Toward Modular Molecular Composite Nanosystems

K. Eric Drexler, PhD

berkeley nanotechnology forum 2009

U.C. Berkeley

26 April 2009

Intended take-away messages:

Paths are now open toward complex, self-assembled, heterogenous nanosystems

Diverse problems are ready for work, and their solutions will support a new technology base

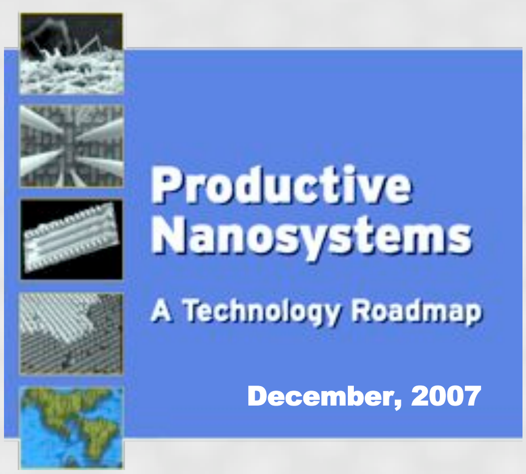
The Battelle roadmap

The circuit-board problem

Modular molecular systems

Challenges and directions

Toward productive nanosystems



Hosts:

Oak Ridge

Brookhaven

Pacific Northwest

Leadership:

Battelle Memorial Institute

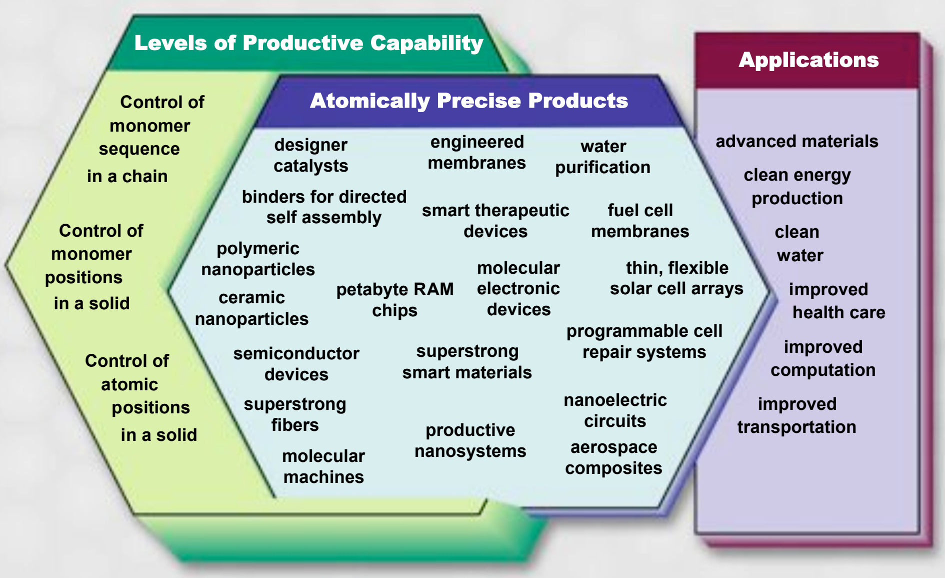
Organized by:

Sponsors:

Hosting National Labs:

Roadmap partners:

Productive Nanosystems: capabilities and applications



The Battelle roadmap

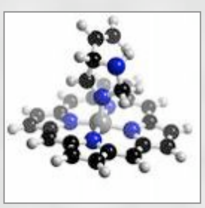
The circuit-board problem

Modular molecular systems

Challenges and directions

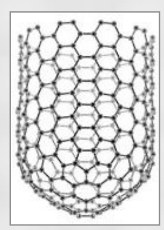
Toward productive nanosystems

Specialized functional structures

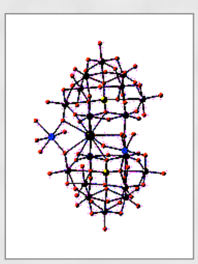


Porphyrins

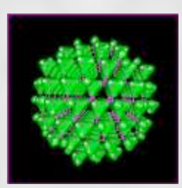
electronic, chemical,
biological, structural,
electronic, optical,
optoelectronic,
electromechanical,
electrochemical...



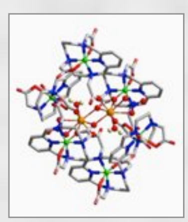
Nanotube segments



Metal-oxide clusters



Quantum dots



Metal complexes

© 2009, K.E.Drexler

What we have: components

Missing pieces: sockets & circuit boards

Modular molecular composite nanosystems:

	~ circuit boards	~ sockets	~ components
	DNA	**Protein***	**Specialized**
Limitations	narrow range of functions, limited binding	small structures, difficult design, slow production	non-modular, seldom much design freedom
Strengths	large structures, easy design, fast production	broad range of functions, versatile binding	unlimited range of materials and functions
Natural roles	structural frames, large-scale pattern organization	assembly interfaces, precise alignment, diverse functions	catalytic, optical, mechanical, electronic...

* and peptoids, other foldamers

Combine *components* to build *systems:*

- 3D atomically precise scaffolds, easily re-configured
- 100s to 1000s of parts in addressable locations

The Battelle roadmap

The circuit-board problem

Modular molecular systems

Challenges and directions

Toward productive nanosystems

Prospective molecular nanosystems:

Components:

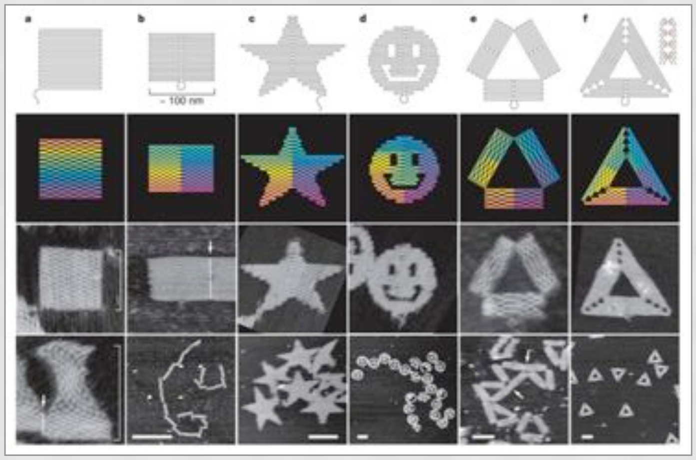
Structure, sockets = DNA, protein, foldamers

Active components = Nanoparticles, nanotubes, metal complexes... (+ DNA, protein, foldamers)

Application systems:

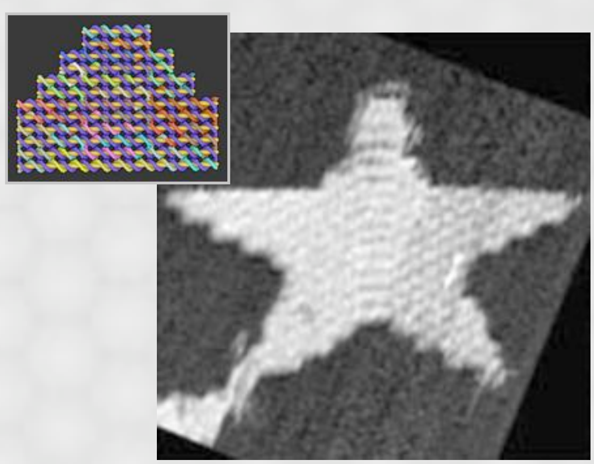
Gene readers, sensors, plasmonic circuits, LEDs, photovoltaics, fuel cells, digital memories, nanoparticle templates, chain synthetases, productive nanosystems...

“Folding DNA to create nanoscale shapes and patterns”



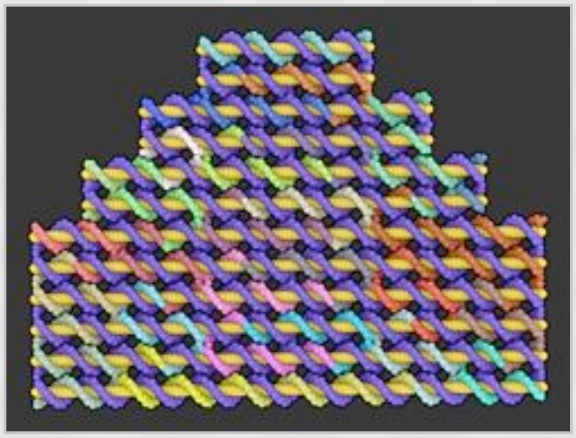
Rothemund P.W.K., *Nature*, 440:297–302 (2006).

Structural DNA nanotechnology: AFM image



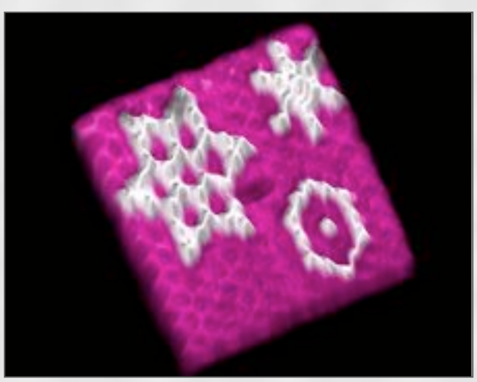
Paul Rothemund, *Nature* 440:297 (2006)

Structural DNA nanotechnology: Design

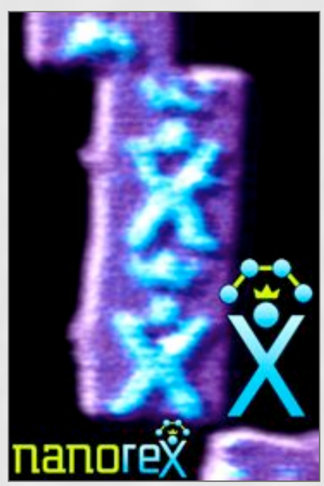


Mark Sims, design using Nanoengineer-1 (2007)

Fast, routine, reliable design & fabrication

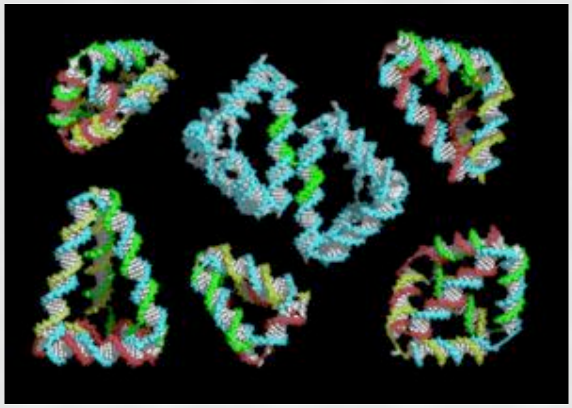


Paul Rothemund (2005).



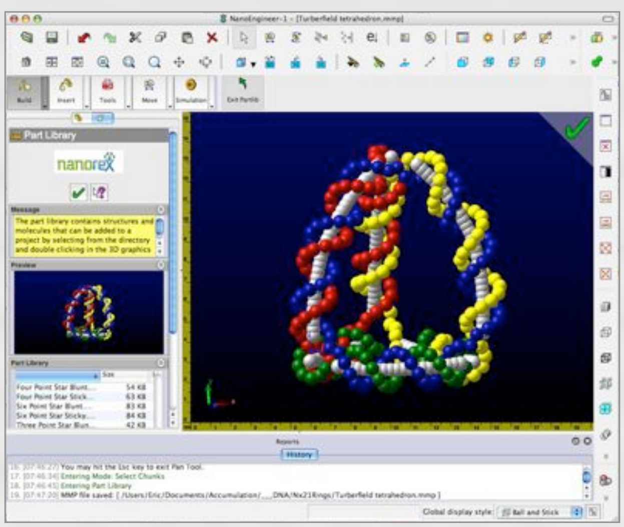
Mark and Erika Sims,
21–25 August (2006)

“Rapid chiral assembly of rigid DNA building blocks for molecular nanofabrication”



~10nm

R. P. Goodman *et al.*, *Science* **310**, 1661 -1665 (2005)



NanoEngineer-1

(Open source, from Nanorex Inc.)

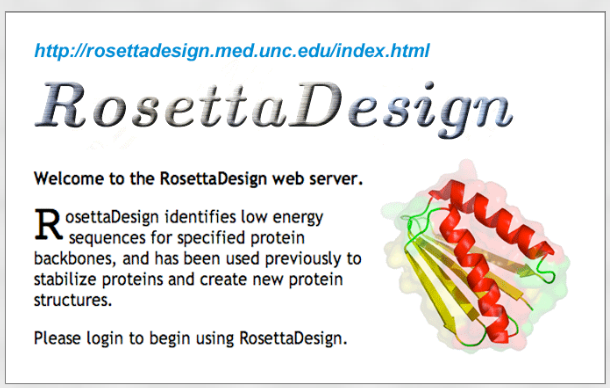
© 2009, K.E.Drexler

"Design of a Novel Globular Protein Fold with Atomic-Level Accuracy"

Kuhlman *et al., Science* **302:**1364–68 (2003)

"RosettaDesign server for protein design"

www.rosettadesign.med.unc.edu



Liu and Kuhlman, *Nucleic Acids Res* **34**:W235–W238 (2006)

DNA/protein interface technology

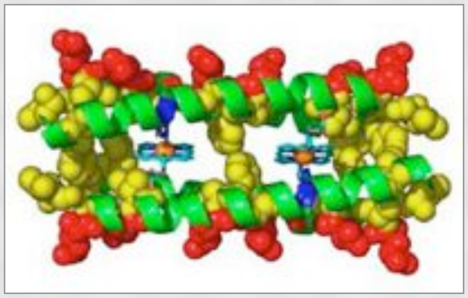
Zinc finger protein (blue) binding DNA (orange)

Zinc-finger design software online

Zinc Finger Consortium, www.zincfingers.org

© 2009, K.E.Drexler

"Computational *de novo* design and characterization of a four-helix bundle protein that selectively binds a non-biological cofactor"



F. V. Cochran *et al., J Am Chem Soc,.* **127**:1346–1347 (2005)

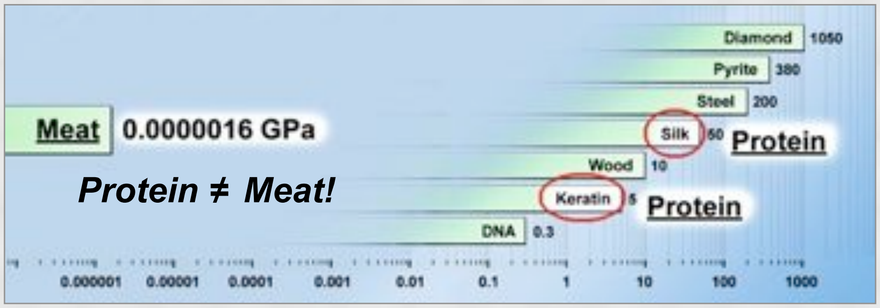
Modular molecular composite nanosystems:

~ circuit boards ~ sockets ~ components

	DNA	Protein*	Specialized
Limitations	narrow range of functions, limited binding	small structures, difficult design, slow production	non-modular, seldom much design freedom
Strengths	large structures, easy design, fast production	broad range of functions, versatile binding	unlimited range of materials and functions
Natural roles	structural frames, large-scale pattern organization	assembly interfaces, precise alignment, diverse functions	catalytic, optical, mechanical, electronic...

* and peptoids, other foldamers

Young's modulus of some biomolecular and inorganic materials



Young's modulus (GPa)

Mechanical stiffness is a key parameter for restricting thermal fluctuations

The Battelle roadmap

The circuit-board problem

Modular molecular systems

Challenges and directions

Toward productive nanosystems

Structural DNA engineering:

~100 nm scale; 10^6 atoms; 10^3 addressable binding sites; ~10^{11+} instances per run

~$1,000 for major variant structures;
~1 day production cycle; good predictability;
$/mg, prospect of $/kg (G. Church roadmap)

Challenges and limitations: defect rate; stiffness/flexibility; substrate attachment; physical stability; need better design software; characterization bottleneck

— *need more cryo-electron tomography facilities!* —

Foldamer engineering:

~3 nm scale; 10^3 atoms; generalized binding capabilities; ~10^{16+} instances per run

Proteins: $? per structure; ~30 day production cycle (~1 day with cell-free translation systems); software design tools give moderate predictability;

Peptoids: low equipment investment;
~$100 per structure; ~1 day production cycle; limited software design tools and predictability

Challenges and limitations : defect rates; physical and chemical stability; need for better design software; characterization bottleneck

Special-structure development:

1 – 10^{3+} nm scale; 10^{2+} atoms; 1 to 10^{23+} instances per production run

Highly variable costs, production cycle times, characterization requirements

Challenges and limitations: diversity of methodologies, lack of broad combinatorial design spaces

Examples of potential applications:

"Nanochips in microsockets" for general purpose digital systems
(a major yield/reliability challenge)

Epitaxial macromolecular crystals on nanolithographic patterns: stacked RAM cells for petabit chips
(a lesser yield/reliability challenge)

Gene readers, workbenches for nanoscience
(moderate reliability typically OK)

Defect and stability issues, approaches:

Defect reduction by solution-phase separation

– Solubility-engineering techniques and constraints
– Design to facilitate separation

Stabilization by post-processing

– Transfer to non-aqueous or dry environment
– Cross-linking, coating, or embedding
– Dissolution, etching, or pyrolysis of organics

The Battelle roadmap

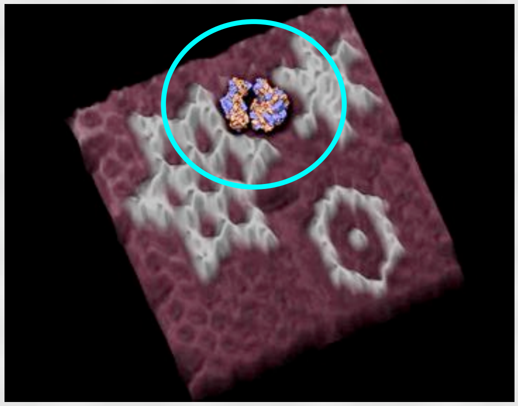
The circuit-board problem

Modular molecular systems

Design and design domains

Toward productive nanosystems

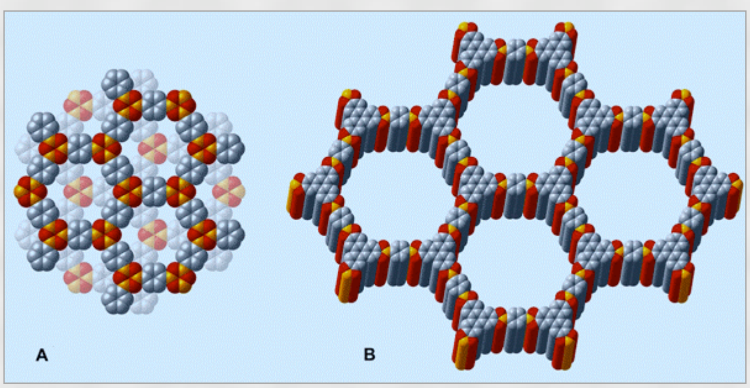
Ribosome shown to scale: A ~25 nm nucleoprotein-based productive nanosystem for peptide foldamers



Biomimetic targets: Productive nanosystems for artificial foldamers

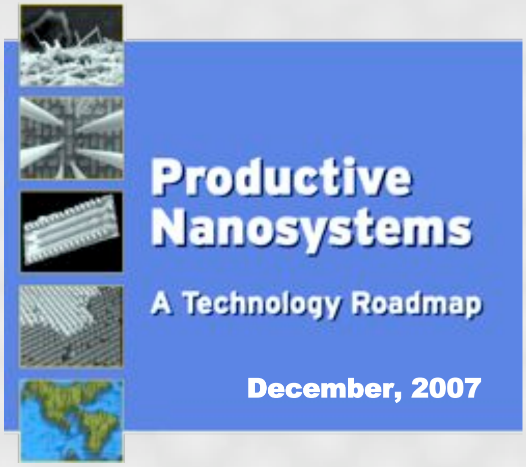
More advanced targets: Productive nanosystems for 2D, 3D structures

"Structural representations of (A) COF-1 and (B) COF-5 based on powder diffraction and modelling projected along their c axes (H atoms are omitted)"



A range of crystalline structures (metal-organic frameworks) assembled from synthetic building blocks under mild conditions

A. P. Côté et al., *Science,* **310:**1166 -1170 (2005)



Hosts:

Oak Ridge
Brookhaven
Pacific Northwest

Leadership:

Battelle Memorial Institute

For downloads: ericdrexler.com/roadmap

Take-away messages revisited:

Paths are now open toward complex, self-assembled, heterogenous nanosystems

Diverse problems are ready for work, and their solutions will support a new technology base

On the web:

Website:

ericdrexler.com

Blog:

ericdrexler.com/blog

Technology Roadmap:

ericdrexler.com/roadmap