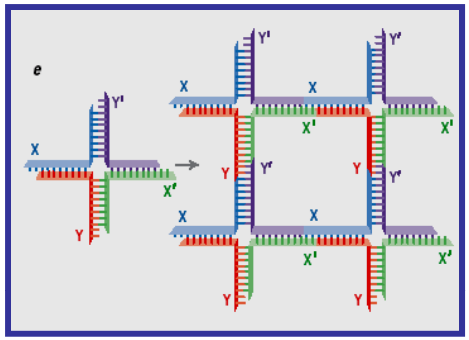
Supramolecular Chemistry with DNA: Using Synthetic Molecules to Direct DNA Assembly

Hanadi Sleiman

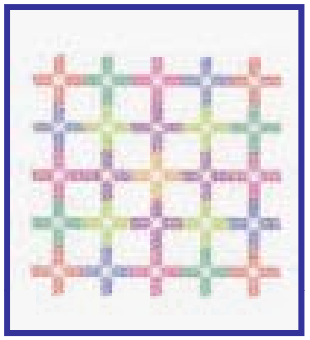
Department of Chemistry,
McGill University, Montreal, Canada

Structural DNA Nanotechnology

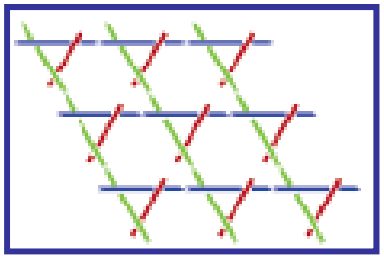
DNA Tile Assembly



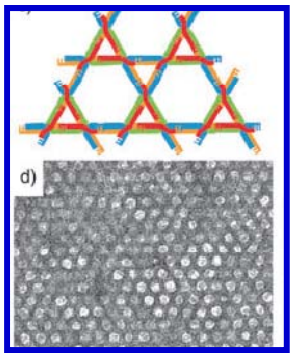
Seeman, Nature 2003, *421*, 427



Yan, et al. J. Am. Chem. Soc. 2005, 127, 140.

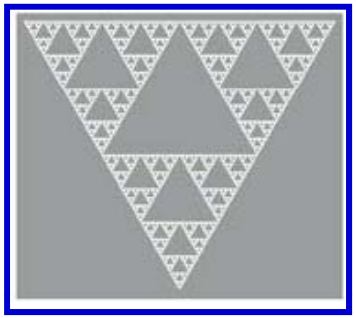


Mao, C.D. et al *J. Am. Chem. Soc.* 2004, *126*, 2324



Turberfield, Angew,. Chem. 2005, 3057

Algorithmic DNA Assembly



Winfree et al, PLoS Biol. 2, e424 (2004)

DNA Origami

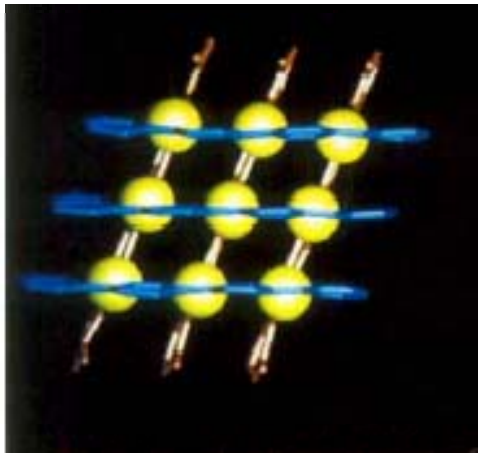
Rothemund, Nature, 2006,440, 297

DNA

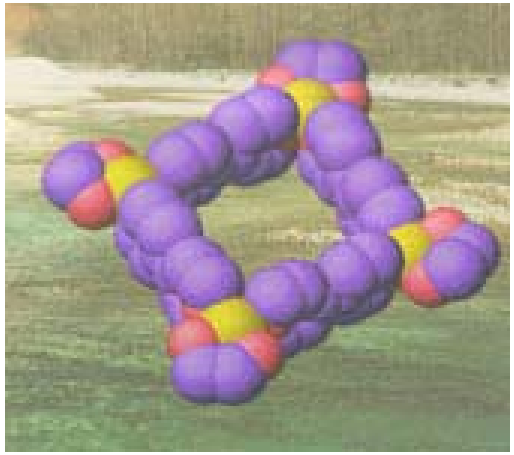
-Architectural control
-Connectivity
-Programmability

Aldaye, Sleiman, *Science*, 2008, *321*, 1795

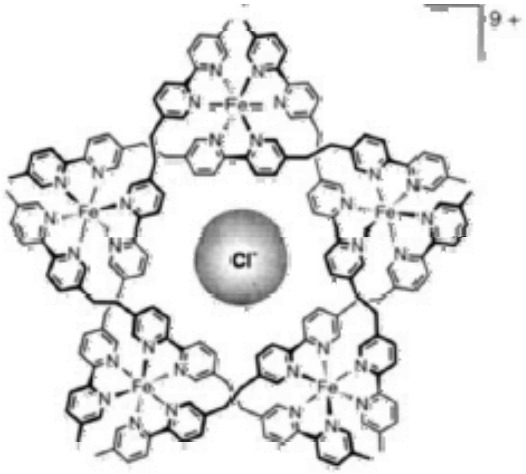
Supramolecular Chemistry: Branched Molecules with Inorganic and Organic Vertices



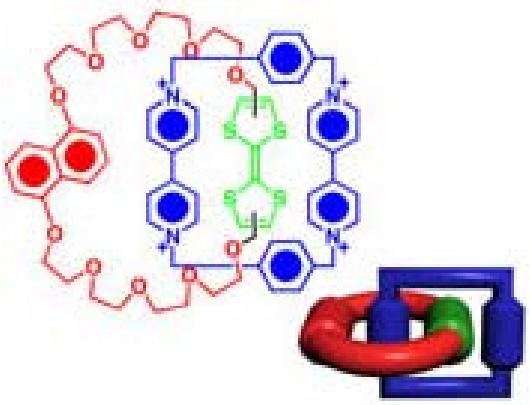
Molecular Grids (Lehn)



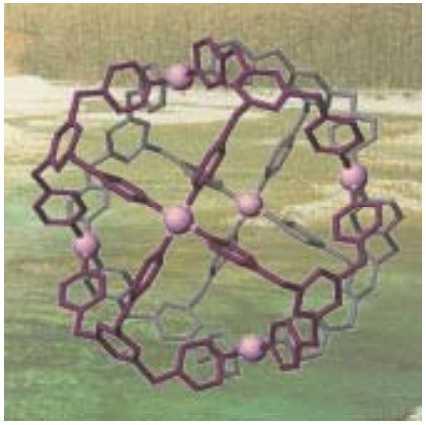
Molecular Squares (Fujita, Stang)



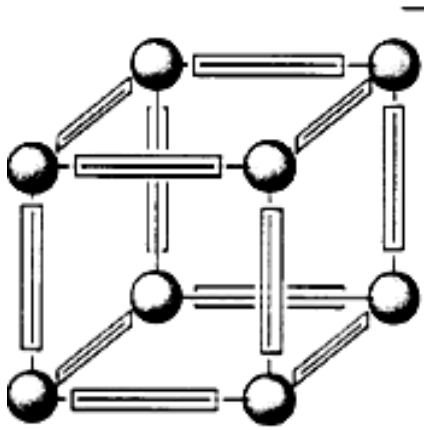
Molecular Flowers (Lehn)



Interlaced Structures (Stoddart, Sauvage, Leigh)

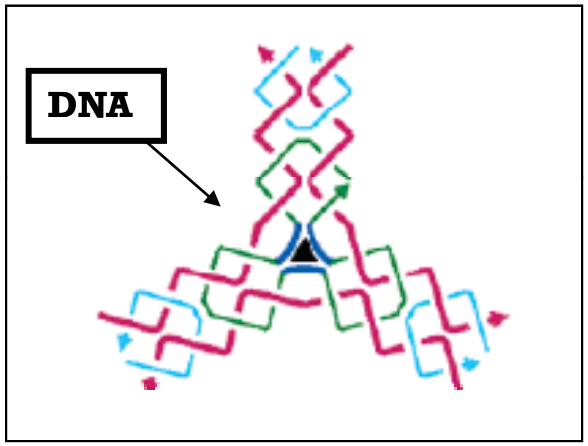


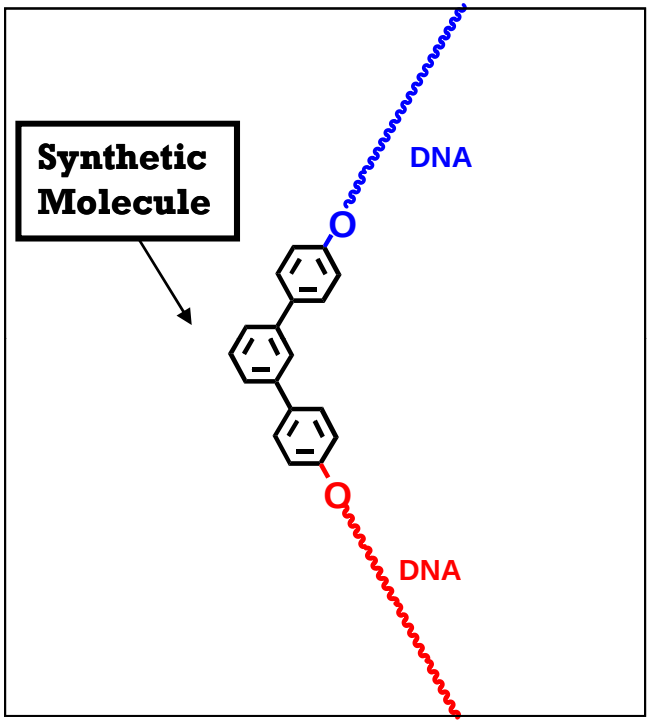
Molecular Spheres (Fujita, Rebek)



Molecular Cubes (Thomas)

Supramolecular DNA Nanotechnology: Synthetic Molecules mediate DNA self-assembly

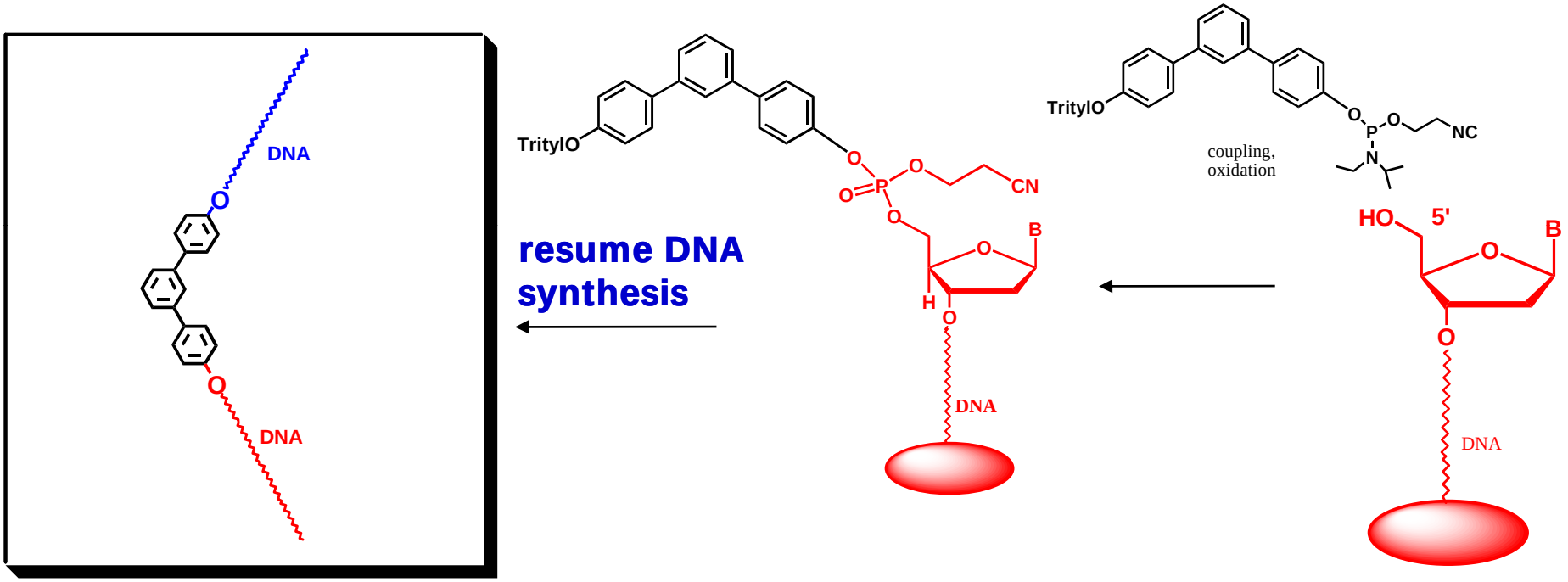




- **Structural diversity:** new motifs
- **Modular** construction
- **Functionality:** luminescence, conduction, magnetic, catalytic
- **Dynamic** structures
- **Error Correction**

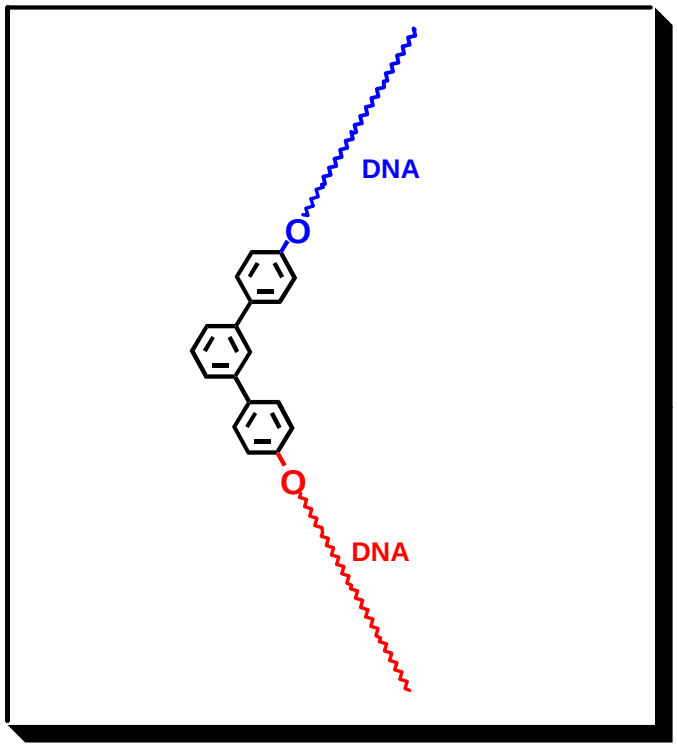
Aldaye, Palmer, Sleiman, *Science*, 2008, *321*, 1795

Branched DNA Complexes with Organic / Inorganic Vertices



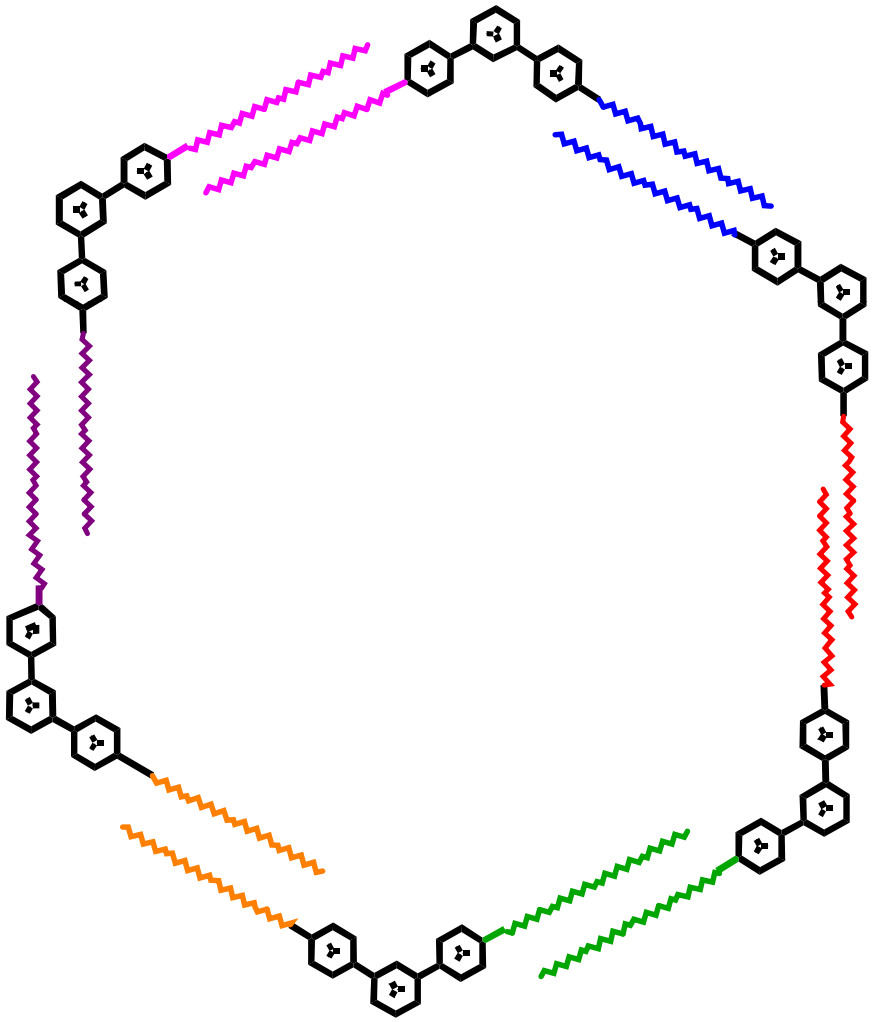
F. Aldaye, H. Sleiman,
Angew. Chem. Int. Ed., 2006, 45, 2204

Synthetic Molecules can introduce architectural control



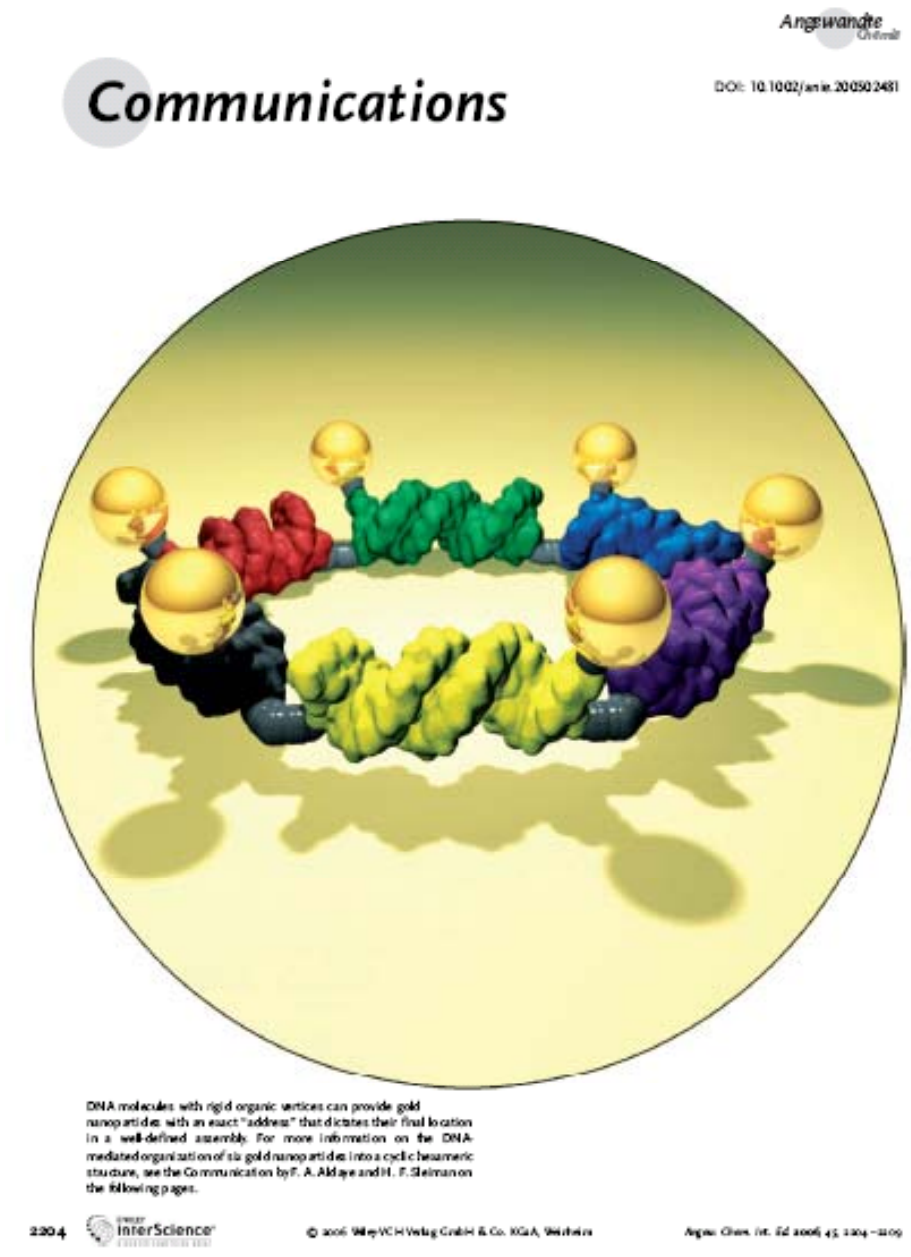
Rigid organic vertex

Self-assembly of DNA hexagon



F. Aldaye, H. Sleiman,
Angew. Chem. Int. Ed., 2006, 45, 2204

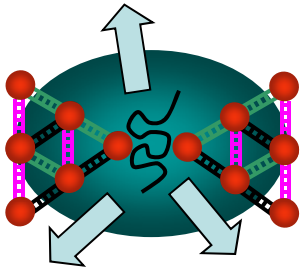
Patterning Components One by One with DNA



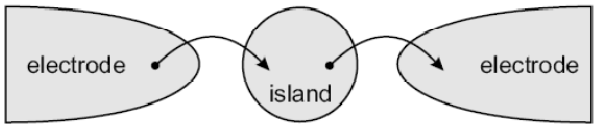
F. Aldaye, H. Sleiman,
Angew. Chem. Int. Ed., 2006,
45, 2204 ("Hot Paper")

Discrete 2D-Particle Assemblies

- Optical antennae, focus field in specific locations (*nano-optical circuitry*)
- Engineered SERS substrates

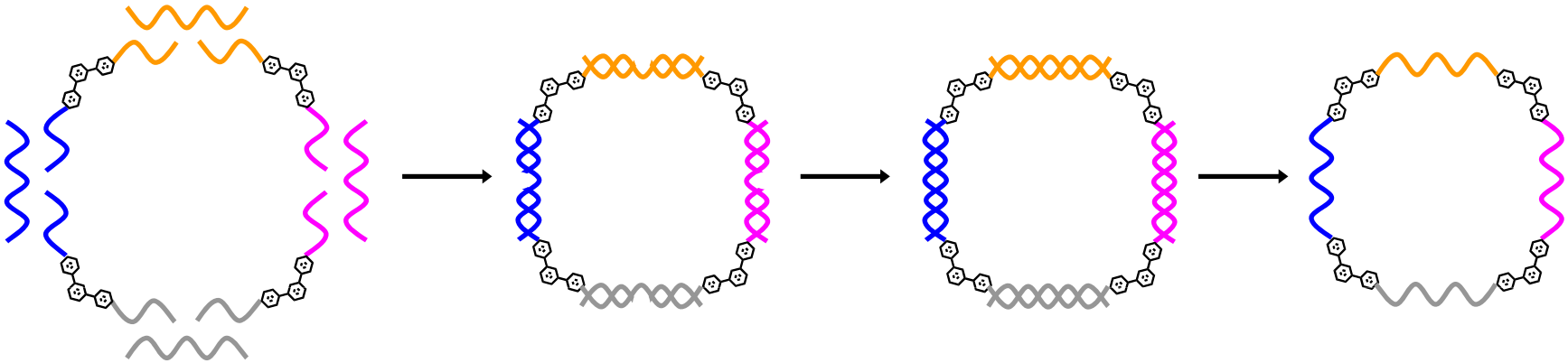


- Single Electron transport Models (*single electronics*)



- Modular *Biodetection* Tools

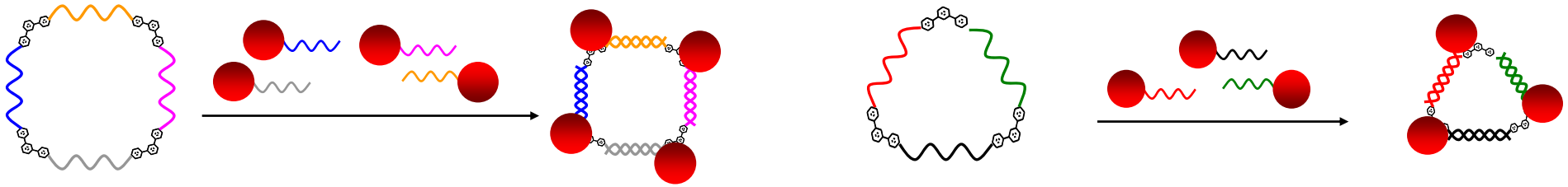
Synthesis of Dynamic DNA Templates

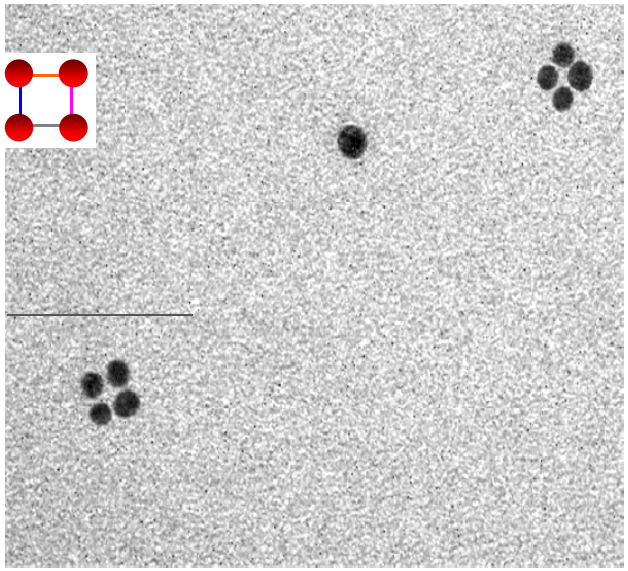


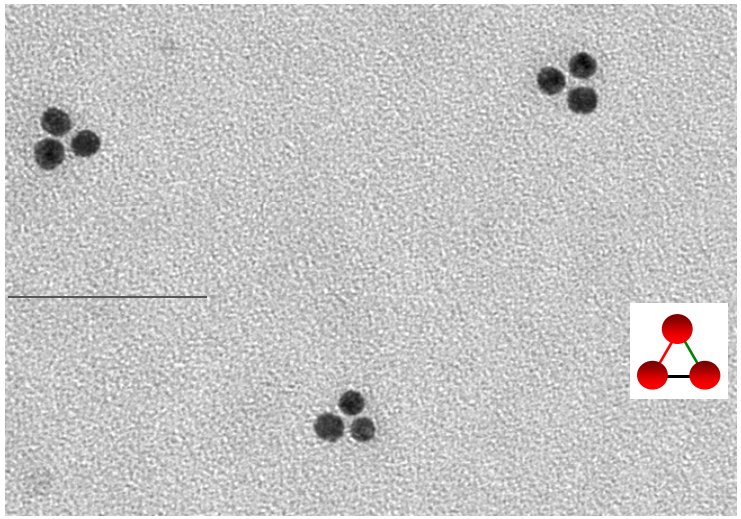
Synthesis Self-Assembly Enzymatic Ligation Denaturation

Dynamic Templates as Blueprints to Position Components

Control of Geometry



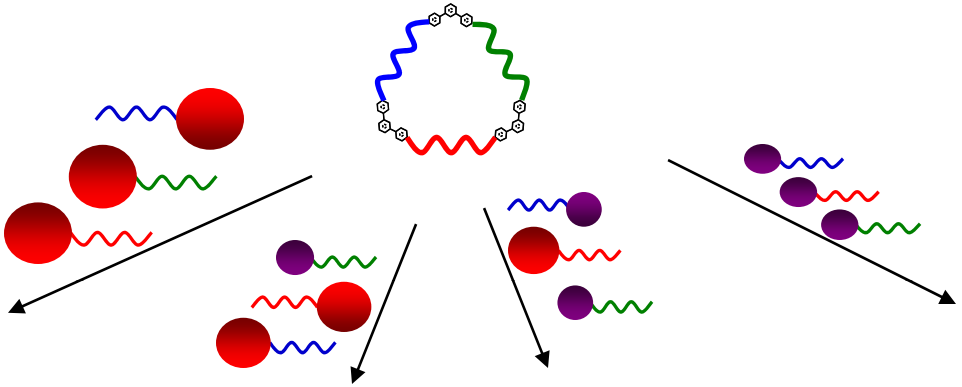


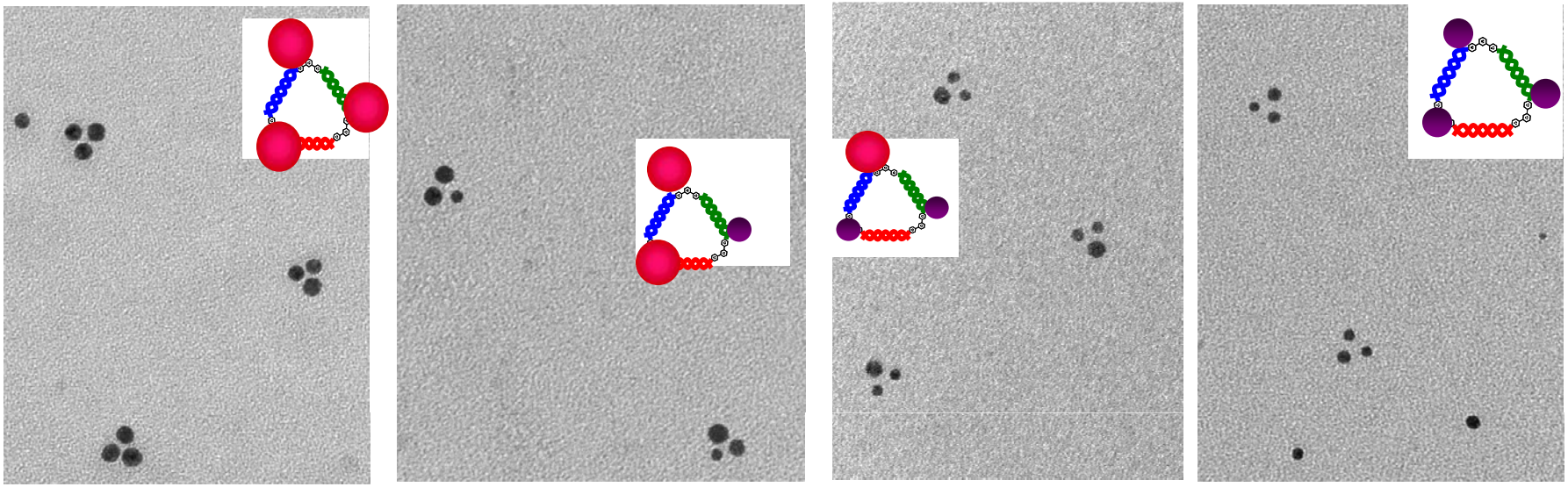


Aldaye, Sleiman, *J. Am. Chem. Soc.* 2007, *129*, 4130

Modularity

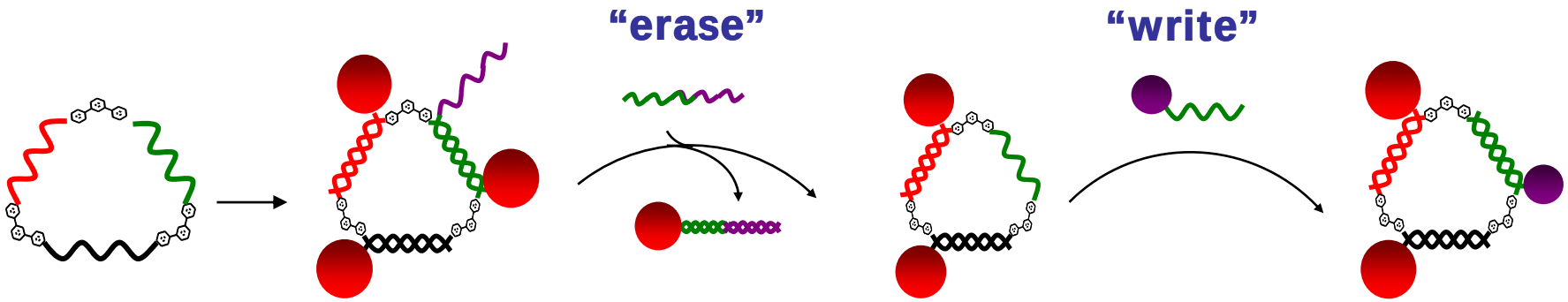
Any combination of gold nanoparticles is accessible from a single template

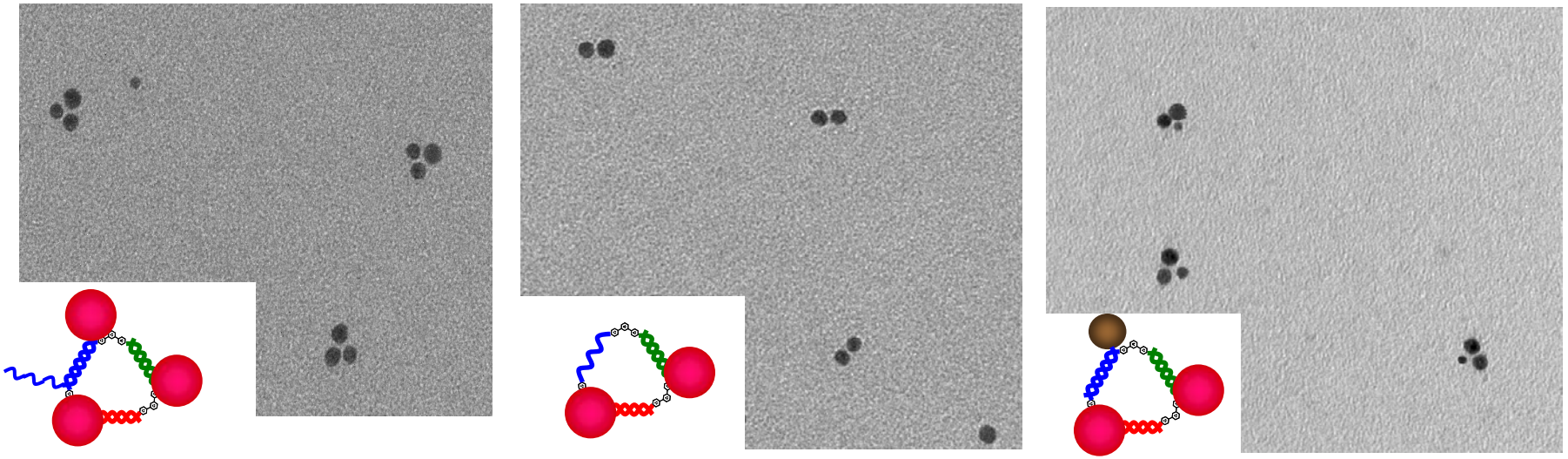




F. Aldaye

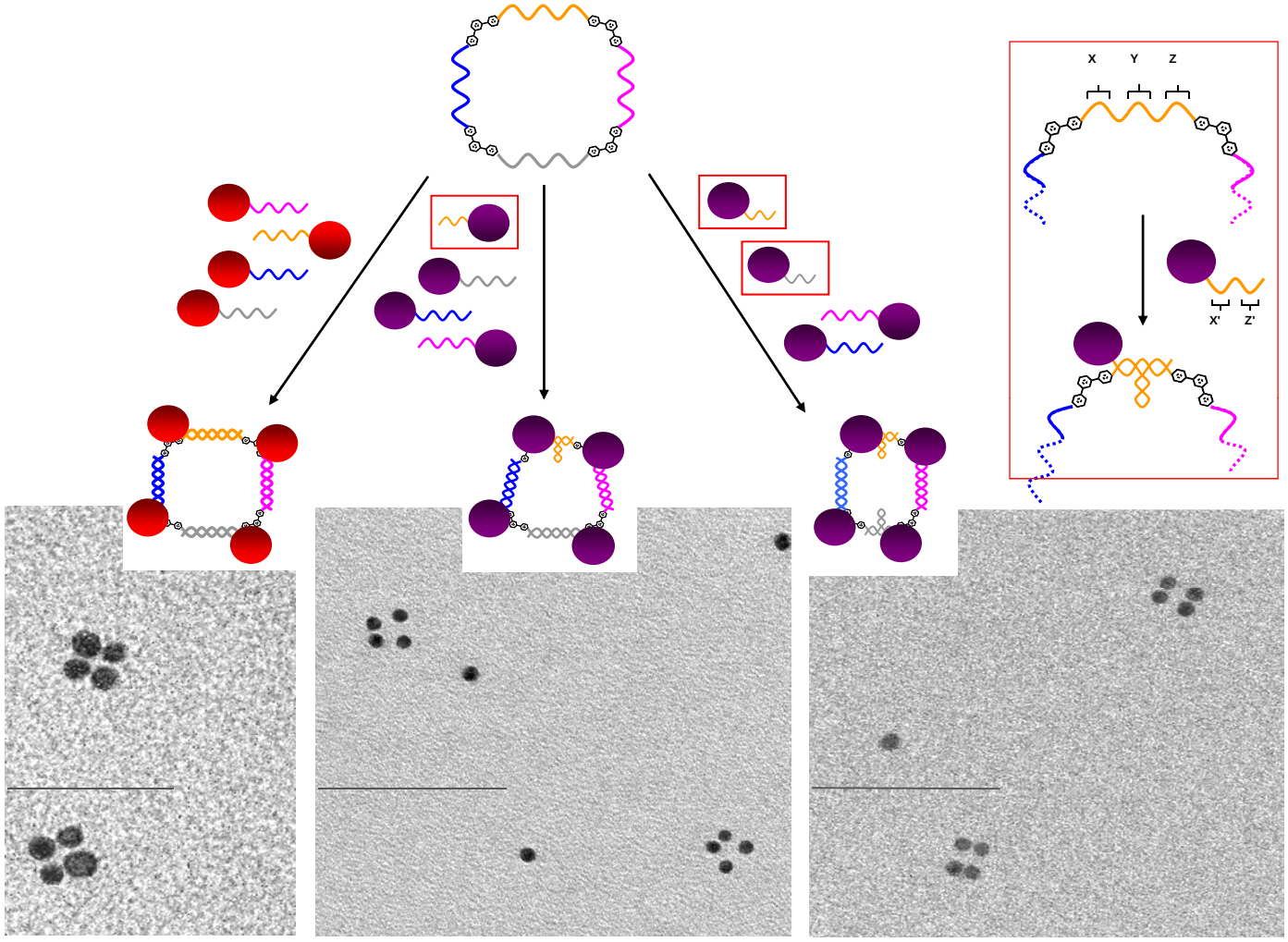
External Control of DNA Organization: WRITE/ERASE



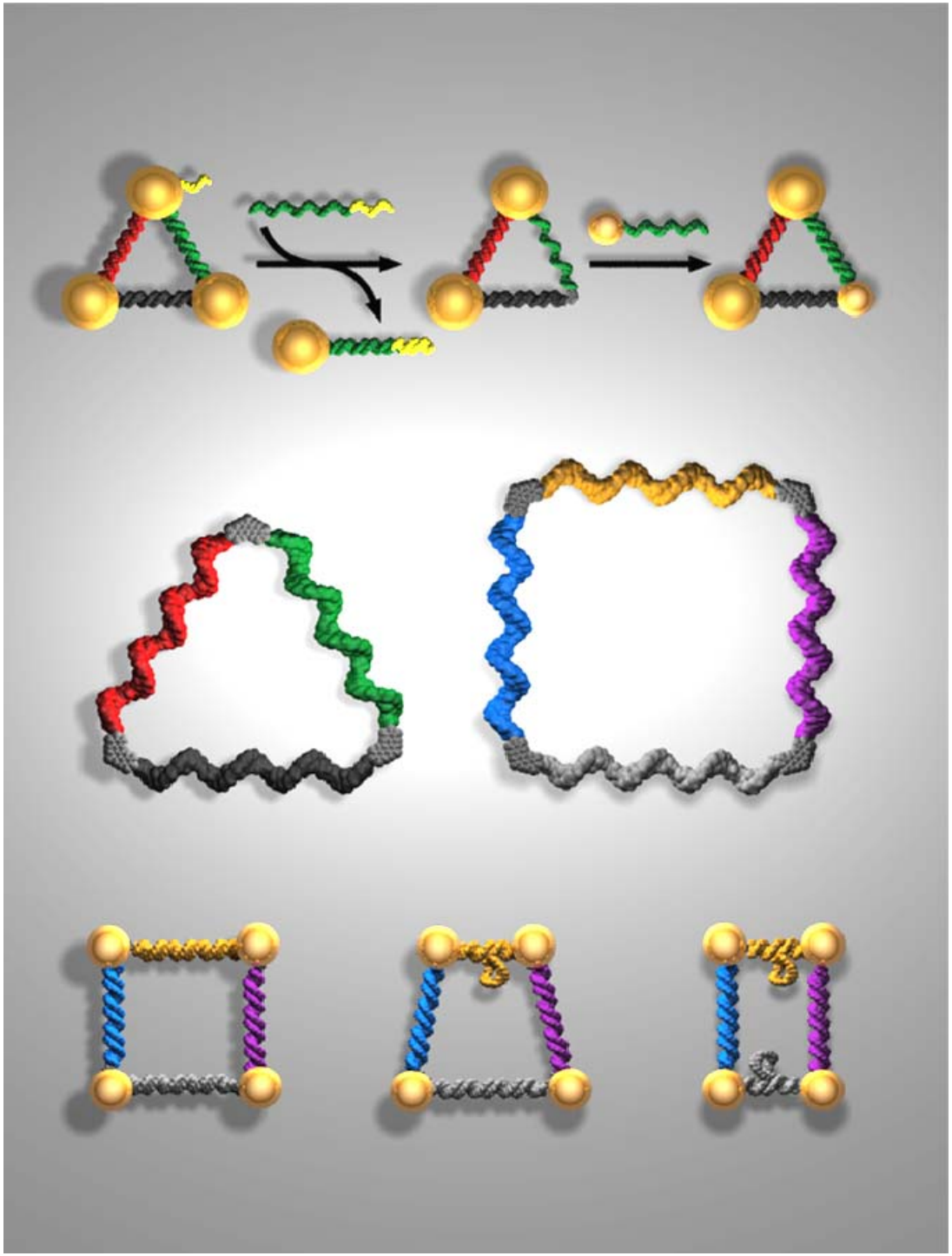


Aldaye, Sleiman, *J. Am. Chem. Soc.* 2007, *129*, 4130

Dynamic DNA Templates: STRUCTURAL SWITCHING



Aldaye, Sleiman, *J. Am. Chem. Soc.* 2007, *129*, 4130



Aldaye, Sleiman,
***J. Am. Chem. Soc.* 2007, *129*, 4130**

Nature Nanotechnology

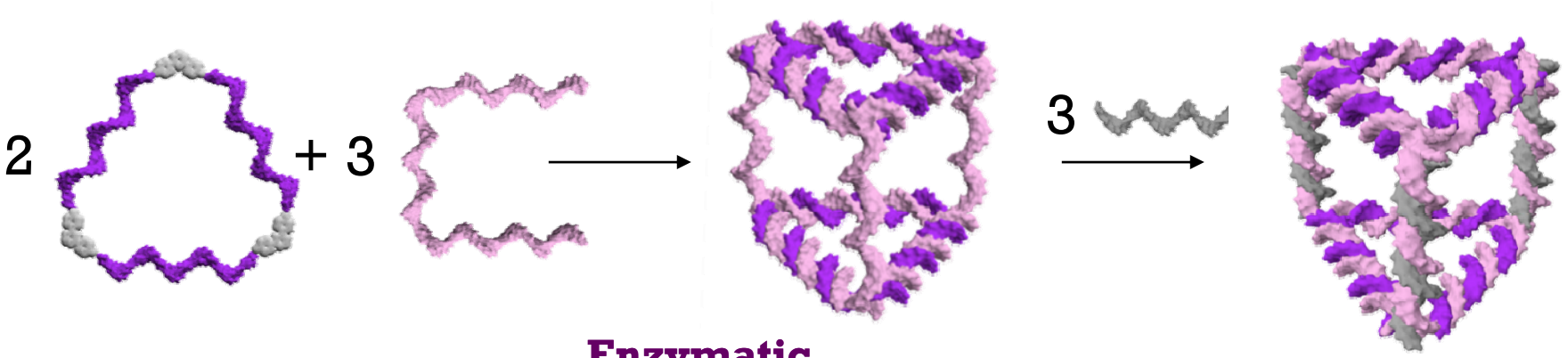
GOLD NANOPARTICLES

DNA builds bridges

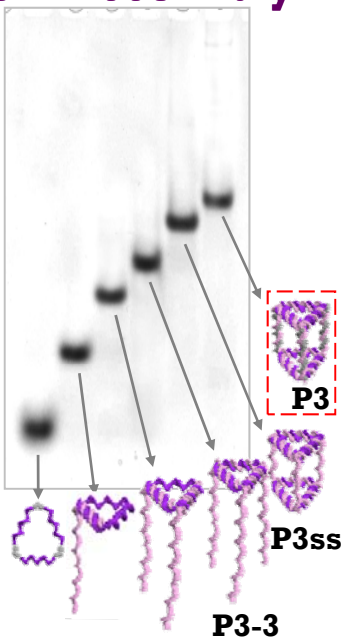
J. Am. Chem. Soc. **129,** 4130–4131 (2007)
Gold nanoparticle assemblies are of interest for a wide range of applications. Yet the arrangement of the nanoparticles, which greatly influences the electronic and optical properties of the material formed, remains challenging. Now, researchers from McGill University in Montreal, Canada have found a way to systematically organize nanoparticles using DNA templates.

Rather than using rigid double-stranded DNA to form gold nanoparticle assemblies, Faisal Aldaye and Hanadi Sleiman have formed triangular and square templates from single-stranded DNA. The templates are mixed with complementary DNA strands that are linked to nanoparticles at one end, which produces well-defined assemblies. Different-sized gold particles (5 and 15 nm) could be assembled in specific positions on a single template.

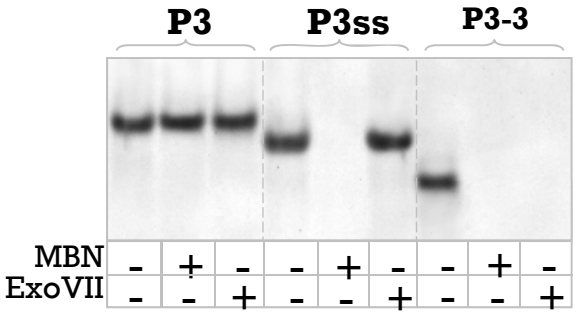
Three-Dimensional DNA Nanocapsules



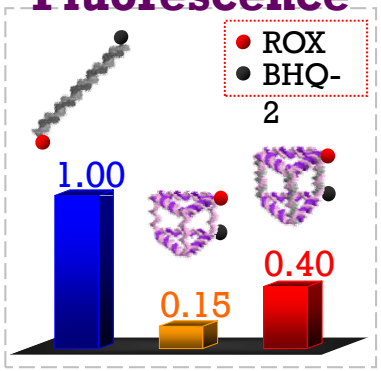
Self-Assembly



Enzymatic

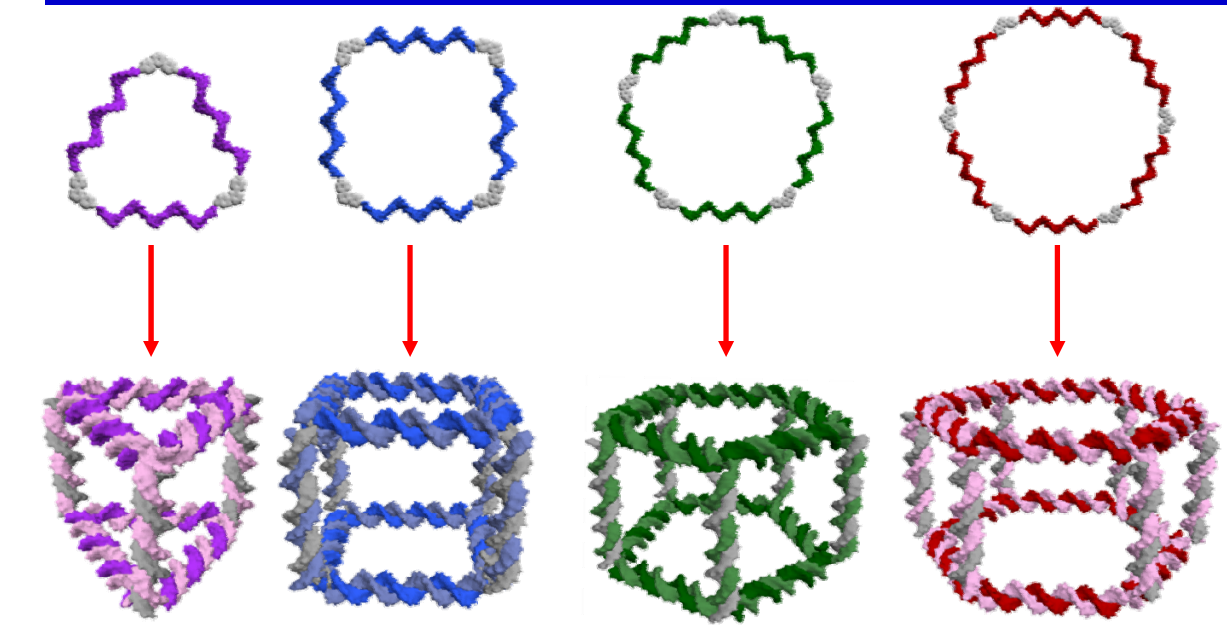


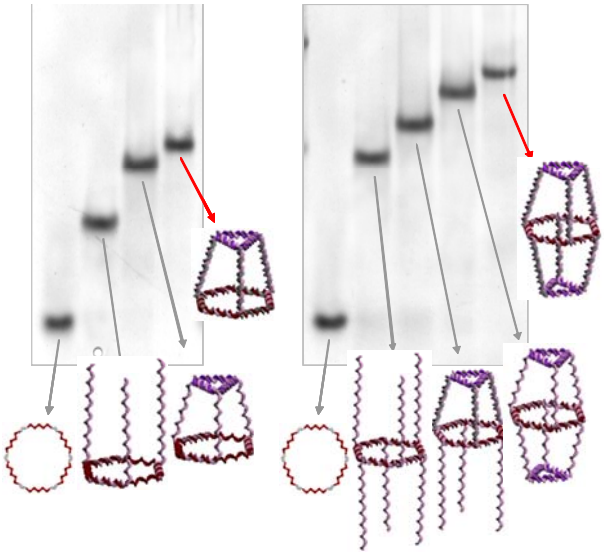
Fluorescence

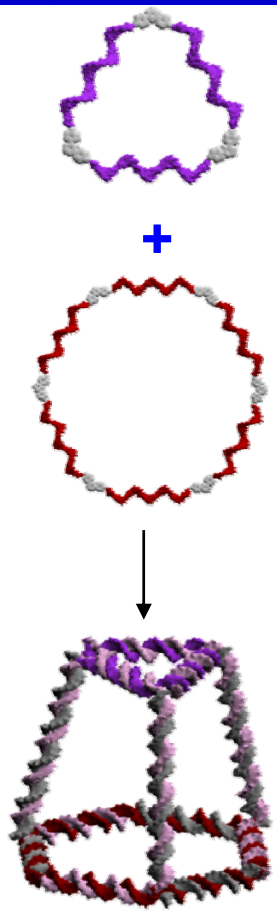


Aldaye, Sleiman, J. Am. Chem. Soc. 2007, 129, 13376

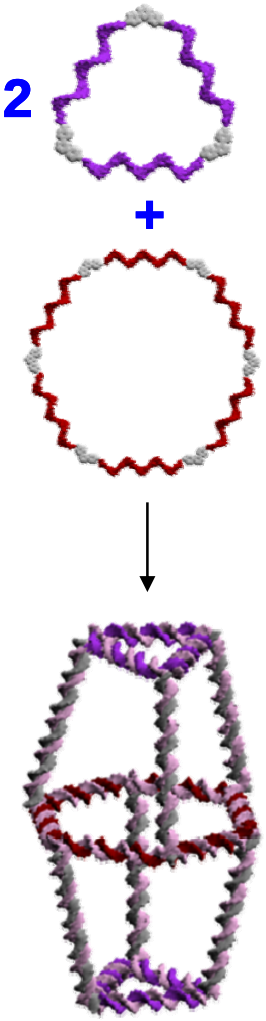
Diversity





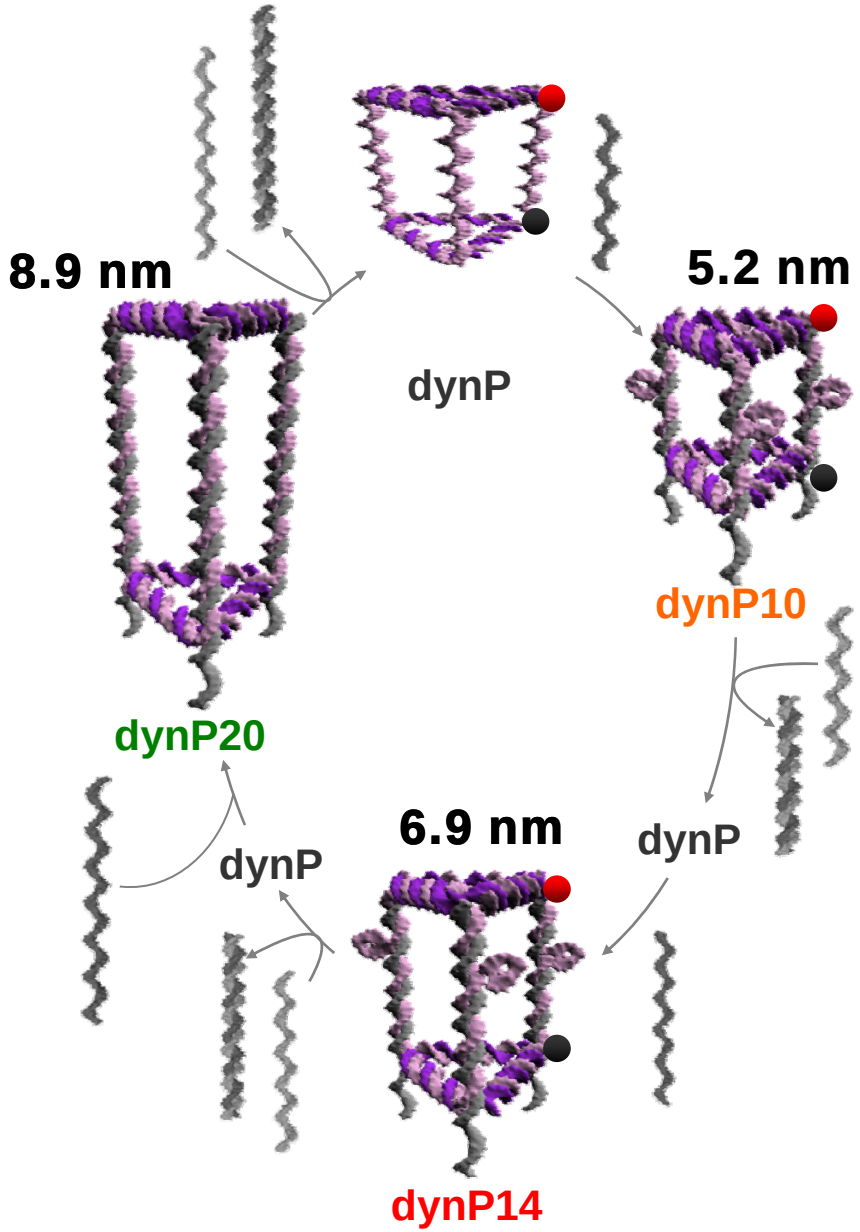


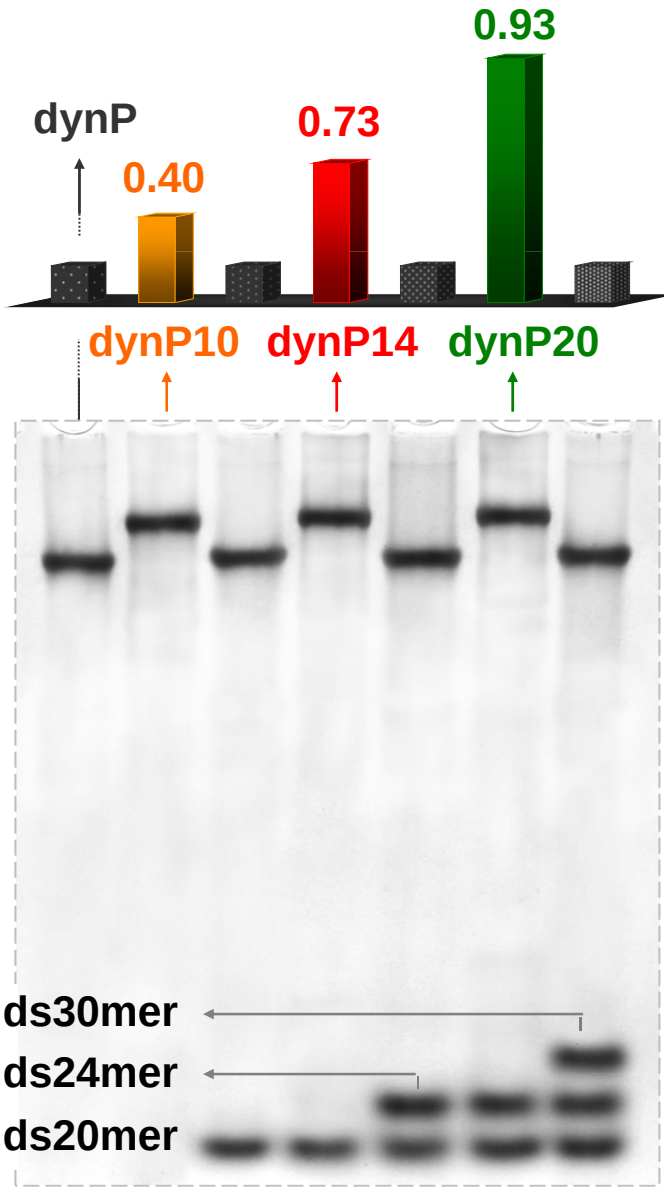
Heteroprism



Biprism

Structural Switching in Real-Time with Added Agents





Modular Access to Structurally Switchable 3D Discrete DNA Assemblies

***Nature* 2007, *450*, 323**

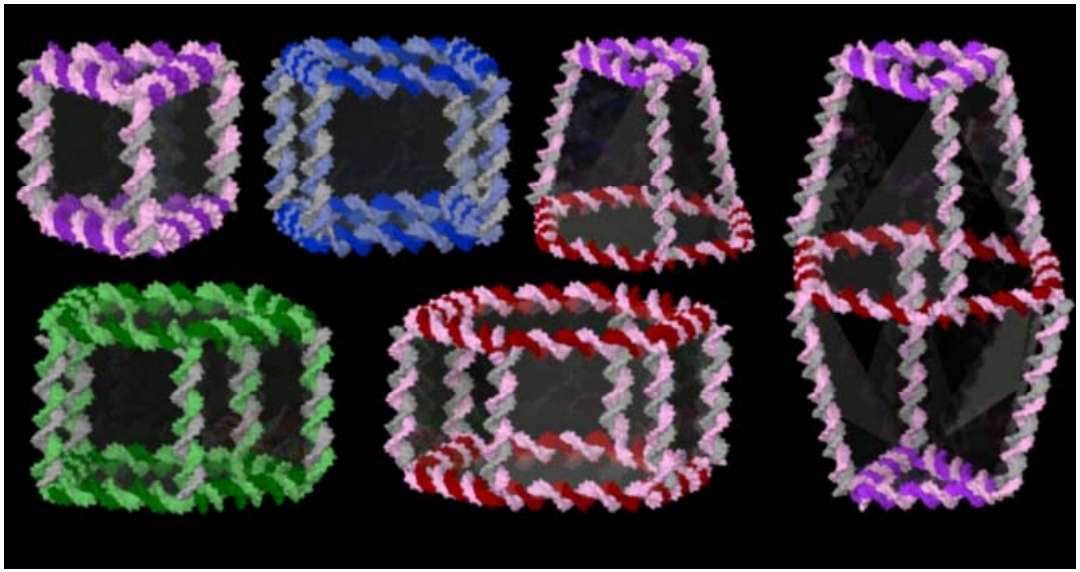
NANOCHEMISTRY

Gene boxes

Faisal Aldaye and Hanadi Sleiman of McGill University in Montreal, Canada, have now developed a versatile way to make various DNA polyhedral nanostructures at a stroke.

***Nature Materials* 2008, *7*, 102**

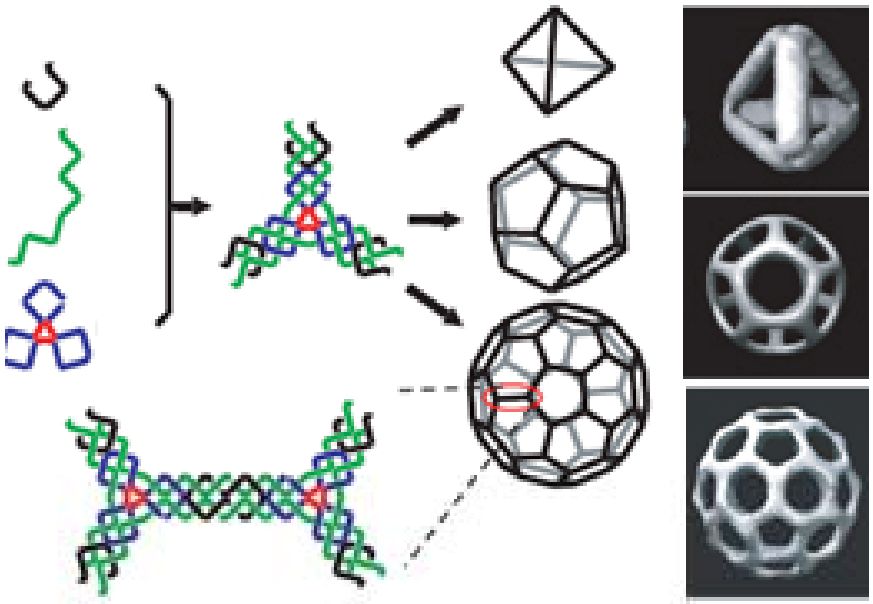
the symposium. For Hanadi Sleiman (McGill University), DNA is a structural molecule — a building block that, together with rigid organic molecules at the vertices, can be used to make 3D polyhedral cages



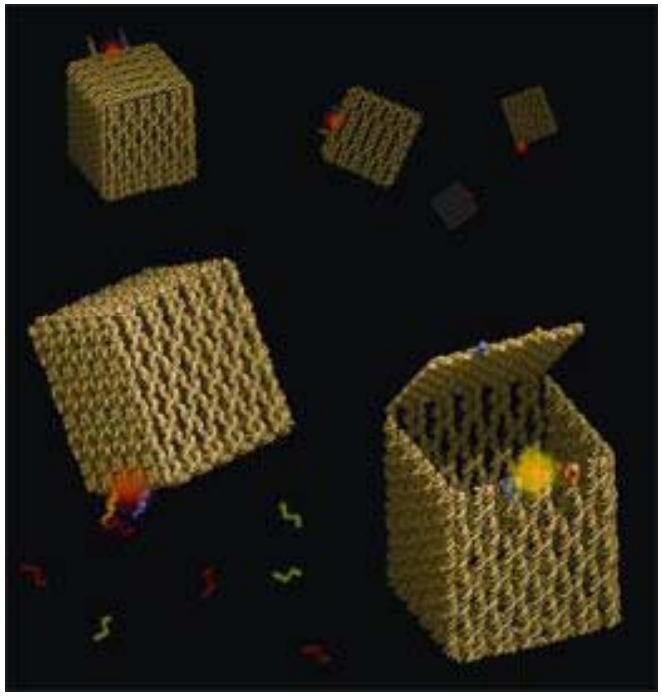
Aldaye, Sleiman,
J. Am. Chem. Soc. 2007, 129, 13376

***ACS NANO* 2008, *2*, 4.**

by Sleiman from McGill University.[12] These cage-like structures used internal loops in the vertices in the polyhedral structures to create a system where multiple cage geometries and cage size could readily be switched, as demon-

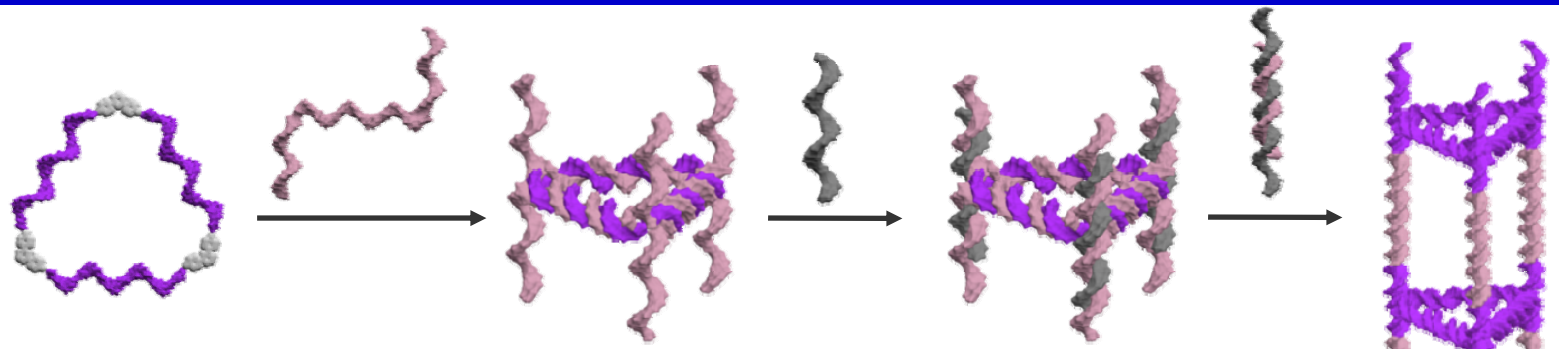


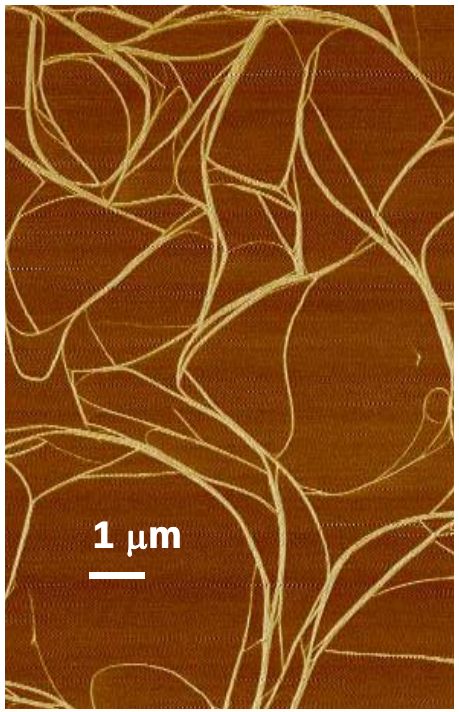
Y. He, *et al, Nature* 452, 198-201 (2008)

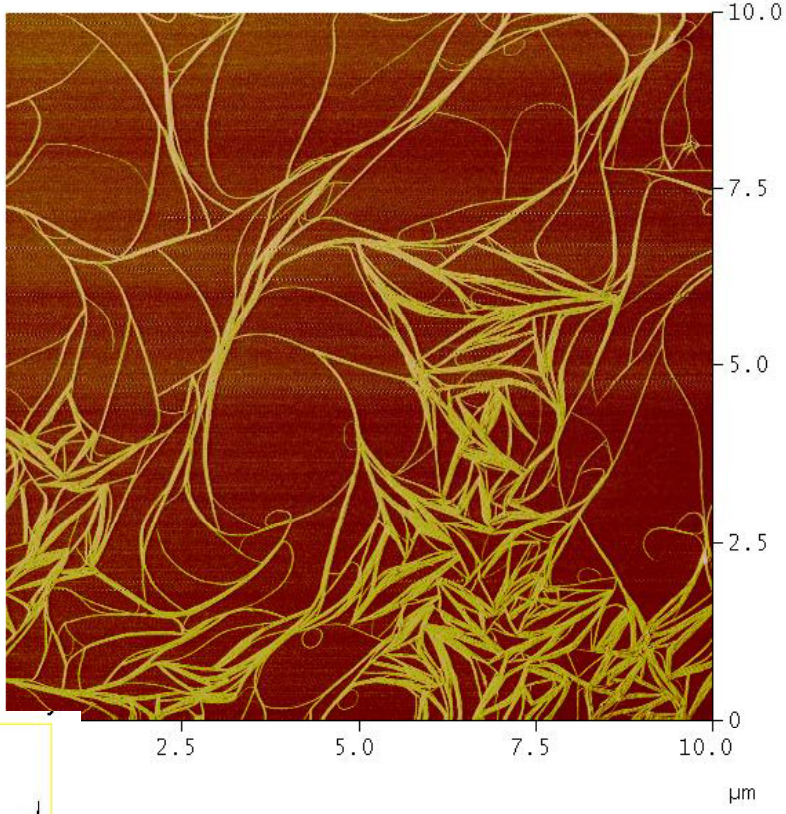


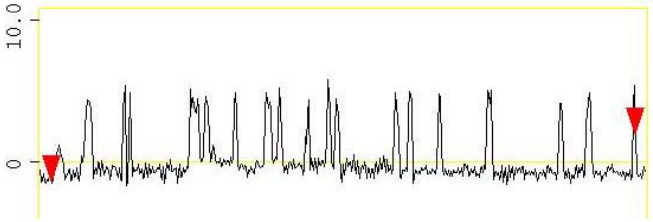
Andersen, E. S. et al.
Nature 459, 73–76 (2009)

TRIANGULAR DNA NANOTUBES



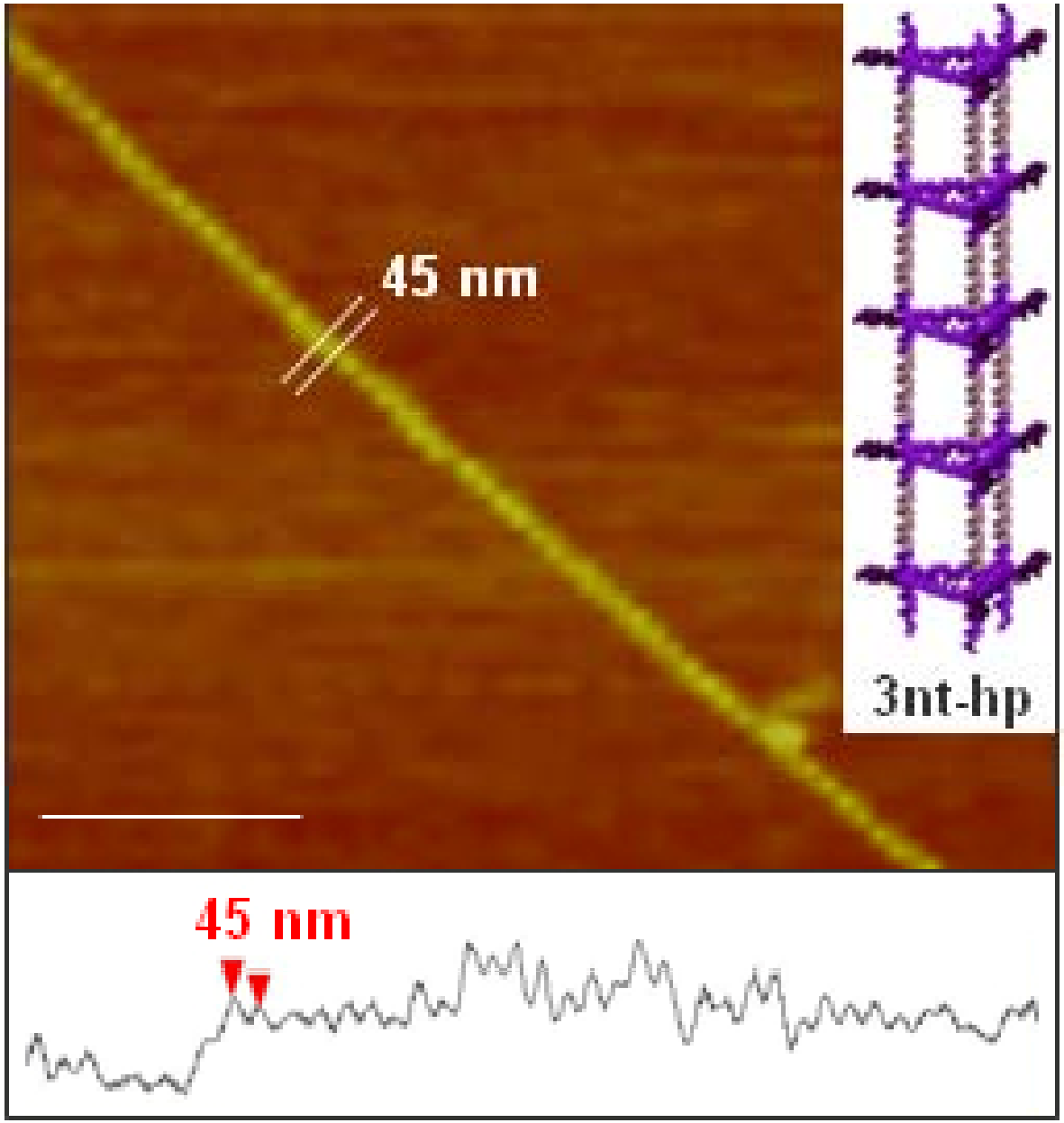


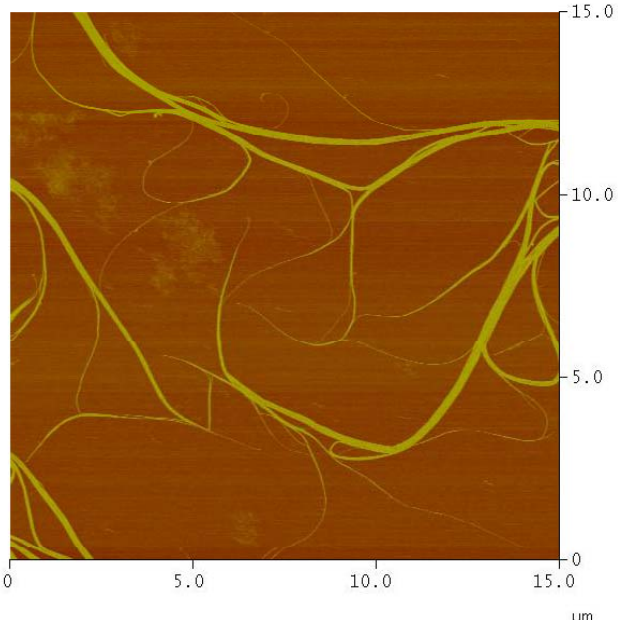




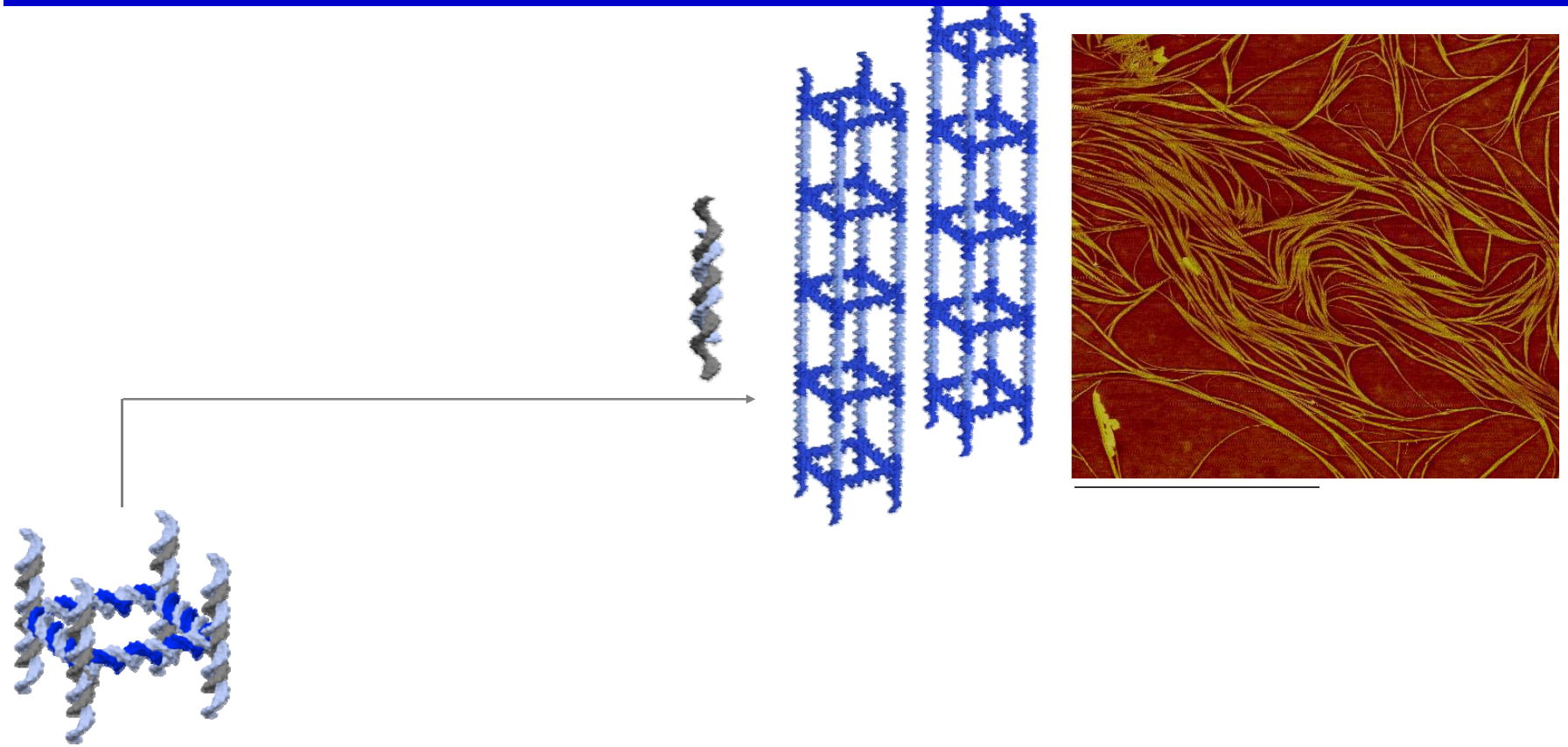
Peggy Lo, F. Aldaye

TRIANGULAR DNA NANOTUBES WITH HAIRPINS



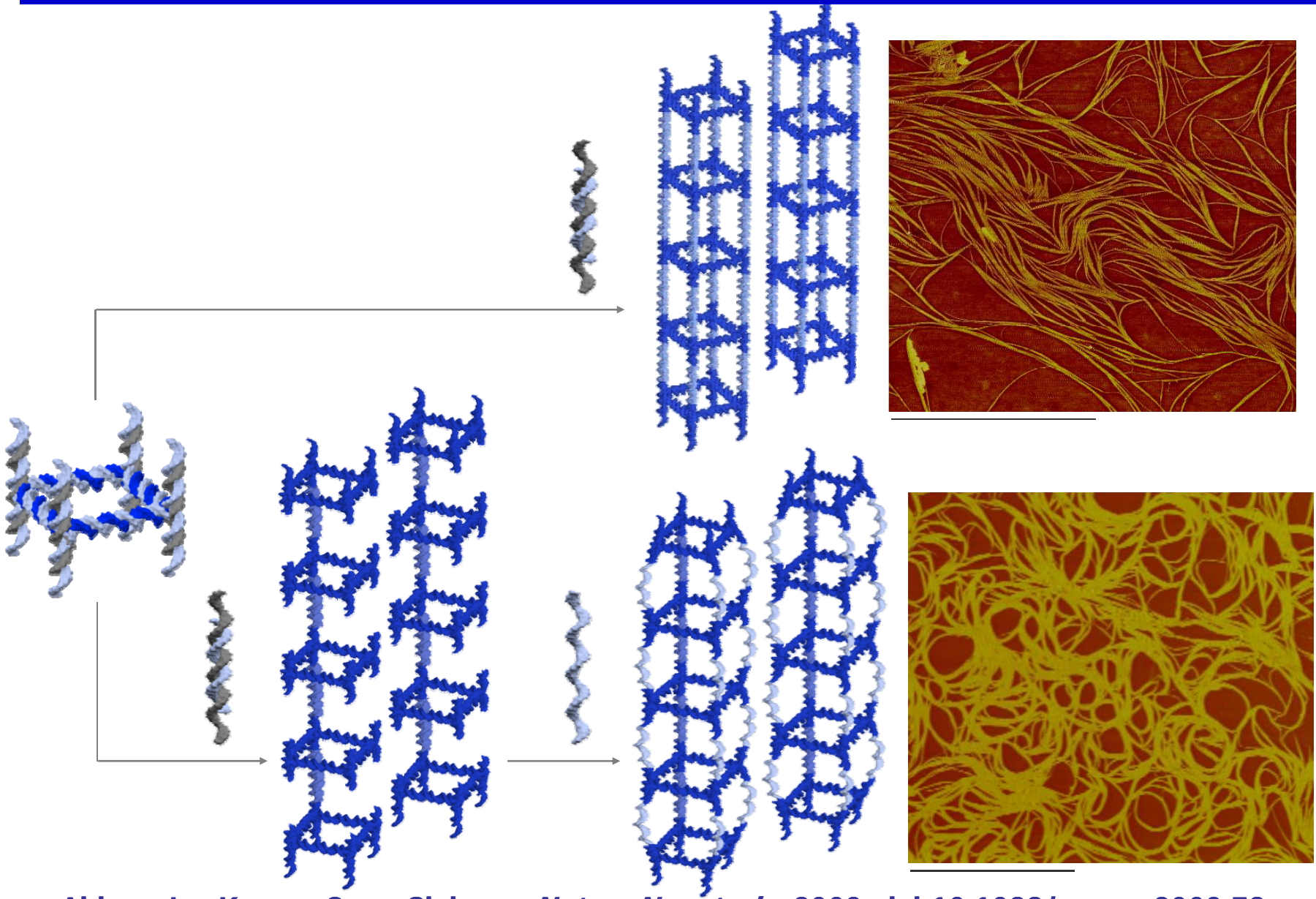


Control of Geometry: CUBIC DNA NANOTUBES



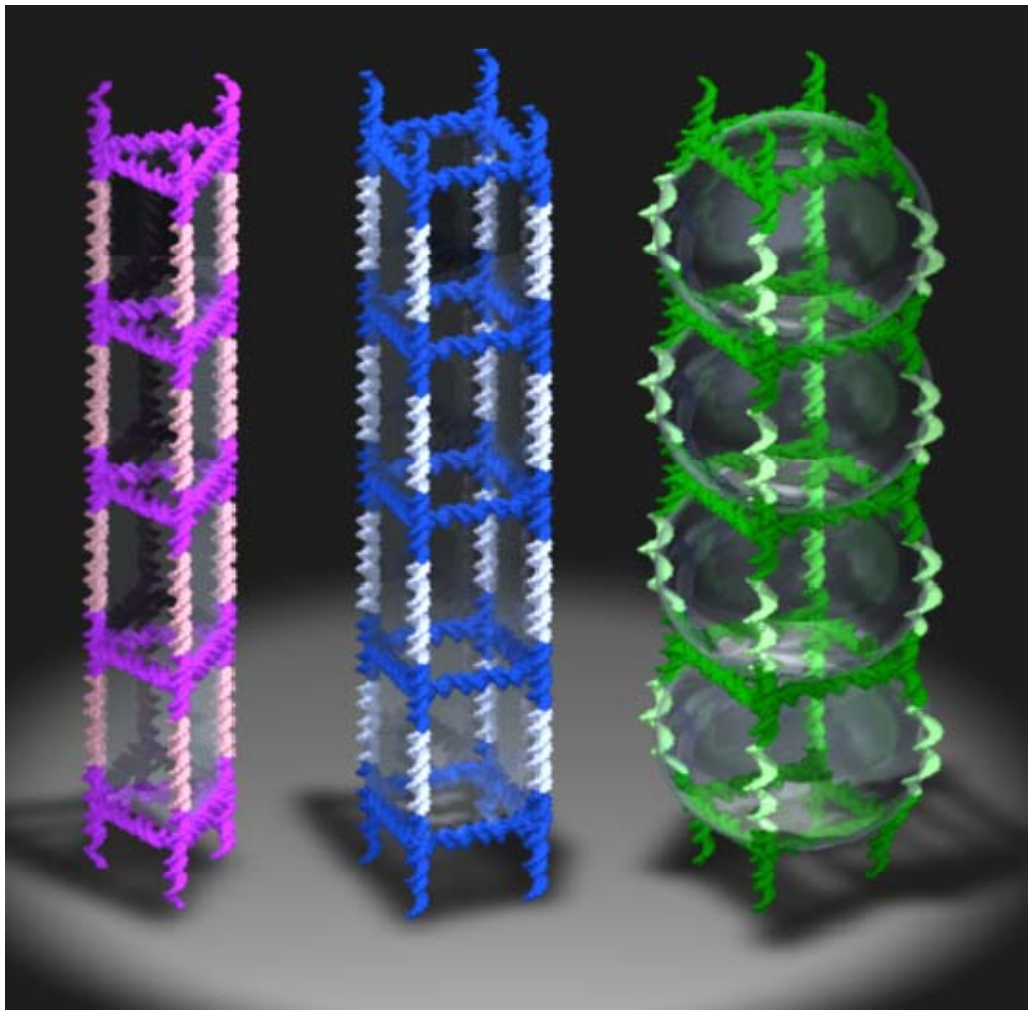
Aldaye, Lo, Karam, Cosa, Sleiman, *Nature Nanotech.*, 2009, doi:10.1038/nnano.2009.72

Single-Stranded 'Open' and Double-Stranded, 'Closed' DNA Nanotubes



Aldaye, Lo, Karam, Cosa, Sleiman, *Nature Nanotech.*, 2009, doi:10.1038/nnano.2009.72

DNA Nanotubes of Programmable Geometry and Permeability

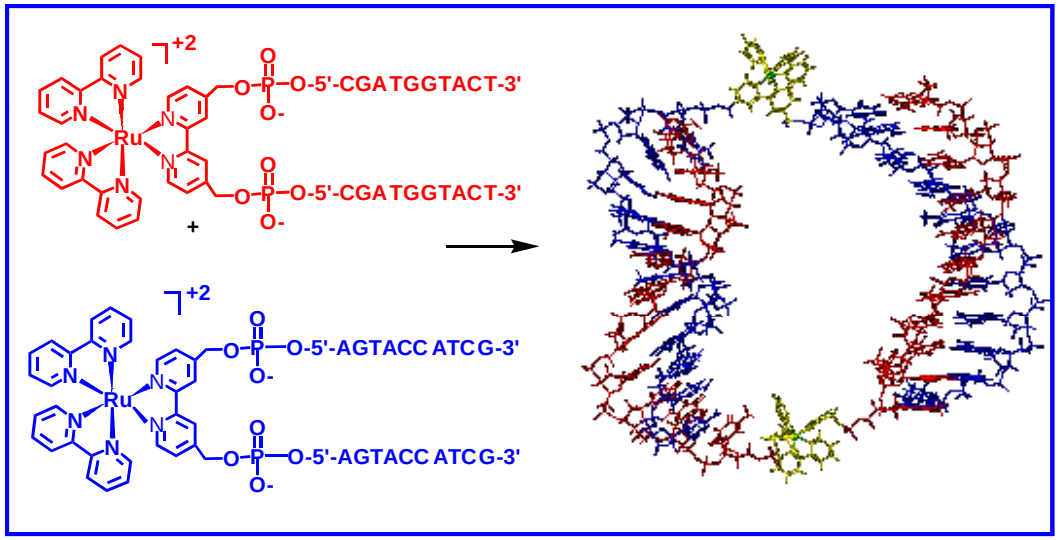


-Delivery of Therapeutics
-Positioning of Devices

Aldaye, Lo, Karam, Cosa, Sleiman, *Nature Nanotechnology*, 2009,
doi:10.1038/nnano.2009.72

Metalation of DNA Junctions

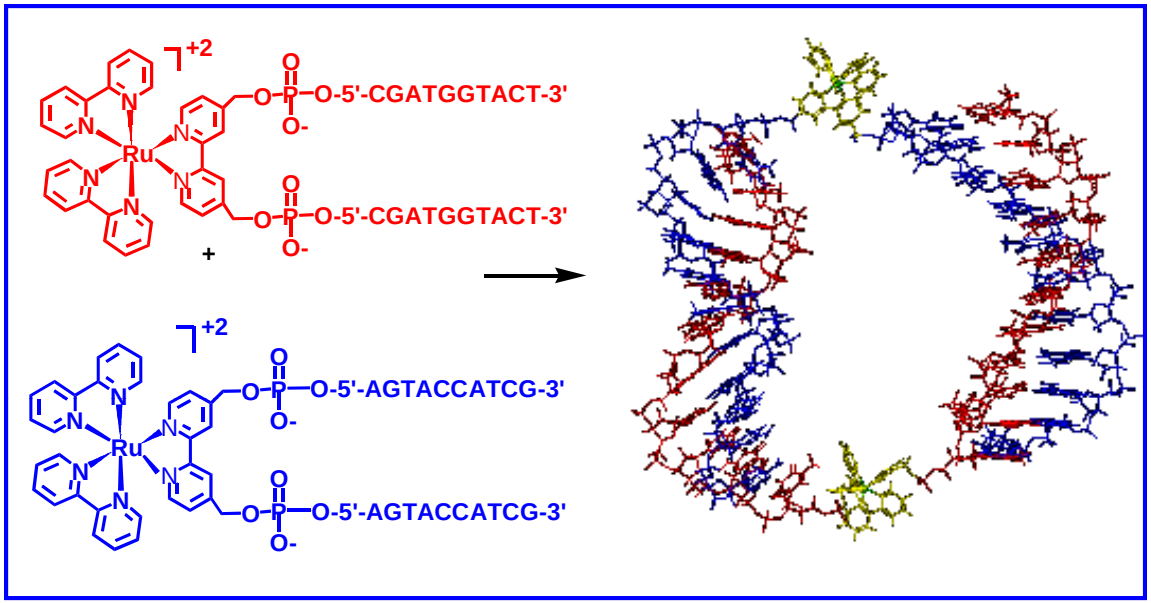
- **Wire DNA:** provide mechanisms for transport (electron, hole, energy)
- **Structural Effects:** Metals can modify DNA self-assembly
- **Functional Materials:** for artificial photosynthesis, multicomponent catalysis, spintronics, high density data storage
- **Monodisperse** materials



- First example of a cyclic metal-DNA nanostructure
- Transition metal directly affects the assembly

Mitra, Di Cesare, Sleiman, *Angew. Chem.*. 2004, 43, 5804; *Angew. Chem.* 2001, 40, 4629

Metalation of DNA Junctions



Limitations: metal must be inert, unreactive with DNA bases/phosphate, must resist DNA synthesis; metals separated by double-standed DNA

Need for a strategy:

- To incorporate more labile metals
- To incorporate electroactive metals (+0.8 to -0.7 V vs. SCE)
- To control metal-metal distance

Metalation of DNA Nanostructures

Yang, Sleiman, Angew. Chem., 2008, 47, 2443

Hua Yang

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Angewandte Chemie

International Edition

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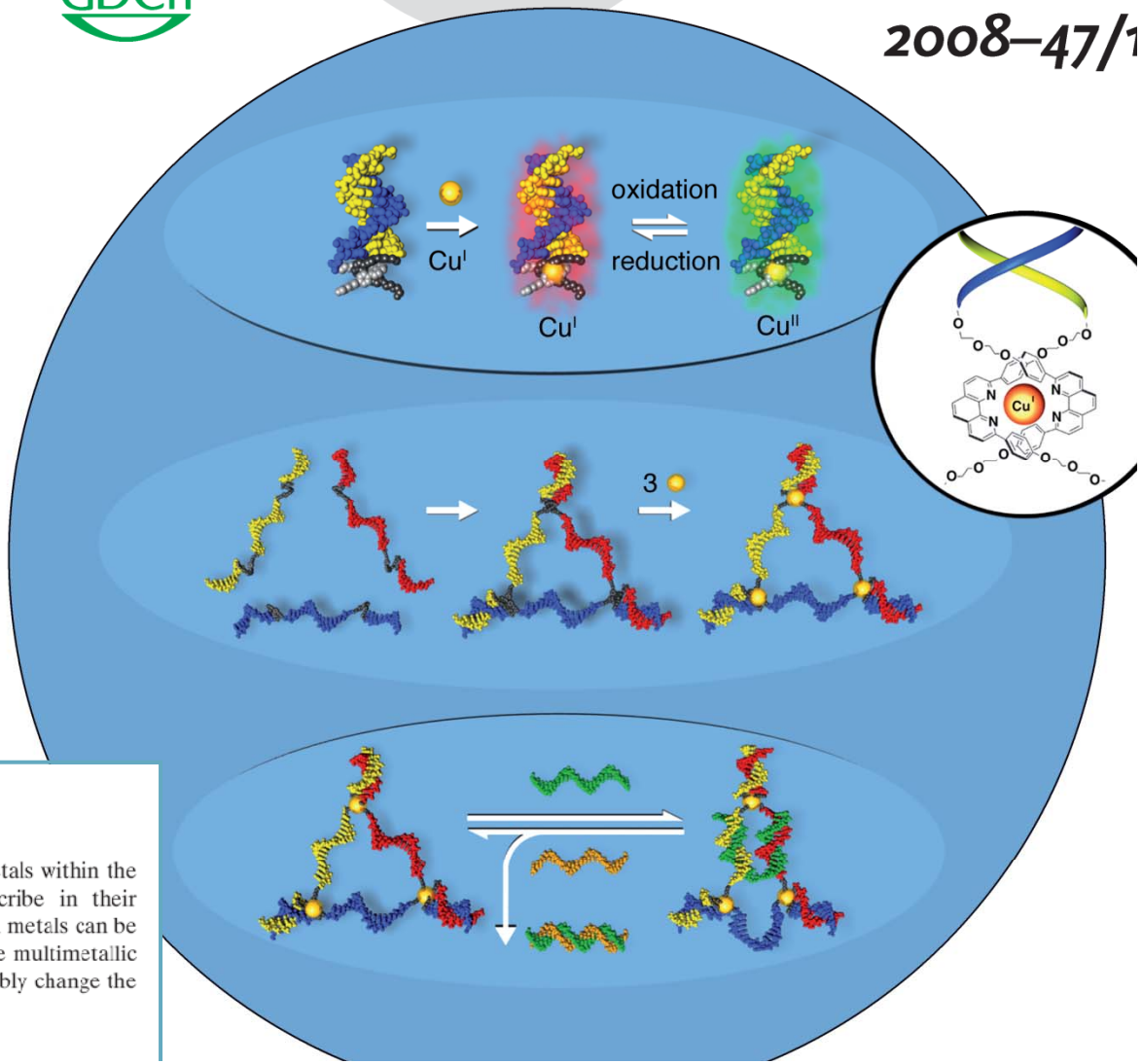
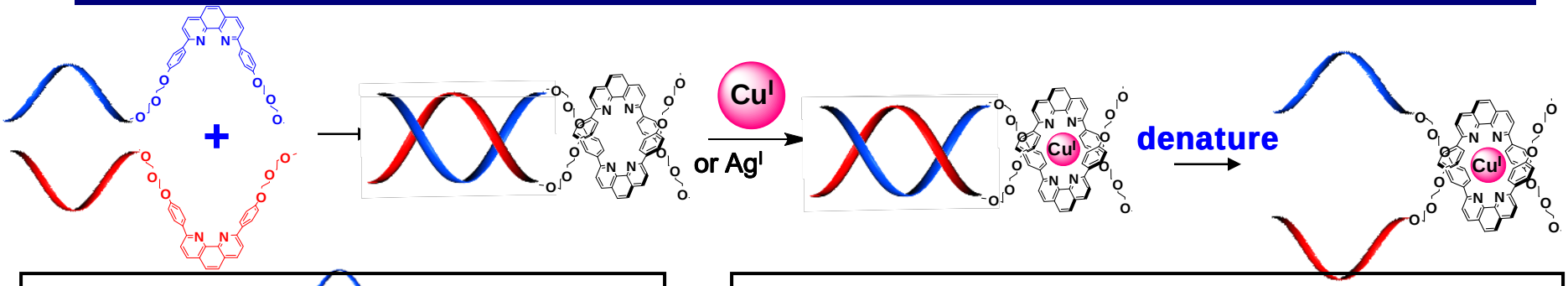
2008–47/1

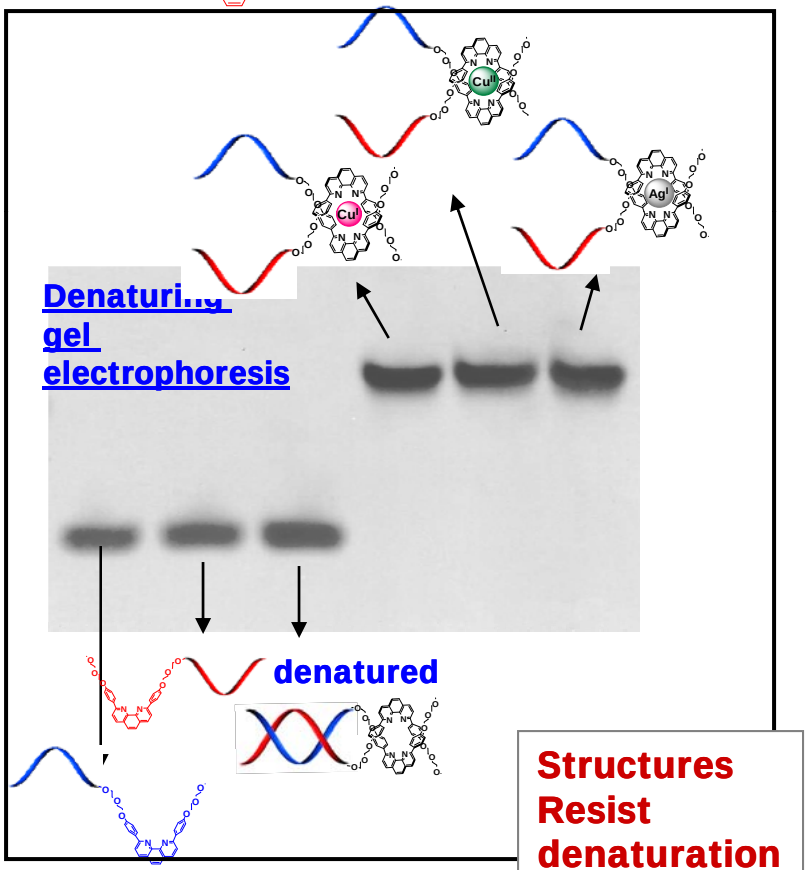


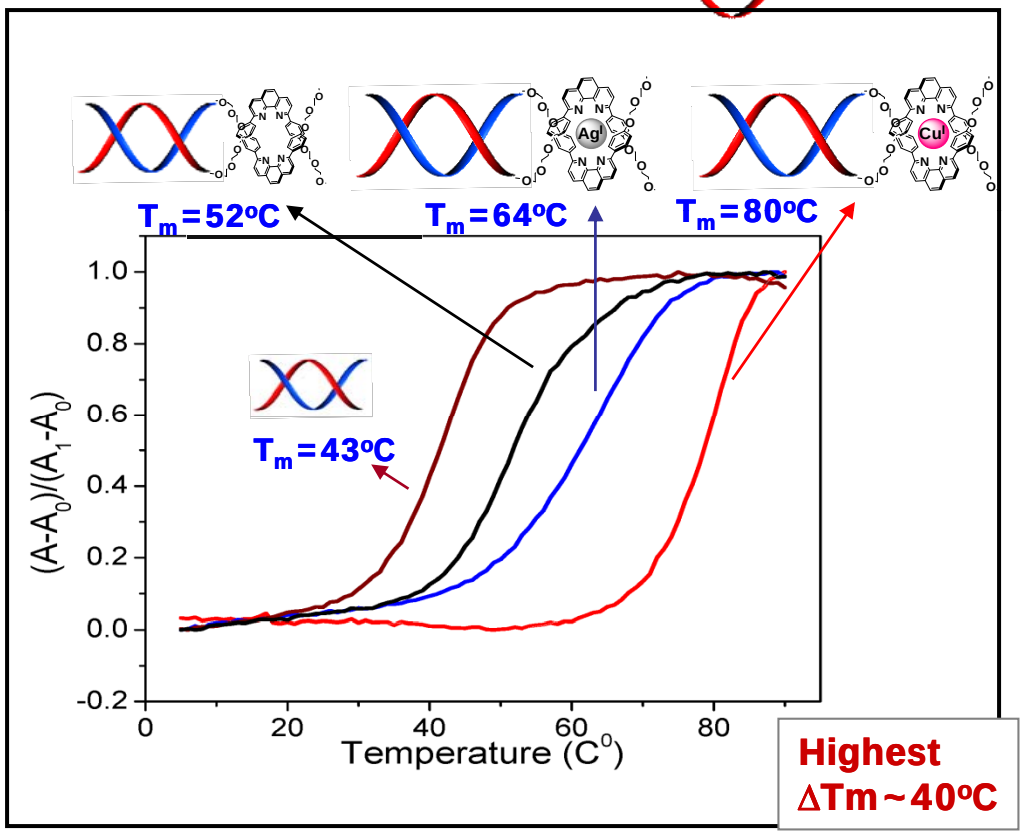
Metalated DNA junctions ...

... can be formed through the templated incorporation of transition metals within the vertices of DNA nanostructures. H. F. Sleiman and H. Yang describe in their Communication on page 2443 ff. how even labile and reactive transition metals can be integrated within DNA vertices to create stable, electroactive, switchable multimetallic DNA nanostructures. The addition of external DNA strands can reversibly change the geometry and metal–metal distances of these nanostructures.

DNA templated metal coordination



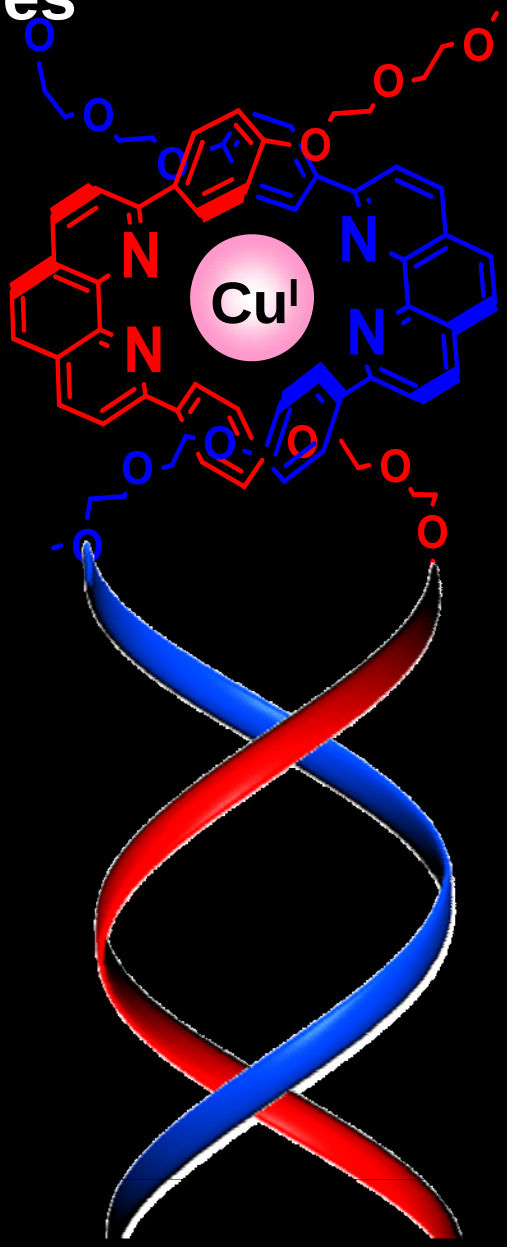


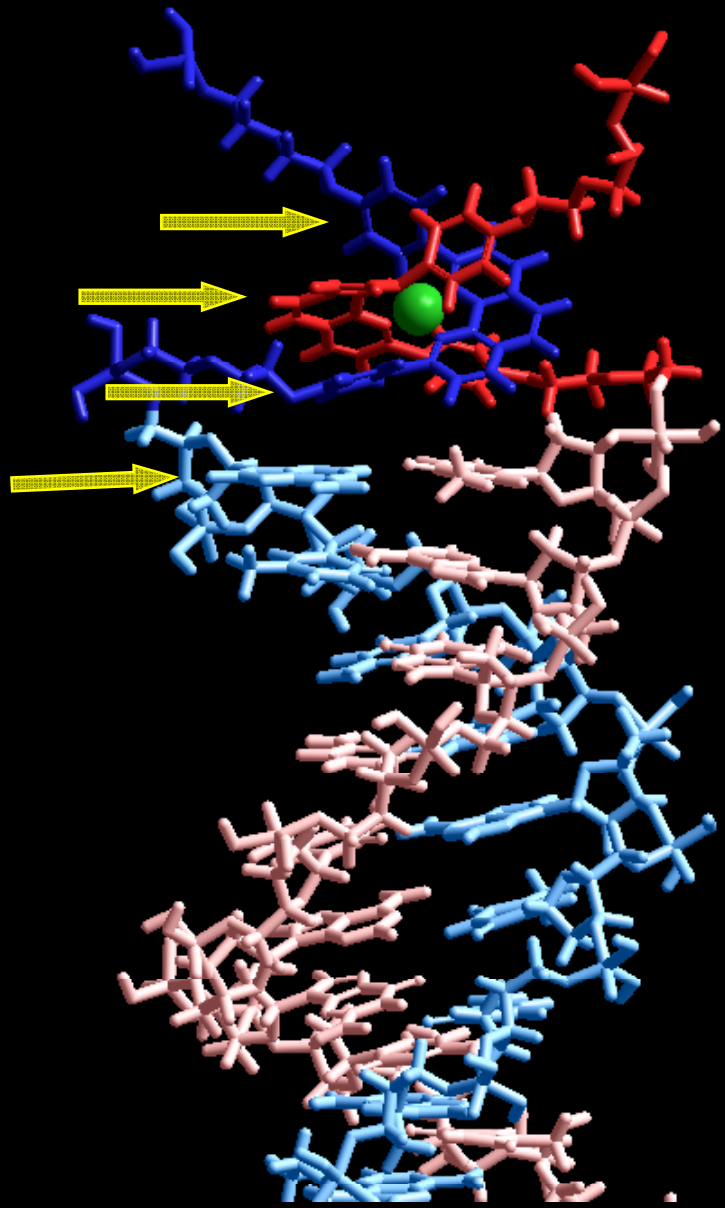


Metal-DNA junctions are remarkably stable

Yang, Sleiman, Angew. Chem. 2008, 47, 2443

Structural Features



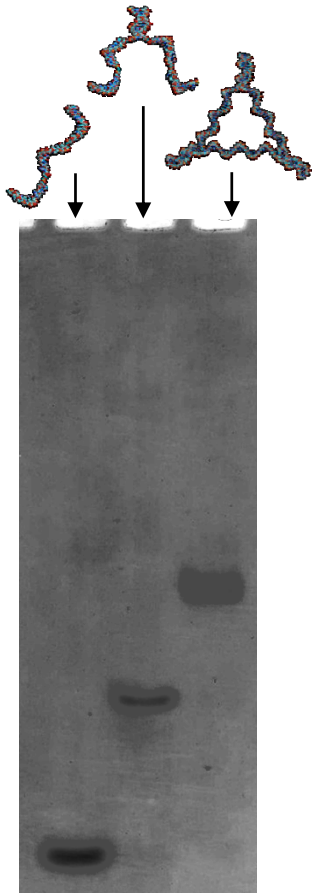


dpp-metal: right handed helicity.

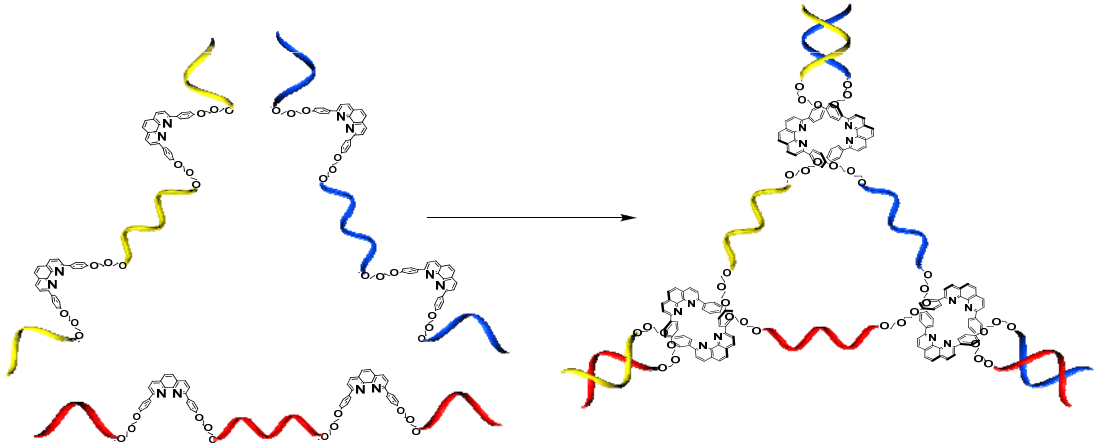
No strain for DNA

π–π stacking and metalation contribute to stabililty

Assembly of Metallo-DNA Triangles

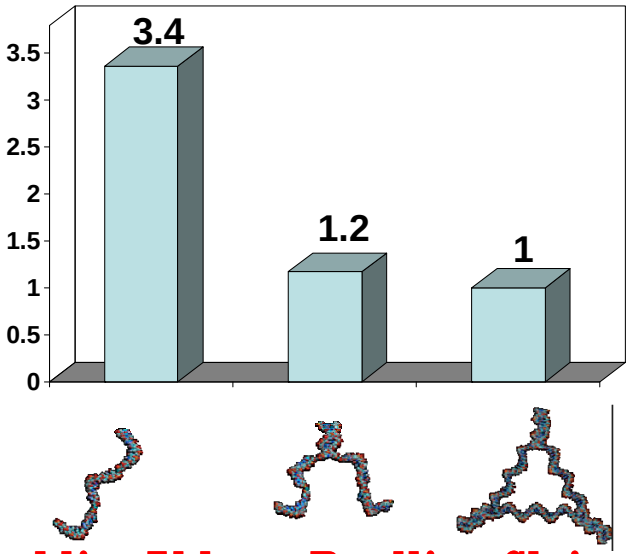


Native PAGE



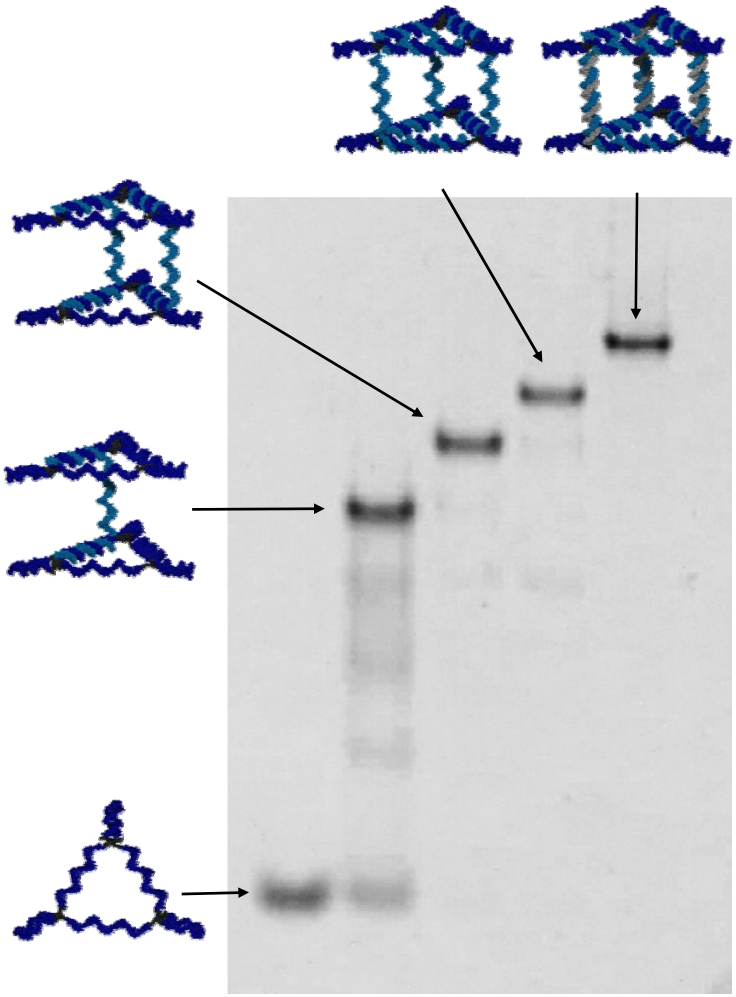
Quantitative assembly of DNA triangle

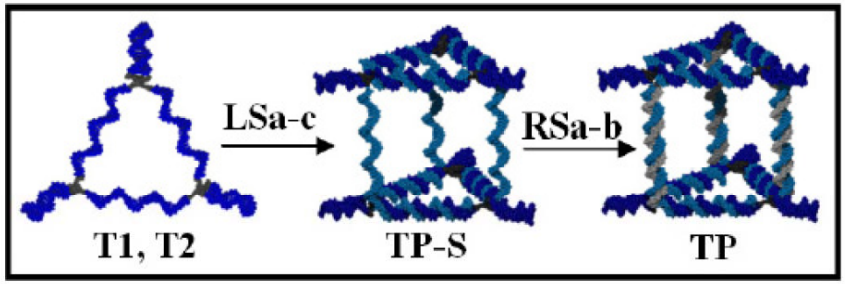
Real-time monitoring by fluorescence



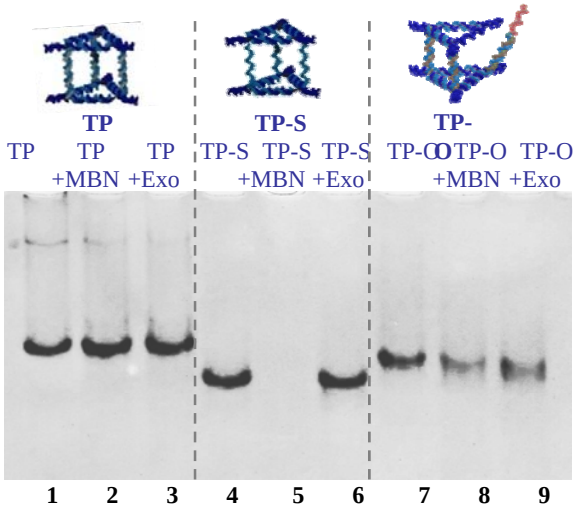
Yang, McLaughlin, Hamblin, Aldaye, Roullier, Sleiman, *Nature Chemistry*, 2009, in press

DNA Cages- Quantitative formation



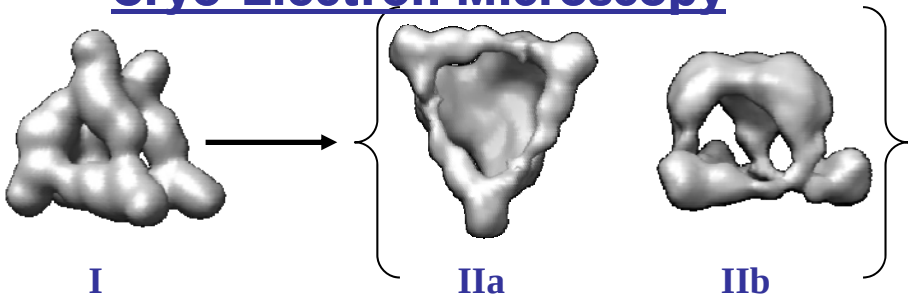


Enzymatic Analysis



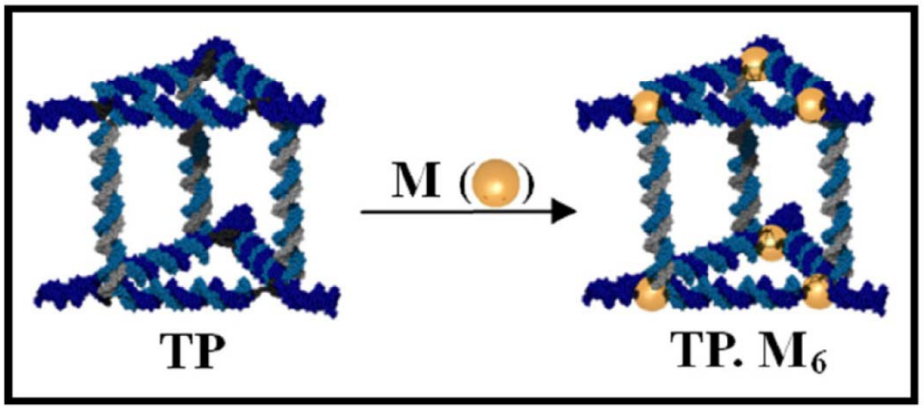
Video

Cryo-Electron Microscopy

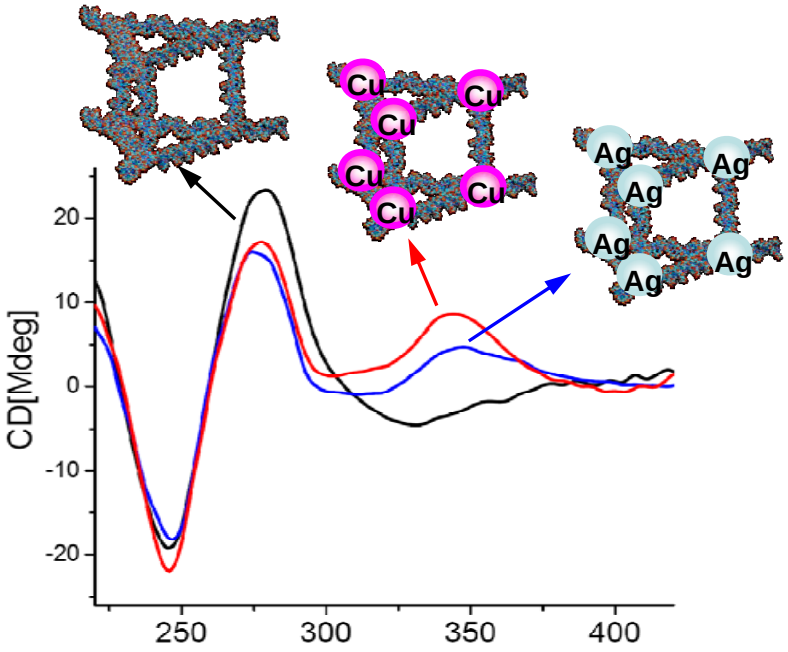


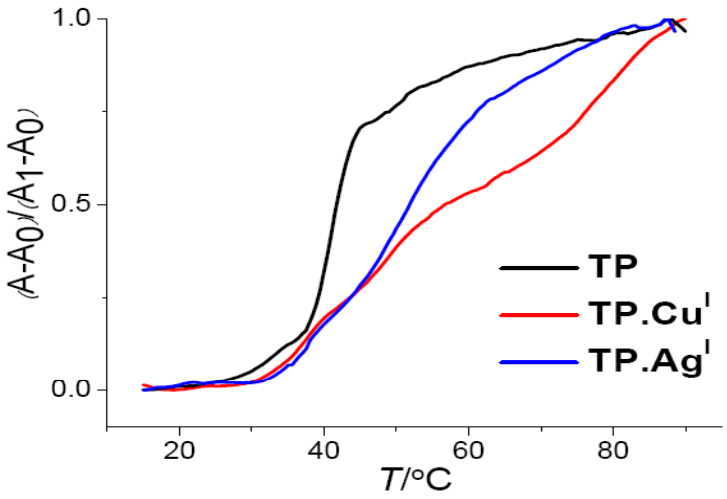
Yang, McLaughlin, Hamblin, Aldaye, Roullier, Sleiman, *Nature Chemistry*, 2009, in press

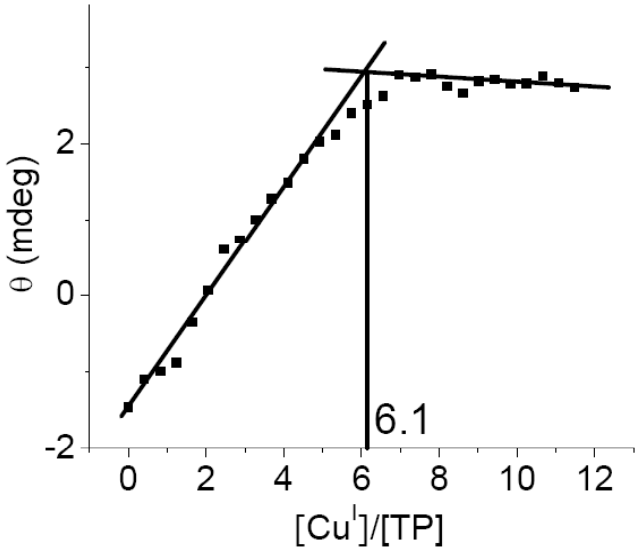
Metal Binding to DNA Prism



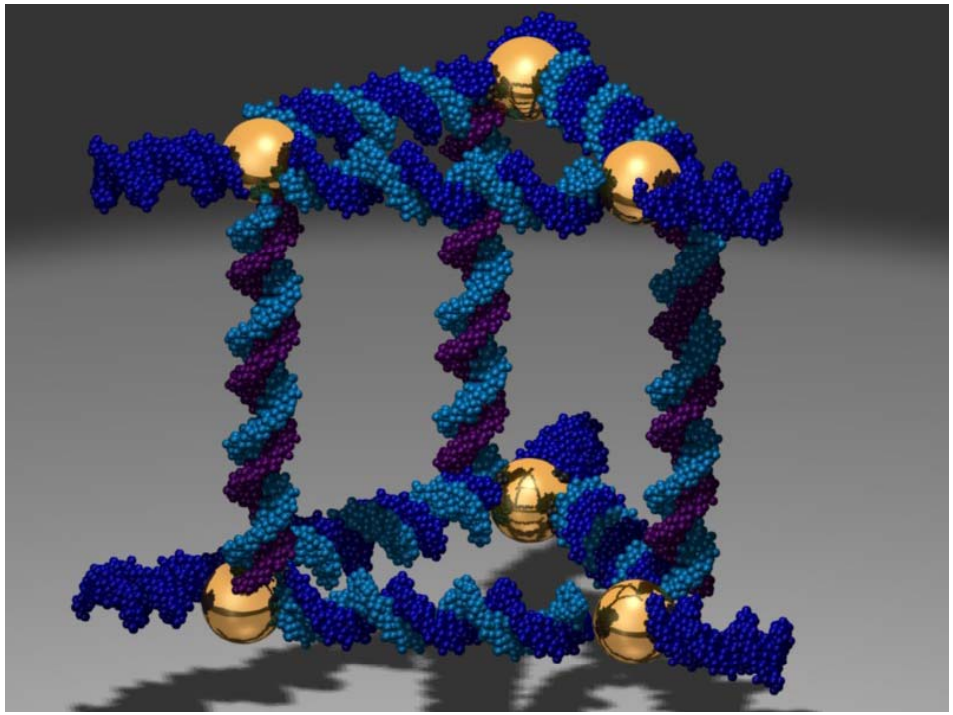
6 Cu^{I} (or Ag^{I}) bind with dpp DNA Prism quantitatively



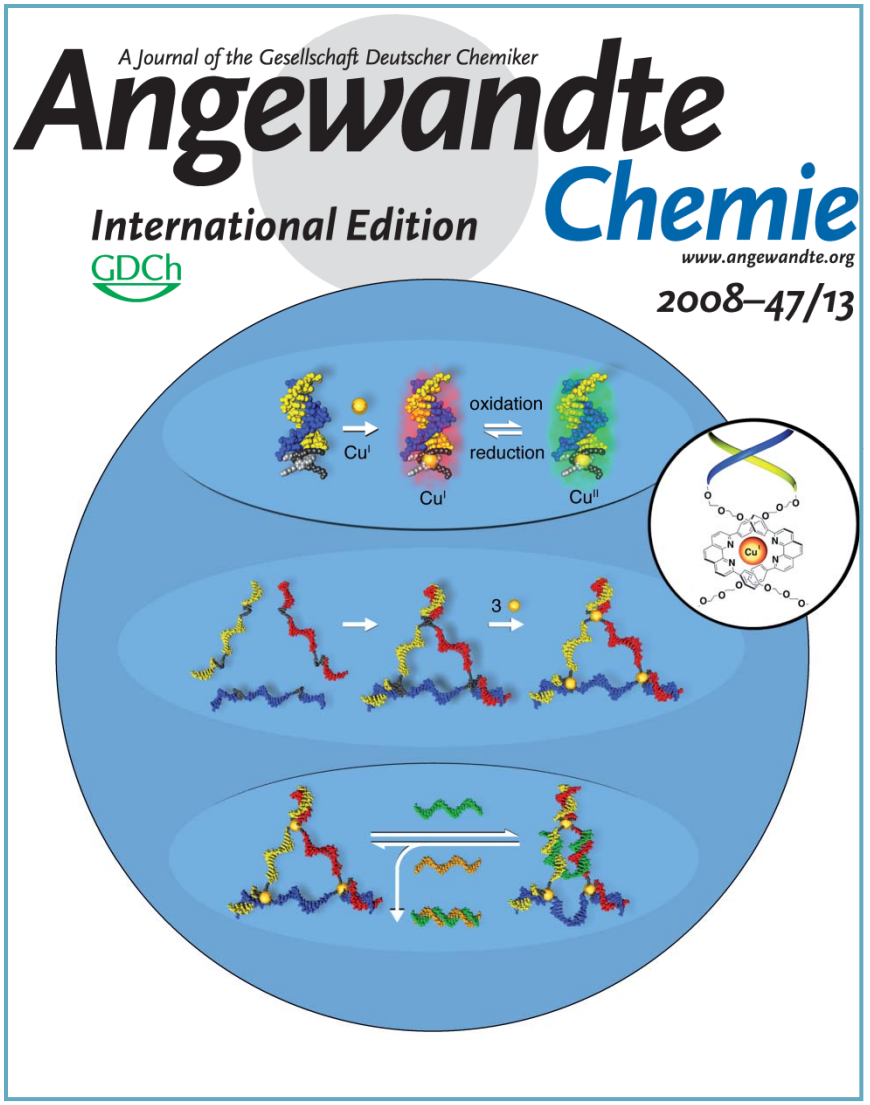




Metallo DNA 3D-Cages

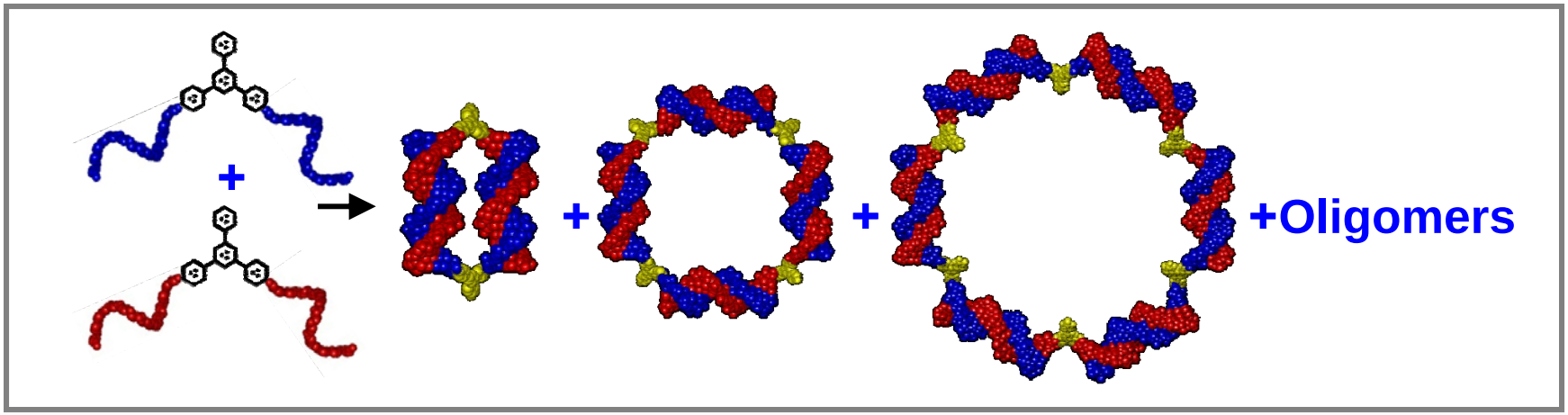


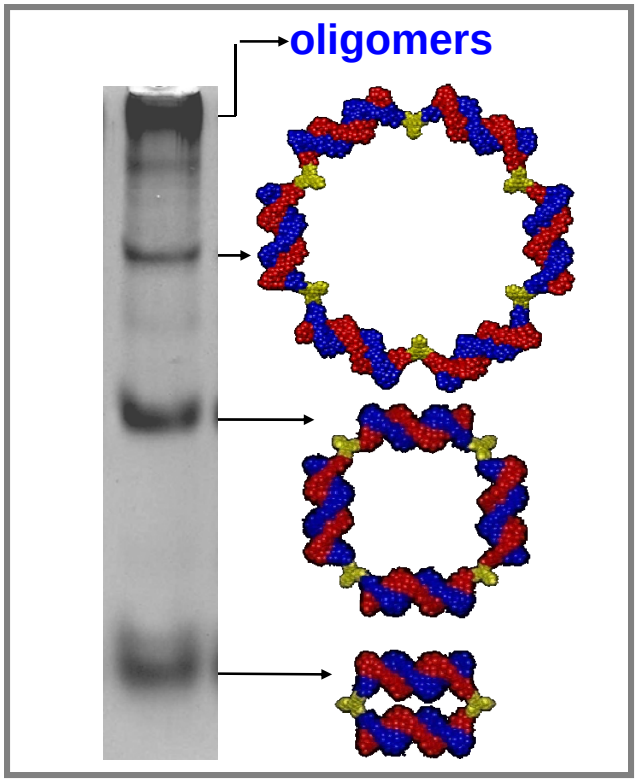
Yang, McLaughlin, Hamblin, Aldaye, Roullier, Sleiman,
Nature Chemistry, 2009, in press



Yang, Sleiman,
Angew. Chem., 2008, 47, 2443

Error Correction in DNA Self-Assembly





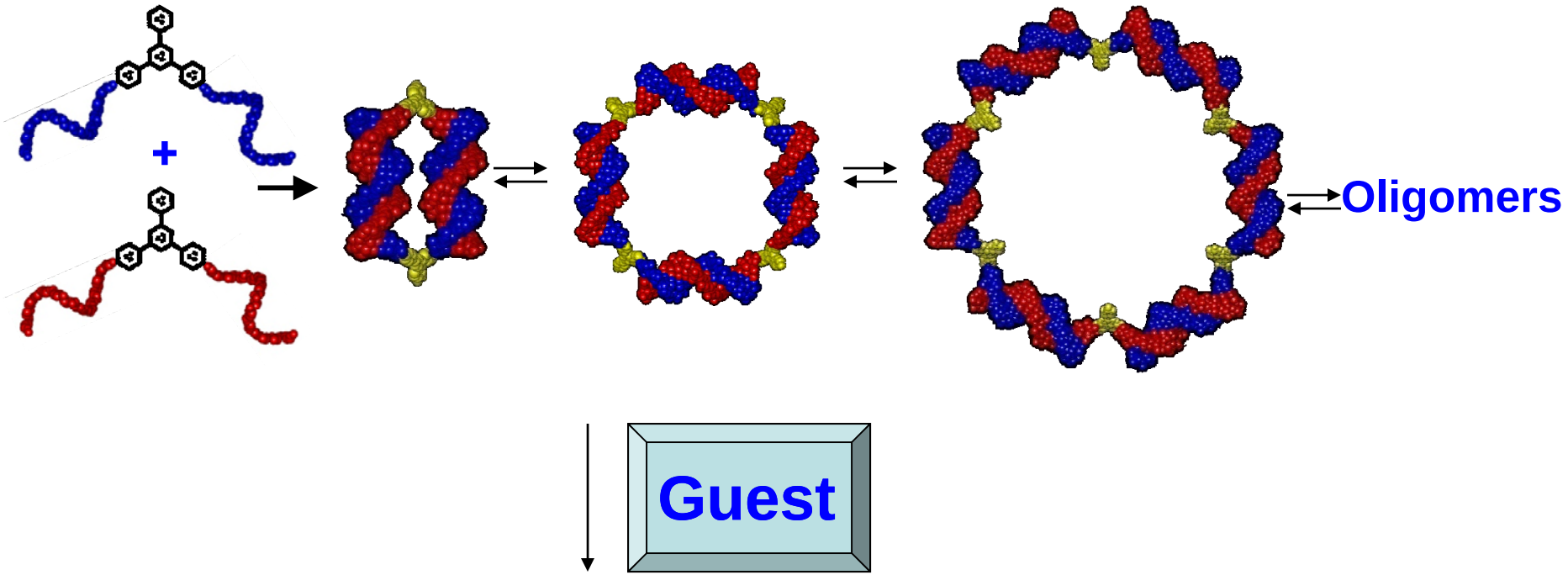
Forms a Library of Cyclic Dimer, Tetramer, Hexamer and Oligomers!

under various hybridization conditions

Mung Bean Nuclease assay confirms cyclic nature

Aldaye, Sleiman, J. Am. Chem. Soc. 2007, 129, 10070

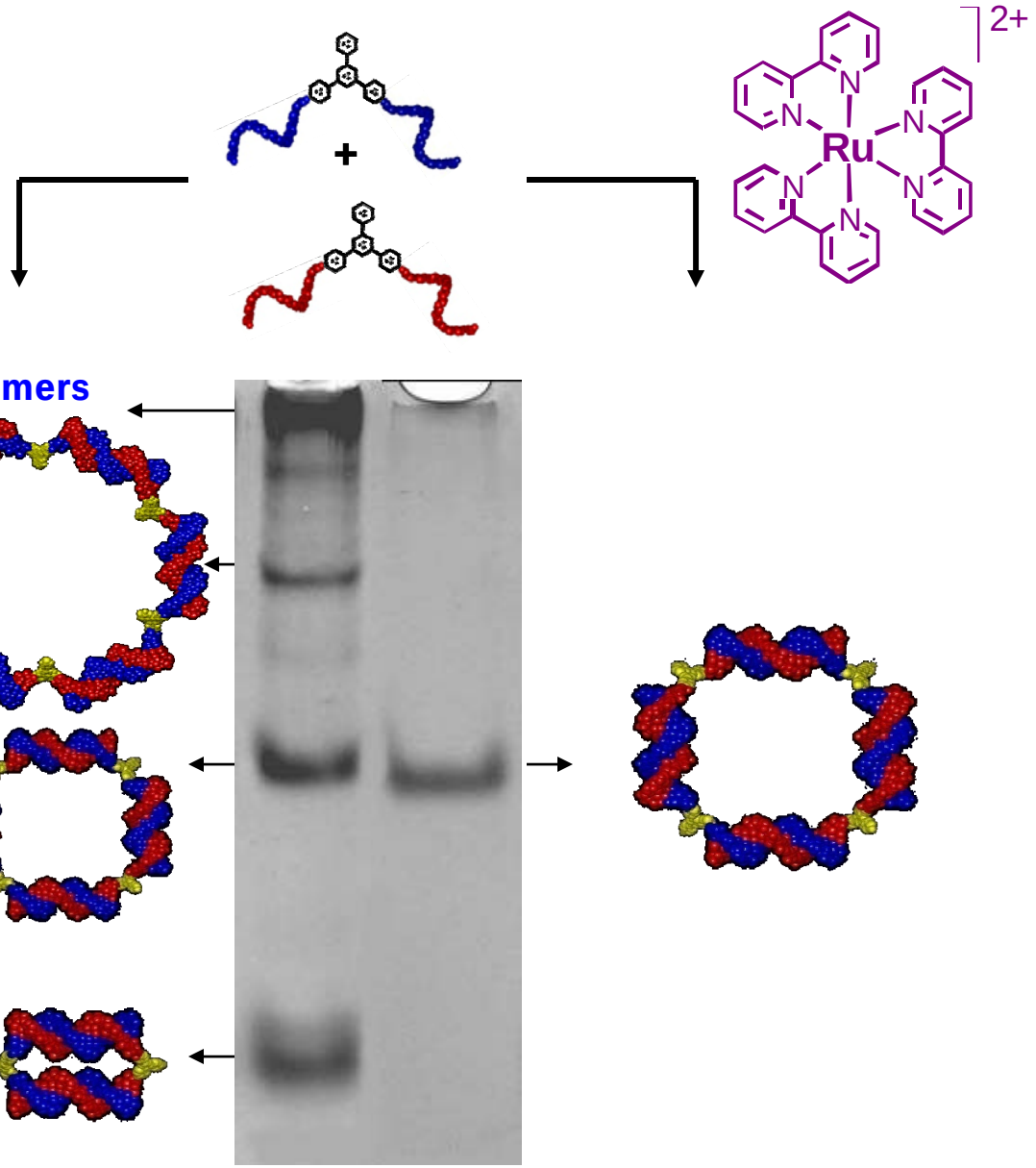
Dynamic Combinatorial Library



Can the mixture re-equilibrate in favor of the best receptor?

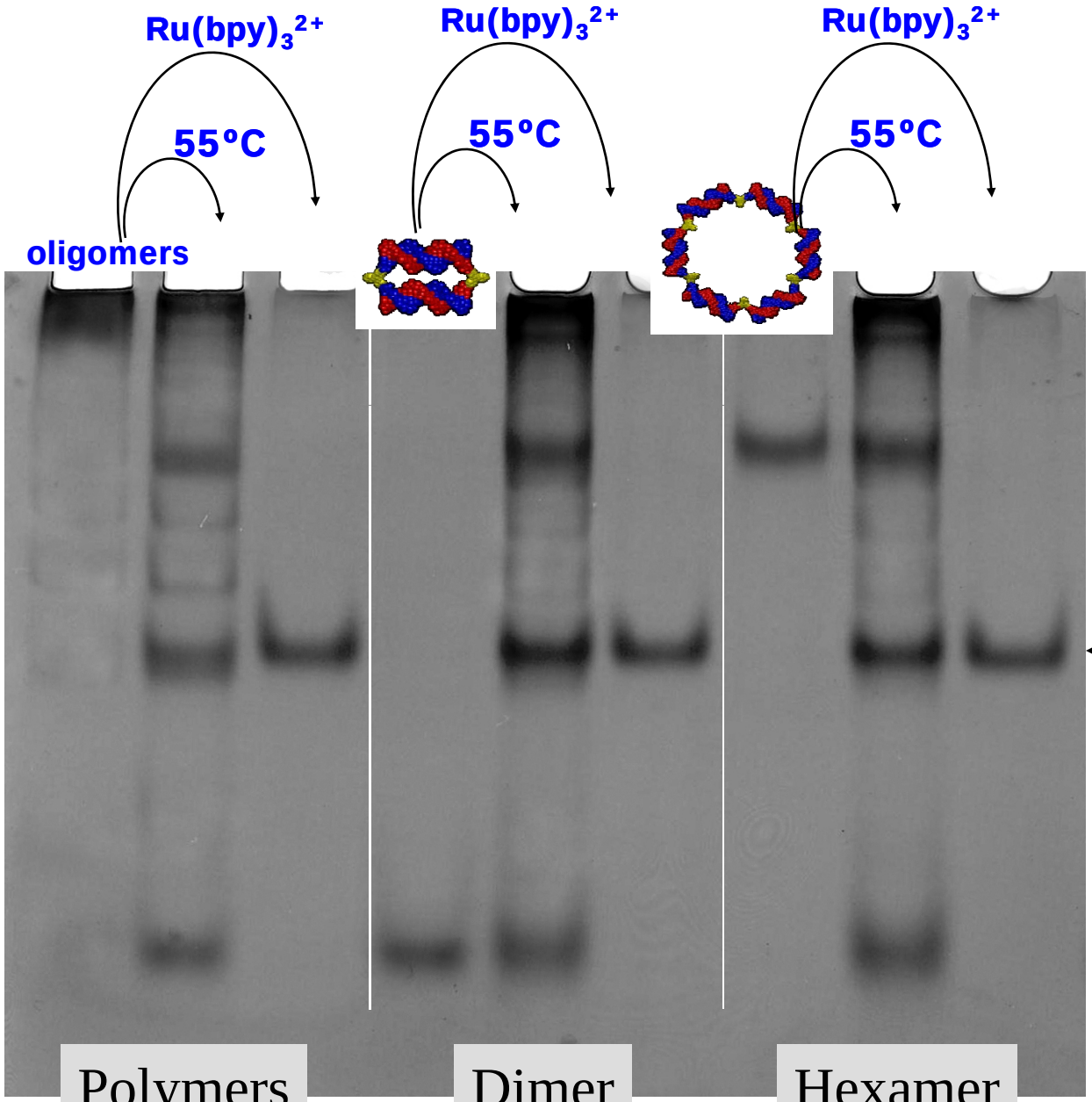
Guest Templated Formation of a Single Nanostructure

Can we template selective access to a single nanostructure in the presence of appropriate guests?



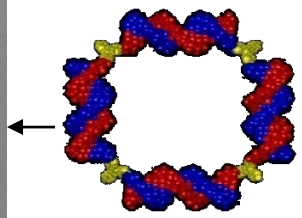
YES!

Guest Induced Re-equilibration of Library Members

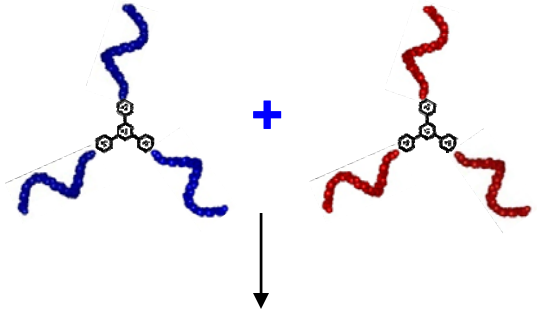


Every member of the library reequilibrates to the square

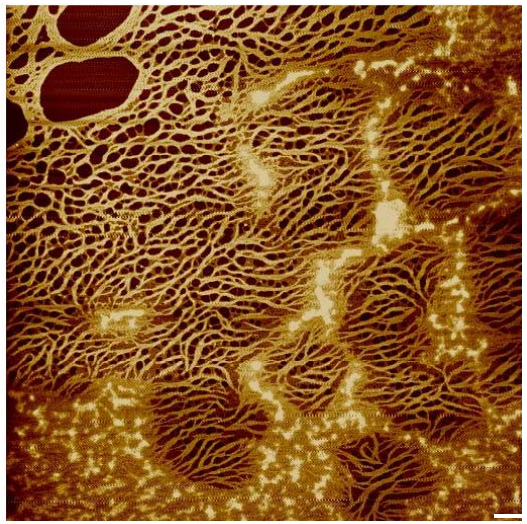
in presence of Ru(bpy)$_3^2$



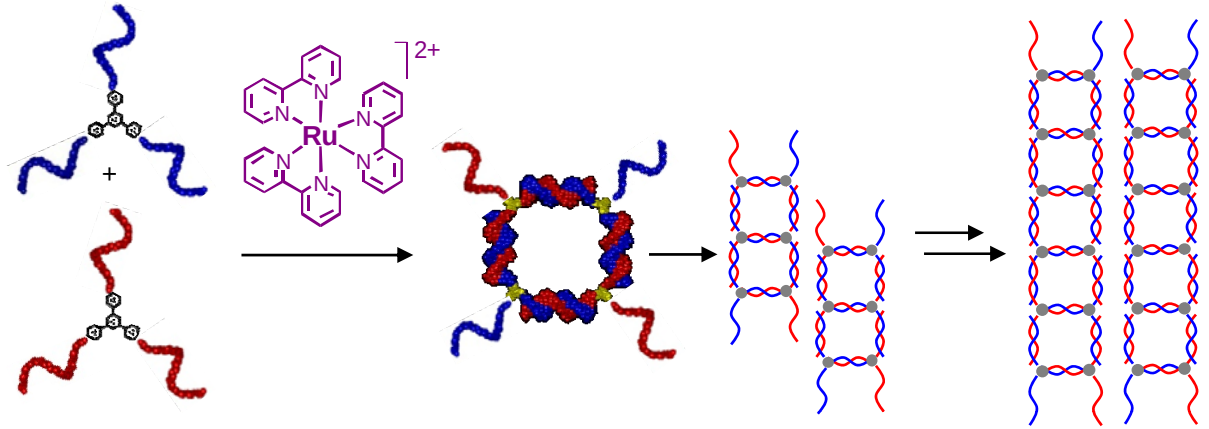
Extended Assemblies

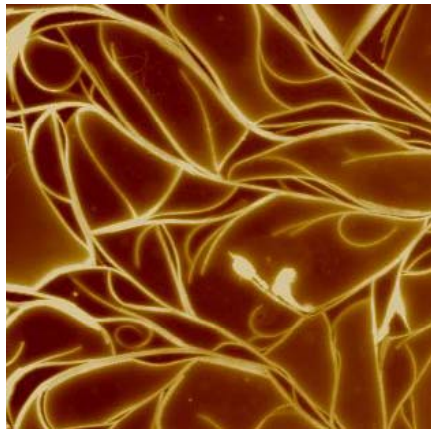


Ill-defined networks

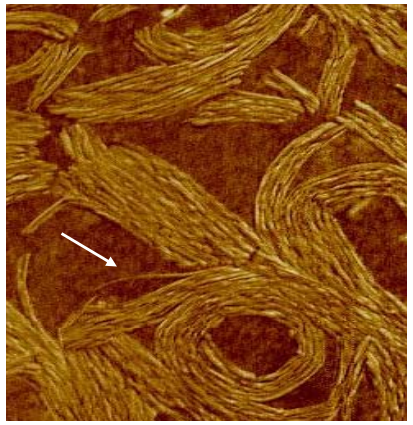


10 μm





10 μm

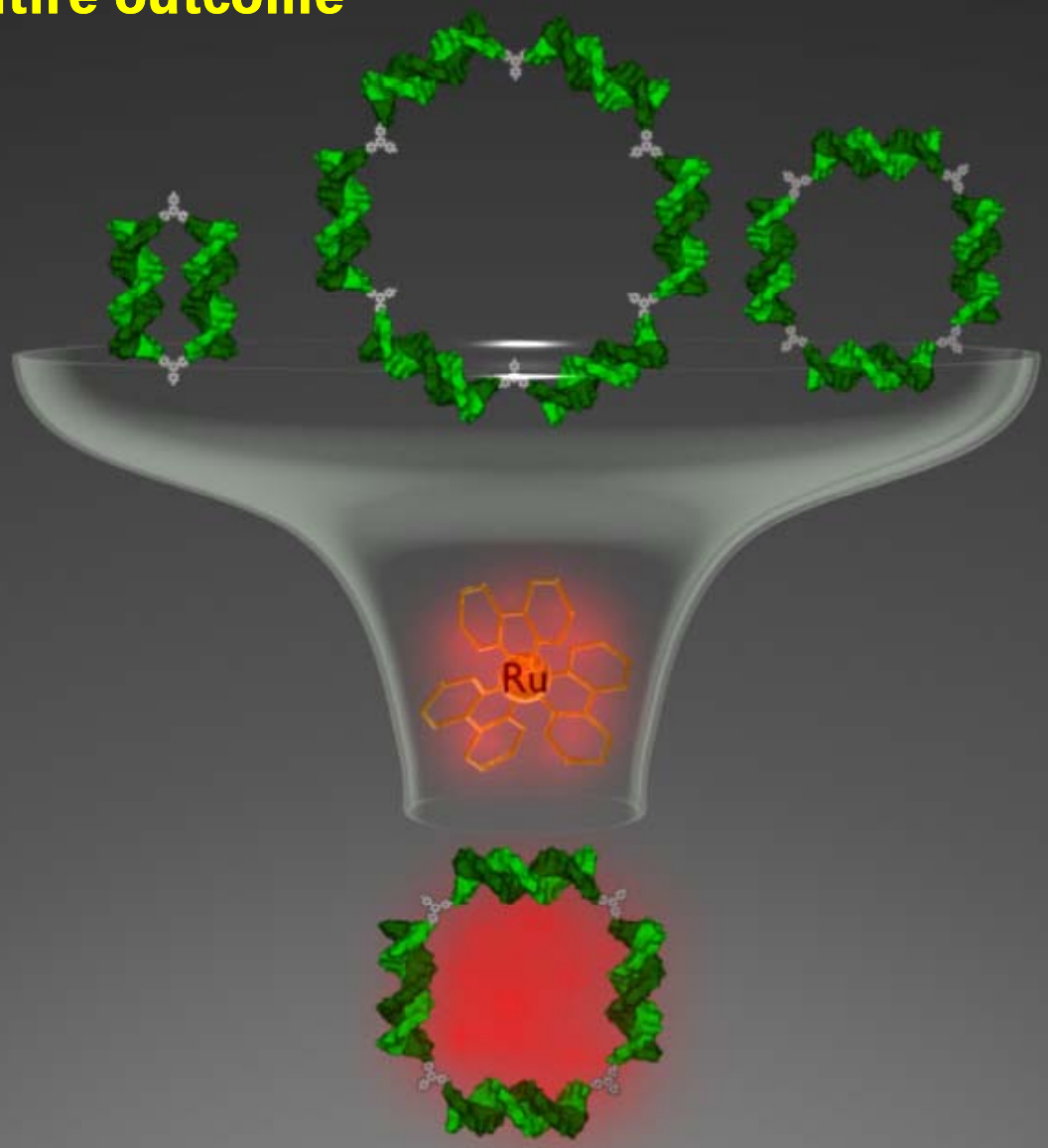


10 μm

2.5 μm

Aldaye, Sleiman, J. Am. Chem. Soc. 2007, 129, 10070

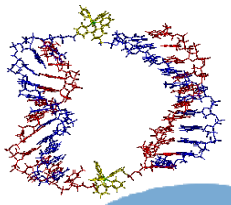
Error Correction in DNA Self-Assembly: A small molecule can change the entire outcome

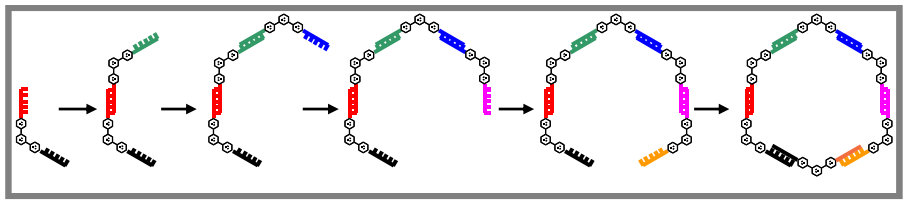


F. Aldaye, H. Sleiman, J. Am. Chem. Soc. 2007, 129, 10070

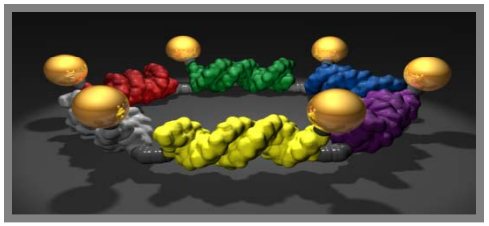
DNA Supramolecular Chemistry

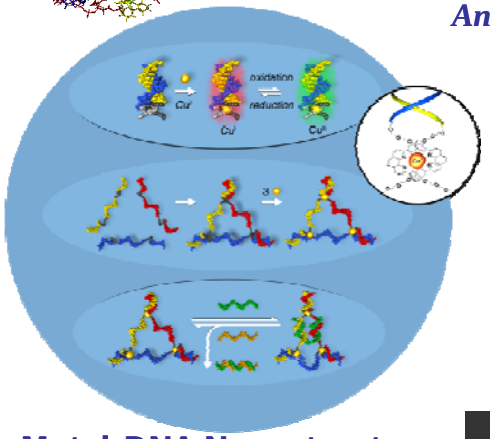
Aldaye, Sleiman, *Science*, 2008, *321*, 1795

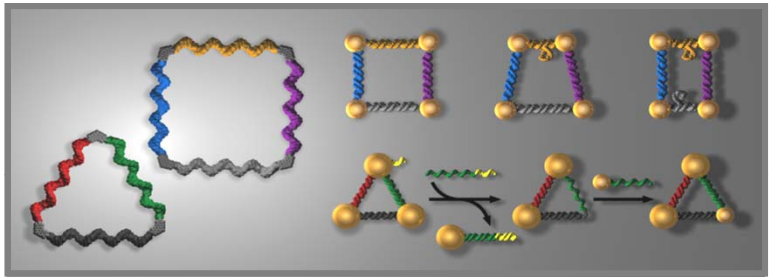




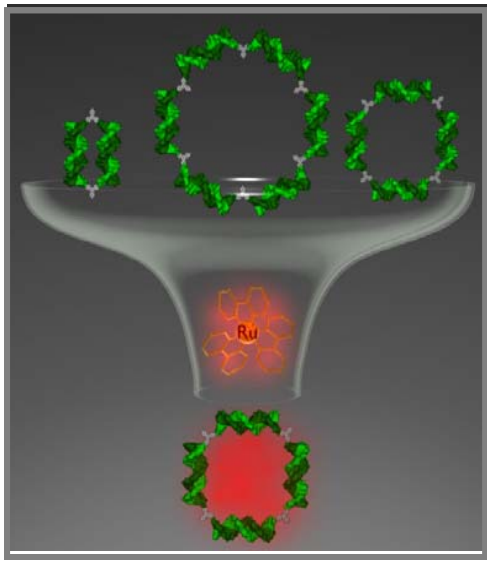
Sequential Self-Assembly of Gold Particle Hexagon,
Angew. Chem. 2006, 45, 2204







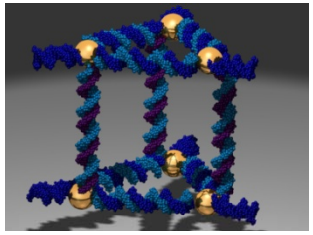
Dynamic Templates for Particle Assemblies
JACS, 2007, *129*, 4130

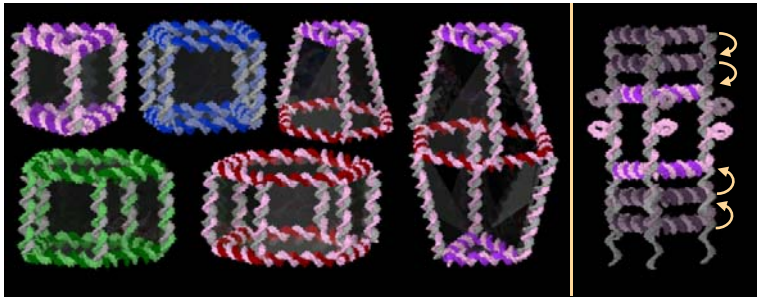


Guest-Mediated Error Correction
JACS, 2007, *129*, 10070

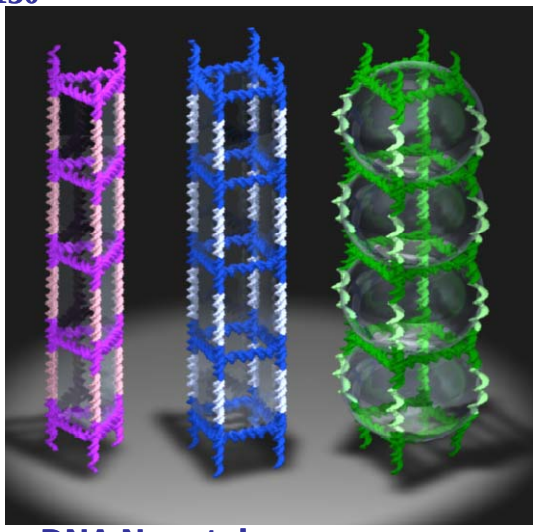
Metal-DNA Nanostructures

Angew. Chem. 2001, 40, 4629
Angew. Chem. 2004, 43, 5804
Angew. Chem. 2008, 47, 2443
Nature Chemistry, in press





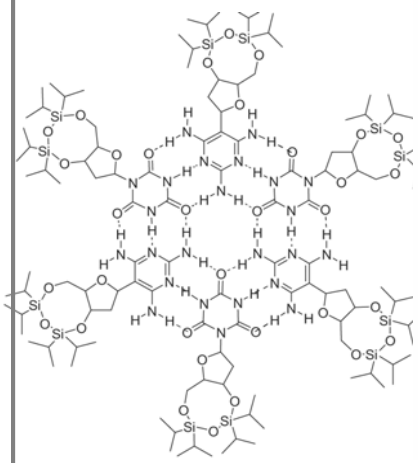
3D DNA Assemblies,
JACS, 2007, 13376

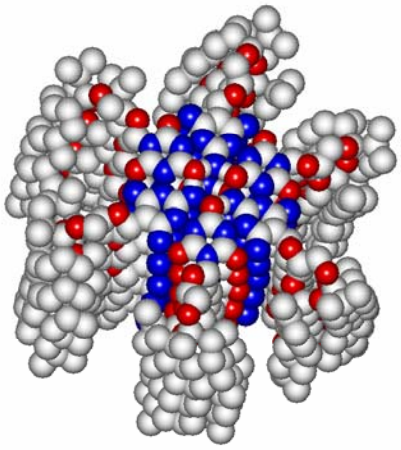


DNA Nanotubes
Nature Nanotechnology, 2009

DNA Supramolecular Chemistry – Expanding DNA Self-Assembly Code

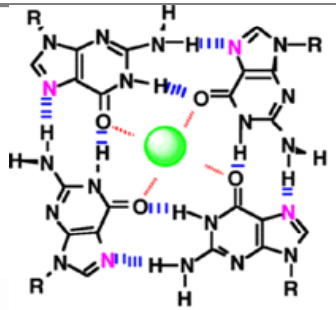
DNA Hexameric Rosettes

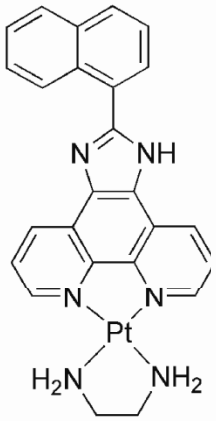


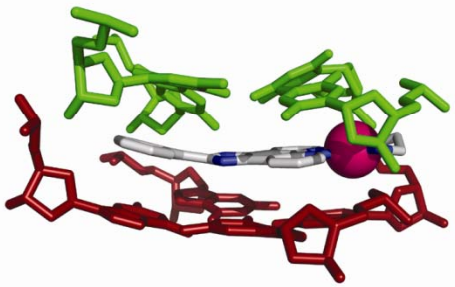


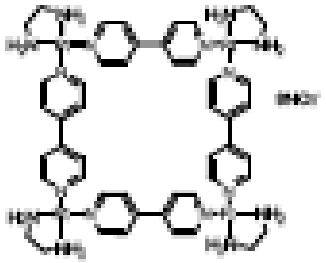
Chem. Commun. 2005, 5441

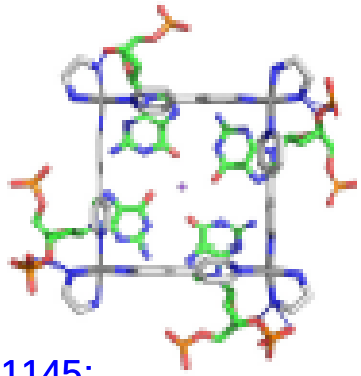
G-Quadruplex Binders in anticancer therapy











Chem. Eur. J. 2008, 14, 1145;
J. Am. Chem. Soc. 2008, 10040

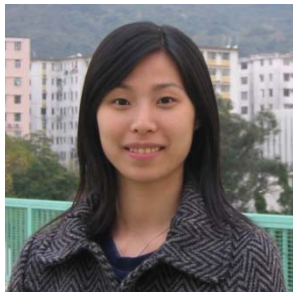
Acknowledgements

People


Faisal Aldaye


Hua Yang


Chris McLaughlin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Karina Carneiro


Mohamed Slim


Yoshi Ishihara


Ignacio Vargas-Baca


Debbie Mitra

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- Research Corporation (Cottrell Scholar Award)
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- Center for Self-Assembled Chemical Structures (CSACS)
- NSERC/CIHR Collaborative Health Program (CHRP)
- NSERC Idea to Innovation Grant (I2I)
- Nanoquebec
- Canadian Institute for Advanced Research (CIFAR)
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- Xerox Corporation