GENERAL DYNAMICS
Advanced Information Systems

Building a Nanofactory

Tihamer Toth-Fejel
General Dynamics Advanced Information Systems
Tihamer.Toth-Fejel@gd-ais.com

http://www.crnano.org/conf2007.htm

Contents

Definition: Nanotechnology

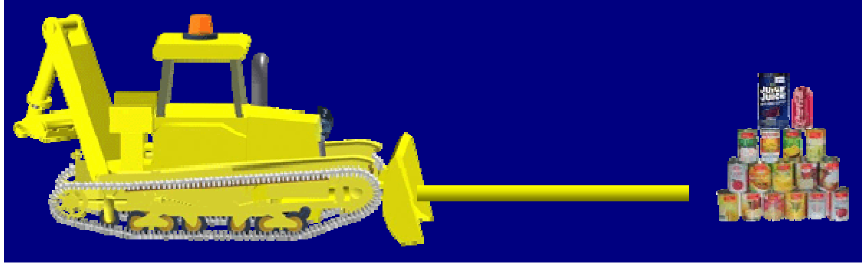
Nanotechnology

1. The understanding and control of matter at dimensions of roughly 1 to 100 nanometers, where unique phenomena enable novel applications.
2. Manipulation of matter at the atomic and molecular level to develop novel devices and productive nanosystems.

Note the difference in emphasis: properties vs. machines

Nomenclature: Nanotech Taxonomy

Top-Down



Bottom Up

Bottom-to-Bottom

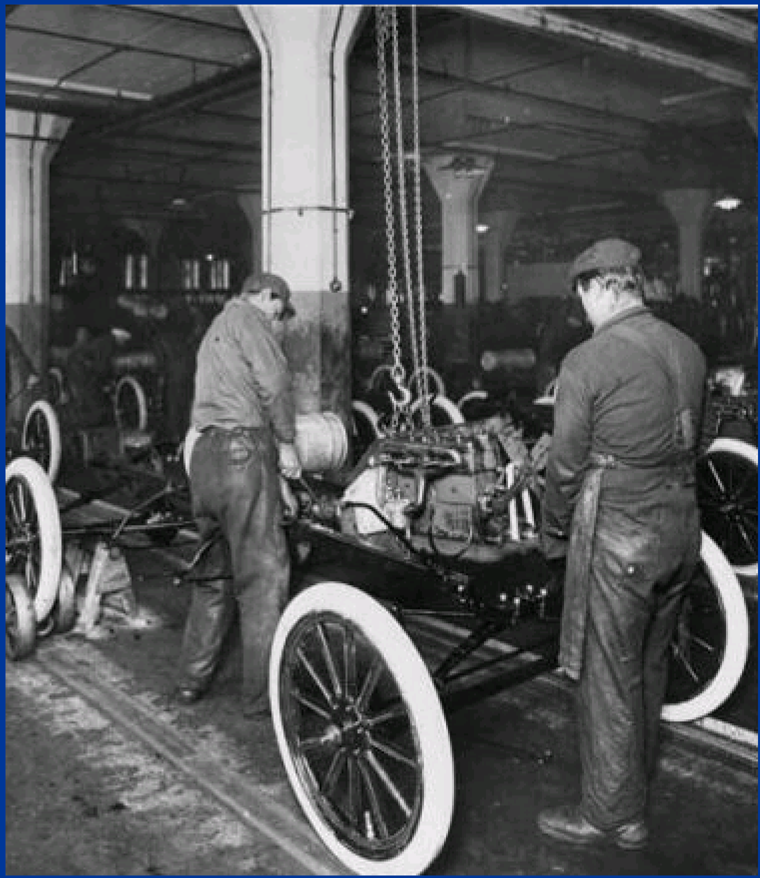
Nomenclature: Factory

Similarities

- Mass Production
- Interchangeable parts
- Input/Process/Output
- Positional Assembly
- Product and Process Design
- Layout/Control/Test
- Low cost

Differences

- Size
- Physical Properties
- Massive Parallelism
- Extreme Automation
- Additive assembly vs. Everything else



Nomenclature: Metrology

If you can’t measure it, you can’t make it.

- **Accuracy**
- **Precision**
- **Reliability, Repeatability and Reproducibility**
- **Traceability, calibration**
- **Tolerance**
- **Surface finish**
- **Quality**
- **Interchangeability**
- **Statistical methods**
- **Hierarchical AMS and ATE from molecular level up**

Nomenclature: 3-D Printers

Nanofactory Similarities

Geometric freedom

No tooling

No waste

No inventory

No assembly

Customization

Differences

Resolution

Orientation

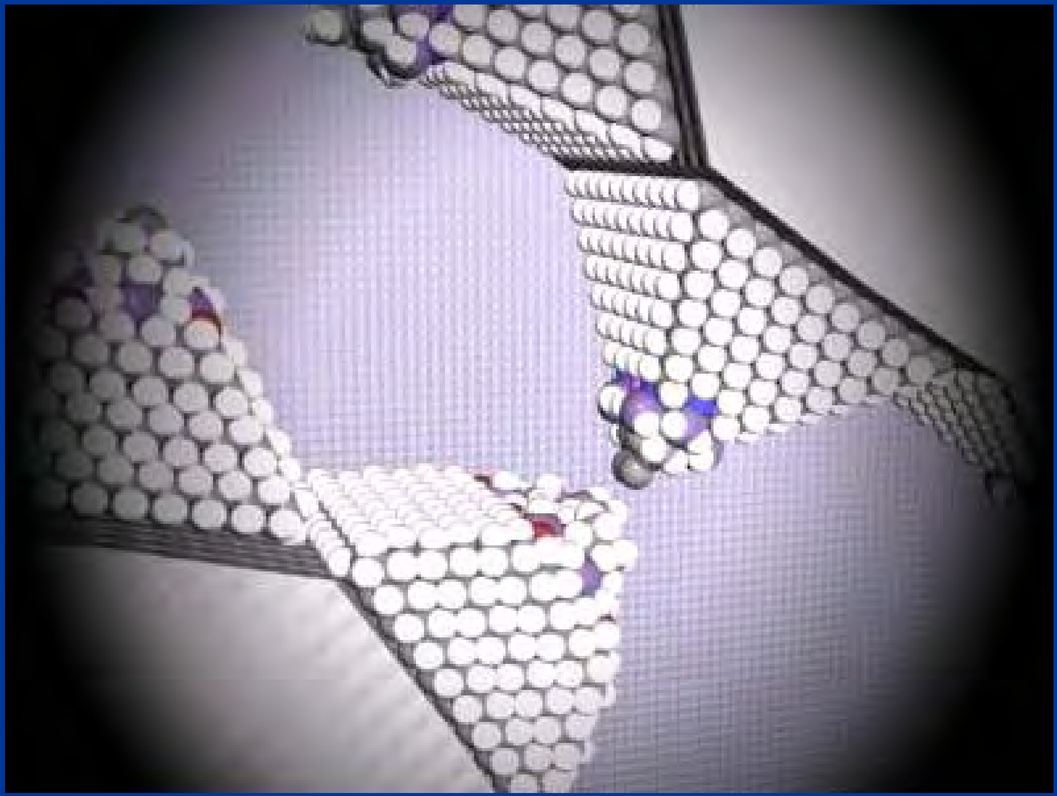
Types of inputs

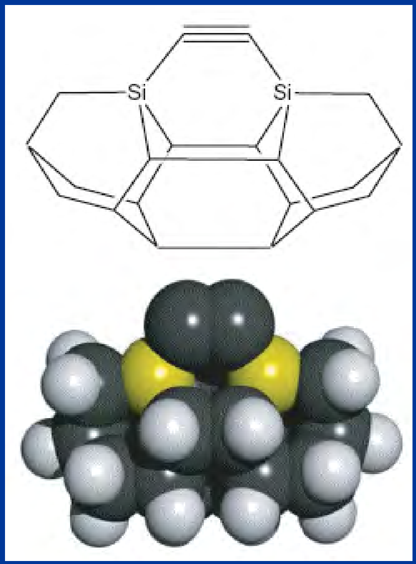
Approach Taxonomies

How do we get there from here?

- Process
  - Assembling Atoms
    - Synthesis
    - Mechanosynthesis
  - Assembling Nanomodules
    - Self-assembly
    - Directed Assembly
  - Error Correction
- Input Envelope
- Output Envelope

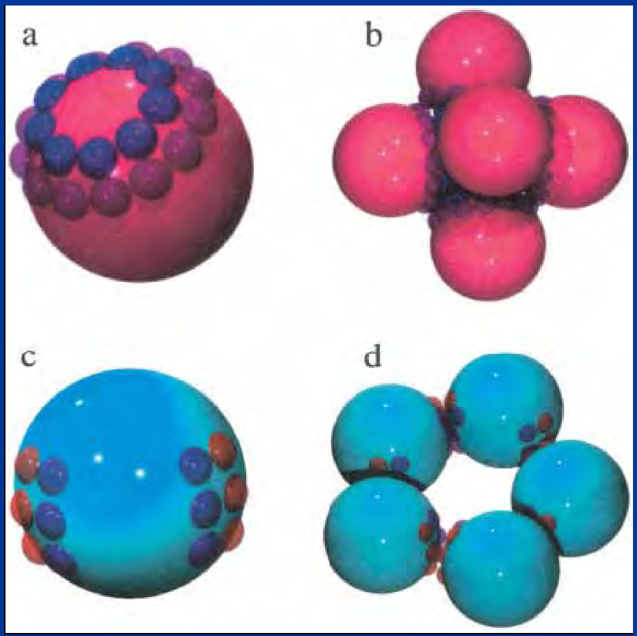
Mechanosynthesis



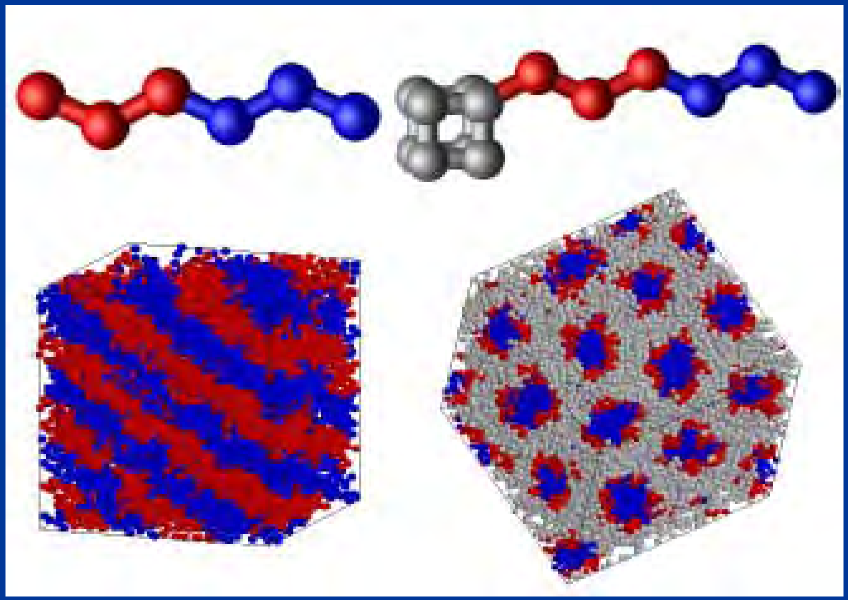


DCB6-Si dimer placement tool tip.

Self-Assembly

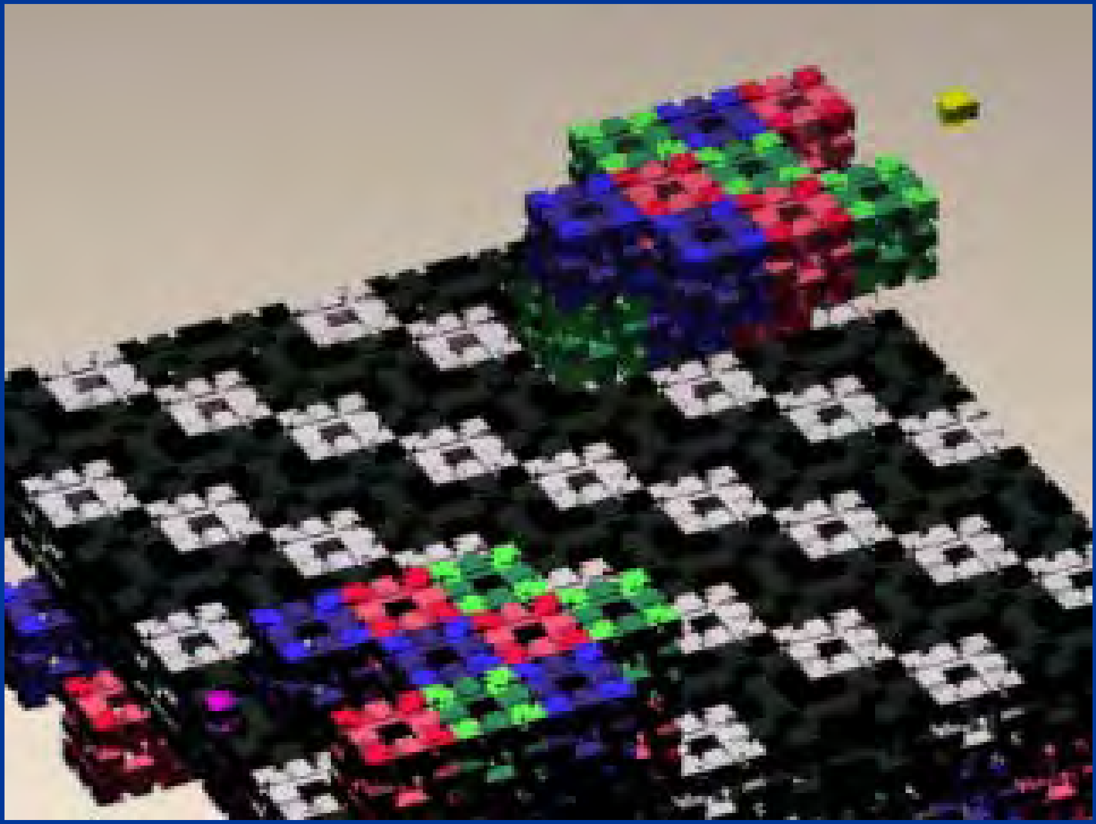


Anisotropically interacting particles and their assemblies



Conventional diblock copolymer and diblock copolymer attached to a nanocube

Self-Replication



Kinematic Cellular Automata

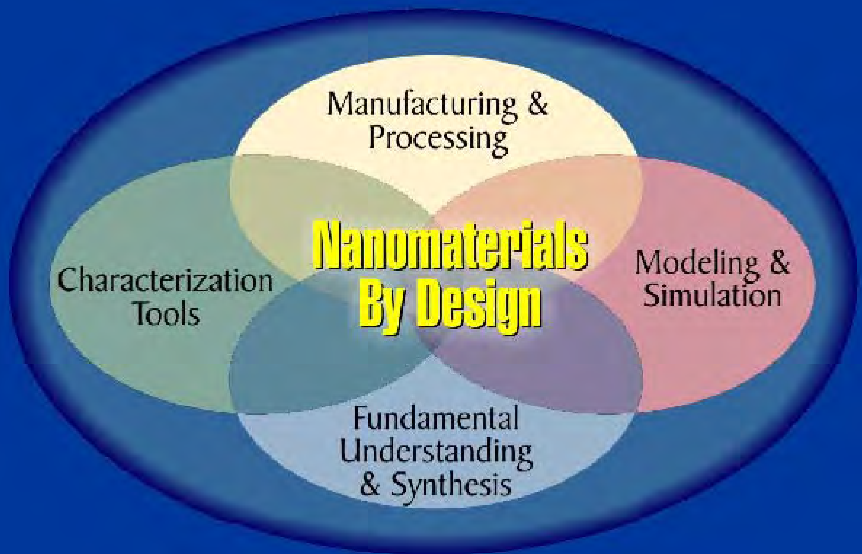
Chemical Industry 2020 Nanomaterials Roadmap: From Fundamentals to Function

Nanomaterials By Design

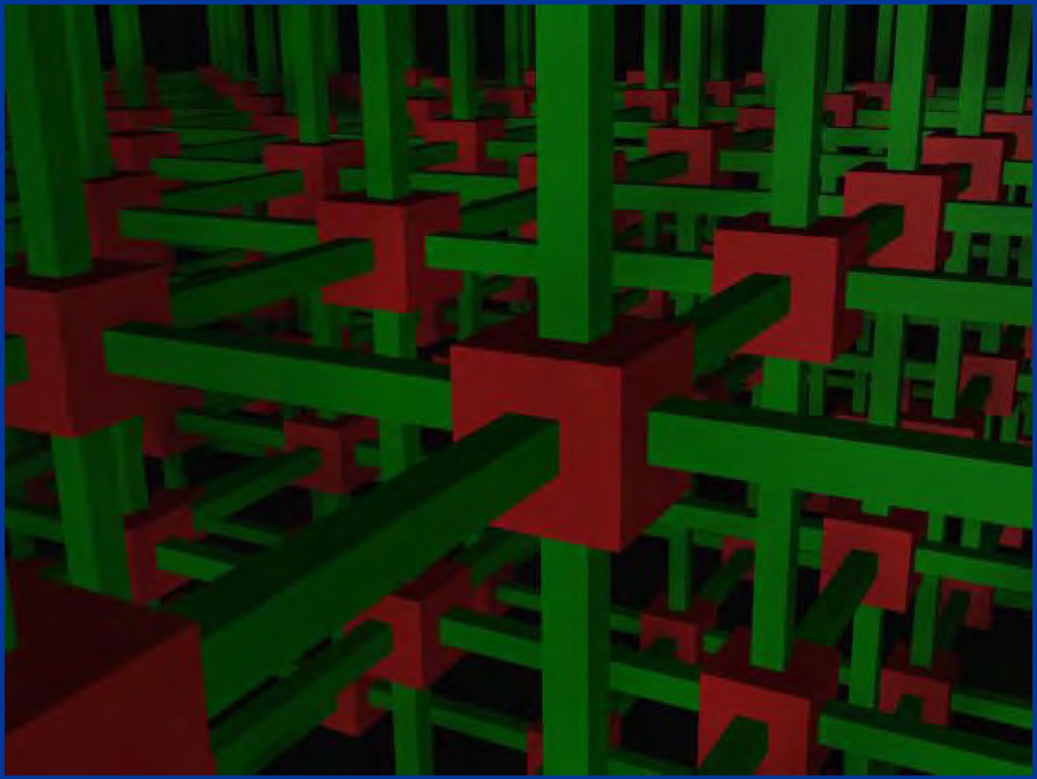
A "library" of nanomaterial building blocks

Research Priorities

- Nano-scale building blocks
- Design strategies for controlled assembly; spatially resolved nanostructures



Nice nanoscale building blocks

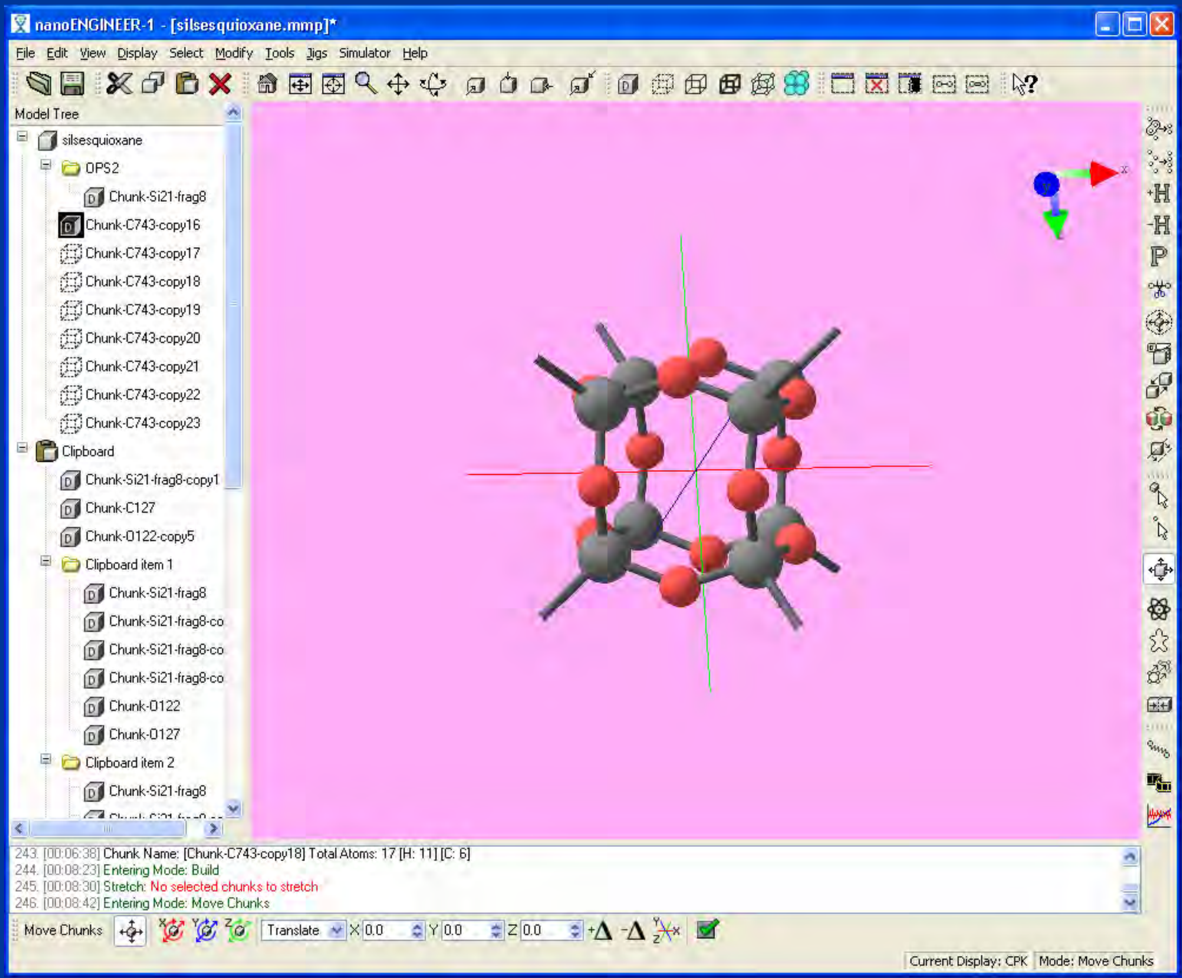


- Orthogonal functionality
- 1-10 nm diameter

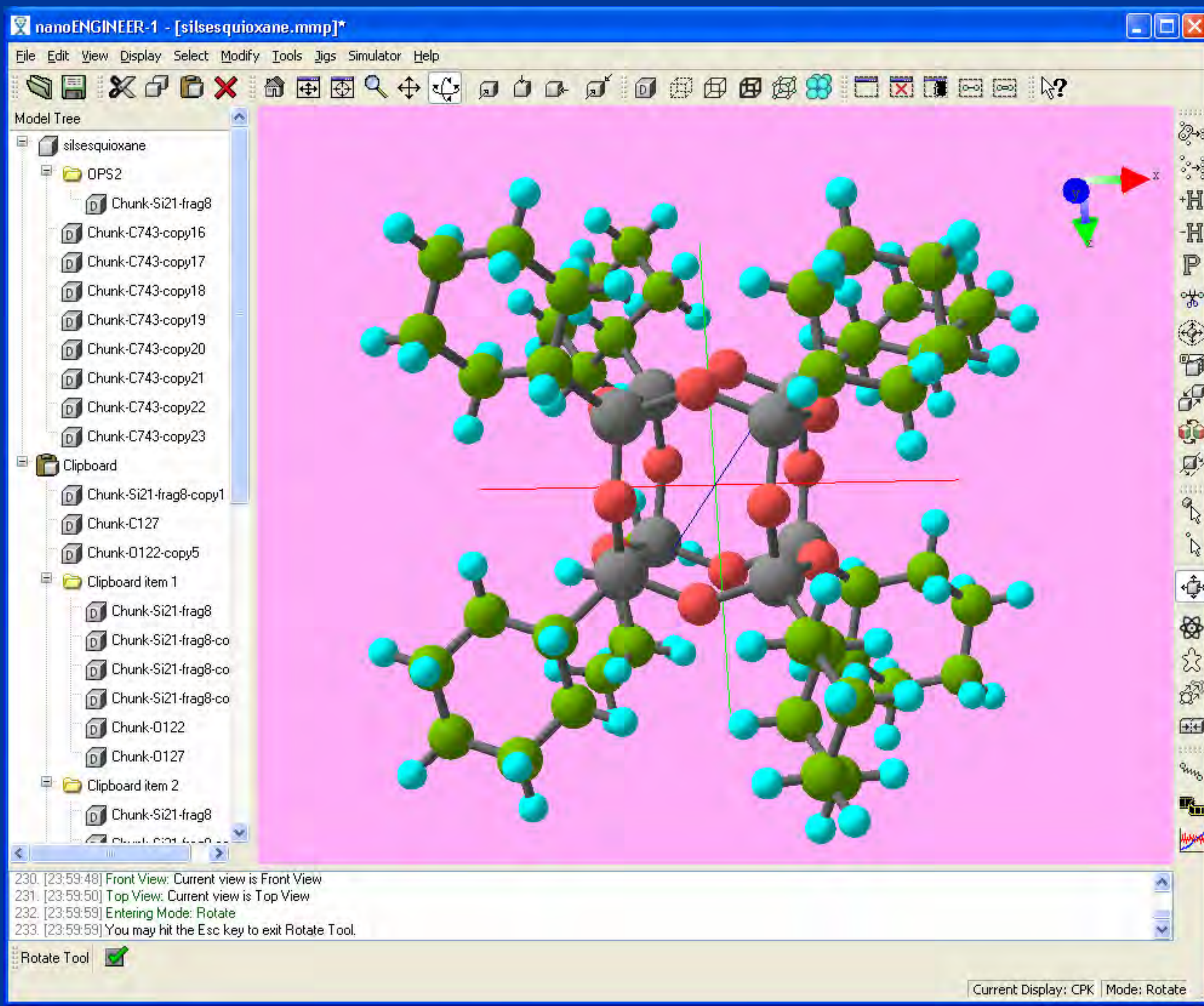
Permits:

- nm x nm x nm Construction
- nm control of periodicity in 1, 2 or 3-D
- Multiple types of building blocks (e.g. conducting, non-conducting, p-type, n-type)

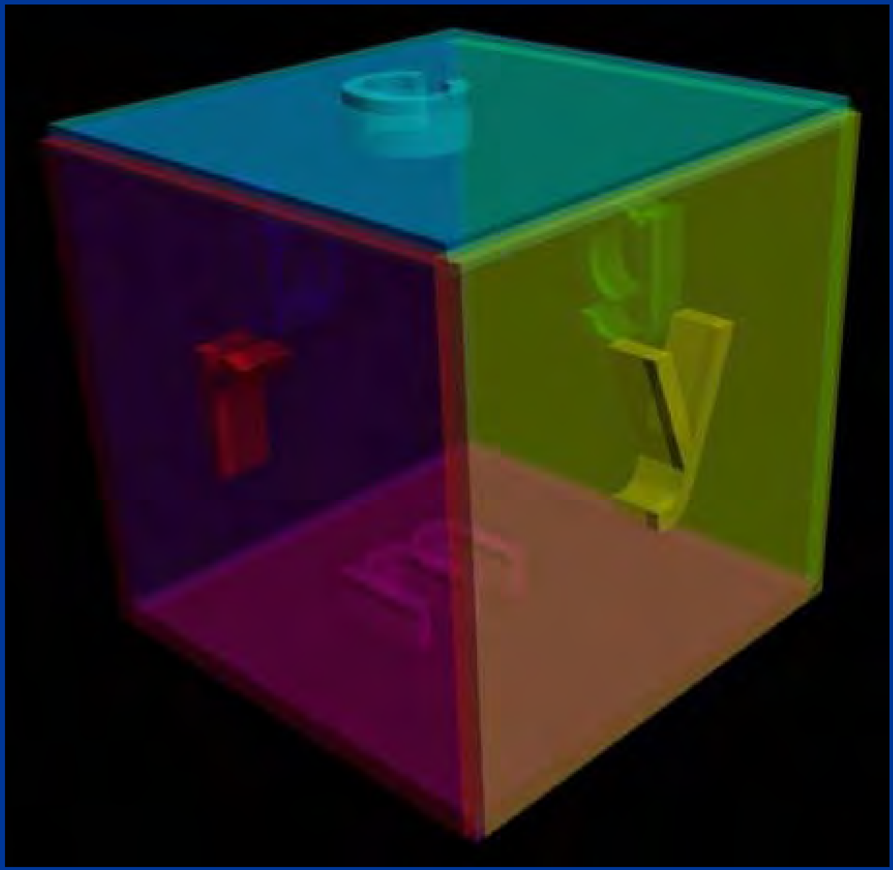
Silsesquioxane Nanocube core



Silsesquioxane Nanocube

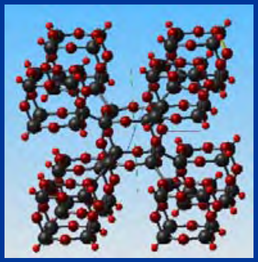


Perfect nano building blocks



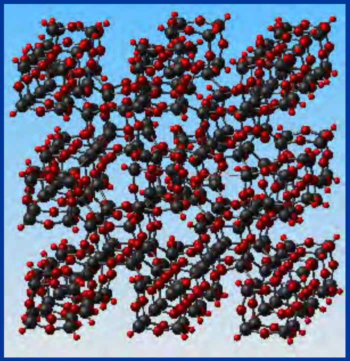
- Face connection (not corner)
- Controllable enantiomeric and anisomorphic functionality
- Step-wise and hierarchical construction
- Arbitrary 3D structures
- Connection properties independent from electrical properties

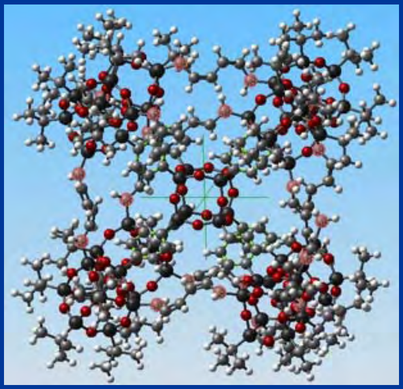
G1 & G2 Silsesquioxane Nanocubes



Ideal G1 nanocubes

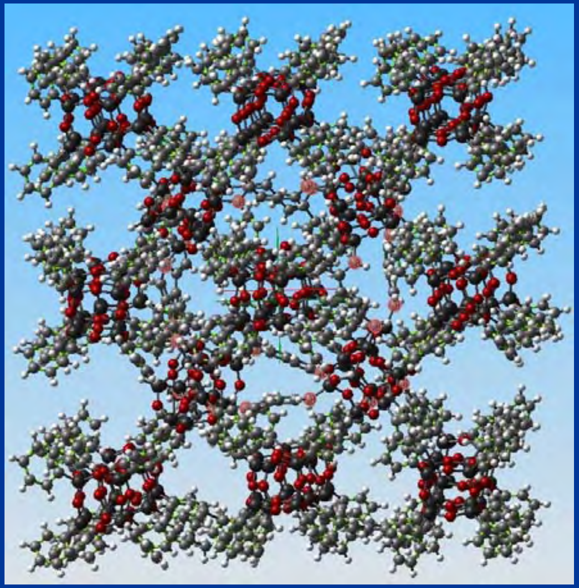
Ideal G2





More realistic G1 nanocube

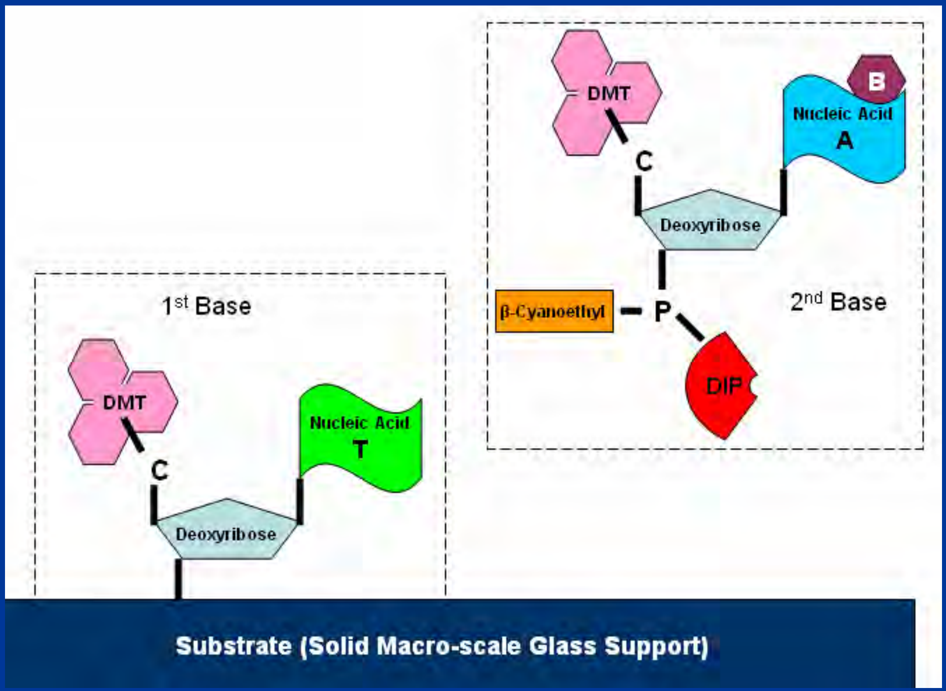
Realistic G2



More Nanocube Requirements

- Inter-cubelet and intercube links must create and preserve desirable properties
- Consistent length of links
- Externally controllable connection chemistry
- Actuator Nanocubes

Solid Phase DNA Synthesis



Step 1: De-blocking/ Deprotection

Step 2: Activation

Step 3: Base Condensation (Coupling)

Step 4: Capping

Step 5: Oxidation

Repeat

Post-Synthesis Processing

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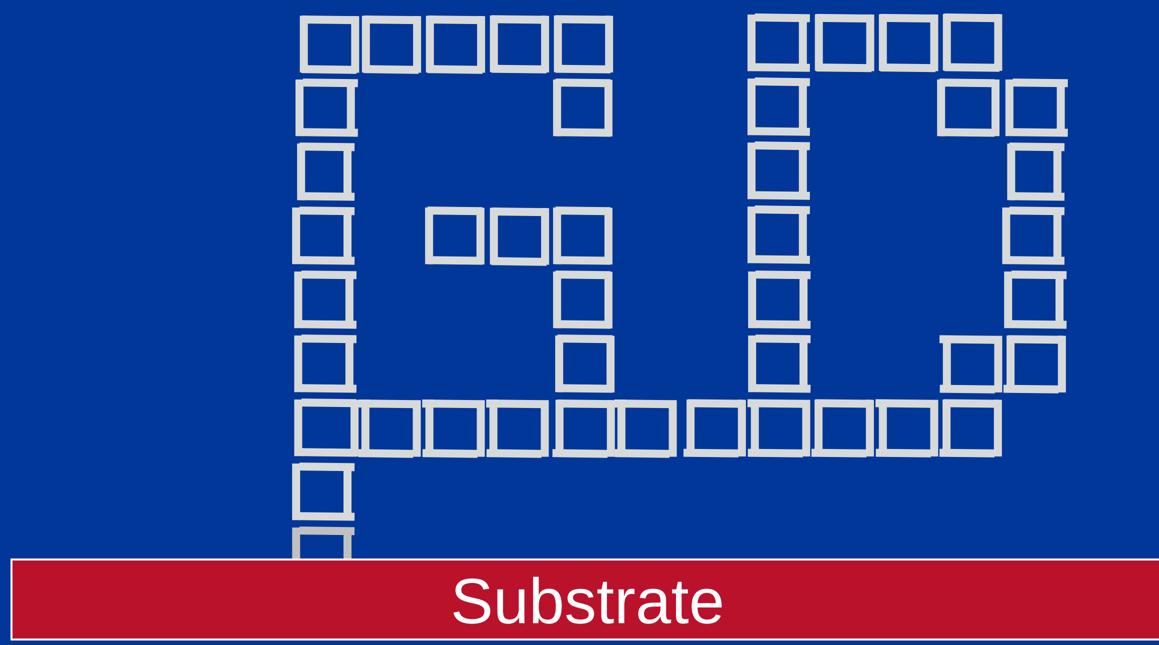
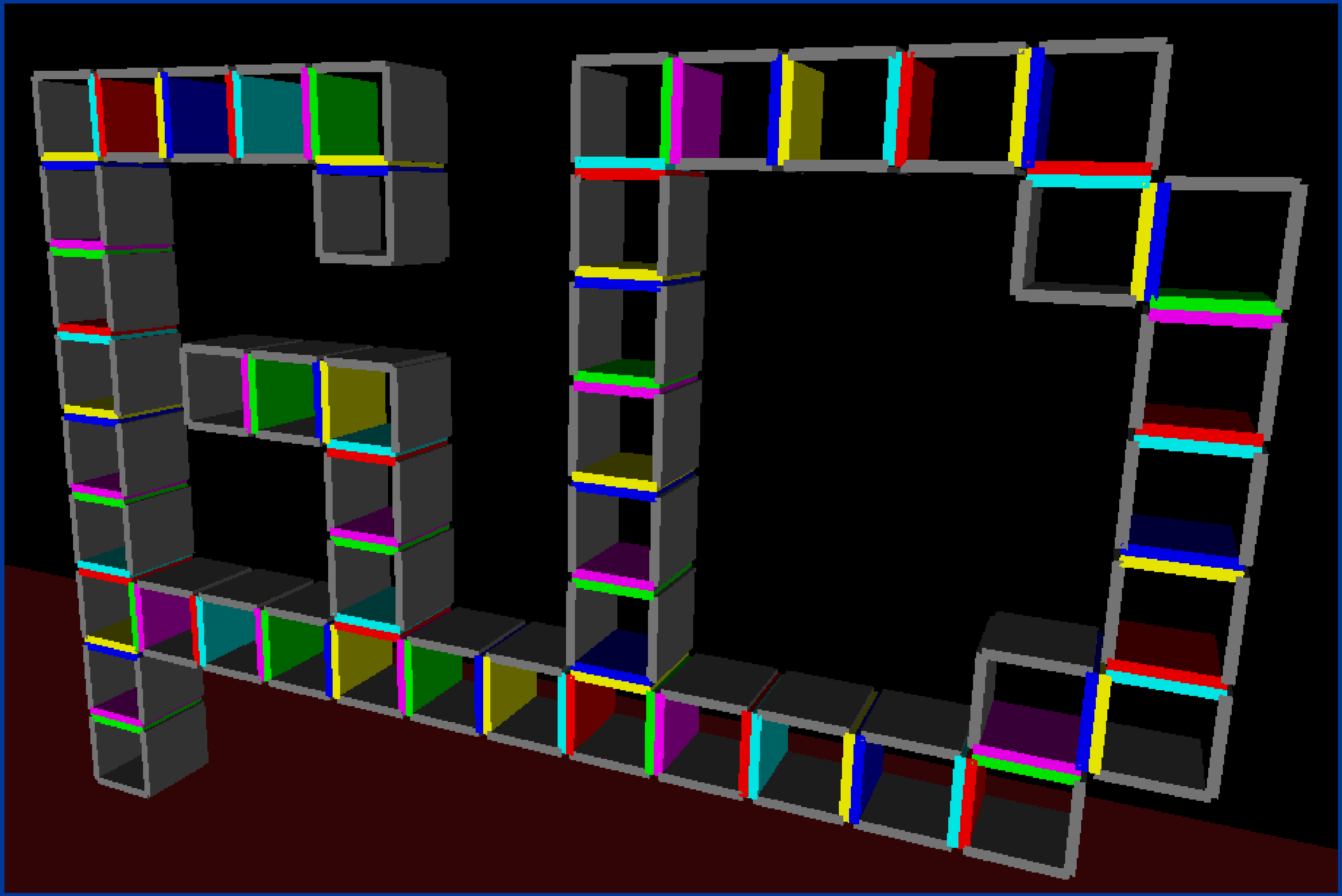
2D Assembly Example

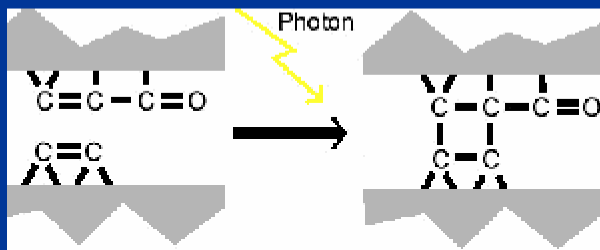


Given an arbitrary structure, how can complementary Wang tiles form them, and in what sequence should they be made?

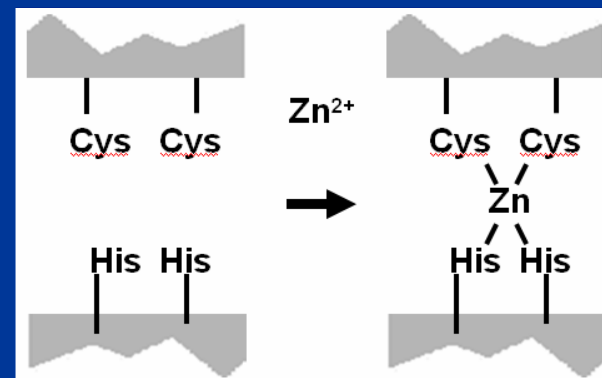
2D Assembly Example



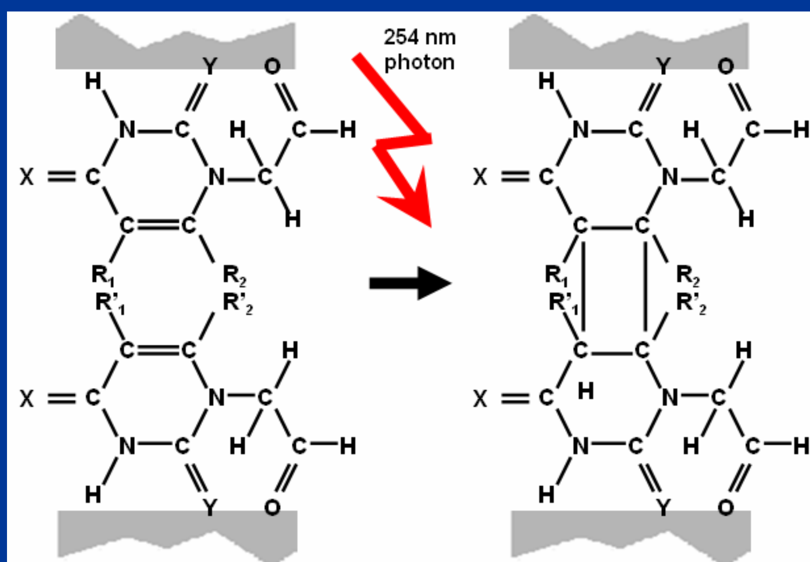
Connecting Nanocubes



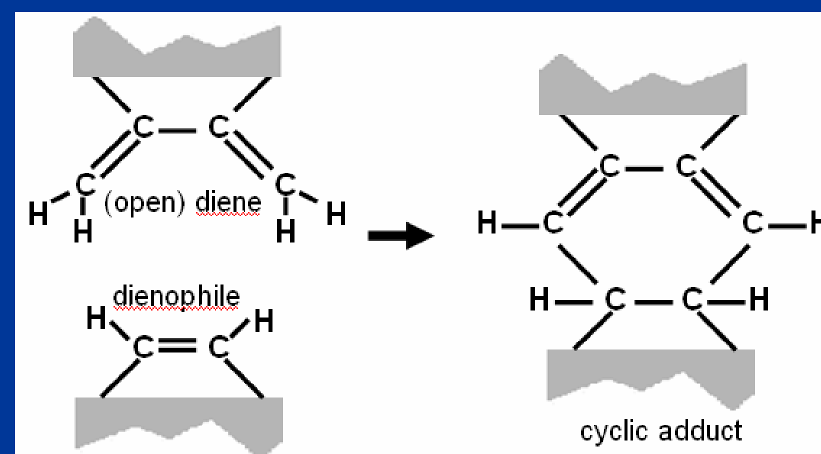
Photochemical bonding



Zinc fingers



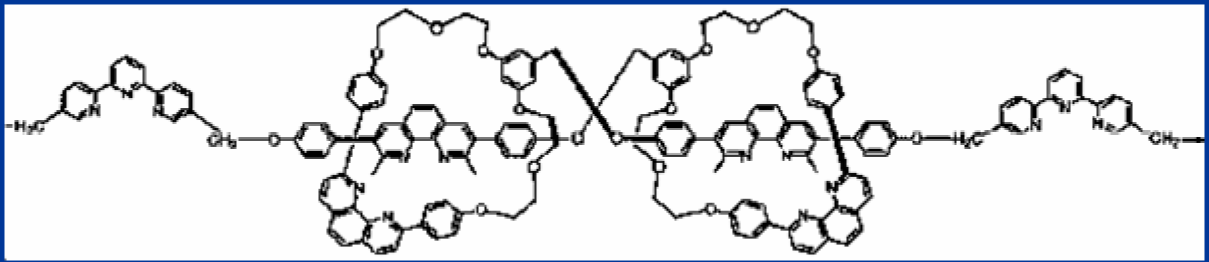
Pyrimidine photodimerization



Diels-Alder cycloaddition

Molecular Actuators

Interlocking Rotaxane Dimers



Jimenez-Molero, Dietrich-Buchecker, and Sauvage, Chemically Induced Contraction and Stretching of a Linear Rotaxane Dimer, Chem. Eur. J. 2002, 8, No. 6

Annulenes

Azobenzene

Poly calix[4]arene-bithiophene

Viral Protein Linear (VPL) motors

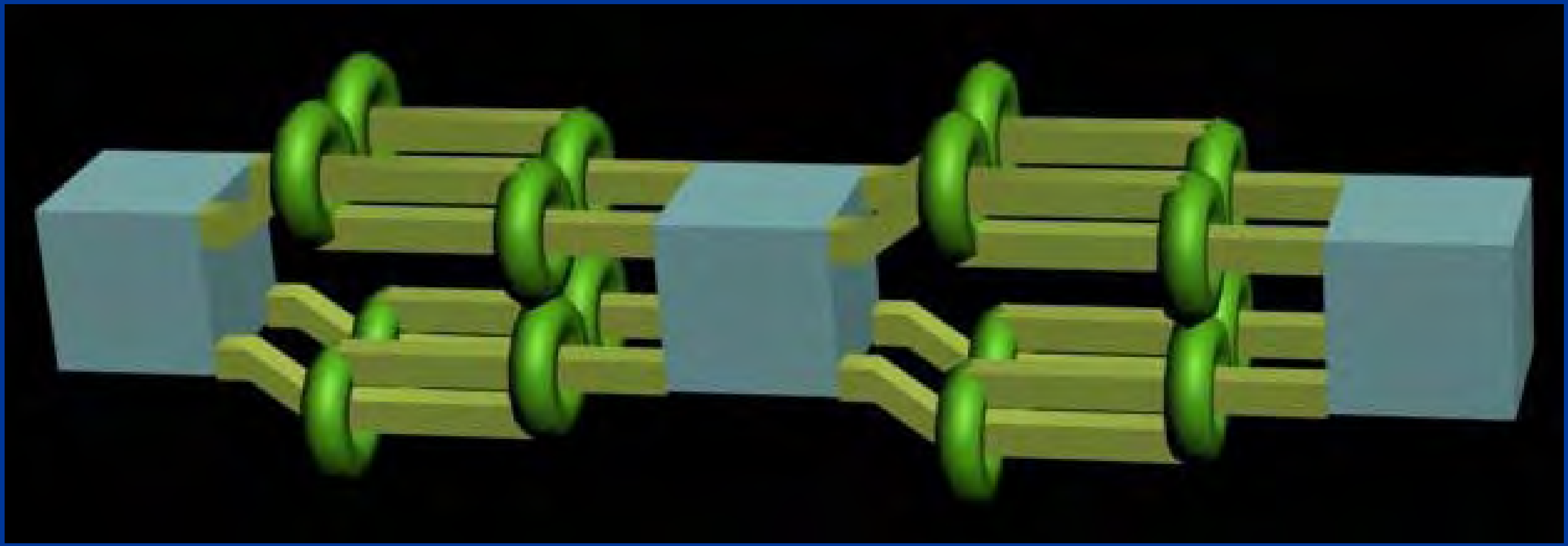
F0 and F1 motors of ATP synthase

Myosin/actin

DNA motors, walkers, and tweezers

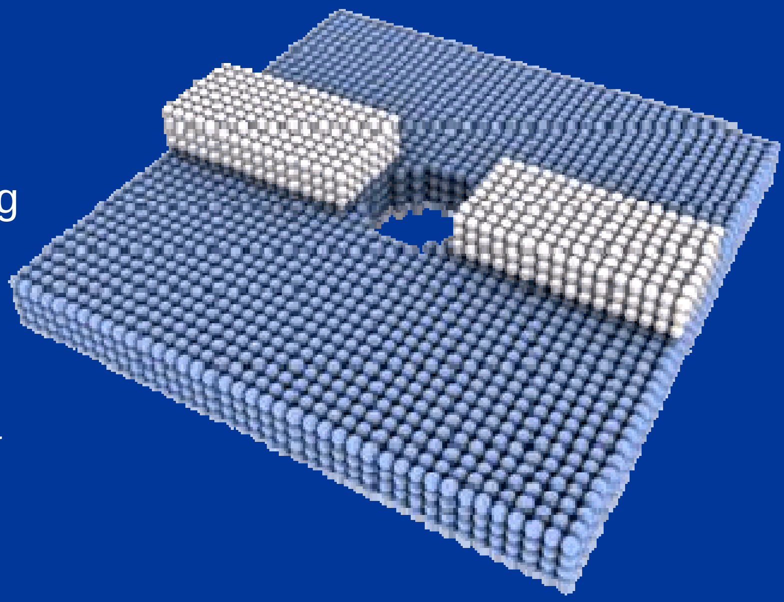
Phosgene-fueled triaminotriptycene/4-(dimethylamino)pyridine assembly

Nanocube Motors



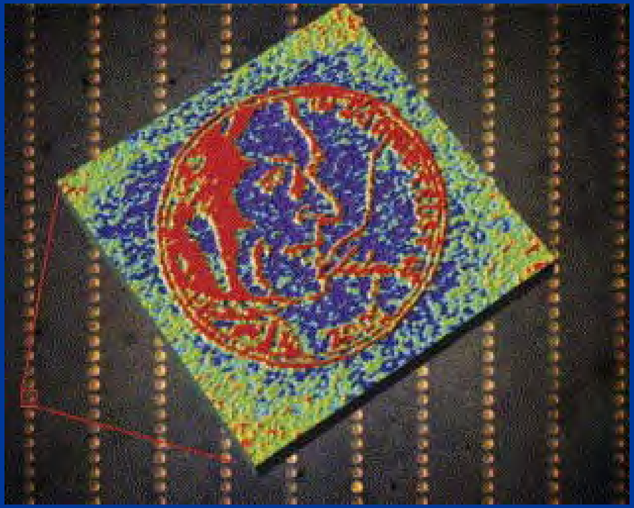
Tip Arrays:
Atomically Precise Manufacturing

- The ability to produce 3D structures with top-down control and atomic precision.
- The inevitable result of continued improvements in ultra-precision manufacturing (IC manufacturing and others)
- The proposed approach is an integration of known techniques and designed to produce a broadly applicable manufacturing process.

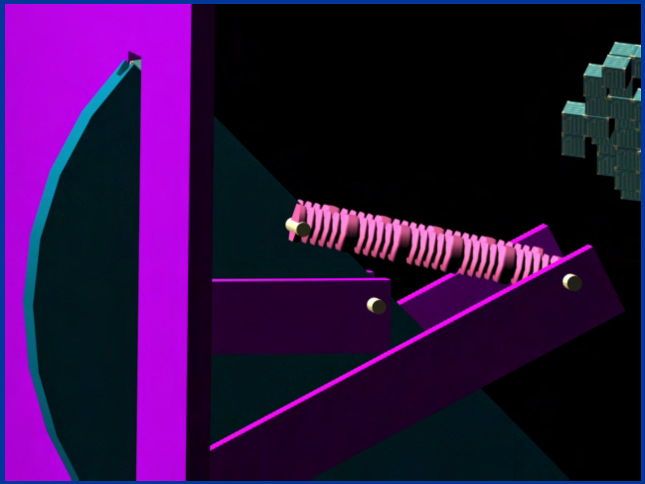


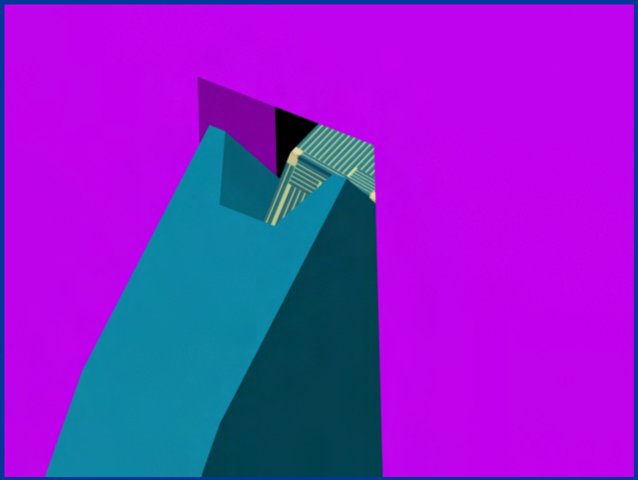
Tip Hyperarrays

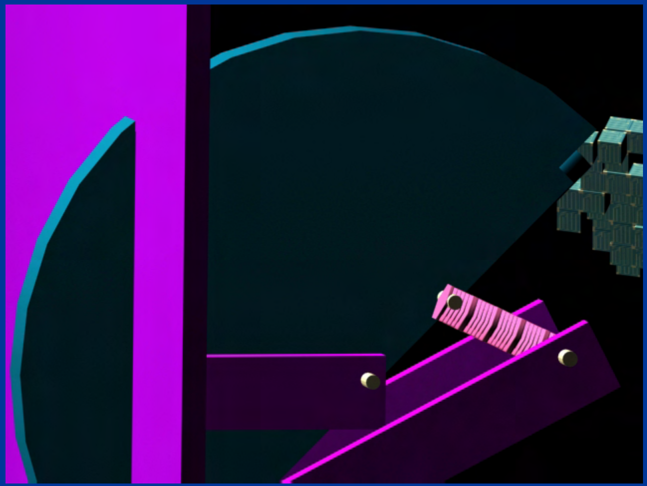
- Dip Pen
- 55,000 tips
- Thermally actuated
- Multiple inks
- 15 nm resolution
- Fast

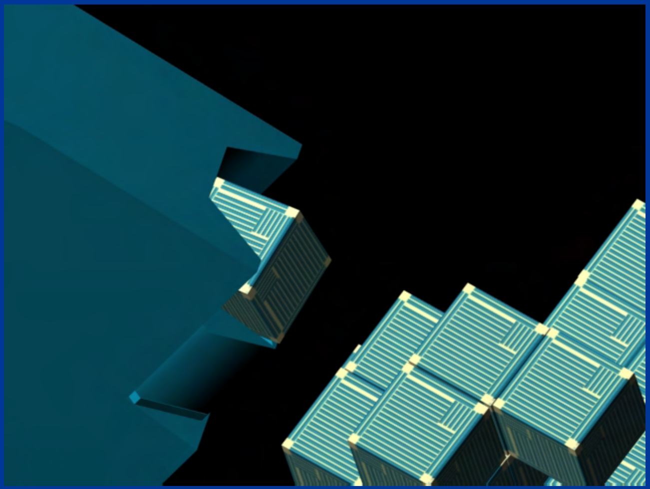


Smart Pores -> Smart Silkscreen



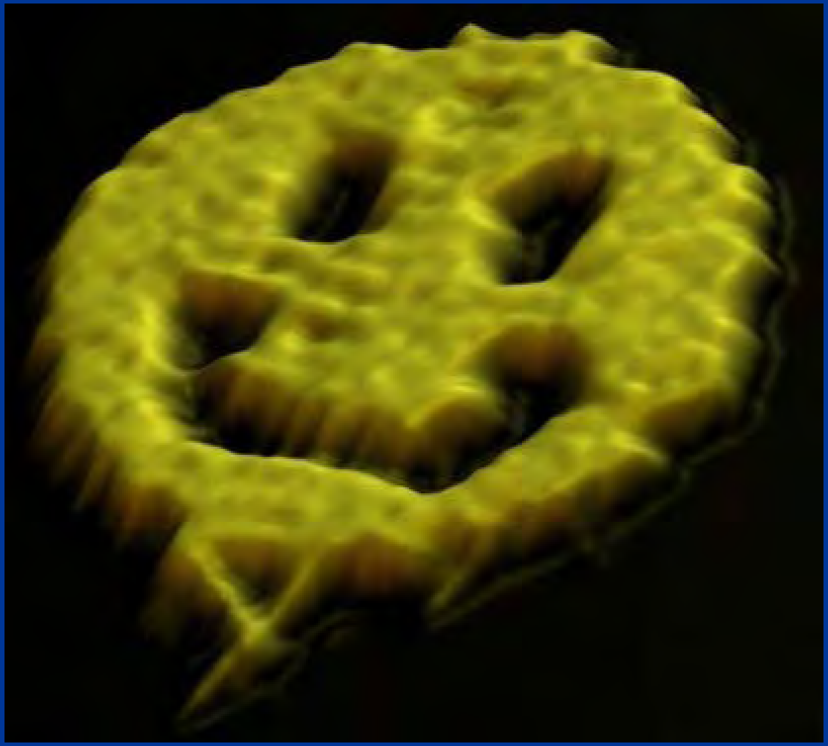






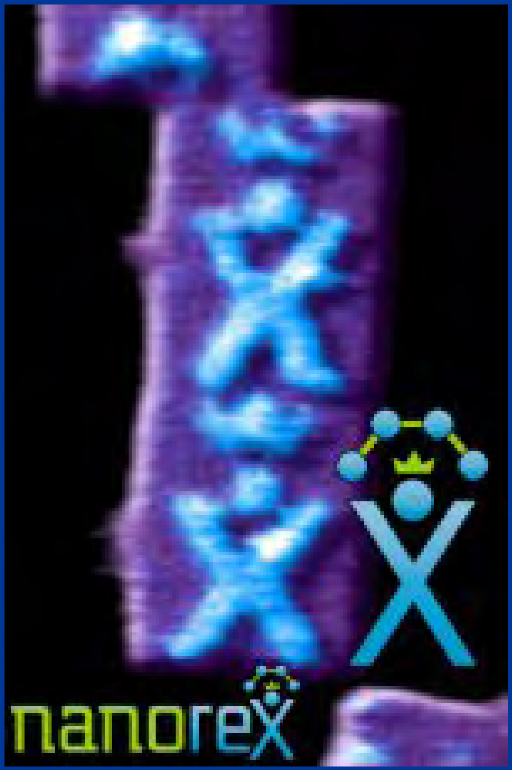
DNA Origami: 50 billion Smiley Faces

Paul W. K. Rothemund, Folding DNA to create nanoscale shapes and patterns, *Nature* Vol 440,16 March 2006



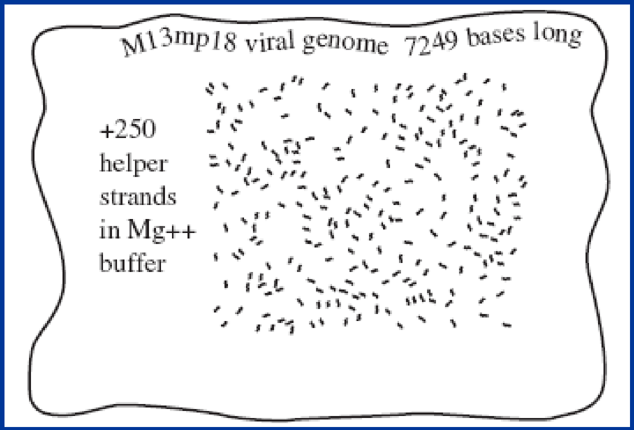
Courtesy Paul Rothemund

Easily reproducible

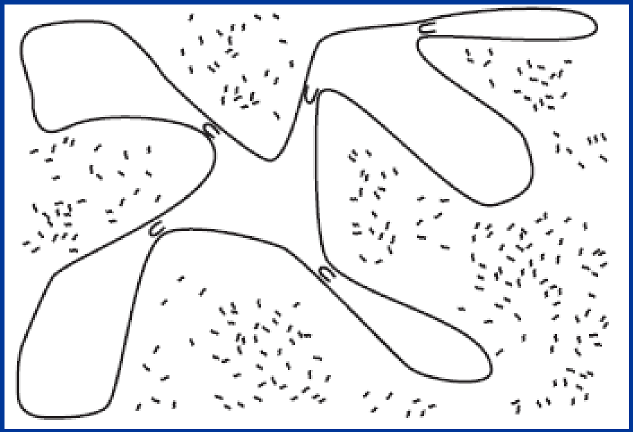


Qian Lulu, et al., Analogic China map constructed by DNA.
Chinese Science Bulletin. Dec 2006. Vol. 51 No. 24

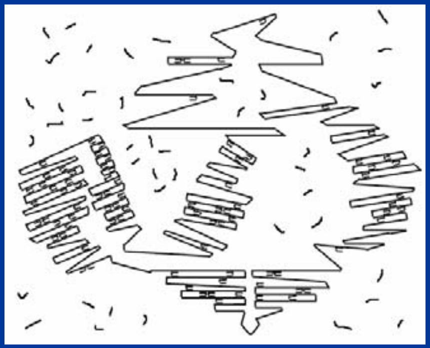
The DNA Origami Process



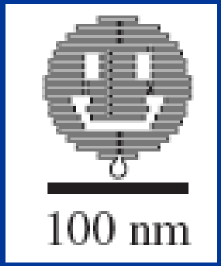
a.



b.



c.

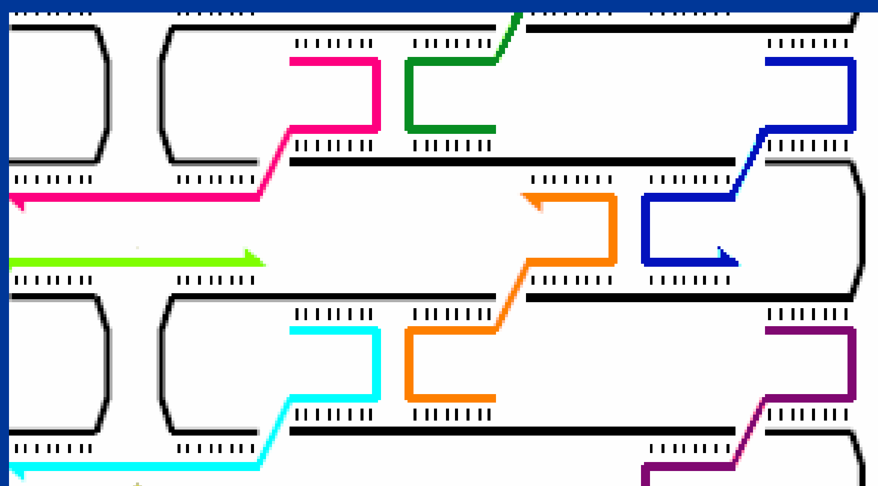


d.

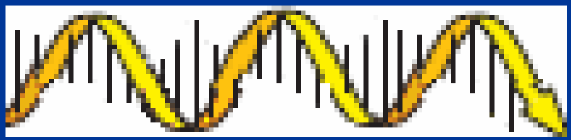
Figure a,b, and d from Paul Rothemund, Design of DNA origami, IEEE/ACM International Conference on Computer-Aided Design. Nov. 2005

Figure c by Toth-Fejel

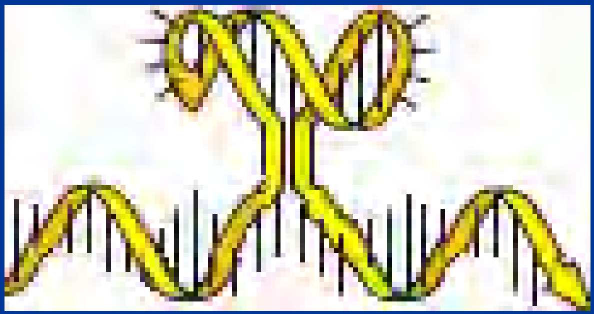
Helper Strands



Helper Strands for Pixilated Origami

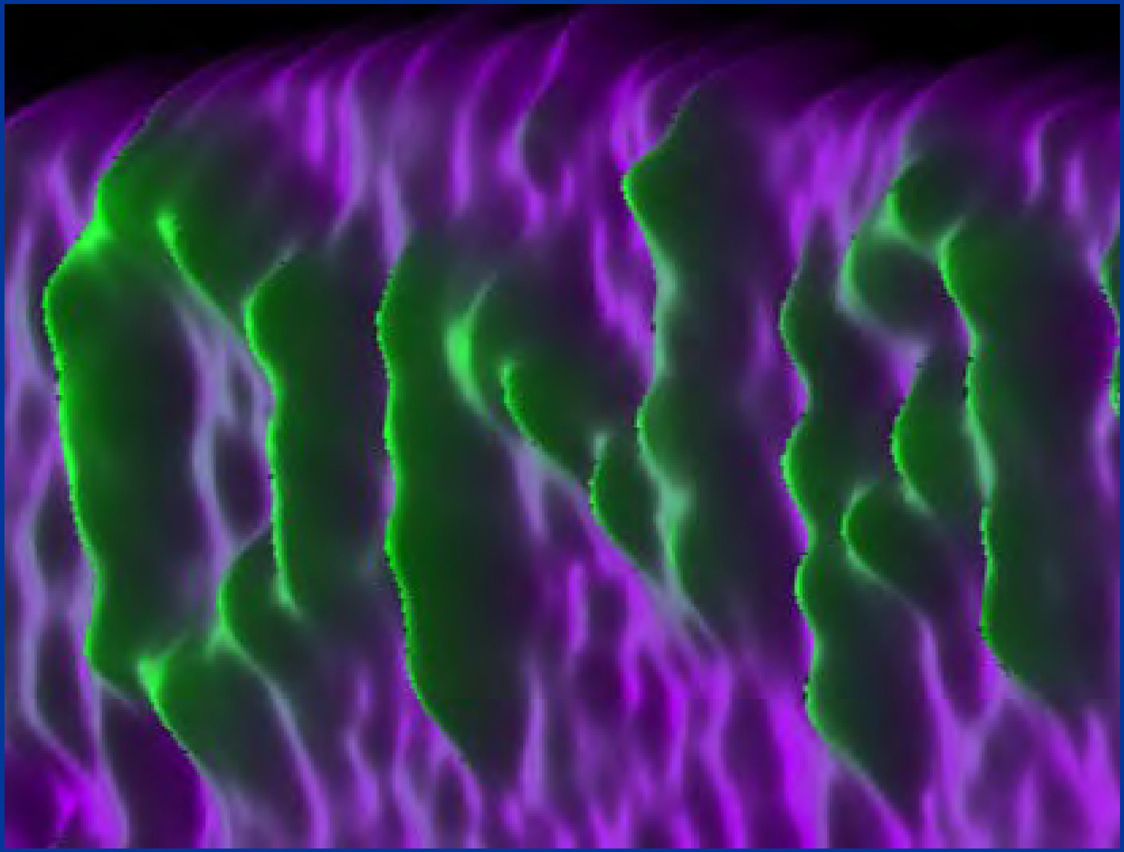


Regular Helper Strand (bit=0)



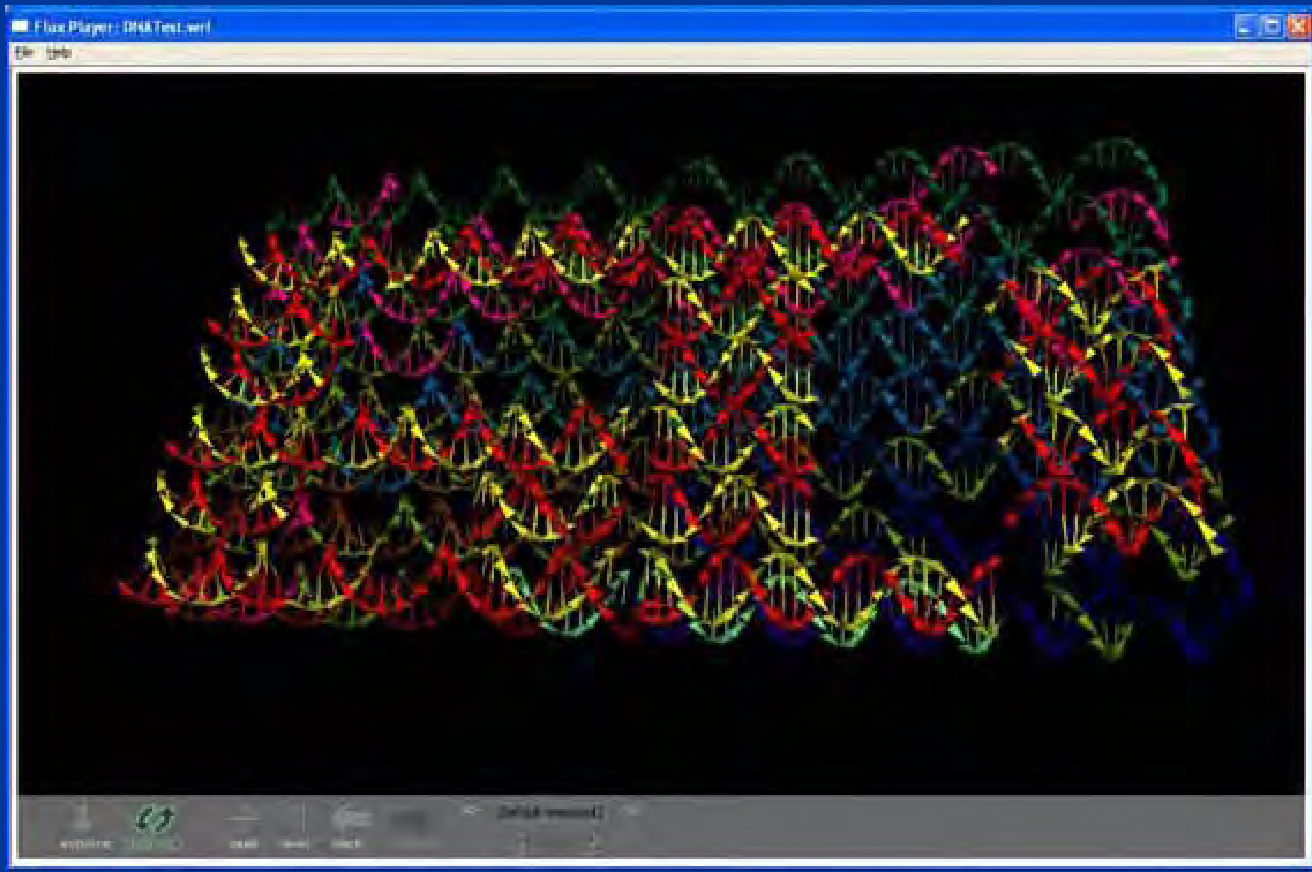
Labeled Helper Strand (bit=1)

Pixelated DNA Origami

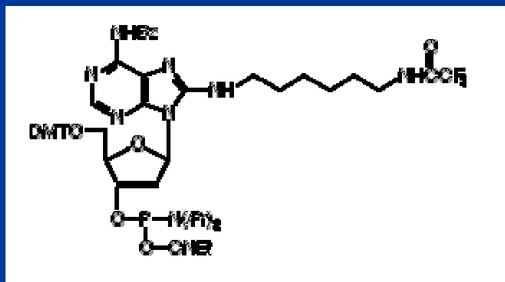


courtesy Paul W. K. Rothemund

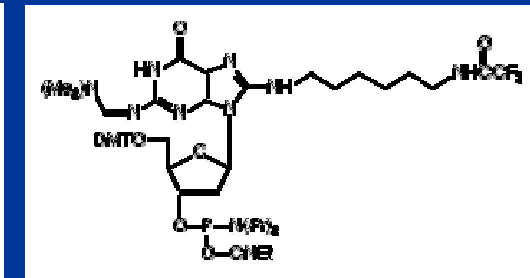
Pixelated DNA Origami



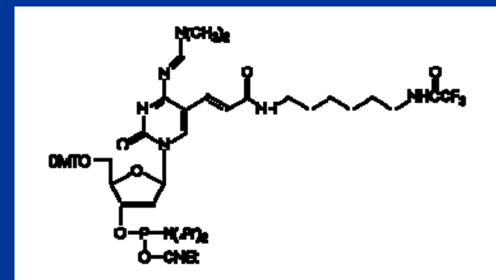
DNA Internal Labeling



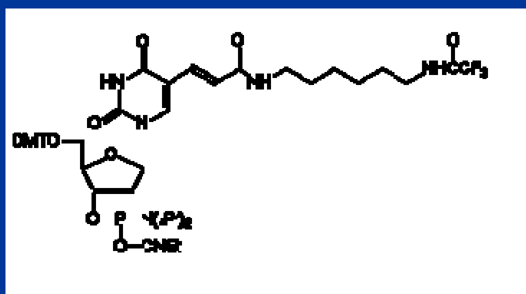
Amino-Modifier C6 dA



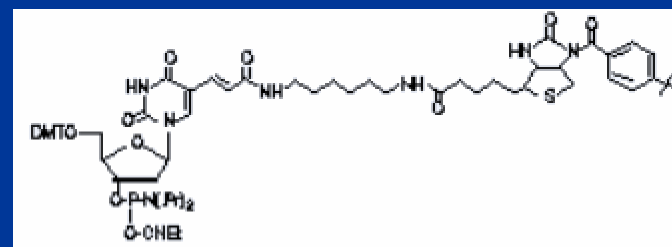
Amino-Modifier C6 dG



Amino-Modifier C6 dC

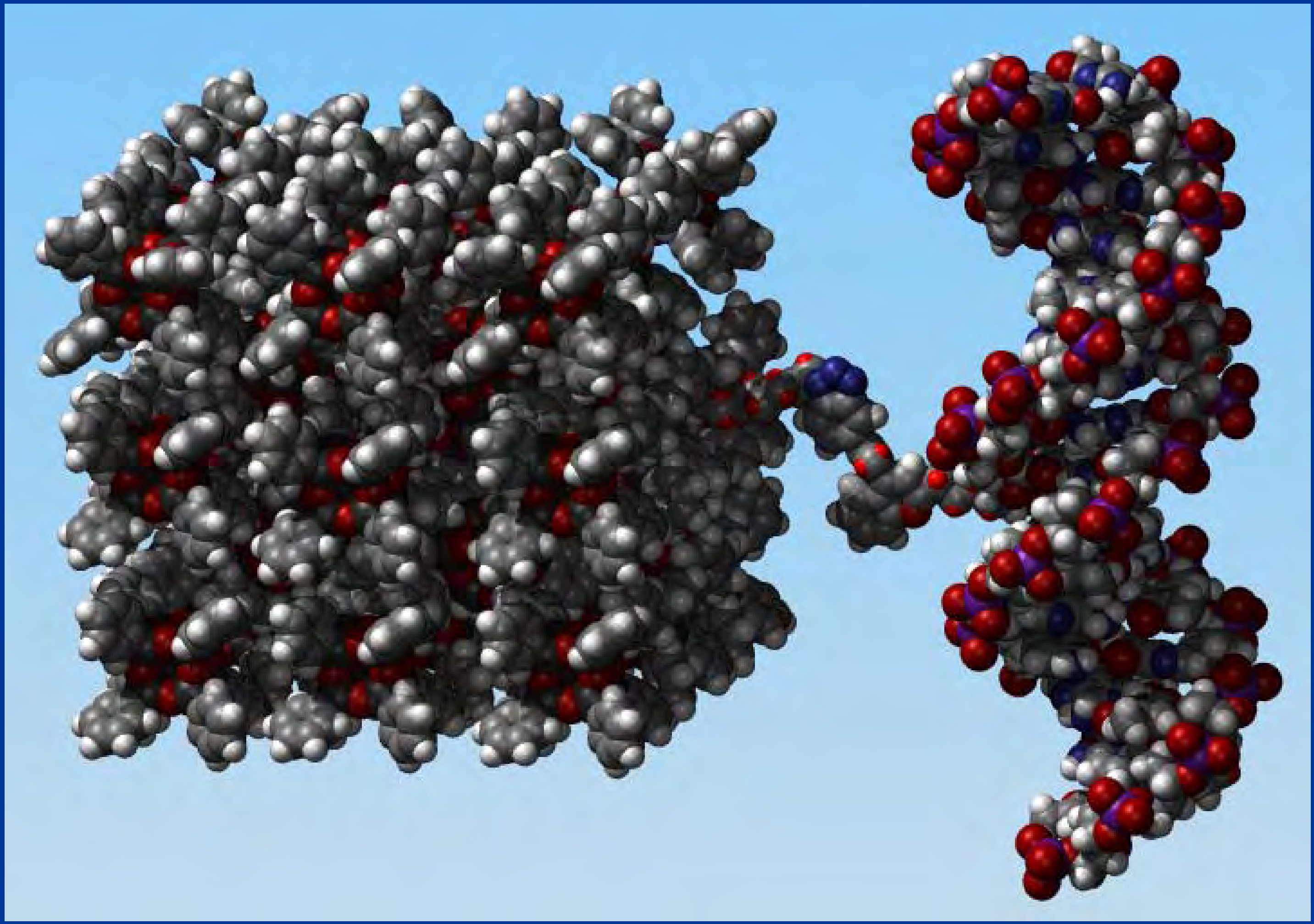


Amino-Modifier C6 dT

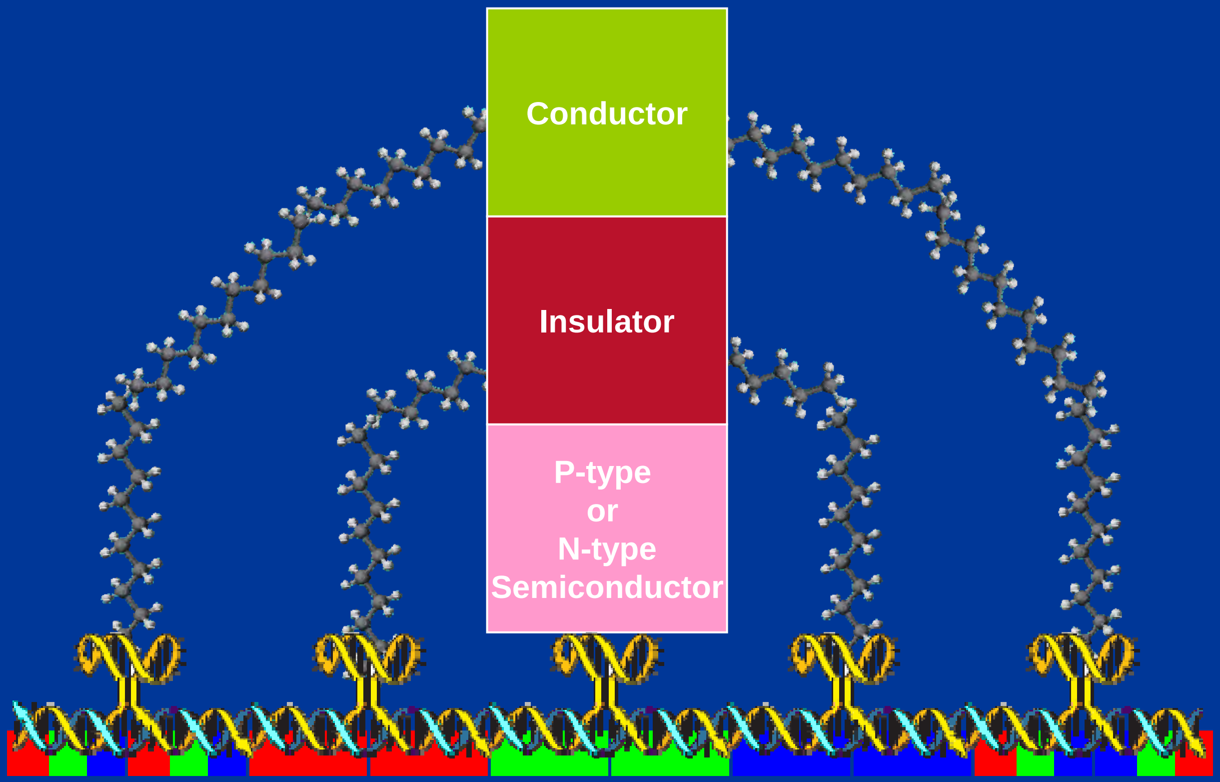


Biotin-dT

DNA-mediated Nanocube Assembly



DNA-mediated Multi-layered Nanocube Assembly



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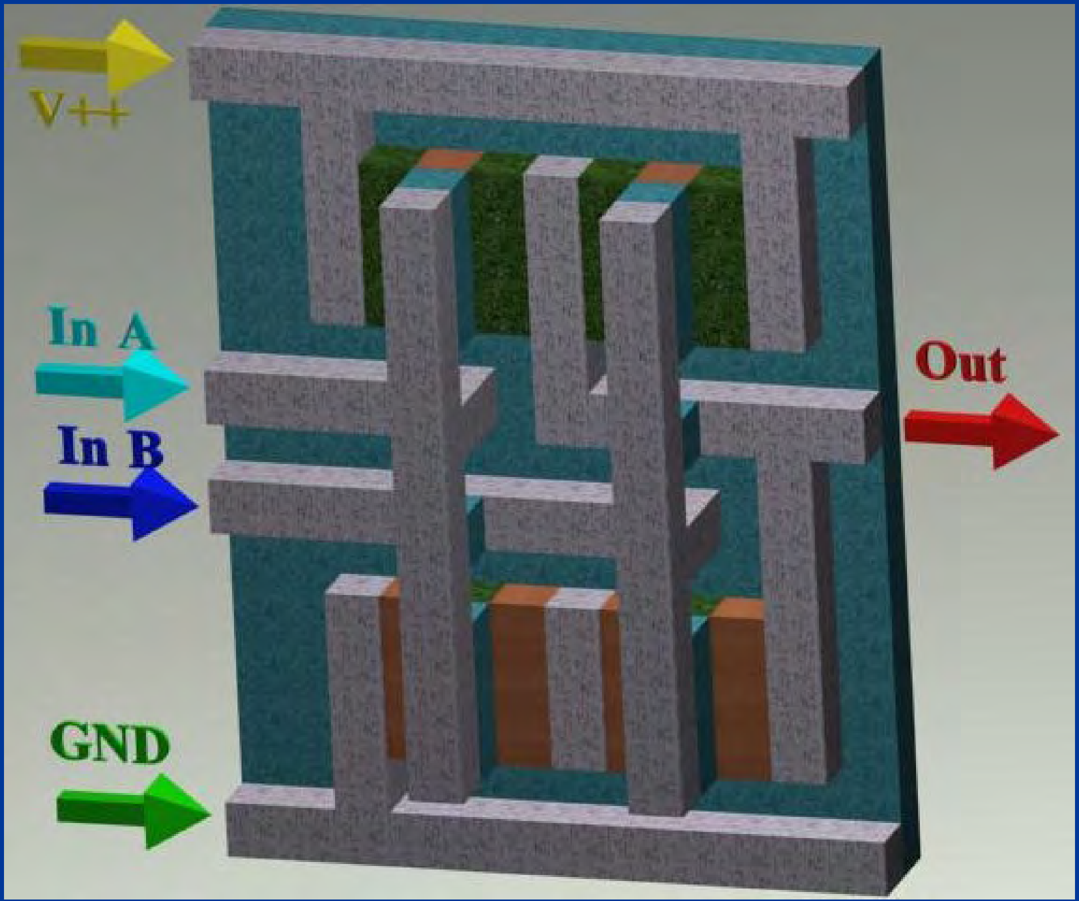
Patent Pending

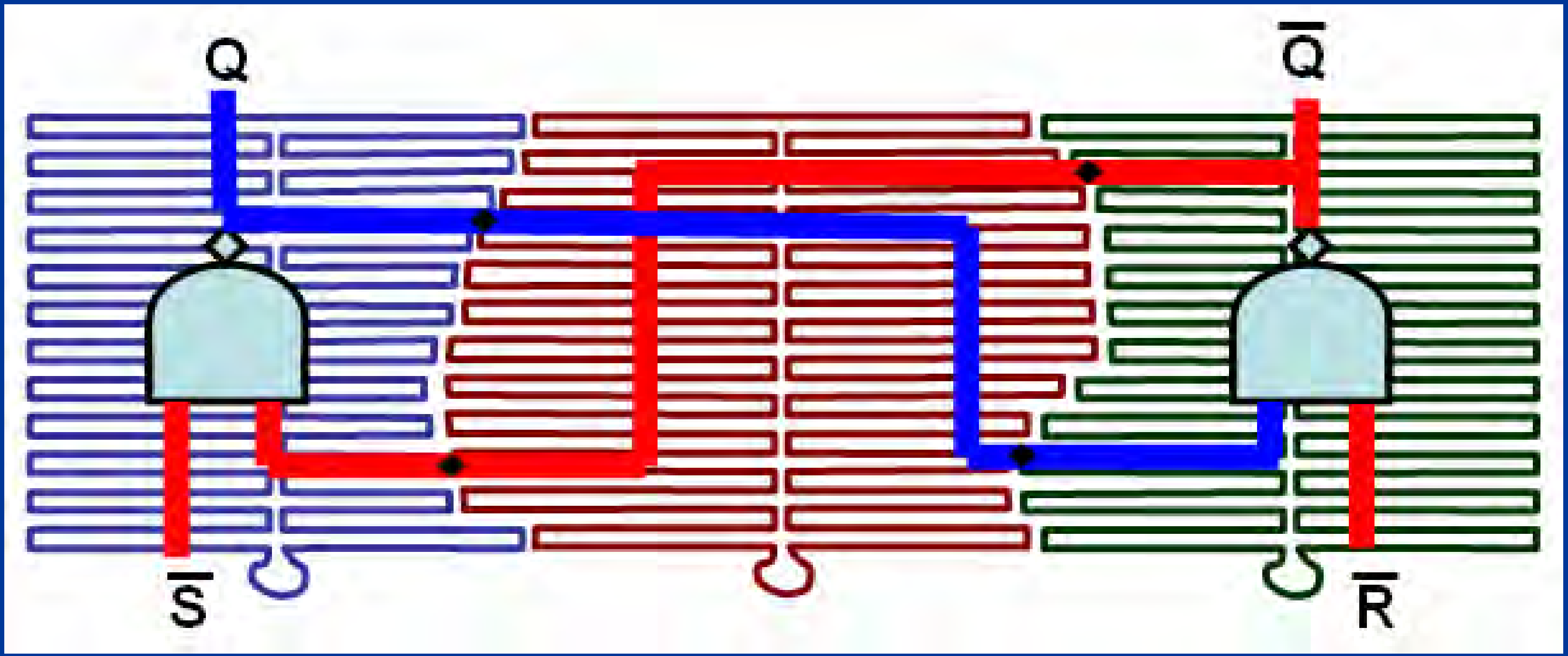
NAND



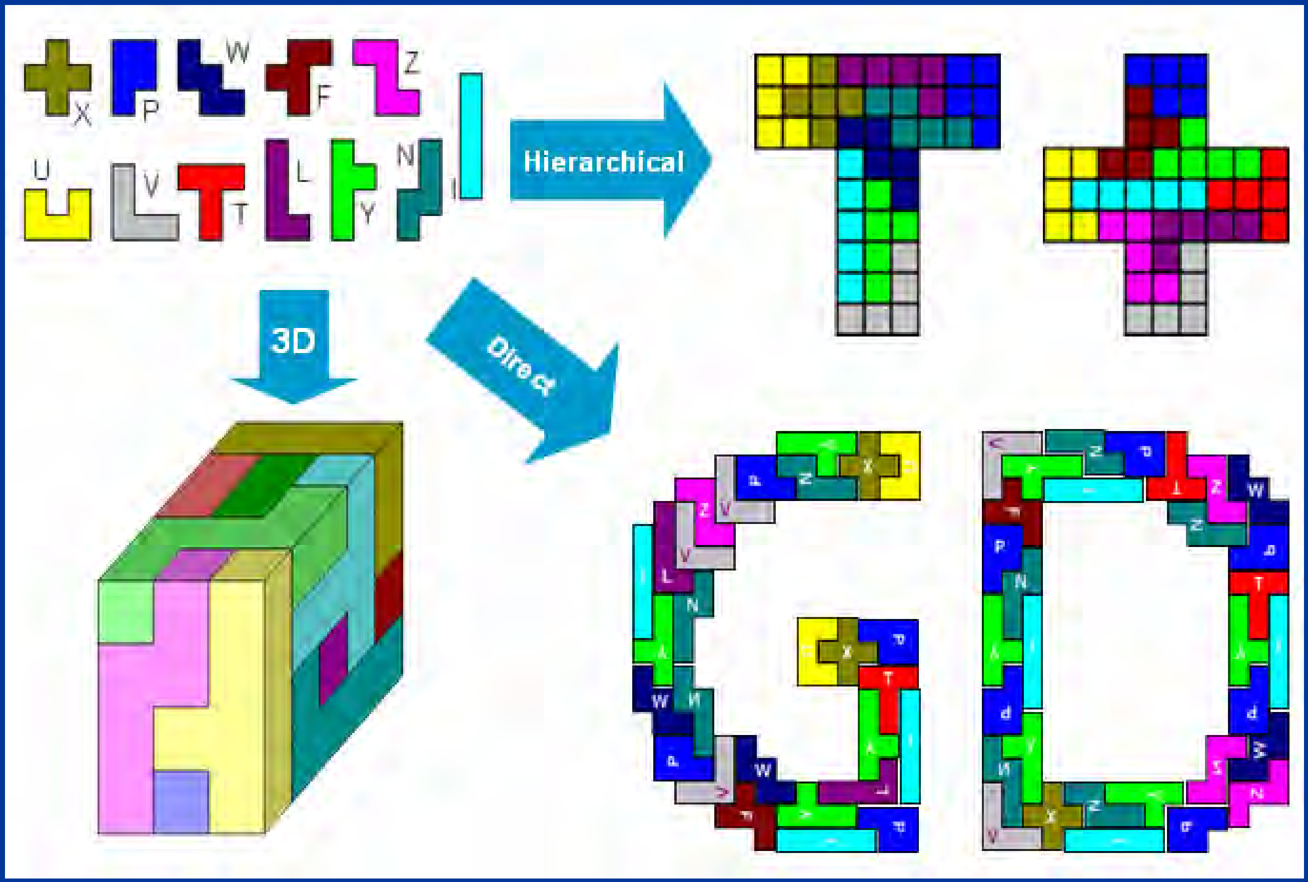
•**Not inherently limited to 2D**

•**Features ~ Bohr exiton radius**

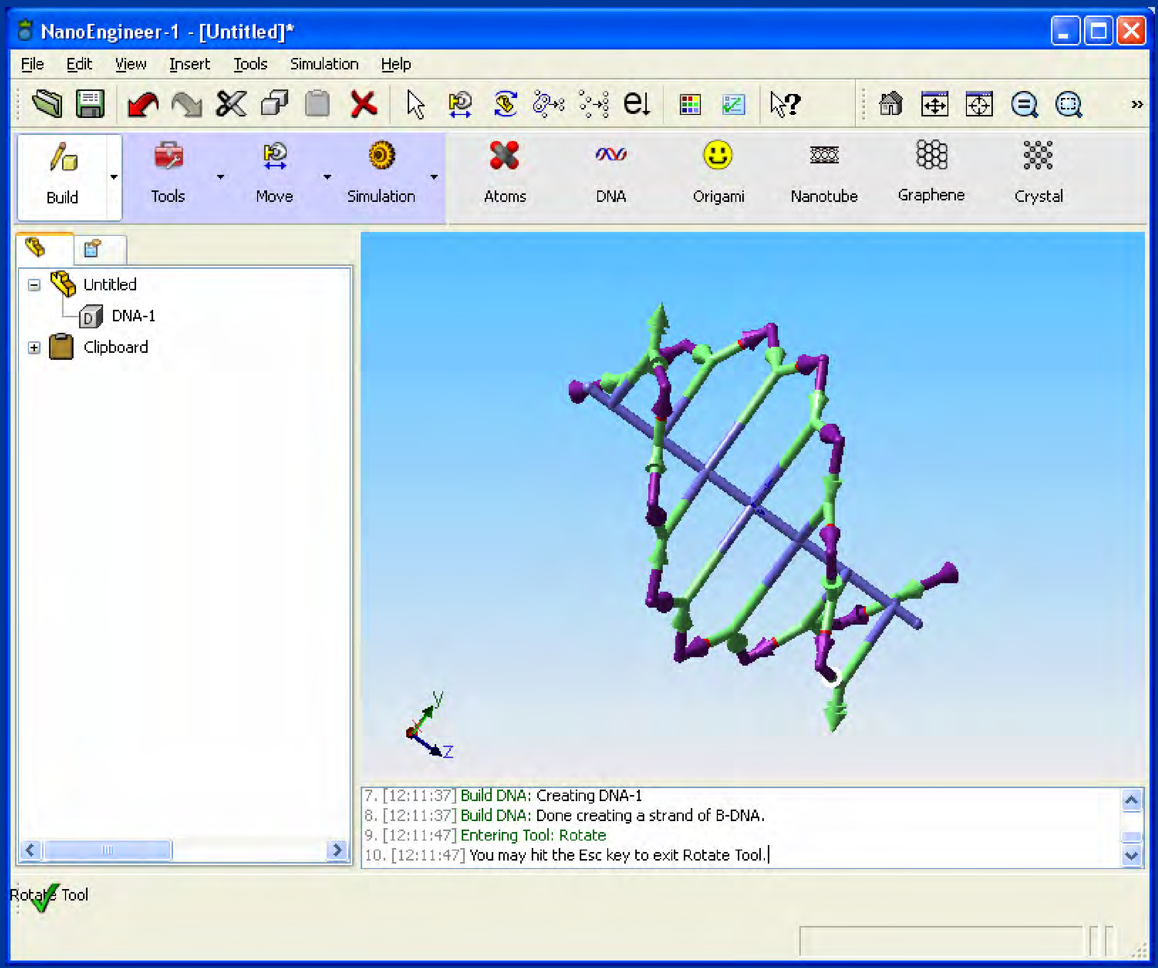
Hierarchical Assembly



Hierarchical Assembly: Polyominoes



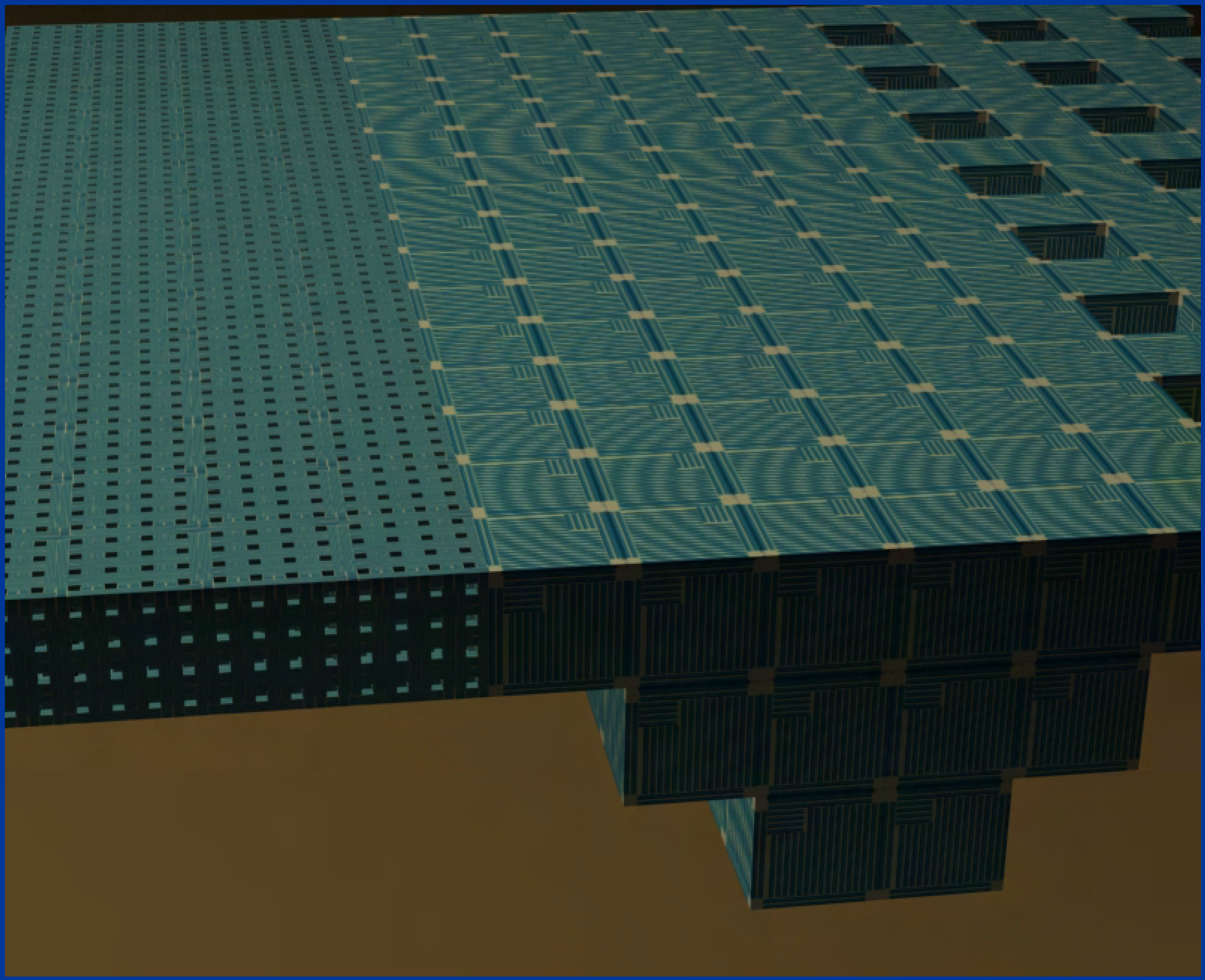
Design-ahead: NanoEngineer-1



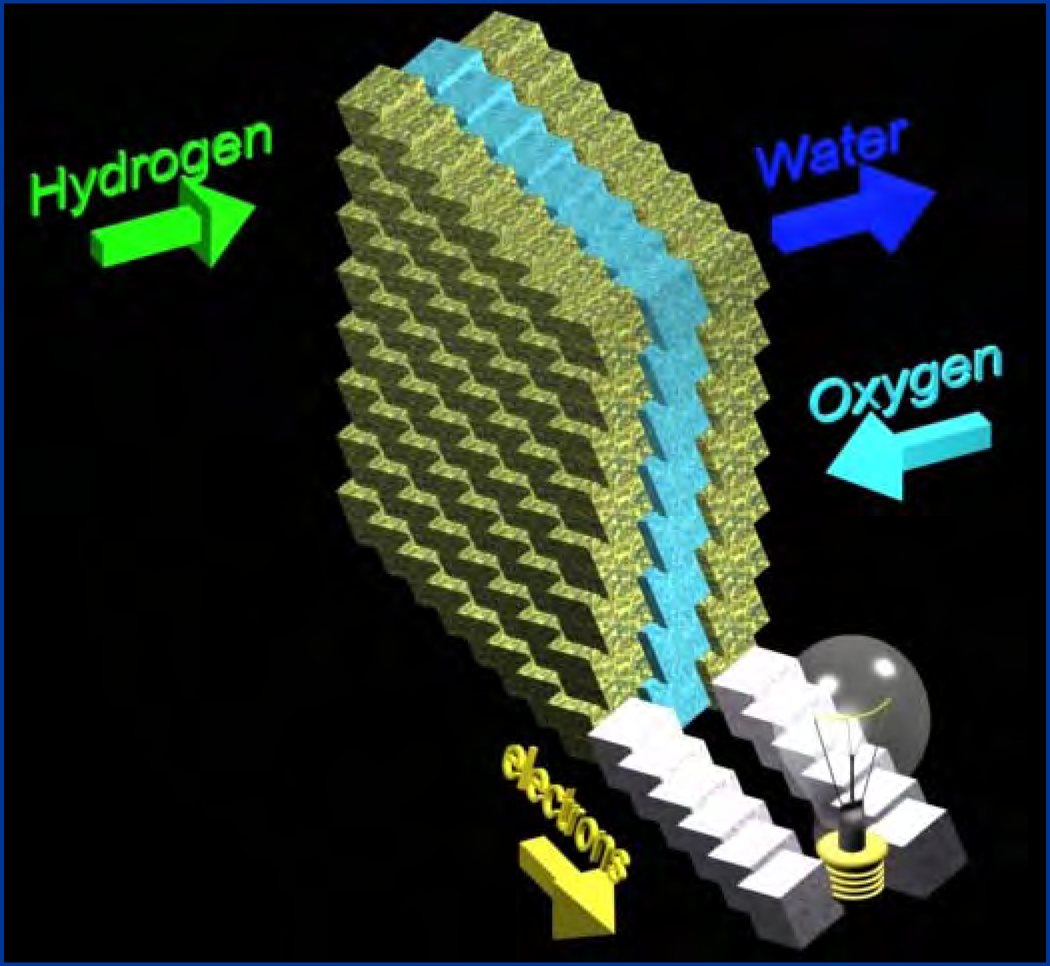
Applications

- Product Desirements
  - ➢ Low cost
  - ➢ High performance
  - ➢ High value
- Nanostructure Manufacturing Capabilities
  - ➢ Arbitrarily complex
  - ➢ Heterogeneous
  - ➢ Molecular precision
  - ➢ Long-range order
  - ➢ Bulk quantities

Pore nanocubes

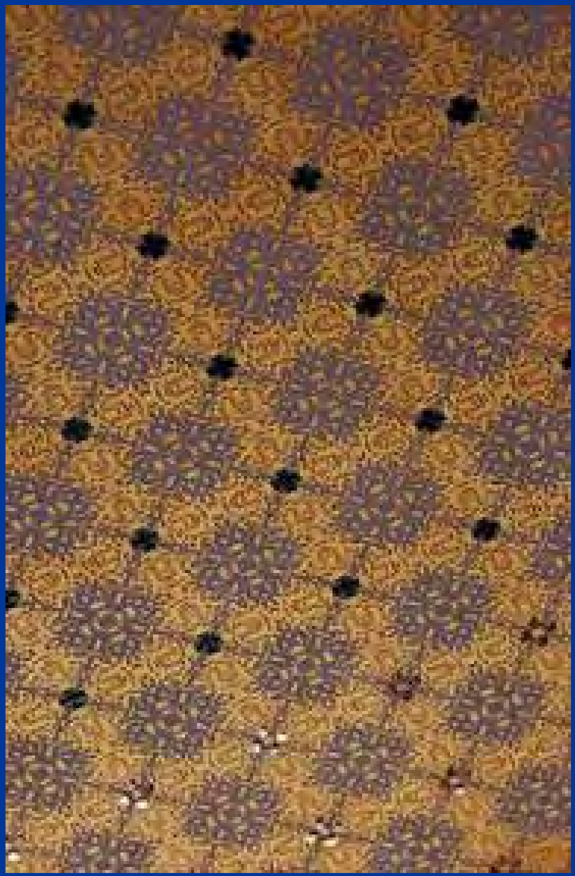


PEM Fuel Cells



Extreme Broadband Reconfigurable Fragmented Aperture Phased Arrays

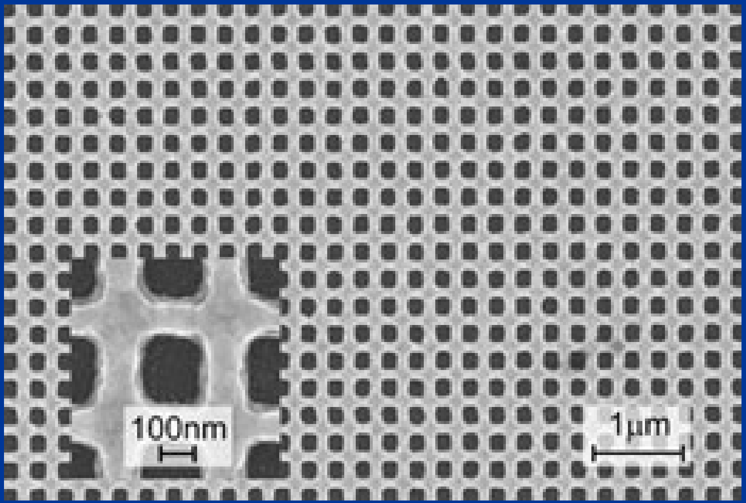
- UV to Radio Wavelengths
- High efficiency
- Conformal and flexible



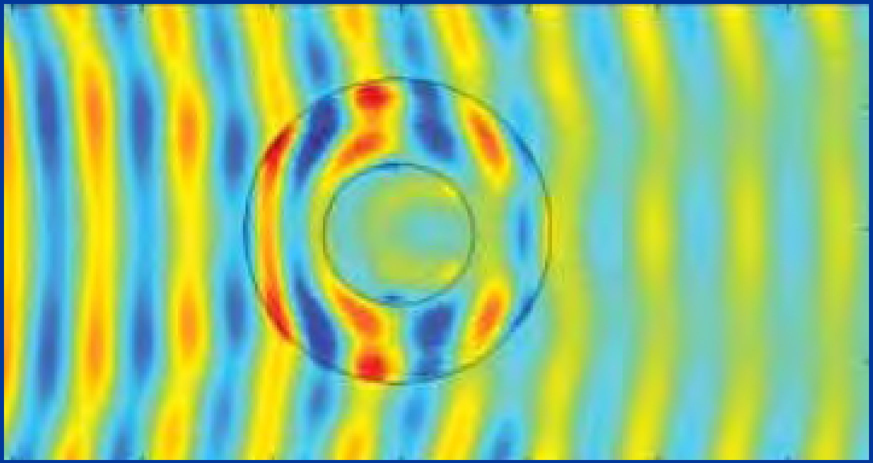
Pringle, et al. A Reconfigurable Aperture Antenna Based on Switched Links Between Electrically Small Metallic Patches. IEEE Trans Antennas & Propagation, V52N6, June 2004

Negative Index of Refraction Metamaterials

- Perfect lens with sub-wavelength resolution
- Unusual nanophotonic devices
- Optical Cloaking/Camouflage



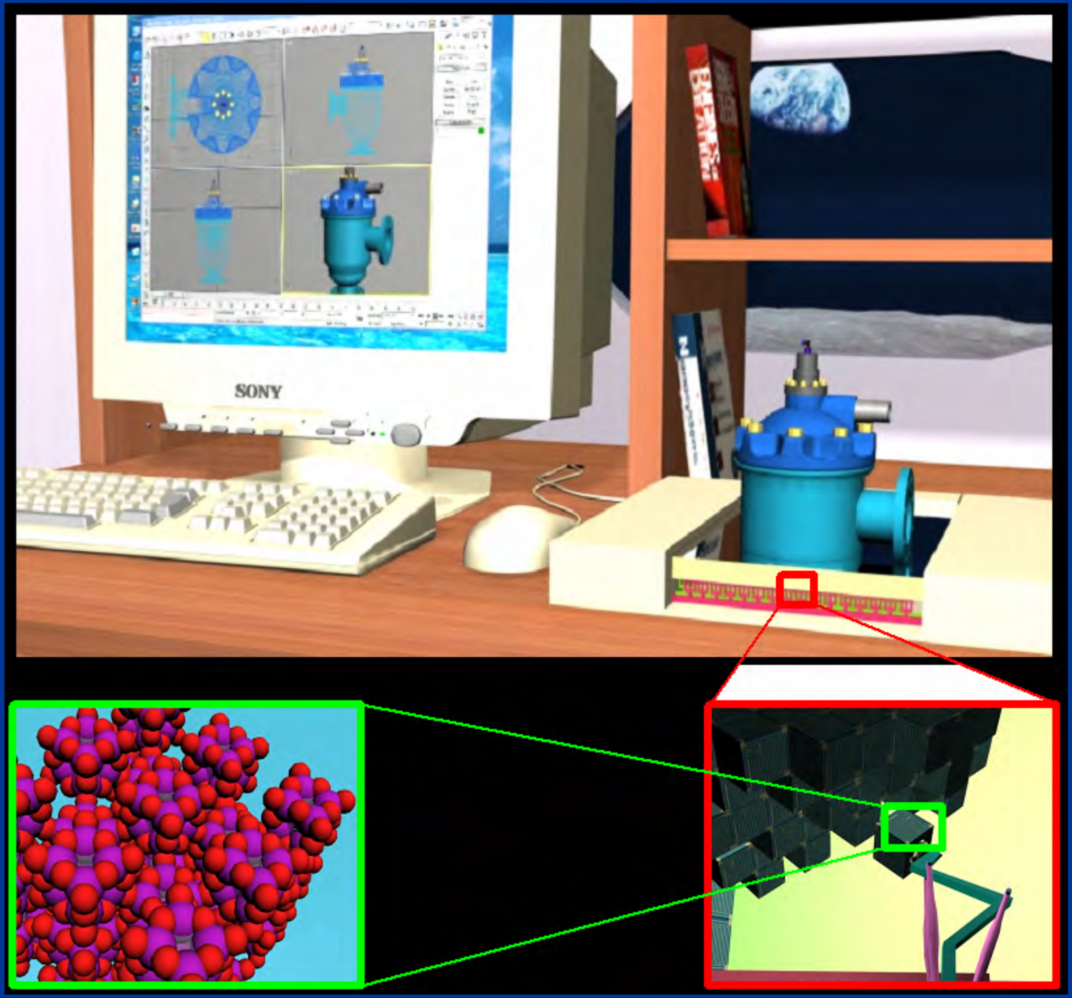
Smolyaninov, et al., Magnifying Superlens in the Visible Frequency Range. Science 315, 1699-1701 (2007)



D. Schurig, *et al.* Metamaterial Electromagnetic Cloak at Microwave Frequencies *Science* 314, 977 (2006);

Inami, et al., Optical Camouflage Using Retro-Reflective Projection Technology ISMAR 2003

Desktop Nanofactory Appliance



GENERAL DYNAMICS
Advanced Information Systems

Molecular Printers, the Tragedy of Commons, Orwell, and Owning Air

Conclusion

- Nanofactories are a tipping point in the industrial revolution
- There are many approaches
- Coming soon to your neighborhood

Tihamer.Toth-Fejel@gd-ais.com