Institute for Molecular Manufacturing

NAVSEA WARFARE CENTERS Carderock Division

FORESIGHT NANOTECH INSTITUTE
Advancing Beneficial Nanotechnology

Technology Roadmap for Productive Nanosystems

David R. Forrest, ScD, PE

SME NanoManufacturing Conference
Framingham, MA
22-23 April 2008

Key Points

- Long term vision: Atomically Precise Manufacturing
- Feasibility debate fading
- Roadmap Origins
  - Document developed by Battelle/Foresight (2005-2007)
  - Response to changing mainstream perception of nanosystems concept, and to call for pathways
- Roadmap Content
  - Impressive document, over 400 pages
  - Compelling reasons to develop and scale up APM
  - Fabrication methods: tip-based, molecular synthesis, hybrid
  - Intermediate applications and enabling technologies

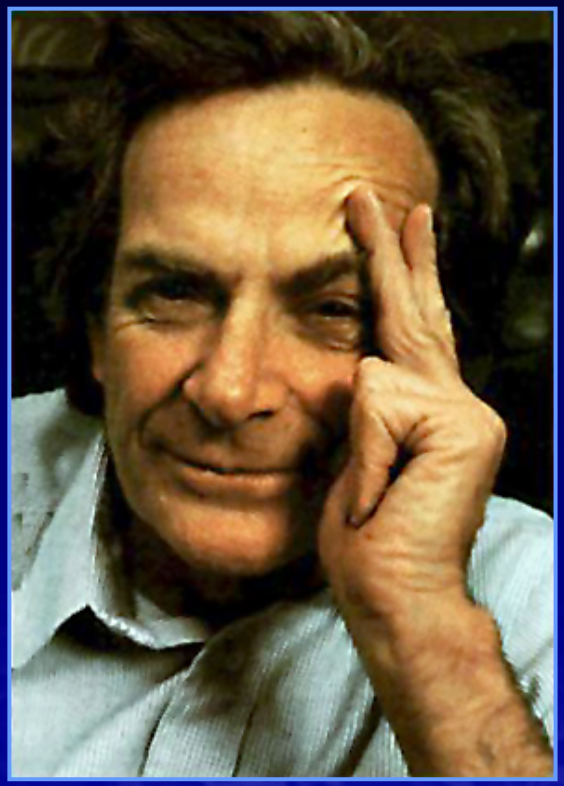
Key Points

- Recommendations
  - Continue roadmapping
  - Nanosystems engineering: improve SE tools and organization of knowledge base
  - Improve fabrication methods
  - Develop tools and methods for assembly of structures and devices
  - Create DARPA-like agency to accelerate progress
  - NSF to work with NNCO on university curriculum
  - Target energy and medicine sectors
  - Create program manager positions at DOE and NIH

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



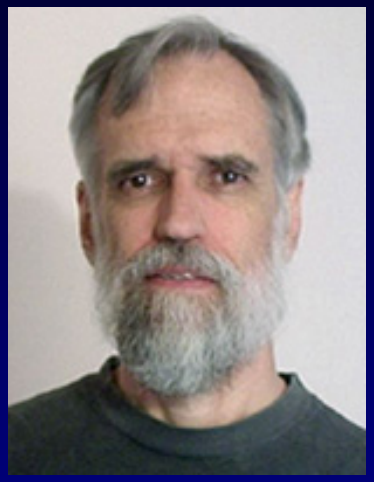
Drexler's Paper PNAS, Sept. 1981

Molecular Engineering: An Approach to the Development of General Capabilities for Molecular Manipulation

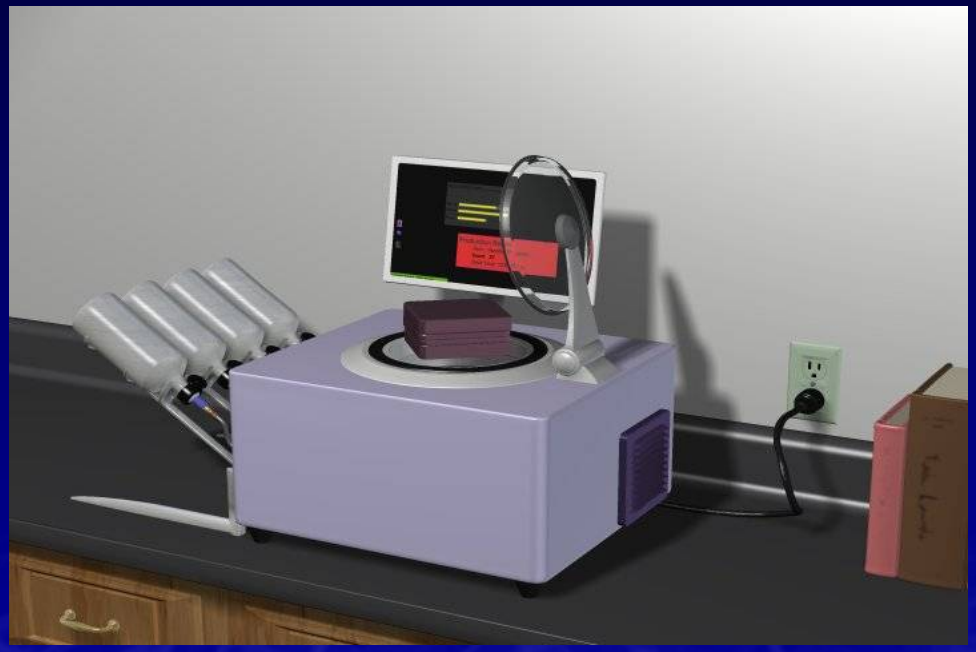
"By one path or another, we will eventually develop tools that enable us to assemble complex structures to atomic specifications. . . [These] assemblers, if supplied with materials and energy, will be able to build almost anything— including more assemblers and more systems for providing them with materials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

Eric Drexler, 1985

Desktop Assembler Animation



John Burch



Eric Drexler

http://foresight.org/nanofactory.mov

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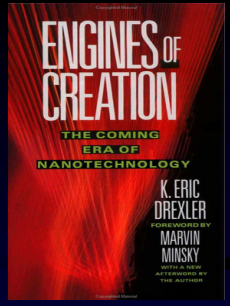
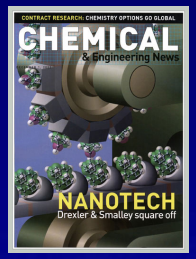
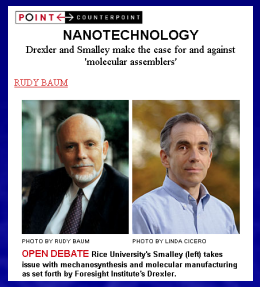
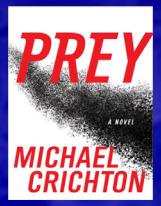
Fading Controversy

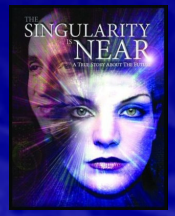


- Engines of Creation 1986: Pop vs. sci communities
- Nanosystems 1992: Helped, but not widely read
- *Ad hominem* attack, Scientific American 1996
- NNI 2000: Positive attention, funding, nanomaterial focus—not nanosystems
- Continued debate
  - Scientific American 2001
  - Chemical & Engineering News 2003
- More scary science fiction









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Fading Controversy

2002: OSTP briefed.

- Time to end debate and move on
- Recommended that feasibility of MNT be studied.

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Preparing for nanotechnology

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Balancing the National Nanotechnology Initiative's R&D Portfolio

A Foresight/IMM White Paper submitted to the White House Office of Science and Technology Policy*

Neil Jacobstein, Ralph Merkle, Robert Freitas

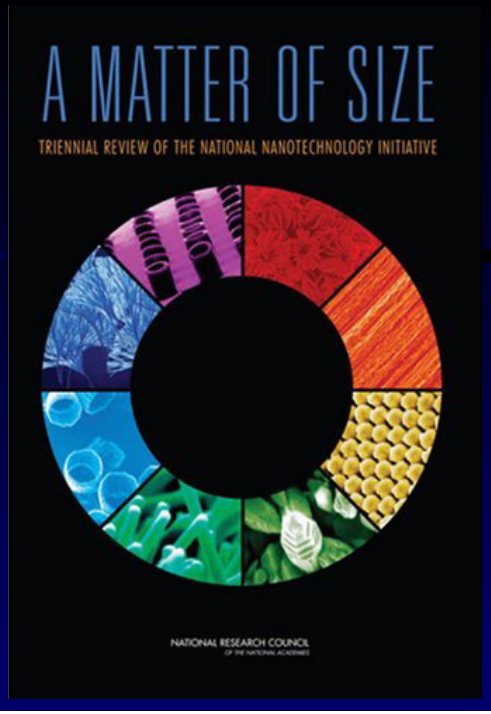
May 29, 2002

http://www.foresight.org/Updates/Update52/Update52.1.html

http://www.imm.org/documents/NNI_White_paper.pdf

NNI Review, Feb 2005

- National Research Council
  - Nanosystem advocates got fair hearing
- Feasibility addressed, but not in detail
- Cautiously favorable, language qualified



Also at Feb. 2005 meeting

↓

Foresight Institute drew criticism for lack of Technology Roadmap

Efforts already in progress: Team and funding in place by June 2005

Technical Feasibility of Site-Specific Chemistry for Large-Scale Manufacturing

Prudent extrapolation of the current research results presented above suggests an amazing future for nanotechnology. Indeed, many scientists foresee a long-term future in which a variety of strategies, tools, and processes allow nearly any stable chemical structure to be built atom by atom or molecule by molecule from the bottom up. However, there is still a gulf between this vision and popular images of nanotechnology in which the bottom-up approach is routinely used to manufacture complex, large-scale industrial objects such as computers or buildings at very low cost. The feasibility of such developments would depend on the attainable *efficiency* of the manufacturing processes. The proposed manufacturing systems[16–19] can be viewed as highly miniaturized, highly articulated versions of today's scanning probe systems, or perhaps as engineered ribosome-like systems designed to assemble a wide range of molecular building blocks in two or three dimensions rather than the linear assembly of amino acids by the ribosome. In this approach, reactions are described with both reagent and product as part of extended "handle" structures, which can be moved mechanically.[20] To be practical for the manufacture

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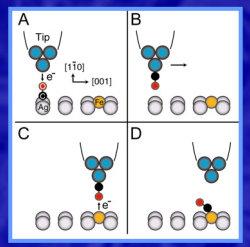
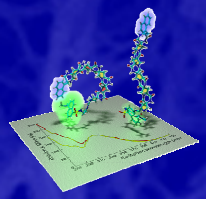
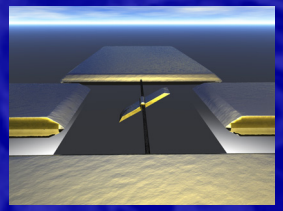
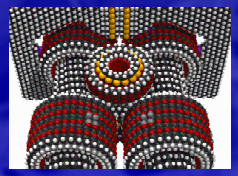
Fading Controversy (Final Note)

- Manipulation of individual atoms
- Positional assembly proven (1999)
  - Single atom chemically bound to single molecule
  - Single atoms mechanically pulled from substrate
- Atomically precise rigid ladder structures
  - Programmable synthesis
- Molecular motor synthesized (2003)
- Molecular electronic devices in development
- Molecular CAD software



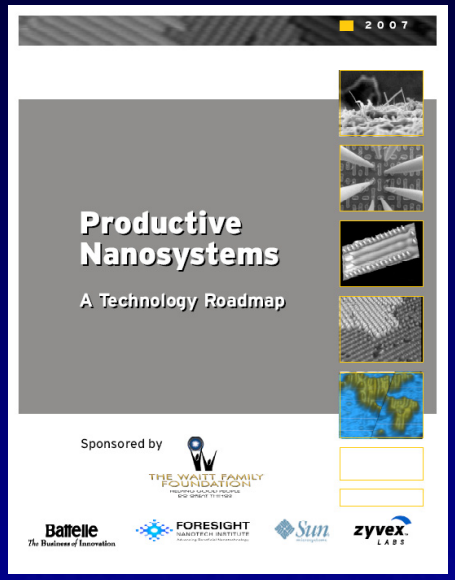






Roadmap Development

- Funding: Waitt Family Foundation
- Kickoff Meeting Foresight Conference, San Francisco, October 2005
- Series of Workshops, 2006
  - Oak Ridge National Lab
  - Brookhaven National Lab
  - Pacific Northwest National Lab
- Working group filled in content
- Document Launch: SME Meeting, Arlington, Oct. 2007
- Final version, Press Release Jan. 2008



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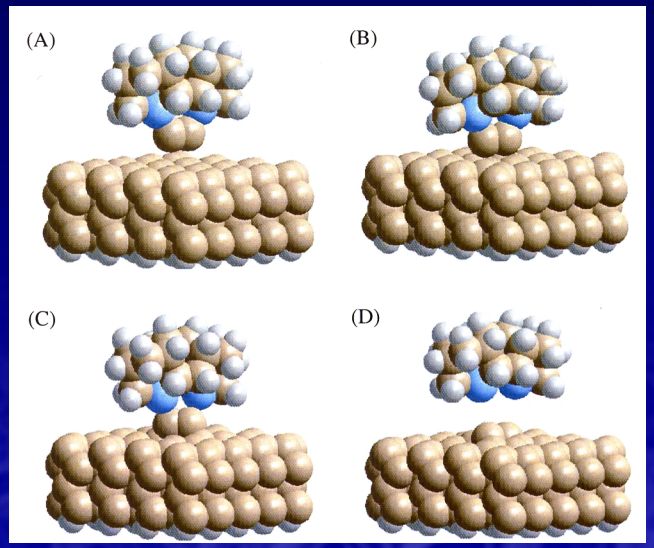
Roadmap Content: Benefits of Atomically Precise Mfg.

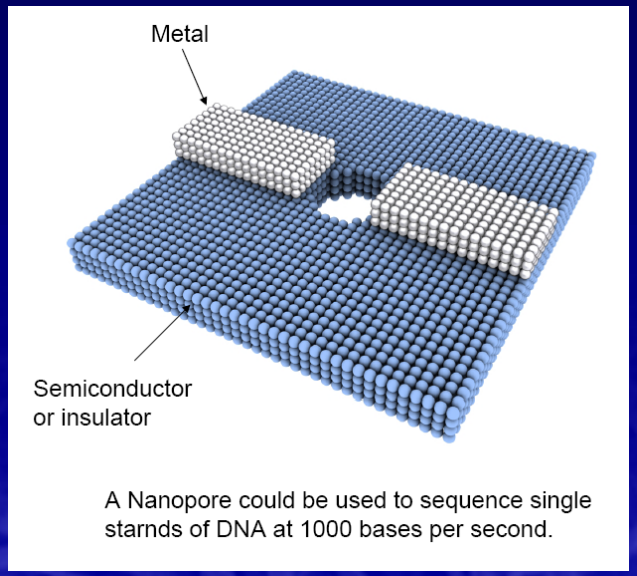
- Agents to precisely target cancer cells
- Efficient solar photovoltaic cells
- Efficient high power density fuel cells
- Order of magnitude reductions in energy dissipation in electronic devices
- High density digital circuitry (up to ~10^{20} devices/cm^3)
- ~100X improvement in strength of materials
  - Weight reduction, energy savings
- Novel materials with integrated devices and sensors
- Precise tools and devices for better APM systems

Roadmap Content: Fabrication Methods

- Tip-based fabrication
  - Serial production
  - Patterned synthesis
  - Scale up with tip arrays



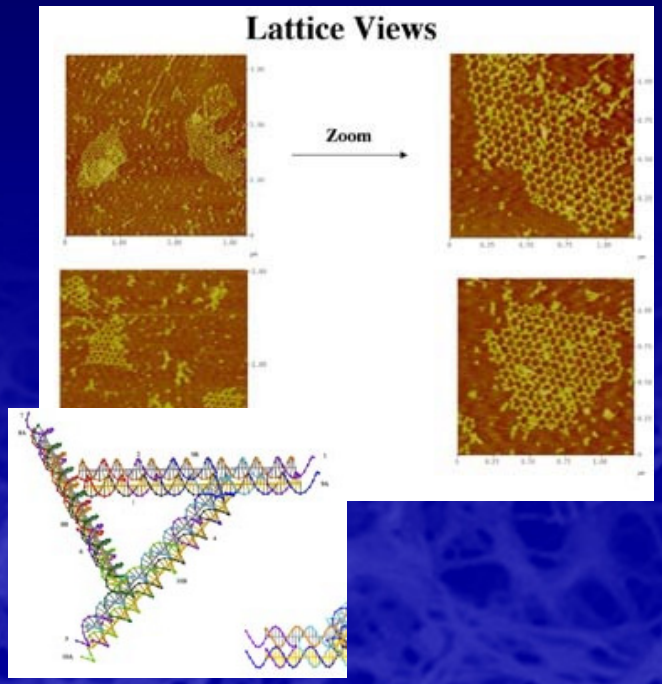
UHV Mechanosynthesis

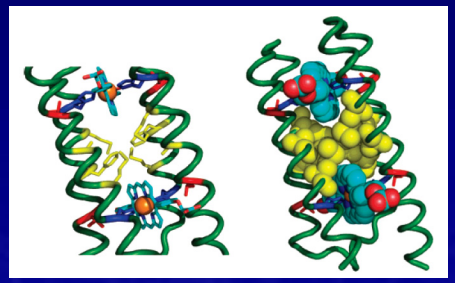


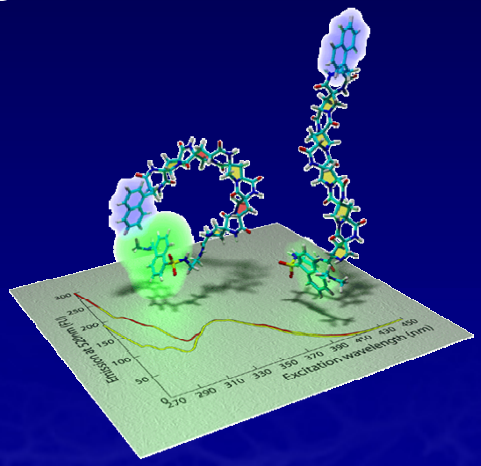
Patterned Atomic Layer Epitaxy

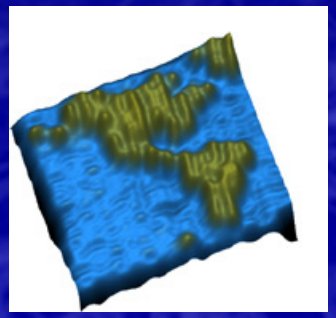
Roadmap Content: Fabrication Methods

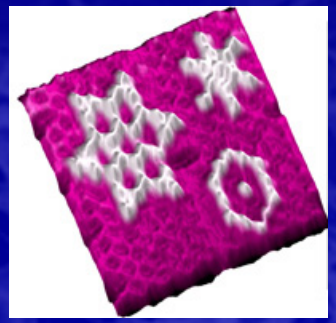
- Organic synthesis / DNA/RNA synthesis / Protein engineering
  - Massively parallel production of atomically precise structures
  - Both functional and structural components
  - Self-assembly and positional assembly





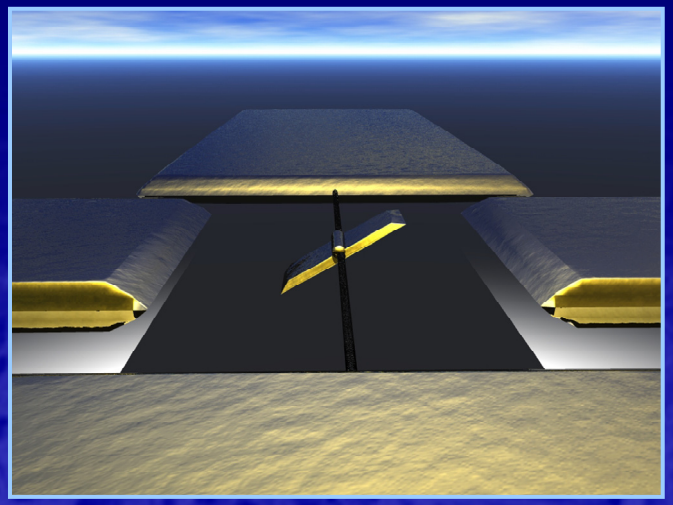


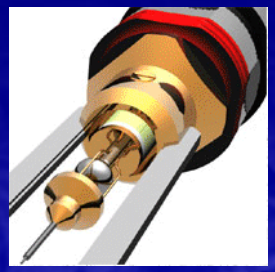


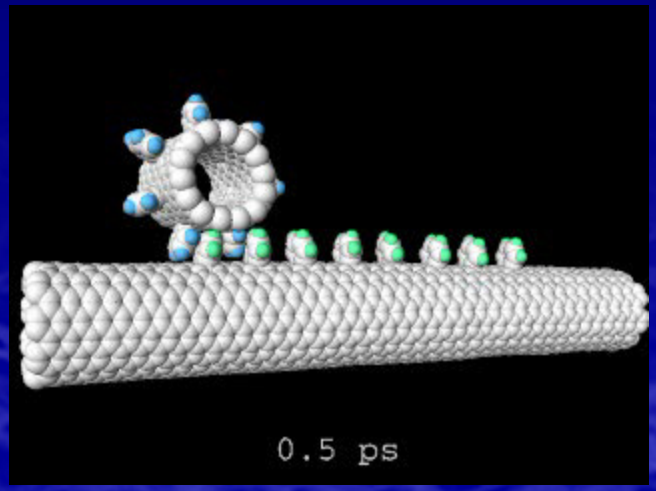


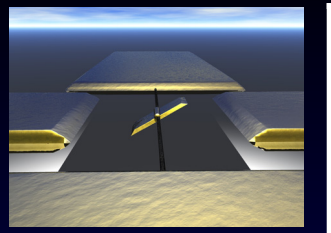
Roadmap Content: Fabrication Methods

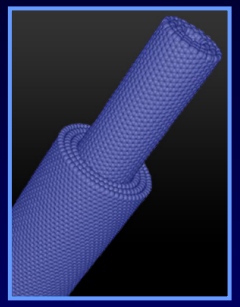
- Hybrid methods—continued evolution
  - Chemical synthesis
  - Lithographic methods
  - Nanomanipulation
  - Nanotube functionalization
- Systems engineering approach

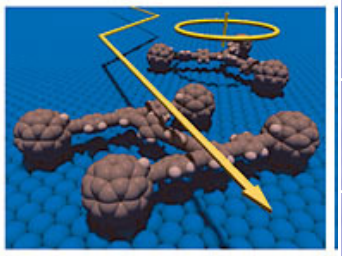












Nanotube Nanomotor	A. M. Fennimore, T. D. Yuzvinsky, Wei-Qiang Han, M. S. Fuhrer, J. Cumings, and A. Zettl, "Rotational actuators based on carbon nanotubes," Nature **424** (July 24, 2003): 408-410
Molecular Actuator	B.C. Regan, S. Aloni, K. Jensen, R.O. Ritchie and A. Zettl, "Nanocrystal-Powered Nanomotor," Nano Letters **5** (2005): 1730-1733.
Molecular Seal	Nguyen TD, et al., "Design and optimization of molecular nanovalves based on redox-switchable bistable rotaxanes" J Am Chem Soc. 2007 Jan 24;129(3):626-34
Molecular Bearings	Cumings, J.; Zettl, A. " Low-Friction Nanoscale Linear Bearing Realized from Multiwall Carbon Nanotubes," *Science* **289** (2000): 602-604.
Nanosprings	P. A. Williams, S. J. Papadakis, A. M. Patel, M. R. Falvo, S. Washburn, and R. Superfine, "Fabrication of nanometer-scale mechanical devices incorporating individual multiwalled carbon nanotubes as torsional springs," Applied Physics Letters, v. **82**, no. 5 (3 Feb 2003): 805-807.
Telescoping Arms	Cummings and Zettl, "Low-Friction Nanoscale Linear Bearing Realized from Multiwall Carbon Nanotubes". Science **289**, 602-604 (2000)
Biomotors	Montemagno, C. D., and Bachand, G. D., "Constructing nanomechanical devices powered by biomolecular motors." Nanotechnology **10** (1999): 225-331
Radio frequency controlled biomolecules	K. Hamad-Schifferli, J.J. Schwartz, A.T. Santos, S. Zhang and J.M. Jacobson, Nature **415**, 152 (2002);
"Nanocar"	Shirai Y, Morin JF, Sasaki T, Guerrero JM, Tour JM, "Recent progress on nanovehicles". Chem Soc Rev. 2006 Nov;35(11):1043-55
DNA-based robotic arm	Ding B, Seeman NC., "Operation of a DNA robot arm inserted into a 2D DNA crystalline substrate." Science. 2006 Dec 8;314(5805):1583-5
Light-driven rotaxane-based motor	Balzani V, Clemente-León M, Credi A, Ferrer B, Venturi M, Flood AH, Stoddart JF., "Autonomous artificial nanomotor powered by sunlight". Proc Natl Acad Sci U S A. 2006 Jan 31;103(5):1178-83

Roadmap Content: Intermediate Applications

- Plenty of applications that would benefit from APT in the long term
  - Fuel cells
  - Solid state lighting
  - Photovoltaics
  - Waveguides
  - Sensors
- But the primary benefits come *after* massive parallelization
- One of the most compelling low volume applications is to use APT to make components for better atomically precise manufacturing systems

Roadmap Content: Intermediate Applications

- Nanomedicine applications focus on existing uses, not intermediate applications of APT
  - Cancer detection with dendrimers
  - Quantum dots and nanoparticles for sensors
- Possible intermediate applications where a modest number of atomically precise devices would be of benefit
  - DNA sequencing
  - Non-viral gene delivery

Recommendations

- Continue roadmapping
  - Develop improved research agenda
- Nanosystems engineering: improve SE tools and organization of knowledge base
- Improve fabrication methods
  - Atomically precise tools
  - Atomic resolution processes
  - Atomically precise components and building blocks
  - Modular Molecular Composite Nanosystems
- Tools and methods for assembly of structures and devices
  - Tip-based positional assembly
  - Artificial ribosomes
  - Self-Assembly
  - Hybrid: evolve lithographically-based systems + systems engineering with existing structures and devices (recommendation buried in report)

Recommendations

- Create DARPA-like agency to accelerate progress
- NSF to work with NNCO
  - Structure a university program to develop APM
- Recommended target areas
  - Energy
  - Medicine
- Create program manager positions
  - DOE Program Manager for Atomically Precise Technologies
  - NIH Program Manager for Atomically Precise Technologies
  - Both: National Nanotechnology Coordinating Office Board

Ongoing Roadmap Efforts

- Ongoing discussions: Foresight, IMM, Battelle
- Possible workshop in DC in 2009
- Outreach to funding agencies
- Outreach to key congressional committee members and staff
- Outreach to a broad range of industries

Summary

- Long term vision: Atomically Precise Manufacturing
- Feasibility debate fading
- Roadmap Origins
  - Document developed by Battelle/Foresight (2005-2007)
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Further Information:

http://foresight.org/roadmaps

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