Introduction to Nanotechnology

From “macro” to “nano”

Science and technology progress

The history of mankind is, among other things, the history of ***knowledge*** of the world and mastering new knowledge through research.

Acquired scientific knowledge generated ***new technologies*** – humanity is moving forward on the path of technological progress.

Technology determines the ***quality of life*** of every member of society and the power of the state.

The history of the world community is a history of ***scientific discoveries*** and ***technological revolutions***.

New technology always stimulates the development of related technologies.

Industrial revolutions

1. Tools	2,000,000 B.C.
2. Metallurgy	3600 B.C.
3. Steam power	1764
4. Mass production	1908
5. Automation	1946

The sixth industrial revolution starts now: transition from micrometer scale to ***nanometer scale devices***

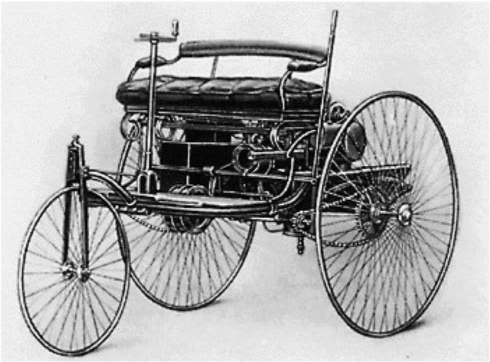
Milestones in the technical development of society

- Compass, gunpowder, printing (XIV - XVI century)
- Steam engine (XVIII century)
- Textiles (XIX century)
- Marine and rail transport (the second half of XIX century)
- Electricity
- Telegraph, telephone, radio
- Cars
- TV
- Nuclear power
- Space exploration
- Computers, internet
- Cellular communication

What examples of the “*revolutionary*” products do you know?

Examples of the “*revolutionary*” products









Introduction to Nanotechnology

“***640 K ought to be enough for anybody***”

Bill Gates supposedly said this in 1981 to note that the 640 KB of memory in IBM’s PC was a significant breakthrough.

NANO technology

From Latin ***nanus*** (“dwarf”)

From Ancient Greek ***νάνος*** (nanos).

Why Nanotechnology?

Smaller is better

- Portable, wearable, lightweight, less power systems
- Cheaper, less material, more scale

New functions, new phenomena can be utilized in chemistry, biology, physics…

Revolutionary technology

Nanotechnology R&D is directed toward understanding and creating improved materials, devices, and systems that exploit these new properties.

Nano technology

The word “nanotechnology “ was first used in ***1974 by Norio Taniguchi*** in an paper entitled “On the Basic Concept of Nano-Technology”, presented at the International Conference on Production Engineering held in Tokyo, Japan.

He wrote:

“In the processing of materials the smallest bit size of stock removal, accretion or flow of material is probably of one atom or one molecule, namely 0.1~0.2 nm in length. Therefore, the expected limit size of fineness would be of the order of 1 nm.

…”Nano-technology” mainly consists of the processing … separation, consolidation and deformation of materials by one atom or one molecule”

By the 1980s people were regularly using and spreading the word ***nanotechnology***.

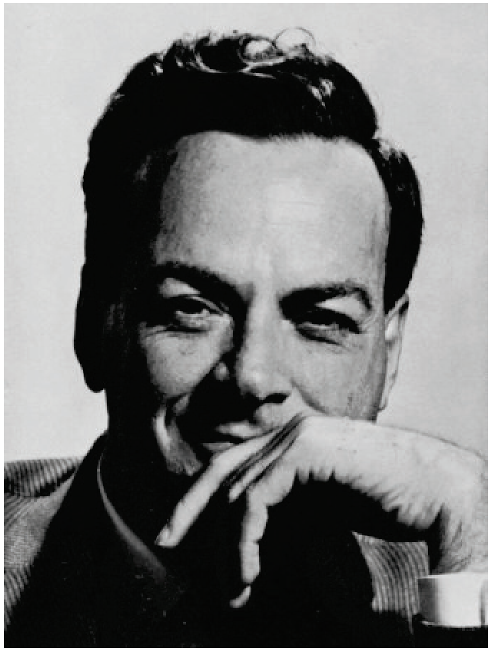
Science and technology progress

Richard P. Feynman gave a lecture «***There's Plenty of Room at the Bottom***»* at California Institute of Technology on December 29, 1959.

In that lecture he discussed methods which later at the end of XX century became fundamentals of what became now known as ***Nanotechnology***.

Feynman proposed shrinking computing devices toward their physical limits, where “wires should be 10 or 100 atoms in diameter”.

He suggested that focused electron beams could write nanoscale features on a surface; this is now called “***e-beam lithography***”



1918 – 1988

Feynman viewed this world from a top-down perspective, as the ultimate frontier for miniaturization.

* http://www.zyvex.com/nanotech/feynman.html

Why Nanotechnology?

Dr. Eric Drexler – nanotechnology research pioneer and the godfather of nanotechnology.

Back in 1977, while an undergrad at MIT, Drexler came up with a mind-boggling idea.

He imagined a sea of minuscule robots that could move molecules so quickly and position them so precisely that they could produce almost any substance out of ordinary ingredients in a matter of hours.

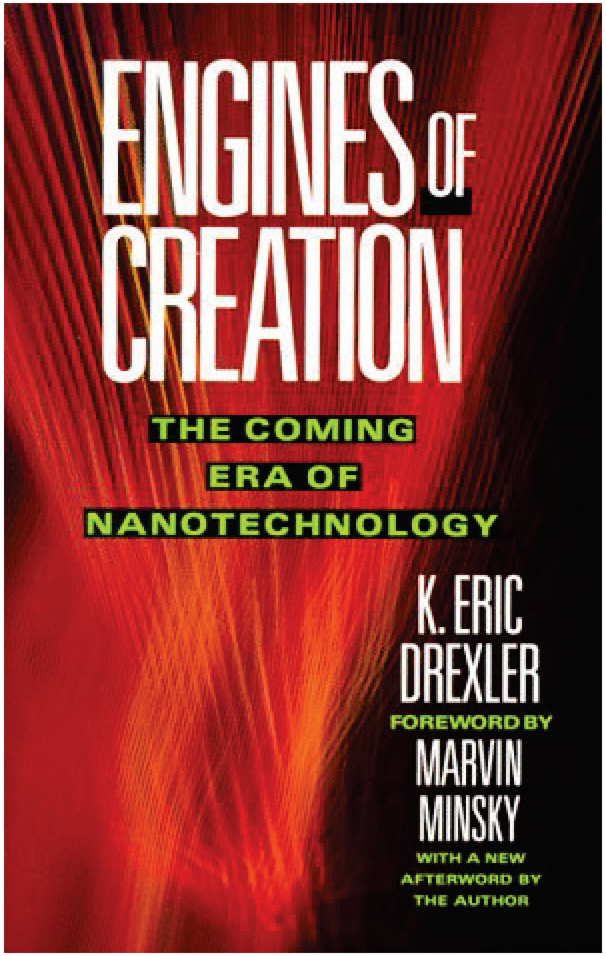
Start with a black box of so-called molecular assemblers, pour in a supply of cheap chemicals, and out would flow a profusion of gasoline, diamonds, rocket ships, whatever, all built without significant expenditure of capital or labor.

In the bloodstream, tiny machines could cure diseases. In the air, they could remove pollutants.

Drexler's vision inspired a generation of chemists, computer scientists, and engineers to focus on science at the nanoscale.

The Incredible Shrinking Man By Ed Regis (http://www.nanotechnologist.com/misc/index.html)

Warning

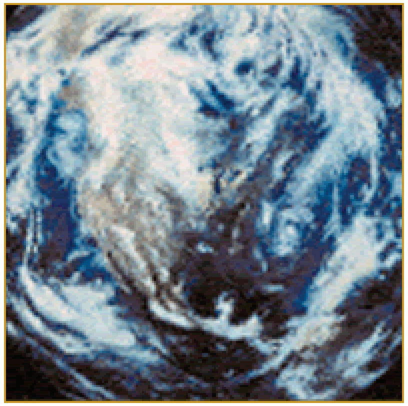


Engines of Creation: The Coming Era of Nanotechnology is a 1986 molecular nanotechnology book written by K. Eric Drexler

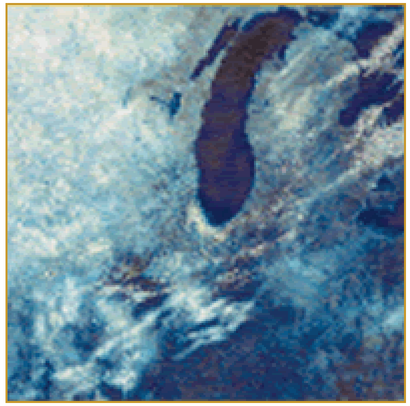
Grey goo is a hypothetical end-of-the-world scenario involving molecular nanotechnology in which out-of-control self-replicating robots consume all matter on Earth while building more of themselves

How small are nanostructures?

Scale of objects – 1



10^8–10^7 m



10^6 –10^5 m

10^4 –10^3 m

10^3 –10^2 m

10^2 –10^1 m

10 –1 m

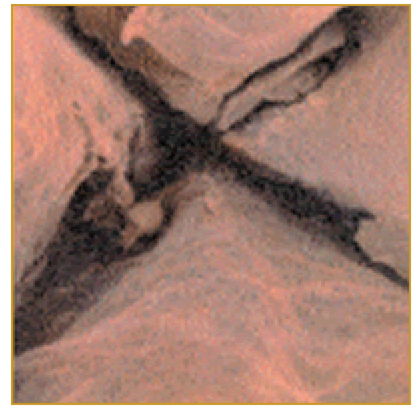
1 m

10^{-1} m

Scale of objects – 2

10^{-2} m

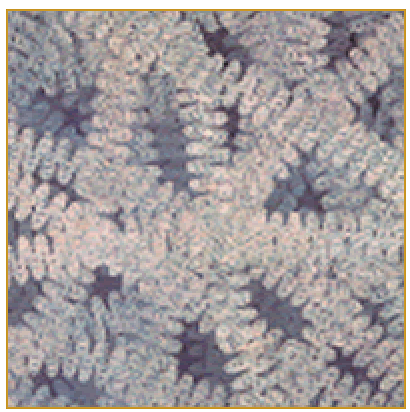
10^{-3} m



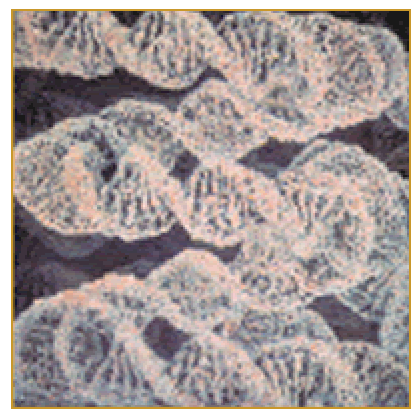
10^{-5} m

10^{-6} m

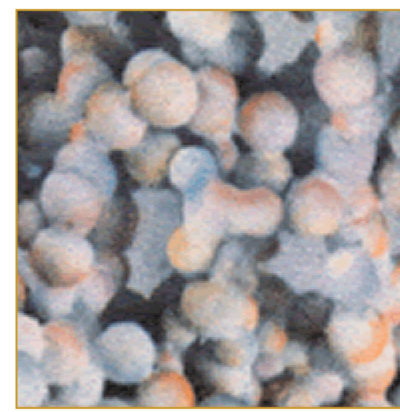
10^{-7} m



10^{-8} m

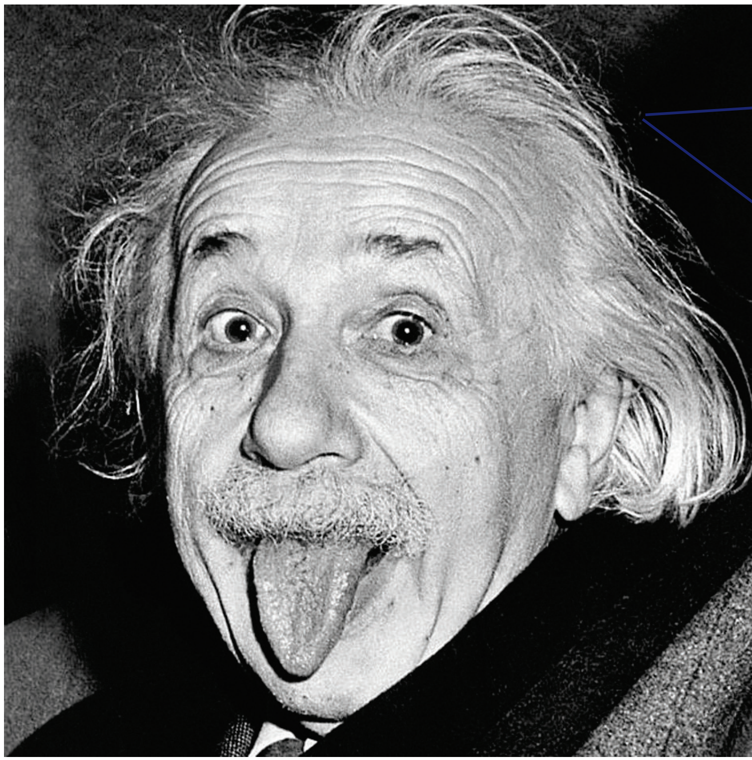


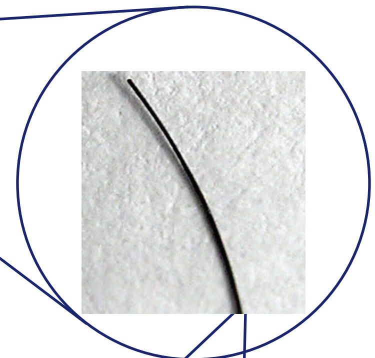
10^{-9} m



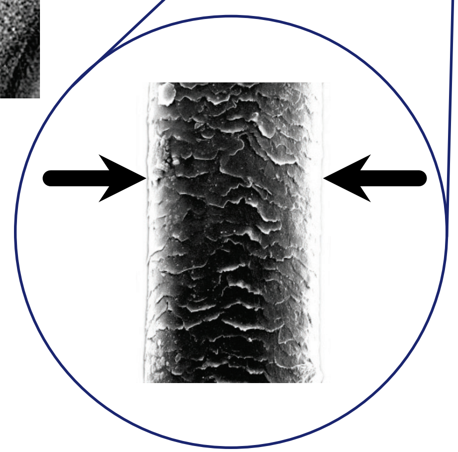
10^{-10} m

How small are nanostructures?





Strand of hair



$\o \approx 0.1$ mm =
= 100 μm =
= **100,000 nm**

1 nm = 1 / 1,000,000,000 m = 10^{-9} m

Definitions of Nanotechnology – 1

National Nanotechnology Initiative: "Nanotechnology is the understanding and control of matter at dimensions of roughly 1 to 100 nanometers, where unique phenomena enable novel applications. Encompassing nanoscale science, engineering and technology, nanotechnology involves imaging, measuring, modeling, and manipulating matter at this length scale"

Merriam-Webster: "The science of manipulating materials on an atomic or molecular scale especially to build microscopic devices"

Definitions of Nanotechnology – 2

Dictionary.com: “A technology executed on the scale of less than 100 nanometers, the goal of which is ***to control individual atoms and molecules***, especially to create computer chips and other microscopic devices”

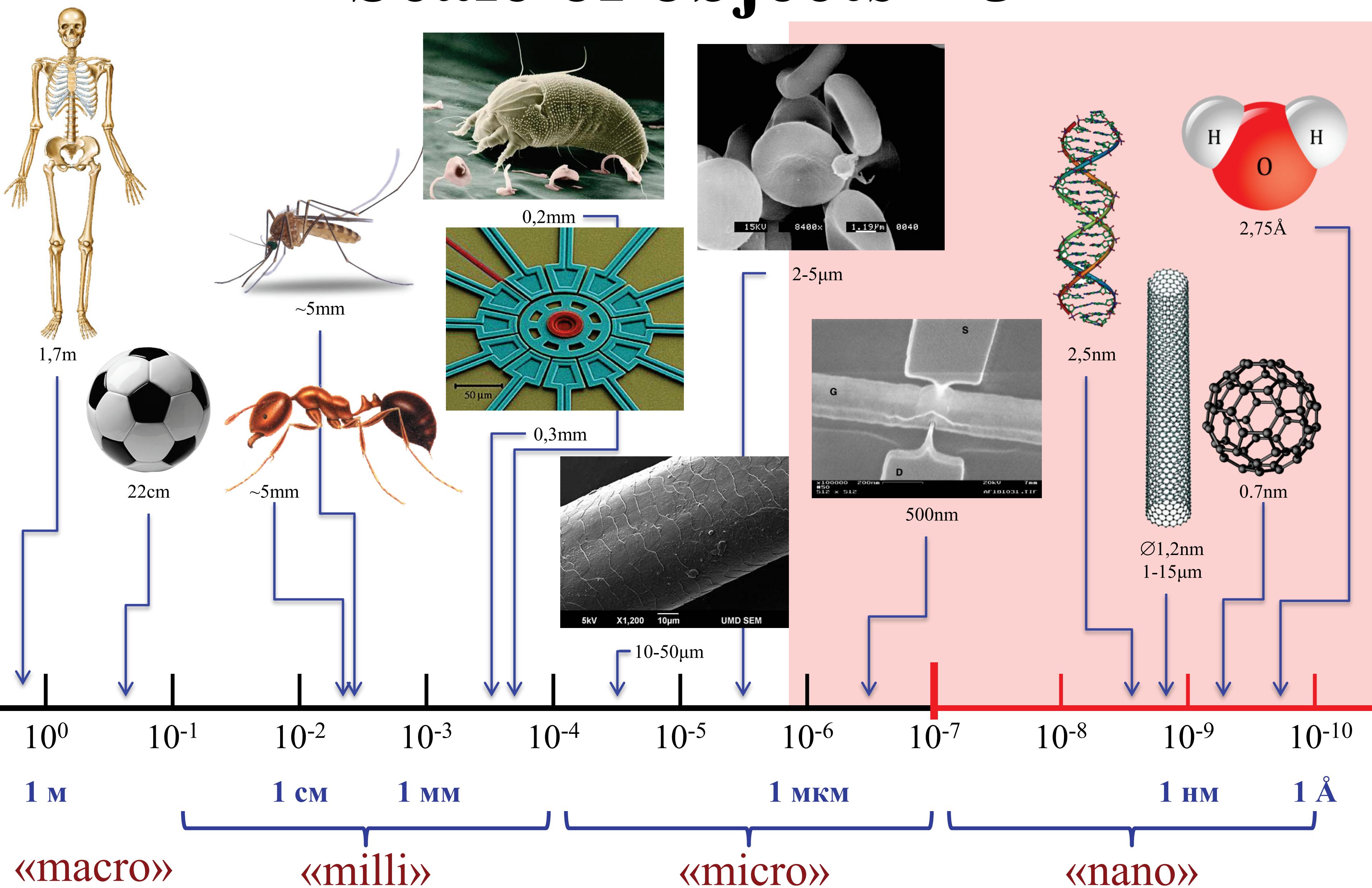
World English Dictionary: “A branch of technology dealing with the manufacture of objects with dimensions of less than 100 nanometres and the manipulation of individual molecules and atoms”

Science Dictionary: ”The science and technology of devices and materials, such as electronic circuits or drug delivery systems, constructed on extremely small scales, as small as individual atoms and molecules”

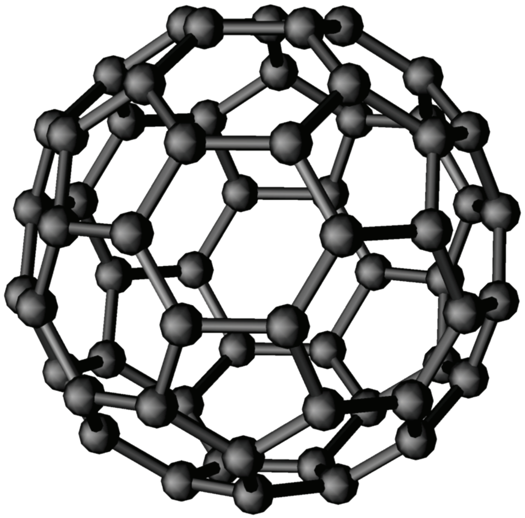
Definitions of Nanotechnology – 3

Key words:	***Comments***:
science; technology	– *More science than technology yet*
less than 100 nm	
manipulation of individual objects	– *opposite to making 1 kg of 100 nm grains*

Scale of objects – 3



Scale of objects – 4



Ø = 12,756.32 km

Ø = 22 cm

Ø = 1.1 nm

νᾶνος

Nano objects

Nano objects are all over around us:

- Bacteria
- Viruses
- Cells
- Fibers
- Nano particles
- Nano films
- Nano whisker

Development of knowledge about the world

The ancient Greek philosopher Democritus is considered to be the founder of atomistic theory.

Demokrit

460 – 394 (370) B.C.

Democritus concept: “infinite number of bodies that are invisible because of their smallness.” These bodies are indivisible, so they are called “***atoms***” [that is not divisible].

Democritus: all atoms are the same and differ from one another only by the shape, the size and location in space. Atoms are in constant motion (like dust particles in the air).

Development of knowledge about the world

John Dalton, an English chemist and natural scientists, revived and developed the atomistic concept of Democritus.

<u>Basic principles of Dalton’s model:</u>

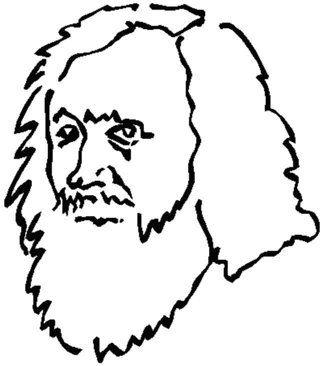
Chemical elements are made up of small particles called ***atoms***.

The atoms of one element differ from all others. Atoms are characterized by an atomic mass.

All atoms of a given element are identical.

Atoms of different elements can combine to form compounds.

Atoms can not be re-created, divided into smaller particles, destroyed by any chemical reactions.



Dalton

1766 – 1844

Nanotechnology timeline

1959 R. Feynman delivers “ Plenty of Room at the Bottom”
1962 Graphene described (Nobel prize in 2010)
1974 N. Taniguchi introduced the term “nano-technology”
1974 First molecular electronic device patented
1981 Scanning Tunneling Microscope (STM) (Nobel prize in 1986)
1981 Quantum dots
1985 Fullerene discovered
1986 Atomic Force Microscopy (AFM) invented
1987 First single-electron transistor created
1991 Carbon nanotubes discovered
2001 US Launches National Nanotechnology Initiative (NNI)

Nanotechnology R&D is interdisciplinary and impacts many industries

- Physics
- Chemistry
- Biology
- Materials Science
- Polymer Science
- Electrical Engineering
- Chemical Engineering
- Mechanical Engineering
- Medicine

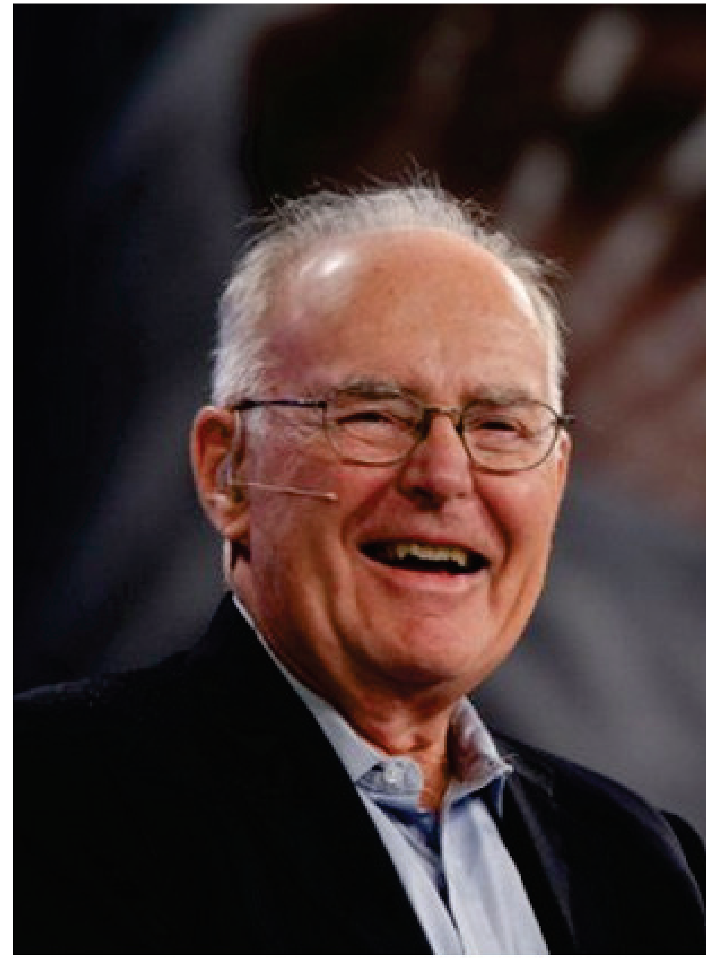
- Electronics
- Materials
- Health/Biotech
- Chemical
- Environmental
- Energy
- Aerospace
- Automotive
- Security

And others

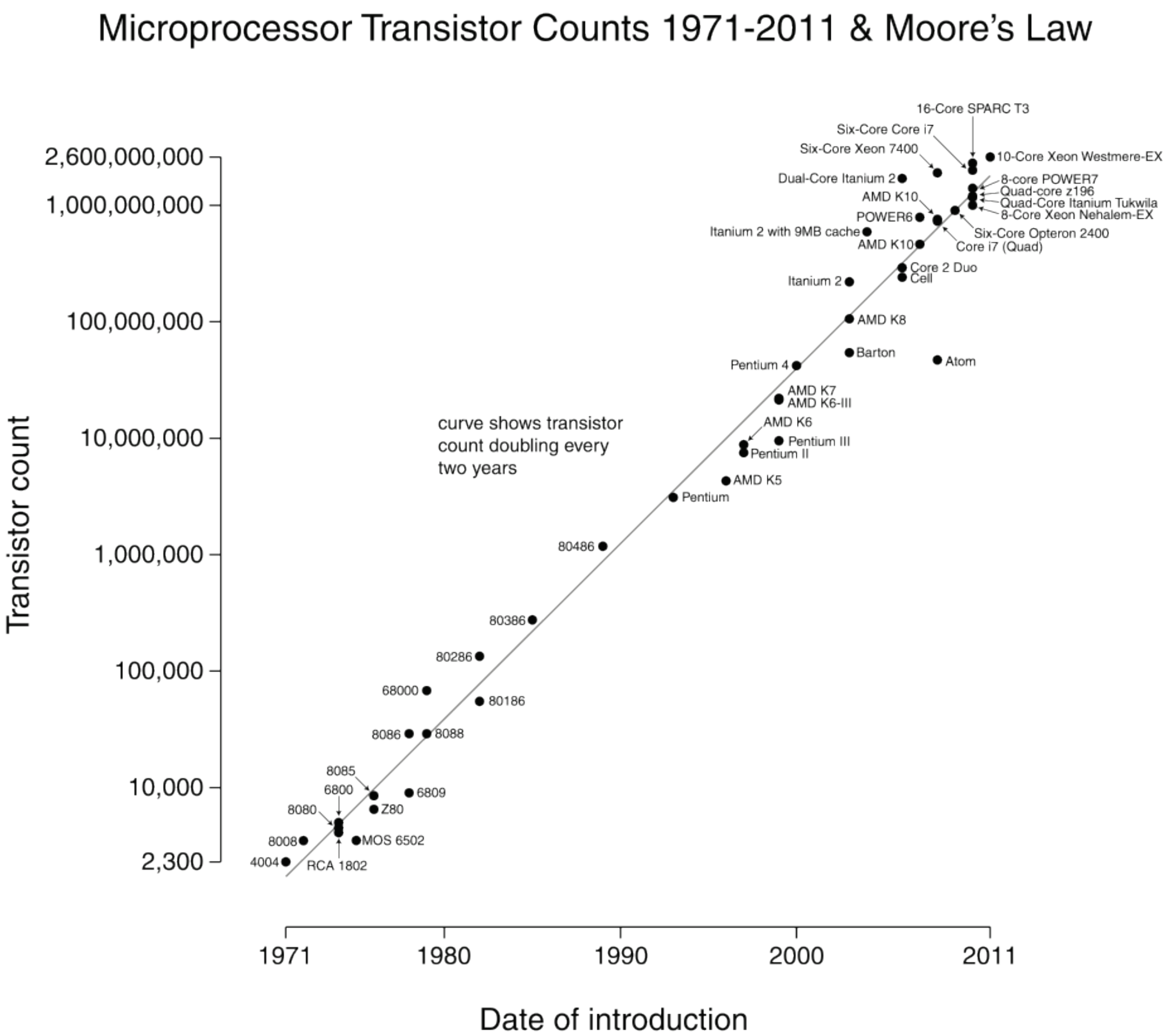
Moore’s law

Gordon Moore (co-founder of Intel) predicted in 1965 that the transistor density of semiconductor chips would double roughly every 18 months.

It’s not a law! It’s a prediction about what device physicists and process engineers can achieve.



Moore's law



Negative consequence of CPU transistor count trend:

power dissipation limited to ~100 W.

BUT increased transistor count needed in Multi-Core CPU era!

Scaling

1990’s was a Golden Era of Scaling

Era of traditional scaling ends up!

Ratio surface/volume increases!

Top traditional scaling limiting factors:

- Source and drain parasitic resistance
- Gate oxide leakage (direct tunneling)
- Carrier mobility degradation due to channel ionized impurity scattering
- Material diffusion

Approaches

Top-down and ***bottom-up*** are two approaches for the manufacture of products.

Top-down – Breaking down matter into more basic building blocks. Frequently uses chemical or thermal methods (i.e. photolithography, deposition, etching, machining)

Bottom-up – Building complex systems by combining simple atomic-level components (self-assembly into some useful conformation or positional assembly)

How to build nano-objects in *top-down* approach?

We have to figure out how to

- drill,
- cut,
- stamp,
- extrude,
- cast
- …

How to build nano-objects in ***bottom-up*** approach?

We have to figure out how to

- assemble,
- glue,
- weld,
- solder,
- extrude,
- stich
- …

Are there problems?

Weight and inertia is not a problem.

But new problems arise:

- Heat conduction
- Viscosity and friction
- Static electricity
- Material compatibility
- Weak Van der Waals force
- Brownian motion (material self-diffusion)

…

Research statistics

Top 20 countries/regions based on number of papers published from 1976 to 2004

Rank	Country/Region	Number of Papers
1	USA	61,068
2	Japan	24,985
3	Germany	21,334
4	Peoples R China	20,389
5	France	13,777
6	England	10,394
7	Russia	7,466
8	Italy	6,879
9	South Korea	6,679
10	Canada	5,017
11	Spain	4,941
12	Switzerland	4,280
13	India	3,869
14	Netherlands	3,635
15	Sweden	3,062
16	Taiwan	2,886
17	Australia	2,788
18	Poland	2,703
19	Israel	2,509
20	Belgium	2,409

Top 20 institutions based on number of papers published from 1976 to 2004

Rank	Institution	Country/Region	Number of Papers
1	Chinese Acad Sci	Peoples R China	5,858
2	Russian Acad Sci	Russia	3,720
3	Univ Tokyo	Japan	2,465
4	CNRS	France	2,395
5	Univ Paris	France	2,374
6	Osaka Univ	Japan	2,134
7	Tohoku Univ	Japan	2,123
8	Univ Illinois	USA	1,960
9	Univ Calf Berkeley	USA	1,809
10	MIT	USA	1,595
11	Tokyo Inst Technol	Japan	1,477
12	Univ Cambridge	England	1,451
13	Univ Sci & Technol China	Peoples R China	1,445
14	CSIC	Spain	1,439
15	Univ Texas	USA	1,438
16	Tsing Hua Univ	Peoples R China	1,387
17	Univ Calif Santa Barbara	USA	1,322
18	Kyoto Univ	Japan	1,309
19	Harvard Univ	USA	1,292
20	CNR	Italy	1,266

Top 5 Nano-Breakthroughs in 2006 (Forbes.com)

1) DNA ORIGAMI: Researcher: Paul W. K.Rothemund (Caltech)

Rothemund developed a technique to fold a single long strand of DNA into any 2D shape held together by a few shorter DNA pieces. He created software to quickly determine what short sequences will fold the main strand into the desired shape, such as the DNA smiley face he built, which is a mere 100nm across and 2nm thick, or his nanoscale map of the Americas.

2) NANOMAGNETS TO CLEAN UP DRINKING WATER: Researchers: Vicki Colvin and colleagues (Rice University)

Rust nanoparticles, which have magnetic properties, bind to arsenic; the rust and arsenic can then be lifted out of the water by nothing more than a handheld magnet. The breakthrough was the realization that the manipulation of nanoscale rust would not require huge magnetic fields, as was expected.

3) ARRAYS CONNECT NANOWIRE TRANSISTORS WITH NEURONS: Researchers: Charles Lieber amd colleagues (Harvard University)

Silicon nanowires link up with the axons and dendrites of live mammalian neurons, creating artificial synapses between the two and allowing scientists to study and manipulate signal propagation in neural networks. The device can measure the brain's electric signals with unprecedented sensitivity, amplifying signals from up to 50 places on a single neuron.

4) SINGLE NANOTUBE ELECTRICAL CIRCUITS: Researchers: Phaedon Avouris and colleagues (IBM's T.J.Watson Research Center; University of Florida; Columbia University)

This year, IBM unveiled the most complex and highest performance electrical circuit based on a single nanotube, demonstrating the applicability of CMOS technology and paving the way for the future of computing. The integrated logic circuit consists of 12 transistors made of palladium and aluminum tracing the length of a single carbon nanotube.

5) NANOPARTICLES DESTROY PROSTATE CANCER: Researchers: Robert Langer and colleagues (MIT; BWH and Harvard; U.of Illinois; Gwangju Institute of Science and Technology, South Korea; Dana Farber Cancer Institute)

Researchers at MIT and Harvard have custom-designed nanoparticles that hone in on prostate cancer cells and deliver doses of targeted chemotherapy. In trials with mice, which were given human prostate cancer, a single injection of these nanoparticles completely eradicated tumors in five out of seven animals, significantly reducing tumor size in the other two.

Timeline for the beginning of industrial prototyping and commercialization of nanotechnology.

(Renn and Roco 2006)

1G ~ 2001 – ***Passive nanostructures*** (coatings, nanoparticles, nanostructured metals, polymers, ceramics)

2G ~ 2005 – ***Active nanostructures*** (3D transistors, amplifiers, targeted drugs, actuators, adaptive structures)

3G ~ 2010 – ***Systems of nanosystems*** (guided molecular assembling, 3D networking and new system architectures, nanorobotics, supramolecular)

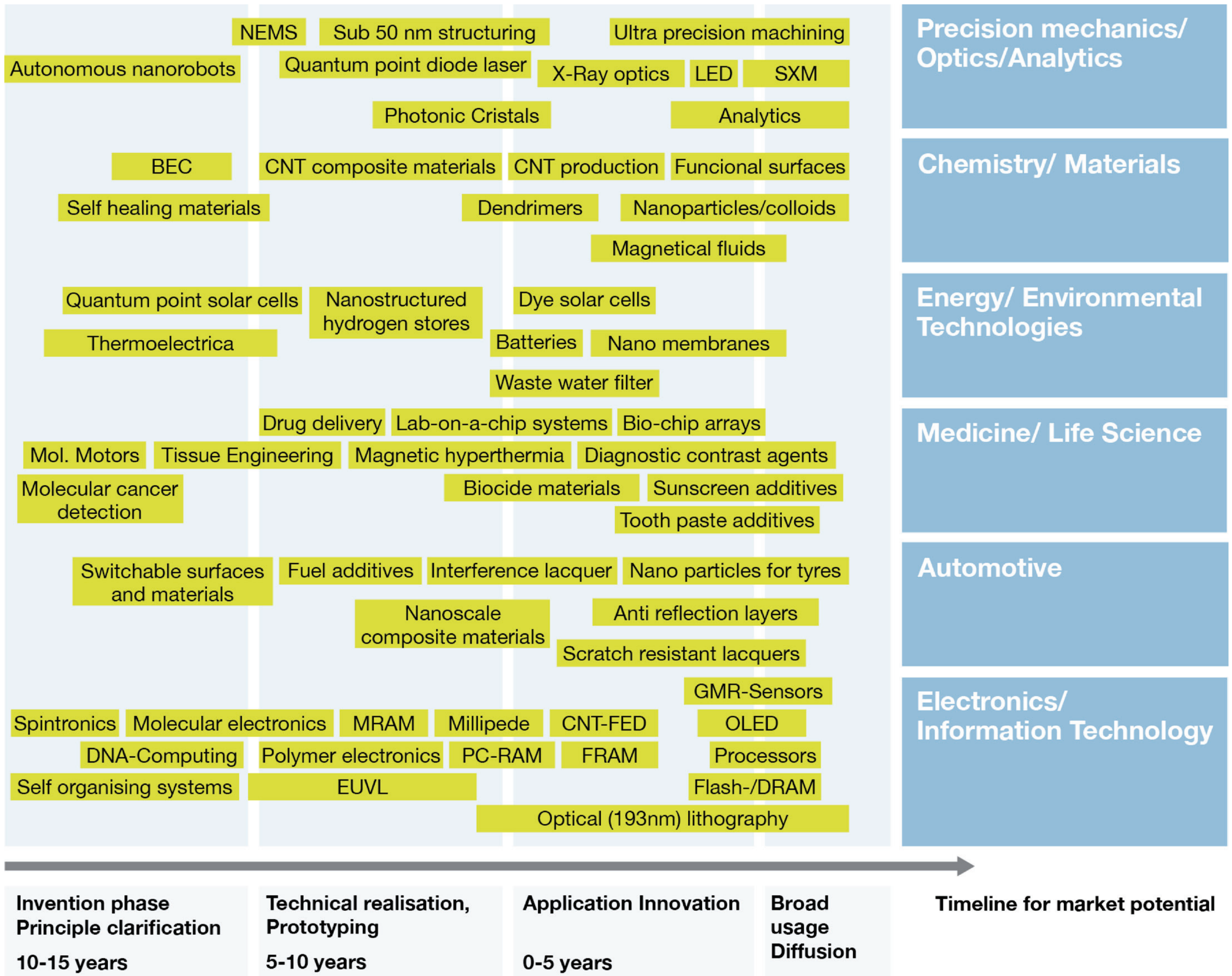
4G ~ 2020 – ***Molecular nanosystems*** (molecular devices ‘by design’, atomic design, emerging functions)

↓ Higher uncertainty and risk

↓ Increased complexity, interdisciplinarity

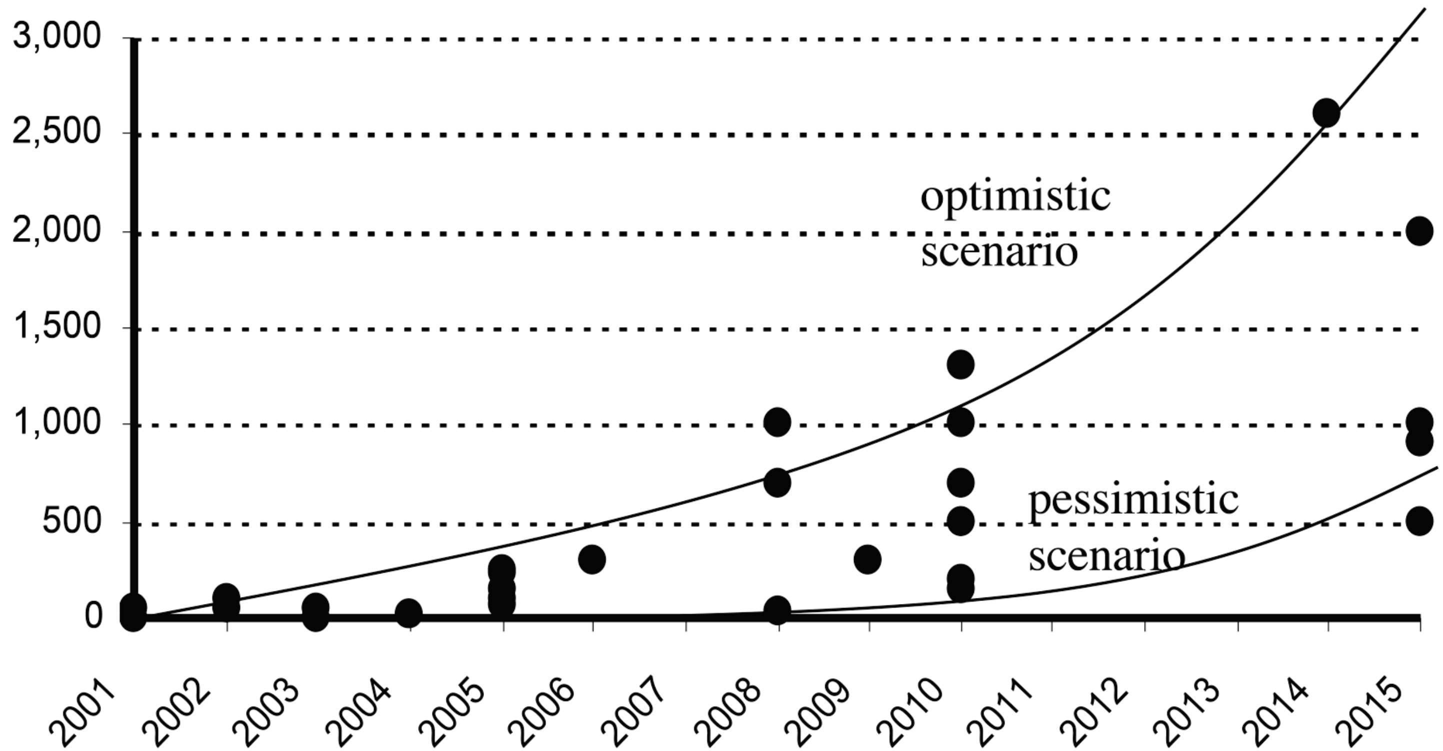
Examples of Development Status and Application Fields of Nanotechnology

(VDI Technologiezentrum, Germany, 2006)



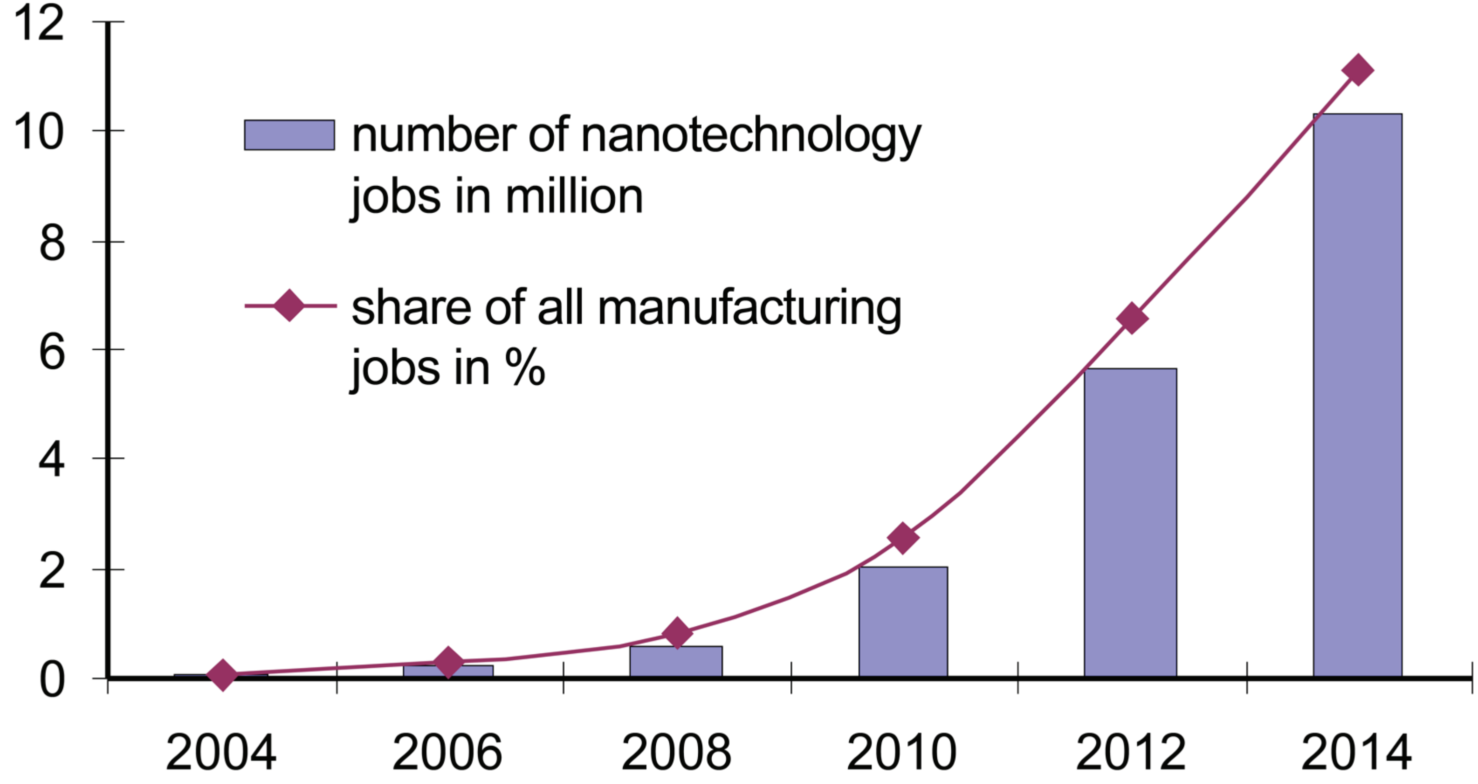
World market forecasts for nanotechnology in billion US Dollar. Diverse sources.

(The economic development of nanotechnology - An indicators based analysis, 2006)



Number of nanotechnology jobs in million and the share of nanotechnology jobs of all manufacturing jobs in percent.

Source: Lux Research, 2004.



Is nanotechnology an evolution or a revolution?

Evolution

- Ultradense memory
- Faster microprocessors
- Customized/specialized microprocessors
- Portable systems
- Medium performance/Low Cost Systems
- Organic compounds as conductors and semiconductors

Revolution

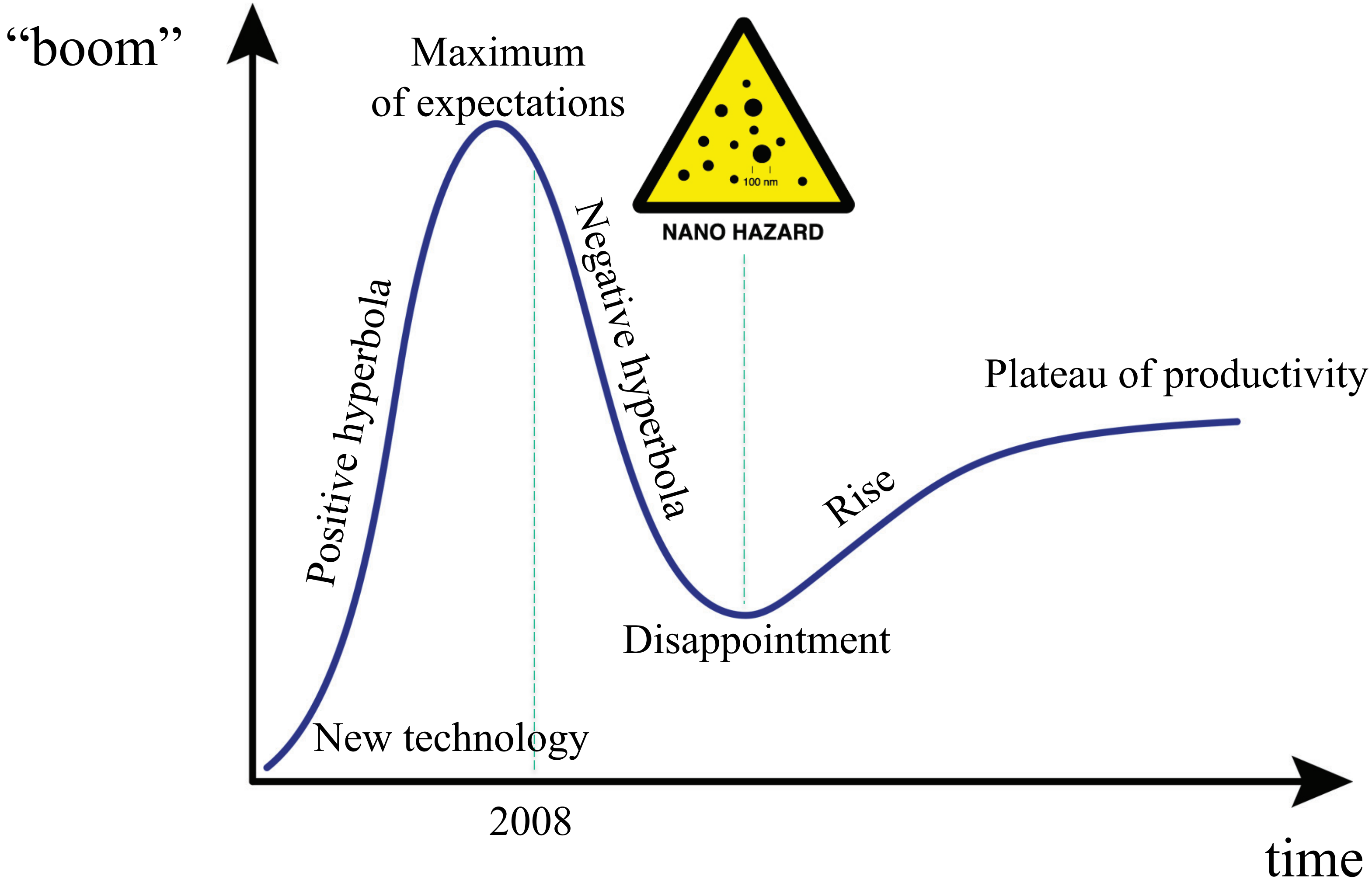
- True Nano ICs (<100 nm)
- Single molecule electronics
- Cellular automata
- Quantum computing
- Self-assembling
- Biomimetic systems
- Bio-hybrids

Nanotechnology today

- $22 billion industry
- Heterogeneous catalysts (Zeolite MCM-41 for higher octane gasoline. Cracking hydrocarbons – 40% of gas produced this way)
- Wilson Tennis Balls
- Oil of Olay and L’Oreal
- NanoPants (Nano-Care Khakis)

Yet poor outcomes

Nanotechnology progress



Near future applications

- Electronics
- Coatings
- Fuel Cells
- Water filters
- Composites
- Drugs
- Cancer Detection & Treatment

Prospective outlook: nano circuits any time soon?

Q. Do we know how to build the needed circuit components?

A. YES, but a lot of research is needed.

Q. Do we have the materials to build them from?

A. YES, but we are still working on new materials.

Q. Can we mass produce these components and make the venture profitable?

A. NOT YET.

Q. Do people really need computers and laptops that small?

A. YES, WE LIKE TOYS ☺

Issues

- Lack of current guidelines and standards (ISO, ANSI, …)
- Increasing concern over the potential health risks (microparticles)
- Nanotech education (80% knew “nothing” to “a little” about nanotechnology)