SAND2017-2394C

# Biomimicry: Looking to Nature to Help Solve Engineering Challenges

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Center for Integrated Nanotechnologies

March 3, 2017

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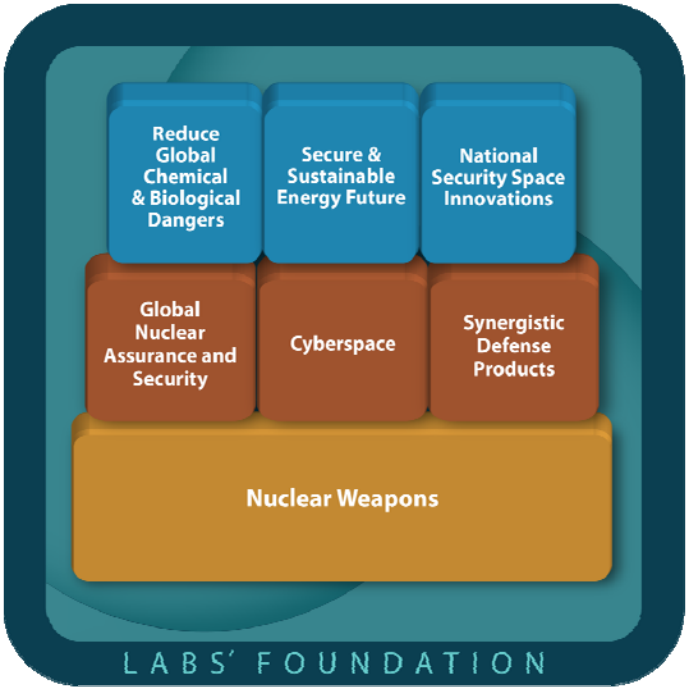
# Sandia National Laboratories

**History:**

- July 1945: Los Alamos creates Z Division
- Non-nuclear component engineering
- November 1, 1949: Sandia Laboratory established

**Today:**

- One of three DOE NNSA labs
- > 10,000 employees; ~$2.6B annual budget
- Locations in Albuquerque, Livermore
- Mix engineering and fundamental science
- Vibrant student internship program

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# Biomimicry – Design by Nature

The design and production of materials, structures, and systems that are modeled on biological entities and processes

http://www.levinegabriella.com/

http://www.mnn.com/

https://lafeber.com

http://jamesfrank.photoshelter.com/


http://www.bostondynamics.com/

http://bdml.stanford.edu/Main/ClimbingAdhesionHome

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# Biomimicry – Design by Nature

http://www.smithsonianmag.com/

http://csnblog.specs-lab.com/2014/09/30/octopus-skin-inspires-dynamic-camouflaging-materials/

http://www.smithsonianmag.com/

Caldwell Lab, UC-Berkeley

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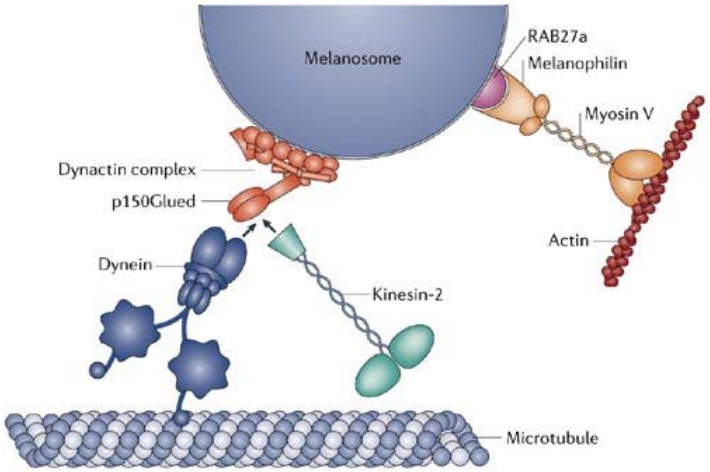
# Color Changing Starts Inside of a Cell

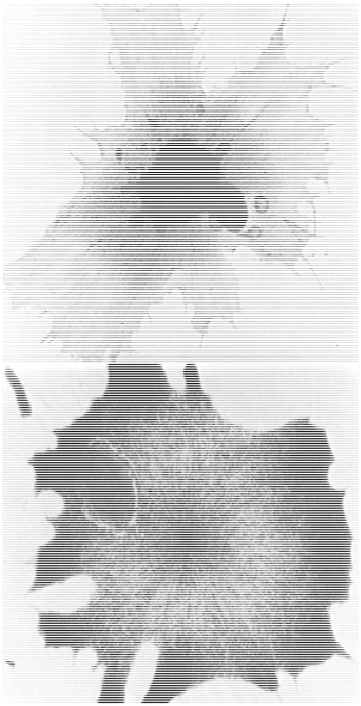
Cytoskeletal molecular motors work collectively to disperse and aggregate pigment-containing organelles

**nanoscale**




Soldati & Schliwa, 2006, Nat. Rev. Mol. Cell Biol., 7, 897

**microscale/ mesoscale**



http://wilkes-fs1.wilkes.edu/~terzaghi/BIO-226/lectures/24.html

**macroscale**

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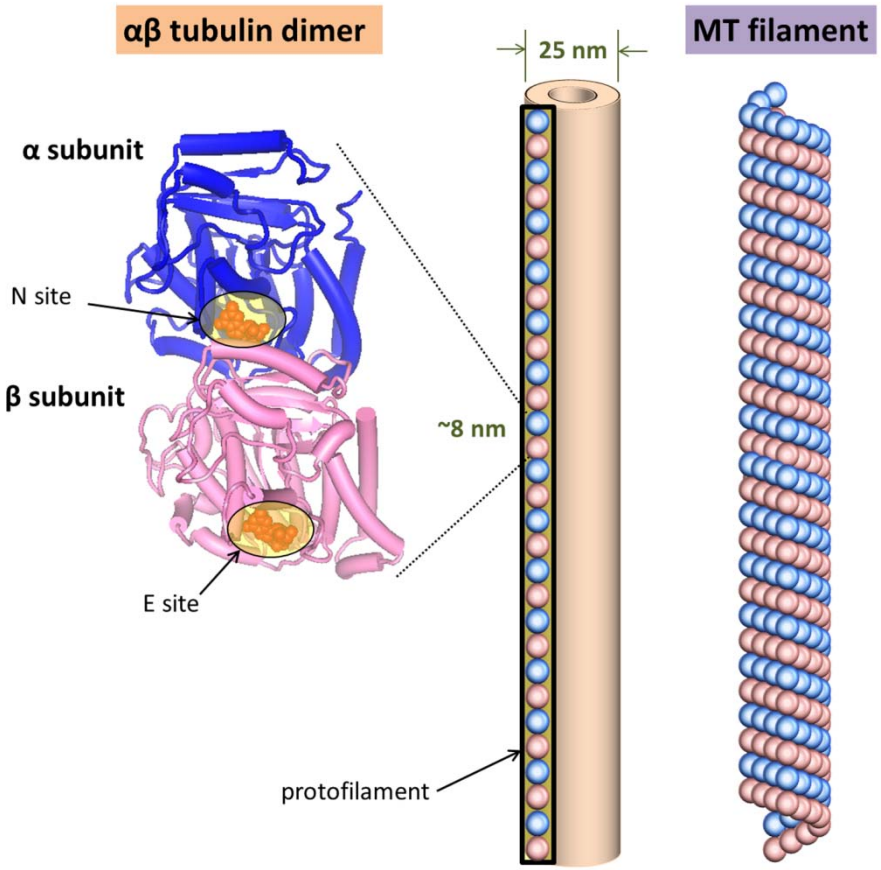
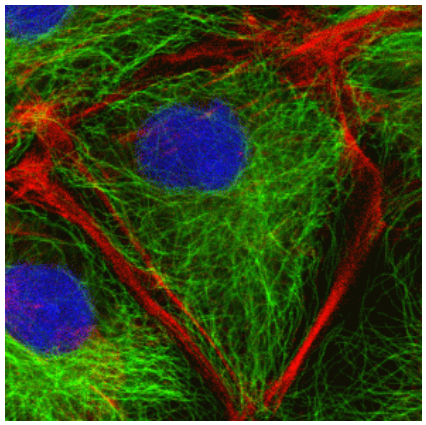
# Cytoskeleton & Intracellular Transport

Cytoskeleton – actin filaments, microtubules, and intermediate filaments

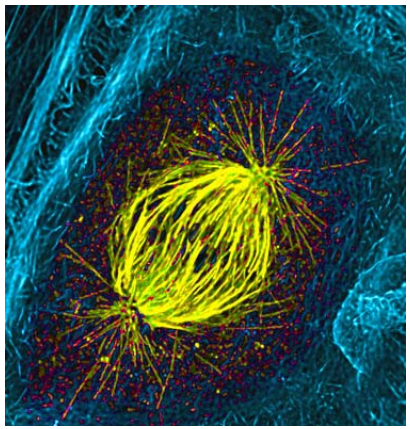



*Microtubule*:

- Assembly of tubulin proteins; ends are different
- Consume guanosine triphosphate (GTP) during growth
- 25 nm diameter; 10s of micron long
- Transportation network ("railways")



http://bscb.org/



http://afracturedreality.tumblr.com/

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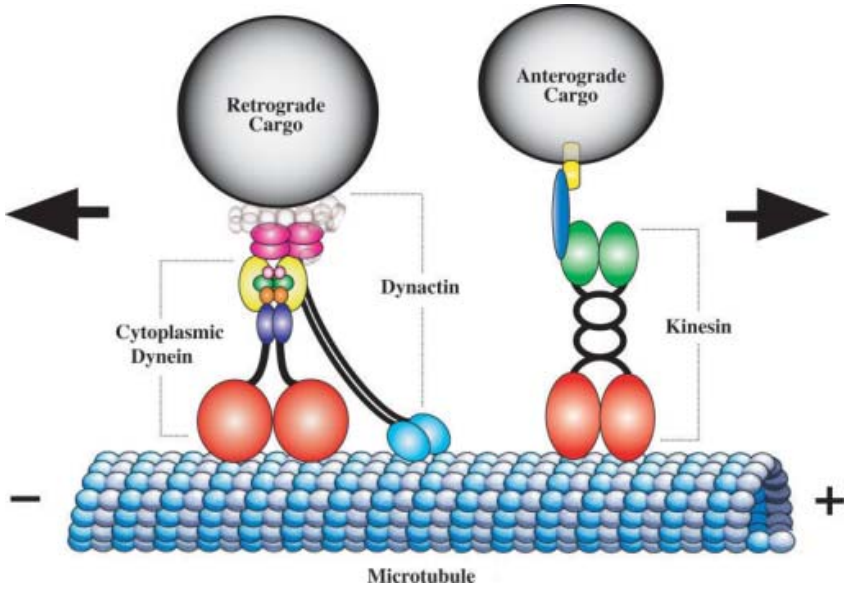
# Cytoskeletal Locomotives

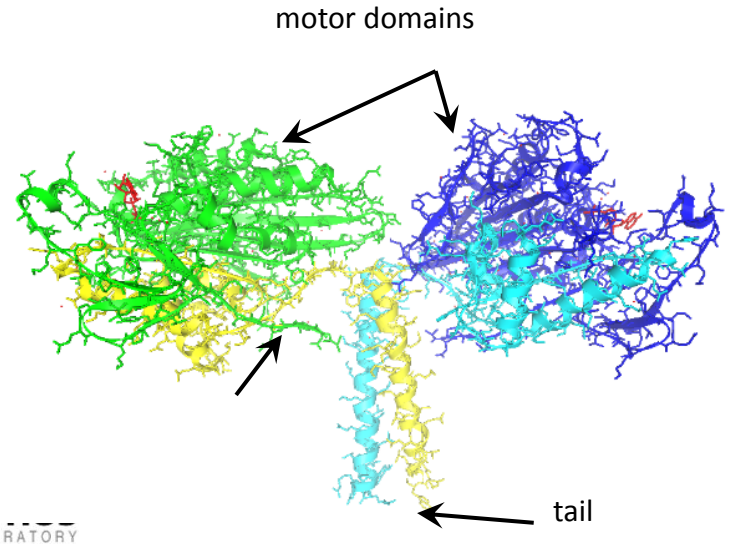
Molecular Motors (locomotives) – dynein & kinesin "walk" along microtubules carrying cargo (organelles)

*Kinesin:*

- Fuel = adenosine triphosphate (ATP)
- "Walk" hand-over-hand toward β-end of microtubule (8 nm step size)
- Transport speed = 0.5 – 12 μm per sec (up to 1500 steps per sec)
- 40 pN•nm work; 50% efficiency




Duncan & Goldstein, 2006, Plos Genet., 29, e124




Cargo not to scale; organelles ≈100x larger than motors

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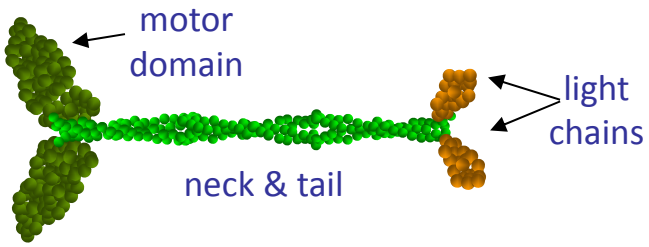
# Intracellular Transport by Kinesin

Intracellular transport of matter in “static” medium avoids issues with fluid flow

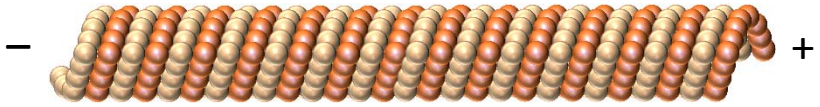
# Kinesin Transport Outside of a Cell

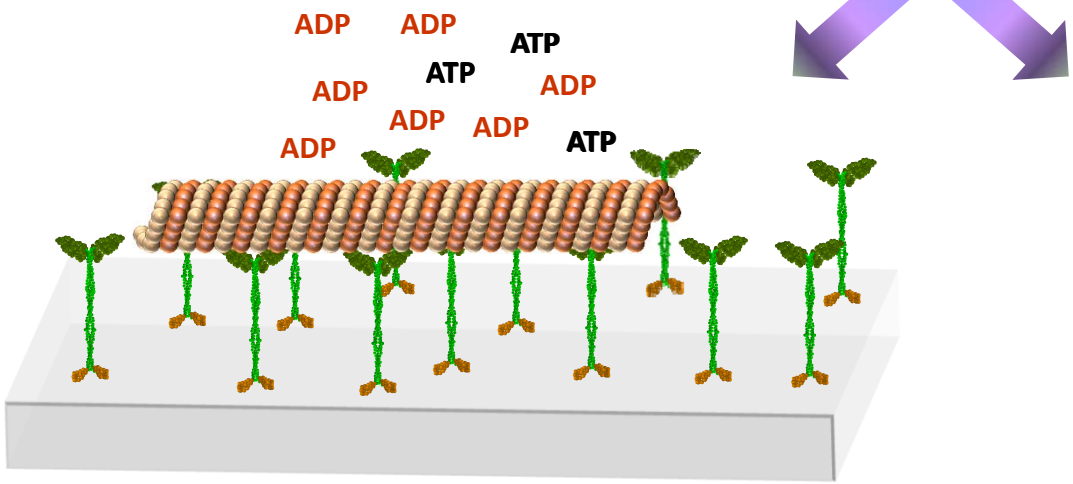
Molecular shuttles in gliding geometry enable “long distance” transport at the nanoscale.

**Kinesin motor proteins**




**Microtubule filaments**
**“molecular shuttles”**

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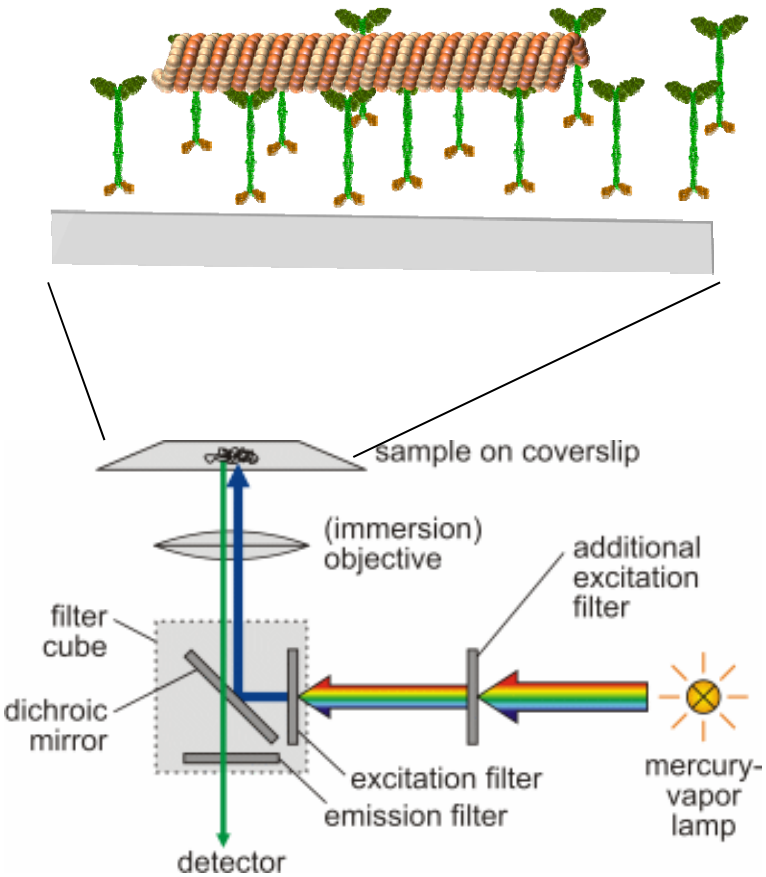
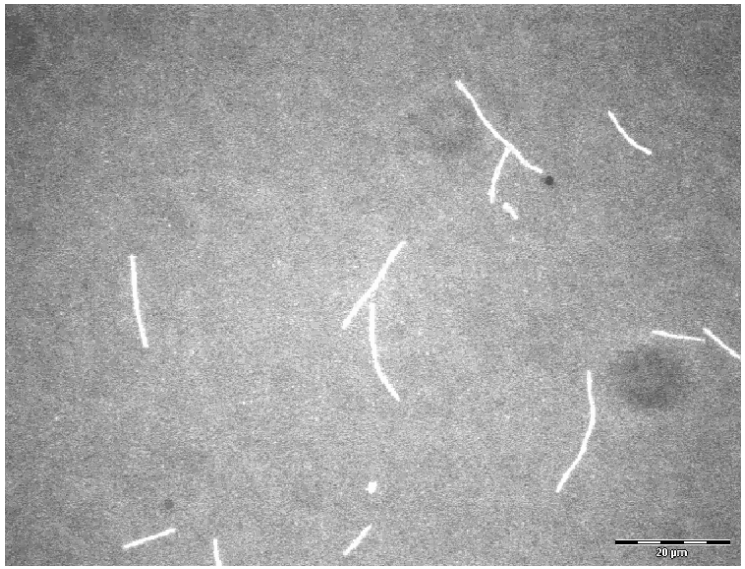
# Visualizing Kinesin Transport

Fluorescence microscopy – easy visualization of microtubule gliding




http://home.uni-leipzig.de

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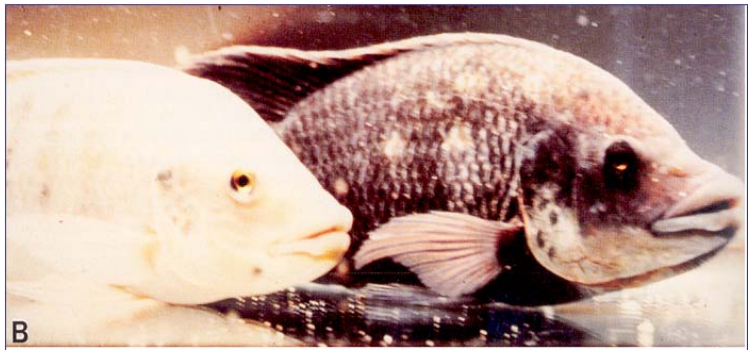
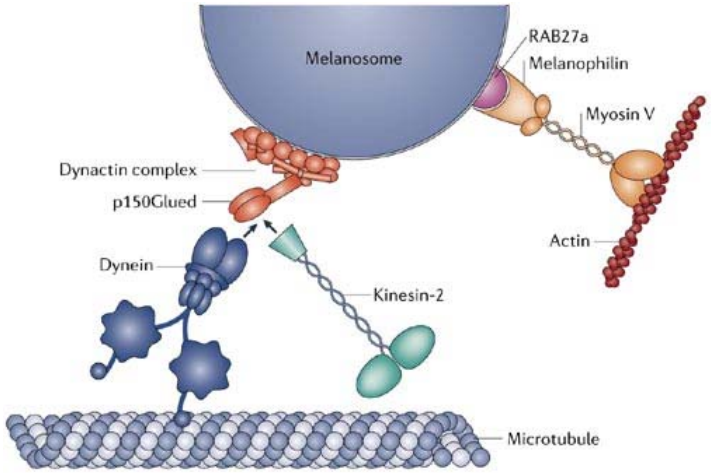
# Hybrid Optical Materials Inspired by Fish

## Nature

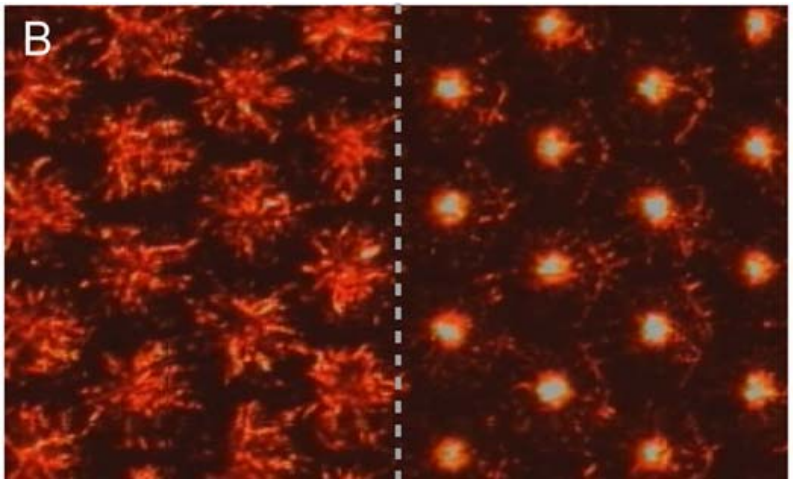
Haimo & Thaler, 1994, *BioEssays* 16, 727.



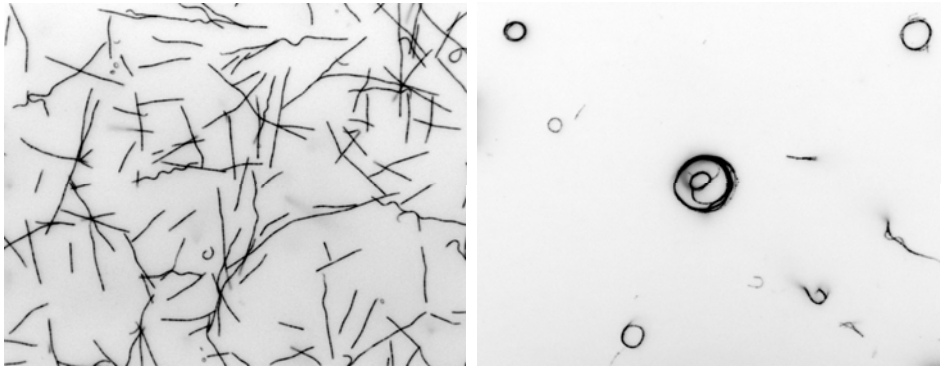




Soldati & Schliwa, 2006, Nat. Rev. Mol. Cell Biol., 7, 897

## Hybrid Materials Systems




Aoyama et al., 2013, *PNAS* 110, 16408



Liu et al. *Adv. Mater.* 20, 4476 (2008)

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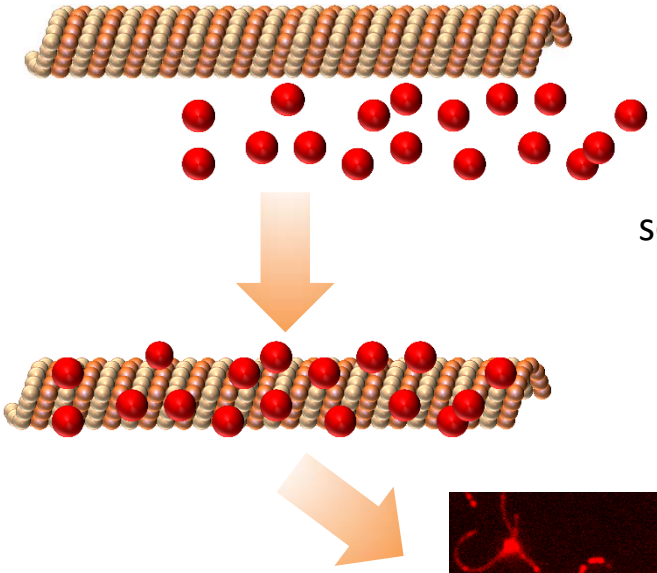
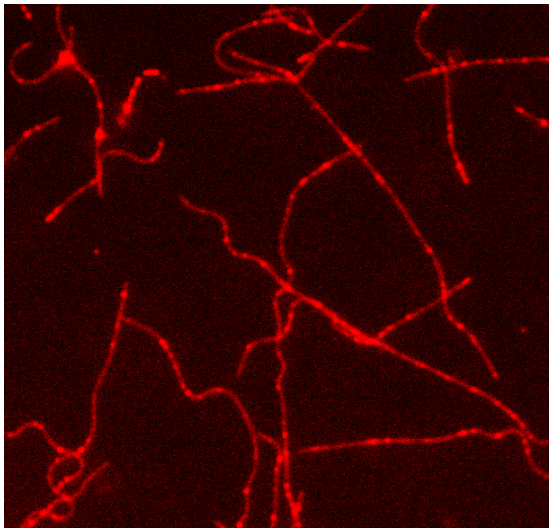
# Hybrid Optical Materials

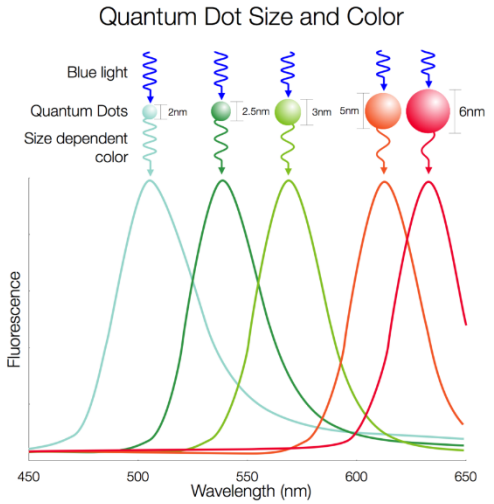


Quantum dots – semiconductor nanocrystal that emit light

http://www.sigmaaldrich.com/

Quantum dots on microtubules





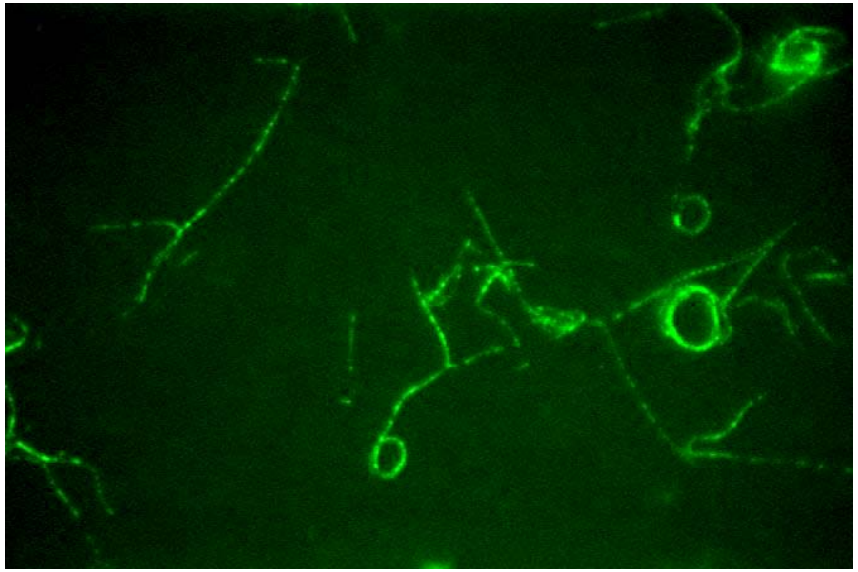

http://www.nanosysinc.com/

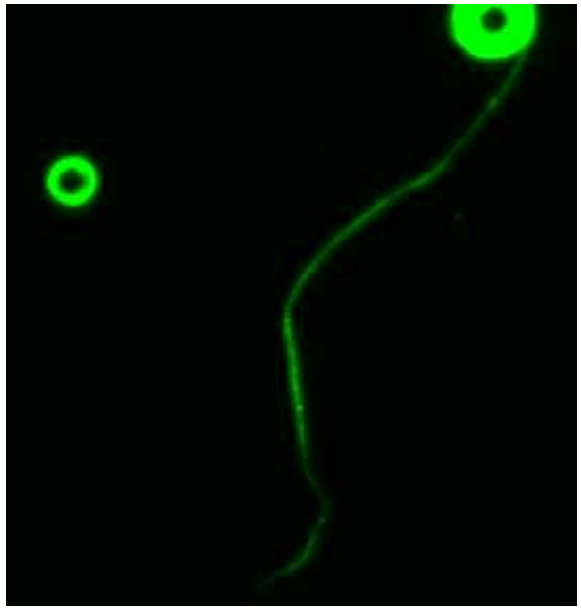
Lam et al. 2016, *Soft Matter* **12**, 988,; VanDelinder et al., 2016, *Biomacromolecules* **17**, 1048; Liu & Bachand, 2011, *Soft Matter,* **7**, 3087; Liu et al., 2008, *Adv. Mater.* **20**, 4076*;* Boal et al., 2006, *Nanotechnology,* **17**, 349; Bachand et al., 2005, *J. Nanosci. Nanotech.,* **5**, 718*;* Bachand et al., 2004, *Nano Lett.* **4**, 817

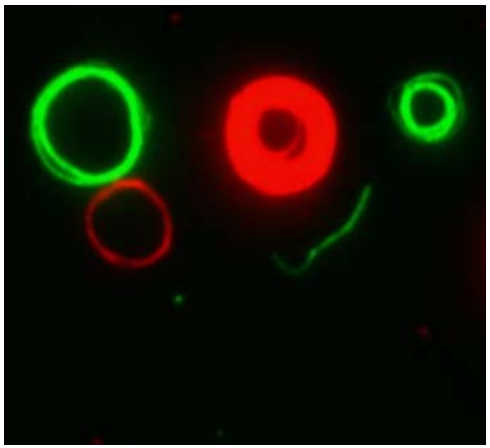
# Hybrid Optical Rings

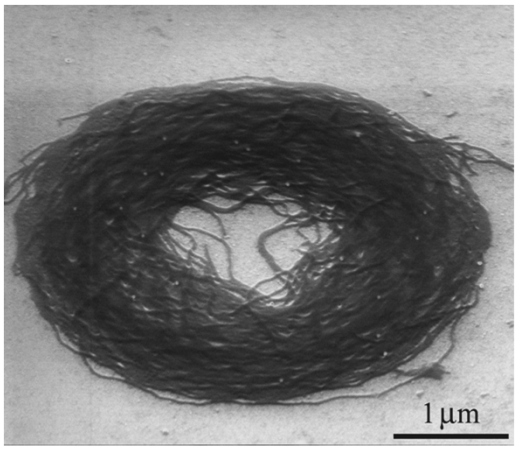
Microtubule carrying quantum dots:

- Become “sticky” while gliding across a surface
- Spontaneously assemble into rings and spool (condensation/aggregation)
- Continue to grow and rotate





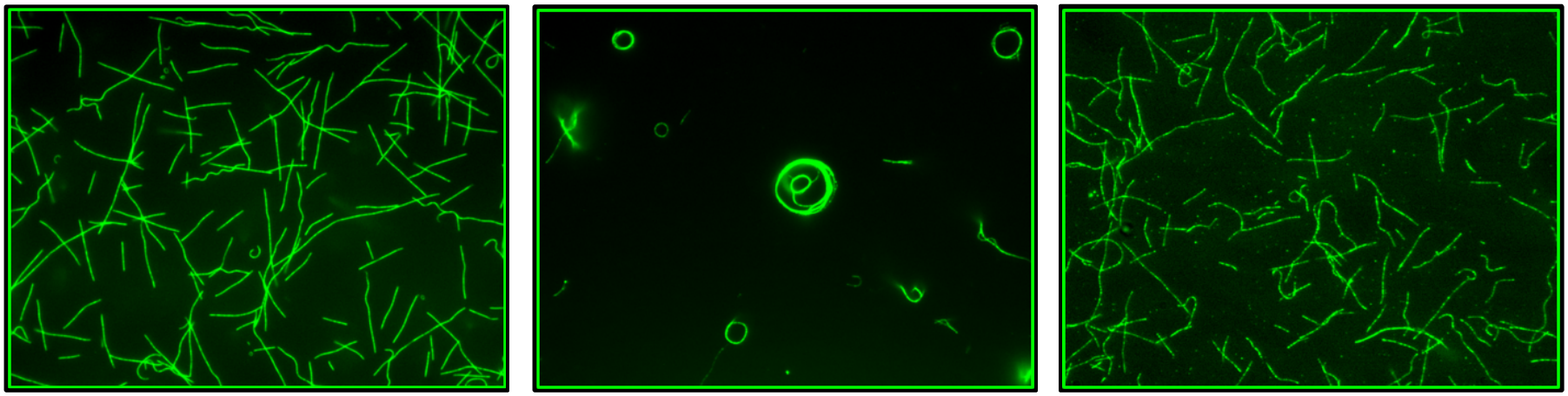




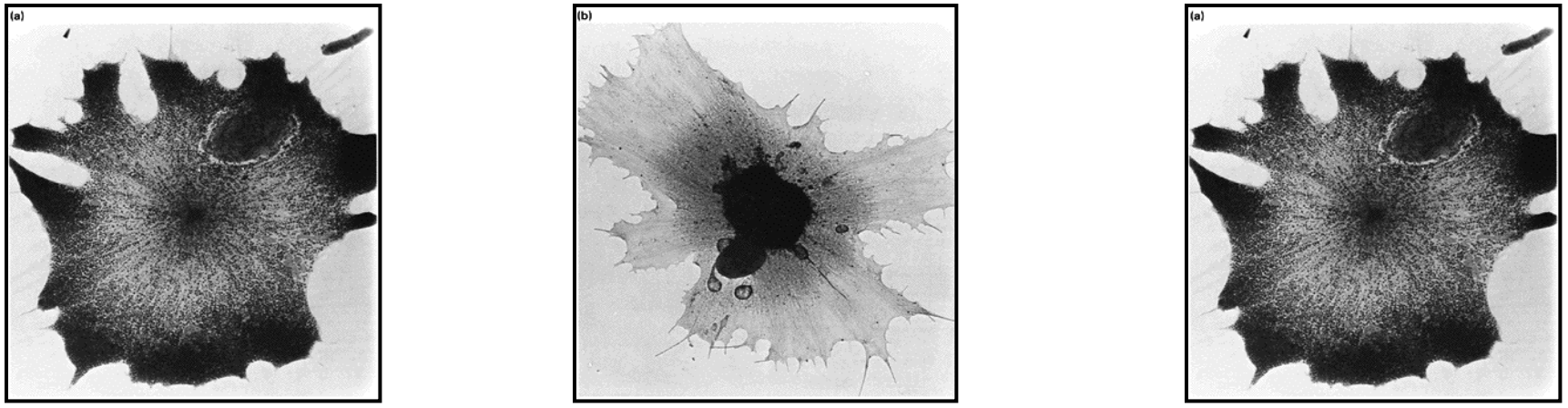

Lam et al. 2016, *Soft Matter* **12**, 988,; VanDelinder et al., 2016, *Biomacromolecules* **17**, 1048; Liu & Bachand, 2011, *Soft Matter,* **7**, 3087; Liu et al., 2008, *Adv. Mater.* **20**, 4076*;* Boal et al., 2006, *Nanotechnology,* **17**, 349; Bachand et al., 2005, *J. Nanosci. Nanotech.,* **5**, 718*;* Bachand et al., 2004, *Nano Lett.* **4**, 817

# Hybrid Optical Rings

Aggregation & dispersion of hybrid optical rings



Color change in melanophore cells




Adapted from: http://wilkes-fs1.wilkes.edu/~terzaghi/BIO-226/lectures/24.html

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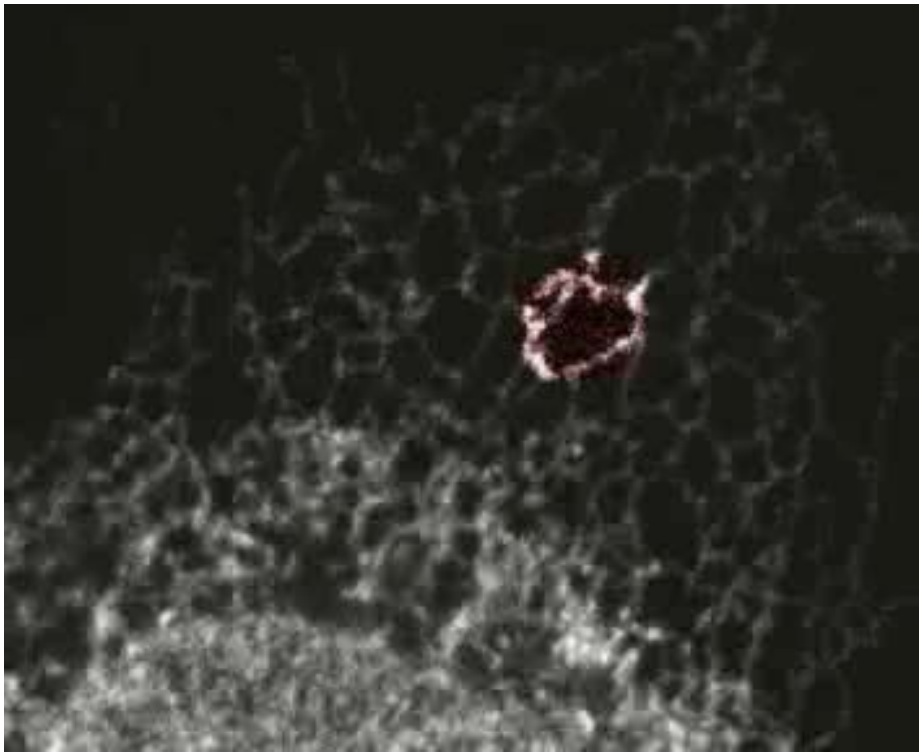
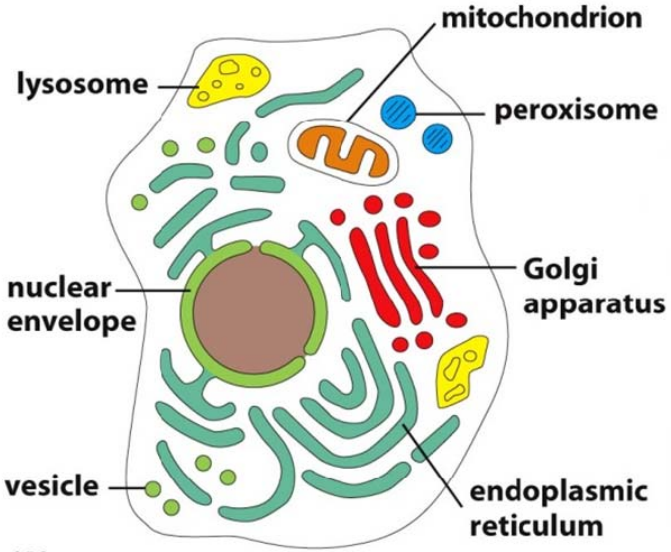
# Molecular Motors and Organelles

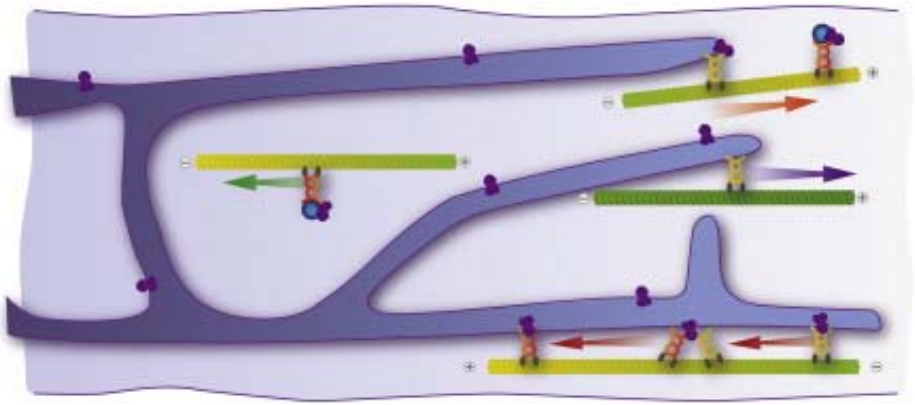
Structure of the endoplasmic reticulum (ER) and Golgi apparatus continuously remodeled by molecular motors such as kinesin



Alberts et al., *Essential Cell Biology* (2010)




Alberts et al., *Essential Cell Biology* (2010)



Valenzuela et al. (2011) *Mol. Cell. Neurosci.*, 48, 269

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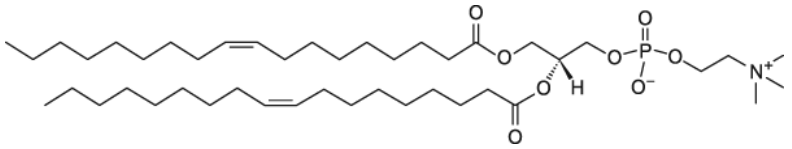
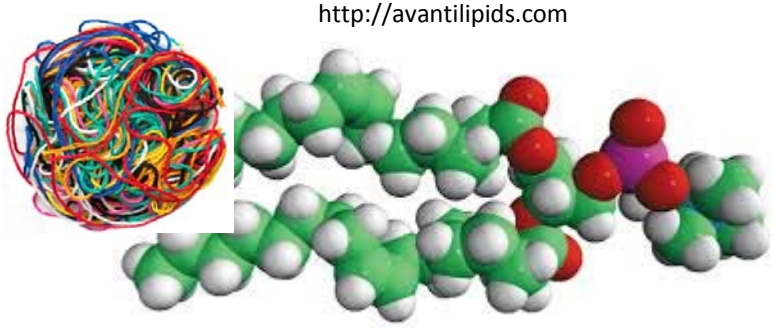
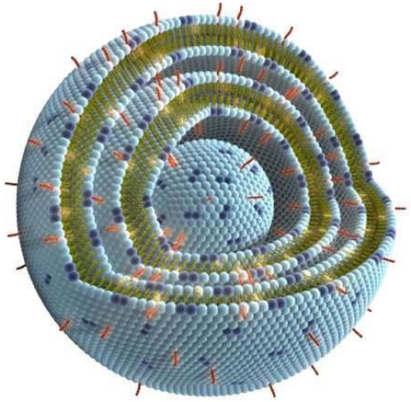
# Membrane Organelles Inspired by ER

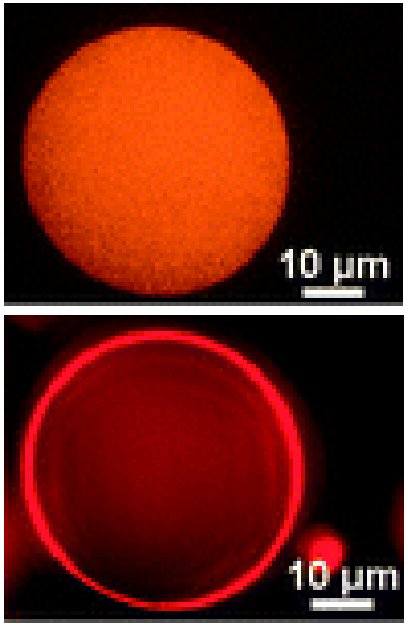


http://avantilipids.com





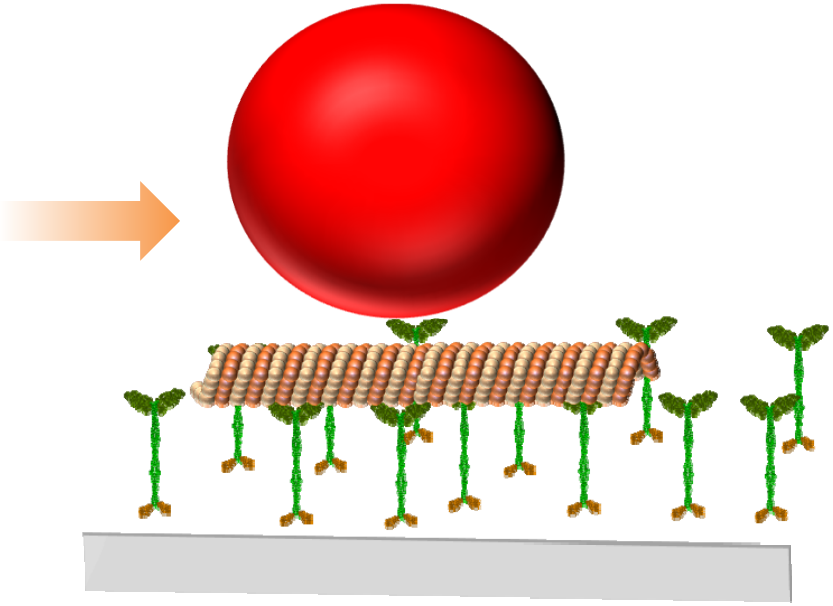
http://phys.org/




Li & Malmstadt, 2013, *Soft Matter,* 9, 4969

Phospholipids:

- Major component of plasma and organelle membranes
- Self-assemble in water to create liposomes (lipid vesicles)



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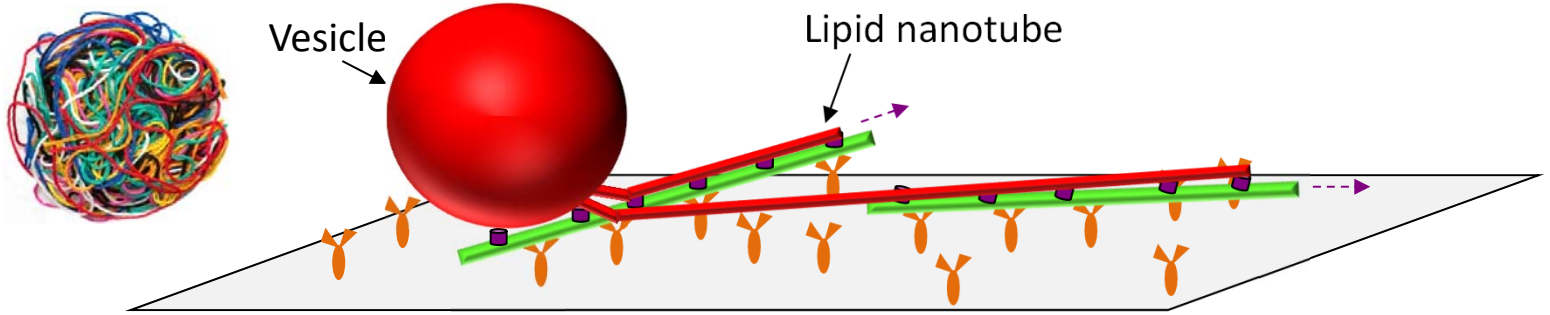
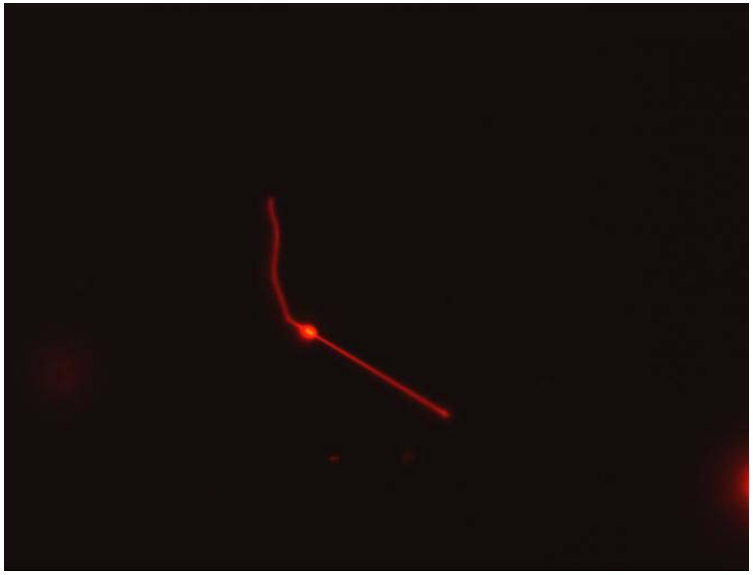
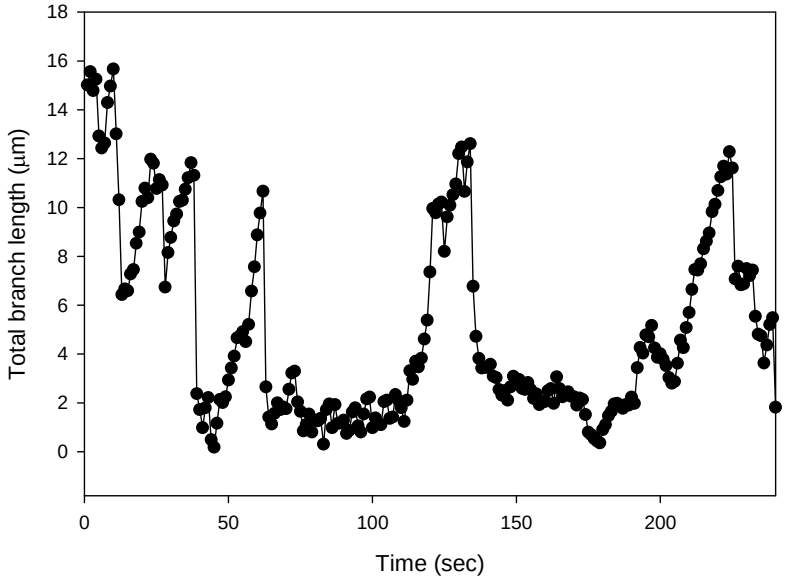
# Membrane Organelles Inspired by ER




"Living" tubules



Vesicle = red; microtubules not visible

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Bouxsein et al., 2013 *Langmuir* **29,** 2992; Paxton et al., 2015, *Nanoscale* **7**, 10998.

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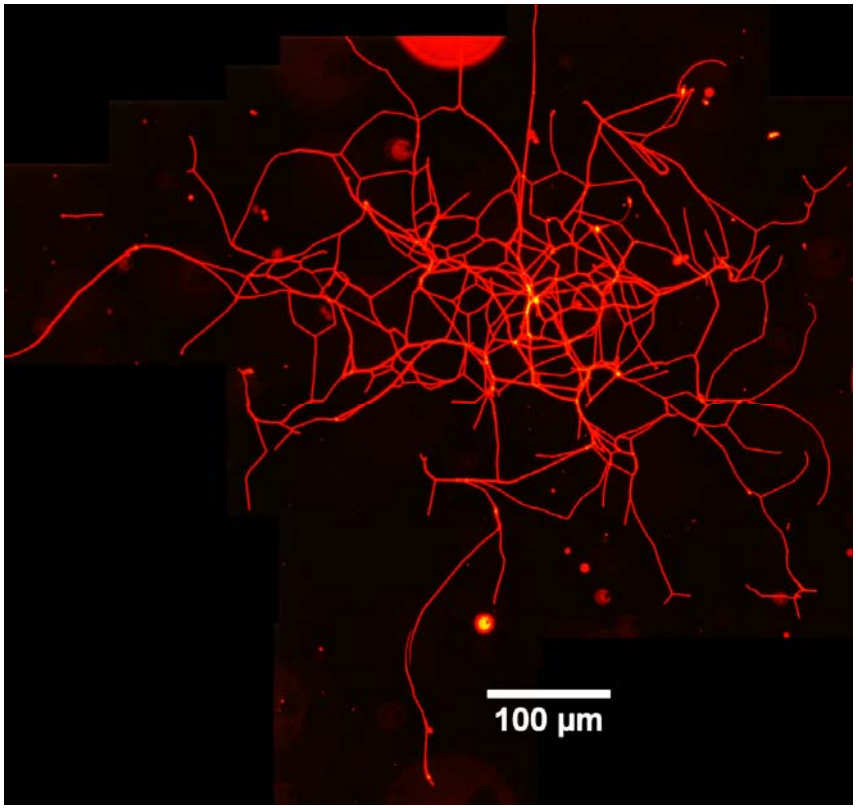
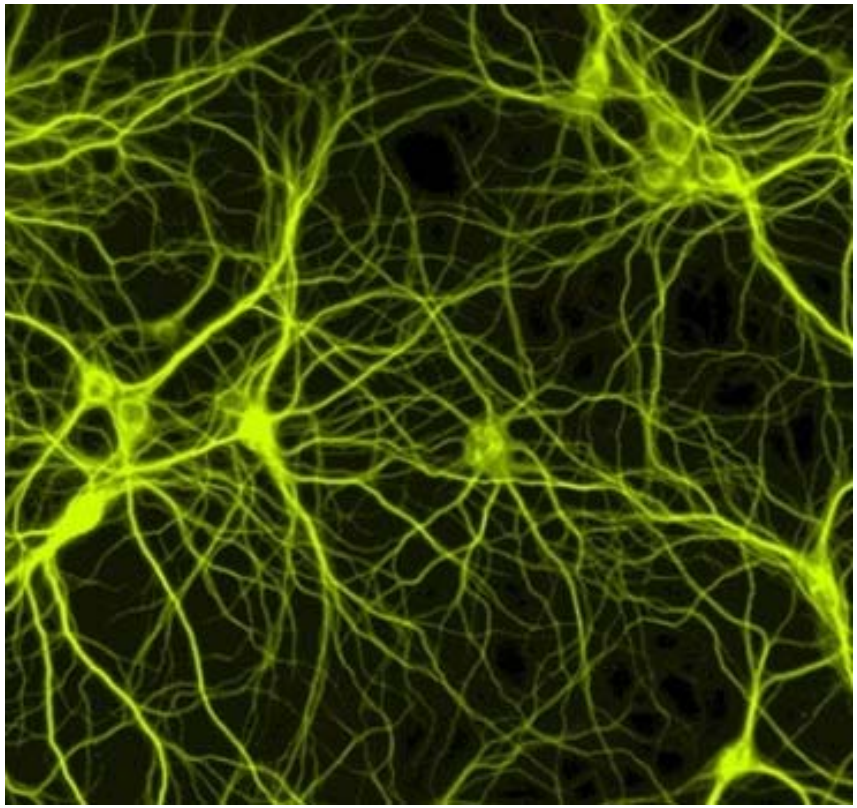
# Large-Scale Networks of Lipid Tubes

"Large" (10-20 μm) lipid vesicles → Large (10 mm) networks of lipid nanotubes

Lipid tubule network




Network of neurons



https://www.extremetech.com/

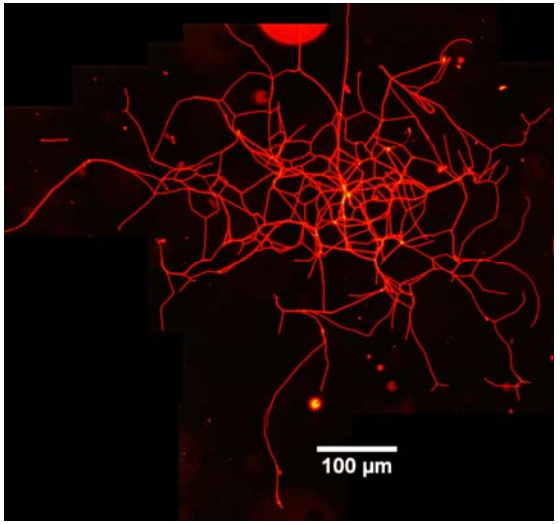
Structure mimics that of neural networks

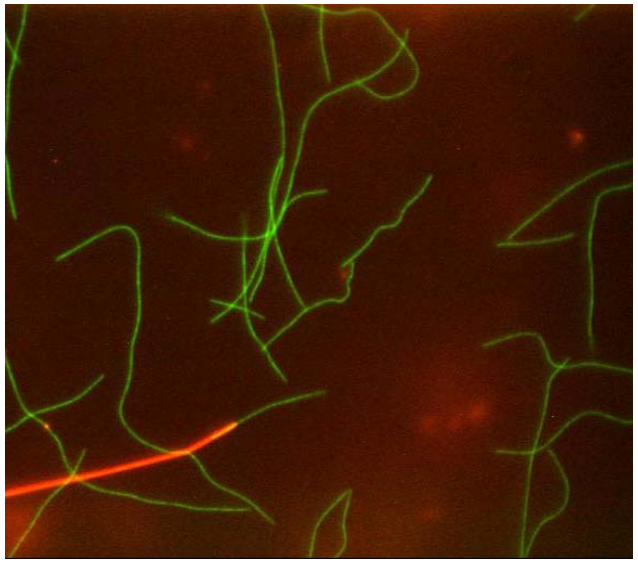
Bouxsein et al., 2013 *Langmuir* **29,** 2992; Paxton et al., 2015, *Nanoscale* **7**, 10998.

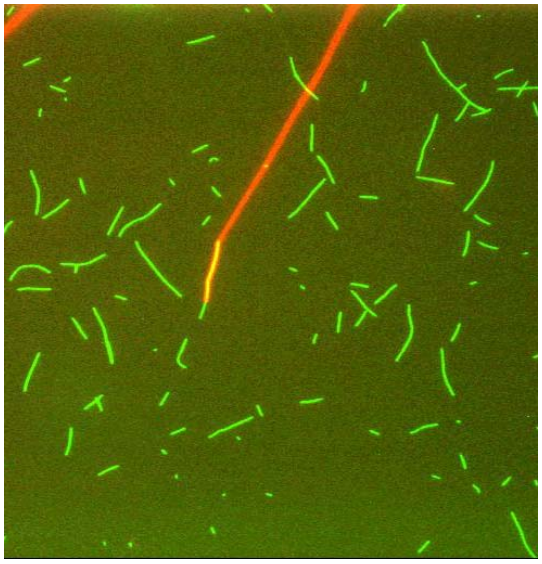
# Membrane Organelles Inspired by ER

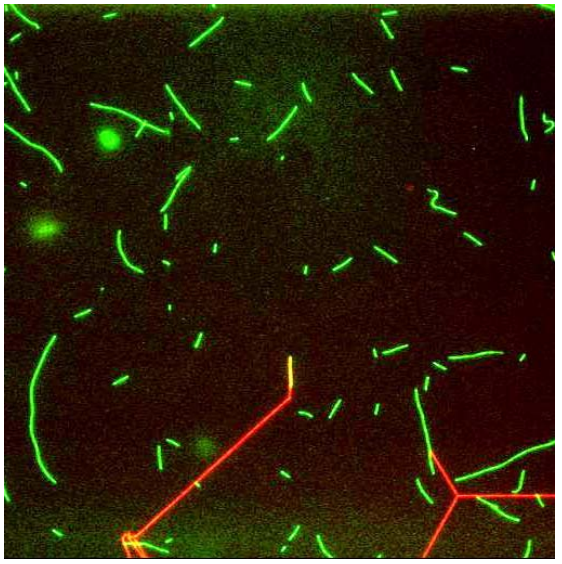
Work done by motors:

- Growth of lipid nanotubes
- Induce bifurcation of nanotubes
- Remove lipids when tension too high
- Impart self-healing architecture to the overall network structure







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Bouxsein et al., 2013 *Langmuir* **29,** 2992; Paxton et al., 2015, *Nanoscale* **7**, 10998.

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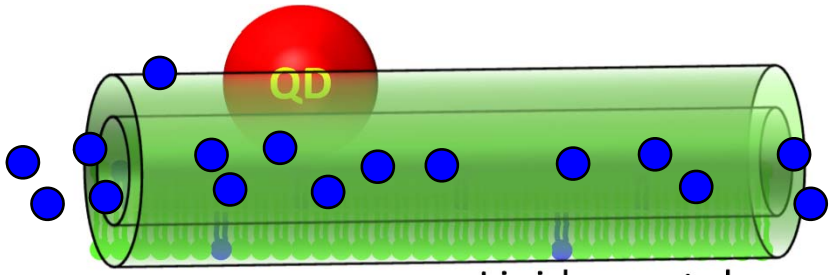
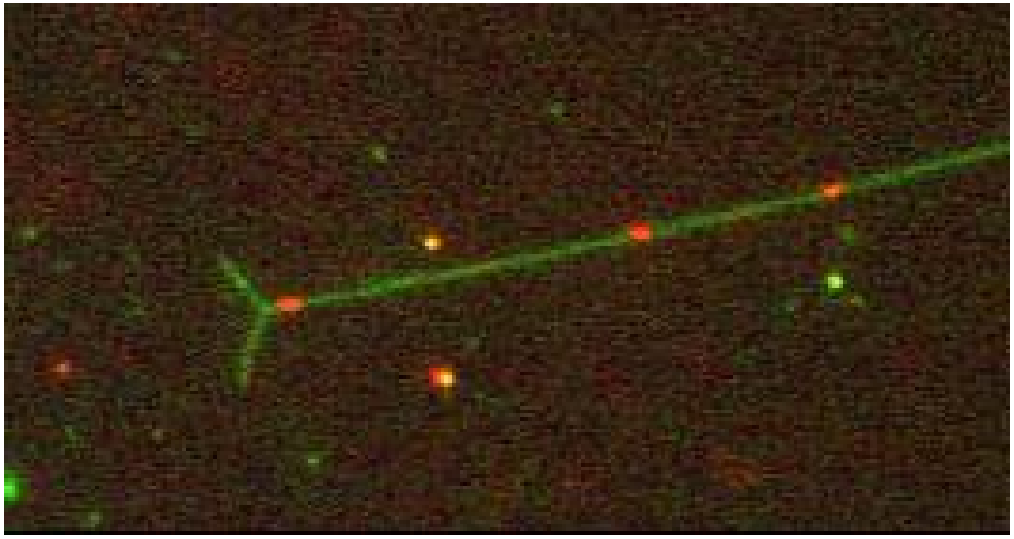
# Transport on Nanotube Networks

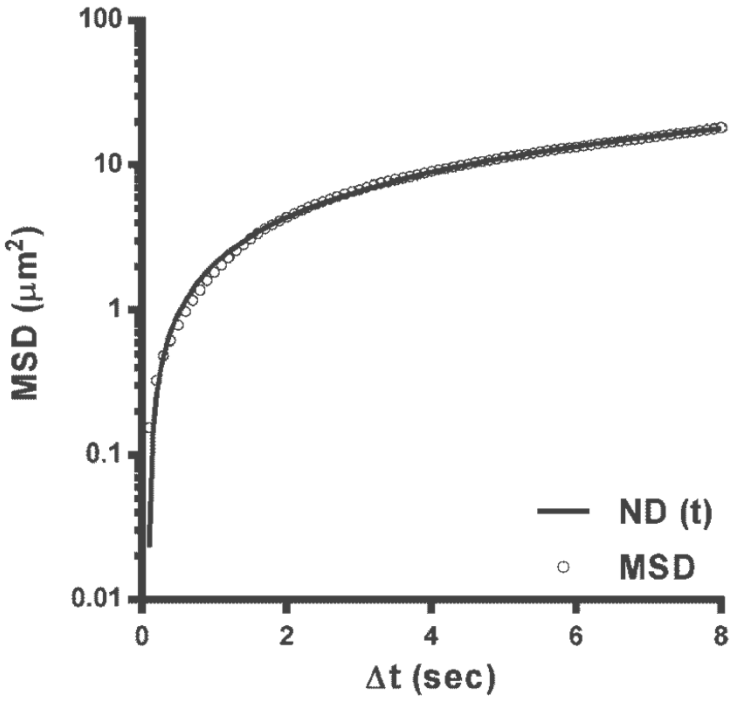
ER & Golgi – critical to transport

Can we use nanotube networks as transportation highways?



Lipid nanotube






Transport → typical 1D diffusion

$D_{QD}$ = 2.3 μm² sec⁻¹

($D_{DOPC}$ = 9.32 μm² s⁻¹)

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Bouxsein et al., 2013 *Langmuir* **29,** 2992; Paxton et al., 2015, *Nanoscale* **7**, 10998.

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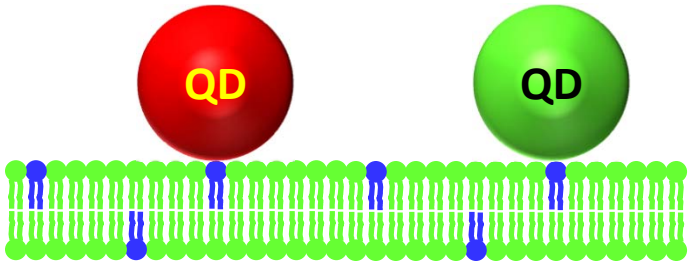
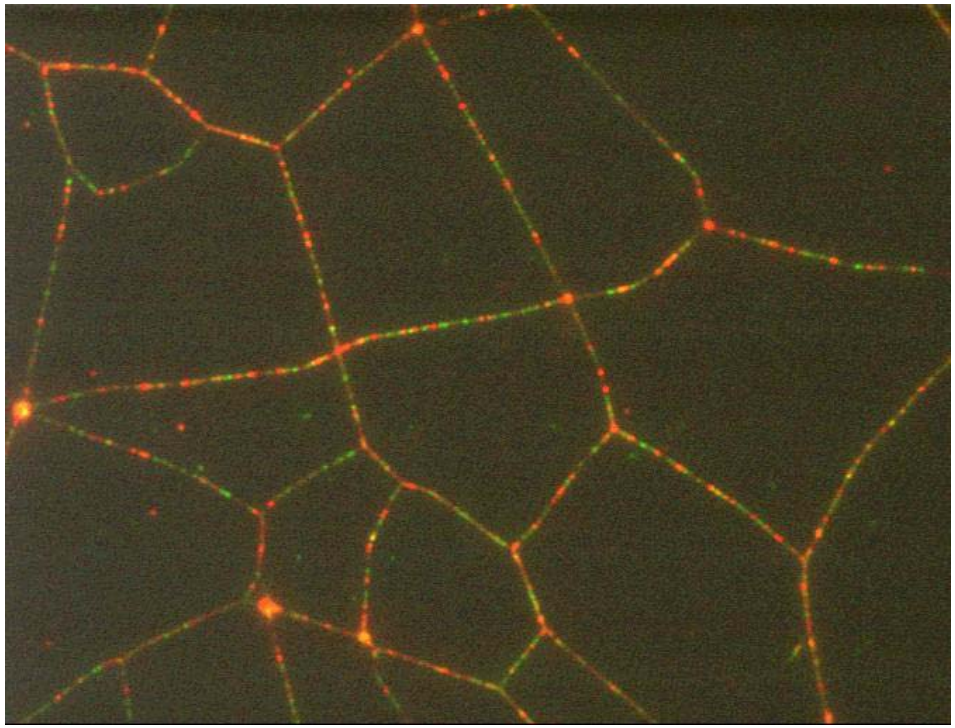
# Transport on Nanotube Networks

At high densities:

- Quantum dots experience traffic
- Single file 1D diffusion



Model for understanding traffic patterns

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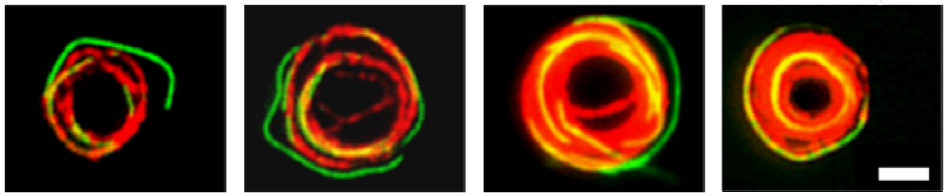
# Conclusions & Future

Motor proteins:

- Convert chemical energy into useful work such as color changing in fish and intracellular reorganization
- Applied outside of living cells to create materials/systems that mimic Nature

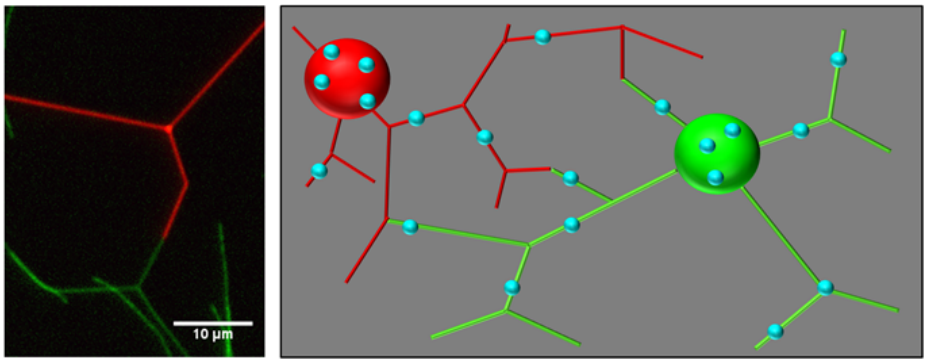
<u>Hybrid optical materials:</u>

- Increase optical complexity
- Study role of defects



<u>Lipid tubules</u>:

- Transport inside of nanotubes
- Multi-network connection and communication

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