Using DNA Information to Control the Structure of Matter in 3D

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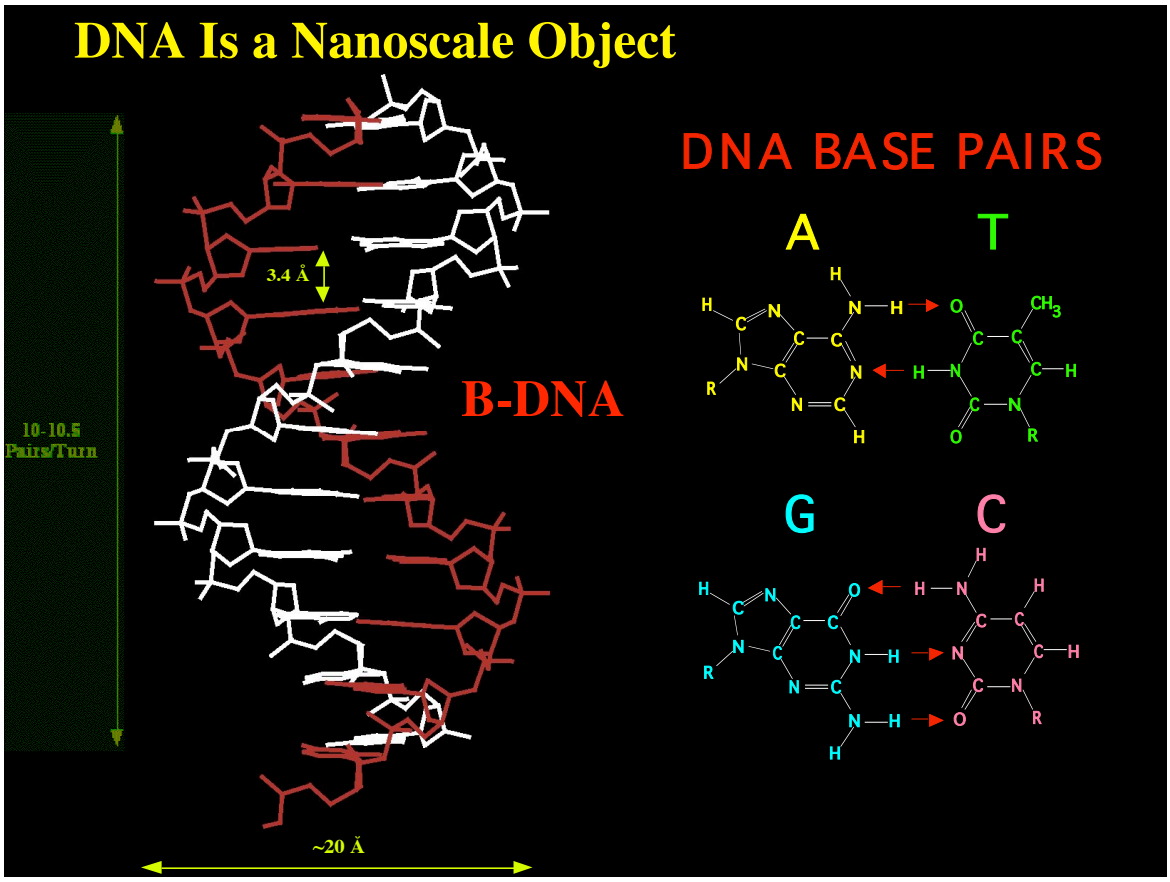
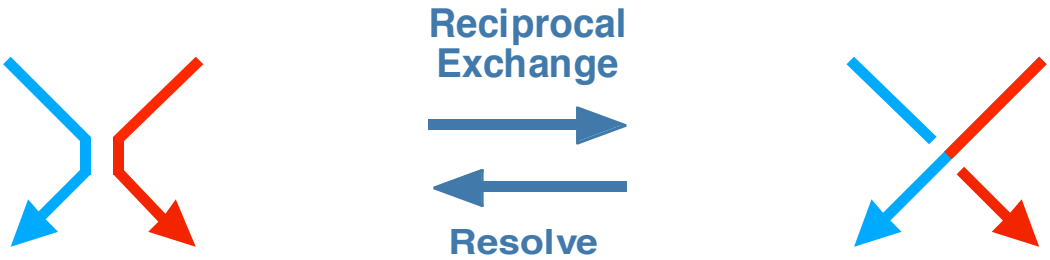
DNA-Based Nanotechnology:
Construction, Mechanics and Electronics
Technische Universität Dresden
May 11, 2009

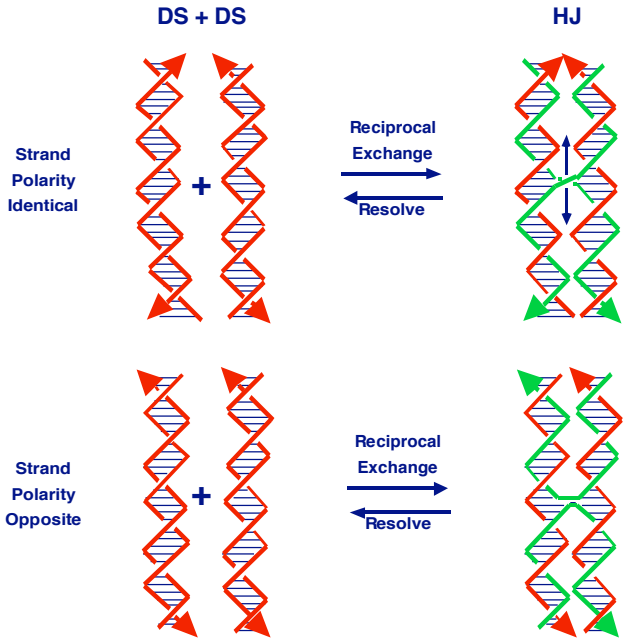


Reciprocal Exchange: A Theoretical Biokleptic Tool To Generate New DNA Motifs



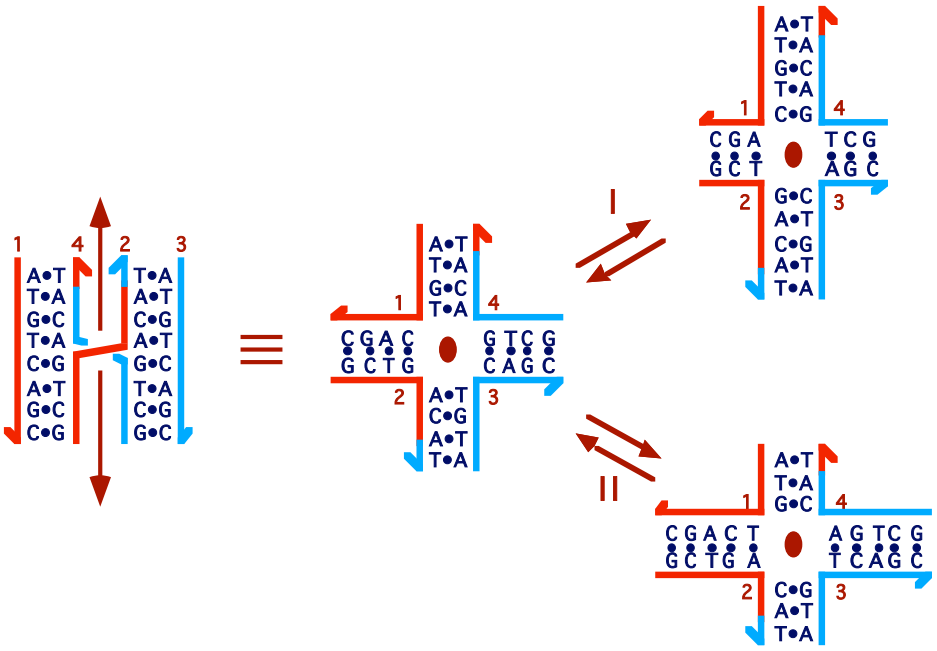
Seeman, N.C. (2001), *NanoLett.* **1**, 22-26.

Reciprocal Exchange in a Double Helical Context

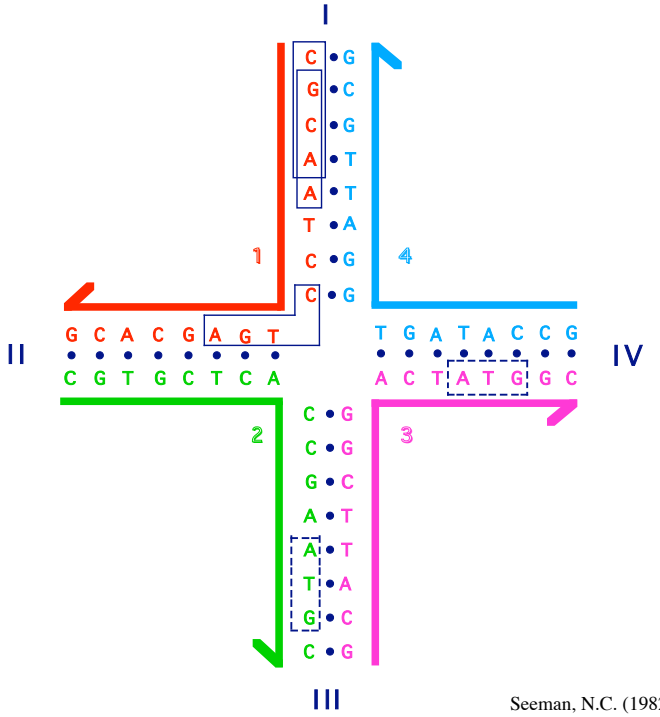


Seeman, N.C. (2001), *NanoLett*. **1**, 22-26.

Biological Reciprocal Exchange: The Holliday Junction

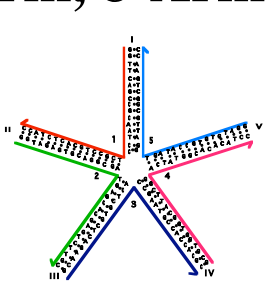


Design of Immobile Branched Junctions: Minimize Sequence Symmetry

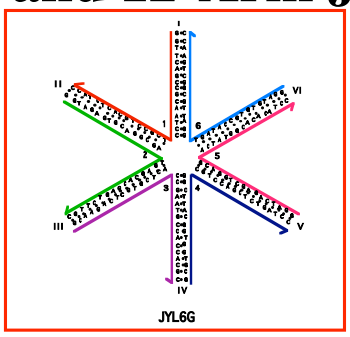


Seeman, N.C. (1982), *J. Theor.Biol.* **99**, 237-247.

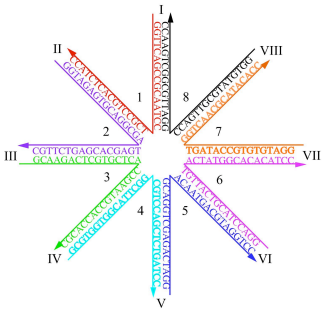
5-Arm, 6-Arm, 8-Arm and 12-Arm Junctions



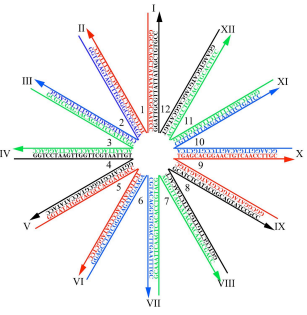
JYL5G



JYL6G



JXW8G

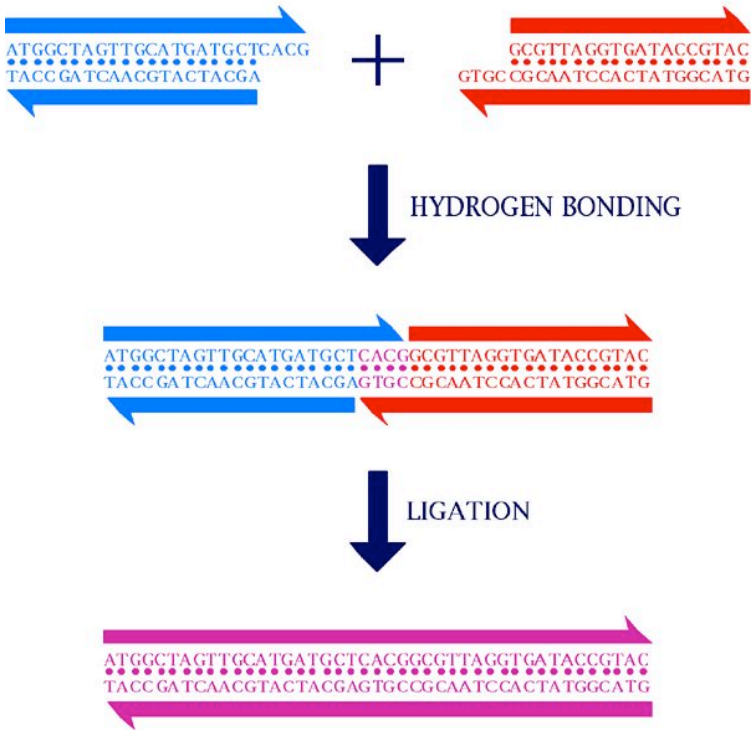


JXW12O

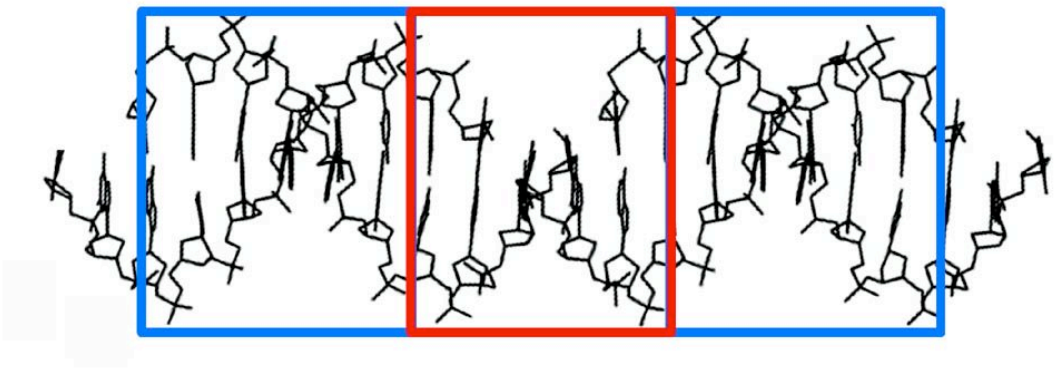
Wang, Y., Mueller, J.E., Kemper, B. & Seeman, N.C. (1991), *Biochemistry* **30**, 5667-5674.
Wang, X. & Seeman, N.C. (2007), *J. Am. Chem. Soc.* **129**, 8169-8176.

Bricks from the Ming Tombs in Nanjing

Sticky-Ended Cohesion: Smart Affinity

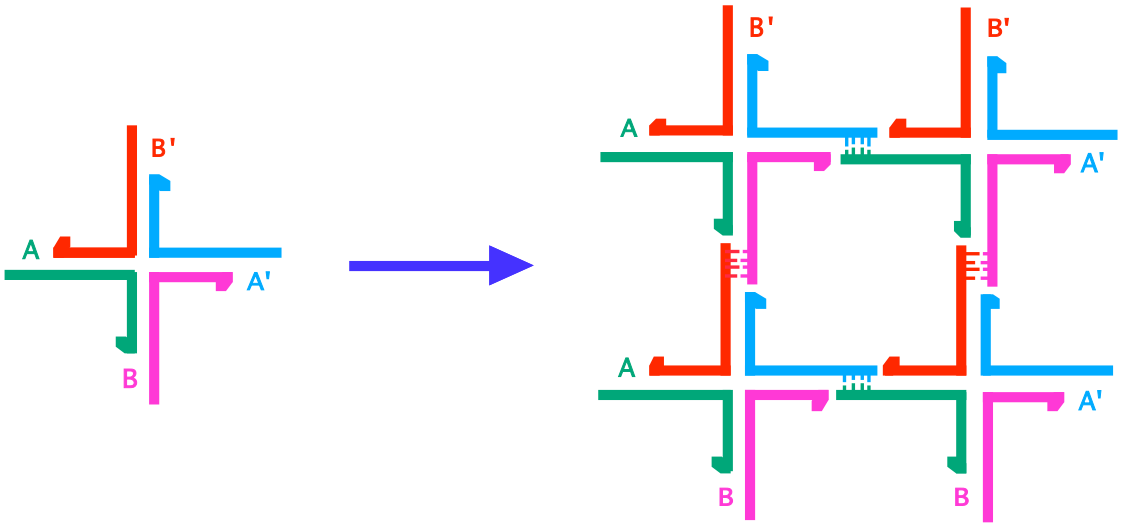


Sticky-Ended Cohesion: Structure



Qiu, H., Dewan, J.C. & Seeman, N.C. (1997) *J. Mol. Biol.* **267**, 881-898.

The Central Concept of Structural DNA Nanotechnology: Combine Branched DNA with Sticky Ends to Make Objects, Lattices and Devices



Seeman, N.C. (1982), *J. Theor.Biol.* **99**, 237-247.

OBJECTIVES AND APPLICATIONS FOR OUR LABORATORY

ARCHITECTURAL CONTROL AND SCAFFOLDING

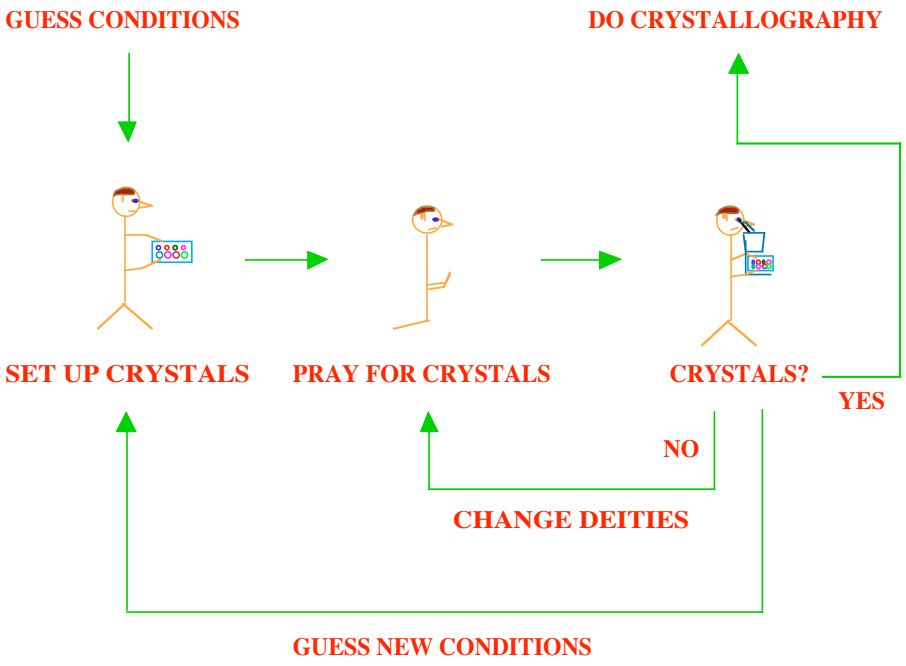
[1] MACROMOLECULAR CRYSTALLIZATION (PERIODIC IN 2D AND 3D).
[2] NANOELECTRONICS ORGANIZATION (PERIODIC IN 2D AND 3D).
[3] DNA-BASED COMPUTATION (APERIODIC IN 2D OR 3D).
[4] CONTROL OF POLYMER AND MATERIALS COMPOSITION & TOPOLOGY.

NANOMECHANICAL DEVICES

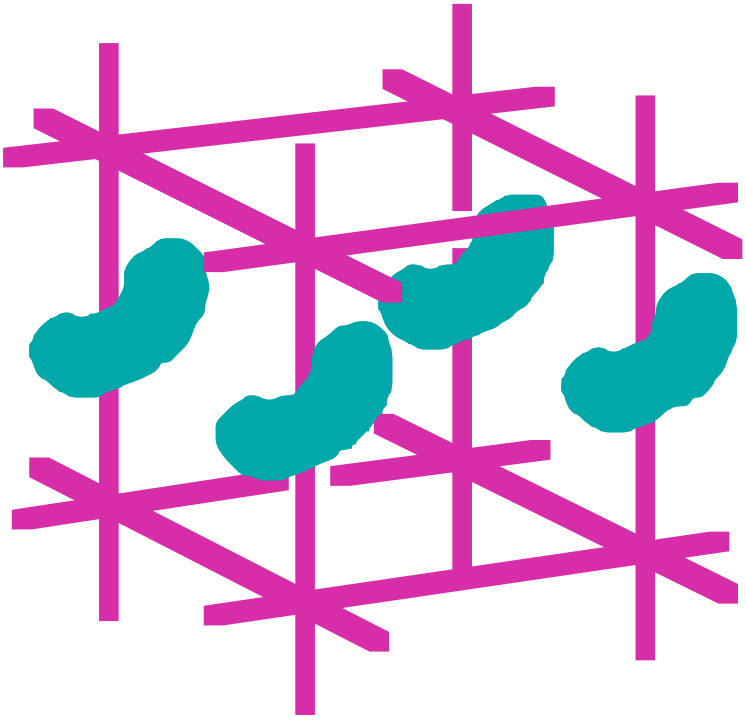
[1] NANOROBOTICS.
[2] NANOFABRICATION.

SELF-REPLICABLE SYSTEMS

CURRENT CRYSTALLIZATION PROTOCOL

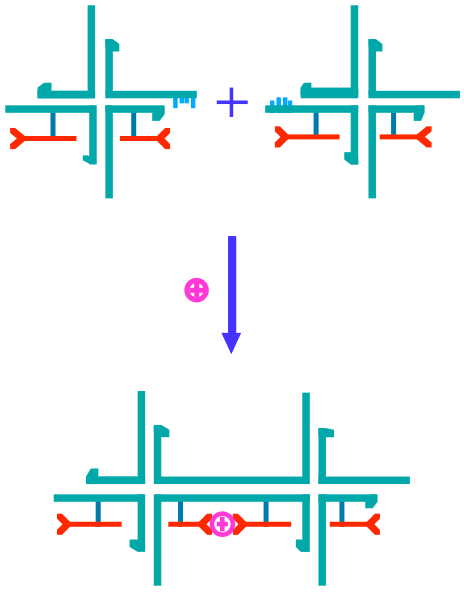


A New Suggestion for Producing Macromolecular Crystals



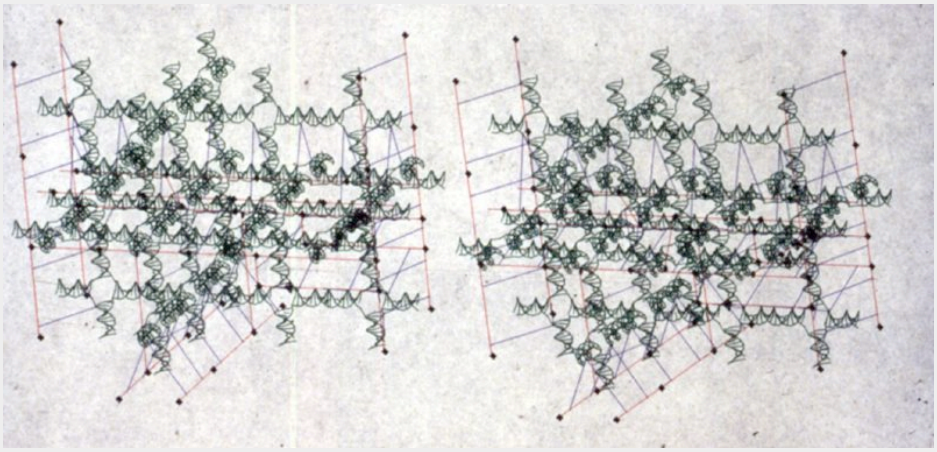
Seeman, N.C. (1982), *J. Theor.Biol.* **99**, 237-247.

A Method for Organizing Nano-Electronic Components



Robinson, B.H. & Seeman, N.C. (1987), *Protein Eng*. **1**, 295-300..

A Suggestion for a Molecular Memory Device Organized by DNA (Shown in Stereo)



Robinson, B.H. & Seeman, N.C. (1987), *Protein Eng*. **1**, 295-300.

Why DNA?

Nucleic Acid Sequences Can Be Programmed and Synthesized, Leading to Information-Based Structural, Dynamic and Catalytic Chemistry

Predictable Intermolecular Interactions:
Both Affinity and Structure.

Can Design Shape by Selecting Sequence:
Robust Branched Motifs Programmable by Sequence.

Convenient Automated Chemistry:
Both Vanilla DNA and Useful Derivatives.

Convenient Modifying Enzymes:
Ligases, Exonucleases, Restriction Enzymes, Topoisomerases.

Locally A Stiff Polymer:
Persistence Length ~500 Å; Stiff Branched Motifs Have Been Developed.

Robust Molecule:
Can Heat Individual Strands without Doing Damage.

Amenable to Molecular Biology and Biotechnology Techniques:
Gels, Autoradiography, PCR.

Externally Readable Code when Paired:
Different Points in a Lattice Can be Addressed.

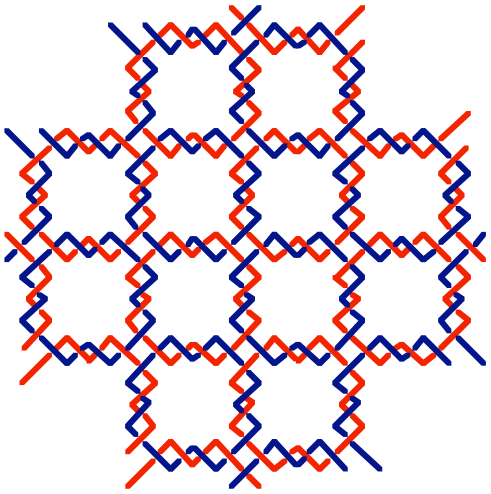
High Functional Group Density:
Every 3.4 Å Nucleotide Separation.

Prototype for Many Derivatives:
The Gene Therapy Enterprise Has Generated Hundreds of Analogs

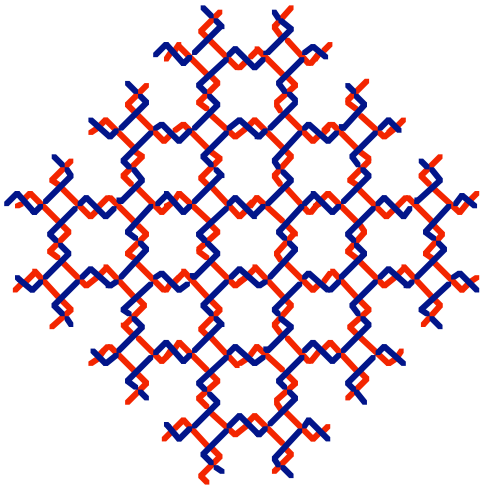
Potentially Self-Replicable and Selectable:
May be Able to Make and Improve Constructs Inexpensively.

DNA Topology Affects DNA Nanoconstructions

Chain Mail



Interwoven



What Is the Intellectual Goal of Structural DNA Nanotechnology?

Controlling the Structure of Matter in 3D to the Highest Extent (Resolution) Possible, so as to Understand the Connection between the Molecular and Macroscopic Scales.

"What I cannot create, I do not understand."
--Richard P. Feynman
(Inverse not necessarily true.)

STRUCTURAL AND TOPOLOGICAL ASSEMBLIES

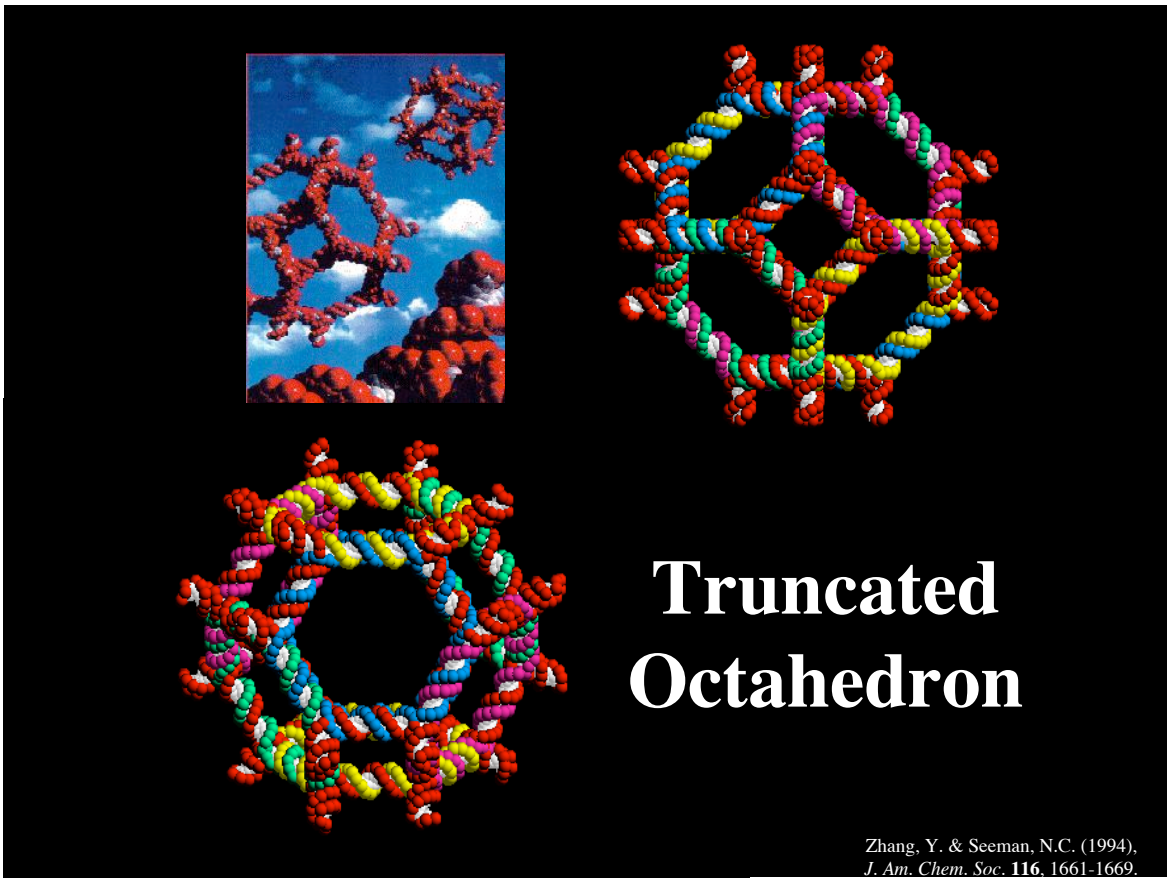
Polyhedral Catenanes

Cube: Junghuei Chen

Truncated Octahedron: Yuwen Zhang

Cube

Chen, J. & Seeman. N.C. (1991), *Nature* **350**, 631-633.


Truncated
Octahedron
Zhang, Y. & Seeman, N.C. (1994),
J. Am. Chem. Soc. **116**, 1661-1669.

Construction of Crystalline Arrays

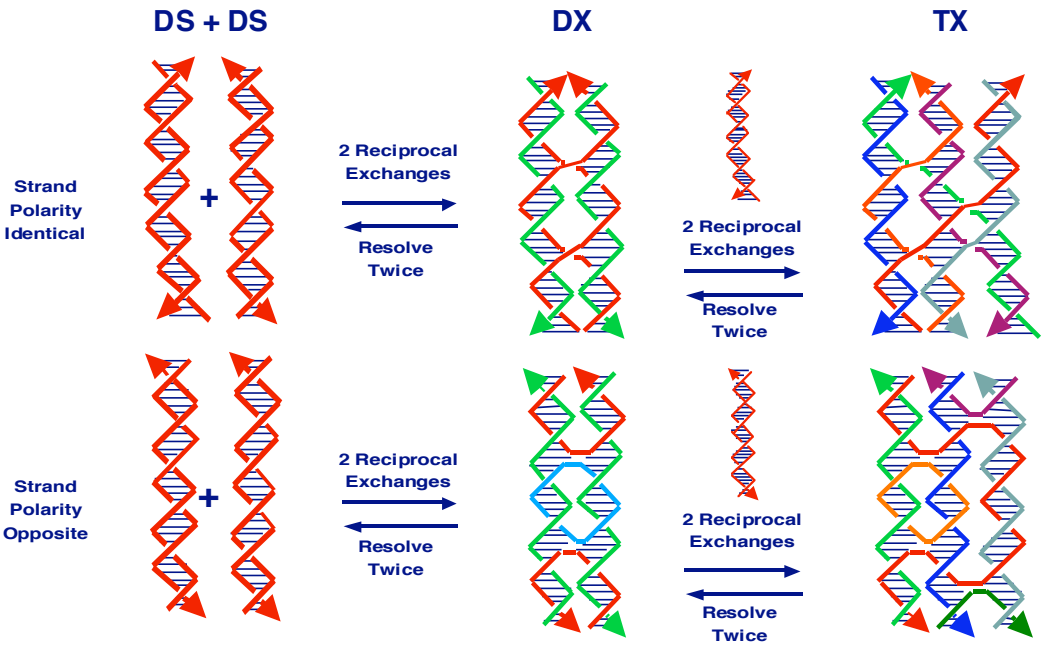
REQUIREMENTS FOR LATTICE DESIGN COMPONENTS

PREDICTABLE INTERACTIONS

PREDICTABLE LOCAL PRODUCT STRUCTURES

STRUCTURAL INTEGRITY

Derivation of DX and TX Molecules

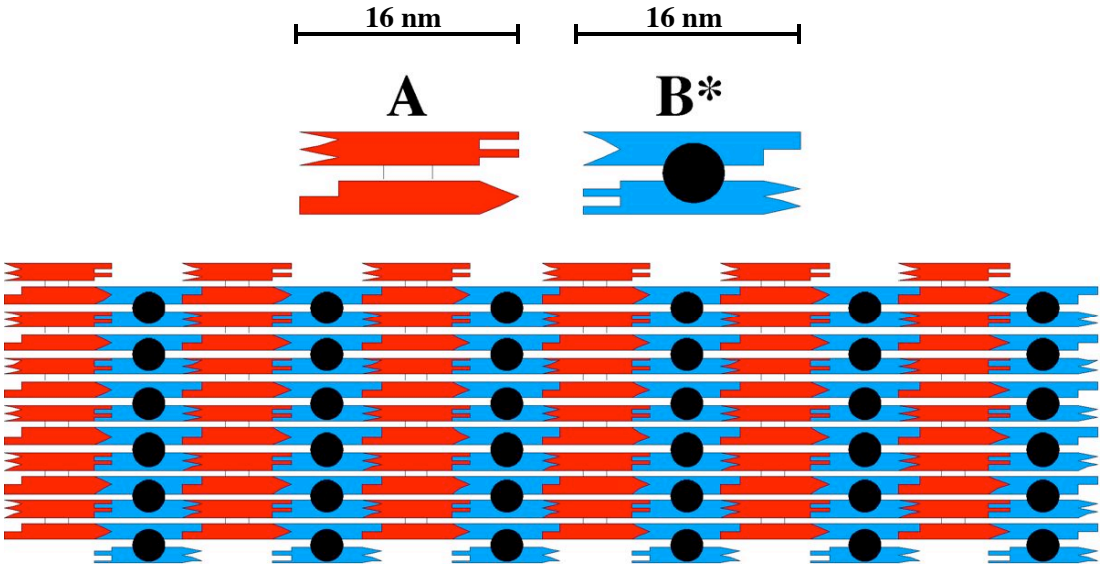


Seeman, N.C. (2001) *NanoLetters* **1**, 22-26.

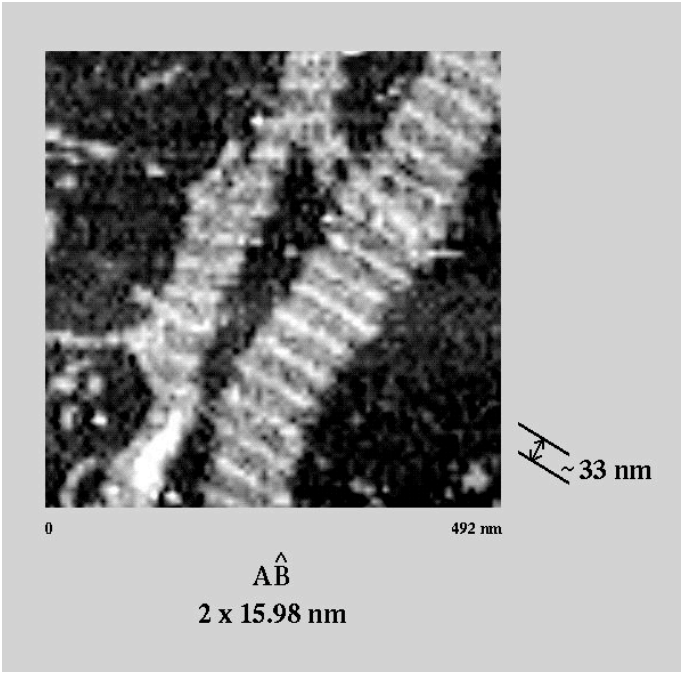
2D DX Arrays

Erik Winfree (Caltech)
Furong Liu
Lisa Wenzler

Schematic of a Lattice Containing 1 DX Tile and 1 DX+J Tile

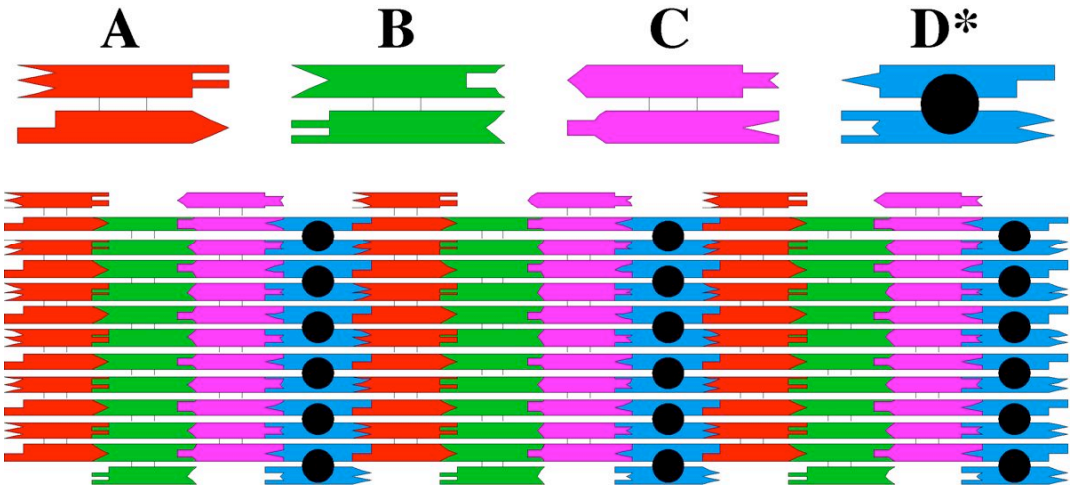


AFM of a Lattice Containing 1 DX Tile and 1 DX+J Tile

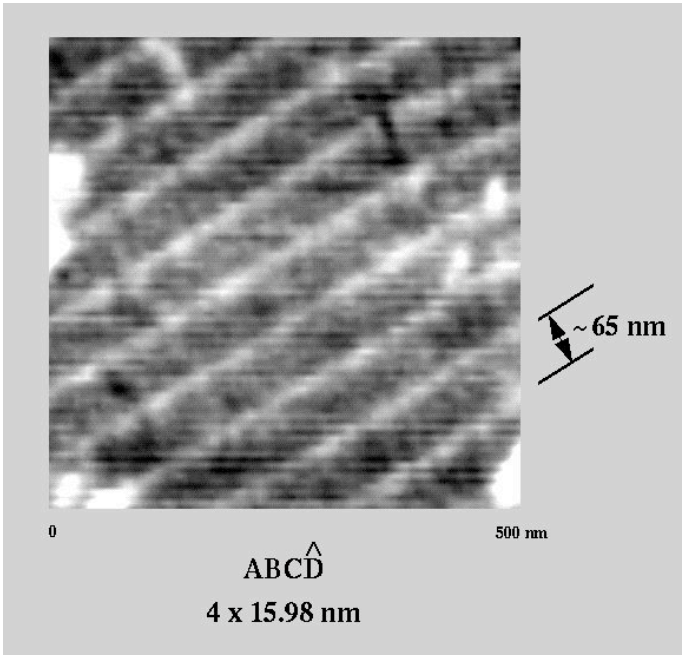


Winfree, E., Liu, F., Wenzler, L.A. & Seeman, N.C. (1998), *Nature* **394**, 539-544.

Schematic of a Lattice Containing 3 DX Tiles and 1 DX+J Tile



AFM of a Lattice Containing 3 DX Tiles and 1 DX+J Tile

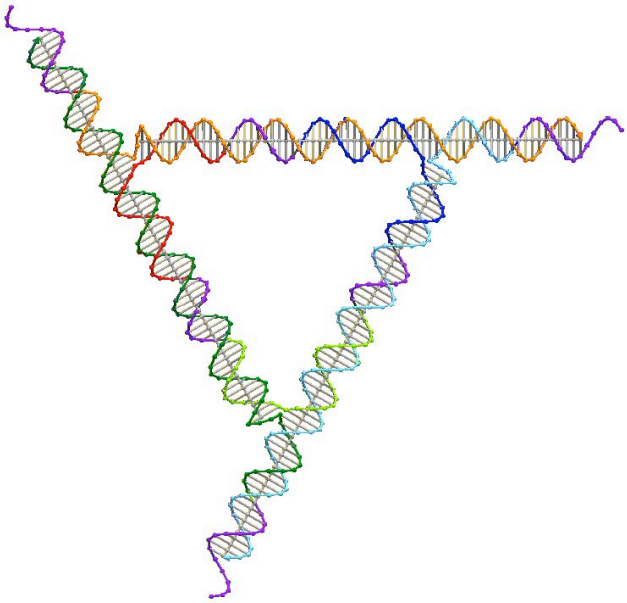


Winfree, E., Liu, F., Wenzler, L.A. & Seeman, N.C. (1998), *Nature* **394**, 539-544.

Robust 2D Arrays: DX Triangles

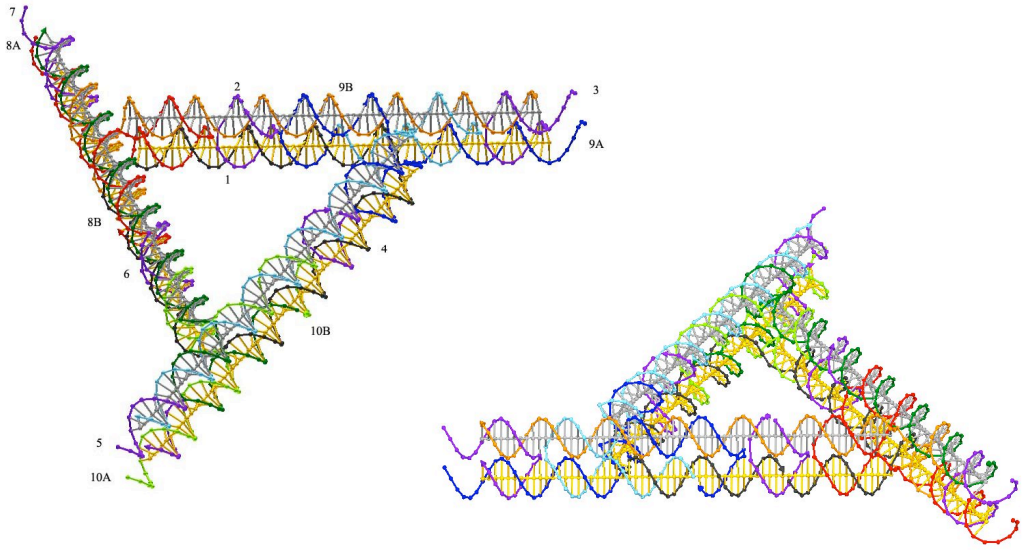
Baoquan Ding

Simple Bulged 3-Arm Junction Triangle (1996)



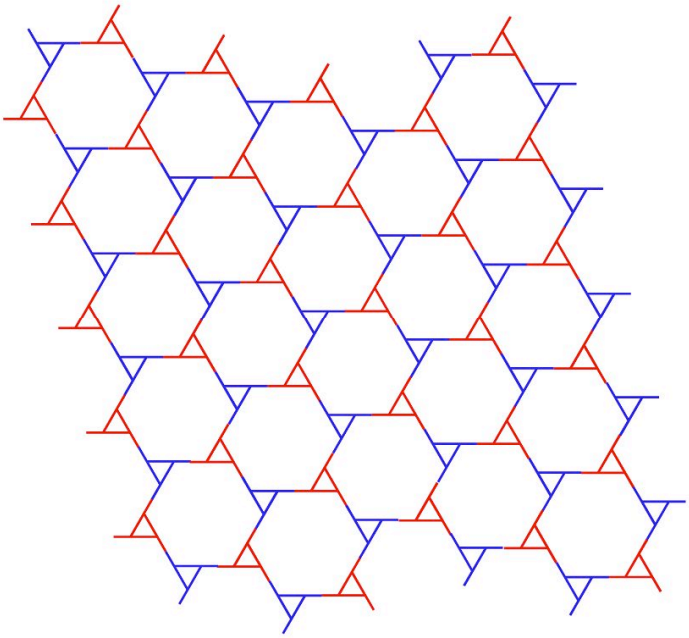
J. Qi, X. Li, X. Yang & N.C. Seeman,
J. Am. Chem. Soc., **118**, 6121-6130 (1996).

DX Bulged Triangle Motif



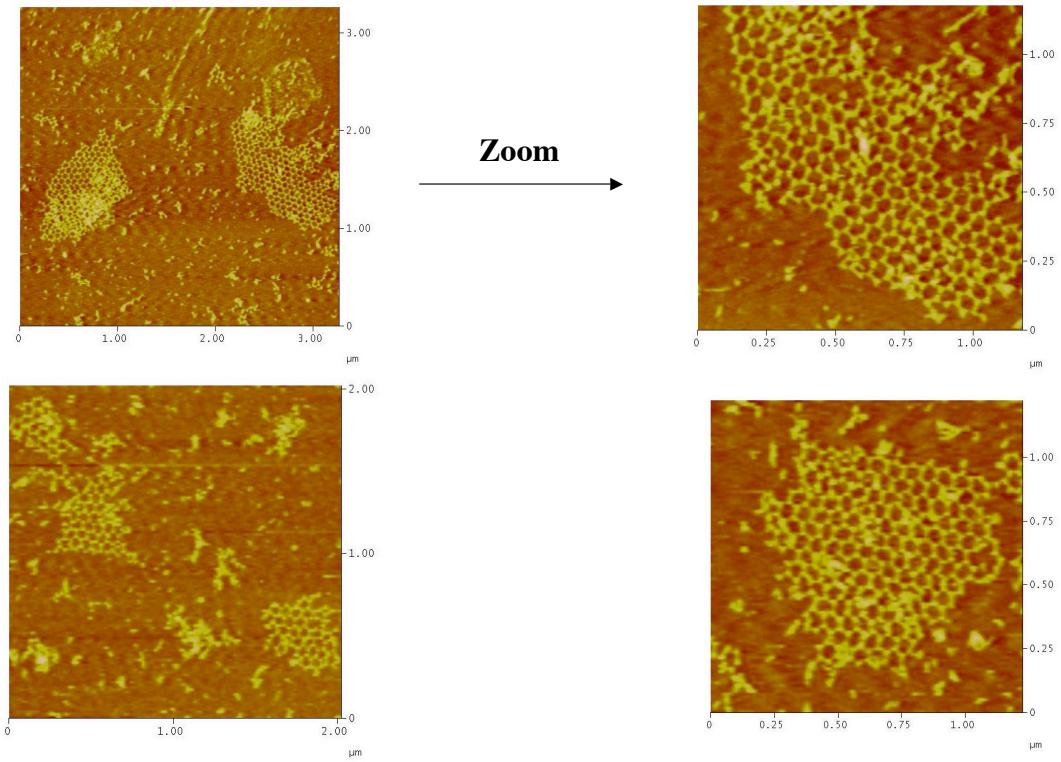
Ding, B. & Seeman, N.C. (2004), *J. Am. Chem. Soc.* **126**, 10230-10231.

Two Trigonal Motifs Form a Pseudohexagonal Trigonal Array



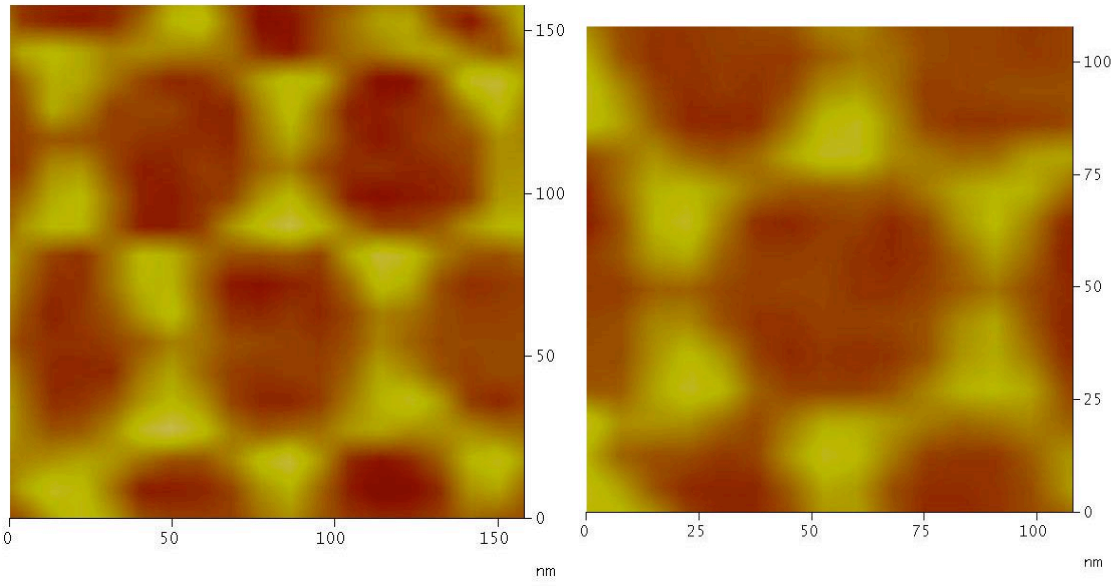
Ding, B. & Seeman, N.C. (2004), *J. Am. Chem. Soc.* **126**, 10230-10231.

Lattice Views



Ding, B. & Seeman, N.C. (2004), *J. Am. Chem. Soc.* **126**, 10230-10231.

Zoomed Images



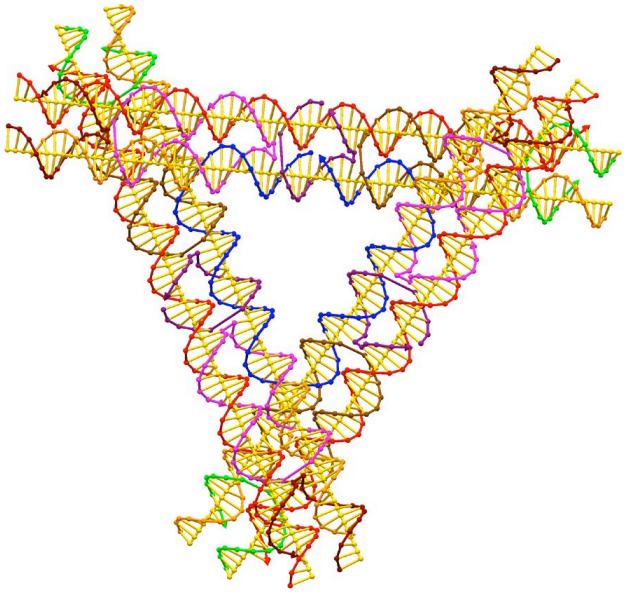
Ding, B. & Seeman, N.C. (2004), *J. Am. Chem. Soc.* **126**, 10230-10231.

DIVERSIFYING THE CHEMISTRY

Organizing 5 and 10 nm Gold Nanoparticles

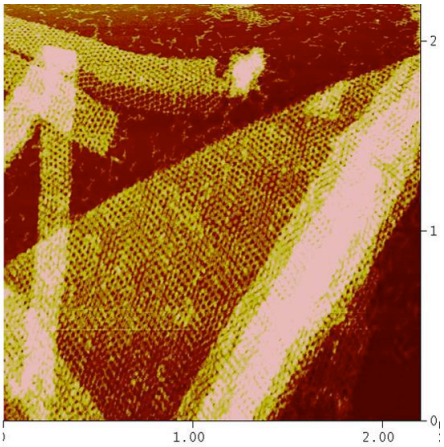
Jiwen Zheng
Pam Constantinou
Christine Micheel (Berkeley)
Paul Alivisatos (Berkeley)
Rick Kiehl (Minnesota)

The 3D-DX Triangle:
A DX Version of the Tensegrity 3D Triangle

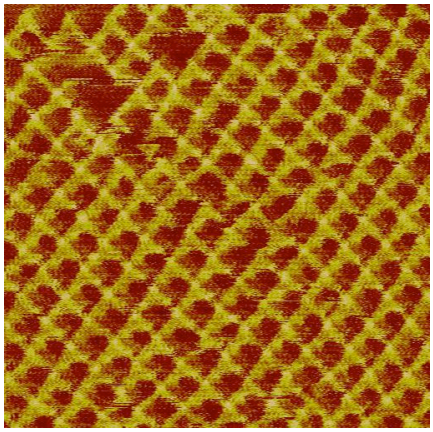


J. Zheng, P.E. Constantinou, C. Micheel, A.P. Alivisatos, R.A. Kiehl & N.C. Seeman, *NanoLetters* **6**, 1502-1504 (2006).

YZ 2D Array of 3D-DX Triangle



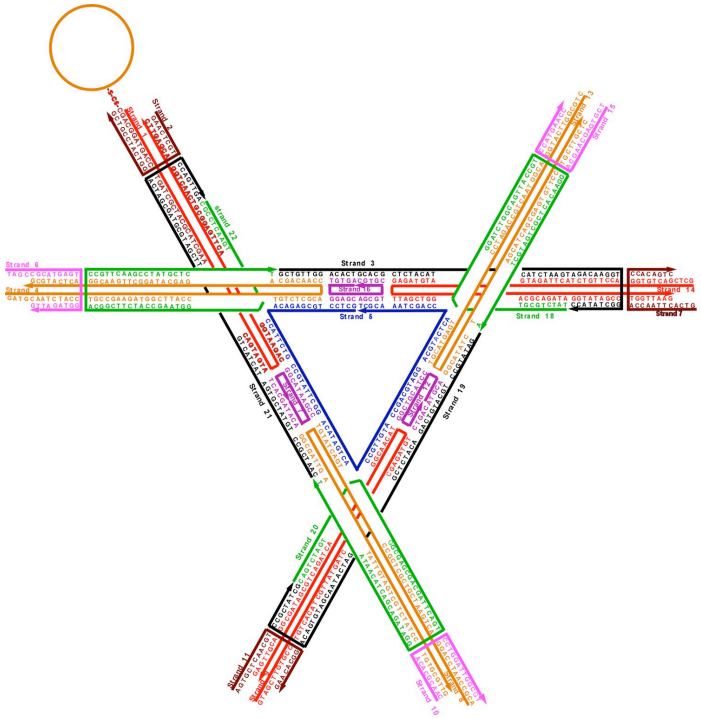
One Tile



Two Tiles

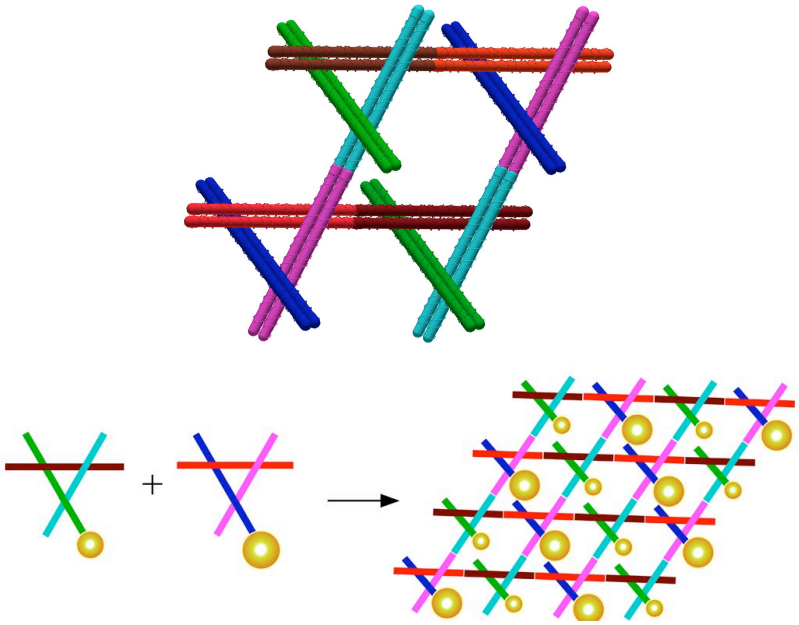
J. Zheng, P.E. Constantinou, C. Micheel, A.P. Alivisatos, R.A. Kiehl & N.C. Seeman, *NanoLetters* **6**, 1502-1504 (2006).

Attachment of a Nanoparticle to the 3D-DX Motif



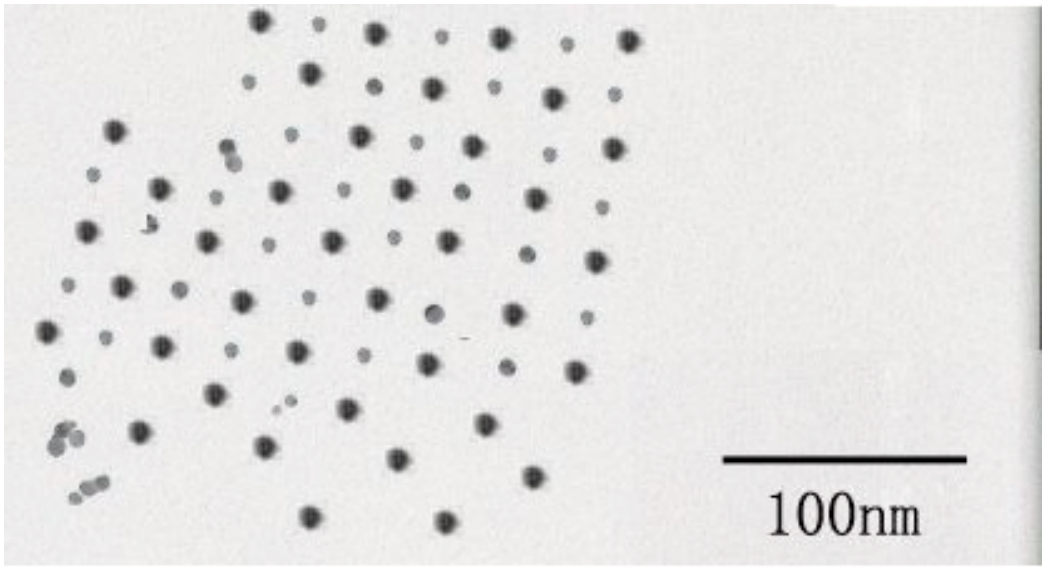
J. Zheng, P.E. Constantinou, C. Micheel, A.P. Alivisatos, R.A. Kiehl & N.C. Seeman, *NanoLetters* **6**, 1502-1504 (2006).

Two Motifs Can Organize Nanoparticles



J. Zheng, P.E. Constantinou, C. Micheel, A.P. Alivisatos, R.A. Kiehl & N.C. Seeman, *NanoLetters* **6**, 1502-1504 (2006).

Organized 5 nm and 10 nm Particles



J. Zheng, P.E. Constantinou, C. Micheel, A.P. Alivisatos, R.A. Kiehl & N.C. Seeman, *NanoLetters* **6**, 1502-1504 (2006).

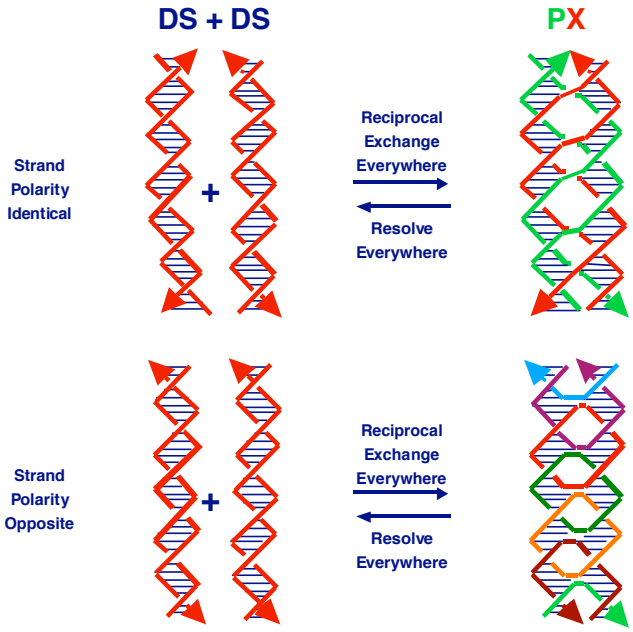
FROM GENES TO MACHINES:

DNA NANOMECHANICAL DEVICES

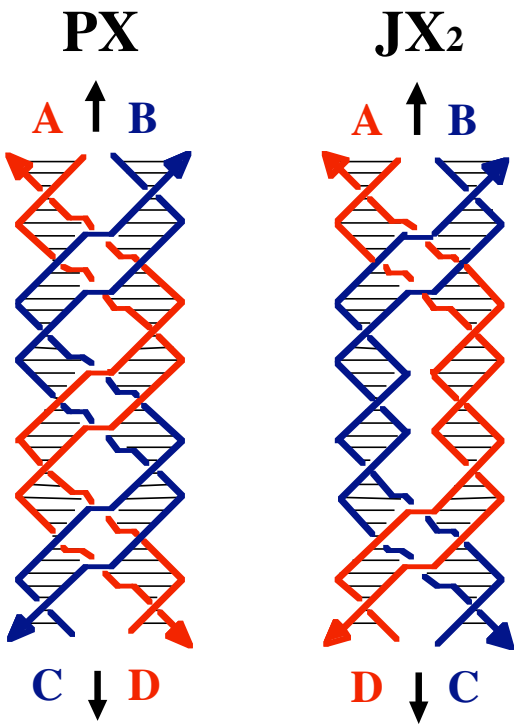
A Sequence-Dependent Device

Hao Yan

Derivation of PX DNA

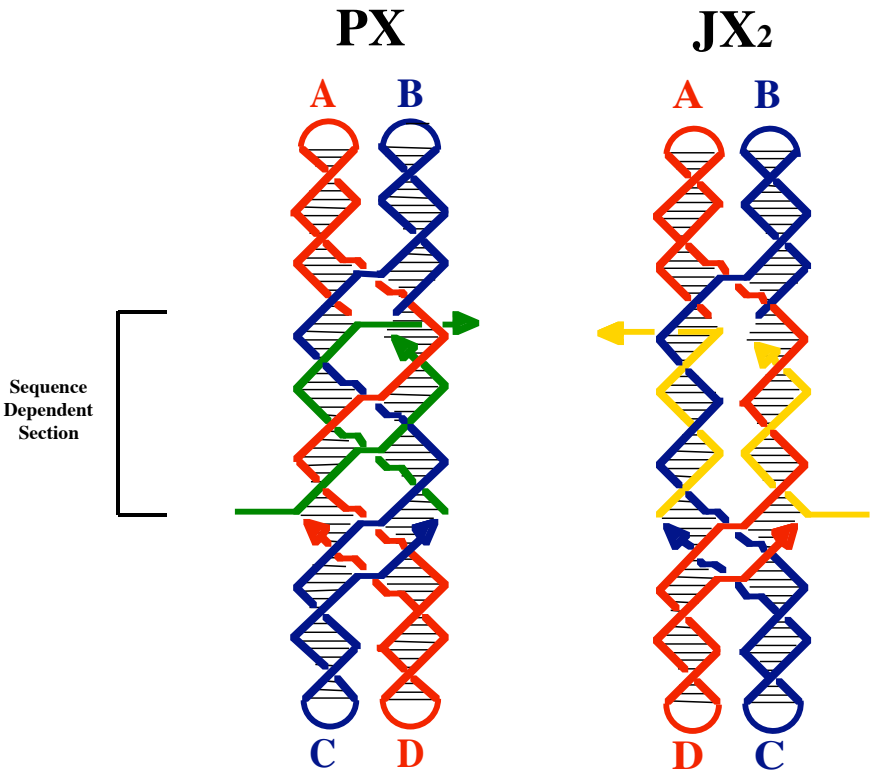


Seeman, N.C. (2001) *NanoLetters* **1**, 22-26.

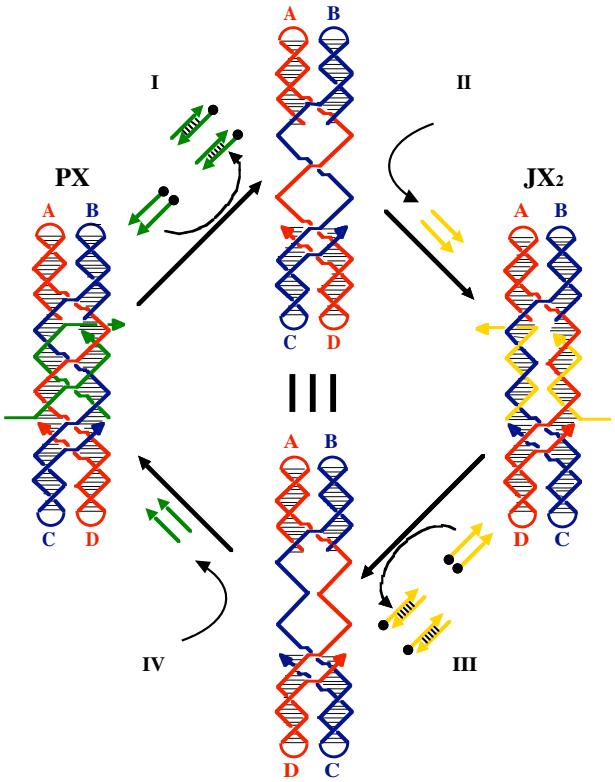


Yan, H., Zhang, X., Shen, Z. & Seeman, N.C. (2002), *Nature* **415**, 62-65..

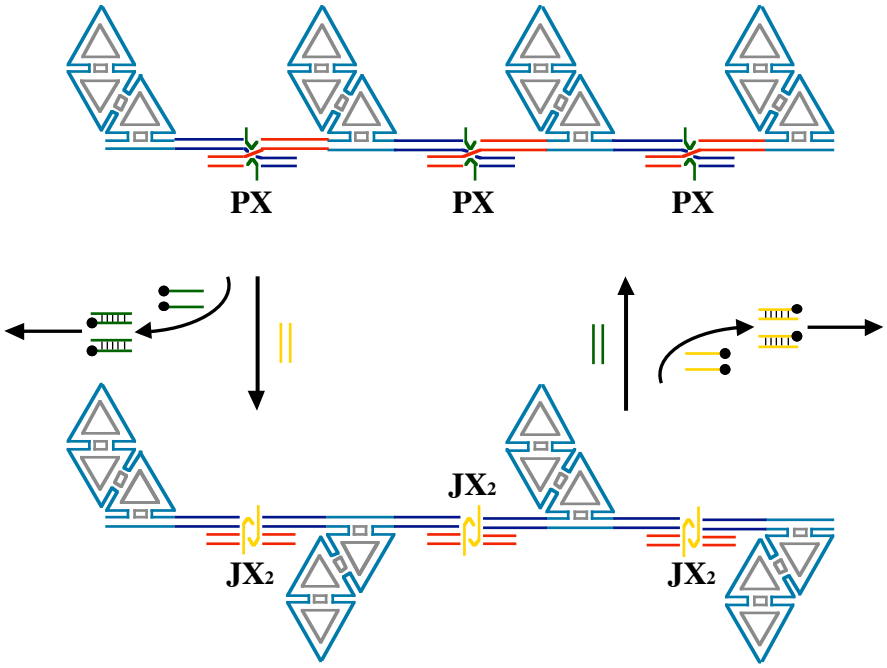
Switchable Versions of PX and JX2



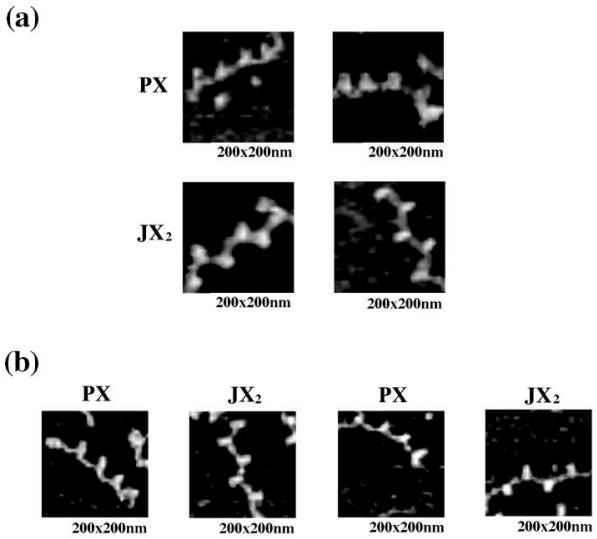
Machine Cycle of the PX-JX$_2$ Device



System to Test the PX-JX$_2$ Device



AFM Evidence for Operation of the PX-JX$_2$ Device

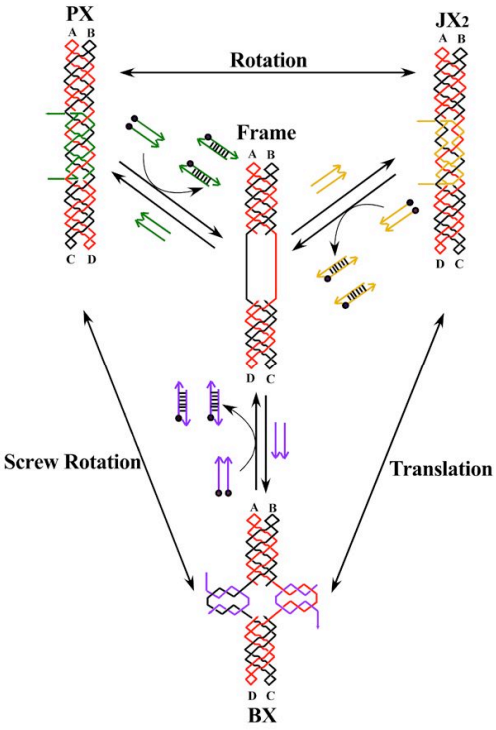


Yan, H., Zhang, X., Shen, Z. & Seeman, N.C. (2002), *Nature* **415**, 62-65.

A Robust 3-State Sequence-Dependent Nanomechanical Device

Banani Chakraborty

Three States of a Nanomechanical Device

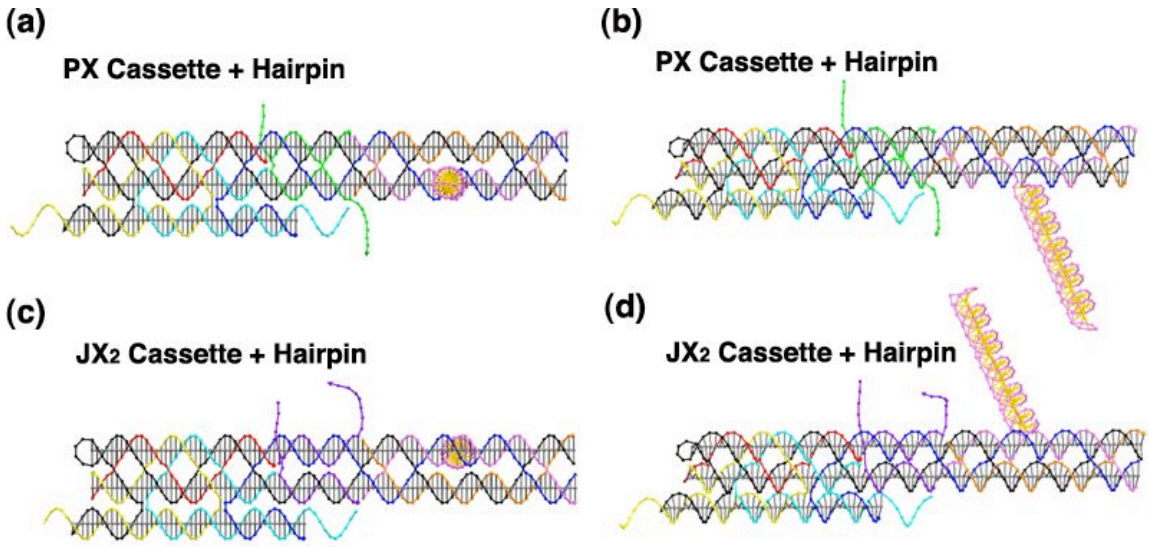


B. Chakraborty, R. Sha N.C. Seeman, (2008), *Proc. Nat. Acad. Sci. (USA)* **105**, 17245-17249 (2008).

Inserting a PX-JX_2 Device into a 2D Array

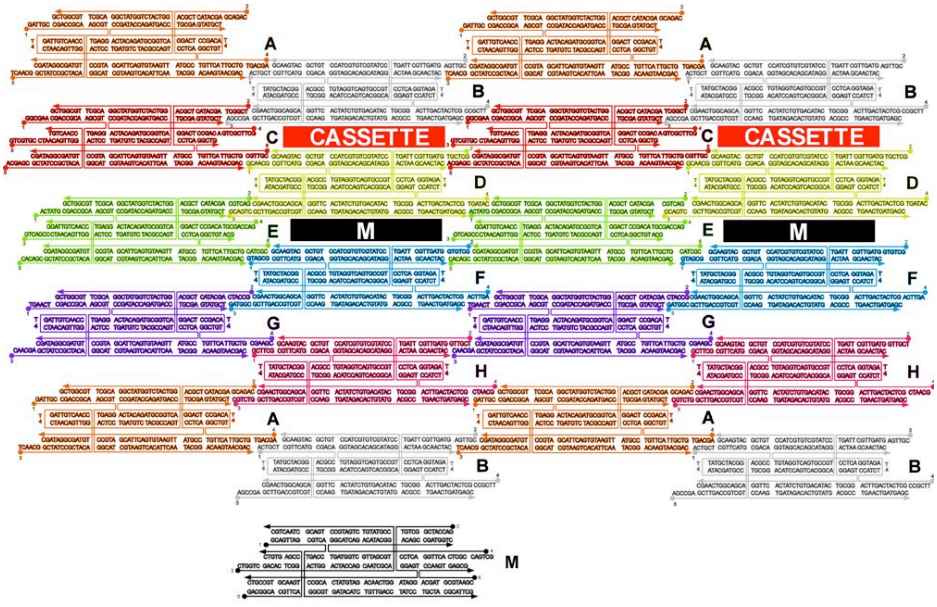
Baoquan Ding

Cassette To Be Inserted



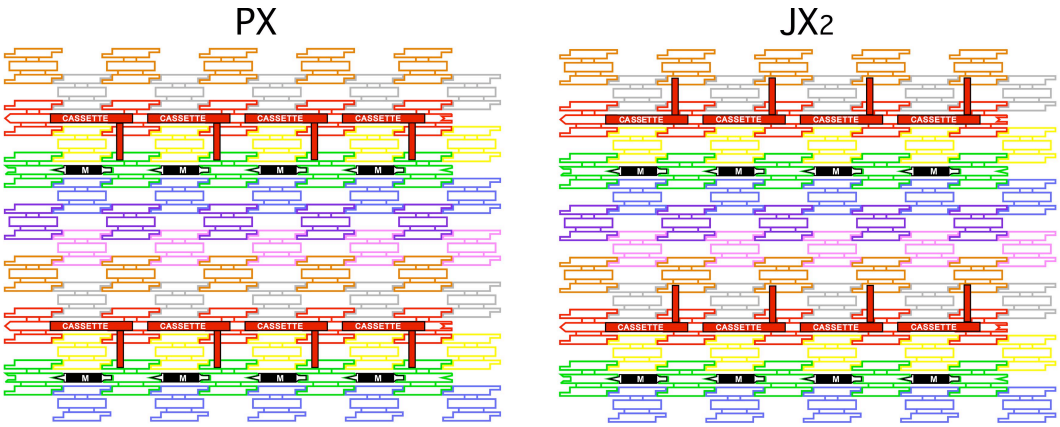
B. Ding & N.C. Seeman, *Science* **314**, 1583-1585 (2006).

Array for Insertion



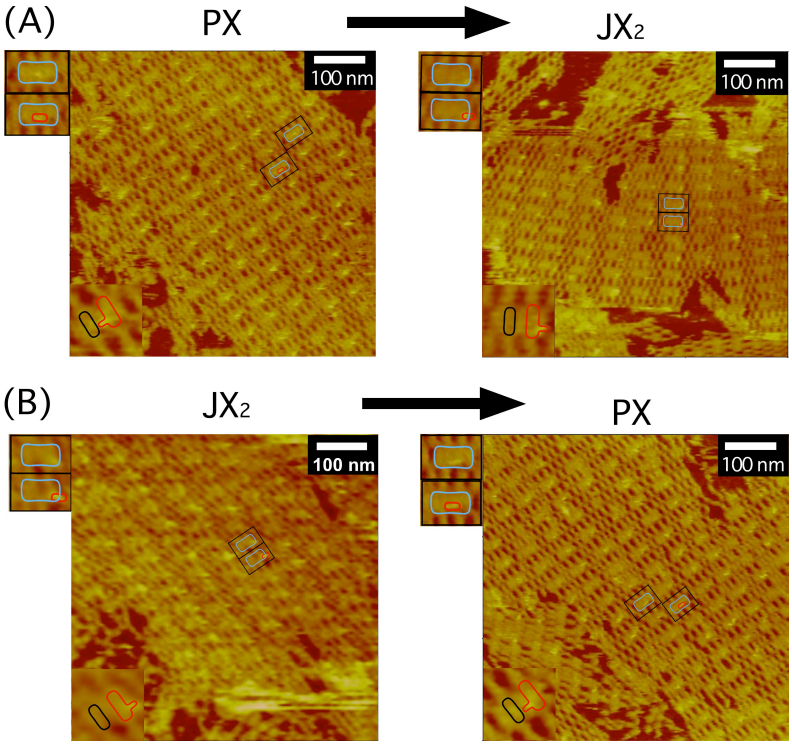
B. Ding & N.C. Seeman, *Science* **314**, 1583-1585 (2006).

Two States of the Array



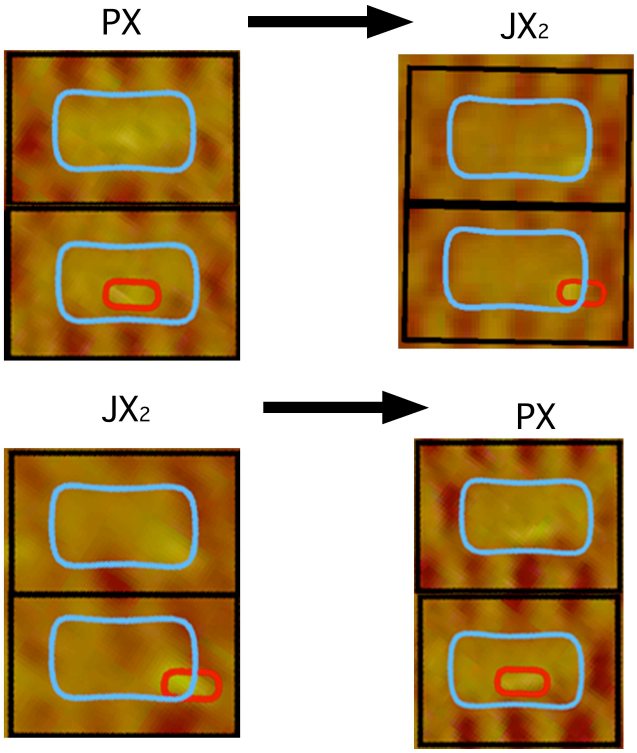
B. Ding & N.C. Seeman, *Science* **314**, 1583-1585 (2006).

Transitions in the Array



B. Ding & N.C. Seeman, *Science* **314**, 1583-1585 (2006).

Transitions in the Array (Zoom)

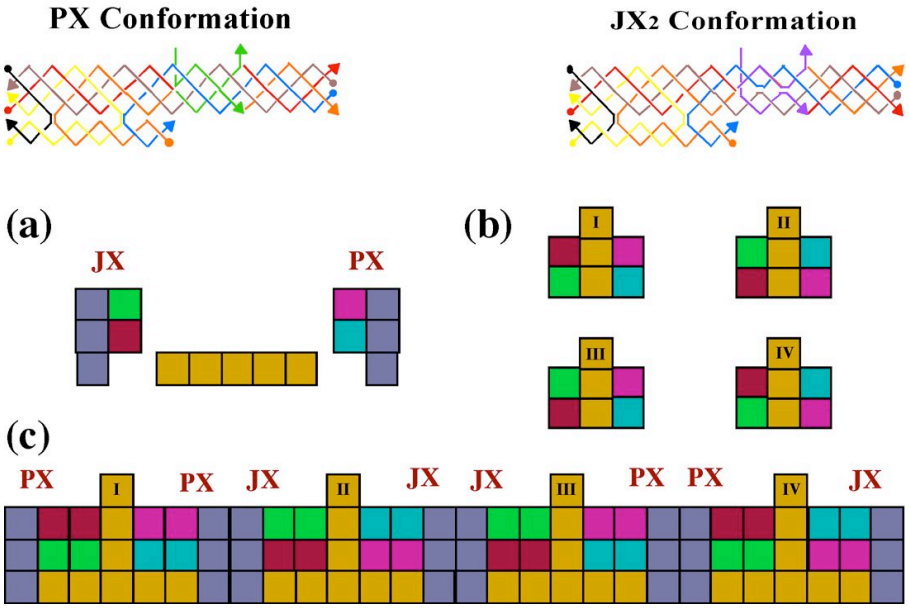


B. Ding & N.C. Seeman, *Science* **314**, 1583-1585 (2006).

Pairs of Inserted PX-JX_2 Devices Used to Program a Pattern

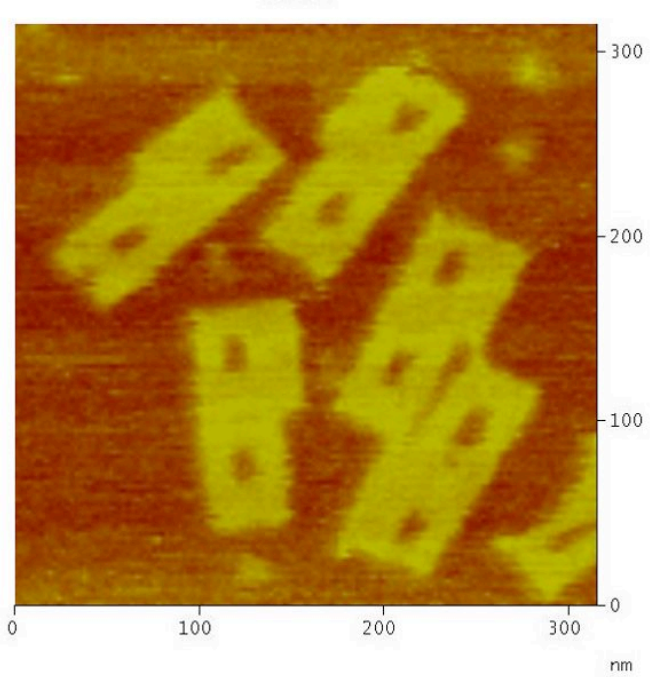
Hongzhou Gu

Programming an Array for Assembly



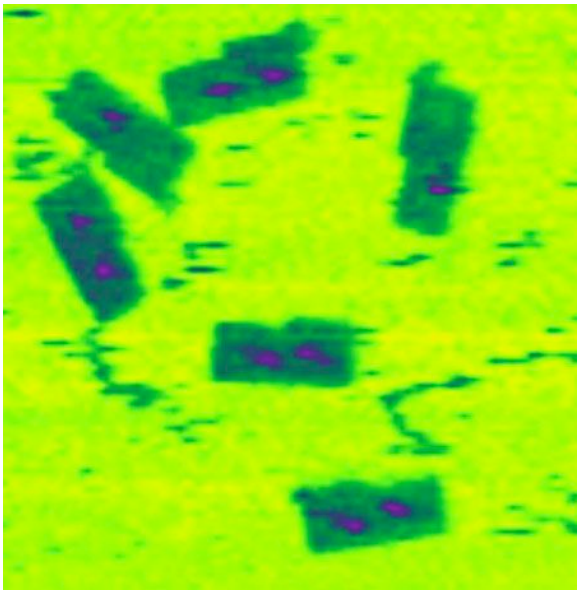
A. Carbone & N.C. Seeman, *Proc. Nat. Acad. Sci. (USA)* **99** 12577-12582 (2002).

AFM Image of Blank Origami Arrays for Insertion



H. Gu, J. Chao, S-J. Xiao & N.C. Seeman, *Nature Nanotech.*, in press, (2009).

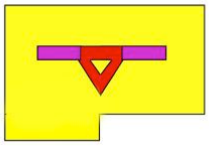
AFM Image of Origami Arrays with Inserted Cassettes



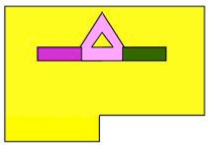
H. Gu, J. Chao, S-J. Xiao & N.C. Seeman, *Nature Nanotech*., in press, (2009).

Schematics of Programmed Patterns Made By Capturing Different Molecules

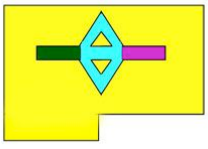
JX-JX



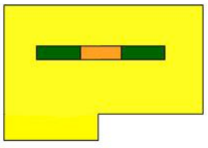
JX-PX



PX-JX

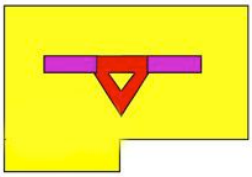


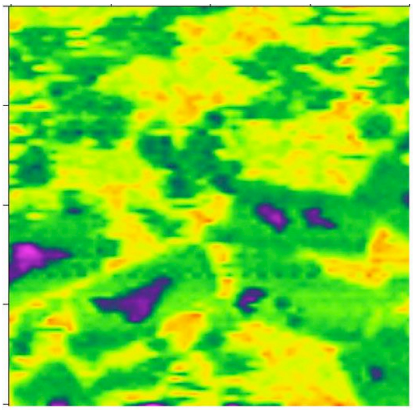
PX-PX



H. Gu, J. Chao, S-J. Xiao & N.C. Seeman, *Nature Nanotech*., in press, (2009).

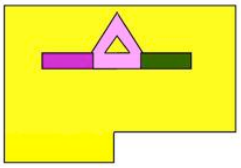
AFM Images of JX-JX Patterns

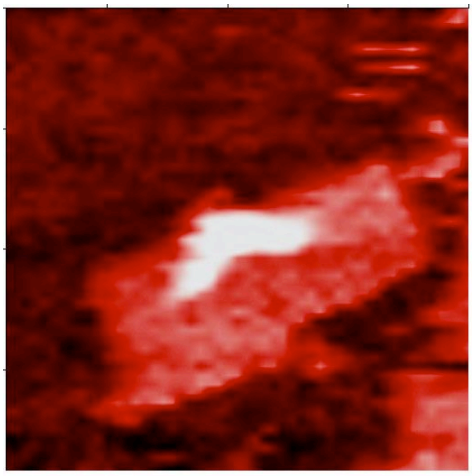




H. Gu, J. Chao, S-J. Xiao & N.C. Seeman, *Nature Nanotech*., in press, (2009).

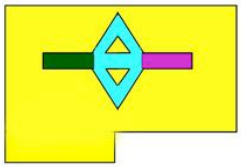
AFM Images of JX-PX Patterns

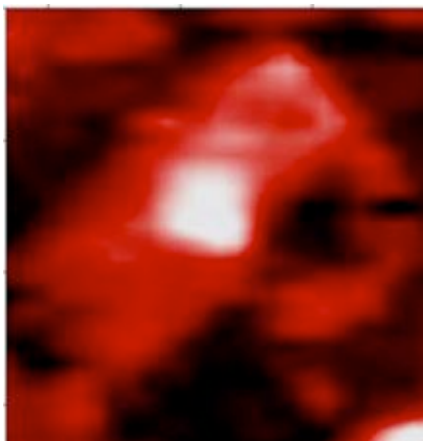




H. Gu, J. Chao, S-J. Xiao & N.C. Seeman, *Nature Nanotech*., in press, (2009).

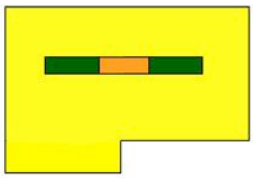
AFM Images of PX-JX Patterns

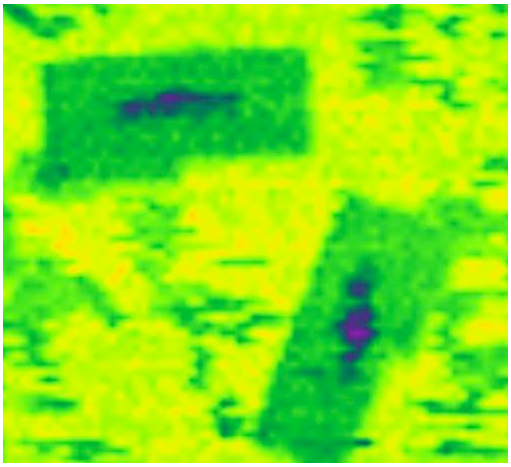




H. Gu, J. Chao, S-J. Xiao & N.C. Seeman, *Nature Nanotech*., in press, (2009).

AFM Images of PX-PX Patterns



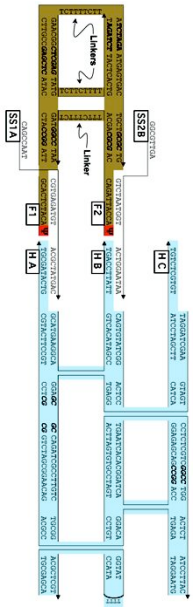


H. Gu, J. Chao, S-J. Xiao & N.C. Seeman, *Nature Nanotech*., in press, (2009).

DNA Walking Biped

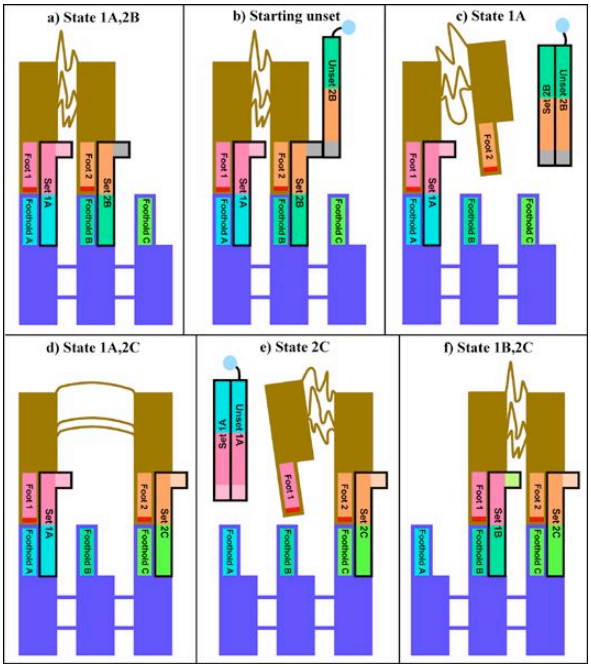
Bill Sherman

Schematic of the Device and Sidewalk



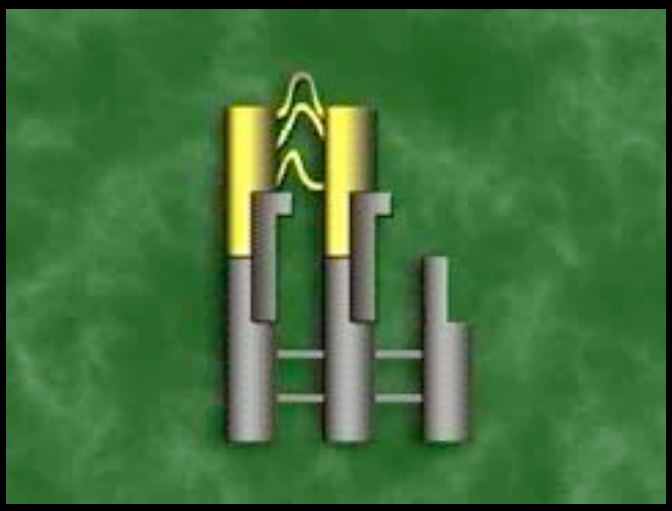
Sherman, W.B. & Seeman, N.C. (2004), *NanoLett*. **4**, 1203-1207.

The Steps in a Walk



Sherman, W.B. & Seeman, N.C. (2004), *NanoLett*. **4**, 1203-1207.

Animation of the Biped Walker

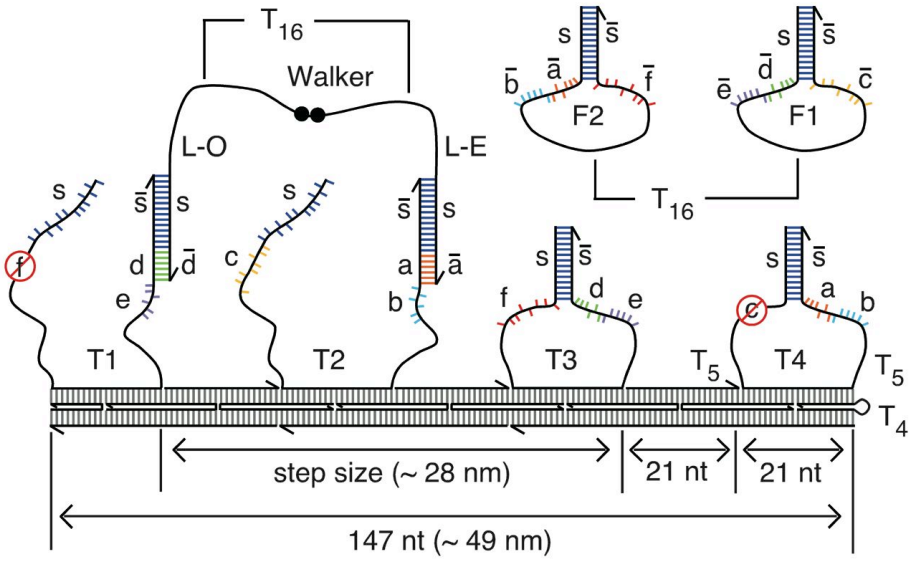


Courtesy of Ann Marie Cunningham and Donna Vaughn of ScienCentral News

Autonomous DNA Walking Biped

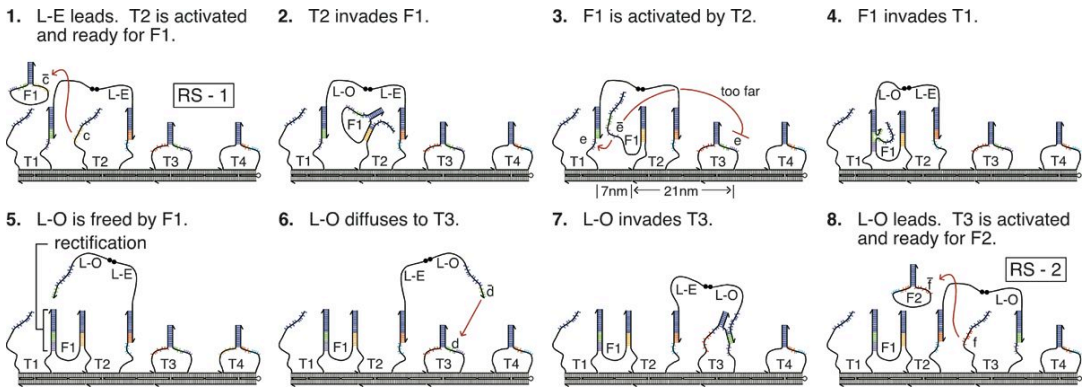
Tosan Omabegho

Autonomous Walker Design



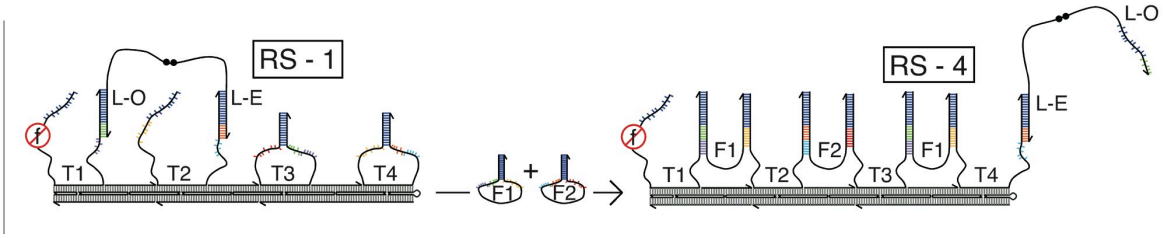
T. Omabegho, R. Sha, & N.C. Seeman**,** *Science* **324**, 67-71 (2009)**.**

Autonomous Walker Movement



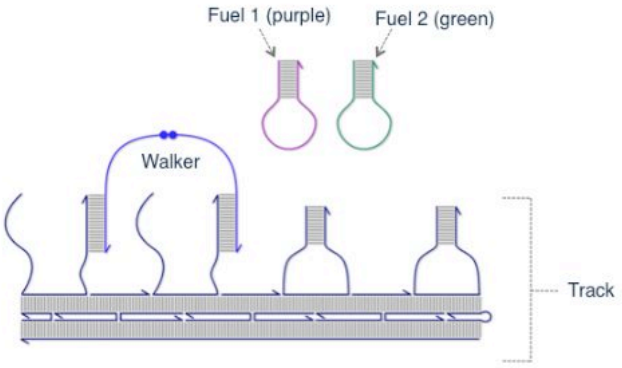
T. Omabegho, R. Sha, & N.C. Seeman**,** *Science* **324**, 67-71 (2009)**.**

Autonomous Walker Uses Up the Track



T. Omabegho, R. Sha, & N.C. Seeman**,** *Science* **324**, 67-71 (2009)**.**

Animation of the Autonomous Walker



T. Omabegho, R. Sha, & N.C. Seeman**,** *Science* **324**, 67-71 (2009)**.**

Summary of Results

- **Polyhedral Catenanes, Knots and Borromean Rings can be Assembled from Branched DNA by Ligation.**
- **2D Lattices with Tunable Features have been Made from Branched DNA Components.**
- **3D Crystals have been Self-Assembled and their Structures have been Determined.**
- **Heterologous Species have been Included in DNA Nanoconstructs.**
- **Nanomechanical Devices have been Assembled from Branched DNA, including a Translation Device a Clocked Walker, and an Autonomous Walker. A Machine has been Incorporated into a 2D Lattice and Used to Capture Pattern Components.**

SUPPORT

National Institute of General Medical Sciences (1982-)
Office of Naval Research (1989-2004; 2009-)
National Science Foundation (1997-)
DARPA/AFOSR (2001-2003)
Army Research Office (2005-)
W. M. Keck Foundation (2006-)
Nanoscience Technologies, Inc. (2003-2006)
Department of Energy -- NYNBIT (2006-2008)

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