Research at the Nano/Bio Interface

Bio-electronic and Bio–optoelectronic Hybrid Systems

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Singh Center for Nanotechnology (2013)

http://www.nano.upenn.edu/

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Penn Nano/Bio Interface Center (NBIC)

NSF Nano Science and Engineering Center

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Bio-electronic and Bio–optoelectronic Systems

Frontier of interfaces between **proteins** and **nanostructured materials** (surfaces, nanoparticles, carbon nanostructures)

Design protein structure, nanostructure and self-organization

Protein-enabled nanosystems with new electronic and optoelectronic activities

A. T. Charlie Johnson, Physics & MSE. Nanoelectronics, graphitic systems

Jeffery G. Saven, Chemistry. Theoretical modeling & design

William F. DeGrado, (UCSF) Biophysics. Protein design and characterization

Dawn Bonnell, Materials Sci & Eng. In situ measurements & lithography

J. Kent Blasie, Chemistry. Proteins at interfaces: assembly & characterization

Bohdana Discher, Biophysics. De novo proteins at surfaces

Christopher Murray, Chemistry & MSE. Nanoparticle synthesis and self-assembly

Marija Drndic, Physics. Nanoscale structures: nanoparticles & graphene

So-Jung Park, (Ewha) Chemistry. Nanoparticle synthesis; hybrid polymers & biopolymers

Michael Therien, (Duke) Chemistry. Chromophore design and synthesis.

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Hybrid nanostructures

- Electronic response
  - Optical properties
  - Charge separation
  - Polarization
  - Current modulation
- Control of structure/function, nano-precision
  - Self-assembly
  - Control of polydispersity
  - Sculpting nanostructures

Nanostructure
or
Surface

Chromophore or Ligand

Protein or Polymer

Protein-Nanostructure Hybrid Systems

- Proteins & Polymers
  - Bio-derived functionality with precisely defined structure
    - Optical activity
    - Chemical recognition
  - Ordering in 2D and 3D
- “Inorganic” Nanostructures
  - Structurally and electronically robust
  - Dimensional control (nanocrystals, nanotubes, graphene)
- Complementary functionality
  - Electronic transduction & Sensors
  - Catalysis
  - Light harvesting, manipulation & charge separation

Capabilities and Synergies

- Protein design & Macromolecular modeling
  - Cofactor & chromophore design *(Therien)*
  - Theoretical and computational protein design *(DeGrado, Saven)*
  - Molecular modeling and simulation *(Saven, Blasie)*
- Synthesis & Fabrication
  - Proteins *(DeGrado, B. Discher, Blasie, Saven, Therien)*
  - Nanoparticles & Carbon Nanostructures *(Drndic, Johnson, Murray, Park, Therien)*
- Controlled integration of proteins and nanostructures
  - Ferroelectric Lithography *(Bonnell)*
  - Graphene and Single Walled Carbon Nanotubes *(Drndic, Johnson)*
  - Directed assembly via liquid interfaces *(Blasie, DeGrado, B. Discher)*
  - Engineered self-assembly *(Murray, Saven, DeGrado)*

Capabilities and Synergies

- Structure & property measurement of hybrid systems
  - Protein structures in solution, at interfaces, and in lattices *(Blasie, DeGrado, B. Discher, Saven)*
  - Electrical and optical response of protein/nano systems *(Bonnell, Blasie, Johnson, Murray, Therien)*

- Towards Bio/Nano enabled opto-electronic devices
  - Plasmonic devices *(Bonnell, Therien)*
  - Sensor elements *(B. Discher, Johnson)*
  - Light harvesting *(Blasie,Therien, Saven, Murray)*

Design of Protein Complexes

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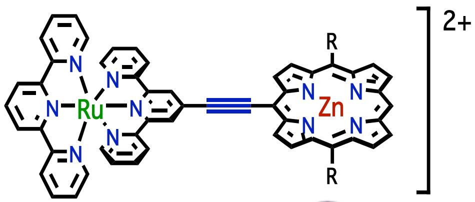
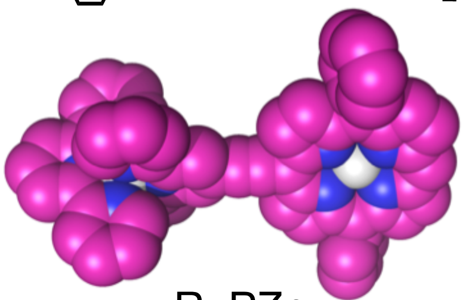
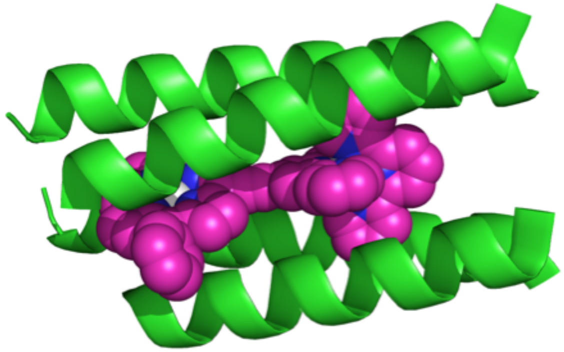
Tailoring protein to NLO cofactor: RuPZn

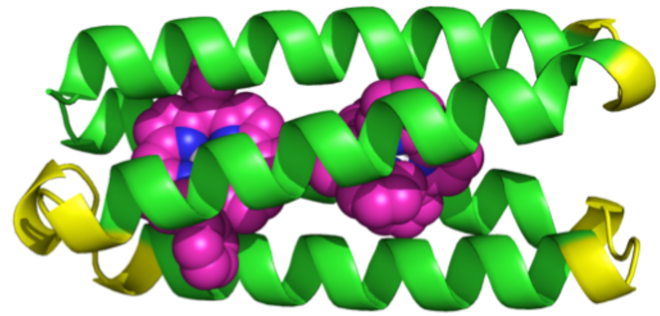




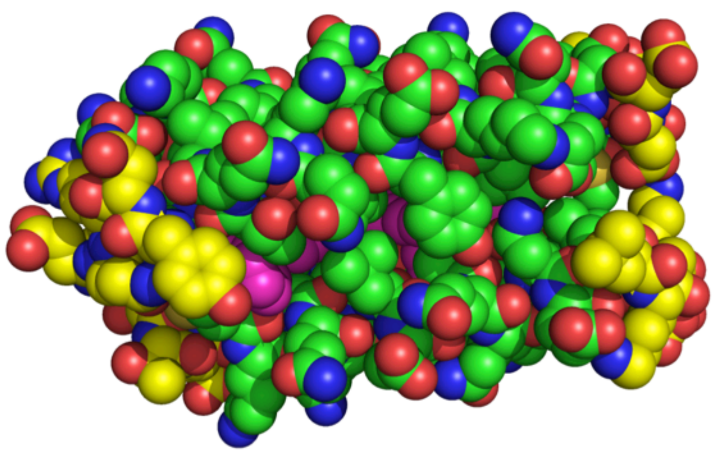
RuPZn

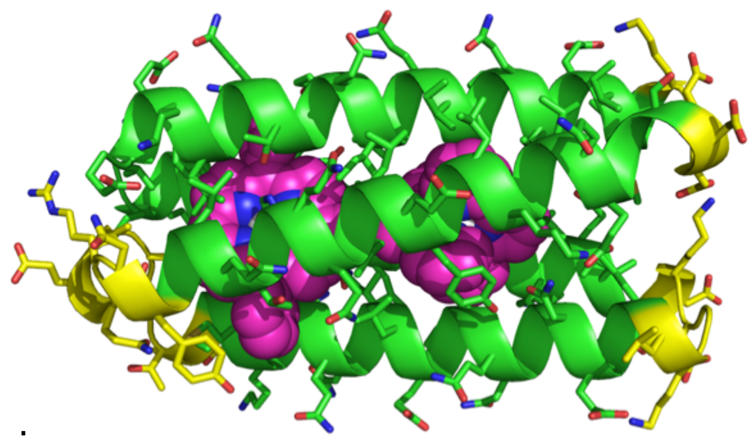


Build helical
bundle



Build loops to arrive at
Single chain





Computational design
of sequence

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Saven, Therien, Blasie, DeGrado. *JACS* 2013

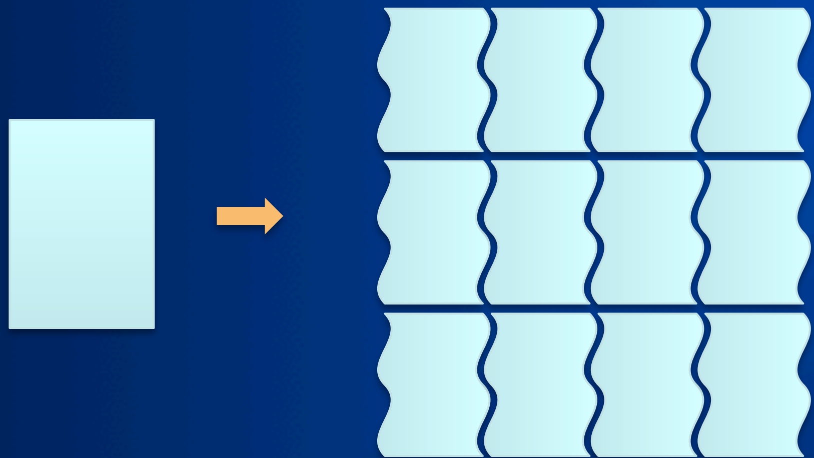
Control of 3D Order: Proteins & Polymers

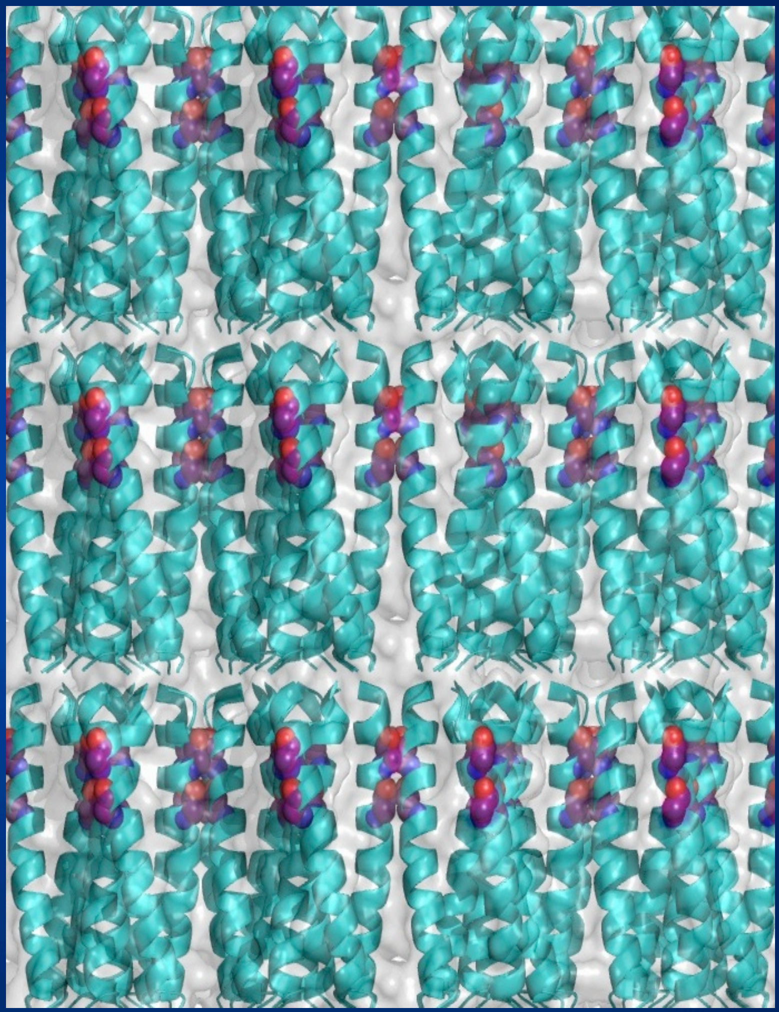
Computational Design of a Protein Crystal

Saven, DeGrado

Protein crystals

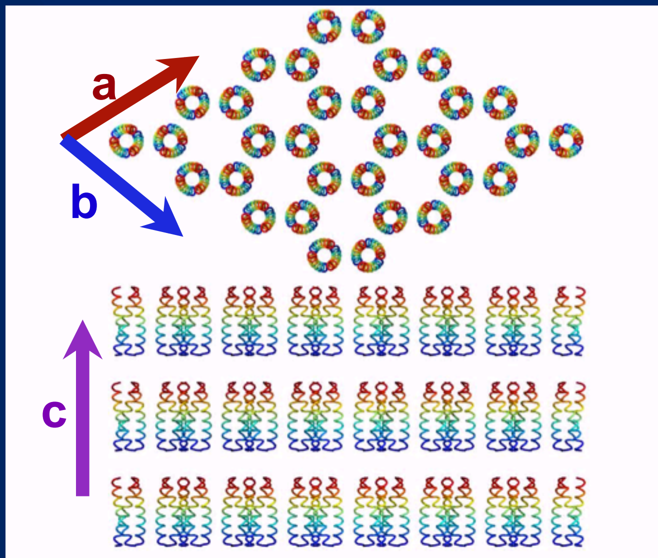
- Engineer multiscale order
- Specify symmetry and structure a priori
- Design proteins



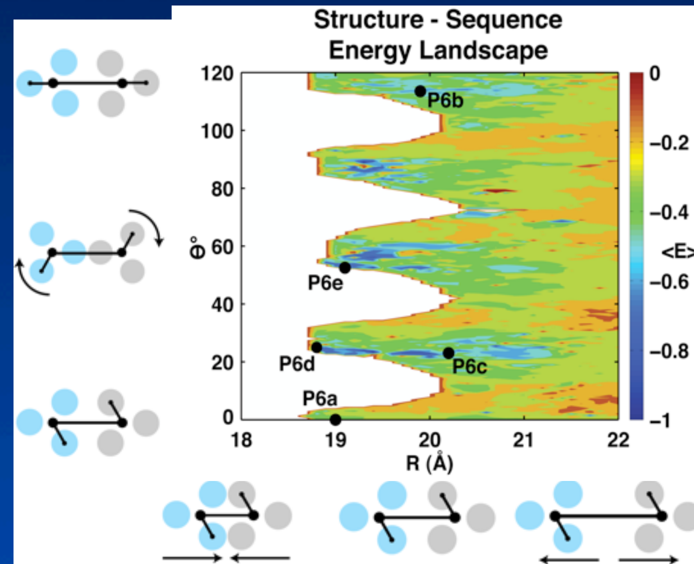


Lanci et al, *Proc. Natl. Acad. Sci USA* (2012)

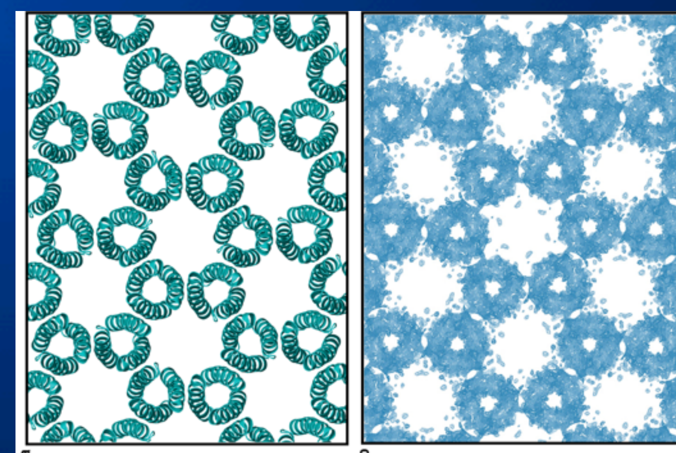
Computational Design of a Protein Crystal



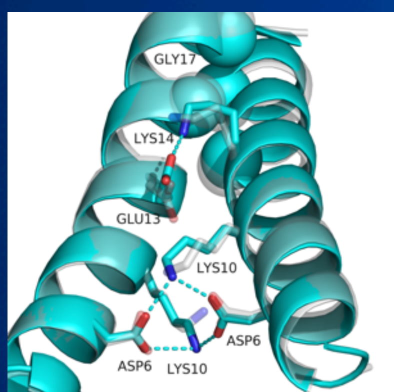
Predetermined crystalline structure

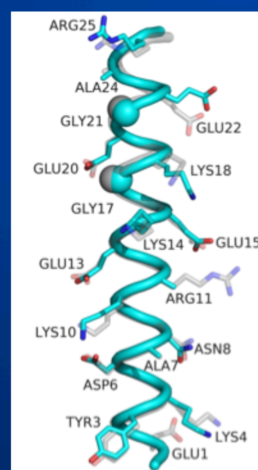


Computational design



X-ray crystallography





Sub-Å agreement with
model template

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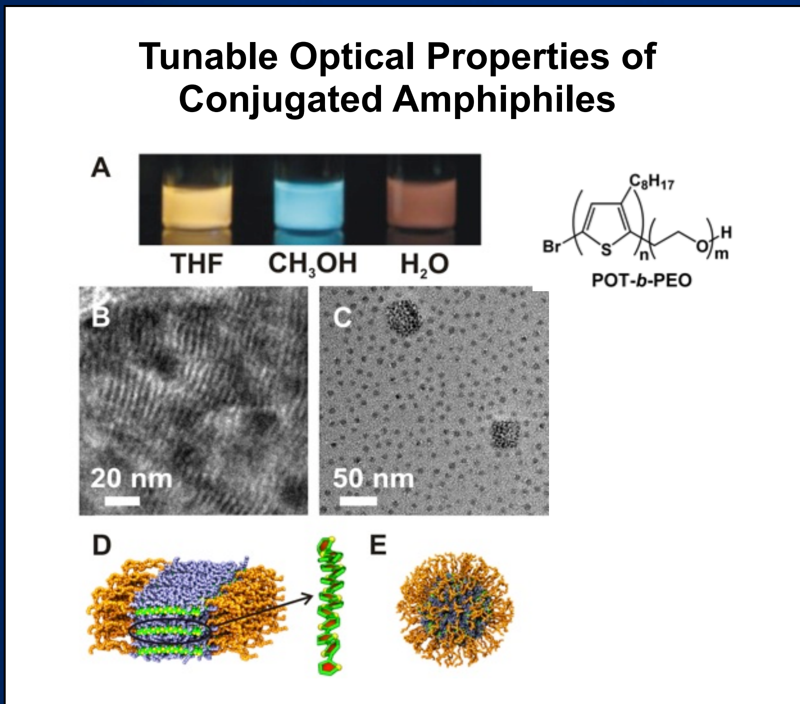
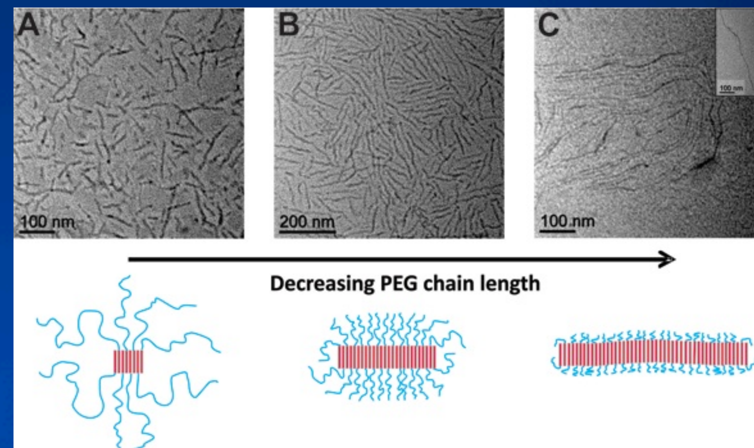
Self-Assembly of Amphiphilic Semiconducting Polymers

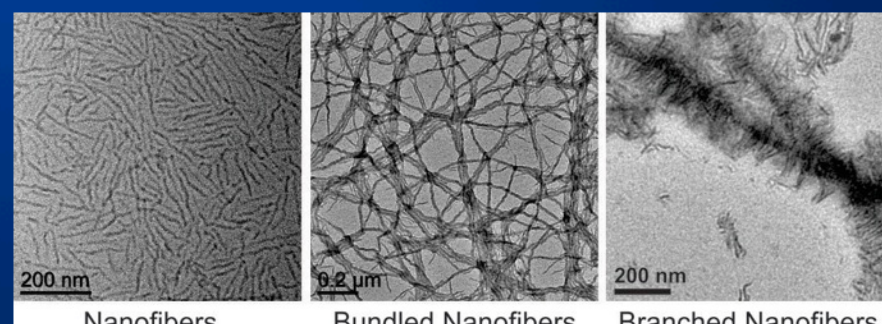


J. Am. Chem. Soc. (2010)

PHT-PEG copolymers form wire-like assemblies



PHT-PEG/PHT yield bundle & branched fibers



ACS Nano (2012)

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Park, Saven

NSF

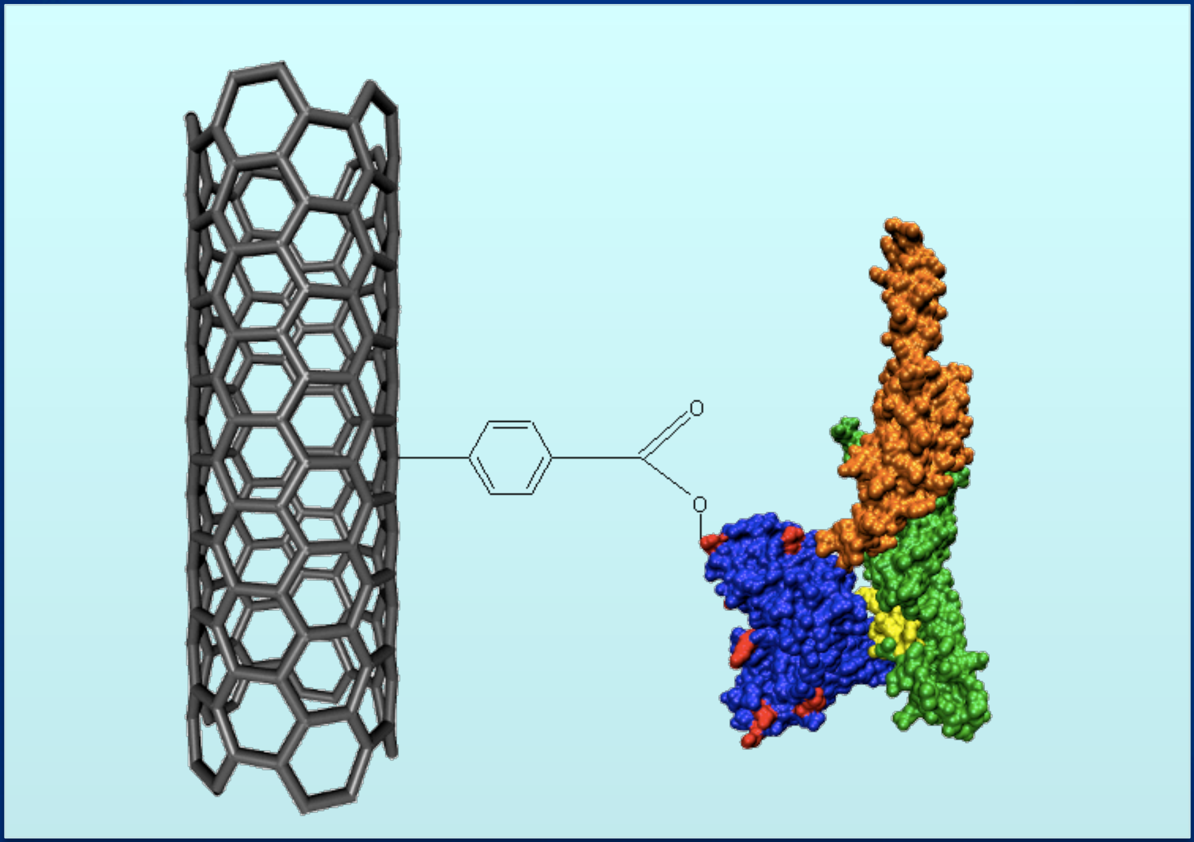
Nano/Bio Integration

Generic Protein Attachment Chemistry

B. Discher, Johnson

Goal: Attach arbitrary proteins to nanotube/graphene devices

Use amide bond or histidine tag of a recombinant protein



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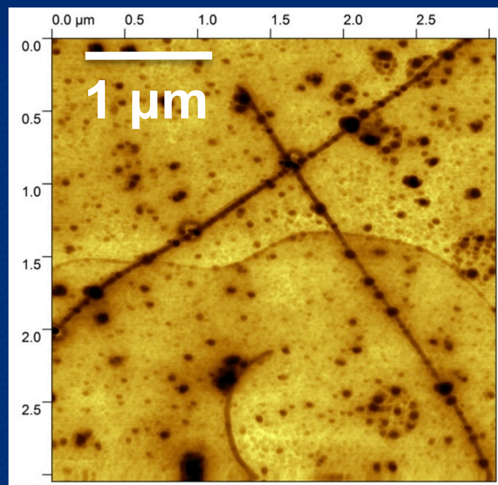
Graff et al, *Chem. Mater.* (2008)

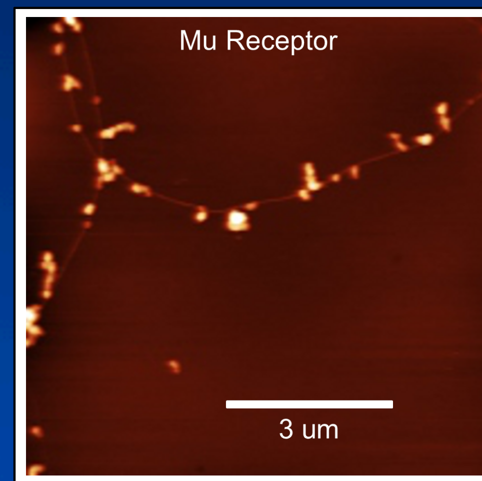
Nanotube (Graphene) - Protein Hybrids
Programmable Bio/Nanoelectronic Devices *B. Discher, Johnson, Saven*

Mouse ORs in micelles

ACS Nano 2011

B. Discher, Johnson





Mu receptor

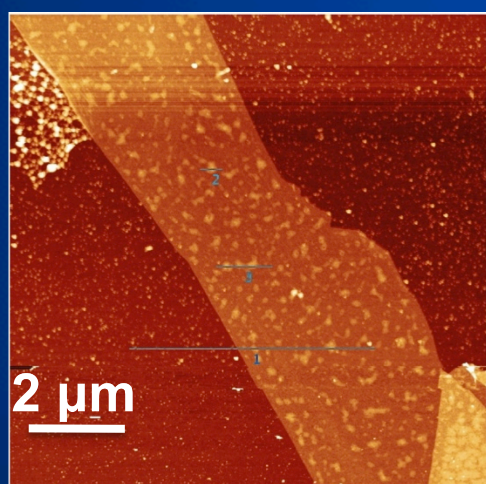
Unpublished

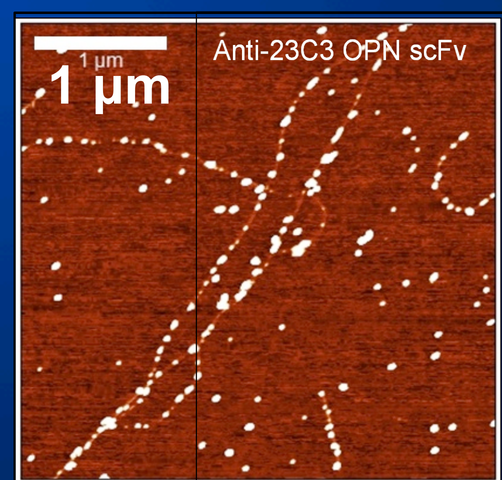
Johnson, Liu, Saven

His-tagged G protein on graphene

APL 2012

B. Discher, Johnson





Anti-OPN scFv

ACS Nano 2012

Resolve target at 1 pg/mL

Johnson, Fox Chase

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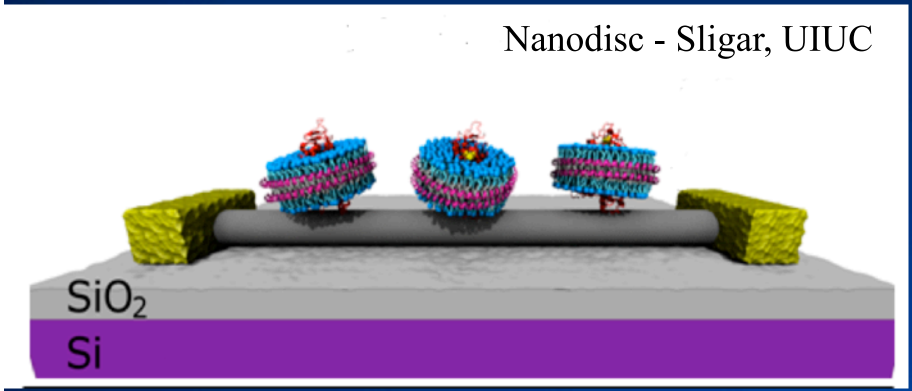
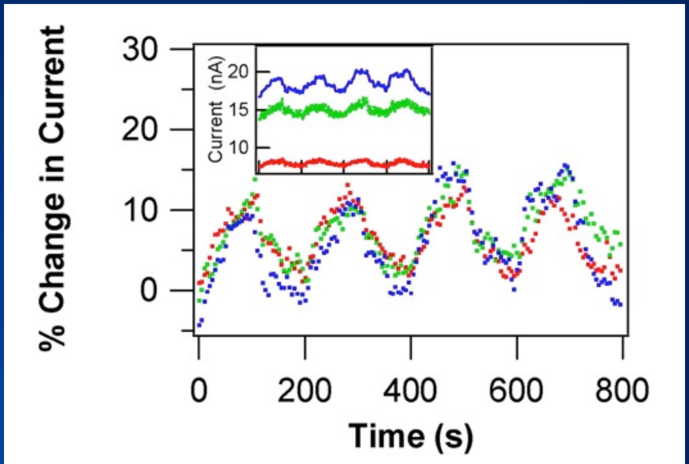
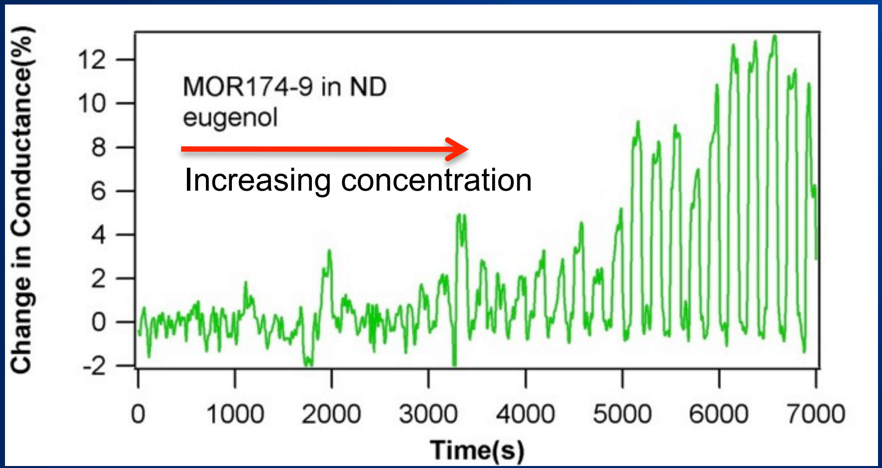
Biomimetic Vapor Sensors Based on Olfactory Receptor Proteins
B. Discher, Johnson *ACS Nano* (2011)

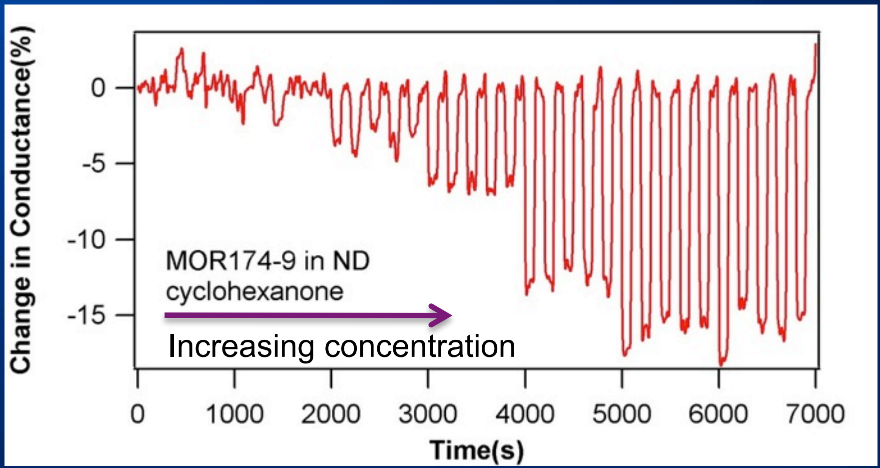




Olfactory receptors coupled to nanotube transistors
ORs encapsulated in micelles or "nanodiscs" (UIUC)
OR-NT sensors show responses congruent
to OR responses "in surrogo" using Xenopus oocytes

Device variation is normalized out
2-3 month device lifetime





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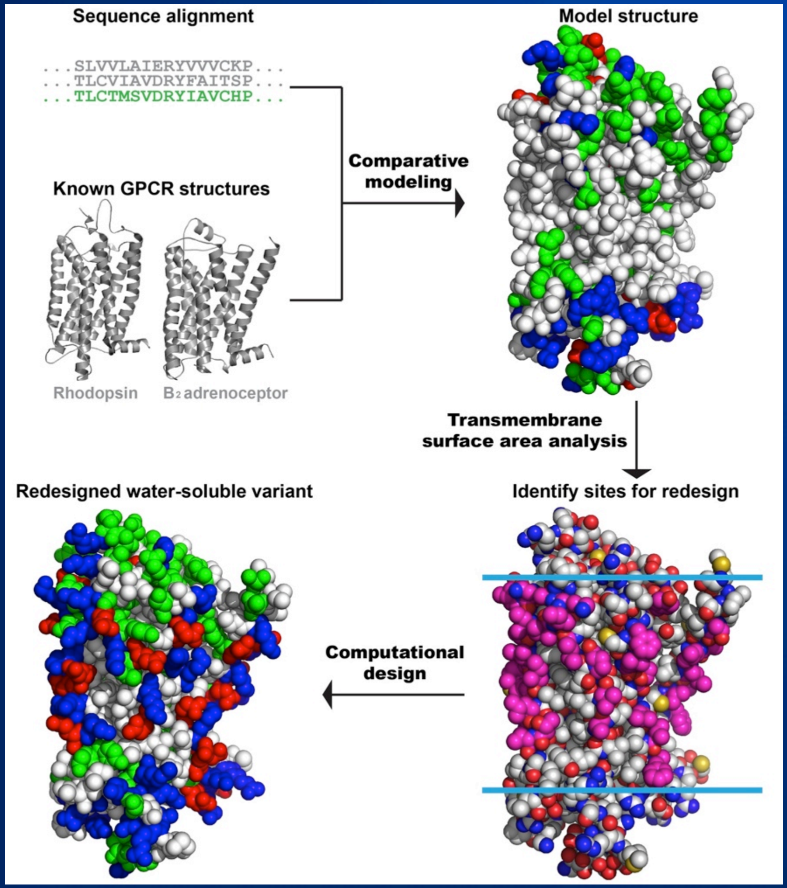
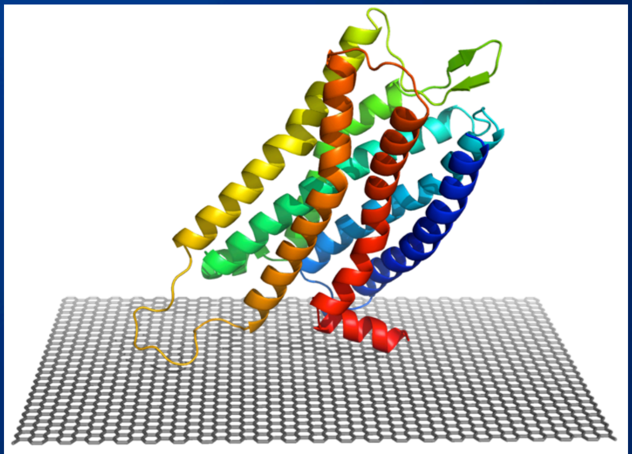
Redesign receptor proteins for integration into graphitic devices



Increase quantities
Facilitate processing
Tailor protein & nanostructure



Perez-Aguilar et al, PLOS One, 2013

Johnson, Discher, Saven

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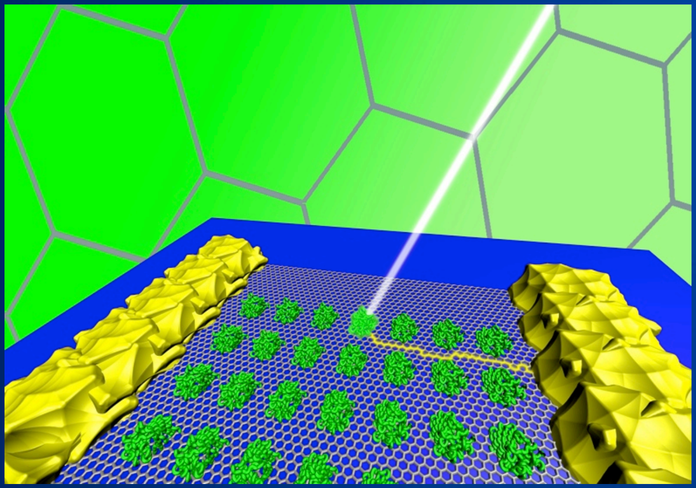
Nano-electronic Readout of Optically Excited Proteins

B. Discher, Johnson



Protein-enabled optical sensor with Graphene transistor readout

Hybrid device photoresponse determined by *protein absorption spectrum*

Appl. Phys. Lett. (2012)