Ecotextile 04, Manchester, UK 7-8 July 2004

Molecular Manufacturing for Clean, Low Cost Textile Production

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NAVSEA
WARFARE CENTERS
Carderock Division

Institute for Molecular Manufacturing

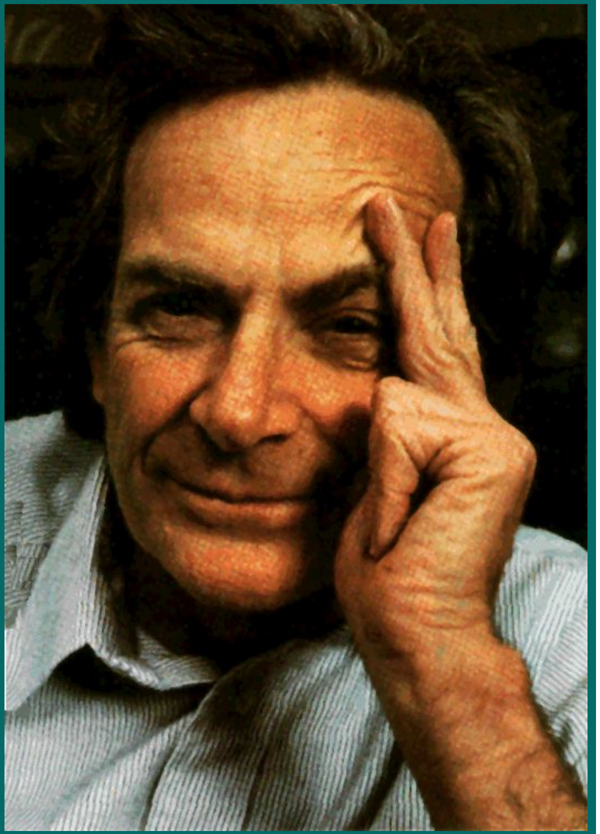
Goals of this talk

- Show that there is a gap between popular and scientific perceptions of molecular mfg.
- Provide examples of "conventional" nanotechnology applications to textiles
- Show that nanotubes, in particular, hold great promise
- Describe the vision for molecular manufacturing
- Show specific progress toward realizing MM
- Show that technological progress is accelerating
- Share thoughts on how MM could impact the textile industry

Feynman's Plenty of Room at the Bottom Talk at CalTech

"The principles of physics, as far as I can see, do not speak against the possibility of maneuvering things atom by atom. It is not an attempt to violate any laws; it is something, in principle, that can be done; but in practice, it has not been done because we are too big."

Richard Feynman, 1959

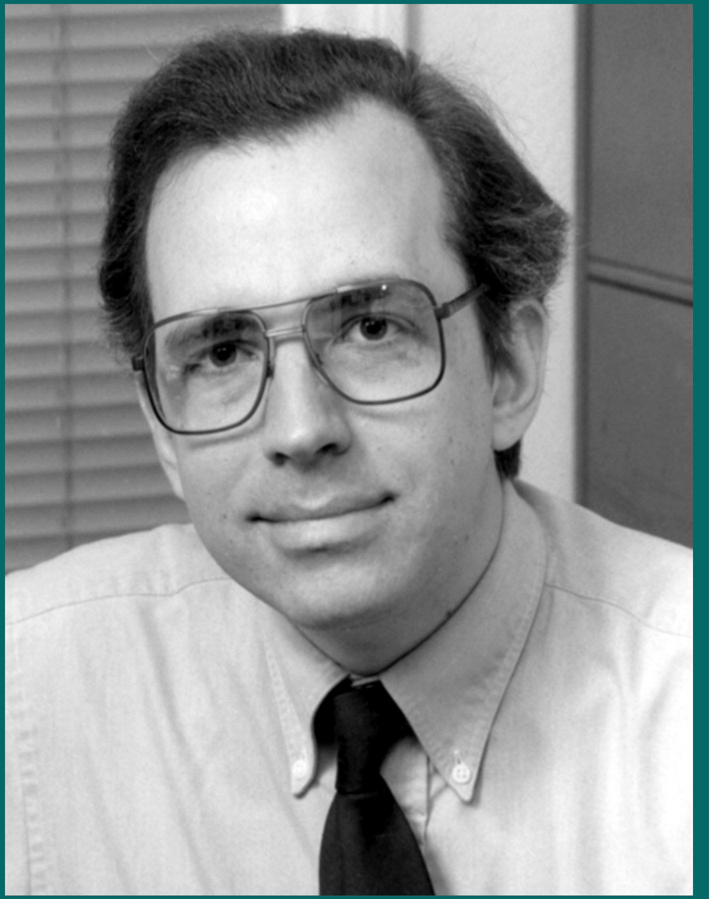


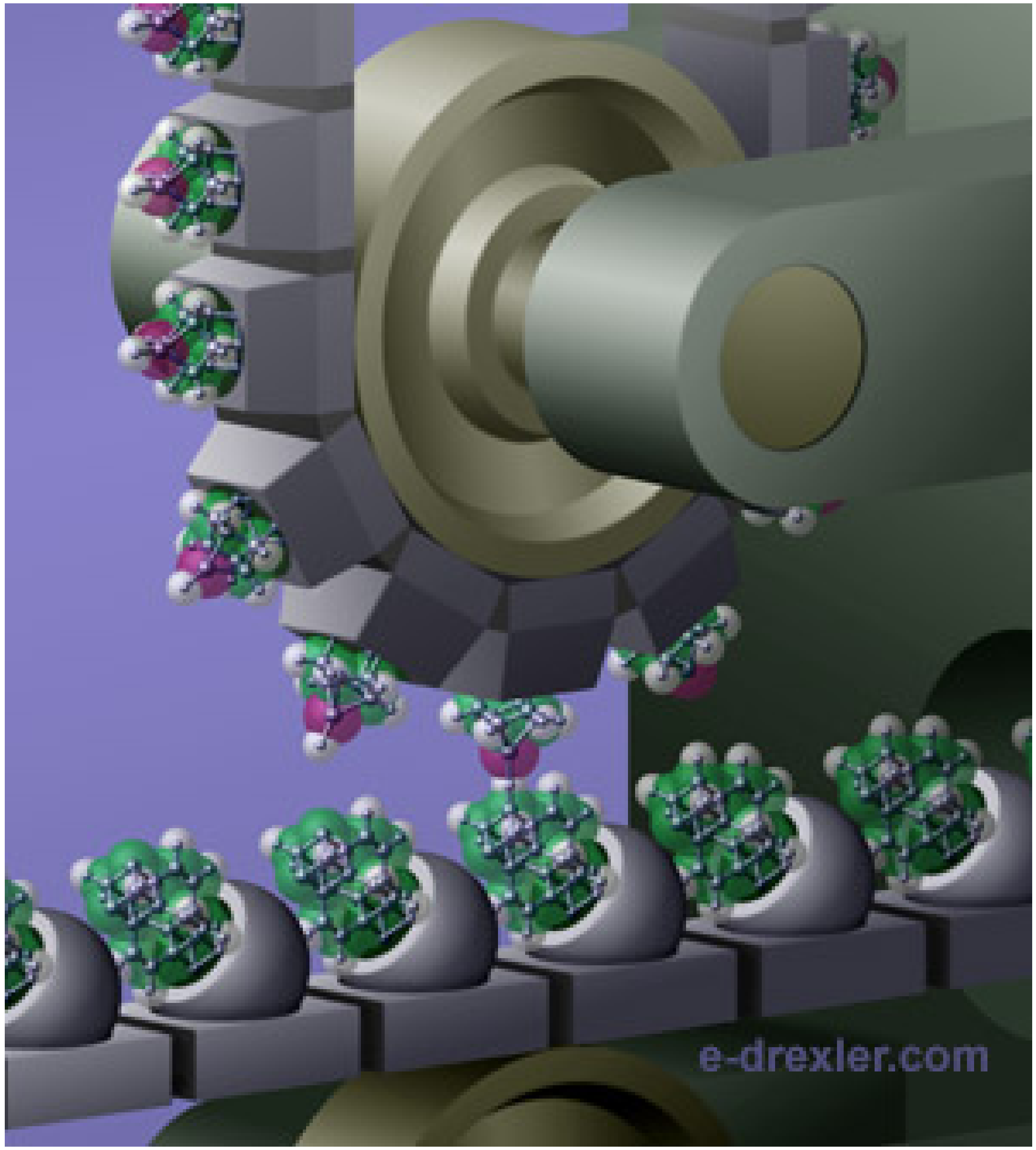
Drexler's paper PNAS, Sept. 1981

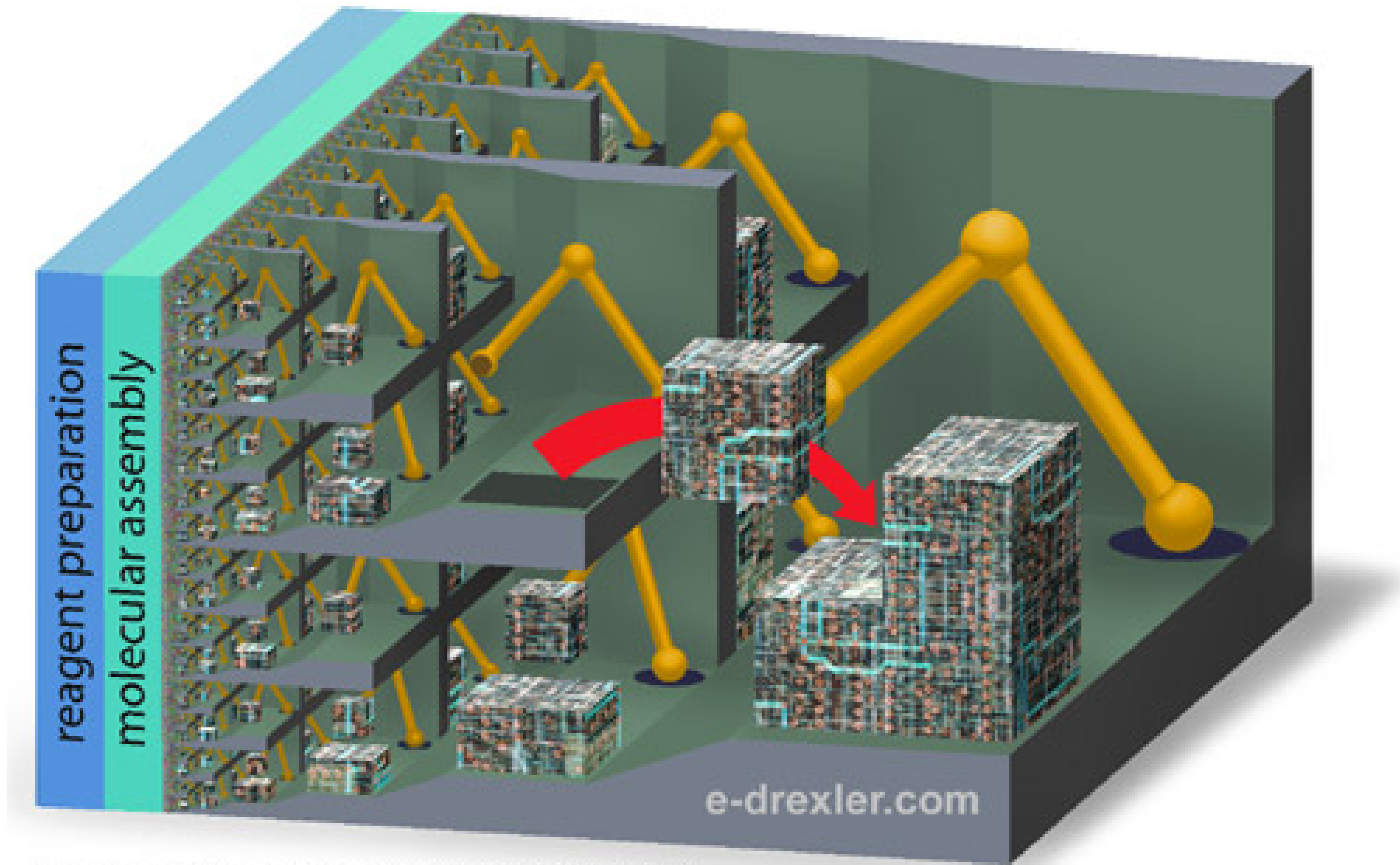
Molecular Engineering: an approach to the development of general capabilities for molecular manipulation

"By one path or another, we will eventually develop tools that enable us to assemble complex structures to atomic specifications. . . [These] assemblers, if supplied with materials and energy, will be able to build almost anything— including more assemblers and more systems for providing them with materials and energy."

Eric Drexler, 1985



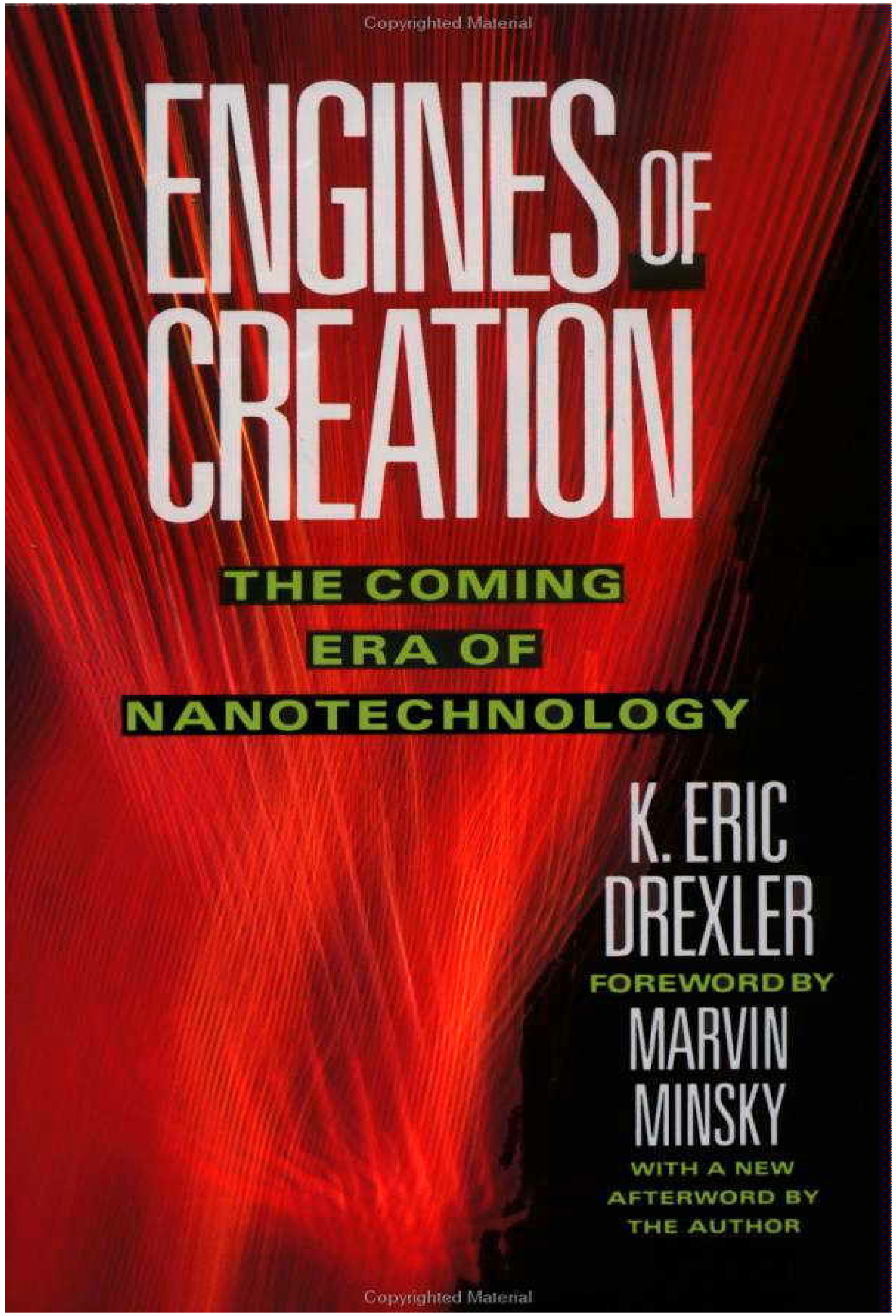

e-drexler.com



Molecular manufacturing (desktop scale)

Envisioned Products

- Powerful desktop computers ~ billion processors
- Abundant energy (solar)
- Cures for serious diseases using medical nanorobots
- New materials 100 times stronger than steel
- A clean environment
- More molecular manufacturing systems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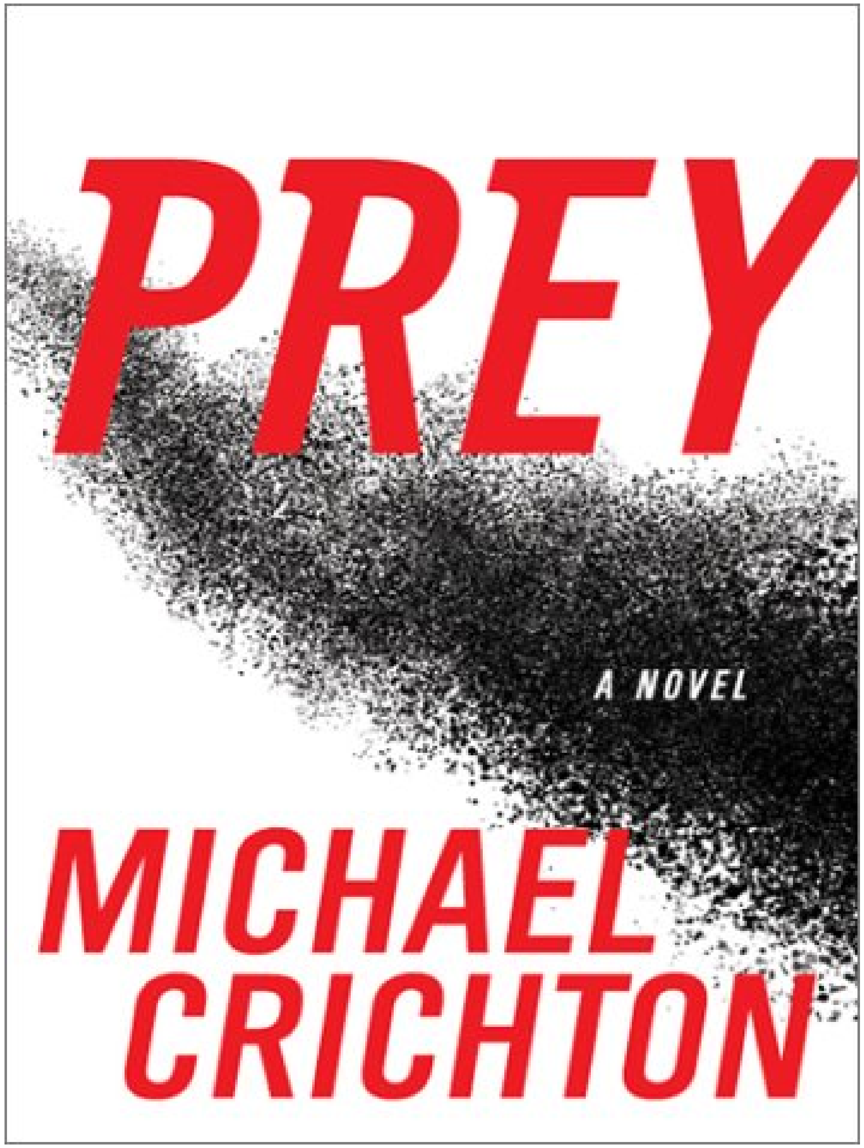
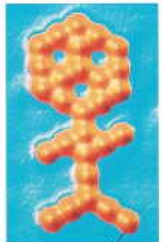
Star Trek (Borg)


PREY
A NOVEL
MICHAEL
CRICHTON

Nanorobots

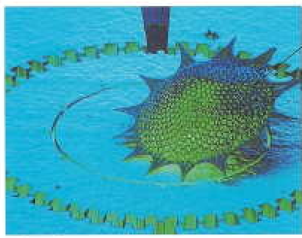
Technology is shrinking fast. Computing technology that would have filled a warehouse 30 years ago can now be squeezed onto a chip a fraction of the size of your thumbnail. The very smallest scale of engineering is called nanotechnology. A nanometer is a billionth of a meter, about the width of ten atoms. Nanotechnology may, one day, be capable of producing fully working robots to that scale, called nanorobots or nanobots. Working at an almost atomic level, nanobots could build complex items cheaply and repair clothes, equipment, and even people without being noticed. They could also be used to rid the atmosphere of pollution and to repair holes in the ozone layer.



Bottom up

Researchers are looking at different ways to construct nanobots. The "bottom up" approach uses individual atoms and molecules as building blocks. This stick figure was created from just 28 carbon monoxide molecules.

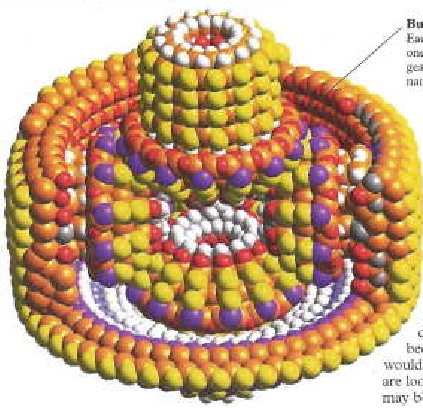
A mere wisp
A row of 20,000 of these stick figures is more narrow than a human hair.



Putting it in context
A plankton skeleton, just 0.008 in (0.2 mm) across, sits on one of the engine's cogs, measuring 0.02 in (0.5 mm).

Top down

Known as "top down," one potential way of building nanomachines is to miniaturize existing machines. There have been some incredible feats, including this fully working electric motor, just 0.07 in (1.8 mm) in size.



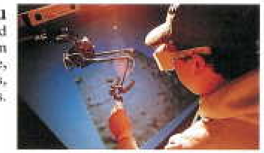
Building atoms
Each ball represents one atom. The whole gear measures just a few nanometers in diameter.

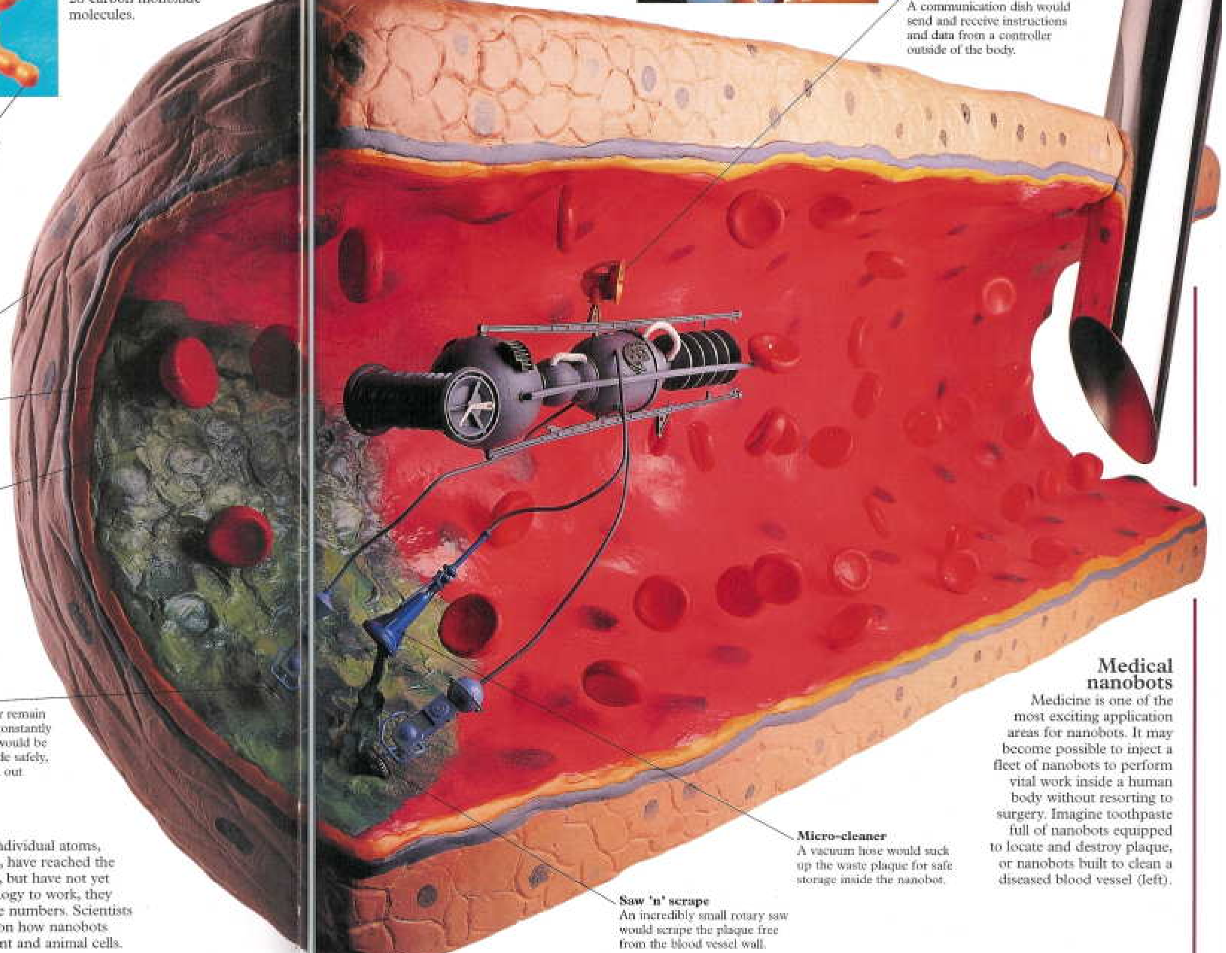
A nanogear

Machines made from individual atoms, like this differential gear, have reached the computer modeling stage, but have not yet been built. For nanotechnology to work, they would need to be made in huge numbers. Scientists are looking to nature for ideas on how nanobots may be self-replicating, like plant and animal cells.

May the force be with you

This nanomanipulator is a big step toward an assembler that can build nanobots from atoms. It uses an atomic force microscope, together with sophisticated handling tools, to manipulate minute particles.





Blood vessel wall

Red blood cell

Plaque attack
The diseased section of the blood vessel is covered with a type of plaque containing cholesterol.

Waste away
The nanobot would either remain inside the blood system, constantly performing its task, or it would be programmed to biodegrade safely, carrying the waste plaque out of the human body.

Getting the needle
A hypodermic syringe, less than 0.02 in (0.5 mm) in diameter, would inject nanobots into the blood vessel.

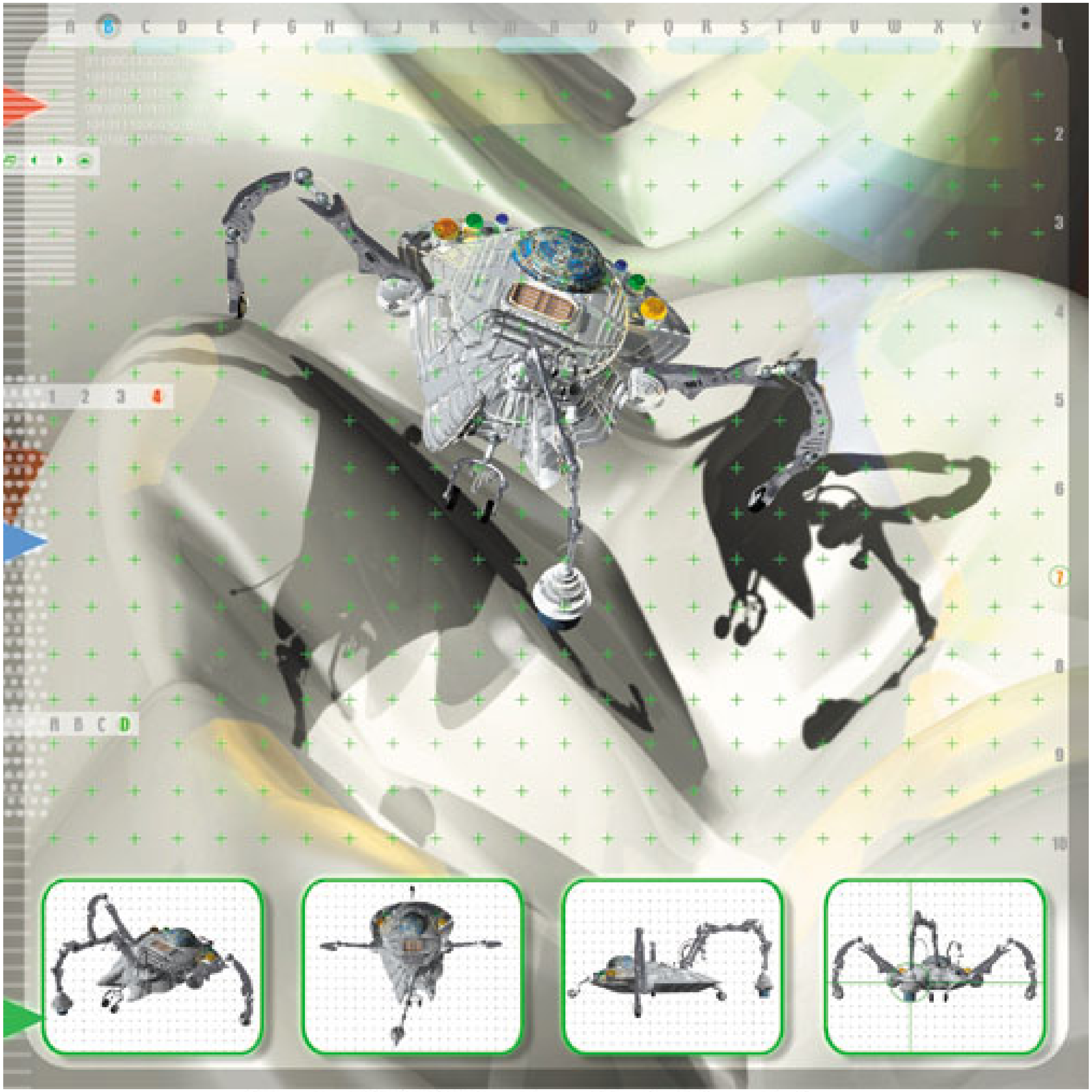
Dishing it up
A communication dish would send and receive instructions and data from a controller outside of the body.

Micro-cleaner
A vacuum hose would suck up the waste plaque for safe storage inside the nanobot.

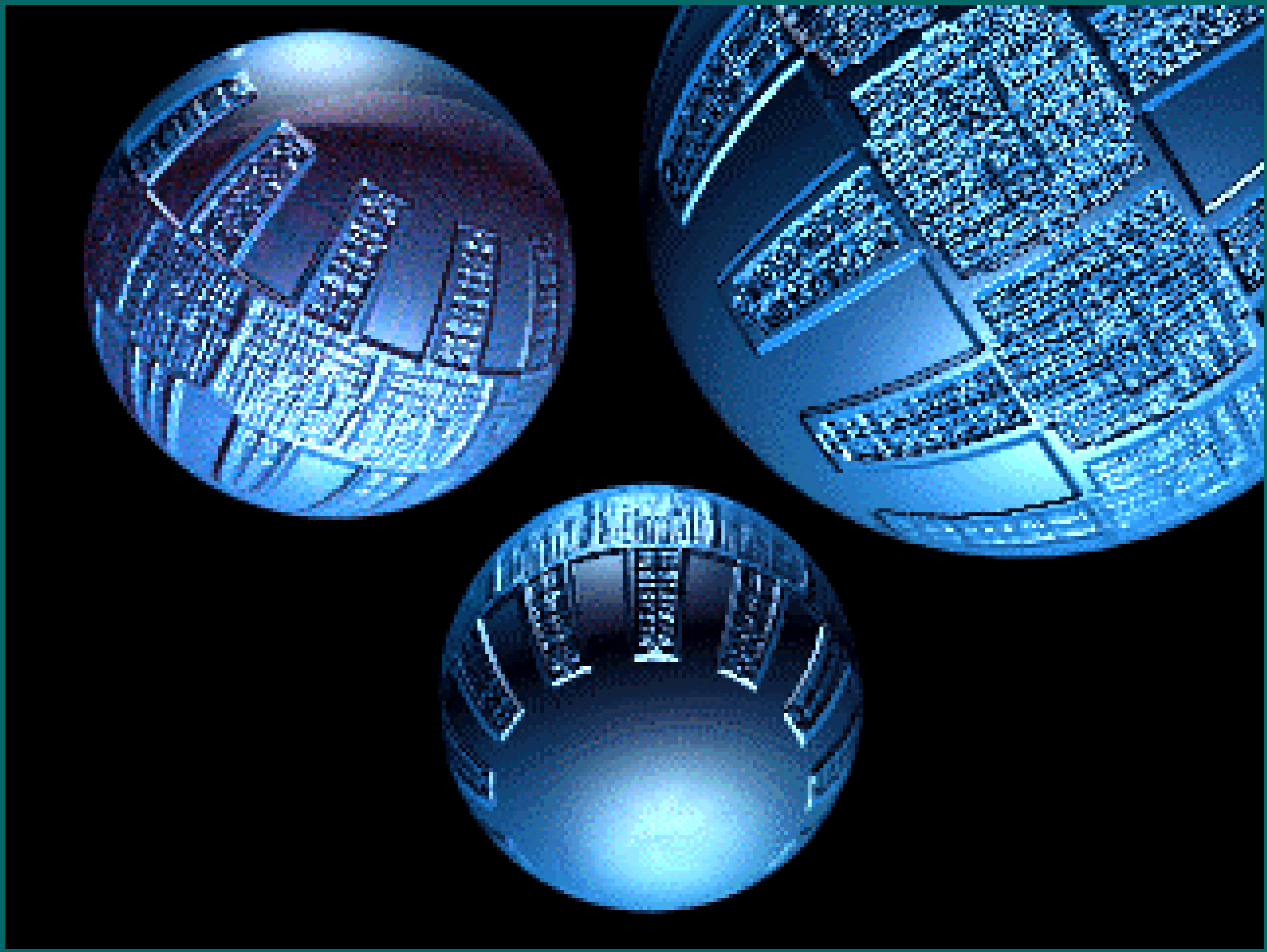
Saw 'n' scrape
An incredibly small rotary saw would scrape the plaque free from the blood vessel wall.

Medical nanobots

Medicine is one of the most exciting application areas for nanobots. It may become possible to inject a fleet of nanobots to perform vital work inside a human body without resorting to surgery. Imagine toothpaste full of nanobots equipped to locate and destroy plaque, or nanobots built to clean a diseased blood vessel (left).



Respirocyte Animation

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SPECIAL ISSUE
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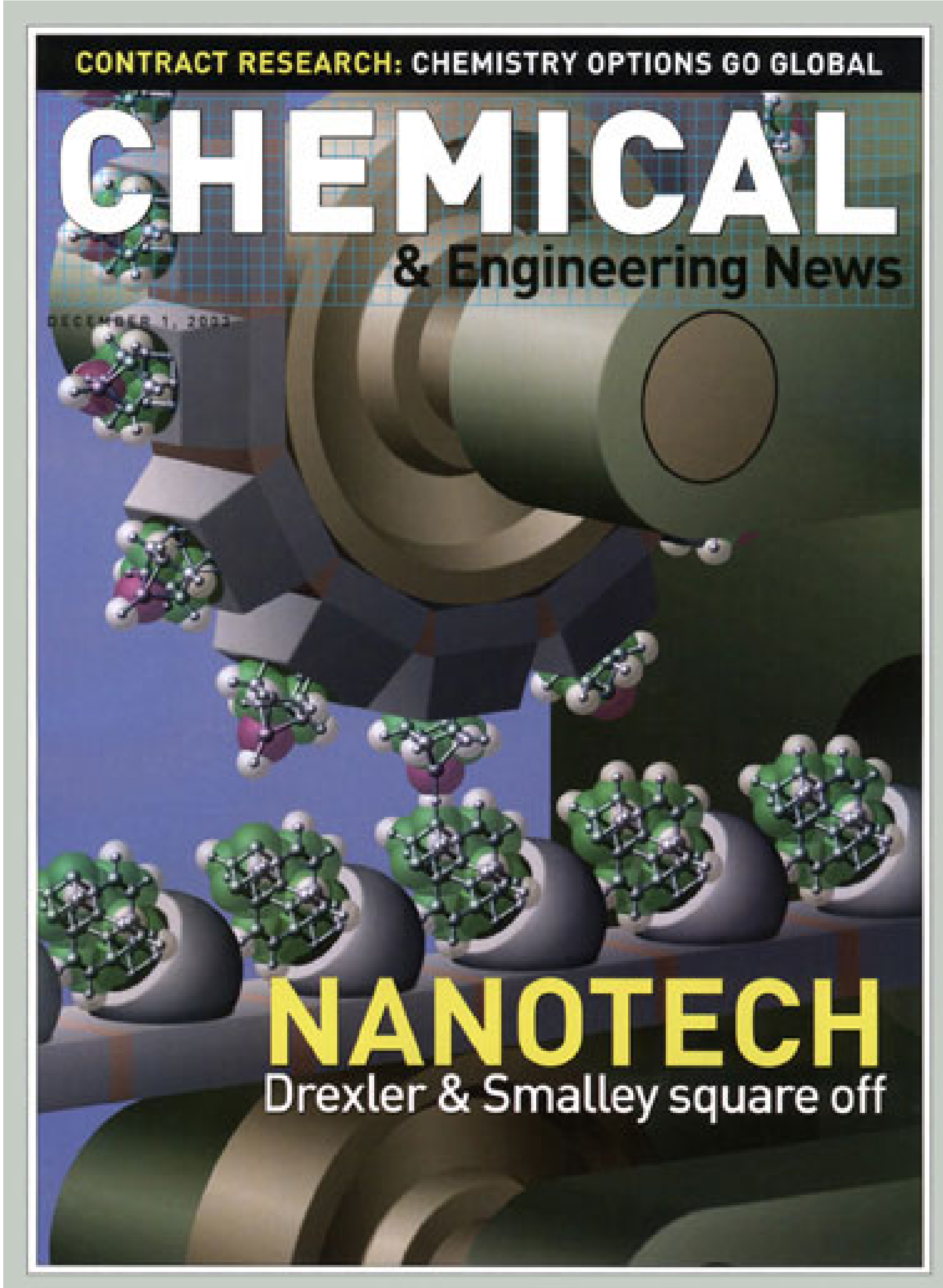
Medical Nanoprobes
Buckytube Electronics
Living Machinery
Atom-Moving Tools
New Laws of Physics
Nano Science Fiction
NANOTECH
The Science of the Small Gets Down to Business
ALSO
Eric Drexler on Nanorobots
and
Richard Smalley on Why They Won't Work
$4.95


CONTRACT RESEARCH: CHEMISTRY OPTIONS GO GLOBAL
CHEMICAL
& Engineering News
NANOTECH
Drexler & Smalley square off

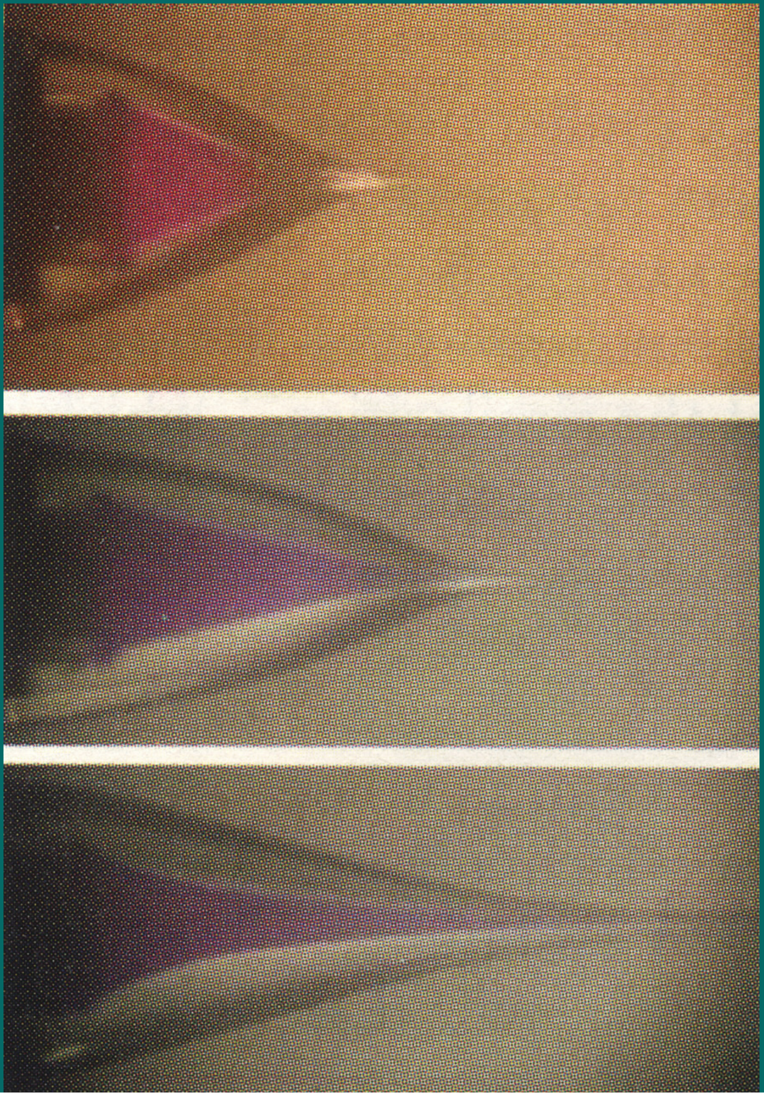
My Assessment

- All the raw ingredients for molecular robots are available now
- Molecular robots will appear soon (2-3 years)
- Assembler systems will emerge by 2015
- Early products of assembler systems will be components for more assembler systems (accelerating development and proliferation)
- Many textile applications—home products

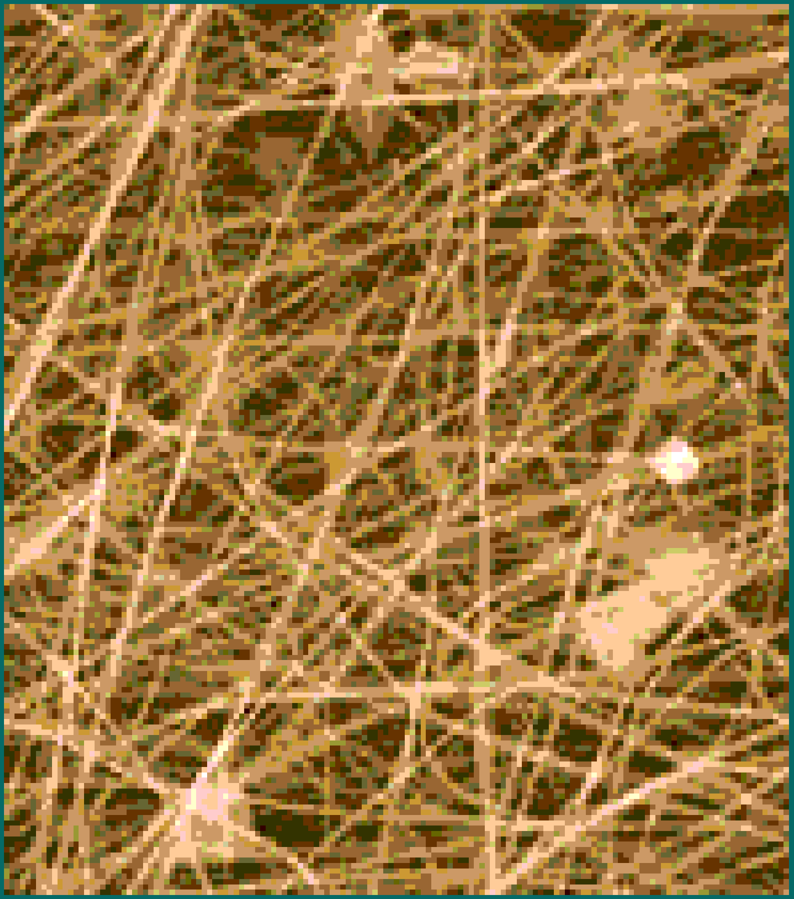
“Conventional” Textile-Related Nanotechnology Development

Cotton treated with clay nanoparticles (Leslie White, ARS SRRC, New Orleans)

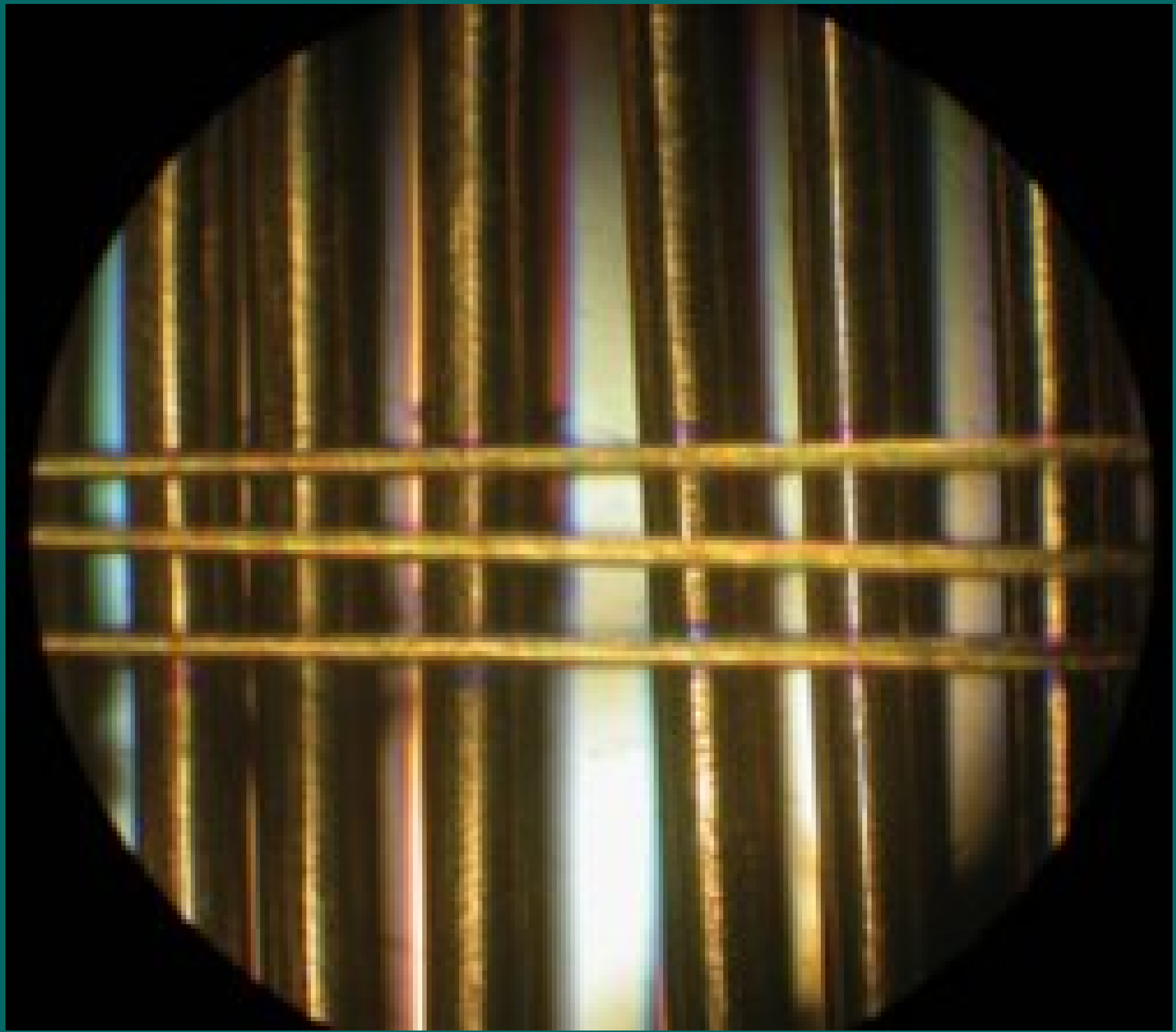
Electrospray coaxial fibers (Loscertales, U. Malaga, Spain)



Fibrinogen wound covering
(Gary Bowlin, Virginia Commonwealth U.)



Transistors as part of fabric (Josephine Lee, U. C. Berkeley)



Aluminum strands, insulating layer, pentacene film

Figure 1 Warfighter Physiological Status Monitoring (WPSM)

USAMRMC/Military Operational Medicine Research Program/Ft. Detrick, MD
POC: COL John P. Obusek (508)233-4811/LTC Karl Friedl (301)619-7301
Graphics: Janet G. Reese

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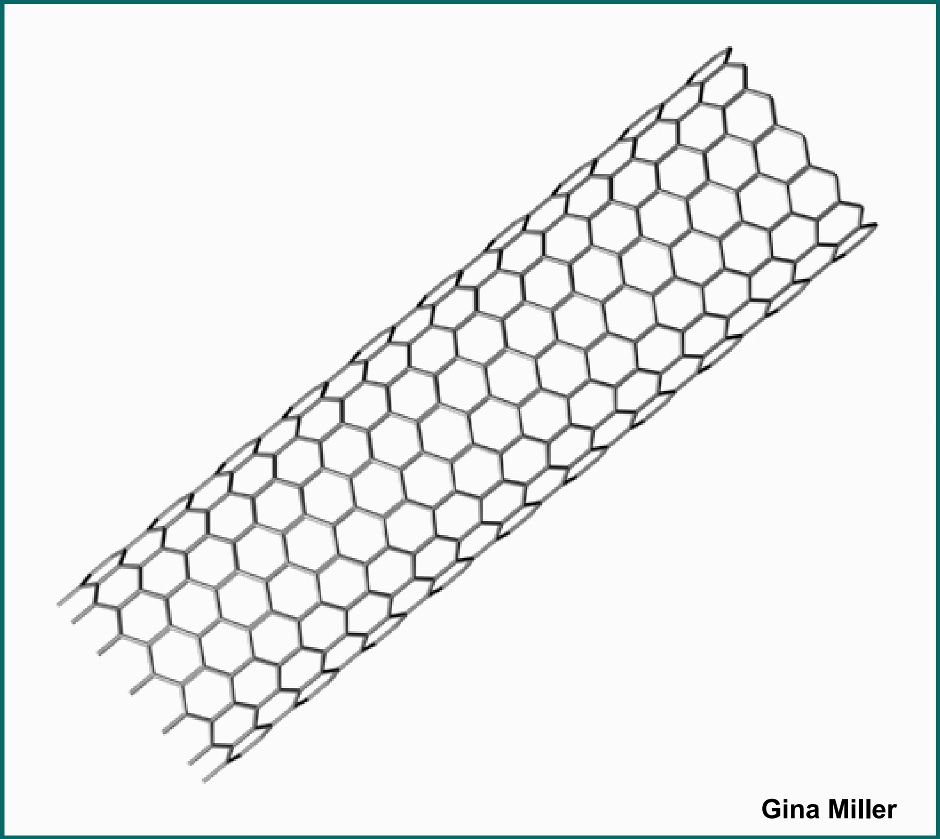
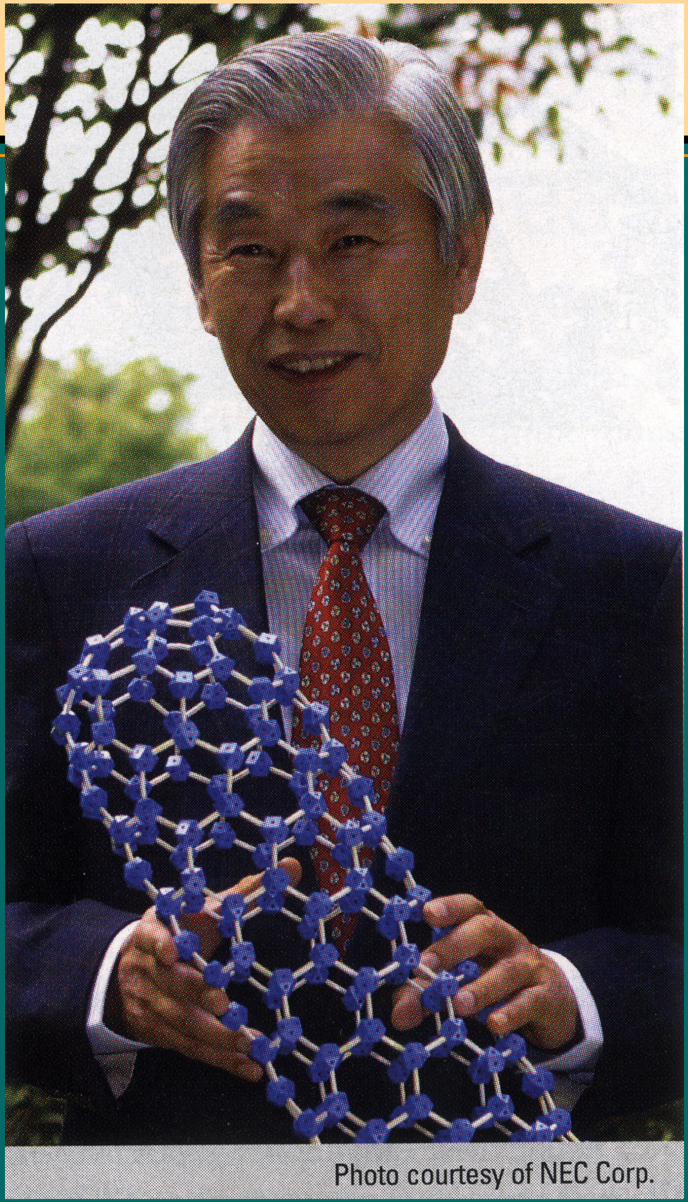
Conventional Development: Focus on Carbon Nanotubes

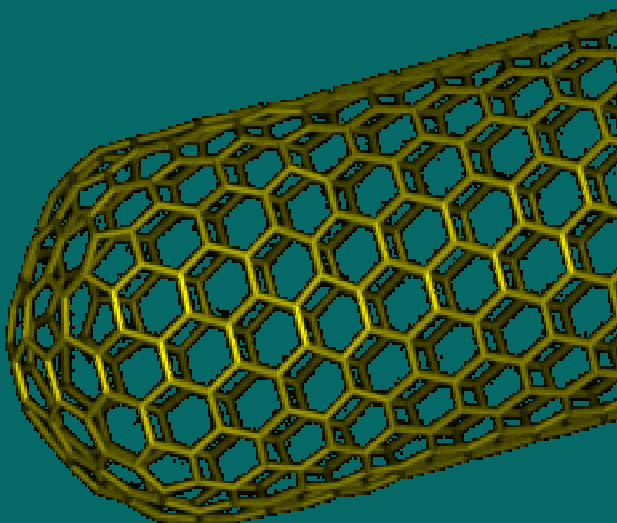
Nanotubes first discovered

(1991 Sumio Iijima, NEC)





Nanotubes: Stiff and strong



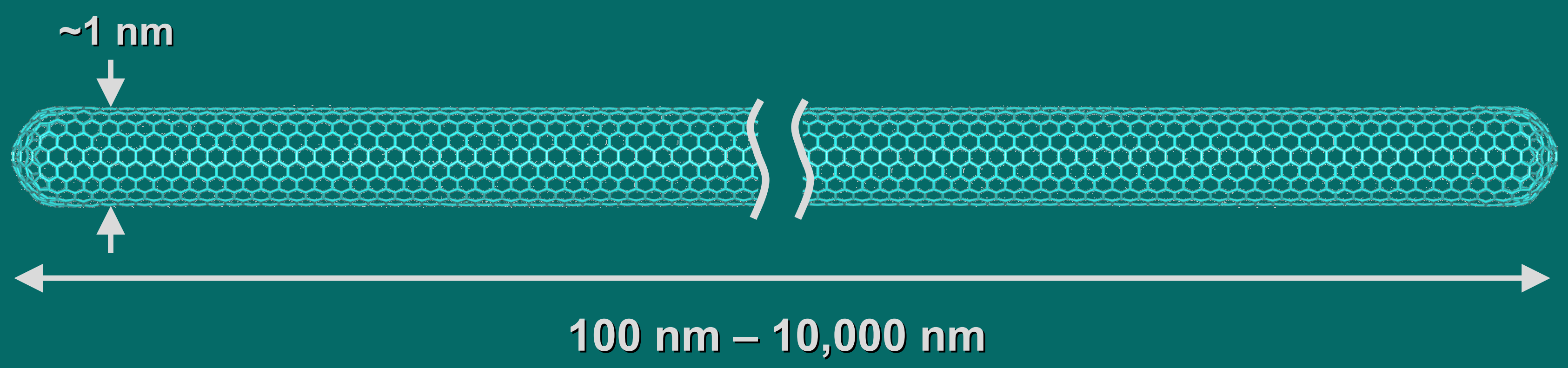
Above: One end of a SWNT. Modified from the original at Richard Smalley's Image Gallery. [11]

	Estimated Modulus (GPa)		Estimated Strength (GPa)
	1400		100
	194	AerMet 100	2

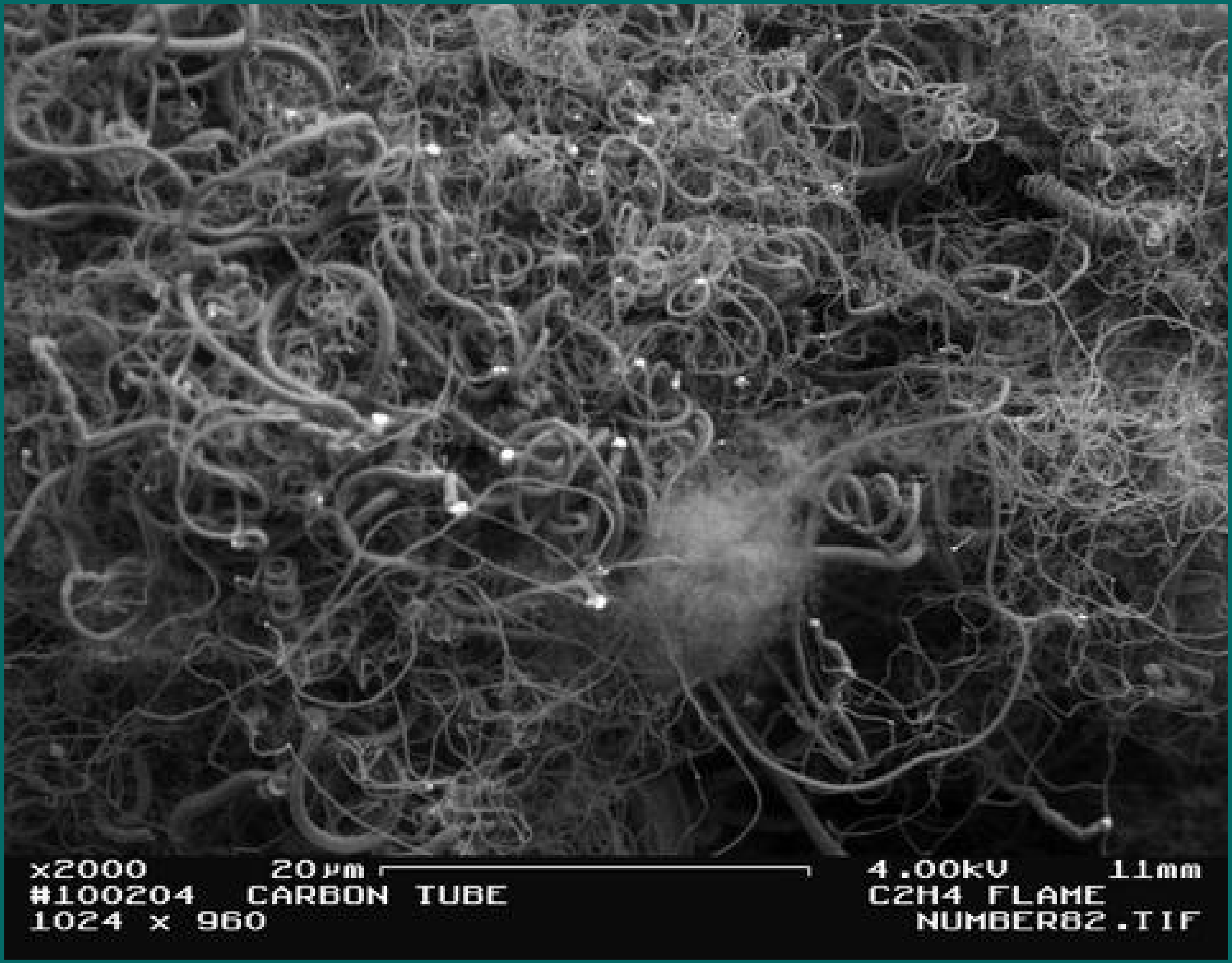
Above: TEM Image of a SWNT. From the Zettle Research Group [21]

Nanotubes: Highly conductive

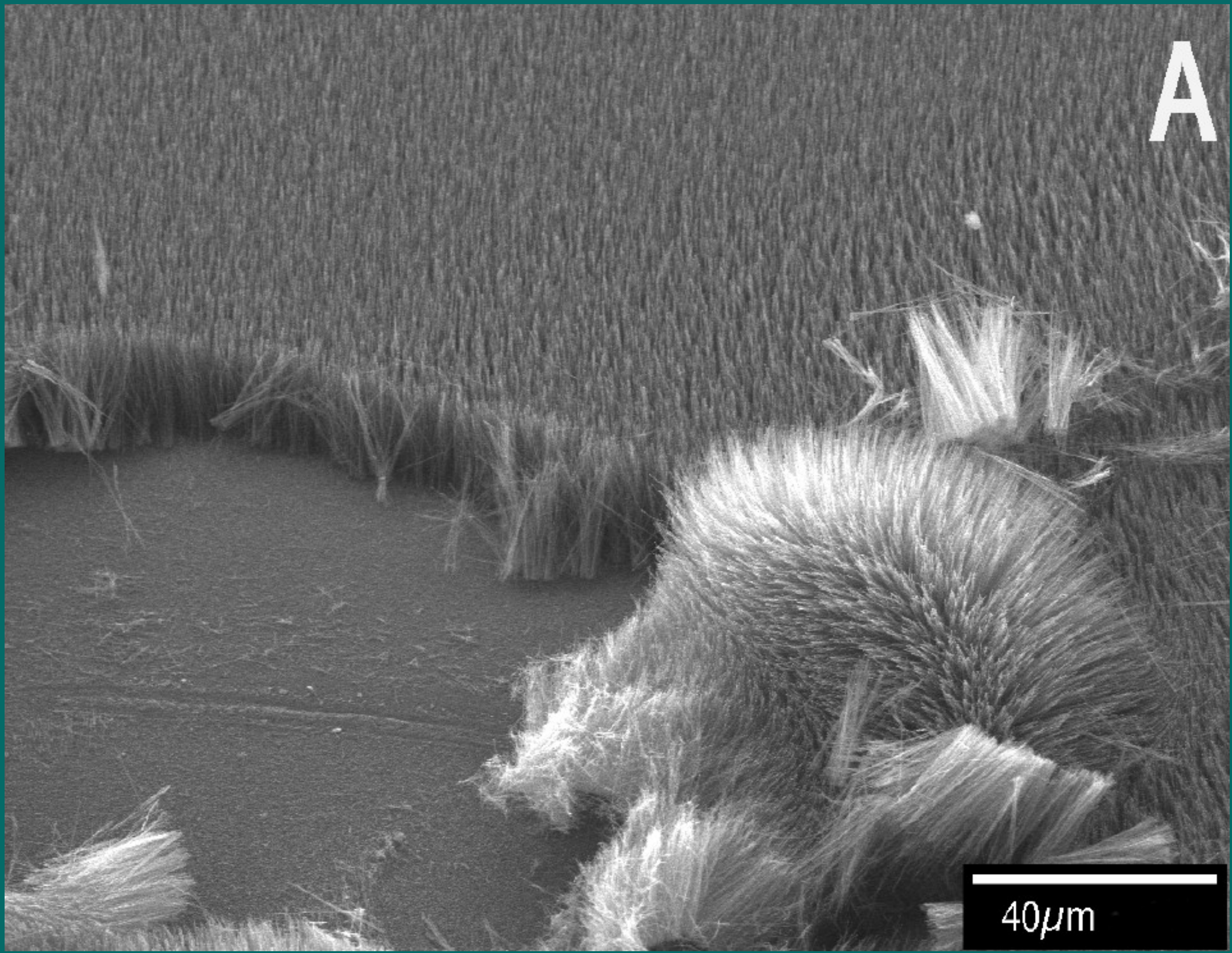
- Electrical conductivity ~ 1X copper
- Maximum current density ~ 10,000X copper
- Axial thermal conductivity ~ 3X Diamond
- Surface can be functionalized → semiconducting
- Theoretically, entire surface is accessible



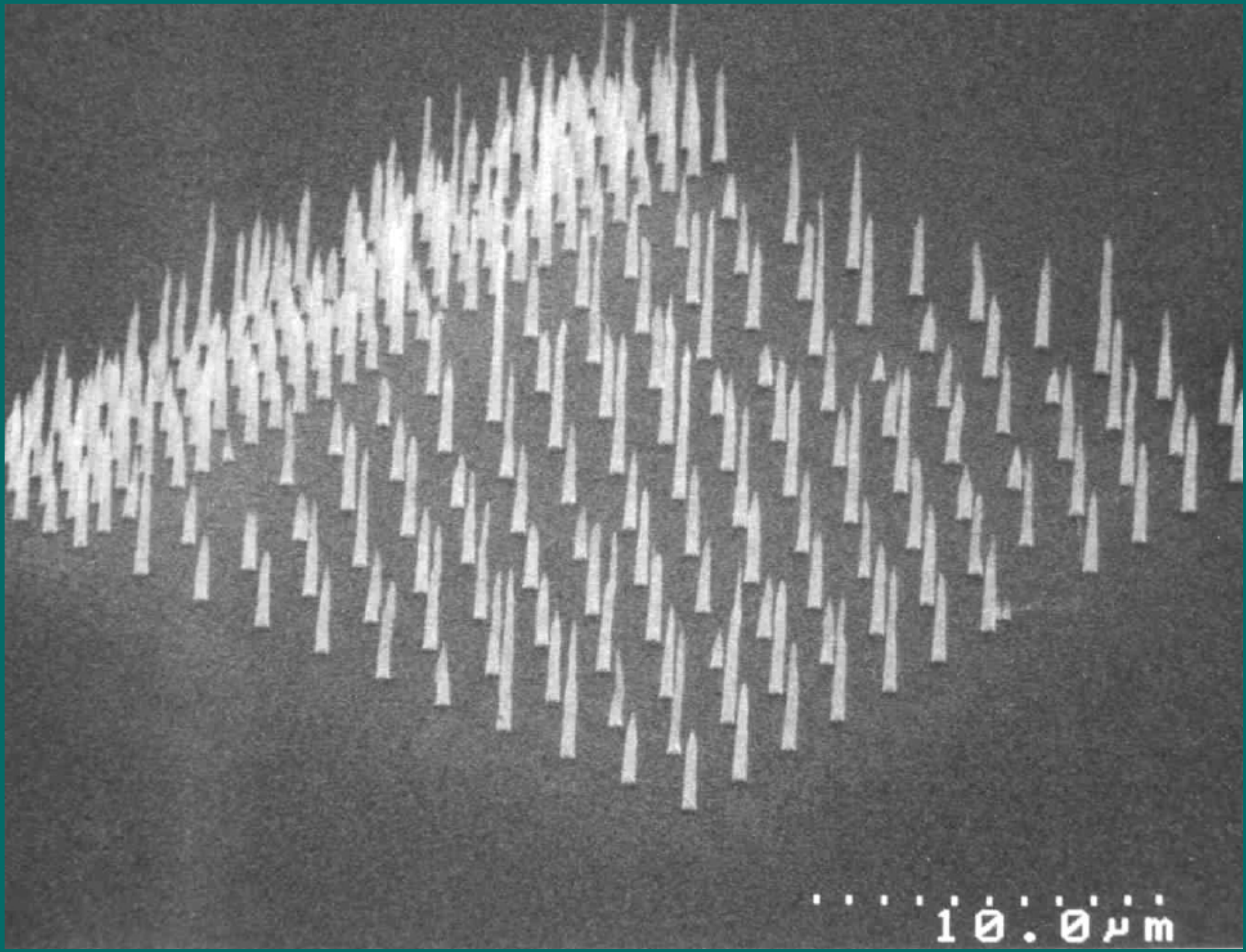
The Problem with Nanotubes



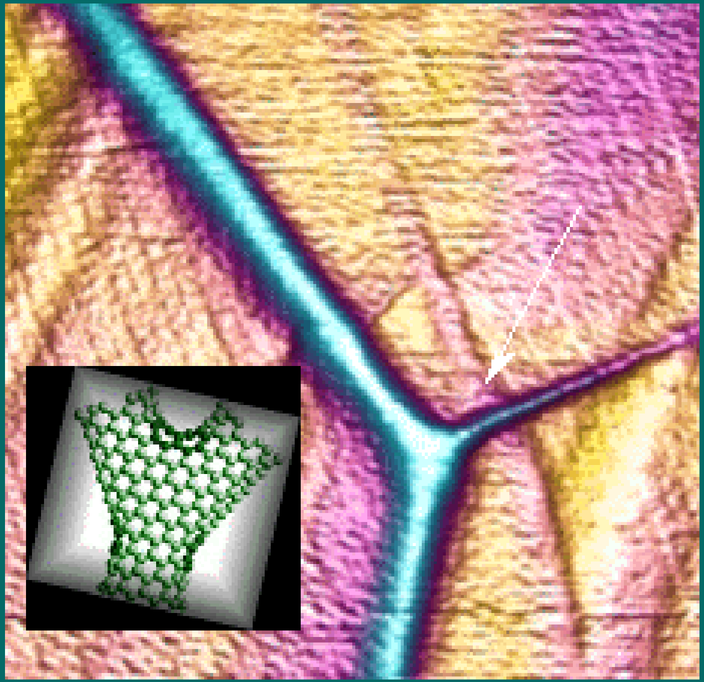
Grown to Length



Grown in Arrays



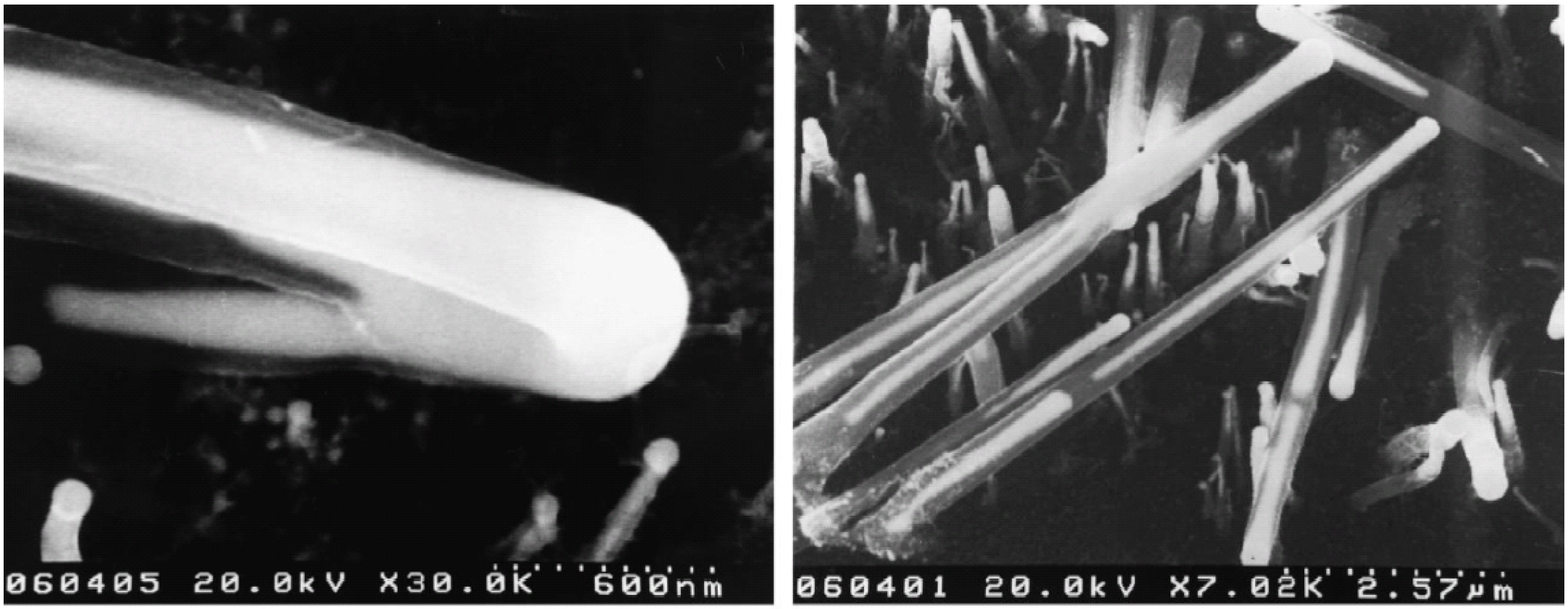
Nanotube Junctions



Z. Klusek, P.K. Datta, W. Kozlowski, P. Byszewski, P. Kowlaczyk, Scanning tunneling microscopy and spectroscopy of Y-junction in carbon nanotubes, Surf. Sci. 507-510, pp. 577-581, (2002).

Branched nanotubes filled with Pd-15 Si — added stiffness, new growth method

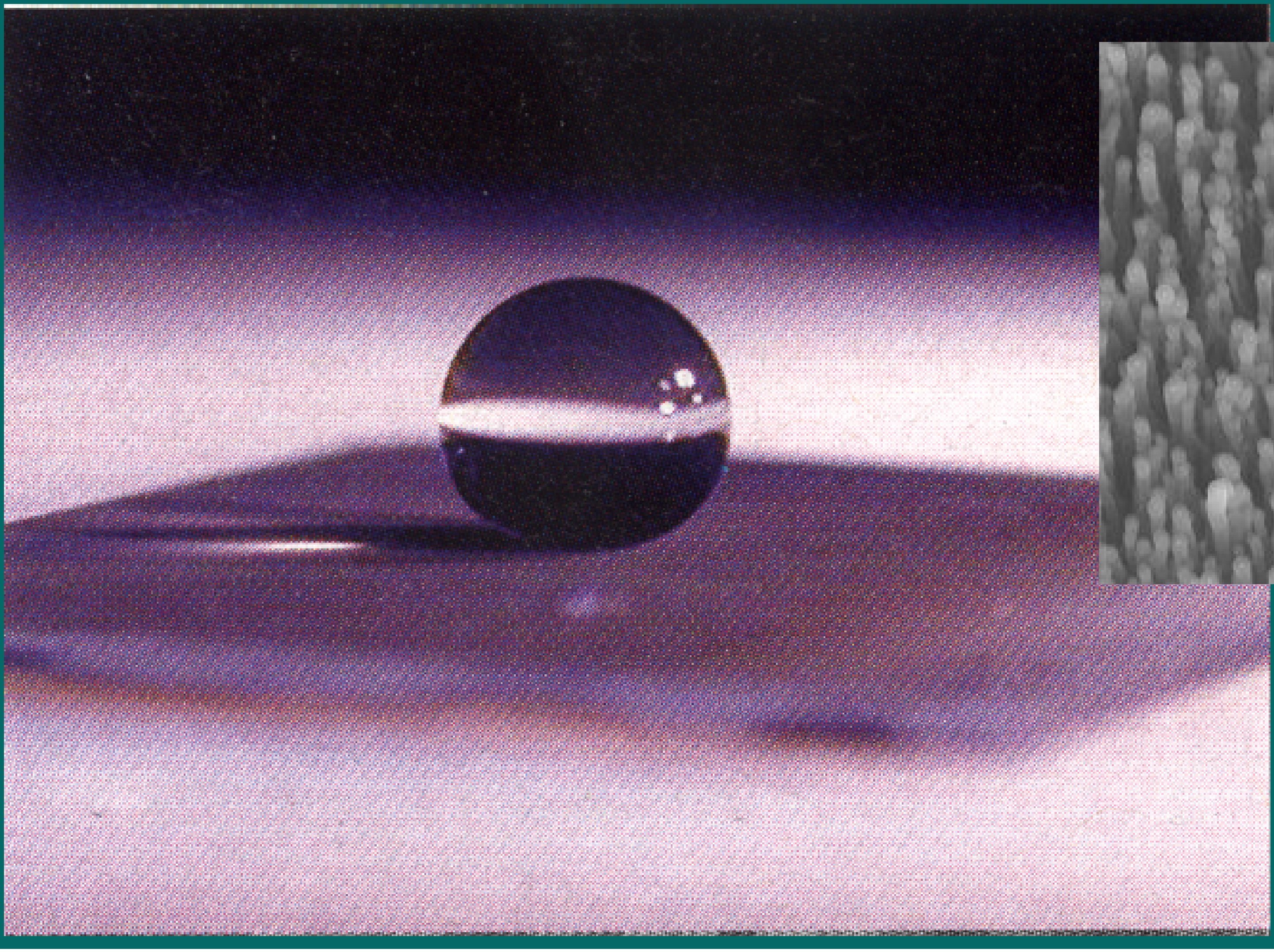
(2000 Tsai, et al., National Tsing Hua U., Taiwan)

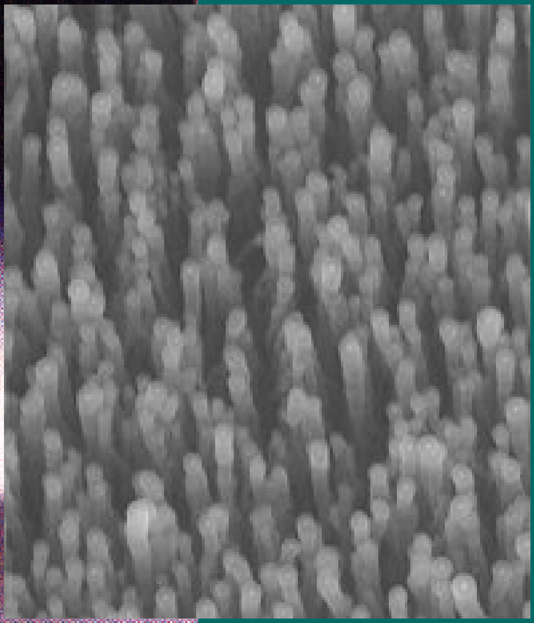


(a) (b)

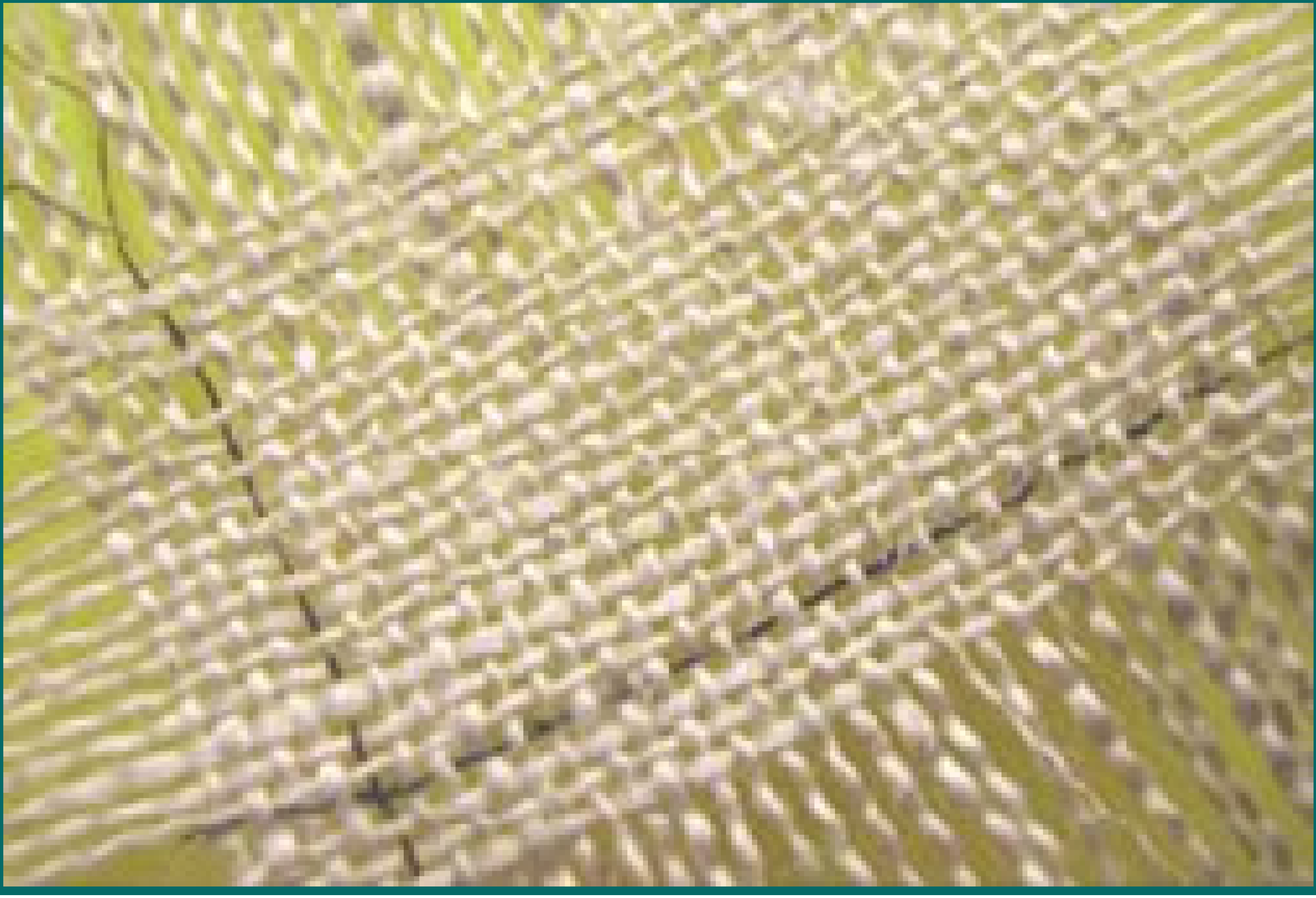
Fig. 2. FESEM micrographs of the branching carbon nanotubes showing (a) completely filled with a Pd-15 at.%Si alloy nanowire, and (b) the initial stage of the branched carbon nanotubes.

Carbon Nanotubes with Teflon-coated tips (Karen Gleason, MIT)

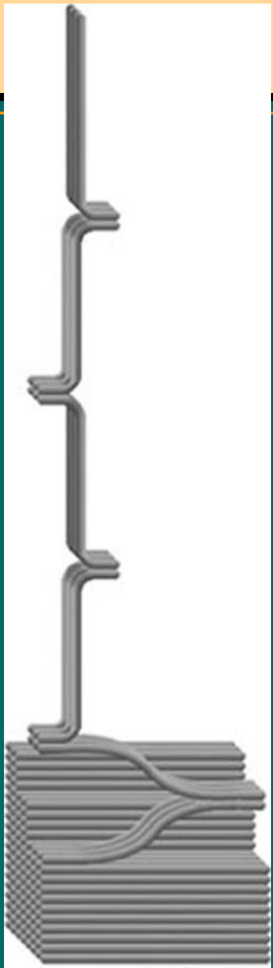




Nanotube fiber supercapacitors (Ray Baughman, U. Texas Dallas)

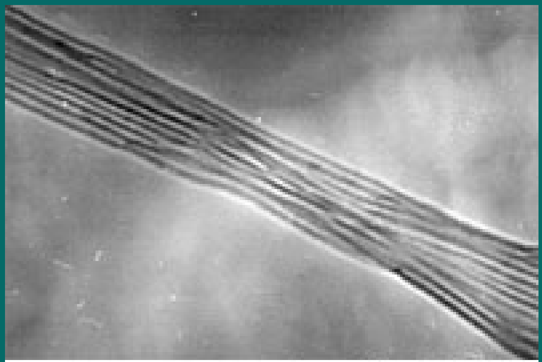


Nanotube fibers
(RPI, Kaili Jaing, Tsinghua U.)



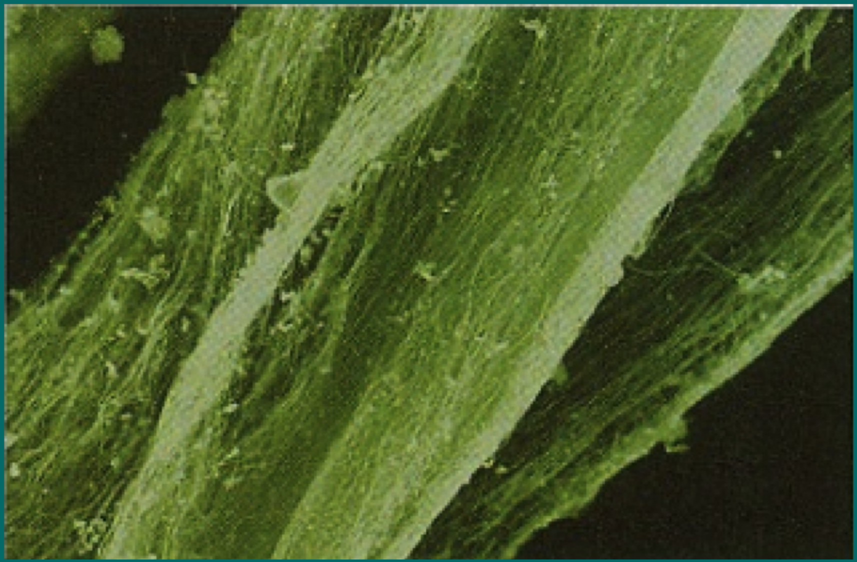
Source: Tsinghua University

This diagram shows how close-packed, aligned nanotubes can be pulled to form long strands. The electrostatic force of attraction between individual molecules is strong enough to hold ends of individual nano-tubes together.

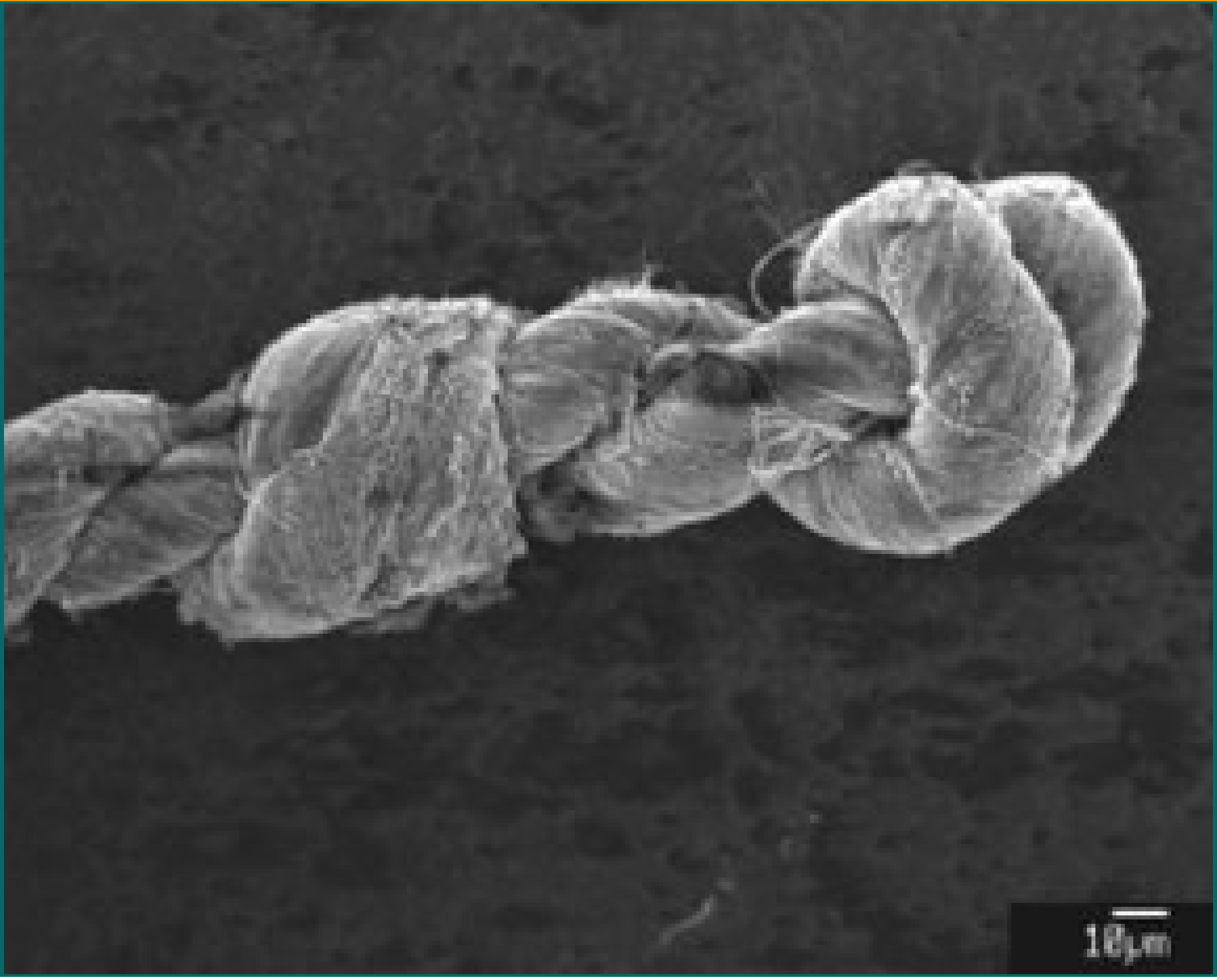


Source: Tsinghua University

Each carbon nanotube in this thread is ten nanometers in diameter, or about the size of 100 hydrogen atoms lined up.



Nanotube fiber – Furnace-Based (Alan Windle, U. Cambridge)



Spun Fibers (Pasquali, Rice U.)

Other Efforts

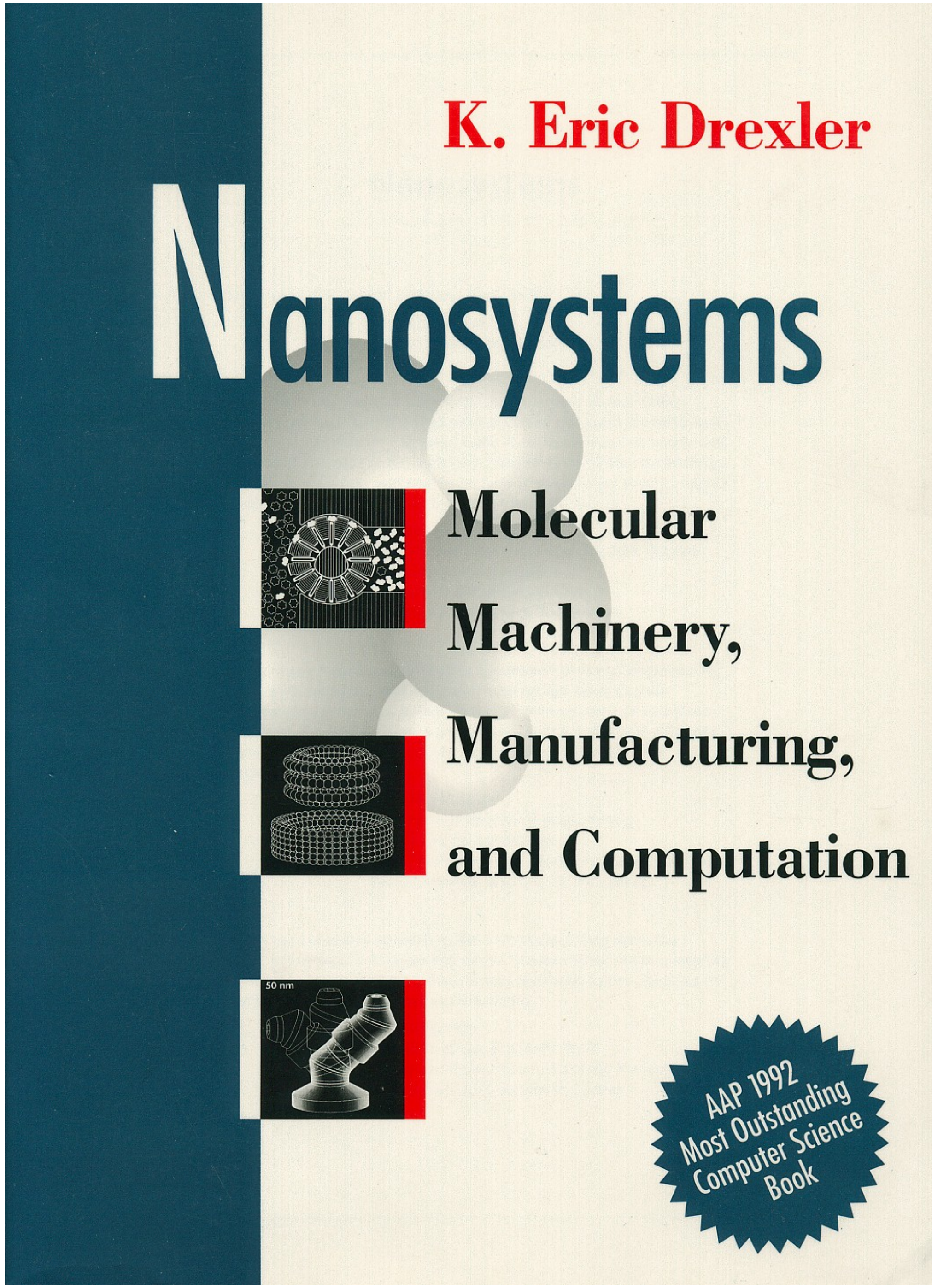
- Philippe Poulin, Paul Pascal Research Laboratory, U. Bordeaux
- Laszlo Forro, Swiss Federal Institute of Technology
- Satish Kumar, Georgia Institute of Technology

The Vision

Molecular Manufacturing

The production of complex structures via nonbiological mechanosynthesis (and subsequent assembly operations).

Mechanosynthesis: chemical synthesis controlled by mechanical systems operating with atomic-scale precision, enabling direct positional selection of reaction sites.


K. Eric Drexler
Nanosystems
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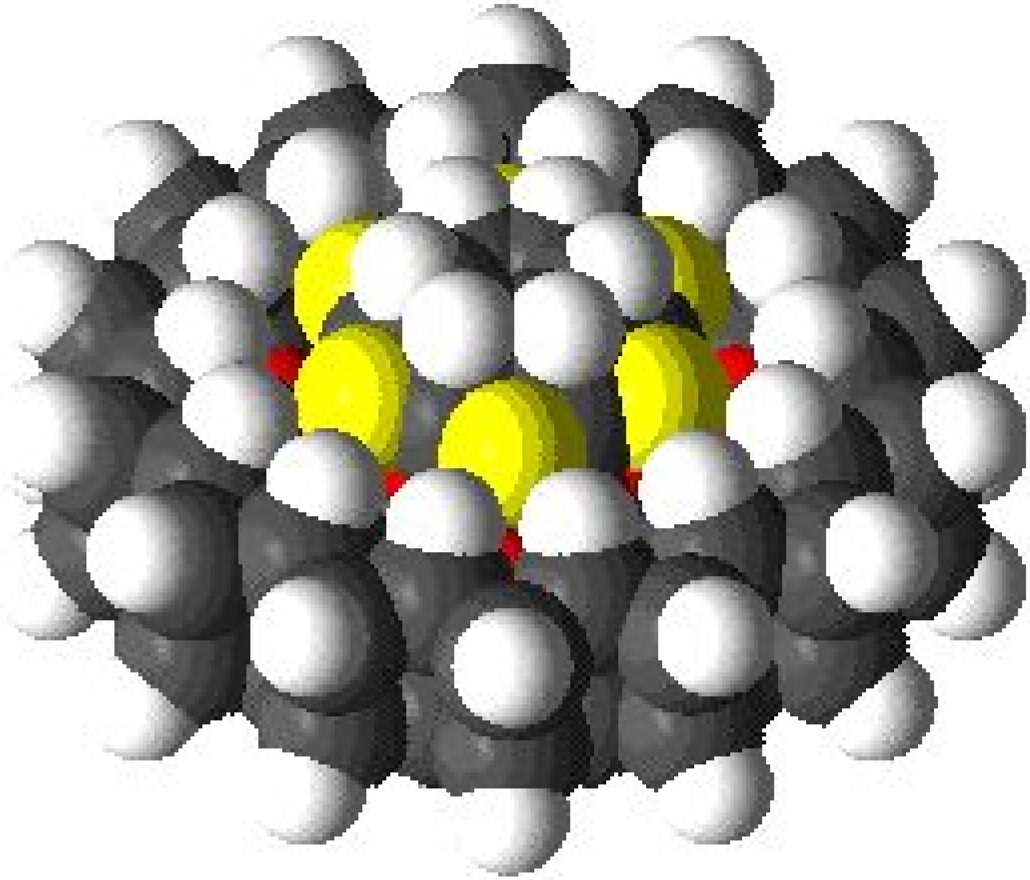
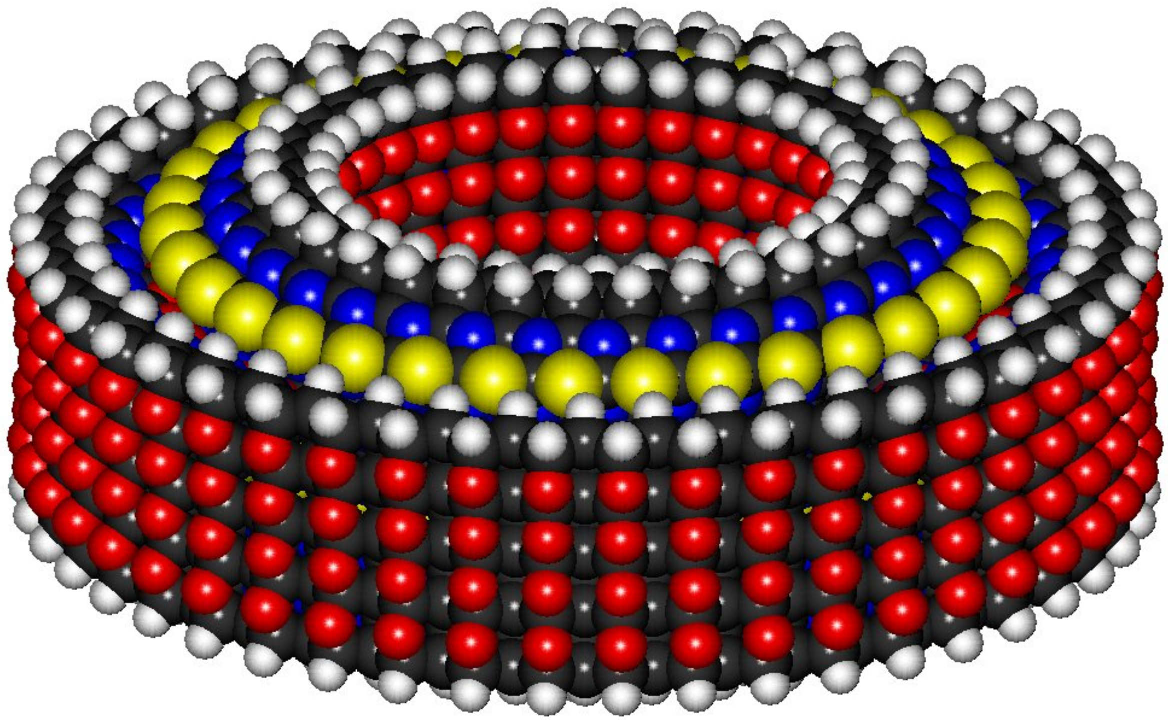
and Computation
50 nm
AAP 1992
Most Outstanding
Computer Science
Book





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YUV420 codec decompressor
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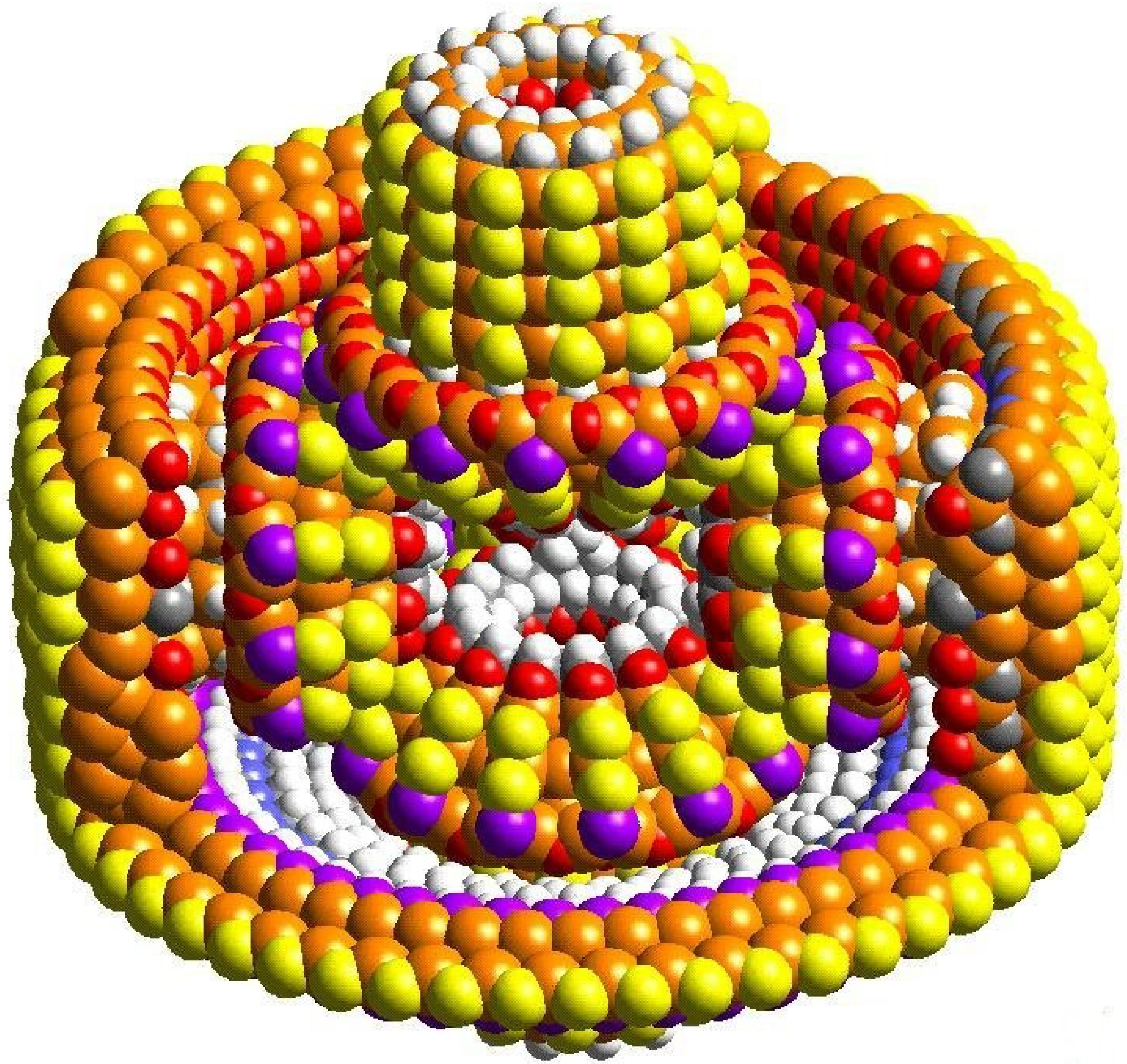

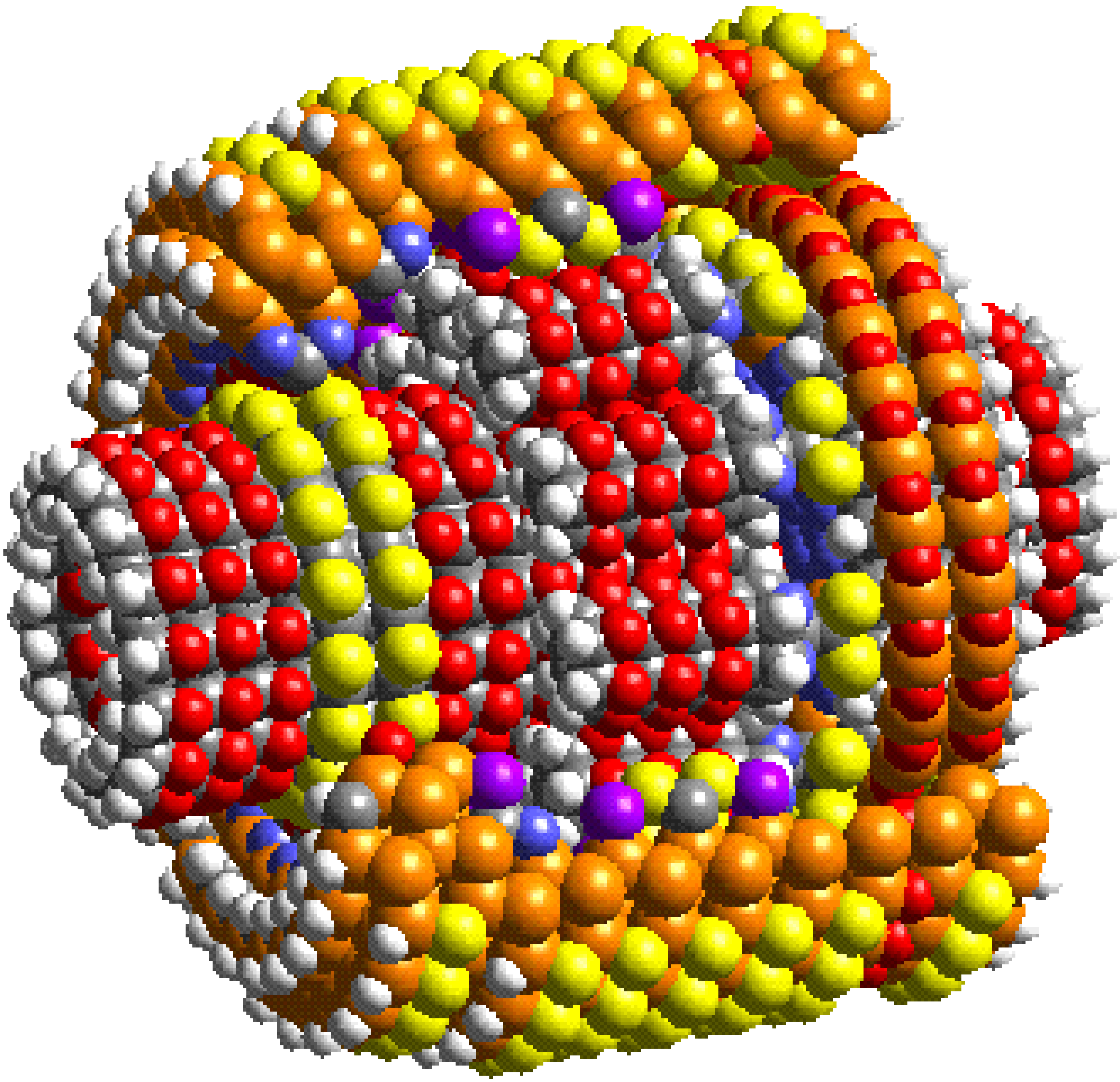

Planetary Gear Operating

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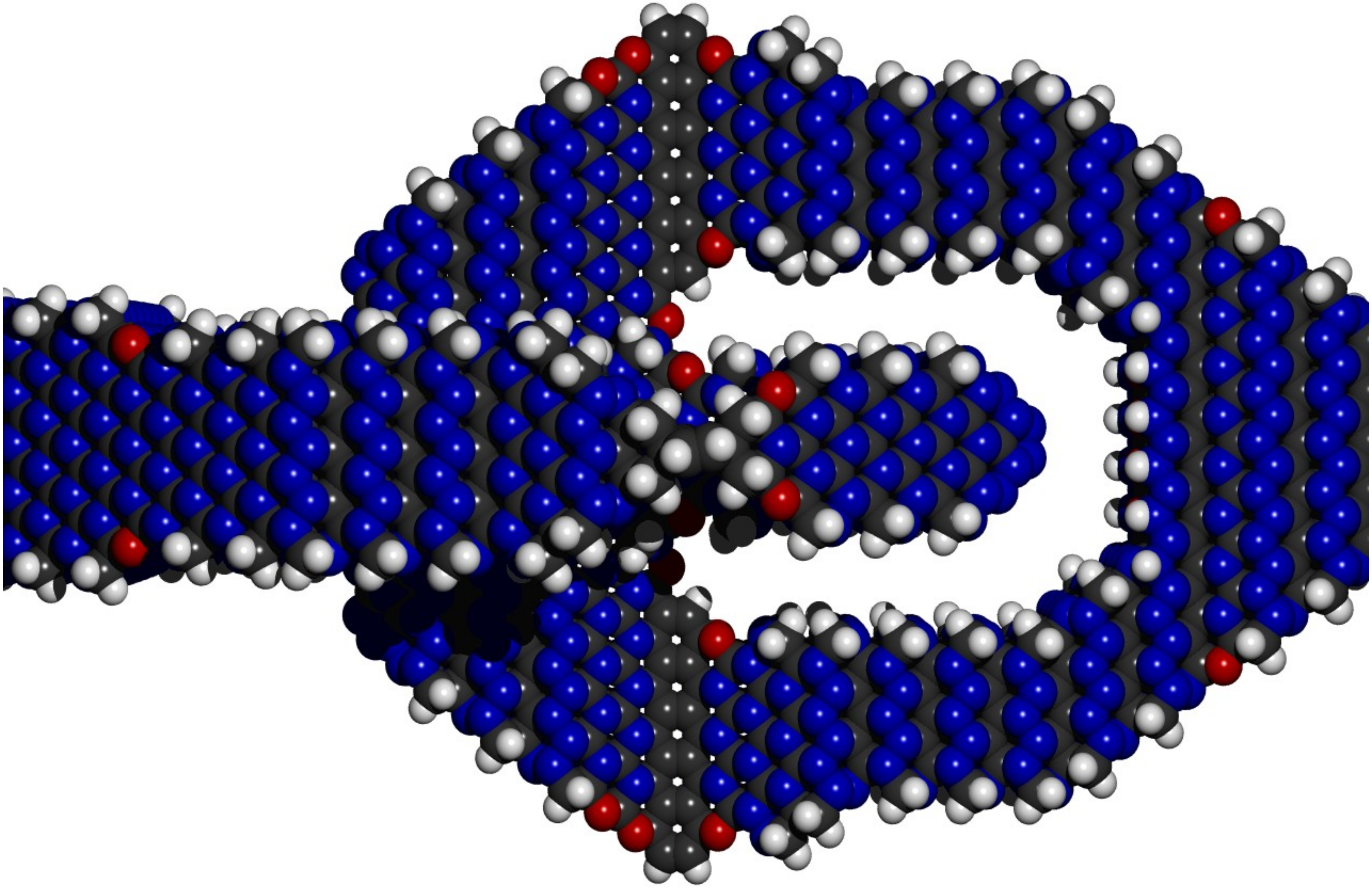
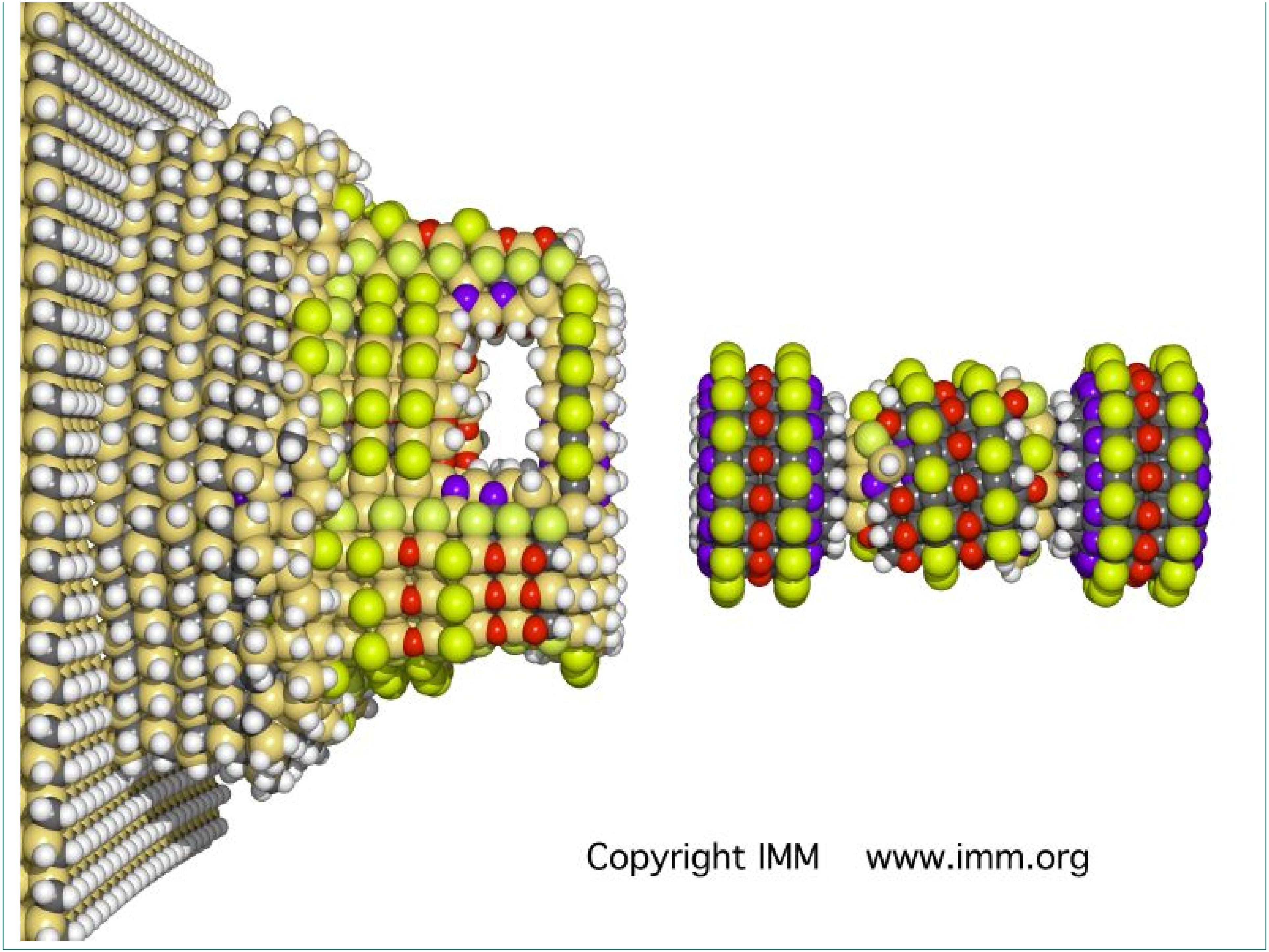
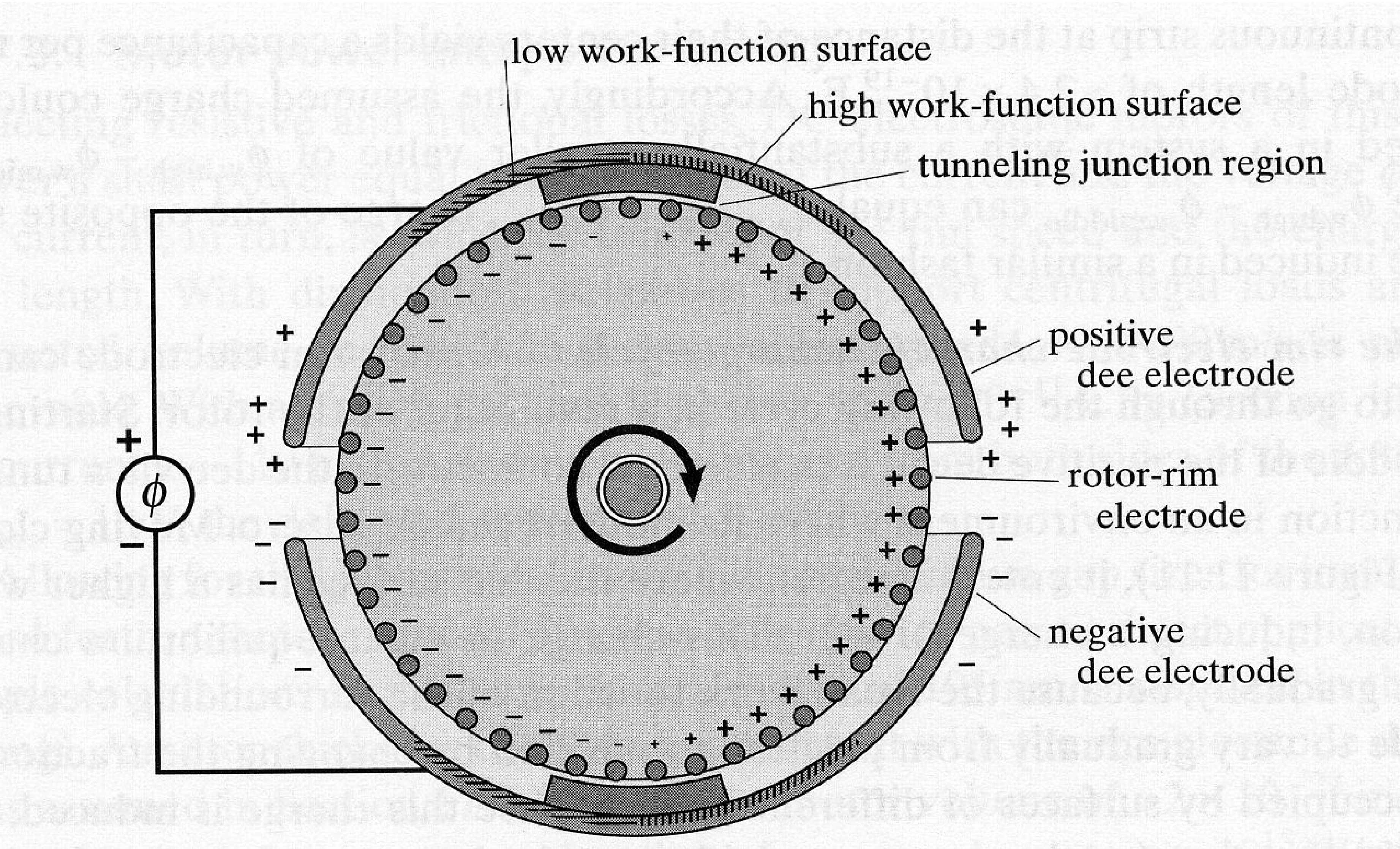
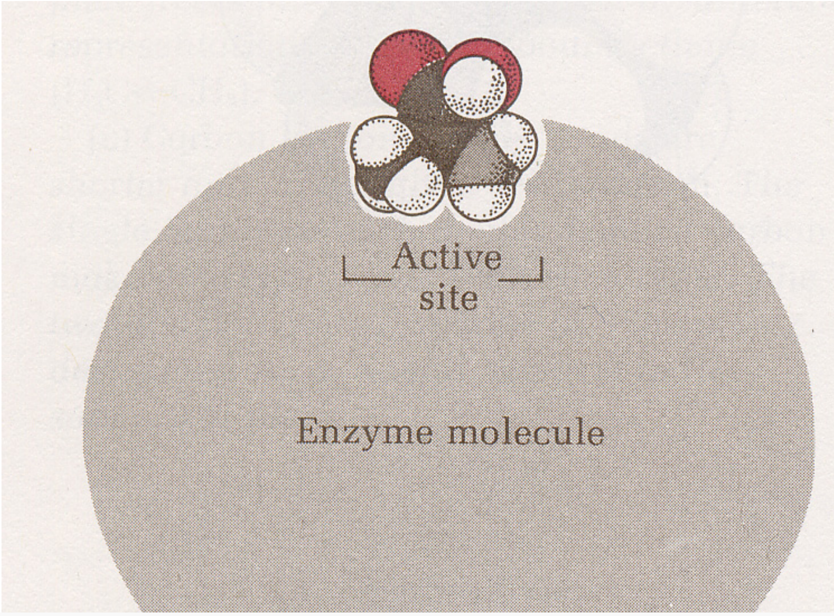
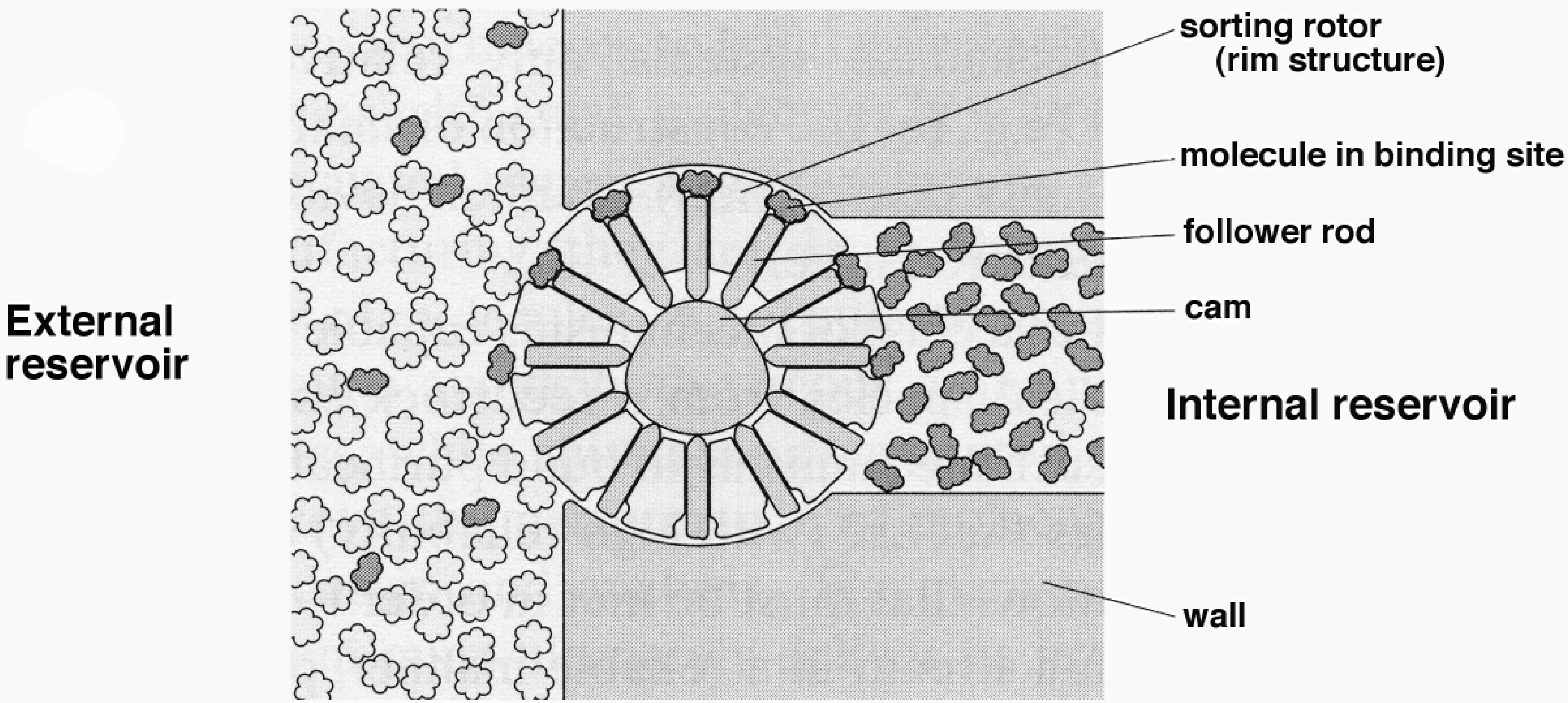


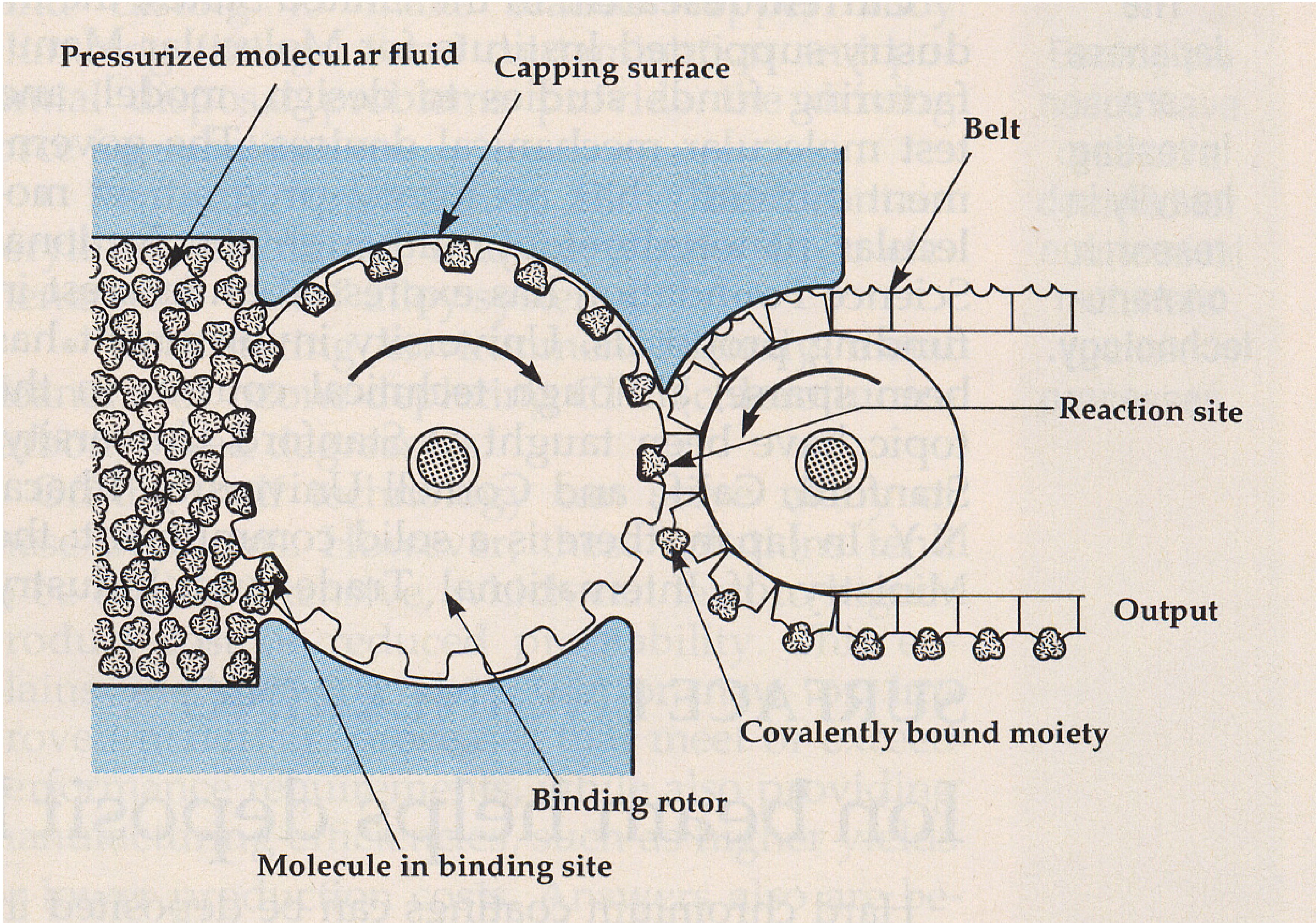


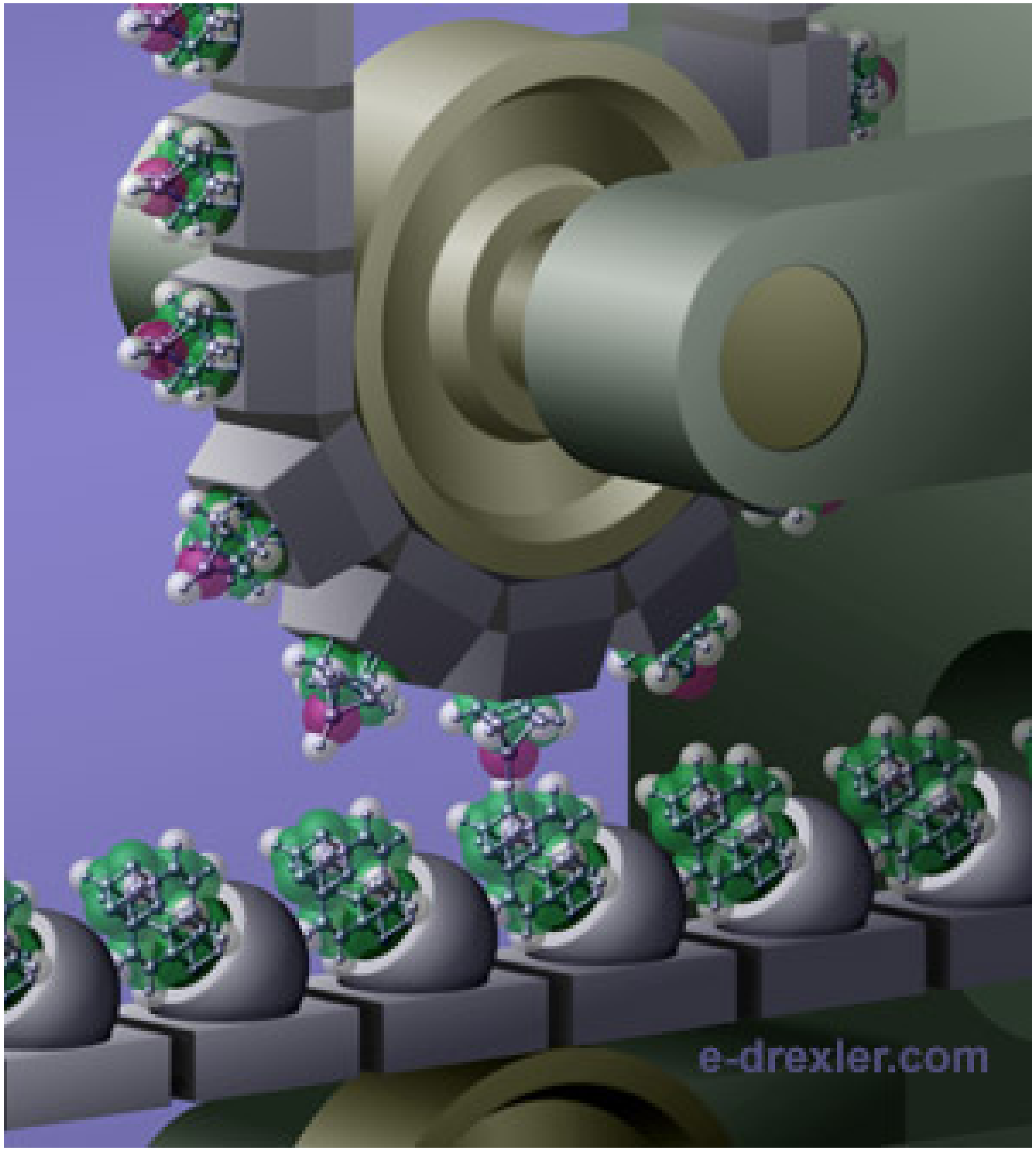


low work-function surface
high work-function surface
tunneling junction region
positive
dee electrode
rotor-rim
electrode
negative
dee electrode
ϕ


Active
site
Enzyme molecule


sorting rotor
(rim structure)
molecule in binding site
follower rod
cam
wall
External
reservoir
Internal reservoir


Pressurized molecular fluid
Capping surface
Belt
Reaction site
Output
Covalently bound moiety
Binding rotor
Molecule in binding site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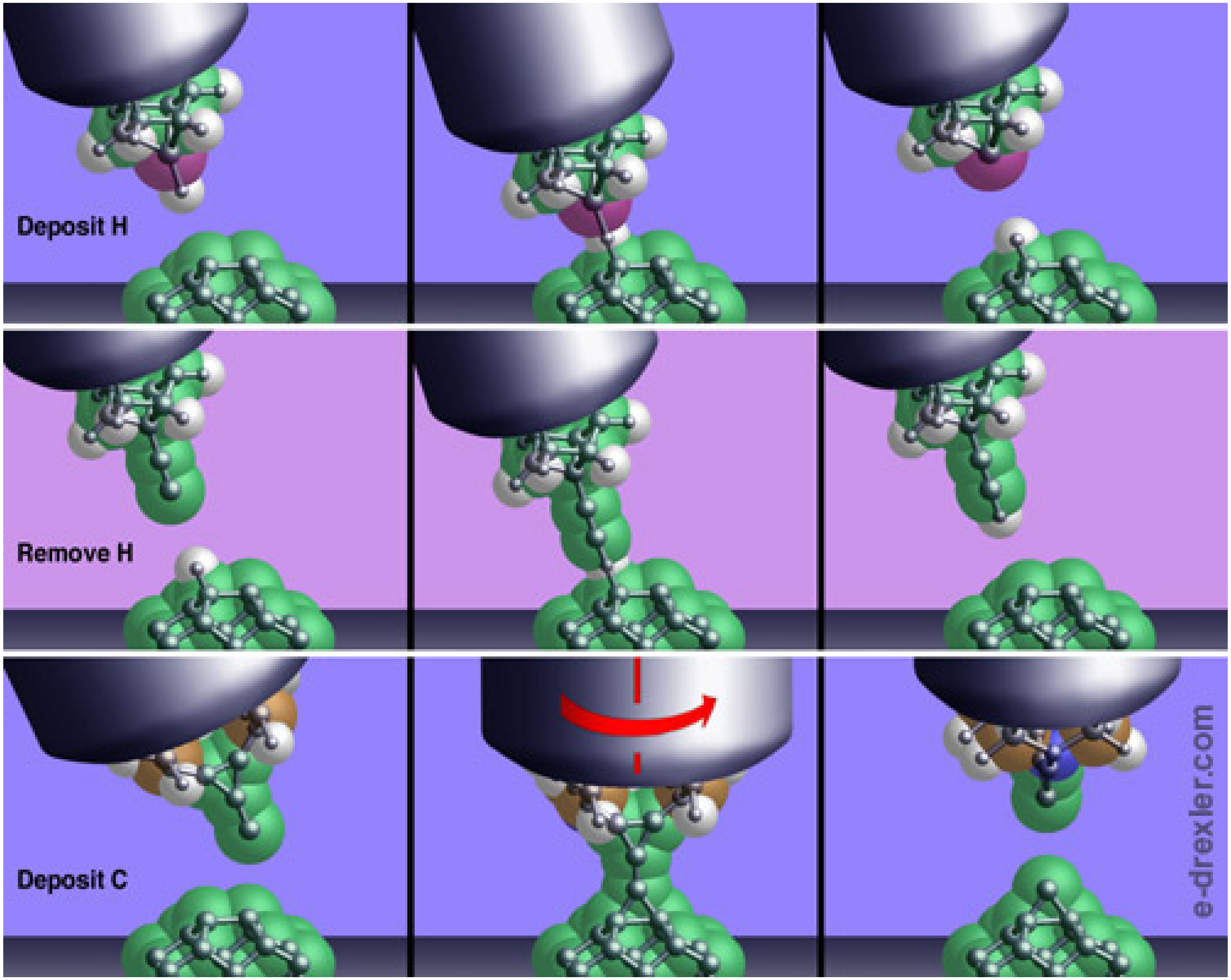

Deposit H
Remove H
Deposit C
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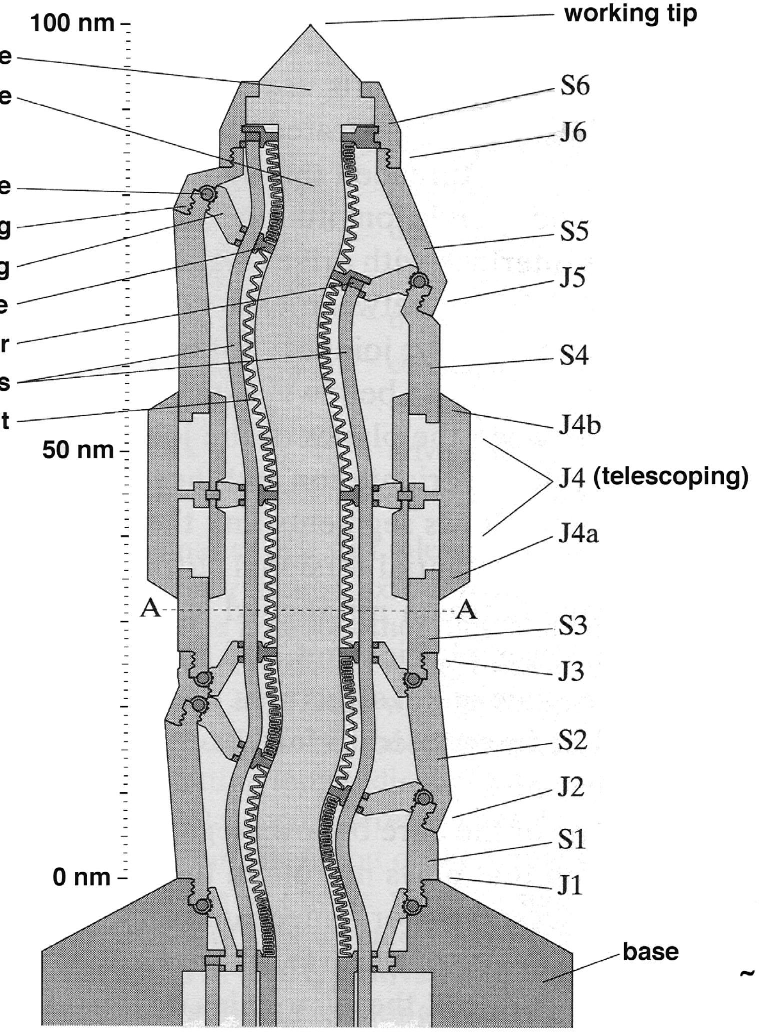
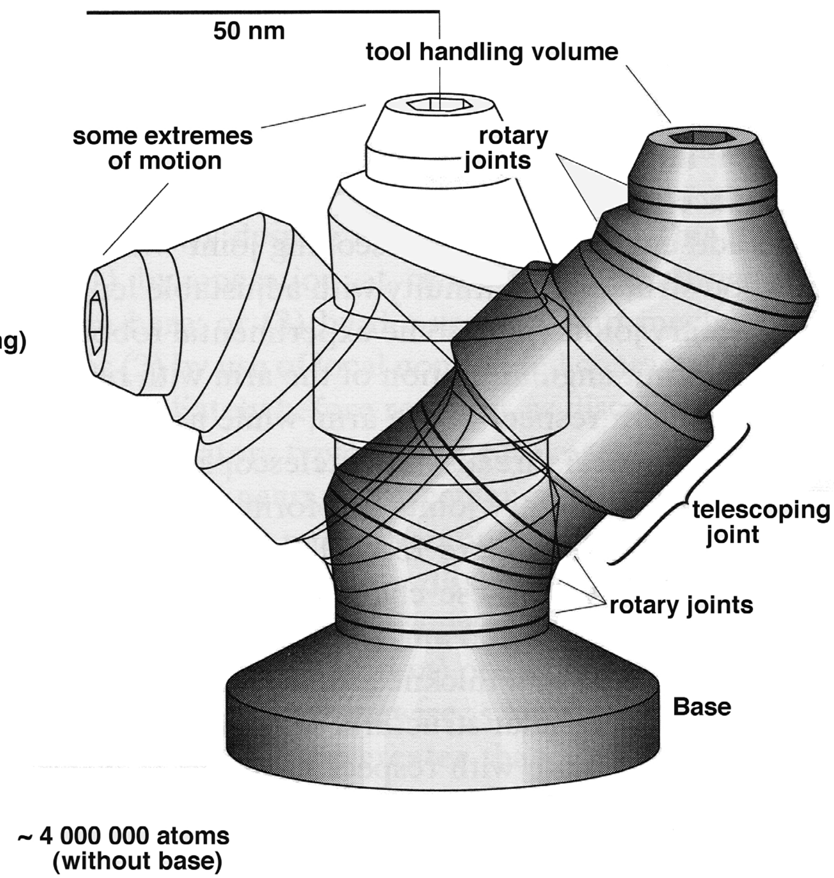
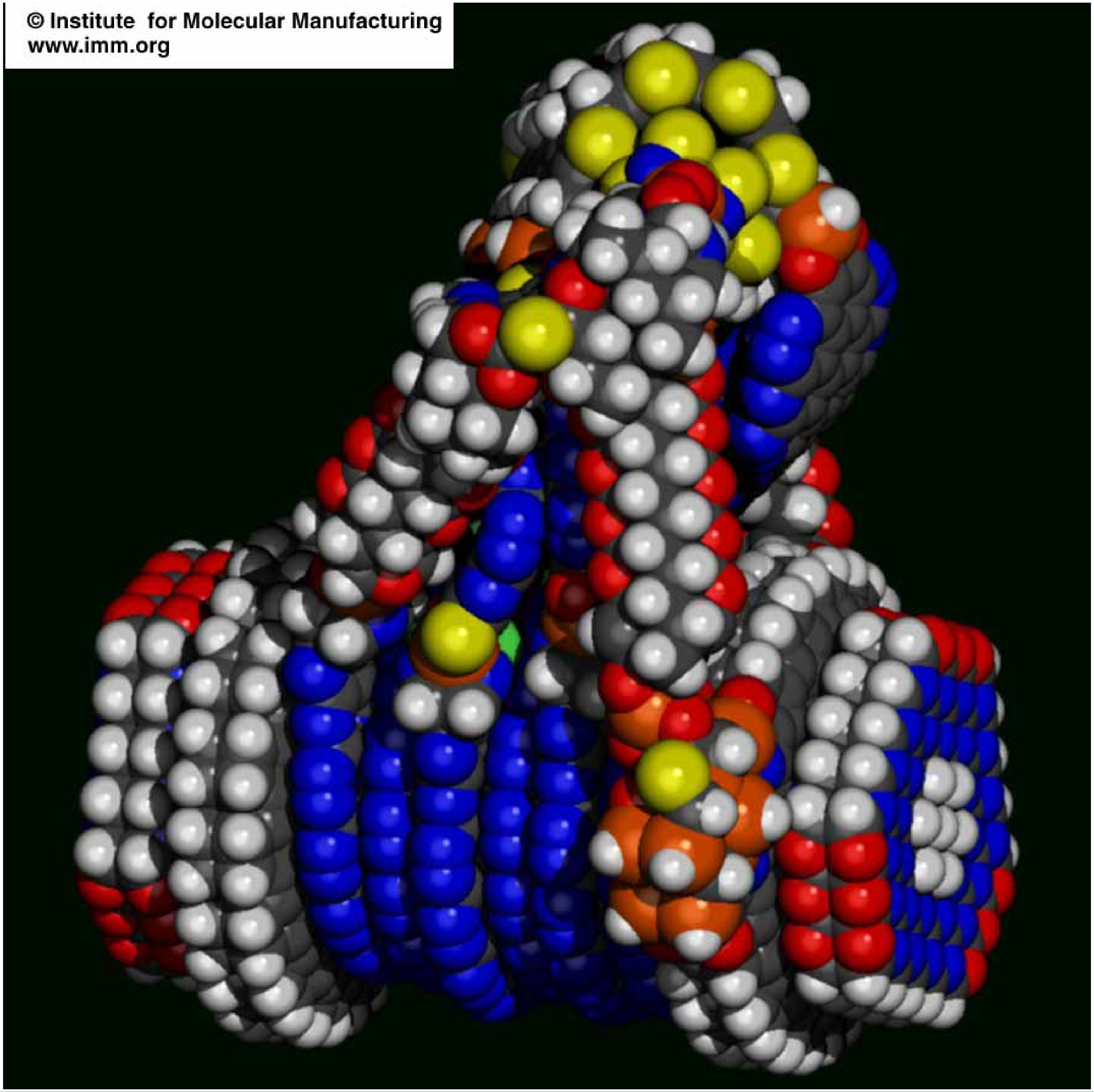

100 nm
50 nm
0 nm
working tip
tool handling volume
tool transport volume
toroidal worm drive
intersegment bearing
threaded drive ring
core plate
drive gear
drive shafts
core bellows segment
S6
J6
S5
J5
S4
J4b
J4 (telescoping)
J4a
A
A
S3
J3
S2
J2
S1
J1
base


50 nm
tool handling volume
some extremes of motion
rotary joints
telescoping joint
rotary joints
Base
~ 4 000 000 atoms (without base)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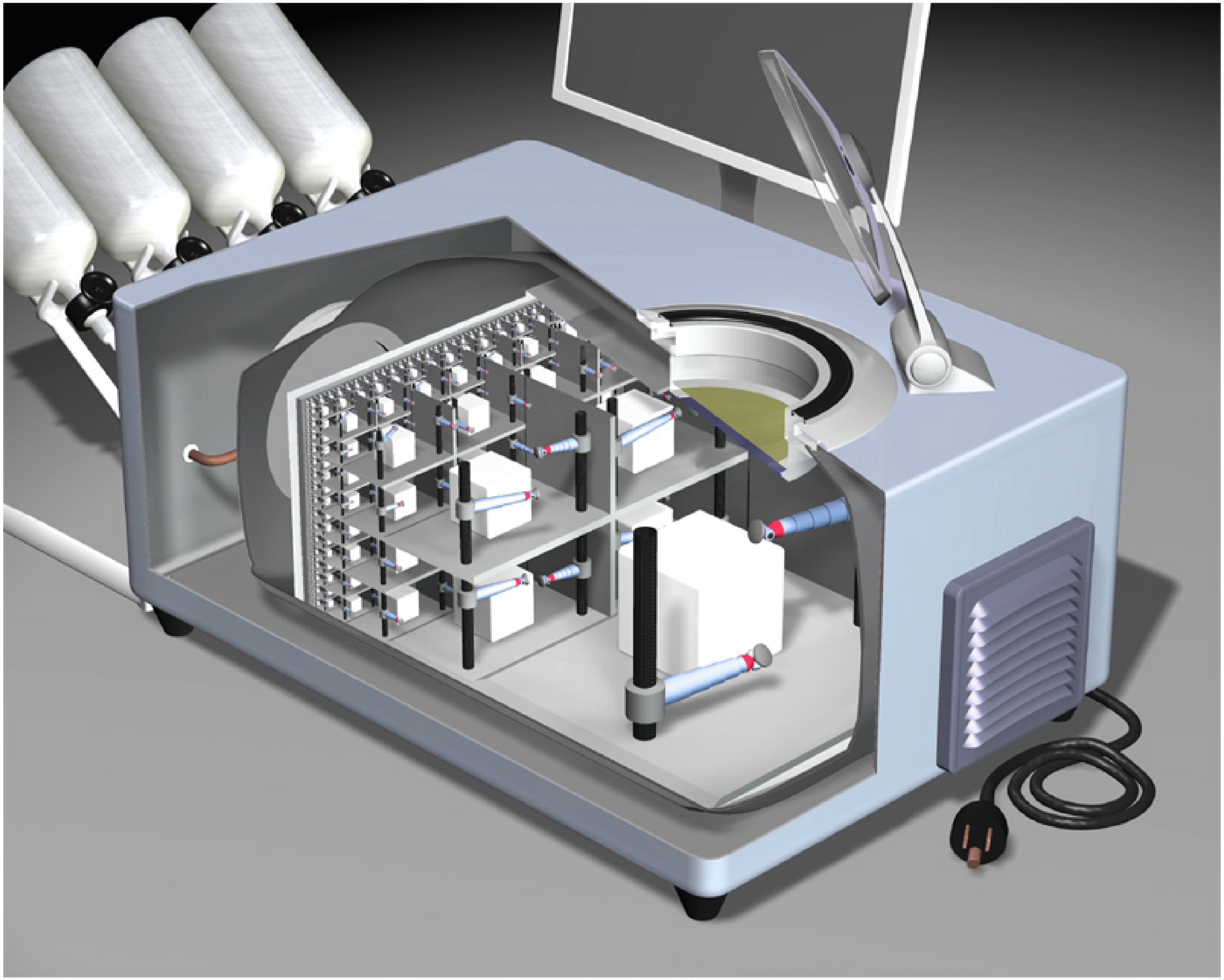


Image by John Burch, Lizard Fire Studios, http://www.lizardfire.com

Proposed desktop-scale molecular manufacturing appliance. Tiny machines join molecules, then larger and larger parts, in a convergent assembly process that makes products such as computers with a billion processors. (Parts shown as white cubes.)

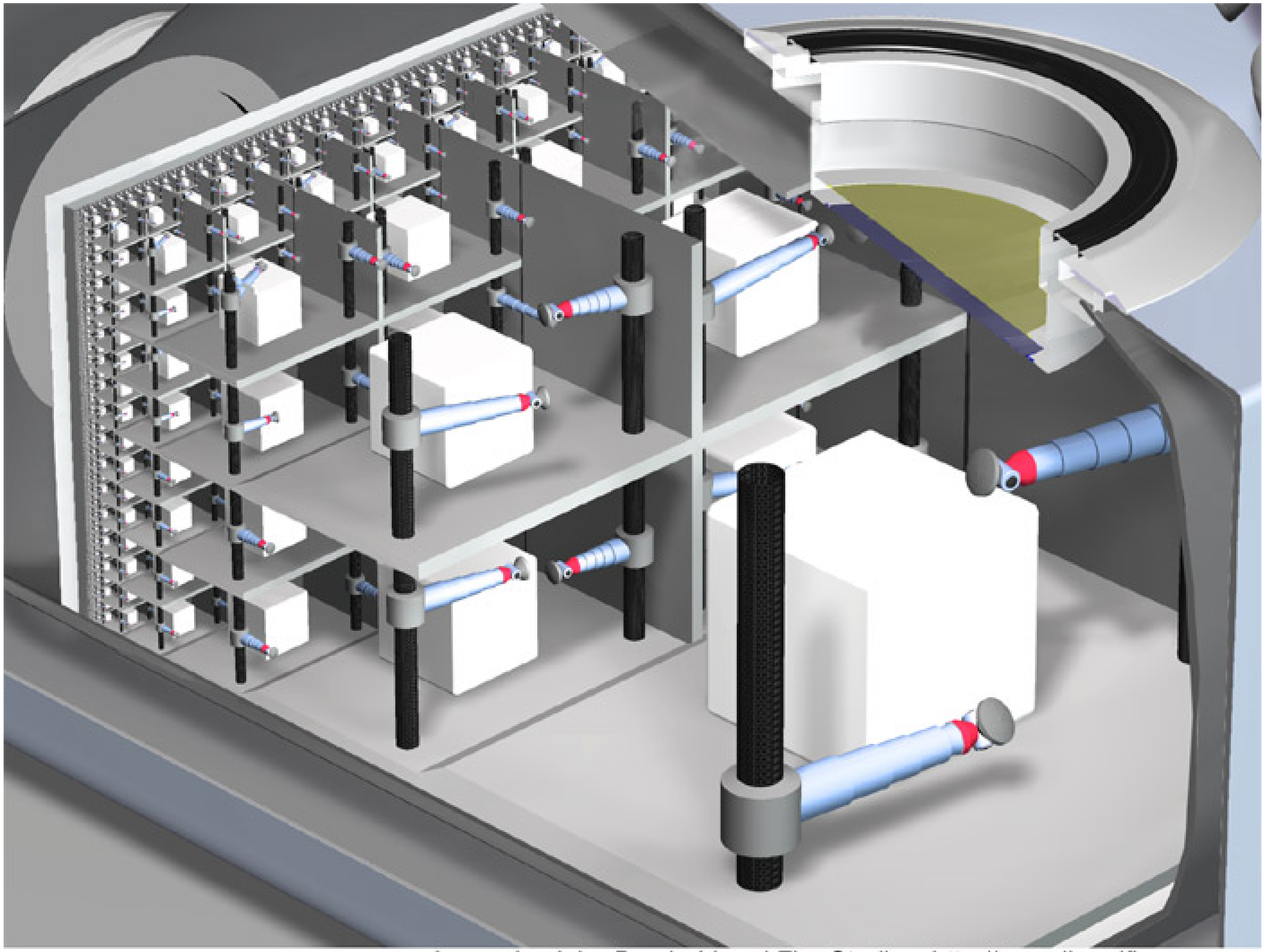
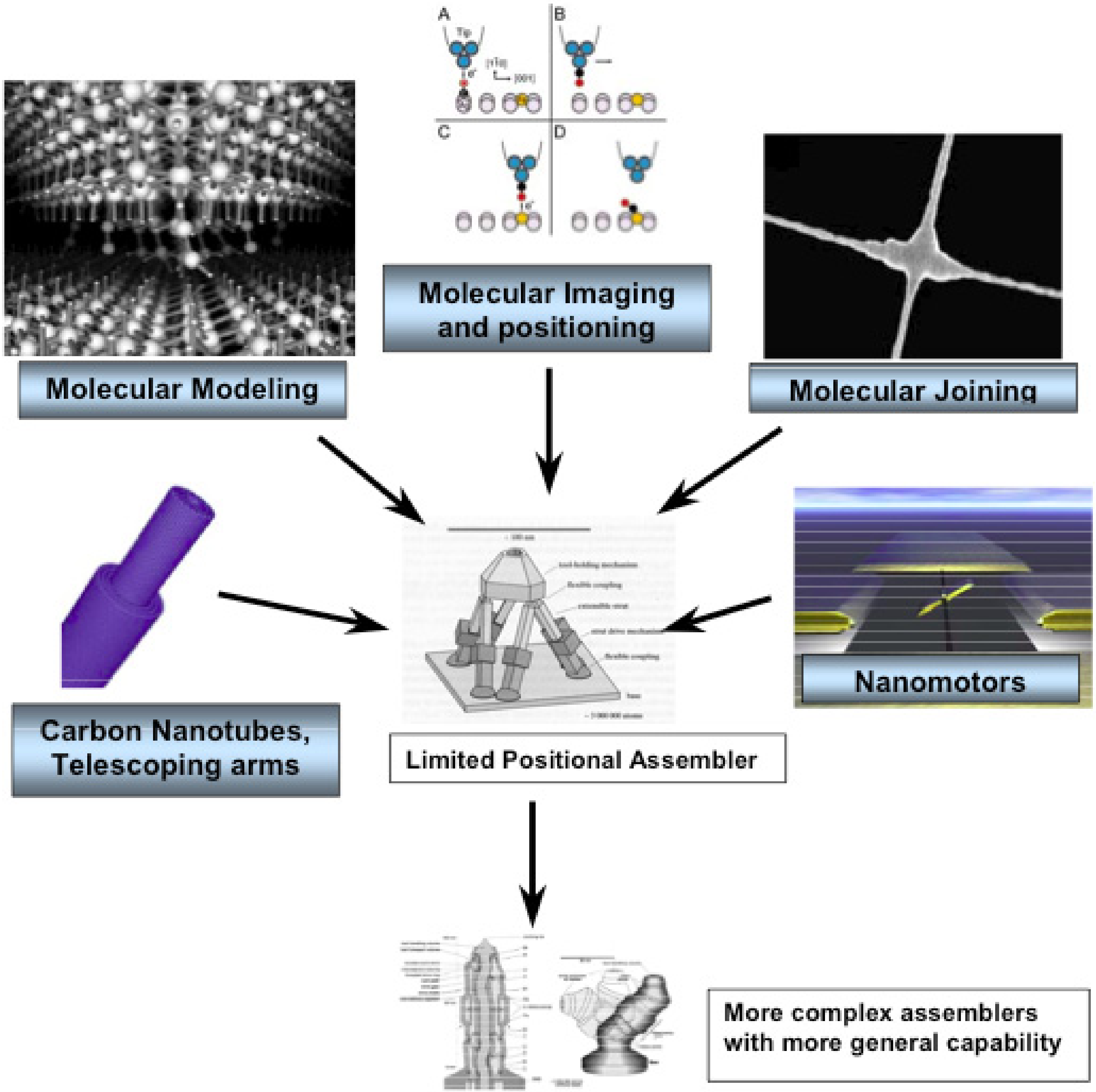


Image by John Burch, Lizard Fire Studios, http://www.lizardfire.com

Core mechanism of a proposed desktop-scale molecular manufacturing appliance.
Tiny machines join molecules, then larger and larger parts, in a convergent assembly process that makes products such as computers with a billion processors. (Parts shown as white cubes.)

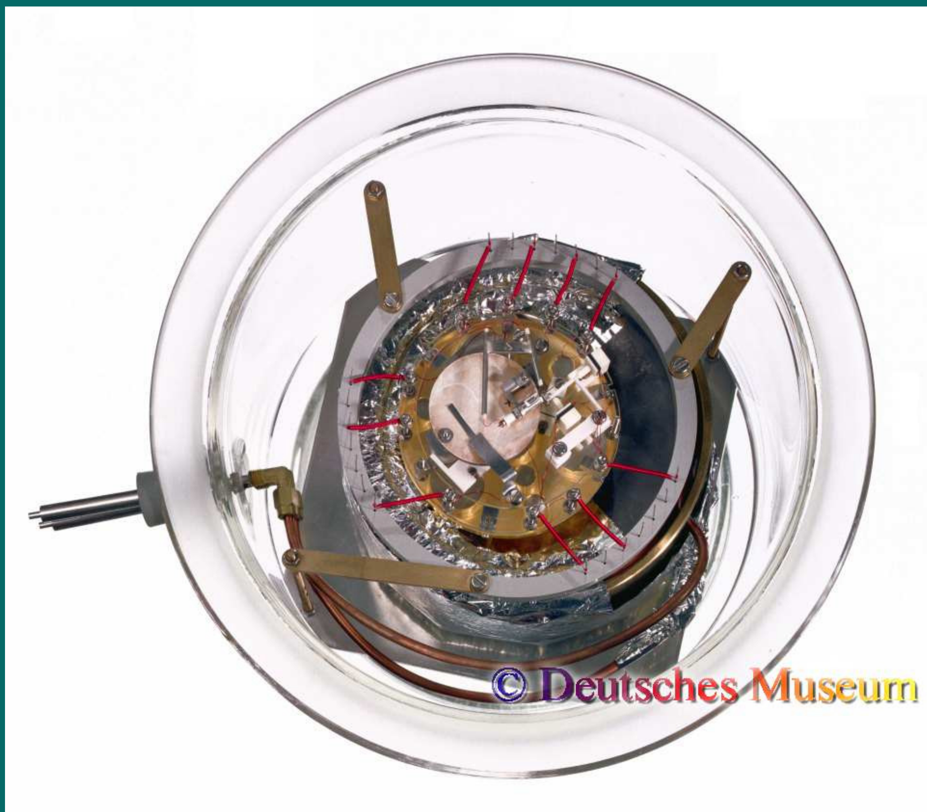
Advances in Molecular Assembly and Molecular Robotics

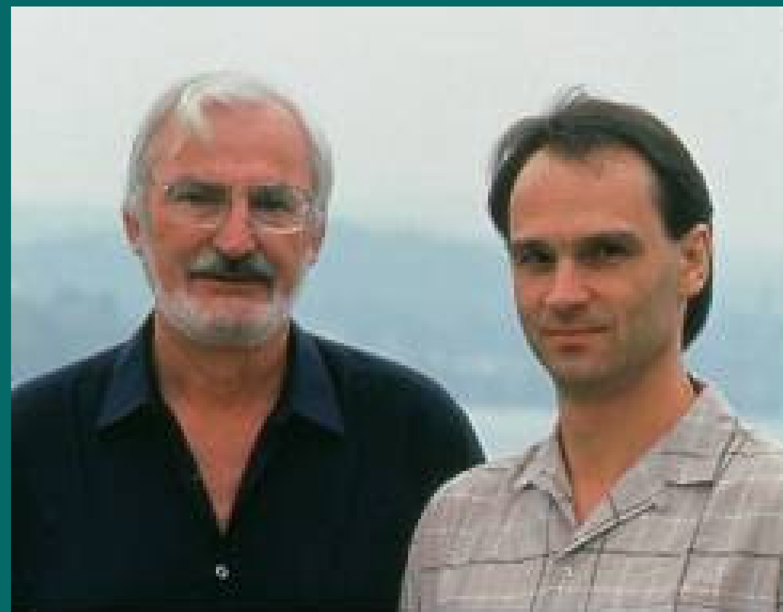
Binnig and Rohrer	Invention of STM
Eigler	Manipulation of atoms
Ho and Lee	Single-molecule assembly
Iijima	Discovery of carbon nanotubes
Banhart	Welding of nanotubes
Biological/Zettl	Molecular motors


Molecular Modeling
Molecular Imaging and positioning
Molecular Joining
Carbon Nanotubes, Telescoping arms
Nanomotors
Limited Positional Assembler
More complex assemblers with more general capability

Scanning Tunneling Microscope

(1981 Binnig and Rohrer, IBM Zurich)

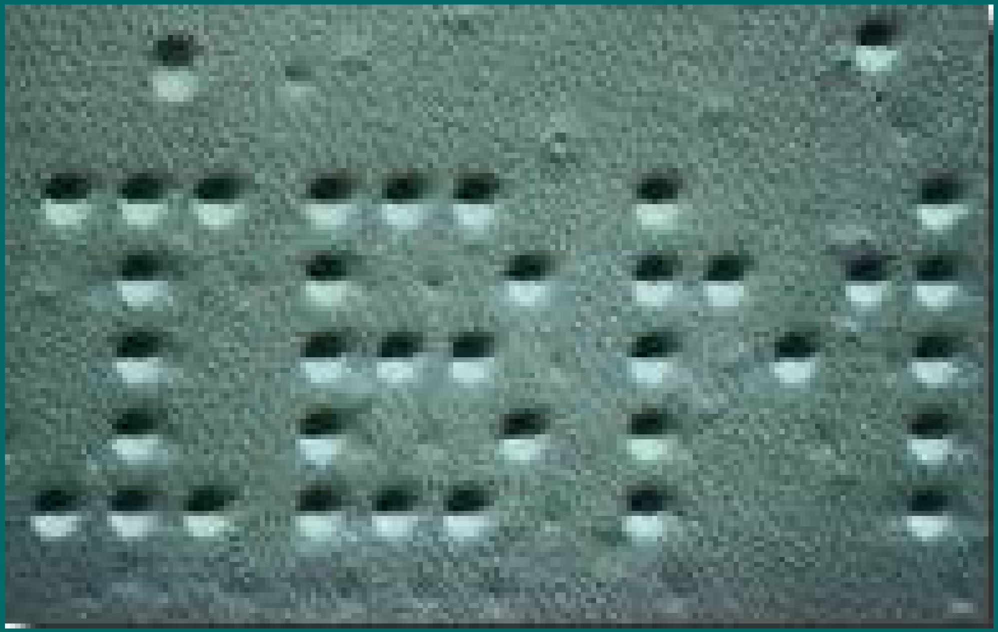




Heinrich Rohrer and Gerd Binnig

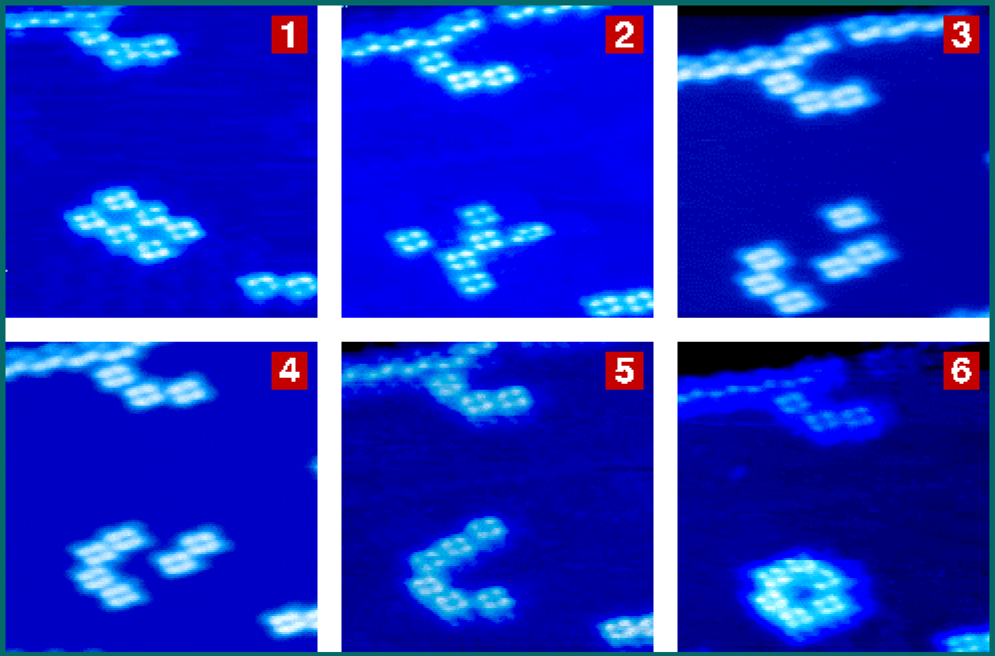
Moving Xenon Atoms

(1989 Eigler, IBM Almaden)



35 Xenon atoms, near absolute zero

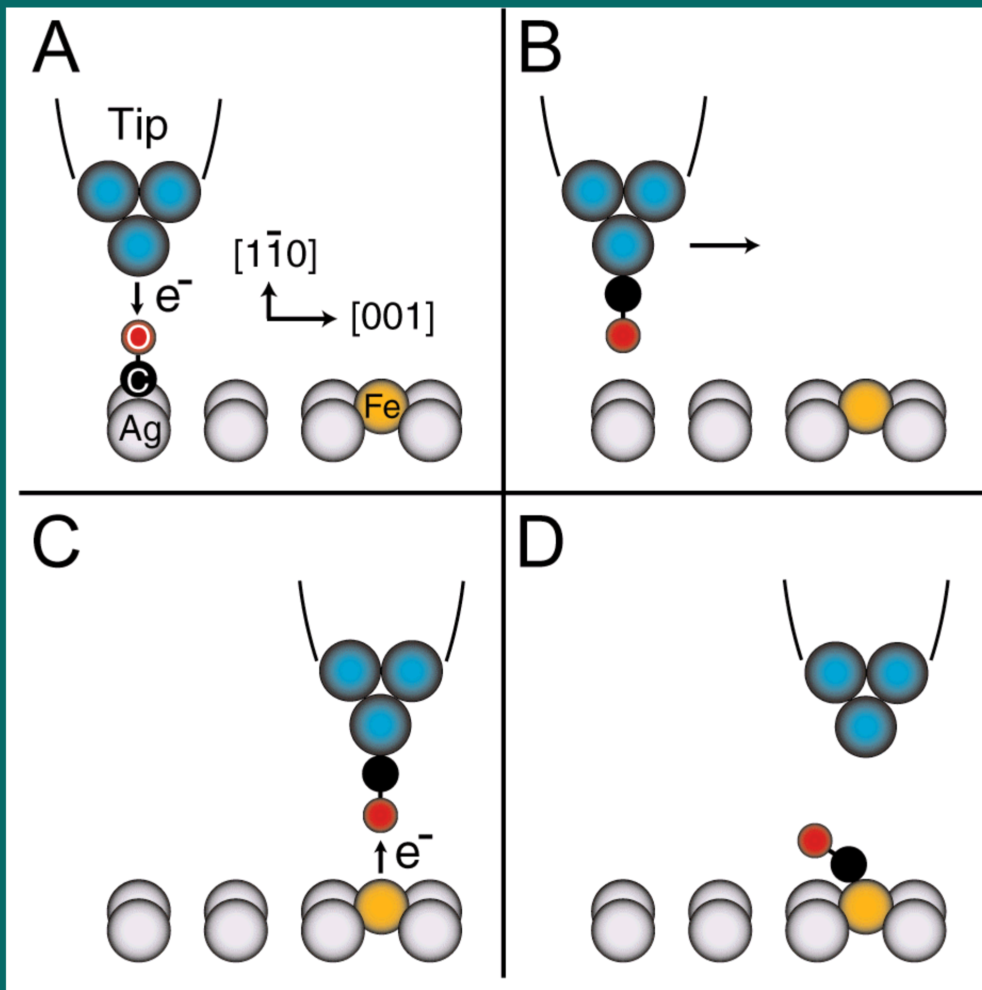
Progress: We Can Move Individual Molecules with Scanning Probe Microscopy
(Gimzewski et al.)

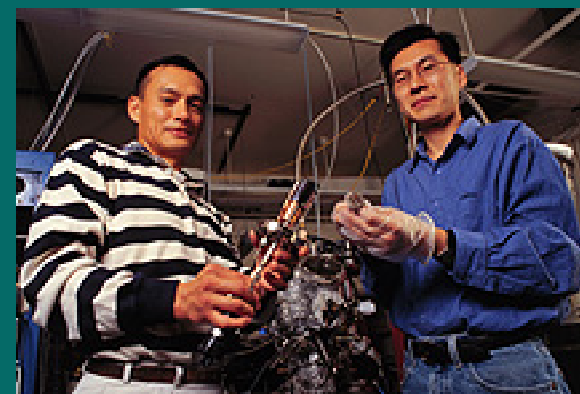


http://www.chem.ucla.edu/dept/Faculty/gimzewski/

Proof of Concept: STM bonded CO to Fe

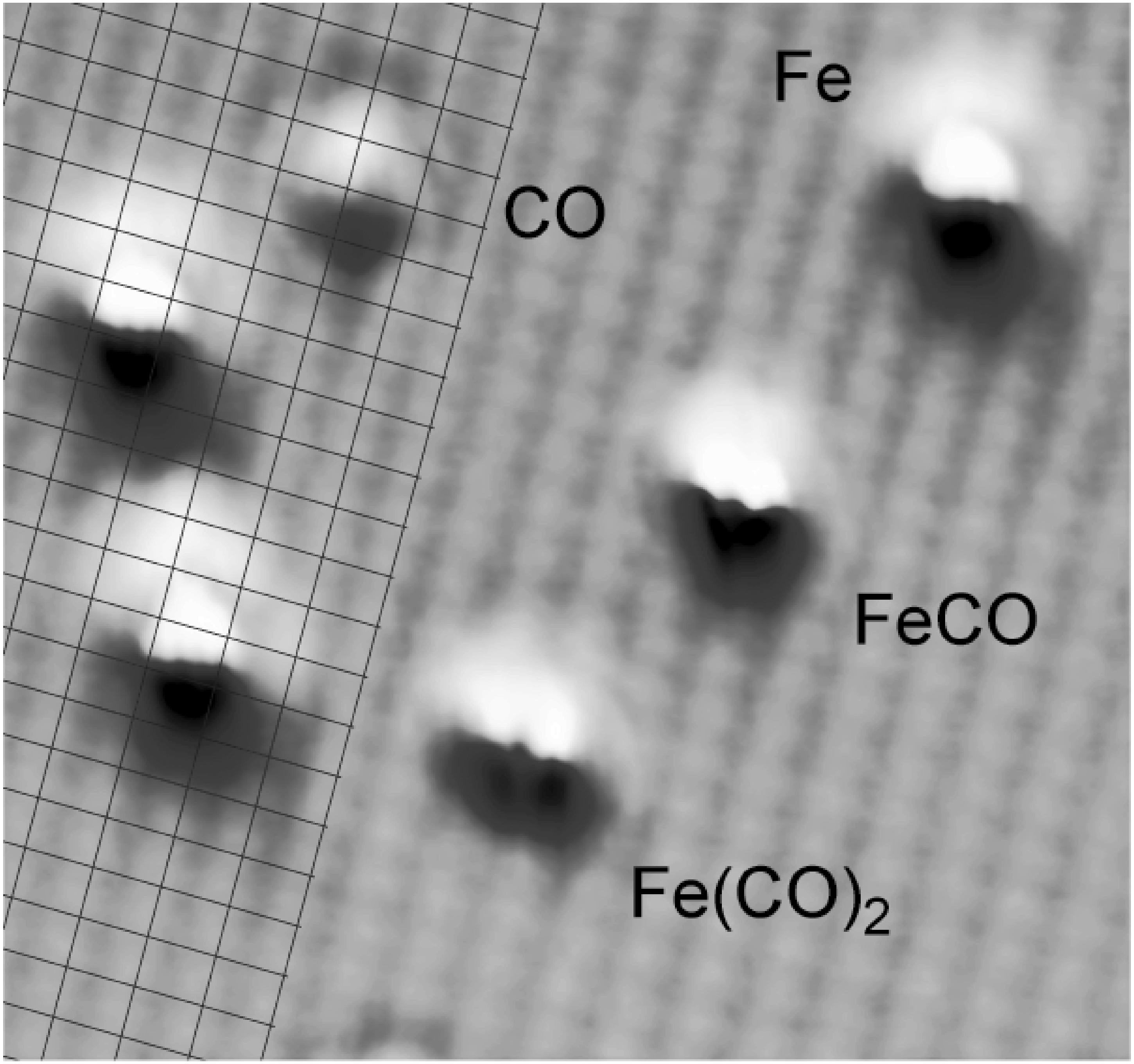
(1999 Ho and Lee, Cornell)

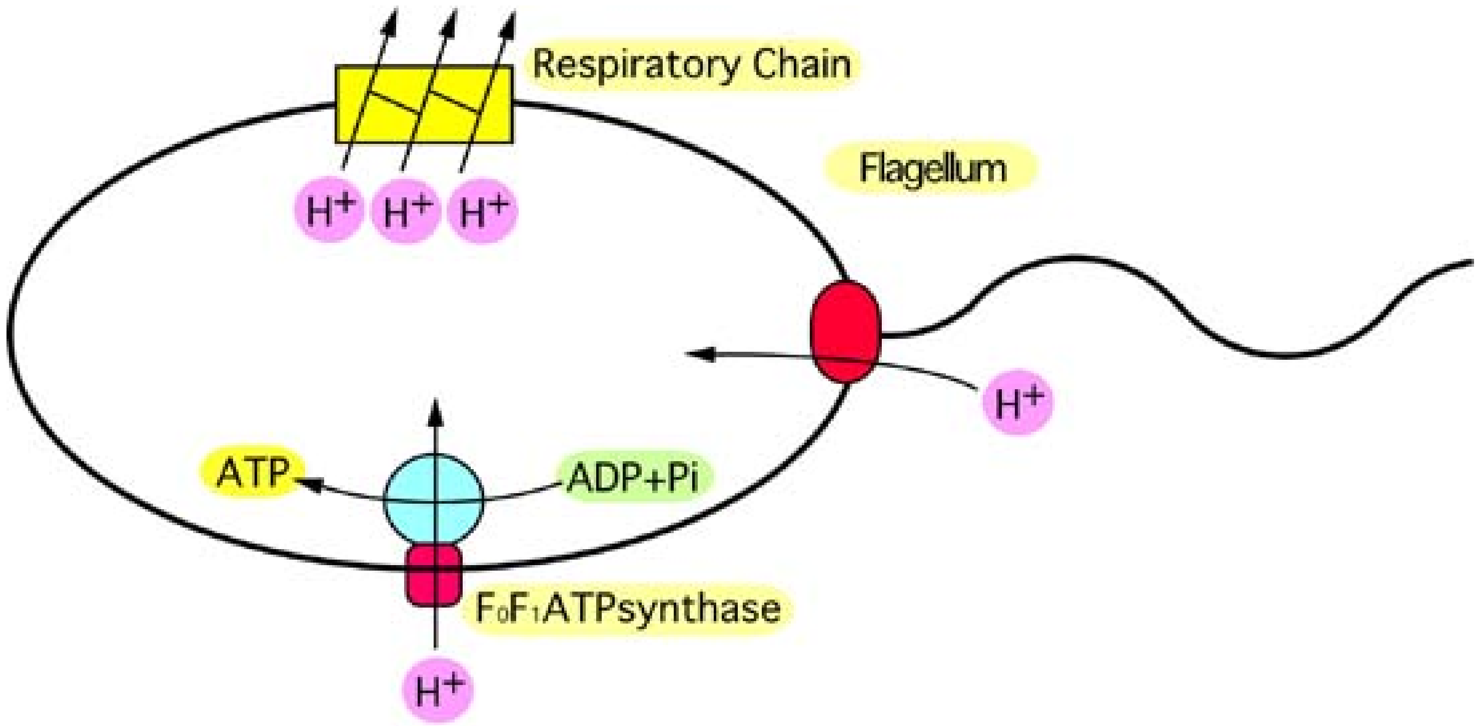




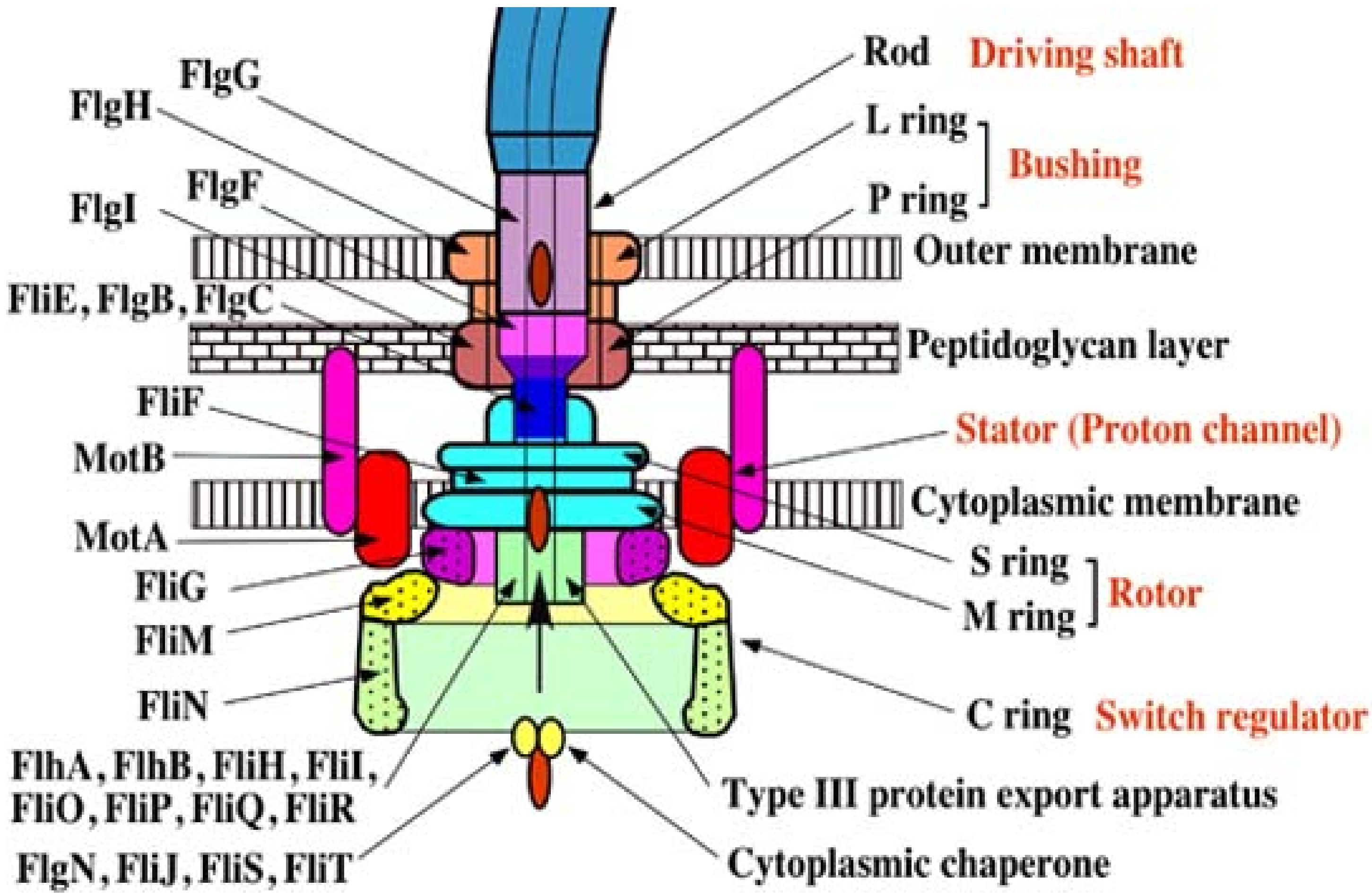
Wilson Ho and Hyojune Lee

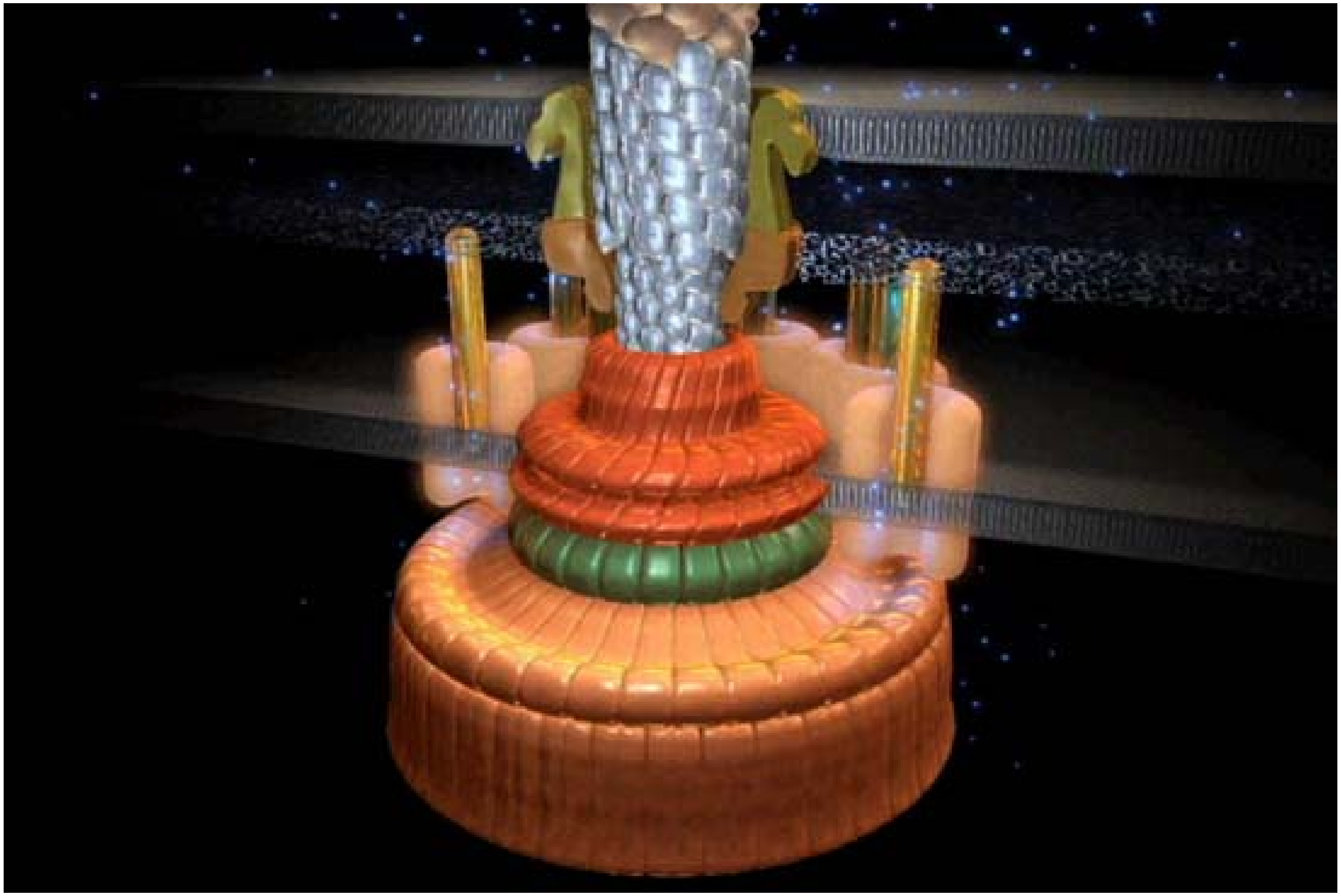
13 K

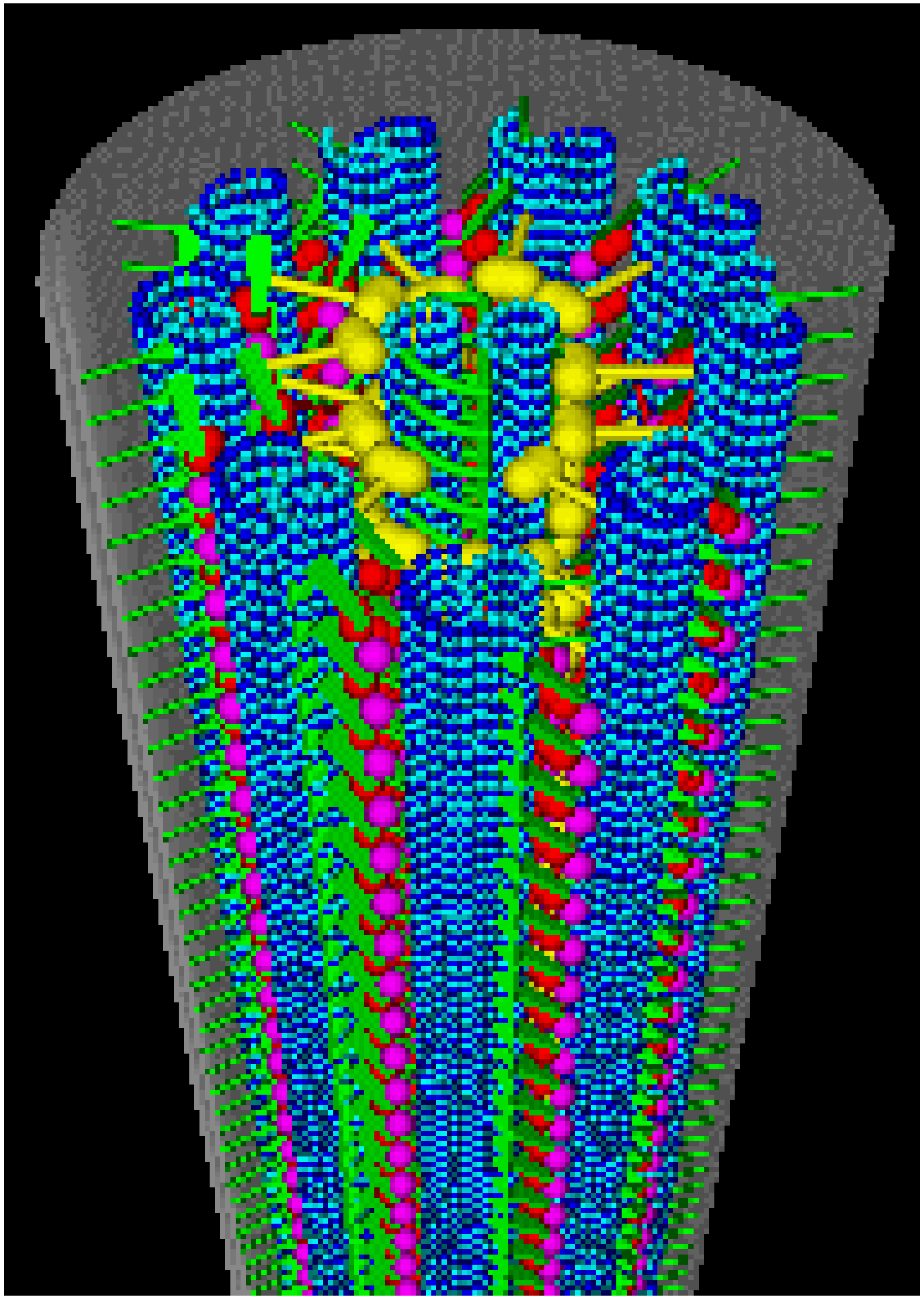

Fe
CO
FeCO
Fe(CO)2



Flagellar motor is powered by the proton motive force just as F_0F_1ATPsynthase

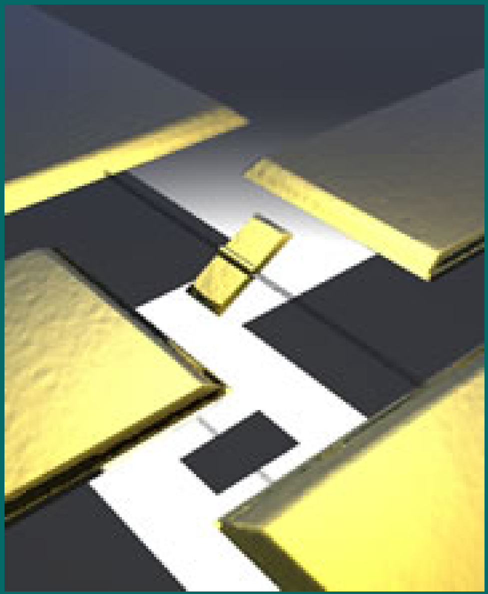

Rod
Driving shaft
FlgG
FlgH
L ring
P ring
Bushing
FlgF
FlgI
Outer membrane
FliE, FlgB, FlgC
Peptidoglycan layer
FliF
Stator (Proton channel)
MotB
Cytoplasmic membrane
MotA
FliG
S ring
M ring
Rotor
FliM
FliN
C ring
Switch regulator
FlhA, FlhB, FliH, FliI,
FliO, FliP, FliQ, FliR
Type III protein export apparatus
FlgN, FliJ, FliS, FliT
Cytoplasmic chaperone

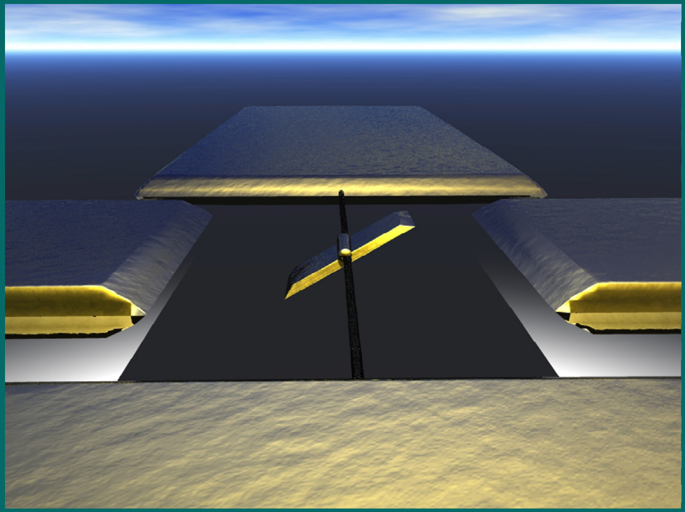


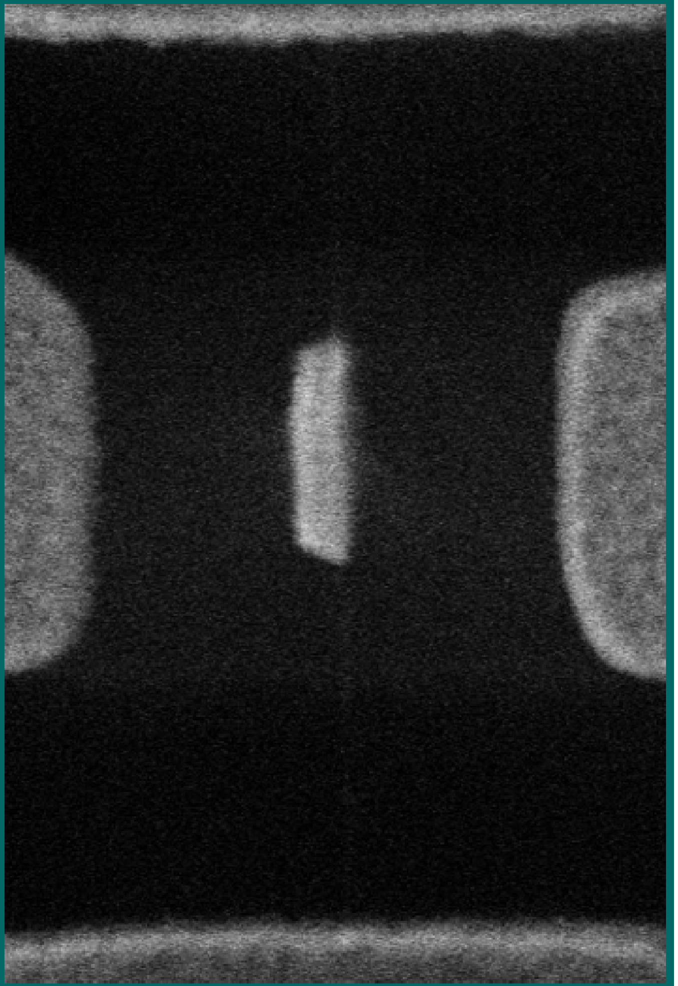


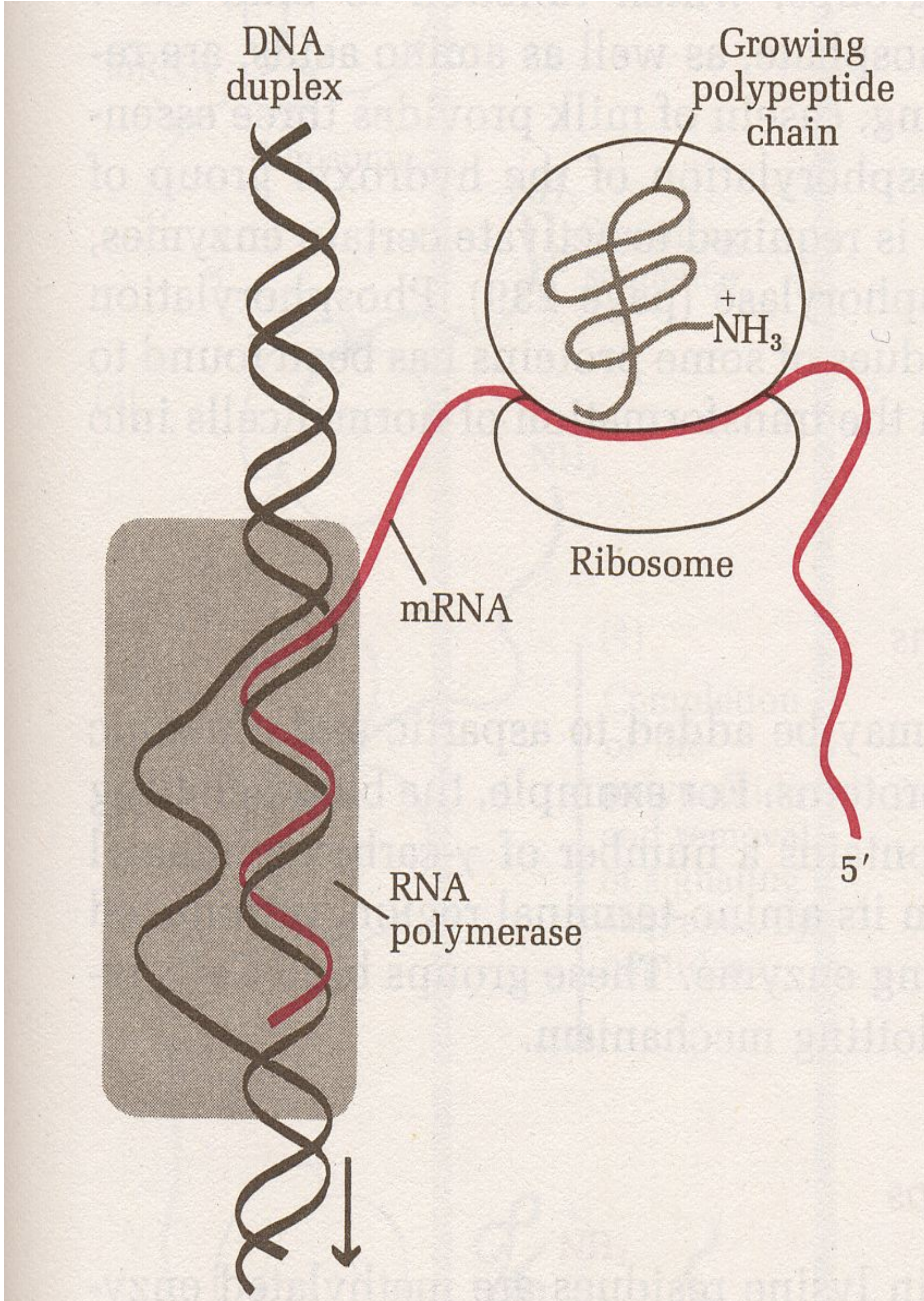
QuickTime™ and a
decompressor
are needed to see this picture.

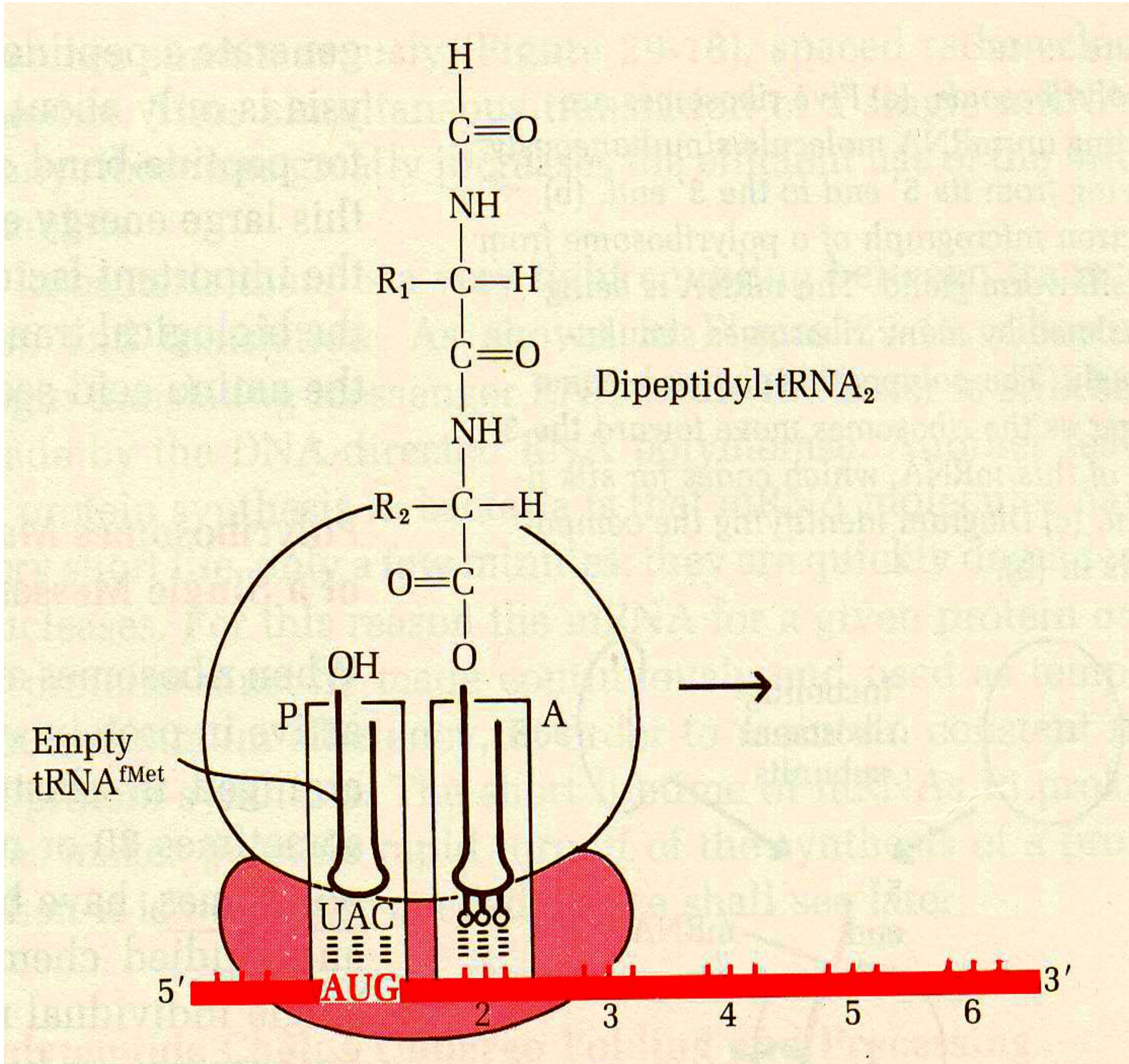
Molecular Motor (Zettl, LLNL)





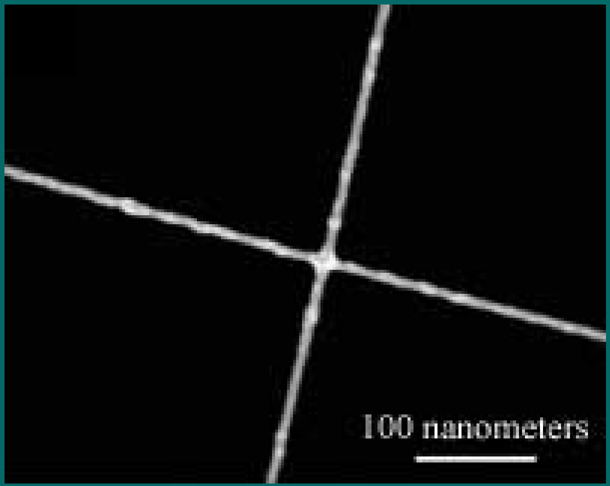


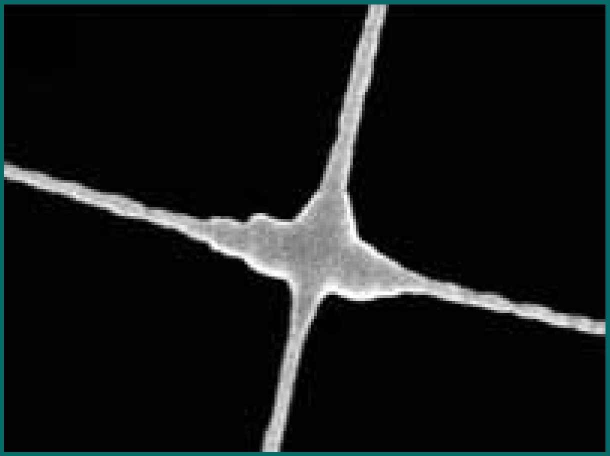

DNA
duplex
Growing
polypeptide
chain
$\overset{+}{N}H_3$
Ribosome
mRNA
RNA
polymerase
5′


H
C=O
NH
R1—C—H
C=O
Dipeptidyl-tRNA2
NH
R2—C—H
O=C
O
OH
P
A
Empty
tRNAfMet
UAC
5′
AUG
2
3
4
5
6
3′

Nanotubes soldered

(2001 Banhart, U. of Ulm, Germany)

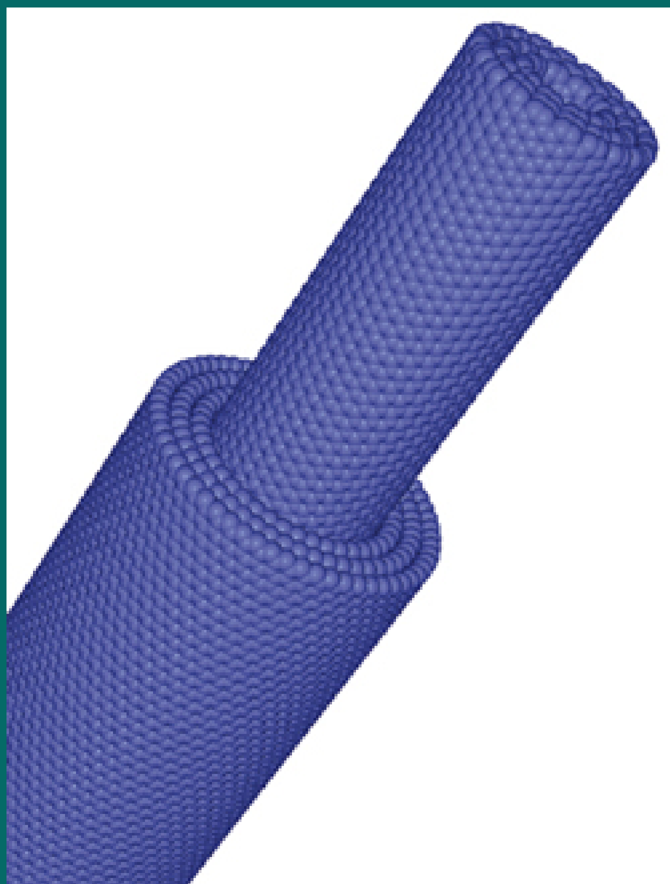


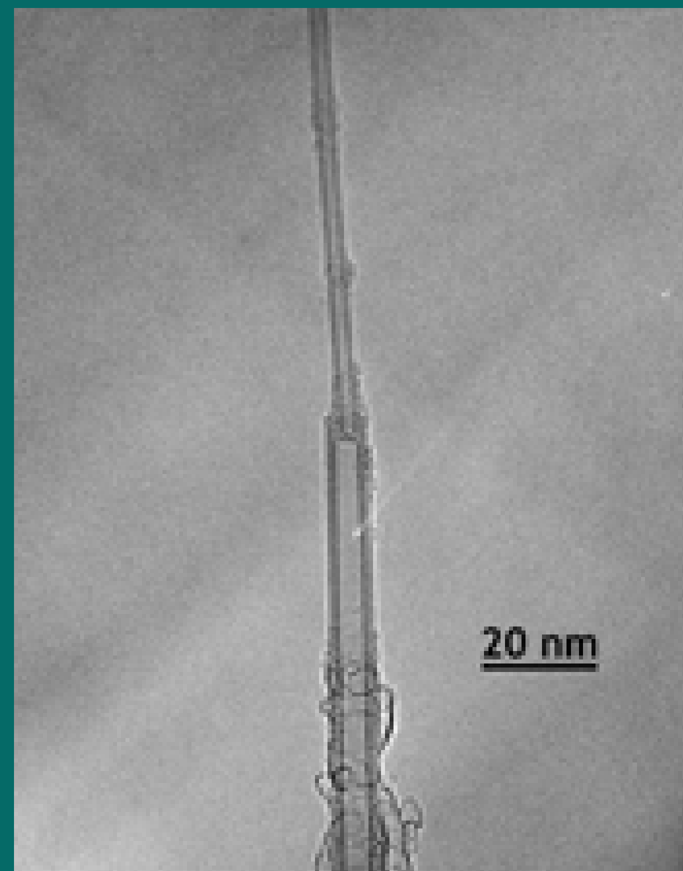


Florian Banhart, "The formation of a connection between carbon nanotubes in an electron beam," Nano Letters 1, 329-332 (2001).

Telescoping Nanotubes (linear motor)

(2001, Zettl, Lawrence Berkeley Laboratory)

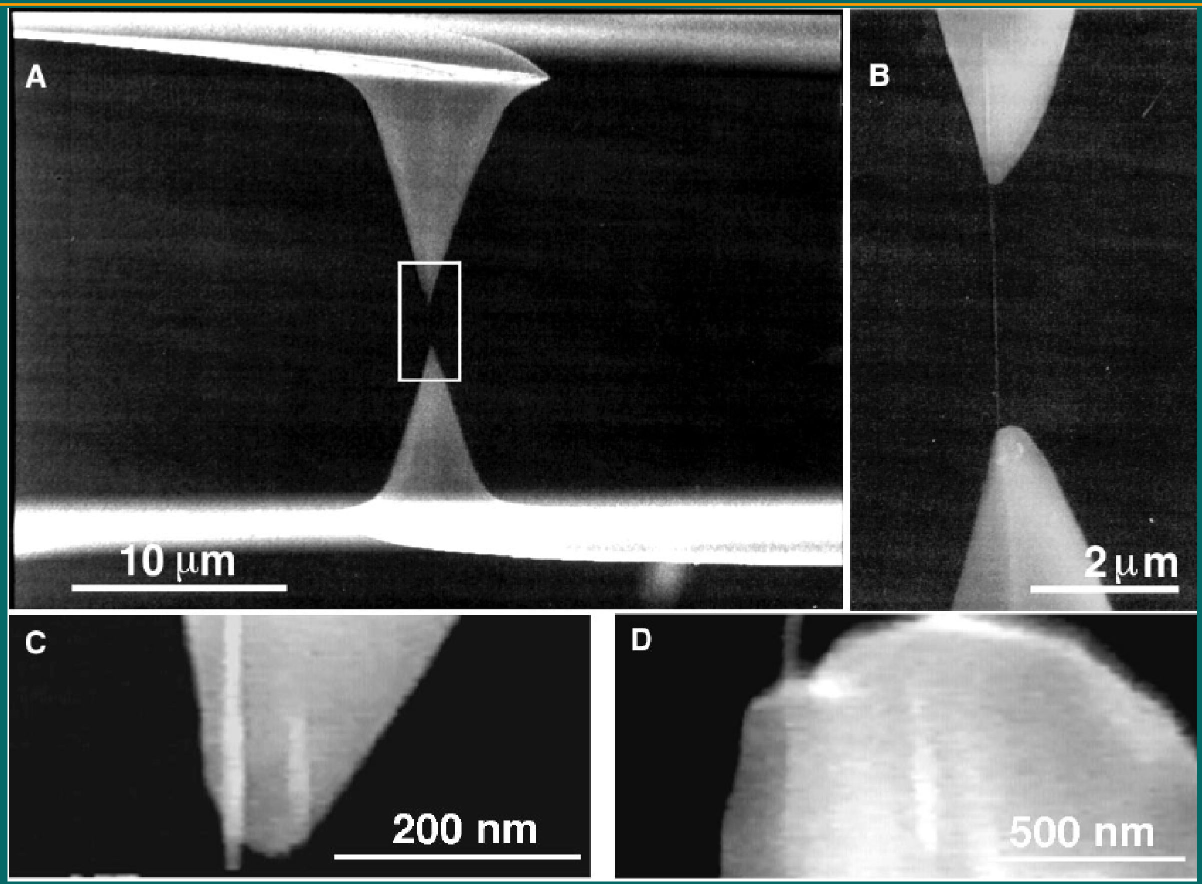




http://www.lbl.gov/Science-Articles/Research-Review/Magazine/2001/Fall/features/02Nanotubes.html

Nanotube joined to probe and tested

(2000 Ruoff, Northwestern)

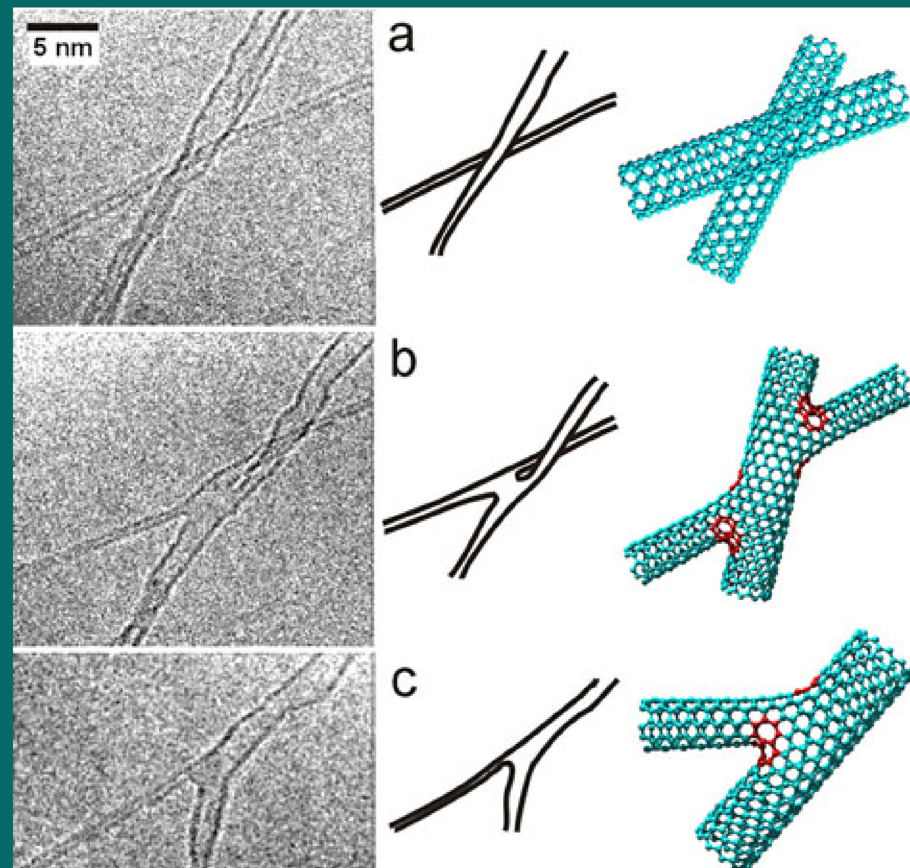


Min-Feng Yu, Oleg Lourie, Mark J. Dyer, Katerina Moloni, Thomas F. Kelly, Rodney S. Ruoff, "Strength and Breaking Mechanism of Multiwalled Carbon Nanotubes Under Tensile Load, *Science*, 287, 28 Jan. 2000, p. 637-640.

Nanotubes fused

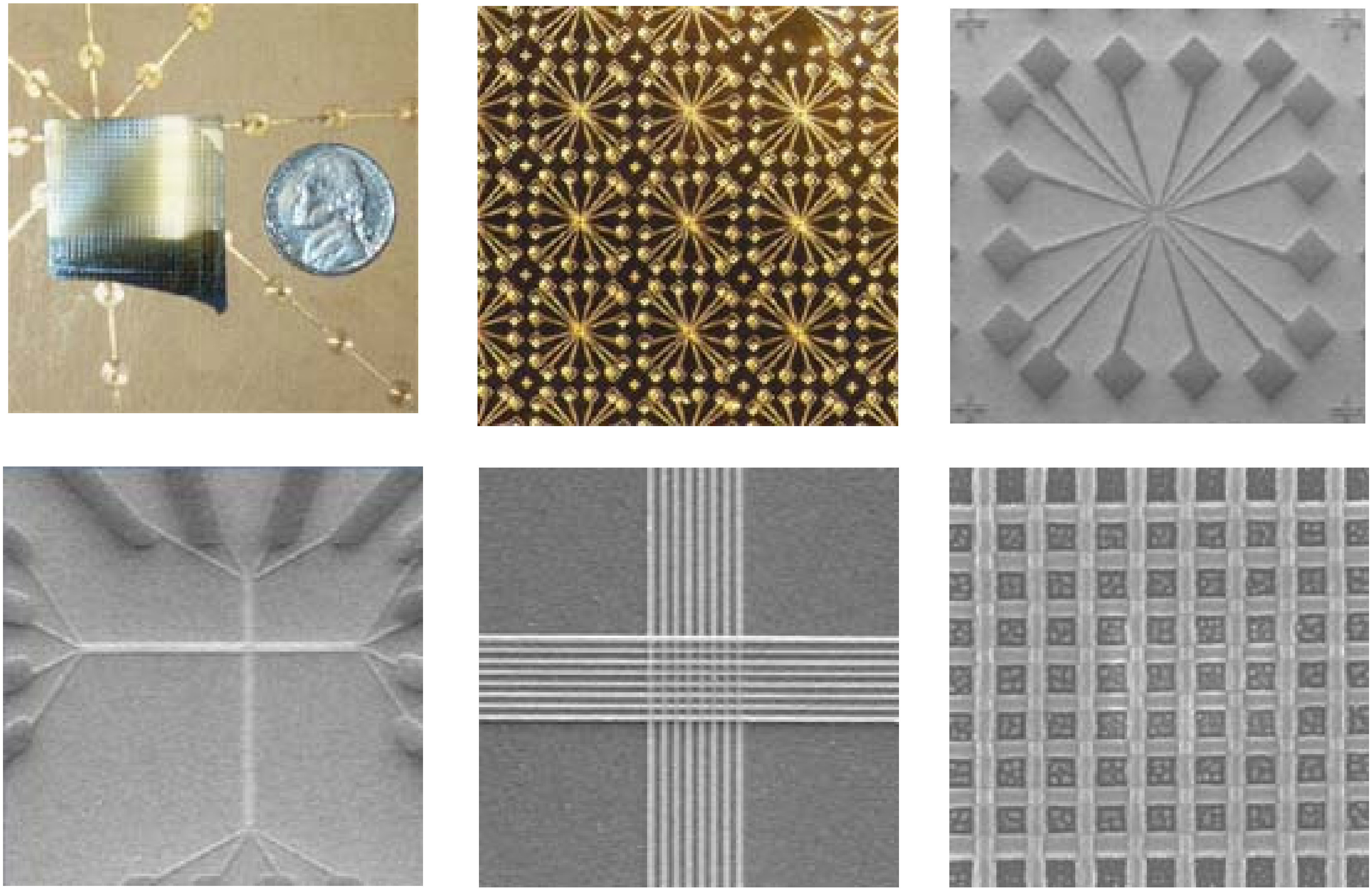
(2002 Terrones,U. Sussex Fullerene Science Centre)

M. Terrones, F. Banhart, N. Grobert, J.-C. Charlier, H. Terrones and P.M. Ajayan "Molecular junctions of single-walled nanotubes" Phys. Rev. Lett. 89, 075505 (2002)

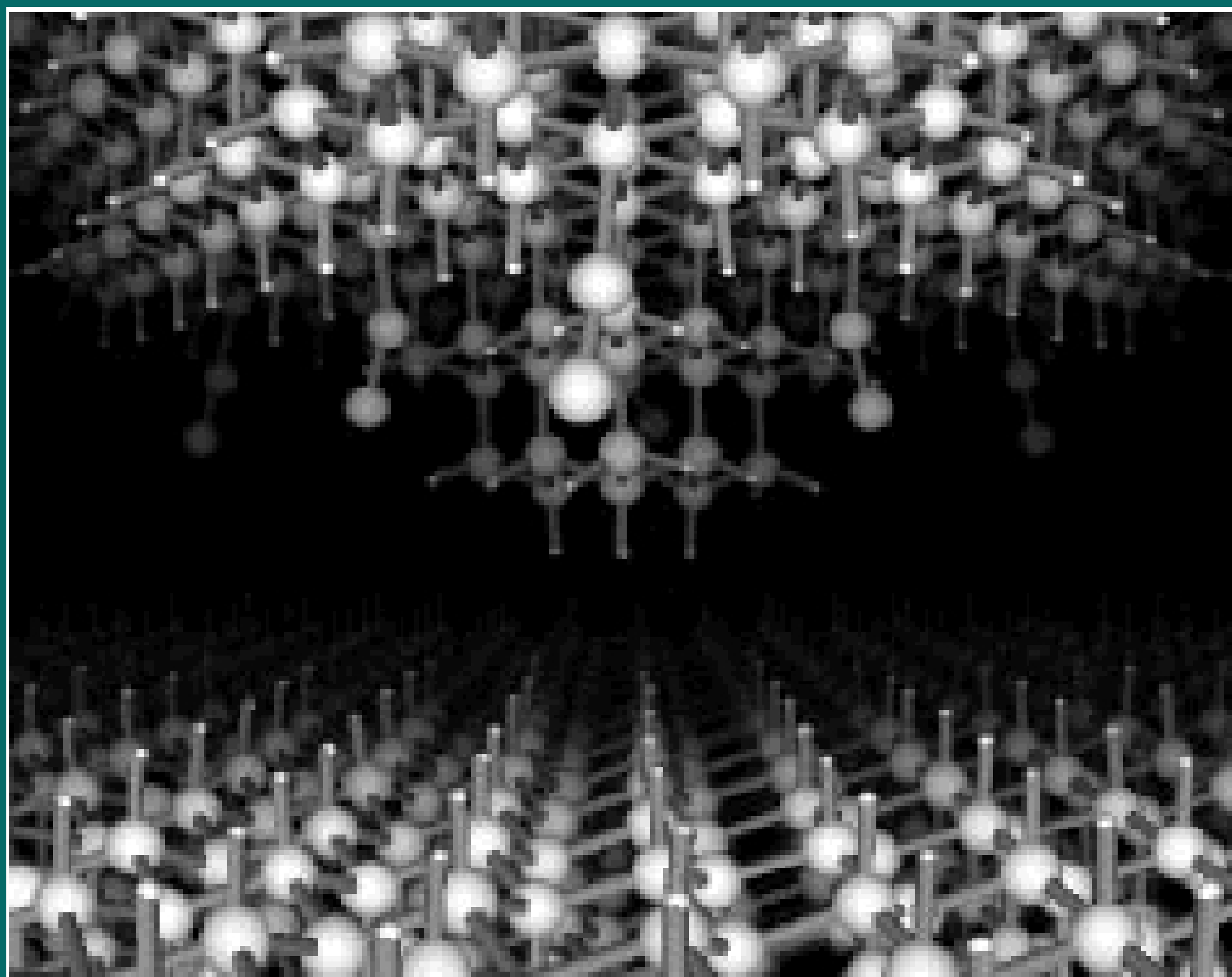


Formation of a SWNT junction under electron irradiation (1.25 MeV) at T = 700°C in an electron microscope

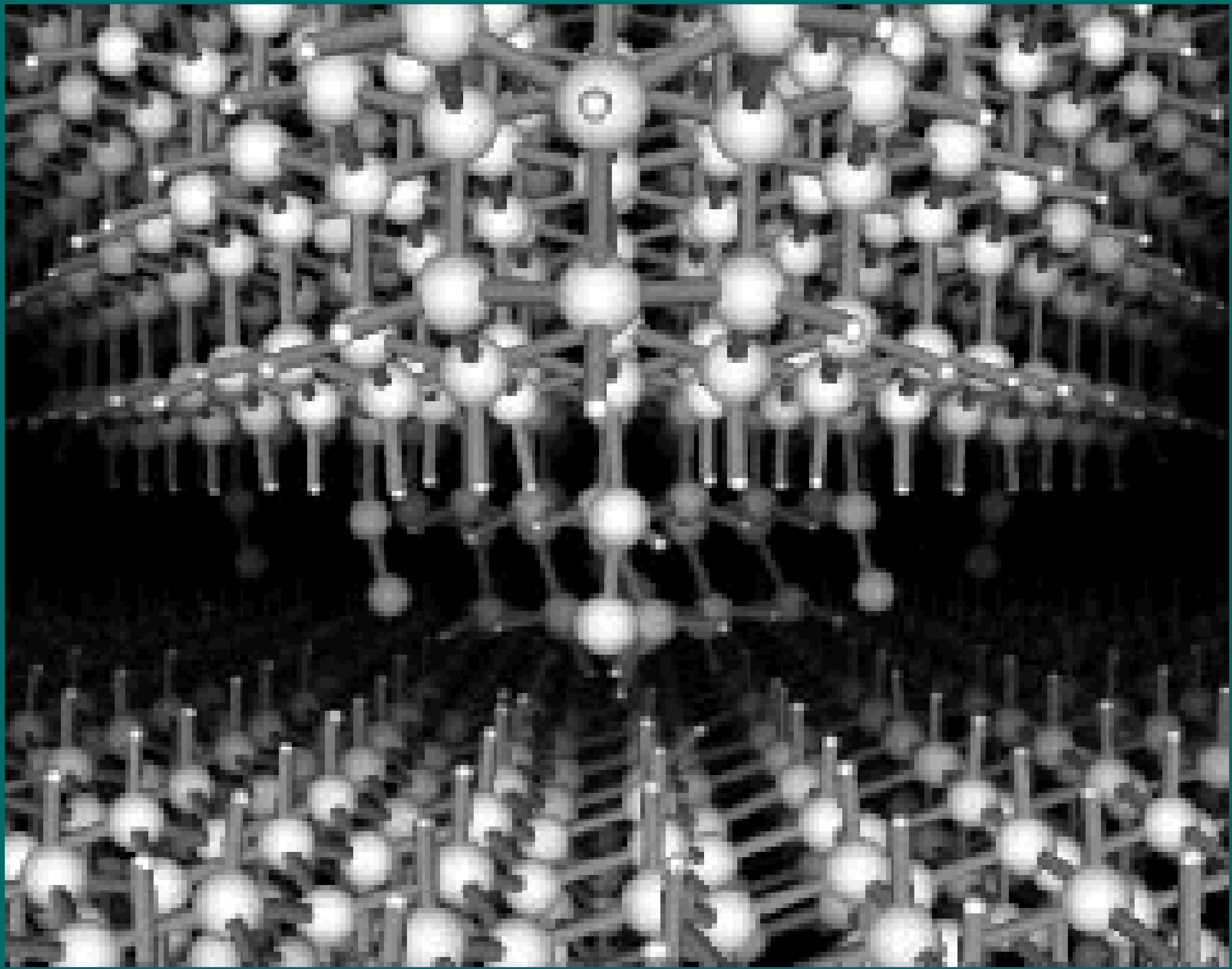
Molecular Computing (Hewlett Packard)



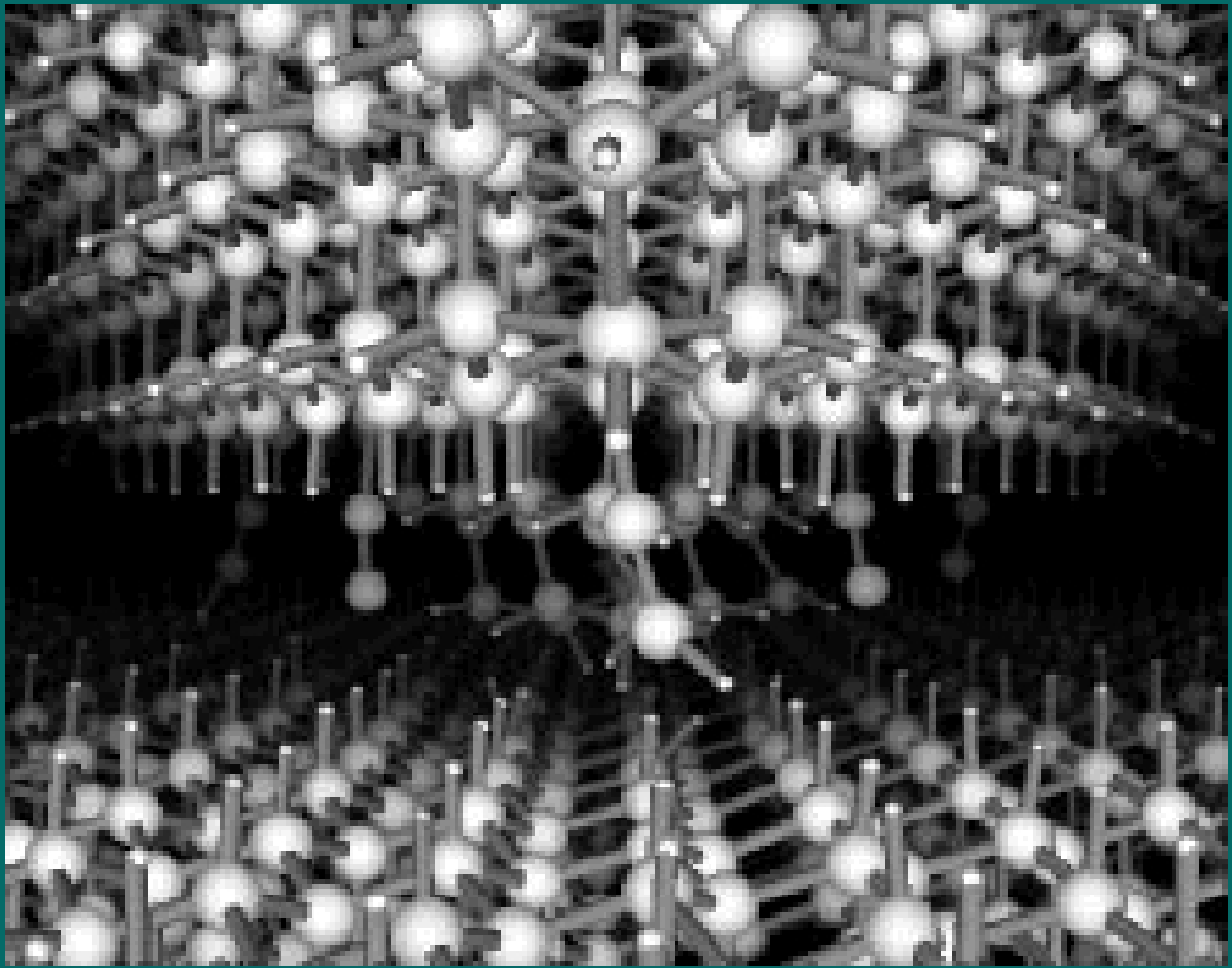
Hydrogen Abstraction



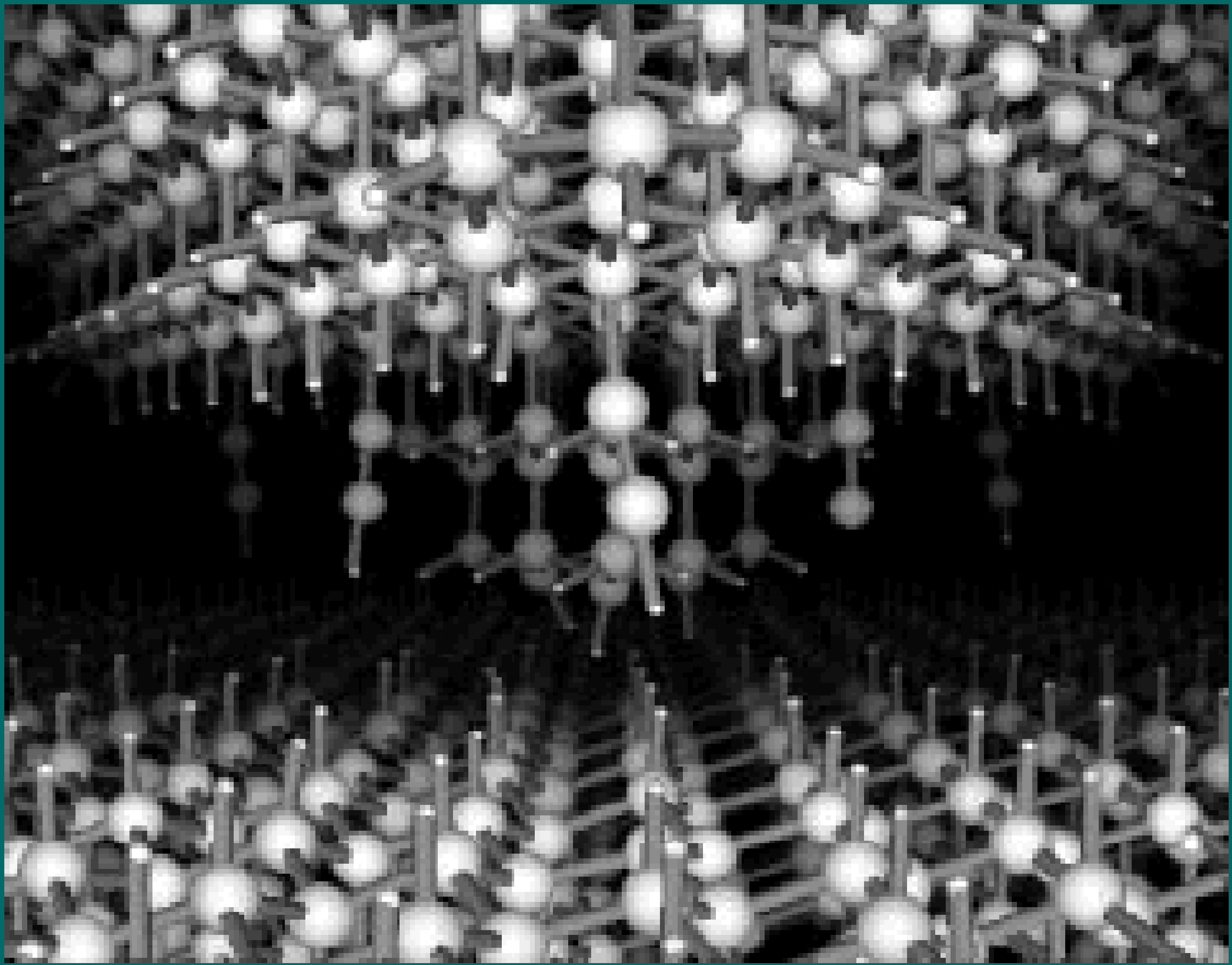
Hydrogen Abstraction



Hydrogen Abstraction



Hydrogen Abstraction



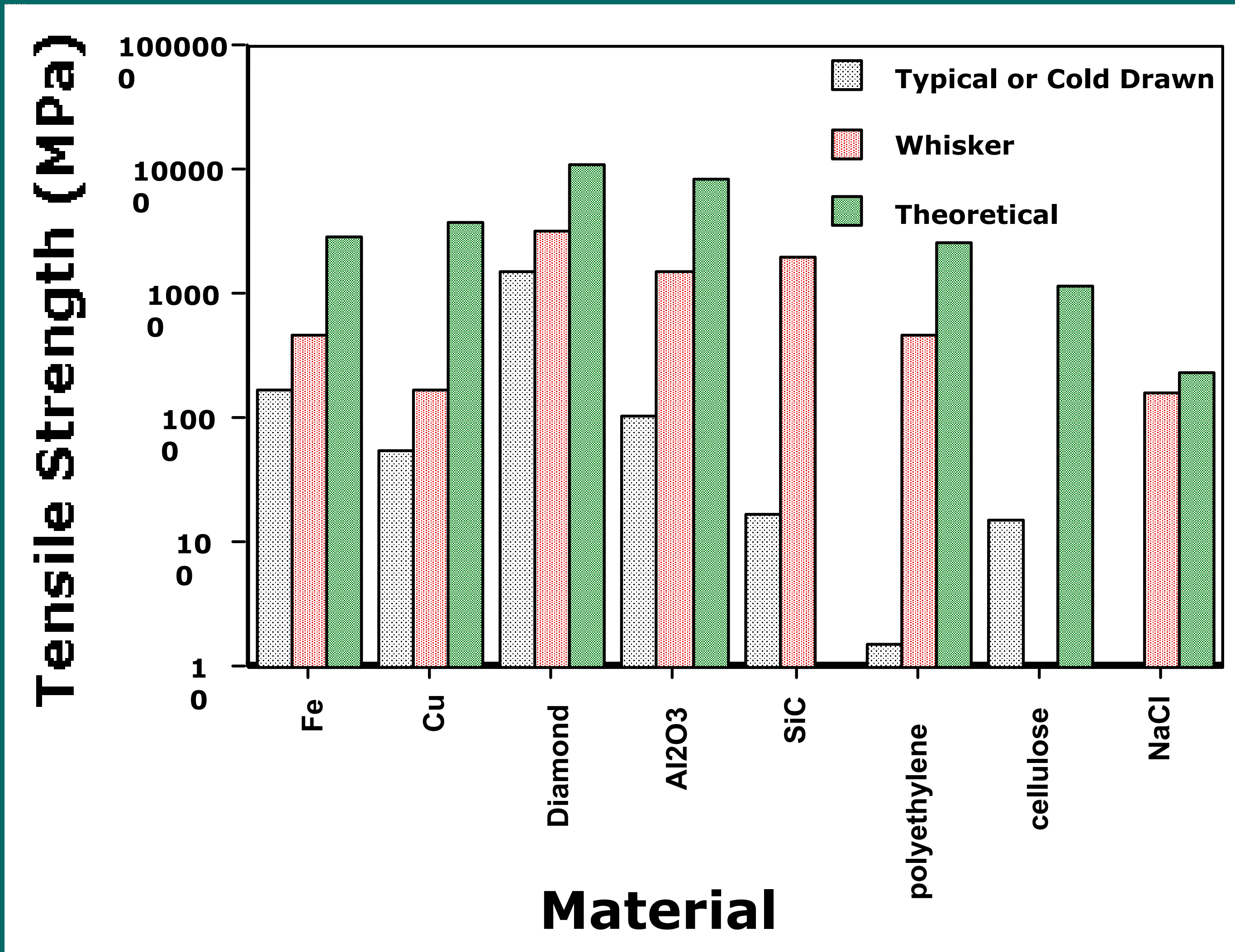
Molecular Dynamics – Planetary Gear

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

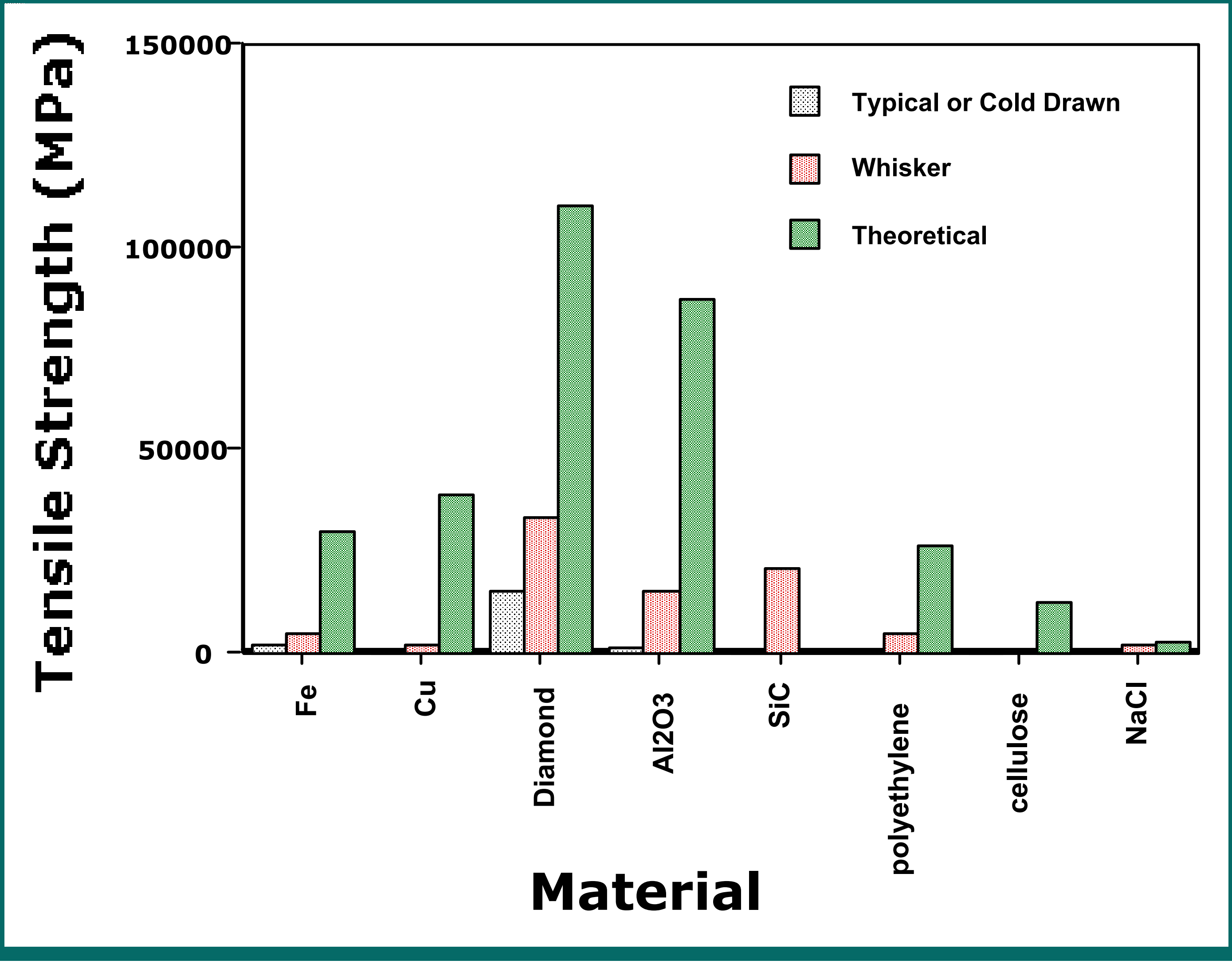
Implications for Textiles

- Improved Strength
- Heat resistant fabrics
  - Carbon nanotubes are stabile in air to 1000°C
  - High axial thermal conductivity
- Completely new fabrics
- Seamless fabrics
- Integrated "plumbing" to transport moisture
- . . . or contaminants (self-cleaning)
- Integrated sensors and repair robots
- Active materials

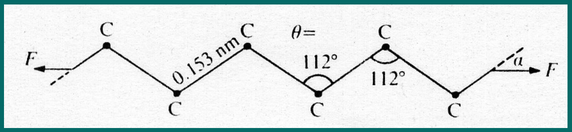
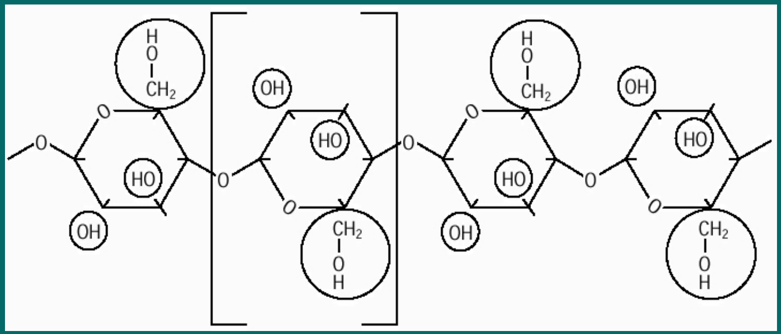
General Improvements in Materials Properties



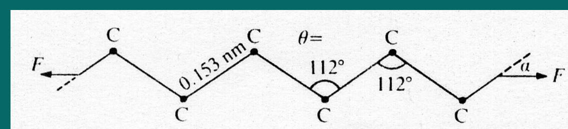
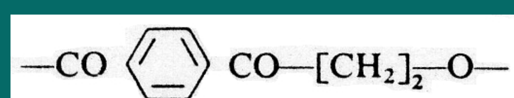
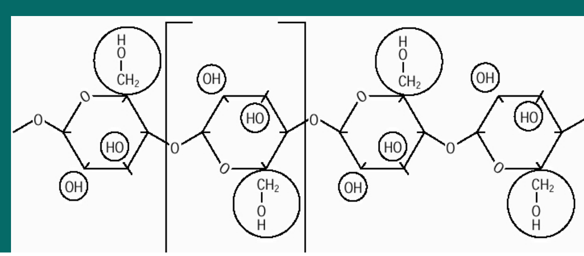
General Improvements in Materials Properties



Theoretical Properties of Polymers – Strength of Aligned Linear Molecules

		Theoretical Strength (MPa)	Typical Strength (MPa)
Polyethylene		19,000-36,000	15
PTFE	$-[CF_2]-$	15,000-16,000	21
Cellulose		12,000 - 19,000	150

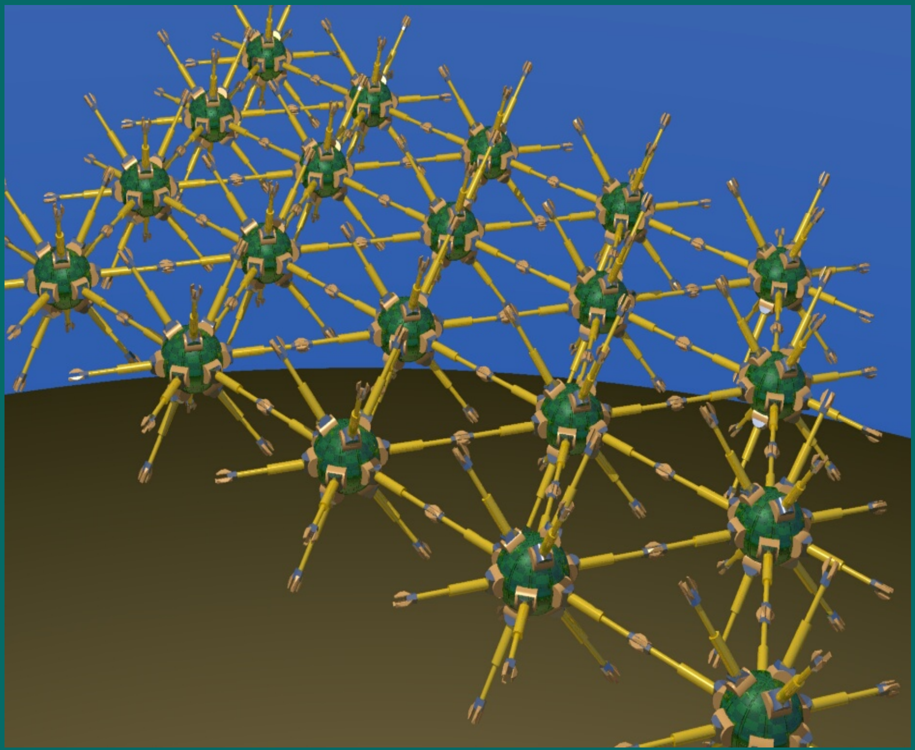
Theoretical Properties of Polymers – Stiffness of Aligned Linear Molecules

		Theoretical Modulus (GPa)
Polyethylene		182-340
Nylon-66	–[CH$_2$]$_6$NHC O–	196
PTFE	–[CF$_2$]–	160
Polyethylene terephthalate		122
Cellulose		56.5

Materials Engineering Implications
Programmable Materials

- Rich integration of computers, sensors, and actuators → programmable materials

Illustration by Josh Hall

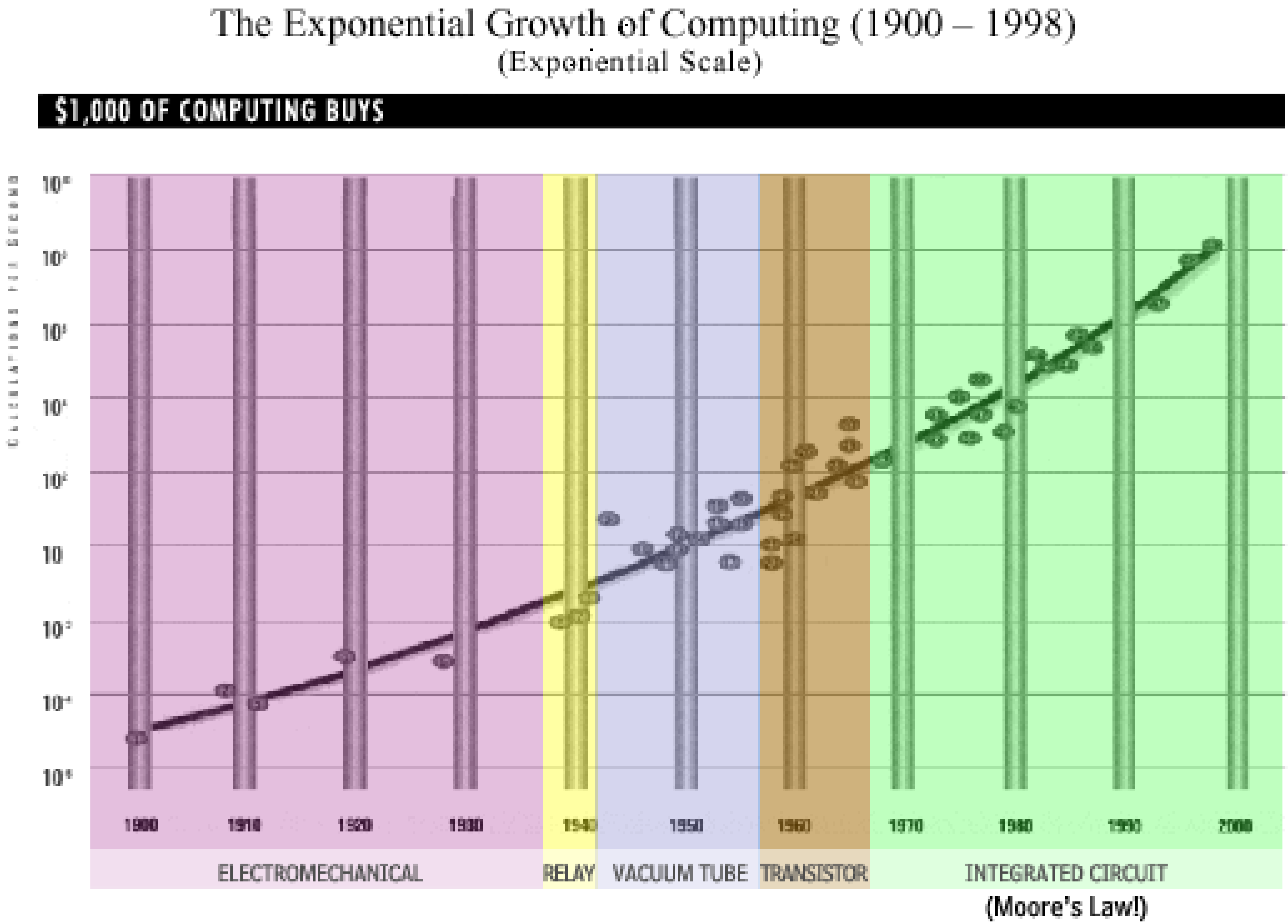


We Are (starting to) Experience the Most Powerful Accelerating Forces in History

- **(Double) Exponential Trends in the price performance of all information based technologies**
  - Not just the acceleration of computation
  - (and that acceleration itself goes beyond just Moore's Law)
  - Exponential and interacting trends apply to a wide range of technologies which affect all industries:
    - Computation
    - Memory
    - Communications
    - Genetic scanning and other aspects of biotechnology
    - Brain scanning
    - Human Longevity
    - Human knowledge and intellectual property in all fields
    - Miniaturization of all electronic and mechanical technologies
    - Paradigm Shift rates (the overall rate of technical progress)

Ray Kurzweil

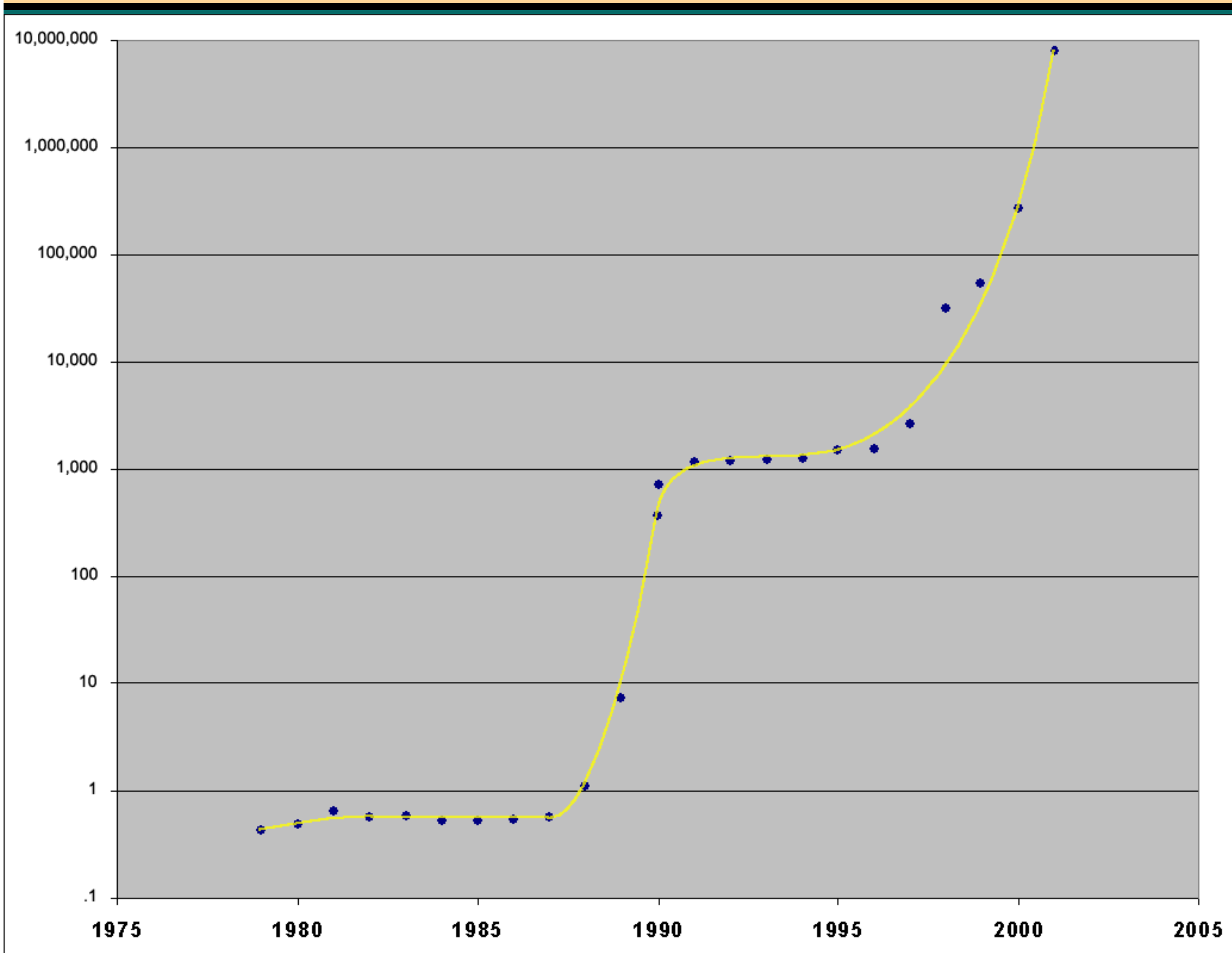
Moore's Law Was Not the First, but the Fifth Paradigm To Provide Exponential Growth of Computing



Note that the following two charts reflect the same data

- but one is on an exponential plot (where the trends take place)
- and the other is on a linear plot (which is how we actually experience technological change)
- Also note that the exponential trends are a cascade of "S" (sigmoid) curves
  - An S curve is exponential growth followed by the reaching of a limit for a particular paradigm
  - But paradigm shift is what keeps the overall exponential growth continuing after any particular paradigm has reached its limit
  - We see this repeatedly: ongoing paradigm shifts keeps exponential growth continuing in each technology category

Increase in Bits-Per-Second/$, Based Upon ISP Costs (Exponential Scale)

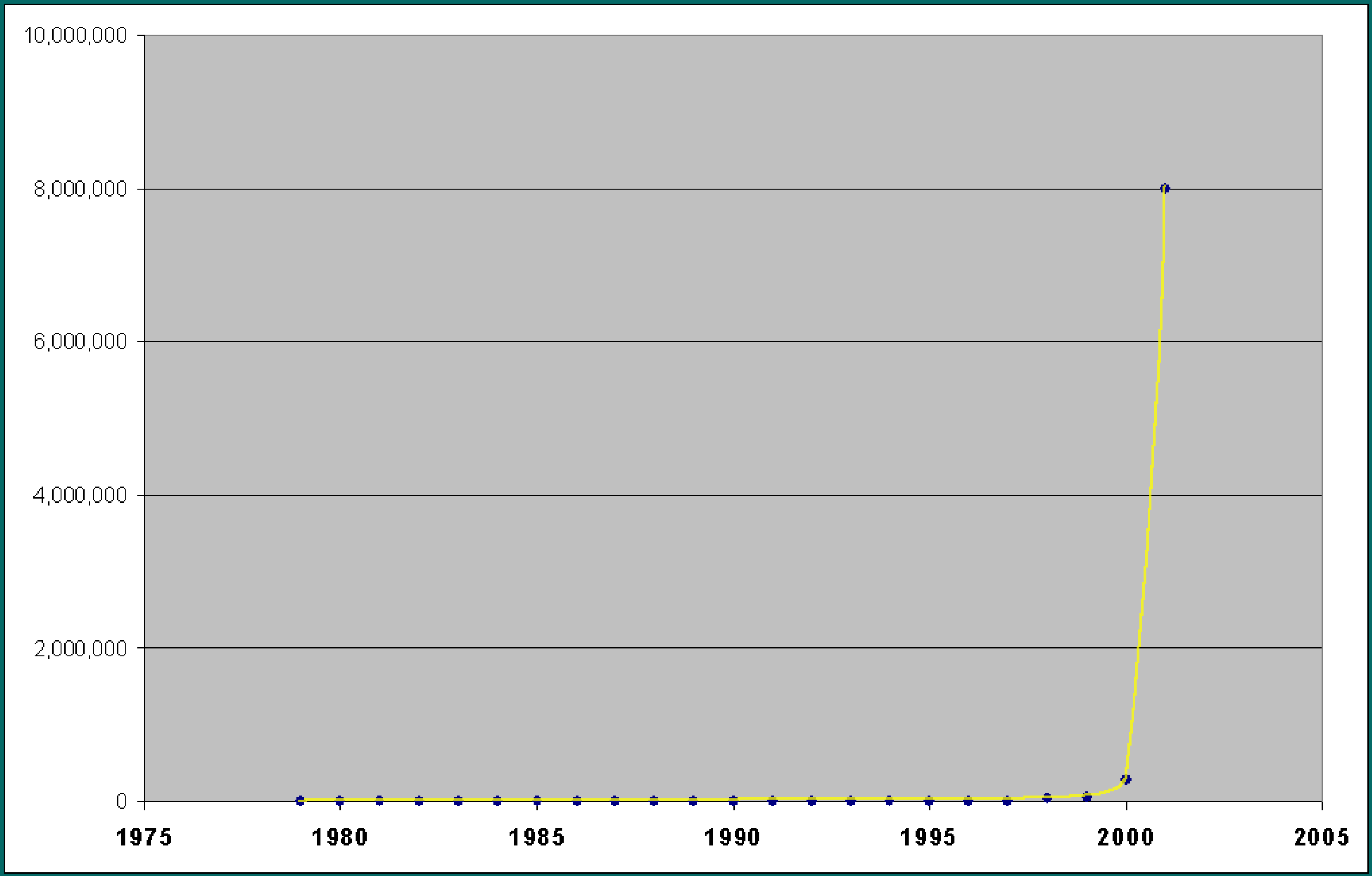


Notice Cascade of "S" Curves

Doubling Time: 12 months

Increase in Bits-Per-Second/$, Based Upon ISP Costs

(Linear Scale)

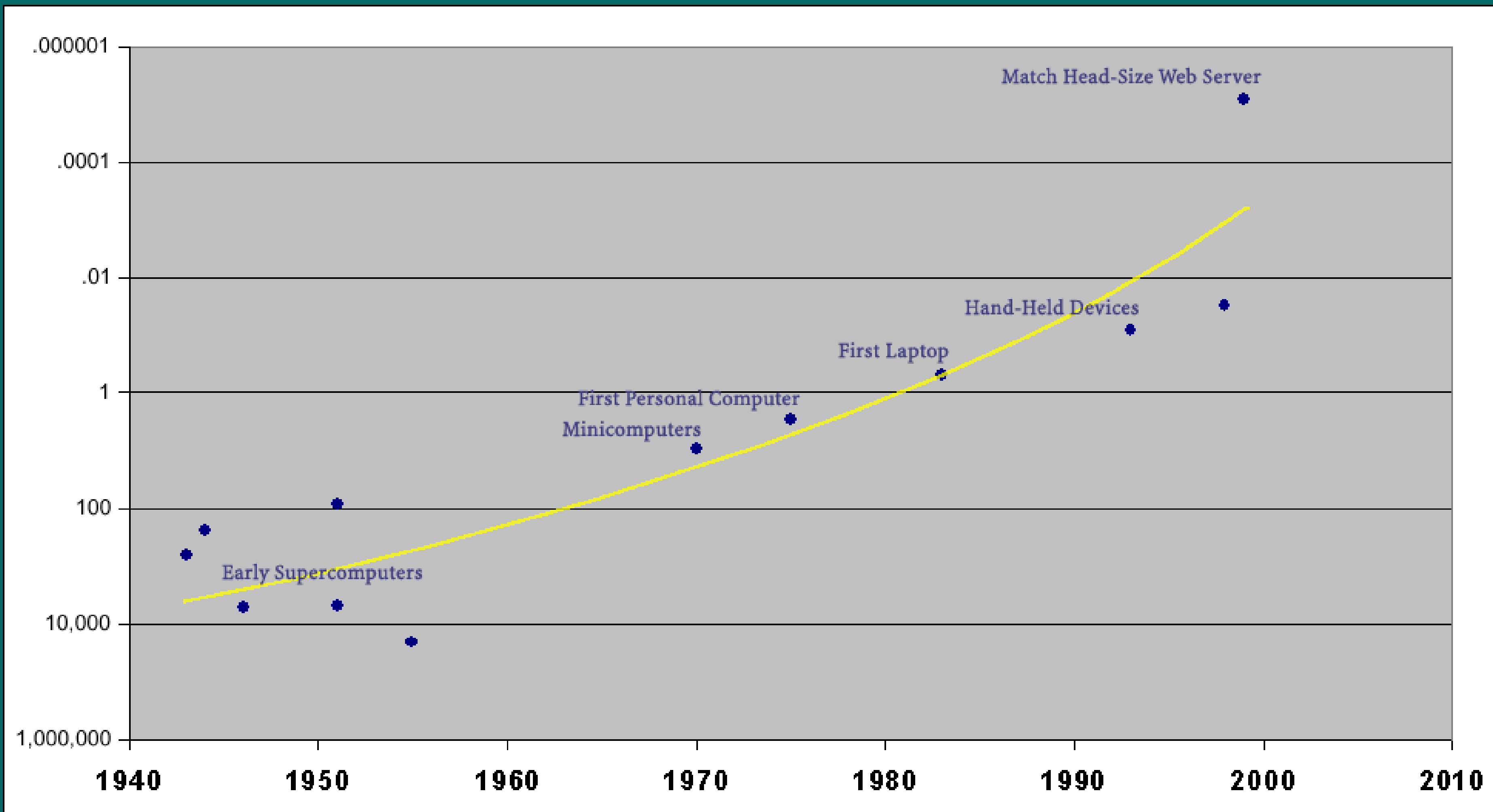


Exponential Growth is not noticed until it “explodes”

Doubling Time: 12 months

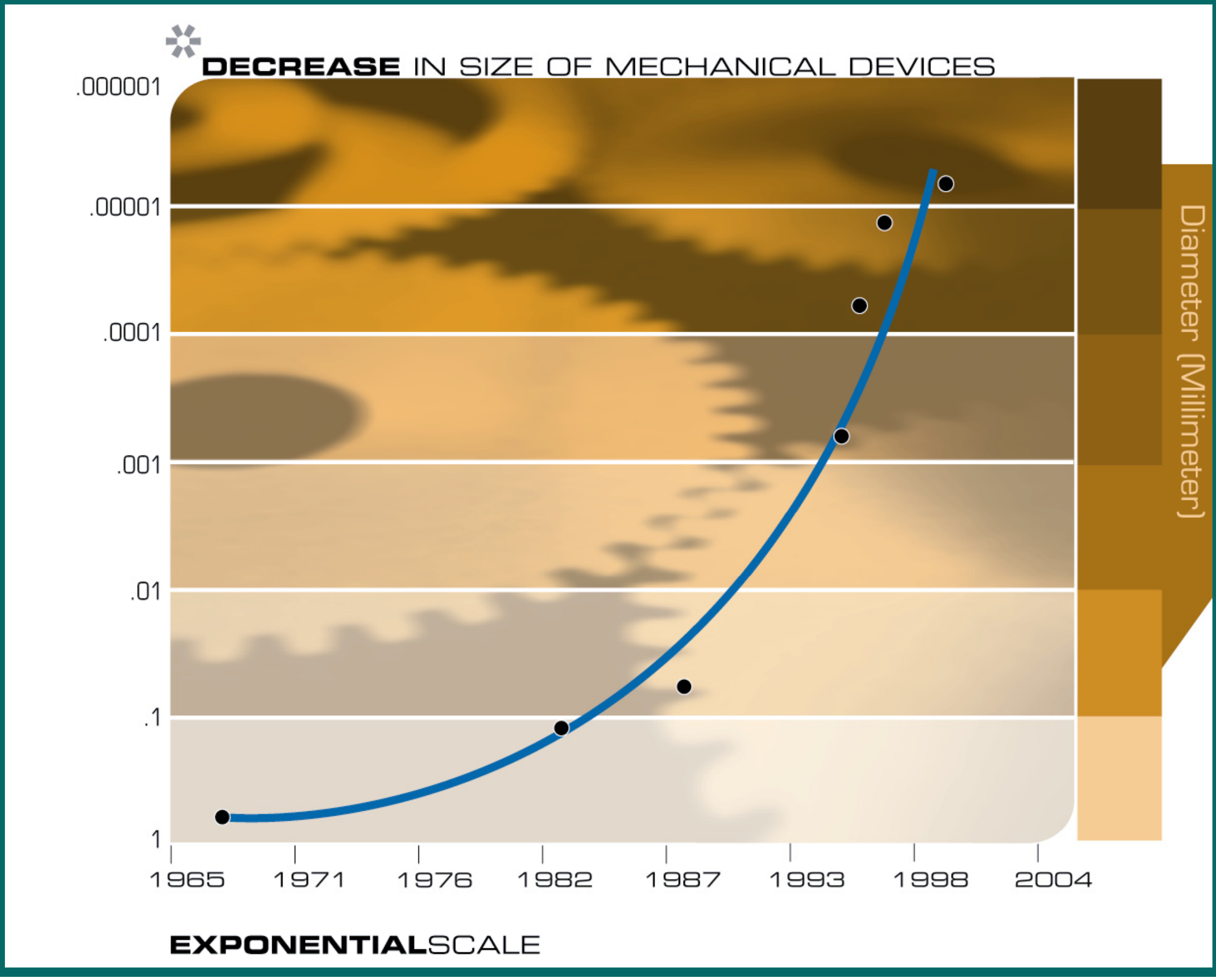
Decrease in Size of Computers, in Cubic Meters

(Exponential Scale)



Decrease in Size of Mechanical Devices, Diameter in Millimeters

(Exponential Scale)



Paradigm Shift Rates

Now Doubling Every Decade:

The 21st Century will = 20,000 years of progress (at today's rate of progress)

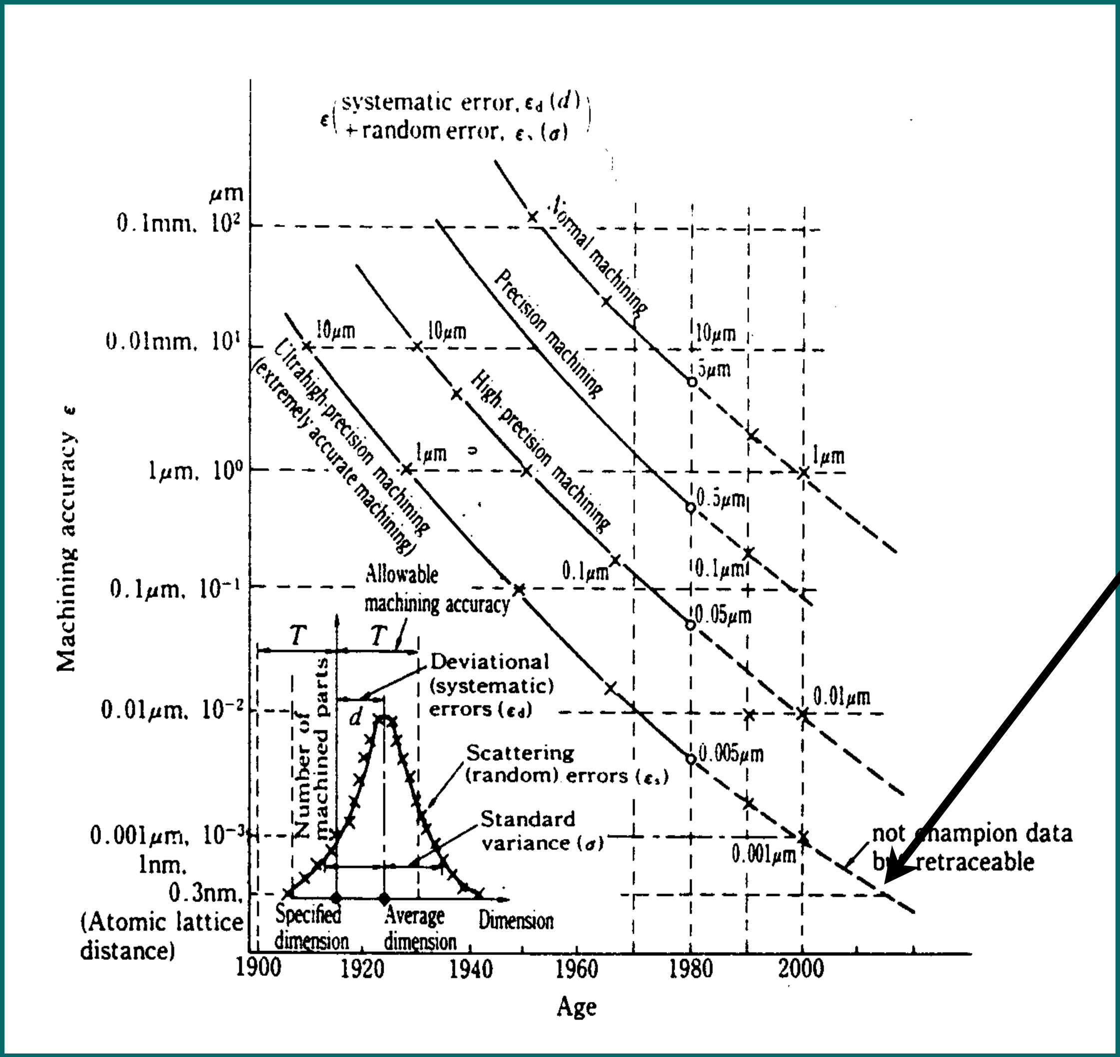
The "Intuitive Linear" View of Technology

- Even though the pace of progress has been accelerating,
- observers (even sophisticated ones) quickly internalize the recent past
- and thus assume that progress will continue at the current rate
- so the common (but invalid) expectation is that we'll see 10 years of progress (at the current rate) in the next 10 years

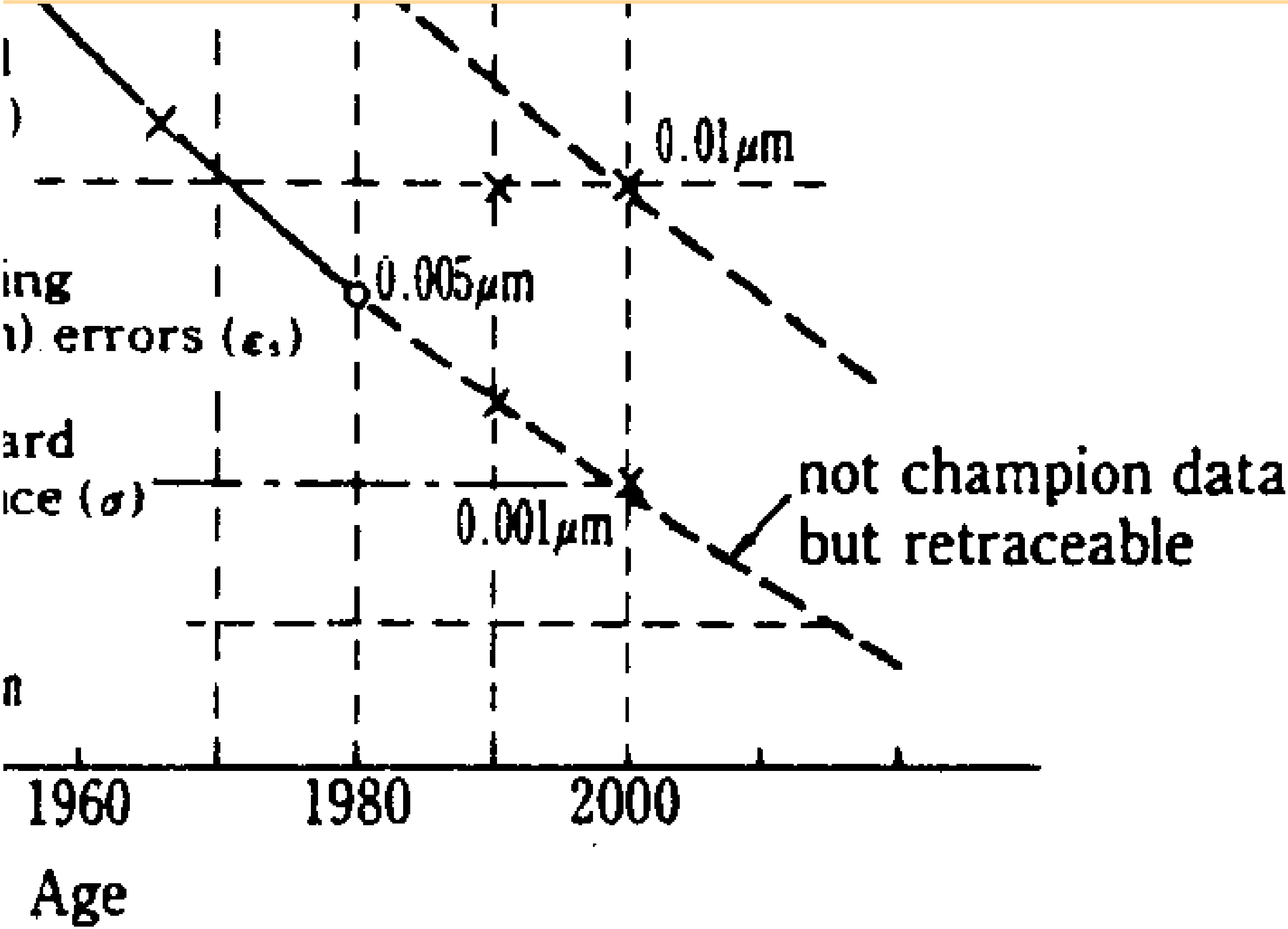
vs. the "Historical Exponential View" of Technology

- But the pace of progress has been accelerating since the advent of technology (indeed since the dawn of biological evolution)
- and will continue to do so
- We're currently doubling the rate of technological progress every decade
- So the next decade will be like 20 years, not 10 years
- And the next century will be like 20,000 years, not 100 years
- Yet the Twentieth Century was only like 25 years of progress (at today's rate) because progress was accelerating up to today's rate

Implication for Molecular Manufacturing



Building large atomically exact structures ~2015



0.01μm
ing
errors (ϵ_s)
0.005μm
ard
ice (σ)
0.001μm
not champion data
but retraceable
1960
1980
2000
Age

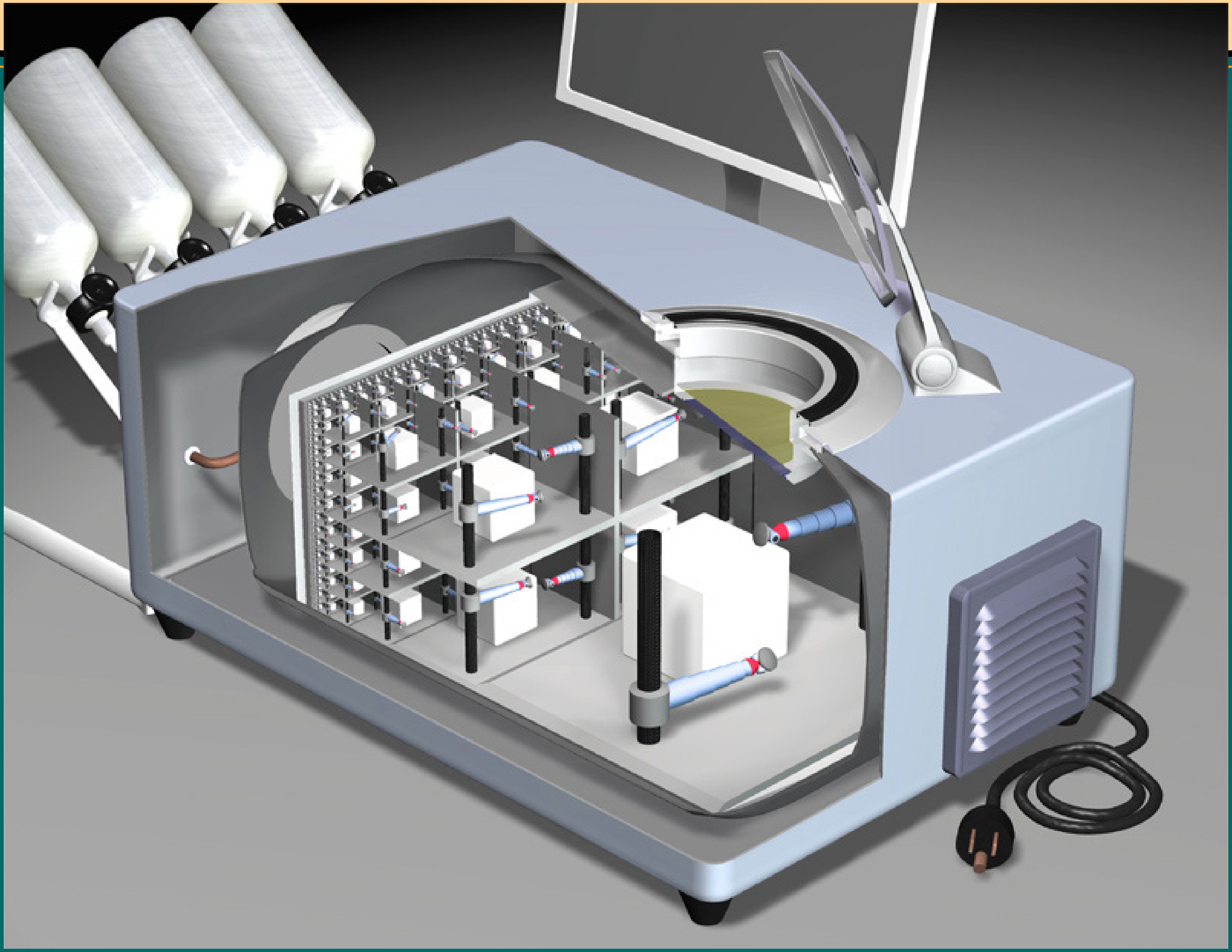
Summary

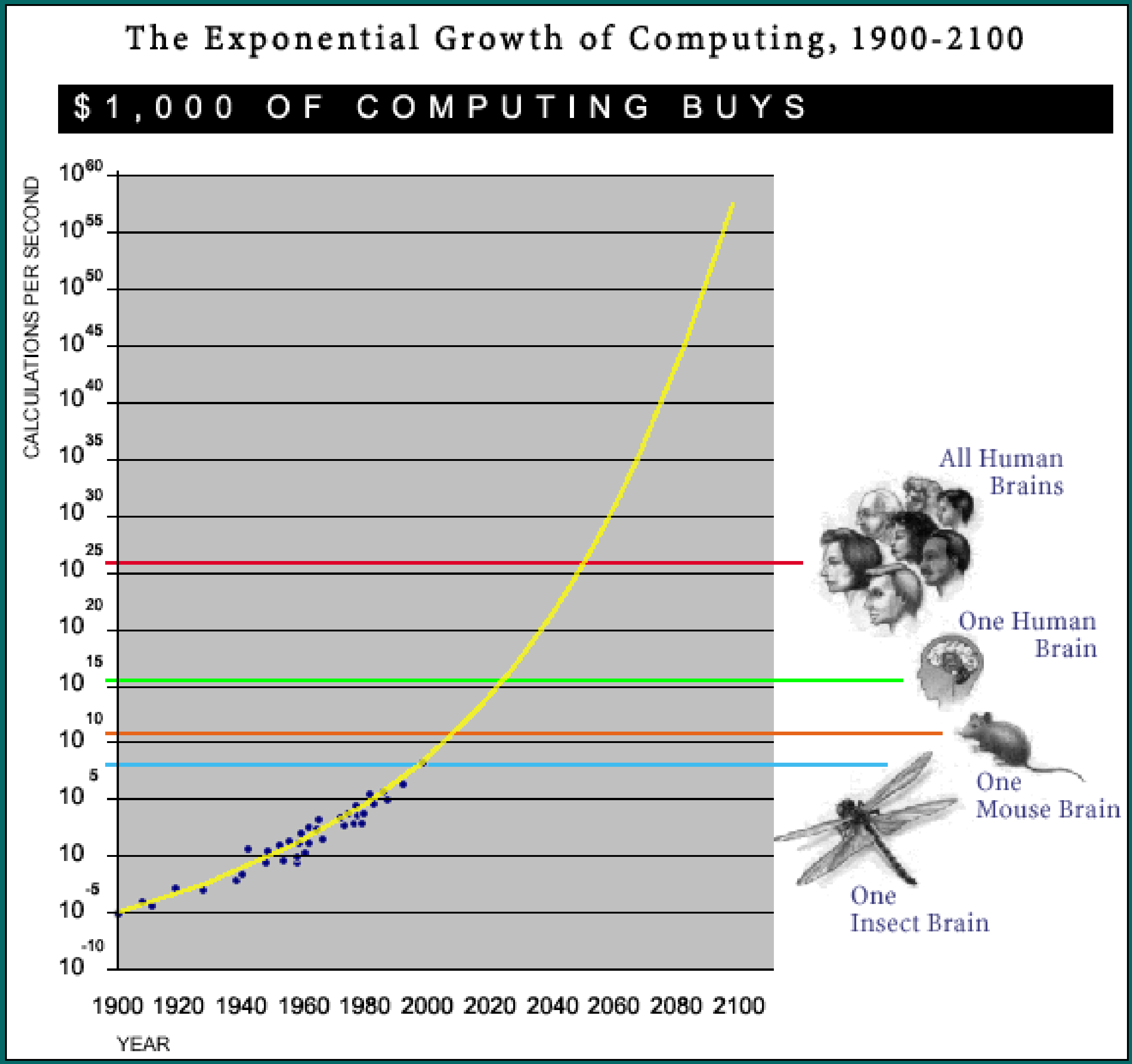
- Gap between popular and scientific views is wide. Will there be a backlash of distrust?
- "Conventional" nanotechnology finding its way to advancing textile performance
- Nanotubes hold great promise. Current difficulties readily surmounted with MM
- Molecular robots are all but made
- The pace of technological progress is accelerating; molecular assemblers will be here sooner than we think, sooner than we're ready for
- MM will provide significant, new capabilities for textile products

Summary

- Molecular manufacturing can address the most important and basic issues of our times. . .
  - Poverty: Food, clothing, shelter
  - Disease and human suffering
  - Peace and security
  - Cleaning and preserving our biosphere
- . . . and the
  - Human intelligence
  - Expansion into space

Thank you!





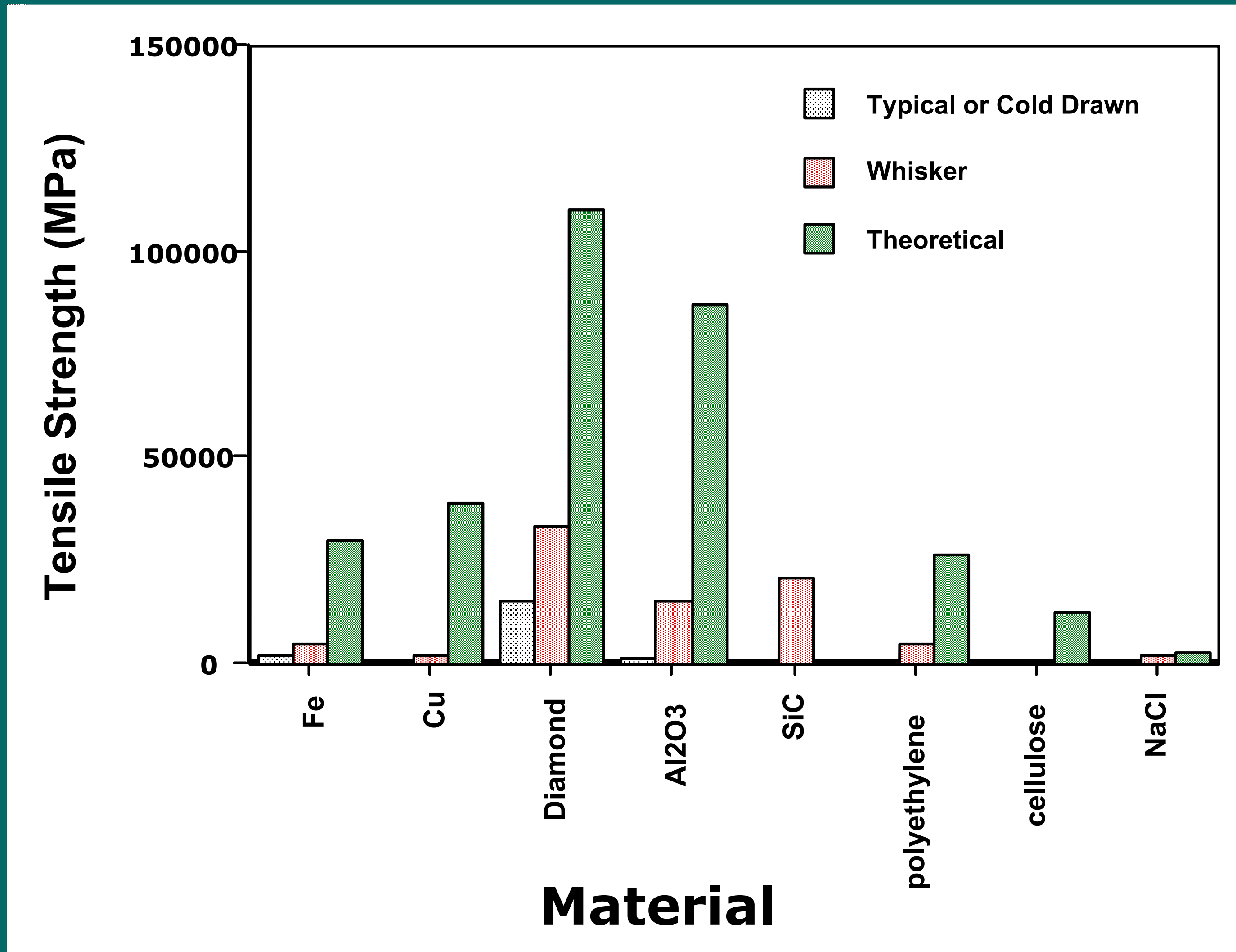
(Exponential Scale)

Double Exponential Growth Through Two Centuries

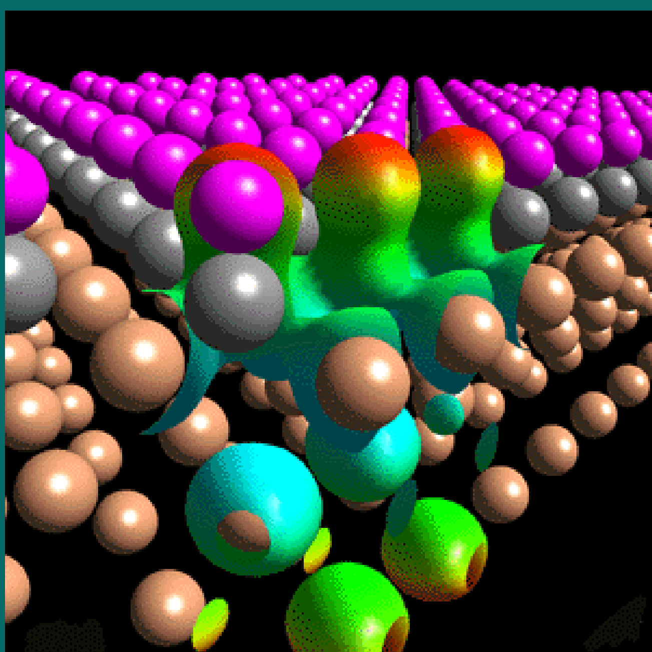
Materials Engineering Implications
Property Improvements

Strong materials

Vehicles, structures 100X lighter



Materials Engineering Implications
Property Improvements

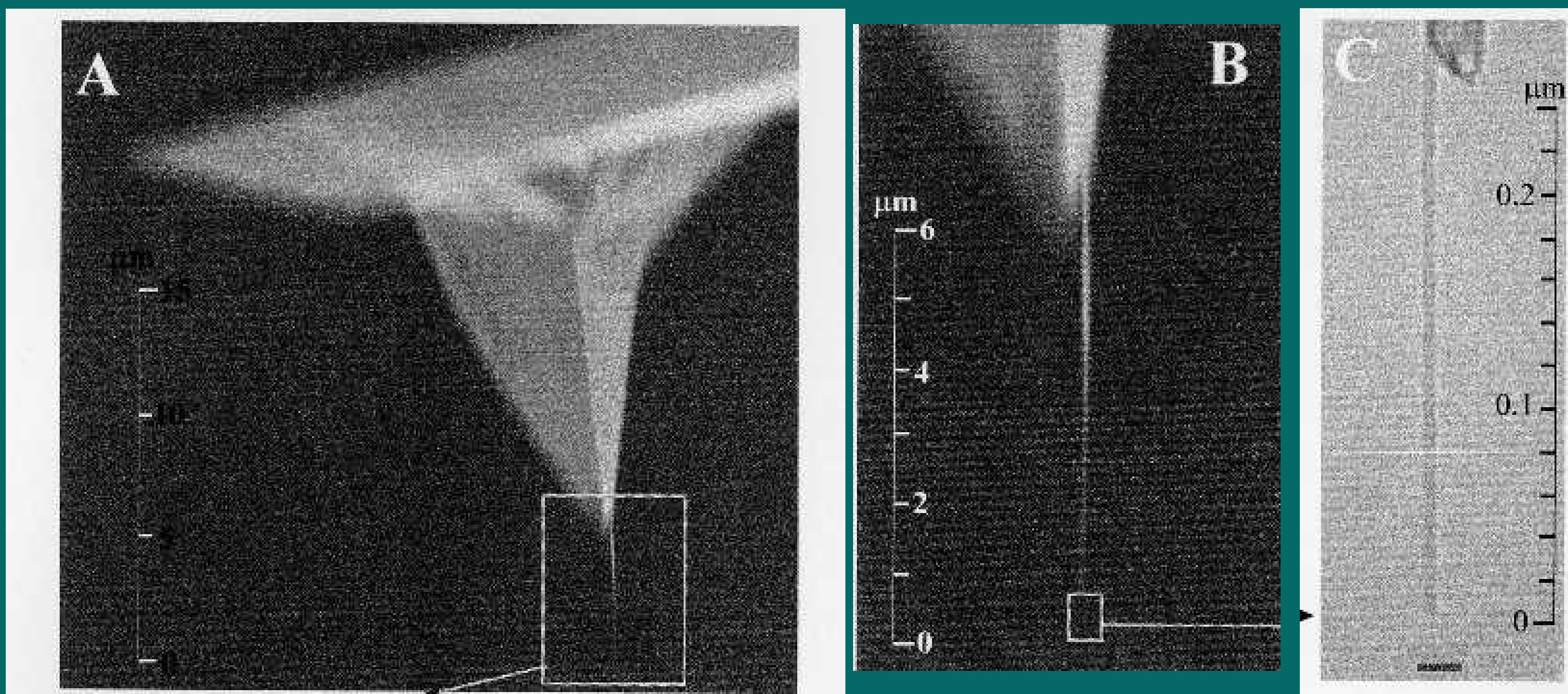


- **Near-Perfect Structures**
  - Excellent toughness (initiators gone)
  - Low friction, low wear (atomically smooth surfaces, contaminants sealed)
  - Good corrosion resistance (initiators gone; coherent, inert terminating surfaces)
  - Good fatigue strength (initiators gone)
  - Reduced creep (no initial dislocations, hard to form)
  - Good oxidation resistance (intermetallics, practical oxides)

Materials Engineering Implications—Structural materials and surfaces

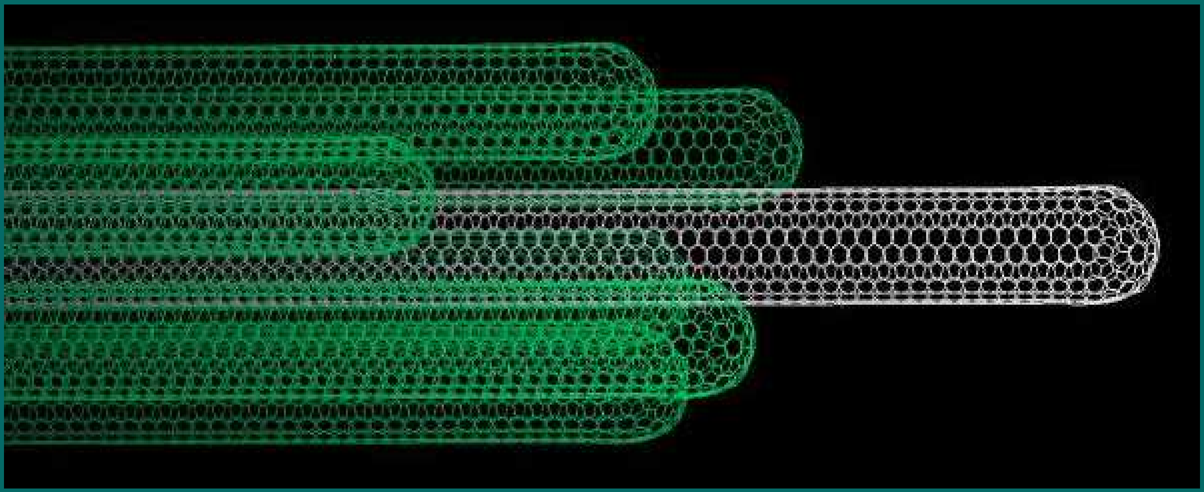
- Armor and structures with the strength of diamond but toughness of a composite, ~10¢/kg
- Atomically smooth surfaces
  - Low friction
  - Low noise
  - Signature
- Atomically engineered surfaces
  - Turbulence control
  - Low noise
  - Actively damped acoustic and optical signature
- Self-repairing systems
  - Sensors
  - Robotics

Carbon Nanotube Used as SPM Tip (Dai et al.)



http://cnst.rice.edu/TIPS_rev.htm

Carbon Nanotubes



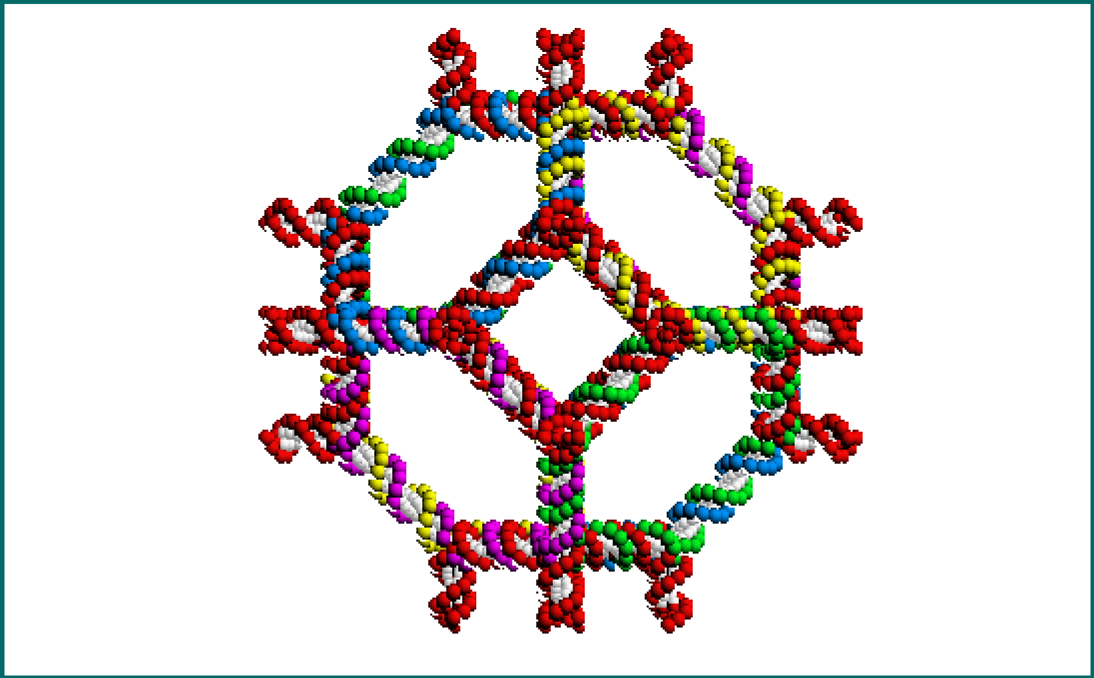
http://cnst.rice.edu/TIPS_rev.htm

Space Elevator

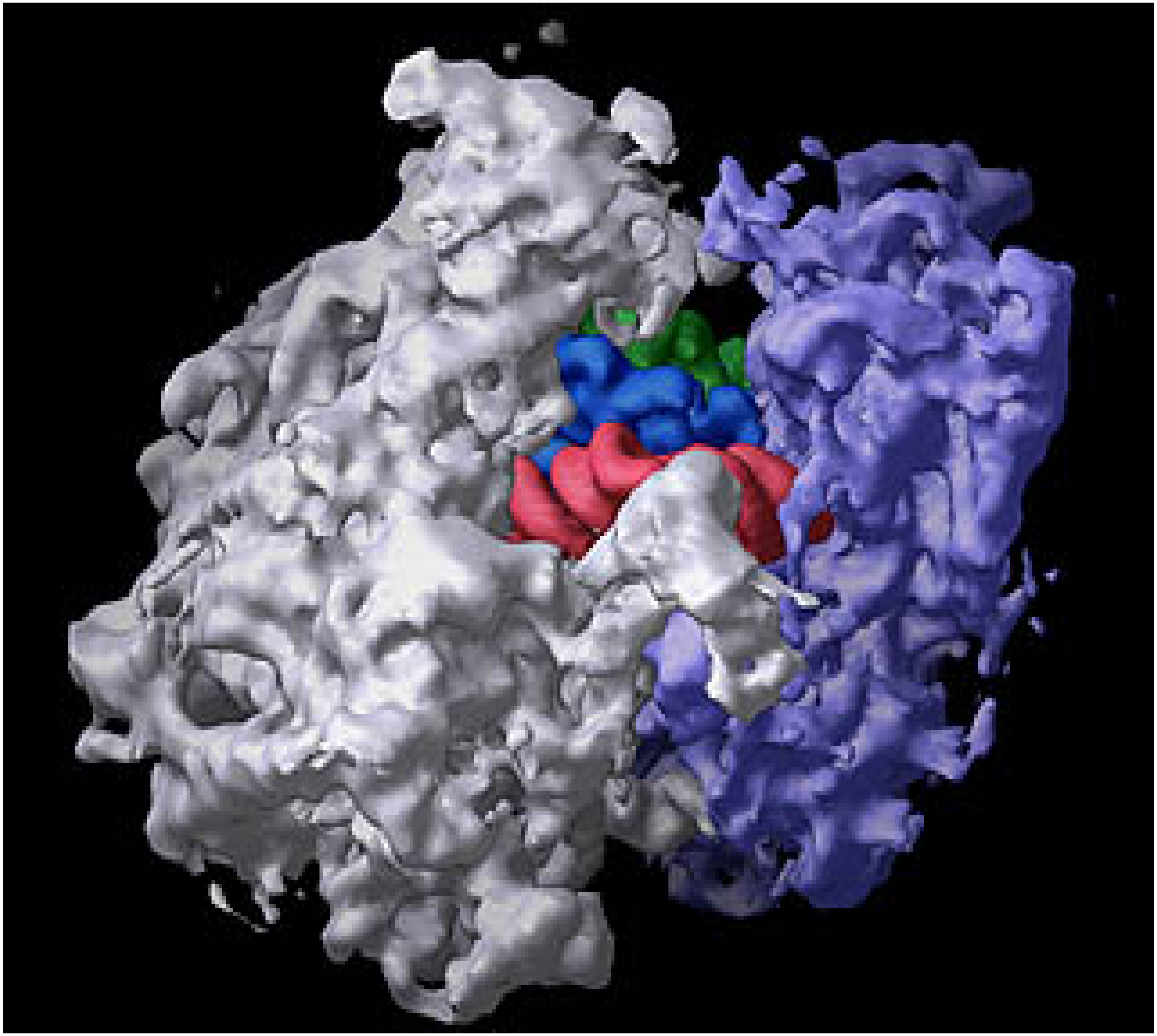
SWNT and MWNT Properties

Property	SWNTs	MWNTs
Tensile Strength	100-200 GPa	up to 63 GPa
Stiffness	1.4 TPa	0.6-1 TPa
Elongation	20-30%	0.5-5%
Electrical Conductivity	Rope: 10^4 S/cm	
Current Density Field-Emission	10^7-10^{13} A/cm^2	?
Pure Electrical Types	Yes	No
Polarizability	Highest known	?
Electron Transport Mechanism	Ballistic	Diffusive
Thermal Conductivity	~6000 W/m·K	<2000 W/m·K

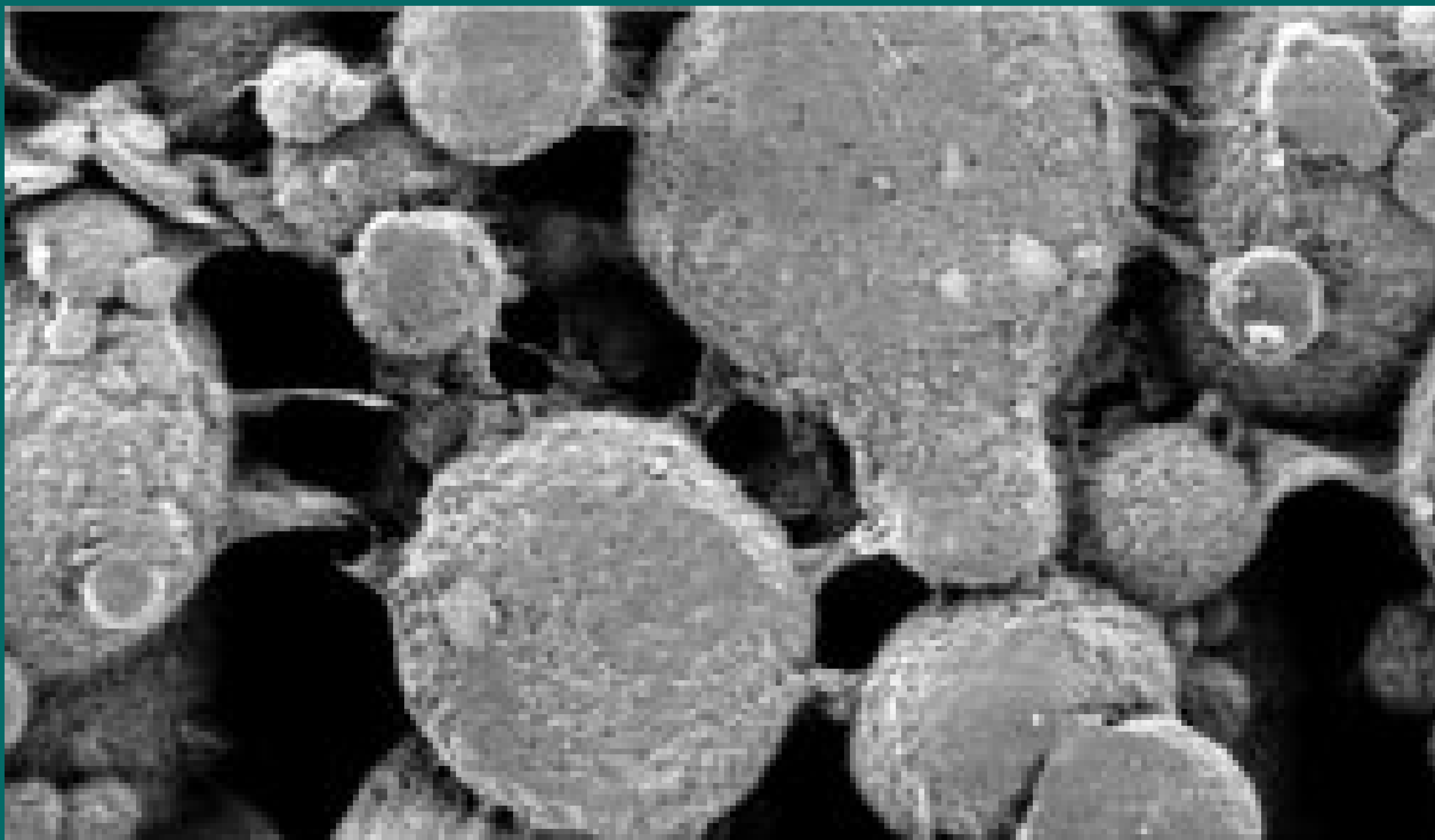
Seeman's Self-Assembled DNA Octahedron



http://seemanlab4.chem.nyu.edu/nano-oct.html



Micelles in Silk
Kaplan, Tufts U.



NanoTex, Stain Repellant