BOISE STATE UNIVERSITY

# Atomic Force, Optical, and Super-Resolution Microscopy of DNA-Based Nanostructures

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*Micron School Materials Science & Engineering*

*Boise State University*

Advances in Structural & Chemical Imaging (ASCI) Workshop

20 May 2016

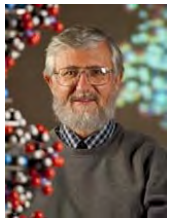
PREMIER NETWORK

Boise State University Nanoscale Materials and Device Group

## Acknowledgments

- Nanoscale Materials & Device Group: Faculty & Staff

Bill Knowlton


Bernard Yurke

Wan Kuang

Jeunghoon Lee

Will Hughes

Natalya Hallstrom

Paul Davis

Reza Zadegan

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# Acknowledgments

- Nanoscale Materials & Device Group: Students

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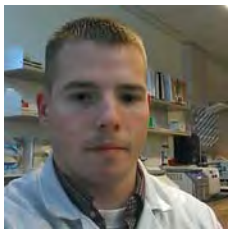
# Acknowledgments

- Students

Sadao Takabayashi

Juan Flores-Estrada

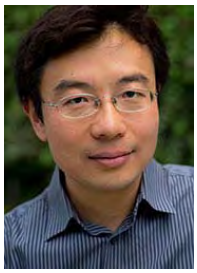


Will Klein

Nick Schmidt

- Collaborators

Dr. Scott Sills
*Micron Technology*



Dr. Peng Yin
*Harvard University*

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# Acknowledgments


## Funding

- W.M. Keck Foundation
- National Science Foundation
- Micron Foundation
- Semiconductor Research Corporation
- NASA Idaho Space Grant Consortium
- DARPA
- Osher Lifelong Learning Institute
- National Institutes of Health
- INBRE Program of the National Center for Research Resources


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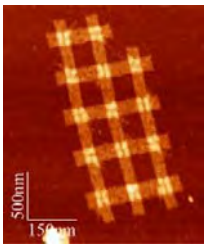
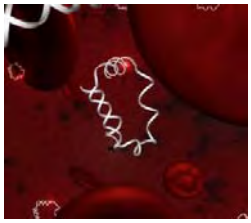
# Nanoscale Materials & Device Group

- What do we do?

- **Engineering DNA to enable control of material structure and properties at the nanometer scale.**



***Nanophotonics*** ***Nanofabrication*** ***Biosensors*** ***Nucleic Acid Memory***

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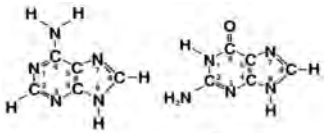
# Nucleotides

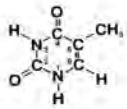
Nucleotides = Base + Sugar + Phosphate Group



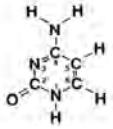
**Adenine (A)**



**Guanine (G)**

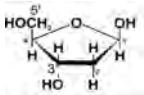


**Thymine (T)**

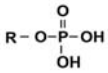


**Cytosine (C)**

Sinden, R. R. (1994). *DNA structure and function*. San Diego: Academic Press.

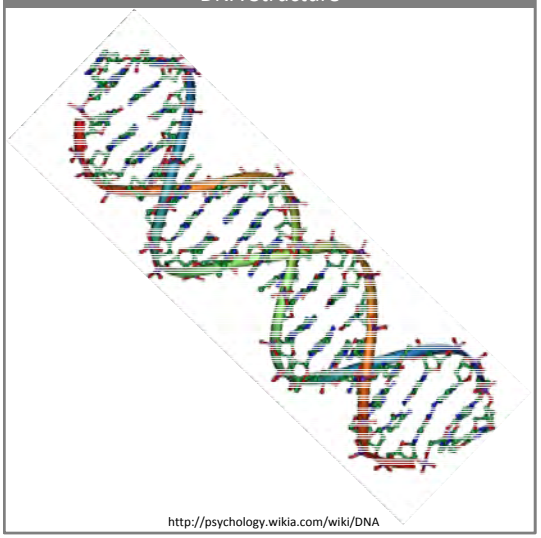


β-D-2-Deoxyribose



Phosphate

DNA Structure



http://psychology.wikia.com/wiki/DNA

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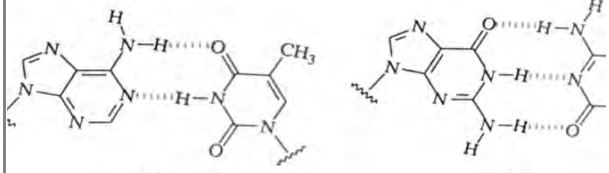
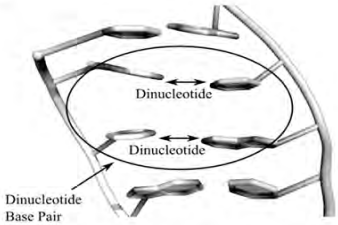
# Hybridization

Hybridization = Hydrogen Bonding + Base Stacking

**Adenine-Thymine (A-T)** **Guanine-Cytosine (G-C)**



(a) (b)




(c)

Sinden, R. R. (1994). *DNA structure and function*. San Diego: Academic Press.

## Hydrogen Bonding

- 2-3 kcal/mole

## Base Stacking

- π–π interactions
- Van der Waals
- Hydrophobic interactions

| Base Pairs | Stacking Energies (kcal/mol) |
|---|---|
| (GC)-(GC) | -14.59 |
| (CA)-(TG) | -10.51 |
| (GA)-(TC) | -9.81 |
| (CG)-(CG) | -9.69 |
| (CC)-(GG) | -8.26 |
| (AG)-(CT) | -6.78 |
| (AC)-(GT) | -6.57 |
| (AT)-(AT) | -6.57 |
| (AA)-(TT) | -5.37 |
| (TA)-(TA) | -3.82 |

Kabsch et al. (1982)

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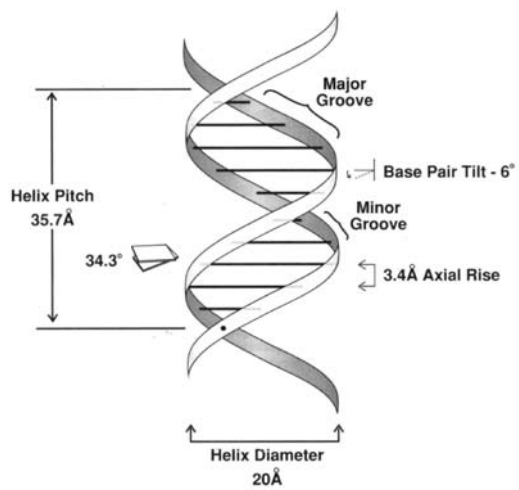
# Geometry

Angular Dependence Double Stranded B-Form DNA




Sinden, R. R. (1994). *DNA structure and function*. San Diego: Academic Press.

STRUCTURAL FORMS
- A, B, Z-form DNA
- B-form is adopted

HELICAL TURN
- ~10.5 bp per turn
- 34.3° rotation per residue

| Base Pairs | Twist Angle (deg) |
|---|---|
| (GC)-(GC) | 40.0 ± 1.2 |
| (CA)-(TG) | 34.5 ± 0.9 |
| (GA)-(TC) | 36.9 ± 0.9 |
| (CG)-(CG) | 29.8 ± 1.1 |
| (CC)-(GG) | 33.7 ± 0.1 |
| (AG)-(CT) | 27.7 ± 1.5 |
| (AC)-(GT) | 34.4 ± 1.3 |
| (AT)-(AT) | 31.5 ± 1.1 |
| (AA)-(TT) | 35.6 ± 0.1 |
| (TA)-(TA) | 36.0 ± 1.0 |

Ornstein et al. (1978)

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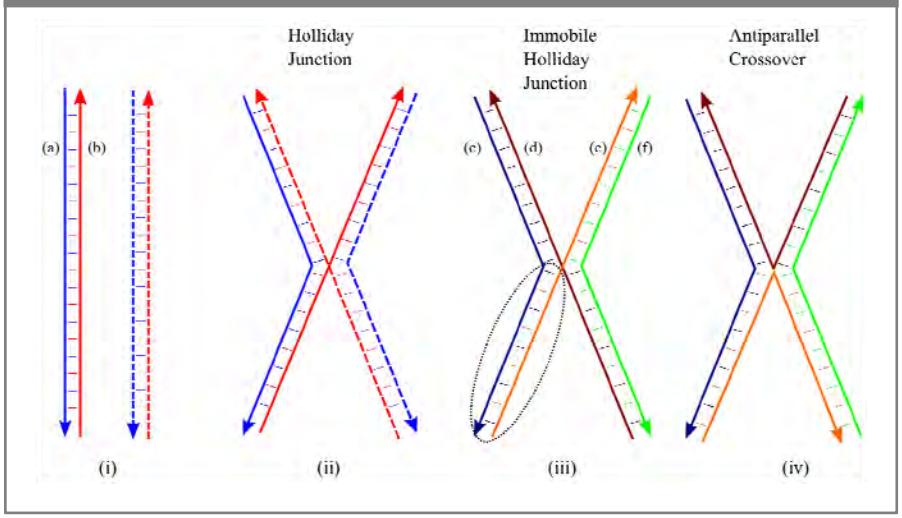
# Structures

DNA Branched Junctions




STRUCTURAL CROSS MEMBERS – for scaffolding applications

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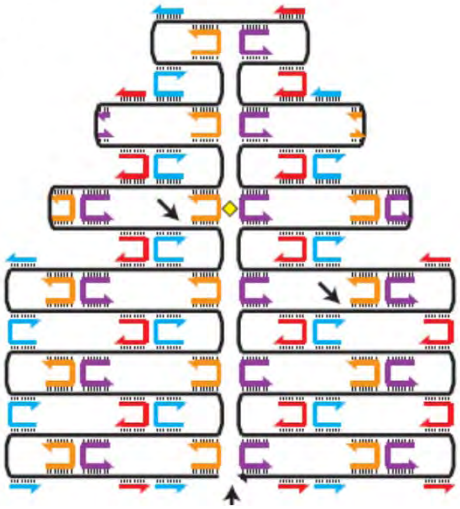
# DNA Origami

- Forming specific shapes with DNA by folding long single-stranded DNA using short “staple” strands
- Using DNA to build structures - Ned Seeman
- DNA Origami - Paul Rothemund



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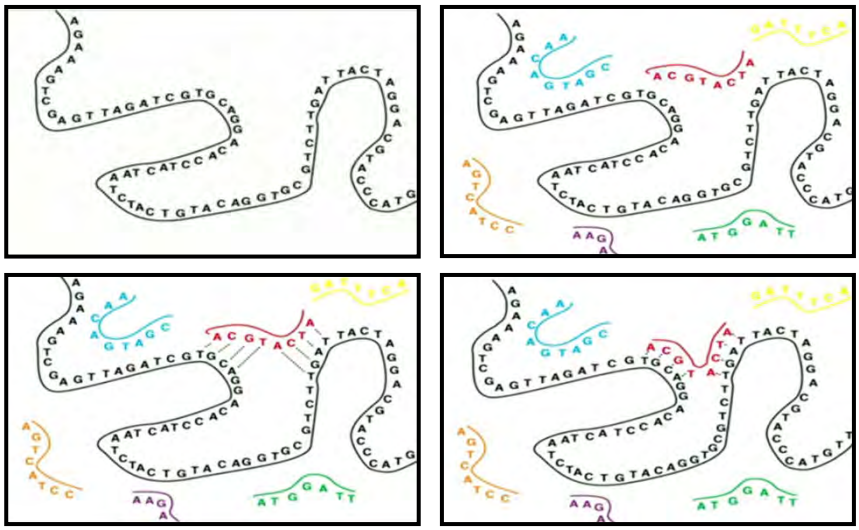
# DNA Origami

- Each staple strand binds to multiple locations of the scaffold strand.



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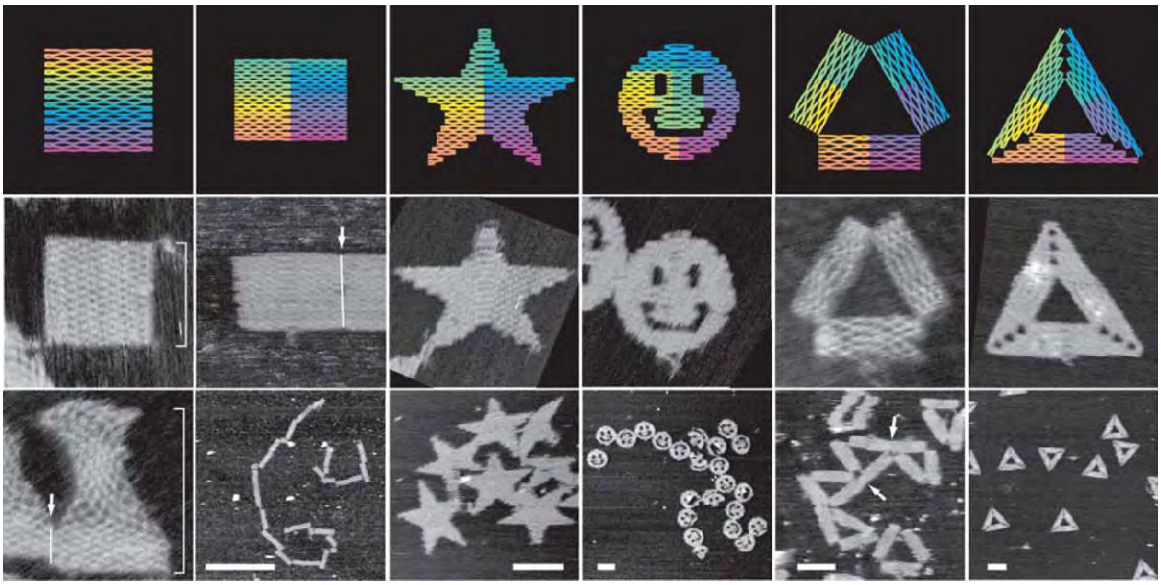
# 2D DNA Origami



P. Rothemund, *Nature*,440, 16 (2006)

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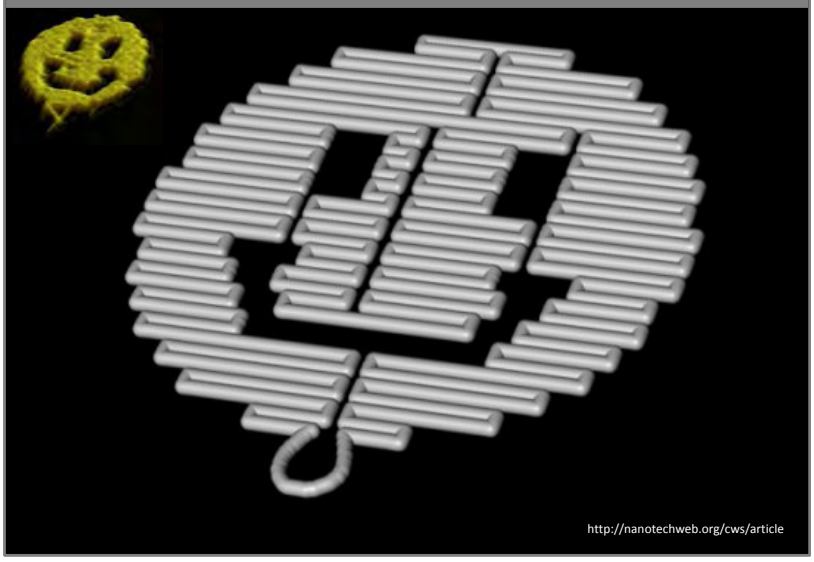
# DNA Origami

Three-hole disk

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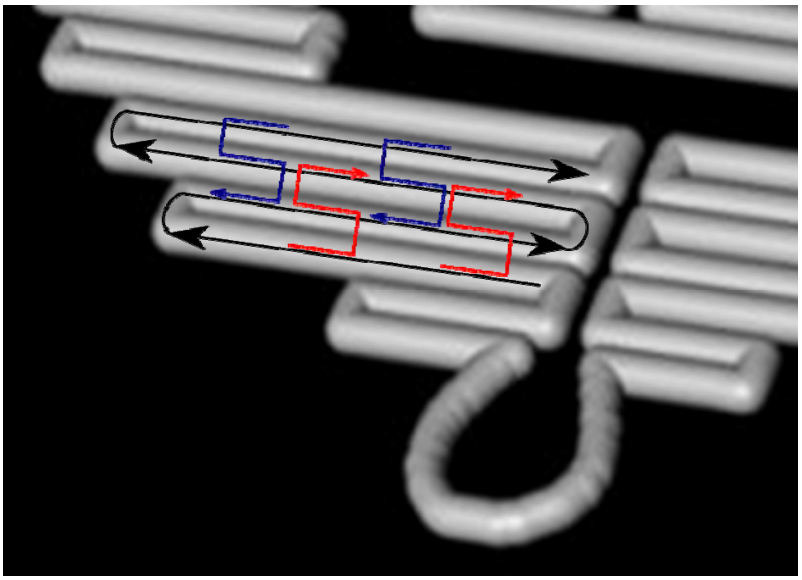
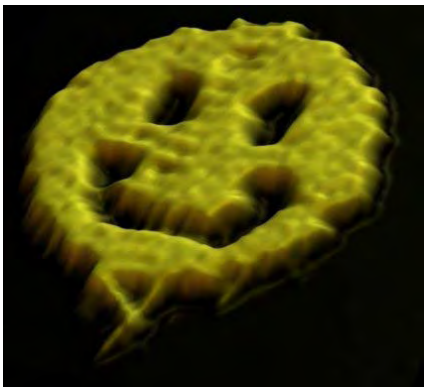
# DNA Origami





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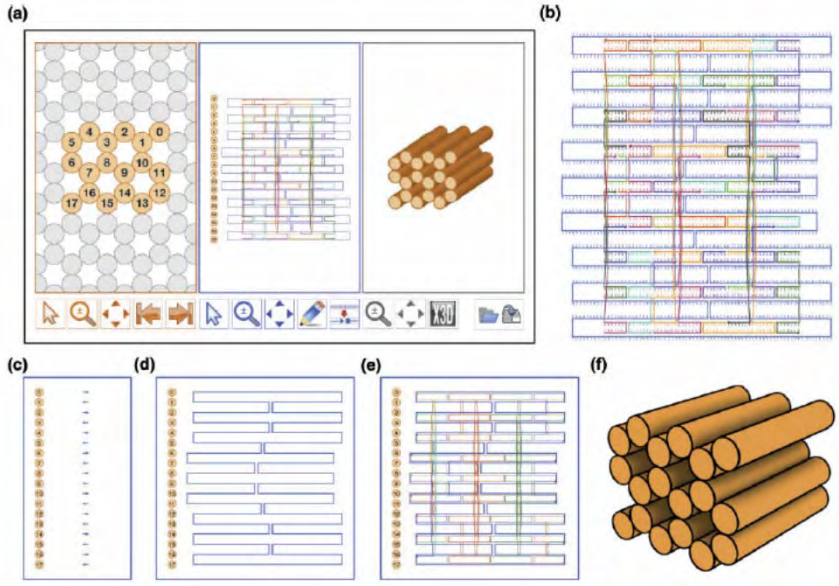
# DNA Origami CAD




S.M. Douglas et al., *Nucl. Acid. Res.* 37 (2009).

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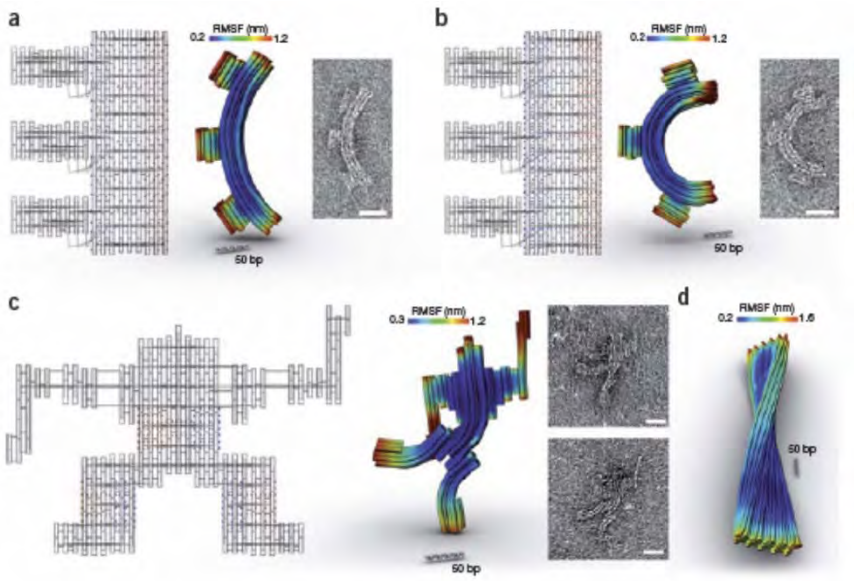
# 3D DNA Origami Modeling




C.E. Castro et al., *Nat. Meth.* 8 (2011).

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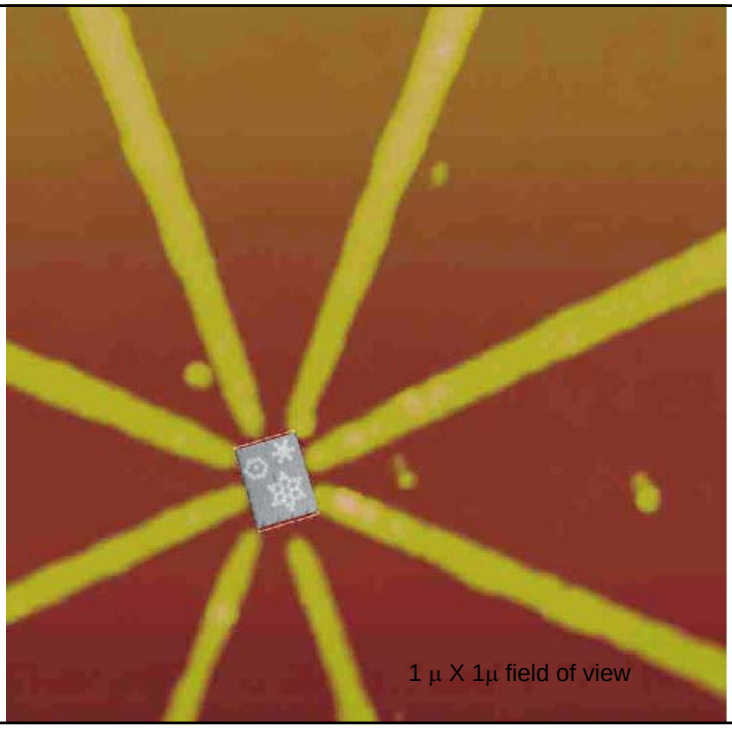


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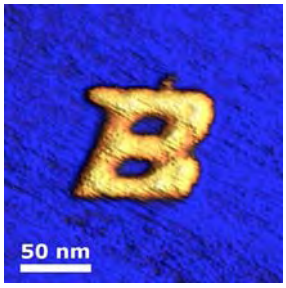
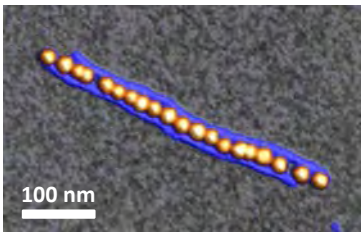
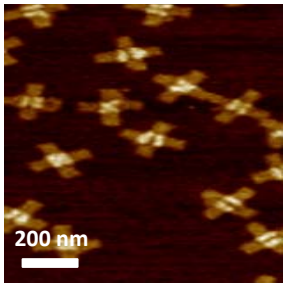
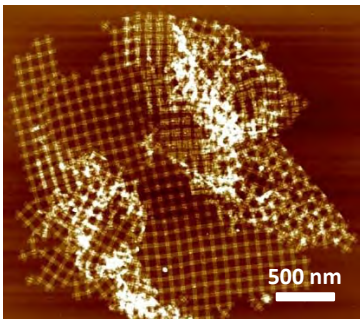
## DNA Origami at Boise State

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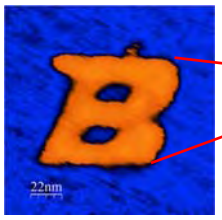
## Scale



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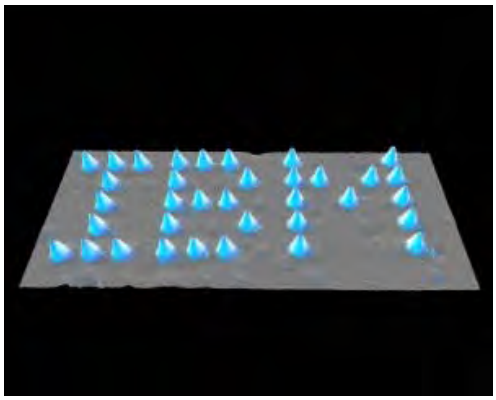
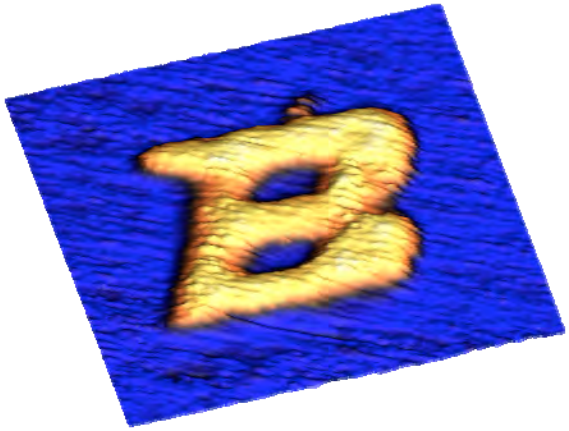
# Throughput





Fabrication time: 39 hours
Yield: ~$10^0$ (1)
# of atoms: 35

Fabrication time: 4 hours
Yield: ~$10^{12}$ (1 trillion)
# of atoms: ~46,000

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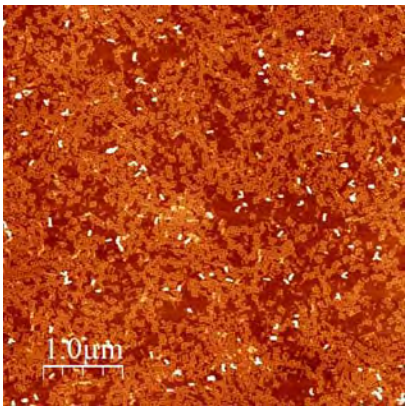
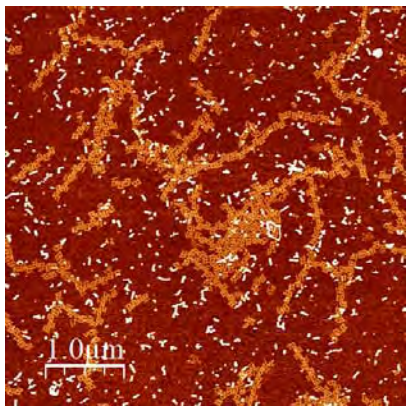
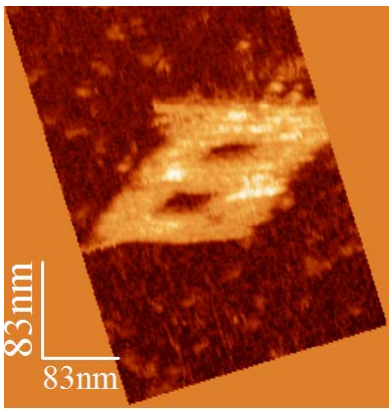
# DNA Origami at Boise State

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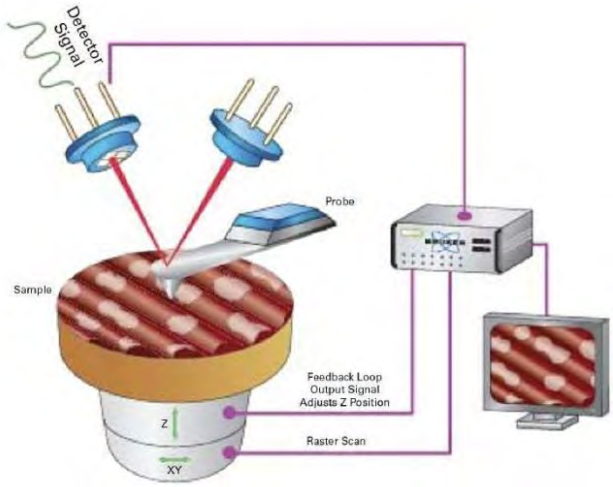
# Atomic Force Microscopy (AFM)




- Cantilever deflection is monitored as probe rasters across surface.
- Feedback electronics control piezoelectric actuators to compensate for changing topography.

http://virtual.itg.uiuc.edu/training/AFM_tutorial/

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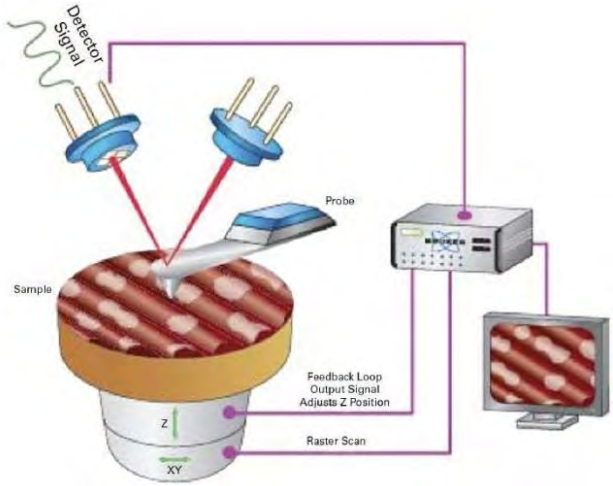
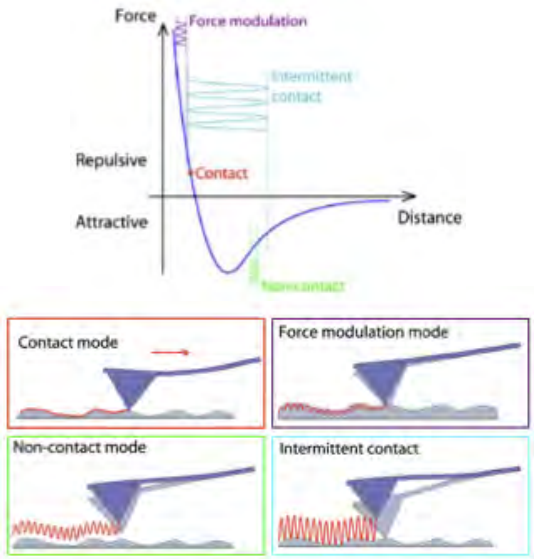
# AFM Topographic Modes

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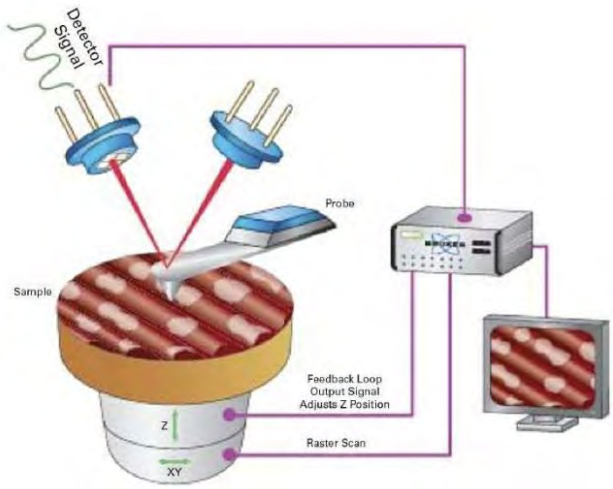
# What can you do with AFM?




- Topography
  - Surface Roughness
  - Particle Analysis
  - Morphology
- Material Properties
  - Mechanical
  - Magnetic
  - Electrical
  - Optical
  - Chemical
- Correlate with other techniques

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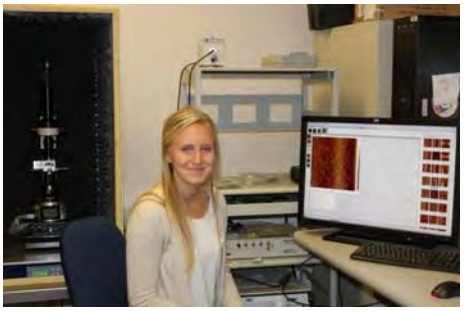
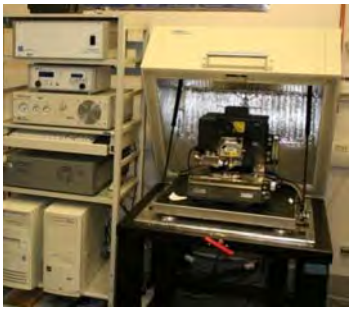
# Surface Science Lab (SSL) Equipment

- Bruker Dimension Icon/BioFastScan AFM
- Bruker MultiMode 8 AFM
- Bruker Dimension 3100 AFM with Hysitron TS 75 TriboScope Nanoindenter
- Phenom SEM

Icon/BioFastScan



MultiMode 8



3100

nano.boisestate.edu/ssl

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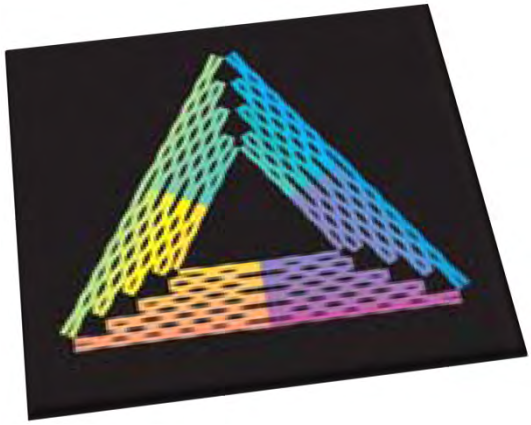
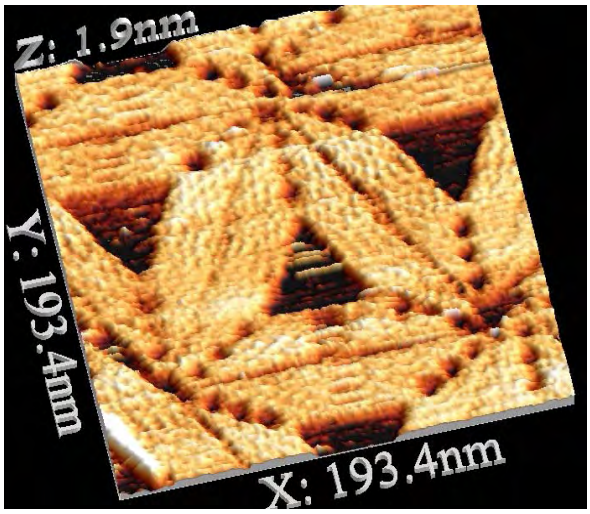
# High Resolution AFM in Fluid






PeakForce Tapping Mode in Fluid

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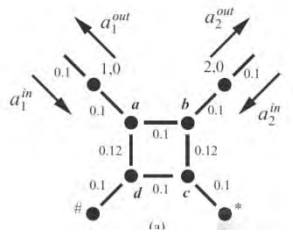
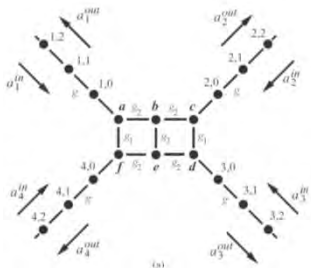
## DNA-Based Nanophotonics

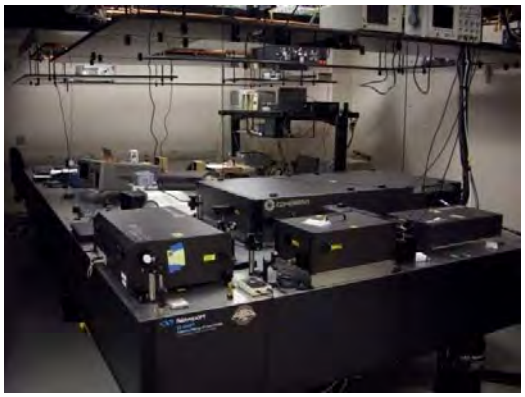
- Plasmonic Transport

Phase Shifter



Crossover Splitter





Controlling information at the nanoscale

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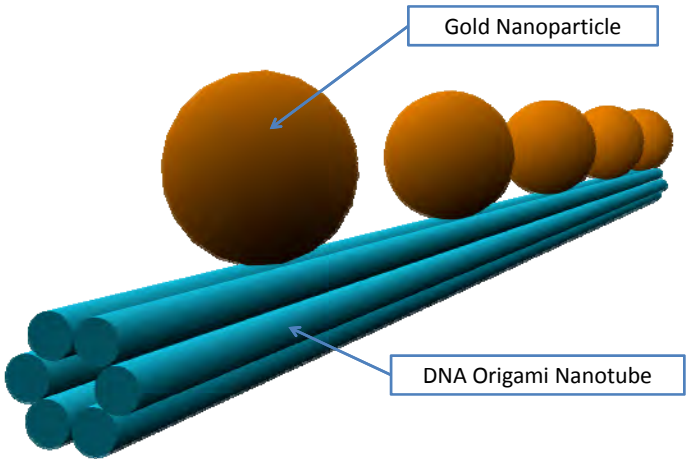
Yurke & Kuang, *Phys. Rev. A* 81 (2010).

## DNA Origami Nanotube for Nanoparticle Arrays

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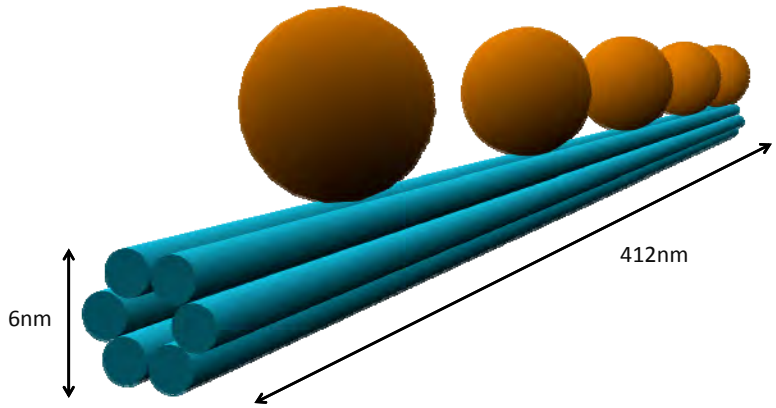
## DNA Origami Nanotube for Nanoparticle Arrays

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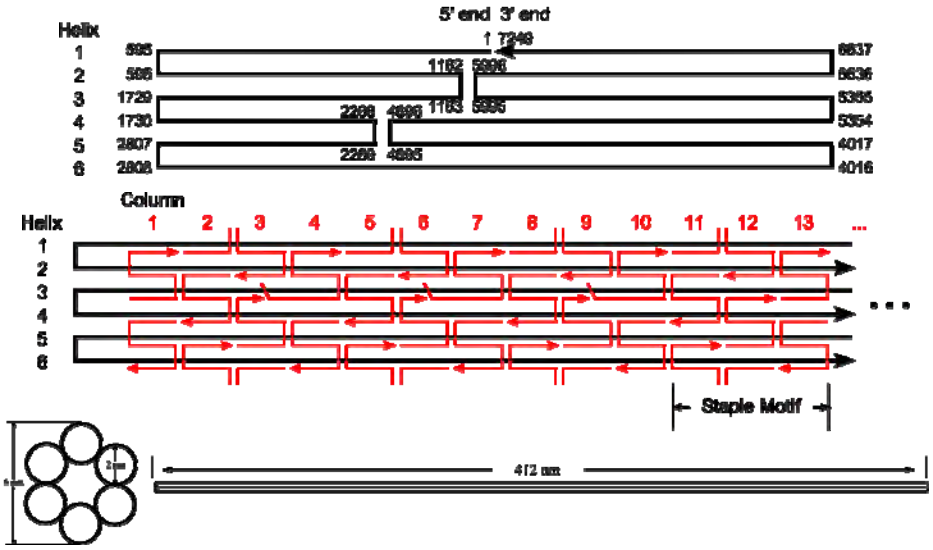
# DNA Origami Nanotube Design




H. Bui et al., *Nano Lett*. 10 (2010).

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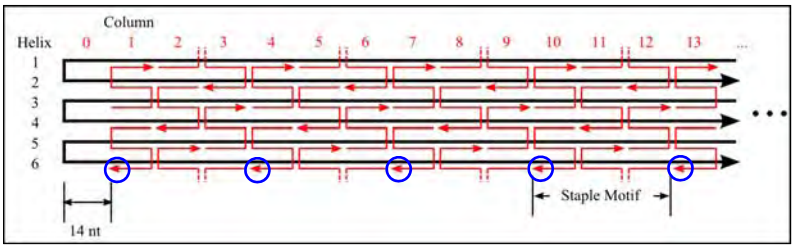
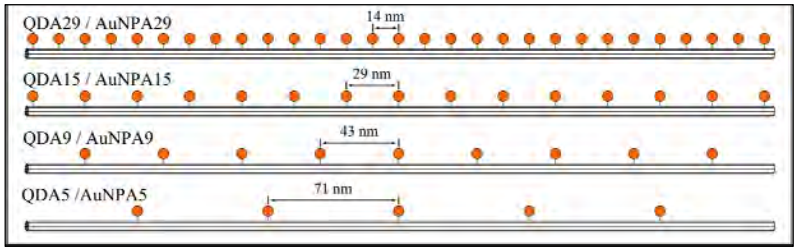
# DNA Origami Nanotube Nanoparticle Arrays




H. Bui et al., *Nano Lett*. 10 (2010).

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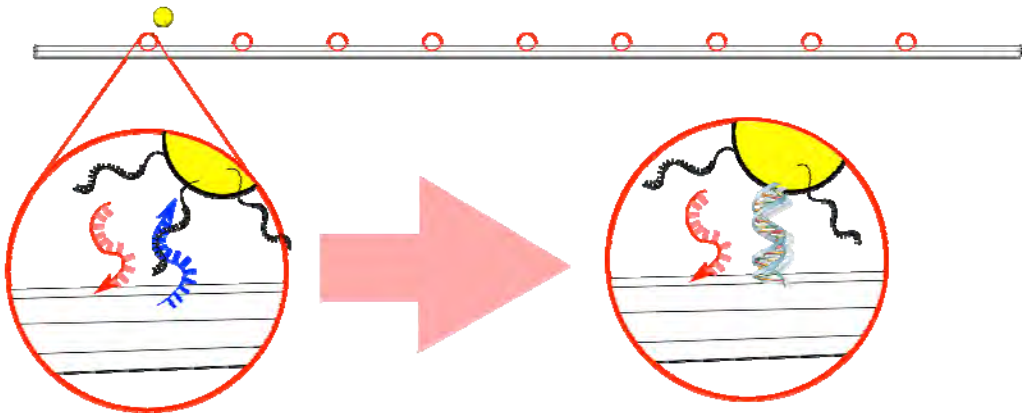
# DNA Origami Nanotube AuNP Arrays



S. Takabayashi et al., *Nanoscale* 6 (2014).

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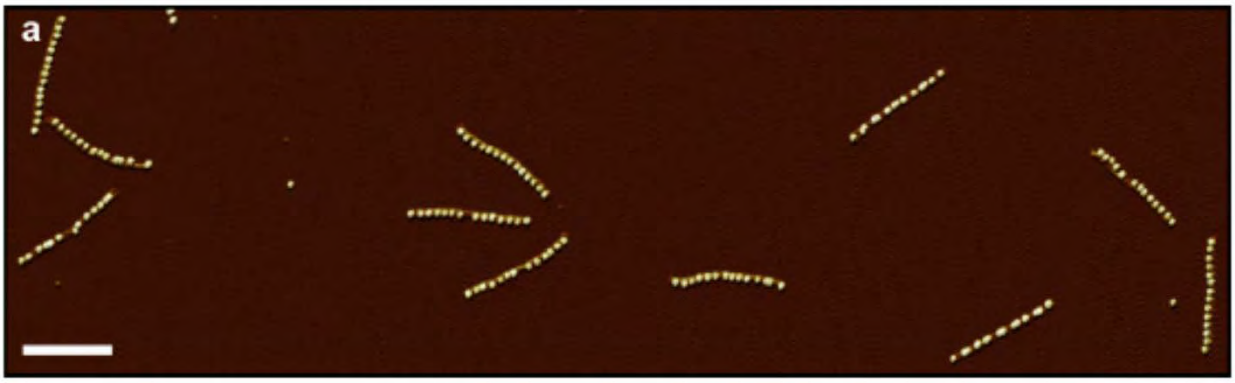
# DNA Origami Nanotube AuNP Arrays




S. Takabayashi et al., *Nanoscale* 6 (2014).

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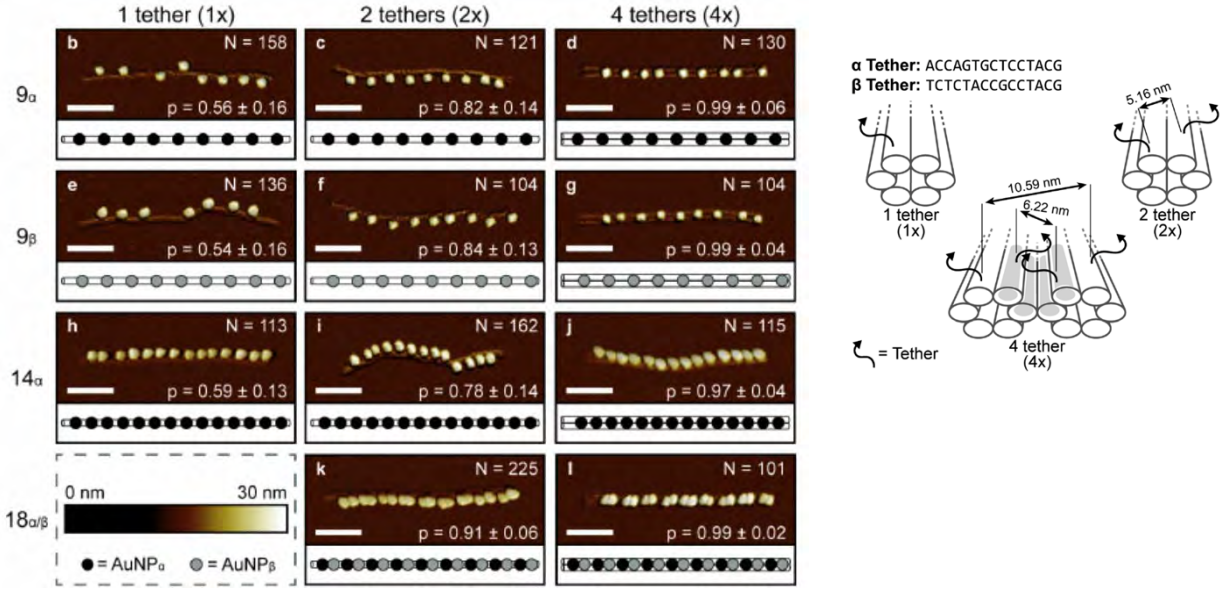
# DNA Origami Nanotube AuNP Arrays




S. Takabayashi et al., *Nanoscale* 6 (2014).

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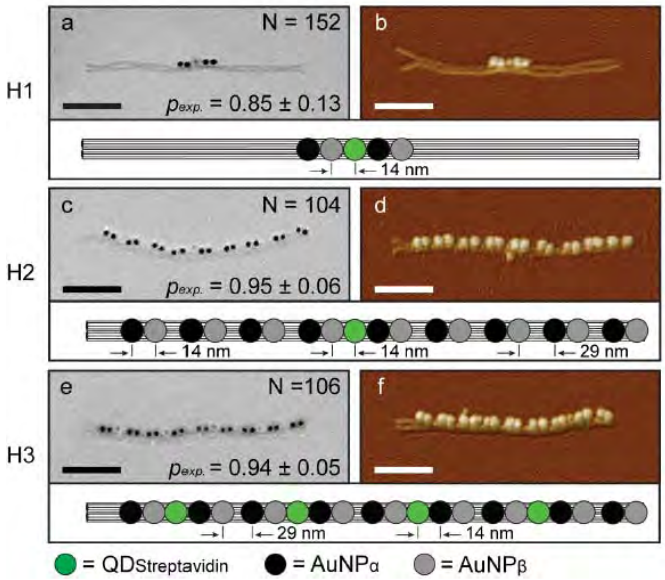
# DNA Origami Nanotube AuNP Arrays




S. Takabayashi et al., *Nanoscale* 6 (2014).

Scale bars: 100nm

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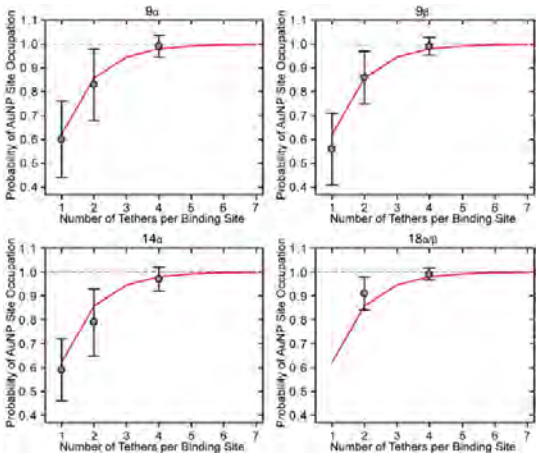
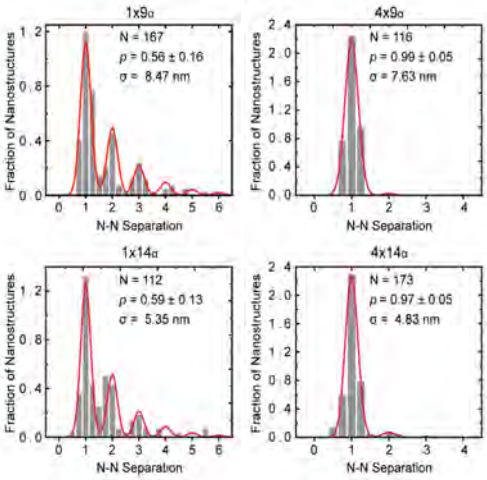
# DNA Origami Nanotube AuNP Arrays

## Yields

### Probability of Attachment




### Precision of Attachment




S. Takabayashi et al., *Nanoscale* 6 (2014).

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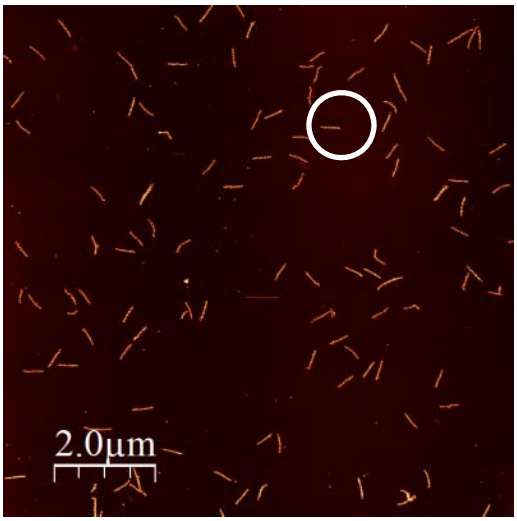
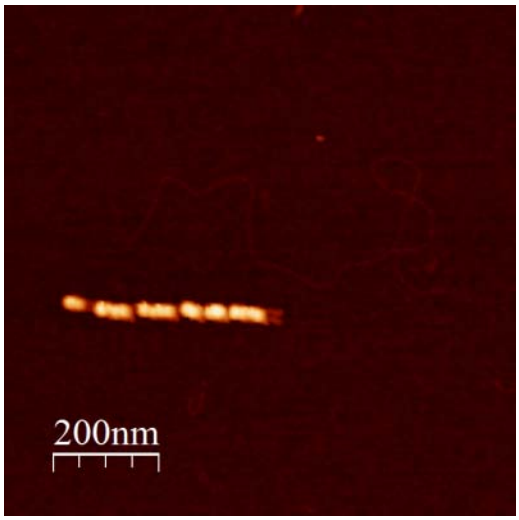
# High Resolution, Large Area Scanning




S. Takabayashi et al. *Nanoscale* 6 (2014).
R. Schreiber et al. *Nat. Comm.* 4 (2013).
W.P. Klein et al. *Nano Lett.* 13 (2013).

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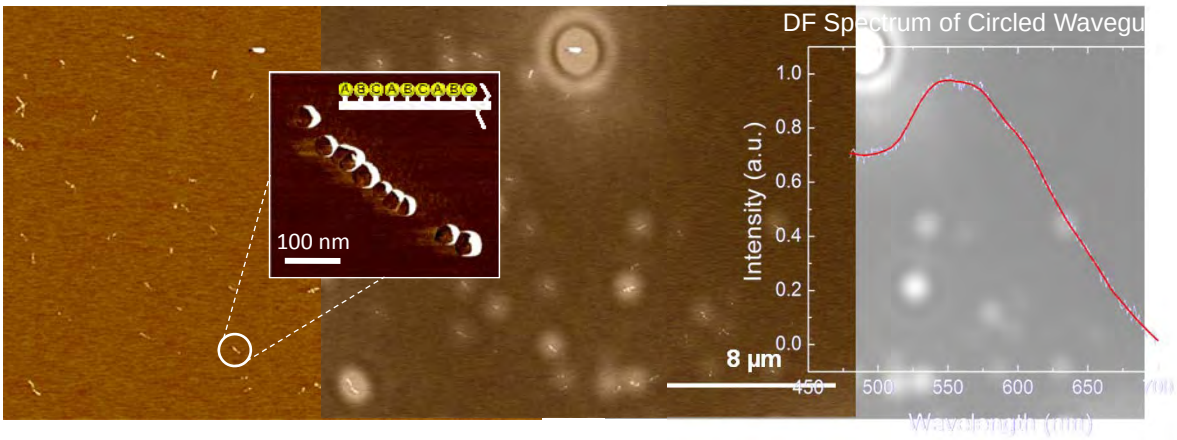
# AFM & Dark Field Microscopy

1. AFM Scan

3. DF Image Overlay on AFM Scan

2. DF Image 100X OBJ




- Four 20 µm x 20 µm AFM scans stitched together.
- 100x DF image resized to match the scale of the AFM scan

DF image is made transparent and overlaid on top of the AFM scan

W.P. Klein, et al. *Nano Lett.* 13 (2013).

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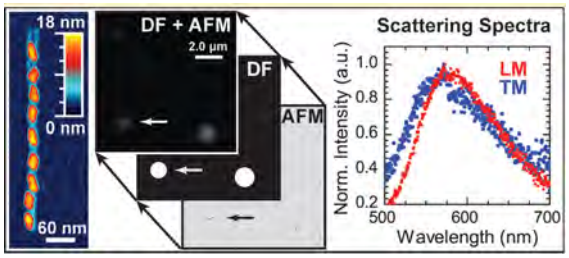
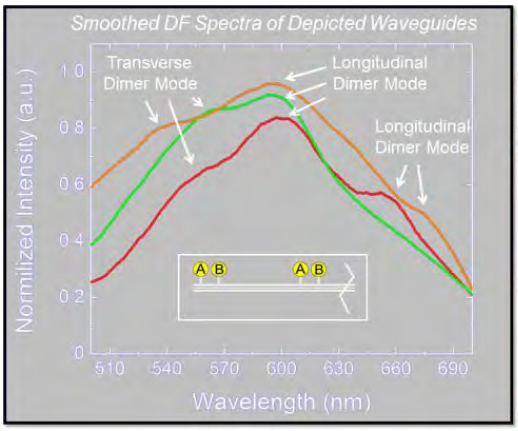
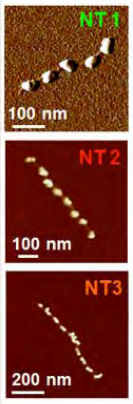
# AFM & Dark Field Microscopy




- For dia. < 80-120 nm
- Rayleigh Scattering
- Photon absorption
- Creation of *surface plasmons*
- Dipole-dipole coupling results in red shift
- Waveguide non-spherical shape → additional *plasmon modes*

W.P. Klein, et al. *Nano Lett.* 13 (2013).

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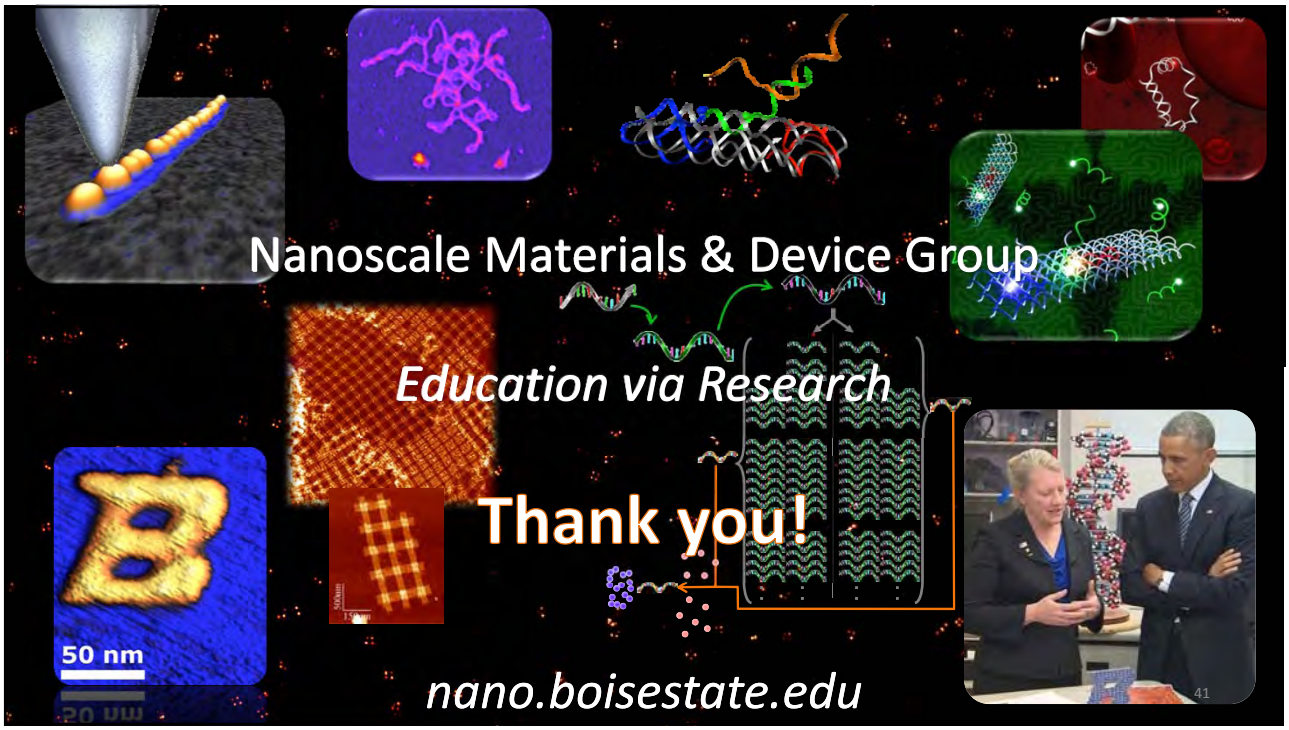
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Education via Research
Thank you!
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