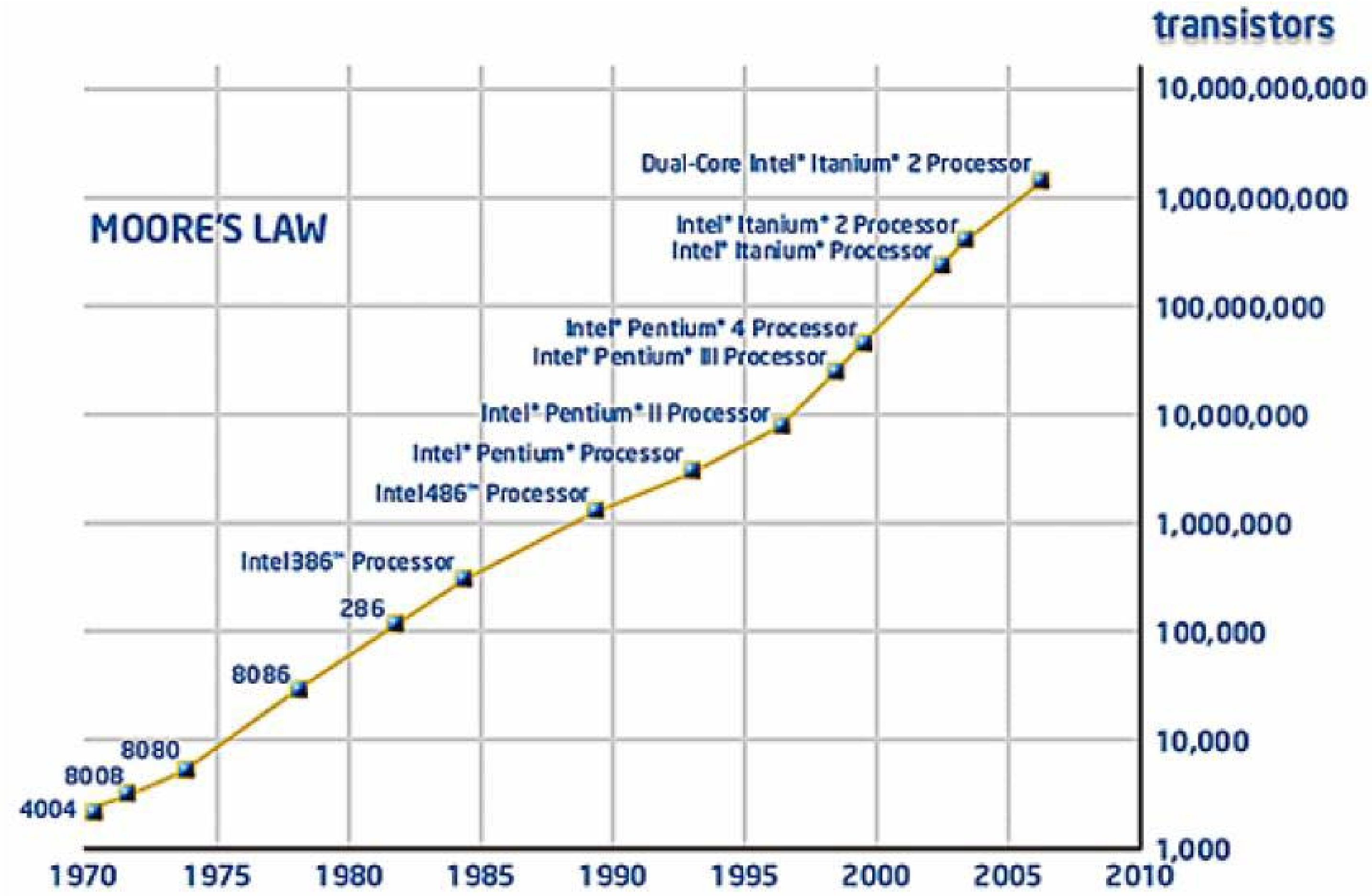
Limit of Moore's Law



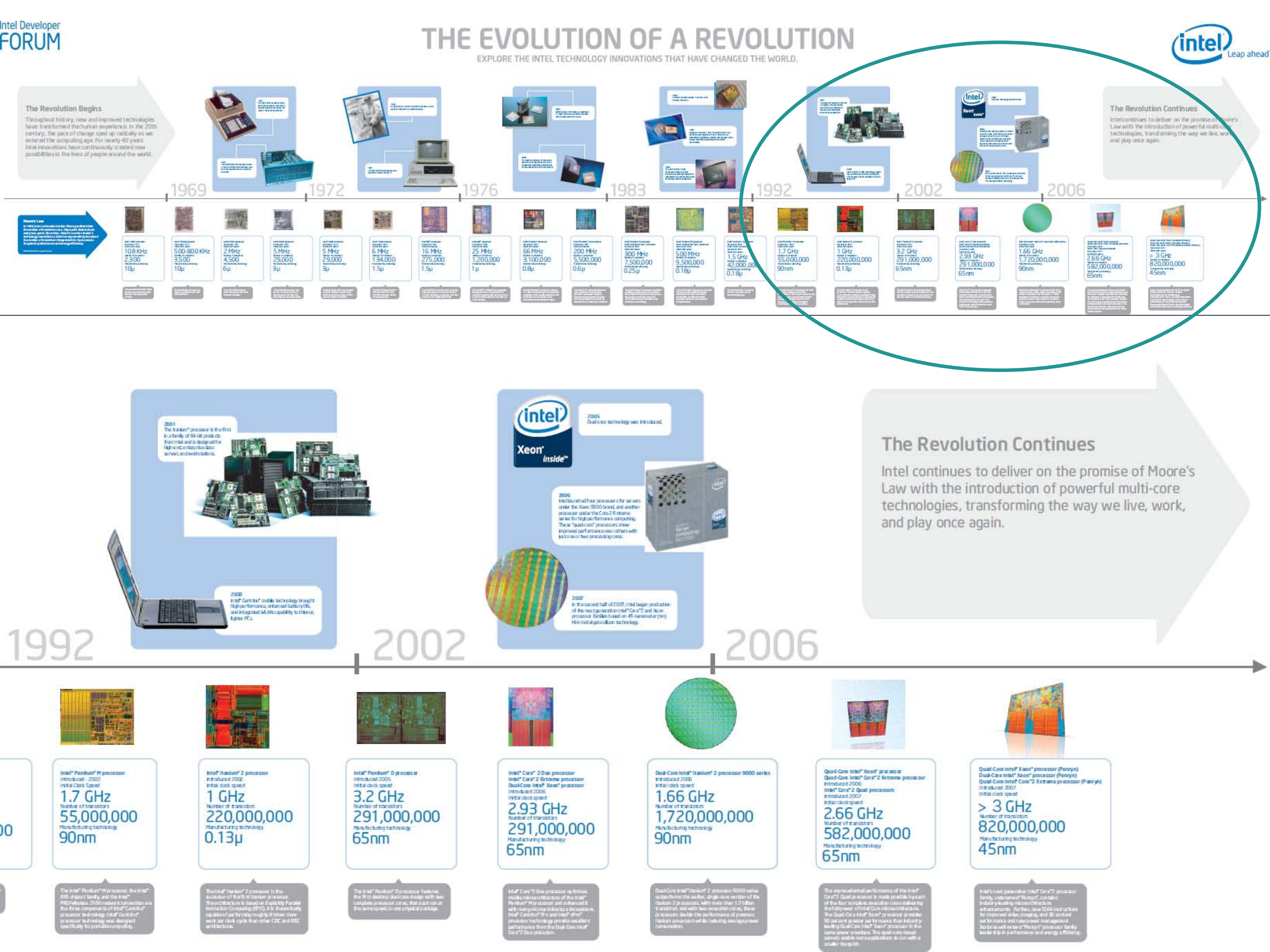
Moore's law describes a long-term trend in the history of computing hardware. The number of transistors that can be placed inexpensively on an integrated circuit *doubles approximately every two years.*

From Intel

Limit of Moore’s Law

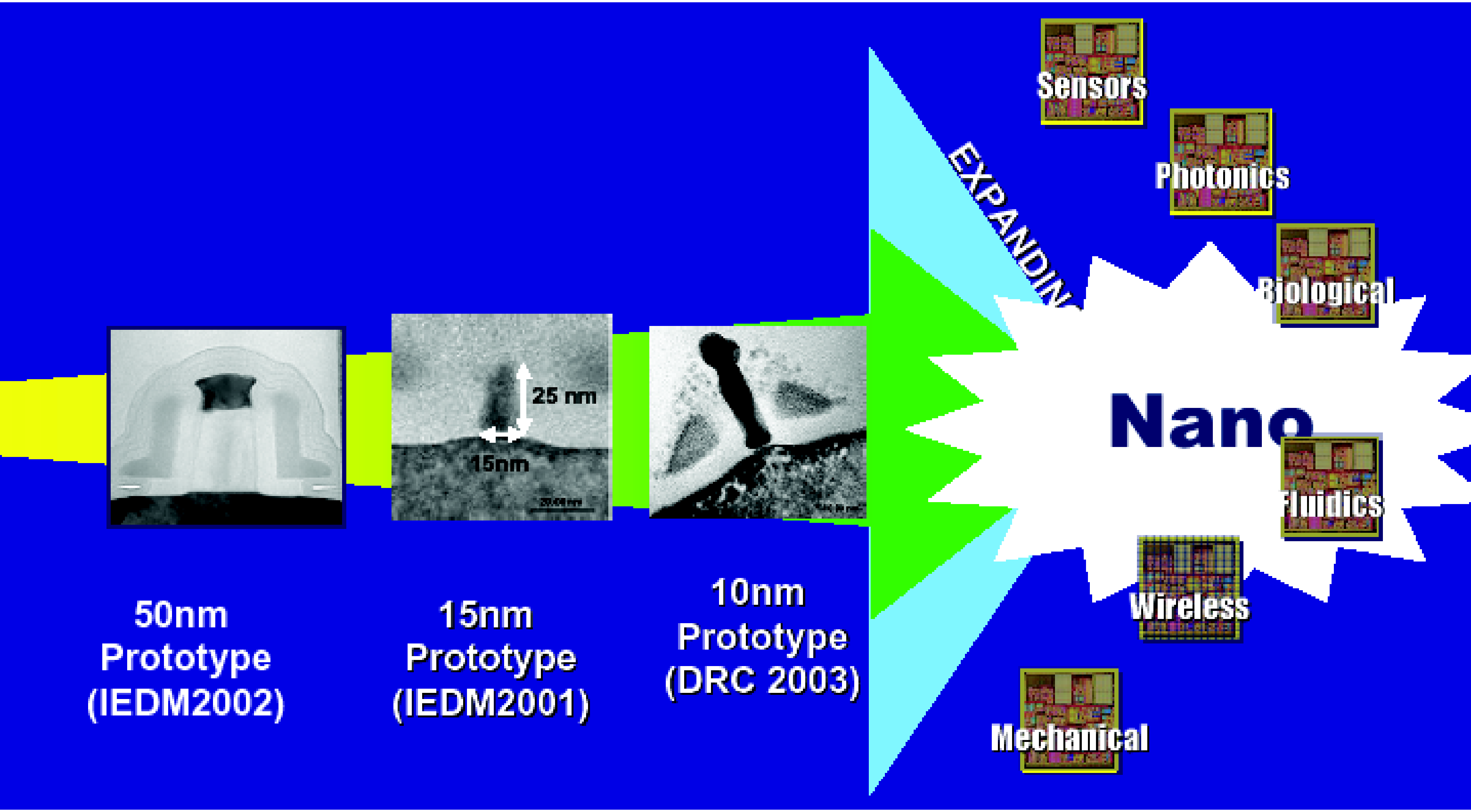


Moore's law describes a long-term trend in the history of computing hardware. The number of transistors that can be placed inexpensively on an integrated circuit *doubles approximately every two years.*



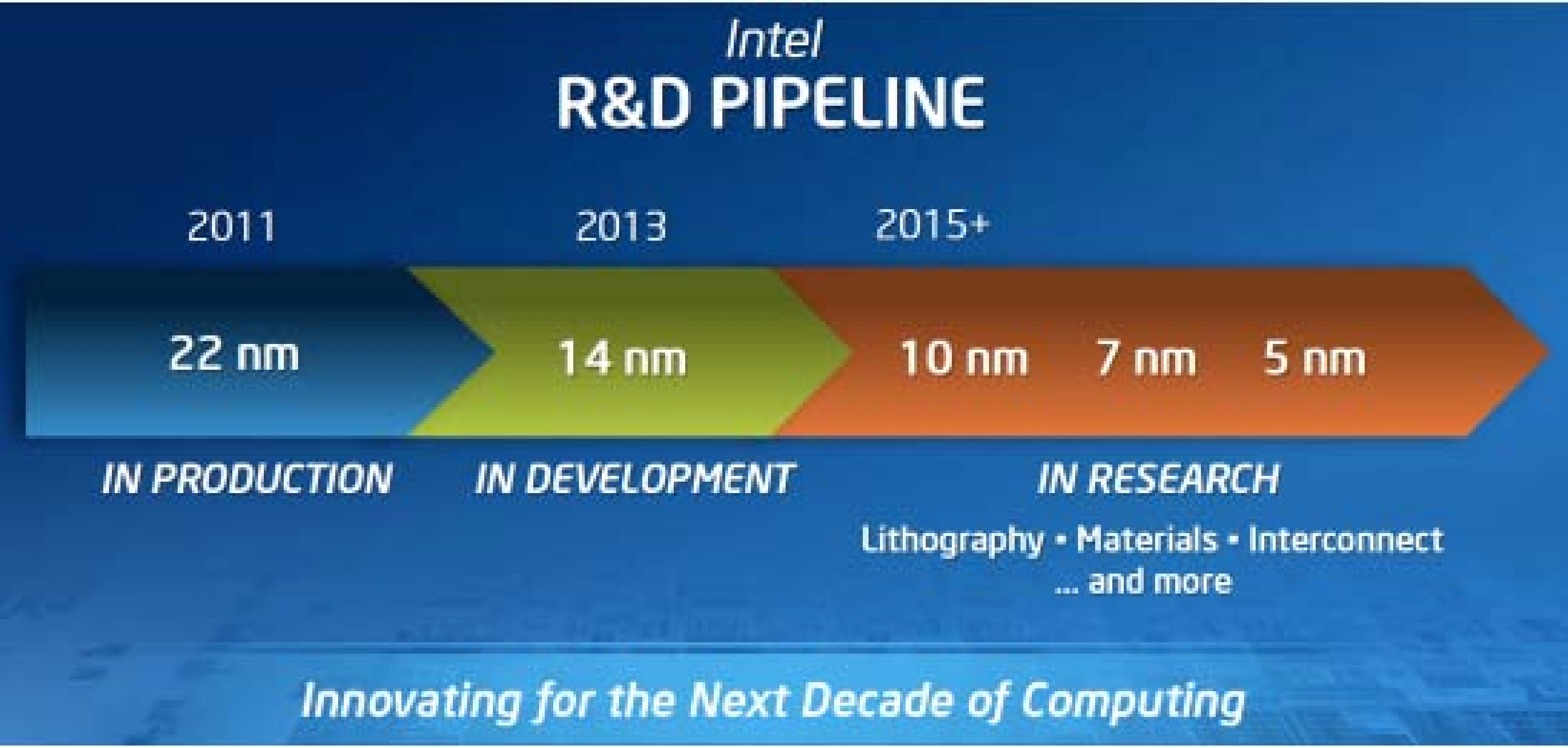
Intel Developer FORUM
THE EVOLUTION OF A REVOLUTION
EXPLORE THE INTEL TECHNOLOGY INNOVATIONS THAT HAVE CHANGED THE WORLD.
intel Leap ahead
The Revolution Begins
The Revolution Continues
1969
1972
1976
1983
1992
2002
2006
2001
The Itanium® processor is the first in a family of 64-bit products from Intel and is designed for high-end, enterprise-class servers and workstations.
2003
Intel® Centrino® mobile technology brought high performance, enhanced battery life, and integrated WLAN capability to thinner, lighter PCs.
intel Xeon inside
2005
Dual-core technology was introduced.
2006
Intel launched four processors for servers under the Xeon 5300 brand, and another processor under the Core 2 Extreme series for high performance computing. These "quad-core" processors show improved performance over others with just one or two processing cores.
2007
In the second half of 2007, Intel began production of the next generation Intel® Core™2 and Xeon processor families based on 45-nanometer (nm) Hi-k metal gate silicon technology.
The Revolution Continues
Intel continues to deliver on the promise of Moore's Law with the introduction of powerful multi-core technologies, transforming the way we live, work, and play once again.
Intel® Pentium® M processor
Introduced - 2002
Initial Clock Speed
1.7 GHz
Number of transistors
55,000,000
Manufacturing technology
90nm
Intel® Itanium® 2 processor
Introduced 2002
Initial clock speed
1 GHz
Number of transistors
220,000,000
Manufacturing technology
0.13µ
Intel® Pentium® D processor
Introduced 2005
Initial clock speed
3.2 GHz
Number of transistors
291,000,000
Manufacturing technology
65nm
Intel® Core™ 2 Duo processor
Intel® Core™2 Extreme processor
Dual-Core Intel® Xeon® processor
Introduced 2006
Initial clock speed
2.93 GHz
Number of transistors
291,000,000
Manufacturing technology
65nm
Dual-Core Intel® Itanium® 2 processor 9000 series
Introduced 2006
Initial clock speed
1.66 GHz
Number of transistors
1,720,000,000
Manufacturing technology
90nm
Quad-Core Intel® Xeon® processor
Quad-Core Intel® Core™2 Extreme processor
Introduced 2006
Intel® Core™2 Quad processors
Introduced 2007
Initial clock speed
2.66 GHz
Number of transistors
582,000,000
Manufacturing technology
65nm
Quad-Core Intel® Xeon® processor (Penryn)
Dual-Core Intel® Xeon® processor (Penryn)
Quad-Core Intel® Core™2 Extreme processor (Penryn)
Introduced 2007
Initial clock speed
> 3 GHz
Number of transistors
820,000,000
Manufacturing technology
45nm

Expanding Moore's Law



From Intel

Expanding Moore's Law



From Intel

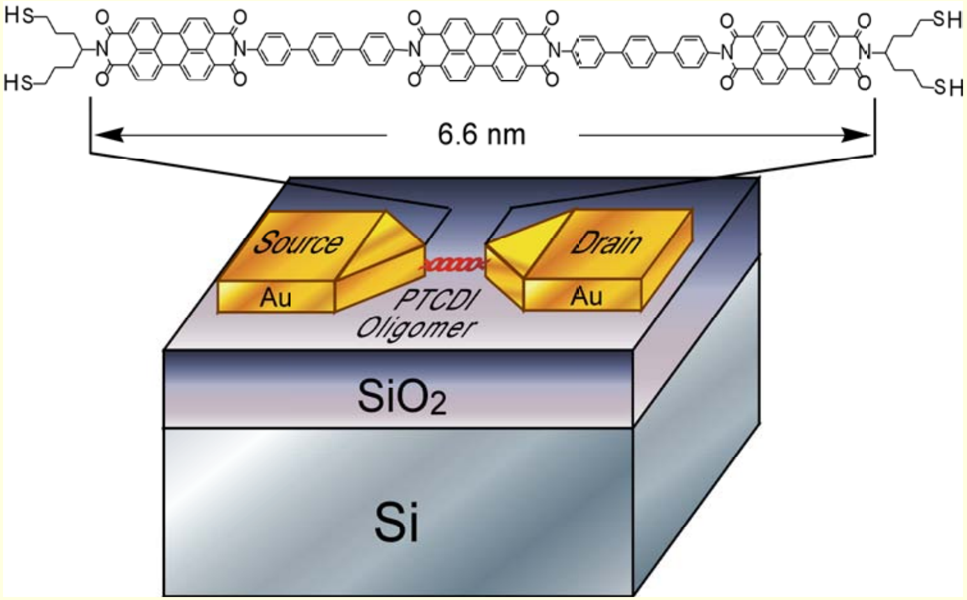
Highly Conductive Molecular Wires

	Cross-section size (nm^2)	Current Density (electrons/nm^2 sec)
1 mm copper wire	~ 3×10^{12}	~ 2×10^{6}
	~ 0.05	~ 4×10^{12}
Carbon nanotube	~ 3	~ 2×10^{11}

Fabrication of a molecular device

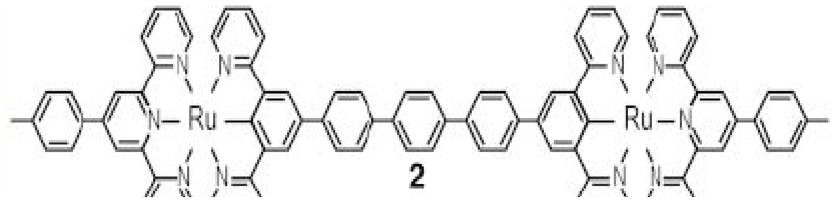
- Nano-gap Electrodes: very low successful yield for fabrication.

- Large molecules: to fit in the nano-gap.

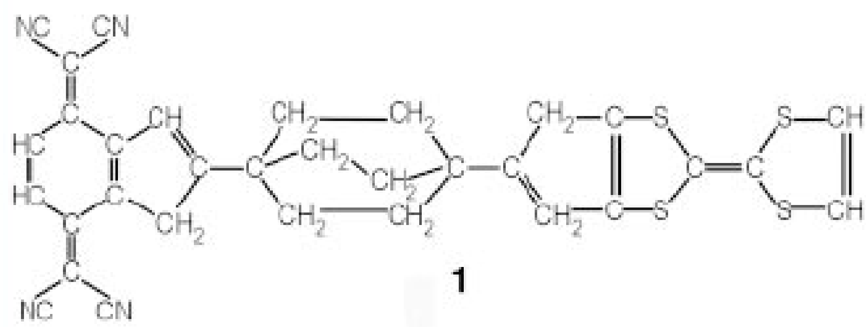


Molecules used for electronic devices

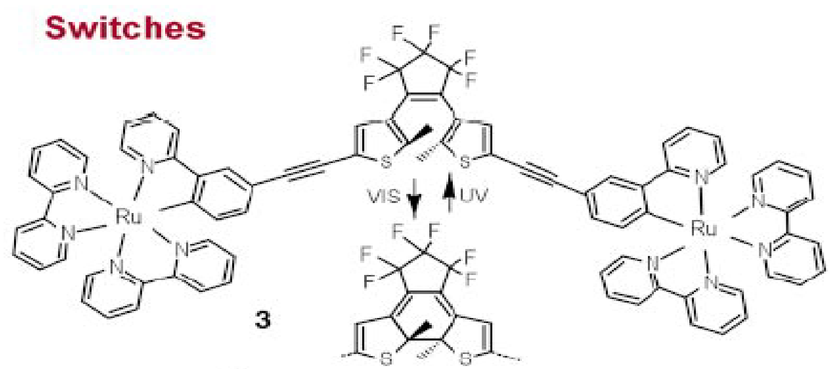
wire



diode



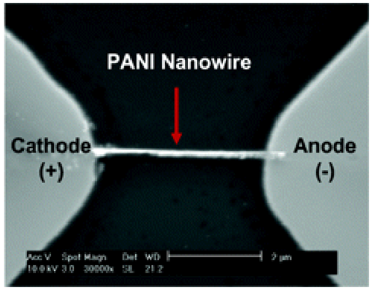
switch



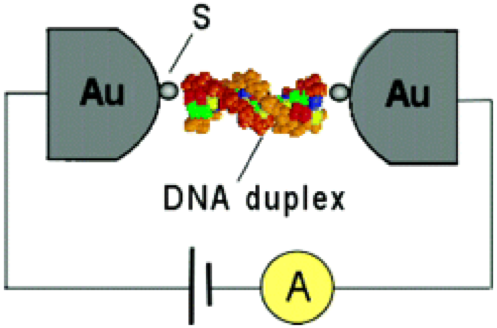
Nature, 2000, vol. 408, page 541.

Fabrication and evaluation of molecular devices:

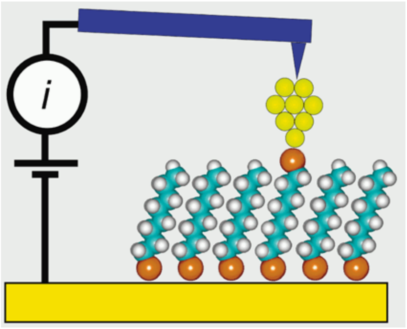
- Surface deposited electrode systems: *distance fixed.*



- Piezo controlled electrode system: *distance adjustable.*



- AFM/STM based measurement: *flexible for various kinds of samples.*



The Biggest Challenge in Molecular Electronics

Ultimate goal --- Interconnecting and integrating **billions** of molecular units into a functional *chip*.

Challenge --- How to organize **billions** of molecules within a 1X1 inch area. An Intel Dual-core Xenon CPU has 820,000,000 transistors!

Self-assembly --- Seems to be the most promising approach, since photolithography method (top-down approach) does not work for molecules.

Prerequisites --- high *recognition* or *selectivity*.

Quad-Core Intel® Xeon® processor (Penryn)
Dual-Core Intel® Xeon® processor (Penryn)
Quad-Core Intel® Core™2 Extreme processor (Penryn)

Introduced 2007

Initial clock speed

> 3 GHz

Number of transistors

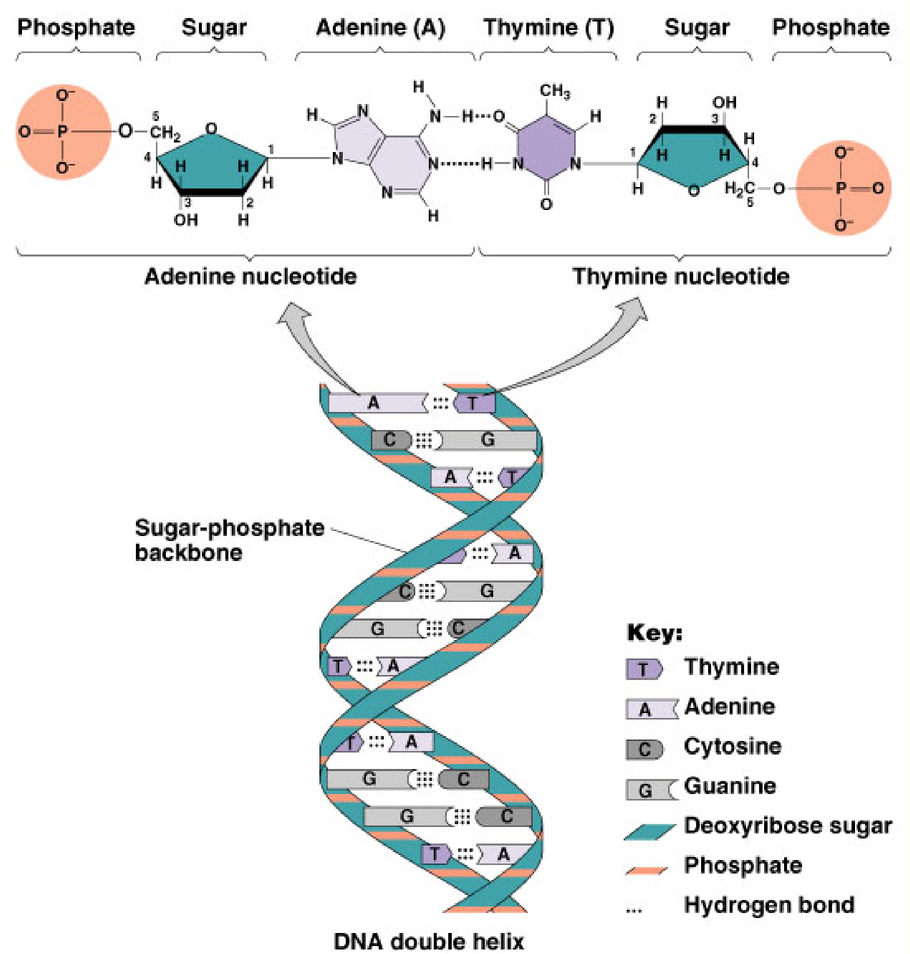
820,000,000

Manufacturing technology

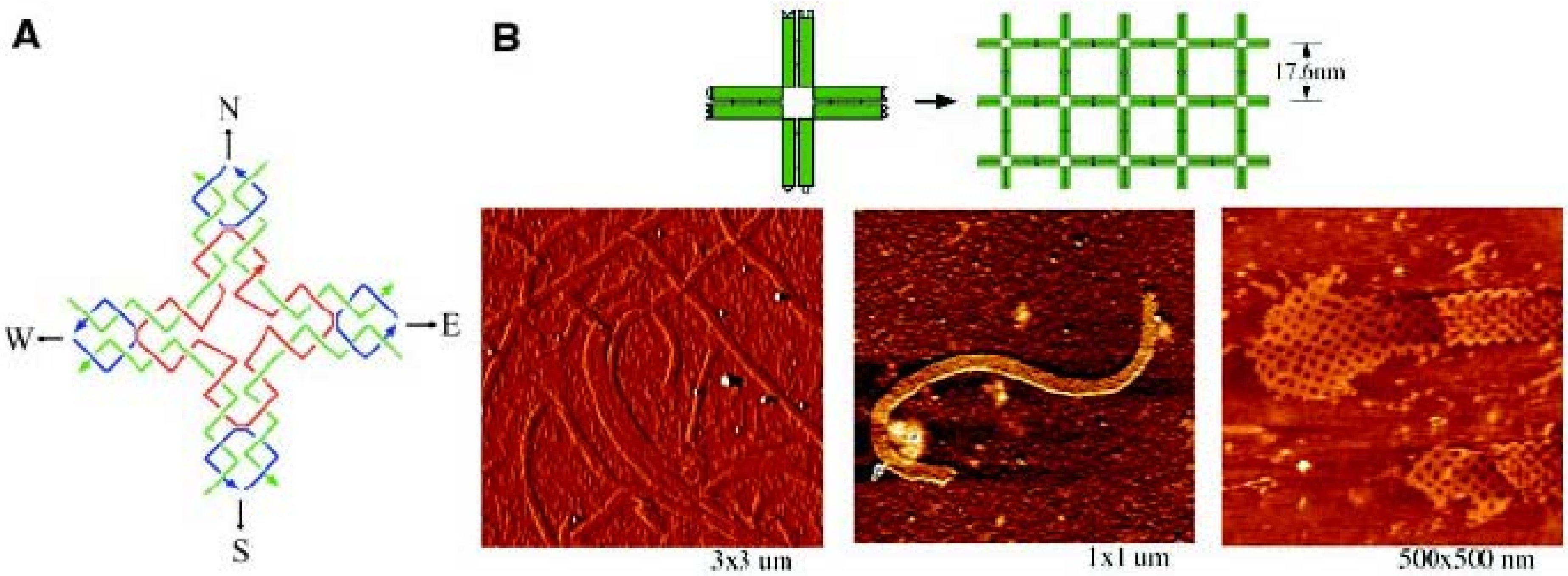
45nm

DNA
--- an Perfect Self-assembler by Nature

- Extremely high selectivity;
- Strong binding via H-bonds;
- Highly flexible for modification;
- Good physicochemical stability;
- Good mechanical rigidity.

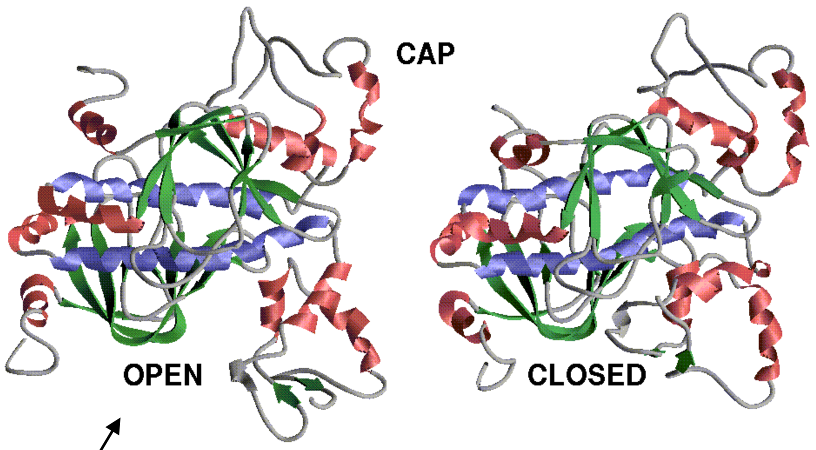


Self-organized nanostructure of DNA

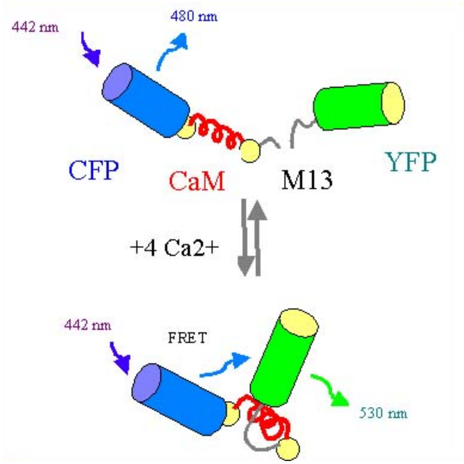


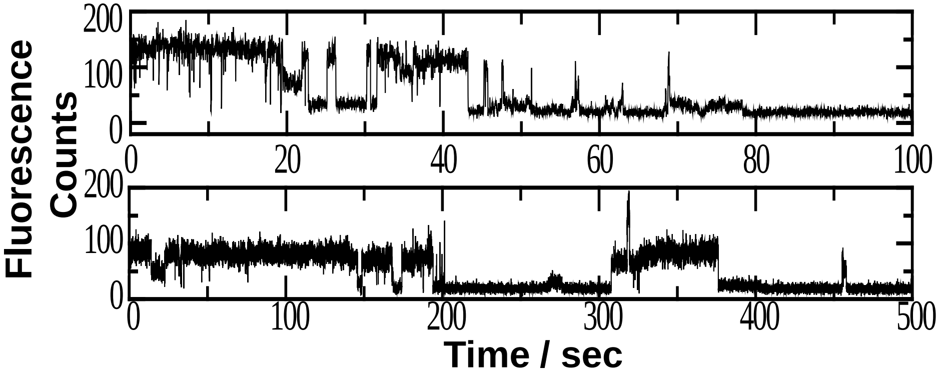
H. Yan, Science, 2003, Vol. 301, page 1882.

Single-Molecule Probing of Protein Systems



Single-molecule sensor





Single-molecule blinking;
movie of protein dynamics in living cells.