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An Introduction and Overview of Interdisciplinary Nanoscience and Nanotechnology

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Invited Presentation for the NASA-Langley Training Wkshp. on Nano-Biotechnology

An Introduction and Overview of Interdisciplinary Nanoscience and Nanotechnology

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14 June 2000

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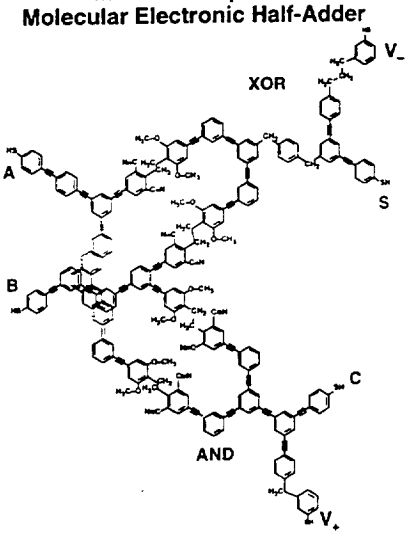
Basis for this Presentation: MITRE's Broadly-Based R&D in Nanotechnology

MITRE's Proposed Molecular Electronic Half-Adder



1 million times smaller than comparable circuit on Pentium II

- Present focus: Investigate and develop architectures for electronic nanocomputers--*esp. molecular electronic computers*
- Full Range of Tasks:
  - Nanocomputer technologies and designs investigations
  - Applying nanocomputers to control micro-mechanisms
  - Improved fabrication & modeling of nanosystems
  - Bio-nanotechnology R&D
  - Economic analysis of nanotechnology

More information at: http://www.mitre.org/technology/nanotech

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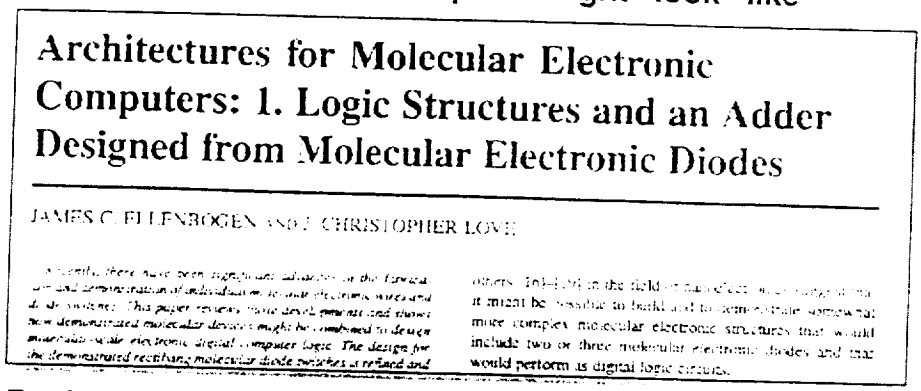
"Pink Book" Recently Published in March 2000 *Proceedings of the IEEE*

- Explains basic ideas of molecular electronics and shows what a molecular-scale computer might "look" like



Architectures for Molecular Electronic Computers: 1. Logic Structures and an Adder Designed from Molecular Electronic Diodes

JAMES C. ELLENBOGEN AND J. CHRISTOPHER LOVE

- Reviews recent experimental and theoretical results in molecular electronics
- Proposes designs for molecular logic circuits and functions

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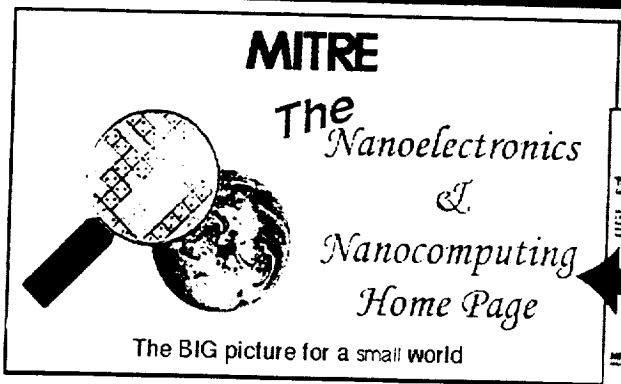
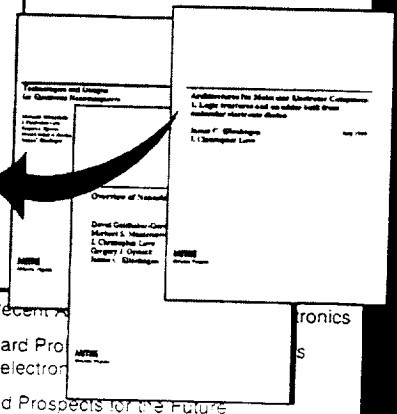
More Nanotech Information on the Internet: Nanoelectronics & Nanocomputing Home Page



Overview articles available on Web site



- What are Nanotechnology and Nanoelectronics?
- Basic References on Nanoelectronics and Nanocomputing
- Who's Who in Nanoelectronics and Nanocomputing
- Links to other WWW Sites Relevant to Nanoelectronics
- Top 10 Recent [illegible]tronics
- Top 10 Hard Pro[illegible]s for Nanoelectron[illegible]
- Status and Prospects for the Future
- *and much more!*

On the Internet at *http://www.mitre.org/technology/nanotech*

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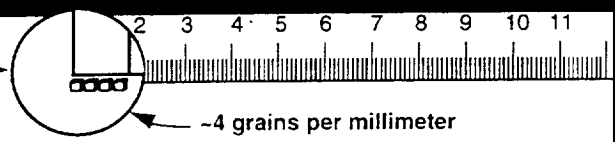
Objectives of this Presentation

Start by focusing on a grain of salt...



...To address the questions:

- What are nanotechnology and bio-nanotechnology?
- What are some key applications of bio-nanotechnology?
- Why is it of particular importance to NASA?
- What are some key challenges to fulfilling the promise of nanotechnology?

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Enter the Nanocosm: Range of Length Scales for Bio-Nanotechnology

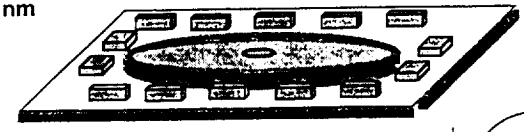
Cells are the micron-scale building blocks of life, but their function relies on complex *nanometer-scale* mechanisms

Grain of Salt
~0.25 mm
250 µm
250,000 nm

Micro-machine
~100 µm
100,000 nm

Cell
~15 µm
15,000 nm

Micro-electronic Transistor
~1 µm
1000 nm



Molecule
(e.g., in cell membrane)
~10 nm

Molecules are at least 10,000 times shorter than cells and 50,000 to 100,000 times shorter than a salt grain

1 micron (µm) = 1 millionth of a meter
1 nanometer (nm) = 1 billionth of a meter ≈ 10 atomic diameters

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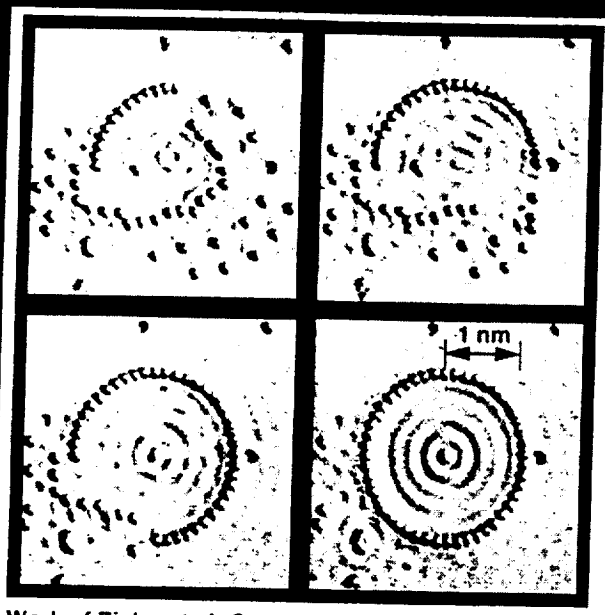
This is Nanotechnology: Engineering on the Atomic & Molecular Scale



Work of Eigler *et al.* Source: IBM Almaden Rsch. Labs

- Sequence at right shows the assembly of a 2 nanometer (nm) circle of iron atoms on a copper surface
- 1 nm ≈ 10 atomic diameters
- Quantum effects are ubiquitous
- "Quantum corral" is assembled arduously, atom-by-atom at very low temperatures, using a "nanoprobe"
- Nanoprobe both manipulates and images the atoms

Reference: Crommie, Lutz, & Eigler, Science, 8 Oct. 1993, pp. 218-220.

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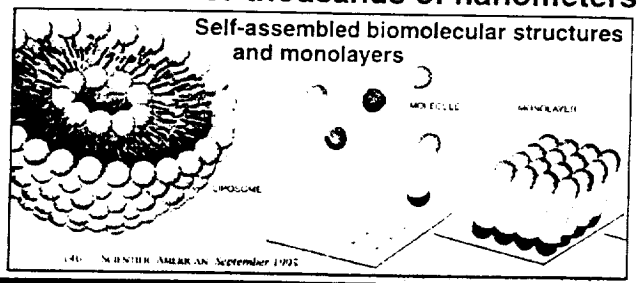
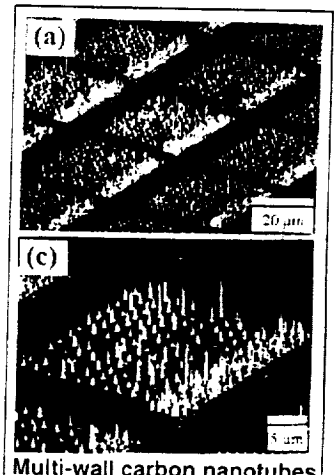
This is Nanotechnology: Molecular Self-Assembly

- Putting molecules where you want them by clever use of the "natural" physico-chemical properties of atoms, molecules, and nanometer-scale metal clusters
- Highly parallel processes effective for organizing many, many atoms or molecules all at once
- Create structures much larger than molecules with extended order over hundreds or thousands of nanometers





Multi-wall carbon nanotubes grown on nickel nano-dots

LH graphic from: G. Whitesides, Sci. Am., Sept. 1995, pp. 145-146.
RH graphic from: Ren et al., *Appl. Phys. Lett.*, v. 75, pp. 1086-1088, 1999.

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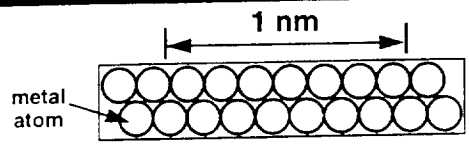
As requested by S. Venneri at NanoSpace 2000 Conference:

Nanotechnology: A More Formal Definition

- A *nanometer* is a billionth of a meter (10^{-9} m) and spans approximately 10 atomic diameters



- *Nanotechnology* is:
  - Technology for designing, fabricating, and applying nanometer-scale devices or systems ("nanosystems")
    - Entire systems having dimensions < 100 nanometers
    - Interdisciplinary technology (a synthesis of electrical engineering, physics, chemistry, and biotechnology)
  - Engineering on the nanometer scale
    - Involving the exploration or integration of nanometer-scale components in/into a nanometer-scale device or system
    - Involving nanostructured materials, devices, or systems "with every atom or molecule in its place" by design*

* Last definition on bottom adapted from comments of R. Merkel of Zyvex Corp.

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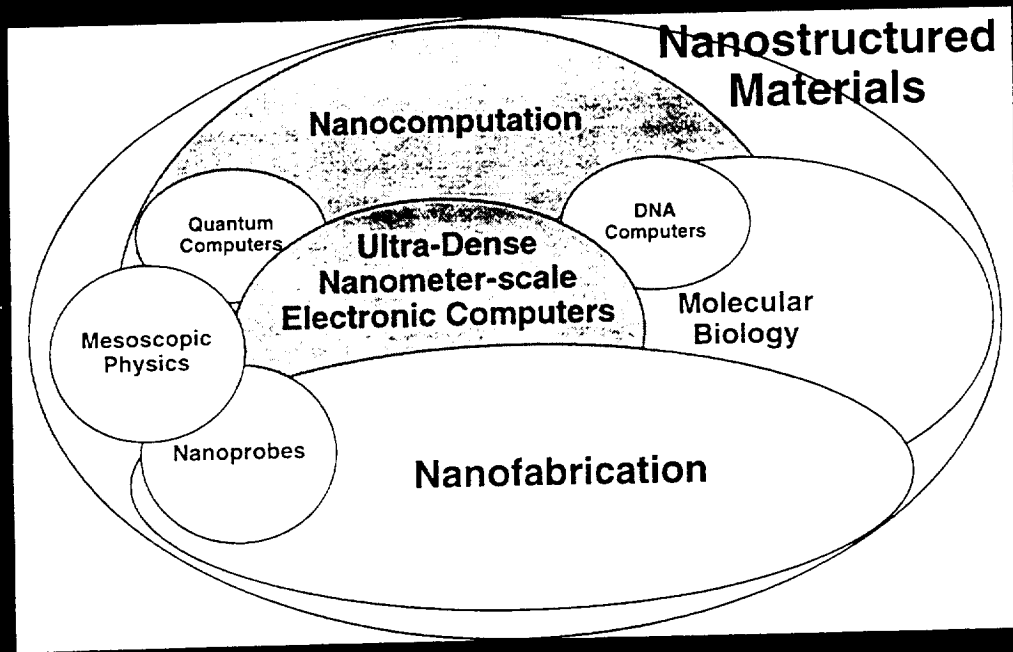
Domains of Nanotechnology: An Interdisciplinary Field



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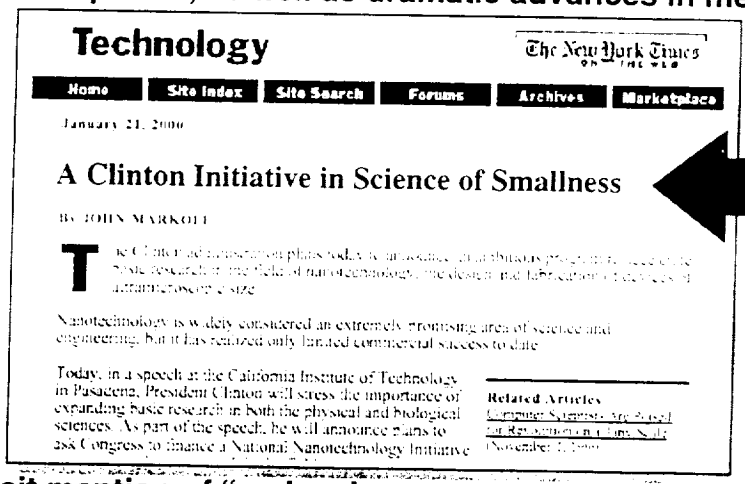
National Nanotechnology Initiative Proposed by the President in January

- Interdisciplinary effort--"Grand Challenges" to include tinier computers, as well as dramatic advances in medicine



Technology

The New York Times ON THE WEB

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January 21, 2000

A Clinton Initiative in Science of Smallness

BY JOHN MARKOFF

The Clinton Administration plans today to announce [illegible] basic research in the field of nanotechnology, the science [illegible] atomic or molecular size.

Nanotechnology is widely considered an extremely promising area of science and engineering, but it has realized only limited commercial success to date.

Today, in a speech at the California Institute of Technology in Pasadena, President Clinton will stress the importance of expanding basic research in both the physical and biological sciences. As part of the speech, he will announce plans to ask Congress to finance a National Nanotechnology Initiative

Related Articles

[illegible]

- Explicit mention of "molecular computers" in State of Union speech implicitly referred to R&D at MITRE and elsewhere

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Trends and Potential for Nanotechnology

- *Over the next decade*: Ascent of nanotechnology and nanocomputers--esp., molecular electronic computers
  - Investment essential to maintain the vigor of the present information technology revolution*
- *Over the next 20 years*: Ascent of bio-nanotechnology
  - Powerful combination of molecular biology with physical methods for nanofabrication
  - New vistas for both medicine and engineering--harness mechanisms of the cell for medicine & manufacturing
- *Ultimately*: Matter as software
  - e.g., distributed desktop manufacturing to make objects "downloadable" from the Internet
  - Bring the "information economy" to material goods--desirable physical & economic properties like software

* Issue highlighted in 1996 & 1997 MITRE review articles and in recent article by P. Packan, Science, 23 Sept. 1999, pp. 2079-2080.

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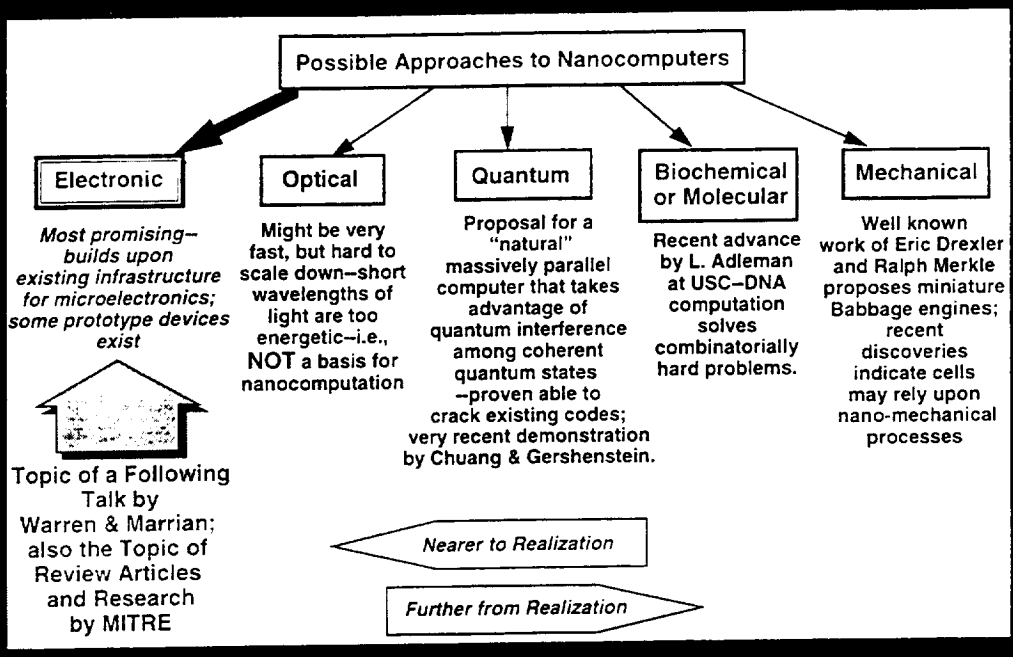
Range of Proposed Approaches for Building Future Nanocomputers



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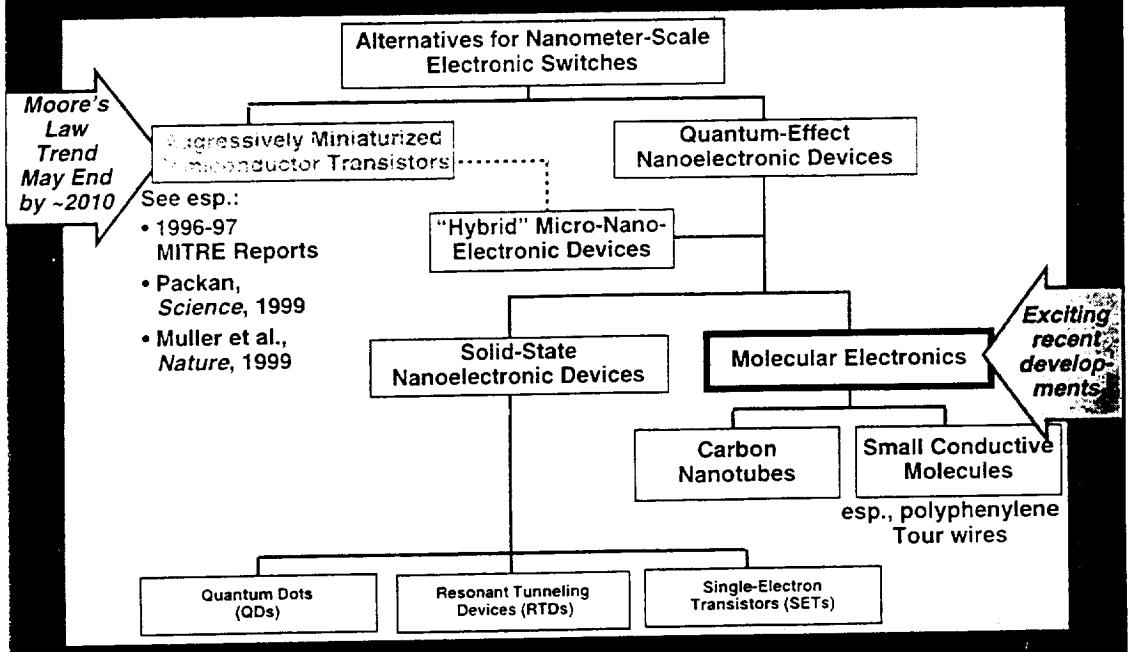
Approaches to Nanometer-Scale Switches: "Overview of Nanoelectronic Devices"*



* Title of MITRE-written paper that appeared in April 1997 issue of the *Proceedings of IEEE*, which is dedicated entirely to nanoelectronics.

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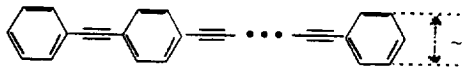
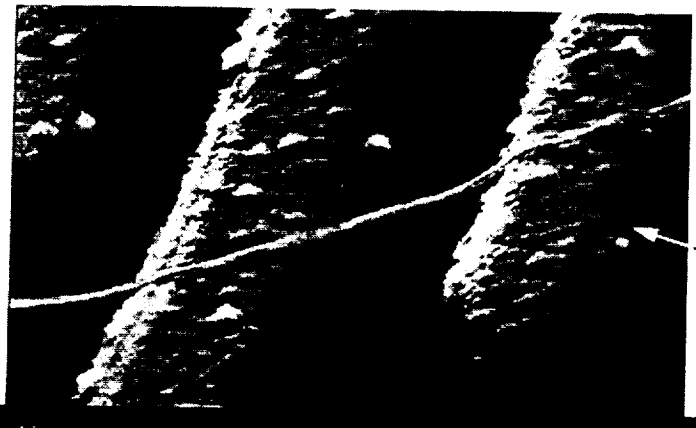
Molecular Wires and Switches Already Have Been Demonstrated (1996-97)

- Individual small molecules: polyphenylene "Tour wires"



- Also, carbon nanotubes (CNTs) have been interfaced with nanofabricated metal & silicon to make wires and switches



NOTE: Graphic extracted from the work of S. Tans and C. Dekker, TU Delft, The Netherlands. Published in Nature, 1997.

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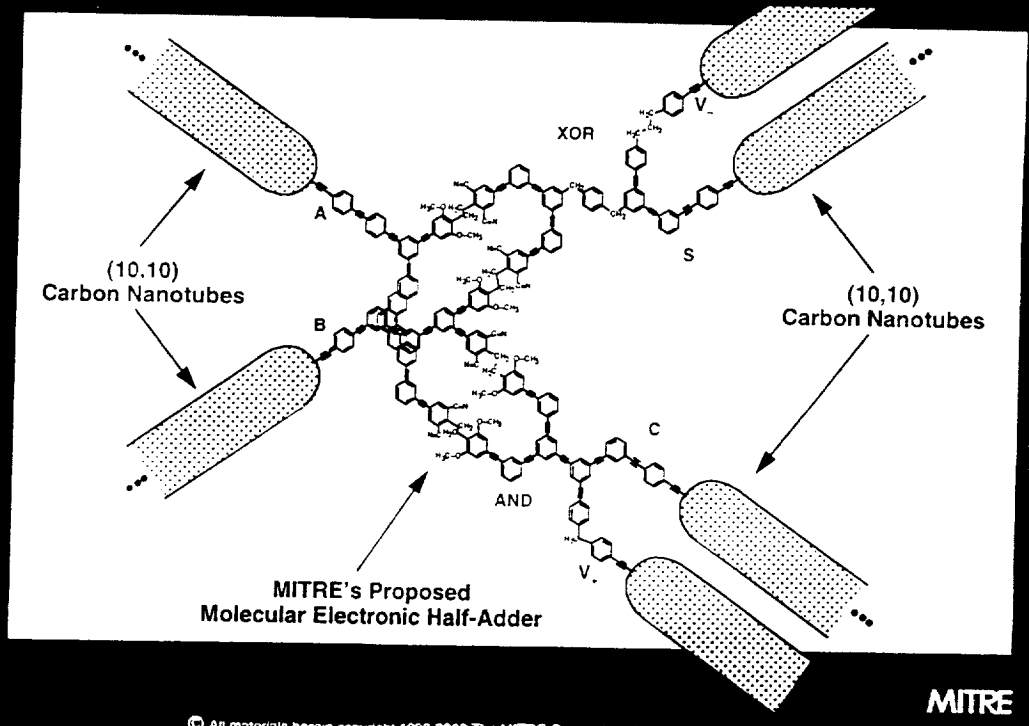
Might Use Nanotubes and Tour Wires Together in Molecular Computer Circuits



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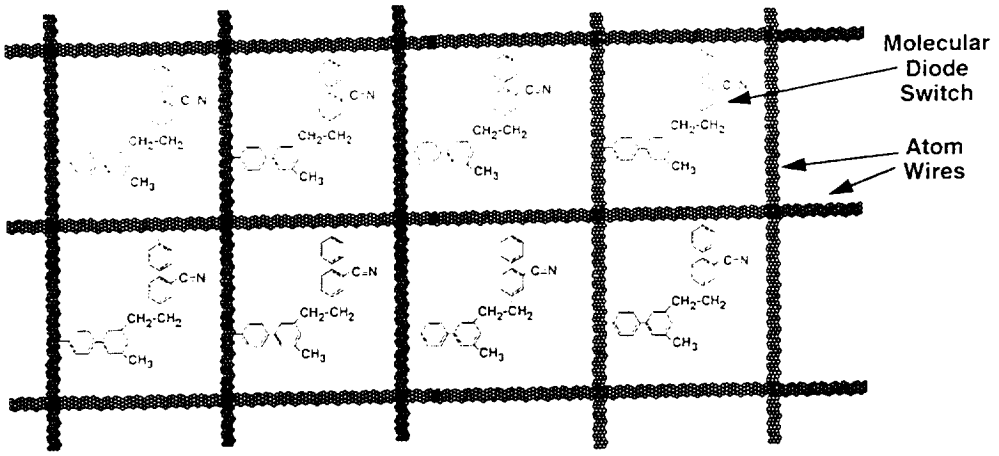
Higher-Level Nanocomputer Architectures: Molecular Switches in Grids of Atom Wires

- Stanley Williams & Phil Kuekes of H-P envision grid of atom wires linking array of molecular diode switches



- Above, MITRE-designed molecular diodes are made from substituted backbone of polyphenylene-based Tour wires

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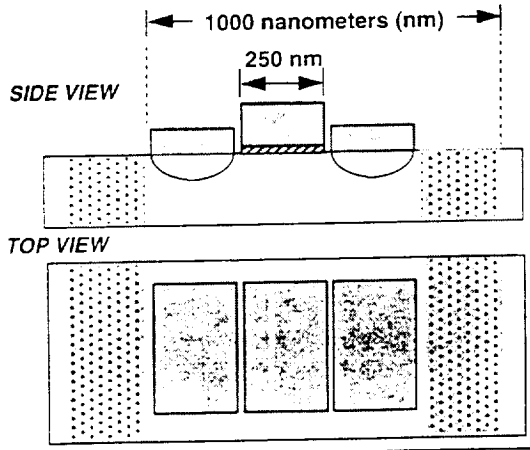
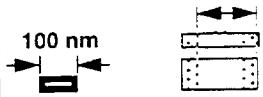
Future Miniaturization of Electronic Switches: Industry's Roadmap and Beyond

	1997 e.g., transistor on Pentium II Chip	2011 or 2012 Projected by 1997-98 SIA Roadmap, *if* scaling can continue
		 based upon 50 nm linewidth *Beyond* Reed-Tour Molecular Switch (Demonstrated in 1997) MITRE Molecular Electronic Adder (Proposed for 2003-2005)
Memory Chips	256 Megabit	64 Gigabit
CPUs	3.7 M devices/cm^2	180 M devices/cm^2

SIA = Semiconductor Industry Association

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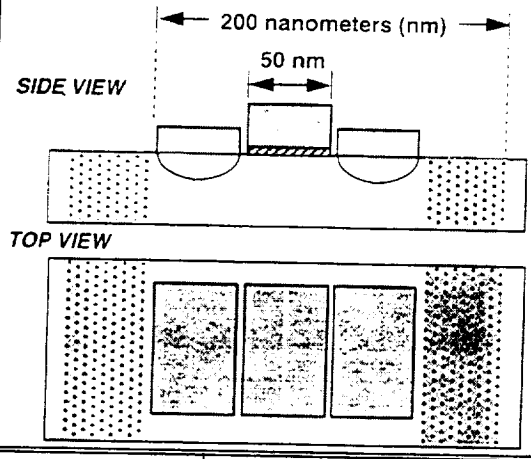
Future Molecular Electronics: Outpacing the Semiconductor Industry Roadmap

Transistor in 2011 or 2012 ??
Projected by 1997-98 SIA Roadmap, *if* scaling can continue



Before 2010
Beyond the Roadmap

~3 nm
Reed-Tour Molecular Switch (Demonstrated in 1997)

MITRE Molecular Electronic Adder (Proposed for ~2003)
~10 nm

***Potential:** A simple molecular computer where the Roadmap would place only one switch*

Memory Chips	64 Gigabit	>1.0 Terabit Memory Chip*
CPUs	180 M devices/cm²	>BG on a grain of salt

* Based on only 2-dimensional tiling of devices;
Note also: SIA = Semiconductor Industry Association

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Challenges Posed by Nanoelectronics and Nanotechnology

- Development of nanoelectronics
  - Design, development, and fabrication of nanometer-scale switches and wires
  - Devising new designs and architectures for ultra-dense nanoelectronic computers with trillions of components
  - Fabrication and packaging
    - Arranging trillions of nanometer-scale components
    - Protecting tiny components
    - Interface to micron-scale/macroscopic worlds
- Discovery, exploration, refinement, and mass production of other nanostructured materials with novel, useful properties
- Application and integration of nanoelectronics and nanotechnology--esp., into Space Systems

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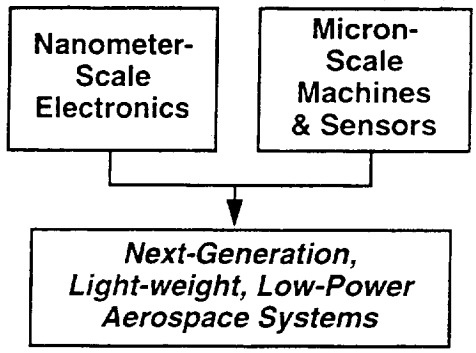
Implications of Nanotechnology/Nanoelectronics for Aerospace Information Systems

- *Much* more densely integrated, faster computers
  - *More powerful computers,* computationally
  - *Smaller , lighter computers* integrated with smaller electrical & mechanical devices
- Lower power consumption
- Denser memory--Terabyte mass storage with no moving parts
- Nanocomputers integrated with micro-electromechanical systems (MEMS) and devices--e.g., focal plane arrays (FPAs)



- Higher redundancy, more reliability in the vehicle
- "Smart", instrumented, self-repairing aerospace materials and life-support systems
- Nano- & pico-scale robotic planetary explorers
- etc.

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Space Nanoscience & Nanotech Are The Keys To Planetary Exploration

- Improved Platforms: Lower launch costs & more capability
  - Nanostructured materials--lighter, stronger, self-healing
  - Lower Power Electronics
  - New Fuels & Novel Fuel Storage
- Enhanced Endurance of Crew: Nanomedicine
  - The 21st Century is/will be the "Biotech Century"
  - Explosion of knowledge about life processes at the molecular level
  - Building a better human & keeping him/her well longer
- Maintenance of Crew and Systems in Space & On Planets
  - Distributed manufacturing of necessities & luxuries
  - "Downloading" spare parts, food, and medicine
- *Conceptual blockbusting*--e.g., the elevator to orbit??

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