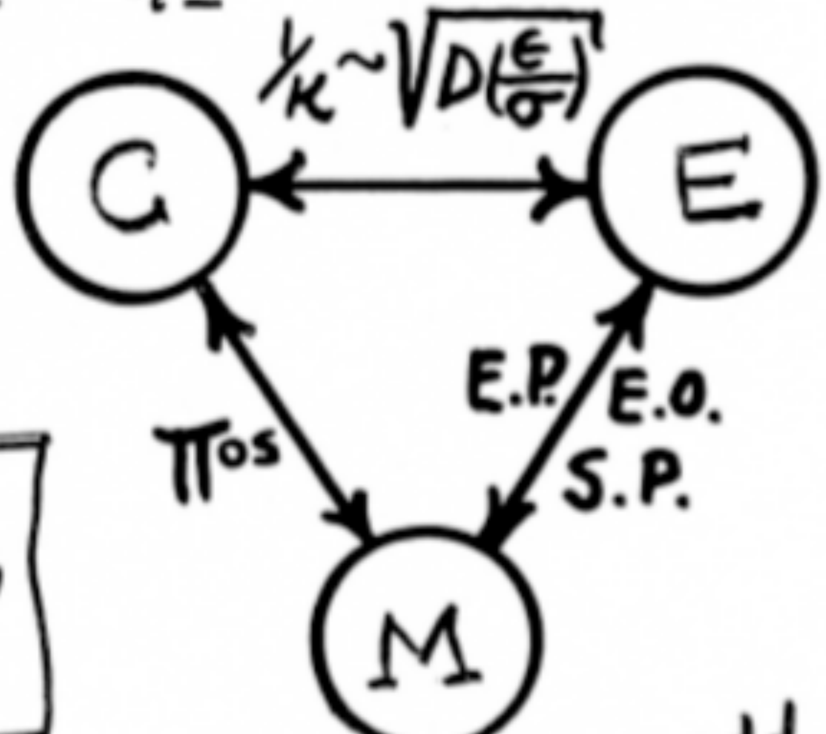
430: "Complete Description" of Coupled Transport and Biomolecular Interactions

$\underline{N}_i = -D_i \nabla c_i + \frac{z_i}{|z_i|} u_i c_i \underline{E} + c_i \underline{v}$

$\frac{\partial c_i}{\partial t} = -\nabla \cdot N_i + R_{vi}$



$\nabla \cdot \epsilon \underline{E} = \rho_e = \sum_i z_i F c_i$

$(\underline{E} = -\nabla \Phi)$

$\nabla \cdot \underline{J} = -\frac{\partial \rho_e}{\partial t}$

$\underline{J} = \sum_i z_i F \underline{N}_i$

"EQS"

Fields, Forces, & Flows

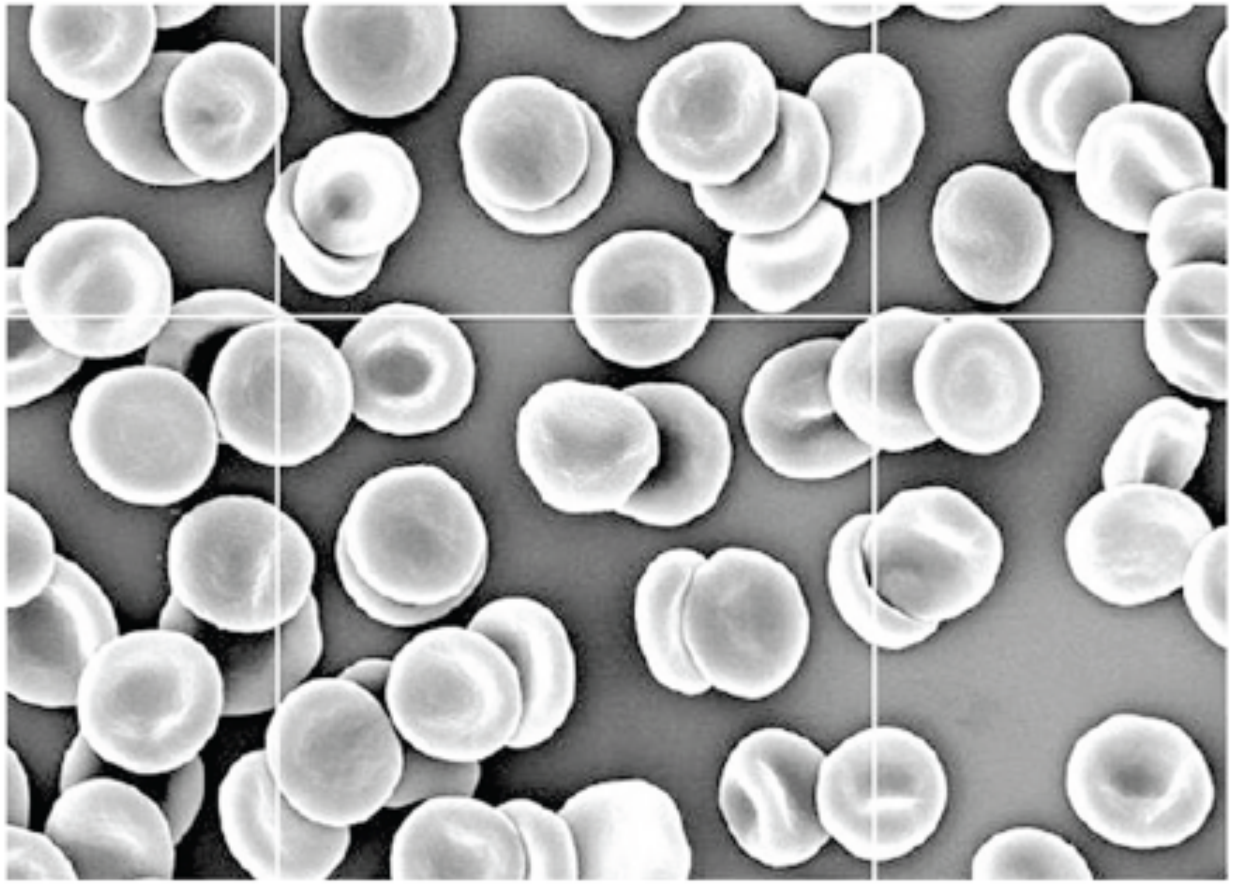
$$\Rightarrow \quad \rho_0 \frac{D\underline{v}}{Dt} = -\nabla p + \mu \nabla^2 \underline{v} + \overbrace{\rho_e \underline{E}}^{\text{add}} + \ldots$$

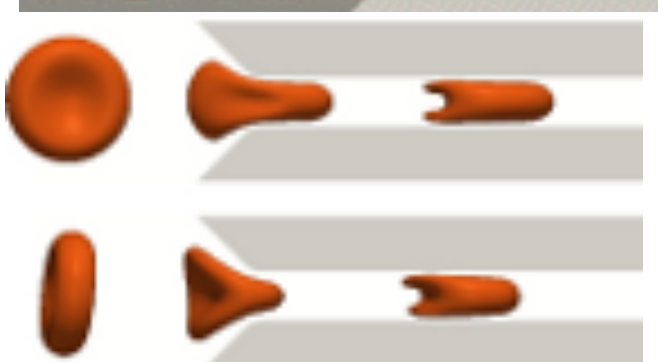
$(+\underline{p} \cdot \nabla \underline{E}) + \ldots +$ other

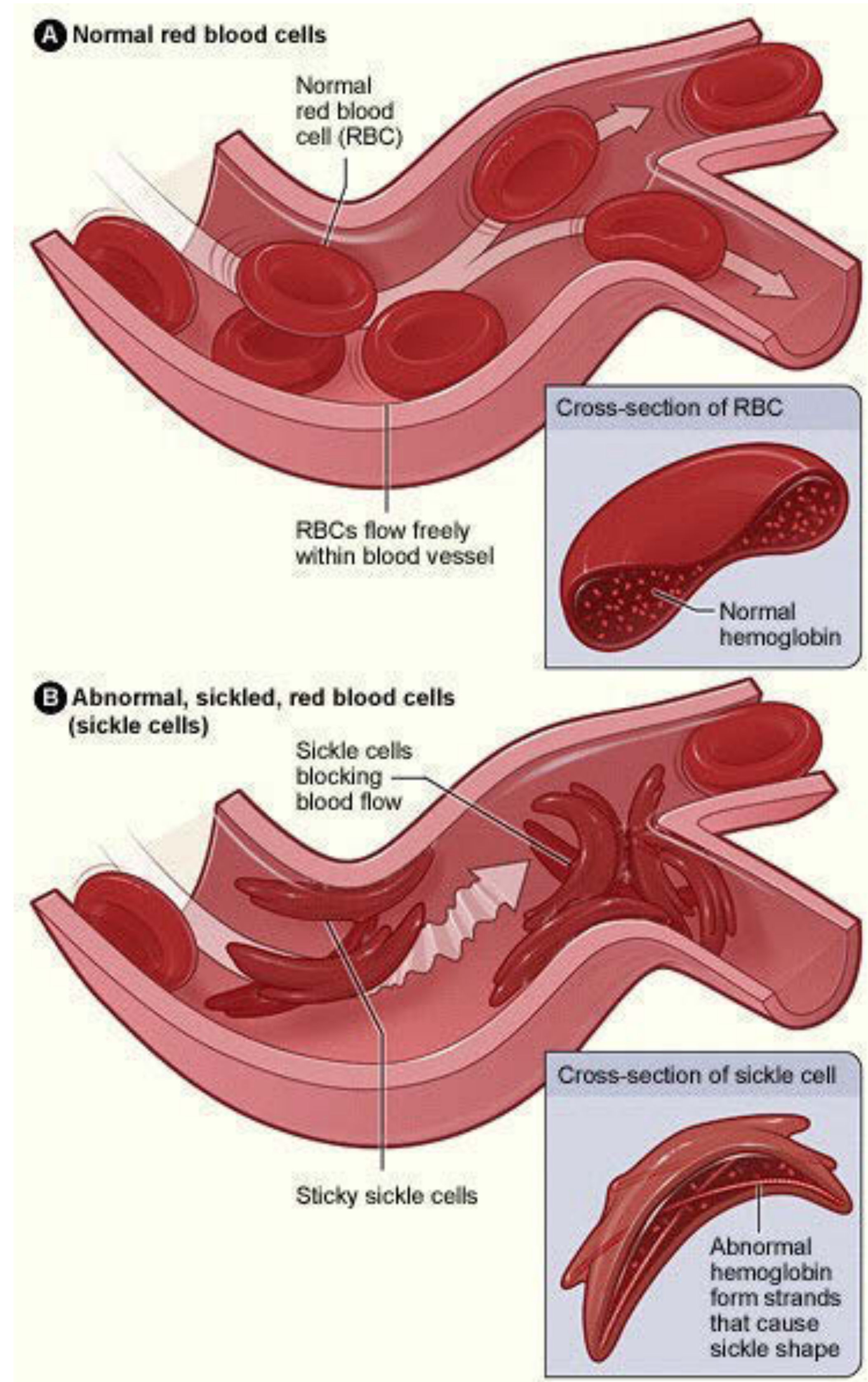
$\nabla \cdot \underline{v} = 0$ (incomp. fluid)

$$\left(\text{where } \frac{D\underline{v}}{Dt} = \frac{\partial \underline{v}}{\partial t} + (\underline{v} \cdot \nabla)\underline{v}\right)$$

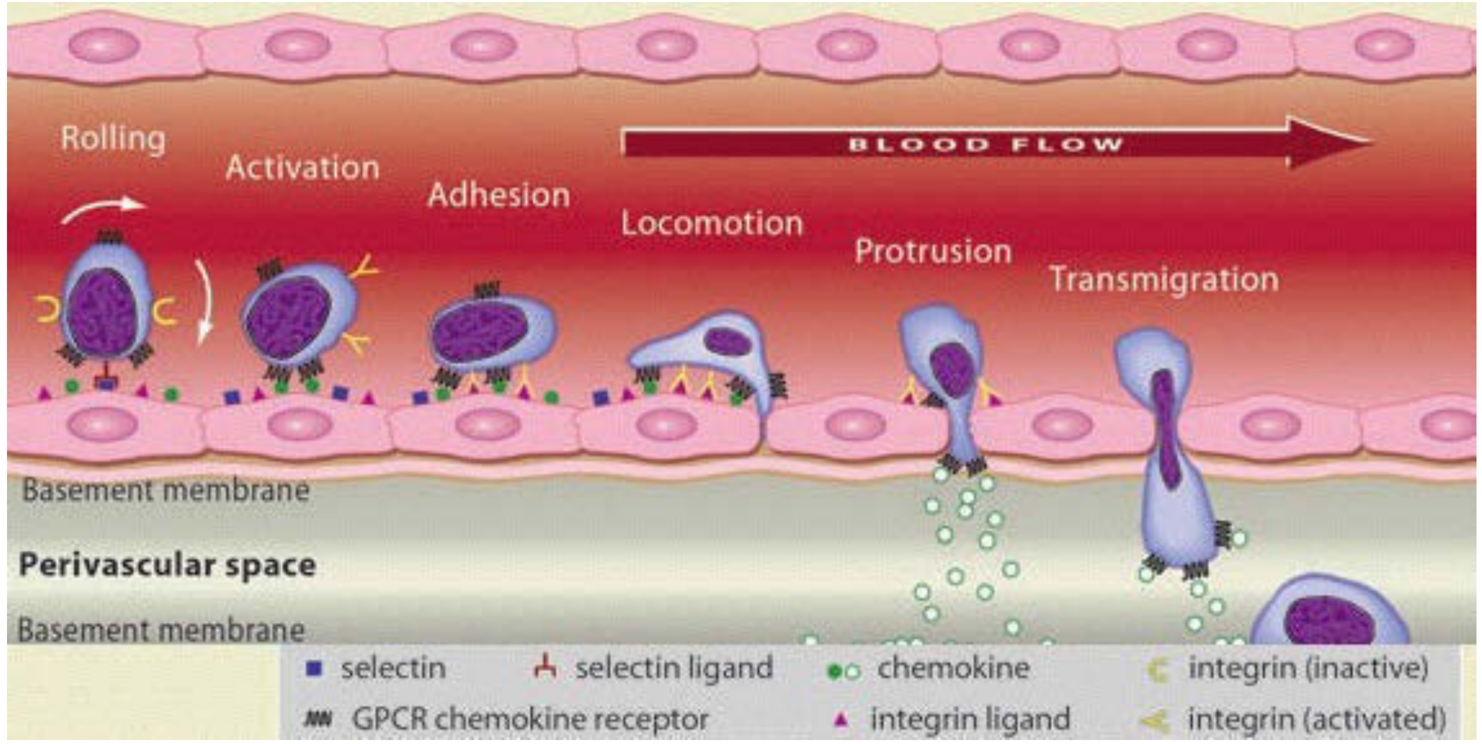
Red blood cell rheology



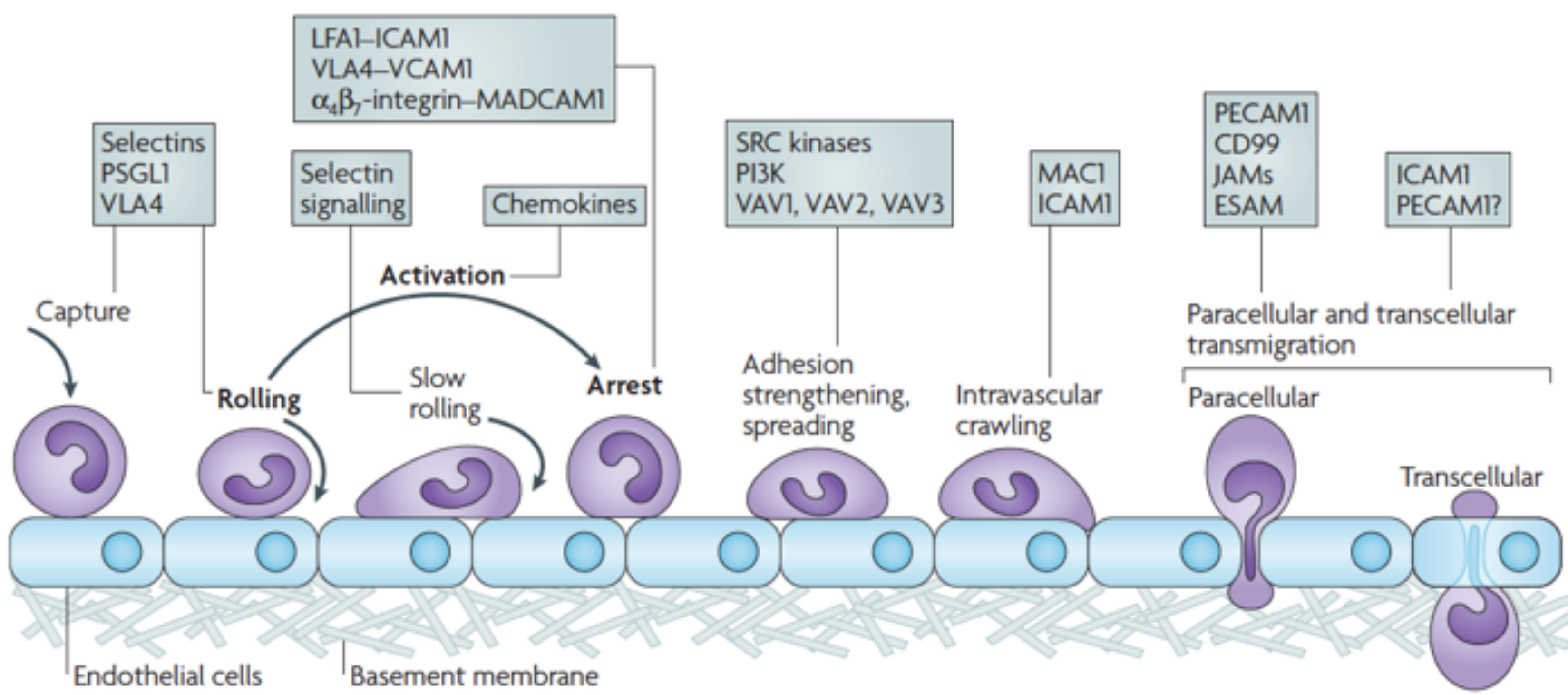




White blood cell rolling, adhesion, and extravasation



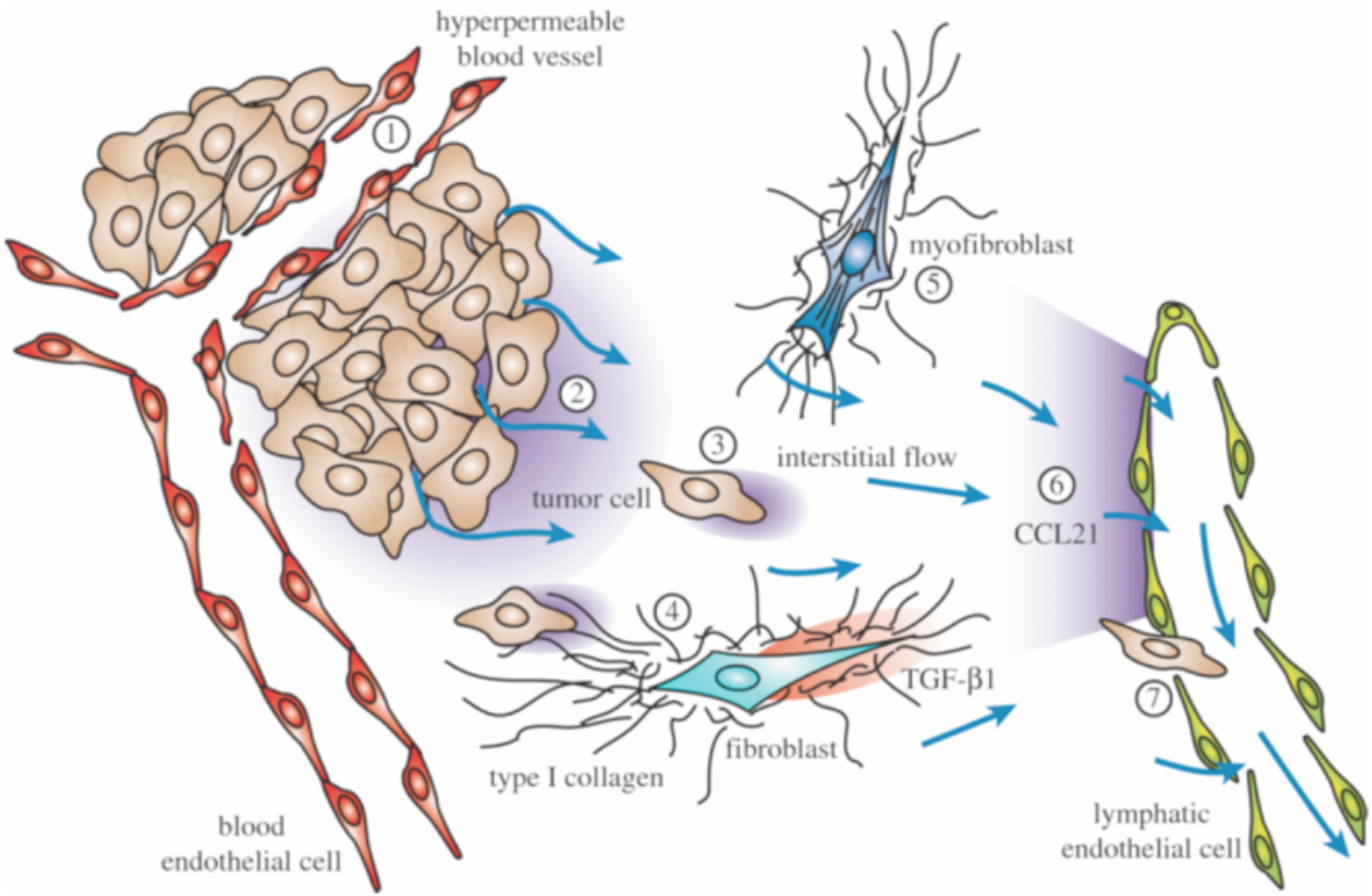
Source: Man, Shumei, Eroboghene E. Ubogu, and Richard M. Ransohoff. "Inflammatory cell migration into the central nervous system: a few new twists on an old tale." Brain Pathology 17, no. 2 (2007): 243-250.



Ley et al., *Nat Reviews Immunol* 2007

Source: Ley, Klaus, Carlo Laudanna, Myron I. Cybulsky, and Sussan Nourshargh. "Getting to the site of inflammation: the leukocyte adhesion cascade updated." Nature Reviews Immunology 7, no. 9 (2007): 678-689.

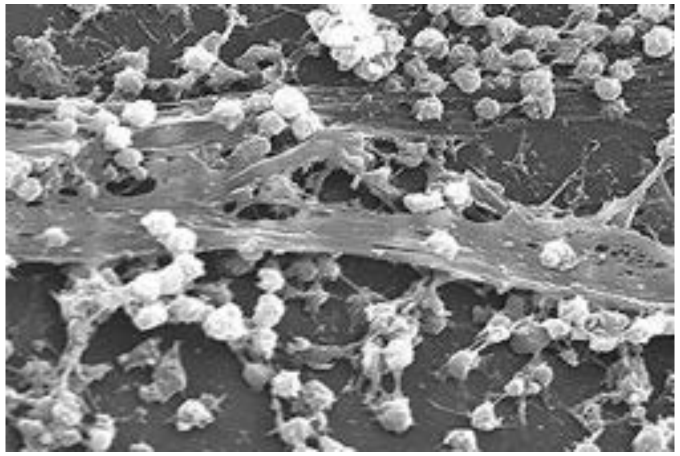
Interstitial fluid flow in cancer & drug delivery



Shieh and Swartz, Physical Biology, 2010

Source: Shieh, Adrian C. and Melody A. Swartz. "Regulation of tumor invasion by interstitial fluid flow." Physical Biology 8, no. 1 (2011): 015012.

Microbial biofilm growth and dispersion



Courtesy of Centers for Disease Control and Prevention; image in the public domain.

Figure of biofilm formation and dispersal removed due to copyright restrictions. Source: Forier, Katrien et al. "Lipid and polymer nanoparticles for drug delivery to bacterial biofilms." Journal of Controlled Release 190 (2014): 607-623.

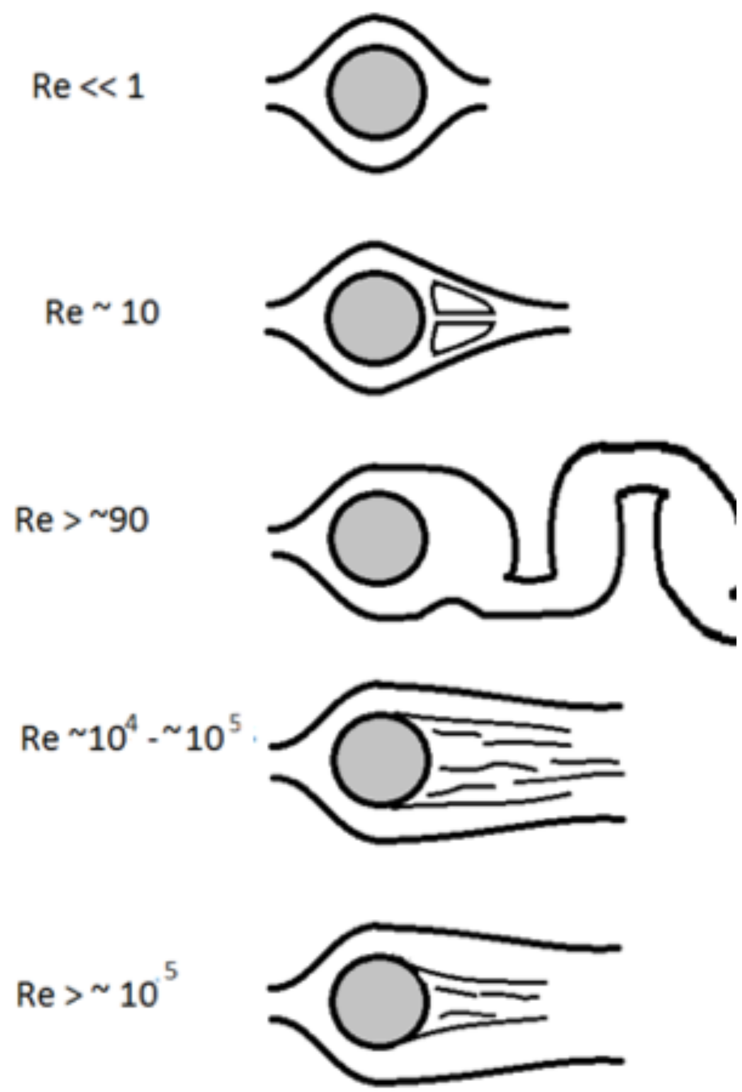
Reynold's Number: Inertial versus viscous forces

$$\mathrm{Re} = \frac{\text{inertial forces}}{\text{viscous forces}} = \frac{\rho \mathbf{v} L}{\mu} = \frac{\mathbf{v} L}{\nu}$$

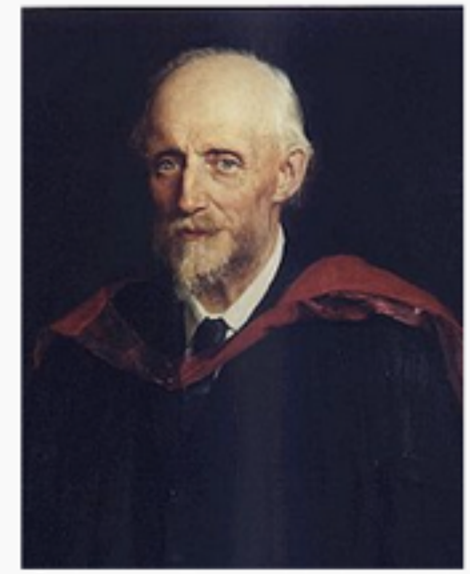
Re tells us:

Whether inertia or viscosity dominates

Which momentum conservation equations we need to solve (Stokes versus Bernouilli)



Osborne Reynolds



Osborne Reynolds in 1903

Born	23 August 1842 Belfast, Ireland
Died	21 February 1912 (aged 69) Watchet, Somerset, England
Nationality	United Kingdom
Fields	Physics
Alma mater	Queens' College, Cambridge Victoria University of Manchester
Known for	Fluid dynamics, Reynolds number
Notable awards	Royal Medal in 1888

http://en.wikipedia.org/wiki/Reynolds_number

Macroscopic Swimming in Fluids (Re >> 1)

Text from "Slip N Slide" article on wikipedia removed due to copyright restrictions.

https://www.youtube.com/watch?v=3wAjpMP5eyo

Courtesy of Imokurnotok on wikipedia; photo in the public domain.

What are the forces on the glider?

Phase 1: acceleration

Phase 2: flight

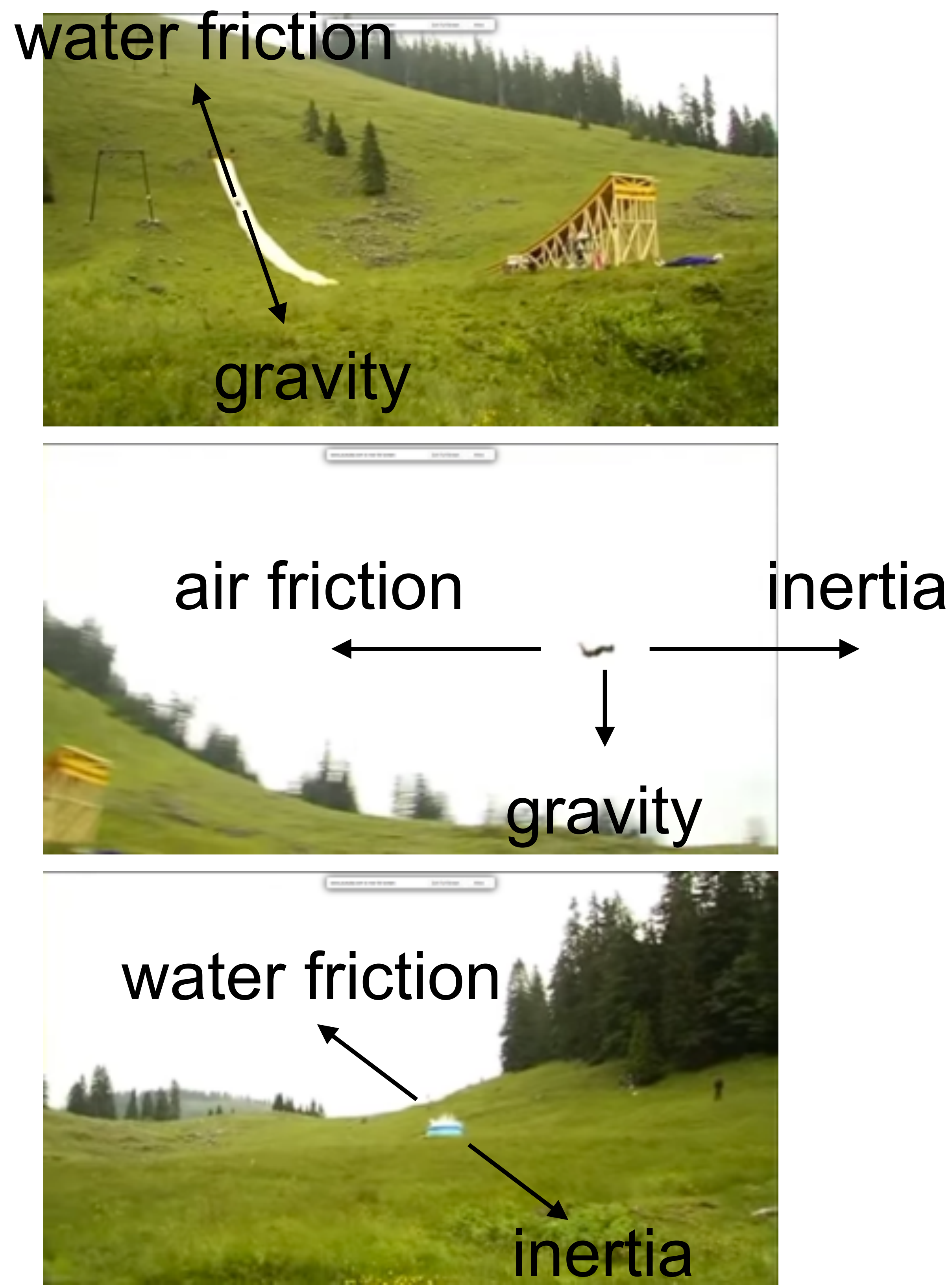
Phase 3: landing

What are the forces on the glider?

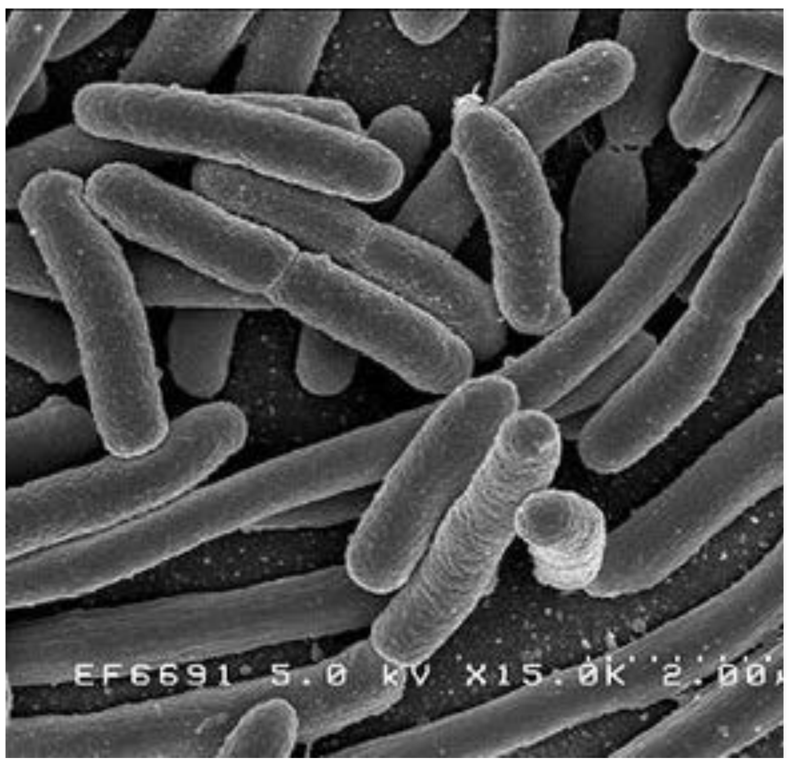
Phase 1: gravity versus water friction (plus some air friction)

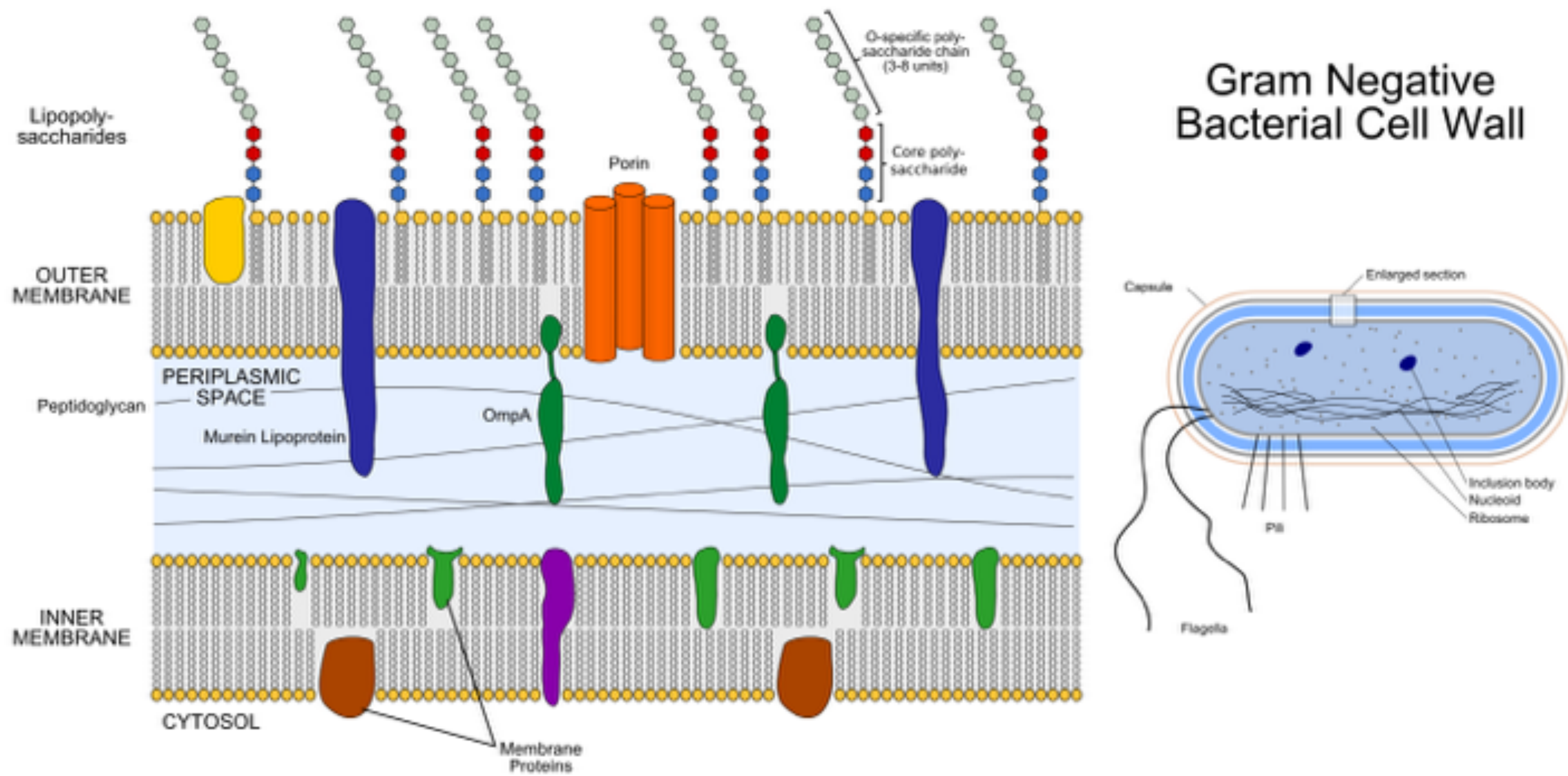
Phase 2: gravity and inertia versus air friction

Phase 3: inertia versus a lot of water friction



Life at low Reynolds Number is very different





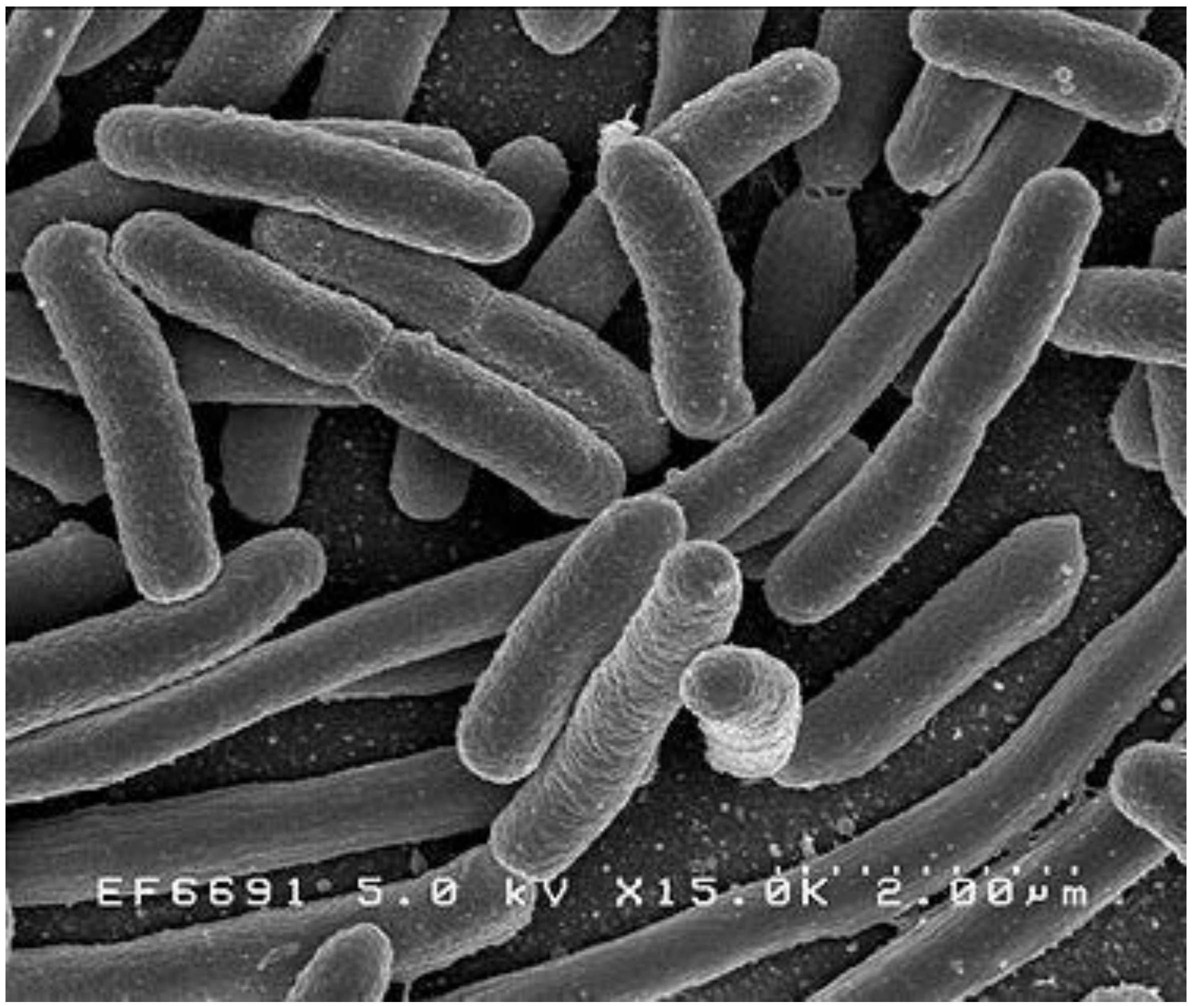
E. coli is a gram negative bacterium that propels itself using flagella

E. coli uses flagella to swim and “tumble”

Images of *E. coli* with flagella removed due to copyright restrictions.

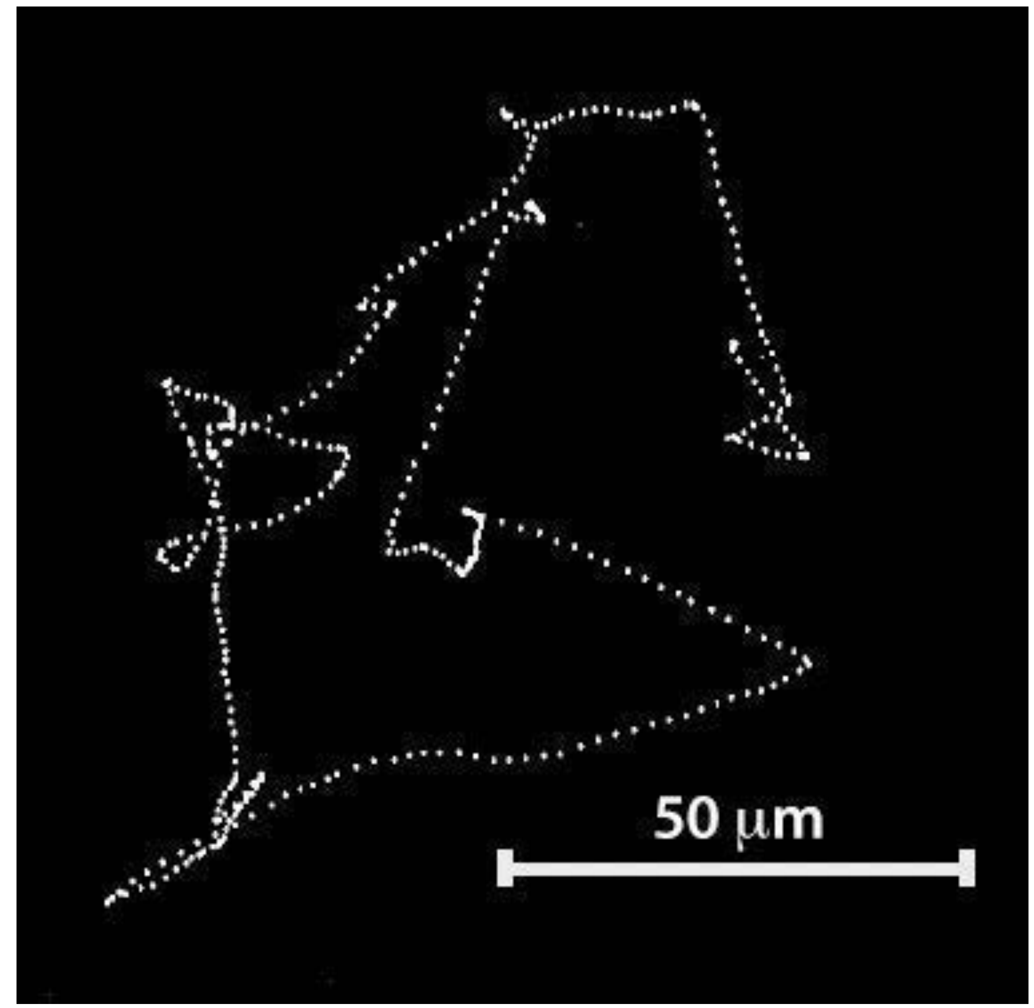
E. coli swimming (Re << 1)

Length ~5-10 microns



Courtesy of Rocky Mountain Laboratories, NIAID, NIH; image in the public domain.

Speed ~ 30 microns/sec

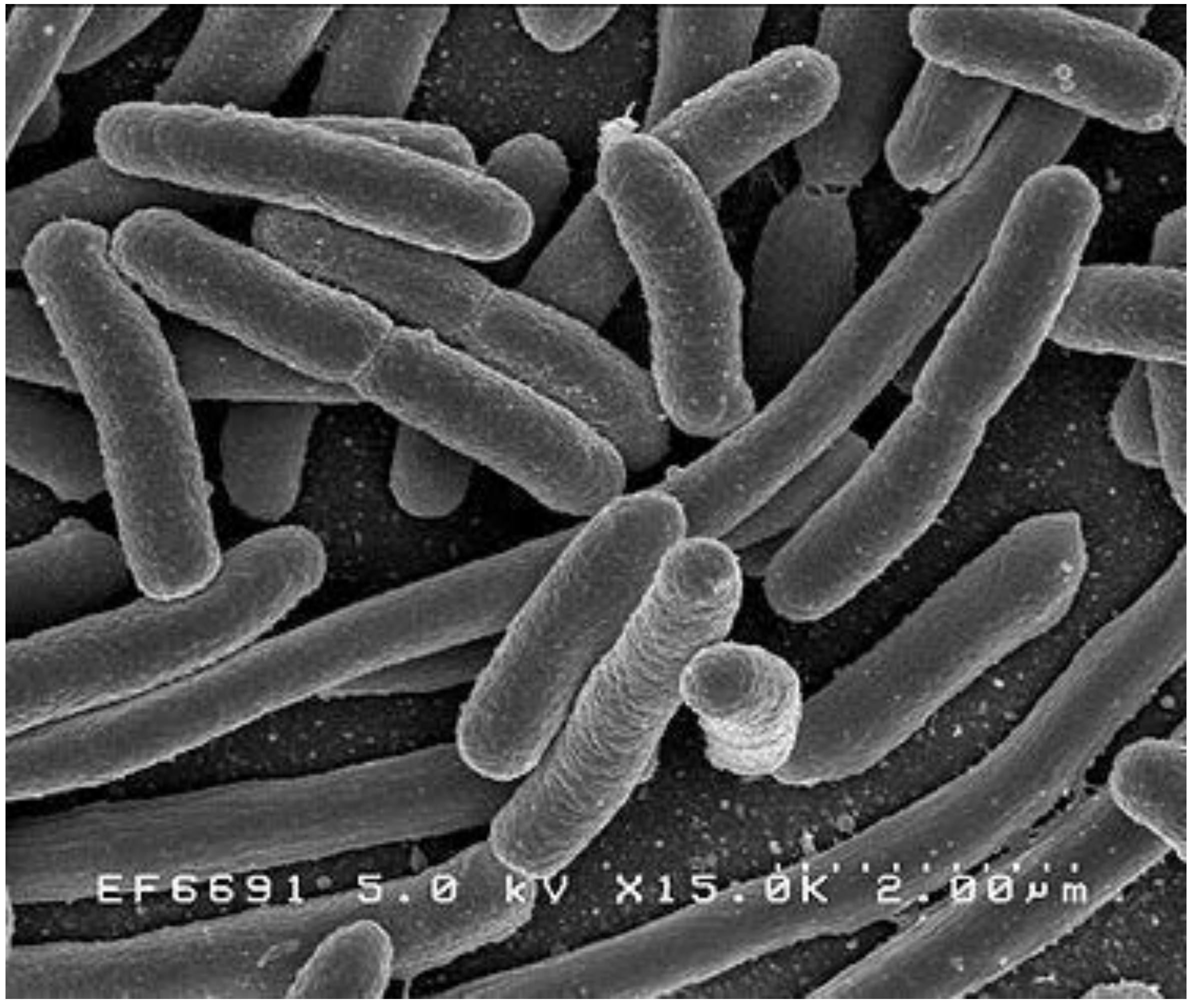


Courtesy of Howard Berg. Used with permission.

Q: How long does it take E. coli to "glide" to a halt if their flagella stop beating?

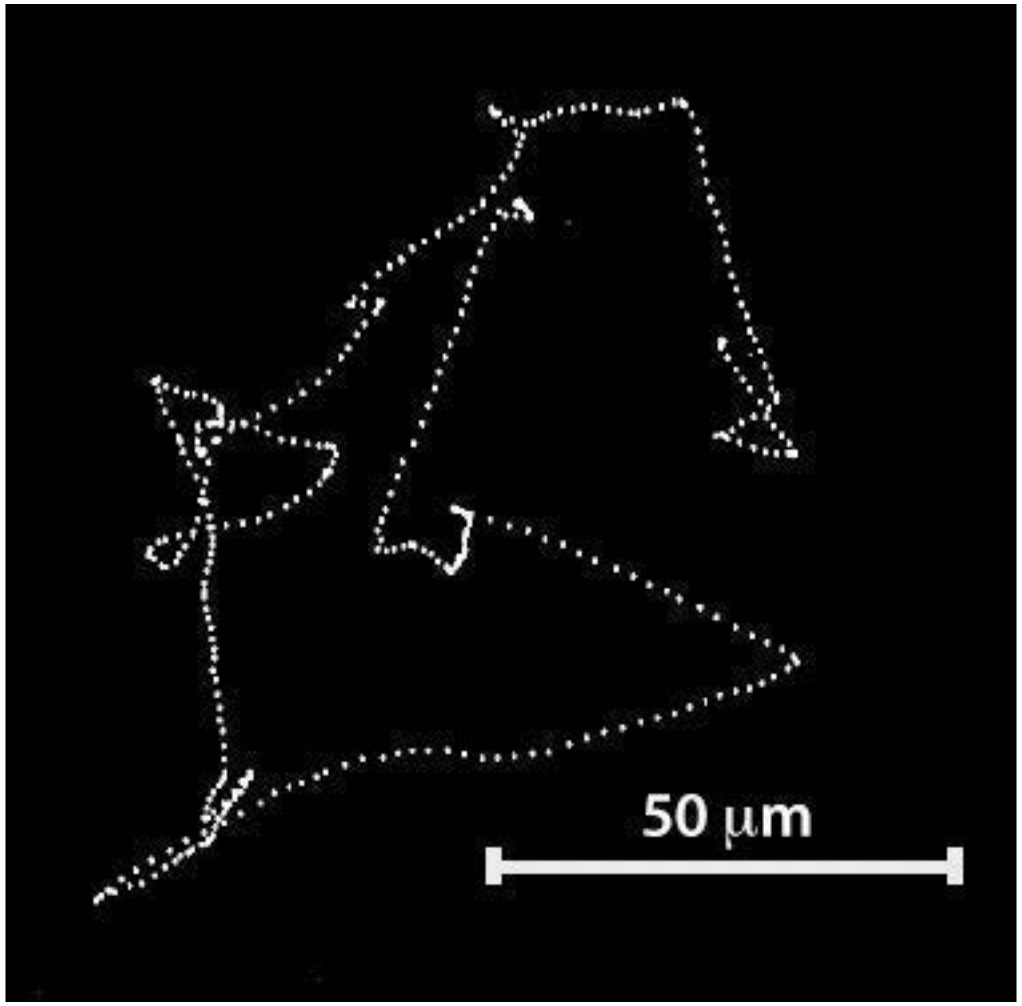
E. coli swimming (Re << 1)

Length ~5-10 microns



Courtesy of Rocky Mountain Laboratories, NIAID, NIH; image in the public domain.

Speed ~ 30 microns/sec

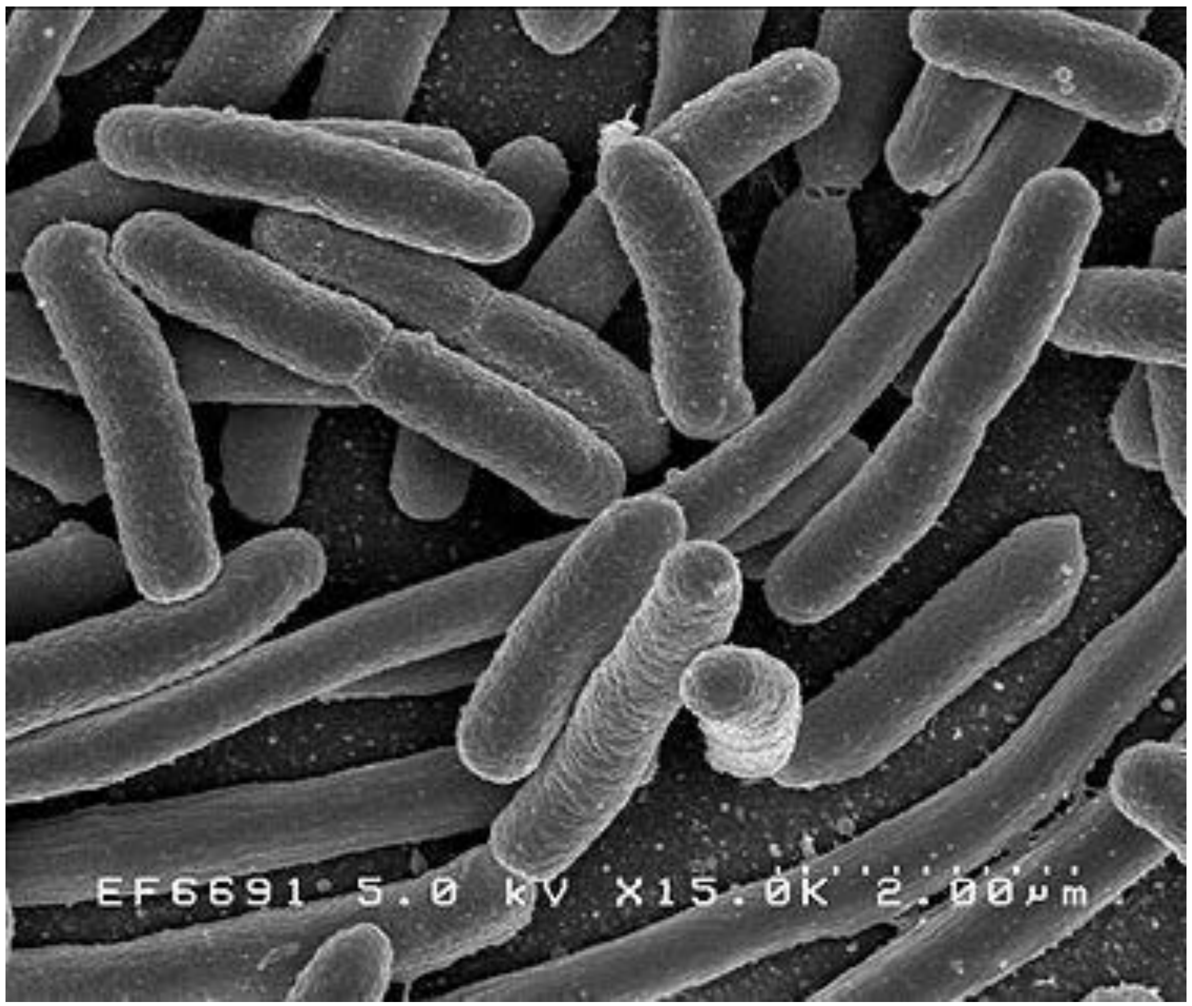


Courtesy of Howard Berg. Used with permission.

Q: How long does it take E. coli to “glide” to a halt if their flagella stop beating?
A: Less than 1 Angstrom!

E. coli swimming (Re << 1)

Length ~5-10 microns



Courtesy of Rocky Mountain Laboratories, NIAID, NIH; image in the public domain.

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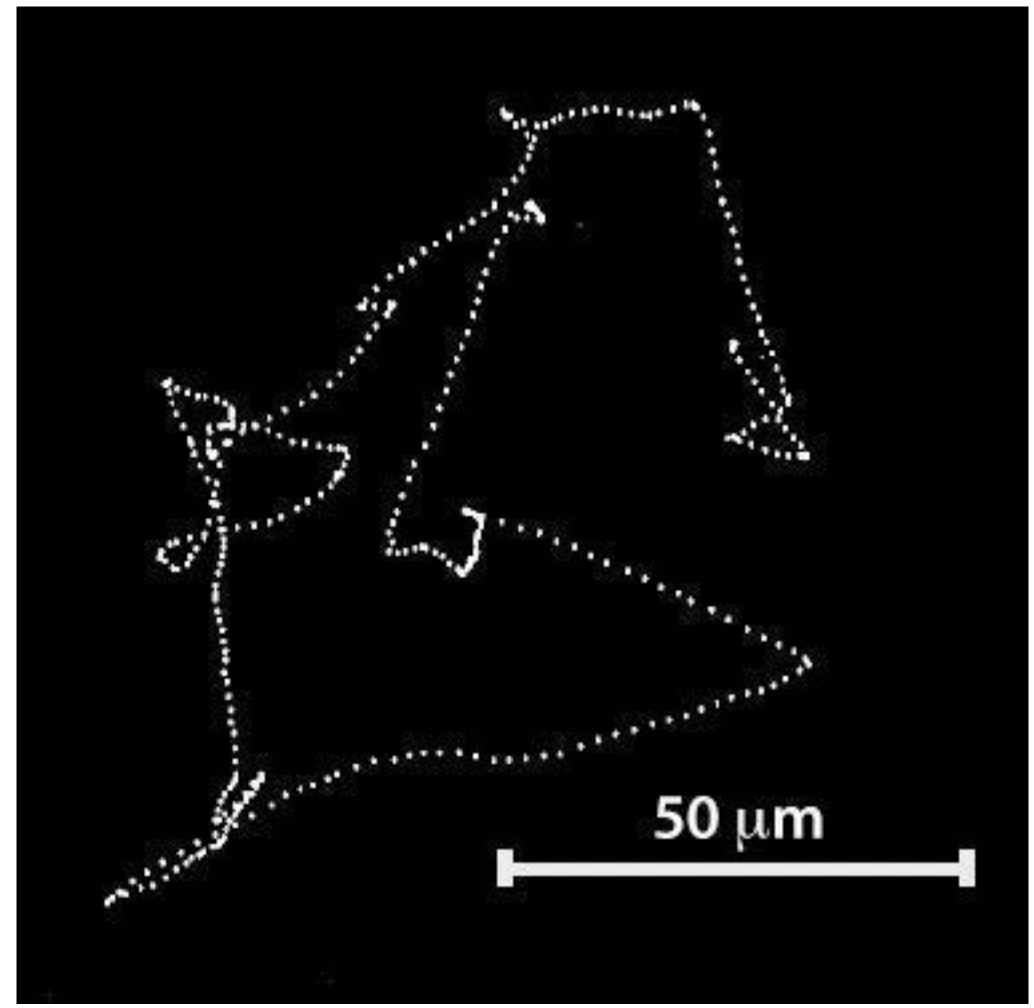
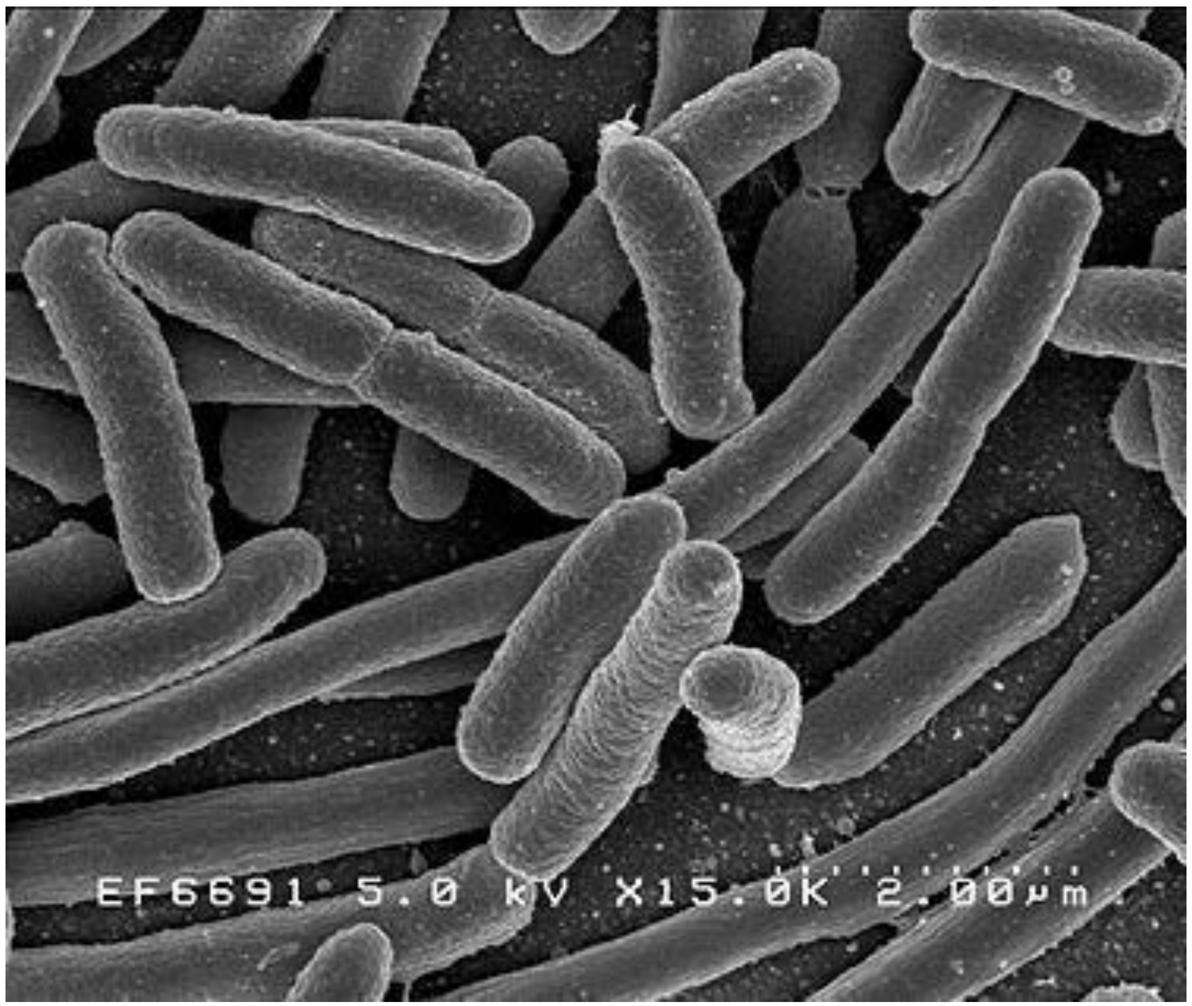


Courtesy of Howard Berg. Used with permission.

Q: What is the diffusivity of an E. coli?

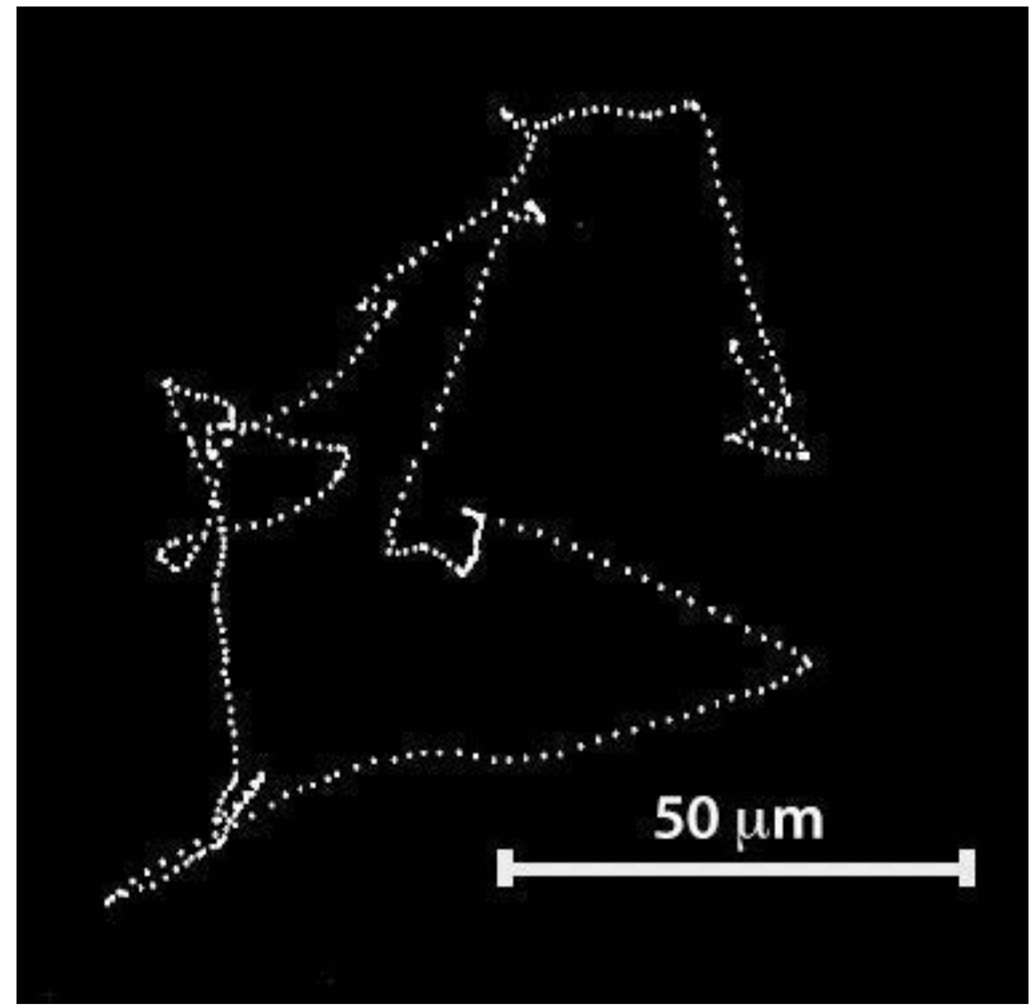
E. coli swimming (Re << 1)

Length ~5-10 microns



Courtesy of Rocky Mountain Laboratories, NIAID, NIH; image in the public domain.

Speed ~ 30 microns/sec



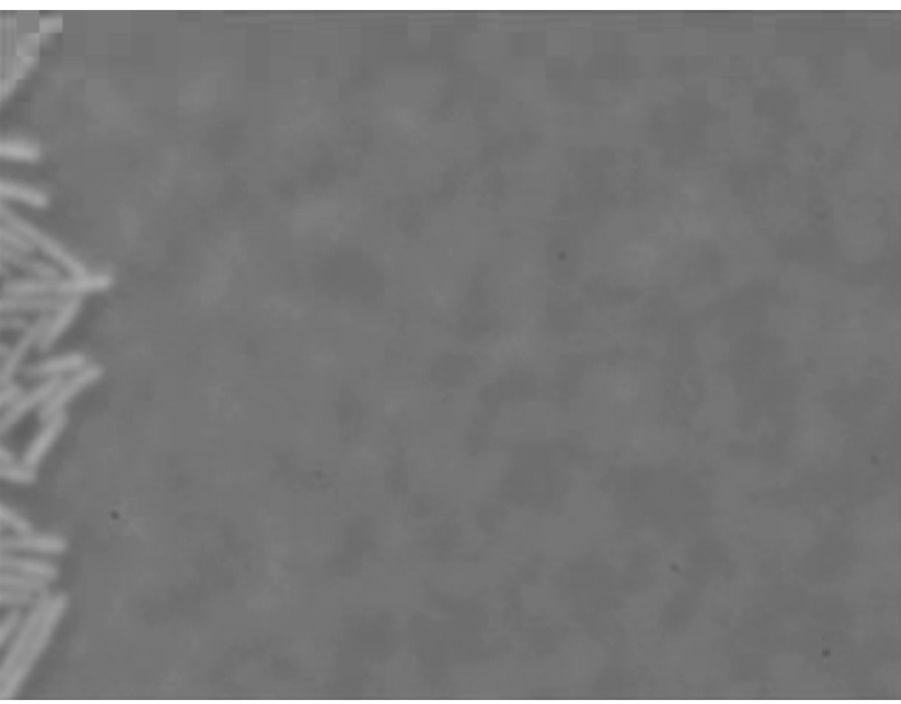
Courtesy of Howard Berg. Used with permission.

Q: What is the diffusivity of an E. coli?
A: D = 0.1 um^2/sec in water at room temp (using Stokes-Einstein with a = 1 um)

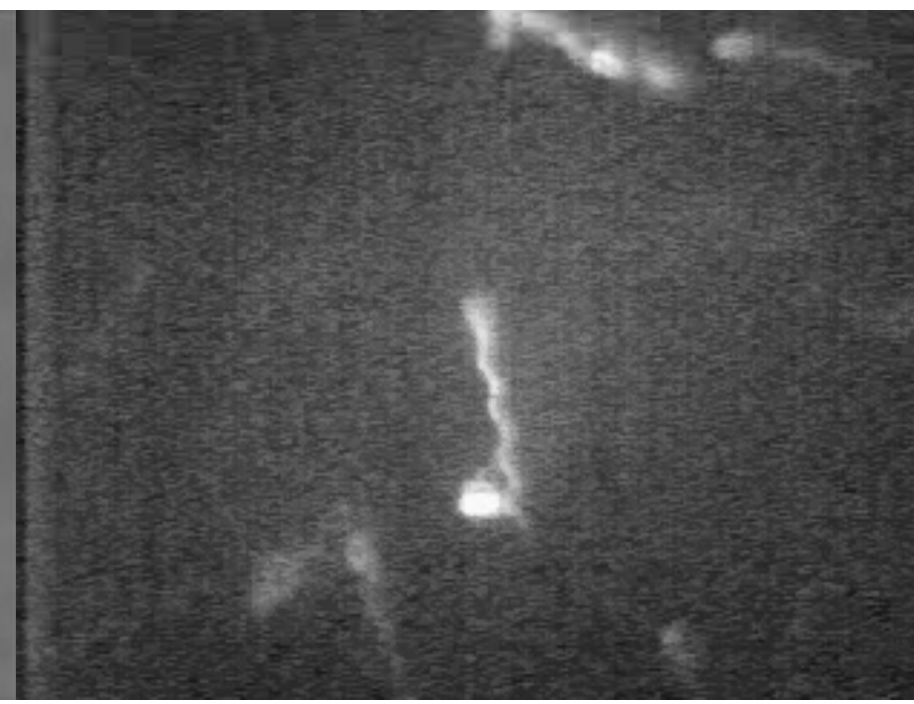
Imaging E. coli swimming

Howard Berg
Harvard University
Physics & MCB

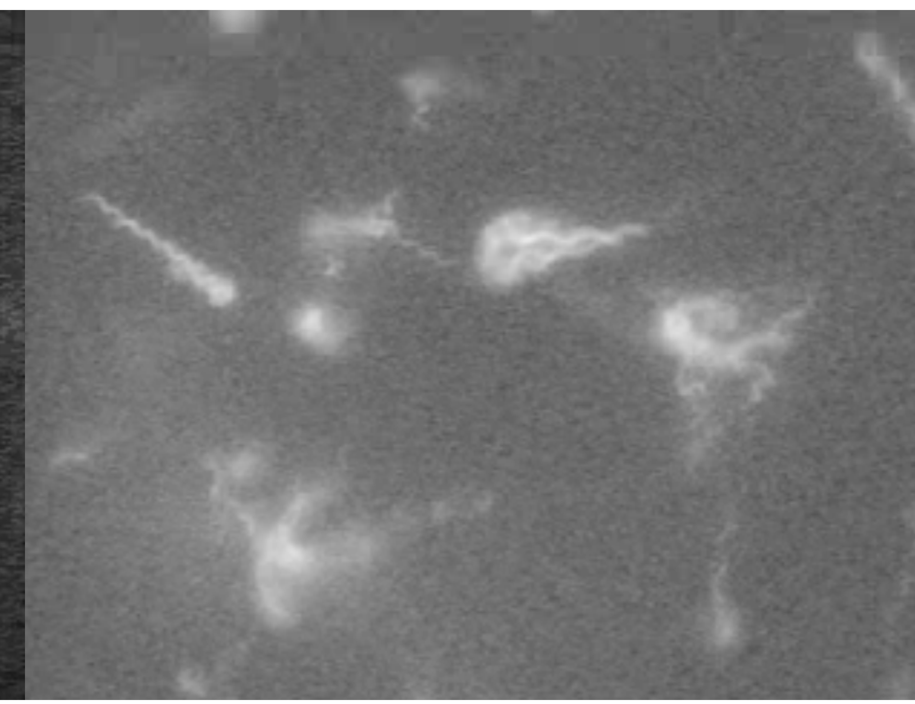
Swarm motility



Straight swimming



Swimming & tumbling



Movies of nanomotors in bacteria courtesy of Professor Howard Berg, from the Berg Laboratory, Bacterial Motility and Behavior:http://www.rowland.harvard.edu/labs/bacteria/index.html

Q: What is the diffusivity of an E. coli?
A: 0.1 um2/sec in water at room temp.

Low Reynolds Number Flow: Re < 1
(How to swim in corn syrup)

Part 1:
http://www.youtube.com/watch?v=4h079P7qRSw&feature=relmfu

Part II:
http://www.youtube.com/watch?v=2kkfHj3LHeE

Part III:
http://www.youtube.com/watch?v=s_5ygWhcxKk&feature=relmfu