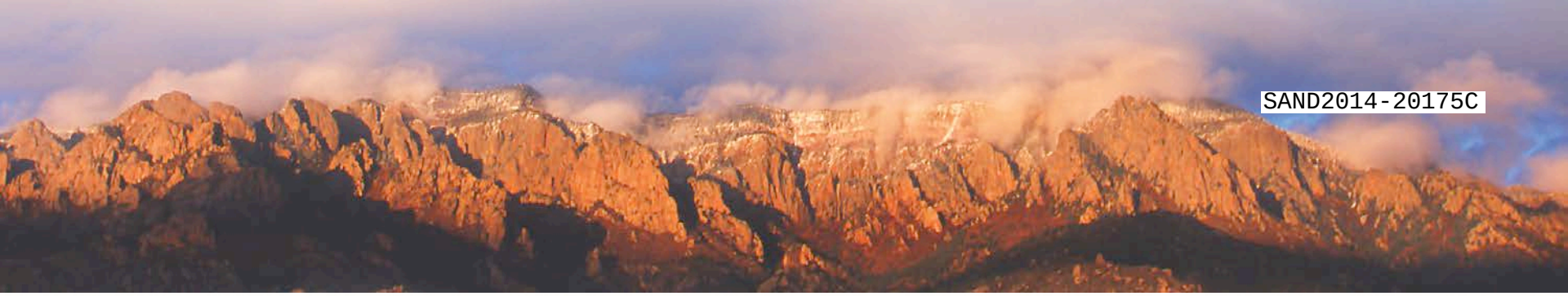


SAND2014-20175C

Directed Self-Assembly of 1D Microtubule Nano-Arrays

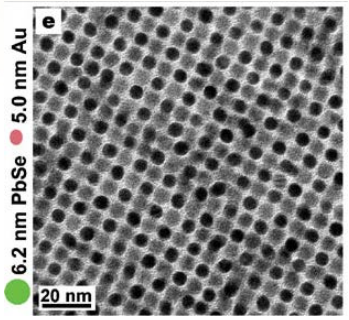
Marlene Bachand, Shengfeng Cheng, Nathan Bouxsein, Mark Stevens, and George D. Bachand

2014 MRS Fall Meeting
Symposium F: Reverse Engineering of Bioinspired Nanomaterials

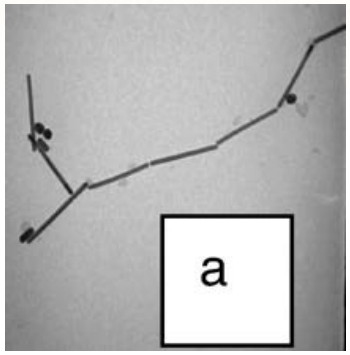
December 3, 2014

Self-Assembly of Nanoscale Building Blocks

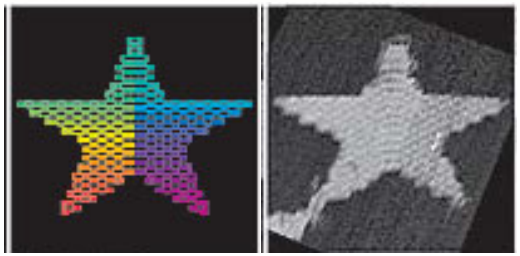
Large numbers of short-range interactions can be tailored to self-assemble nanoscale materials increasing structural and functional complexity.



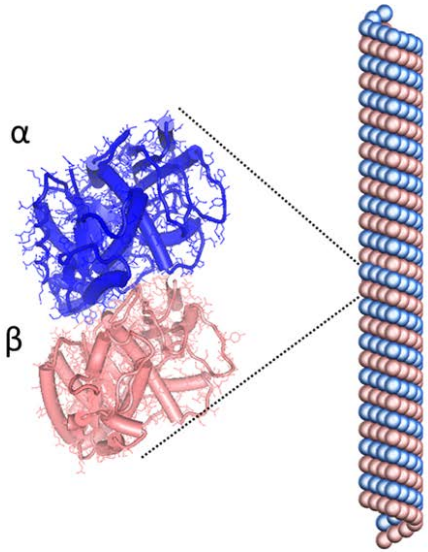
Shevchenko et al., *Nature* **439**, 55 (2006)

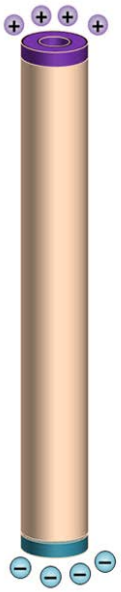


Caswell et al., *JACS* **125**, 13914 (2003)



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





Microtubules (MTs):

- Hollow filament – 25 nm diameter, 10s of microns in length; intrinsic anisotropy/polarity
- Persistence length ~5 mm; linear charge density of ~260e^{-} μm^{-1}
- Highly dynamic; stabilized *in vitro* w/ taxol
- Electrostatically repulsive rigid rods with attractive ends

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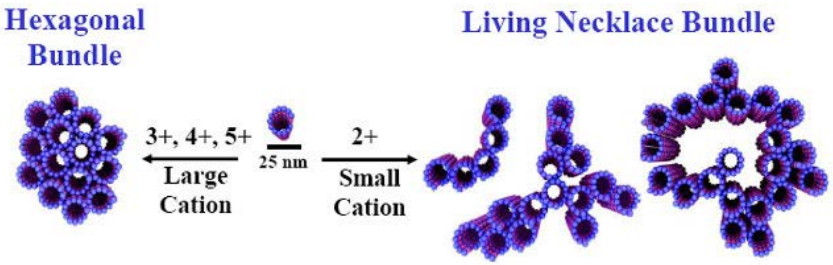
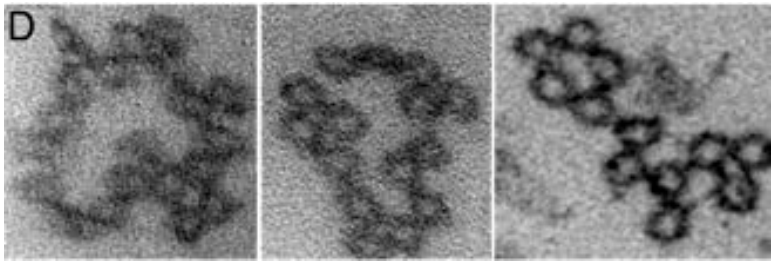
Higher Order Assemblies of Microtubules

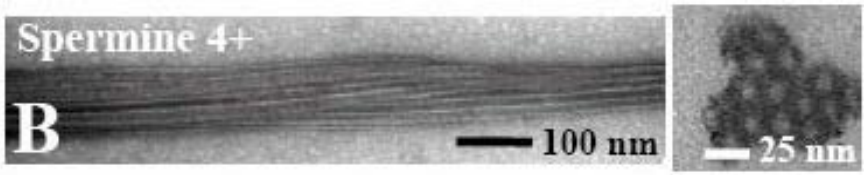
Lateral self-assembly

MTs bundles form in the presence of multivalent metal ions

- Short-range attractions caused by counterions form microtubule bundles



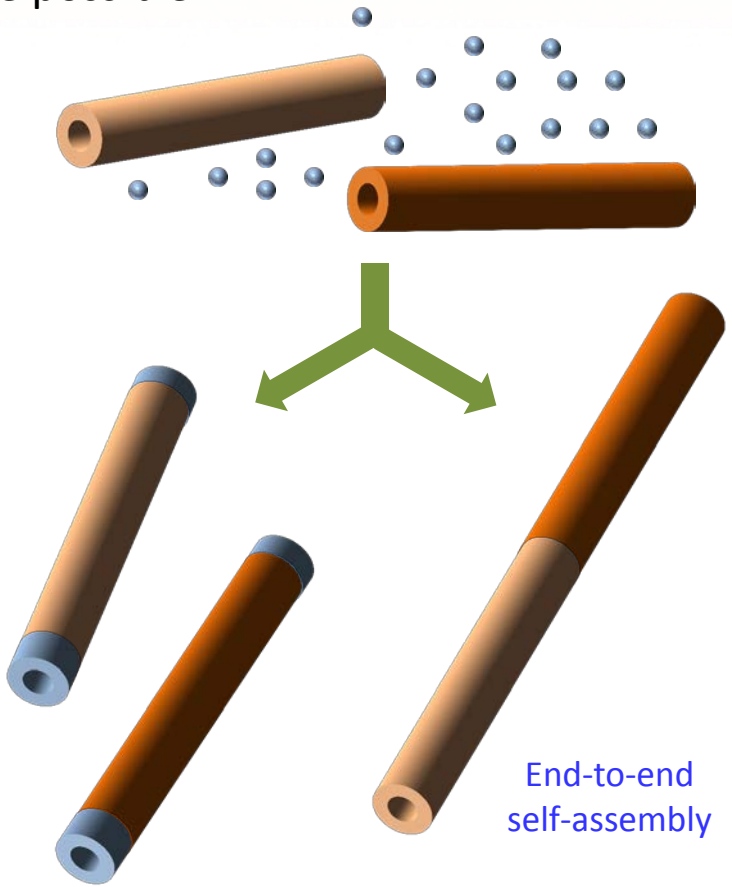




Needleman et al., *Proc. Nat. Acad. Sci.* **101**, 16099 (2004)

Longitudinal self-assembly?

End-to-end self-assembly of MTs may also be possible



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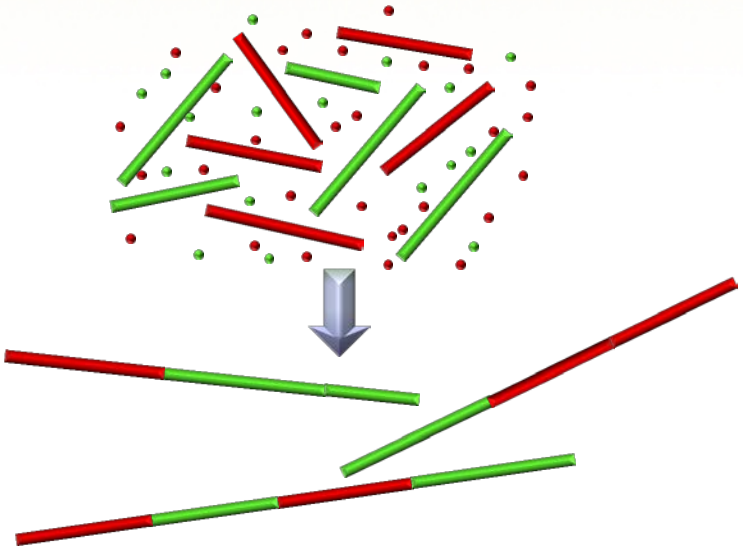
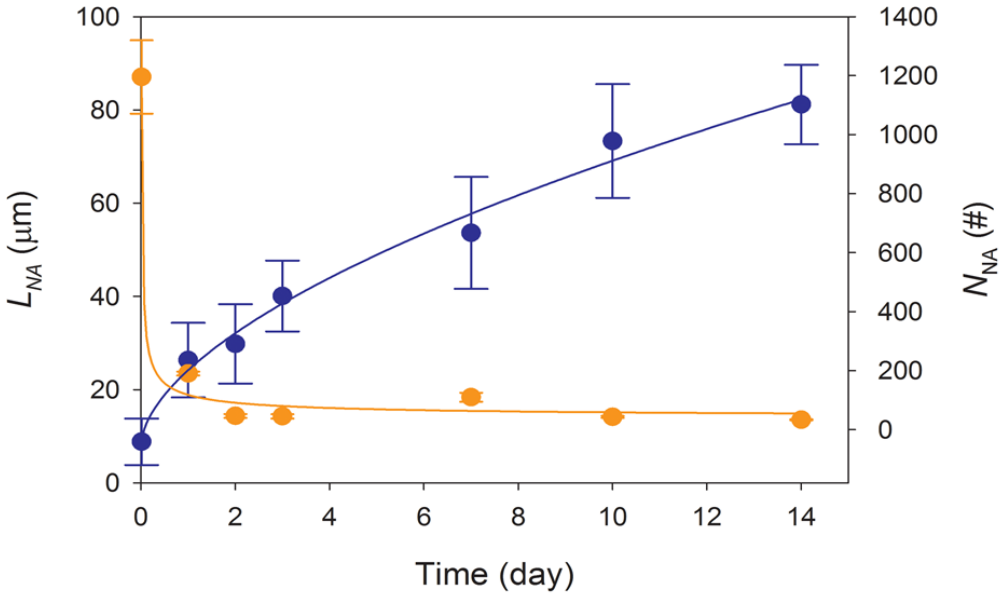
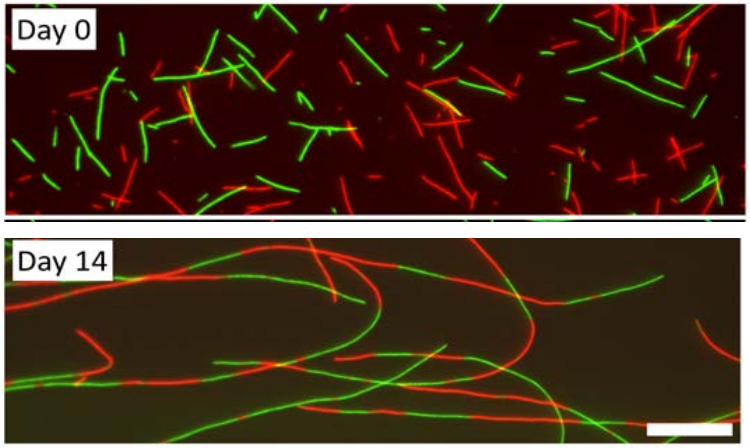
Directed Self-assembly (DSA) of MTs

Taxol-stabilized MTs self-assemble head-to-tail to form extended 1D oligomeric nano-arrays (NAs)







- Average length increased by >10–fold over 14 days
- Δ in the number & length of NAs inversely correlated (Spearman rank correlation = -0.893; $P < 0.001$)
- Δ in length = DSA, not seeded polymerization

Bachand et al., *RSC Adv*. **4,** 51641 (2014)

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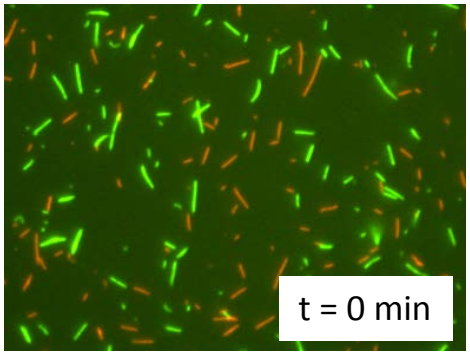
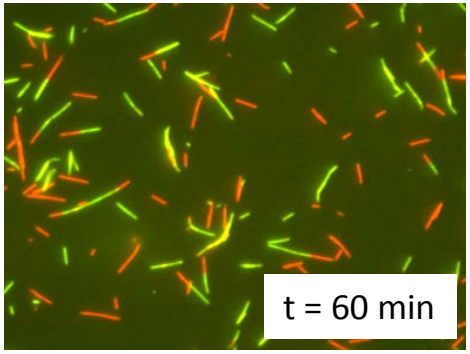
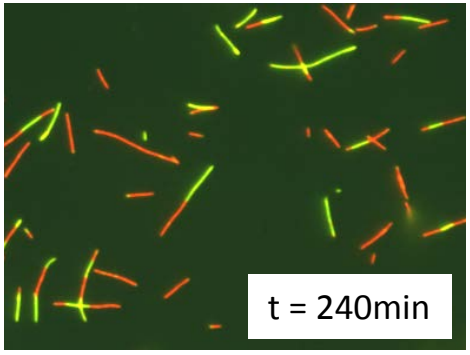
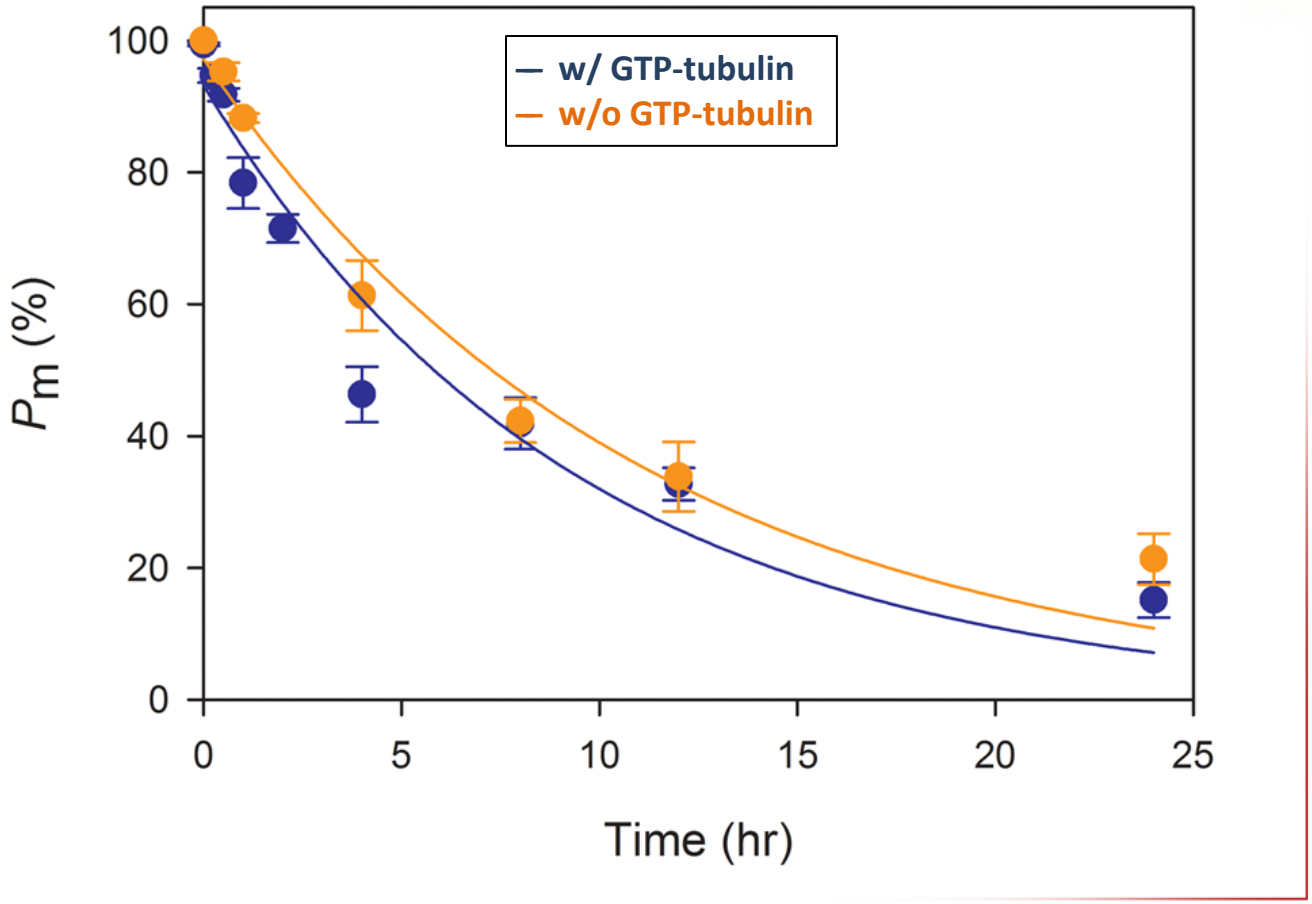
Reaction Rate of Self-Assembly

Kinetics of NA assembly characterized by disappearance of “monomers” over time. Data suggest that DSA follows **second-order reaction kinetics.**









Bachand et al., *RSC Adv*. **4,** 51641 (2014)

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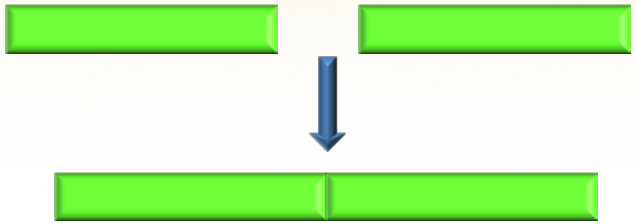
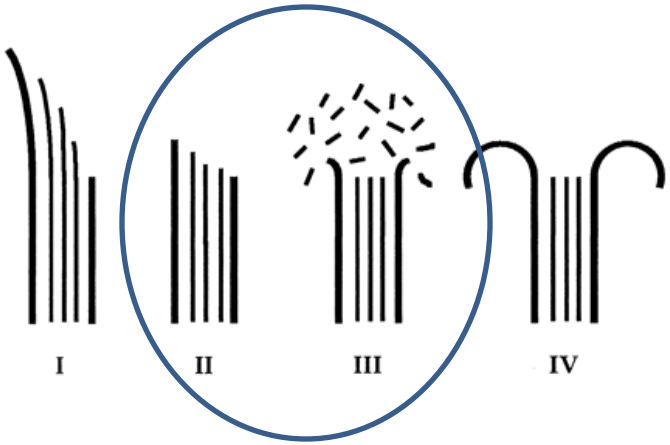
Understanding the Mechanism of DSA

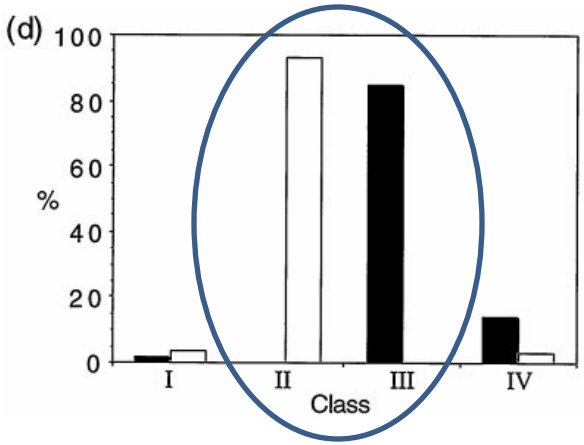
Simplest mechanism:

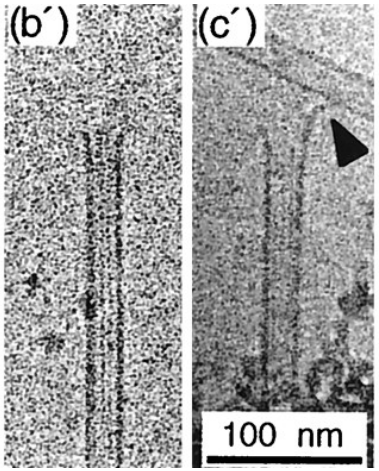
- Microtubule ends collide via thermal fluctuation
- Short-range interactions join two segments
- Stable junction formed b/w segments



Microtubule ends are rarely blunt end. What happens at junctions between assembling segments?







Muller-Reichert et al., *Proc. Nat. Acad. Sci.* **95**, 3661 (1998)

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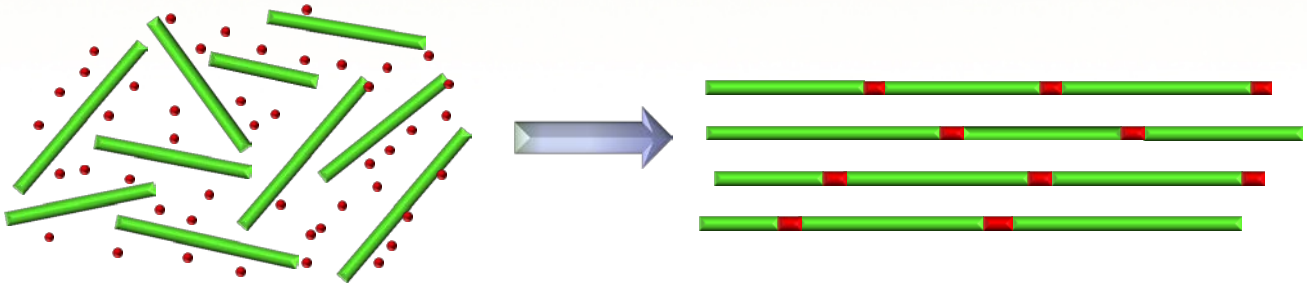
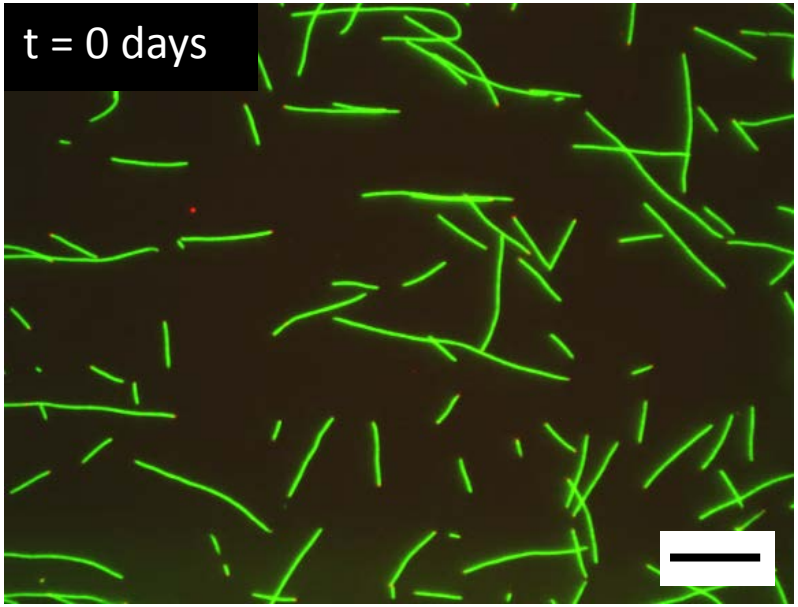
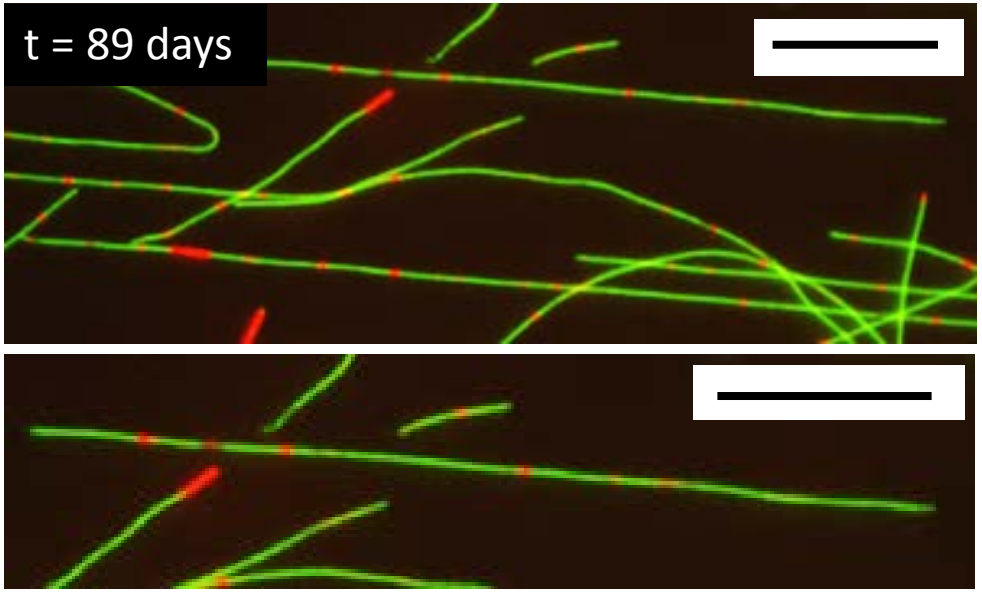
Two-Step Process for MT DSA

Addition of free red tubulin to green microtubules supports two-step mechanism in the overall fusion process.







BUT…what is the exact mechanism?

Bachand et al., *RSC Adv*. **4,** 51641 (2014)

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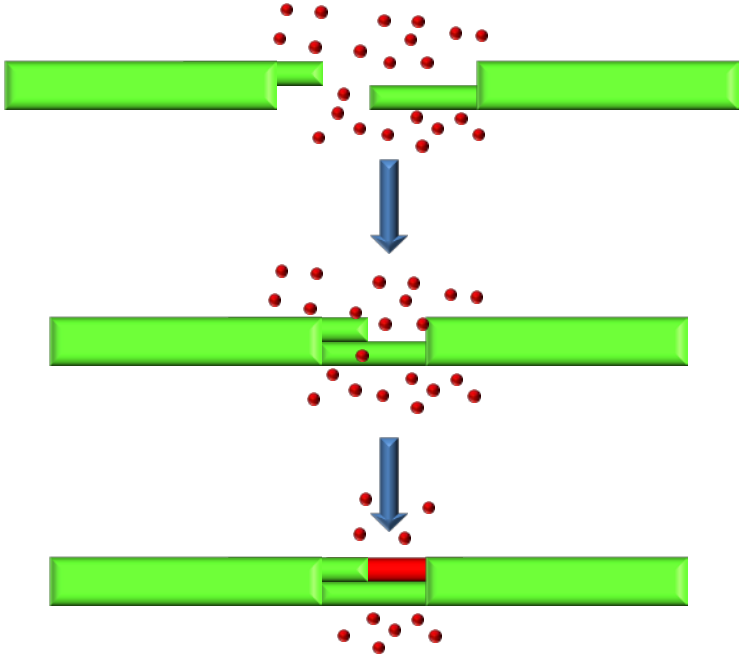
Proposed Mechanisms for MT DSA

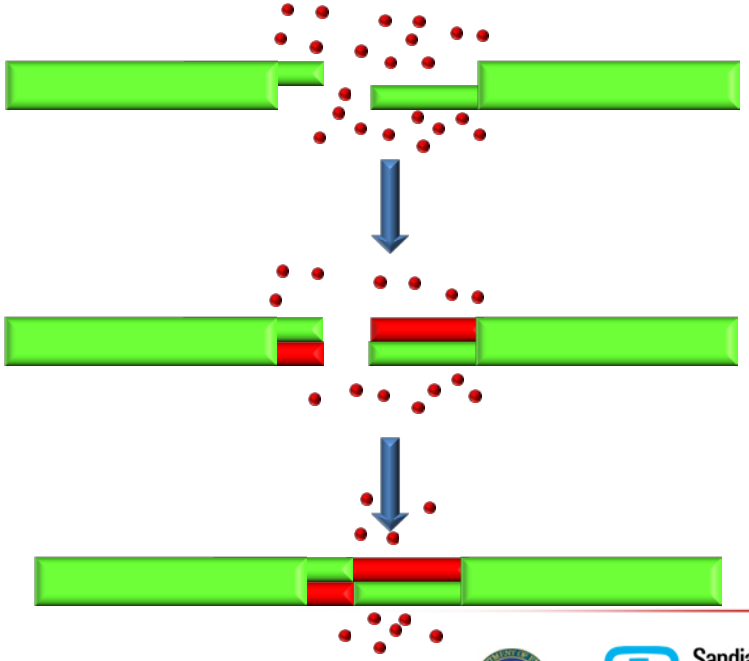
1 – Vacancy Filling

- MT ends collide via thermal fluctuation
- Short-range interactions hold segments together weakly (with defect)
- Free GTP-tubulin dimers fill lattice vacancies and stabilize the junction



2 – Blunt ending

- Free GTP-tubulin dimers polymerize at the MT ends forming a blunt end
- MT ends collide via thermal fluctuation
- Short-range interactions hold segments together until junction forms



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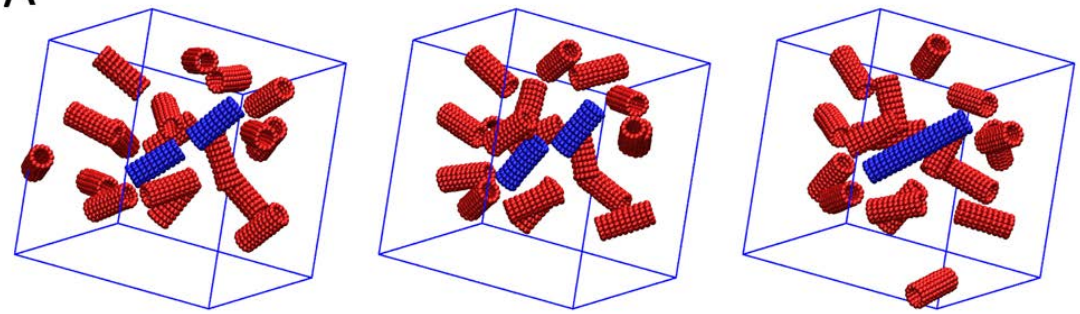
Two-Step Process for DSA of MTs

MD simulations of fusion support all of the mechanisms, suggesting that all may play a role in the direct assembly process.

A



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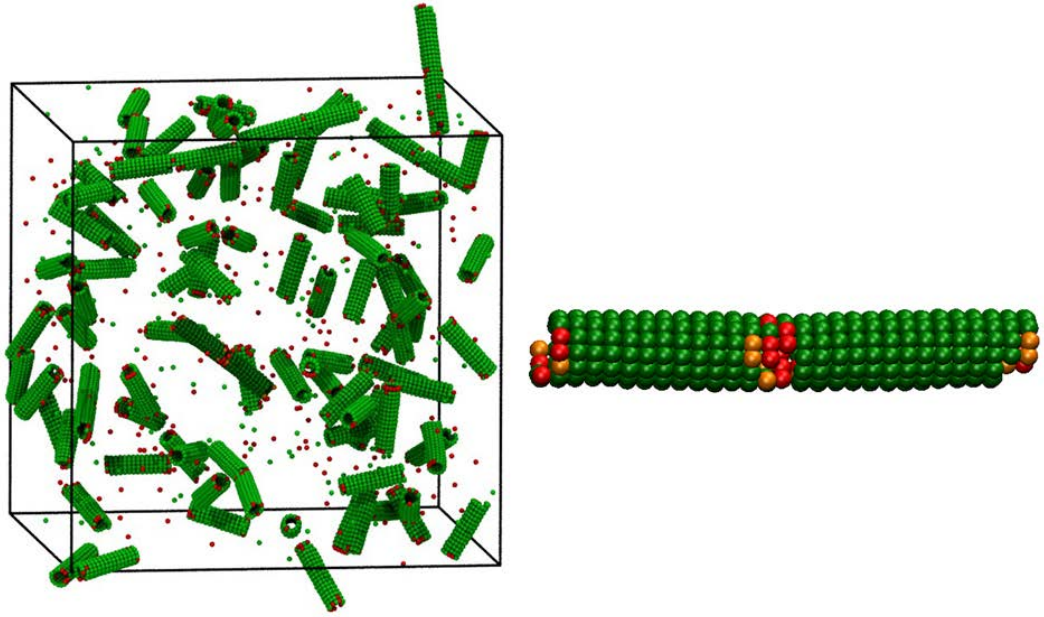

MD simulation demonstrates that blunt-ended MTs will self-assemble into extended 1D structures

Simulations with jagged-ended MTs demonstrate that:

- Seeded polymerization occurs at ends
- Jagged-ends MTs will assemble
- Vacancies filled by free & dissociated dimers

Bachand et al., *RSC Adv*. **4,** 51641 (2014)

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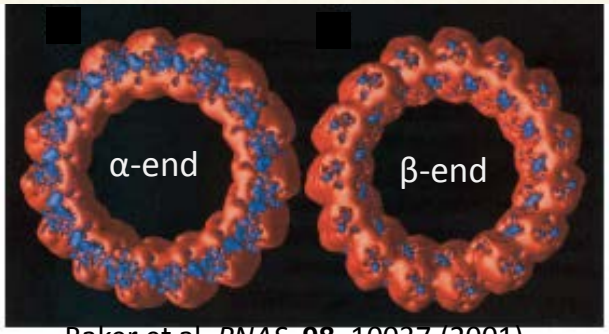
Role of Short-Range Electrostatics

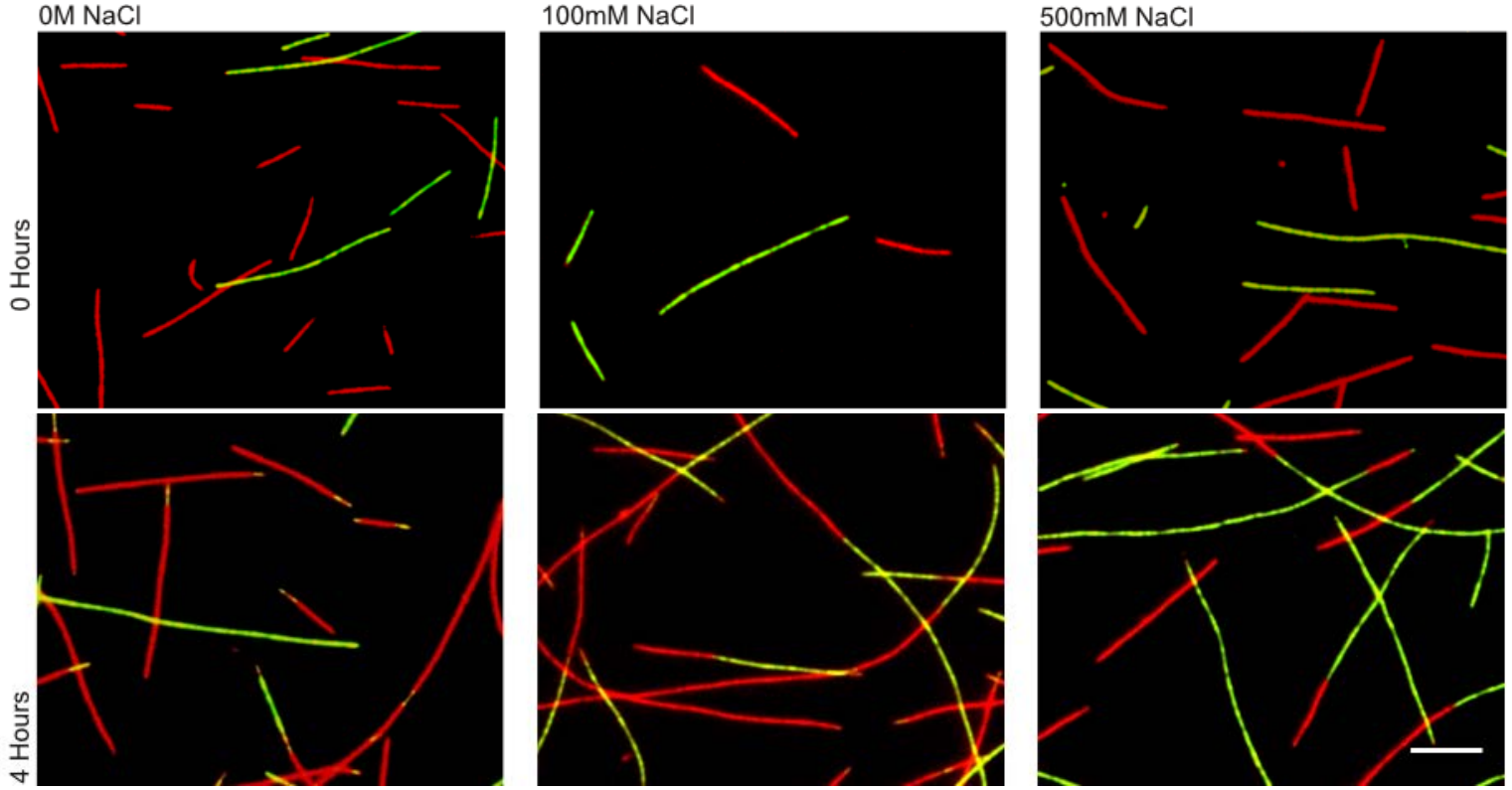
Bonds among dimers in MTs:

- ΔG longitudinal bond > ΔG lateral bonds
- Hydrophobic and electrostatic interactions
- α- and β-ends are electrostatically attractive



Baker et al. *PNAS*, **98**, 10037 (2001)

Will MTs self-assemble if the Coulomb interactions are screened?



Charge neutralization appears to increase the rate of self-assembly

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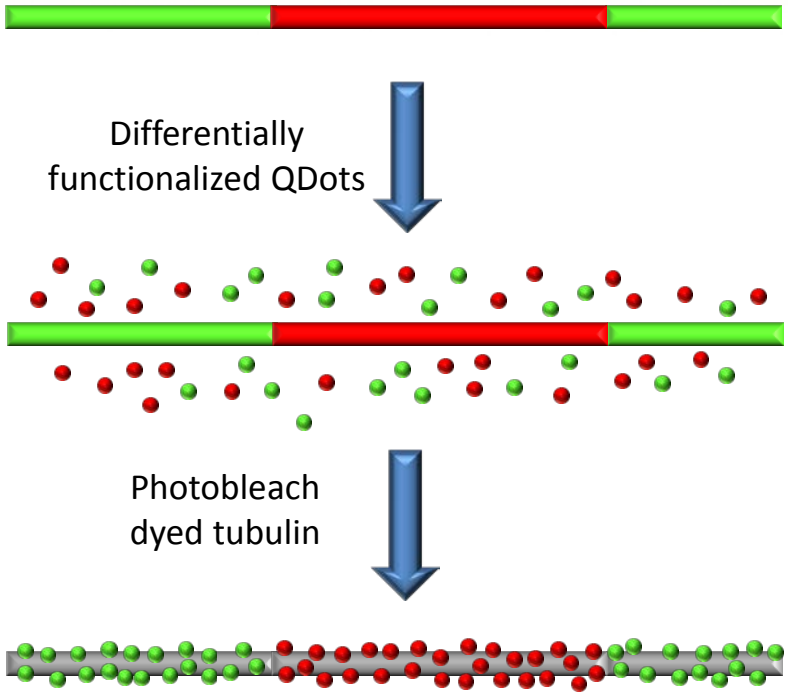
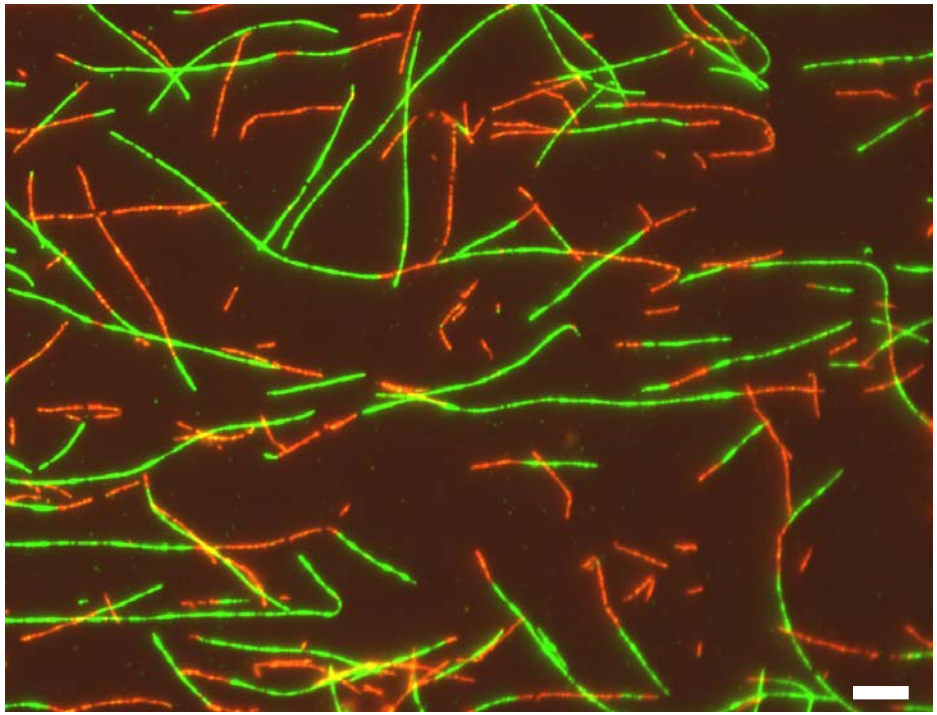
Future: Heterostructured Nanowires

1D heterostructured nanowires (aspect ratio >3,000>1) can be formed from assembled microtubule structures where individual segments have unique chemical functionality.





Morphology of these nanowires can be tuned by altering the assembly process (e.g., shearing one segment type to achieve uniform size distribution).

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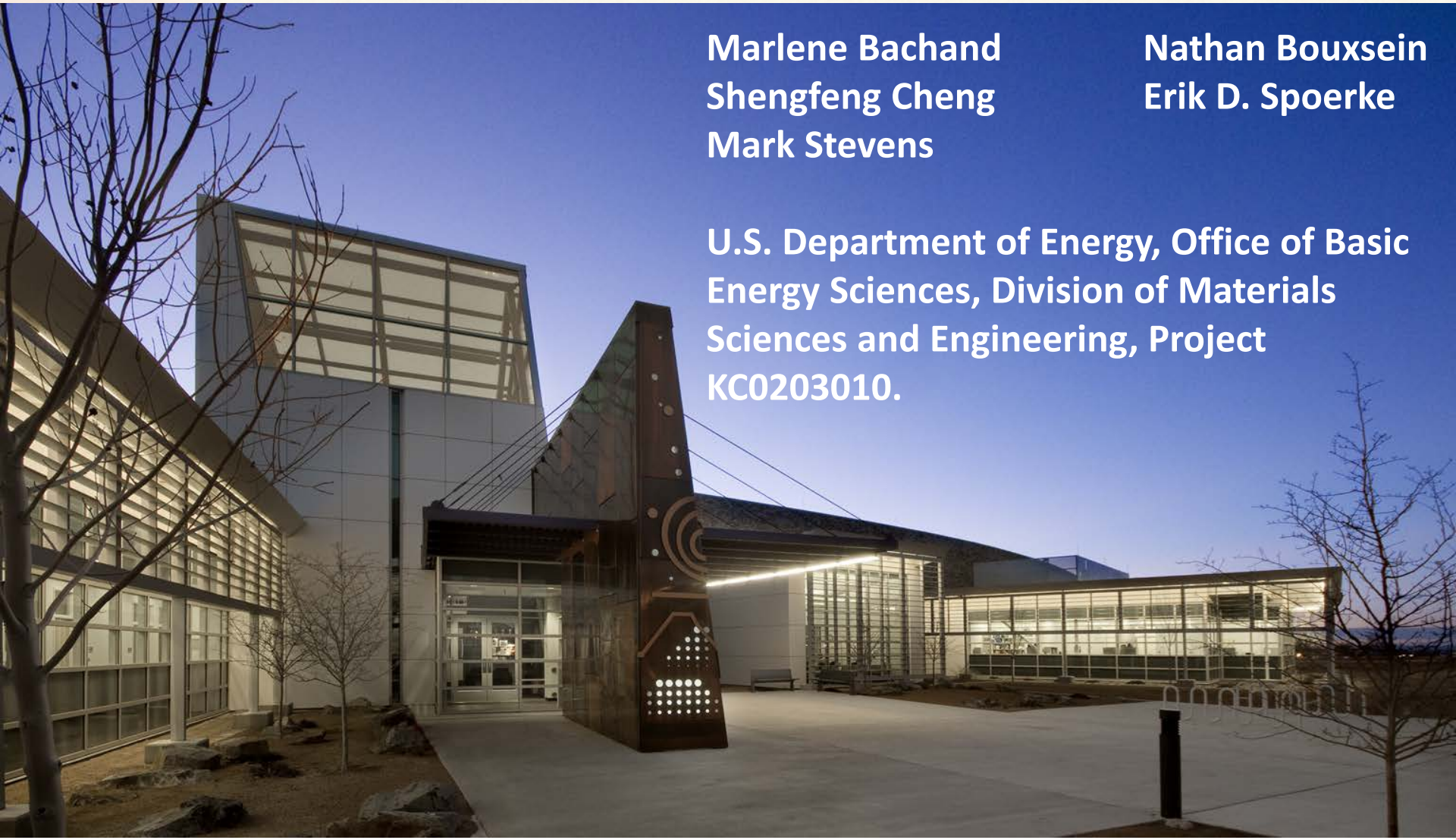
Acknowledgments



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