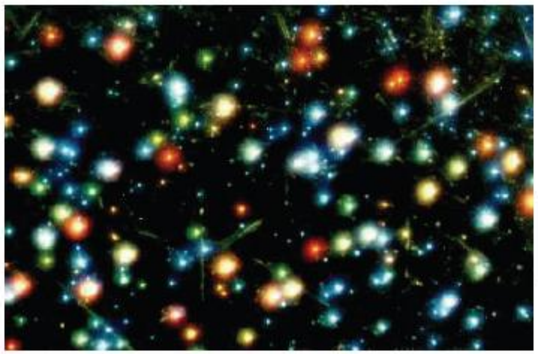
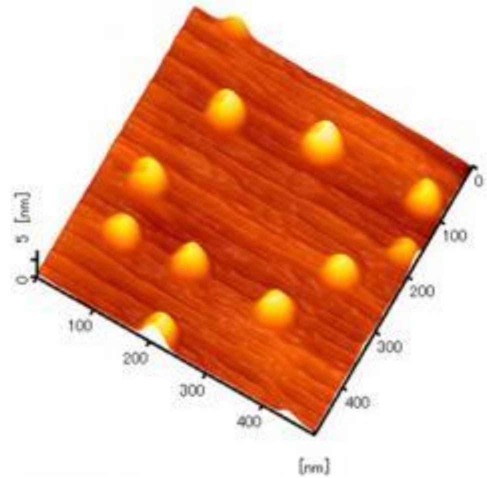
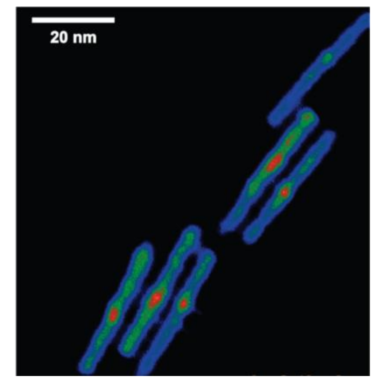
Lighting Up the Nanoscale





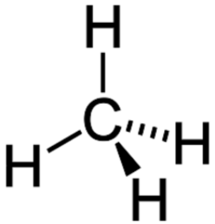


Prashant Jain

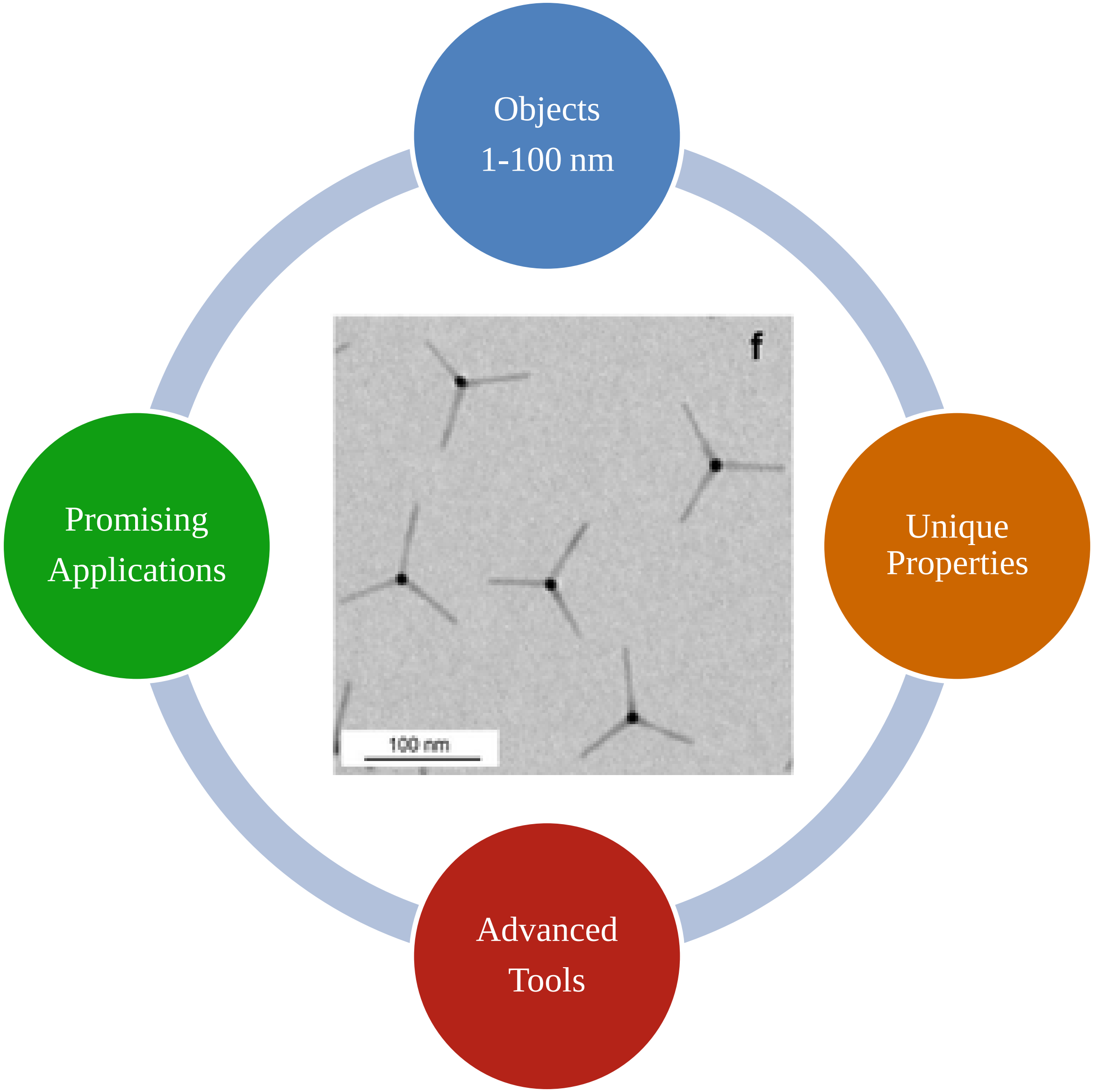
Miller Fellow

University of California Berkeley

Nanoscience and Nanotechnology

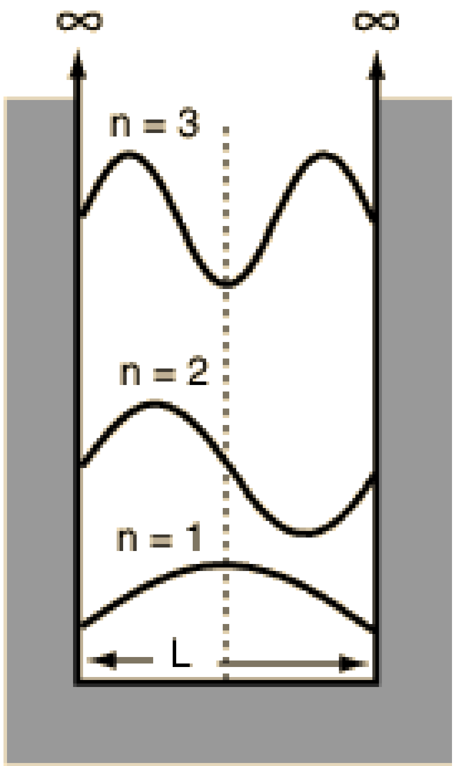


Molecule



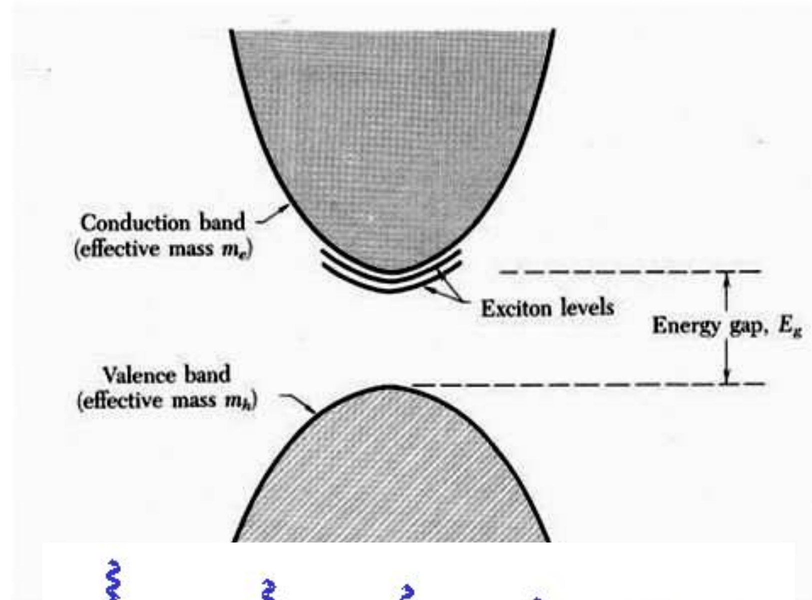
Bulk crystal

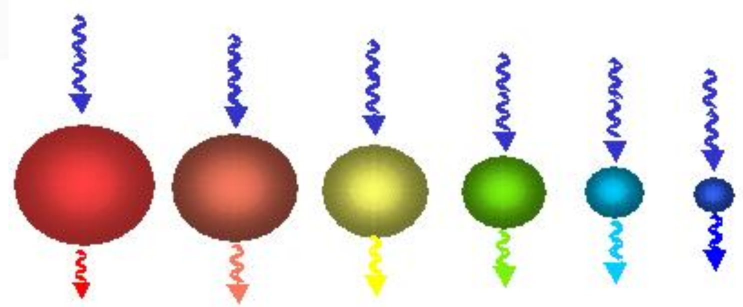
How I Found Nanoscience?

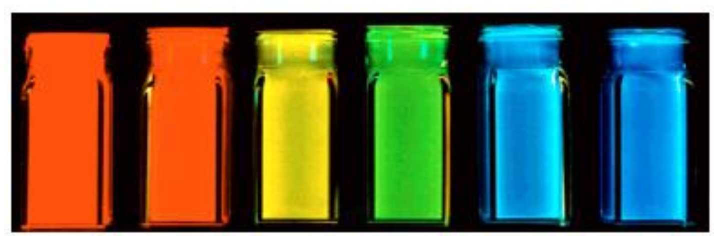


x = 0 at left wall of box.

$$\Psi(x) = A \sin kx, \quad \Psi(0) = \Psi(L) = 0$$





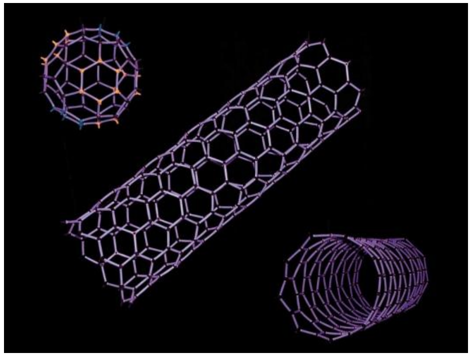


How I Found Nanoscience?

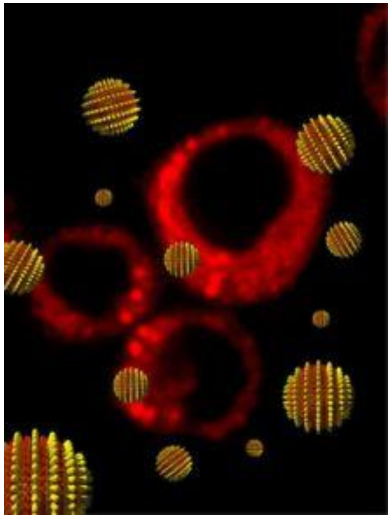
Prof. Mostafa A. El-Sayed, Regents Professor and Julius Brown Chair, Georgia Tech
Physical Chemist and spectroscopist, National Medal of Science 2008

Why Do We Care About Structuring, Controlling, and Understanding Matter at the Nanoscale ?

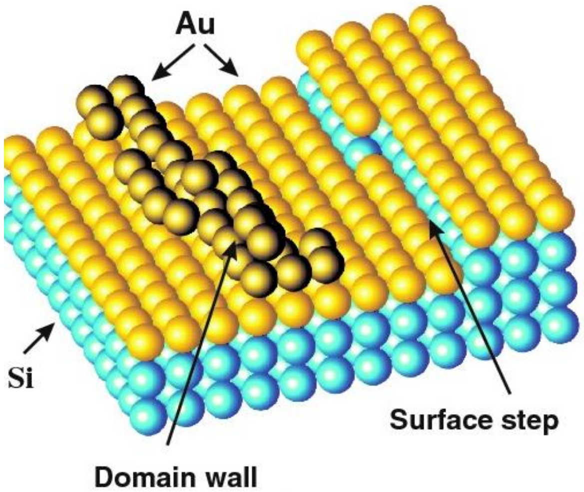
Novel Physics and Chemistry



New Processes and Materials



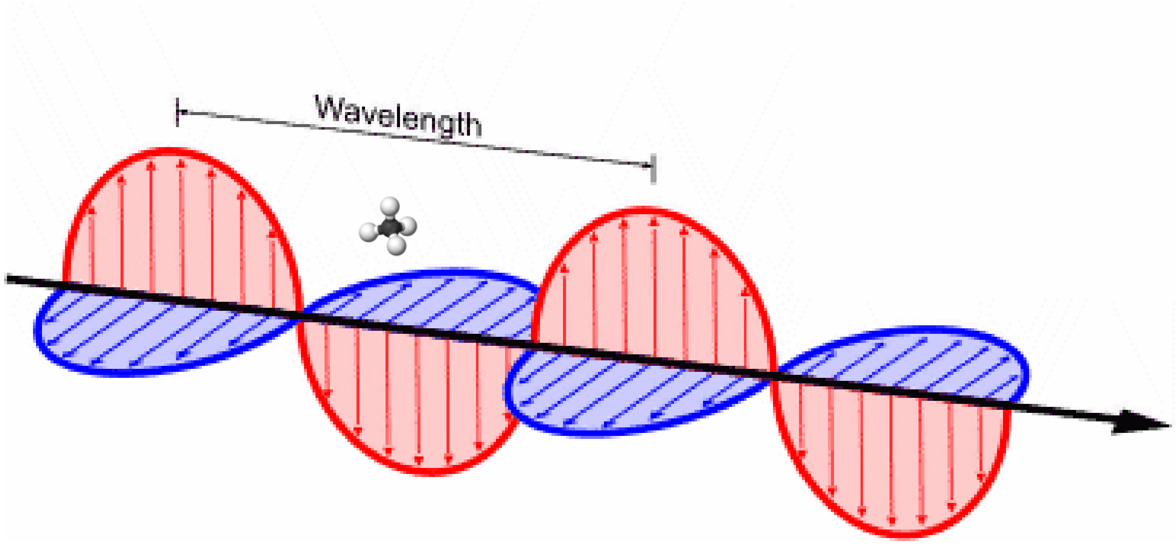
The right size for integration



Surfaces and interfaces

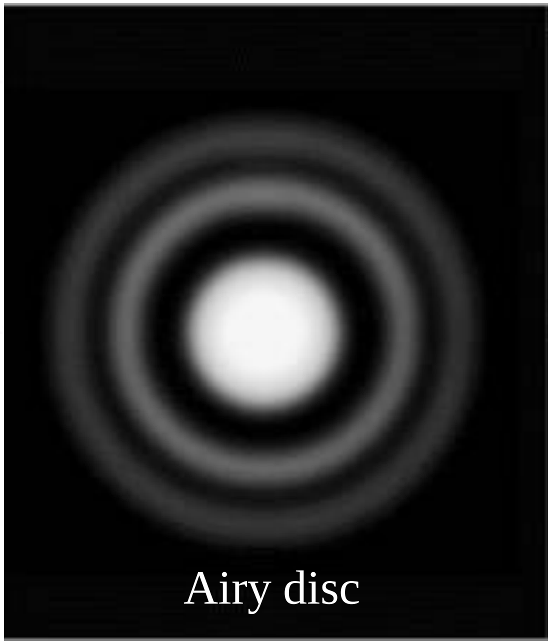
Interfacing to the molecular world using light

Biosensing, structure determination, solar cell or water splitting, optical data writing



A molecule and light

a/ λ << 1



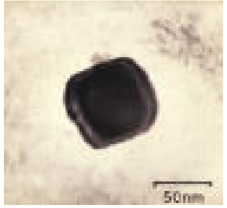
Focusing of light is limited by diffraction
There is a limit on realizable light-molecule interactions

Bright Color from Metals at the Nanoscale

Luster decorated XVI century
Renaissance pottery, Gubbio, Italy

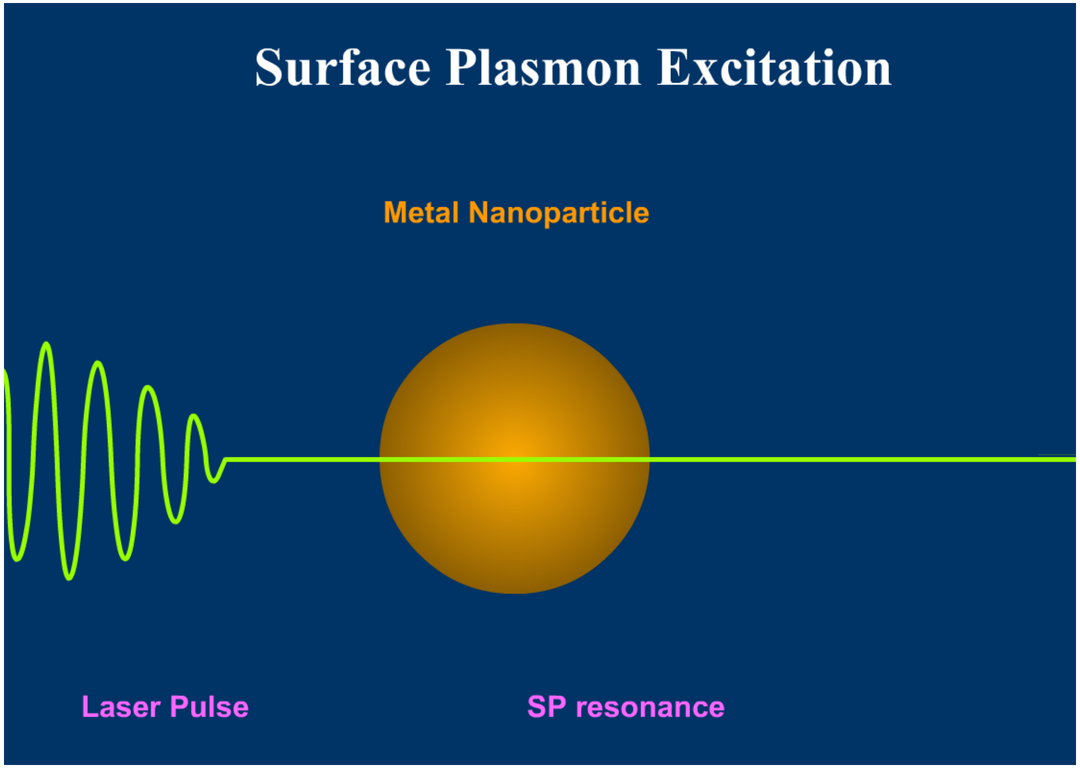
The Lycurgus Cup, Roman glass IV century

70% silver and 30 % gold



Padovani et al., *J. Appl. Phys*. 2003, 93, 10058 .

Light Can be Confined to the Nanoscale Using Metal Nanostructures



Light "confined" to the nanoscale by means of a resonant coherent free electron oscillation

Jain, Huang, El-Sayed, and El-Sayed , *Acc. Chem. Res.* 2008, 41, p1578

Color and quality of nanoscale confined light is size, shape, and medium dependent

$$\alpha(\omega) = (1+\kappa)\varepsilon_0 V \left(\frac{\varepsilon(\omega) - \varepsilon_m}{\varepsilon(\omega) + \kappa\varepsilon_m} \right)$$

α = Polarizability of the metal sphere

ε_0 = Permittivity of free space

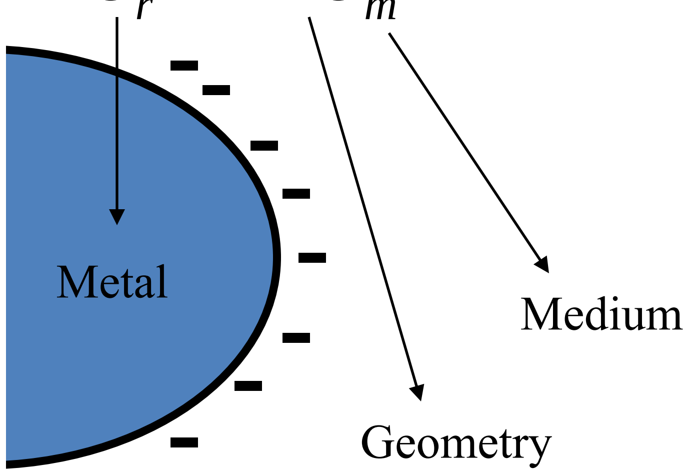
ε_m = Dielectric constant of medium

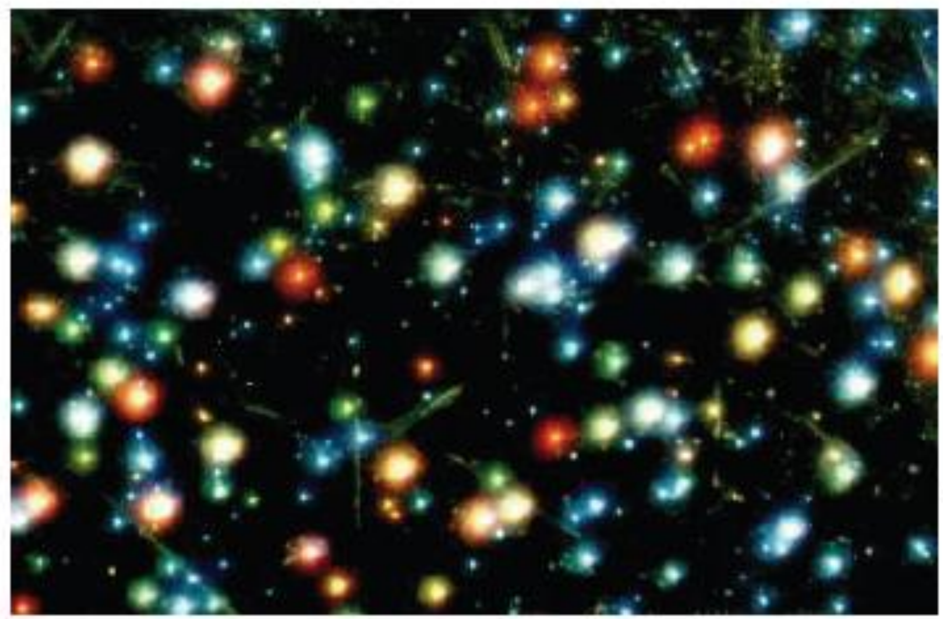
ε = Complex dielectric function of metal

κ = Geometric factor

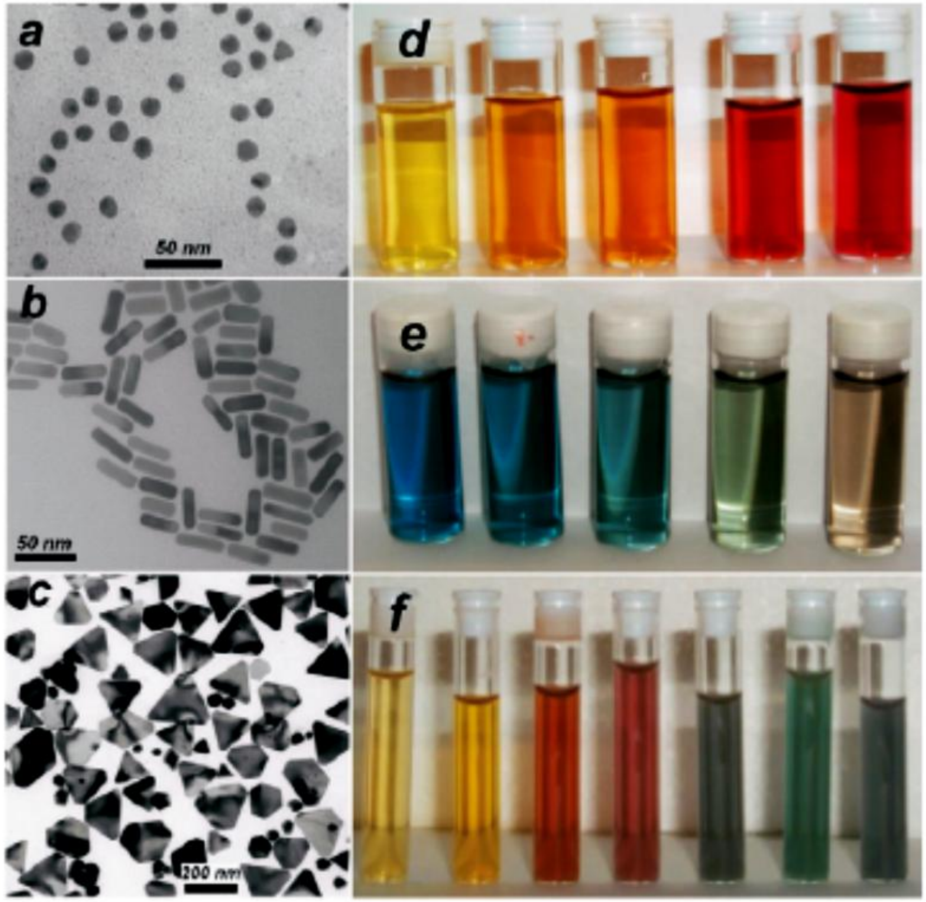
Max at ω_{lspr} where:

$$\varepsilon_r = -\kappa\varepsilon_m$$





Size- and shape-dependent color



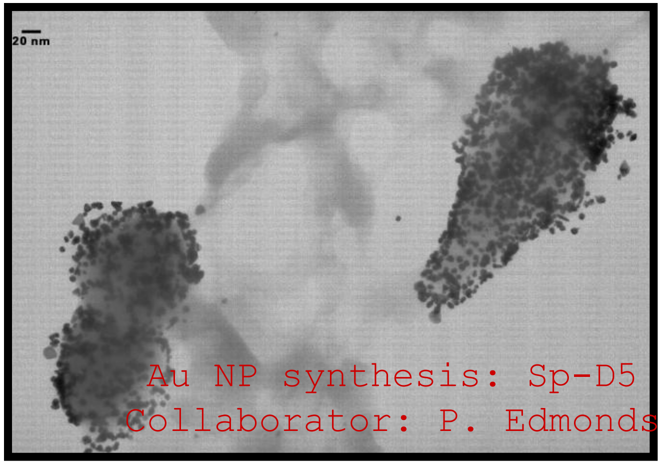
Ag, Au

Picture from Liz-Marzan, L. M., *Materials Today* (2004), **7** (2), 26

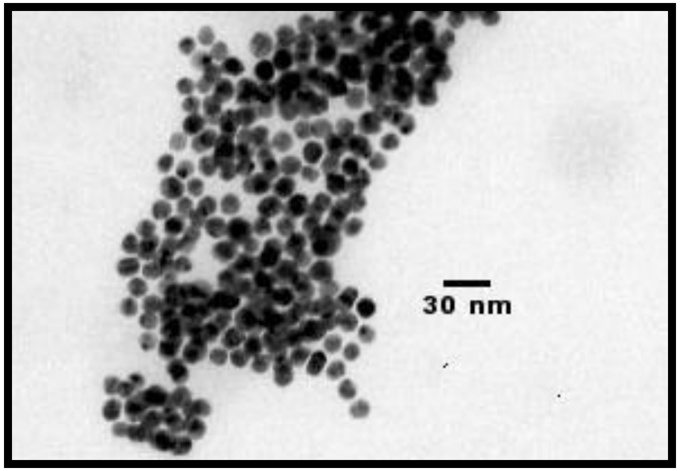
Synthesizing Metal Nanostructures

Bacteria

Reduction of
Ionic Gold



Sodium Citrate
(Turkevich/Frens)

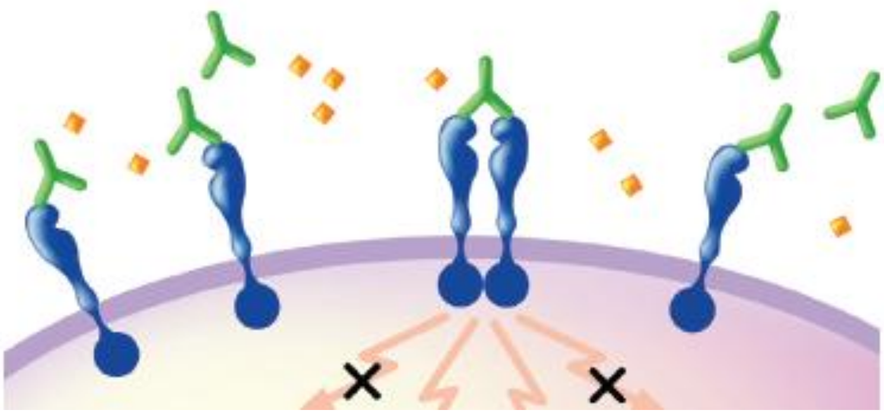


Average diameter: 13 nm

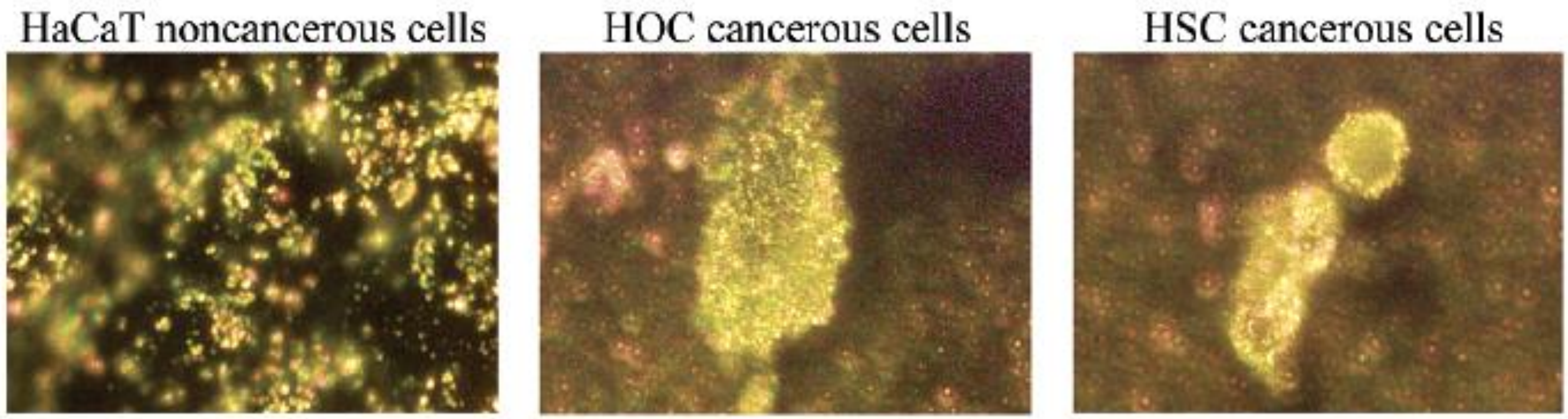
Michael Faraday's colloidal gold

Prashant K. Jain, Wei Qian, Mostafa A. El-Sayed, *J. Phys.Chem. B*, 110(1), 2006, 136-142.

Targeting Cancer Cells Using Nanoparticle Bioconjugates

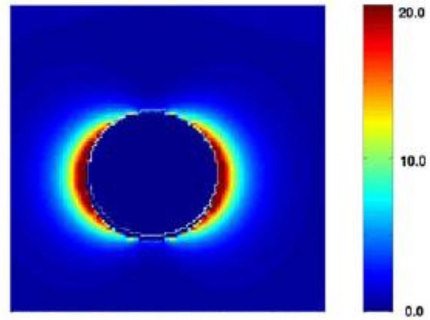


Epithelial Growth Factor Receptor over expressed on cytoplasmic membrane of most epithelial cancer cells. 35-nm Au nanoparticles are conjugated to anti-EGFR monoclonal antibodies for selective targeting.

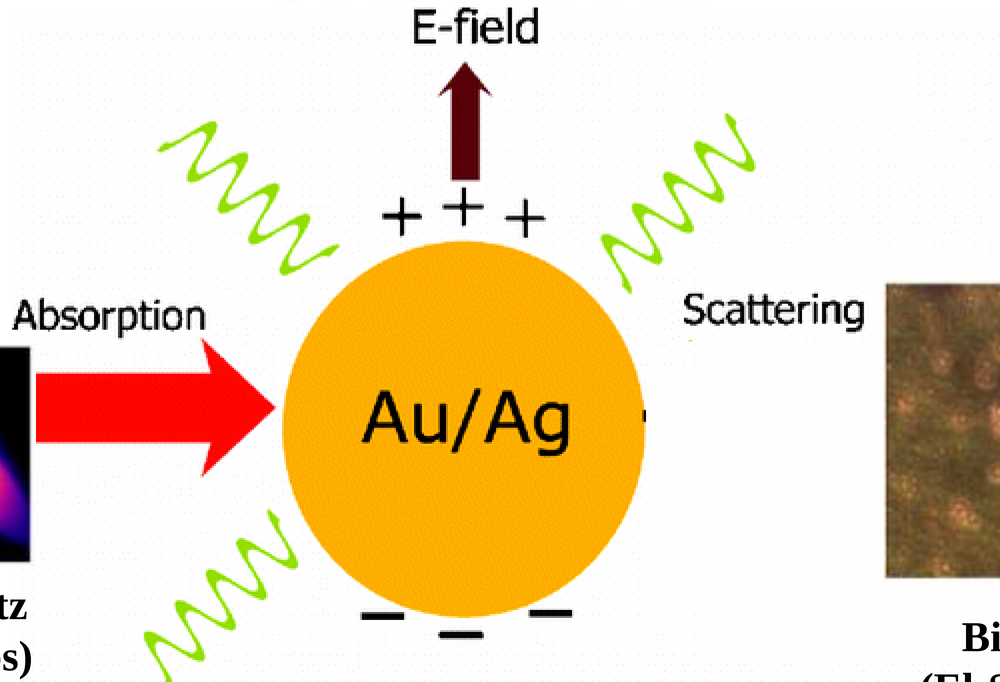


El-Sayed, I.H.; Huang, X., El-Sayed, M.A. *Nano Letters* **2005**, 5, 829.

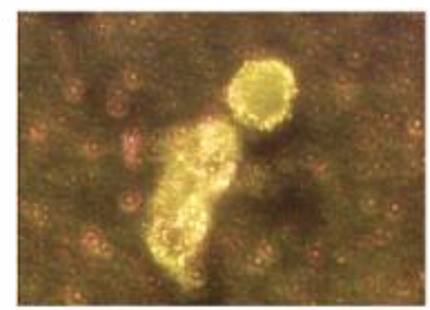
What can we do with this Confined Light?



Field-enhancement of light-matter interactions



Cancer Therapy, Nanopartz (Halas and El-Sayed groups)

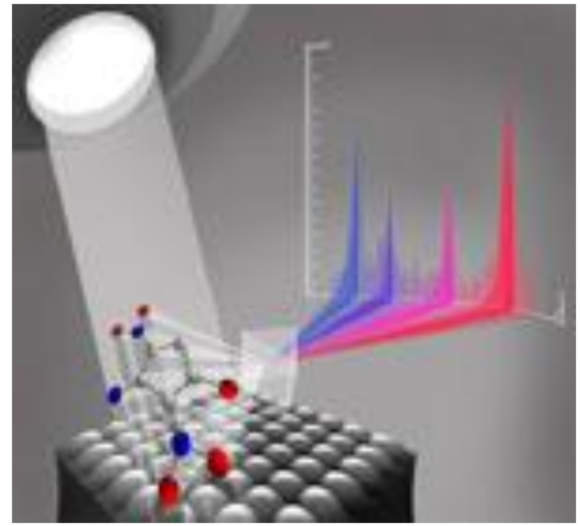


Bio-Imaging (El-Sayed group)

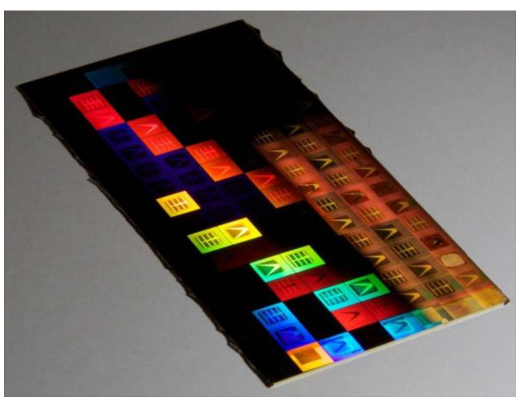
Huang, Jain, El-Sayed, El-Sayed, *Nanomedicine*, 2(5), 2007, 681; Jain, Lee, El-Sayed, El-Sayed, *JPCB*, 2006, 110, p7238,;

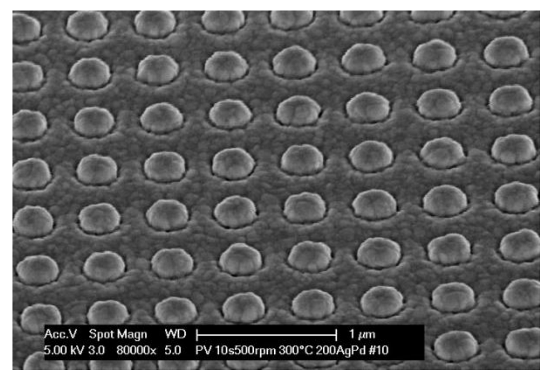
Optical Processes and Signals Can Be Enhanced Using Confined Light

C. V. Raman and his spectrometer



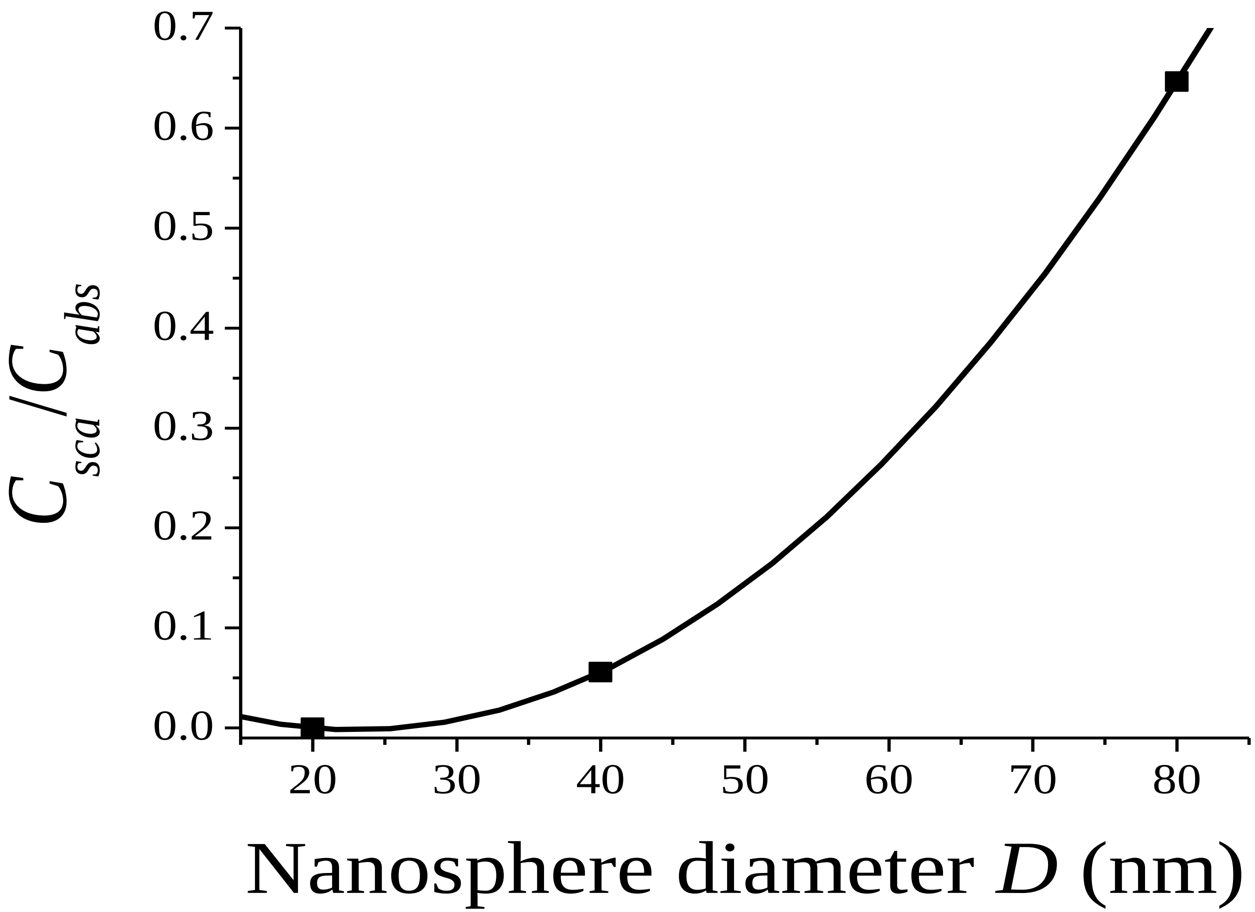
$\boldsymbol{E}^4$ or 10^6-10^7 enhancement of Raman

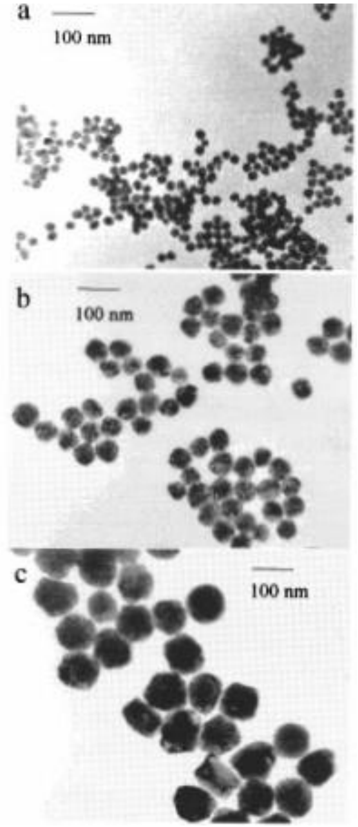




Atwater group: Ultrathin solar cells using light trapping abilities of metal nanostructures

Tuning Nanoparticle Size for Imaging/Therapy



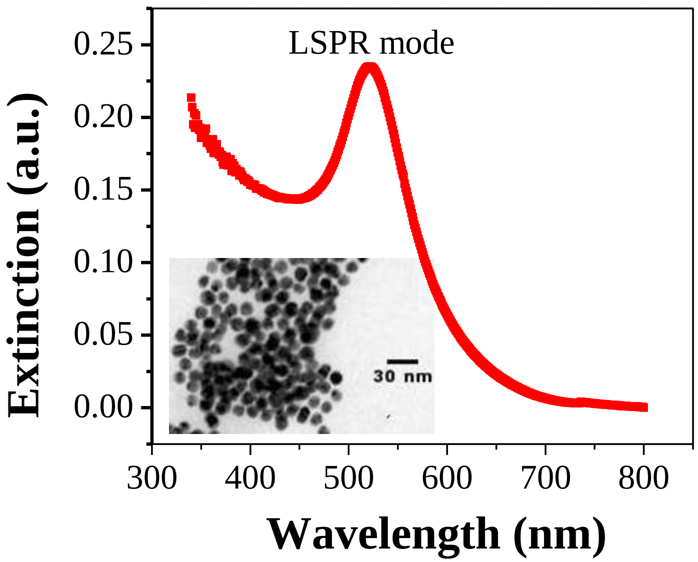


Link et al.

P. K. Jain, K. S. Lee, I. H. El-Sayed, M. A. El-Sayed, *J. Phys. Chem. B* 110(14), **2006**, 7238-7248.

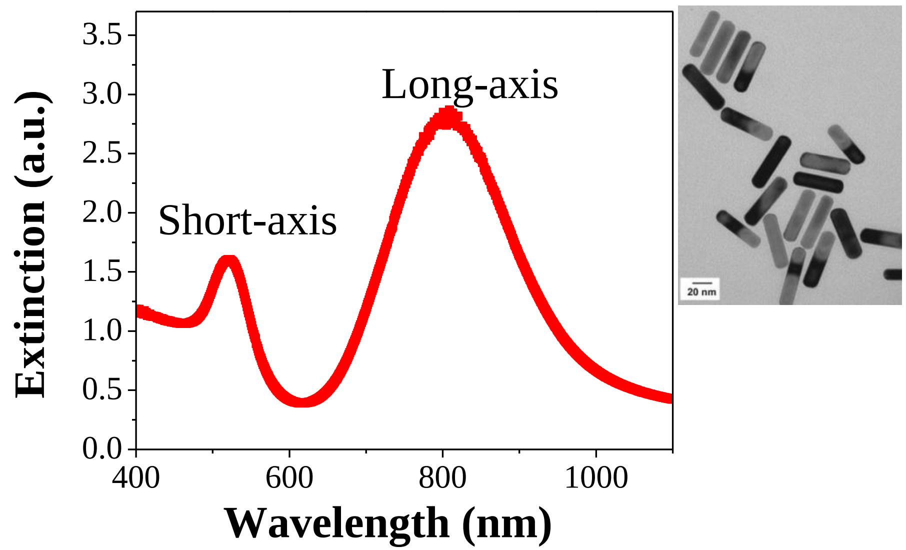
Shape Tunability of Properties at the Nanoscale

SPHERE

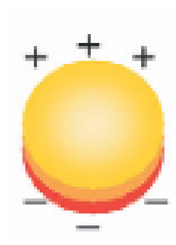


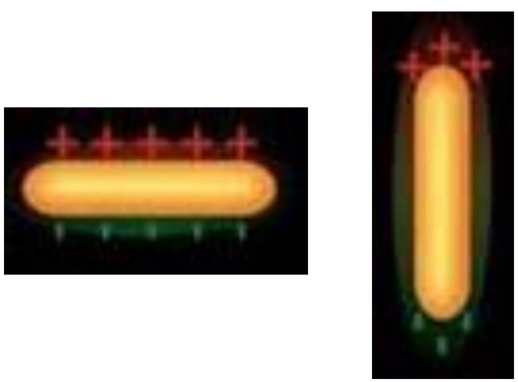
13-nm Au NS via citrate method

ROD

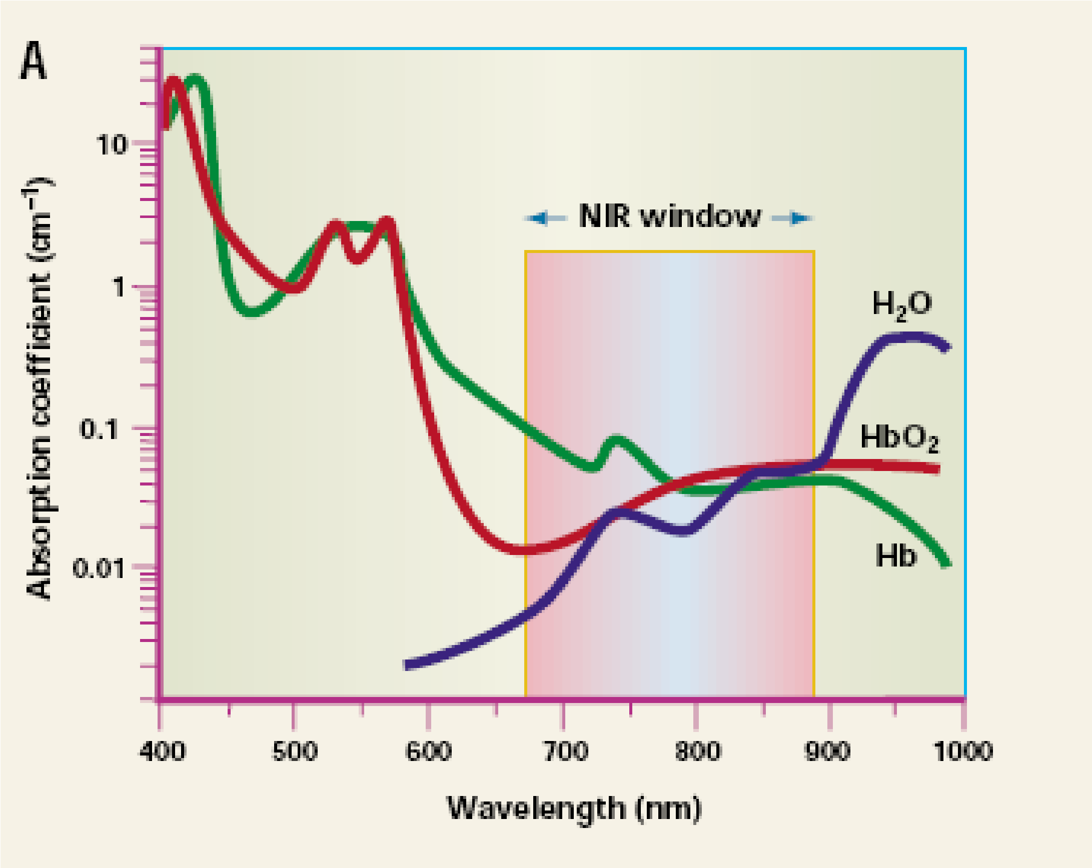


3.2 AR Au NRs via Murphy method





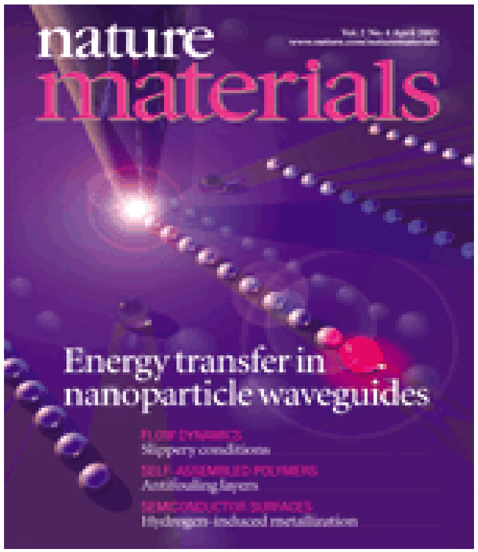
Biological Water Spectral Window in NIR



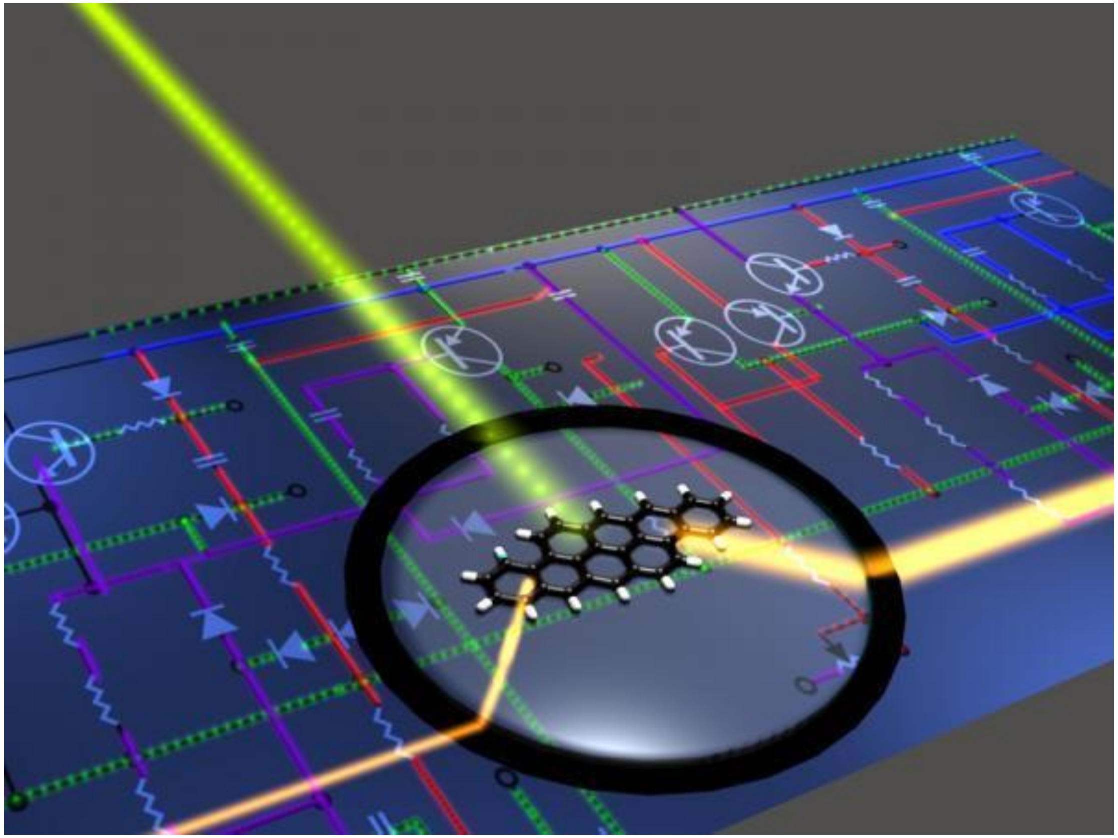
NIR light-resonant nanoparticles required for tissue penetration.

Weissleder, R., *Nat. Biotechnol.* 2001, 19, 316

Using Photons Instead of Electrons For Computing

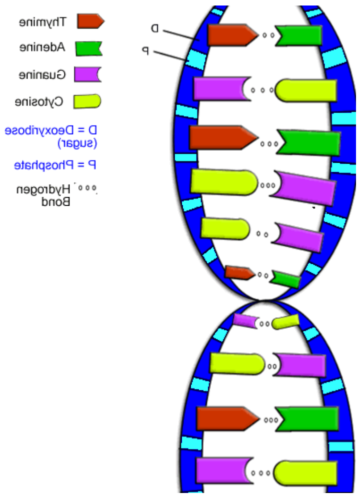


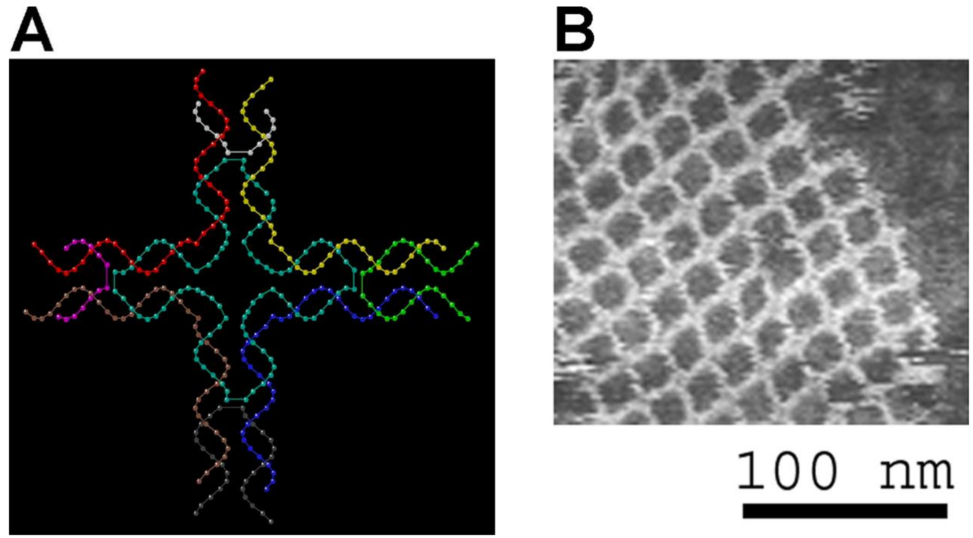
Coupling can be used to guide light in a nanoscale circuit

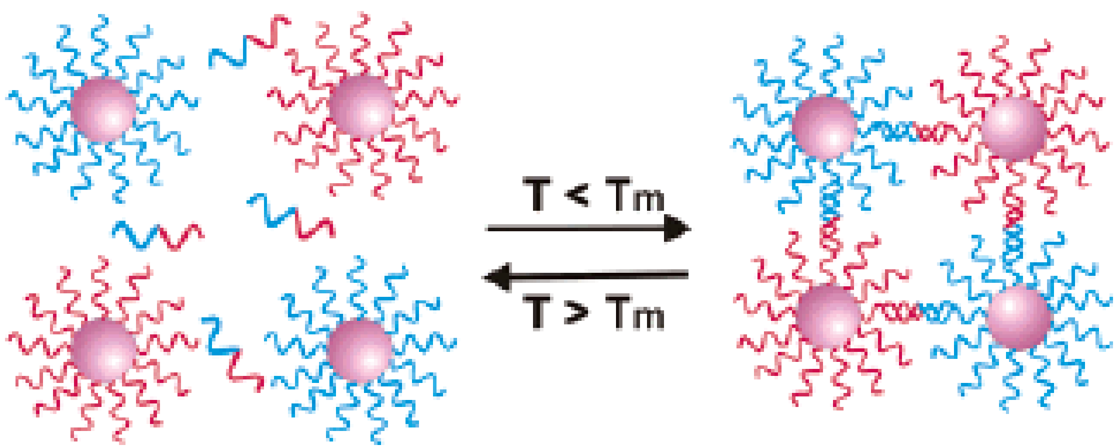


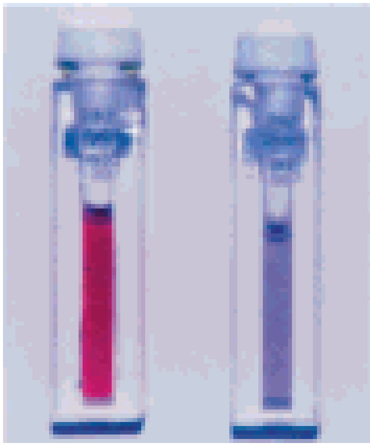
Lower heat generation, faster data transfer rates

Self-assembly of nanostructures using molecular recognition



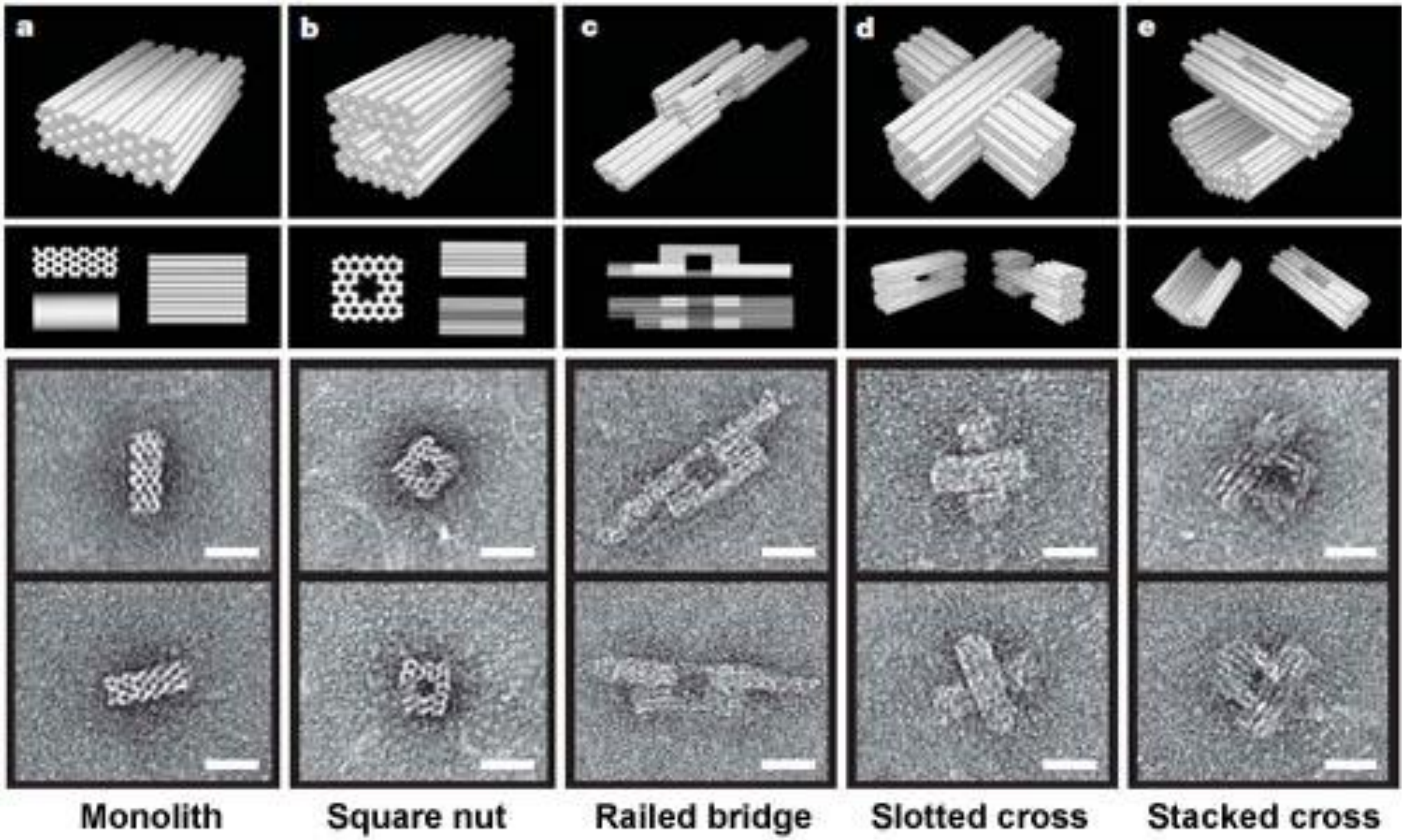






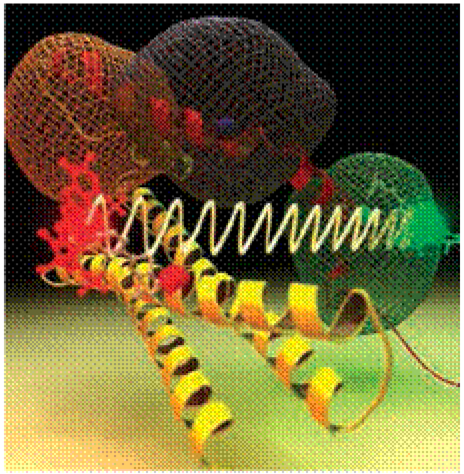
DNA Assembly method by Mirkin and coworkers

DNA Nanotechnology

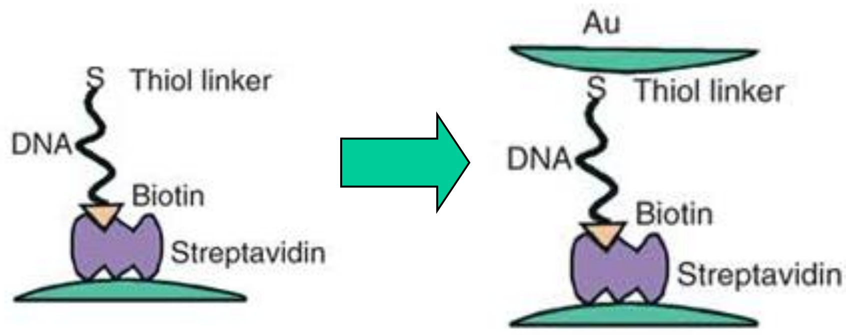


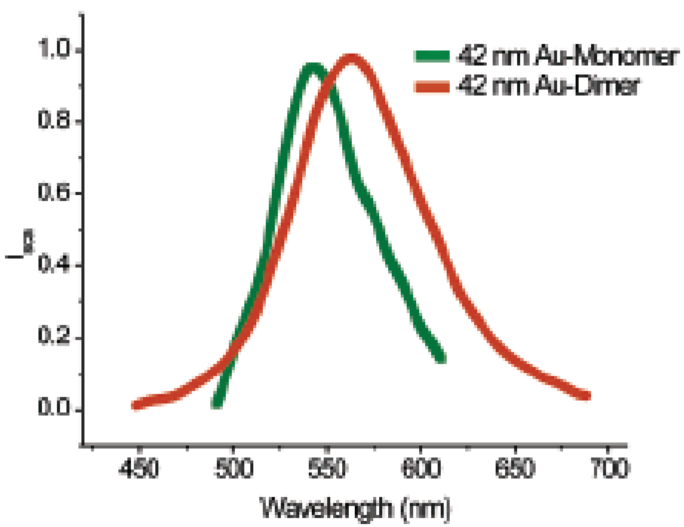
Shawn Douglas

Nanoscale Distance Rulers



R.F. Service, *Science*, 2005, 308, p1099



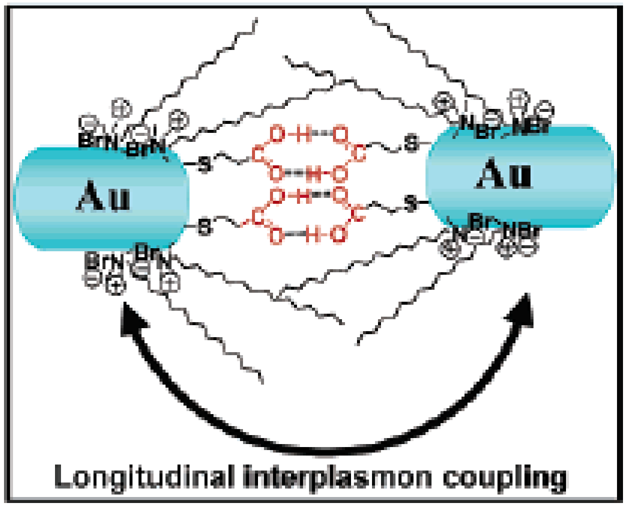


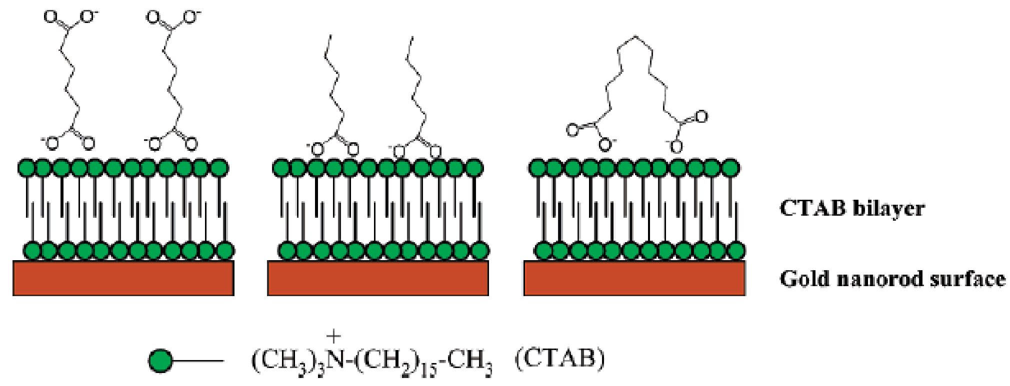
Change in spectral maximum →
Readout for nanoscale distance
and biomolecular activity

Plasmon field coupling can be used to measure nanoscale distances in biological systems

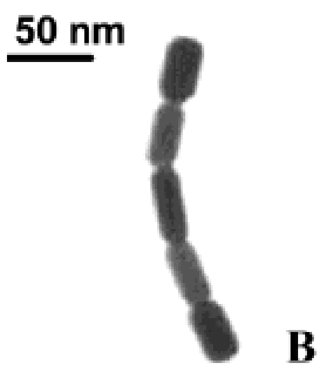
Sonnichsen, Reinhard, Liphardt, and Alivisatos, *Nature Biotech.* 2005, 23, p741

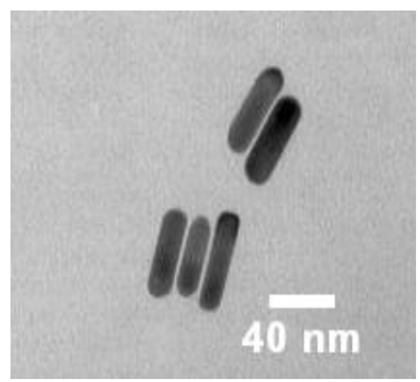
Controlled assembly of gold nanorods

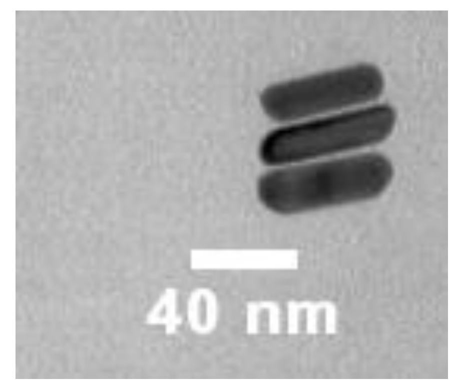




Orendorff, Hankins, & Murphy Langmuir, 2005, 21, p 2022.



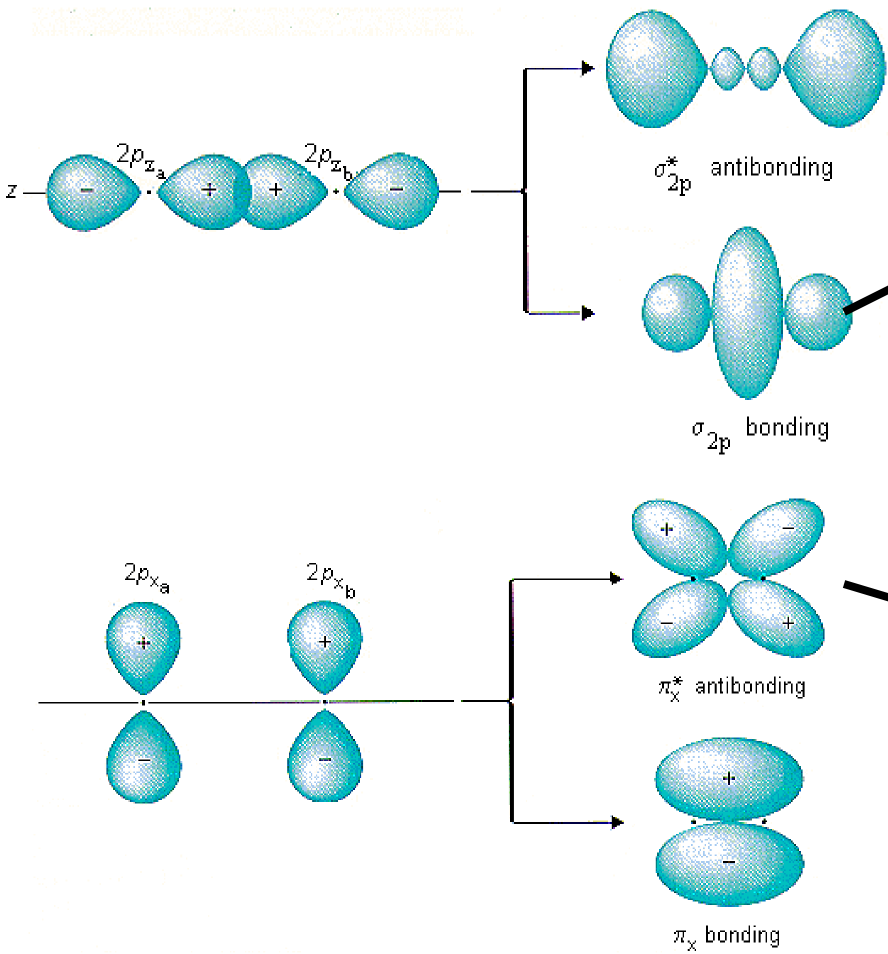




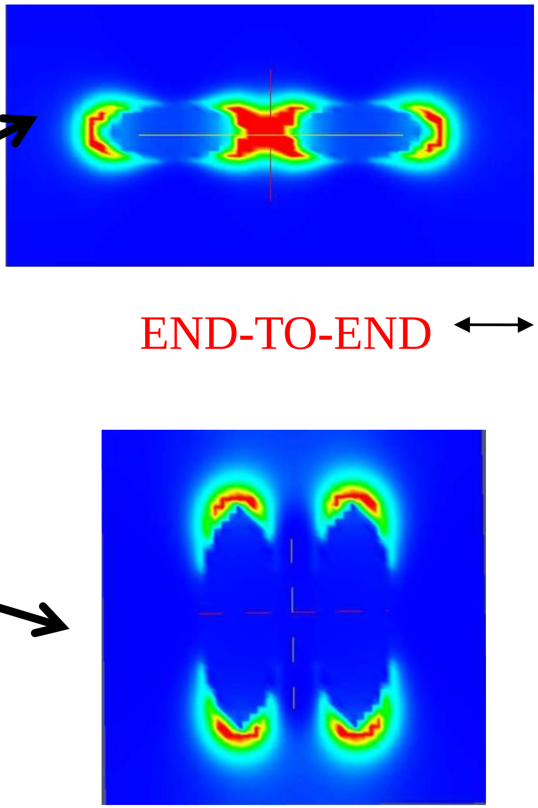
Jain, Eustis, and El-Sayed , *J. Phys. Chem. B*, 2006, 110, p18243.

Just like electronic orbitals confined photons can hybridize too

MOLECULAR ORBITALS



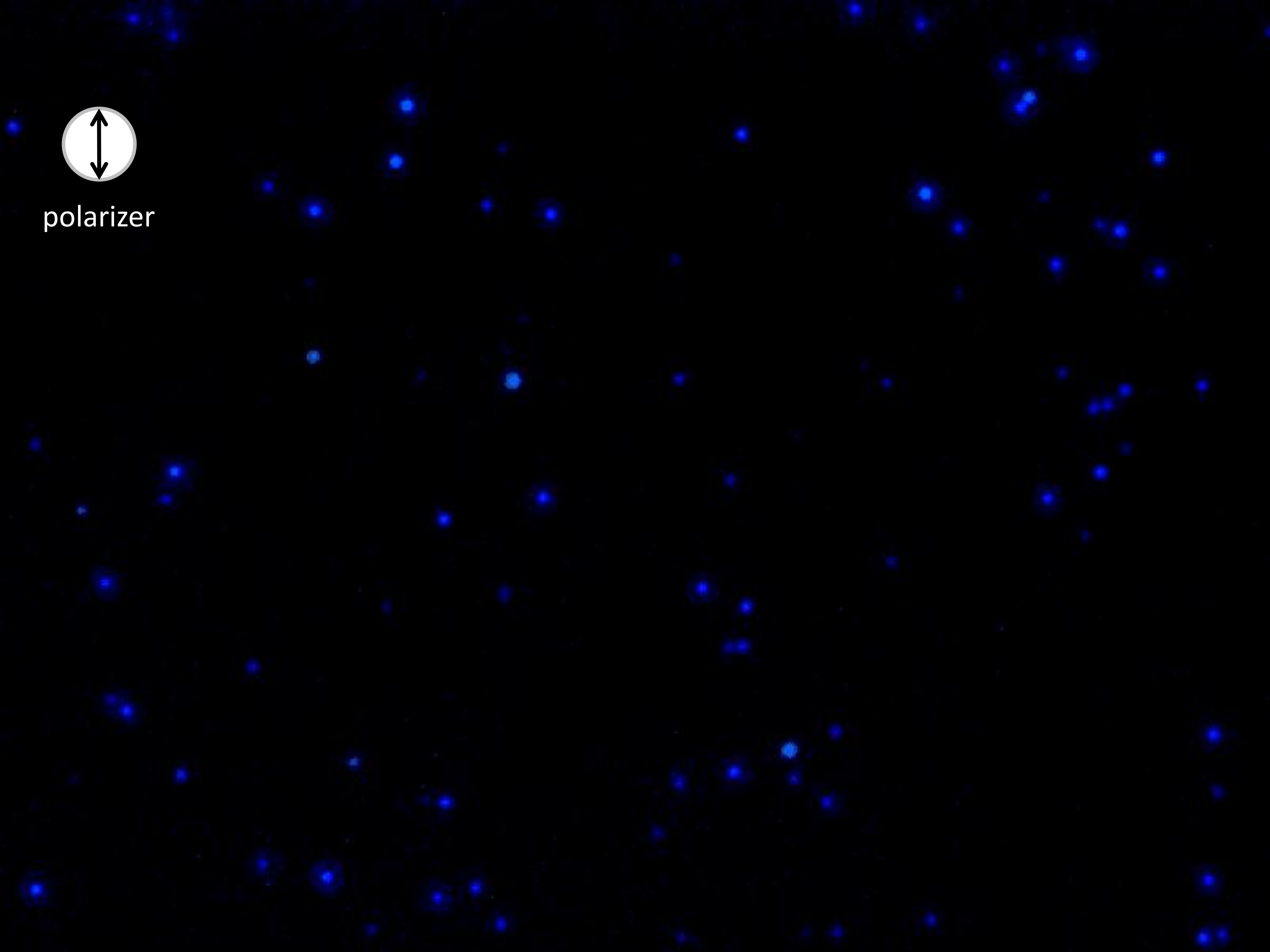
COUPLED PLASMONS



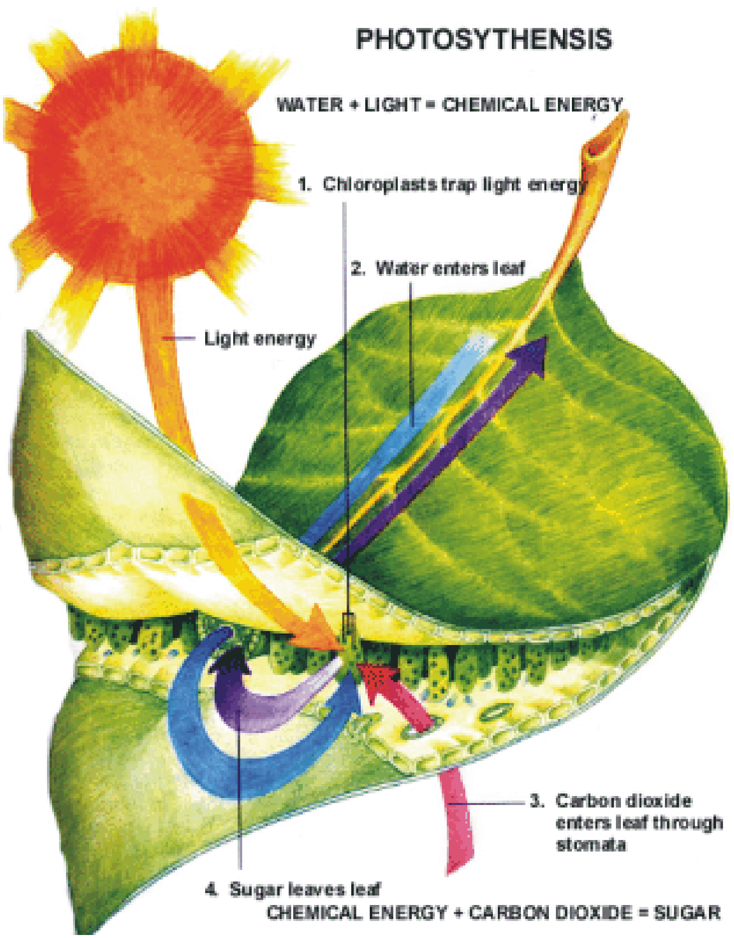
END-TO-END ↔

SIDE-BY-SIDE ↕

Using “nanoparticle molecules” to sculpt the field of the light


polarizer

Renewable Energy and Photosynthesis

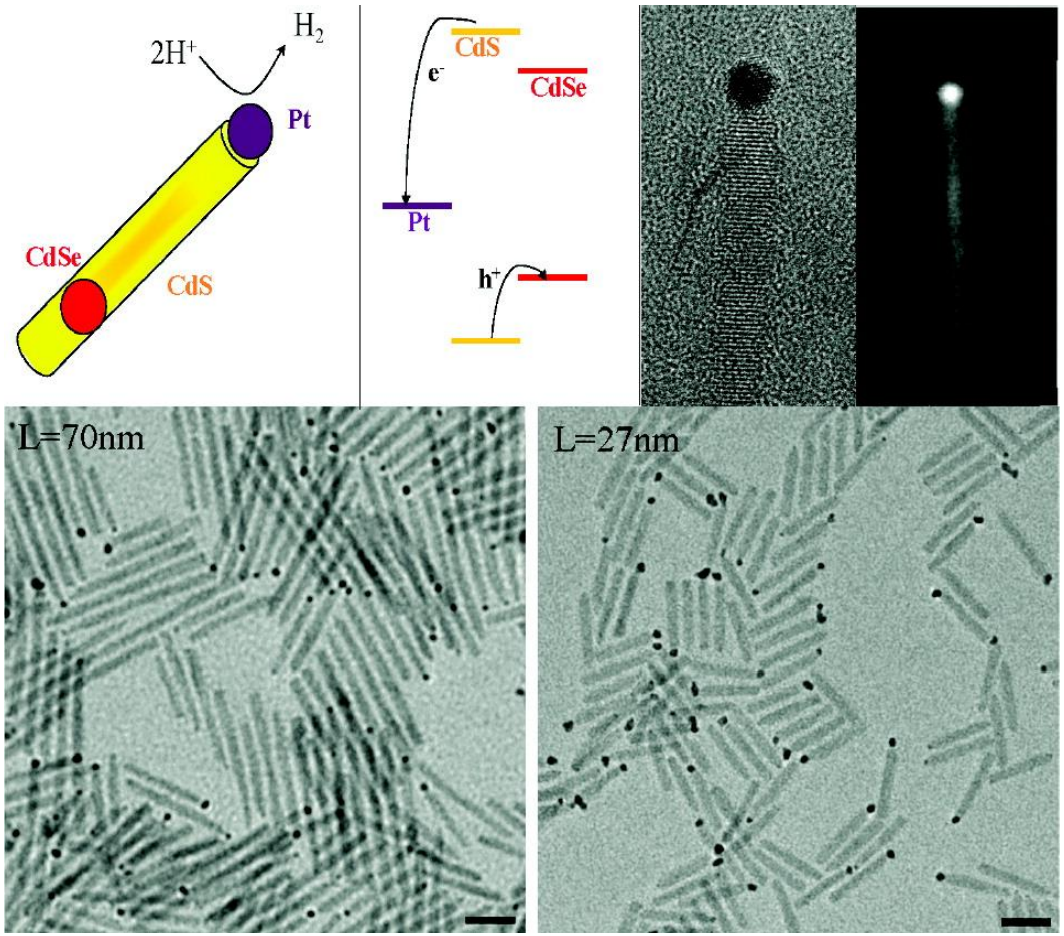


Sunlight and water: Abundant sources

Hydrogen: Fuel that can be stored and Transported

Can we use light energy to split water into hydrogen and oxygen efficiently?

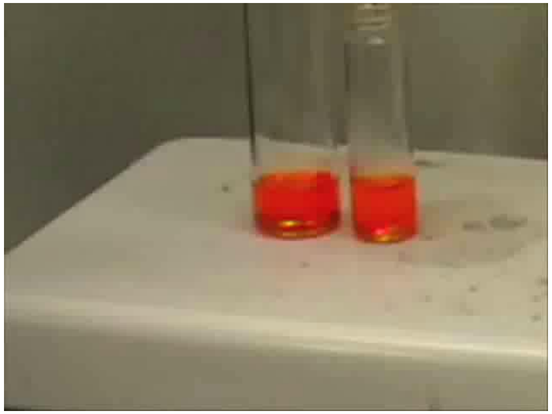
Nanostructures for Artificial Photosynthesis



High Surface Access at the Nanoscale

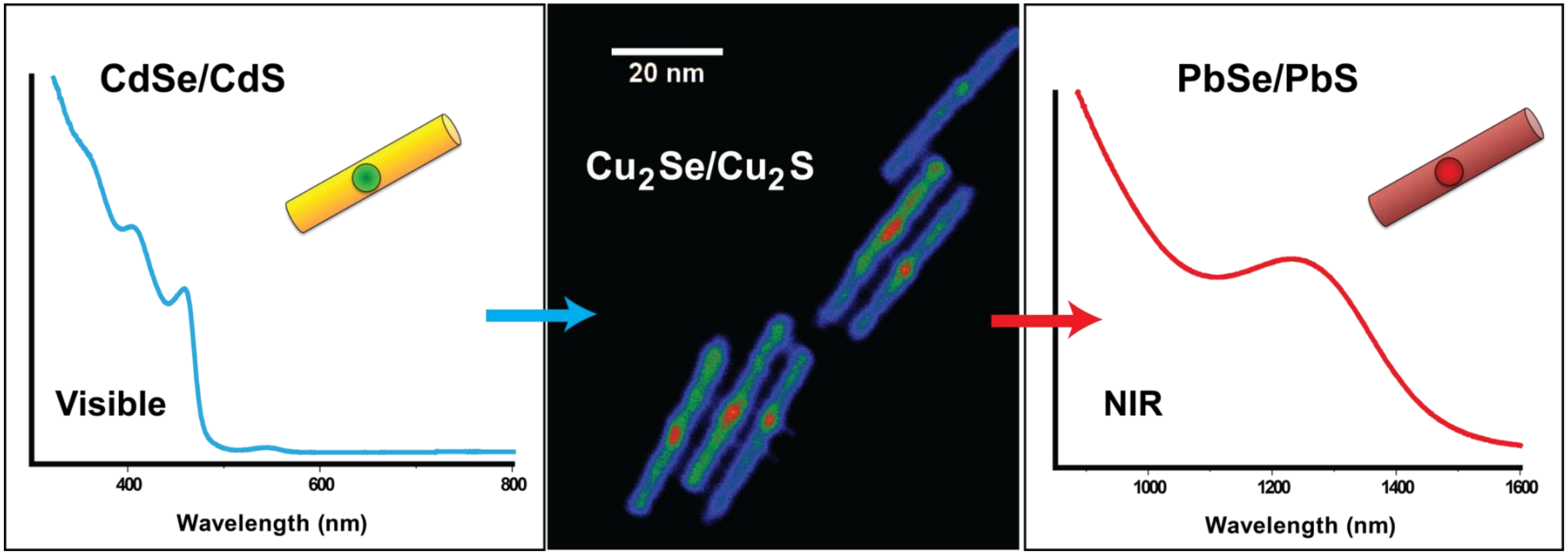
$(A^+B^- + C^+ \rightarrow C^+B^- + A^+)$

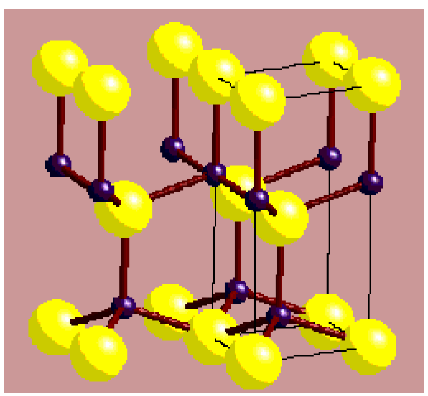
Son, Hughes, Yin, and Alivisatos, *Science*, 2004, 306, 1009

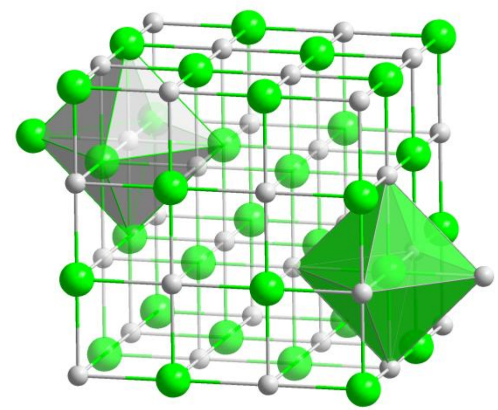


Courtesy: Bryce Sadtler

Templated Access to New Materials





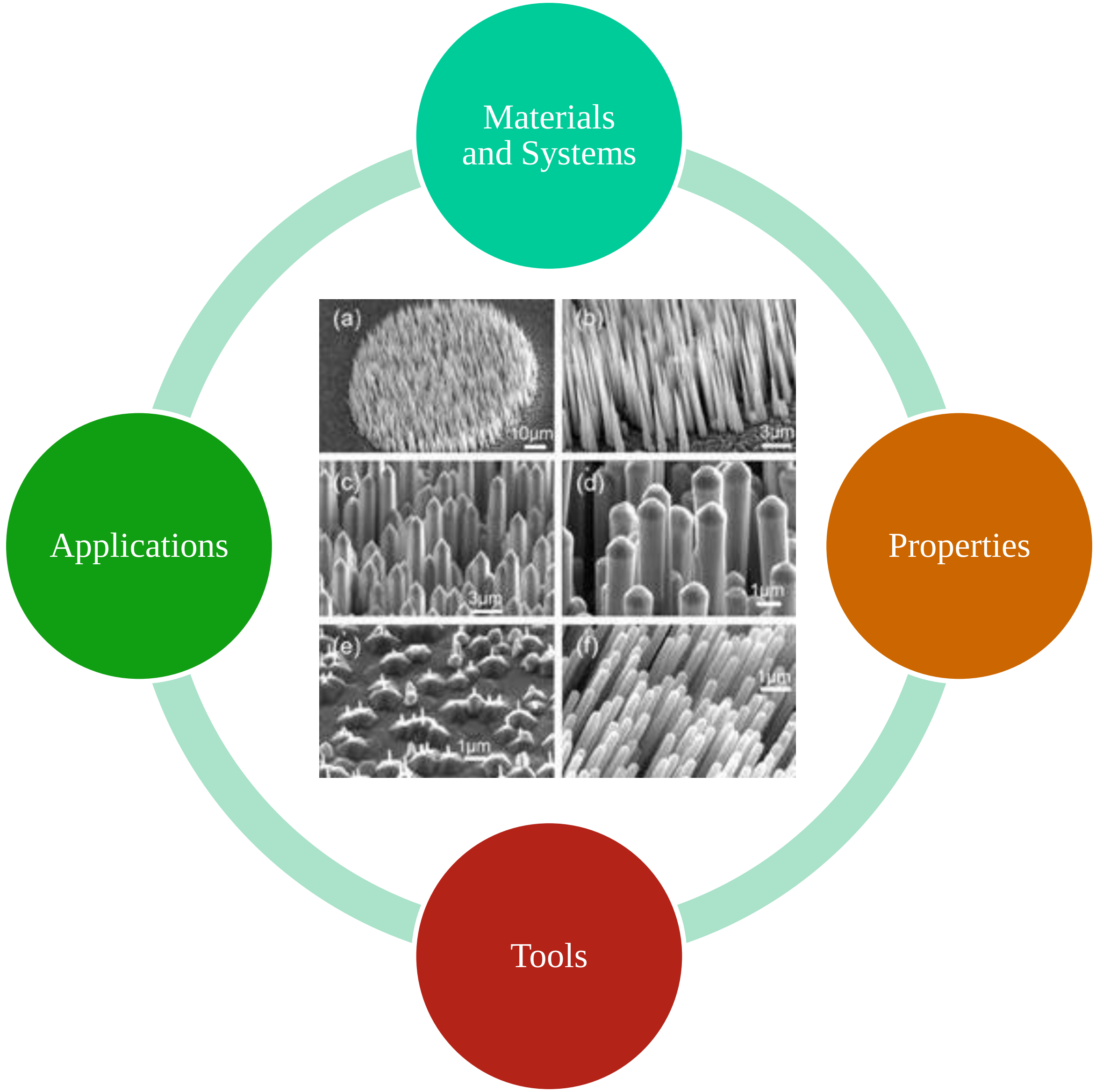


Wurtzite → c-axis

Rock-salt → symmetric

Jain*, Amirav*, Aloni, and Alivisatos, *JACS*, 2010, 132, p9997.

Nanoscience



Acknowledgements

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Prof. Mostafa El-Sayed

Xiahoua Huang

Georgia Institute of Technology Center for Computational Molecular Science and Technology

The University of California 1868

Prof. Paul Alivisatos

Lilac Amirav

Jessica Smith

VE RI TAS

Prof. Adam Cohen

Harvard University Center for Nanoscale Systems