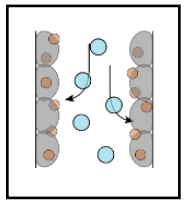
Background

Analogies exist between biological and physicochiemical methods of remediation

Synthetic

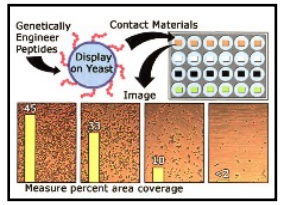
Ion-exchange



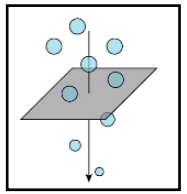
Adsorption

Strategy #1

Cell surface display

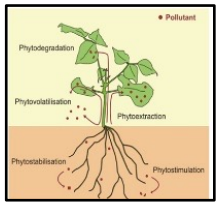


Phytoremediation



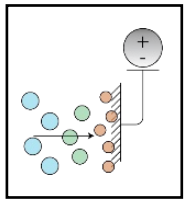
ElectroChem

Strategy #2

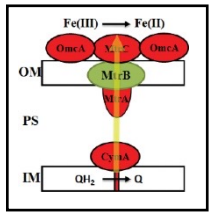


Oxidases & Reductases

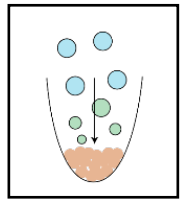
Biological



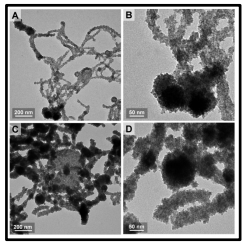
Precipitation



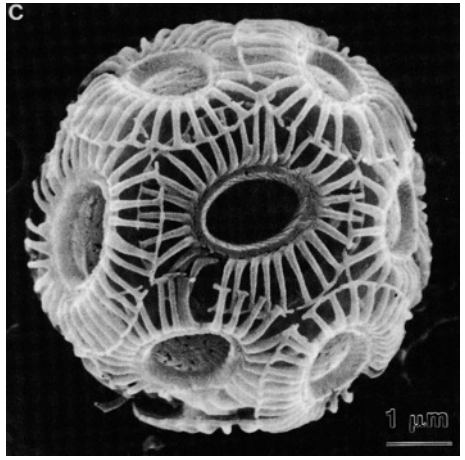
Biomineralization



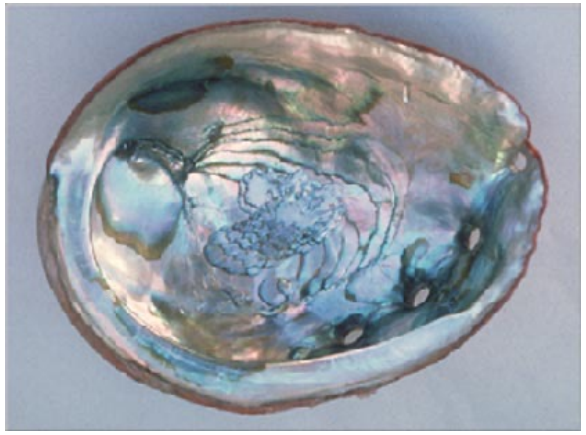
Strategy #3

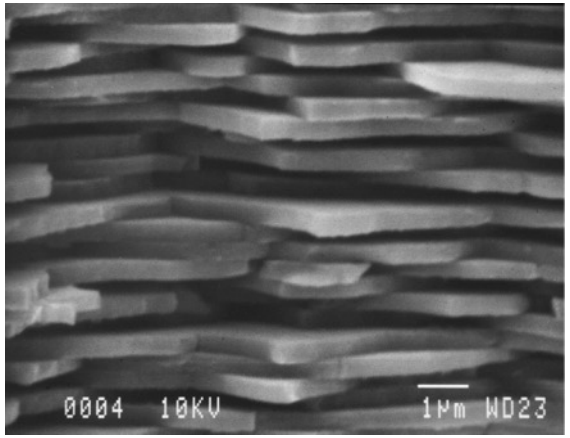


Natural Biomaterials

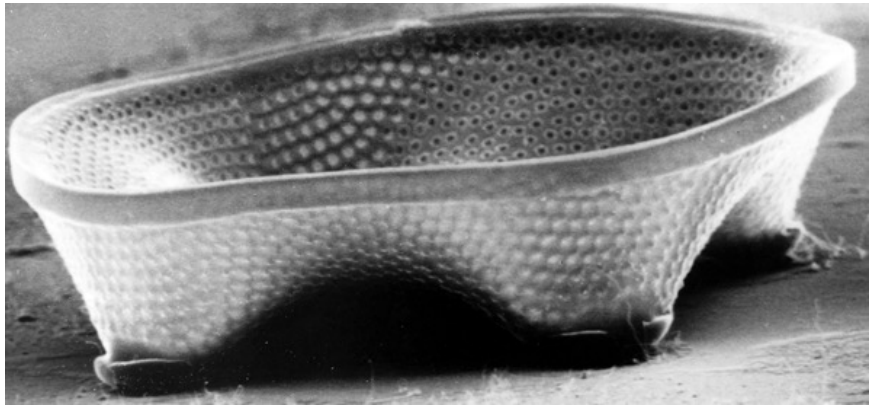


Coccosphere $CaCO_3$
Mann, 1996

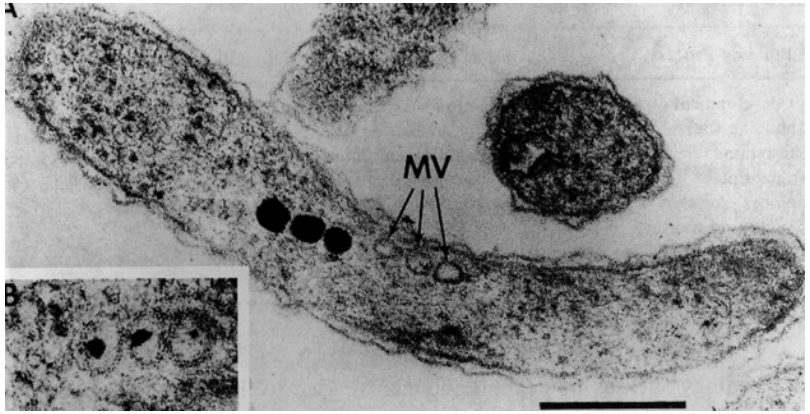




Abalone shell $CaCO_3$

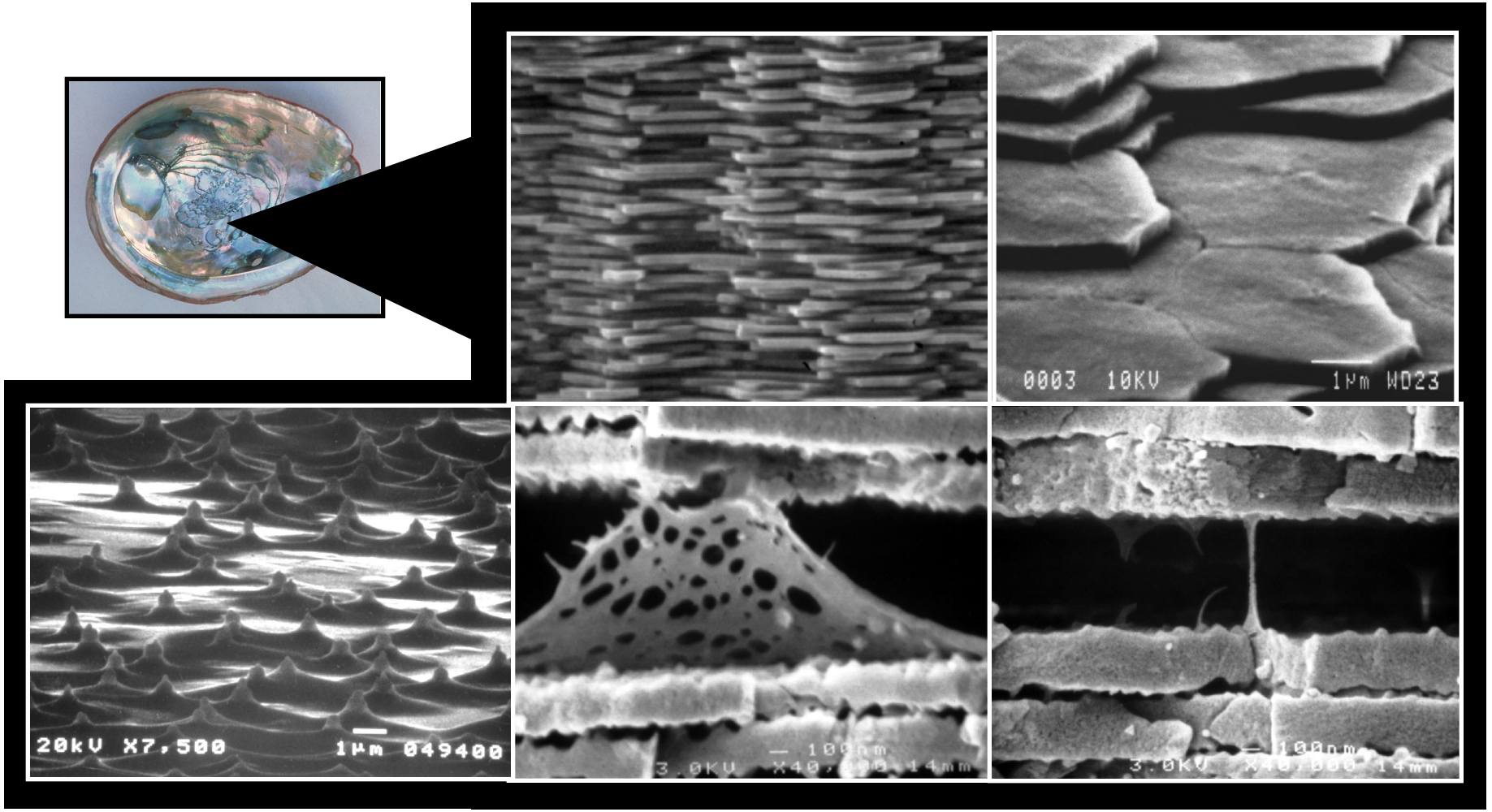


Diatom SiO_2, Belcher, 1990

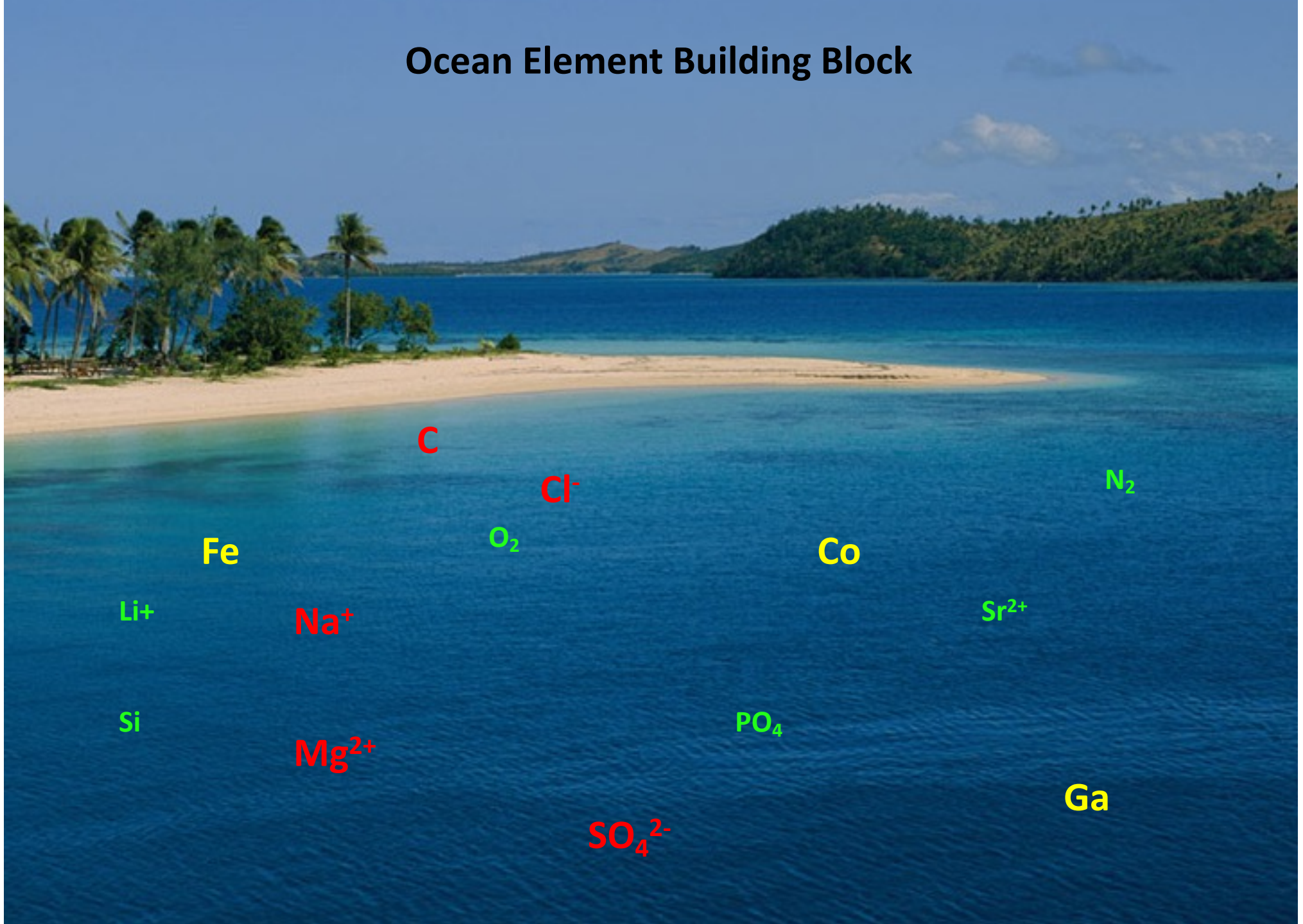


Magnetotatic bacterium Fe_3O_4
Gorby, 1988

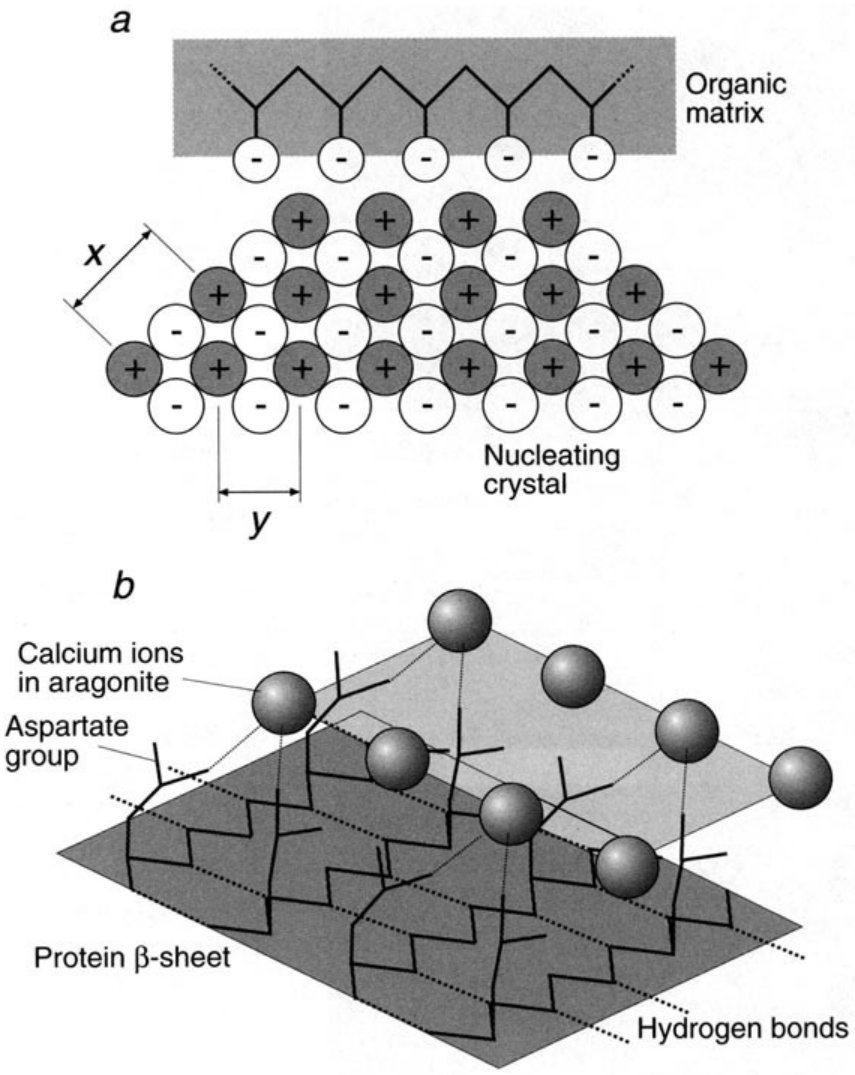
Shell Structure Imaged via SEM

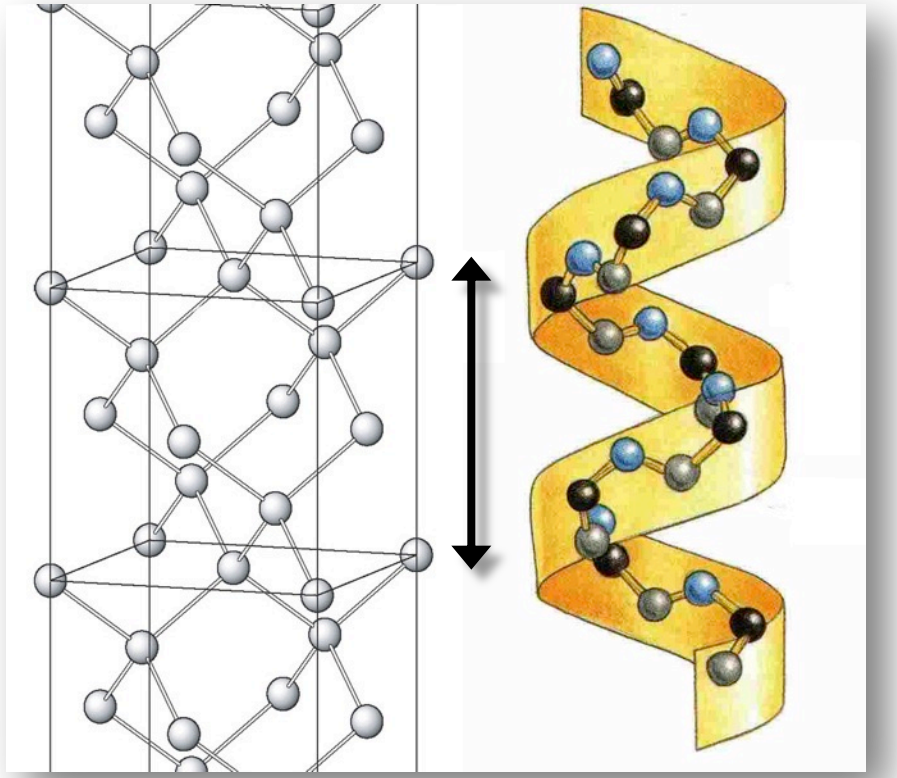


Ocean Element Building Block

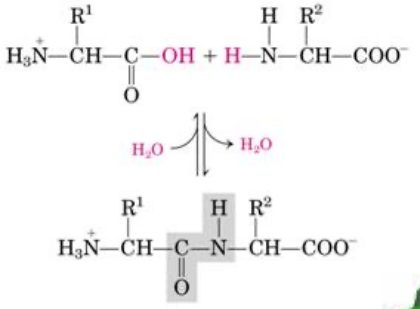


Protein Mediated Crystal Growth

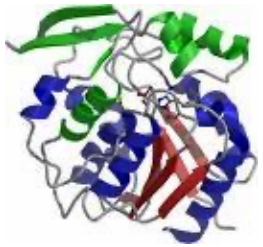


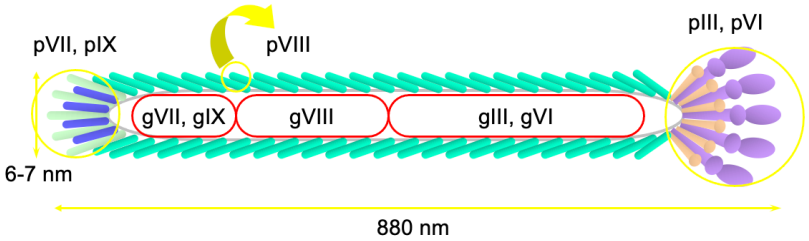


(Ball, 1997)

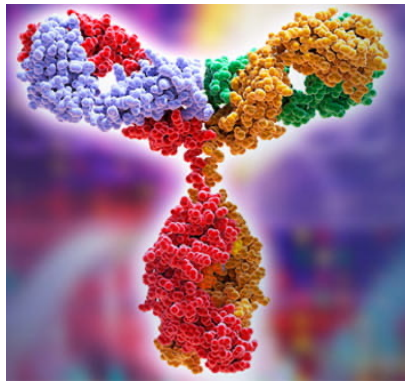


Amino acids, peptides, and proteins



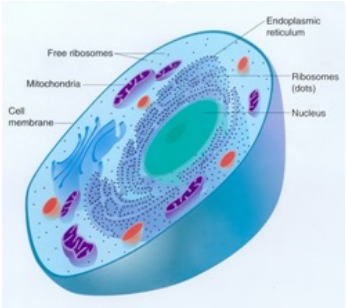


Viruses

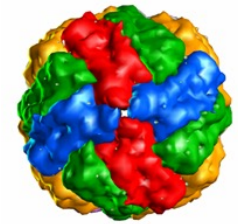


Antibodies

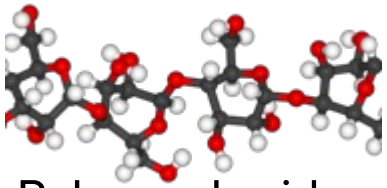
Biological Tool Kit



Cells as factories



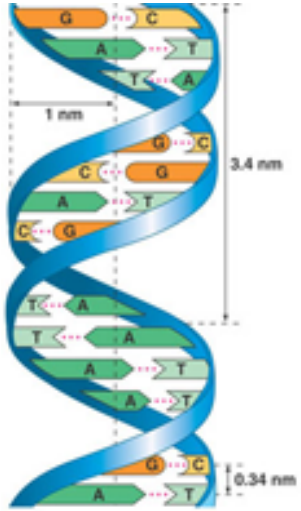
Protein Cages

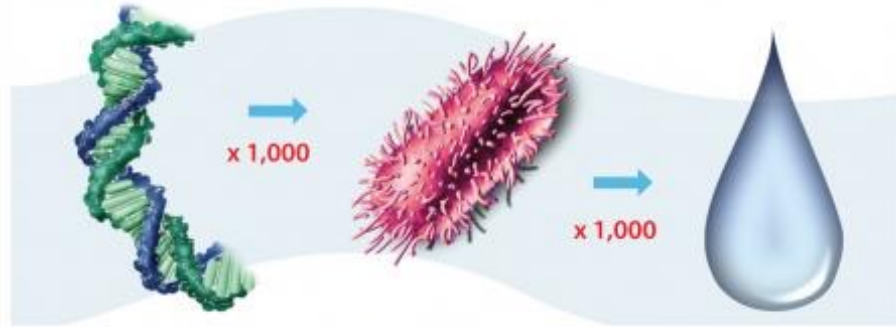


Polysaccharides

Microbes

Nucleic Acids





DNA
2.5 nanometers
diameter

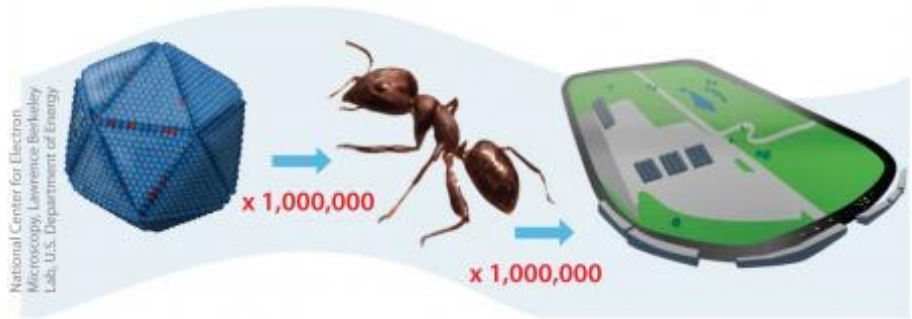
Bacterium
2.5 micrometers
long

Large Raindrop
2.5 millimeters
diameter

Single-walled Carbon Nanotube
1 nanometer diameter

Strand of Hair
100 micrometers
diameter

House
10 meters
wide



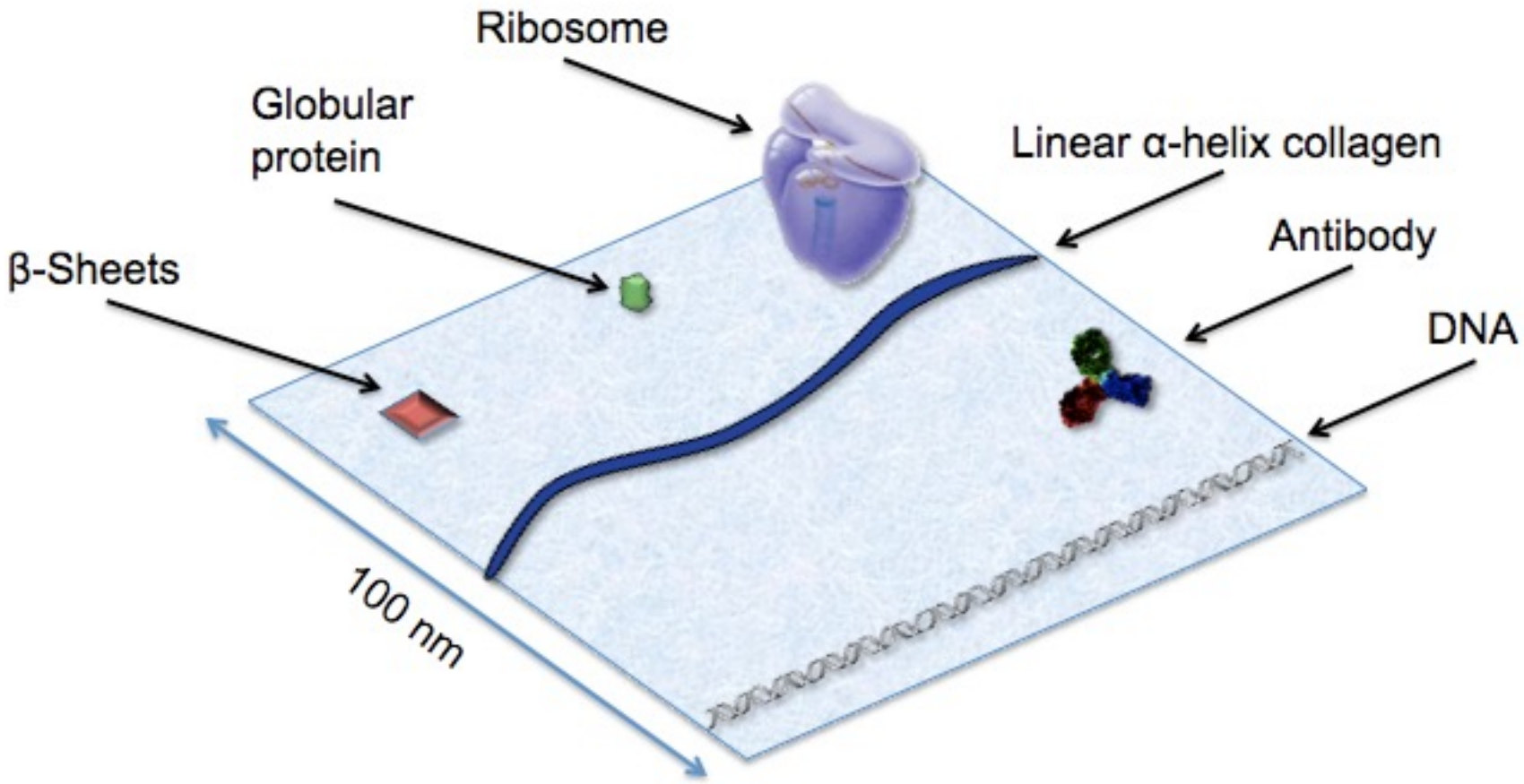
National Center for Electron Microscopy, Lawrence Berkeley Lab, U.S. Department of Energy

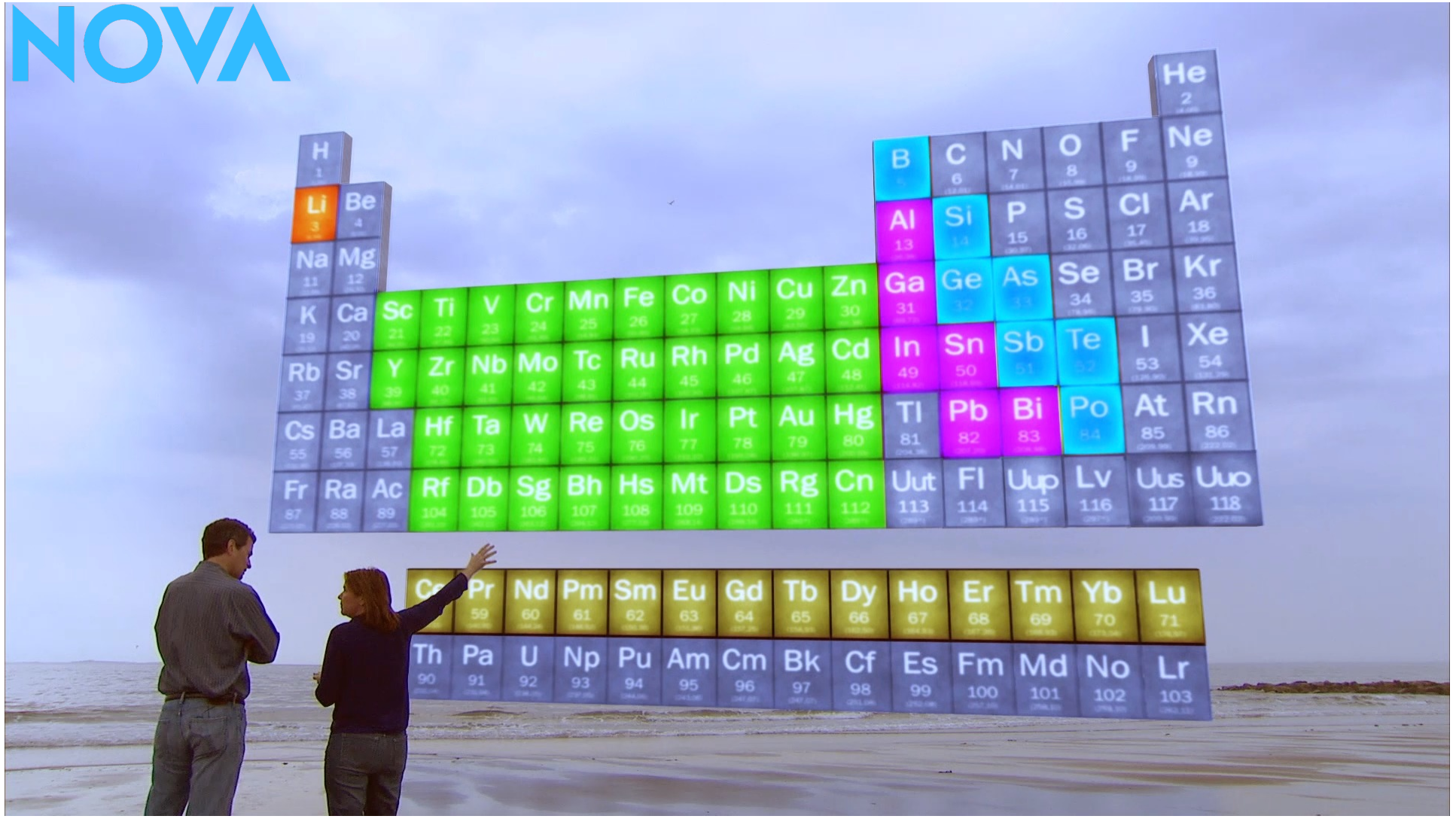
Nanoparticle
4 nanometers
diameter

Ant
4 millimeters
long

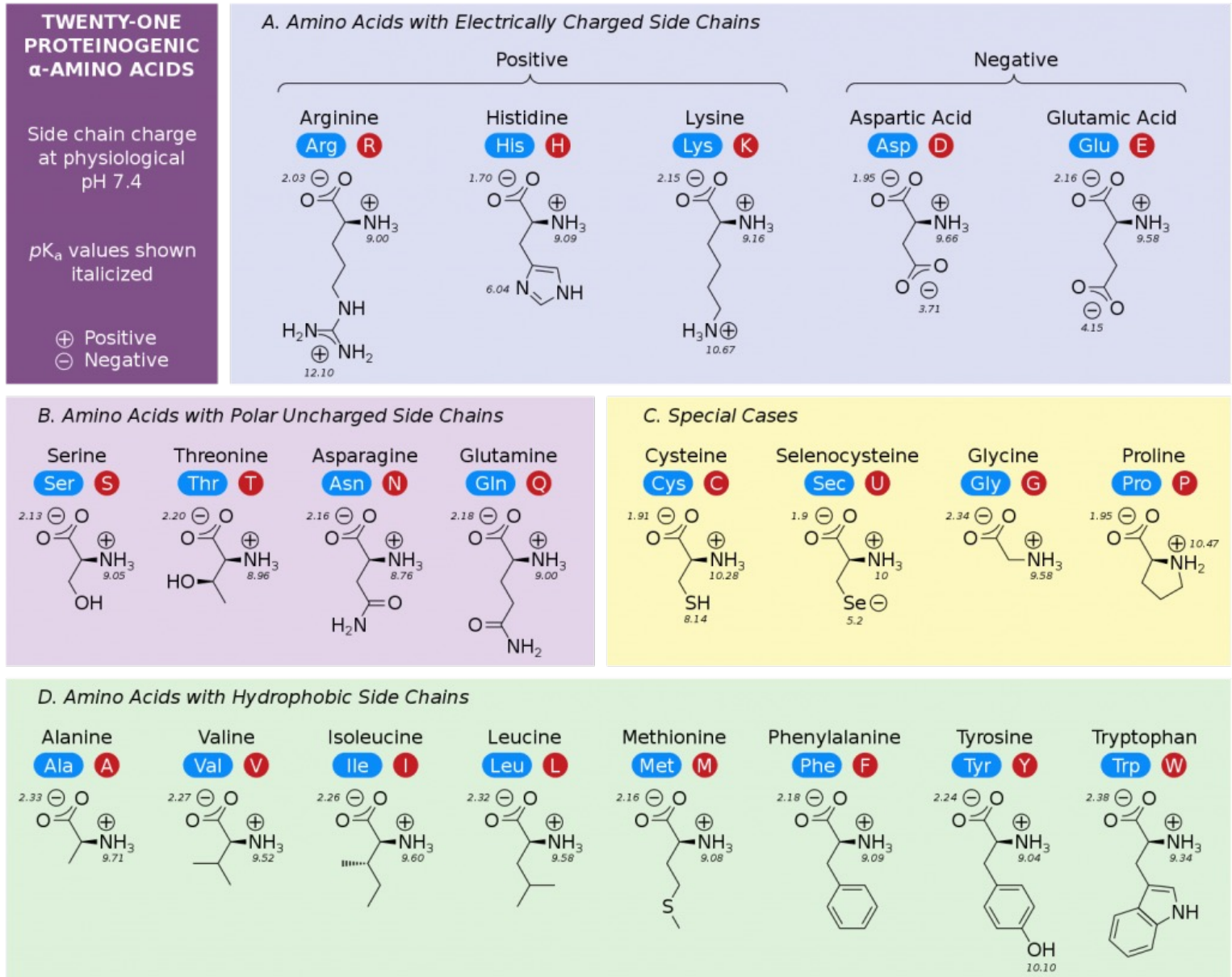
Indianapolis Motor Speedway
4 kilometers per lap

Nanoscale Biomolecules as Tool-kit





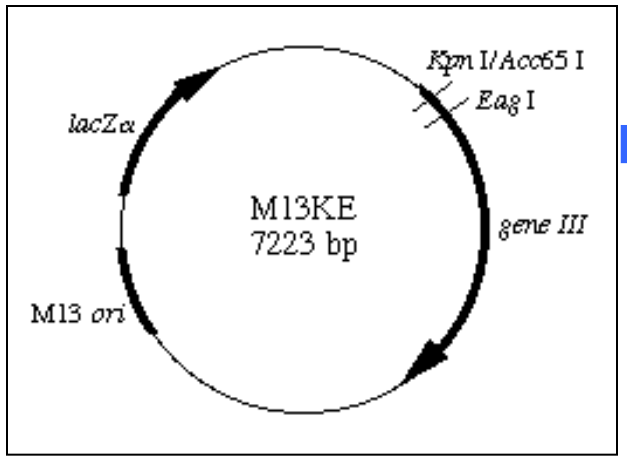
Making Stuff Wilder
Host David Pogue travels the globe to explore new technologies inspired by nature. Aired October 23, 2013 on PBS


TWENTY-ONE PROTEINOGENIC α-AMINO ACIDS
Side chain charge at physiological pH 7.4
pKa values shown italicized
⊕ Positive
⊖ Negative
A. Amino Acids with Electrically Charged Side Chains
Positive
Negative
Arginine Arg R
Histidine His H
Lysine Lys K
Aspartic Acid Asp D
Glutamic Acid Glu E
B. Amino Acids with Polar Uncharged Side Chains
Serine Ser S
Threonine Thr T
Asparagine Asn N
Glutamine Gln Q
C. Special Cases
Cysteine Cys C
Selenocysteine Sec U
Glycine Gly G
Proline Pro P
D. Amino Acids with Hydrophobic Side Chains
Alanine Ala A
Valine Val V
Isoleucine Ile I
Leucine Leu L
Methionine Met M
Phenylalanine Phe F
Tyrosine Tyr Y
Tryptophan Trp W

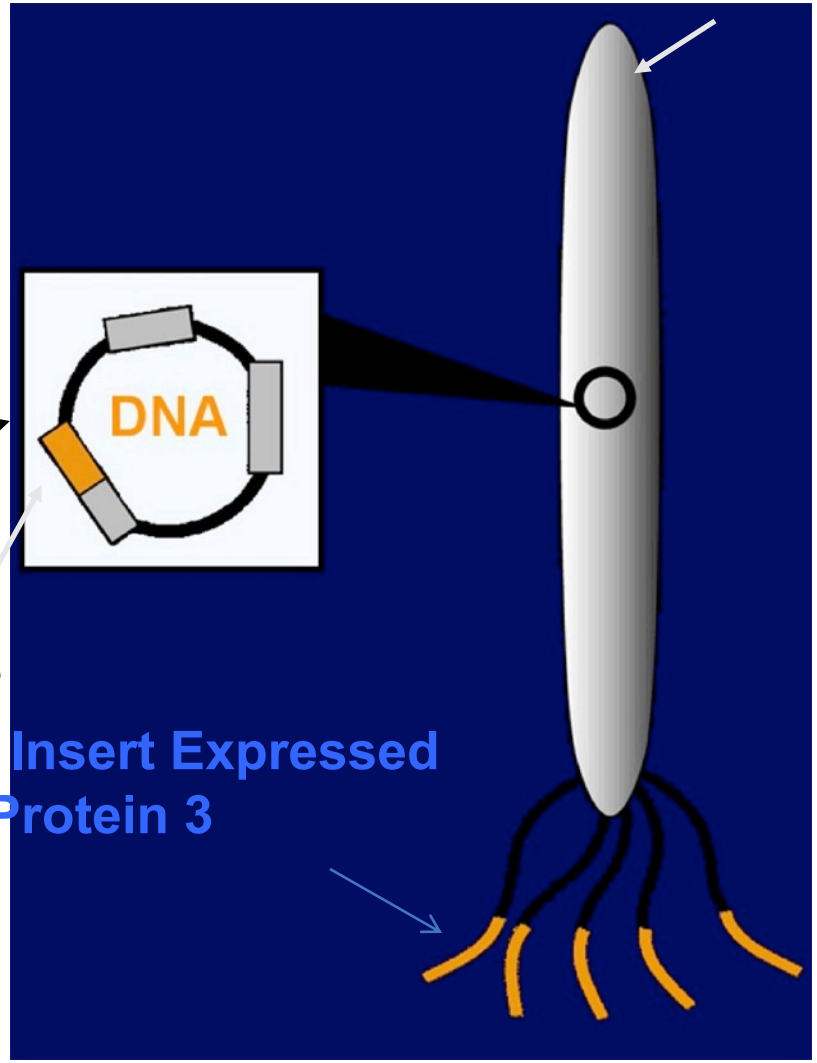
A Combinatorial Approach…..

Using Bacteriophage, or "phage"

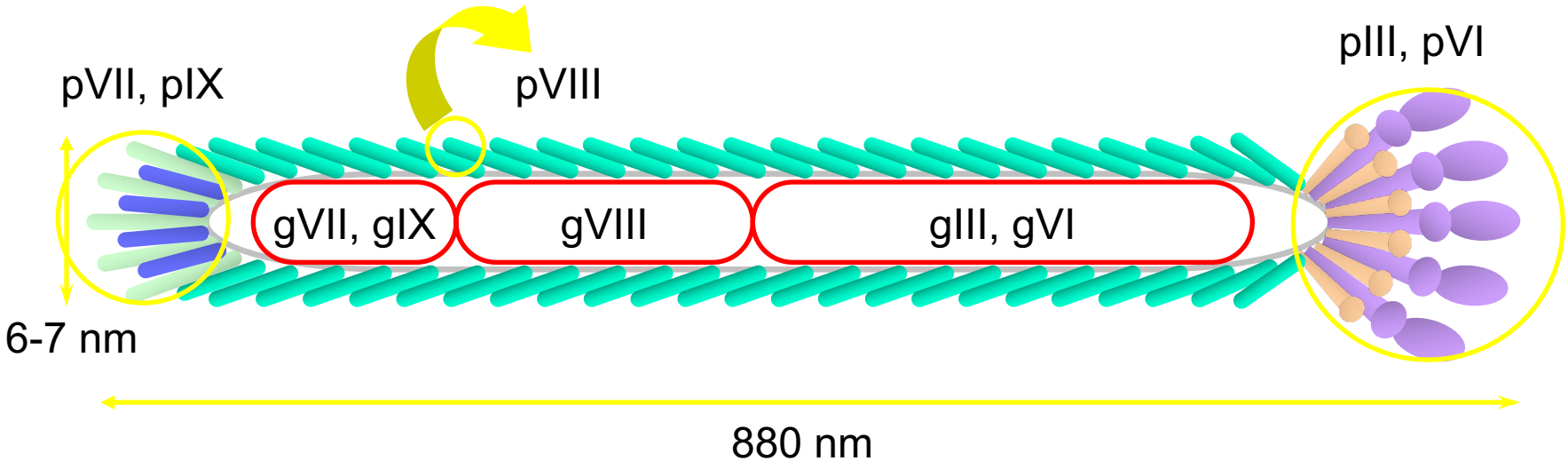
A virus that infects bacteria



(New England BioLabs)

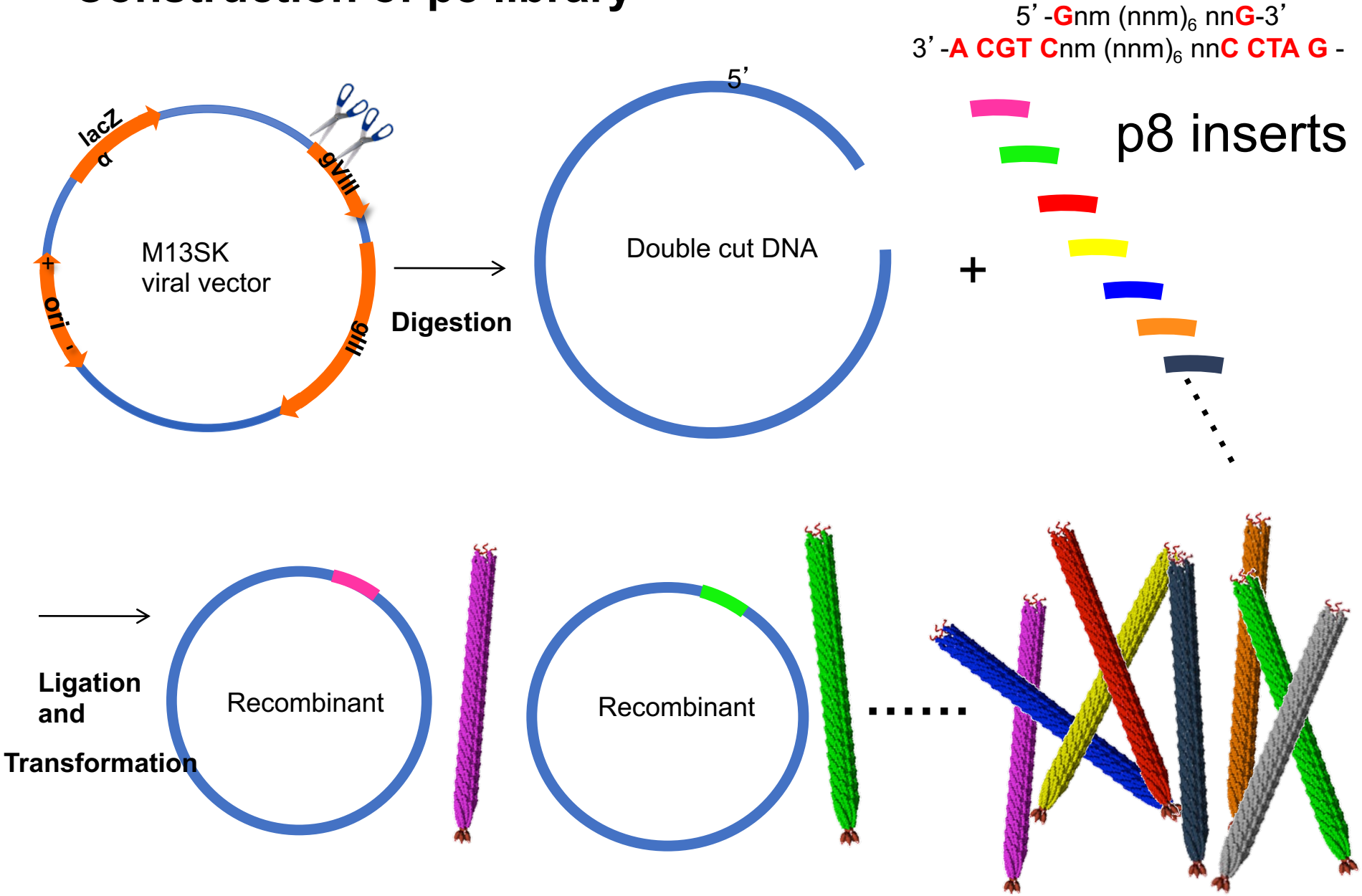


M13 Bacteriophage

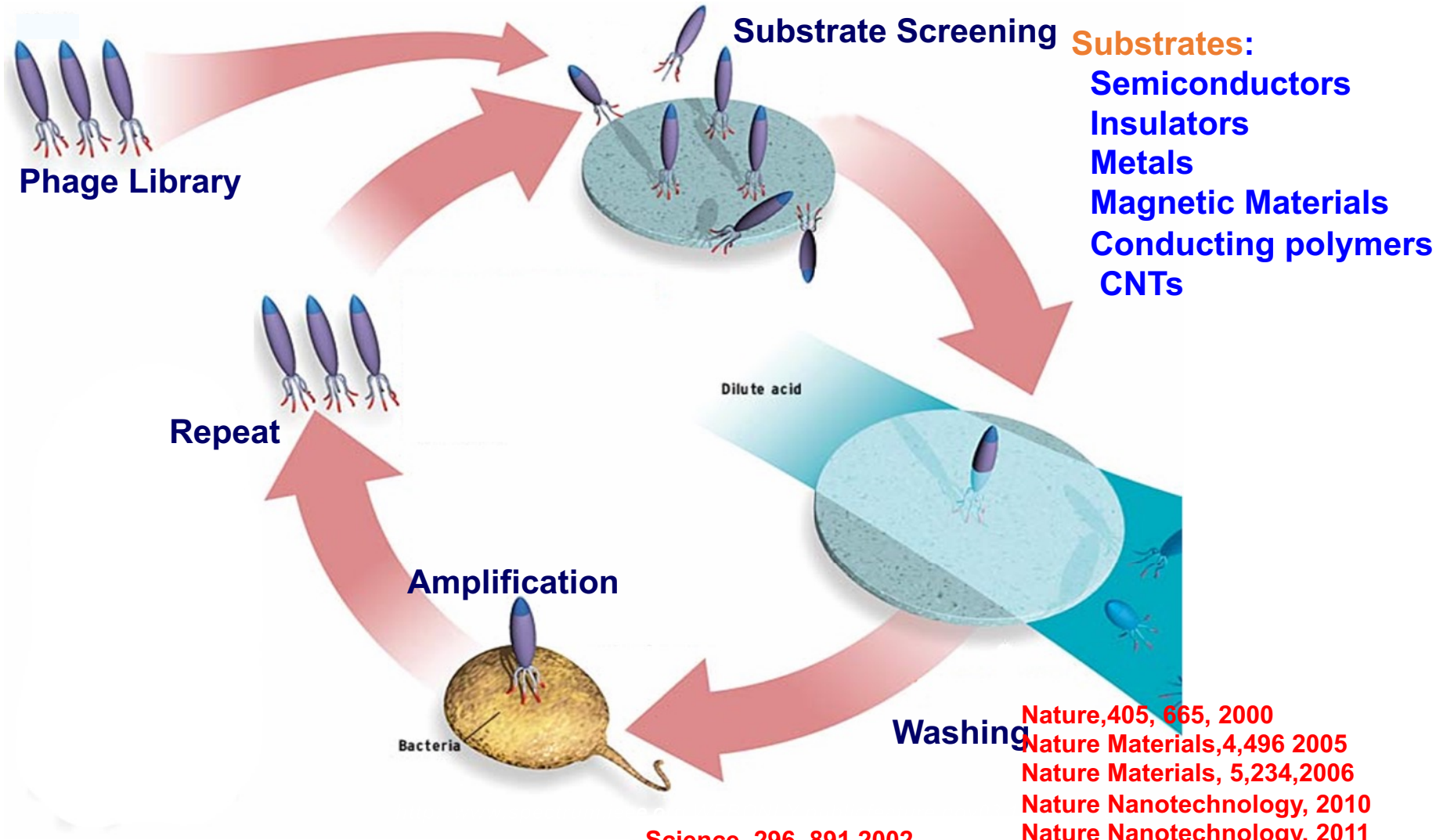


Protein	pVII	pIX	pVIII	pIII	pVI
Residues	33	32	73	427	112
# of Copies	5	~5	~2,700	3-5	~5

Construction of p8 library

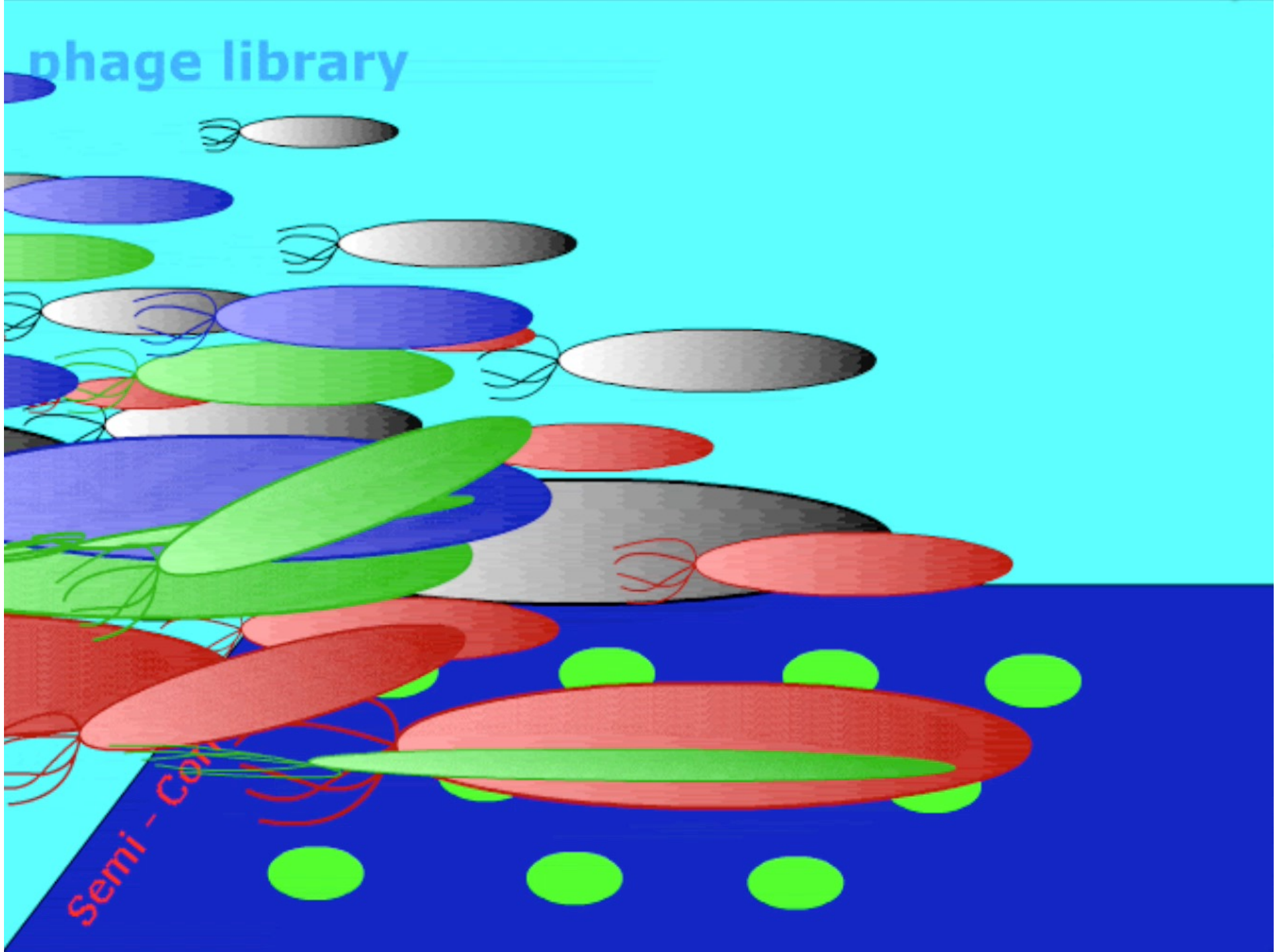


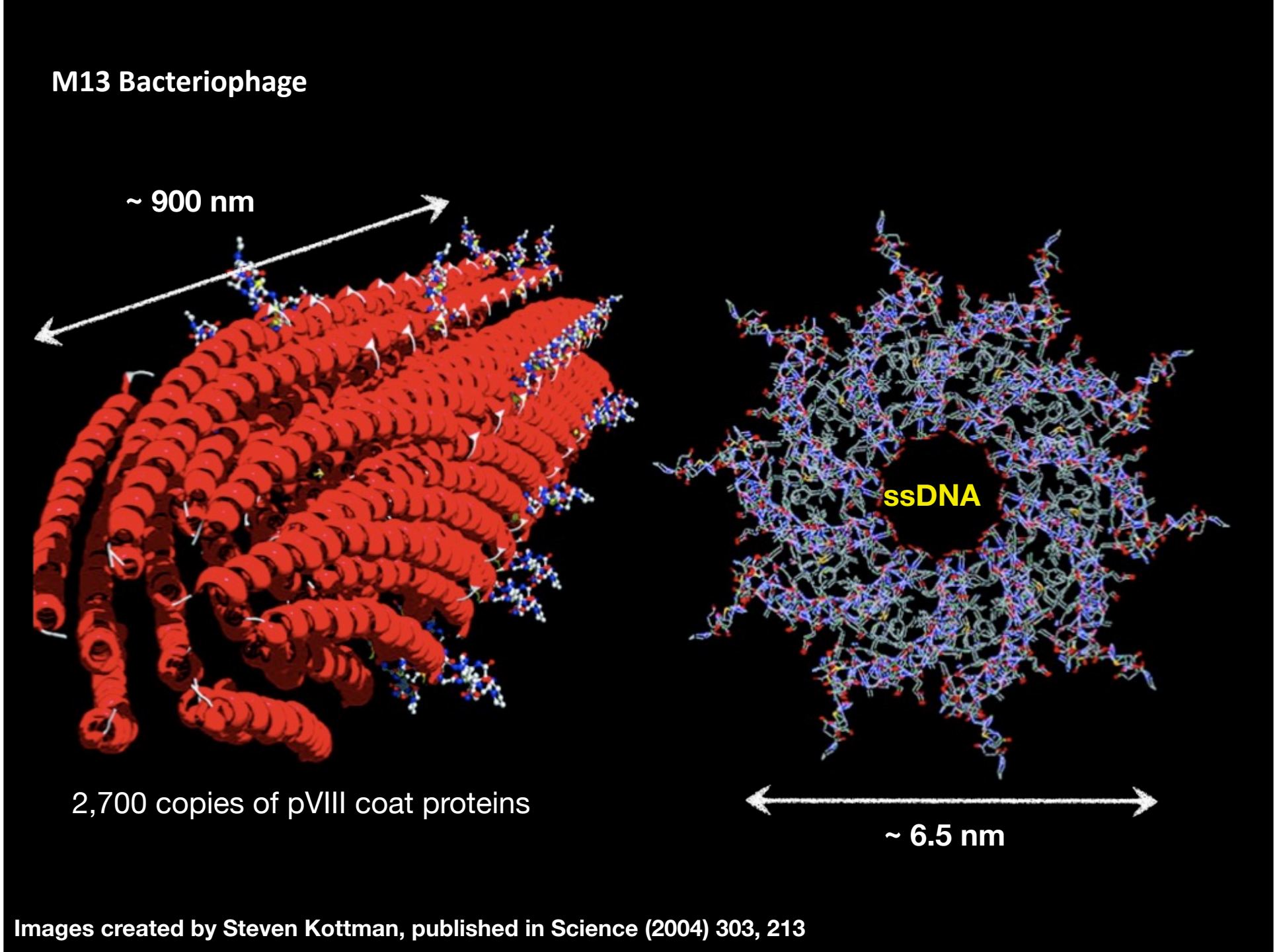
Peptide Libraries & Selection



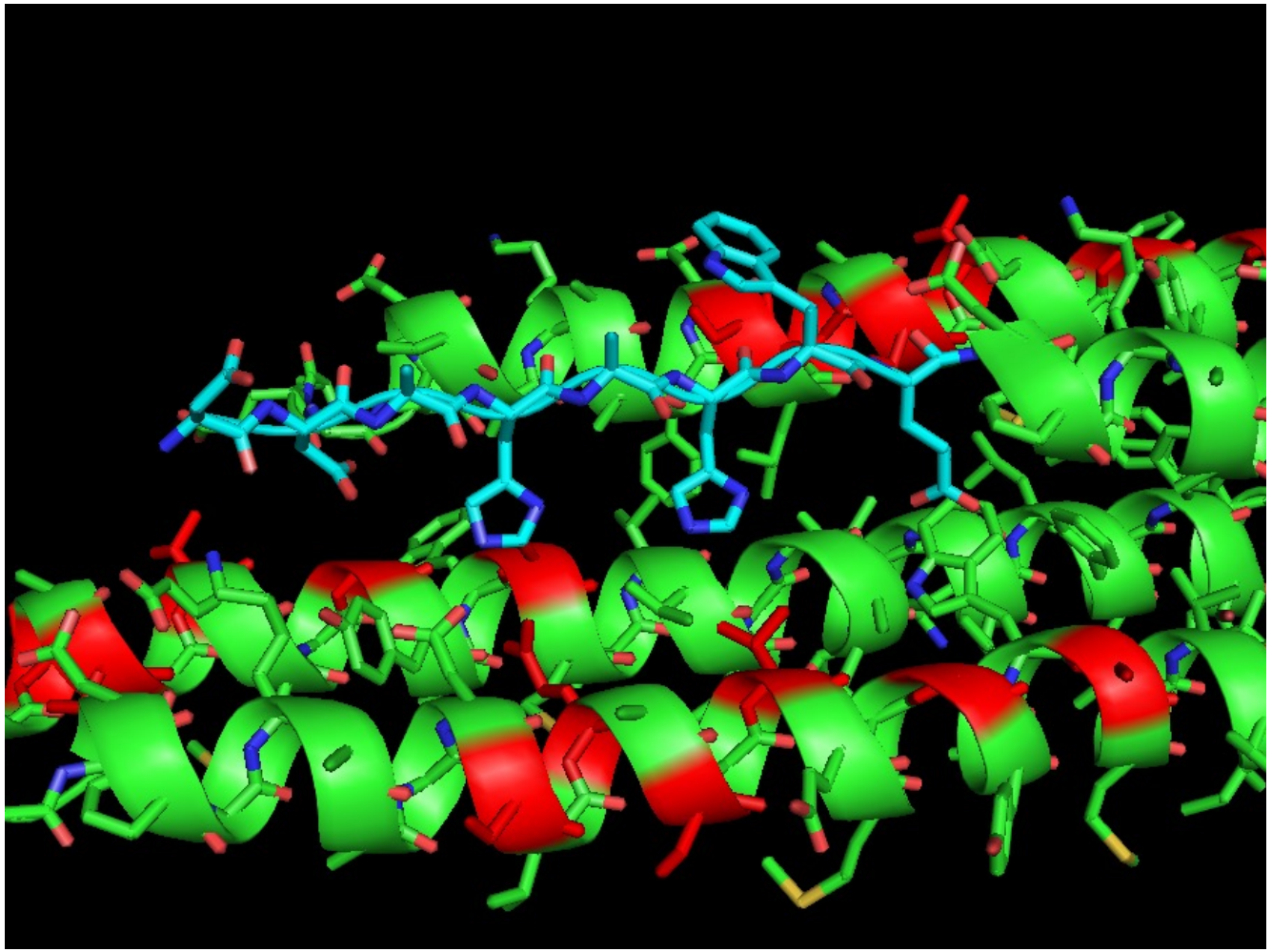
Science, 296, 891,2002
Science, 303, 213, 2004
Science, 312,885, 2006
Science , 324,1051, 2009

Nature,405, 665, 2000
Nature Materials,4,496 2005
Nature Materials, 5,234,2006
Nature Nanotechnology, 2010
Nature Nanotechnology, 2011
Nature Nanotechnology, 2012
Nature Communications, 2013
Nature Communications, 2014
Nature Materials, 2015

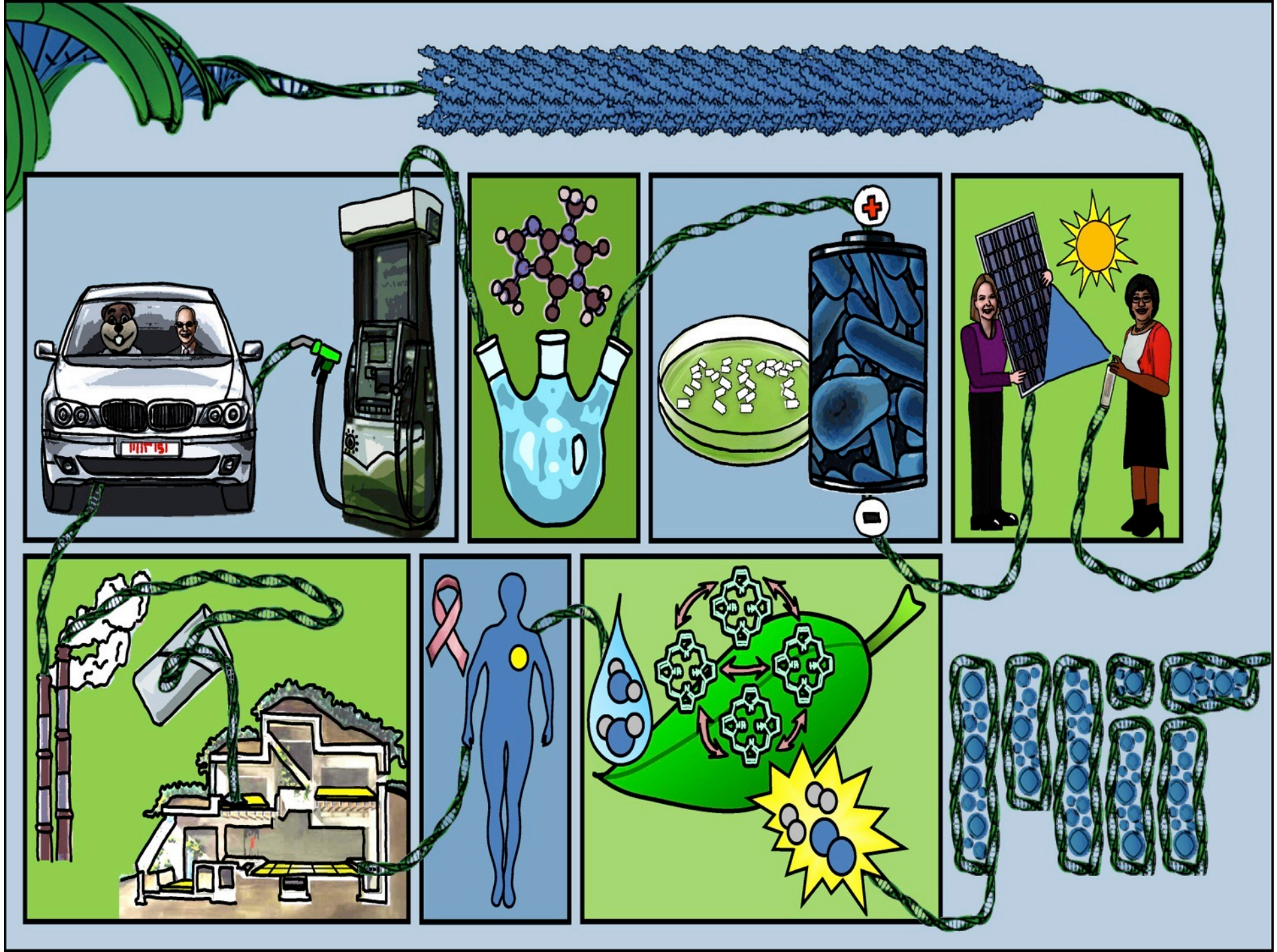

phage library
Semi - Co



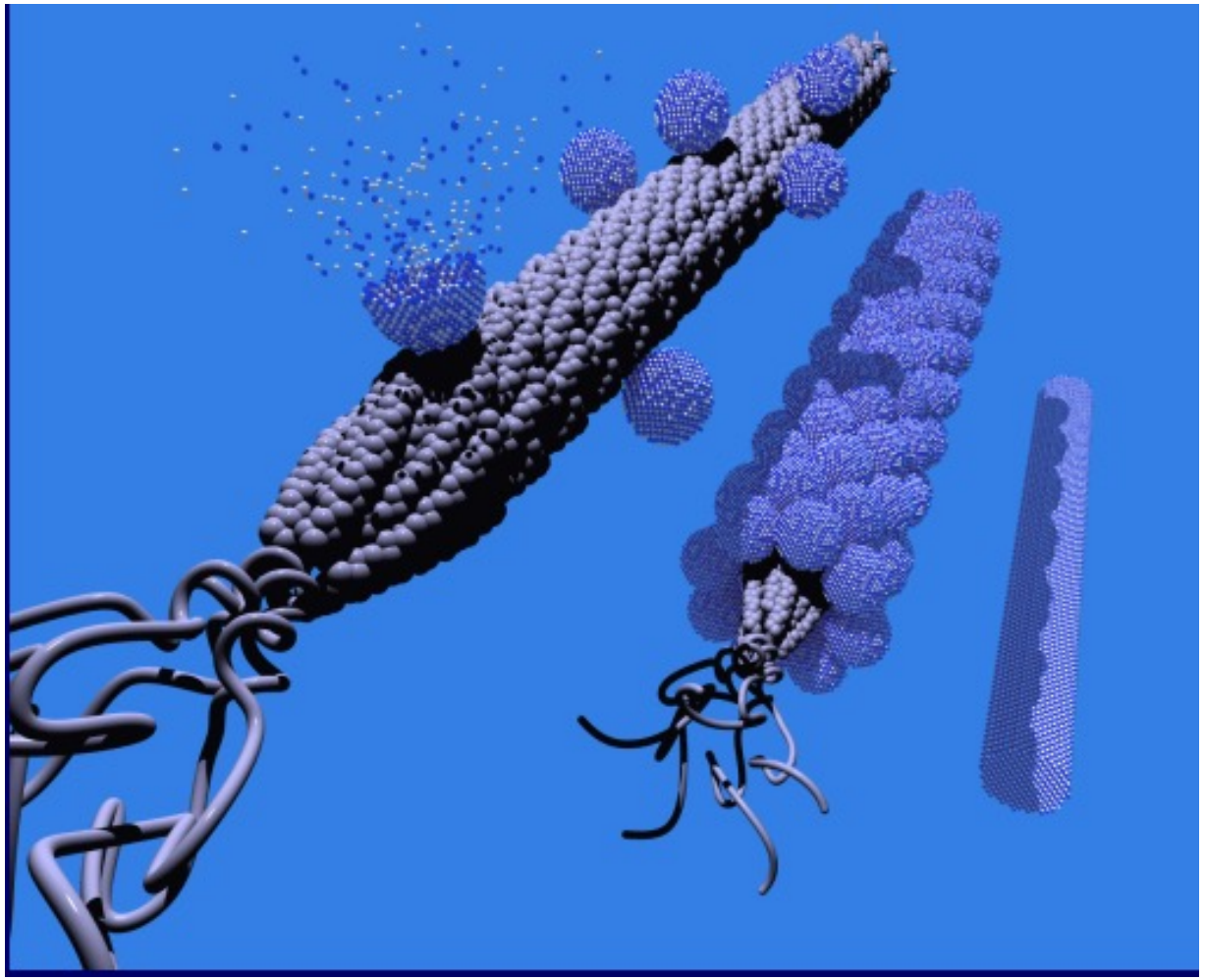
Images created by Steven Kottman, published in Science (2004) 303, 213



4 strands of pVIII with a DDAHVHWE peptide added to the end of one strand

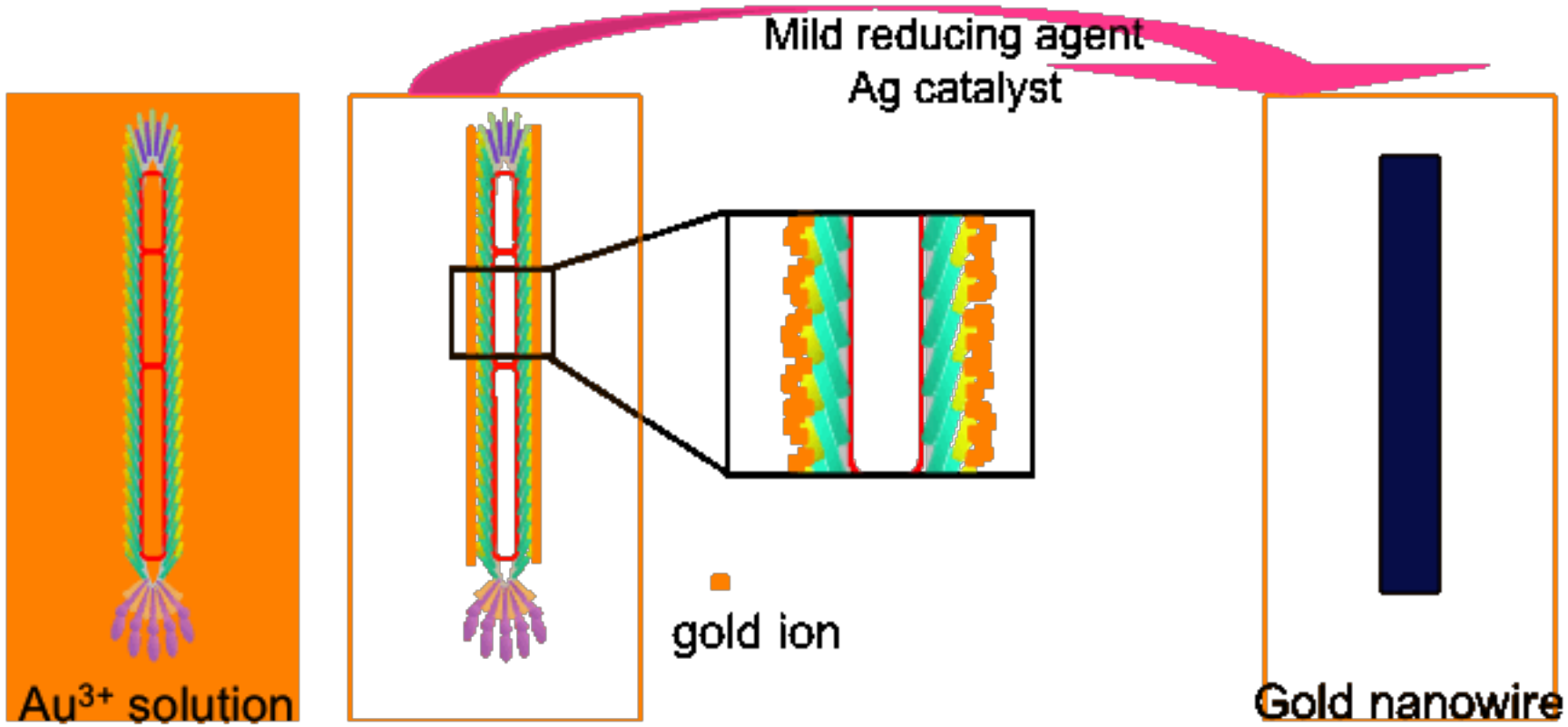


Single Crystals Nanowires



Science, 303, p213, 2004

Schematic Diagram for Gold Nanowire



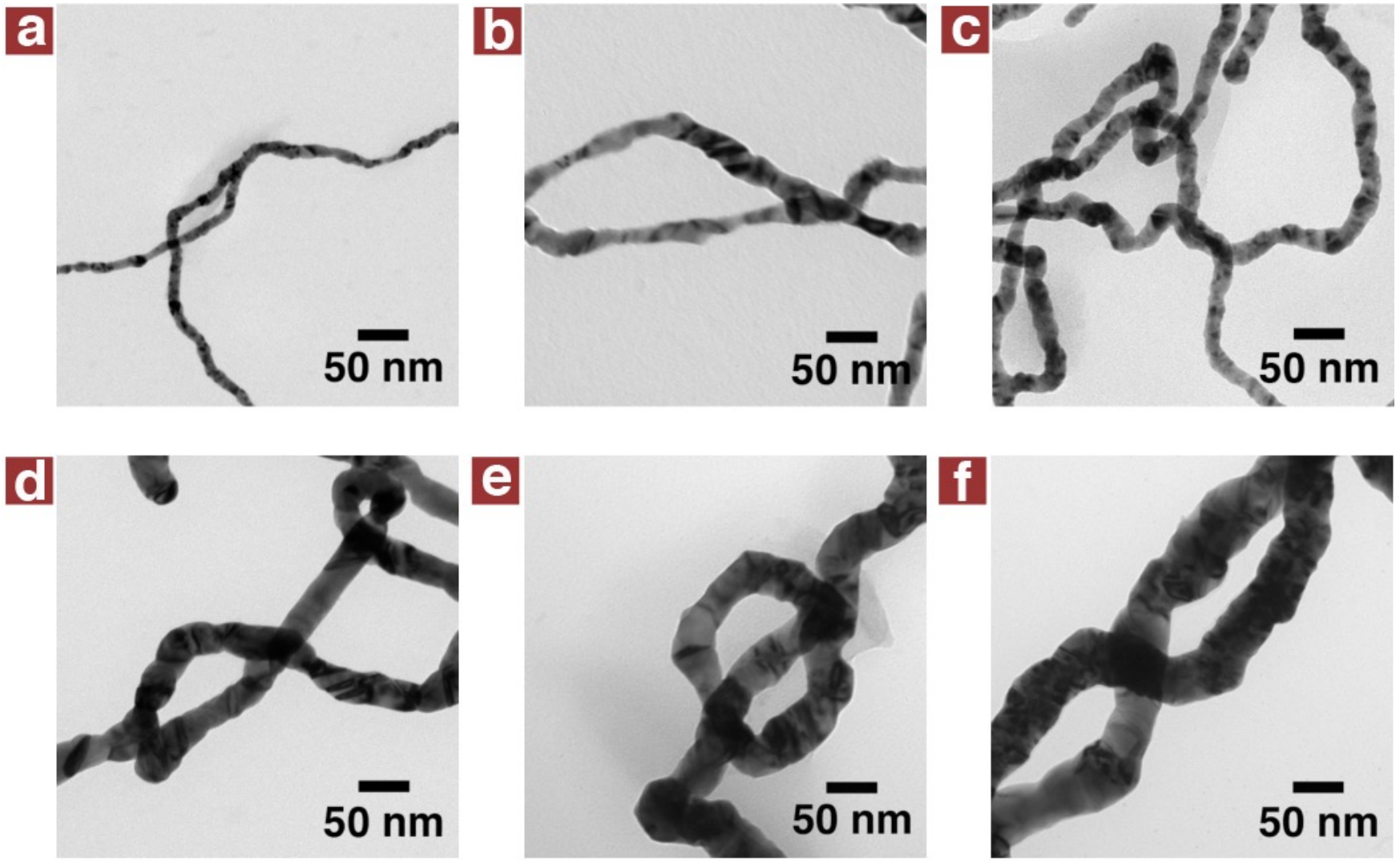
- Gold ions
  - Incubated with p8#9
  - Partly reduced by ascorbic acid
  - Formation of nanowires in static condition with silver catalyst

(VSGSSPDS) Chung-Yi Chiang

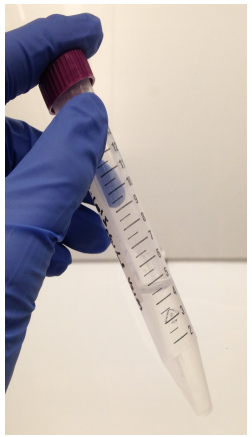
Youjin Lee

TEM Images of Gold nm Nanowires

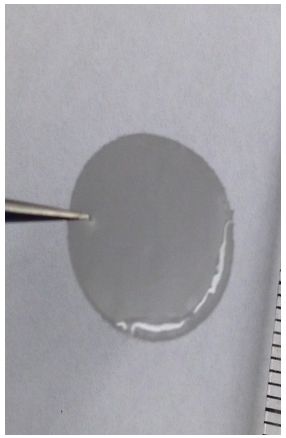
Relatively uniform diameter along the length 10,15, 20, 25, 30, 50 nm



Battery Materials can be Deposited onto Virus-Templated Metal Nanofoams

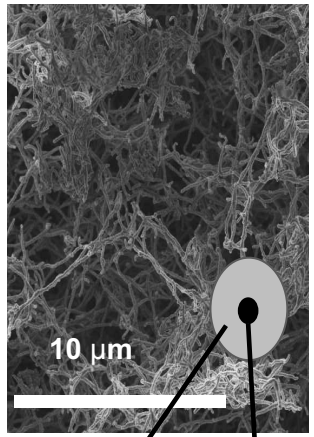


(1) Phage Solution
Y21ME3 Clone

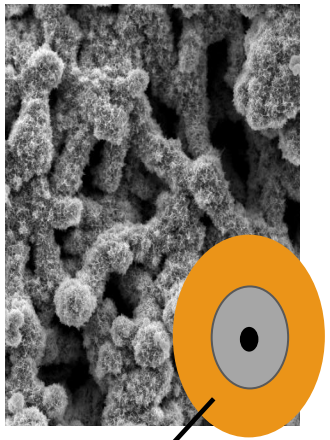


(2) Cross-Linking

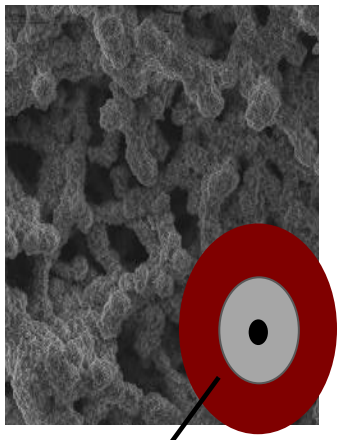
(3) Sensitization



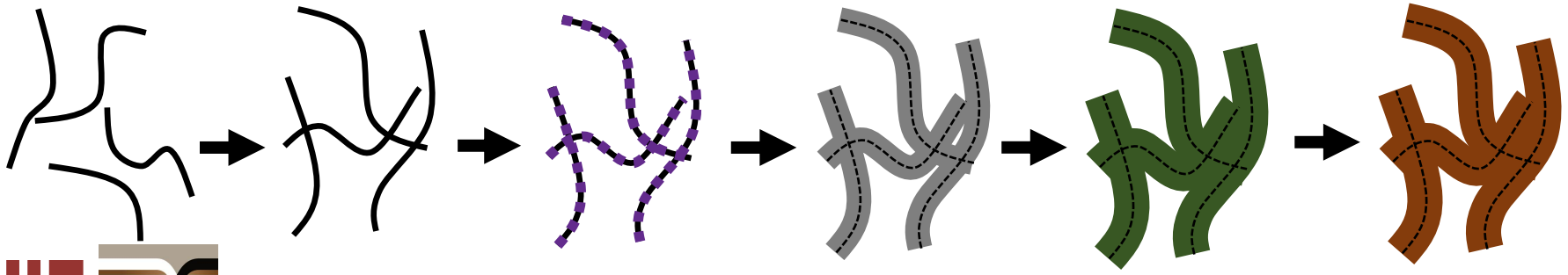
(4) Electroless Metallization



(5) Electrodeposition of precursor

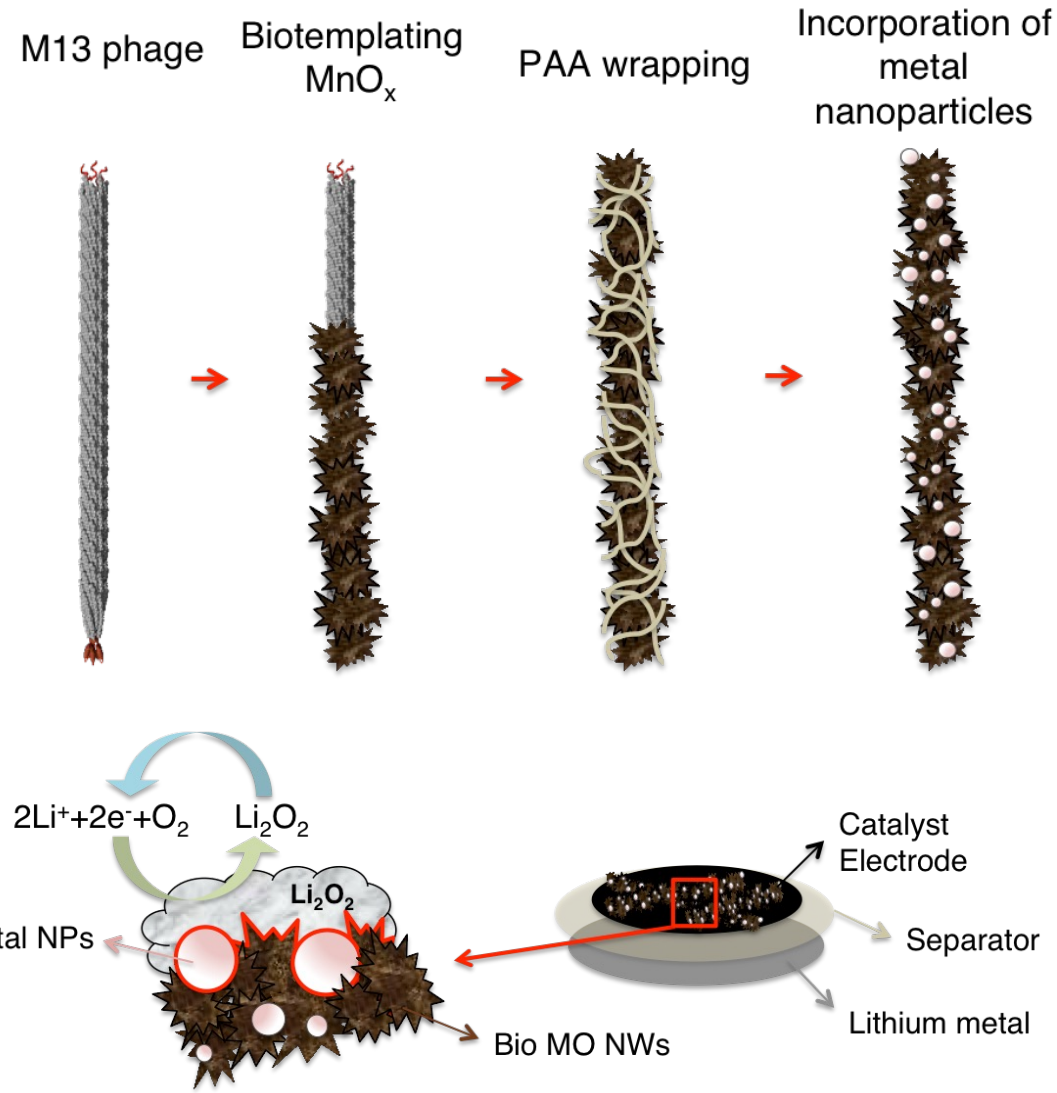


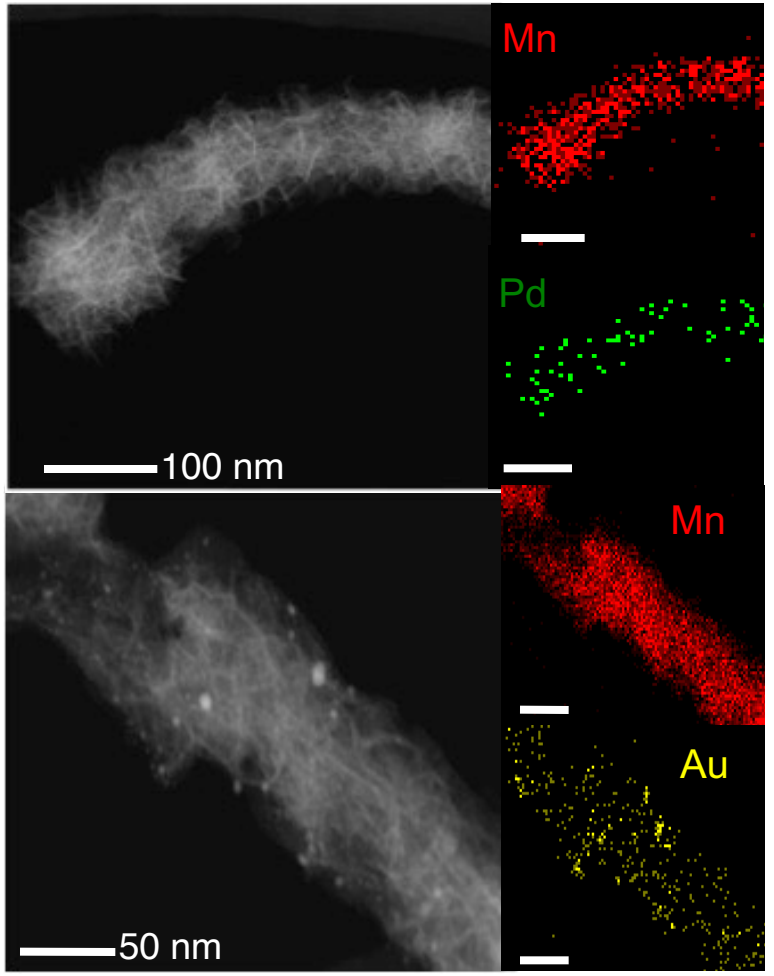
(6) Thermal Lithiation



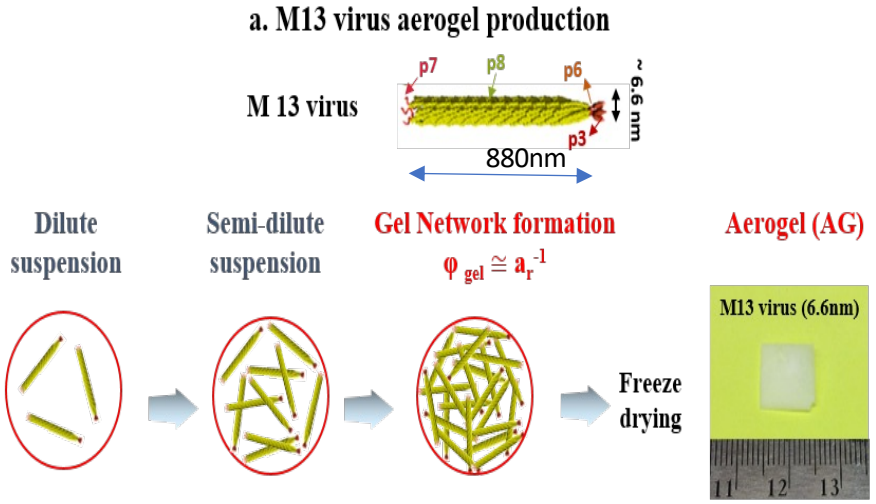
More Improvement in Catalytic Activities By Compositing Small Amounts of Pd Nanoparticles

Synthesis steps





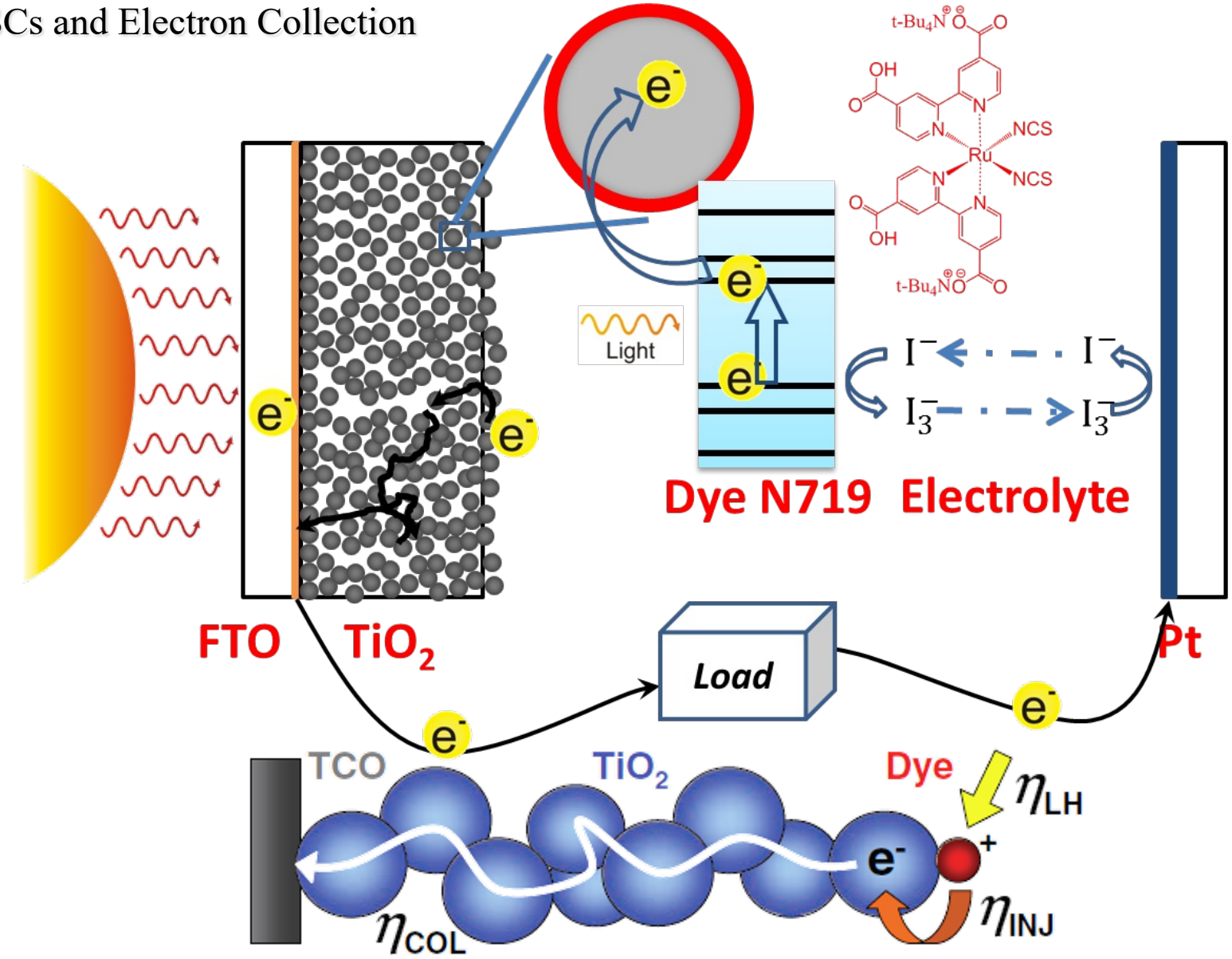
Oh, Nature Comm, 2013



extremely light-weight, for M13-AG: 2mg/cm^3 ,
for M13-CFO AG: 13mg/cm^3;
M13-Ru AG: 10mg/cm^3
high porosity of 99.8 % for viral AG

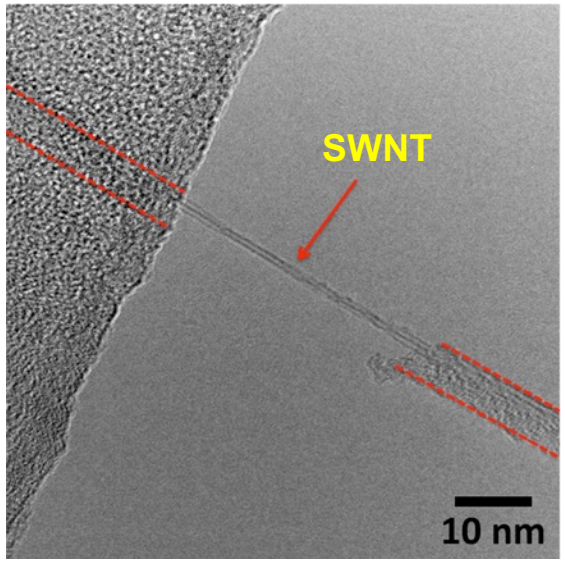
Jifa Qi, Advanced Functional Materials 2016

DSSCs and Electron Collection



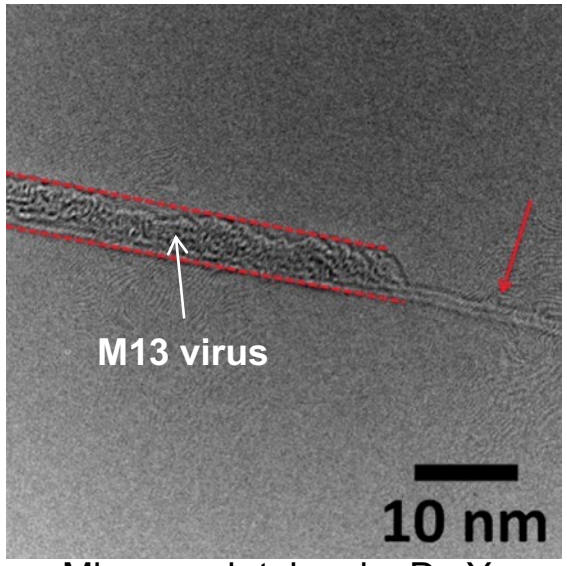
SWNTs Stabilized by M13 Virus

M13-SWNT



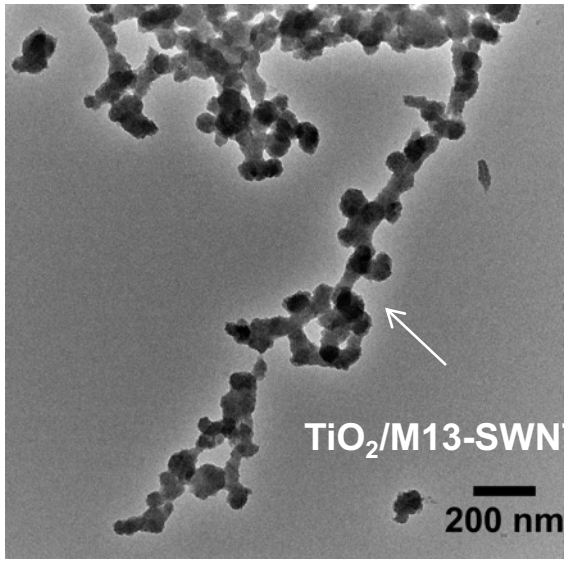
Micrograph taken by Dr. Yun

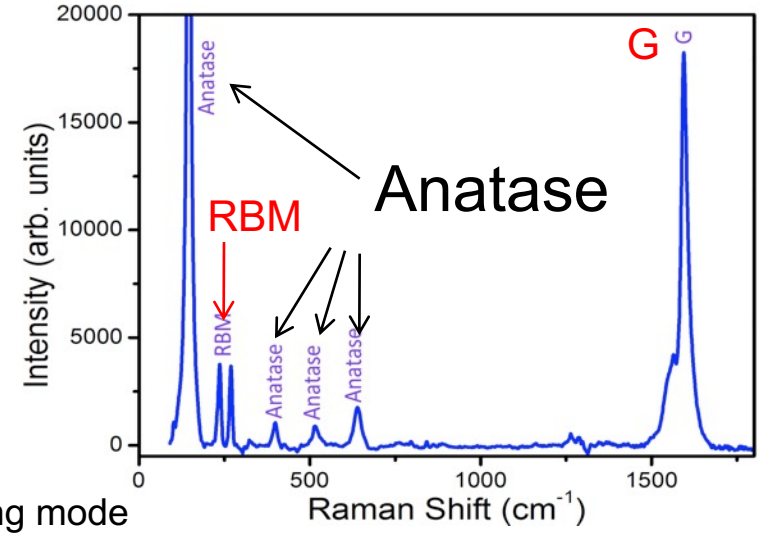
M13-SWNT



Micrograph taken by Dr. Yun

M13-SWNT-TiO_2





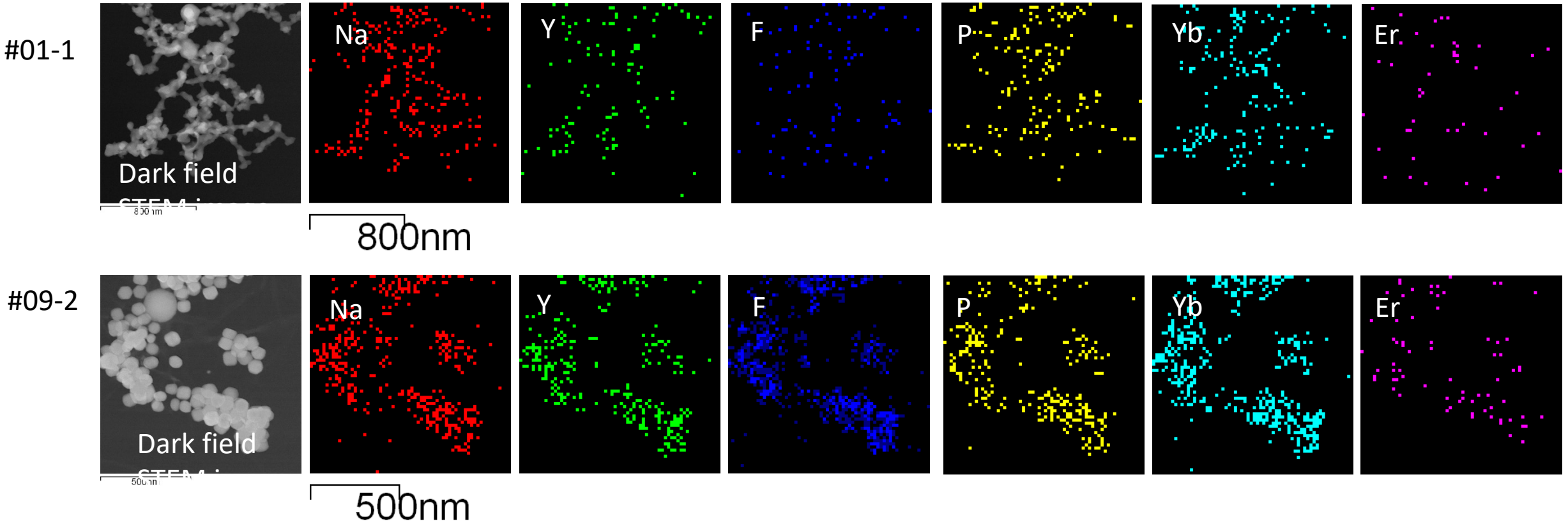
RBM: radial breathing mode

Xiangnan Dang*, Hyunjung Yi*, *et al*., *Nature Nanotechnology* **6** 377 (2011)

Bio-INC

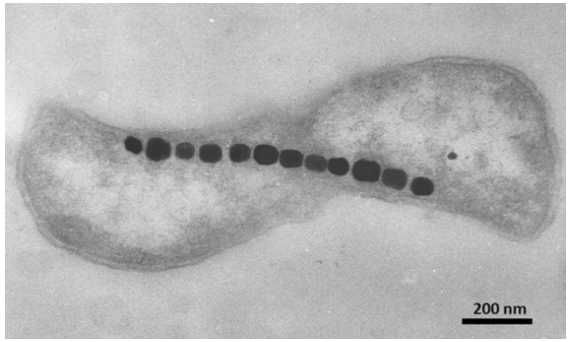
Biological synthesis of sodium rare-earth fluorides nanoparticles;

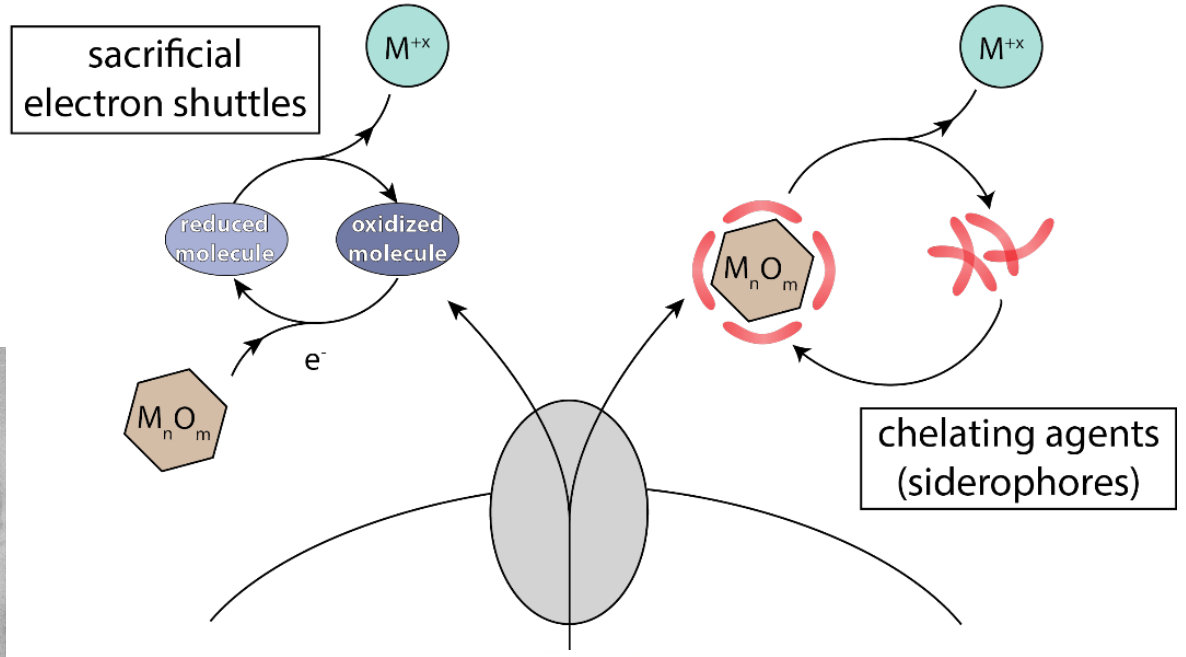
STEM-EDX elemental mapping of Bio-$NaYF_4$:Yb,Er samples showing all the elements of Na, Y, F, Yb, Er are overcoat on the biotemplates (P from DNA).



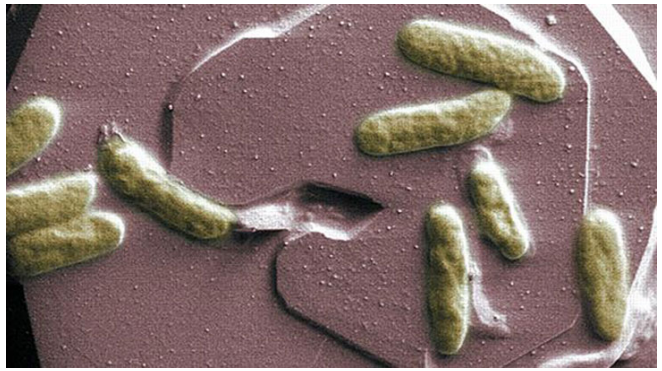
Strategy #3: *a.k.a.* precipitation

Magnetosomes





Metal eating microorganisms



Mineralized materials

Dr. George Sun

Small digression:

Nothing in life is free

Metal Reduction

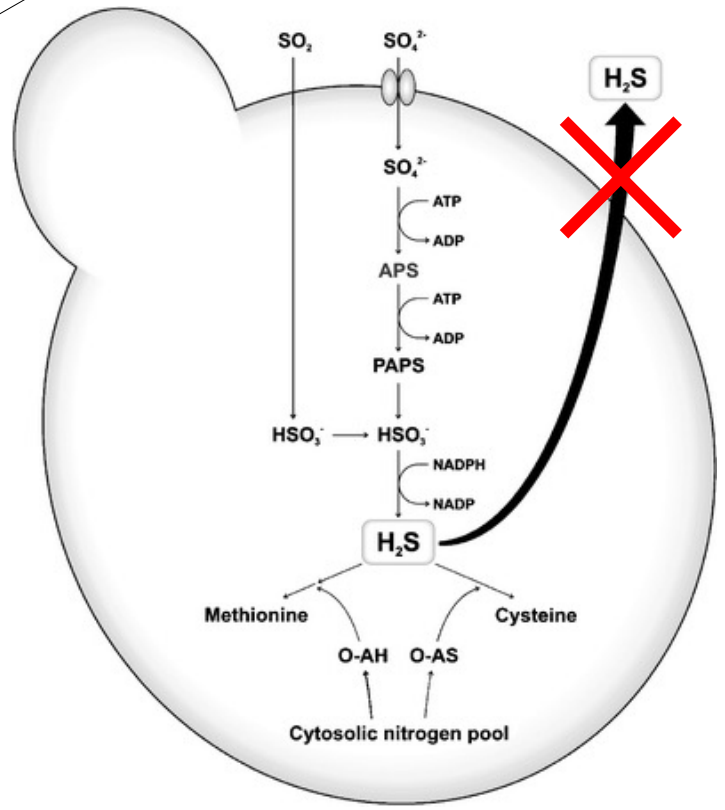
- Electrons (e^-) have to come from somewhere
- Donations of e^- have to overcome metals redox potential (ΔG^o ~usually high)

Chemical precipitation

- Metals need to react with something
- Reactive species that produce insoluble compounds (CO_3^{2-}, PO_4^{3-}, SO_4^{2-}) are not common
- Require changes in pH

Wine Industry

- Fermentation caused yeast to produce gaseous odors
- Primary culprit was sulfur compounds



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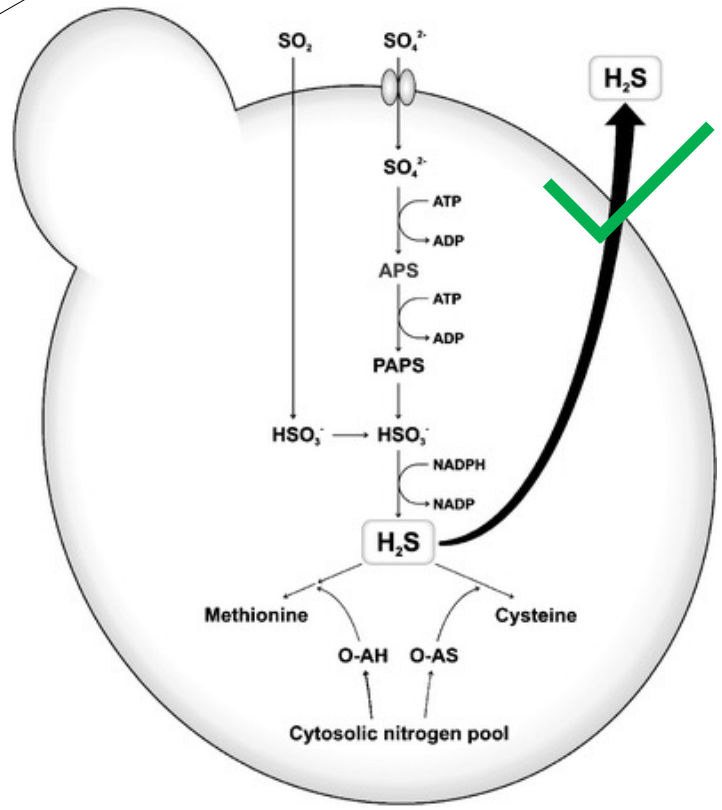
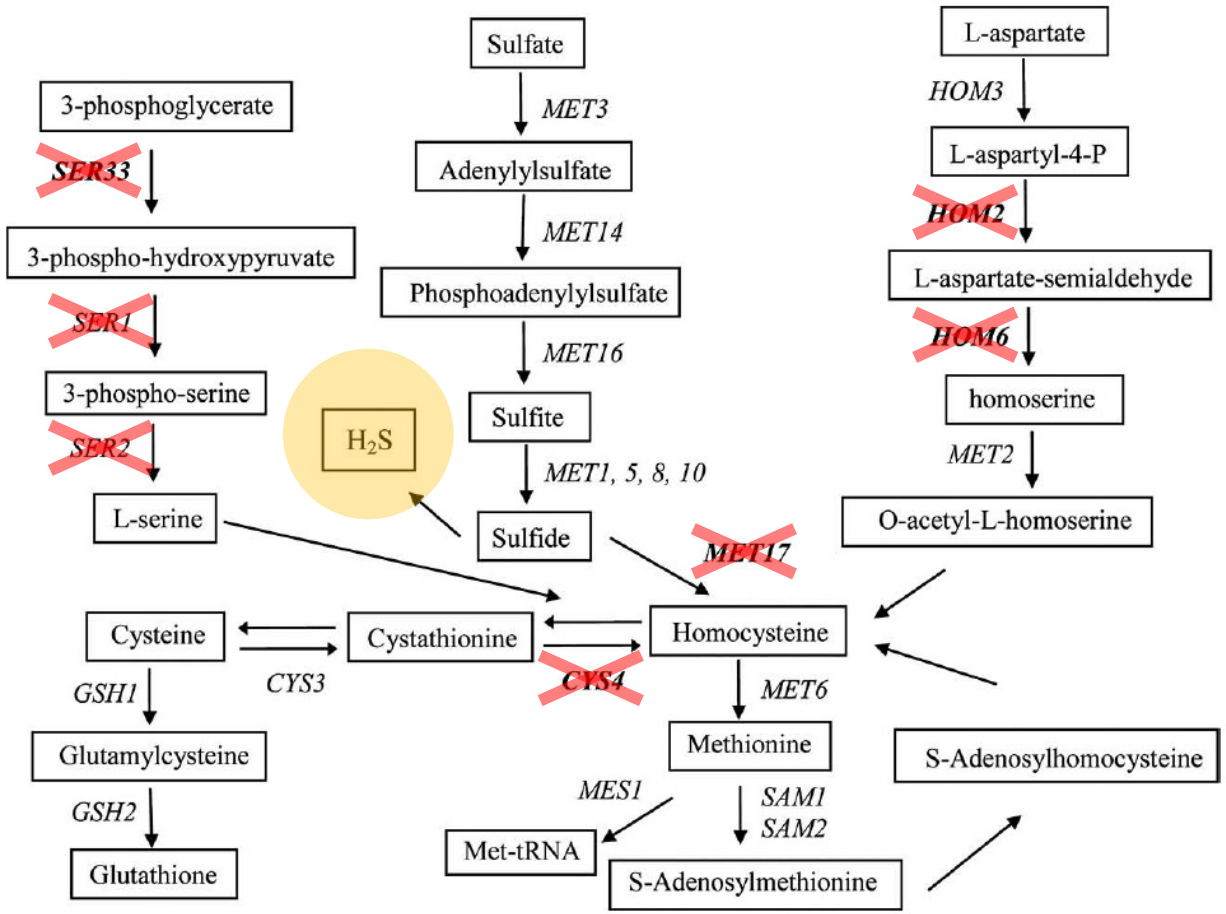


Metabolic engineering for H_2S production

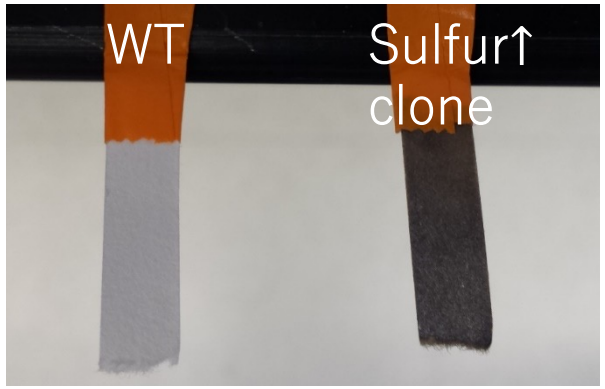
Engineering H_2S strains



Linderholm, A. L., et. al. Identification of Genes Affecting Hydrogen Sulfide Formation in Saccharomyces cerevisiae. *Appl. Environ. Microbiol.* **74,** 1418–1427 (2008).

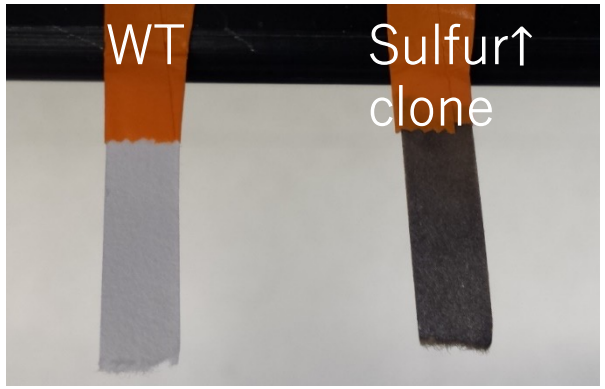
Engineering H_2S strains

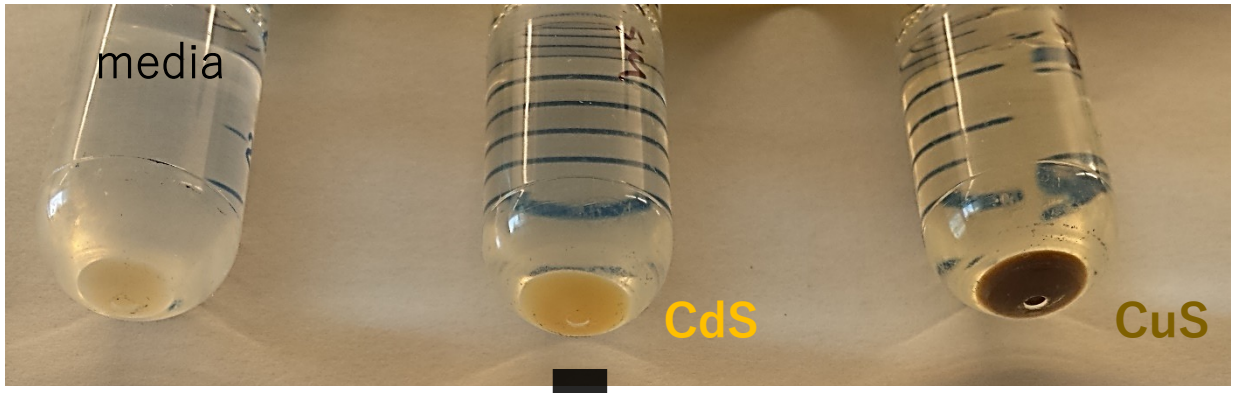
Lead acetate indicator strips

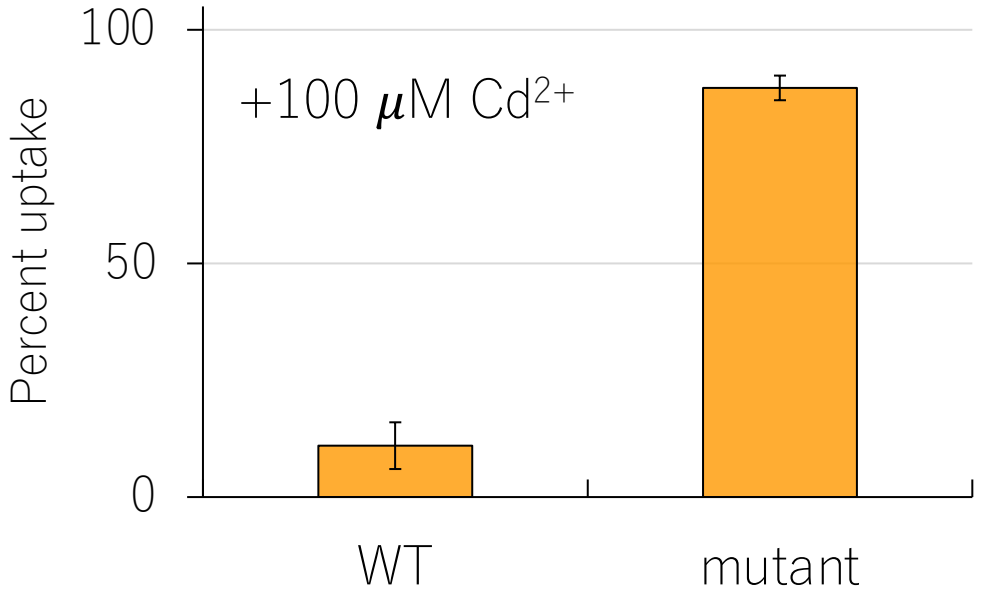


Using yeast by-products to reduce and react heavy metals

Lead acetate indicator strips

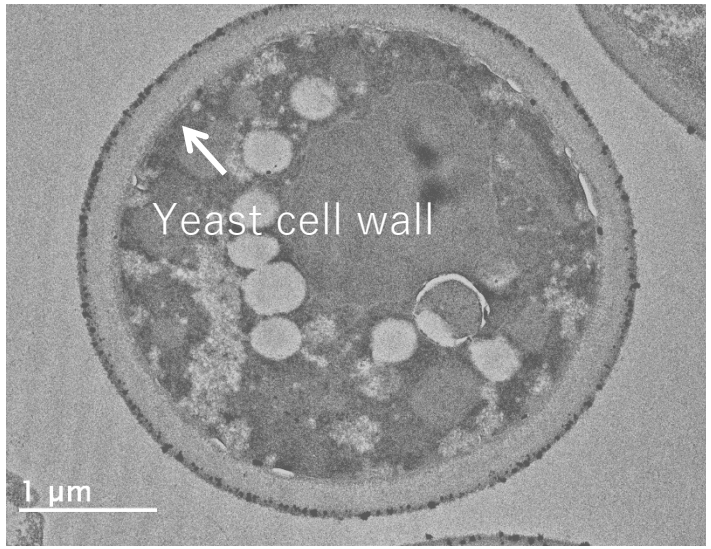


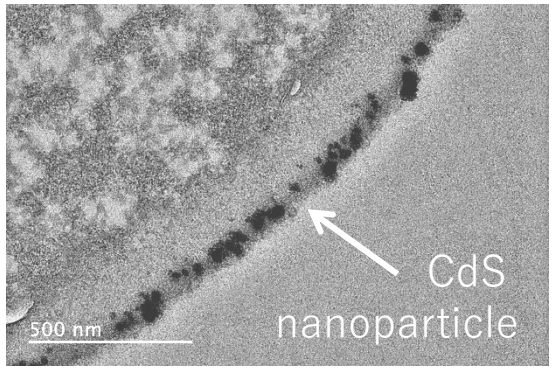


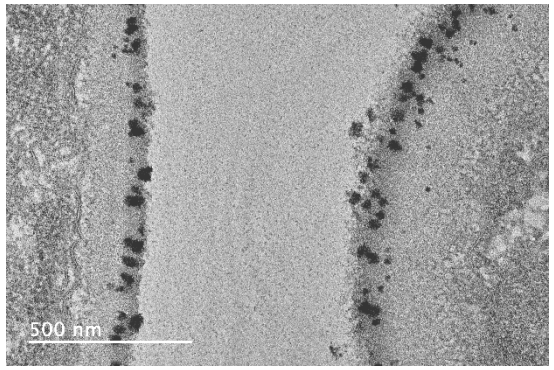


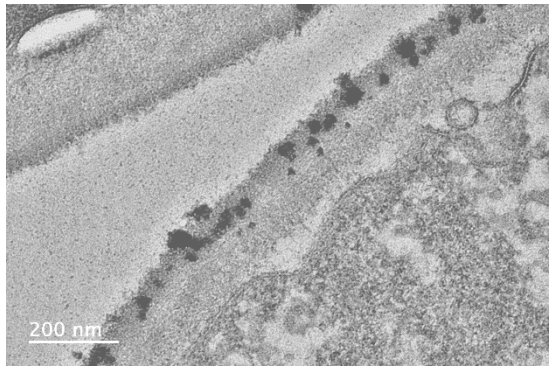
Taking a closer look: quantum dot synthesis

CdS precipitation

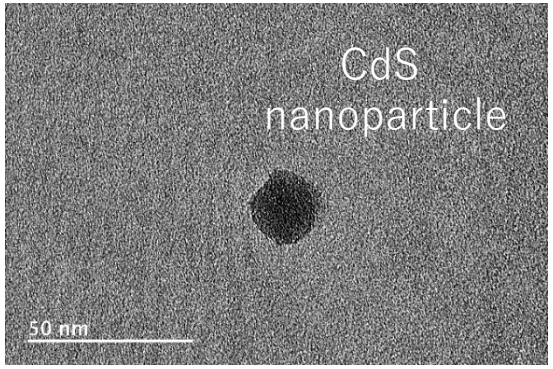


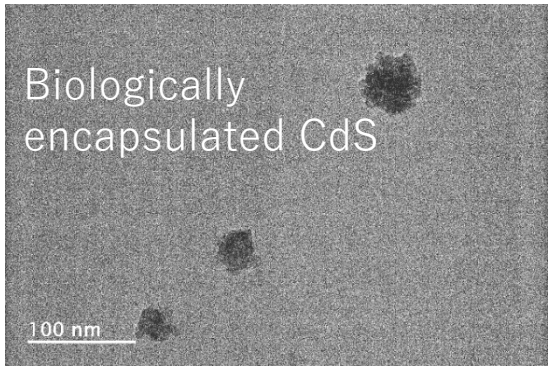






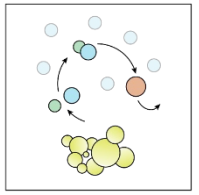
Purified CdS
from yeast



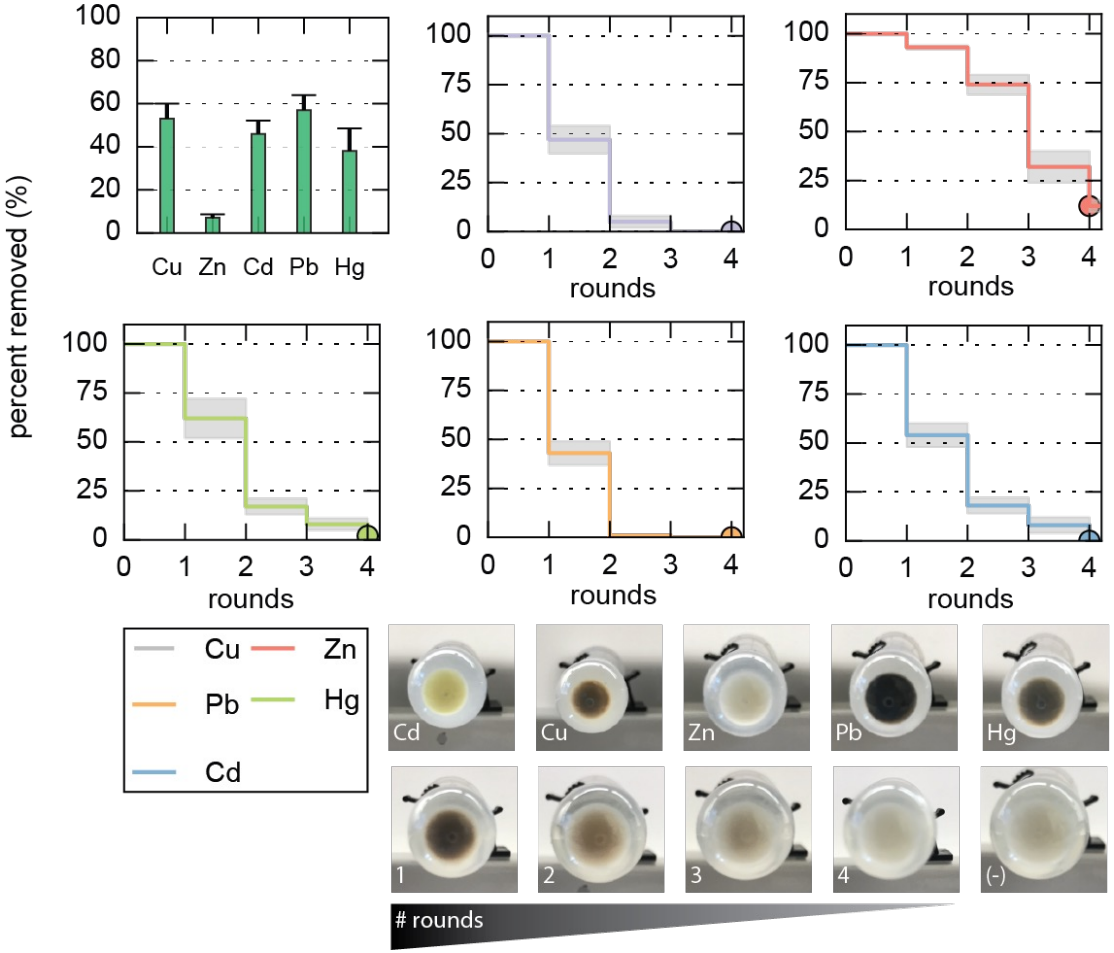


Alberta Canada Oil Sands

Bio-precipitation of heavy metals

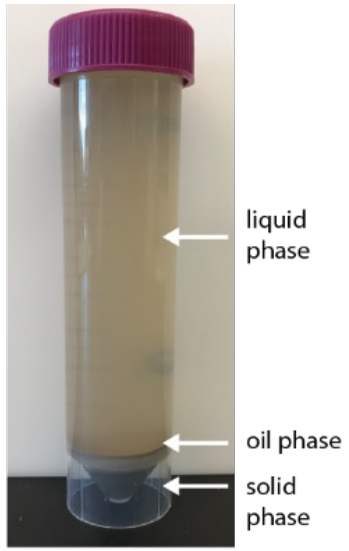


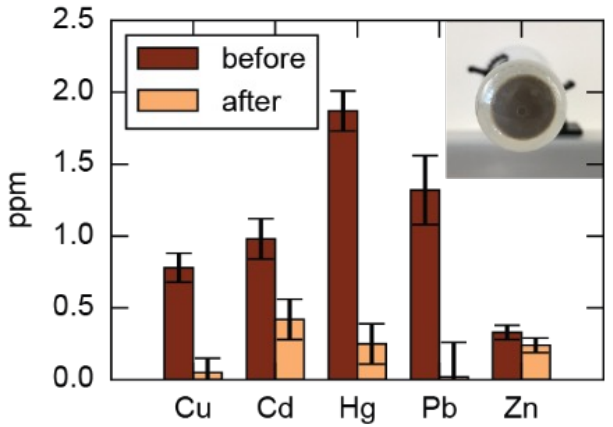
Metabolic engineering for heavy metal precipitation, *we can clean to EPA standards for Cu, Pb, Hg, Cd, Zn*



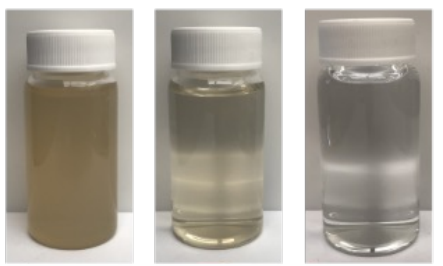
Nat Sustain **3,** 303–311 (2020)

Real world example:
Canadian Athabasca Oil Sands



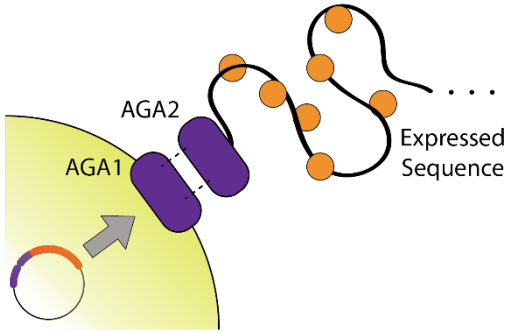


Before---middle--after



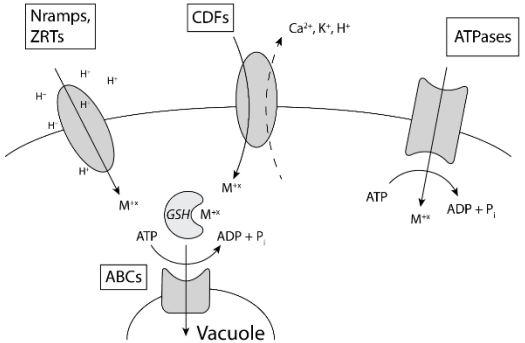
Yeast has proven to be a promising platform for metal remediation

Strategy #1: *a.k.a.* ion-exchange



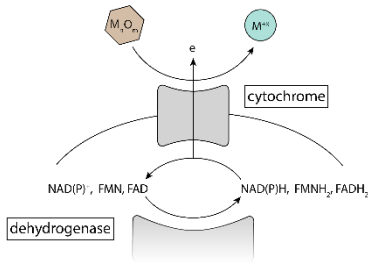
- Use "multiplier" proteins to enhance capture capacity
- Either use computational or experimental methods to create metal-specific capture motifs

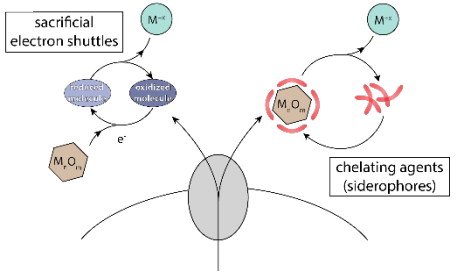
Strategy #2: *a.k.a.* absorption



- Metal transporters are an effective method to sequester specific metals
- There exist multiple options to engineer enhanced meta hyperaccumulating in yeast

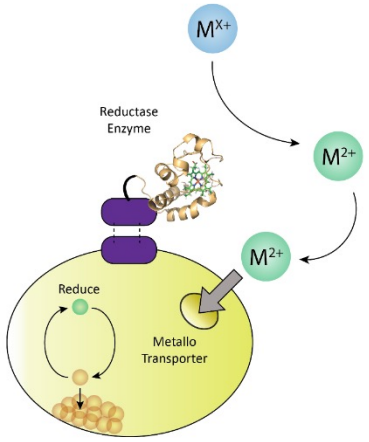
Strategy #3: *a.k.a.* precipitation





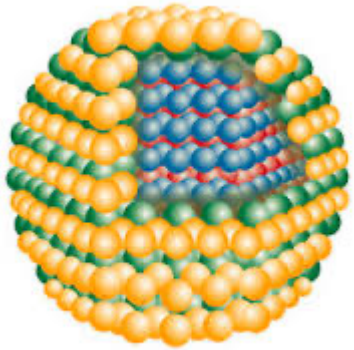
- Use byproducts to react or precipitate metal species
- Reacted compounds can be useful for other applications
- Use biomineralization peptides to facilitate the growth of precipitated metals

Combination Strategy

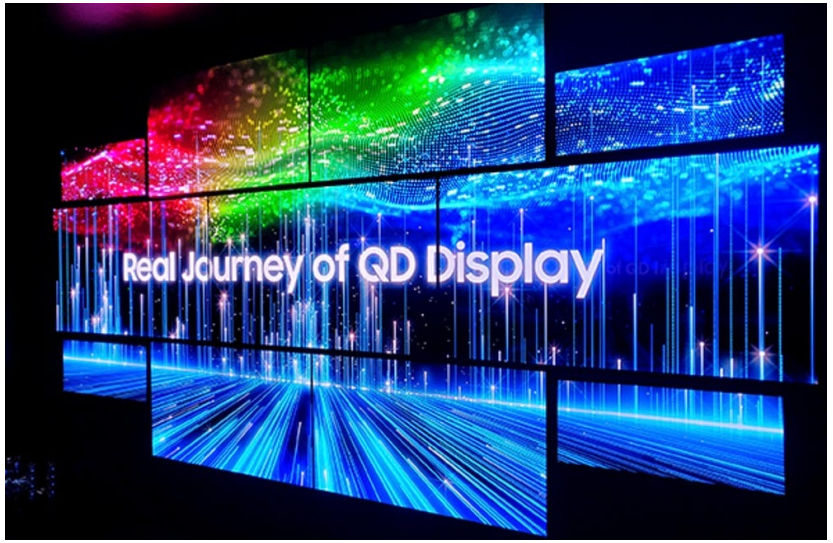


- Intelligently combine strategies 1—3 to create multi-purpose bioremediating yeast.
- Work with beer and wine industries to scale and package yeast for environmental applications

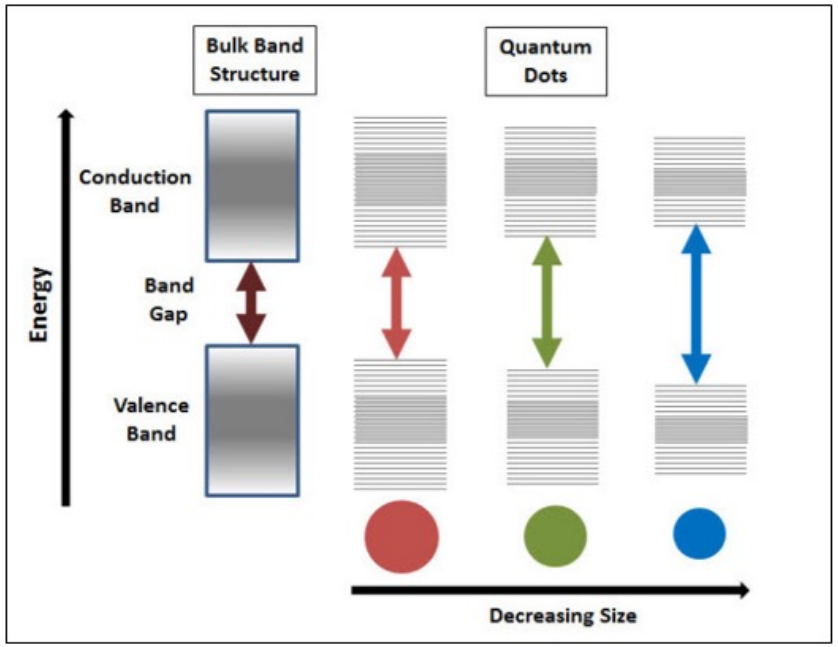
Quantum Dot (QD)

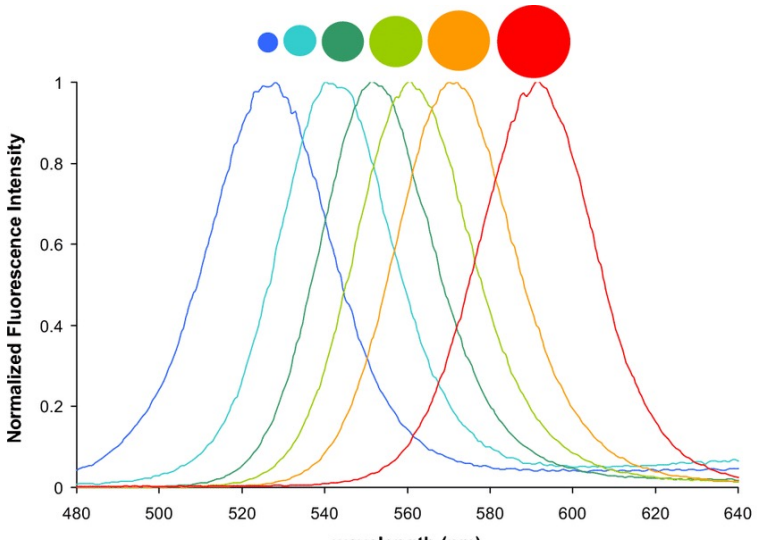


2023 Noble prize winer Prof. Bawendi and his II-VI QDs



by Samsung Display Co





Size tunable CdSe QDs' fluorescence spectra

Topics in Current Chemistry 378(2)
DOI:10.1007/s41061-020-0296-6