Institute for Molecular Manufacturing

FORESIGHT NANOTECH INSTITUTE
Advancing Beneficial Nanotechnology

Progress in Molecular Manufacturing

David R. Forrest, ScD, PE

13th Foresight Conference on Advanced Nanotechnology
San Francisco, CA
24-27 October 2005

Overview

Vision for Molecular Manufacturing

- Molecular robotic systems
- Products built to atomic precision
- High performance
- Low cost

Overview

State of the Technology

- Mechanosynthesis
  - Experiment
  - Theory
- Molecular machines
- Molecular structures → building blocks
- Biological/inorganic hybrid machines
- Instruments → improved capability
- Computational tools

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.

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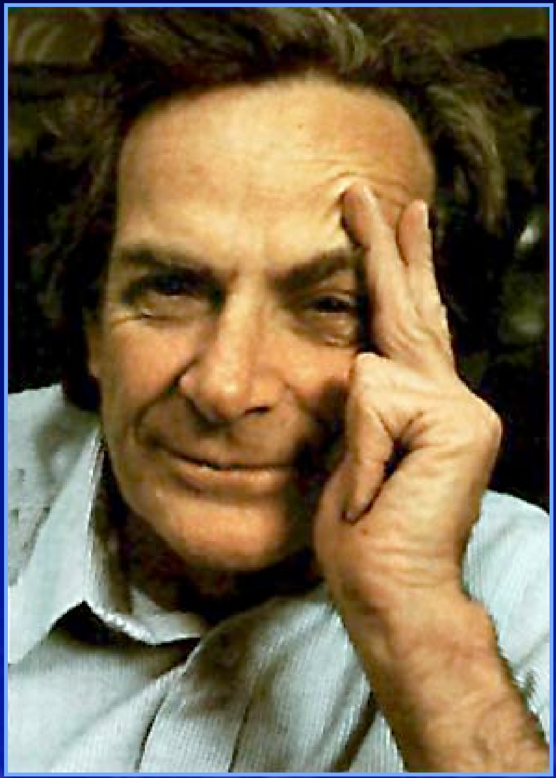
Feynman's Plenty of Room at the Bottom Talk at CalTech

"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



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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

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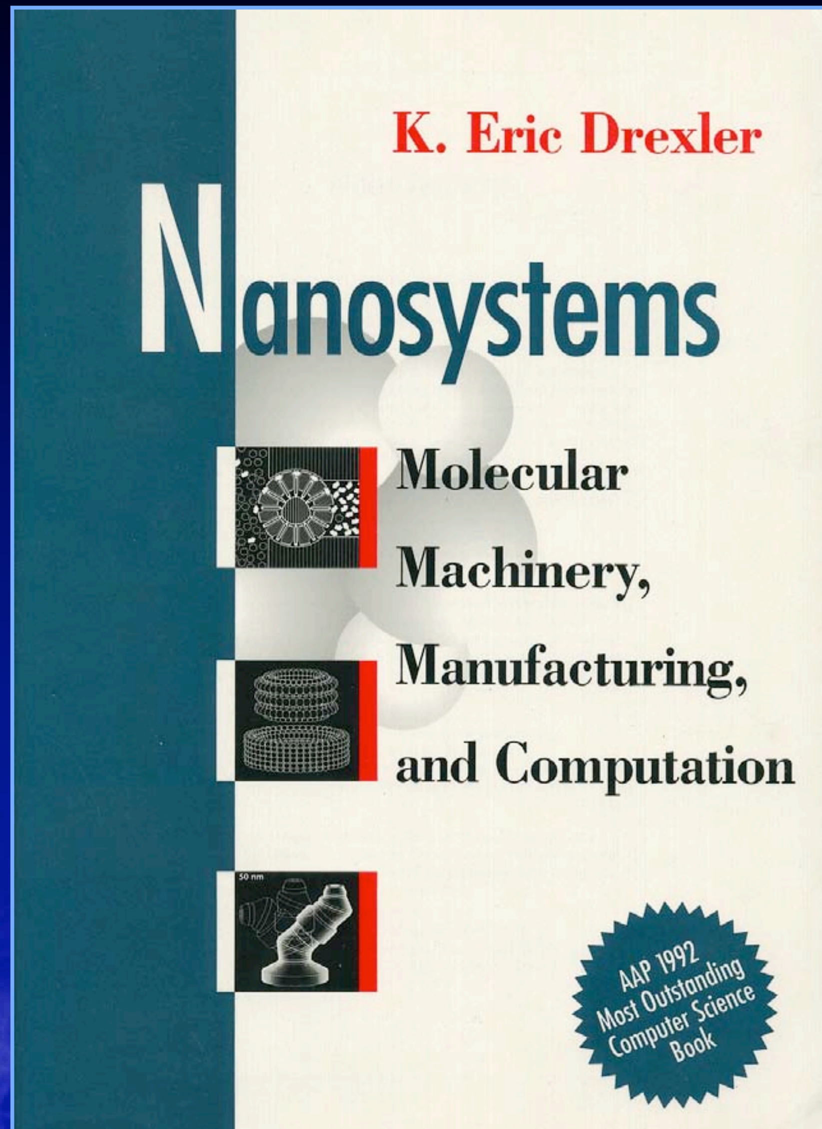

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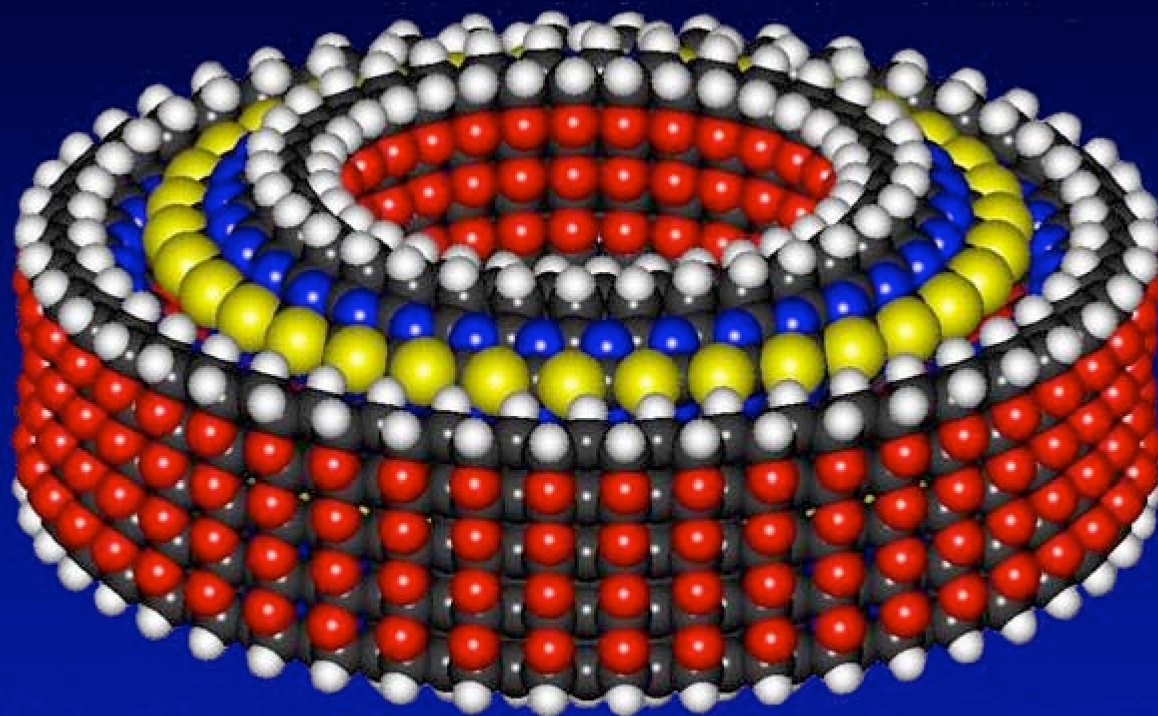
Molecular Bearing



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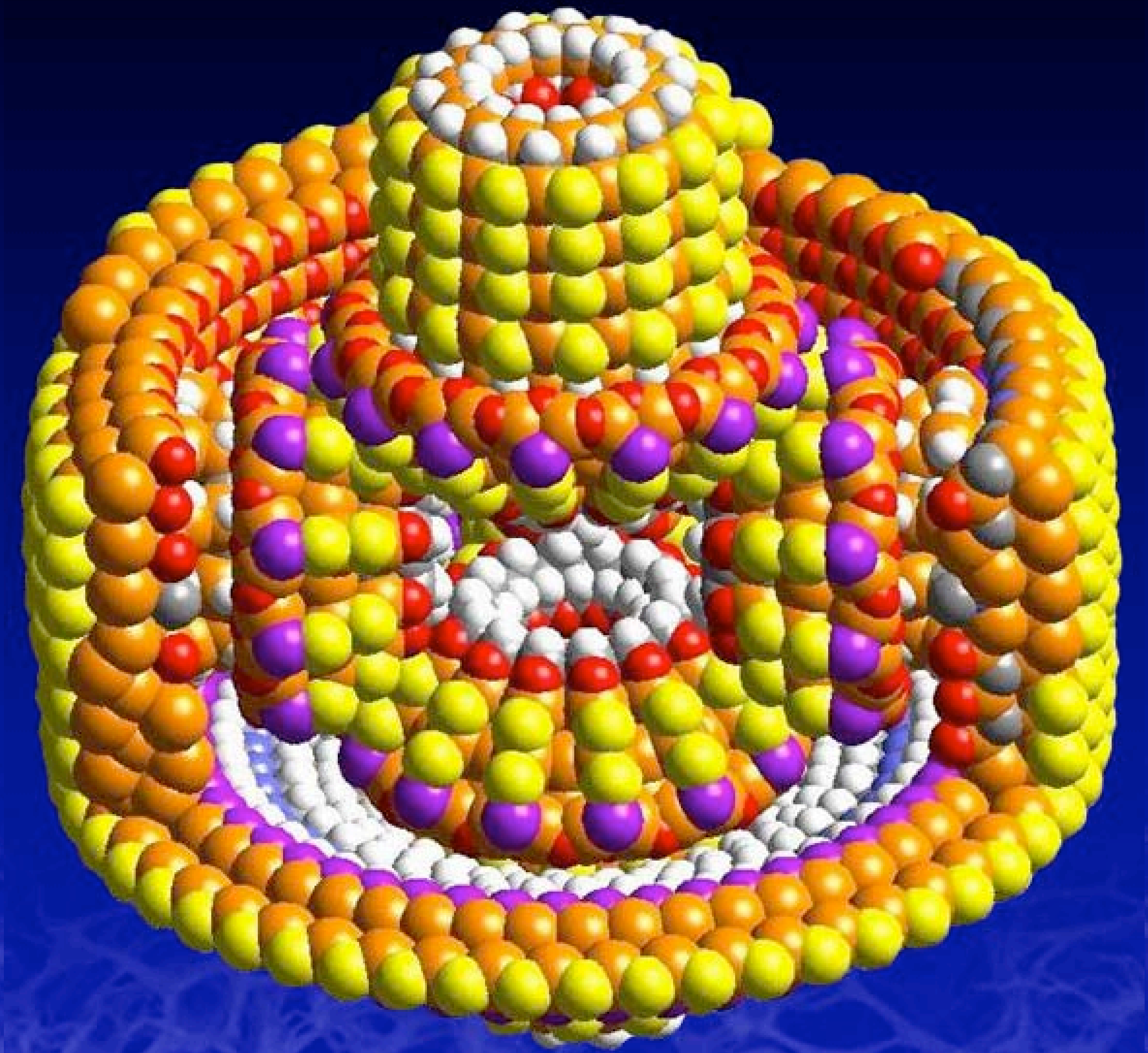
Differential Gear



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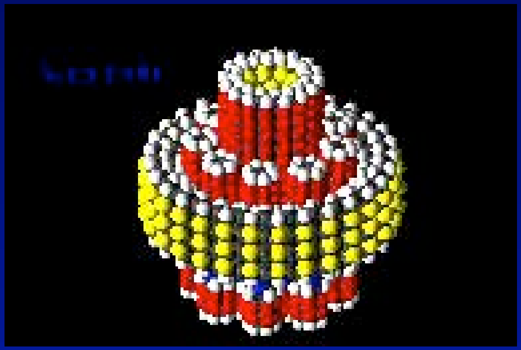
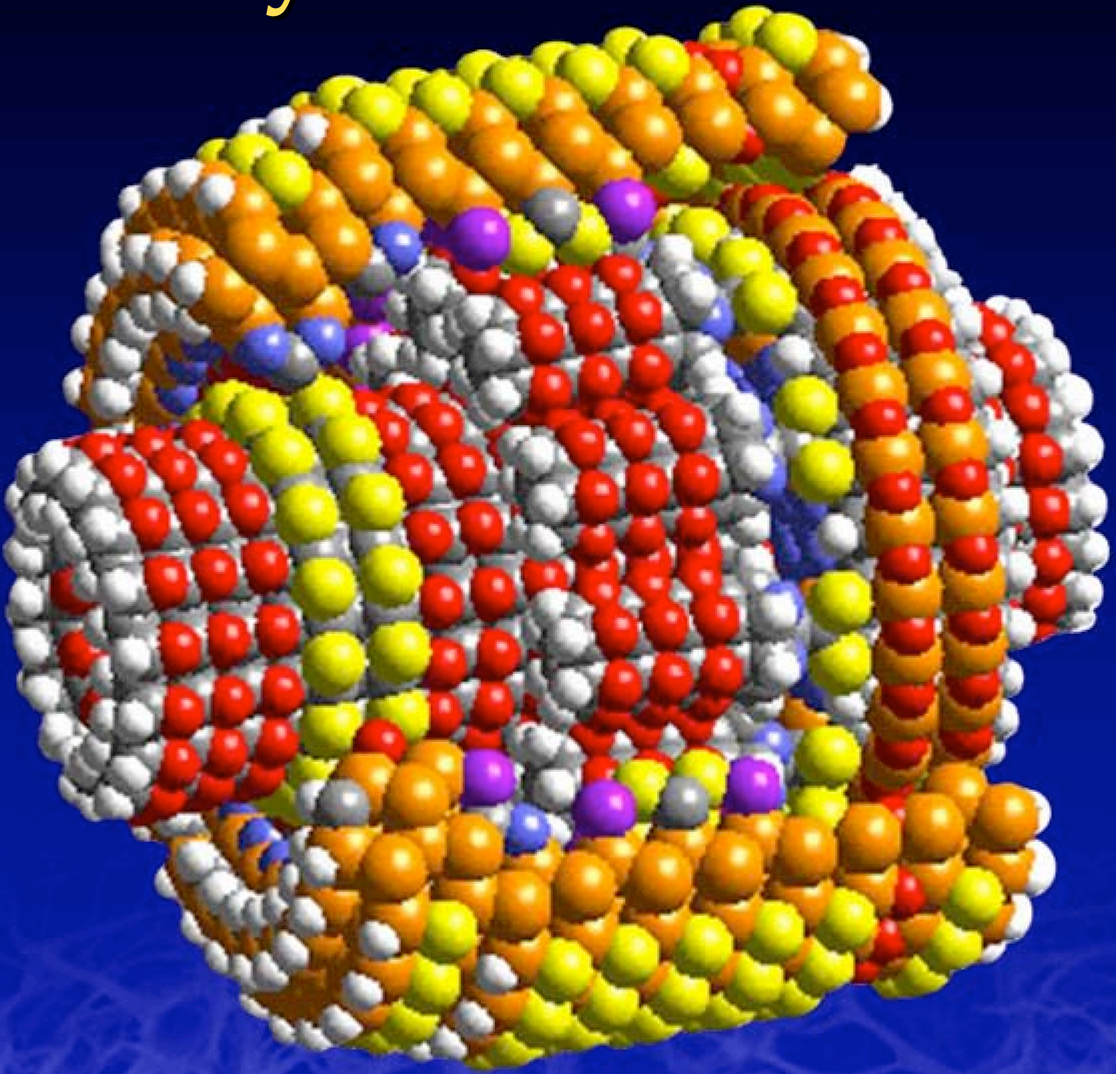
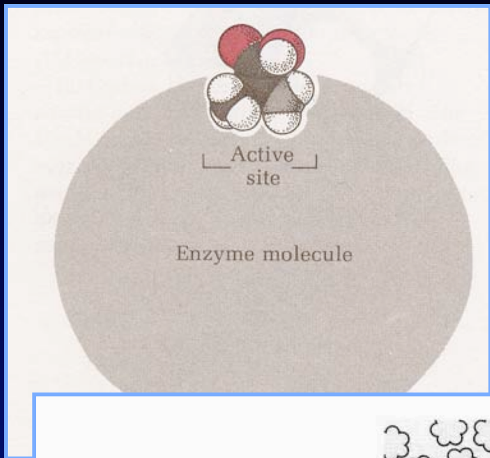
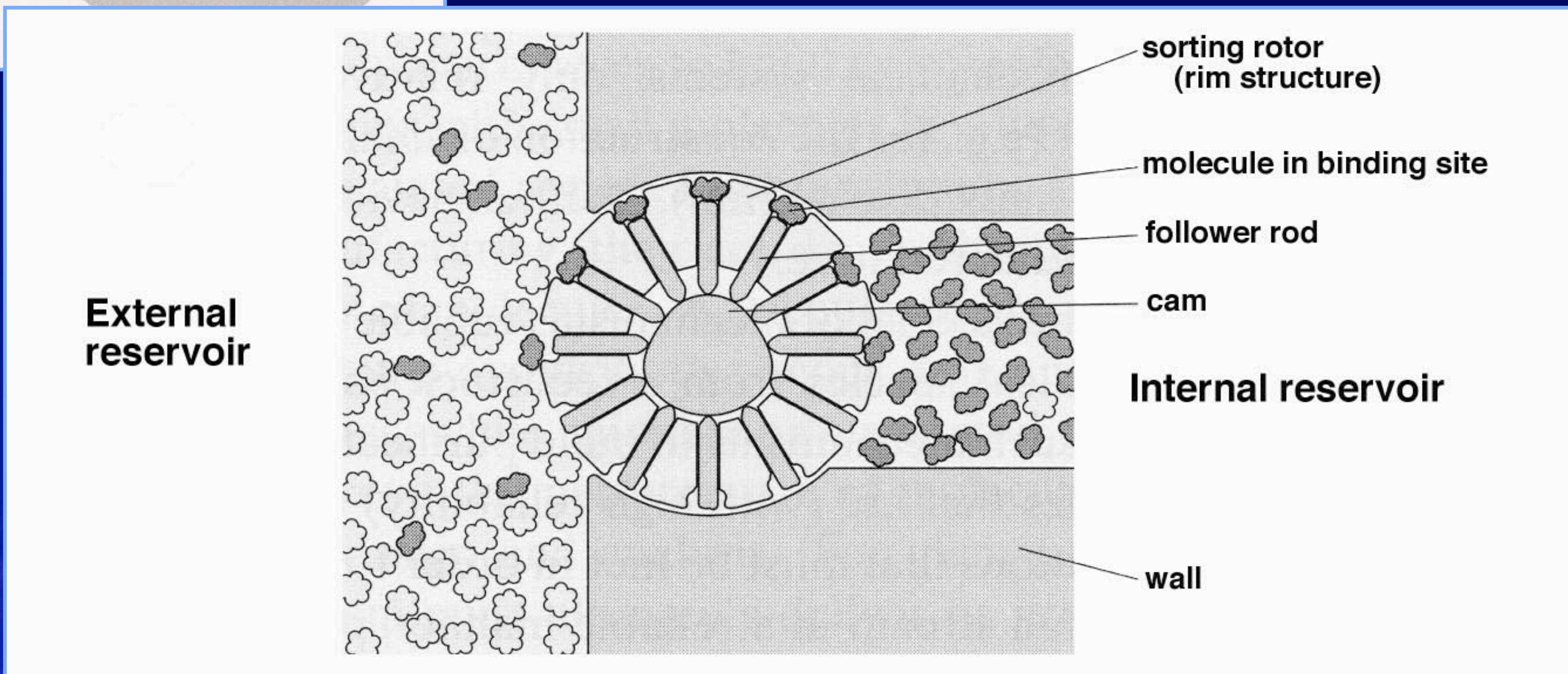
Planetary Gear

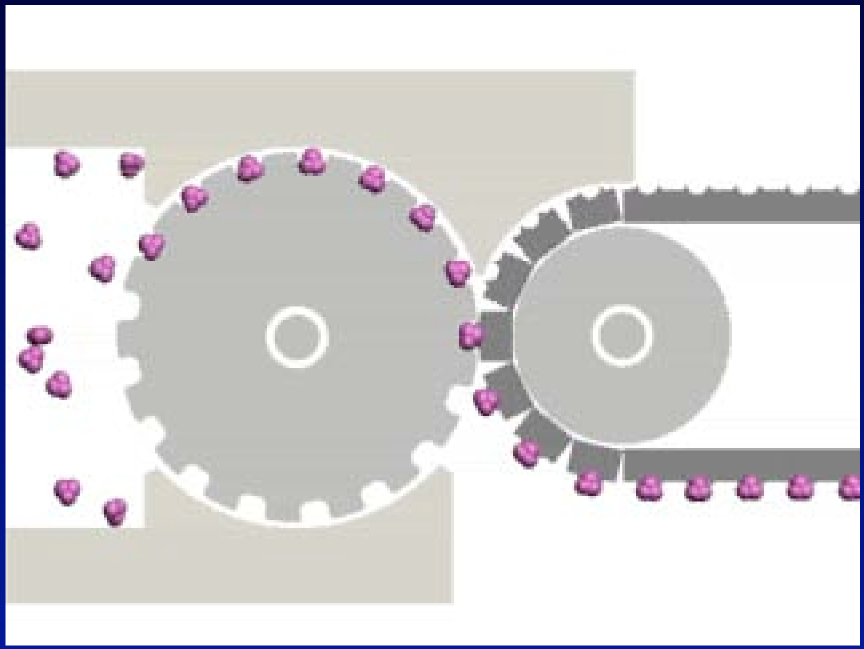




Sorting Rotor







Based on a schematic design in
Nanosystems: Molecular Machinery, Manufacturing, and Computation
by K. Eric Drexler.

Animation: ©2005 Gina Miller.

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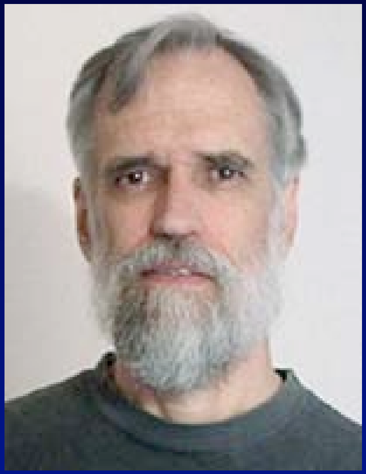
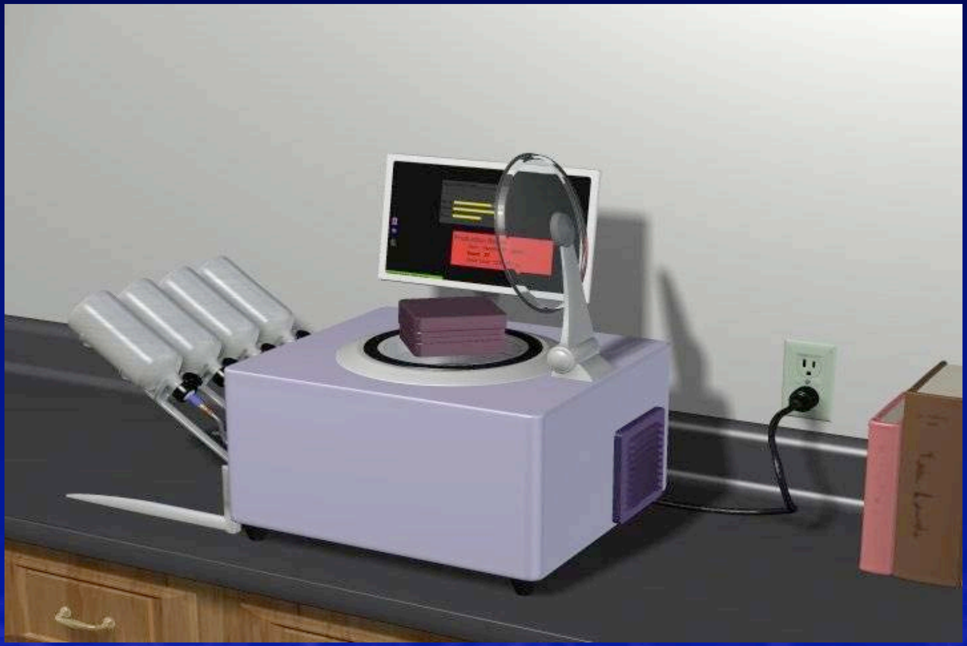
Desktop Assembler Animation



John Burch



Eric Drexler

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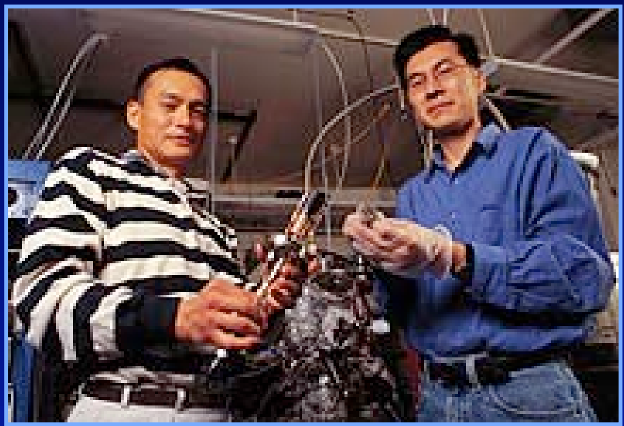
Advances in Molecular Assembly and Molecular Robotics

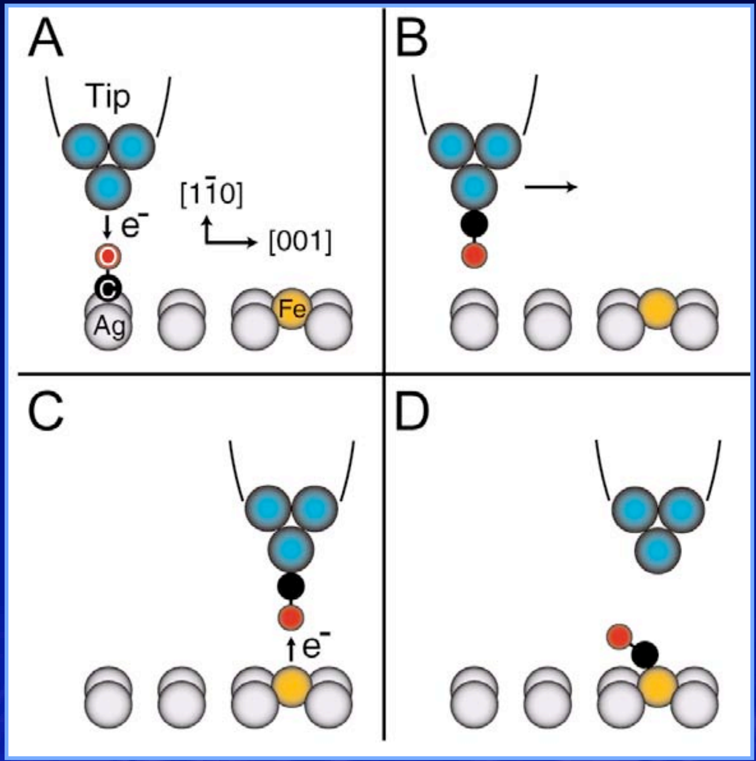
Binnig and Rohrer	Invention of STM
Eigler	Manipulation of atoms
Ho and Lee	Single-molecule assembly
Iijima	Discovery of carbon nanotubes
Ruoff, Banhart	Welding of nanotubes
Biological/Zettl	Molecular motors

State of the Technology: Positional Assembly – Experiment

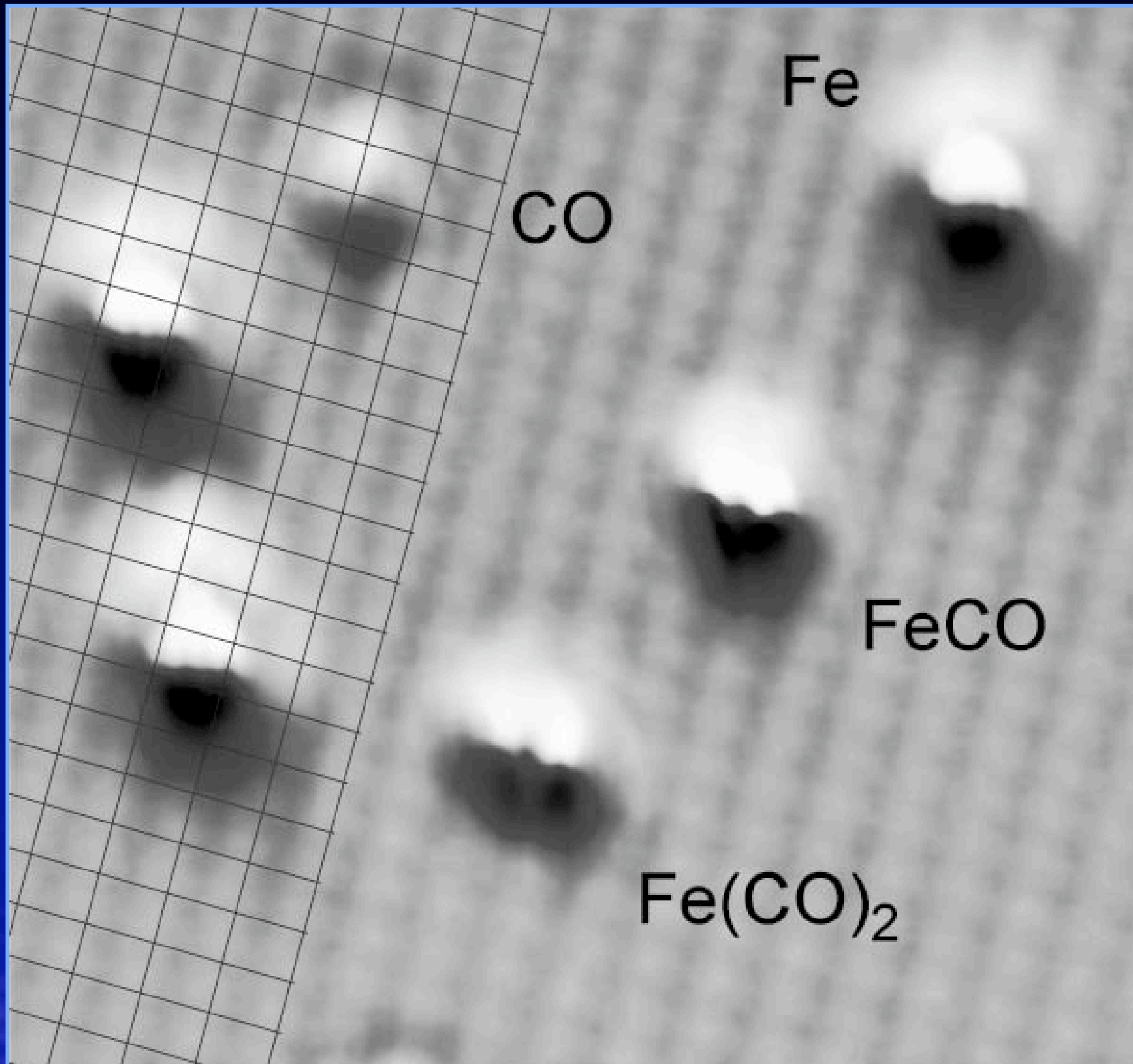
(Ho and Lee, Cornell, 1999)



Wilson Ho and Hyojune Lee

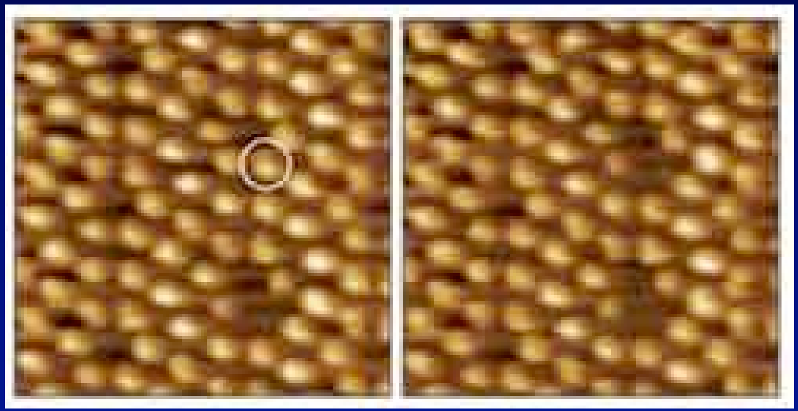


CO bonded to Fe, 13 K


Fe
CO
FeCO
Fe(CO)2

State of the Technology: Positional Assembly – Experiment

Oyabu, et al.,
http://link.aps.org/abstract/PRL/v90/e176102

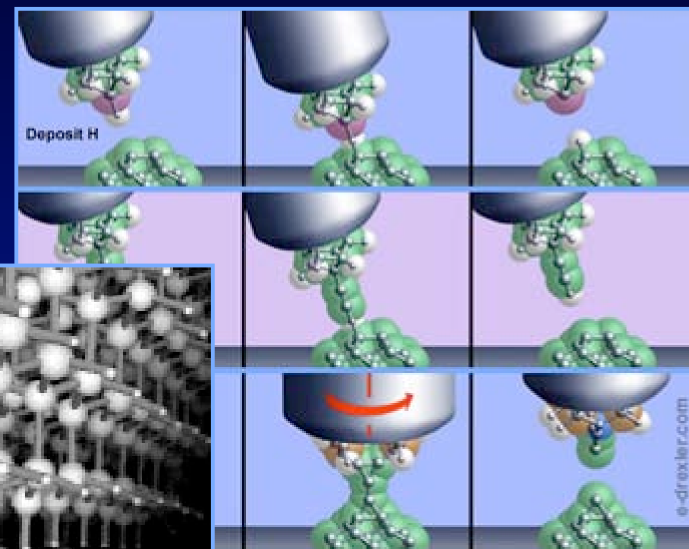


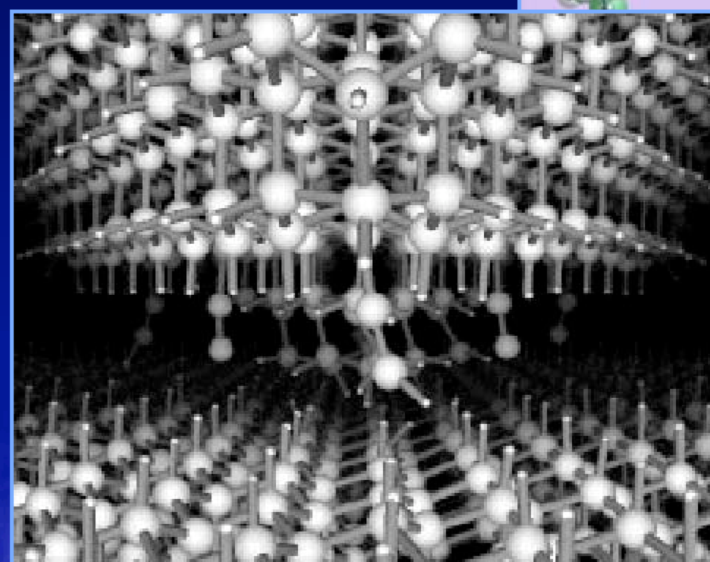
Silicon atom, no voltage

Hersam, M. C., Abeln, G. C., and Lyding, J. W. (1999), "An Approach for Efficiently Locating and Electrically Contacting Nanostructures Fabricated via UHV-STM Lithography on Si(100)," Microelectronic Engineering, 47, p. 235.

State of the Technology: Positional Assembly – Theory

- Musgrave, Brenner
- Merkle, Freitas
- Drexler
- Others

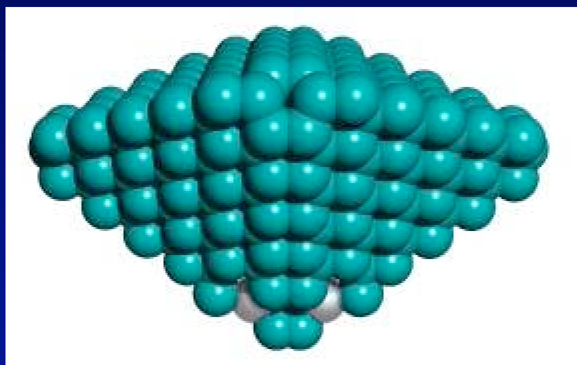


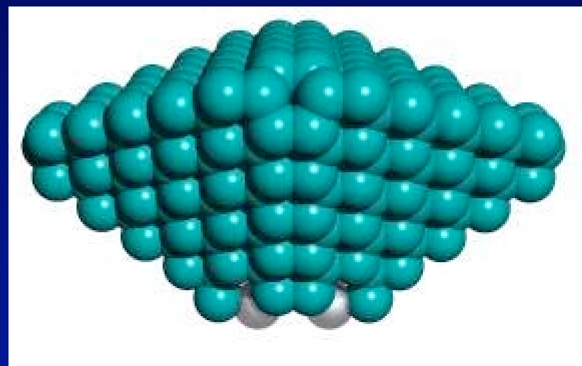


http://www.foresight.org/stage2/mechsynthbib.html

Theory: Diamondoid Mechanosynthesis

http://www.molecularassembler.com/Papers/DMSToolbuildProvPat.htm





U.S. Provisional Patent Application
No. 60/543,802

Robert Freitas

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Theory: Diamondoid Mechanosynthesis

Allis, D.G. and K.E. Drexler (2005) Design and Analysis of a Molecular Tool for Carbon Transfer in Mechanosynthesis, *J. Comput. Theor. Nanosci* **2:**45-55
http://e-drexler.com/p/04/04/0330drexPubs.html

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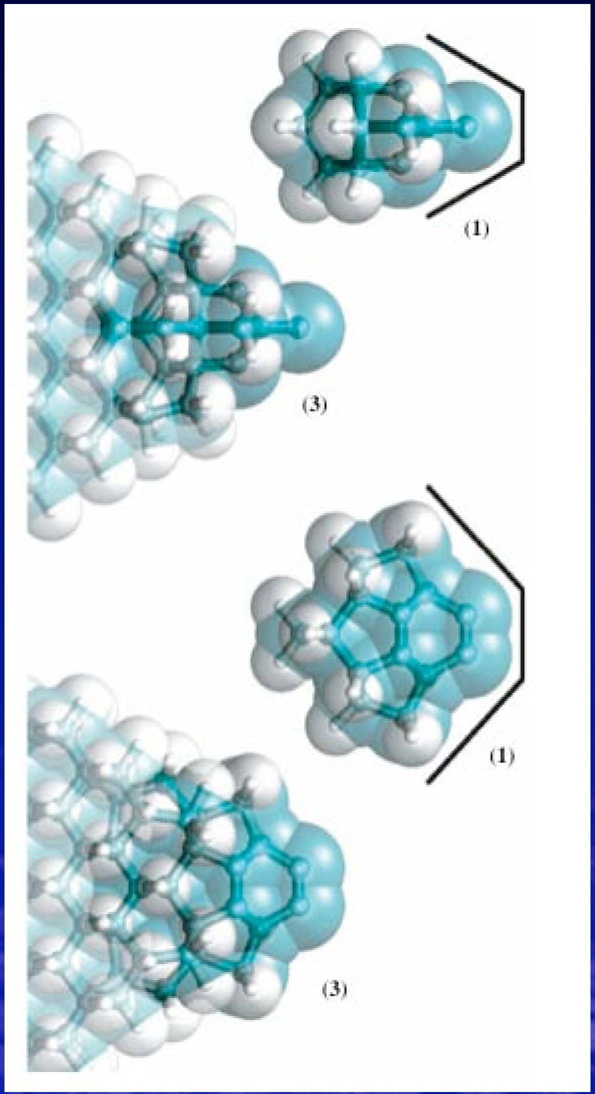
Theory: Diamondoid Mechanosynthesis

Allis, D.G. and K.E. Drexler (2005) Design and Analysis of a Molecular Tool for Carbon Transfer in Mechanosynthesis, *J. Comput. Theor. Nanosci* **2:**45-55

- Tool for building diamondoid structures
- DFT-based analysis
- Extensive treatment of reliability and failure modes



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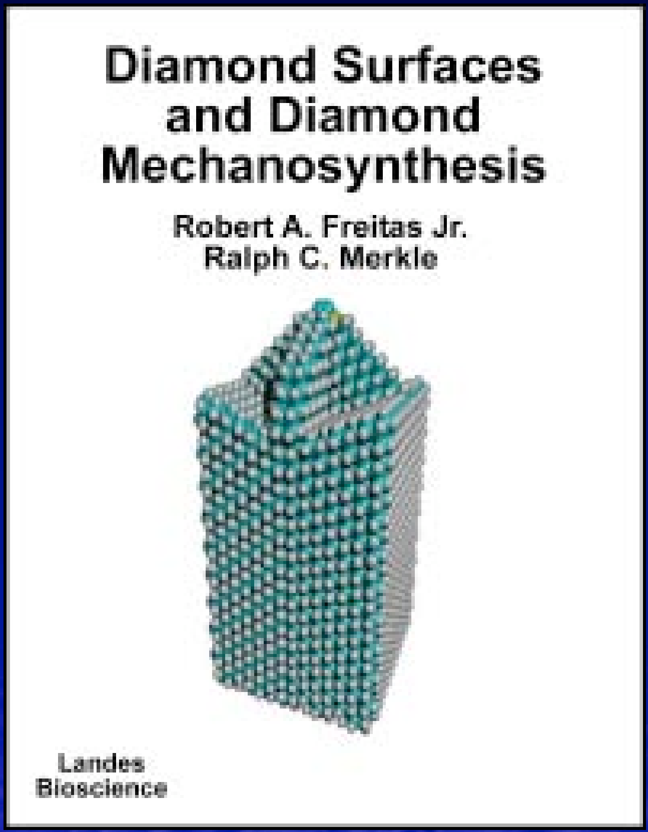
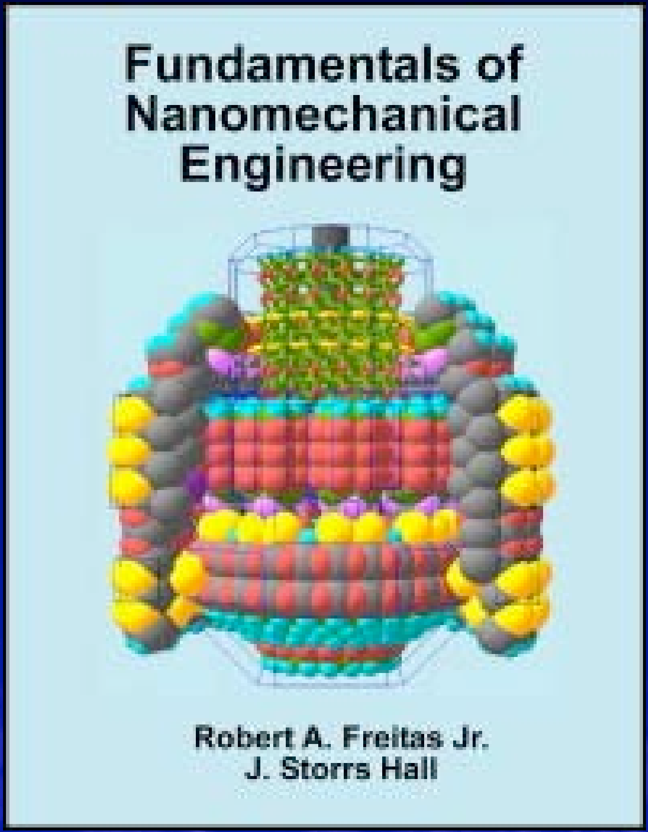
More coming. . .

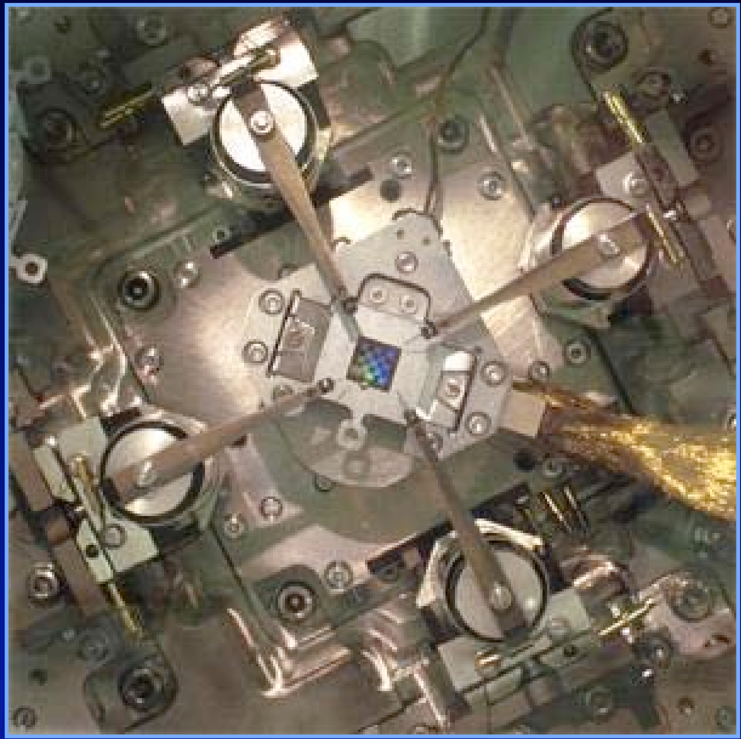


Diamond Surfaces and Diamond Mechanosynthesis
Robert A. Freitas Jr.
Ralph C. Merkle
Landes Bioscience



Fundamentals of Nanomechanical Engineering
Robert A. Freitas Jr.
J. Storrs Hall

State of the Technology: Hardware Omicron 4-head STM/SEM



- 4 SPM heads + SEM
- Repositioning to 30 nm
- 50K to 500K
- UHV

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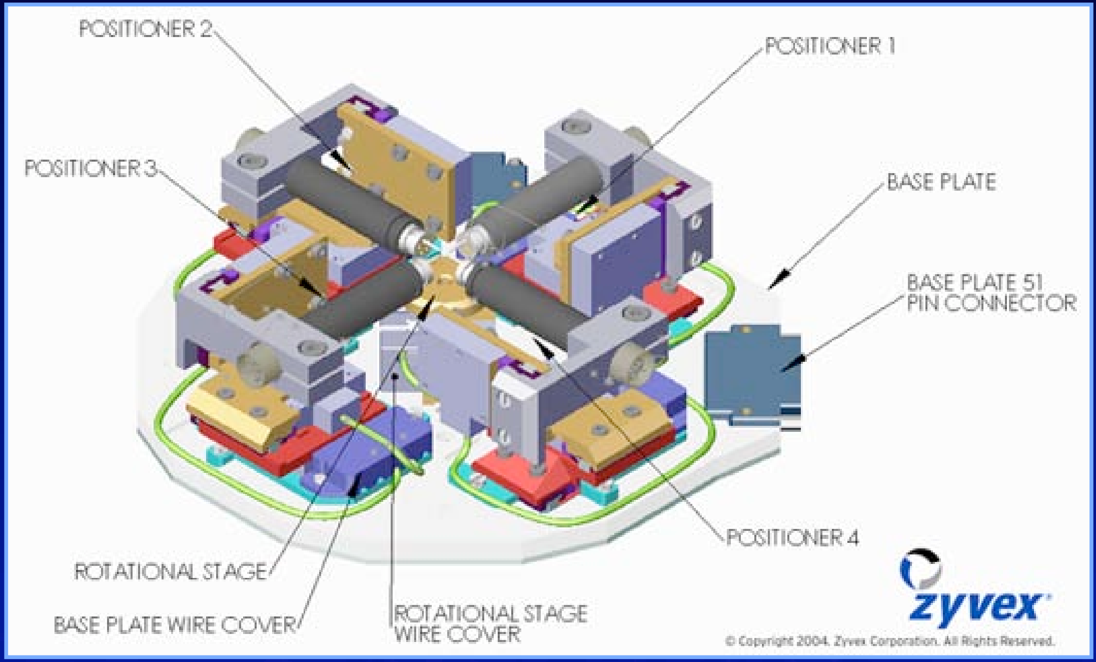
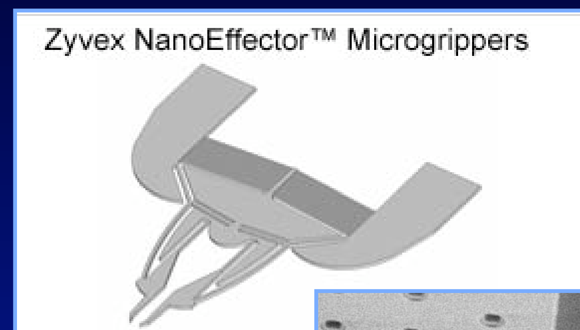
State of the Technology: Hardware Zyvex Nanomanipulators

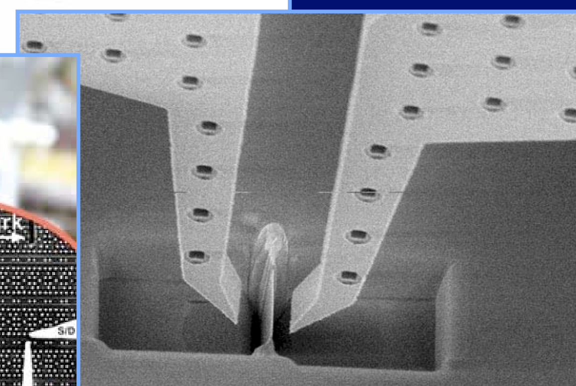
- 4 Positioners
- Retrofit to electron microscopes
- Fine positioning to 5 nm

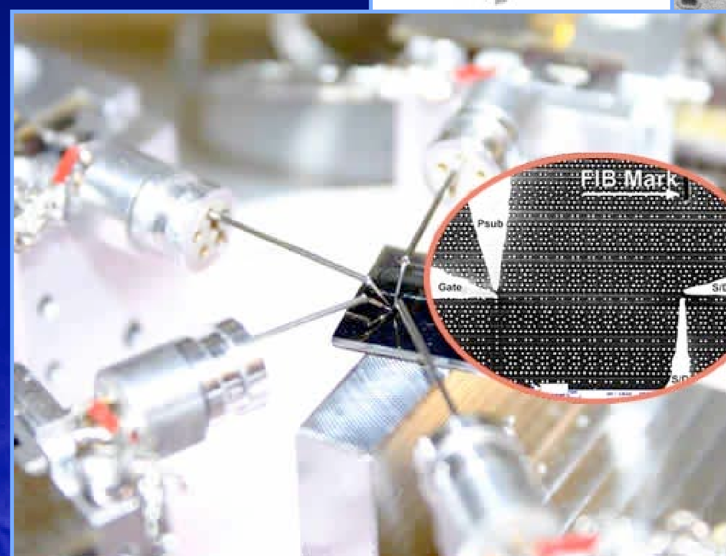


Zyvex Nanoeffector Probes and Microgrippers

- Tungsten wire probe to 65 nm
- Grip 1-500 μm objects



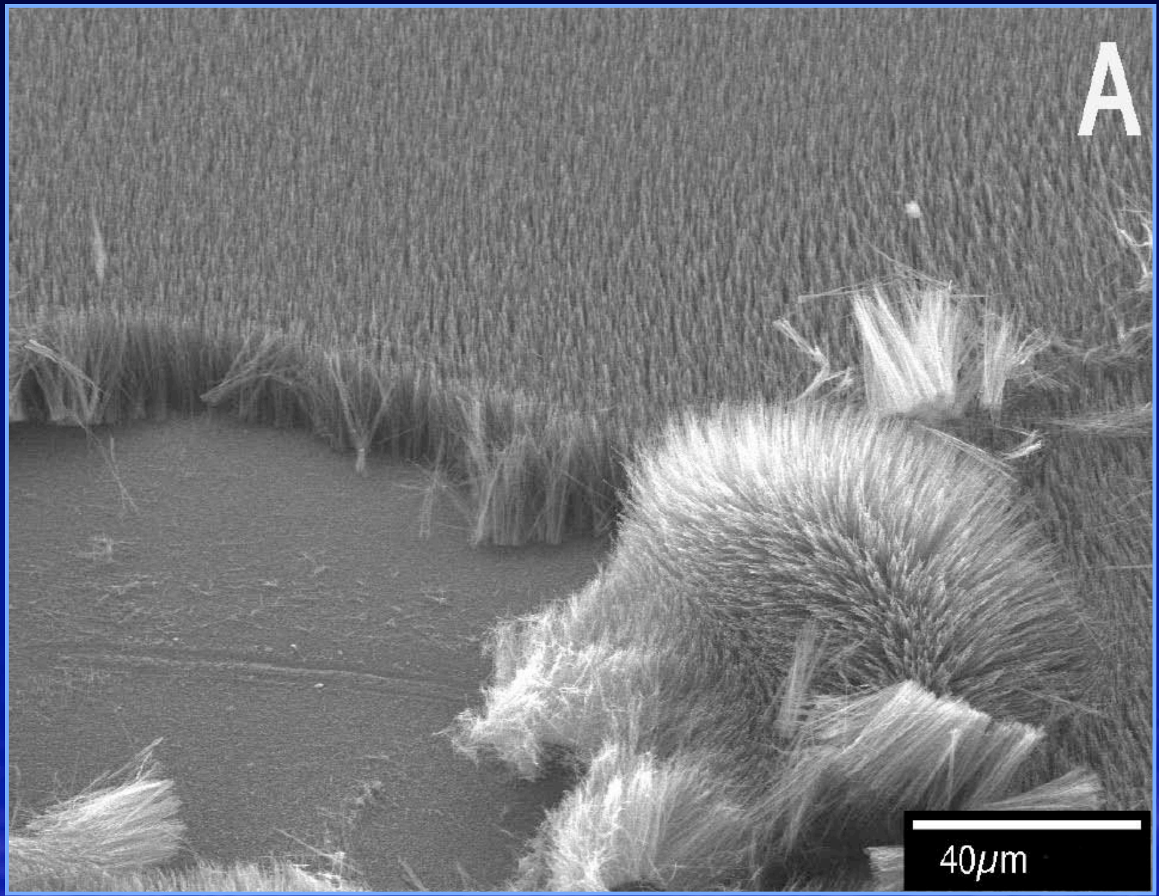




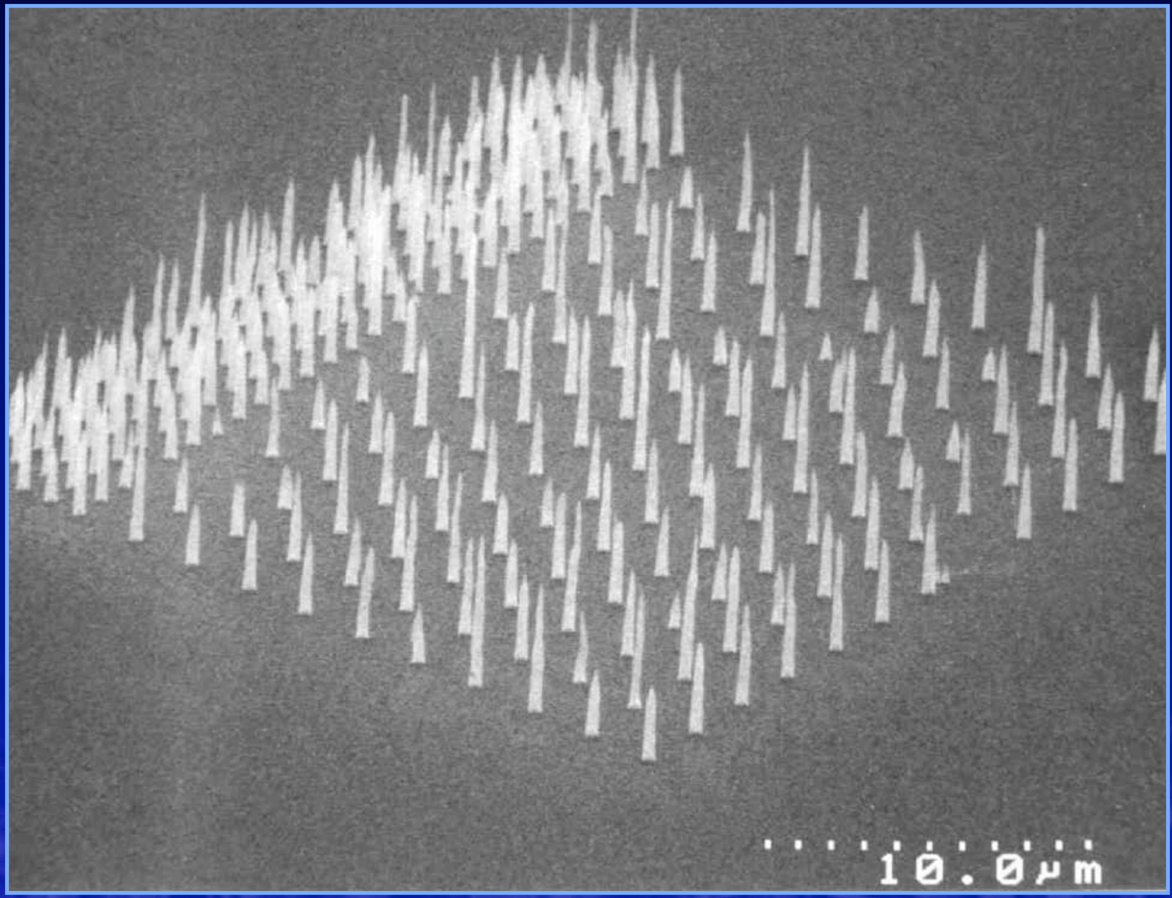
Manufacturing Capability – Exemplified by Nanotube Advances

- Structural members
  - Stiff
  - Strong
  - Join
  - Bend
  - Break
  - Manipulate
- Chemical Reactants
  - Functionalize surface
  - Coat surface
  - Grow from catalysts
- Mechanical Devices
  - Bearings, rotating parts
  - Telescoping arms, sliding parts
- Thermal Devices
  - High thermal conductivity along axis
- Electronic Devices
  - Excellent conductivity
  - High current density
  - Field emitters
  - Can be semiconducting
  - Field effect transistors

Grown to Uniform Length

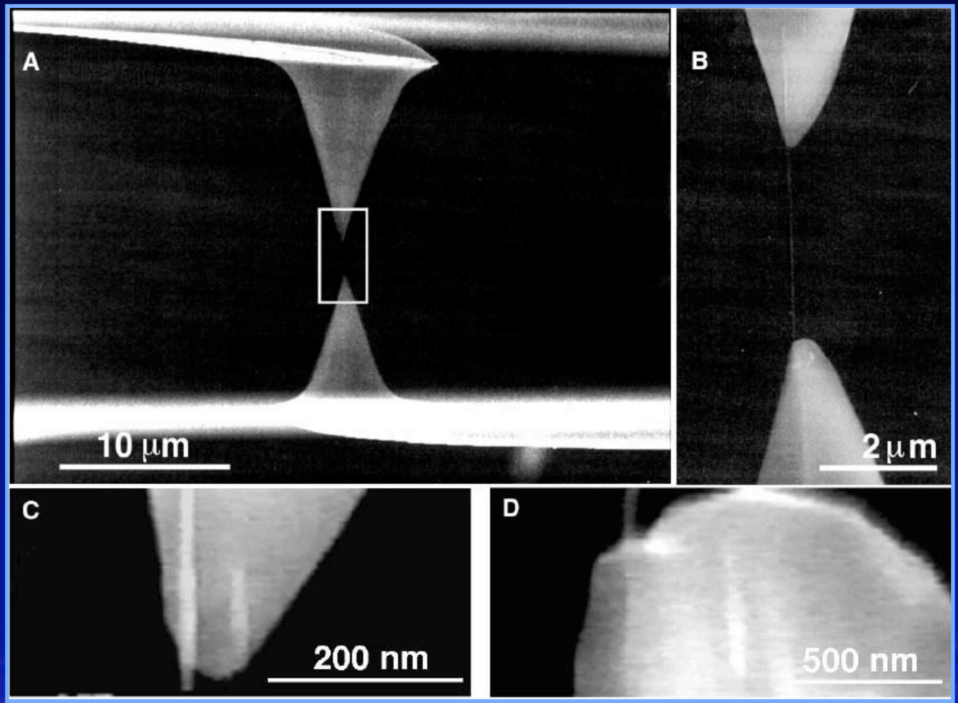


Grown in Arrays



Nanotube Joined to Probe and Tested

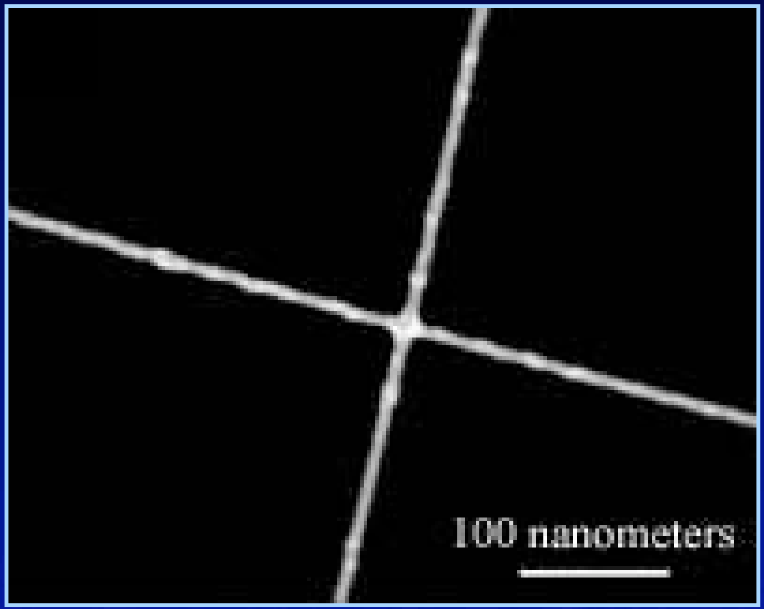
(2000 Ruoff, Northwestern)

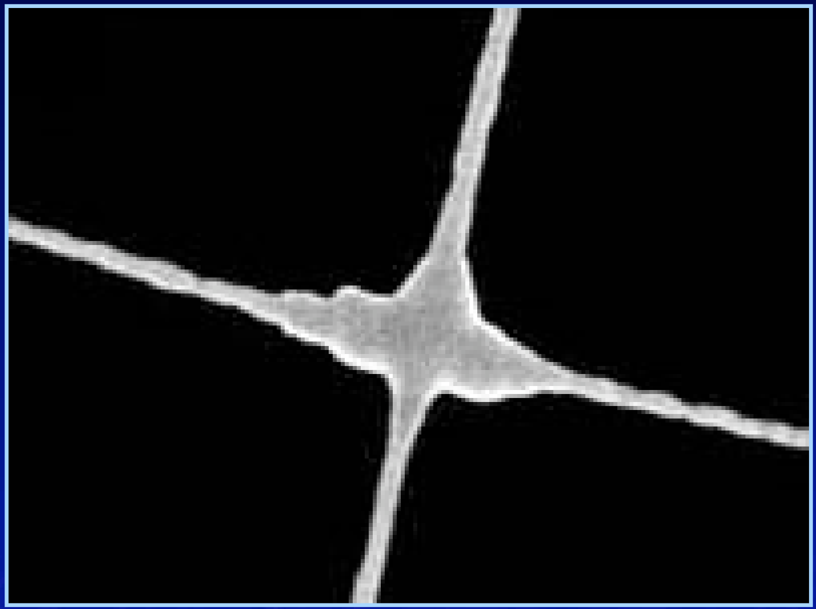


Min-Feng Yu, Oleg Lourie, Mark J. Dyer, Katerina Moloni, Thomas F. Kelly, Rodney S. Ruoff, "Strength and Breaking Mechanism of Multiwalled Carbon Nanotubes Under Tensile Load, *Science*, 287, 28 Jan. 2000, p. 637-640.

Nanotubes Soldered

(2000 Banhart, U. of Ulm, Germany)



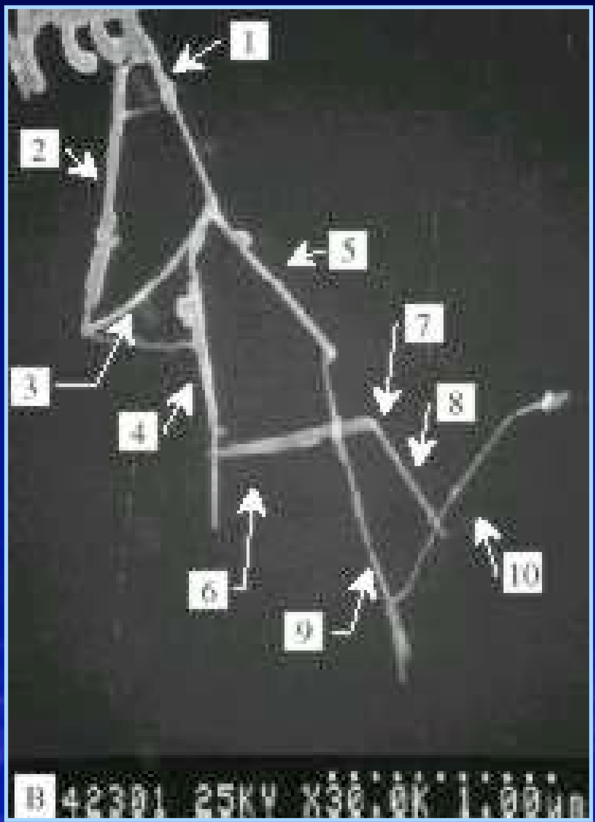


Florian Banhart, "The formation of a connection between carbon nanotubes in an electron beam," Nano Letters 1, 329-332 (2001).

Nanotube Scaffolding and Weaving

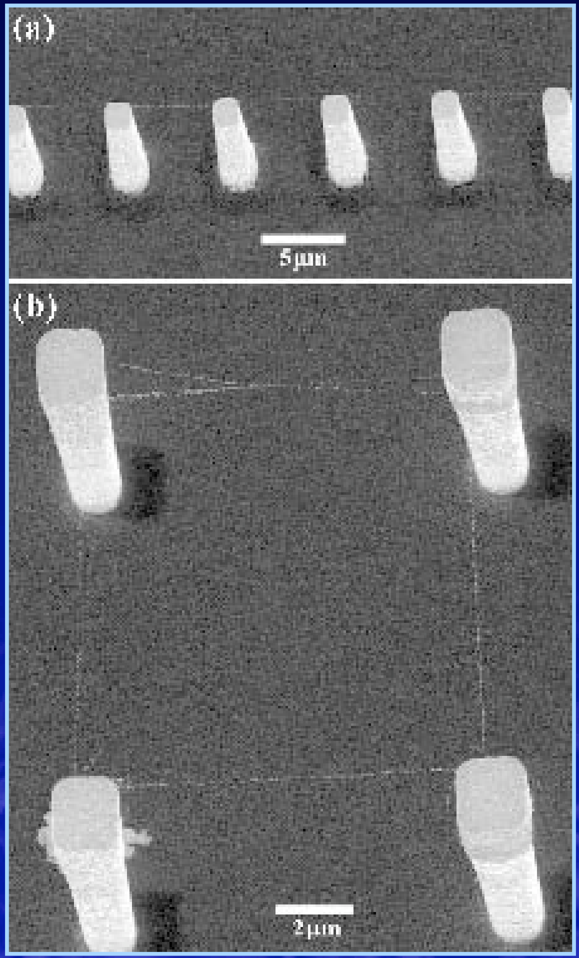
Skidmore, et al., 1999

http://people.nas.nasa.gov/~globus/papers/NanoSpace1999/paper.html



Nanotubes Between Silicon Towers

(Cassell, et al., 1999)



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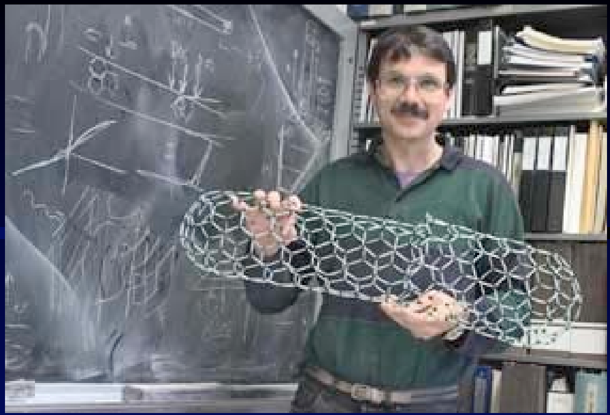
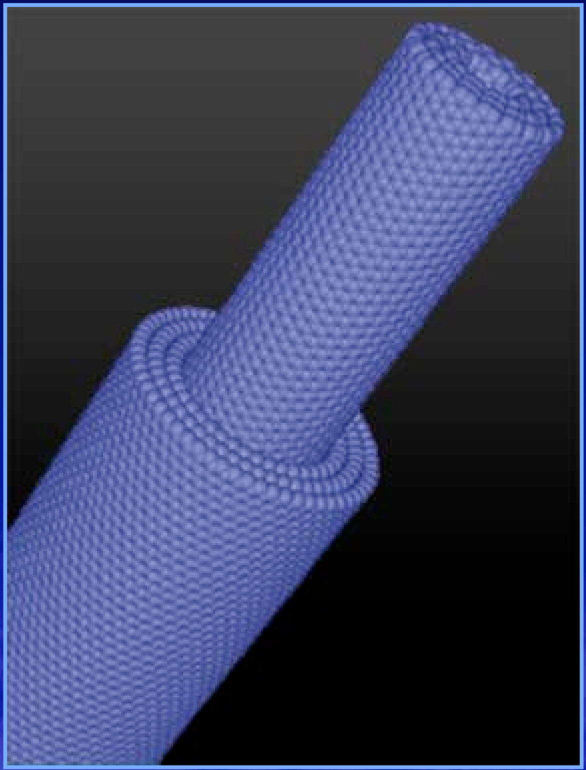
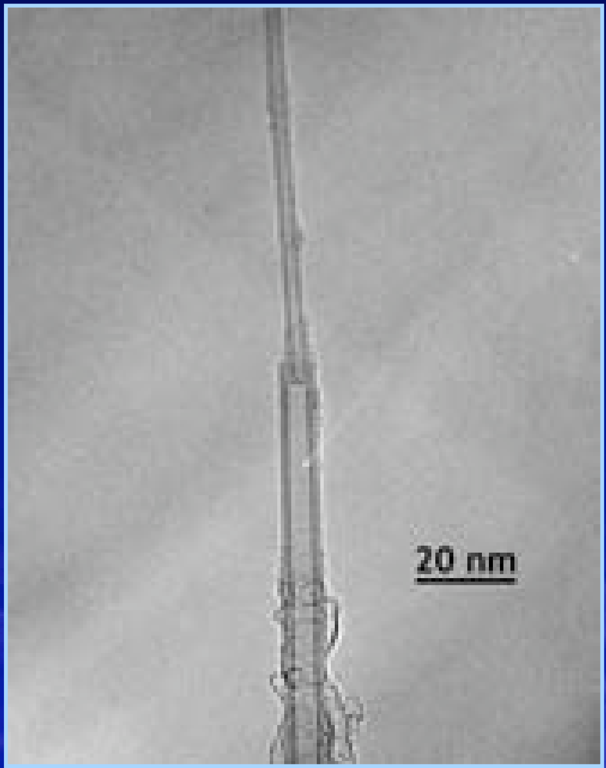
Telescoping Nanotubes

(Zettl, Lawrence Berkeley Laboratory, 2001)

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

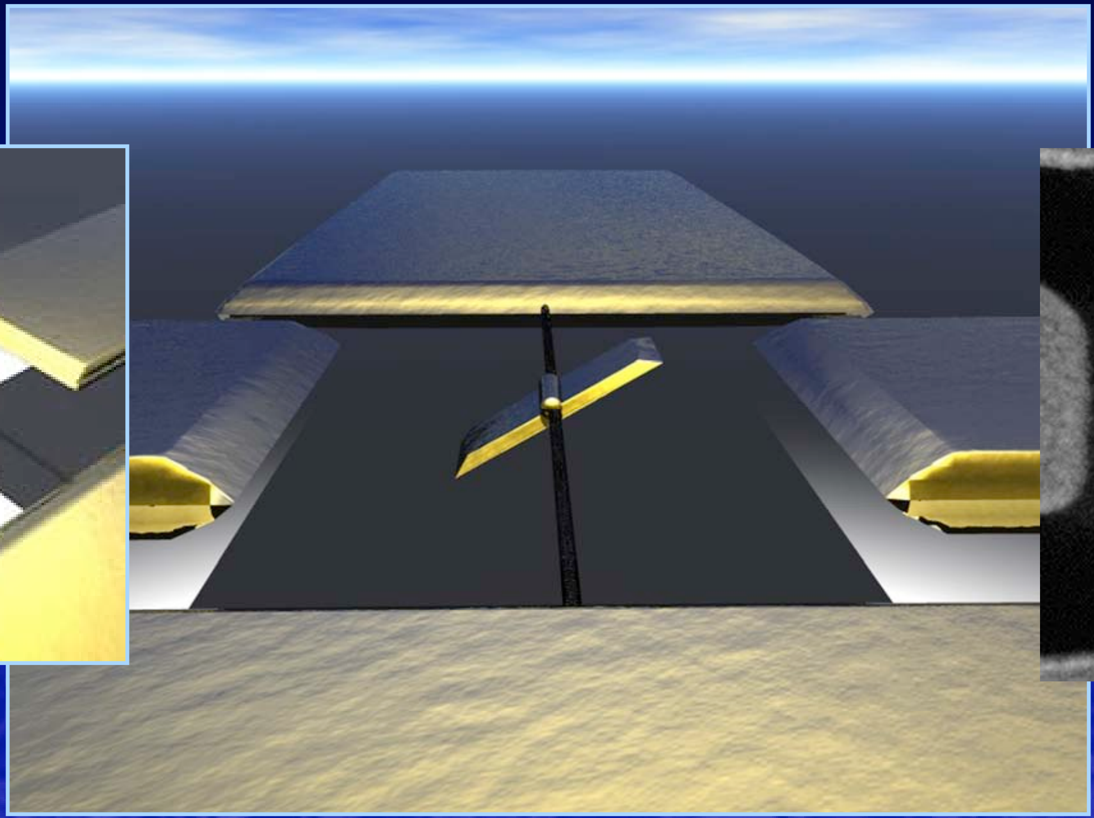


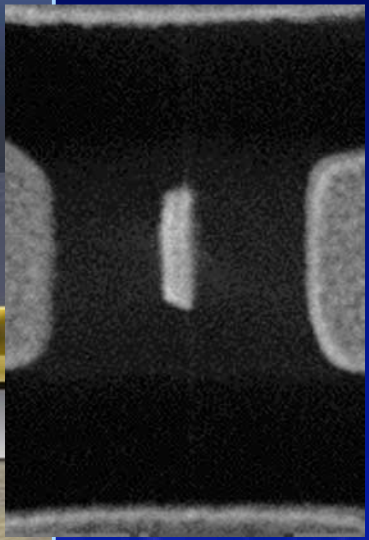




Molecular Motor

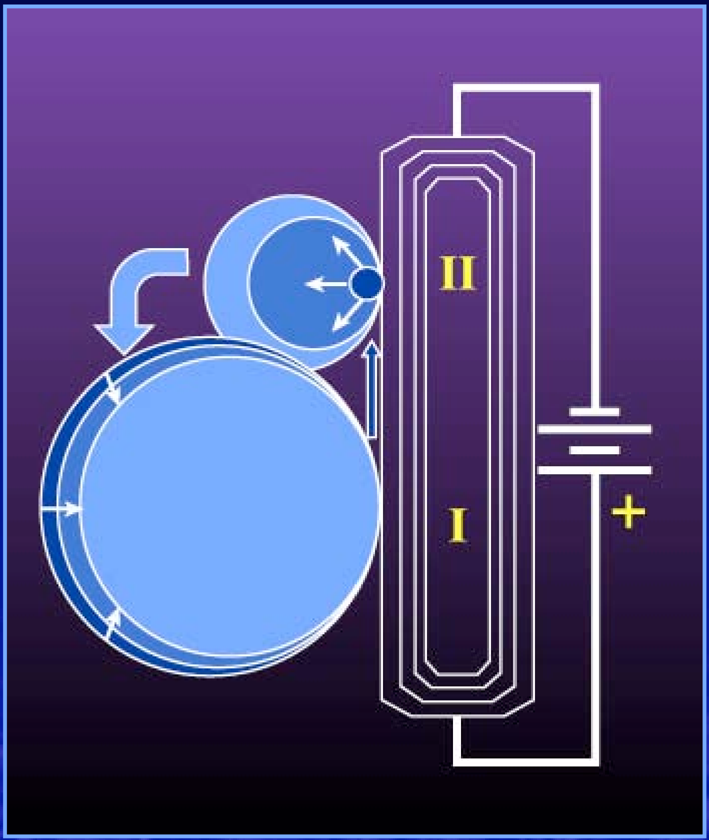
(Zettl, LLNL and U.C. Berkeley, 2003)

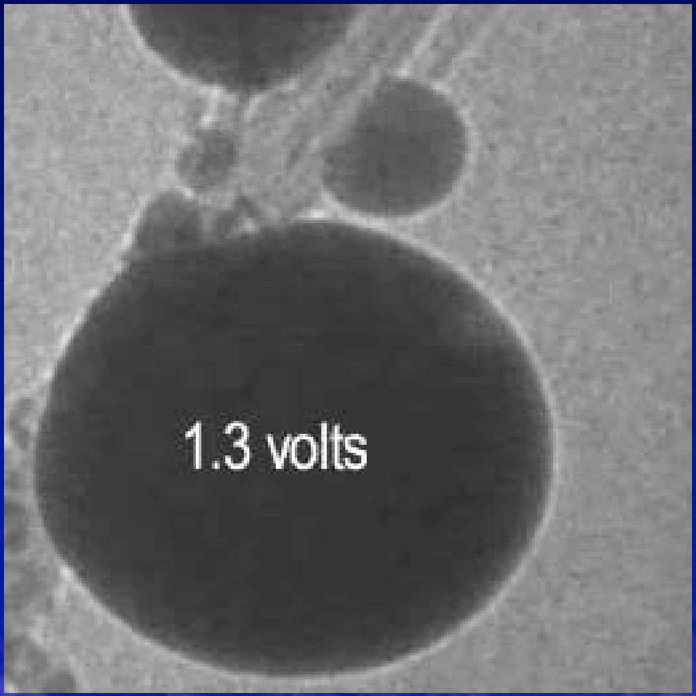




Nanoelectromechanical Relaxation Oscillator

(Regan, et al., U.C. Berkeley, 2005)

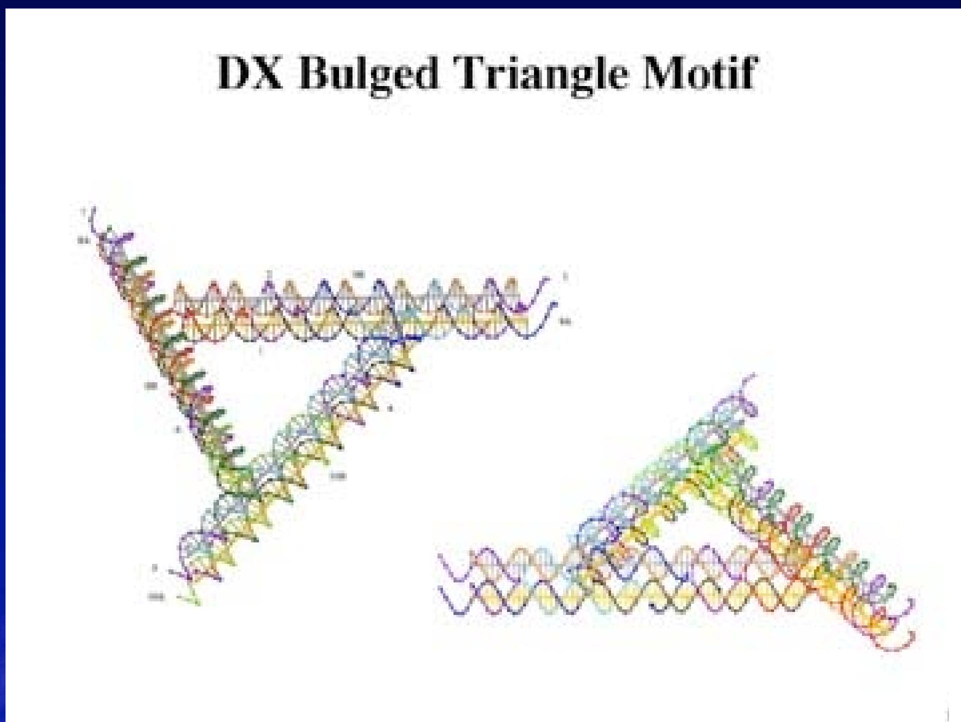


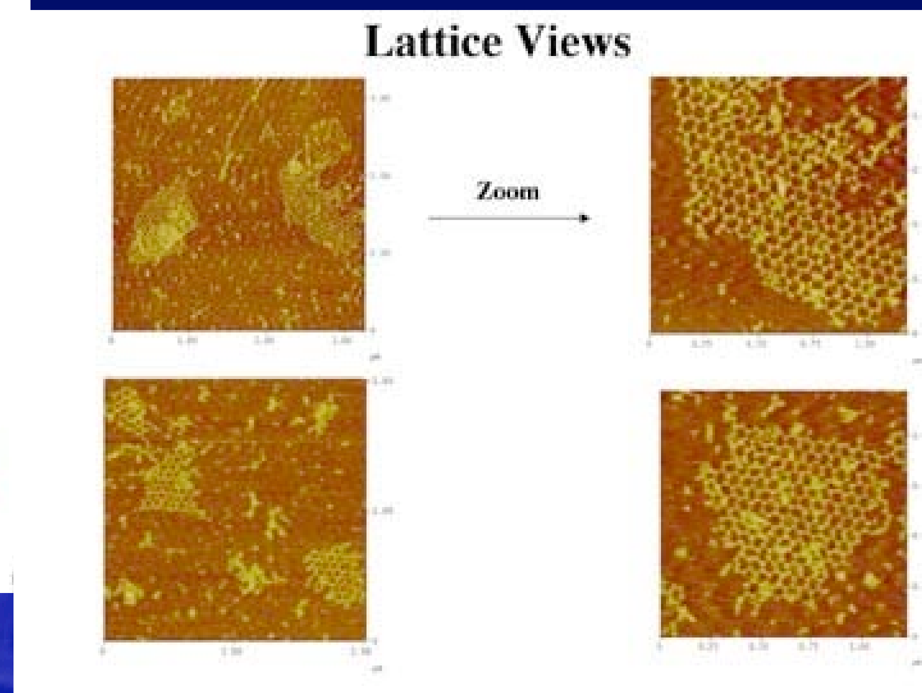


Courtesy Zettl Research Group, Lawrence Berkeley National Laboratory and University of California at Berkeley

State of the Technology: Building Blocks

http://seemanlab4.chem.nyu.edu/Trig.arrays.html

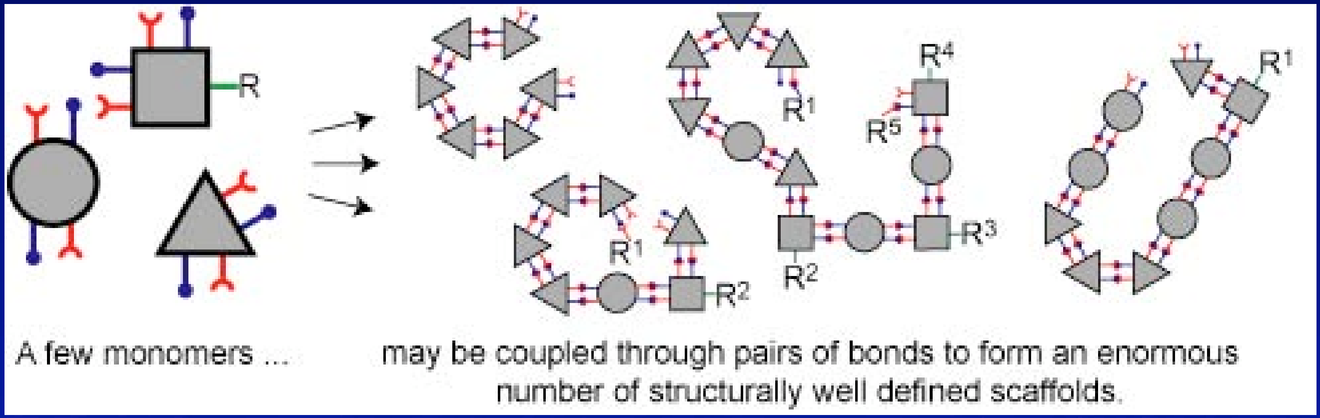




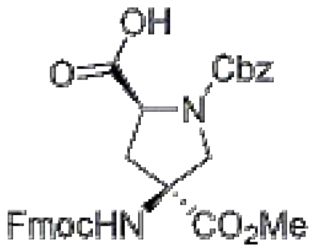
State of the Technology: Molecular Building Blocks

http://meisterlab.chem.pitt.edu/tlab/bin/view/Main/ResearchOverview

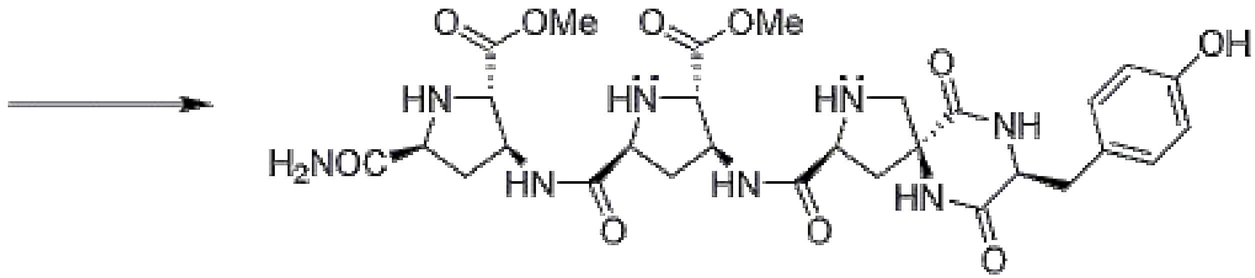
Chris Schafmeister
U. Pittsburgh



Schafmeister Building Blocks

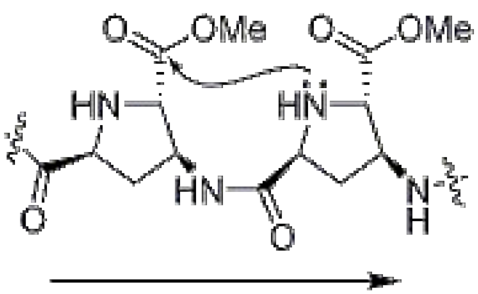


Bis-amino acids monomers

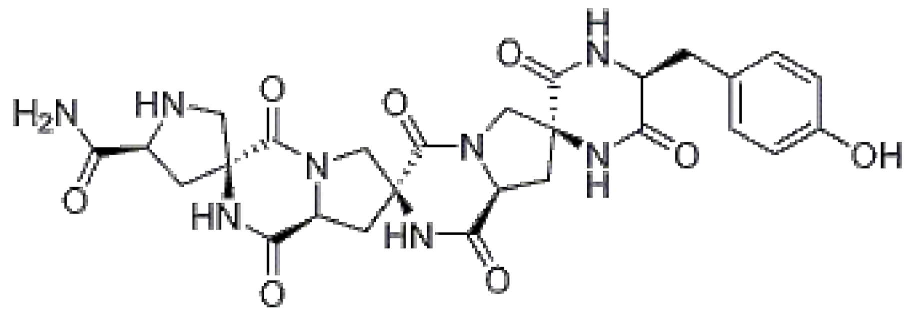


are assembled using synthetic chemistry.

The flexible chain that results

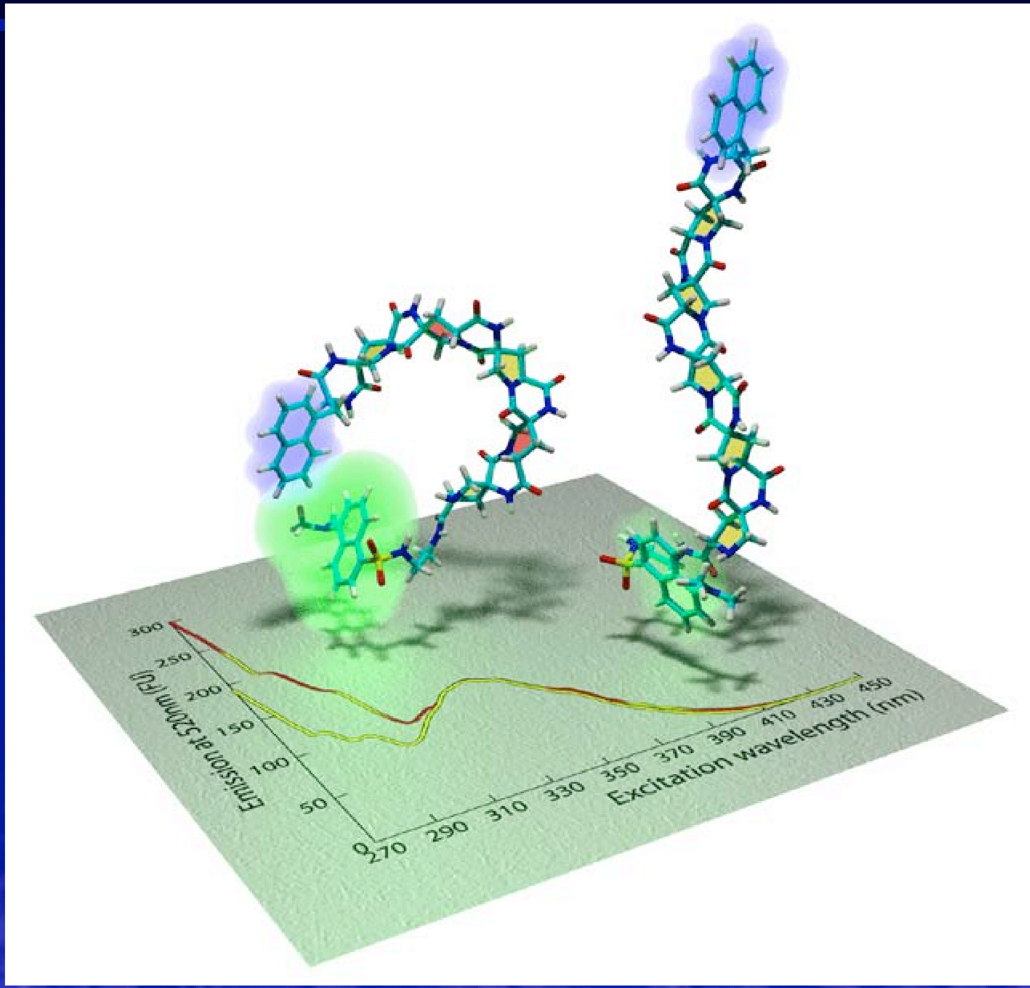


is rigidified by creating a second bond between every pair of adjacent monomers



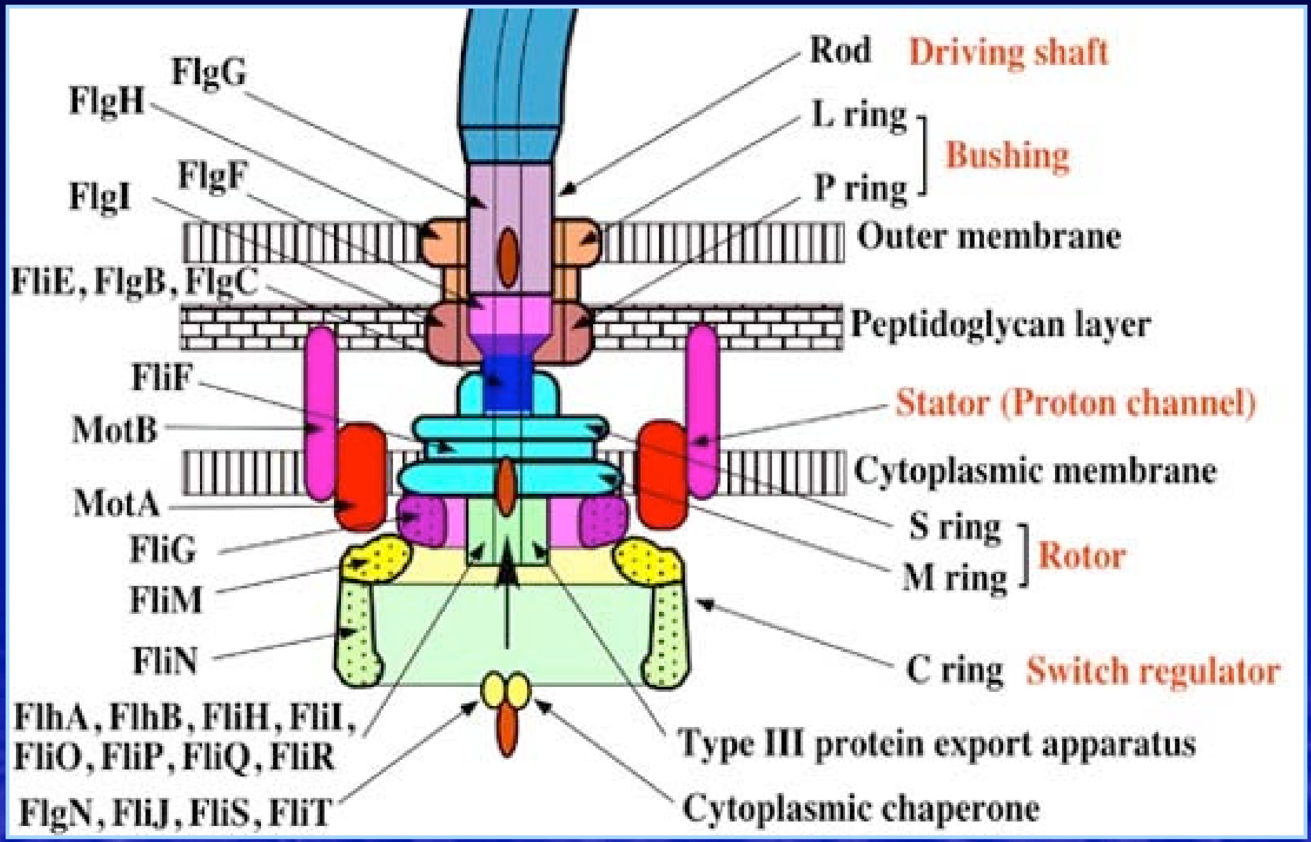
to create a rigid molecule with a designed 3D shape.

Schafmeister Building Blocks



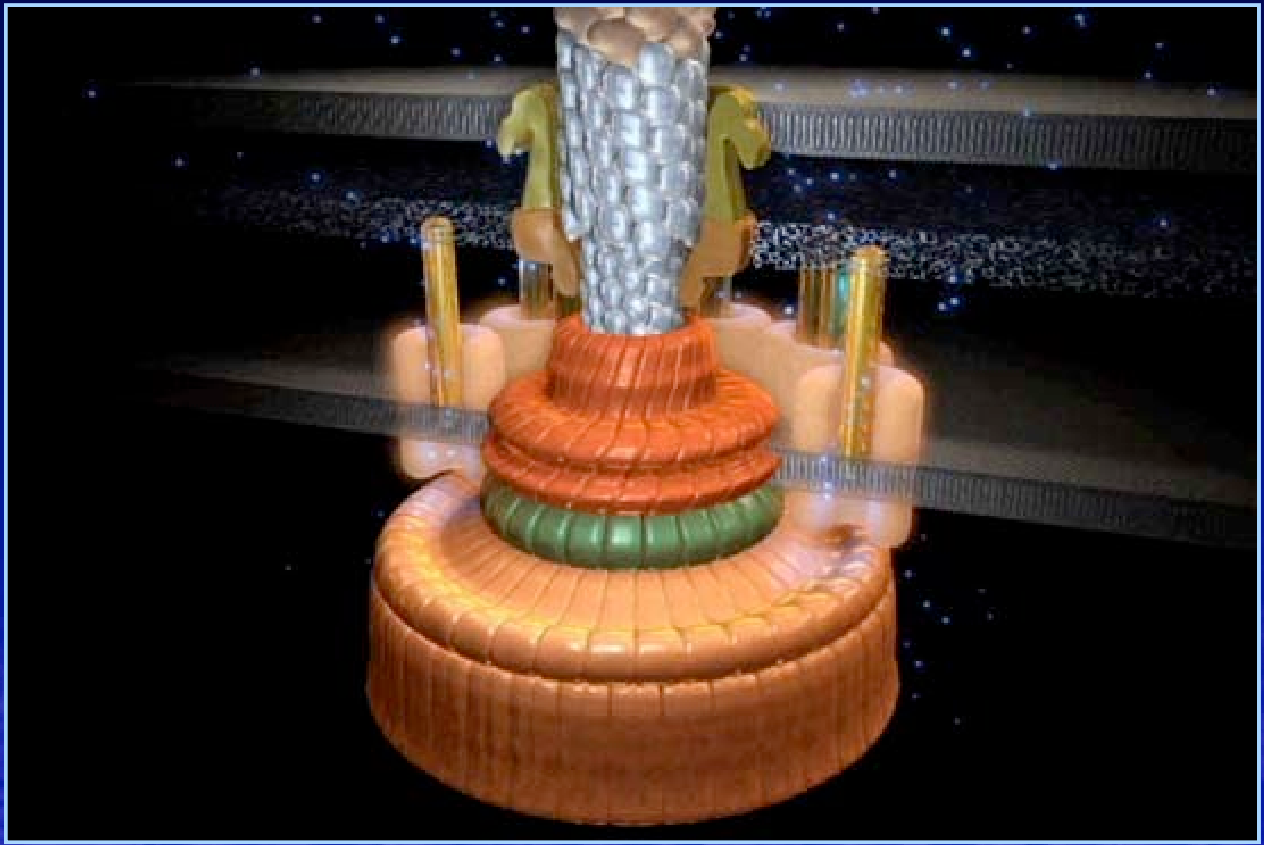
Laboratories for Nanobiology Protonic Nanomachine Group

(Namba, Osaka U. Graduate School)



Flagellar Motor (30-40 nm diameter, 20,000-100,000 rpm)

Protonic Nanomachine Project, ERATO
http://www.fbs.osaka-u.ac.jp/en/seminar/09a.html



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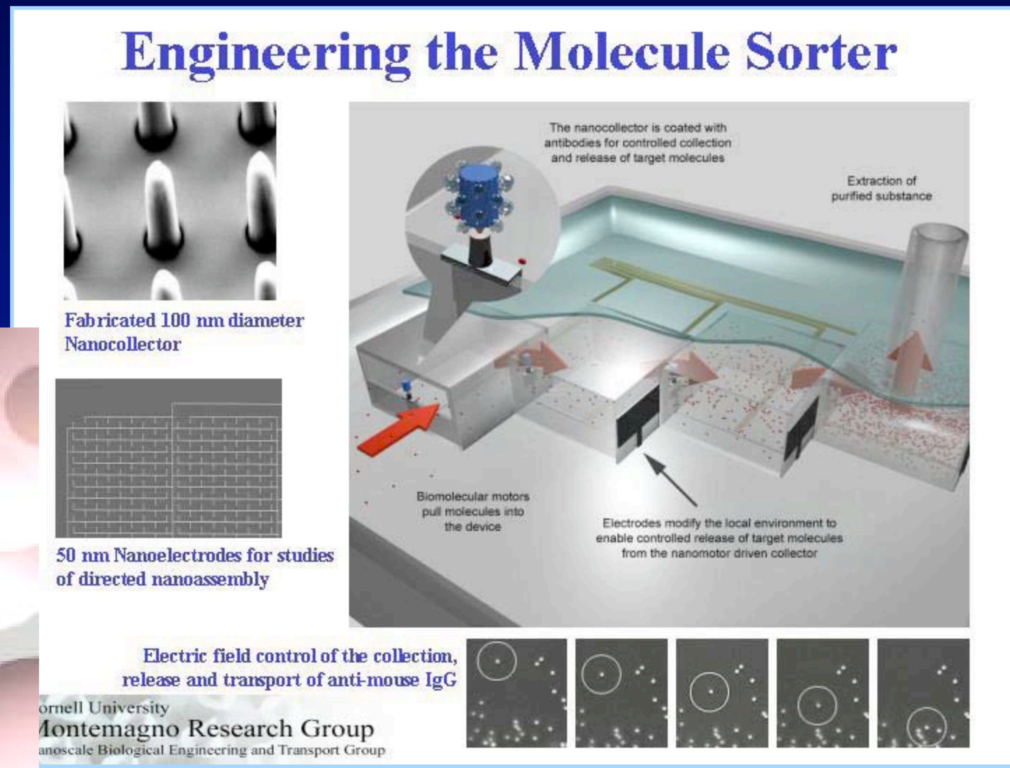
State of the Technology: Hybrid Machines

(Montemagno, www.cnsi.ucla.edu/faculty/montemagno_c.html)



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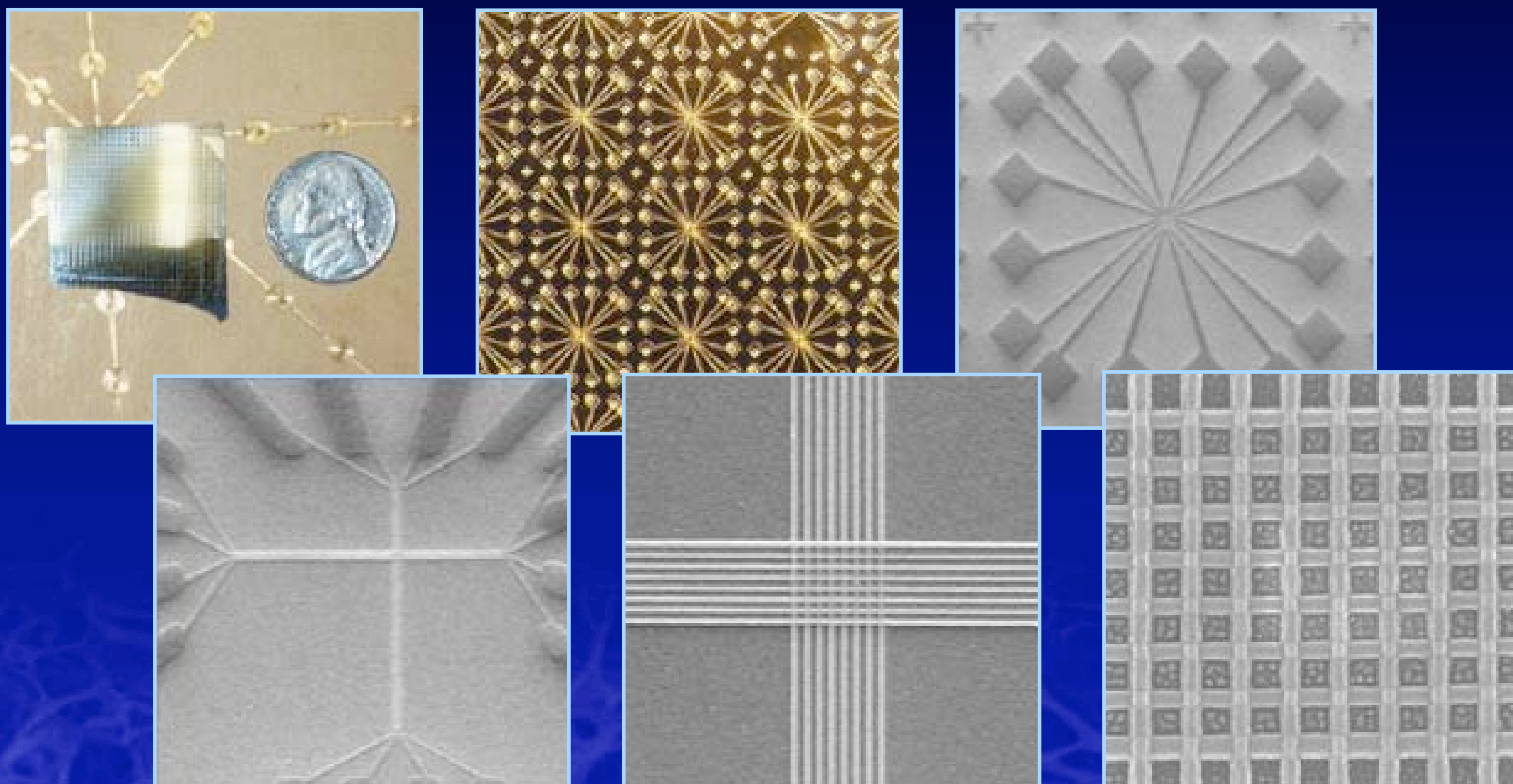
State of the Technology: Molecular Electronic Devices

Reed (Yale)	http://www.eng.yale.edu/reedlab/
Tour (Rice)	http://www.ruf.rice.edu/~kekule/
Williams (HP)	http://www.hpl.hp.com/research/qsr/
Avouris (IBM)	http://www.research.ibm.com/nanoscience/
Nantero	http://www.nantero.com/
Ellenbogen (MITRE)	http://www.mitre.org/tech/nanotech
Wilson (U. London)	http://www.qmw.ac.uk/~ugap735/MolElec.html

Molecular Computing

(Hewlett Packard, http://www.hpl.hp.com/research/qsr/)



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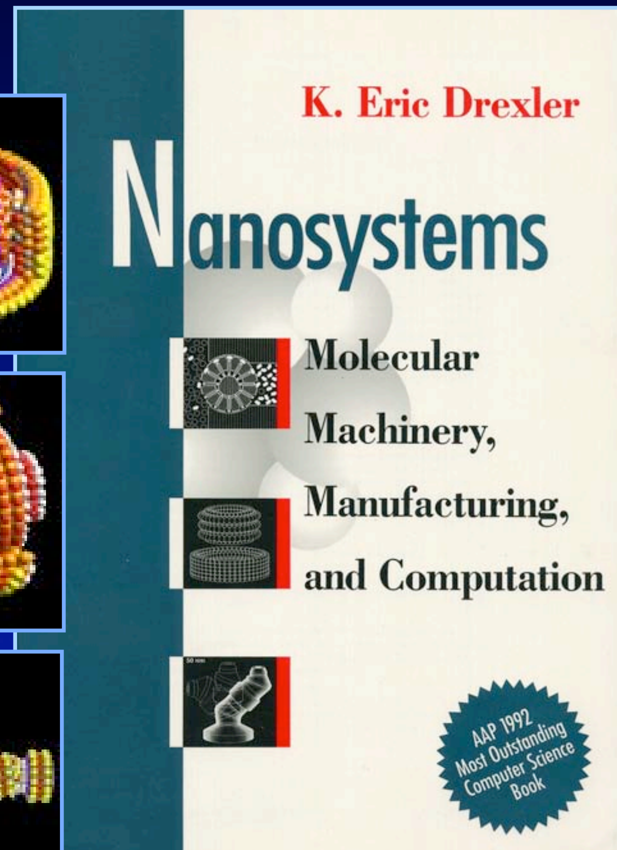
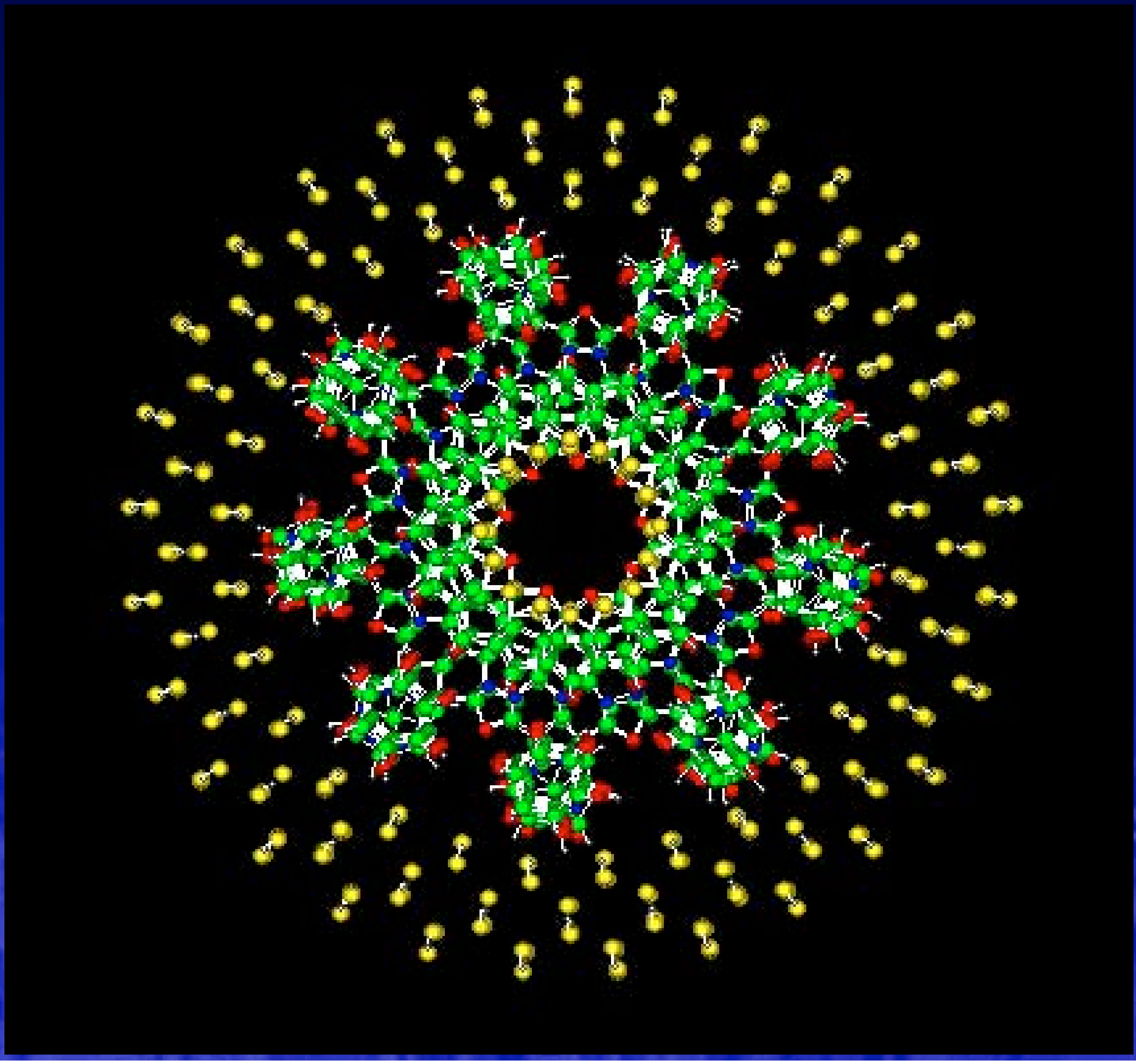
State of the Technology: Design

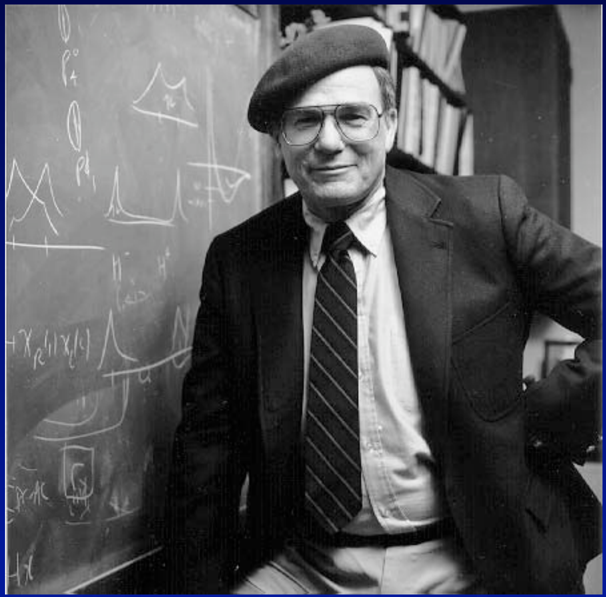
- Significant body of work
- Drexler
  http://e-drexler.com/
- Merkle
  http://www.merkle.com/



Molecular Dynamics – Planetary Gear

(W.A. Goddard, Caltech)





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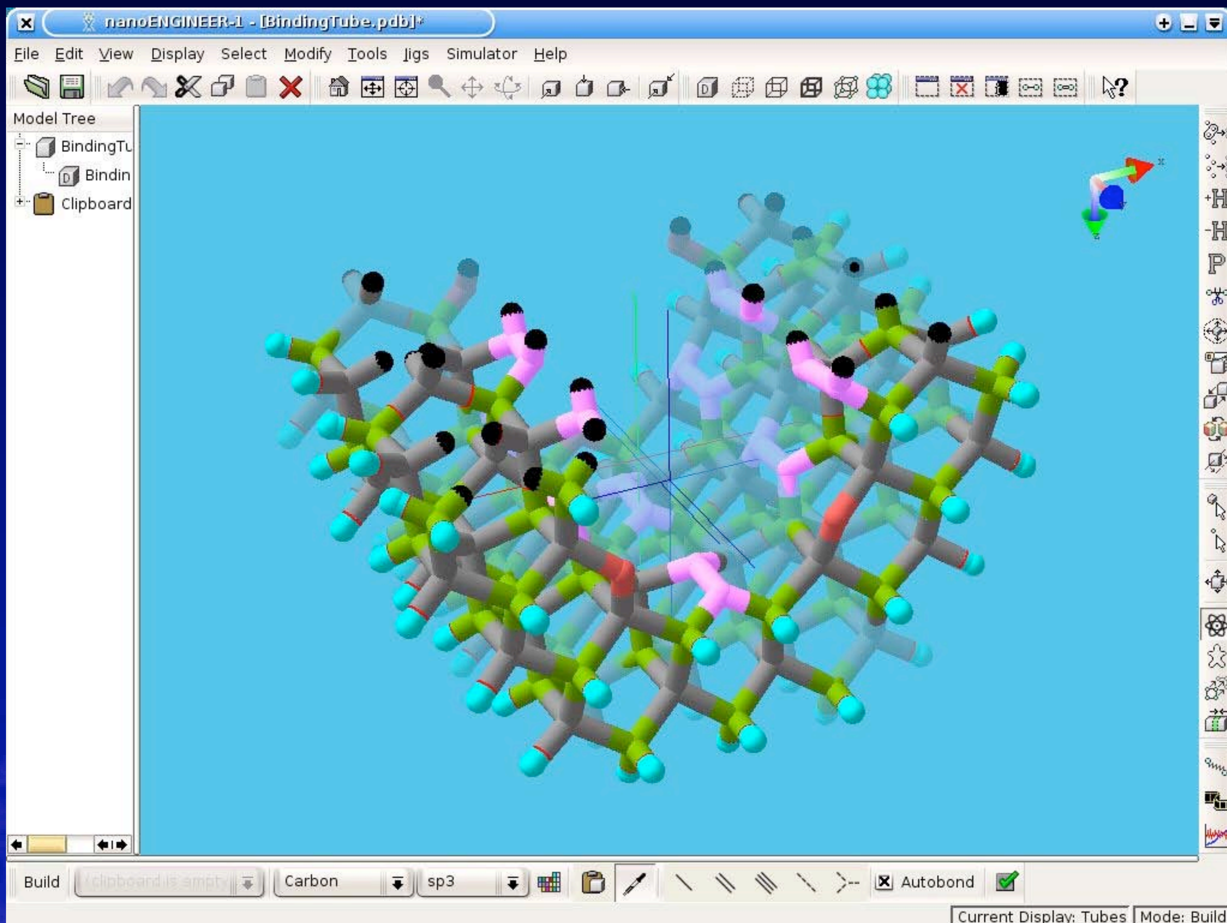
Josh Hall



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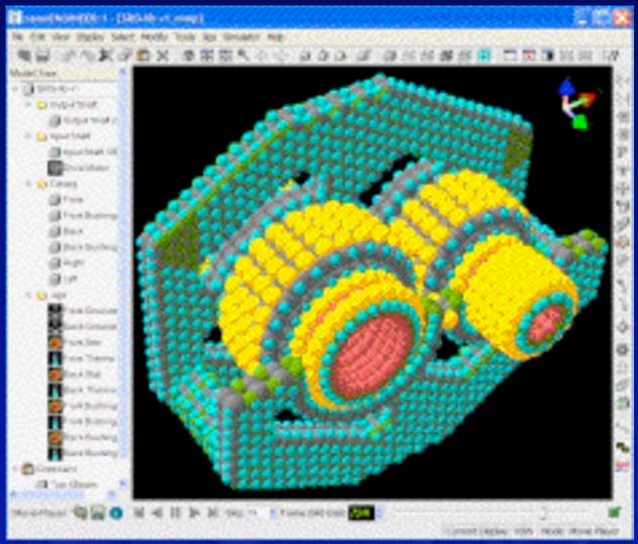
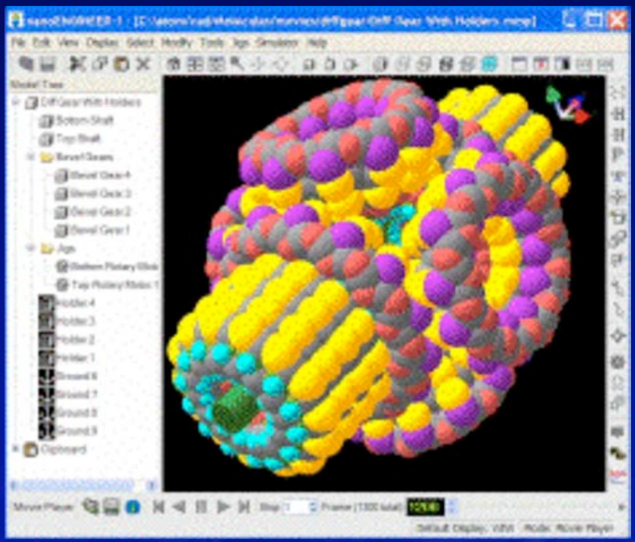
Computational Tools – NanoRex

http://www.nanoengineer-1.com/mambo/





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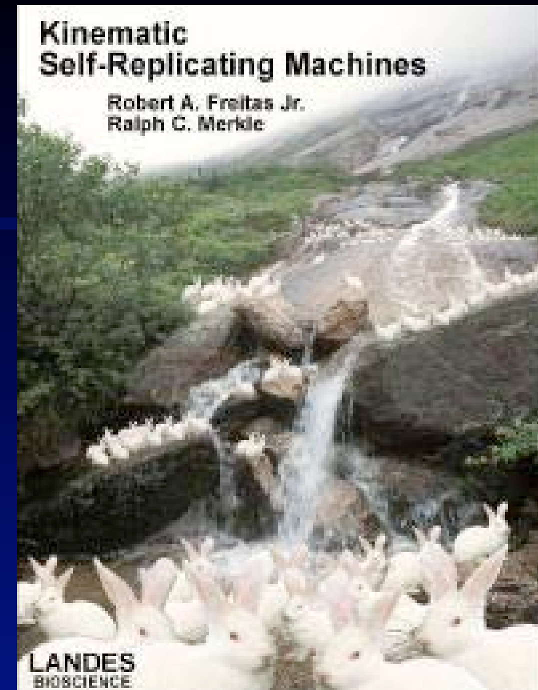
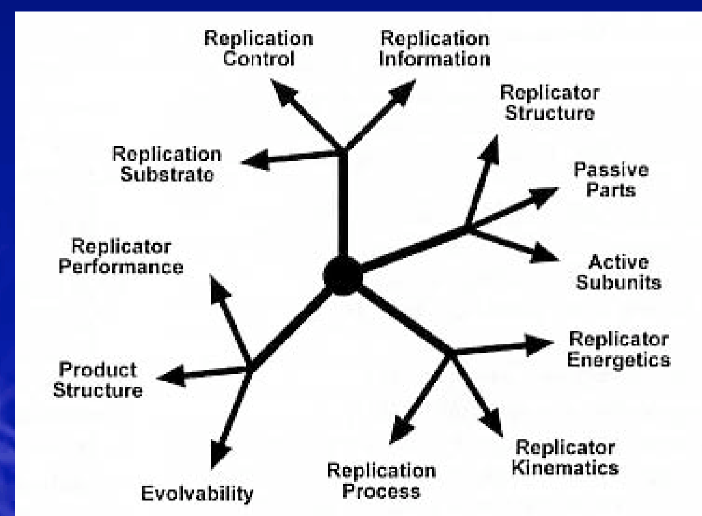
Self-Replication

http://www.molecularassembler.com/KSRM.htm

- Exhaustive review of historical and current work
- 137-dimensional map of the entire kinematic replicator design space
- Distinguishes between different kinds of replicators





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"Pathways"

- Feynman (larger machines making smaller ones)
- Lithographic techniques
- Self-organizing materials, supramolecular chemistry
- Self-assembly
- DNA engineering
- Protein engineering
- Hybrid biological and inorganic structures
- STM technology with manipulator tools
- Molecular robots

All of the Above

Factors That Affect the Timeline

- Quality and focus of effort
- Focus on technology, not just science
- Magnitude of funding
- Perception of proximity to realization
- Designer talent pool (funding)

Technological Challenges

- Improved capability of instrumentation
  - Precision
  - Manipulation
- Molecular tips for mechanosynthesis
- Richer library of molecular building blocks
- Improved computational tools for analysis and design of molecular manufacturing systems
- Design of massively parallel manufacturing systems

Summary

- There is a clear vision of molecular manufacturing
- Theoretical basis established through engrg. analysis
- Positional molecular assembly is experimentally proven
- Molecular machines based on carbon nanotubes have been made
- Self-assembling molecules → building blocks
- Can exploit capabilities of existing biological molecular machines
- New instruments → improving manipulation/imaging
- New software → improved design tools

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Thank you!