Trabalhos: Relatórios

- Máximo de 10 páginas de conteúdo (sem contar capa, índice e referências);
- Word, latex, libre office...
- Discutir conceitos básicos aplicáveis: viscosidade, vorticidade, escoamento laminar/turbulento, fluido newtoniano/não-newtoniano, etc;
- Equações de movimento: Difusão, Euler, Navier-Stokes, etc;
- Interação fluid-sólido: tensão de cisalhamento, condições de contorno, força de arrasto e de levantamento, etc;
- Resultados de simulações, experiências e/ou cálculos analíticos;
- Escrever com as próprias palavras (não copiar trechos de outros lugares);
- Títulos podem ser outros que não os da tabela;
- Incluir bibliografia.

Creeping flow (Stokes)

- Approximation of the class of fluid flow called creeping flow.
- Other names for this class of flow include Stokes flow and low Reynold number flow.
- As the latter name implies, these are flows in which the Reynolds number is very small ($Re << 1$).
- By inspection of the definition of the Reynolds number, $Re = \rho VL/\mu$, we see that creeping flow is encountered when either ρ, V, or L is very small or viscosity is very large (or some combination of these).

$$R_e = \frac{L \cdot V}{\nu} \qquad \mu = \rho \cdot \nu$$

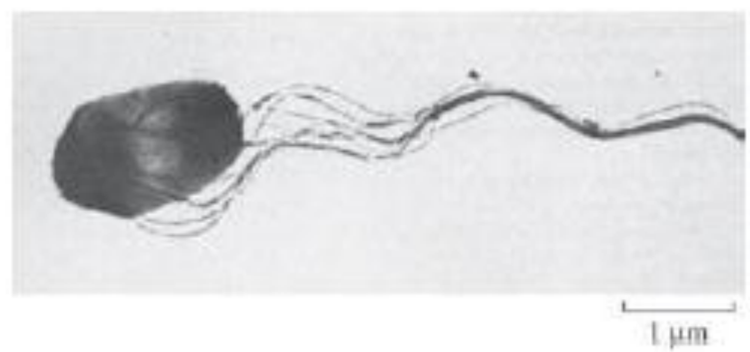
Sec. 10.3, Çengel

Stokes flow

- Another example of creeping flow is all around us and inside us, although we can't see it, namely, flow around microscopic organisms. Microorganisms live their entire lives in the creeping flow regime since they are very small, their size being of order a few microns, and they move very slowly, even though they may move in air or swim in water with a viscosity that can hardly be classified as "large". $\mu_{air} \cong 18.5\ \mu N{\cdot}s/m^2$ and $\mu_{water} \cong 1.002\ mN{\cdot}s/m^2$ at room temperature – for comparison, $\mu_{honey} \cong 6\ N{\cdot}s/m^2$.

- Salmonella bacterium swimming through water. The bacterium's body is only about 1 μm long; its flagella (hairlike tails) extend several microns behind the body and serve as its propulsion mechanism. The Reynolds number associated with its motion is much smaller than 1 (typically, Re=10^{-5} – 10^{-4}).

(a)



(b)

Stokes flow

- For simplicity, we assume that gravitational effects are negligible, or that they contribute only to a hydrostatic pressure component, as discussed previously.
- We also assume either steady flow or oscillating flow, with a Strouhal number of order unity ($St < 1$) or smaller, so that the unsteady acceleration term is orders of magnitude smaller than the viscous term [1/Re] (the Reynolds number is very small).
- The advective term is of order 1, so this term drops out as well.

Thus, we ignore the entire left side of NS, which reduces to

Nondimensionalized Navier–Stokes:

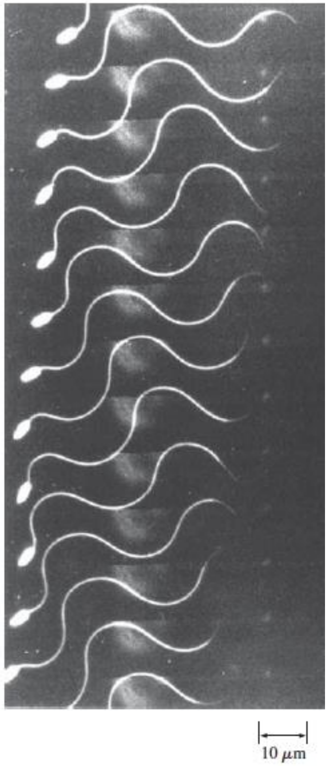
$$\cancelto{0}{[\mathrm{St}]\frac{\partial \vec{V}^*}{\partial t^*}} + \cancelto{0}{(\vec{V}^* \cdot \vec{\nabla}^*)\vec{V}^*} = -[Eu]\vec{\nabla}^* P^* + \cancelto{0}{\left[\frac{1}{\mathrm{Fr}^2}\right]\vec{g}^*} + \left[\frac{1}{\mathrm{Re}}\right]\nabla^{*2}\vec{V}^*$$

Creeping flow approximation:

$$[\mathrm{Eu}]\vec{\nabla}^* P^* \cong \left[\frac{1}{\mathrm{Re}}\right]\nabla^{*2}\vec{V}^*$$

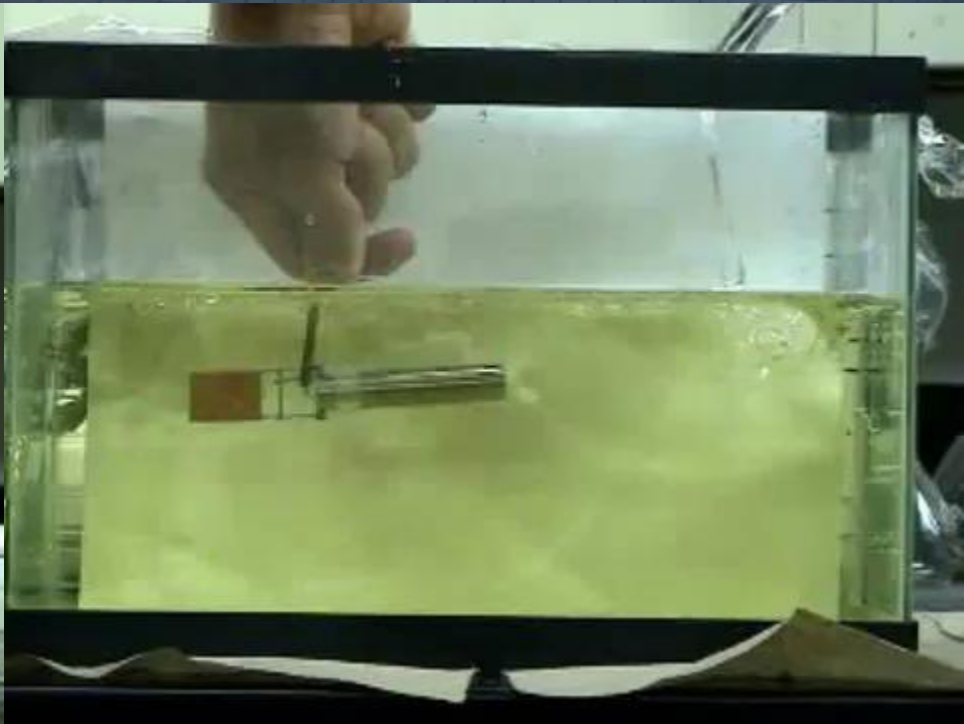
Approximate Navier–Stokes equation for creeping flow: $\boxed{\vec{\nabla} P \cong \mu \nabla^2 \vec{V}}$

You rely on inertia when you swim. For example, you take a stroke, and then you are able to glide for some distance before you need to take another stroke. When you swim, the inertial terms in the Navier–Stokes equation are much larger than the viscous terms, since the Reynolds number is very large.

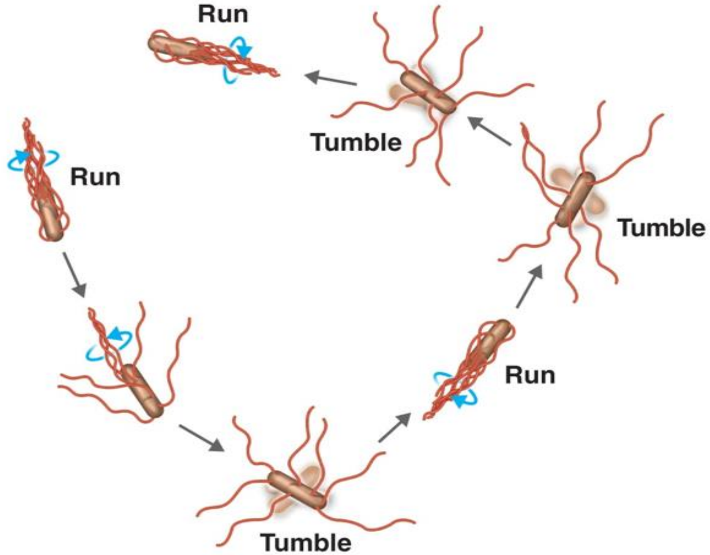


For microorganisms swimming in the creeping flow regime, however, there is negligible inertia, and thus no gliding is possible. In fact, the lack of inertial terms has a substantial impact on how microorganisms are designed to swim. A flapping tail like that of a dolphin would get them nowhere. Instead, their long, narrow tails (flagella) undulate in a sinusoidal motion to propel them forward, as illustrated for a sperm. Without any inertia, the sperm does not move unless his tail is moving. The instant his tail stops, the sperm stops moving.

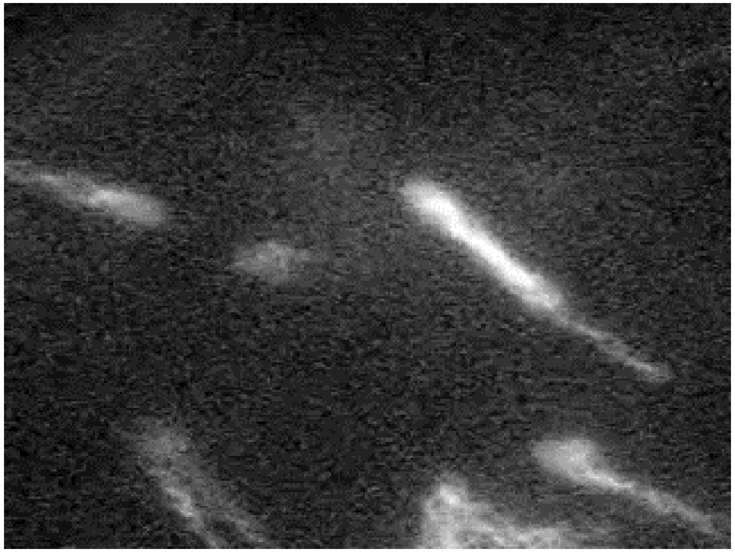
Consequences of kinetic reversibility



How do micro-scale organisms swim?



Microbiology: an introduction. G. Tortora et al., Pearson (2016)



From Howard C. Berg's WEB site

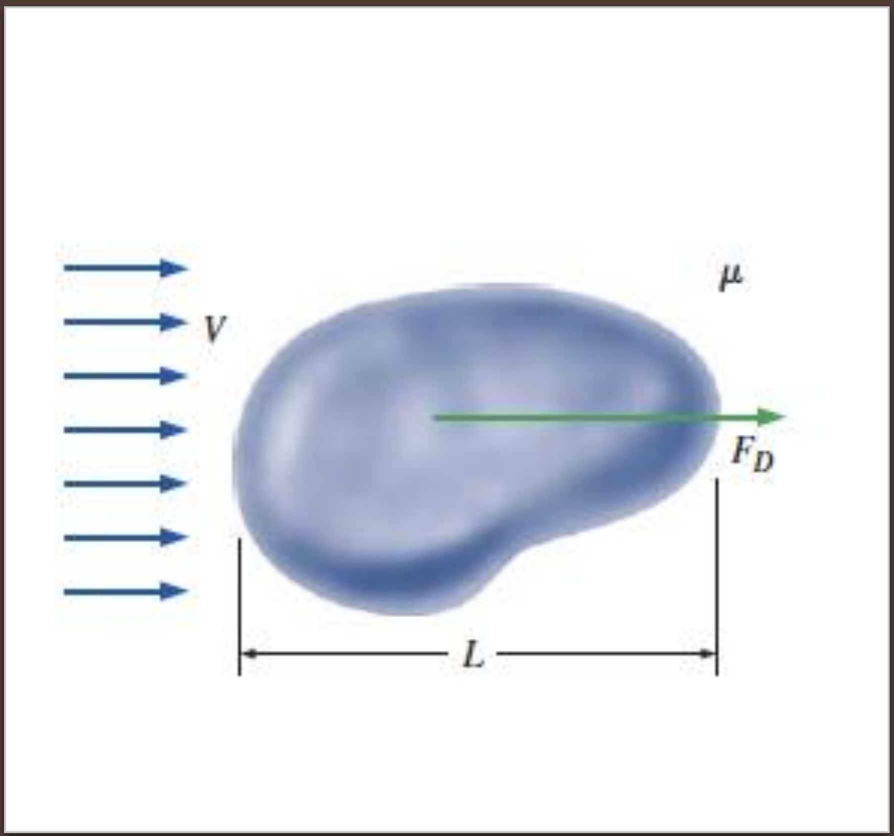
Reynolds number = 10^{-5}

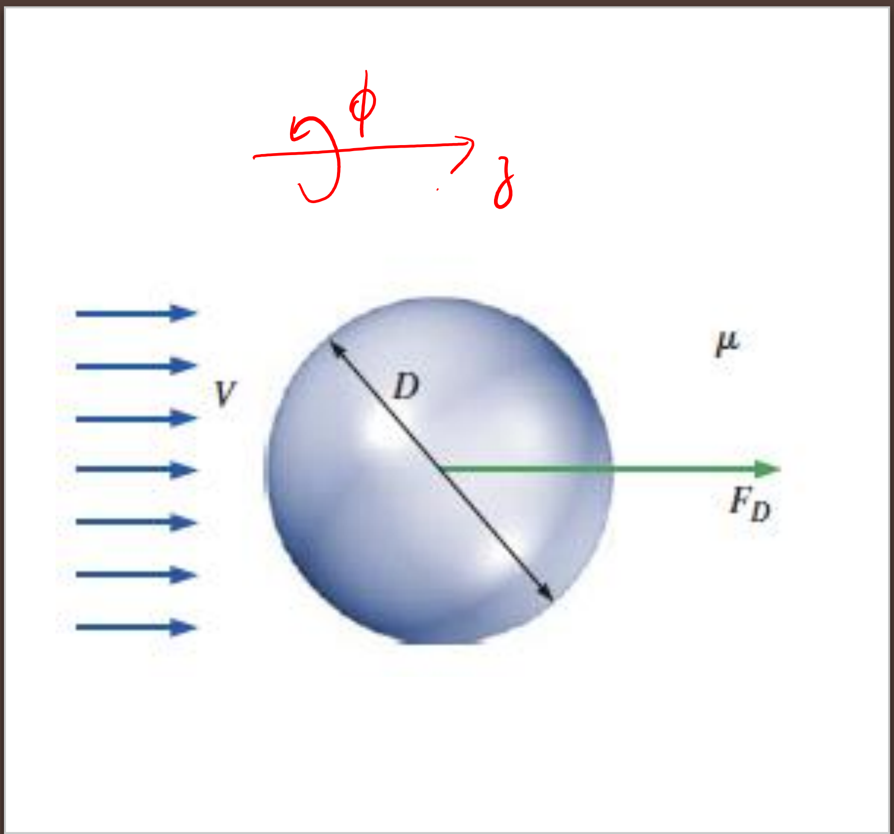
Equivalent to a human swimming on hot tar

Brad Nelson, Robotics and Intelligent Systems at ETH Zürich

Drag in Stokes flow

Drag force on a sphere in creeping flow: $F_D = 3\pi\mu V D$

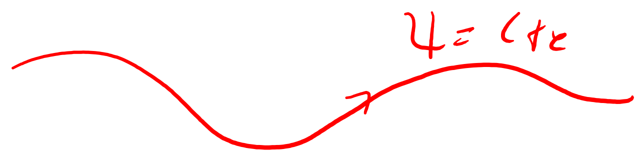




Stokes stream function

(Acheson, page 173)

For axisymmetric incompressible flow, we can write in spherical coordinates:



$$\boldsymbol{u} = \nabla \wedge \left(\frac{\Psi}{r \sin\theta} \boldsymbol{e}_\phi \right)$$

$$u_r = \frac{1}{r^2 \sin\theta} \frac{\partial \Psi}{\partial \theta}, \qquad u_\theta = -\frac{1}{r \sin\theta} \frac{\partial \Psi}{\partial r}$$

The Stokes stream function is constant along streamlines:

$$\frac{D\Psi}{Dt} = \quad (\boldsymbol{u} \cdot \nabla)\Psi = u_r \frac{\partial \Psi}{\partial r} + \frac{u_\theta}{r} \frac{\partial \Psi}{\partial \theta} = 0$$

$$\frac{\partial \Psi}{\partial t} = 0$$