Biomedical Applications of Single-Walled Carbon Nanotubes: Toward Design of Novel Optical Sensors

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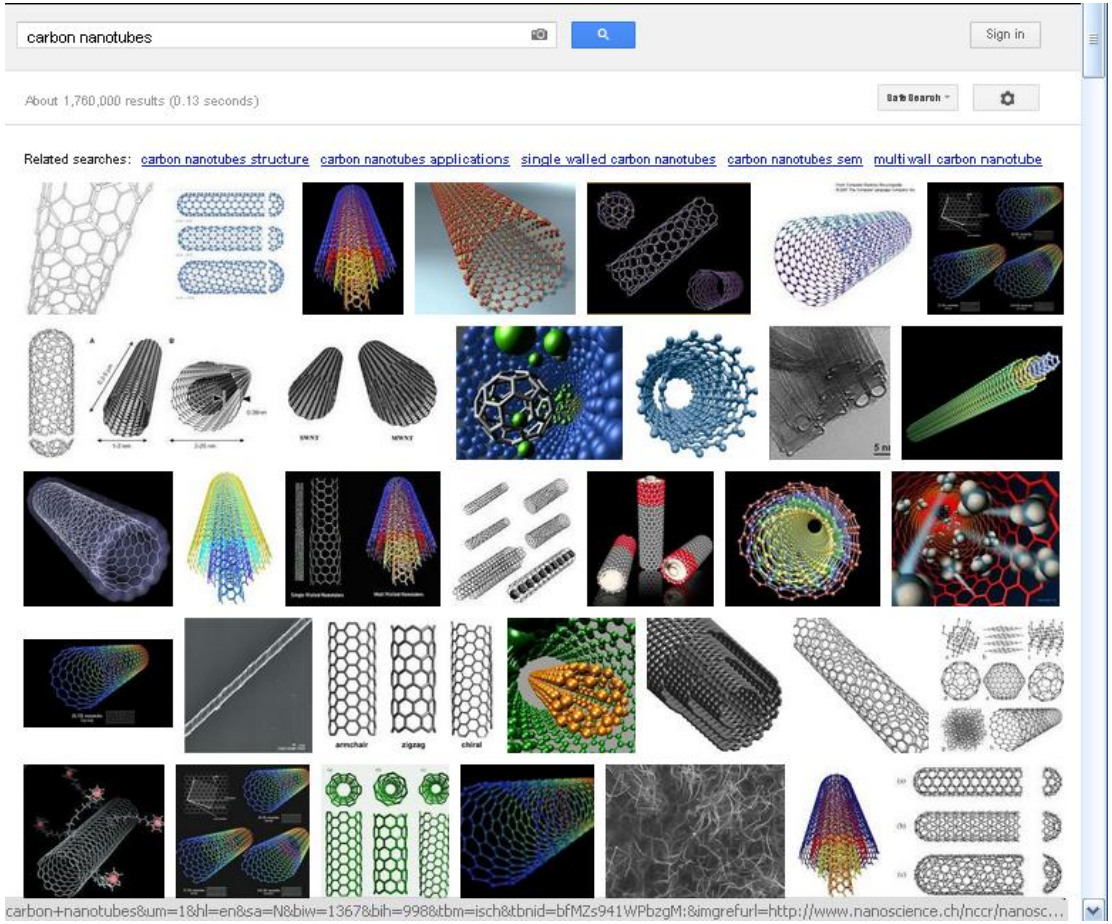
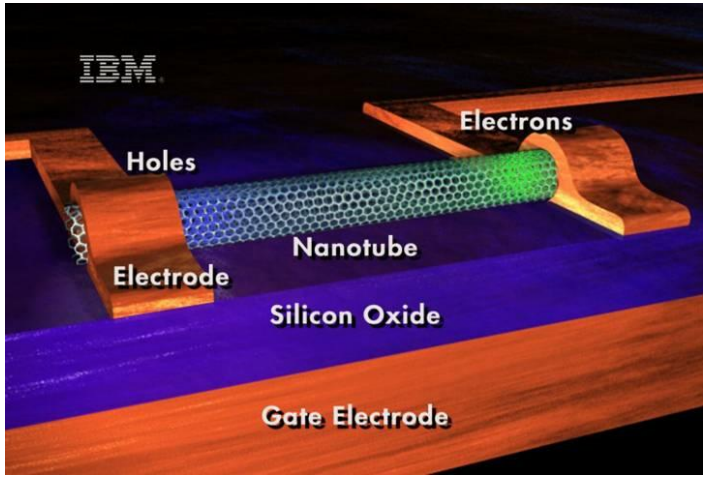
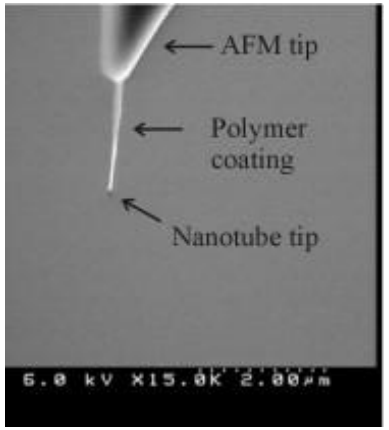
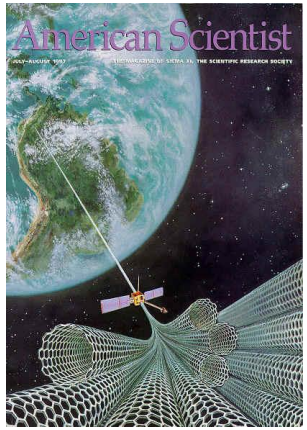
2012/06/26

Carbon Nanotubes are Really Cool!









http://www.research.ibm.com/nanoscience/publications_optics.html
http://www.nanotechbuzz.com/50226711/carbon_nanotube_afm_tip.php

Outline

Introduction of Single-Walled Carbon Nanotubes (SWNTs) → **What ?**

- Structure of SWNTs
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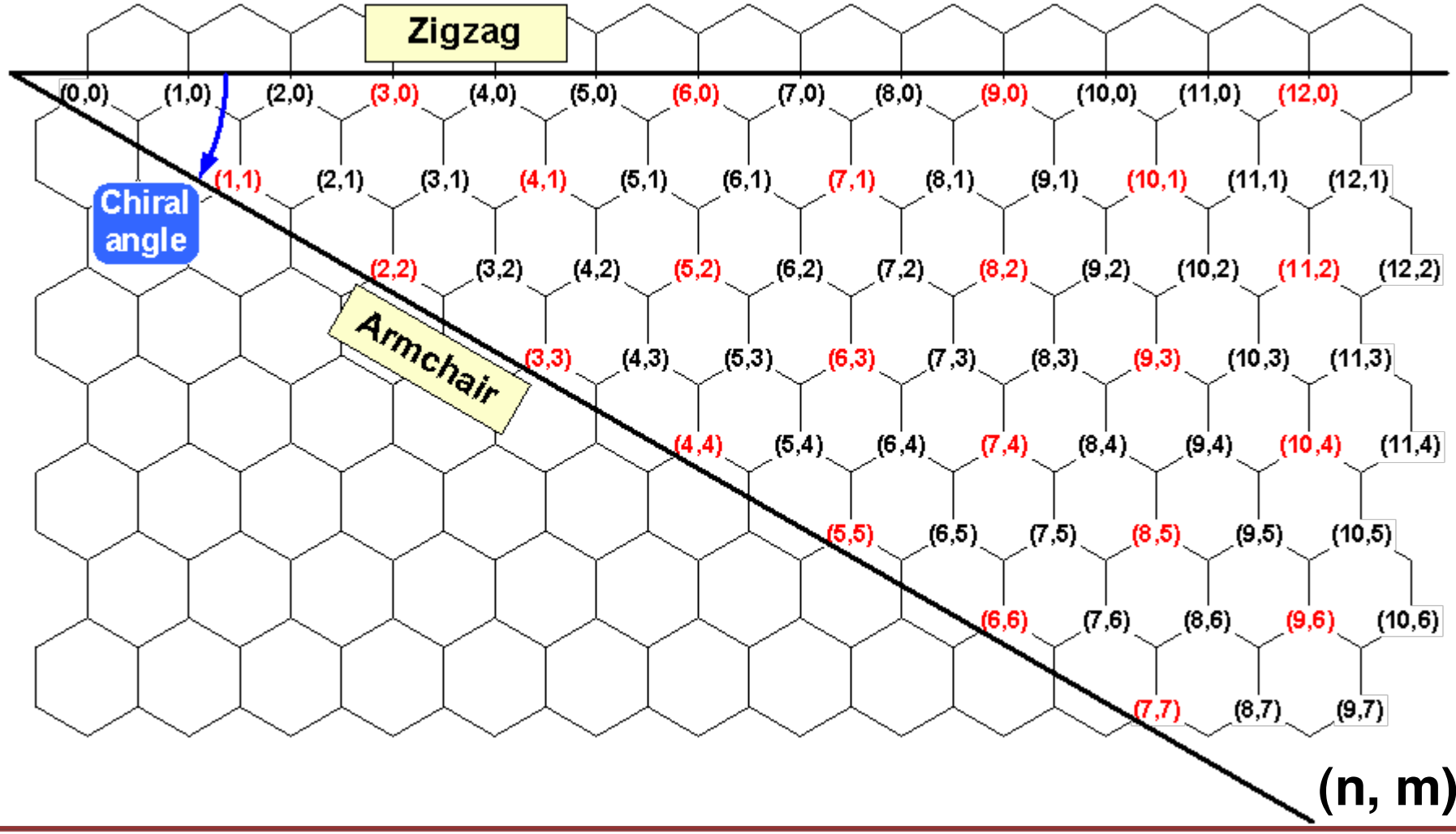
- Detection of DNA Configuration
- Glucose Sensor

Rationale of Molecular Recognition → **Why ?**

Conclusions

Construction of SWNTs from a Graphene Sheet



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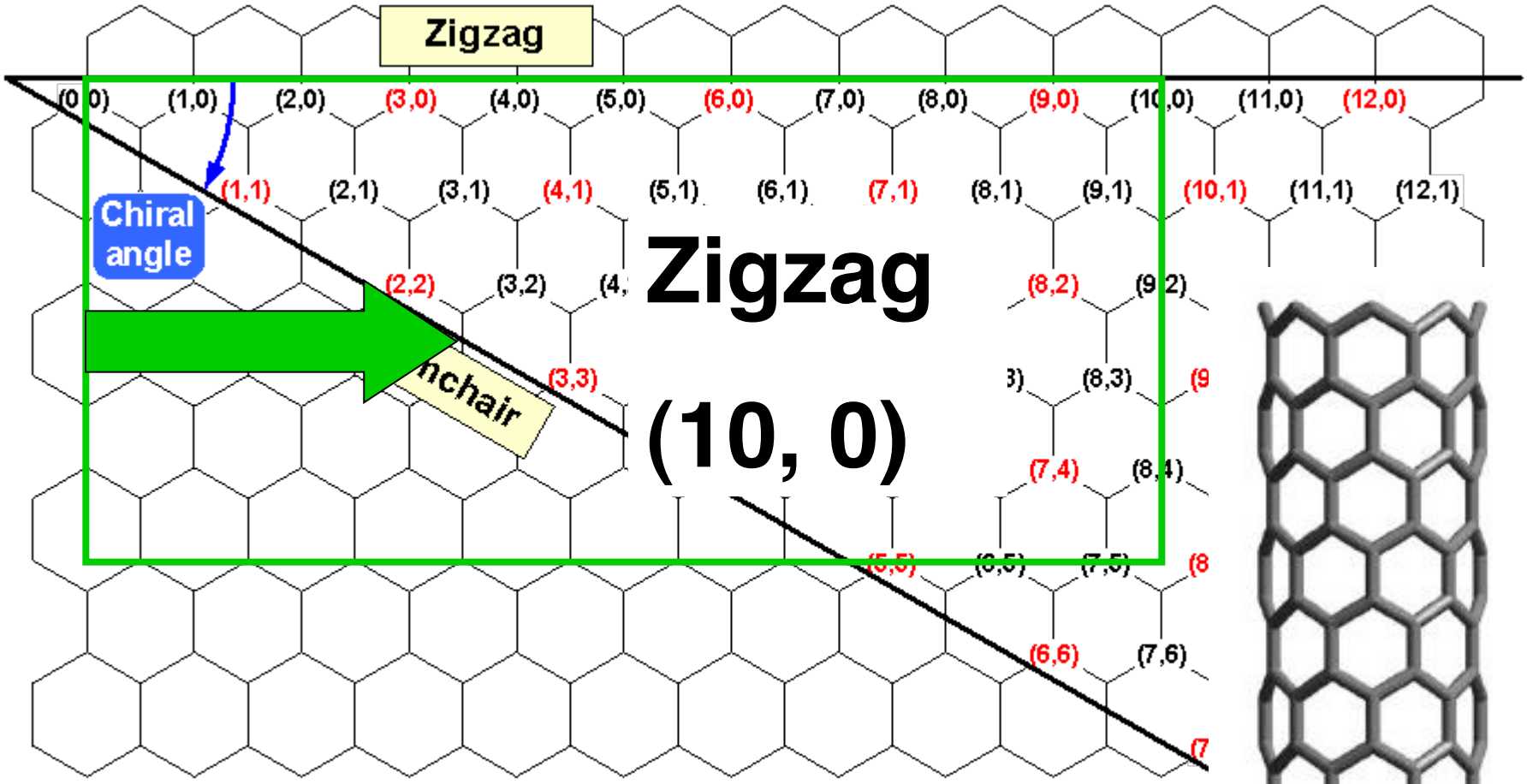

zigzag

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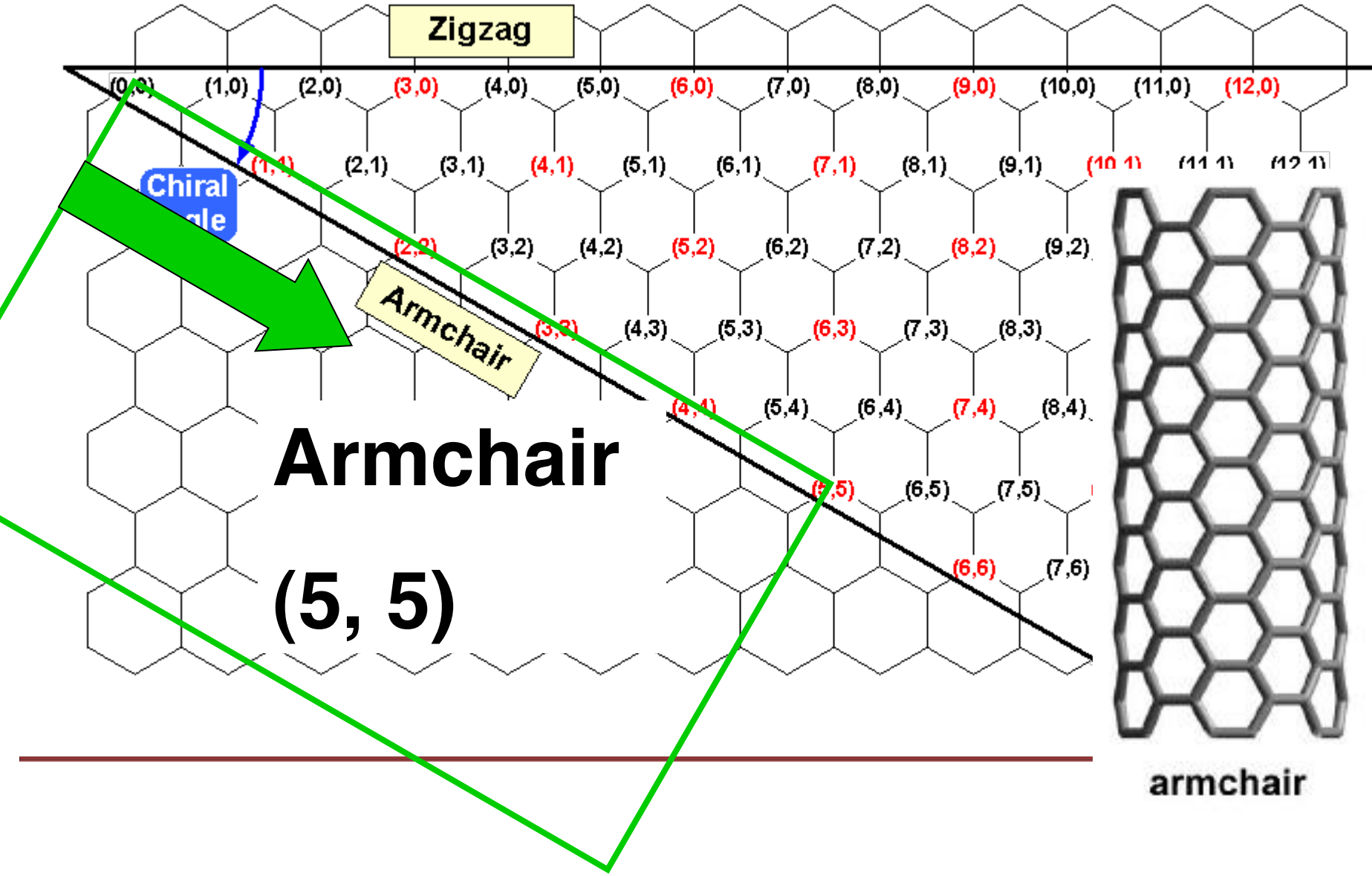

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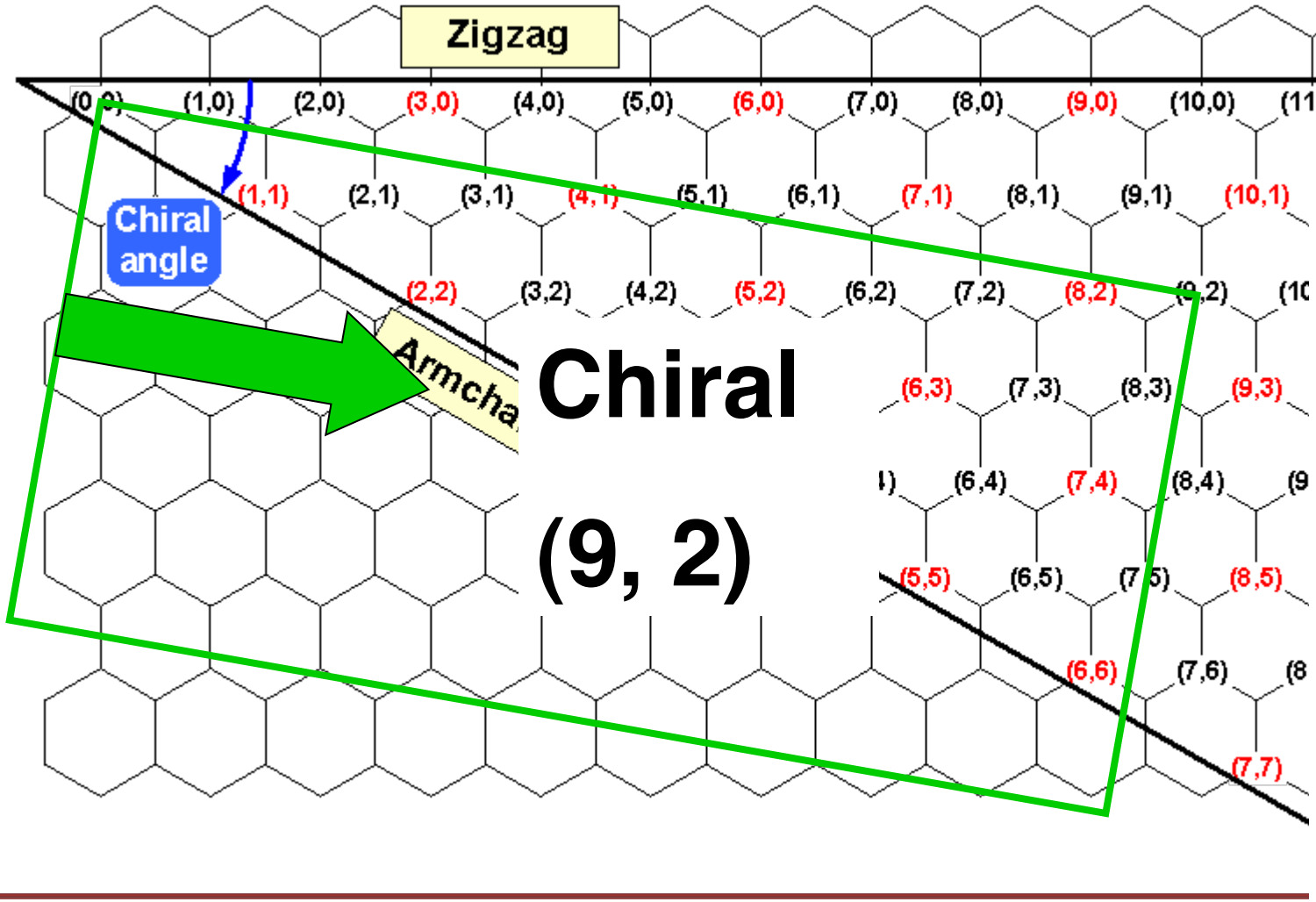
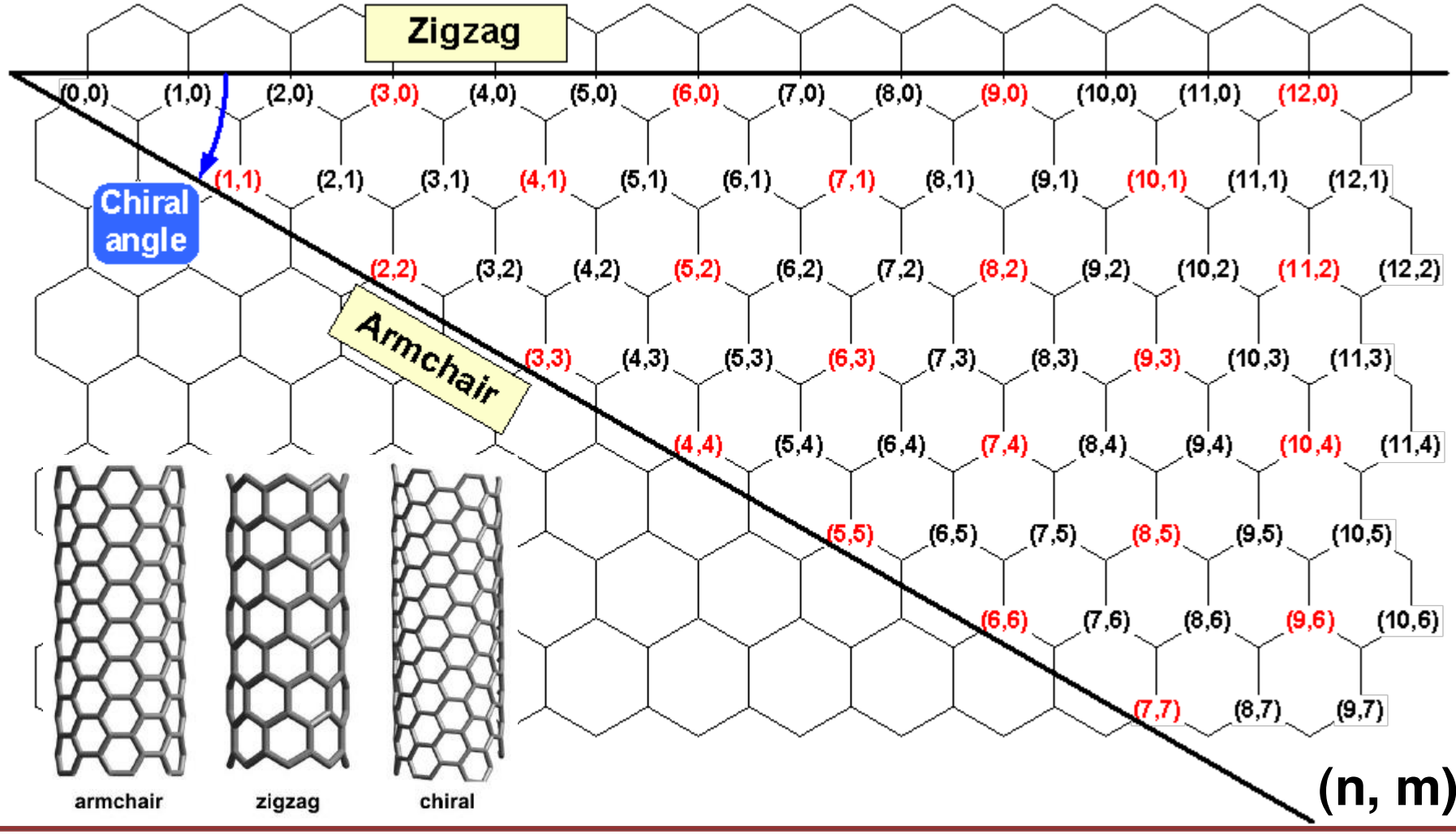
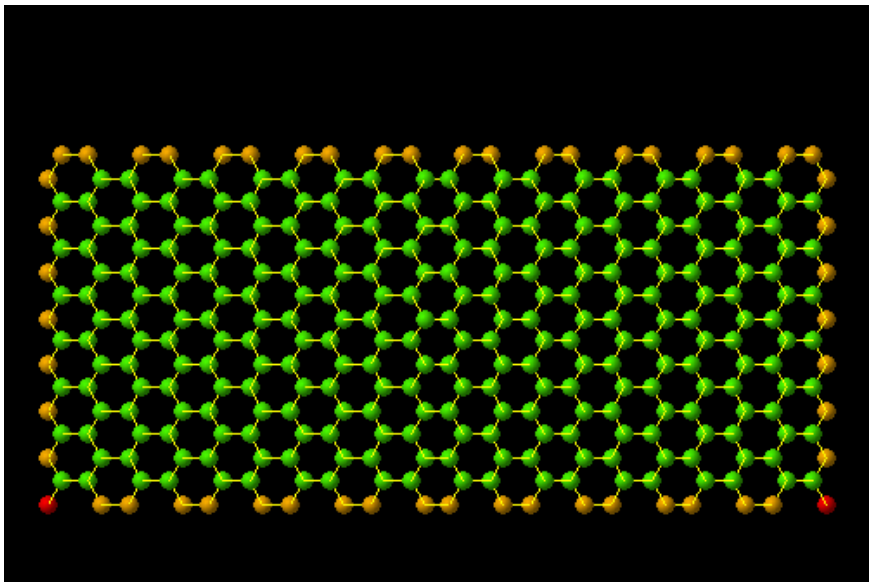


chiral

Construction of SWNTs from a Graphene Sheet



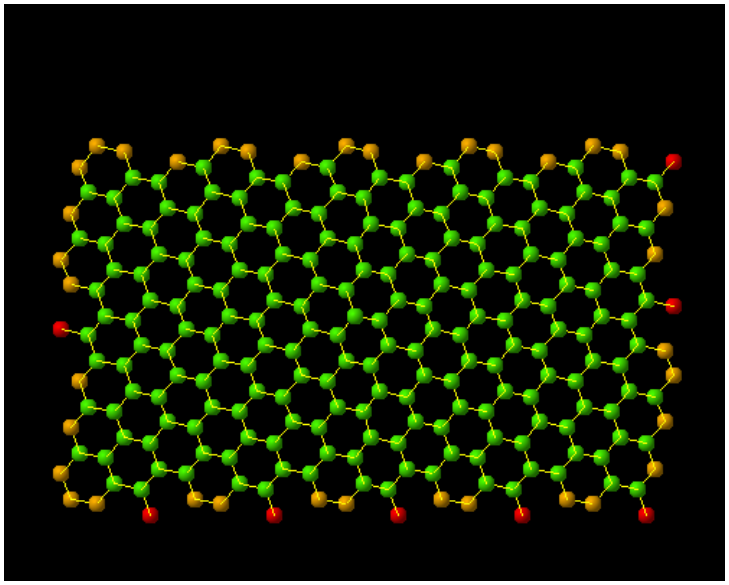
Metallic SWNT vs. Semiconducting SWNT



(n, m) = (10, 10)

$$mod(\frac{n-m}{3}) = 0$$

Metallic SWNT



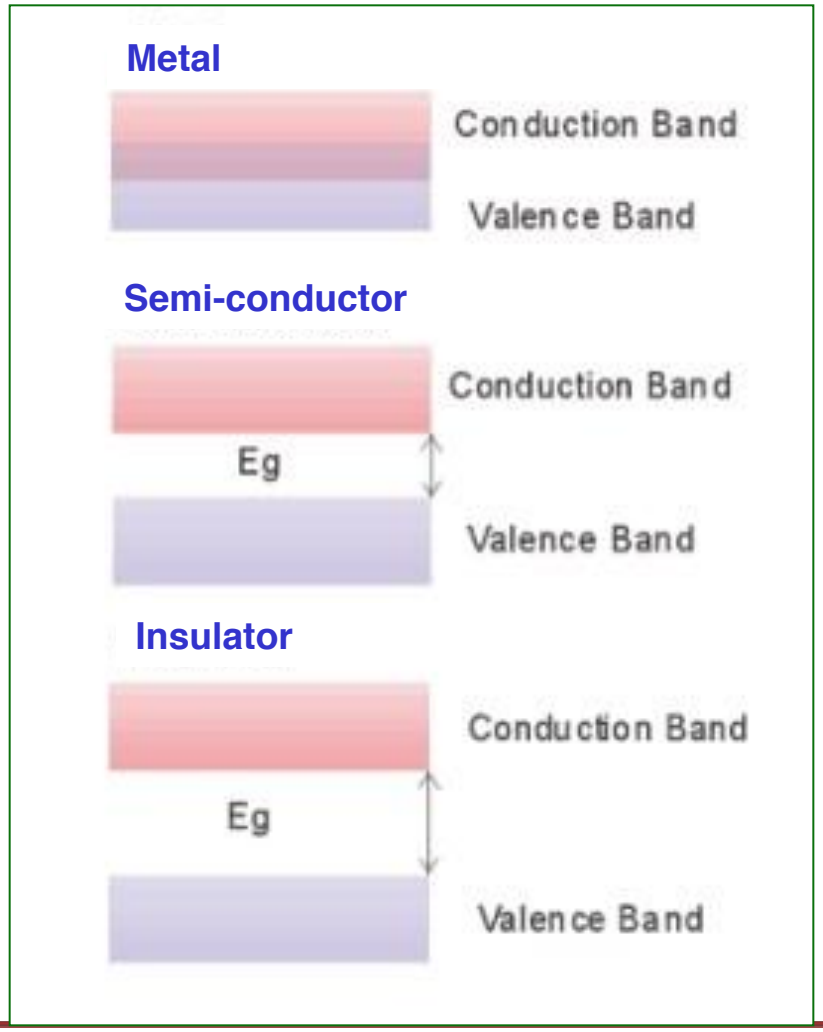
(n, m) = (10, 5)

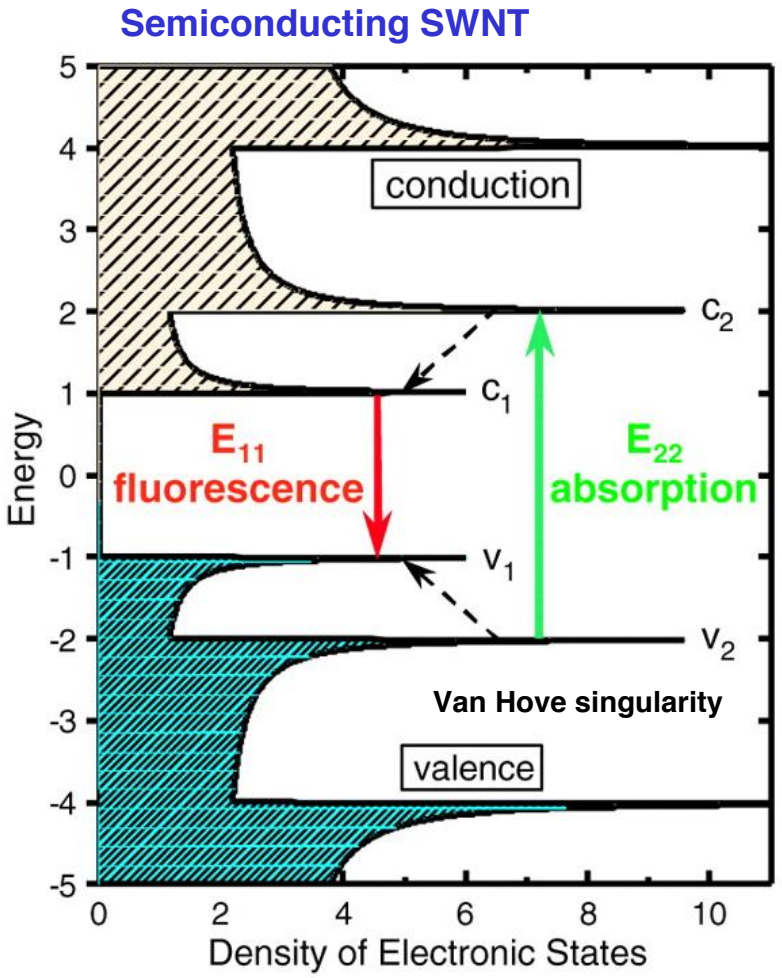
$$mod(\frac{n-m}{3}) = 2 \neq 0$$

Semiconducting SWNT

http://www.photon.t.u-tokyo.ac.jp/

Band Gap Theory





http://people.seas.harvard.edu/~jones/es154/lectures/lecture_2/energy_gap/energy_gap.html

Sergei M. Bachilo, etc. ***Science***, 2002, 298, 2361

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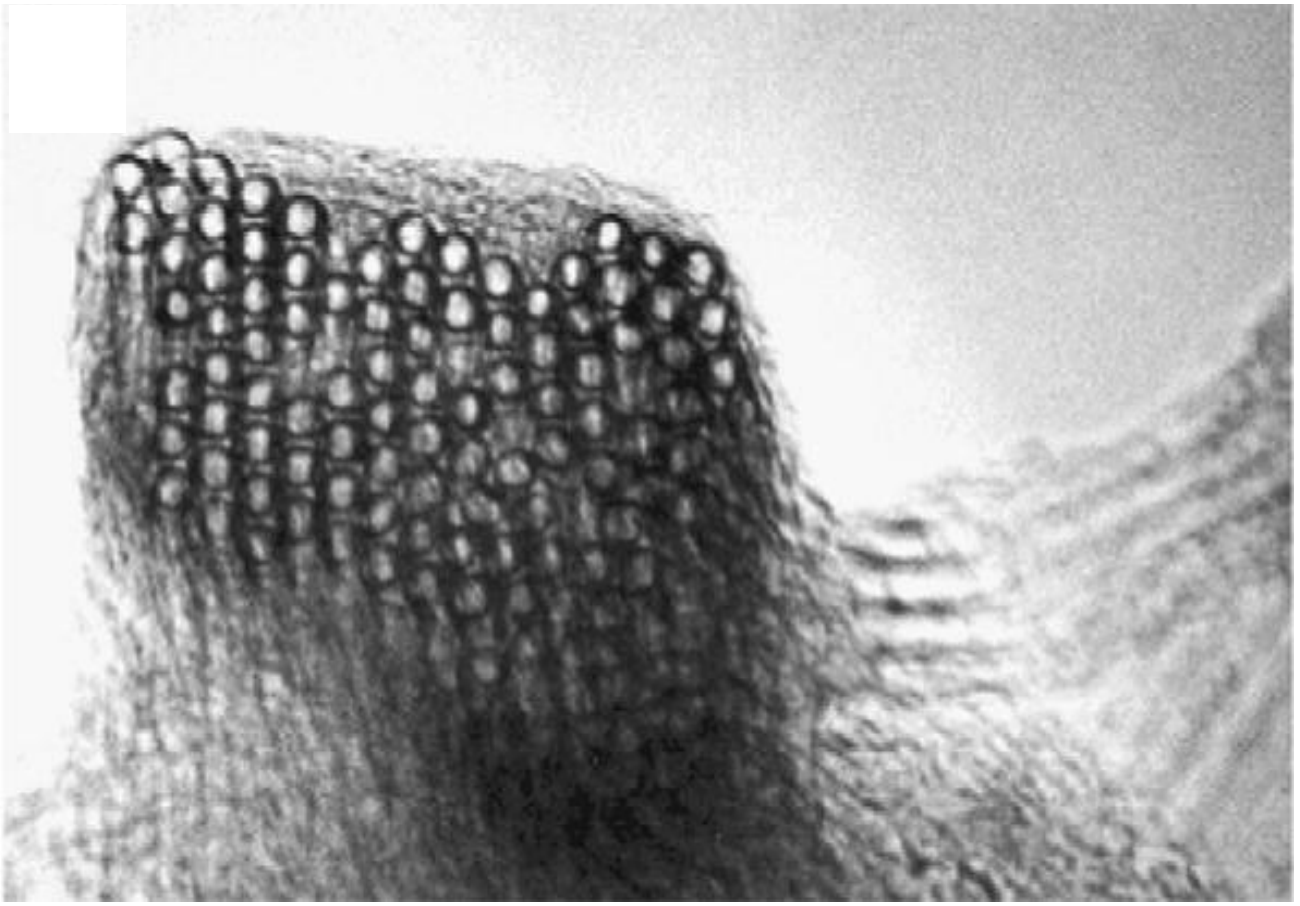
Conclusions

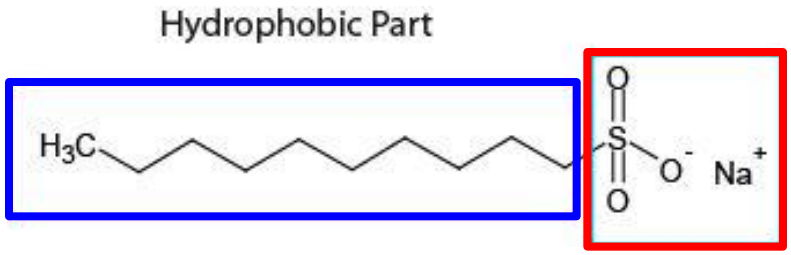
As-Synthesized Bundled SWNTs



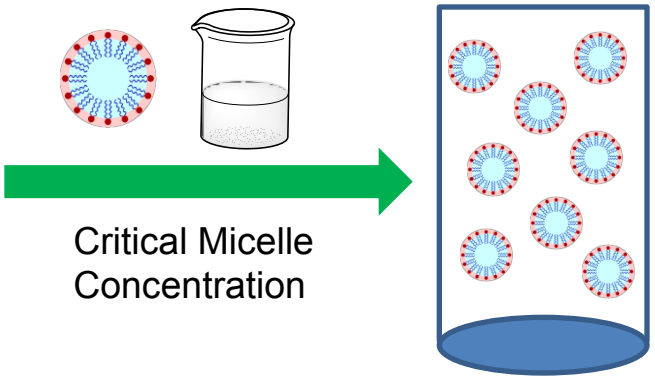
http://maju-indonesia-ku.forumotions.com/t31-bahan-dasar-pembuatan-wahana-siluman

Advances in Colloid and Interface Science 128–130 (2006) 37–46

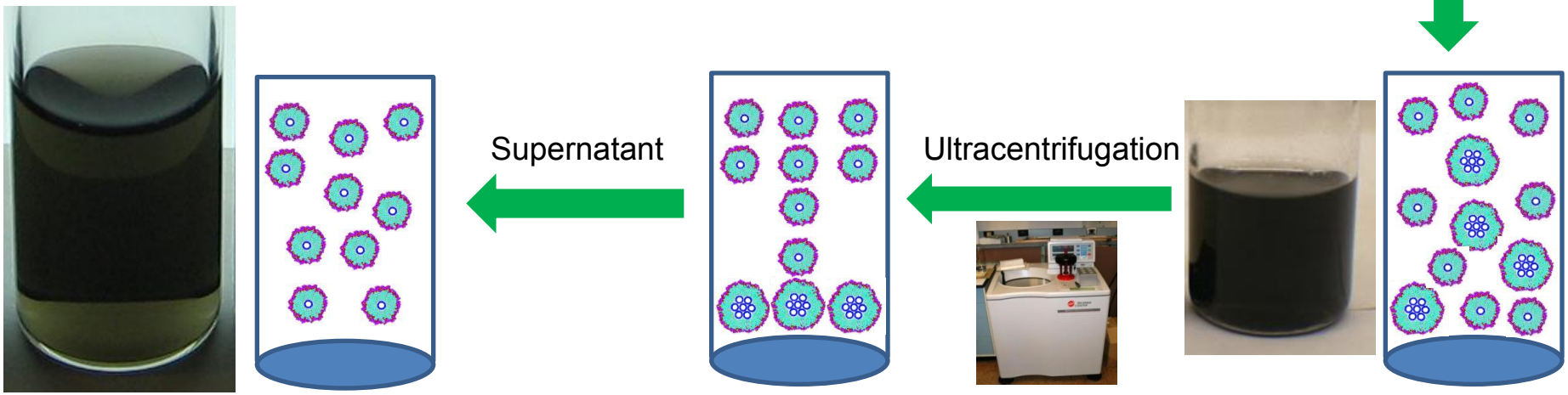
SWNT Solubilization in Water by Surfactants



Sodium dodecyl sulfate (SDS)

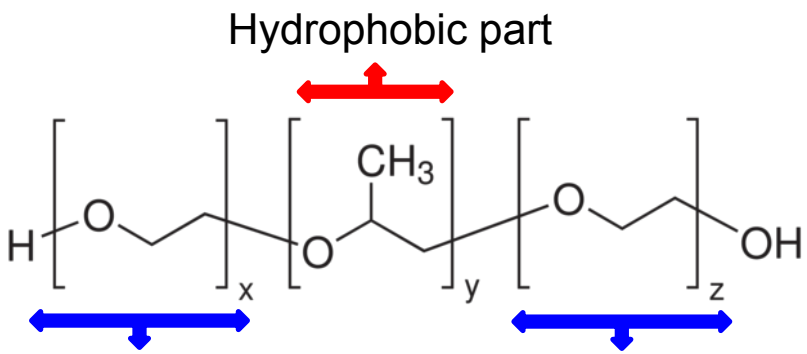


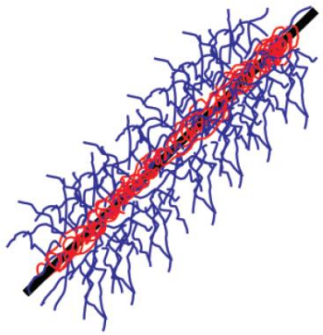
Sonication with SWNT



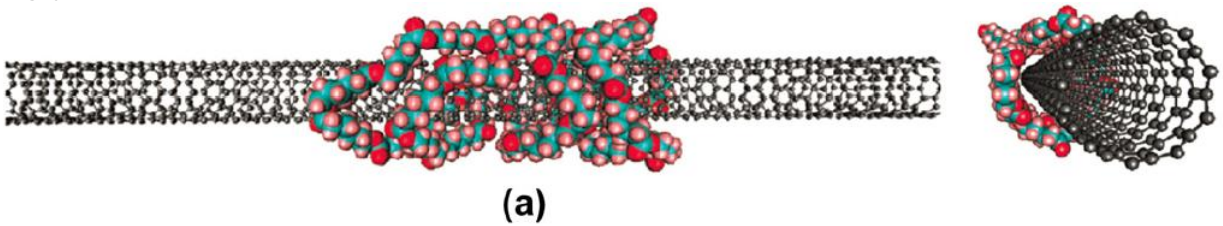
1. http://en.wikipedia.org/wiki/File:Micelle.png

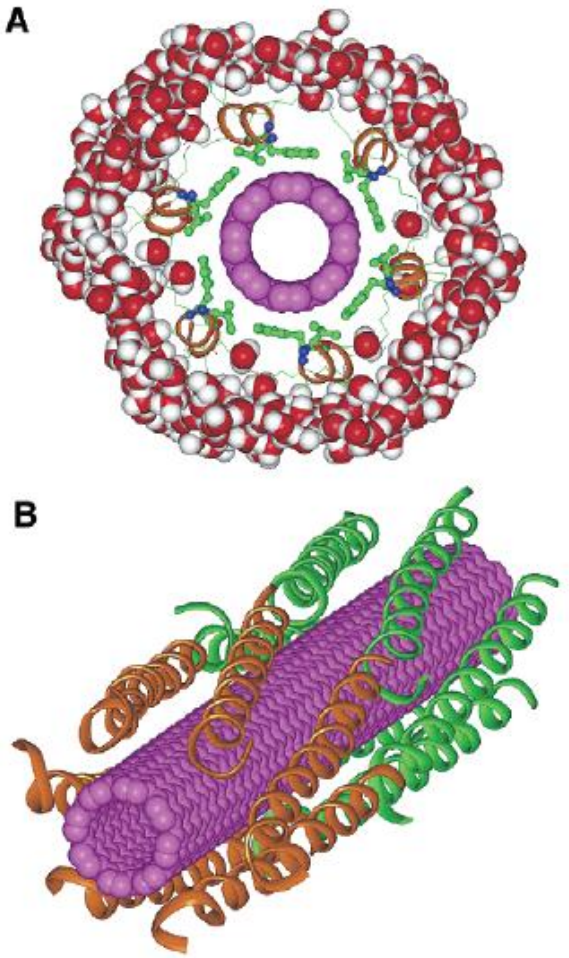
SWNT Solubilization in Water by Polymers





Poly(ethylene glycol)-block-poly(propylene glycol)-block-poly(ethylene glycol): **PEG-PPG-PEG**

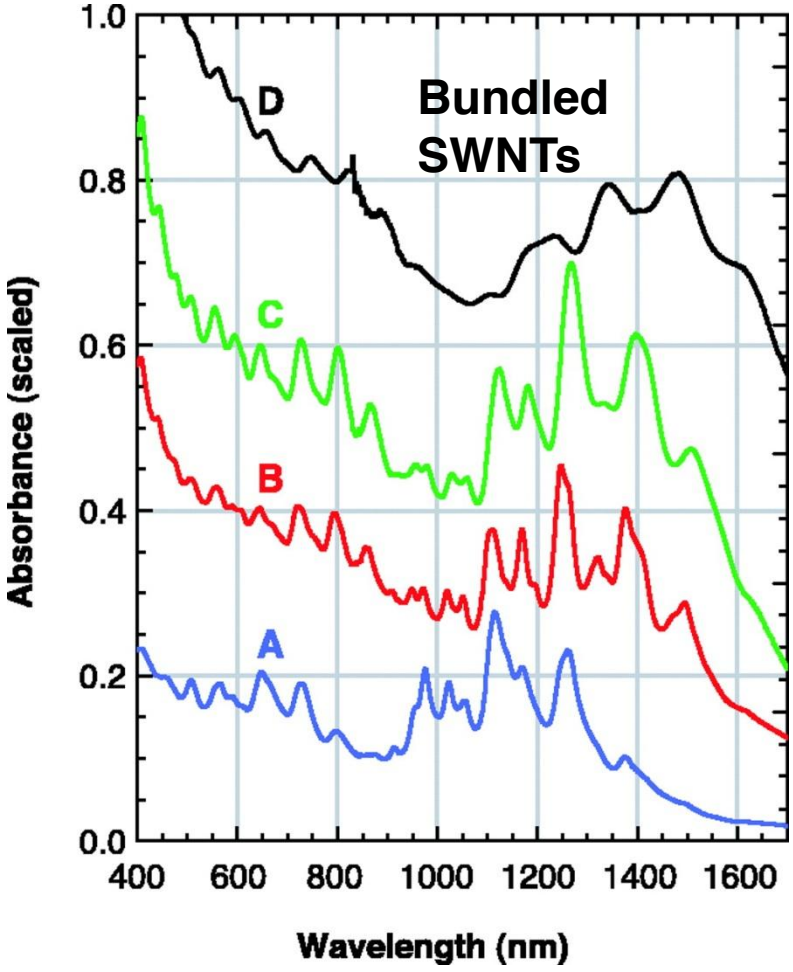


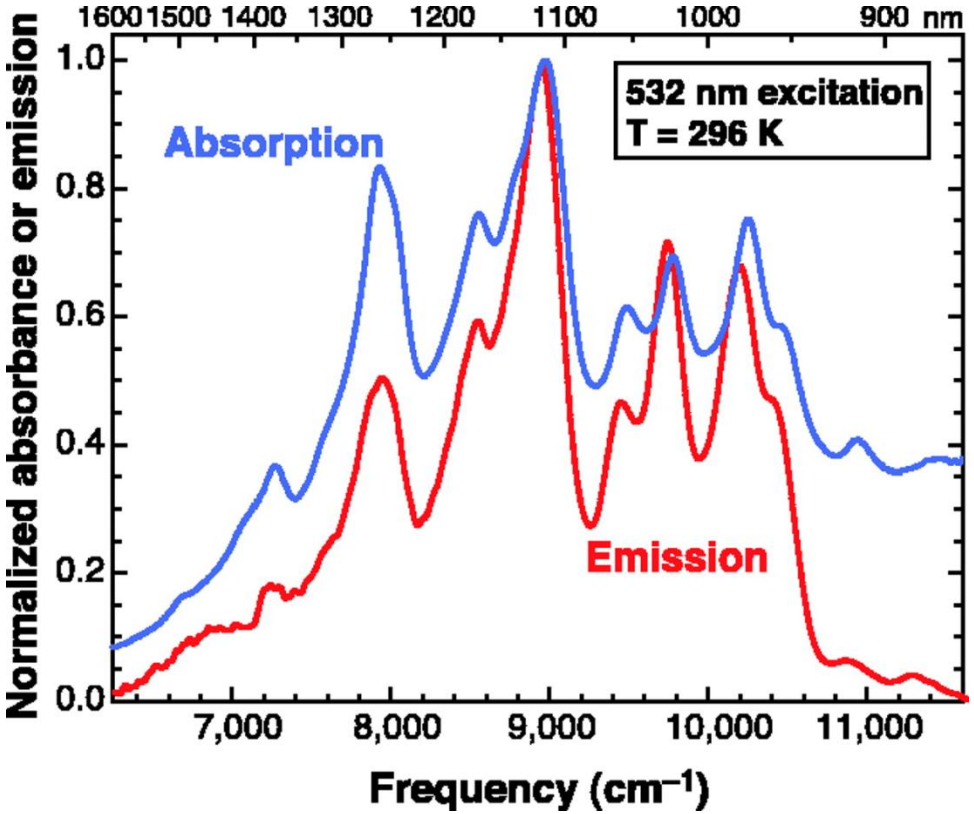


Peptides-SWNTs

Langmuir 2008, 24, 4625-4632; ***JACS***, 2003, 125, 1770 ; ***Composites Science and Technology***, 2011, 72, 72

UV-Visible Absorption and Fluorescence Emission Spectra of SWNTs





Consistent peak position from absorption and emission indicates that the major components are individual SWNTs.

Science 26 July 2002: Vol. 297 no. 5581 pp. 593-596

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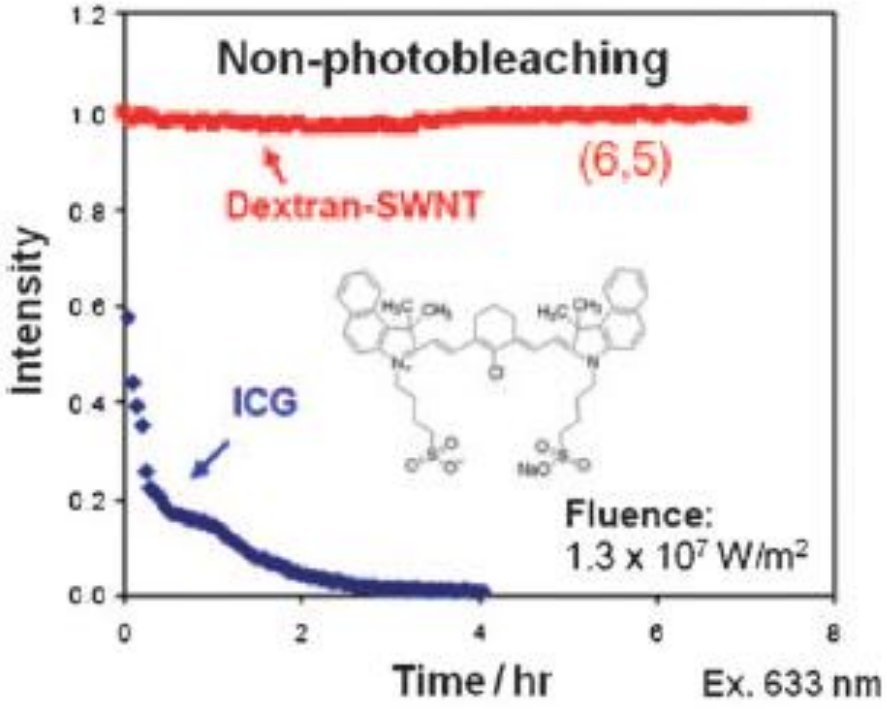
Advantages of Using SWNTs for Optical Sensing



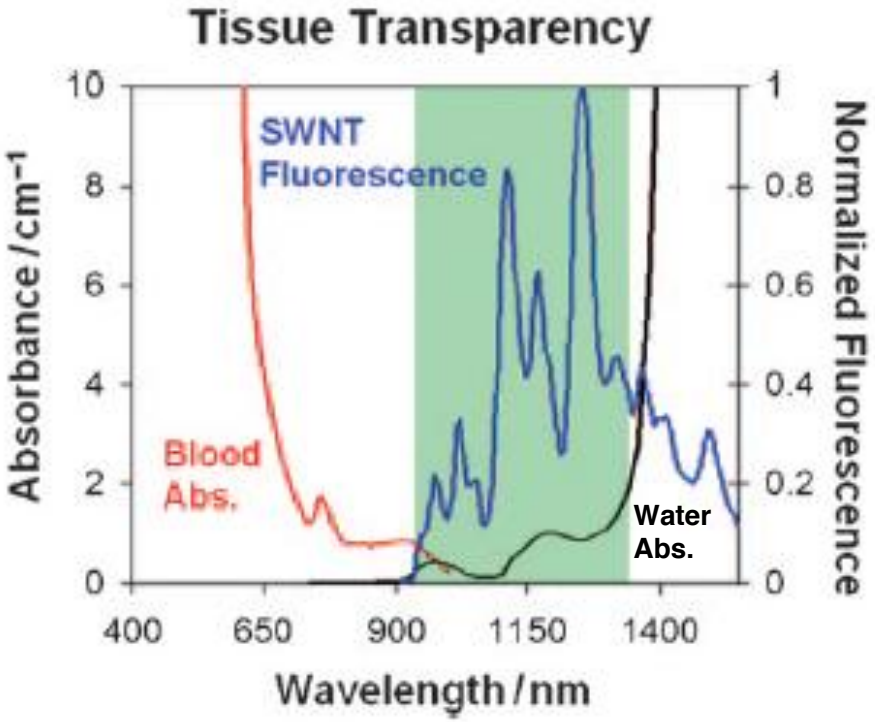


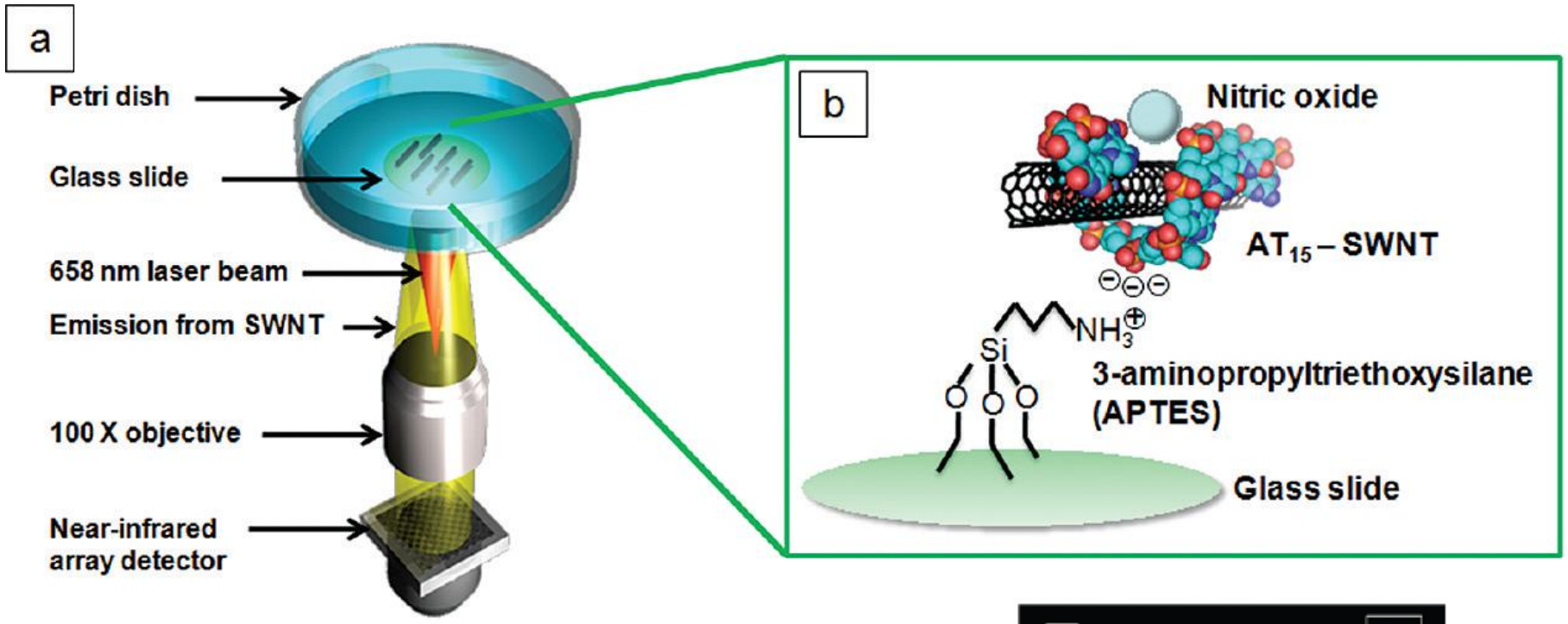
Table 1. Photobleaching tendency of common organic and nanoparticle fluorophores. Adapted from Ref. [19].

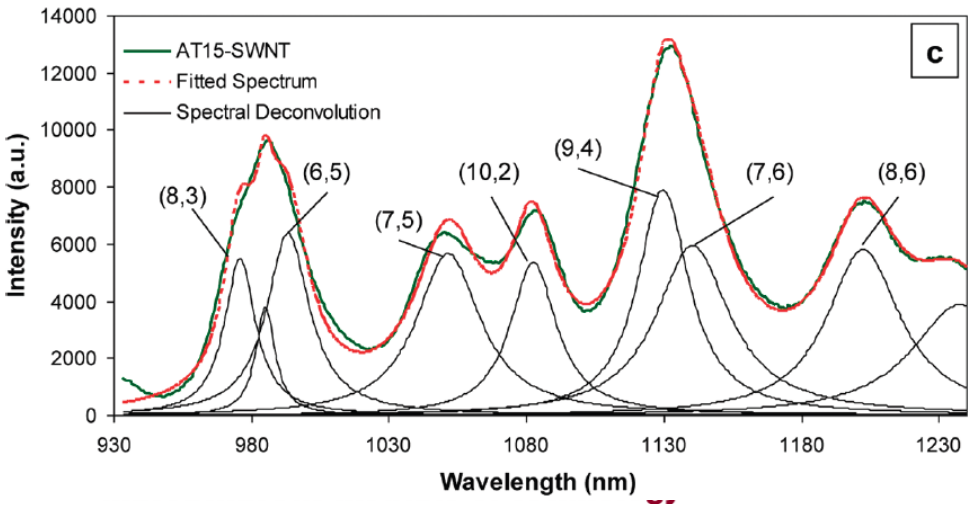
Material	Photobleaching rate constant [h^{-1}]	Fluence [$mW cm^{-2}$]	Nominal sensor lifetime
IR-Dye 78-CA[33]	250.92	600	3.2 s
Cy5[33]	20.52	600	39.1 s
Indocyanine Green[32]	0.0412	28	5.4 h
Type II NIR QD[33]	0.0827	600	2.7 h
SWCNT[1,22g]	0	1.0×10^6	∞

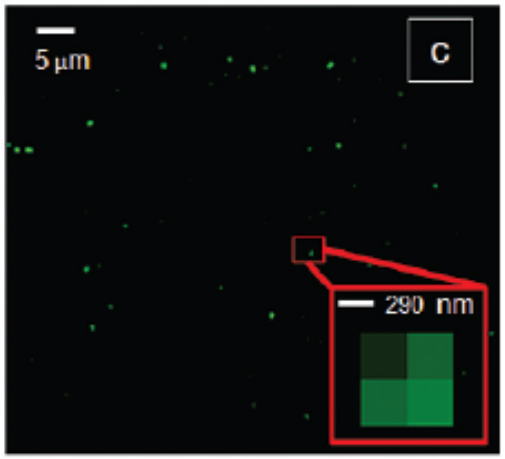
That is what we want!

ChemSusChem, 2011, 4, 848

nIR Fluorescence Sensor Based on SWNTs

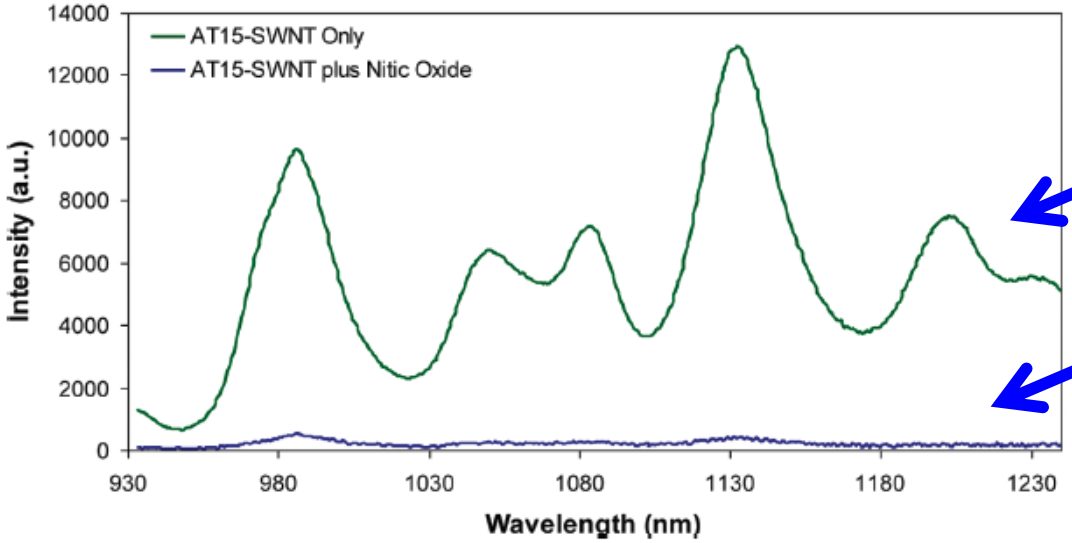






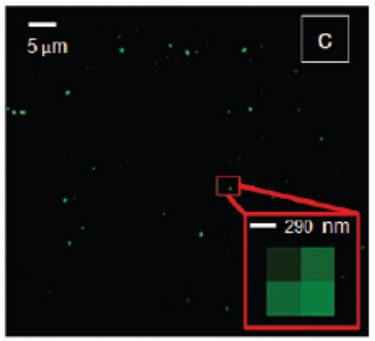
JACS, 2011, 133, 567

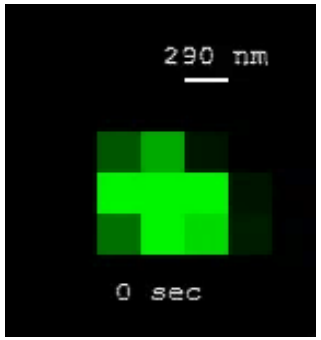
Nitric Oxide Recognition

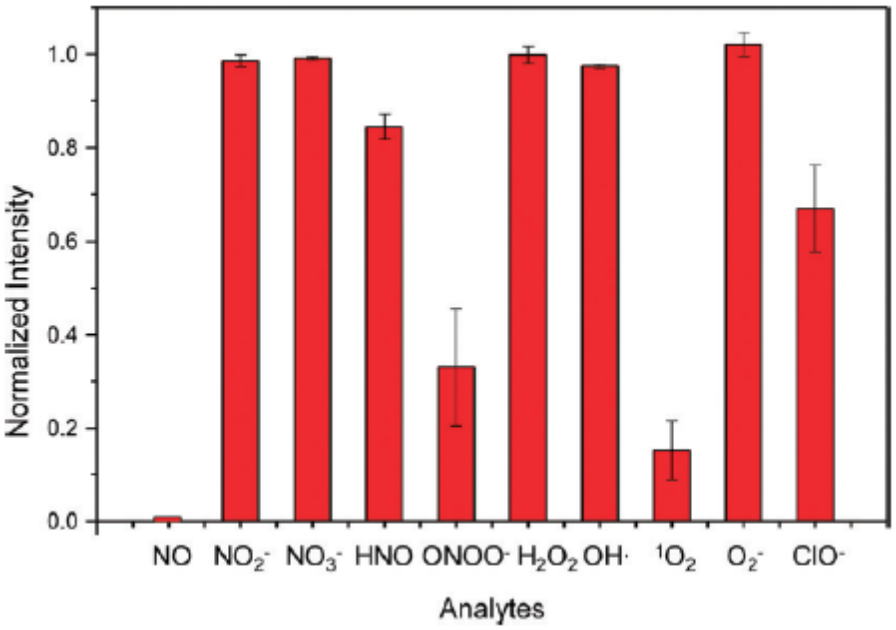


Near Infrared fluorescence spectra of SWNTs dispersed using AT15

After adding NO, fluorescence got quenched!



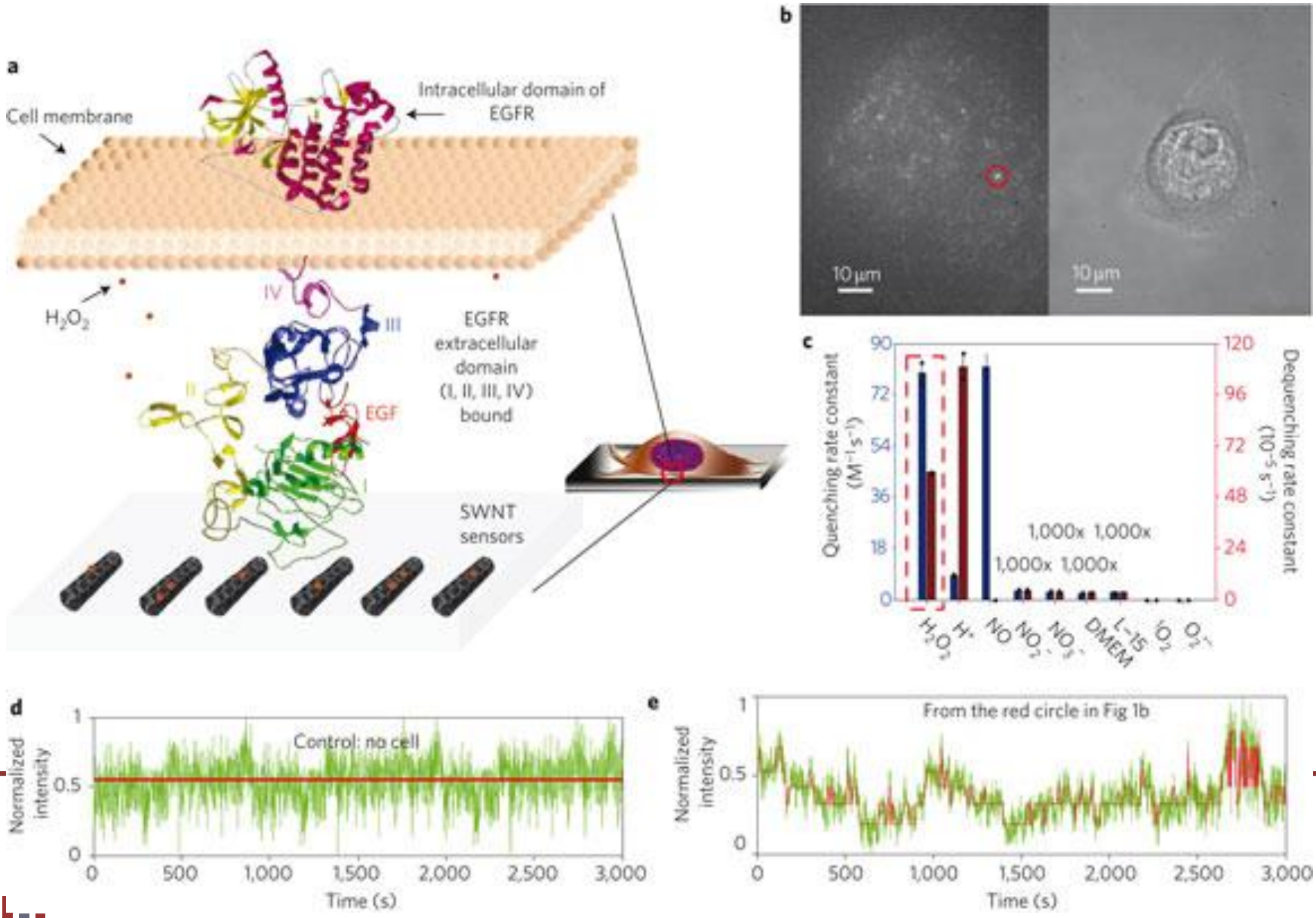




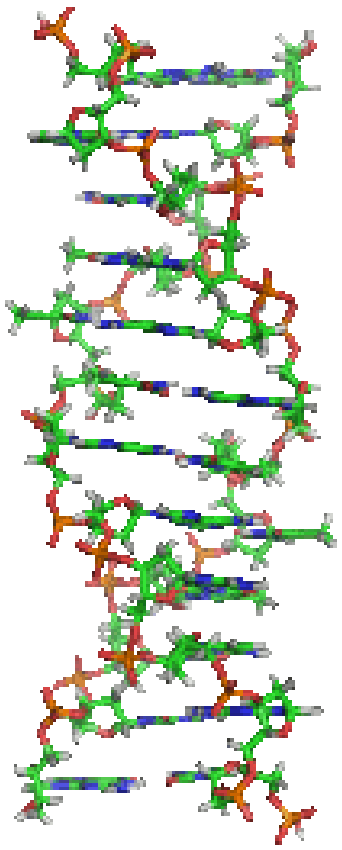
Selectivity measurement demonstrated that NO is the best quencher!

JACS, 2011, 133, 567

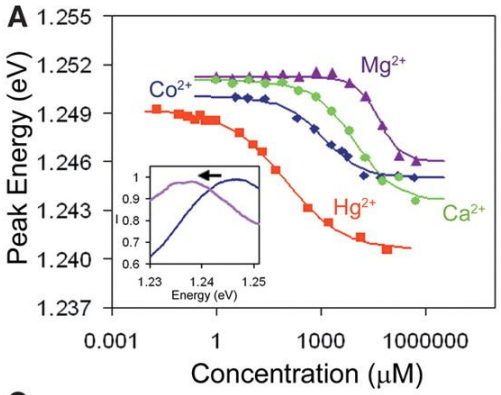
Hydrogen Peroxide Detection

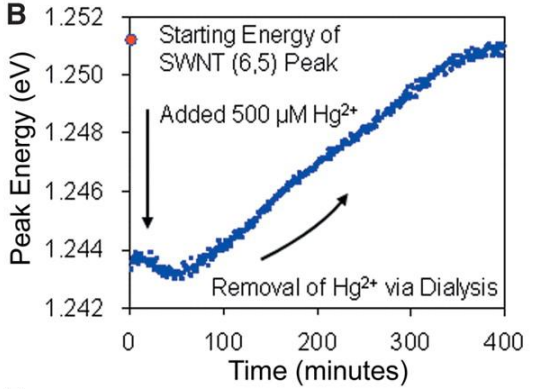


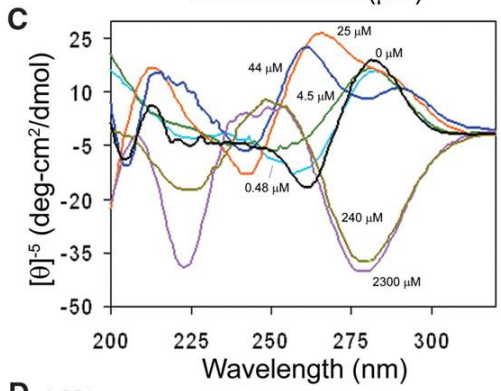
Detection of DNA Configuration

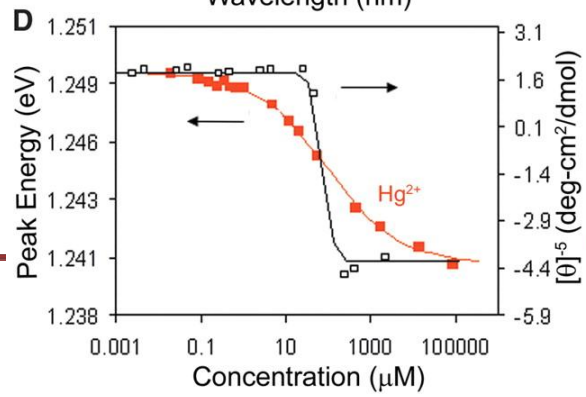


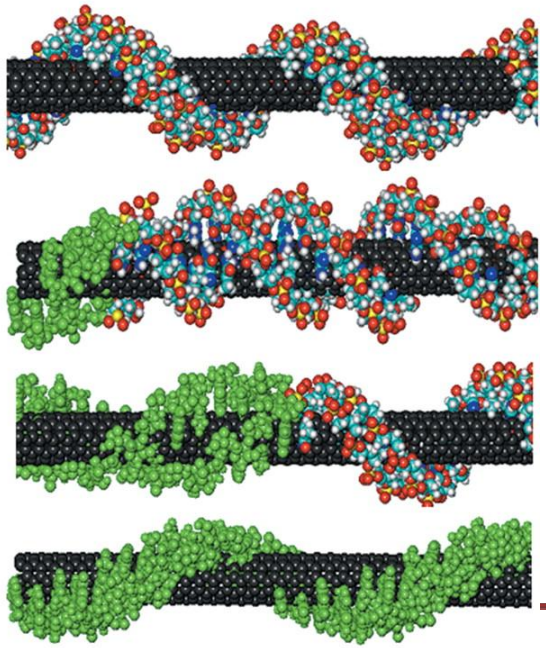
http://en.wikipedia.org/wiki/File:Z-DNA_orbit_animated_small.gif











Science, 2006: Vol. 311 no. 5760 pp. 508

Opportunity for Development of Glucose Sensor

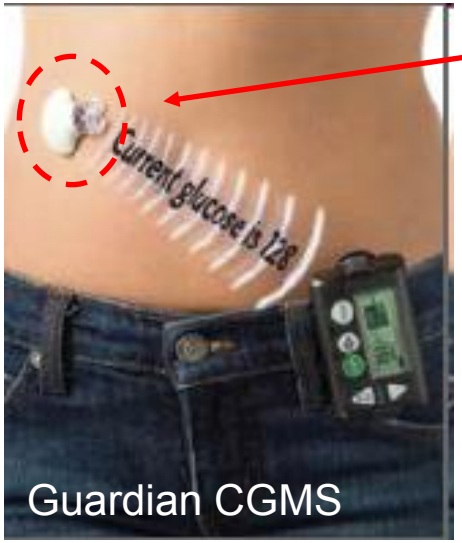
- **Diabetes Mellitus**
  - Affects *17.9 million people* in U.S (5-10% Type I).
  - *1.6 million new cases* are diagnosed each year
  - *7th leading cause of death* in 2010

- **Need**
  - Simple and reliable sensor for *real-time glucose detection* (< 10 min per measurement)
  - Help patients meet *targets in blood glucose* to reduce complications

Current State of the Art

Commercially Available Devices

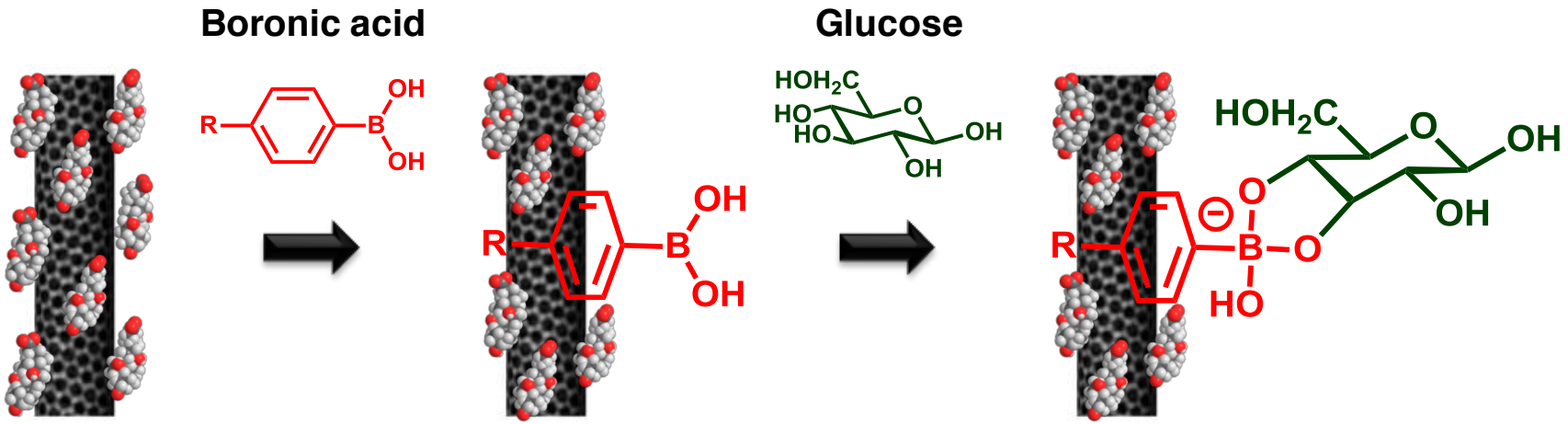
- MiniMed Guardian CGMS
- Dexcom SEVEN CGM
- Abott FreeStyle Navigator

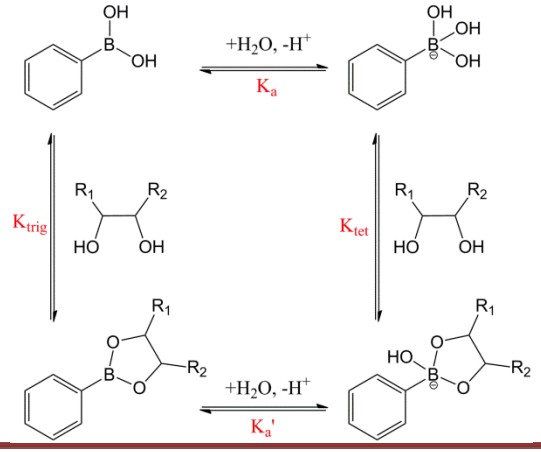


Disadvantages

- Sensor lifetime (3-7 days)
- Frequent calibration
- Open wound
- More susceptible to biofouling

Boronic Acid Based Sensor for Glucose Detection



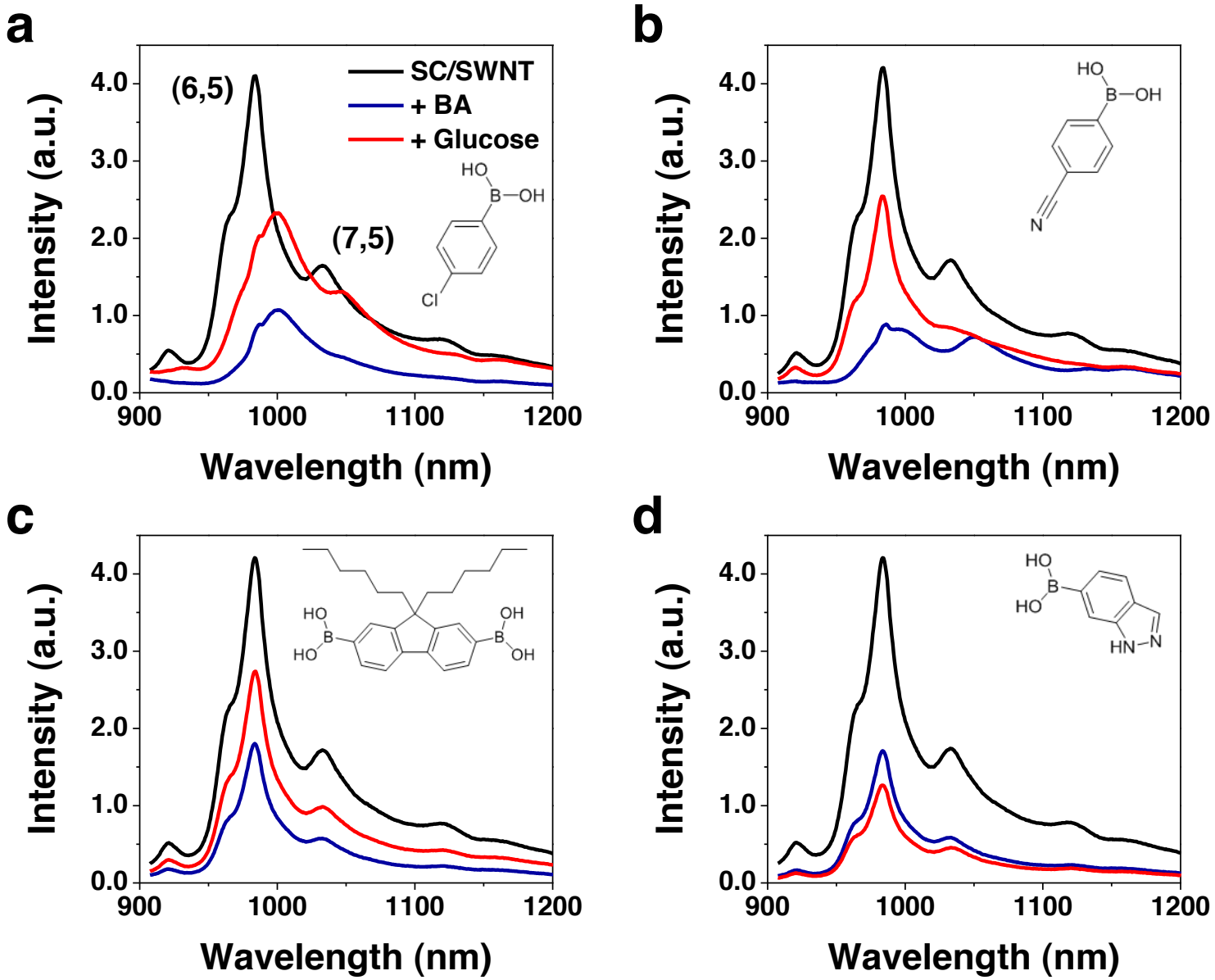


Basic Mechanism: Transduction of glucose binding to boronic acid on SWNT to SWNT fluorescence

Two Fluorescence Detection Signals:
Wavelength Shift (Δλ)
Intensity Change (ΔI)

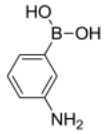
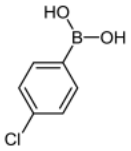
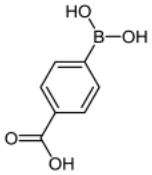
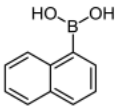
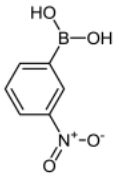
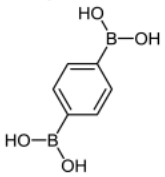
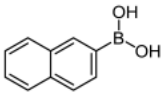
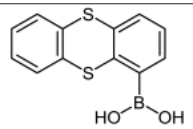
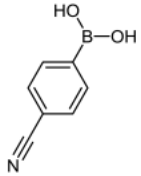
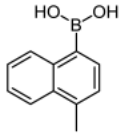
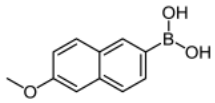
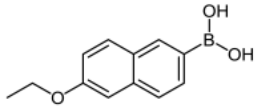
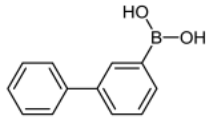
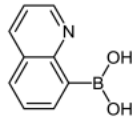
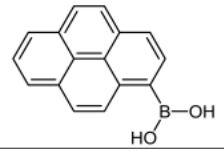
ACS Nano, 2012, 6, 819

Representative Responses

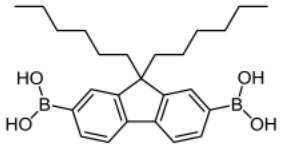
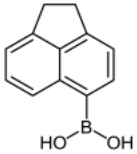
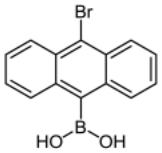
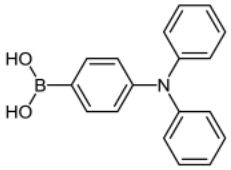
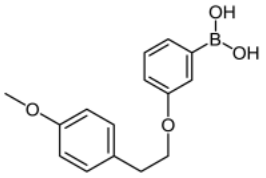
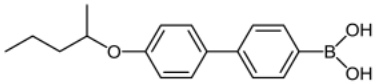
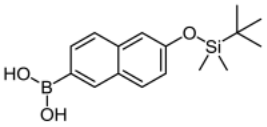


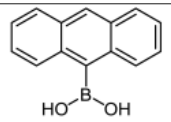
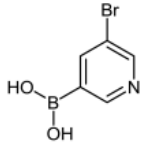
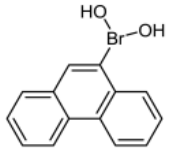
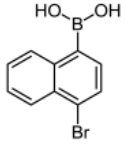
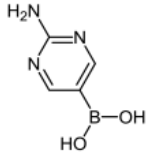
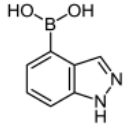
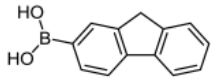
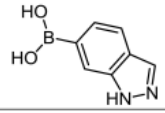
Screening of Boronic Acid Compounds

Table 1. Screening of boronic acid compounds

Entry	Boronic acid	Structure
BA01	3-Aminophenylboronic acid	
BA02	4-chlorophenylboronic acid	
BA03	4-carboxyphenylboronic acid	
BA04	Naphthalene-1-boronic acid	
BA05	3-Nitrophenylboronic acid	
BA06	Benzene-1,4-diboronic acid	
BA07	2-Naphthylboronic acid	
BA08	1-Thianthrenylboronic acid	
BA09	4-Cyanophenylboronic acid	
BA10	4-Methyl-1-naphthaleneboronic acid	
BA11	6-Methoxy-2-naphthaleneboronic acid	
BA12	6-Ethoxy-2-naphthaleneboronic acid	
BA13	3-Biphenylboronic acid	
BA14	8-Quinolinylboronic acid	
BA15	Pyrene-1-boronic acid	

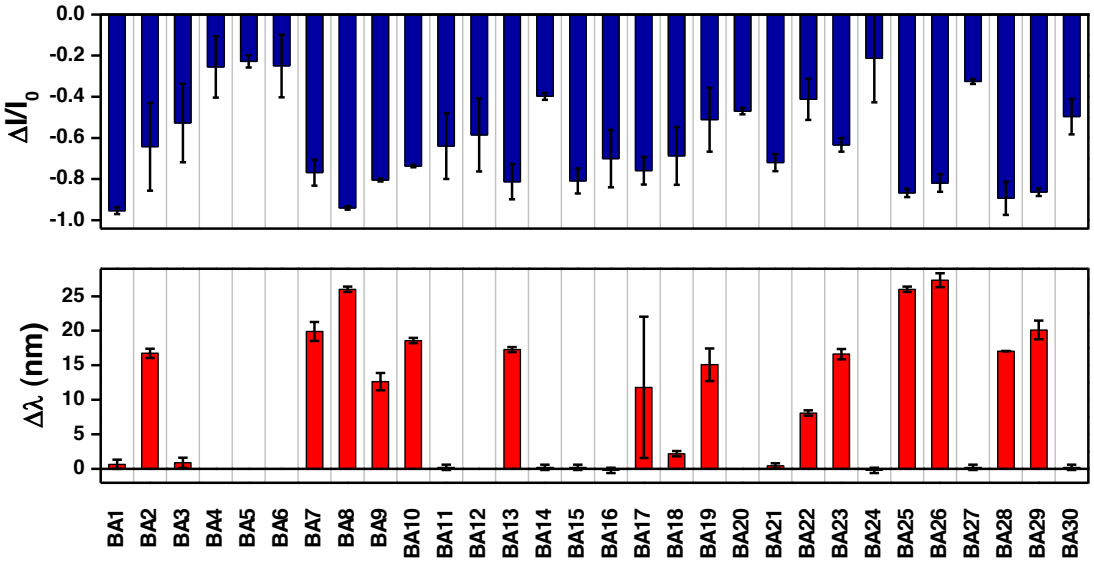
Screening of Boronic Acid Compounds

BA16	9,9-Dihexylfluorene-2,7-diboronic acid	
BA17	Acenaphthene-5-boronic acid	
BA18	10-Bromoanthracene-9-boronic acid	
BA19	4-(Diphenylamino)phenylboronic acid	
BA20	4-(4′-Methoxybenzyloxy)phenylboronic acid	
BA21	4-(4′-(2-Pentyloxy)phenyl)phenylboronic acid	
BA22	2-(tert-Butyldimethylsilyloxy)naphthalene-6-boronic acid	

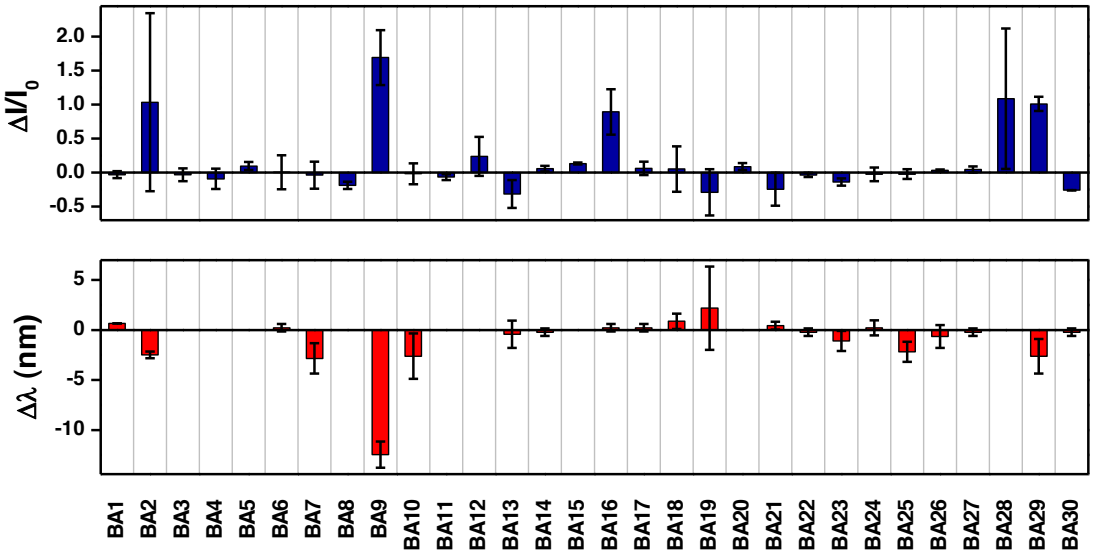
BA23	9-Anthraceneboronic acid	
BA24	5-Bromopyridine-3-boronic acid	
BA25	9-Phenanthracenylboronic acid	
BA26	4-Bromo-1-naphthaleneboronic acid	
BA27	2-Aminopyrimidine-5-boronic acid	
BA28	Indazole-4-boronic acid hydrochloride	
BA29	Fluorene-2-boronic acid	
BA30	Indazole-6-boronic acid	

Screening Results

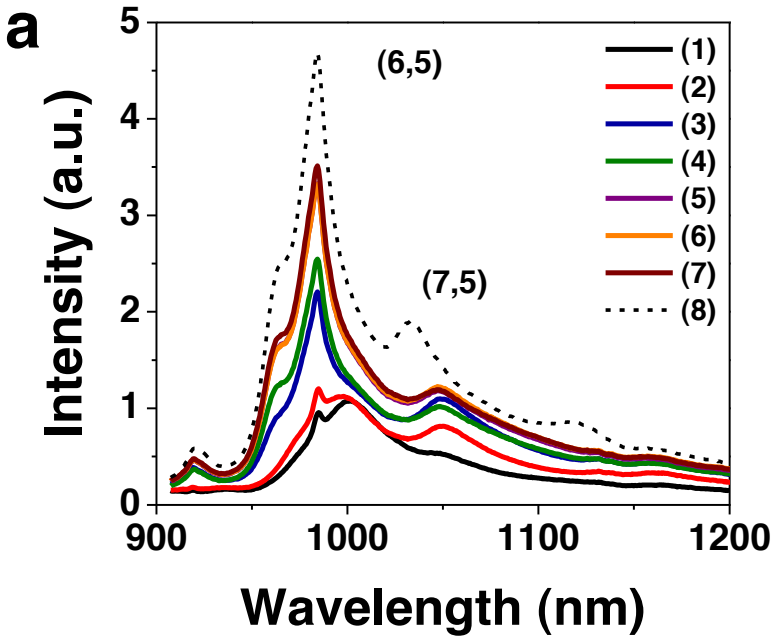
1. Addition of BA to SC/SWNT



2. Addition of glucose to BA + SC/SWNT



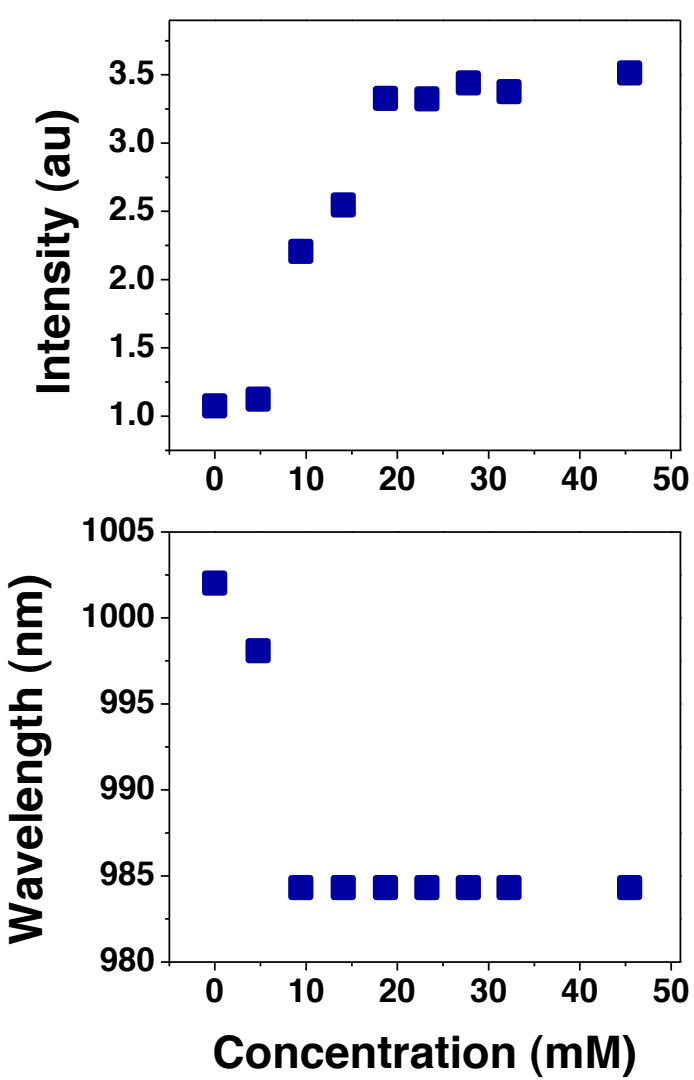
Concentration Curve of Glucose Response (BA9)



Fluorescence recovery of the quenched BA–SWNT complex in the presence of glucose:

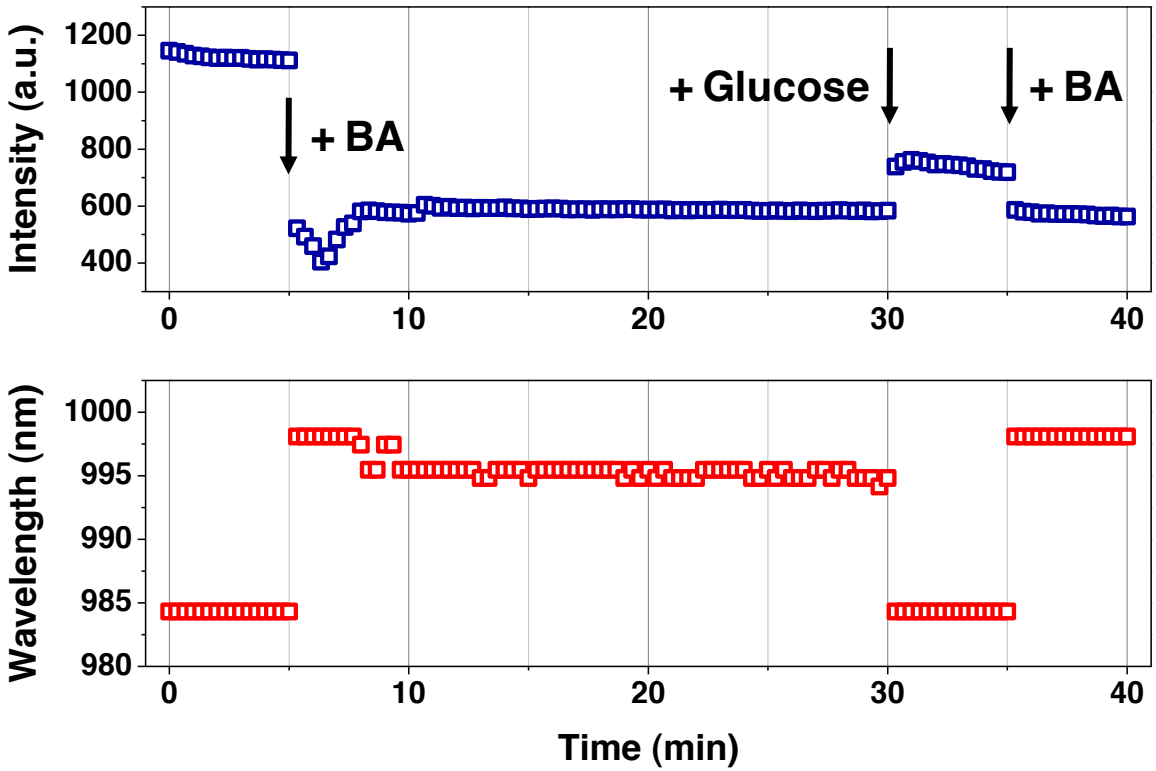
(1) Starting BA–SWNT complex of 4-cyanophenylboronic acid (BA9) and the addition of glucose of 4.7 mM (2), 9.4 mM (3), 14.1 mM (4), 18.7 mM (5), 23.3 mM (6), and 45.5 mM (7).

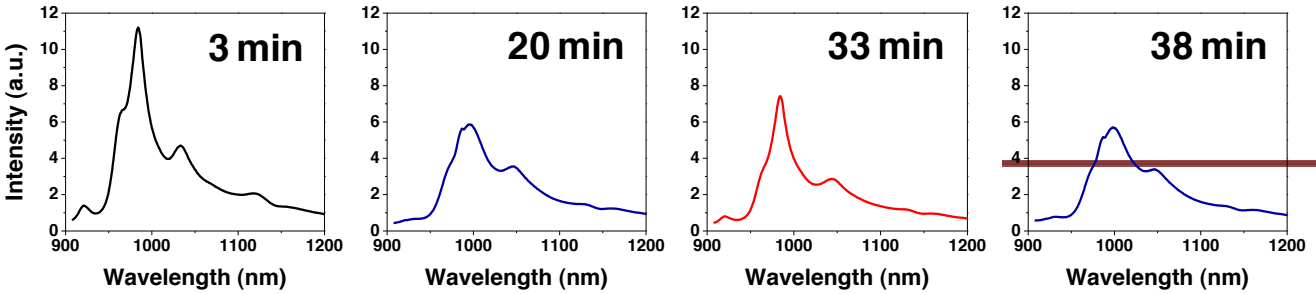
* The dashed black line (8): the original spectrum of SC/SWNTs.



Fluorescence intensity and emission wavelength as a function of glucose concentration.

Rapid, Reversible Dynamic Modulation

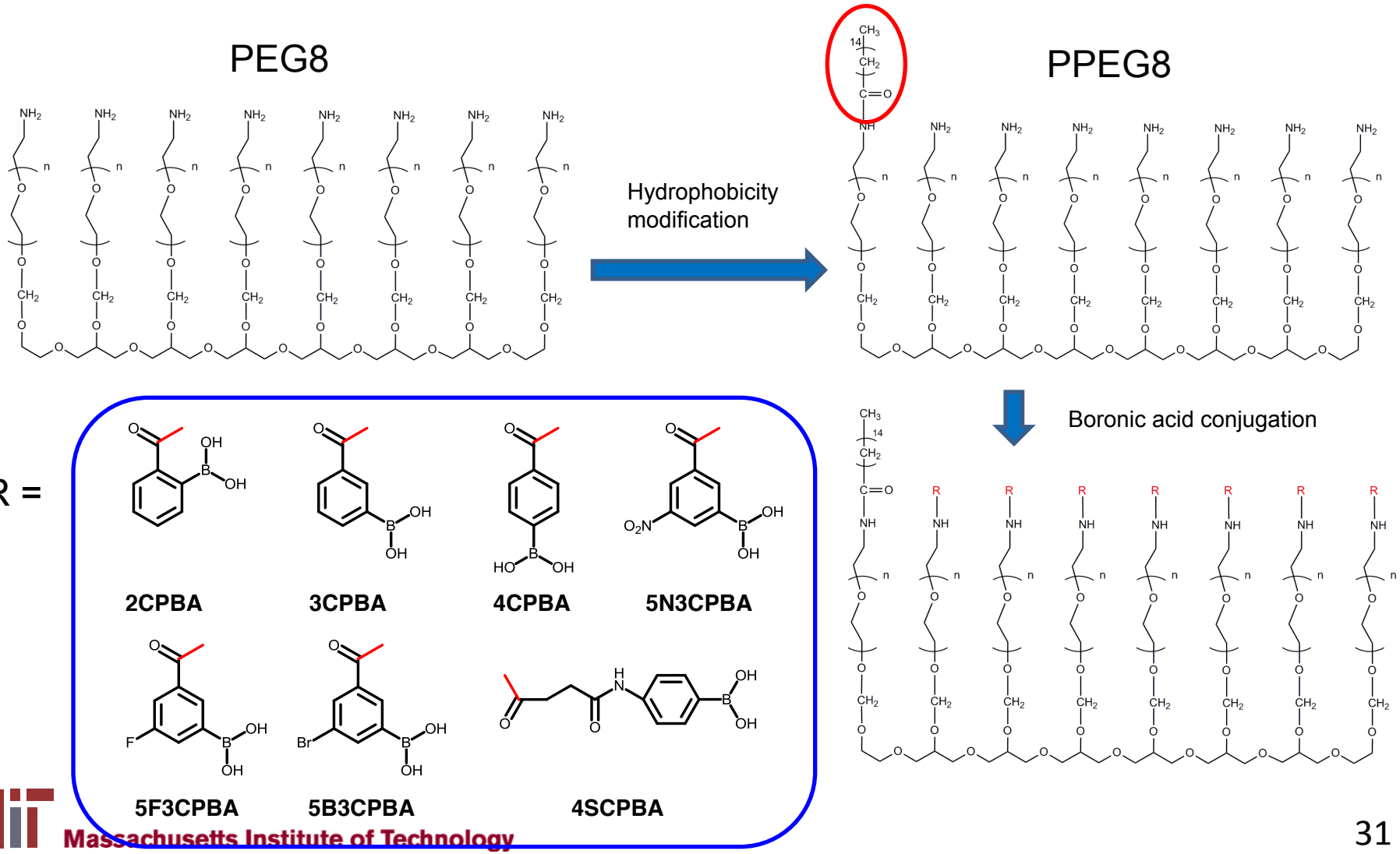




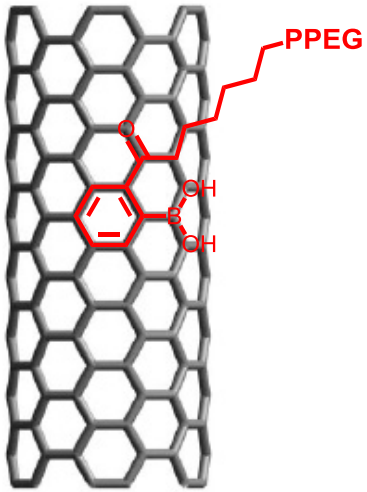
* Fast binding and unbinding kinetics of glucose sensing

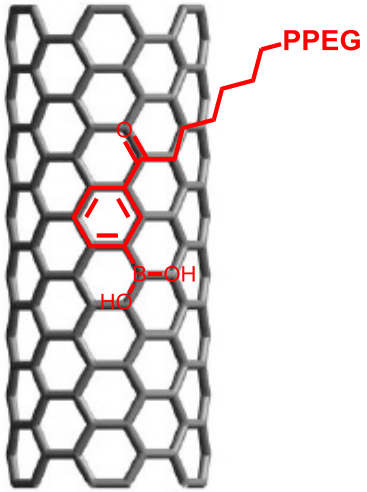
Polymer Synthesis System: Boronic Acid Conjugated Polymers

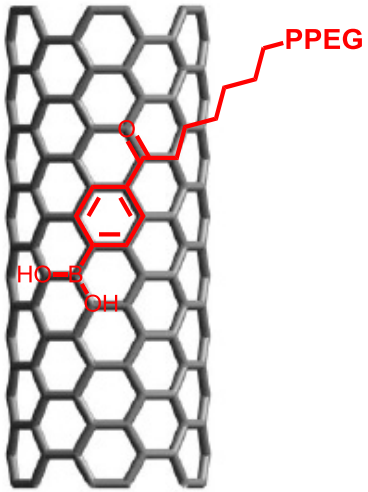
- Molecular structure of PEG8 modified polymers

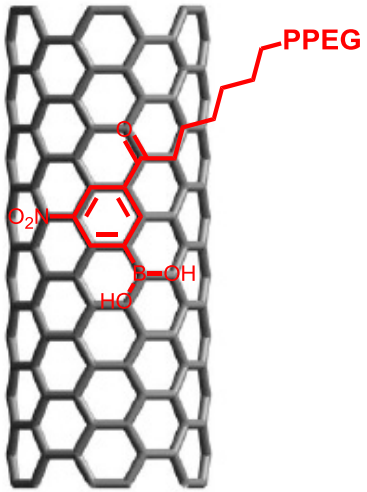


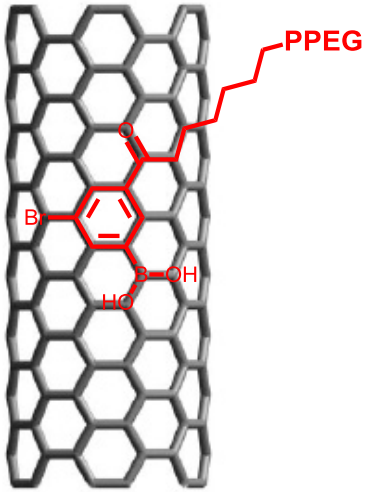
Proposed Wrapping Geometry of Boronic Acids on SWNT

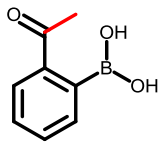




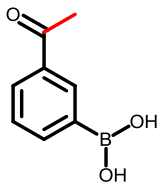




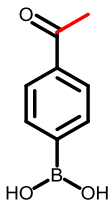




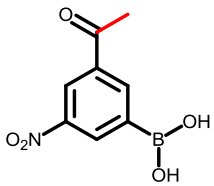
2CPBA



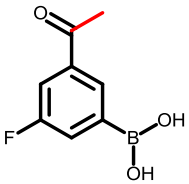
3CPBA



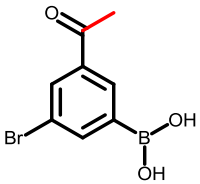
4CPBA



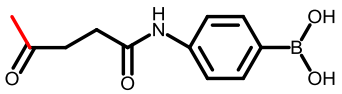
5N3CPBA



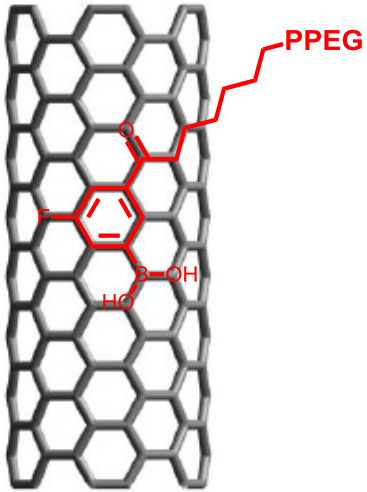
5F3CPBA

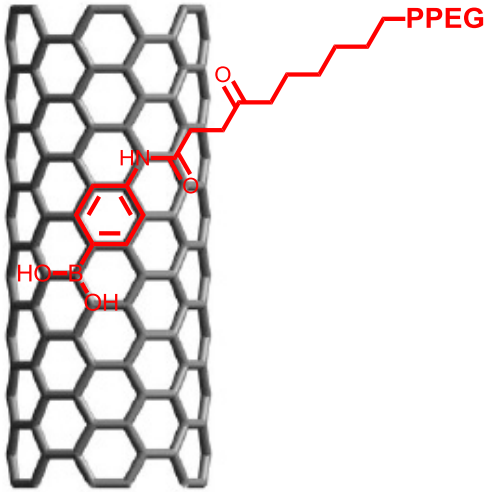


5B3CPBA



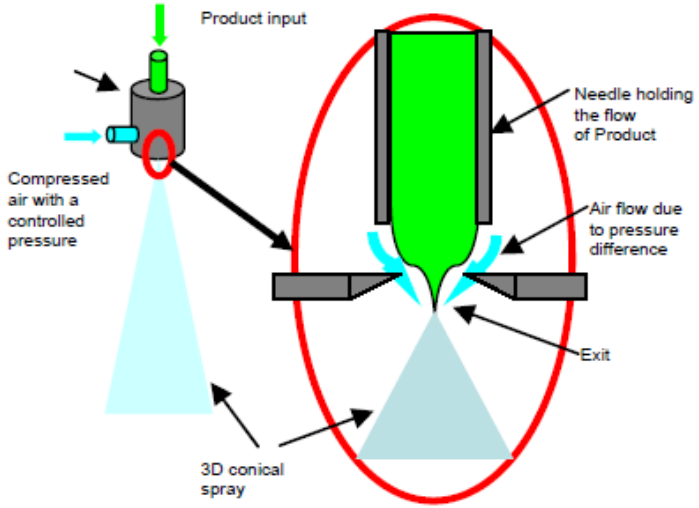
4SCPBA





Encapsulator for Making Hydrogel Bead

Working Principle: Aerodynamic Jetting



Flow Focusing: A Versatile Technology to Produce Size-Controlled and Specific-Morphology Microparticles**

*Lucía Martín-Banderas, María Flores-Mosquera, Pascual Riesco-Chueca, Alfonso Rodríguez-Gil, Ángel Cebolla, Sebastián Chávez, and Alfonso M. Gañán-Calvo**

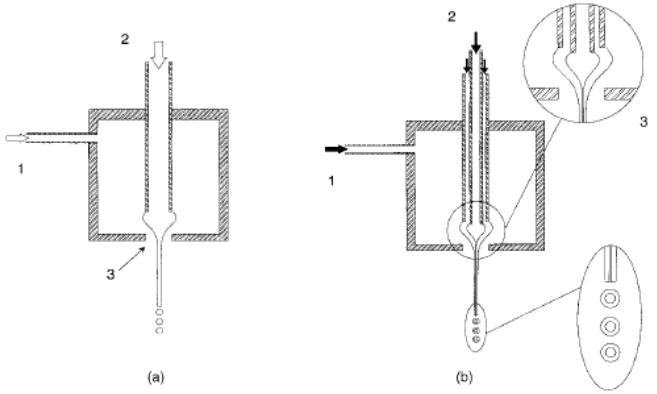


Figure 1. Flow-focusing atomizer. a) Simple jet: 1) focusing fluid, 2) focused fluid, 3) meniscus; b) compound atomizer with two concentric needles: 1) focusing fluid, 2) focused fluids: core fluid and shell fluid, 3) compound meniscus.

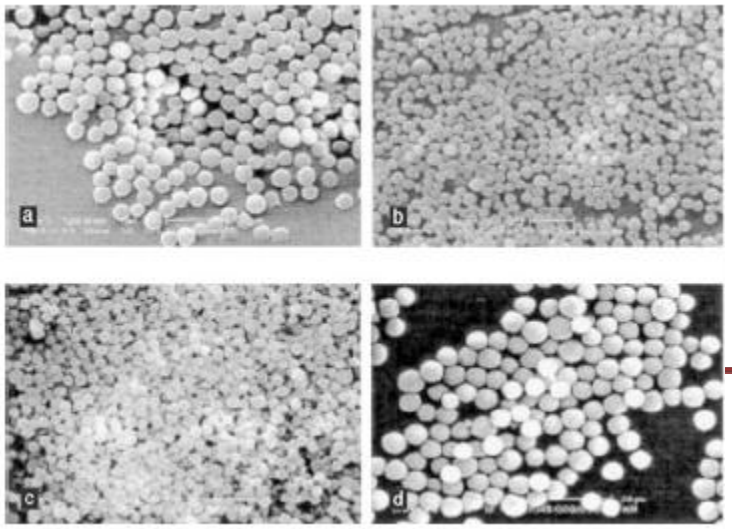


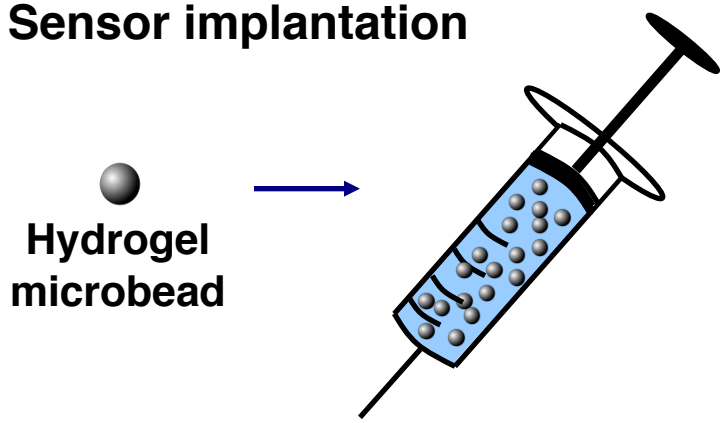
Figure 3. SEM images of freeze-dried 5 μm microparticles

small 2005, 1, No. ■, 2–6

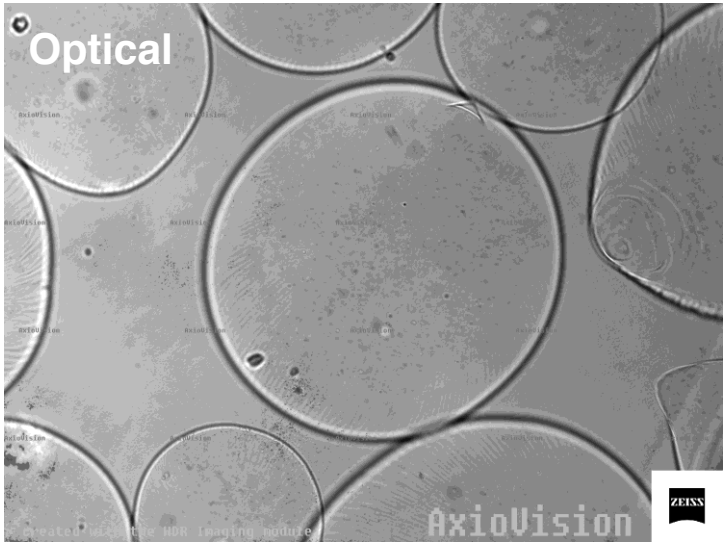
In Vivo Measurement

Subcutaneous injection

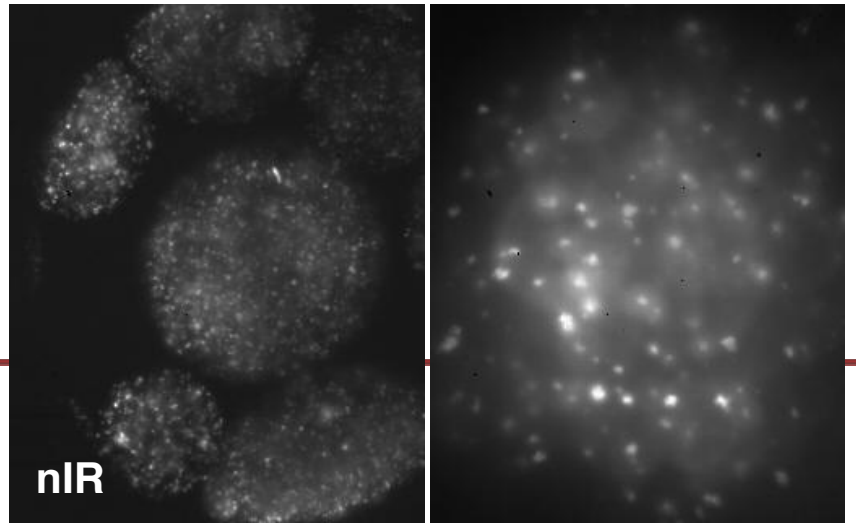
Sensor implantation



Subcutaneous injection = "glucose sensing tattoo"

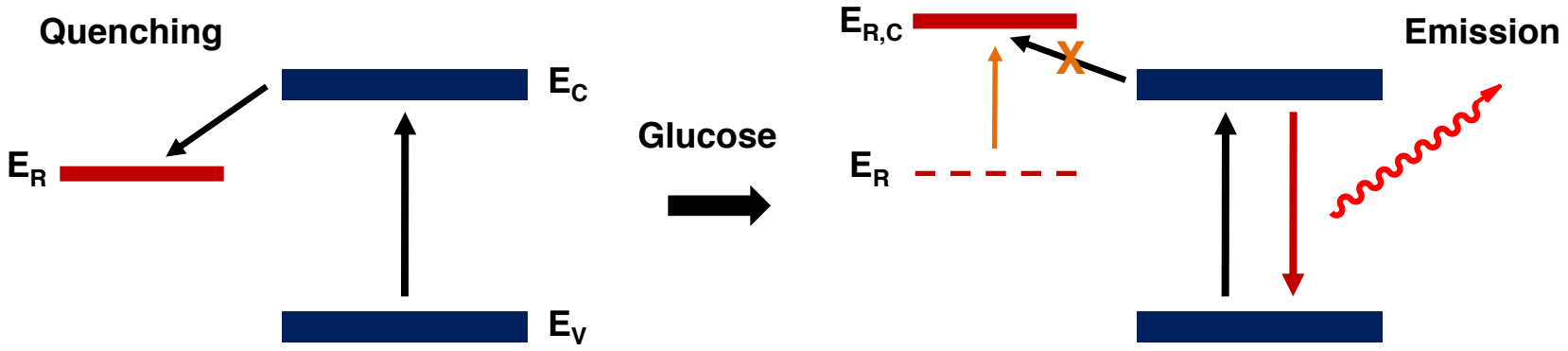


http://web.mit.edu/newsoffice/2010/glucose-tattoo-0528.html



Rationale of Molecular Recognition

- 1) a change of medium polarity near SWNTs, namely solvatochromism;
- 2) electron transfer due to redox potential change;
- 3) steric effect of a quencher due to conformational, structural, or geometric change;
- 4) reversible or irreversible aggregation of SWNTs due to a change of colloidal stability.



Fluorescence quenching mechanism: a *photo-induced excited-electron transfer*

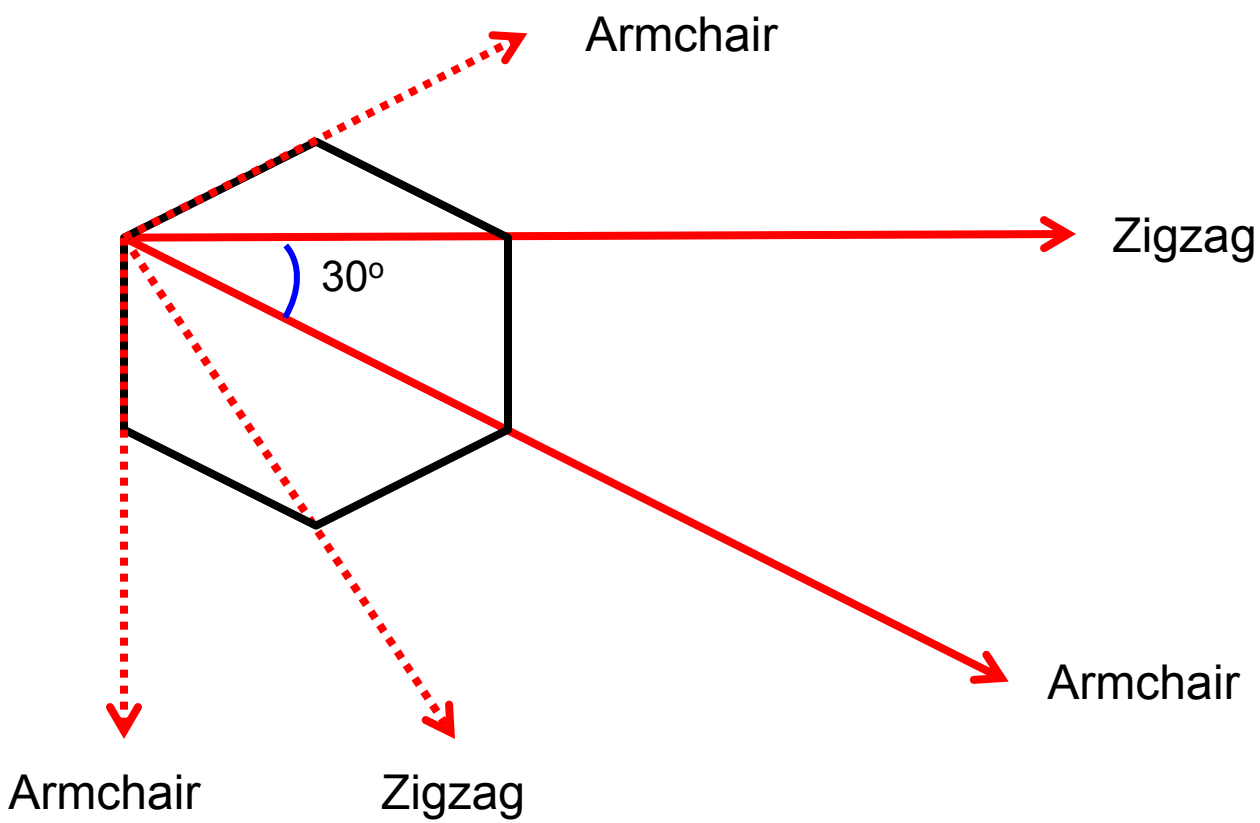
Fluorescence recovery mechanism*: the reduction potential shift upon complexation with glucose*, making the excited-electron transfer less favorable

Conclusions

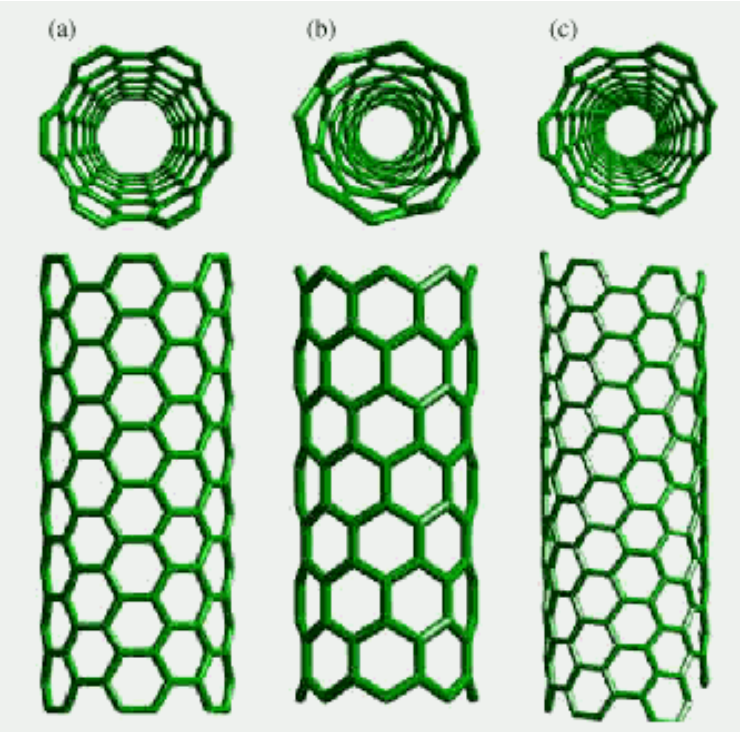
- The fluorescent properties of SWNTs make them ideal for use as sensors in biological systems. Not only does the emission take place at wavelengths that do not interfere with tissue absorption, but is also demonstrates nearly infinite photostability.
- There needs to be more research into computational tools that can predict the structure of adsorbed phases around a nanotube. We need to understand how those nanoscaled structures are modified upon binding of an analyte.
- Efforts to understand interparticle potentials and solubility of SWNTs will advance their development as fluorescent sensors.

Acknowledgement

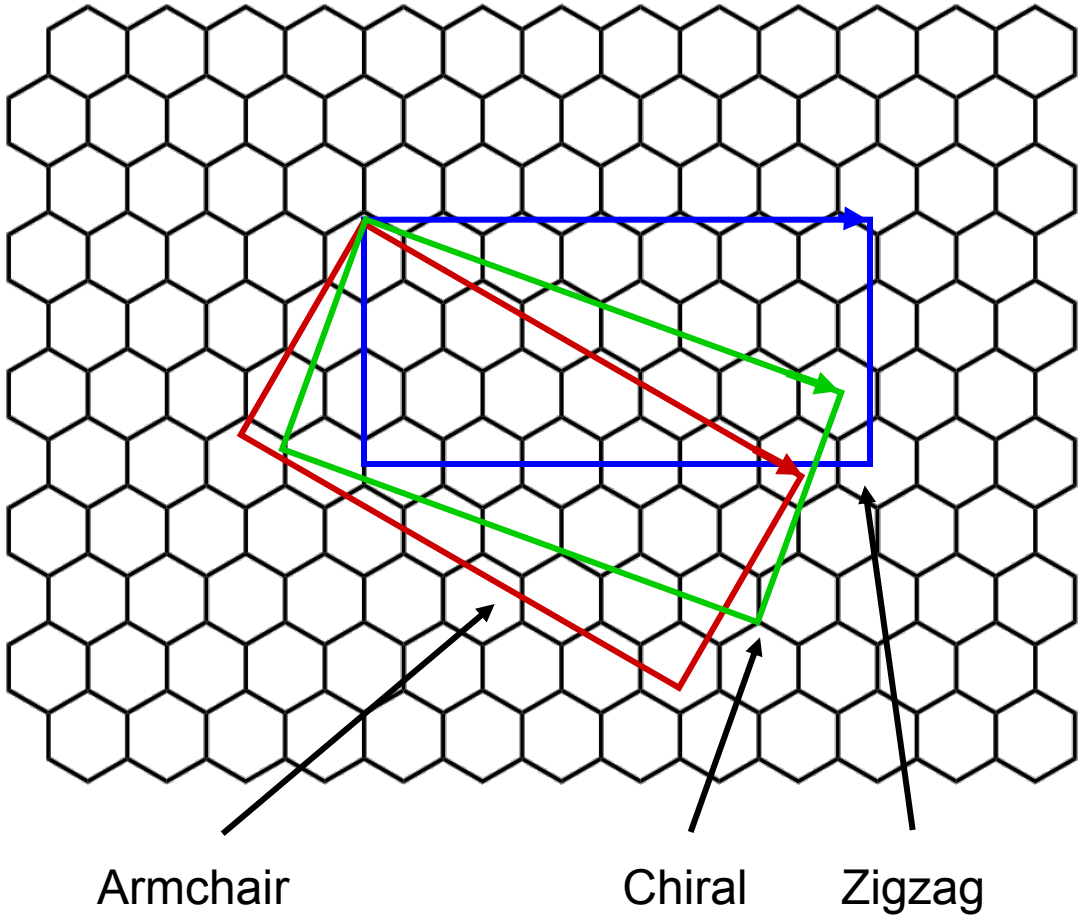
Thank You!


Armchair
Zigzag
30°
Armchair
Armchair
Zigzag

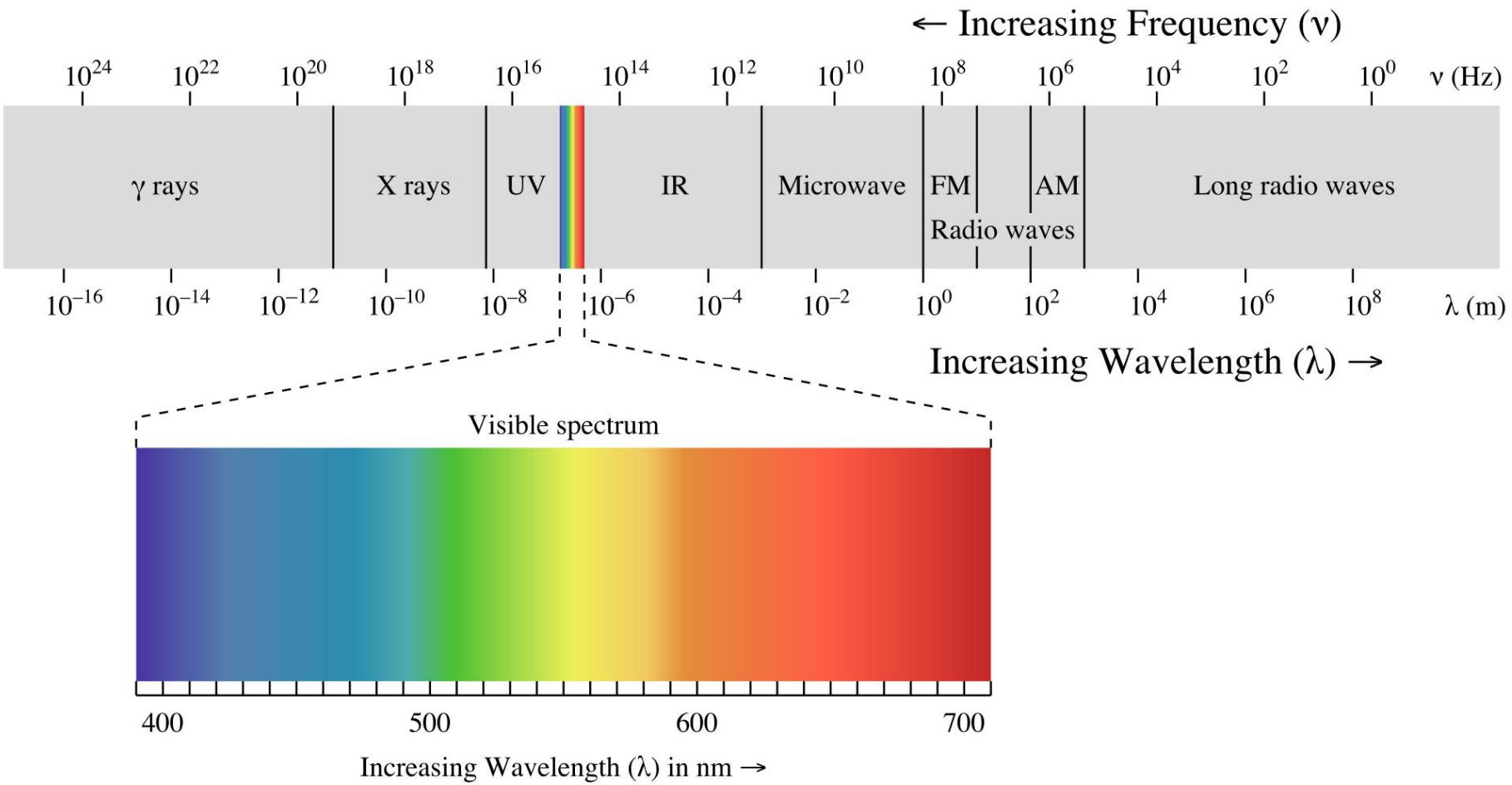
Construction of SWNTs from a Graphene Sheet



(a) armchair, (b) zigzag, (c) chiral



Electromagnetic Spectrum



http://upload.wikimedia.org/wikipedia/commons/thumb/f/f1/EM_spectrum.svg/2000px-EM_spectrum.svg.png