20.330 / 6.023 / 2.793 Fields, Forces and Flows in Biological Systems

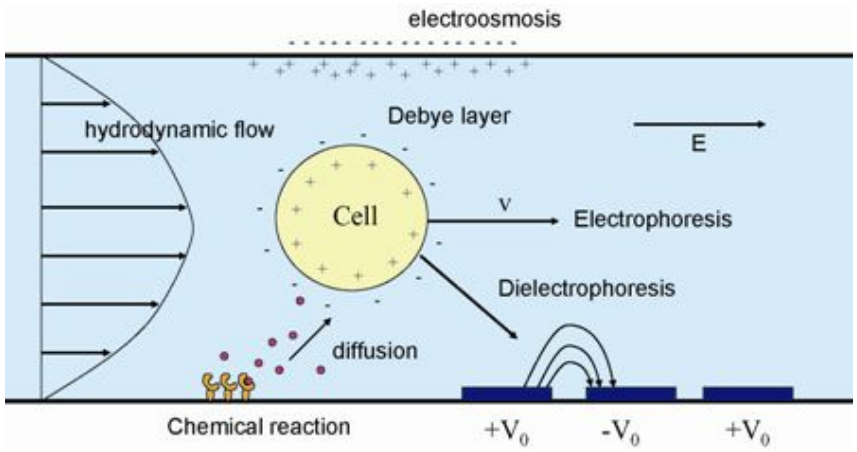
Instructors: Jongyoon “Jay” Han and Scott Manalis

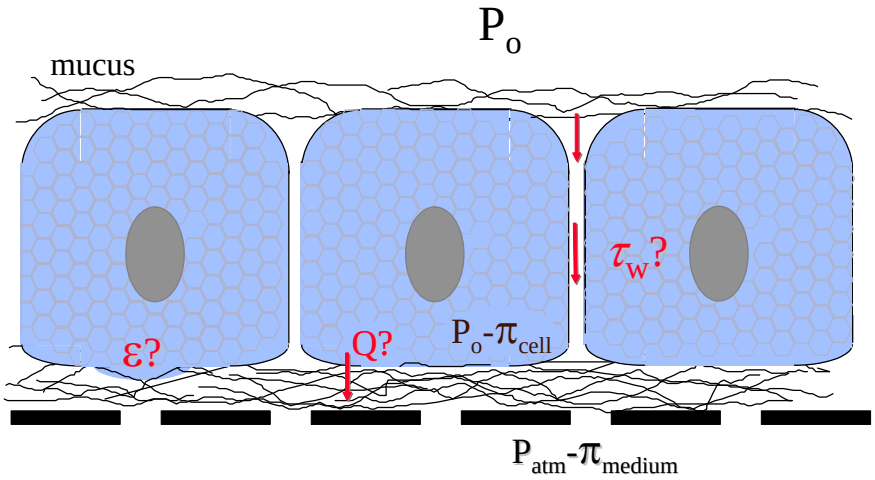
TOPICS

Introduction to electric fields
Maxwell’s equations
Introduction to fluid flows
Transport phenomena in biological systems
Electro-quasistatics
Electrokinetics
Electrophoresis
Van der Waals and other forces

Photo courtesy of ‘elbisreverri’.
http://www.flickr.com/photos/elbisreverri/53226345/

Relevant forces in biological systems and nanoscale





Fields/ forces/ flows/ transport in bio-microsystems (bioMEMS)

Transport in living cell and tissue systems

Monday	Tuesday	Wednesday	Thursday	Friday
2/5 Registration Day	2/6 No class	2/7 L1 Intro (JS) Fluid 1 (J)	2/8 Tutorial: Curl and Divergence	2/9 L2 Fluid 2 (J)
2/12 L3 Fluid 3 (J)	2/13 Office hours	2/14 L4 Fluid 4 (J)	2/15 Office hours	**HW 1 due** 2/16 L5 Fluid 5 (J)
2/19 Presidents' Day	(Monday) 2/20 L6 Fluid 6 (S)	2/21 L7 Fluid 7 (S)	2/22 Office hours	**HW 2 due** 2/23 L8 Fluid 8 (S)
2/26 L9 Fluid 9 (S)	2/27 Office hours	2/28 L10 Fluid 10 (S)	3/1 Office hours	**HW 3 due** 3/2 L11 Field 1 (J)
3/5 L12 Field 2 (J)	3/6 Special office hours for Quiz 1	3/7 Quiz 1 (in class) HW 1-3, L1~10	3/8 Office hours	(Add Date) **3/9** L13 Field 3 (J)
3/12 L14 Field 4 (J)	3/13 Office hours	3/14 L15 Field 5 (J)	3/15 Tutorial: Using the FEMLAB	**HW 4 due** 3/16 L16 Field 6 (J)
3/19 L17 Field 7 (J)	3/20 Office hours	3/21 L18 Field 8 (J)	3/22 Office hours	**HW 5 due** 3/23 L19 Field 9 (J)
3/26 Spring Break	3/27	3/28	3/29	3/30
4/2 L20 Transport 1 (S)	4/3 Office hours	4/4 L21 Transport 2 (S)	4/5 Tutorial / Office hours	**HW 6 due** 4/6 L22 Transport 3 (S)
4/9 L23 Transport 4 (S)	4/10 Office hours	4/11 L24 Transport 5 (S)	4/12 Tutorial / Office hours	**HW 7 due** 4/13 L25 Transport 6 (S)
4/16 Patriots' Day	4/17 (Special office hours for Quiz 2)	4/18 Quiz 2 (in class) HW 4-7, L11~24	4/19 Tutorial/ Office hours	4/20 L26 Transport 7 (S)
4/23 L27 Transport 8 (S)	4/24 Office hours	4/25 L28 Transport 9 (S)	(Drop date) 4/26 Tutorial / Office hours	**HW 8 due** 4/27 L29 EK 1 (S)
4/30 L30 EK 2 (S)	5/1 Office hours	5/2 L31 EK 3 (S)	5/3 Tutorial / Office hours	**HW 9 due** 5/4 L32 EK 4 (J)
5/7 L33 EK 5 (J)	5/8 Office hours	5/9 L34 EK 6 (J)	5/10 Tutorial / Office hours	**HW 10 due** 5/11 L35 EK 7 (J)
5/14 L36 EK 8 (J)	5/15 Office hours	5/16 L37 EK 9 (J)	5/17 Office hours	5/18 Study Period
5/21	5/22 Final Exam Period	5/23 (3 hour long, comprehensive)	5/24	5/25

Textbooks

- Truskey, Yuan and Katz "**Transport Phenomena in Biological Systems**" Prentice Hall (REQUIRED)
- Haus and Melcher "**Electromagnetic Fields and Energy**" Content available on the web for free (http://web.mit.edu/6.013_book/www/)
- "**Physicochemical Hydrodynamics, An Introduction**", by Ronald F. Probstein. (e-reserve)
- "**Electromechanics of Particles**" by Thomas B. Jones, Cambridge University Press (e-reserve)

- Other references:
  - Bird/Stewart/Lightfoot, "Transport Phenomena" Wiley
  - Tom Weiss " Cellular Biophysics" Volume 1. Transport, MIT press.
  - "AC Electrokinetics: colloids and nanoparticles", by Morgan and Green, Research Studies Press.
  - "Principles of Colloid and Surface Chemistry", by Hiemenz and Rajagopalan, Marcel Dekker.
  - "Molecular Driving Forces", by Ken Dill and Sarina Bromberg, Garland Science

How precise can a cell measure the concentration of its environment?

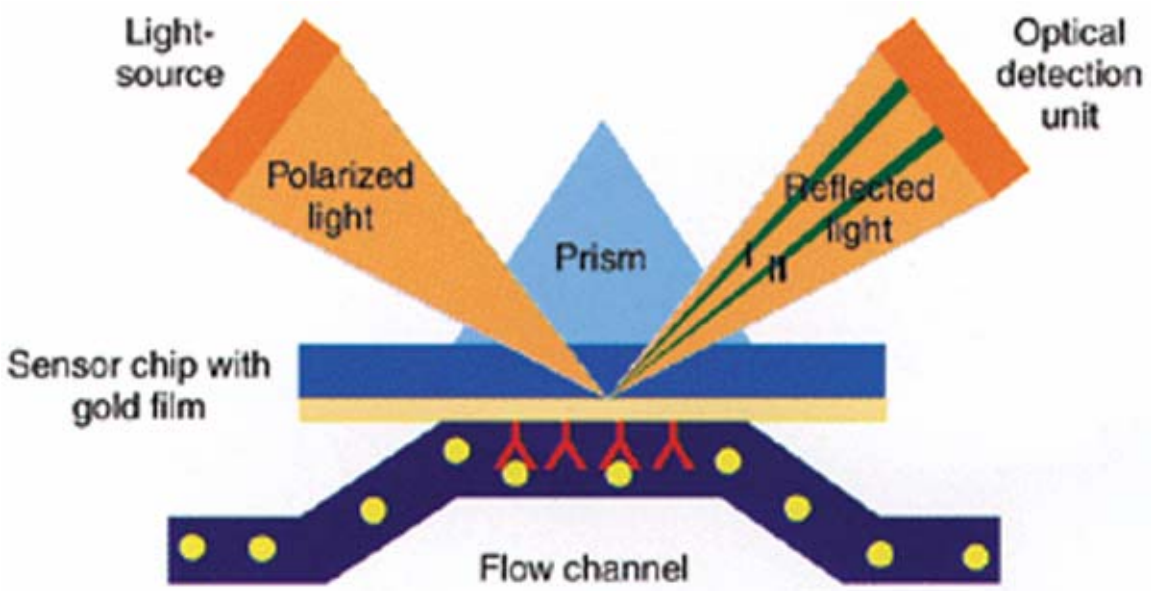
E. Coli trajectory

Images removed due to copyright restrictions. See Figs. 1 & 3.

Berg, Physics Today 2000

http://www.aip.org/pt/jan00/berg.htm

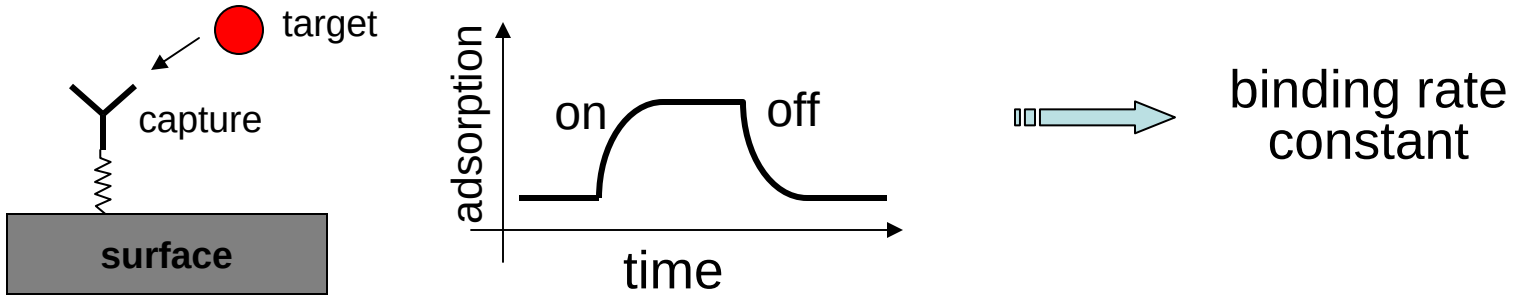
Measuring binding kinetics



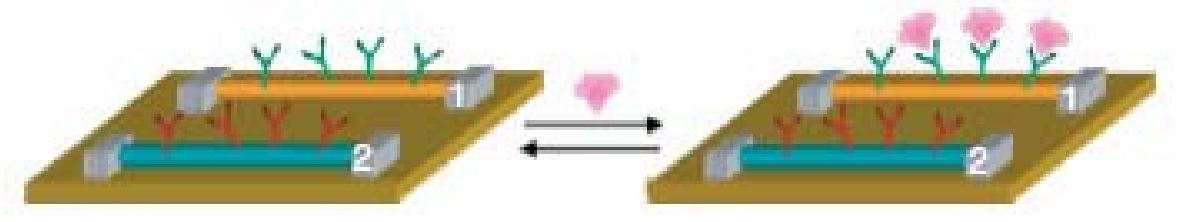
Surface Plasmon Resonance (*Biacore*)

Courtesy of Biacore. Used with permission.

Label-free enables direct readout of K_{on} and K_{off}



Detecting biomolecules on the nanoscale



Nat. Biotech. 23 (2005)

Courtesy of Dr. Charles M. Lieber. Used with permission.
Source: Fig. 1b in Zheng, G., et al. "Multiplexed electrical detection of cancer markers with nanowire sensor arrays." *Nat Biotech* 23 (2005): 1294-1301.

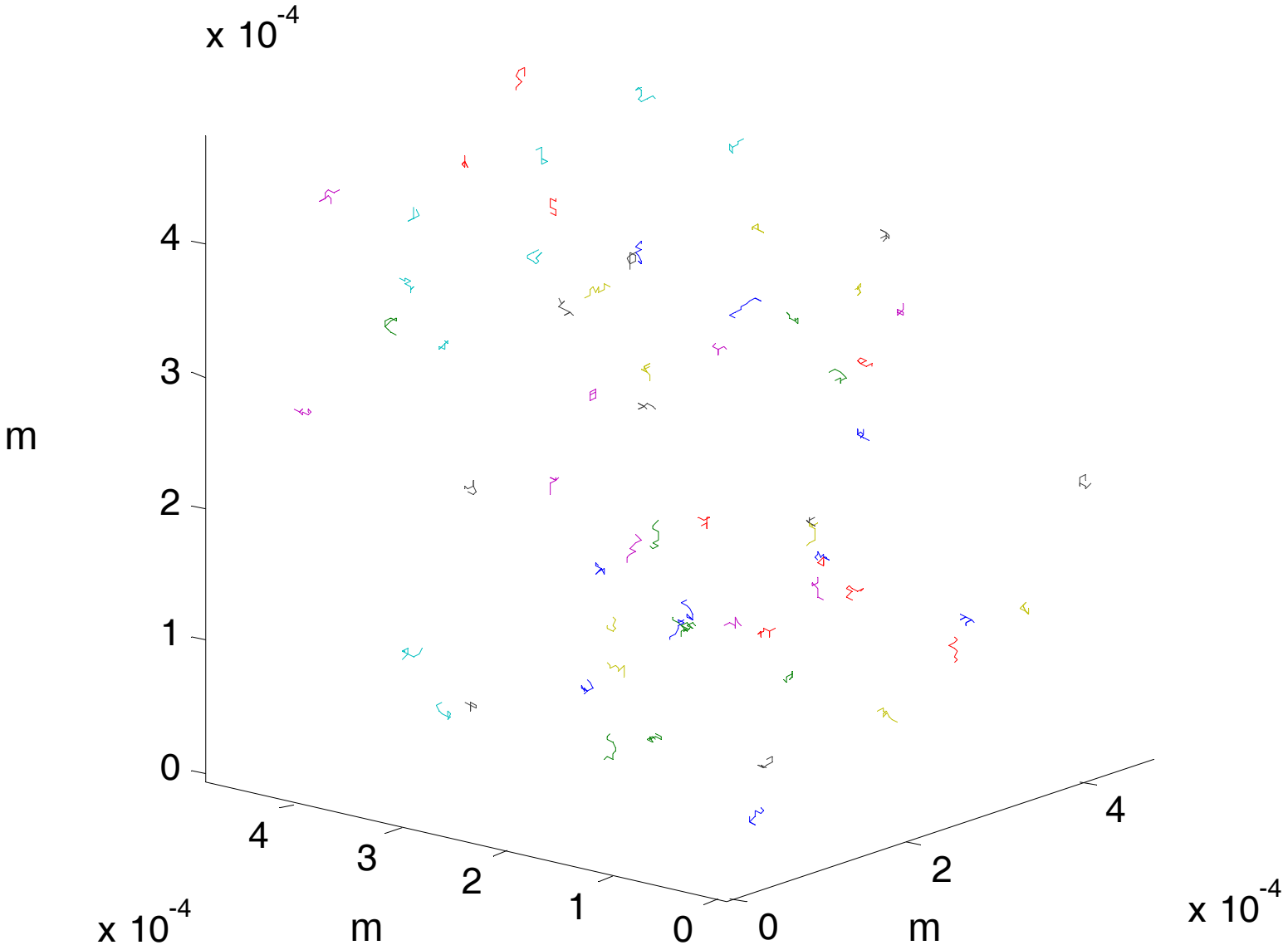
Figure removed due to copyright restrictions.

J. Am. Chem. Soc. 128 (2006)

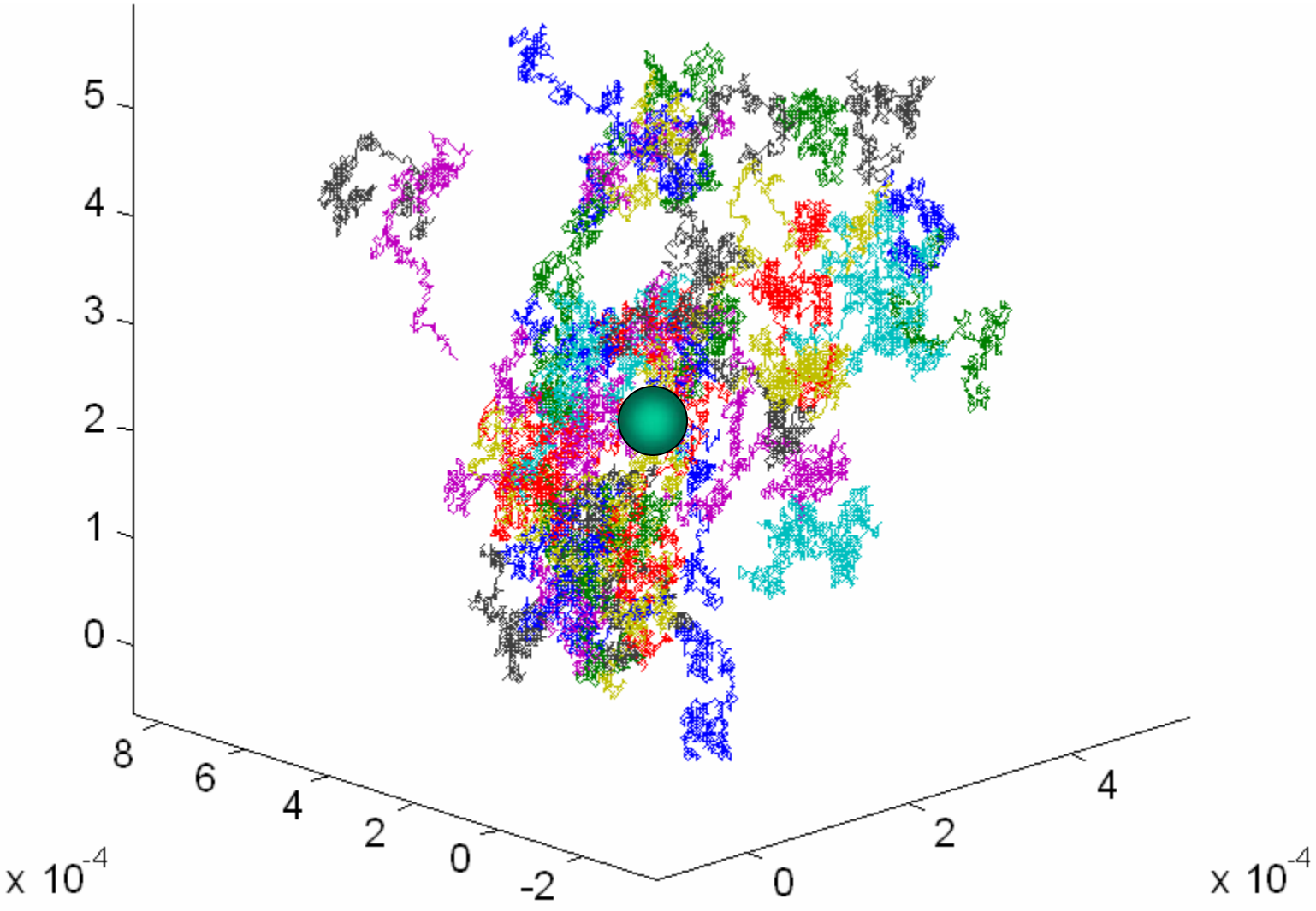
Figure removed due to copyright restrictions.

Nature 445 (2007)

64 oligos at 1 femtomolar concentration



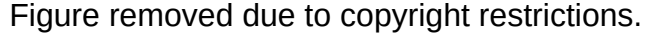
…after 10 seconds



How often do molecules bind to sphere?

Proteins : **3D structure** with complex charge distribution

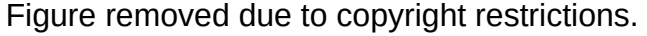
Human Serum Albumin



Sugio, S., Kashima, A., Mochizuki, S., Noda, M., Kobayashi, K. ***Protein Eng.*** **12** ***pp.*** **439 (1999)**

DNA (SDS-proteins) : **Linear polymer** with uniform charge density

DNA



Brown, T., Leonard, G. A., Booth, E. D., Chambers, J, ***J Mol Biol*** **207** ***pp.*** **455 (1989)**

Migratory birds uses magnets for positioning

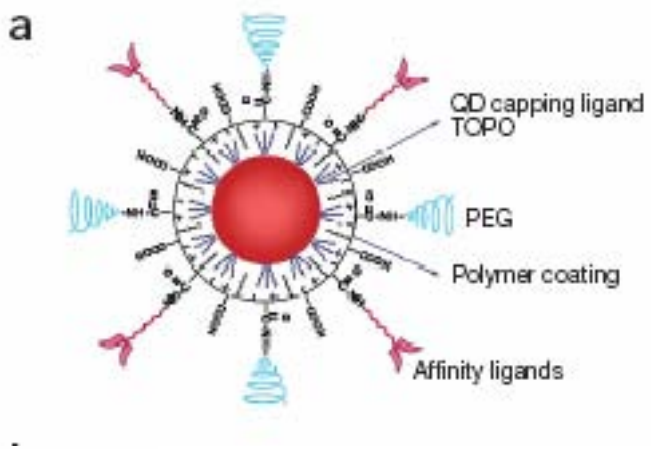
Figure 1 in Mora, Cordula V. "Magnetoreception and its Trigeminal Mediation in the Homing Pigeon." *Nature* 432 (2004): 508-511.

http://www.nature.com/naturebiotechnology

In vivo cancer targeting and imaging with semiconductor quantum dots

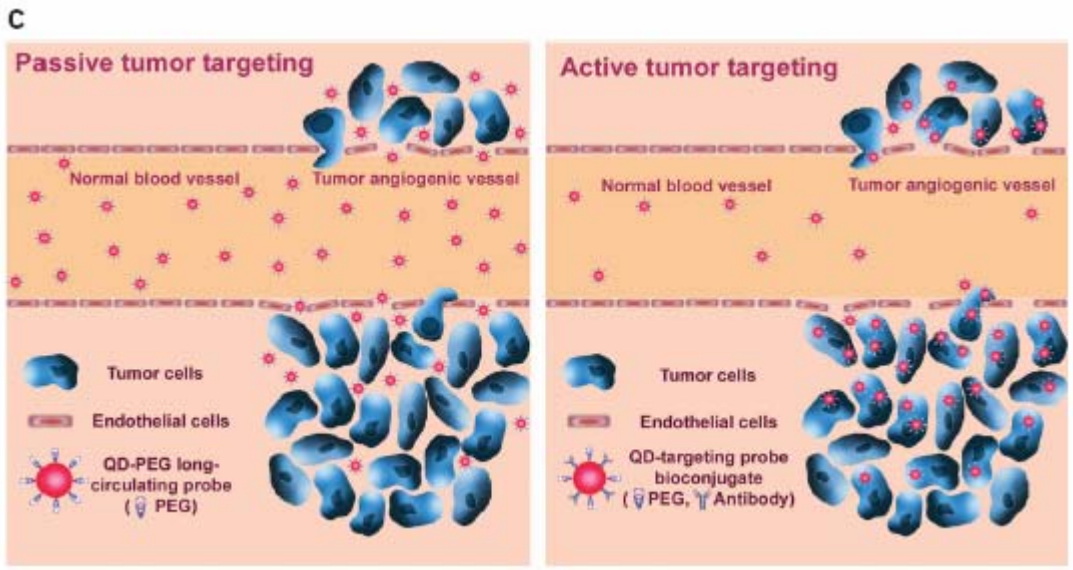
Xiaohu Gao,[1] Yuanyuan Cui,[2] Richard M Levenson,[3] Leland W K Chung[2] & Shuming Nie[1]

We describe the development of multifunctional nanoparticle probes based on semiconductor quantum dots (QDs) for ca
ing and imaging in living animals. The structural design involves encapsulating luminescent QDs with an ABC triblock co
and linking this amphiphilic polymer to tumor-targeting ligands and drug-delivery functionalities. *In vivo* targeting studie
prostate cancer growing in nude mice indicate that the QD probes accumulate at tumors both by the enhanced permeabi
retention of tumor sites and by antibody binding to cancer-specific cell surface biomarkers. Using both subcutaneous inj
QD-tagged cancer cells and systemic injection of multifunctional QD probes, we have achieved sensitive and multicolor f
imaging of cancer cells under *in vivo* conditions. We have also integrated a whole-body macro-illumination system with w
resolved spectral imaging for efficient background removal and precise delineation of weak spectral signatures. These re
new possibilities for ultrasensitive and multiplexed imaging of molecular targets *in vivo*.

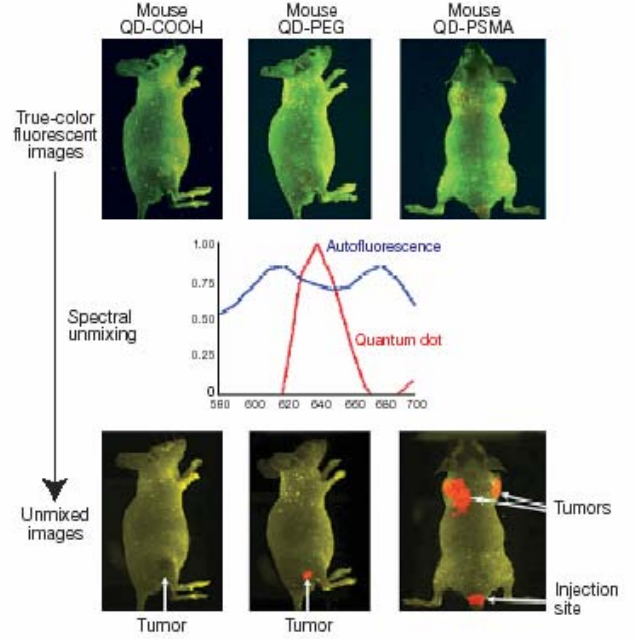


Courtesy of Leland W. K. Chung. Used with permission.

Gao, Cui, Levenson, Chung and Nie, Nature Biotechnology **22**, 969 (2004)



Courtesy of Leland W. K. Chung. Used with permission.



Courtesy of Leland W. K. Chung. Used with permission.

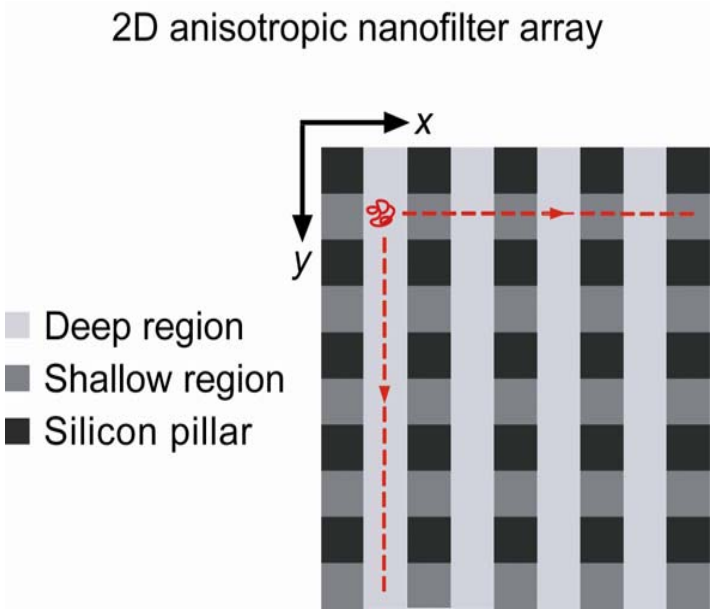
Dielectrophoretic Manipulation of Cells

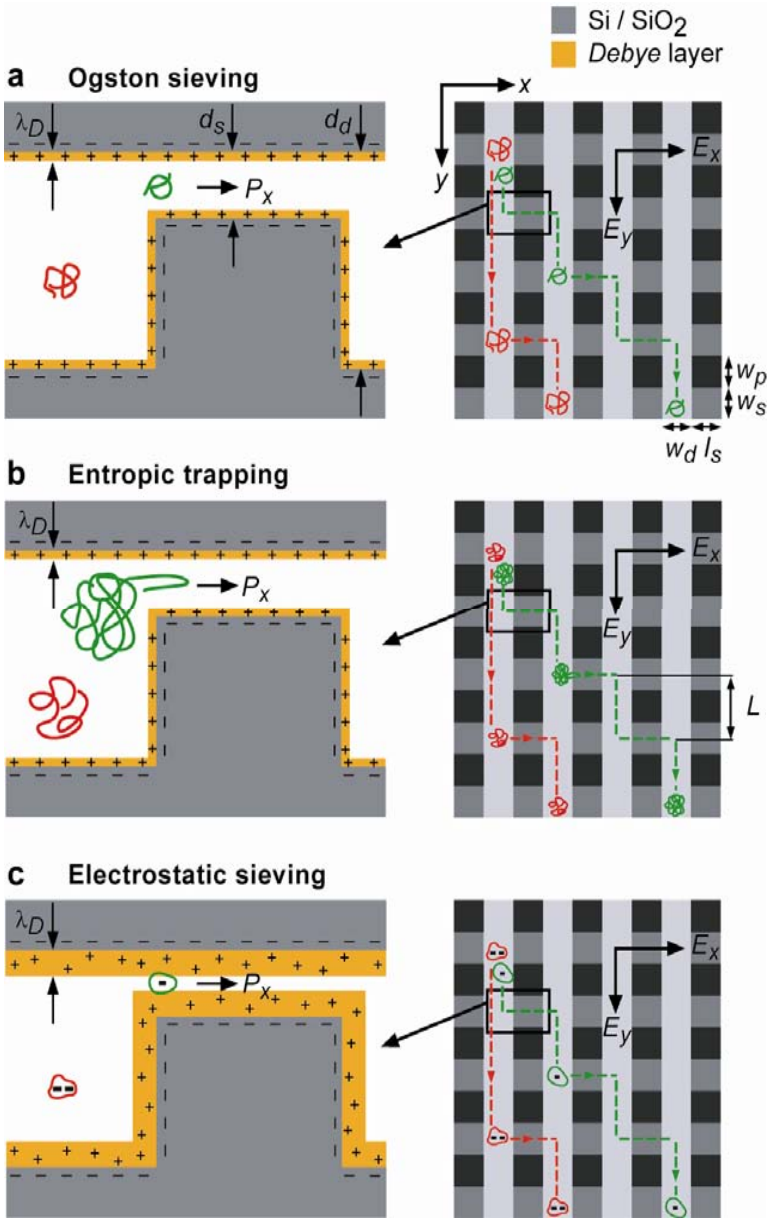
Cells trapped by dielectrophoresis, Gray et al.
Biosensors and Bioelectronics 19 (2004) 1765–1774

Figures removed due to copyright restrictions.

Electrophoresis / Electrokinetics

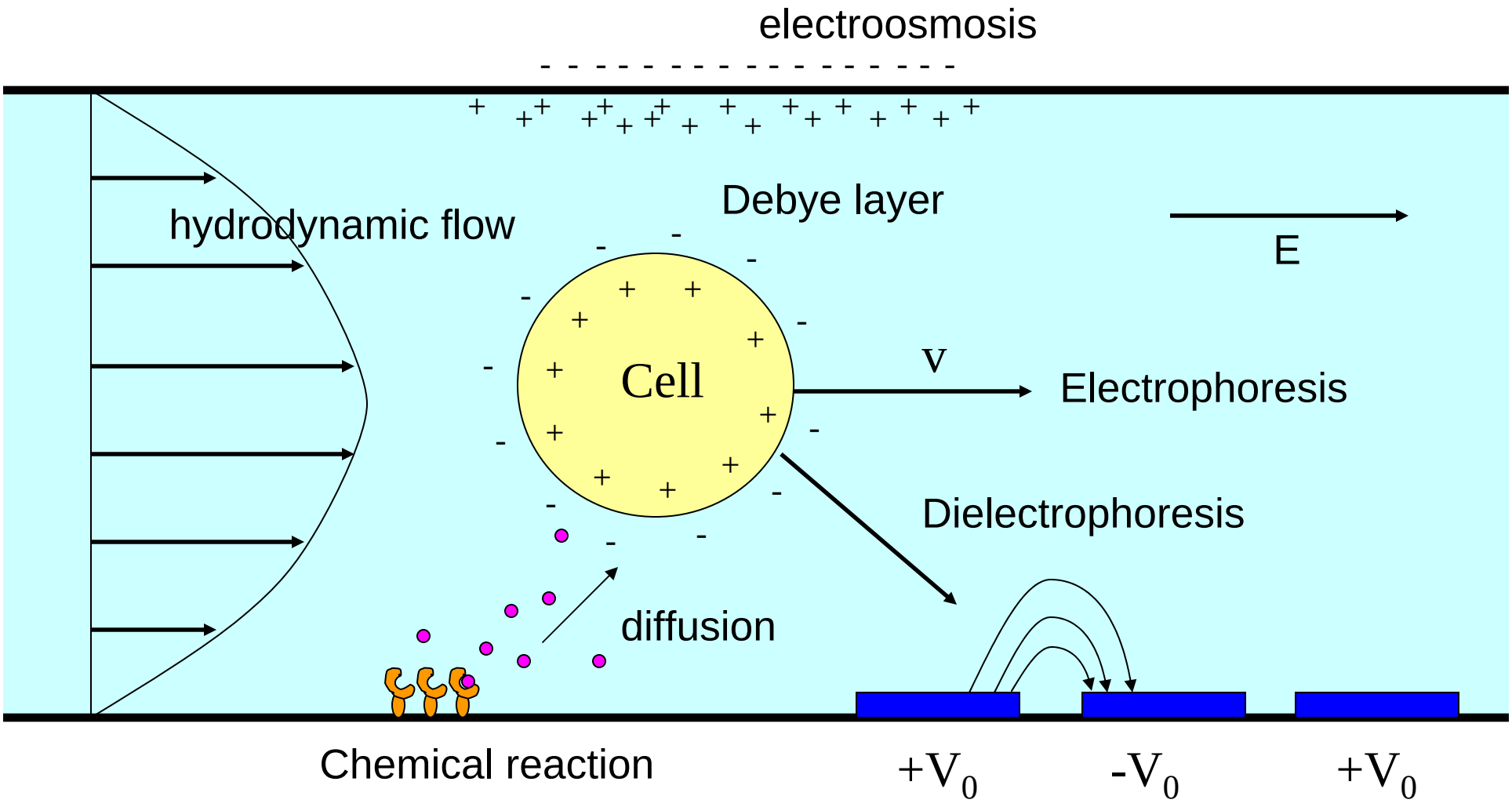
J. Fu *et al. Nature Nanotechnology* (2007).

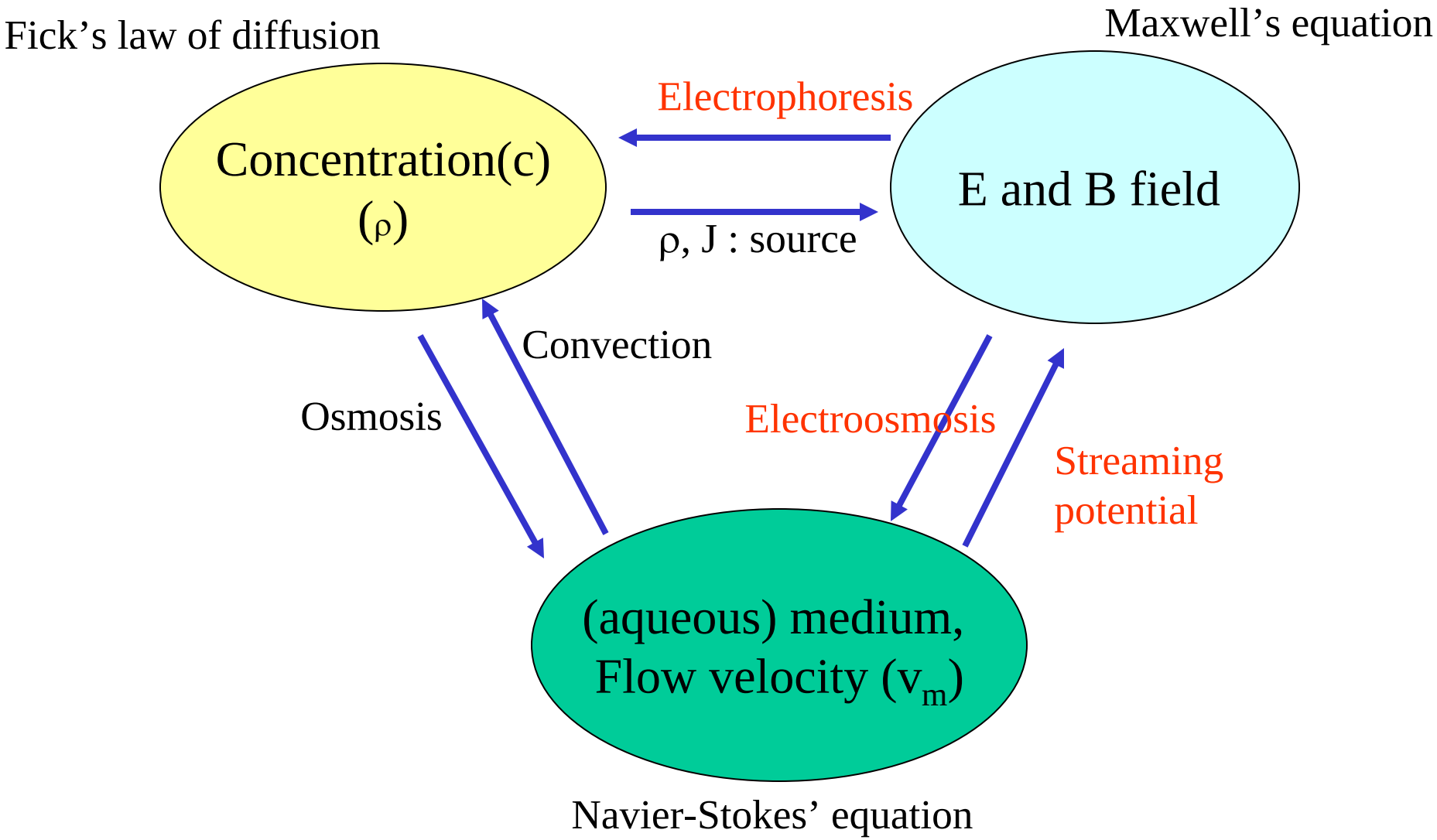




Source: Fu, Jianping, and Jongyoon Han, et al. "A Patterned Anisotropic Nanofluidic Sieving Structure for Continuous-flow Separation of DNA and Proteins." *Nature Nanotechnology* 2 (2007): 121-128.

Example : BioMEMS systems




Fick's law of diffusion
Maxwell's equation
Concentration(c)
(ρ)
Electrophoresis
E and B field
ρ, J : source
Convection
Osmosis
Electroosmosis
Streaming
potential
(aqueous) medium,
Flow velocity (v_m)
Navier-Stokes' equation