Understanding Corona Phase Molecular Recognition Sensors on Single Walled Carbon Nanotubes

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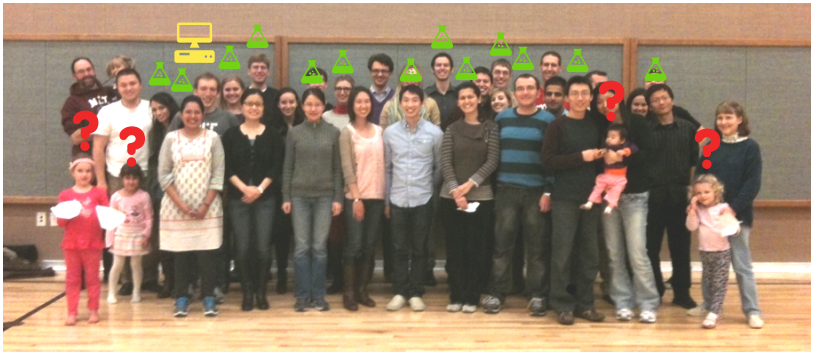
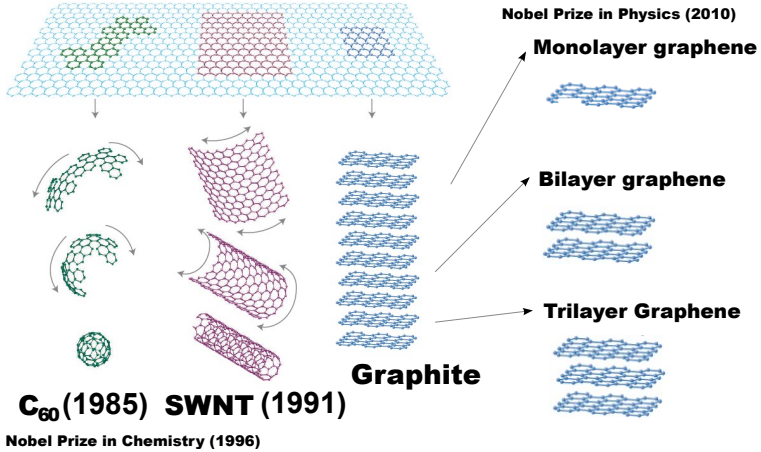
Modeling/Simulations in an Experimental Group

PhD situation different from most CSGF fellows



Strano Group - mostly experimental devices based on low-dimensional carbon materials (carbon nanotubes, graphene, etc.)
Braatz Group - systems engineering, controls, applied math

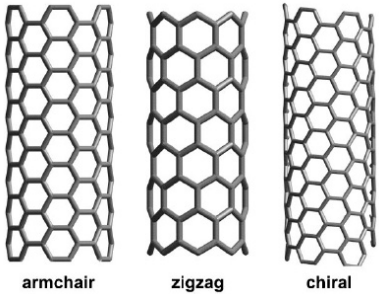
Low-dimensional Carbon Materials

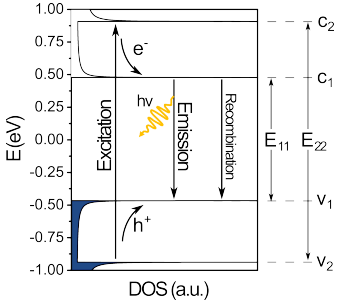


All-carbon materials, but very different electronic structure.

Single-Walled Carbon Nanotube Fluorescence

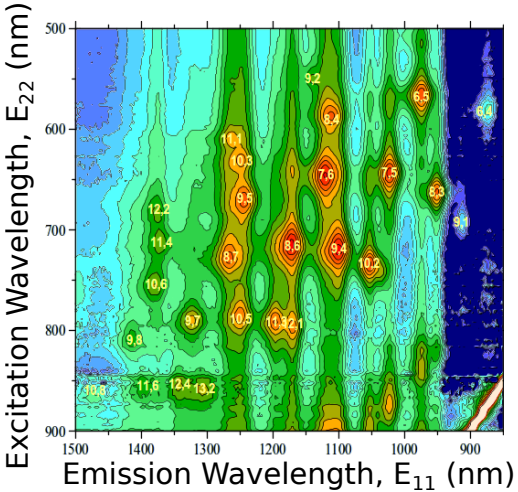
Single-Walled Carbon Nanotubes (SWCNTs) vary in diameter (0.5-2nm) and electronic structure (metal/semi-metal/semiconductor)

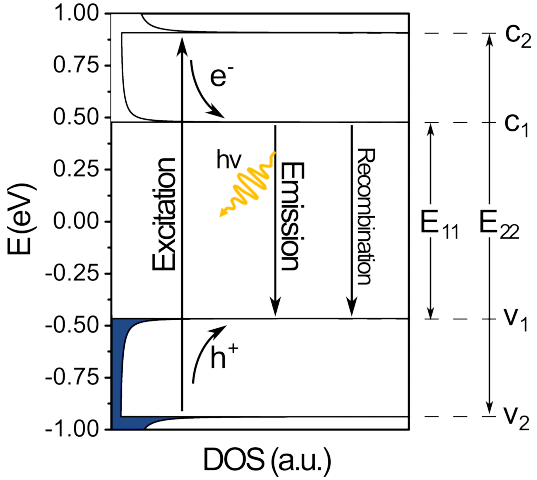




SWCNTs have a very strong fluorescence signal (you can easily see single molecules in a microscope!). Introducing defects reduces fluorescence signal.

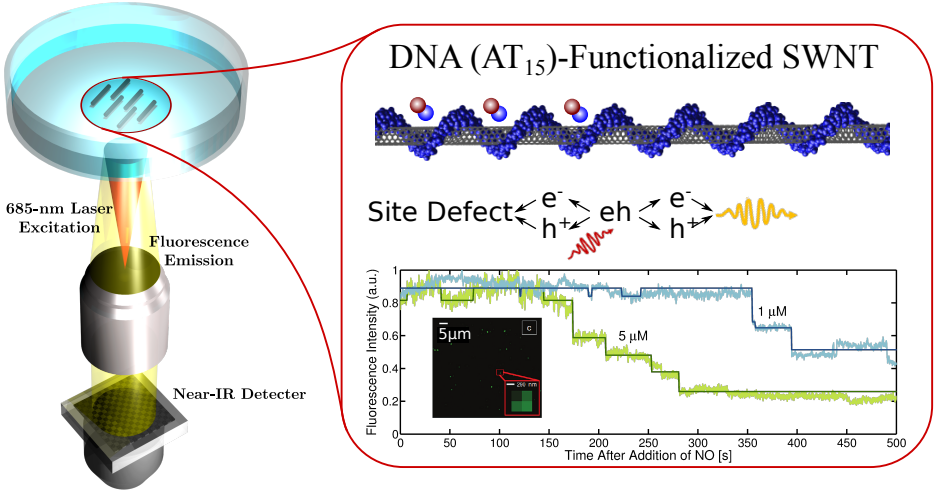
Diversity of Electronic Properties





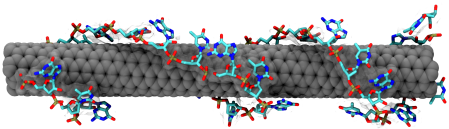
Bachilo, S., Strano, M. S. et al., Science, 298 (2002) 2361

Corona-Phase Molecular Recognition (CoPhMoRe)



Zhang et al. JACS (2011).

Simulations at the nano scale



Many important effects - chemistry, electronic structure, mechanical properties / strain, local environment (surfactant or polymers)

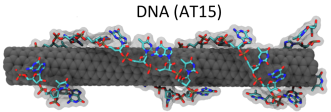
- Experimental evidence that SWCNT electronic structure affects adsorption energies and interactions with polymers. Mechanical effects (strain etc) changes electronic structure.

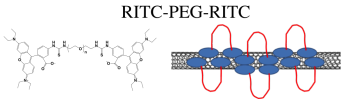
Right time/length scales for readily available simulation ability:

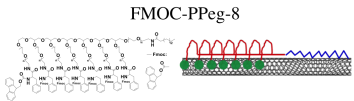
- SWCNT unit cell can be 200-500+ atoms. Calculating electronic structure tractable/fast with tight binding density functional theory.
- SWCNT unit cell + DNA wrapping + 5 nm solution box $\sim$ 100,000 atoms. Tractable for molecular dynamics.

SWCNT Wrappings for Analyte Specificity

Large library of various polymer-analyte interactions built up in the Strano lab

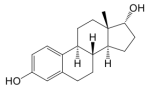




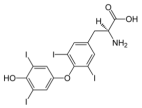


Nitric Oxide

Estradiol

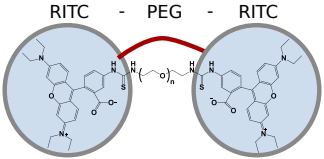


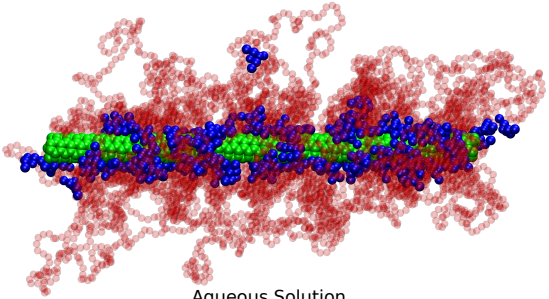
L-Thyroxine

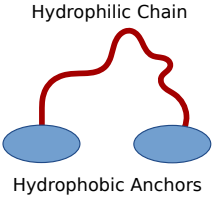


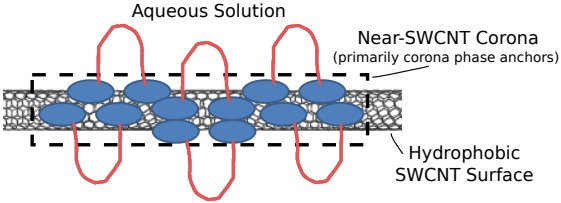
Zhang et al. Nature Nanotechnology 2014. RITC=Rhodamine IsoThioCyanate. FMOC=Fluorenylmethyloxycarbonyl

What does the corona phase look like?









Coarse-grained simulations of RITC-PEG-RITC on SWCNT using the Martini forcefield. Lin et al. Langmuir (2013).

Thermodynamic Surface Adsorption Model

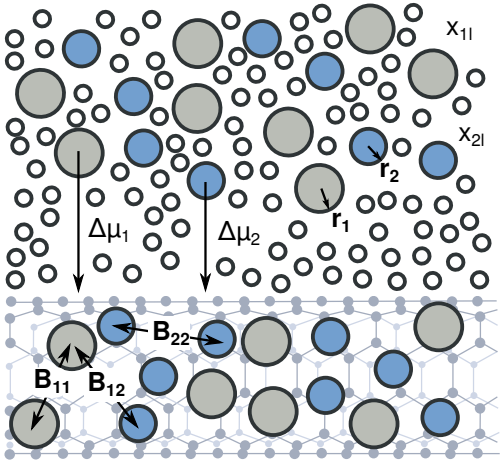
Model adsorption process as a thermodynamic partitioning between two phases:

For each species (polymer anchor or analyte):

- $\Delta\mu_i$ - Adsorption energy
- B_{ij} - van der Waals interactions while on surface
- x_{iL} - mol fraction in solution
- x_i^{σ} - mol fraction on surface
- r_i, a_i - molecular radii/area

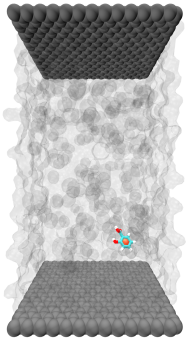
Mulqueen and Blankschtein, Langmuir 1999 15 (26), 8832-8848.

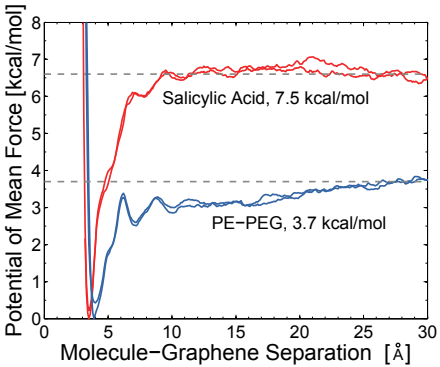
Assume degree of quenching $\Delta I / I_0 \propto$ analyte surface coverage.



Parameter Estimation

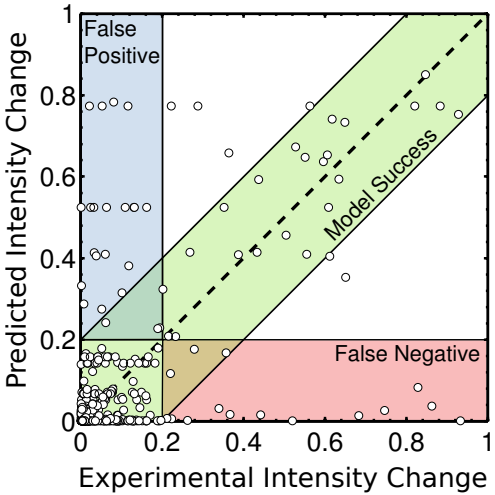
To quickly predict adsorption energies and van der Waals interactions, we borrow tools from the computational drug screening community (CGenFF for force field generation, NAMD for molecular dynamics).





Simulations performed on NICS/Kraken. Approximately 100,000 cpu-hours for 60 adsorption-energy calculations.

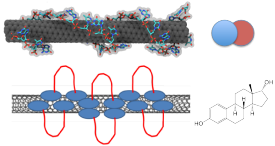
Model Agreement



- Model agreement (within 20%) for 83% of experiments.
- Pre-screening with model would increase success rate of future experiments from 21% to 40% by screening out obvious combinations.

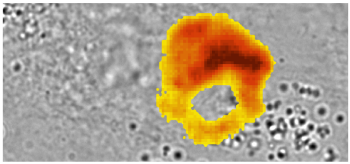
Broader Picture

Wrappings → Specificity



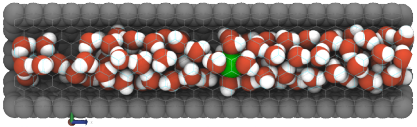
Zhang, Ulissi et al. Nature Nano (2013)
Ulissi et al. Submitted (2014)

Spatio-Temporal NO Sensing *in vitro*



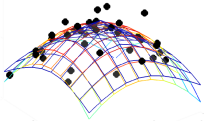
Ulissi et al. Nano Letters (2014)

Diameter-Dependent Pore-Blocking



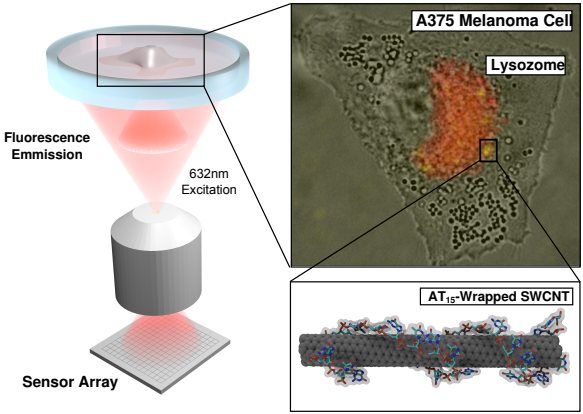
Ulissi et al. JPC Letters (2011)
Ulissi et al. Nature Communications (2013)

Collections of Stochastic Sensors



Ulissi et al. JPC Letters (2011)
Ulissi et al. Comp. & Chem. Eng. (2012)

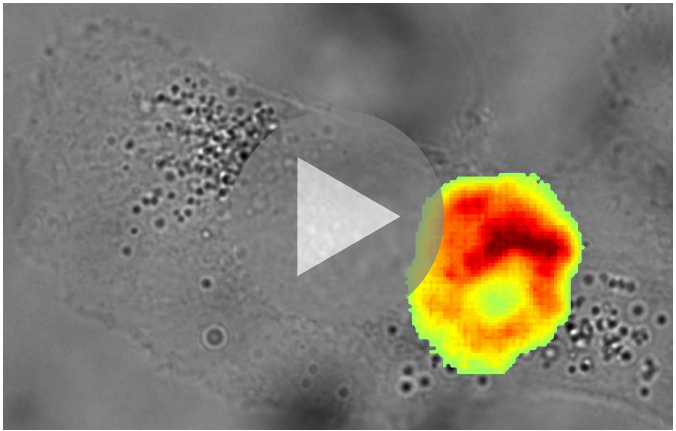
Intracellular SWCNT Sensors

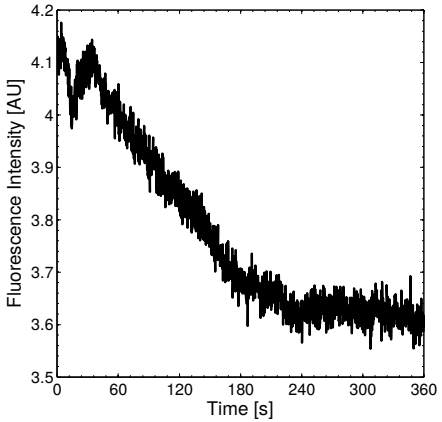


$d(AT)_{15}$ wrapped SWCNT observed to uptake to A375 melanoma cells spontaneously, and co-localized with the lysozome using Lysotracker Red.

Demonstration of Nitric Oxide Sensing

Introduction of a NO-producing agent JS-K leads to SWCNT sensor quenching.





Ulissi et al. Nano Letters (2014).

Acknowledgements

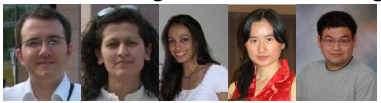
- DOE CSGF, NSF GRFP Fellowships, XSEDE Resources

DOE CSGF

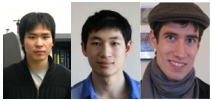
NSF

XSEDE
Extreme Science and Engineering Discovery Environment

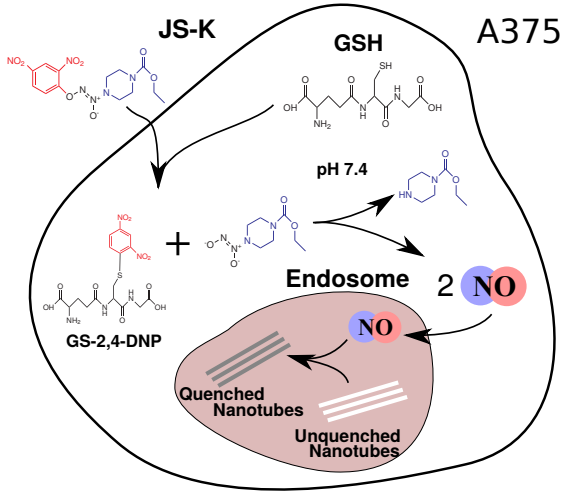
- Advisors - Michael Strano and Richard Braatz, same as Ashlee Ford (CSGF 2010)
- Committee, including Martin Bazant (CSGF 1996)
- The NO/single-molecule subgroups and Mayo Clinic collaborators



- The nanopore subgroup



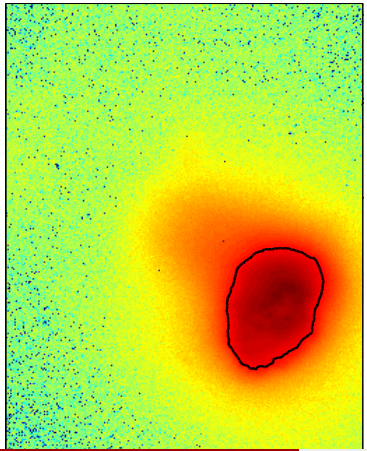
JS-K Degradation Mechanism



Mechanism: Shami et al. Molecular Cancer Therapeutics (2003).

Spatio-Temporal NO Sensing

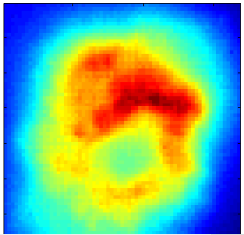
SWCNT sensors behave as point source of NIR illumination within the cell, with produced light scattering and absorbing in media.

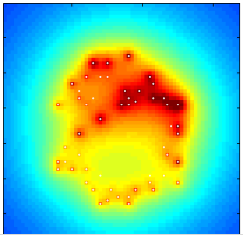


Radial light intensity $\phi(r)$, according to

$$\mu_a \phi - \frac{1}{3(\mu_a + (1-g)\mu_s)} \nabla^2 \phi = \text{Source Term}$$

μ_a, μ_s are wavelength-dependent scattering/absorption coefficients





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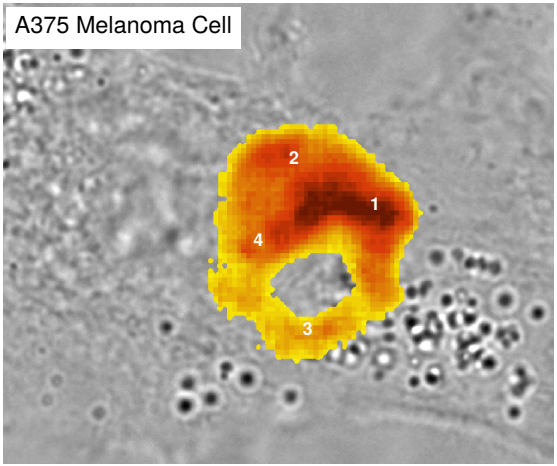

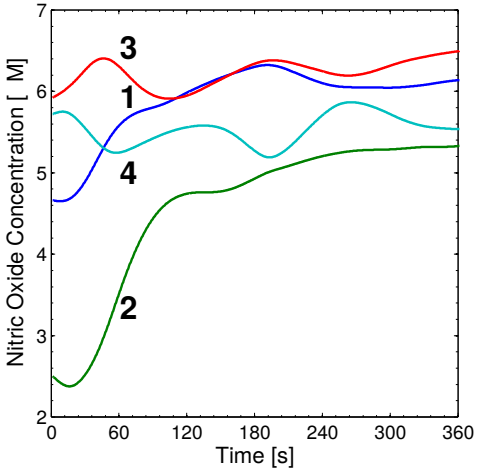

NO Concentration calculated using known NO/SWCNT quenching kinetics