NEXIGHT GROUP

Nanotechnology and Textiles:

From Atomically Precise Manufacturing to Self-Assembling Fabrics

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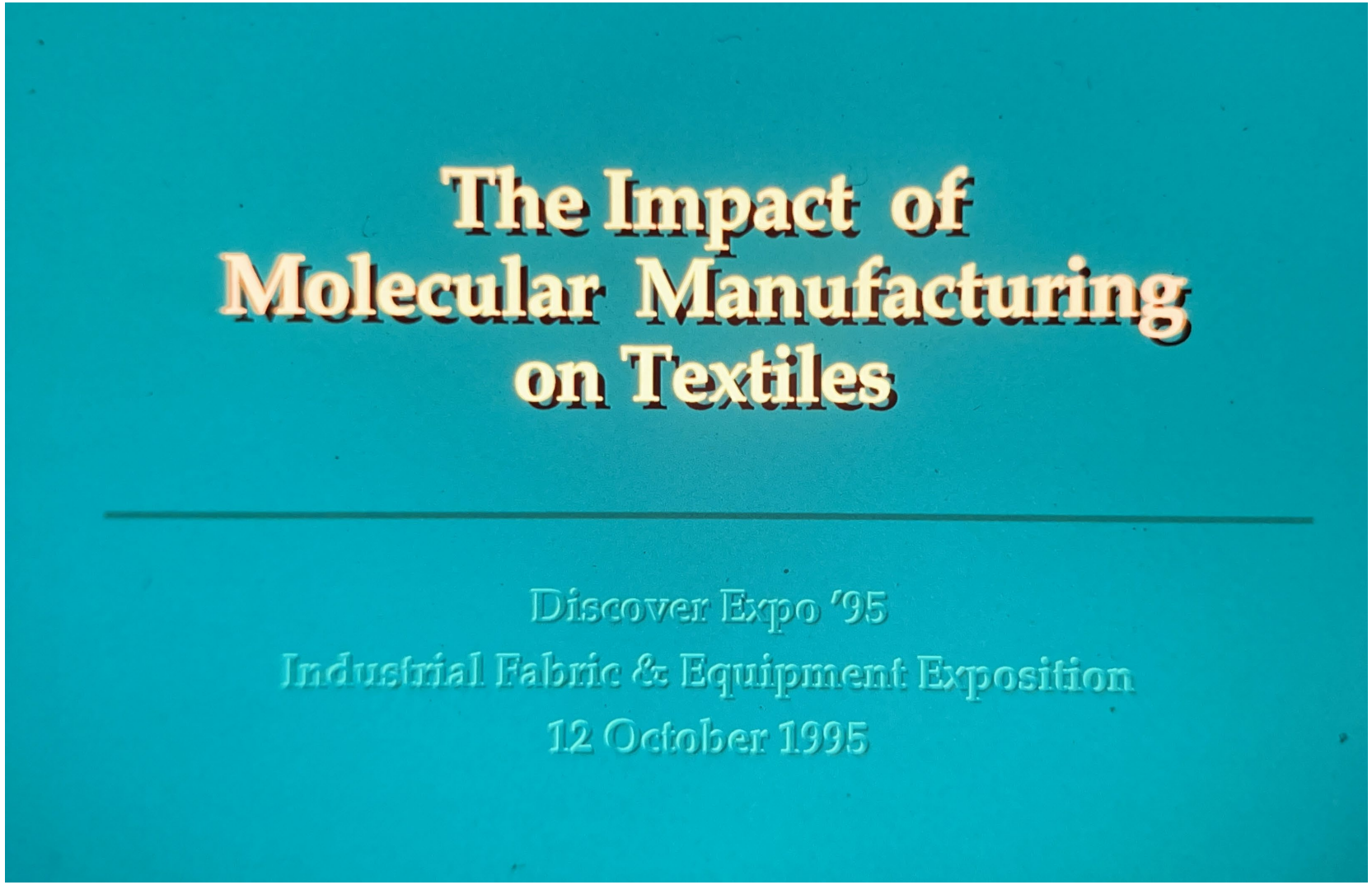
Nexight Group
31 October 2023

Summary

- Retrospective: highlights from Discover Expo ‘95
  - Including a projection of atomic precision between 2010 and 2020
- Explain why atomic precision is important for
  - Energy conservation
  - Greenhouse gas reduction
  - Advanced textiles
  - Manufacturing in general
- Progress: Key advances from 1999 – 2019
  - Positional assembly single atom to molecule
  - Atomically precise membranes



Advanced Textiles EXPO

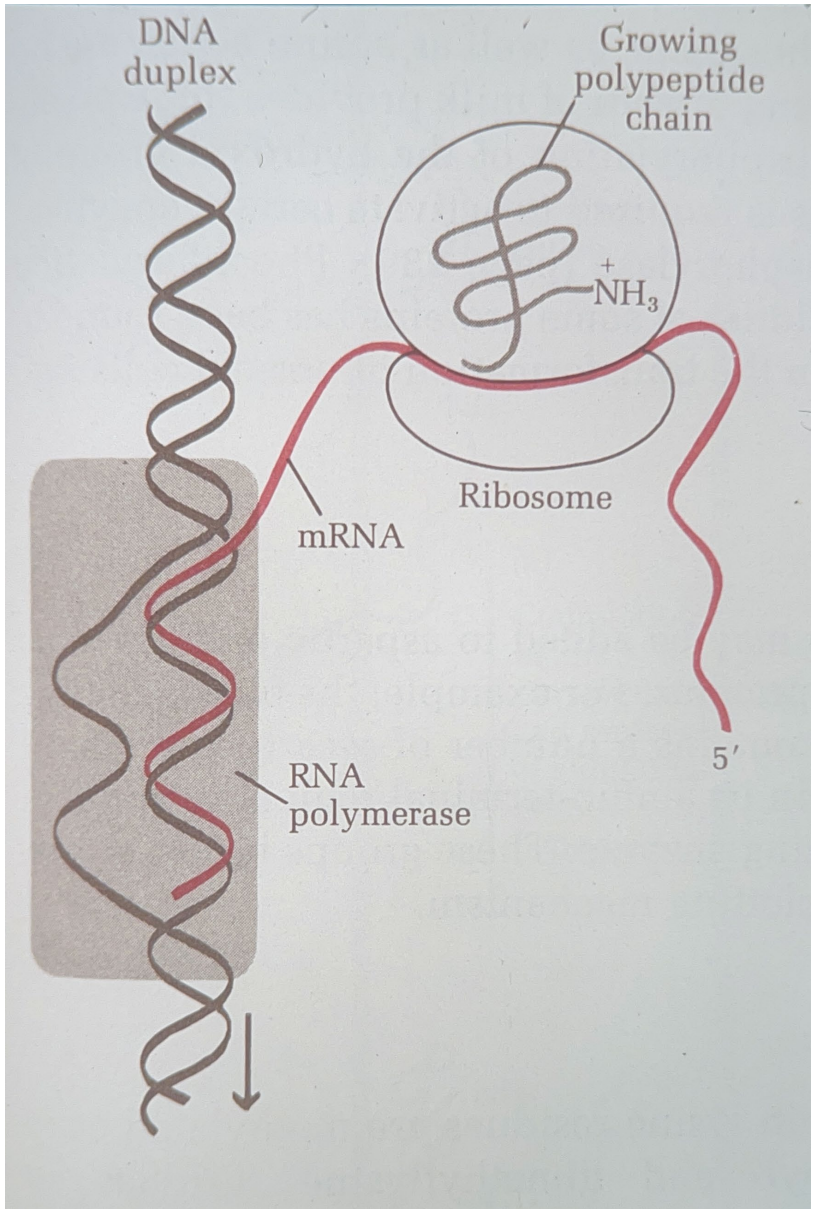
Worsted Spinning and Twisting Plant with 20,500 spindles

Weaving and Warping

Arrays of Parallel Machines

Definition of Molecular Nanotechnology

Thorough, three-dimensional structural control over materials and devices at the molecular level



Ribosome example:

Nature’s atomically precise manufacturing for proteins

Atomically precise bearing design

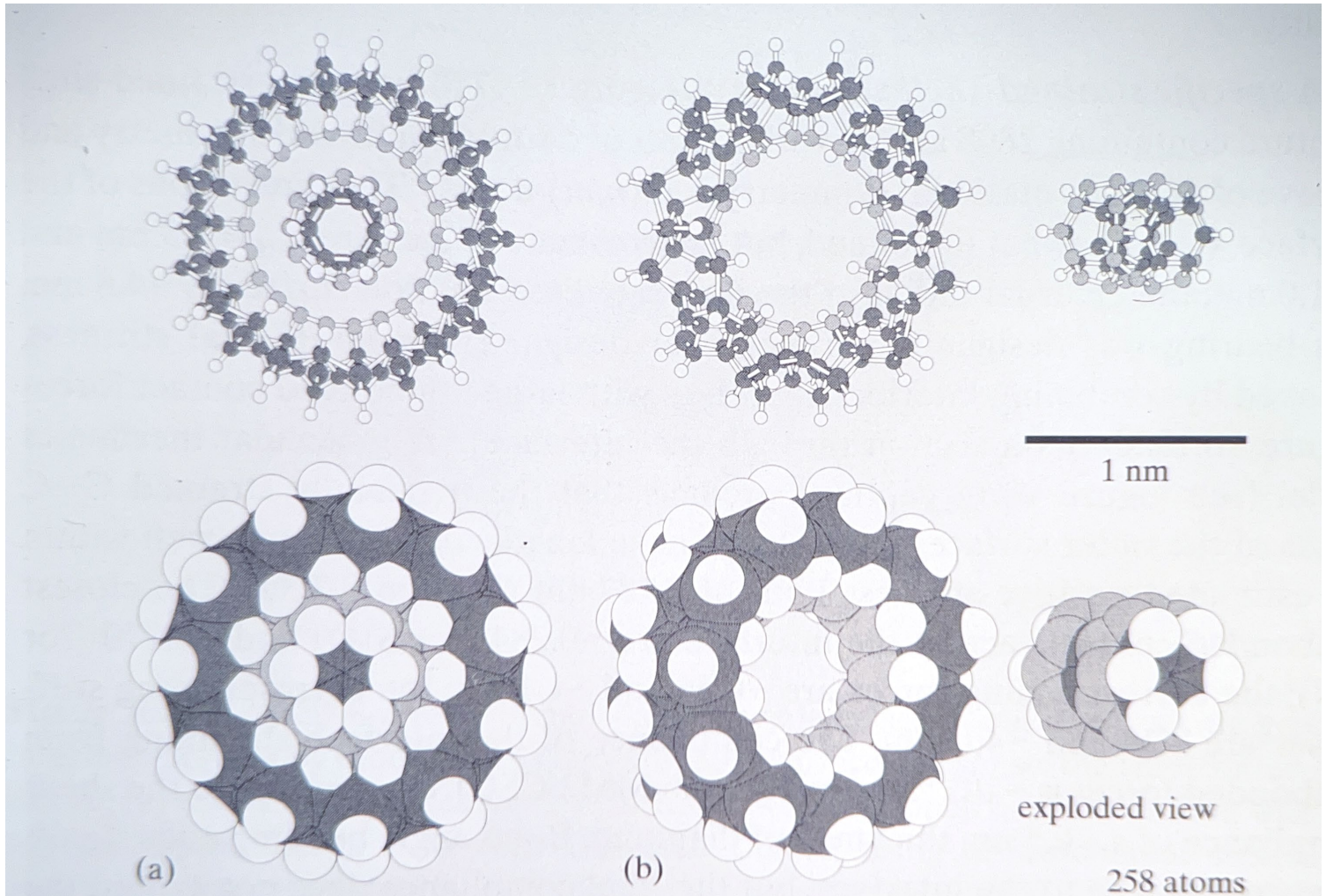
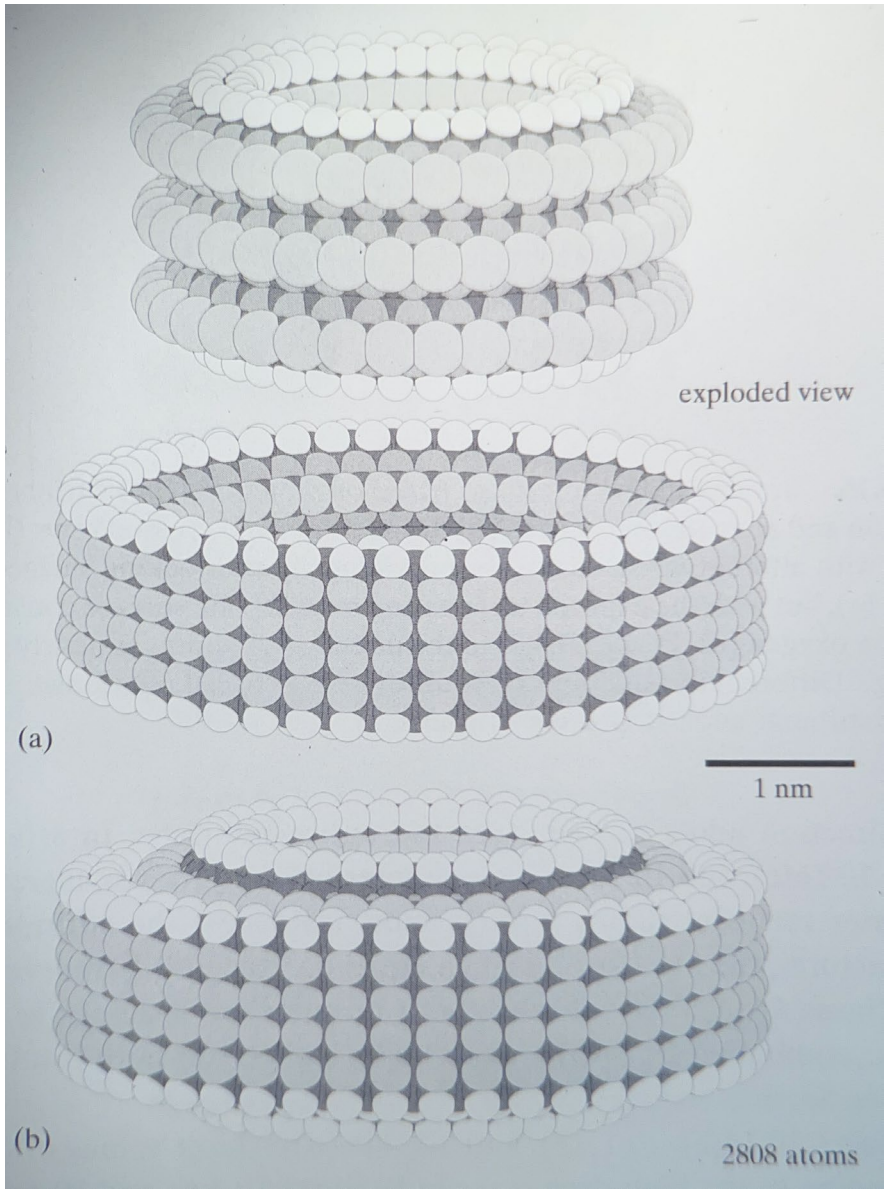
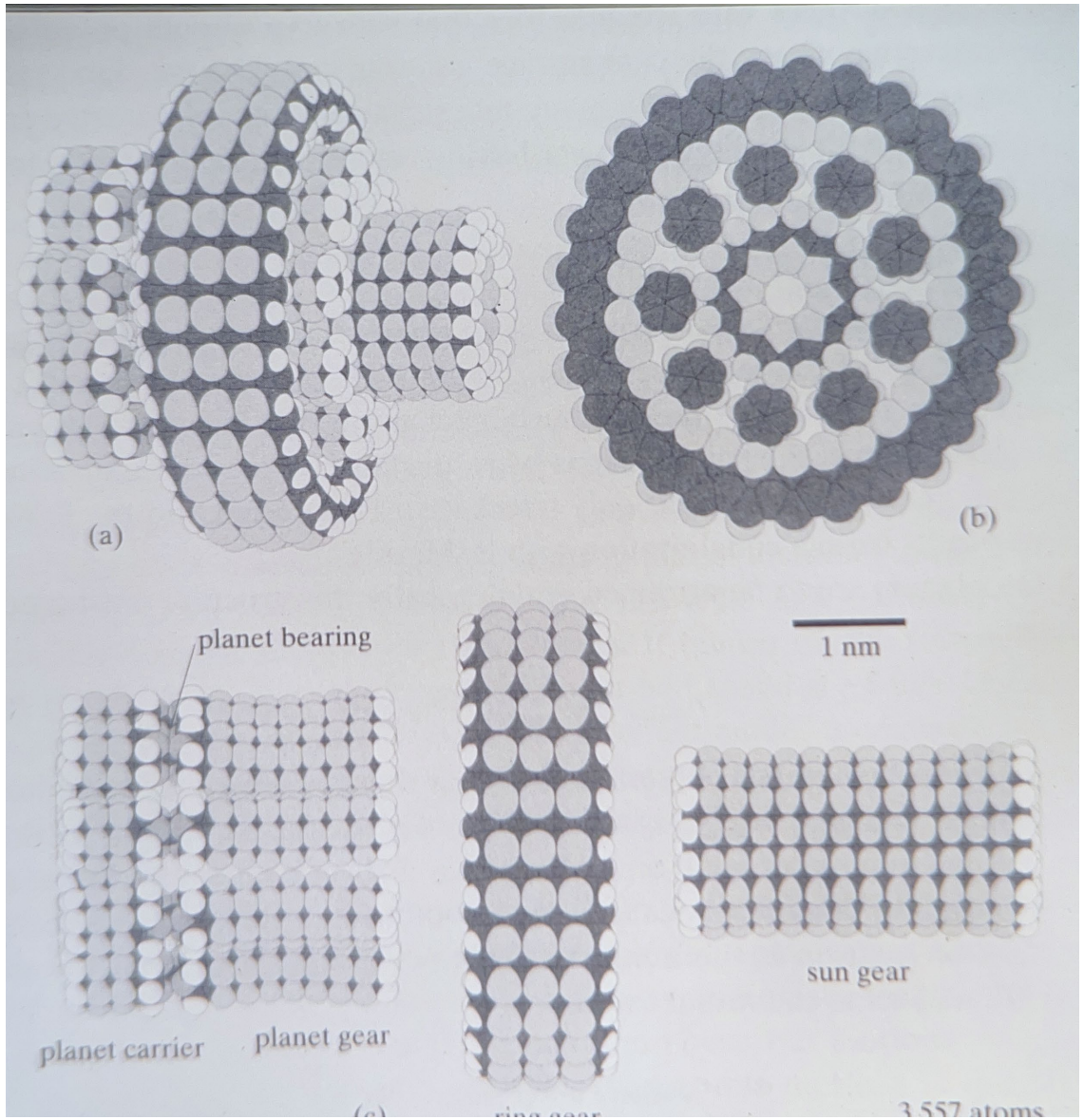


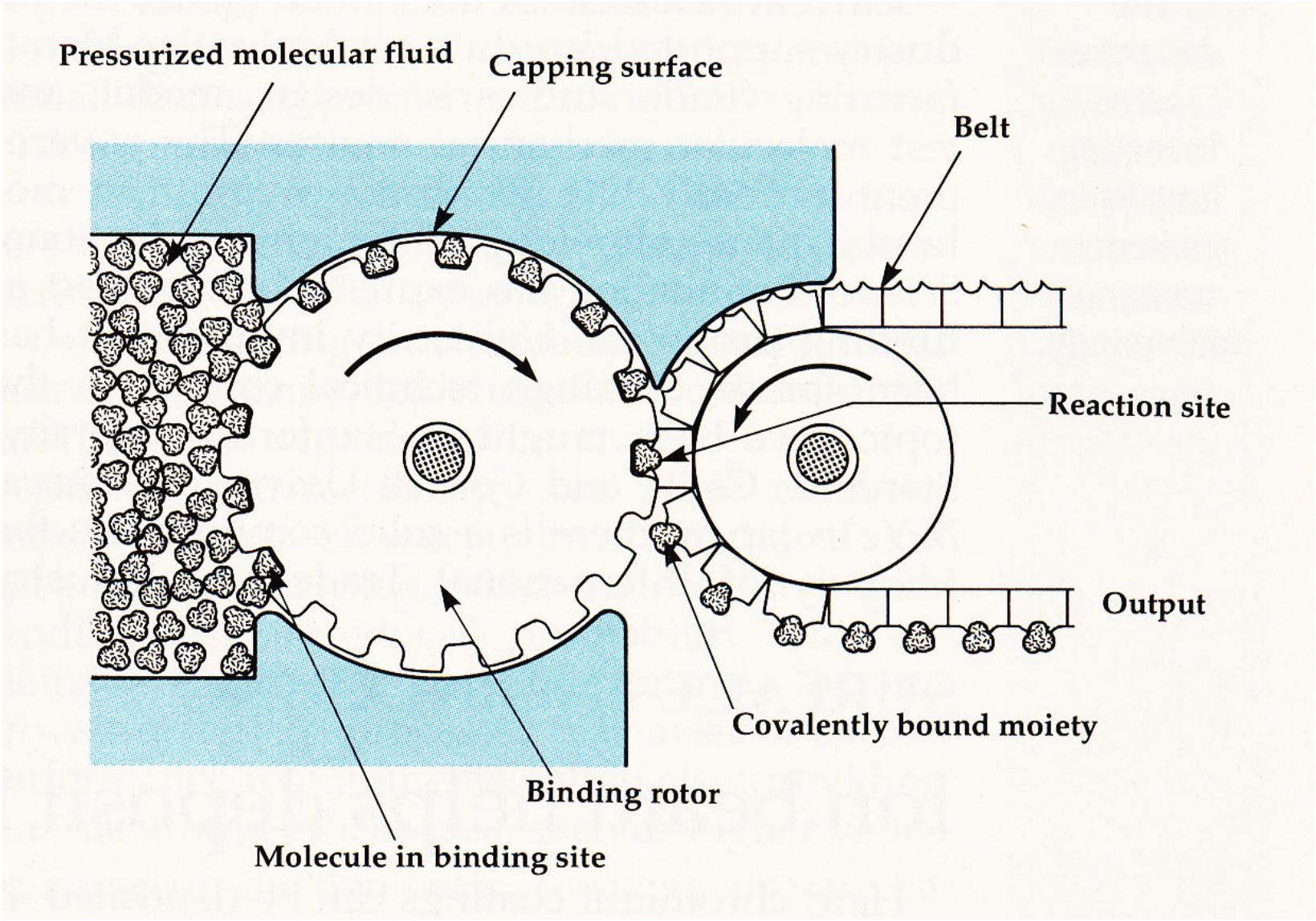
Figure 10.19. Views of a small sleeve-bearing structure: (a) end, (b) exploded.



Atomically precise bearing design

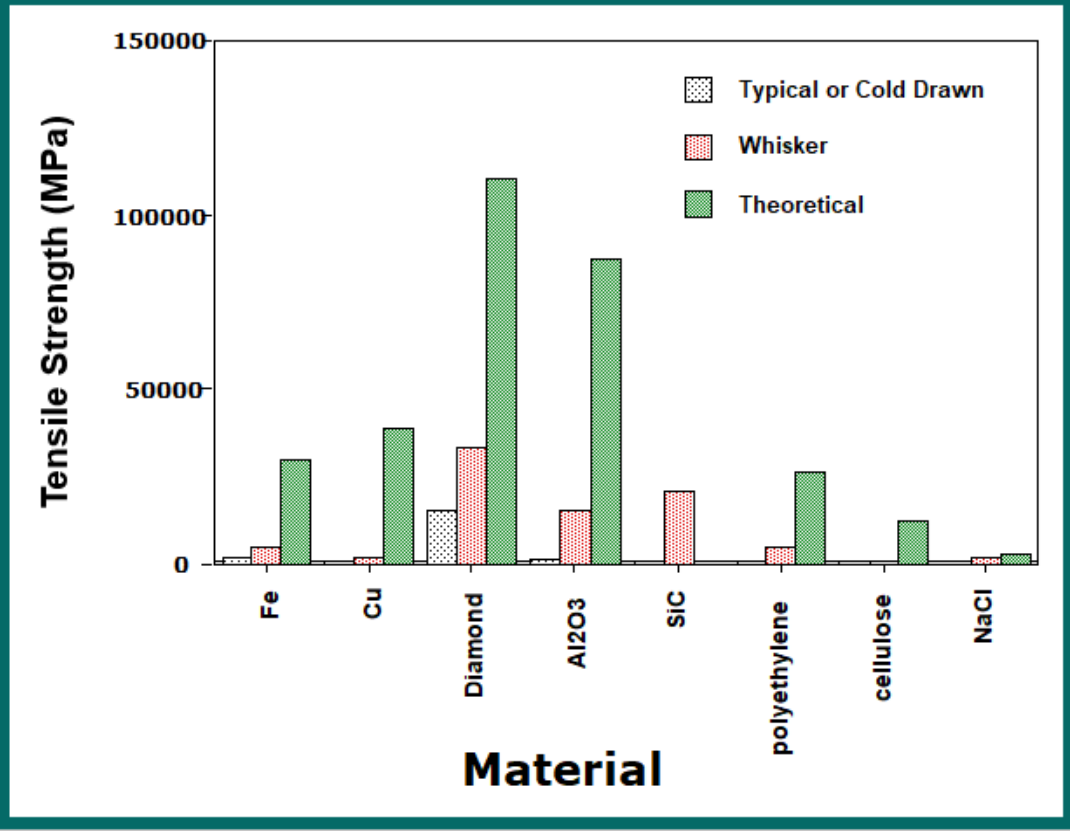
Atomically precise planetary gear design



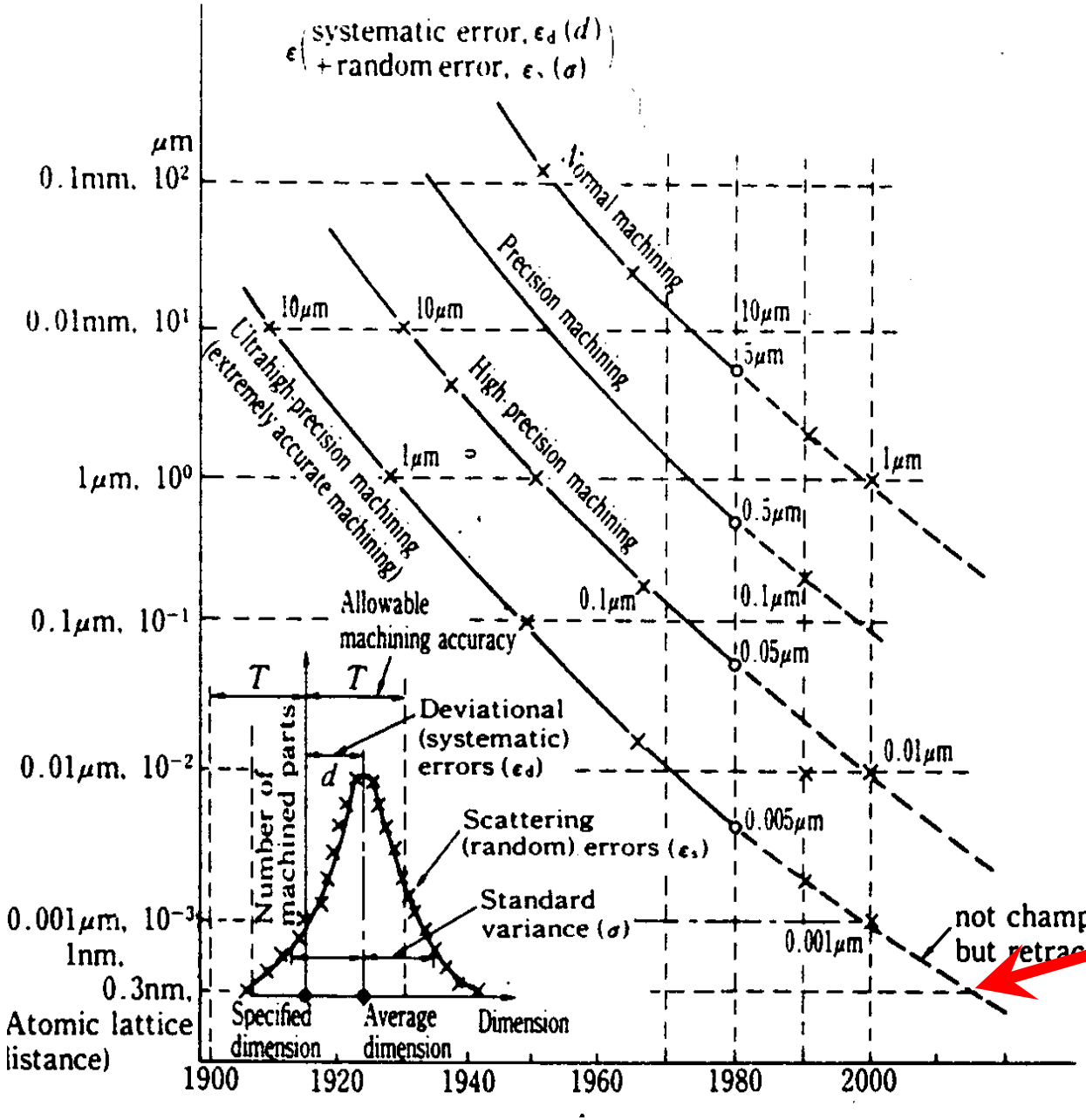


Controlling the trajectory and orientation of molecular building blocks

Comparison of Typical vs. Theoretical Strengths



Machining precision, log scale to nm



Time (years)

Atomic precision projected between 2010 and 2020

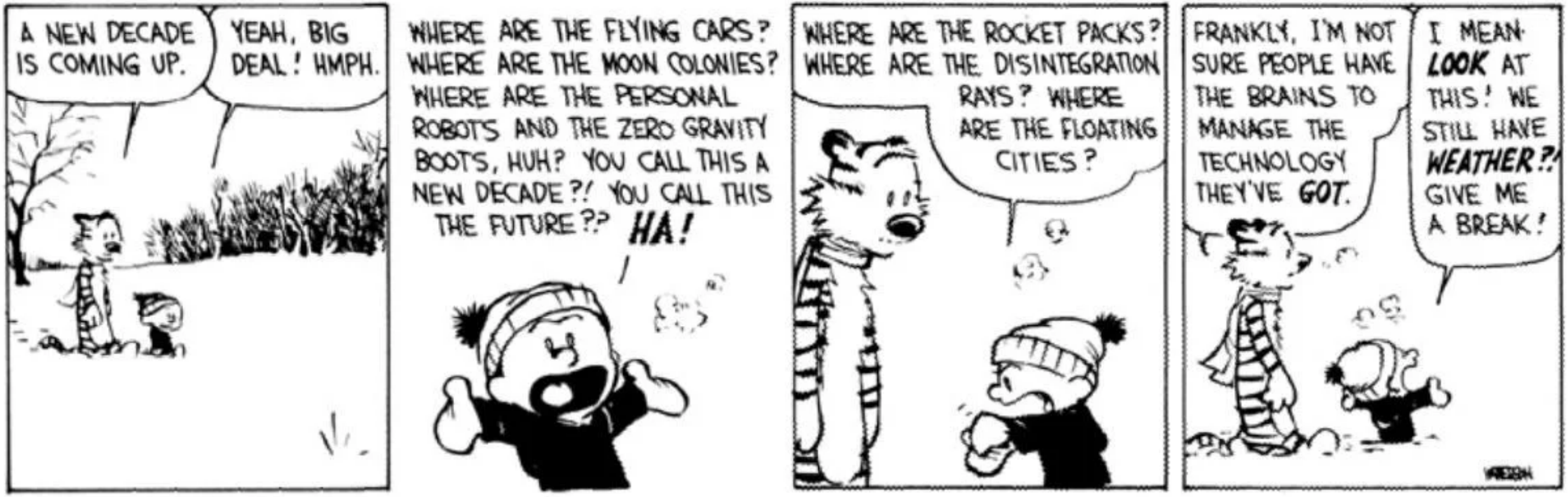
2015 atomic precision

Advanced Textiles EXPO

Molecular Manufacturing may be here soon

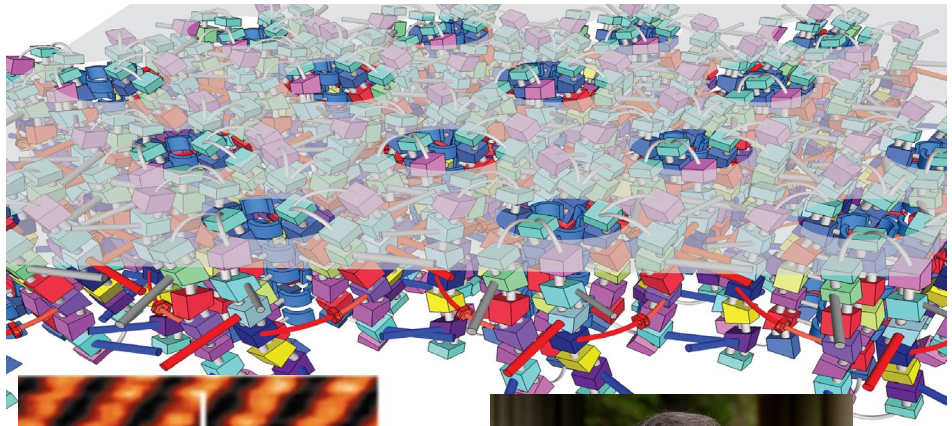
- No single development path
- No new science
- Advances in science and engineering
- Design work can proceed in parallel
- Strong incentives for development
- 1991 MITI $185M towards related technologies
- 1991 key design work at IMM
- 1993 Rice University initiates nanotechnology program
- Quantitative measures of progress

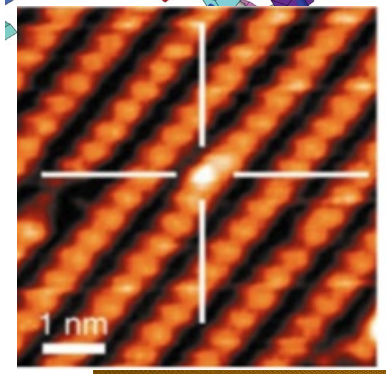
Calvin and Hobbes

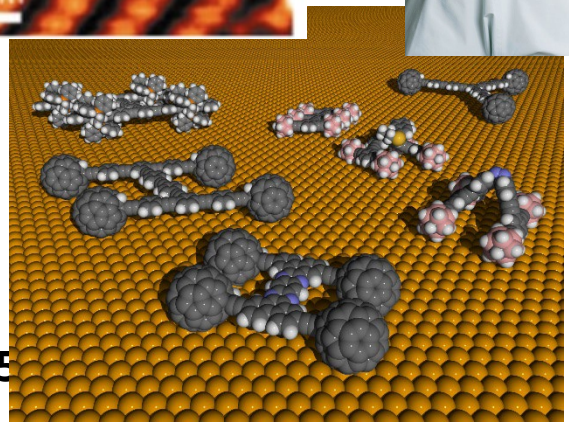


DECEMBER 28, 29, 30, 1989

There *has* been significant progress!

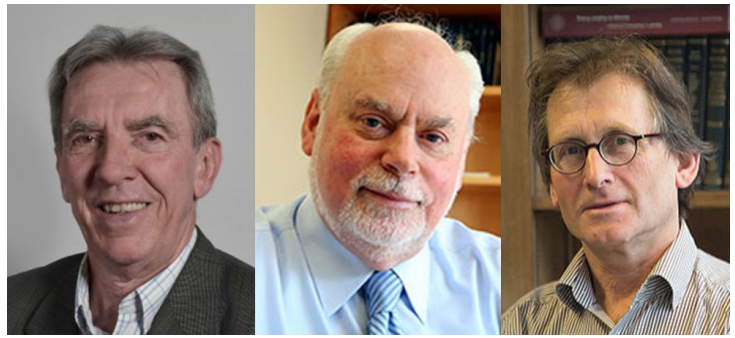


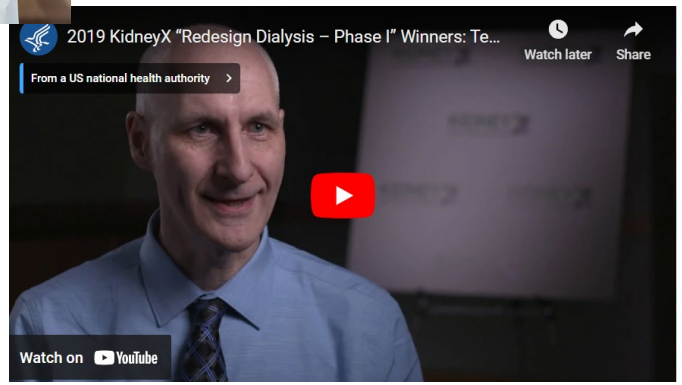


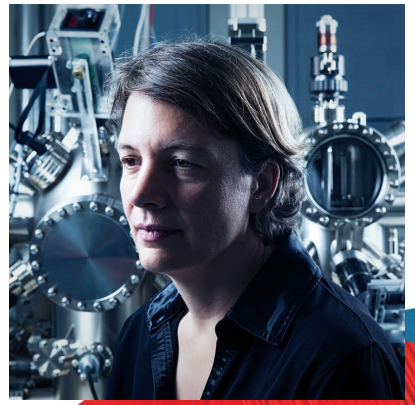


Why is atomic precision important?

Why are nanomachines necessary?







Why is Atomic Precision Important?

Energy

Ability to perform atomically precise manufacturing → major energy implications:

- Things made from materials not near their theoretical strength weigh 10X too much; Extra mass penalty = 50 Quads/year
- Can't perform chemical separations near theoretical efficiencies
  - 2-3 Quads/year penalty
- Can't make molecular switches in CPUs
  - ~2 Quads/year penalty
- Electrical resistance
  - 30% of energy loss: interconnect defects

Why is Atomic Precision Important?

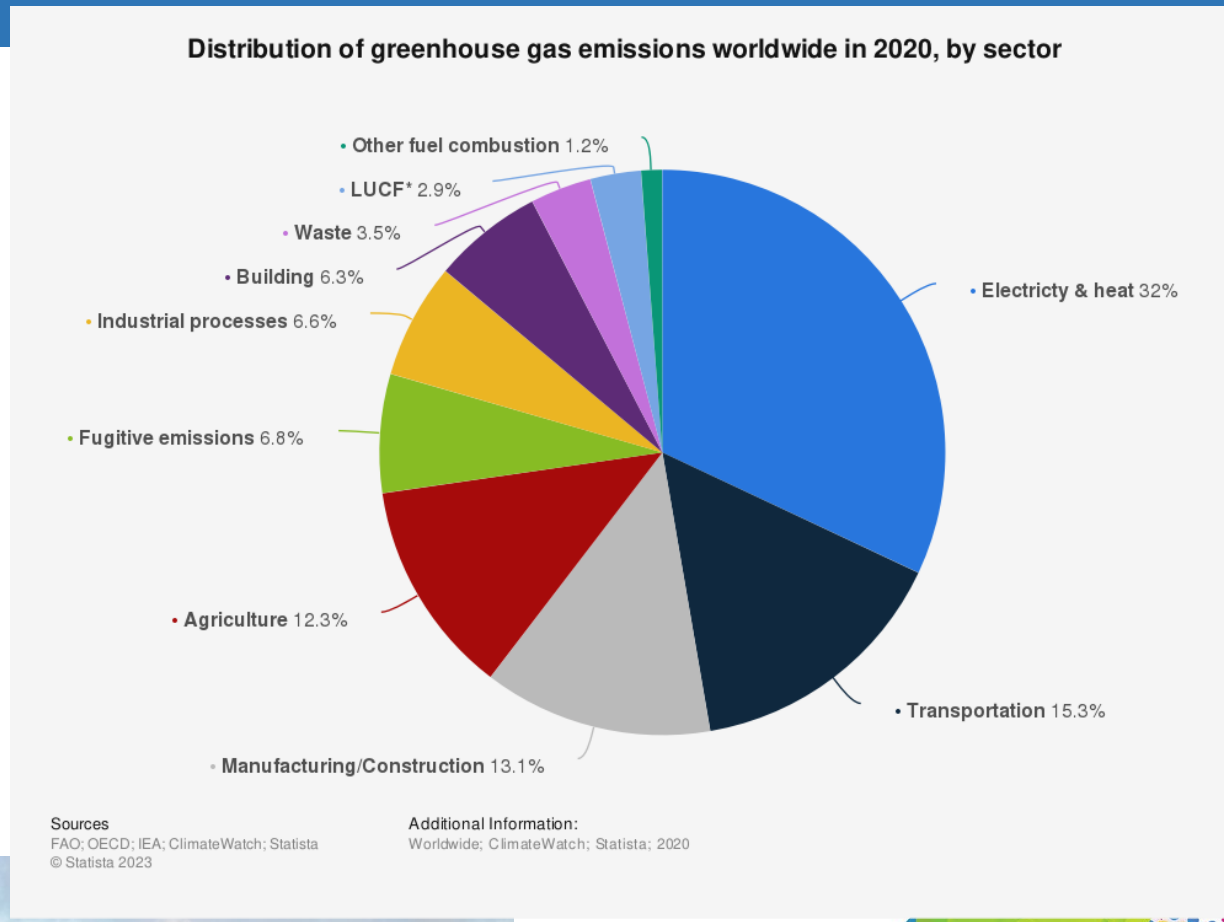
Greenhouse Gas Emissions

Zeroth order from mass reductions

- Transportation: 90% cut in global emission
- Manufacturing: 90% cut in global emission
- Similar, large energy production cuts

Most of all

- Prospect for technologies that inexpensively remove GHGs from the atmosphere



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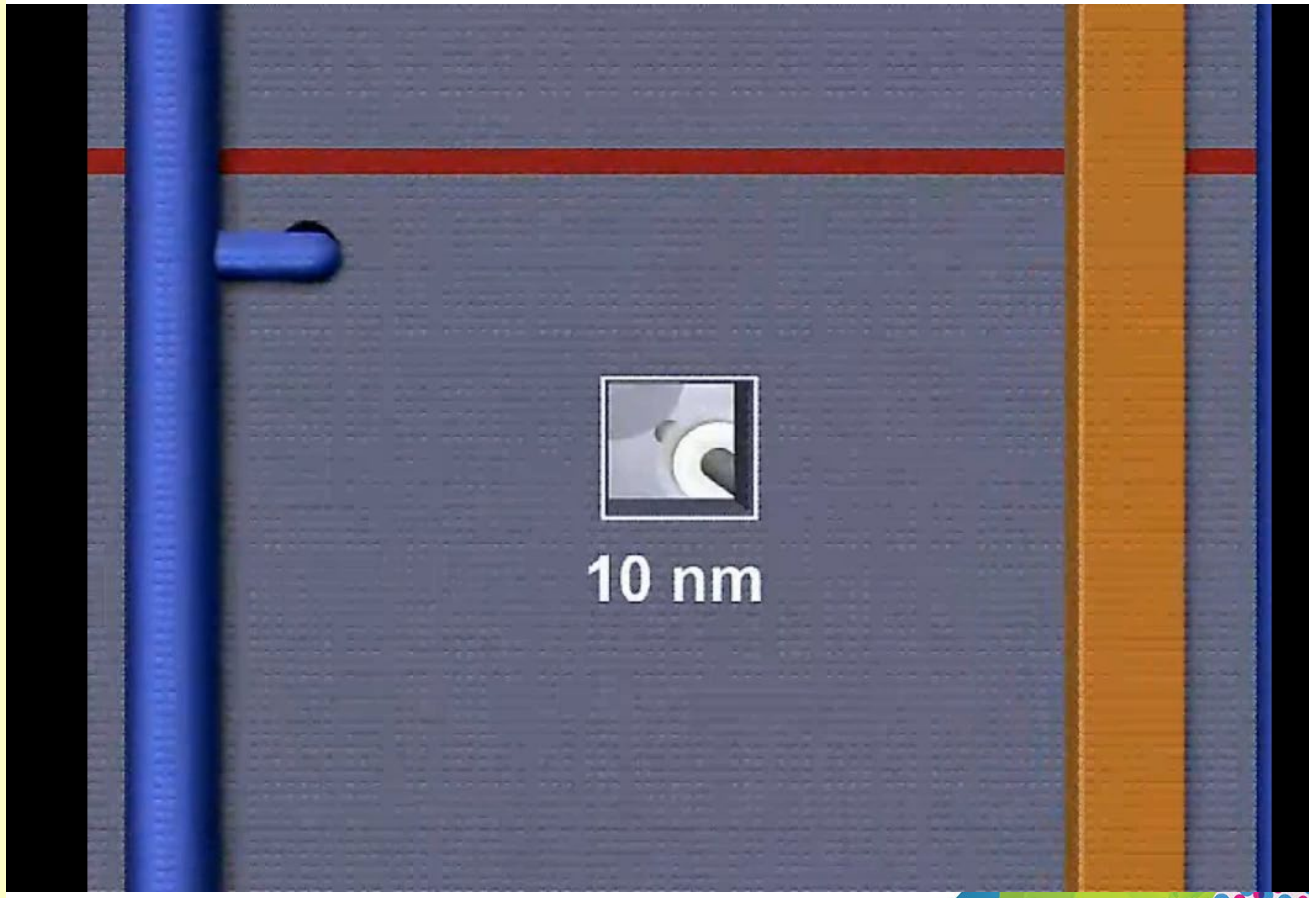
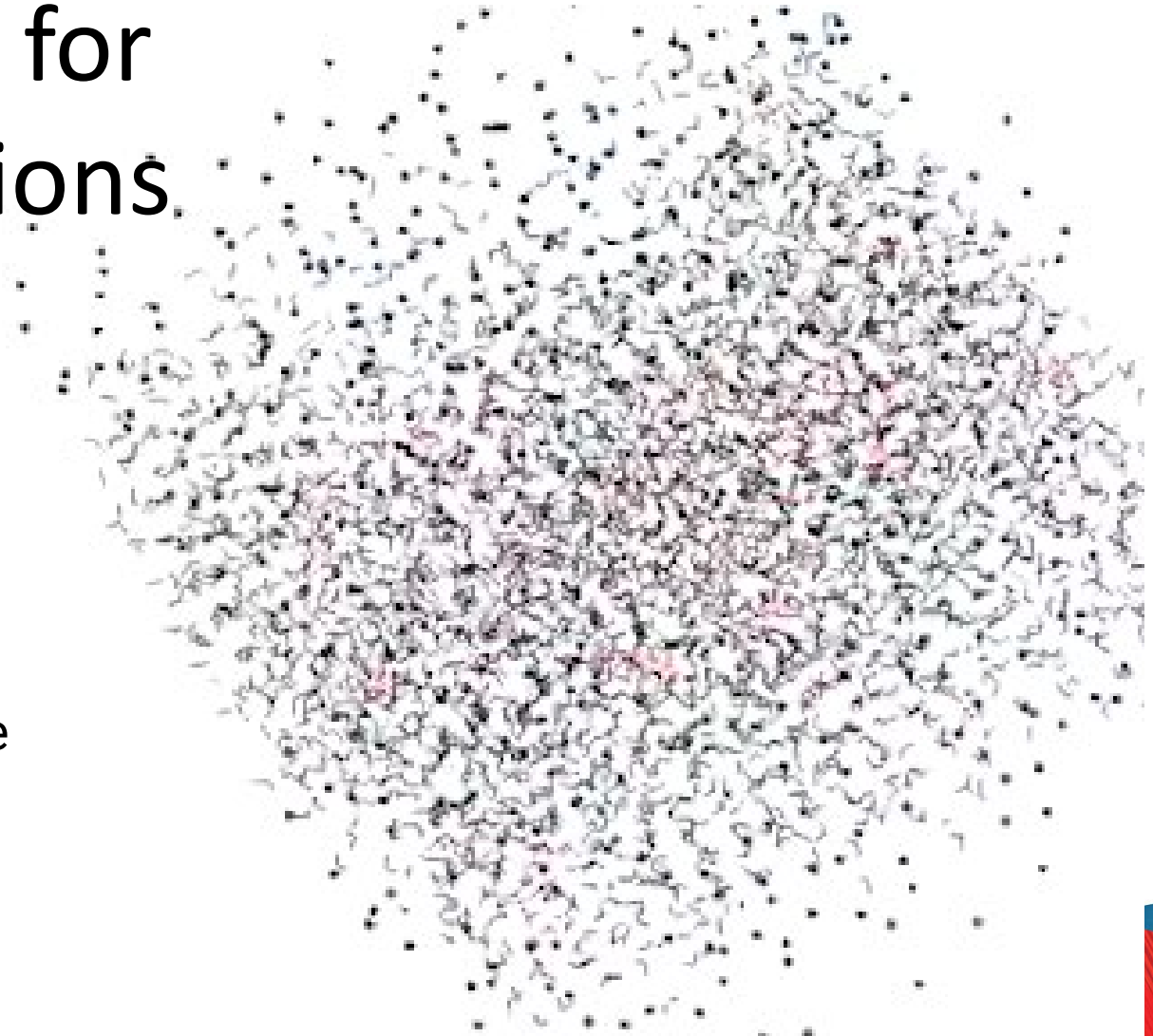


Sorting Rotors

Why is Atomic Precision Important?

Frenetic motion for occasional reactions

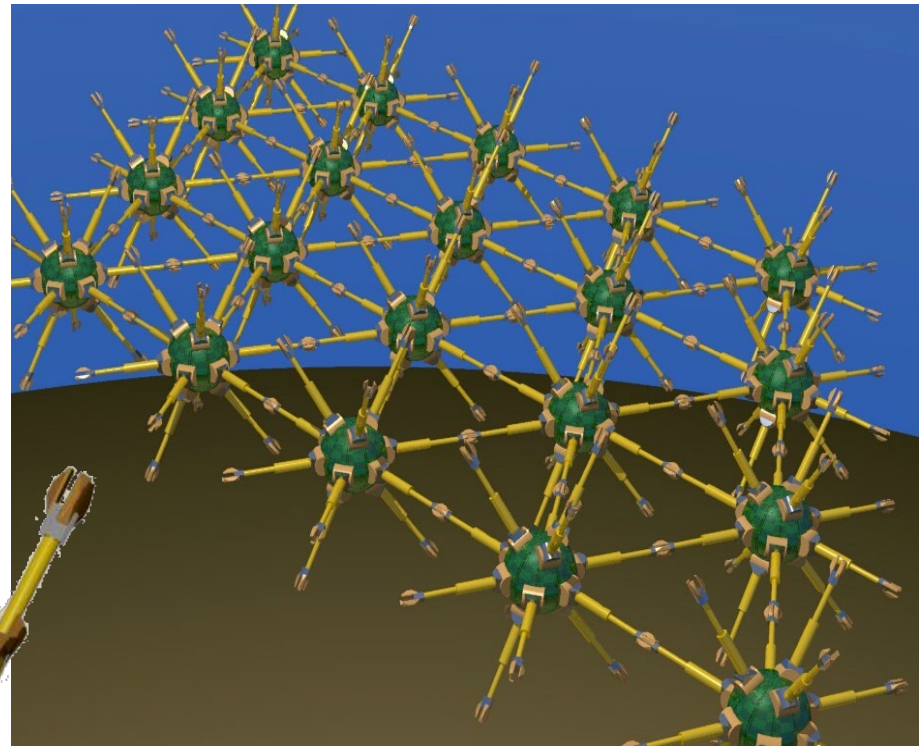


Teraflop Simulation of Methane Hydrate Formation

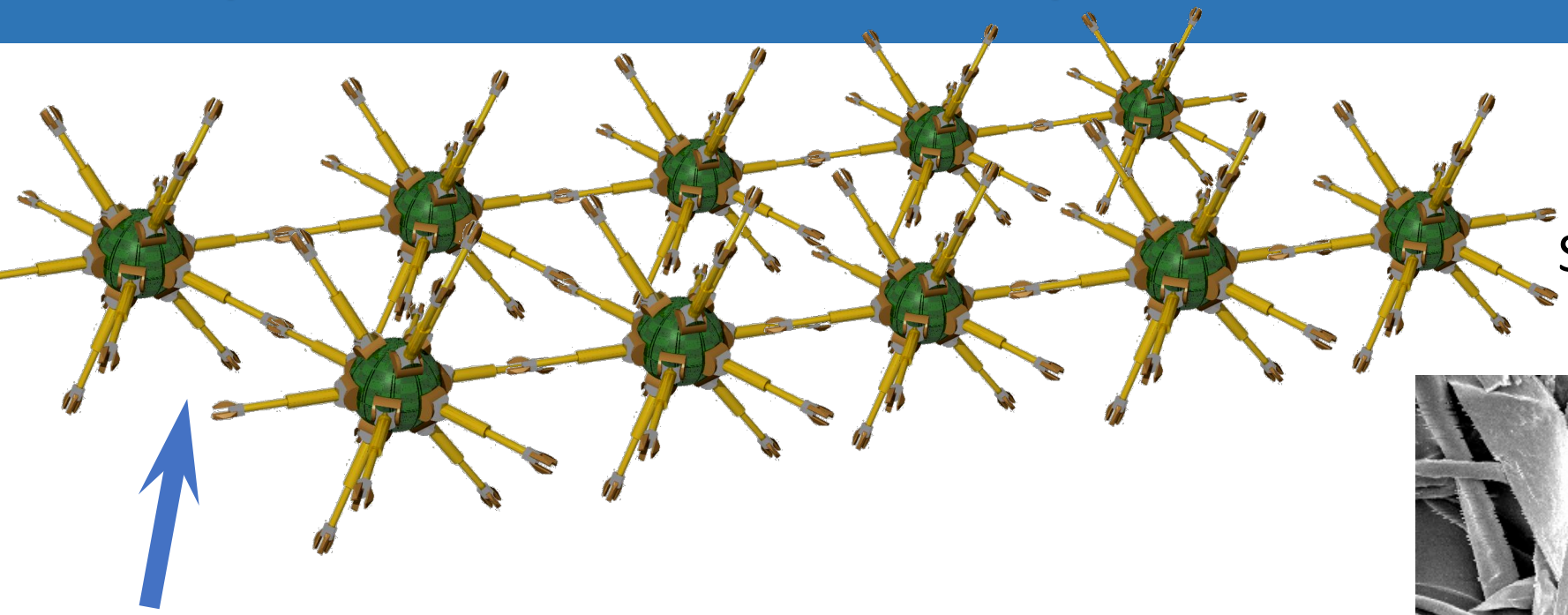
Why is Atomic Precision Important?

Materials, here imagined as "utility fog"

- Integrated computers, motors, power, sensors, communications
- Programmably extend/retract, clamp/unclamp
- Materials that change shape
- Change properties:
  - e.g., Softness—programmed response to external forces
  - Nature of the interconnects: swivel, pliability
  - Connections between layers
  - Woven linear chains
  - Coatings: protein, or protein-like for example
- Micron scale and up



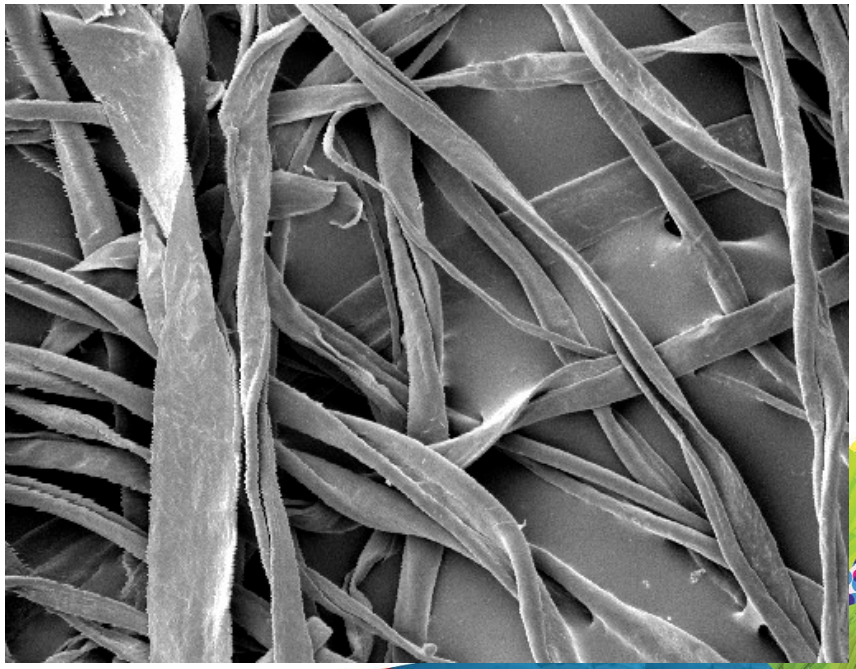
Why is Atomic Precision Important?



Array of nodes connected into a flat ribbon

Ribbon-like arrangement of cotton fibers. . . but programmable

Scanning electron microscope image of cotton fibers



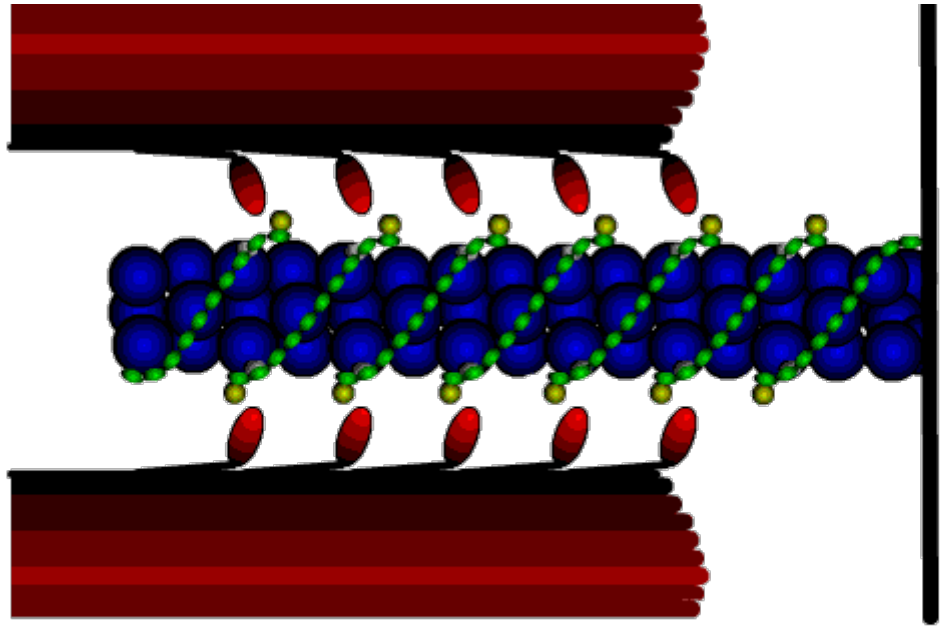
Why is Atomic Precision Important?

Movie special effects seem more plausible, knowing about foglets

Why is Atomic Precision Important?

Sounds familiar. . .

- Broadcasting signals
- Coordinated motion
- Millions of atomically precise molecular machines
- Change the shape and properties of large objects



The action potential inhibits the calcium pumps, and calcium escapes from the **sarcoplasmic reticulum.**

Actin-Myosin
(aka muscles)

Why is Atomic Precision Important?

The Vision for Atomically Precise Manufacturing

- Bottom up construction, atoms to sub-assemblies to products
- The process would use molecular machines that are, themselves, atomically precise
- It would involve positional assembly
- Products made to atomic precision can provide exceptional performance

Search “Nanofactory Animation” on YouTube
Sidewinder77


Production Restart:

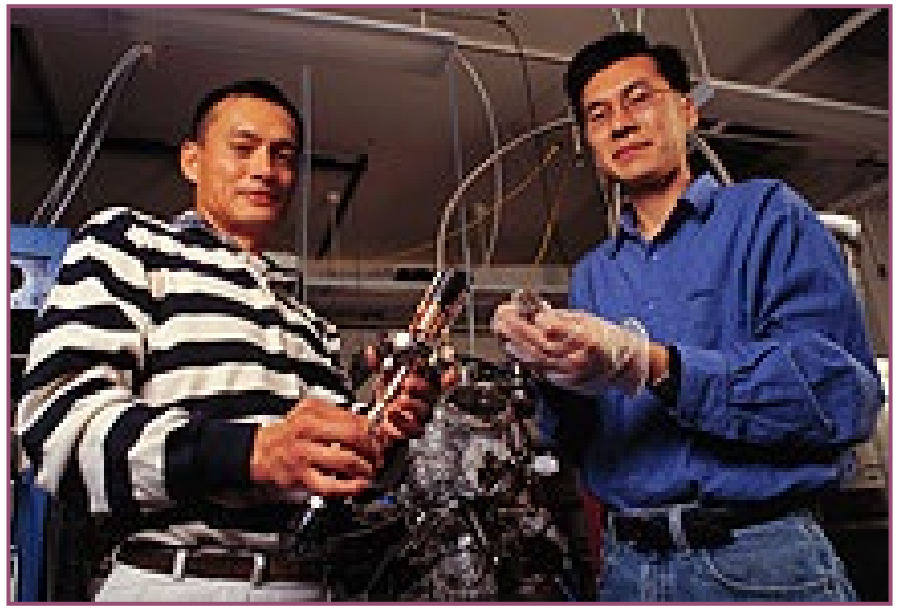
Progress

Much has happened since 1995

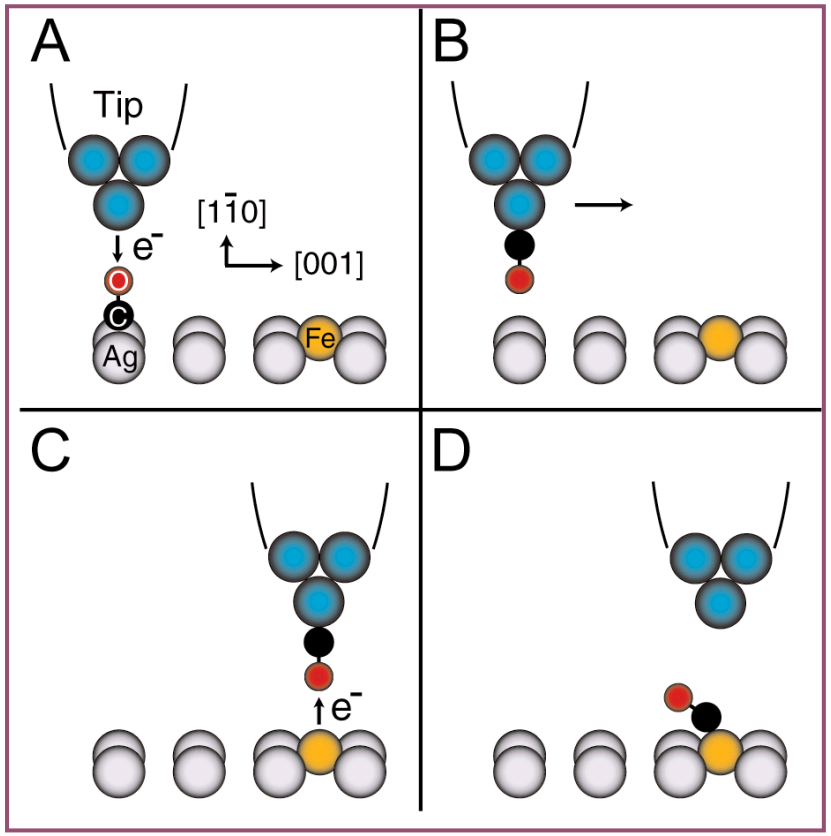
Progress

Positional Assembly Success

(Ho and Lee, Cornell, 1999)

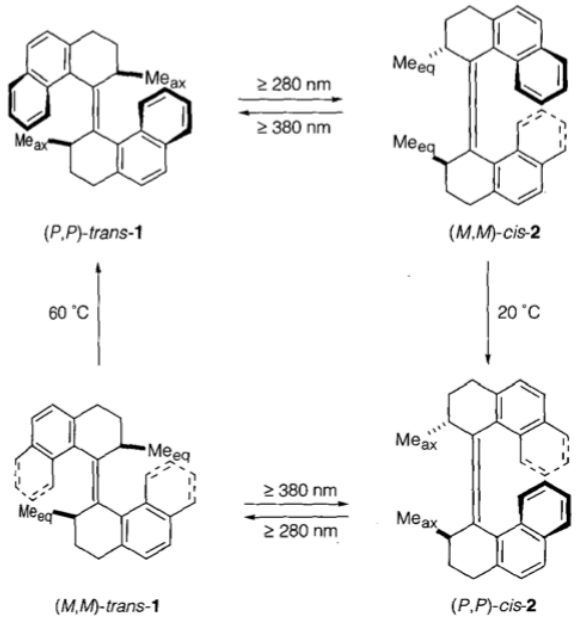


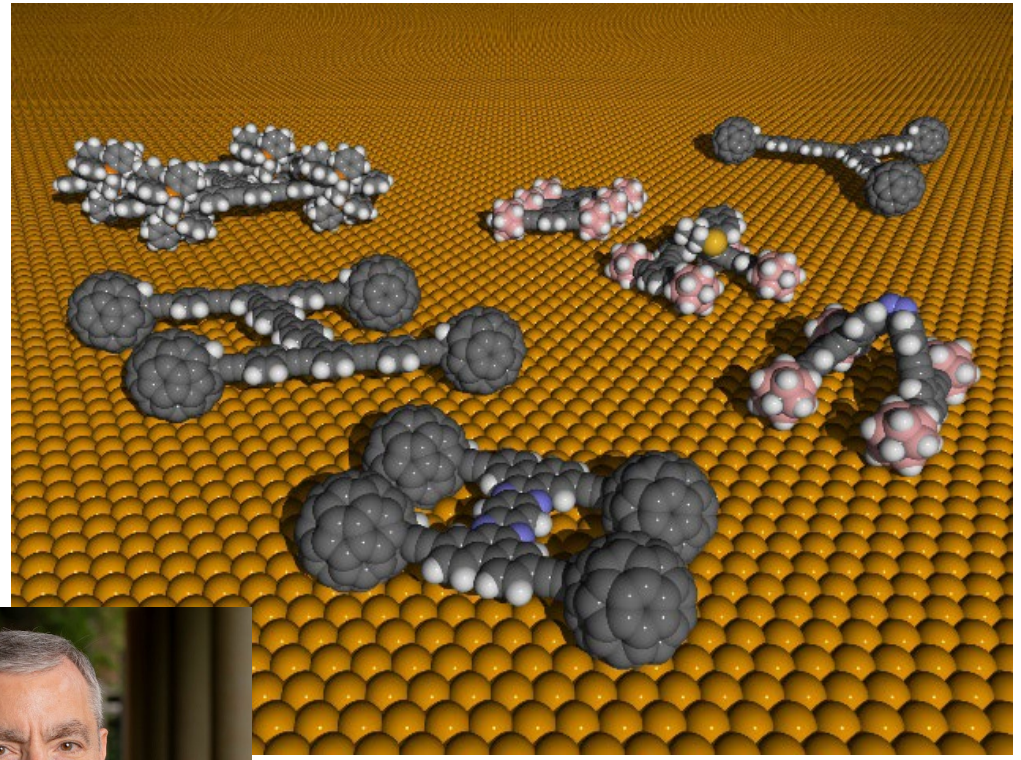
Wilson Ho and Hyojune Lee



CO bonded to Fe, 13 K

Progress





Ben Feringa
1999 Light-driven nanomotor

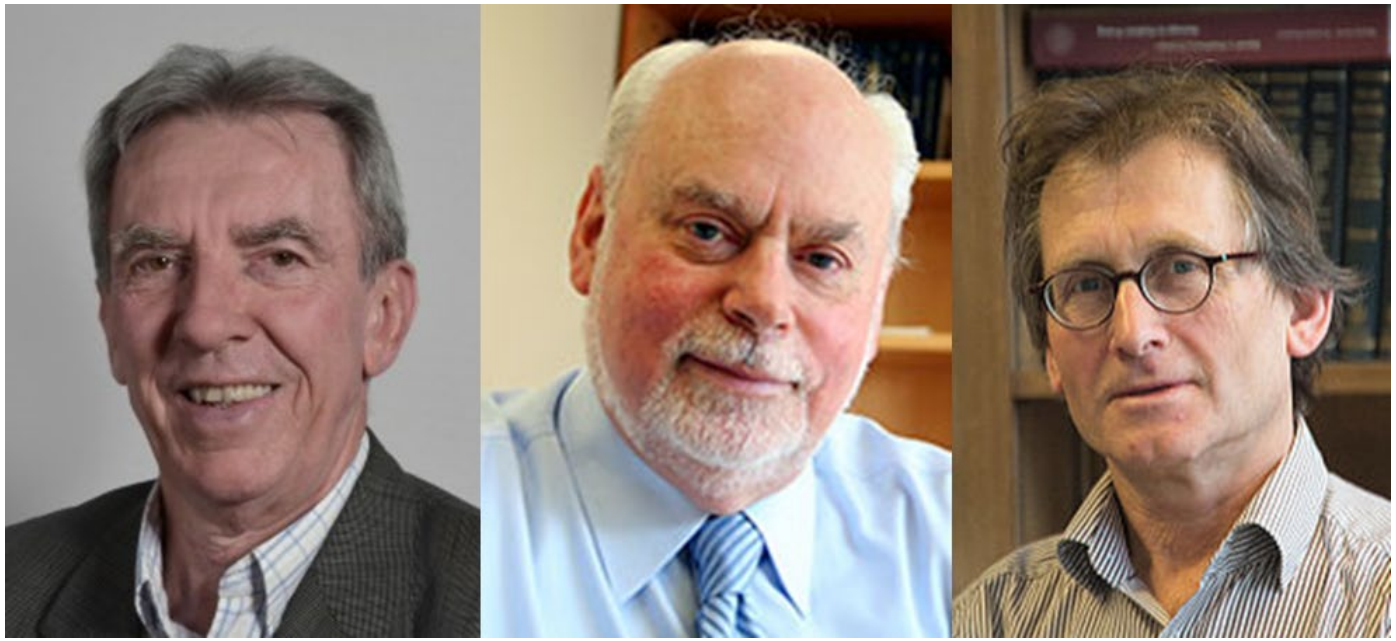
James Tour
2005 Nanocar

2017 Nanocar Race

Progress

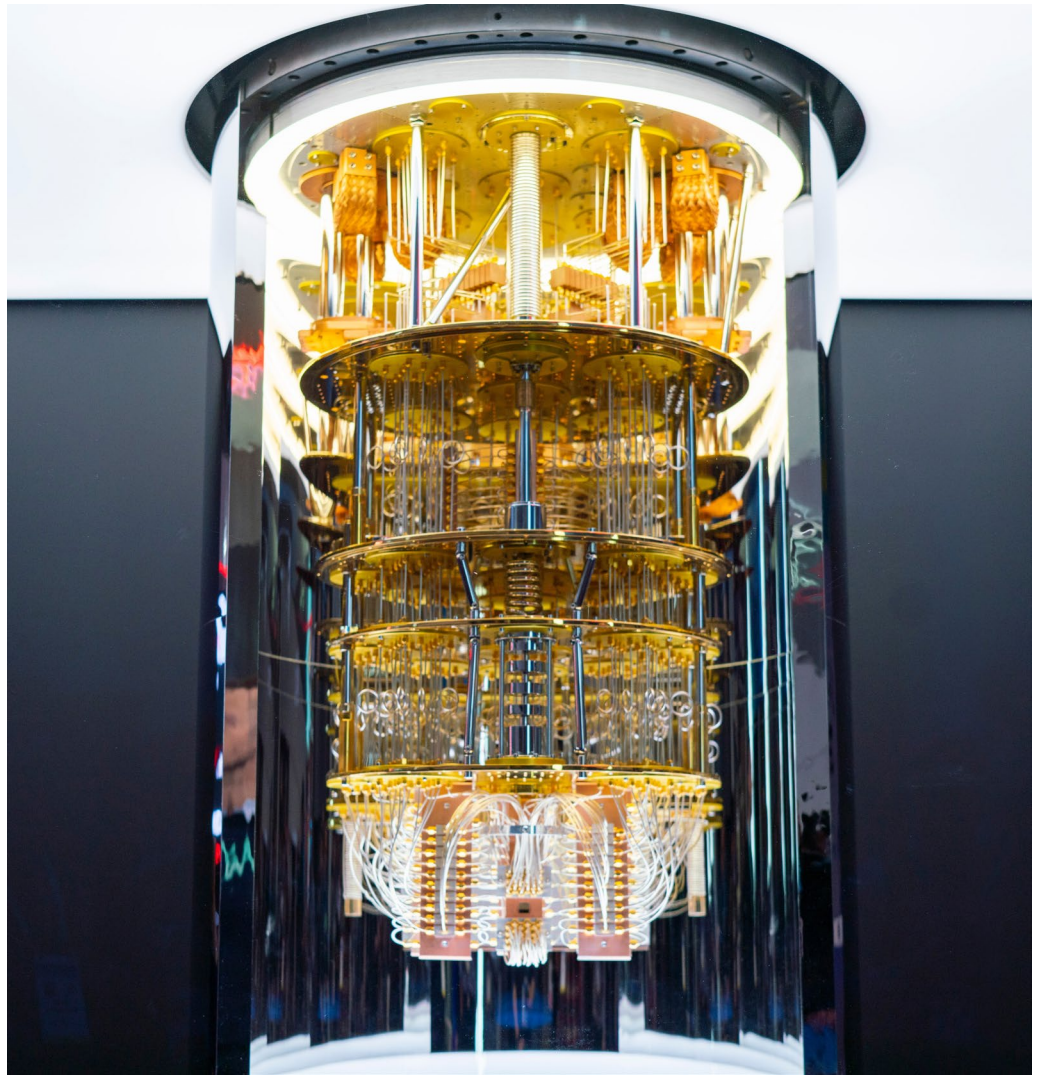
2016 Nobel Prize in Physics

for design and synthesis of molecular machines



Jean-Pierre Sauvage, Sir Fraser Stoddart, and Bernard L. Feringa

Progress



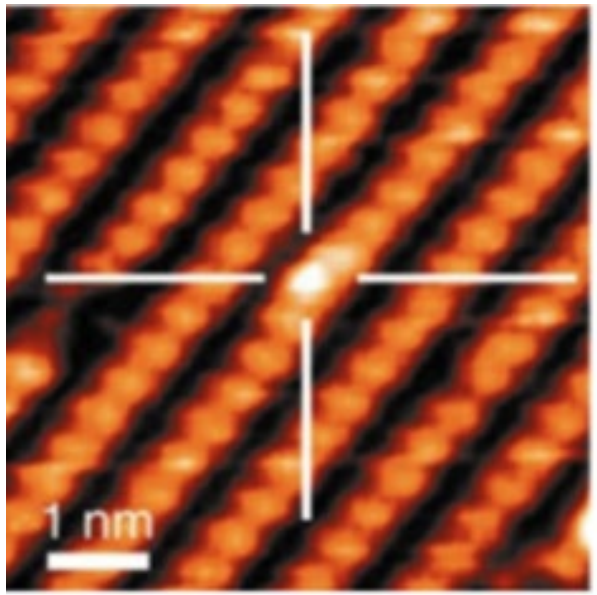
2019: IBM Q System One quantum computer

- 2.7m x 2.7m x 2.7 m airtight glass cube
- 20 superconducting qubits
- Cryogenic temperatures
- Isotopically pure silicon
- Not textile-ready

Progress

1998 *Nature* Bruce Kane, UNSW

- University of New South Wales, Sydney
- Concept: single phosphorus atoms as qubits in a silicon-based quantum computer
- Information encoded nuclear spin



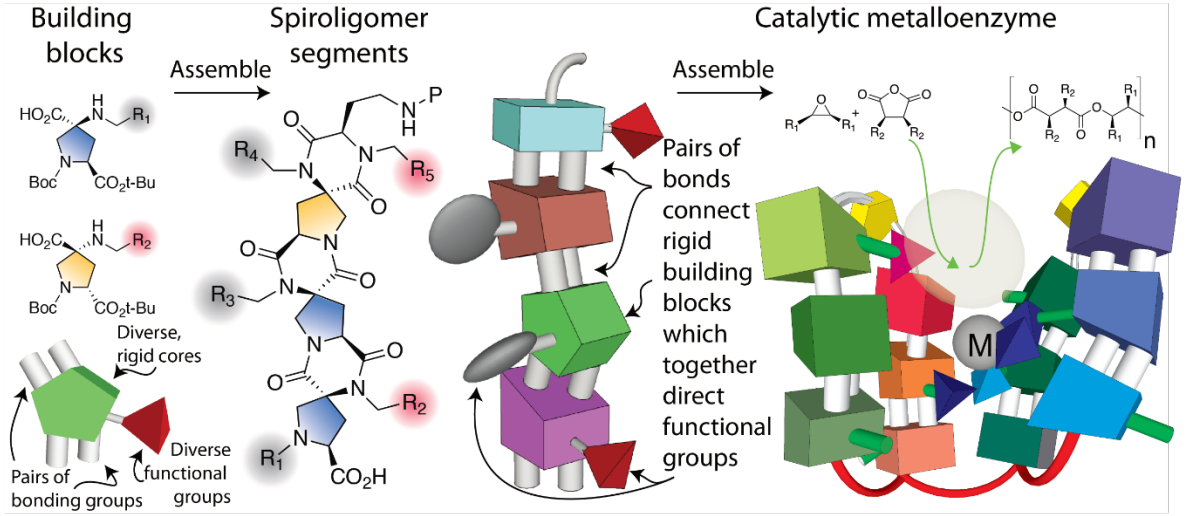
2003 *Phys Rev Letters* UNSW team

- STM Lithography creates single-atom qubit (phosphorus), selective deprotection
- “Bottom up” team at UNSW led by Michelle Simmons

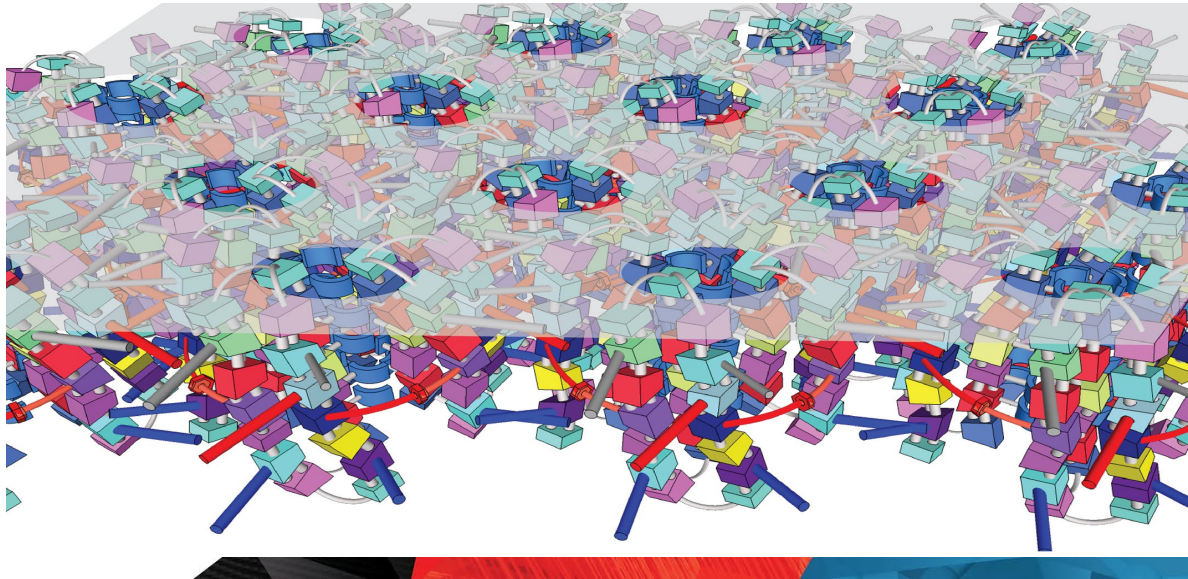
Spiroligomers for Atomically Precise Membranes and Catalysts

Prof. Christian Schafmeister, Temple U.

- Catalysts based on modified amino acids
- Covalent bonds, excellent stability
- 1,000+ times increase in catalytic activity, energy intensity reduction ~50%
- Crafted reaction sites

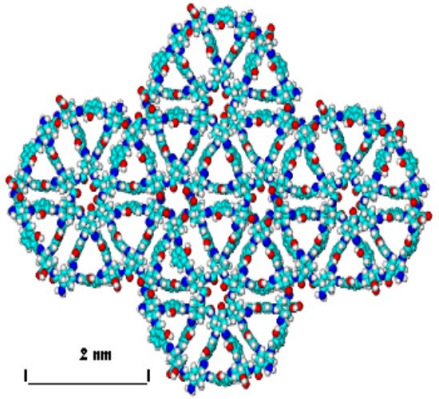


- Atomically flat membranes, one molecule thick
- Atomically precise pores
- Cross-linked, covalently-bound, ordered array; non-fouling
- High permeance, 100% selectivity



Atomically Precise Membranes

- **Make molecular building blocks for assembly into larger structures**
  Methods: Spiroligomers, DNA origami, protein engineering
- **Use self assembly:** Design building blocks that can order themselves, without defects, and be chemically bound



Covalent LLC
Self-assembled AP membrane

Adobe Stock: 2330363

Not much is needed—a few grams of molecules would be enough to cover an entire football field.

Progress

Atomically precise membranes: a critical advance

KidneyX Prize winner: Blood purification alternative to dialysis

- Clean water
- Clean air
- Medical applications
- Pollution cleanup
- Low energy mining of strategic minerals

Progress

Gas Separations

- Separate water from air → ultra-dry air
  - Hair dryers, $2B/year in electricity in U.S.
  - Clothes dryers
  - Air conditioners
  - Paint drying
- Argon from air
- Helium from natural gas
- CO_2 and CH_4 from the atmosphere
- Purification of Hydrogen for Fuel Cells (H_2S, H_2O, CO, NH_3, etc)
- Ethane and propane separated from natural gas

Factoid

- 1% of U.S. energy consumption is condensing water from air in air conditioners
- This energy is completely wasted; we do nothing useful with that water

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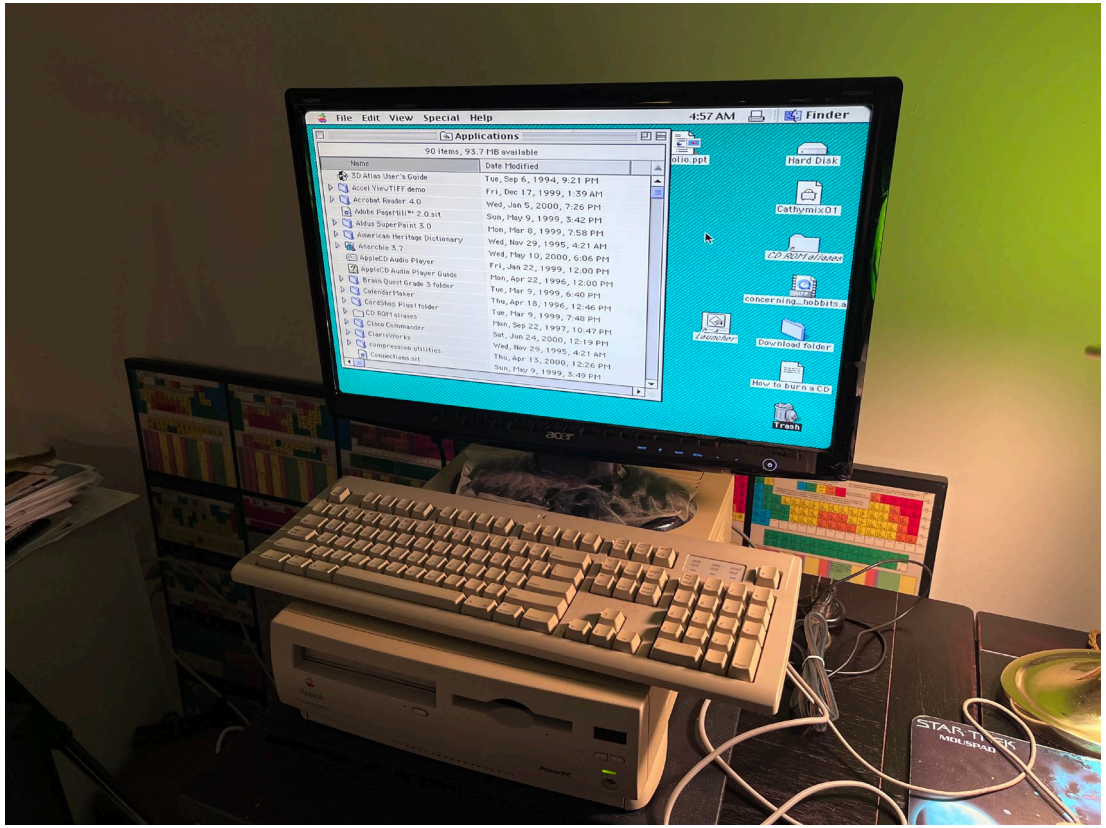
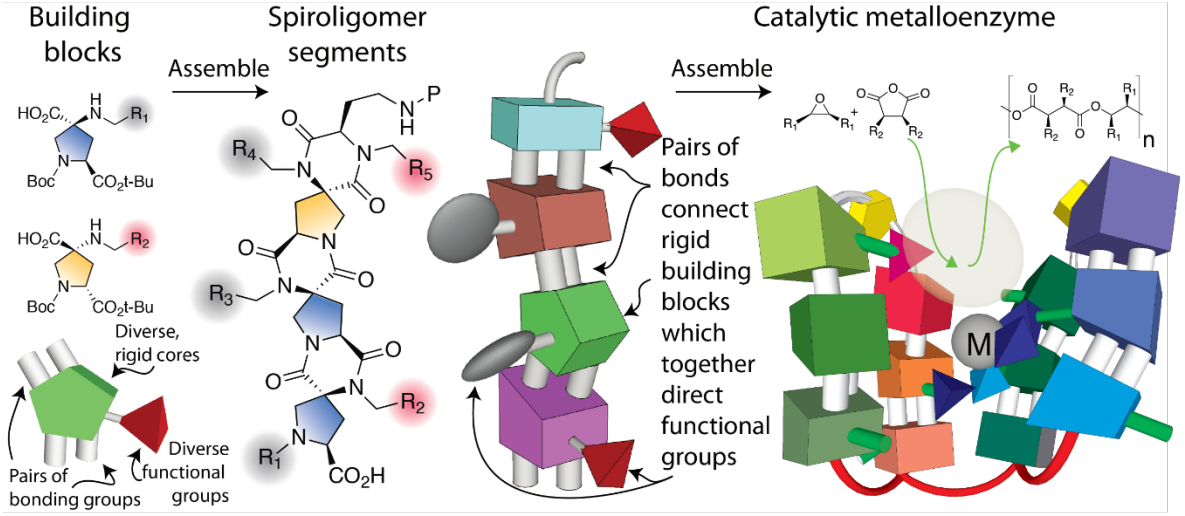
Extra Slides



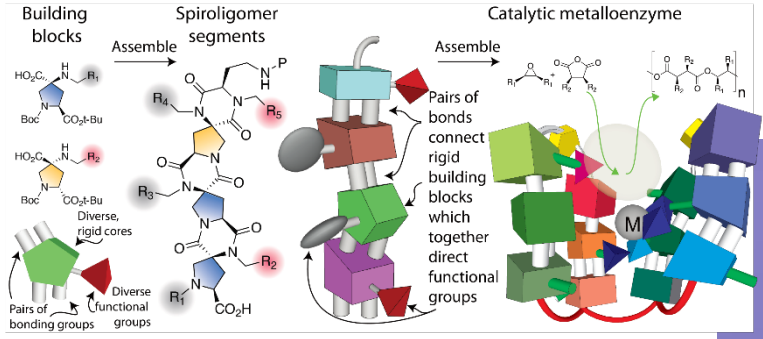
Atomically Precise Metallo-catalysts with Molecular Lego

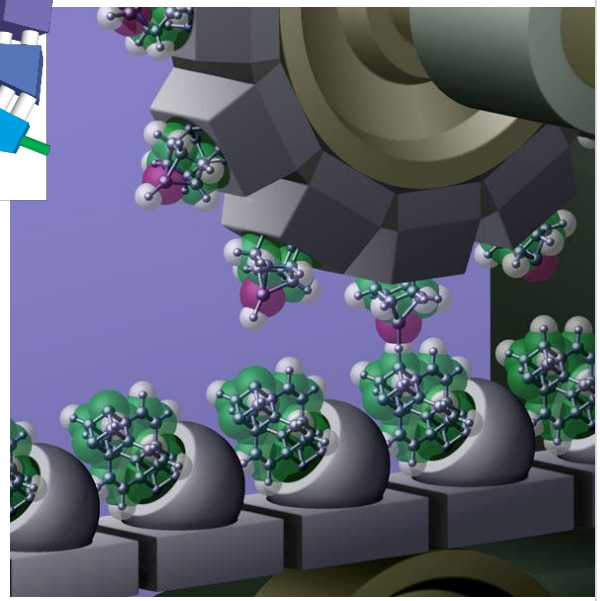
Temple University

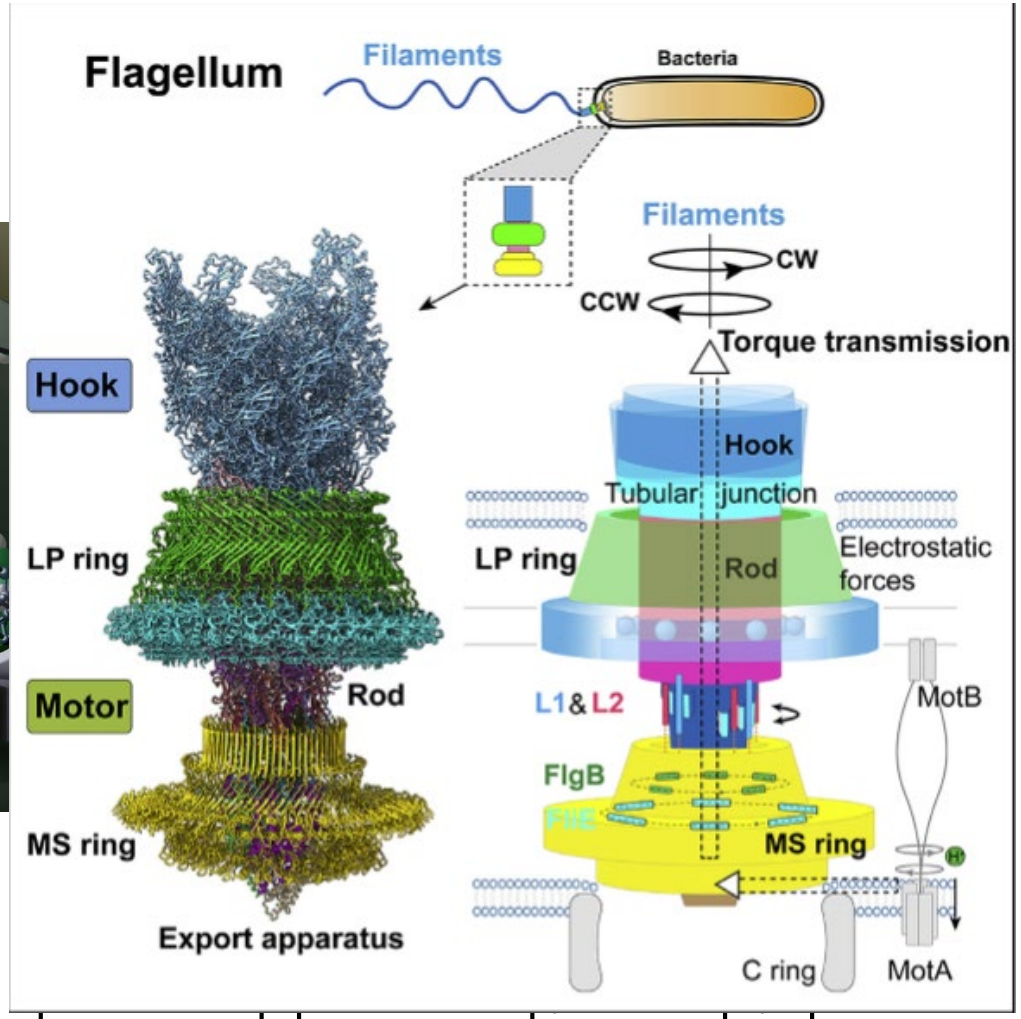
- Catalysts for atomically precise polyester production
- Enormous energy savings by manufacturing at ambient temperatures and eliminating purification steps
  - 1,000+ times increase in catalytic activity may be possible, reducing energy intensity by 50% to 6,000 Btus per lb.
- Use of CANDO software plus computational evaluation to search millions of options and identify promising assembly sequences for pre-made atomically precise ‘spiroligomer’ building blocks
- Spiroligomers will be assembled into atomically precise, highly robust (long life), nanometer-scale metallo-enzyme catalysts (macromolecules of 3,000 to 5,000 Daltons)



Fine-grained approach: atomic positional assembly





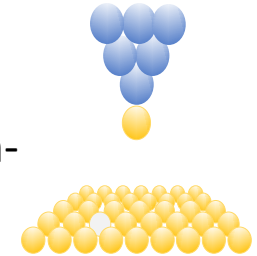


Focus on molecular mills and convergent assembly operations: high throughput workstations and successively larger APM components

Fund All Core APM Technologies

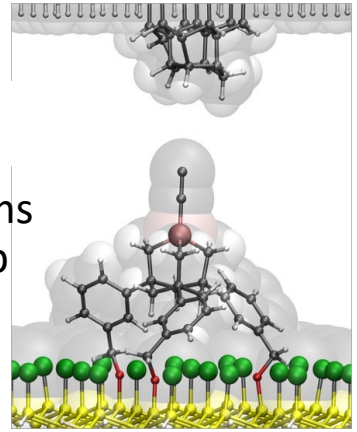
Tip-Based 2D Positional Assembly

- Atomically precise individual atom placement in 2D-designed materials for novel nano-electronic devices
  – *Zyvex Labs ($2.46 M)*
- Single-tip MEMS STM platform for high-speed lithography with atomic scale accuracy
  – *Univ. of Texas at Dallas ($2.42 M)*
- *TipTek SBIR project for better STM tips*



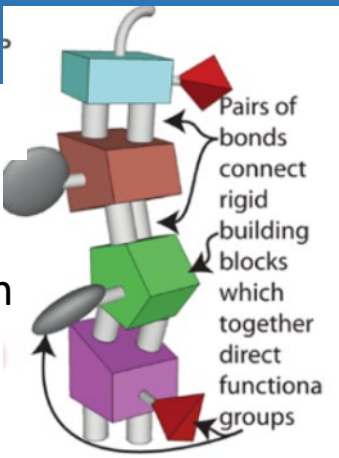
Tip-Based 3D Positional Assembly

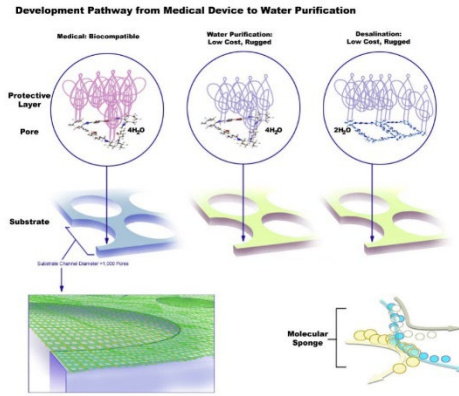
- Mechanosynthetic 3D extraction of atoms to sharpen an atomically precise SPM tip
  – *University of California, Los Angeles ($1.00 M)*



Atomically Precise Catalysts

- Atomically precise metallo-catalysts with Molecular Lego for biodegradable polymer production
  – *Temple Univ. ($0.80 M)*



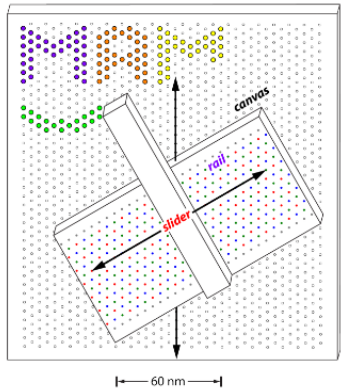


Atomically Precise Membranes

Chemical separations and desalination
– *Temple U. and Covalent LLC*

Molecular Machines for 2D Positional Assembly

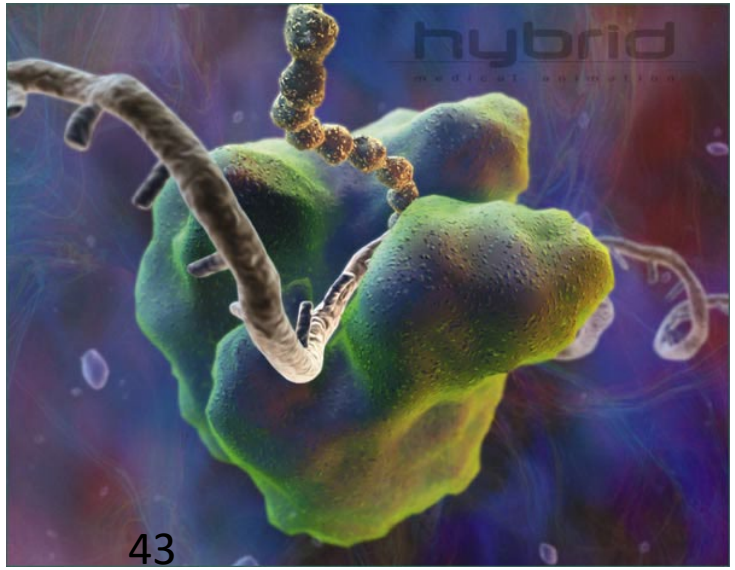
- DNA origami strand displacement driven molecular machines for controlled multi-site 2D patterning
  – *Dana Farber Cancer Institute ($1.21 M)*



Famous molecular machines

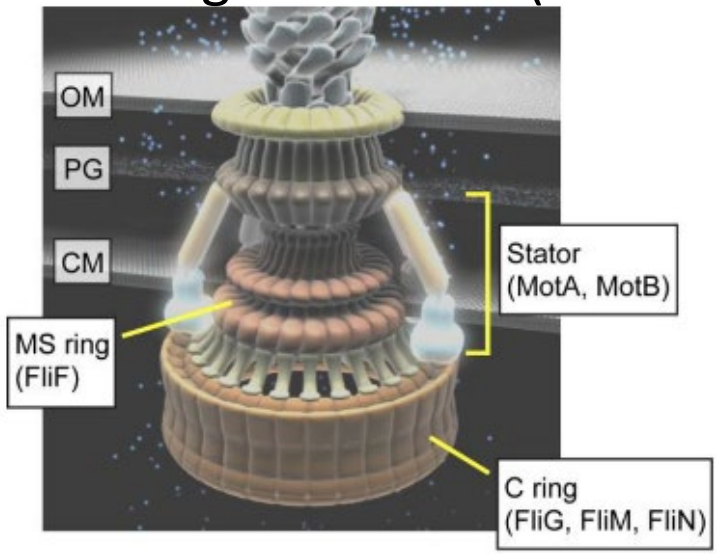
Ribosomes

- Molecular machines that
  - Read a numerical tape (messenger RNA)
  - Grab different transfer RNA molecules according to the numerical instructions
  - Assemble proteins from the peptides on the tRNA
- The animation is realtime
- In the 30 trillion cells in a human body, ribosomes make more than 10^{20} proteins per hour
- In the animation, hemoglobin is produced (100 trillion molecules per second in the human body)
- A single *e. coli* bacterium contains about 20,000 ribosomes
- Up to 10 million ribosomes in a single mammalian cell

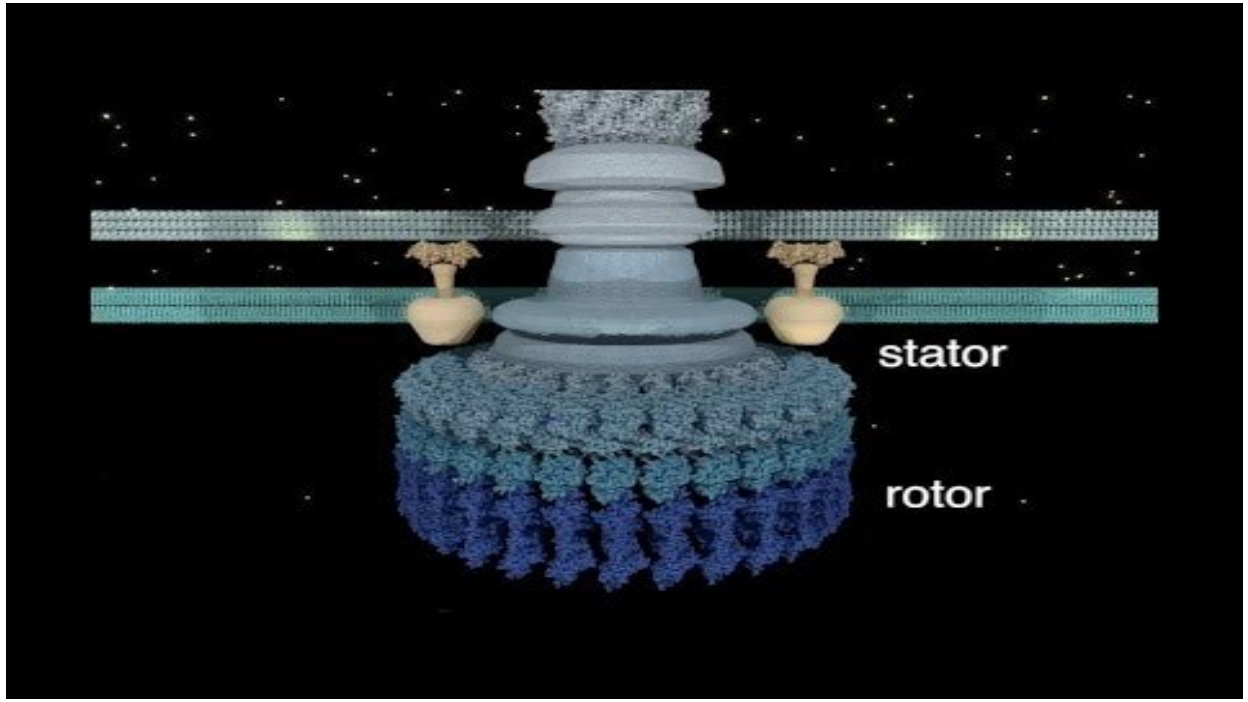


Famous molecular machines

Bacterial flagellar motor (reversible)

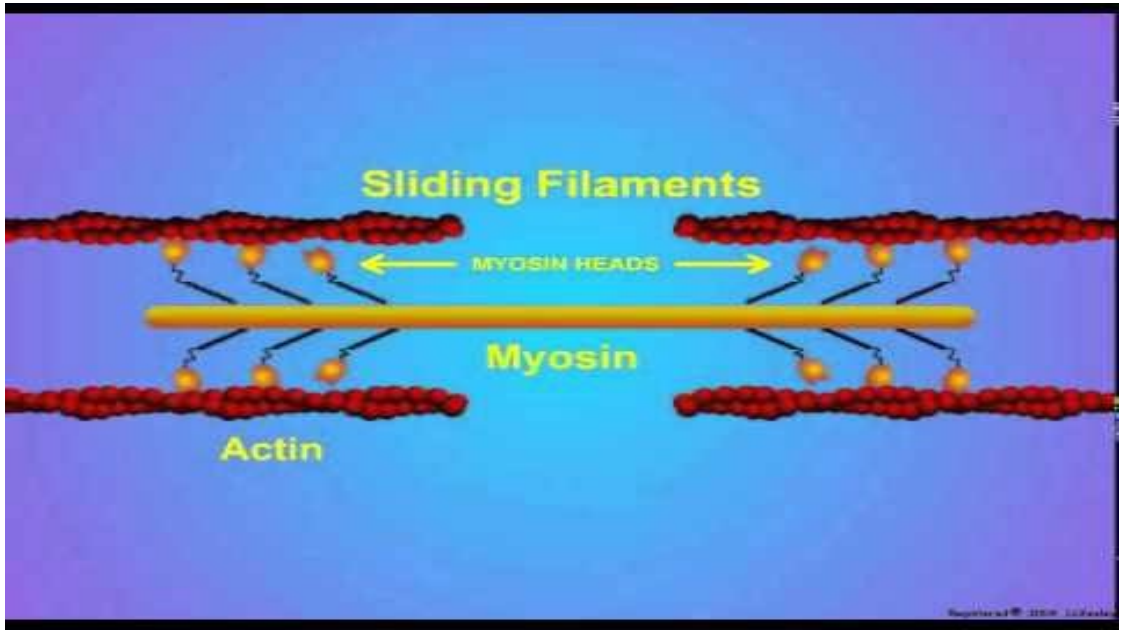


Driving Force	Proton or sodium gradient
Number of Protons per revolution	~ 1000
(energy per proton)	~ 2.5 x 10^{-20} J (6kT)
Maximum rotation rate	300 Hz (protons) 1700 Hz (sodium)
Torque at stall	~ 4 x 10^{-18} Nm
Maximum power output	~ 10^{-15} W
Efficiency	50-100% (stall) ~ 5% (swimming cell)
Number of steps per revolution	~ 50 per torque generator



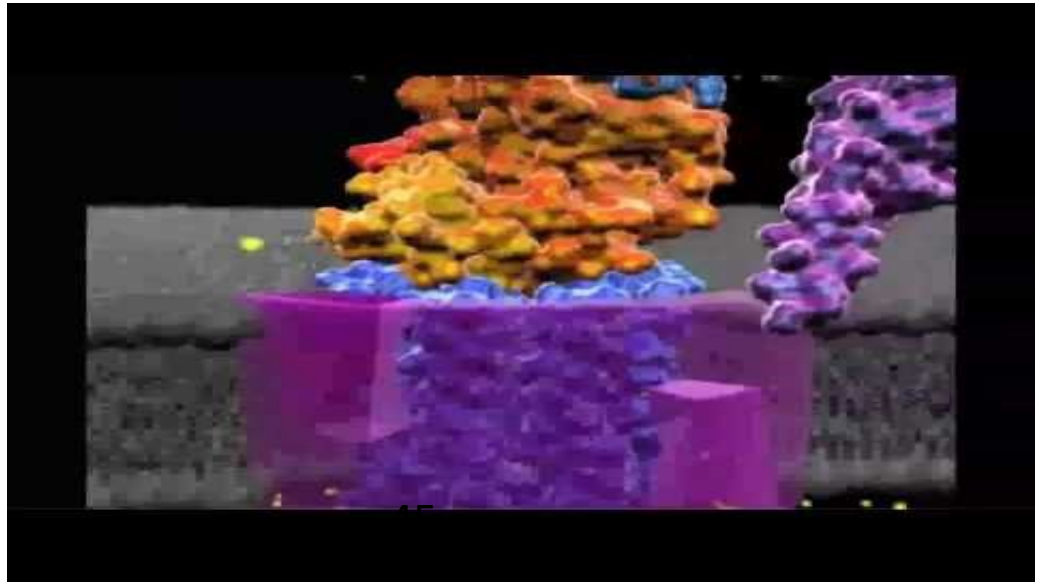
Famous molecular machines

Actin-Myosin (aka muscles)



Kinesin (microtubule transport)

ATP synthase



Progress

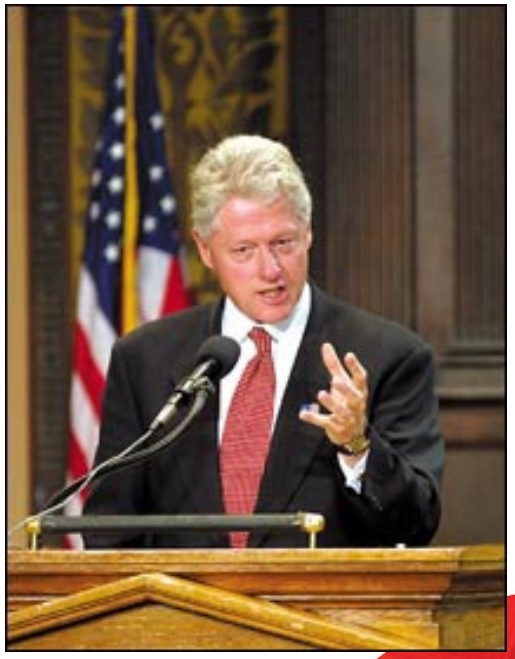
1993 Rice U. Center for Nanoscale Science and Technology

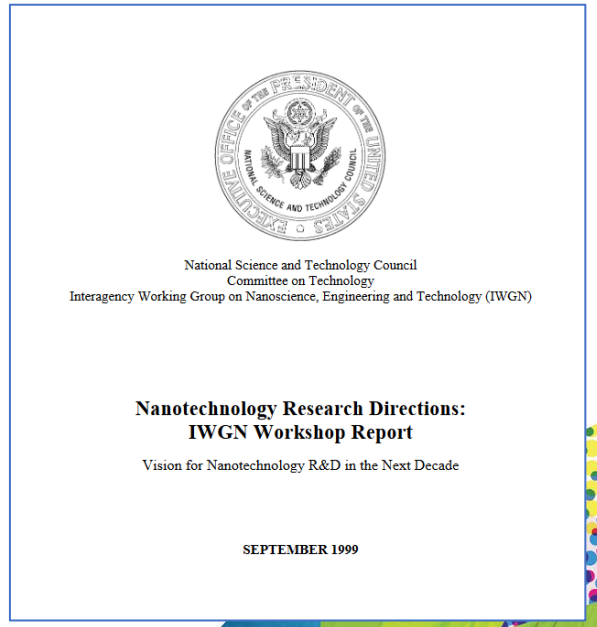
- *No moonshot goal*
- *Didn't address atomic precision*
- *Didn't fund molecular machines*

Jan 2000

US National Nanotechnology Initiative

- Launched with $500M annual funding
- Stated goals, "to manipulate matter at the. . . molecular level," and "materials with ten times the strength of steel"
- Researchers tended to re-label existing efforts; Nanoparticle research remains major focus





National Science and Technology Council
Committee on Technology
Interagency Working Group on Nanoscience, Engineering and Technology (IWGN)

Nanotechnology Research Directions: IWGN Workshop Report

Vision for Nanotechnology R&D in the Next Decade

SEPTEMBER 1999

Progress

China

- 1990-1999: “Climbing Project” on Nanomaterial Science, over 1000 projects
- 2015 Nano Polis research park, Suzhou

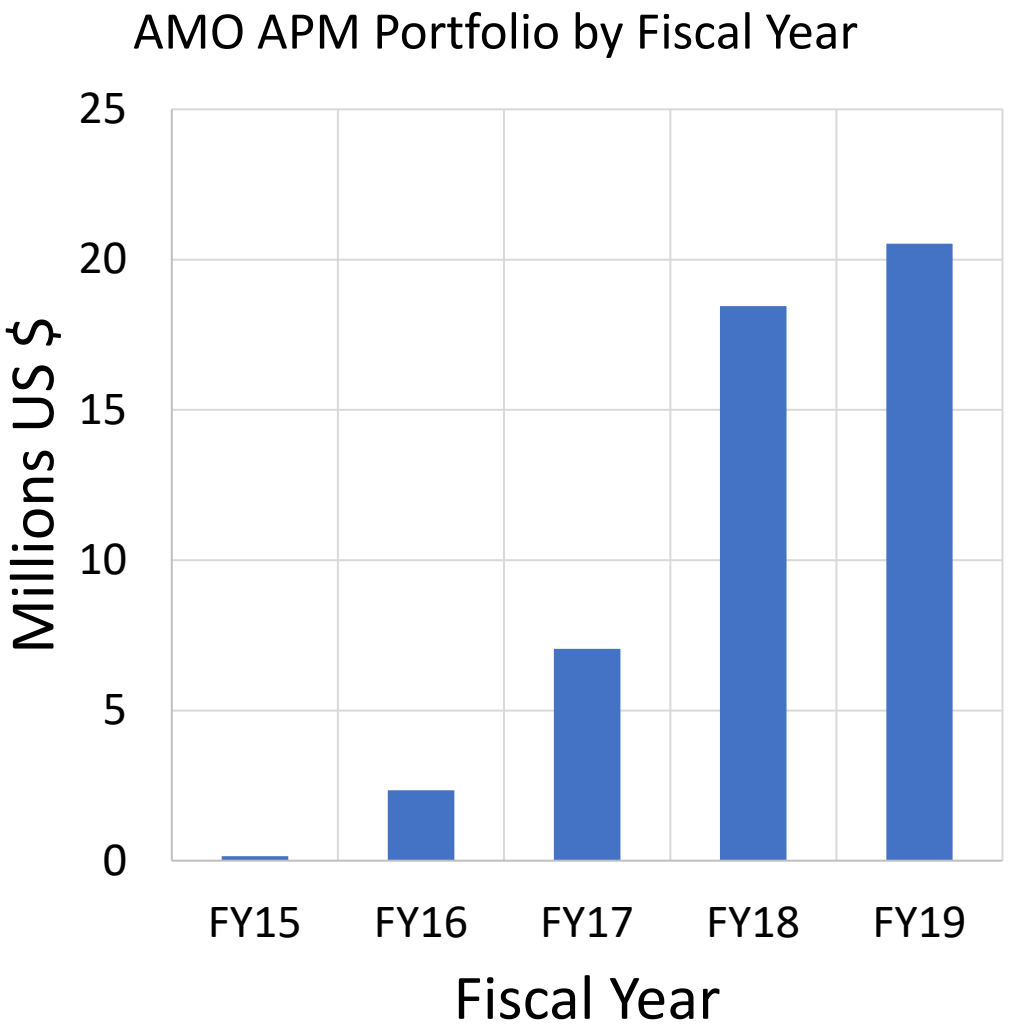
Germany

- 2006-2019: Nanosystems Initiative Munich, 2500 articles published
- Nanoparticle drug delivery, nanophotonics, quantum phenomena, energy

Japan

- 1989-1994: Aono Atomcraft Project, Single-atom deposition and removal
- Nanotechnology Innovation Research Unit

Progress



2015-2019 US Dept. of Energy

- Small program in Atomically Precise Manufacturing
- Peaked at $20M, 19 projects
- Scanning probe positional assembly
- DNA origami
- Atomically precise membranes
- Atomically precise catalysts

Still funding scanning probe qubits