Chemical Engineering 374

Fluid Mechanics

External Flows and Drag

Spiritual Thought

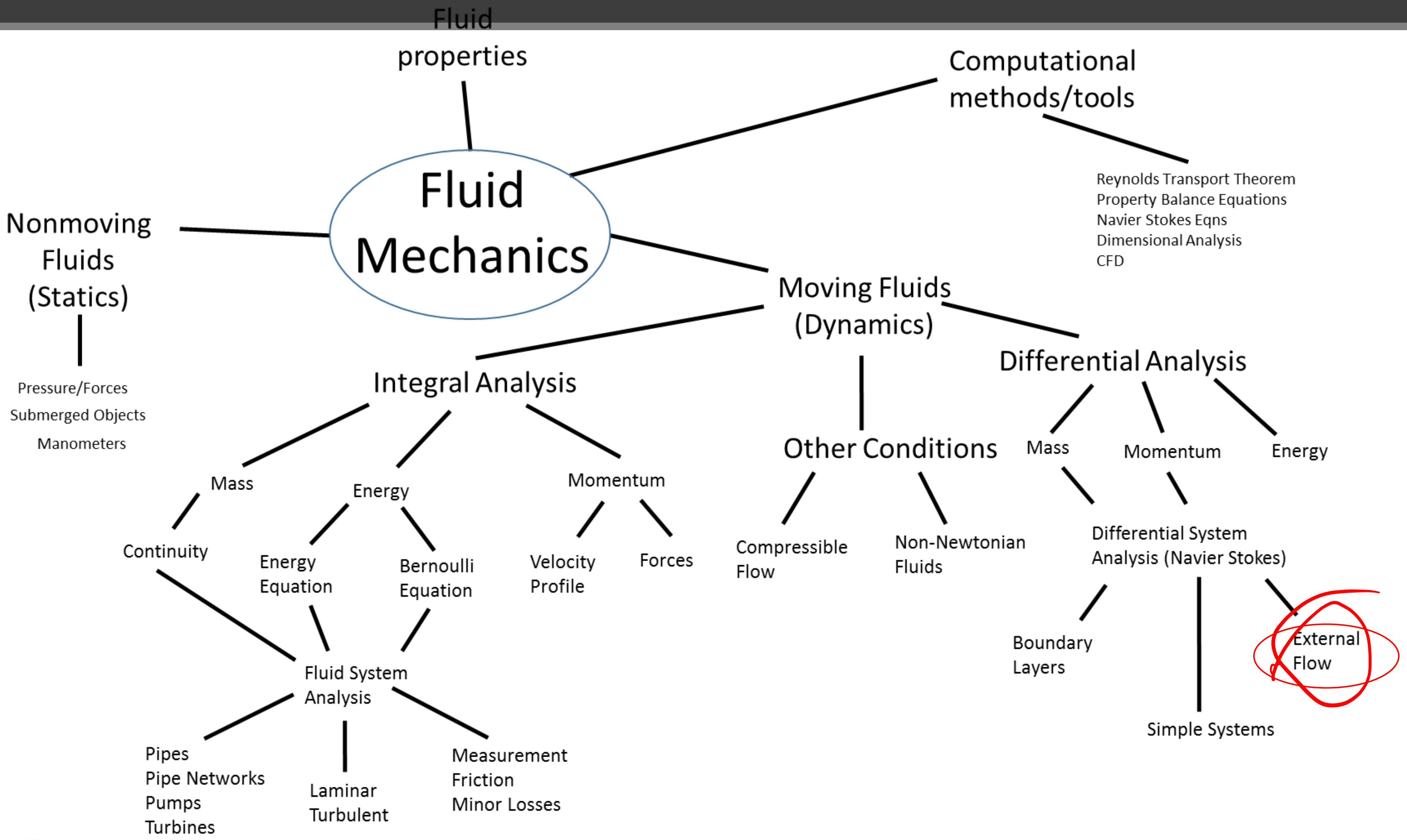
2 Nephi 2:25

25. Adam fell that men might be; and men are, that they might have joy.

“Joy is more than happiness. Joy is the ultimate sensation of well-being. It comes from being complete and in harmony with our Creator and his eternal laws.”

Elder Dallin H. Oaks

Fluids Roadmap



Fluid properties

Computational methods/tools

Reynolds Transport Theorem
Property Balance Equations
Navier Stokes Eqns
Dimensional Analysis
CFD

Fluid Mechanics

Nonmoving Fluids (Statics)

Pressure/Forces
Submerged Objects
Manometers

Moving Fluids (Dynamics)

Integral Analysis

Mass

Continuity

Energy

Energy Equation

Bernoulli Equation

Momentum

Velocity Profile

Forces

Fluid System Analysis

Pipes
Pipe Networks
Pumps
Turbines

Laminar
Turbulent

Measurement
Friction
Minor Losses

Other Conditions

Compressible Flow

Non-Newtonian Fluids

Differential Analysis

Mass

Momentum

Energy

Differential System Analysis (Navier Stokes)

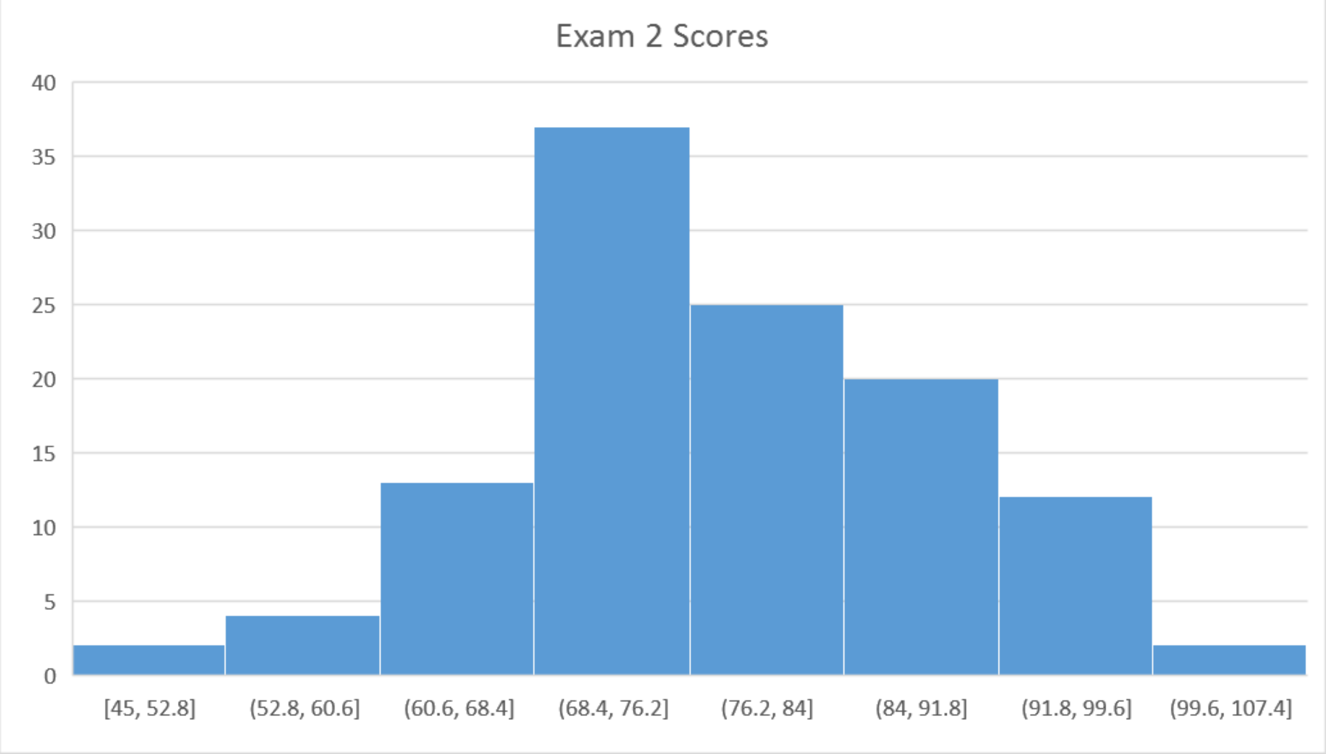
Boundary Layers

Simple Systems

External Flow

Test 2 Results

	Problem 1	Problem 2	Problem 3	Problem 4	Total
Average	20.7	21.0	17.7	18.5	78.0
High	25.0	30.0	25.0	20.0	100.0
Low	13.0	5.0	7.0	7.0	45.0
Median	21.0	20.0	15.0	20.0	76.5
StDev	2.8	6.5	4.7	3.0	10.7

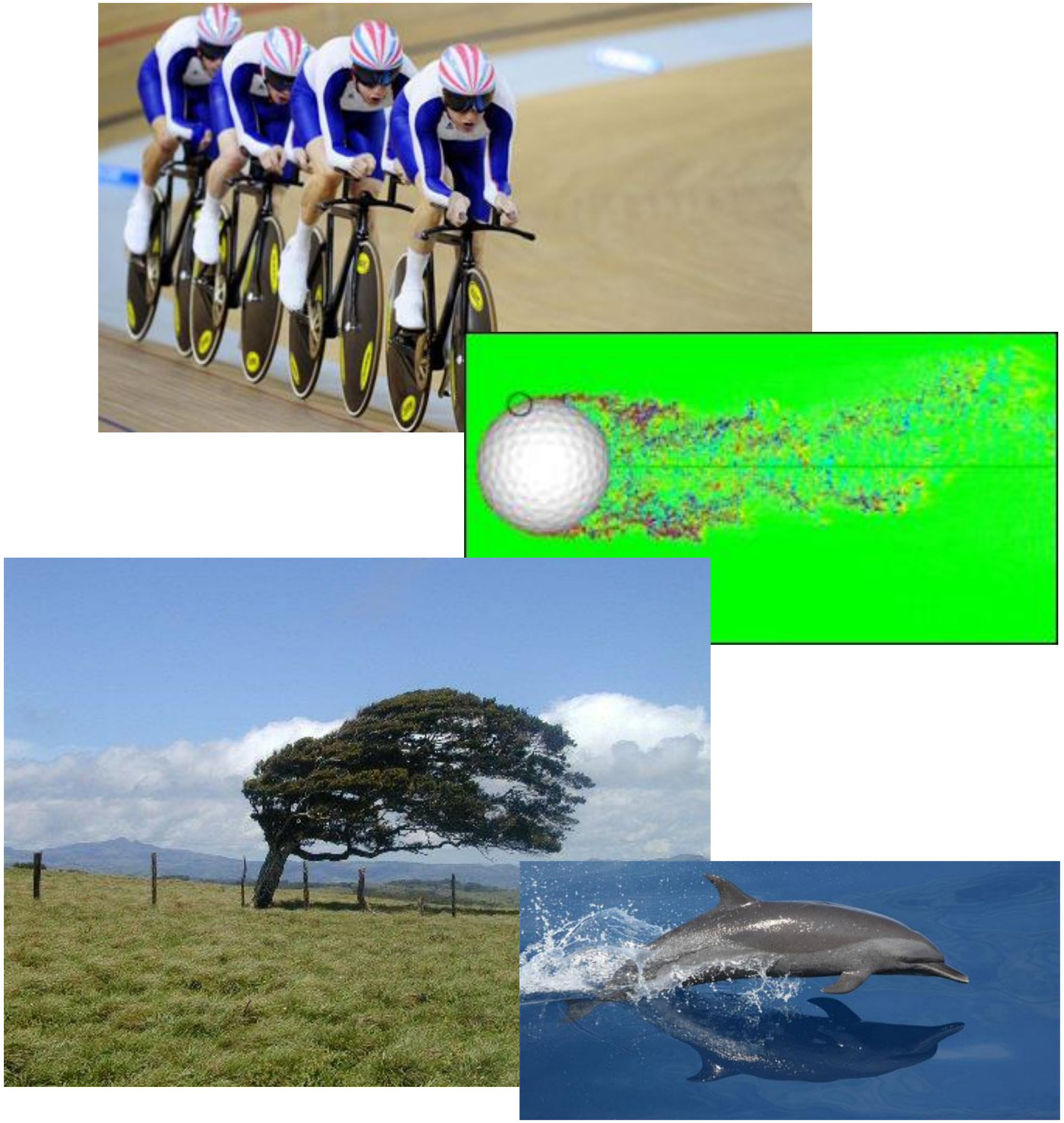


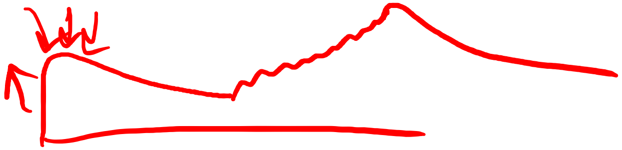
Key Points

- Drag
  - Friction
  - Pressure
- Streamlines/separation
  - Friction effects on streamlines
- Calculating Drag
  - Drag coefficient
  - Projected frontal area
- Examples

Introduction

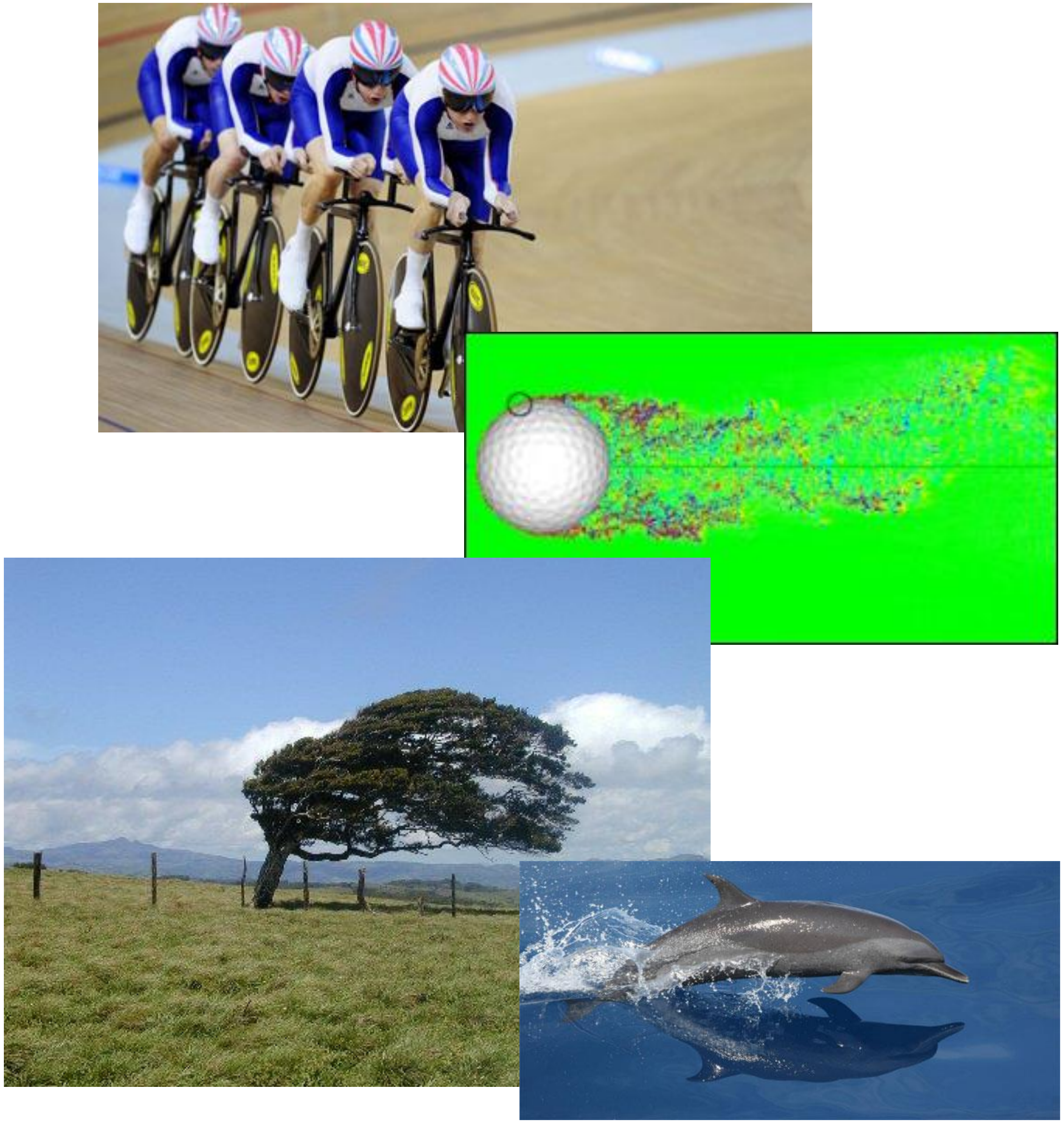
- Previous
  - Internal flows:
  - Flows in pipes
  - Friction
- Last time
  - Boundary layers
- Today
  - Flow around objects
    - Separation
    - Streamlining
  - Drag
    - Coefficients
  - Calculations



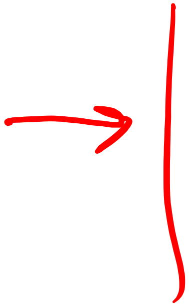


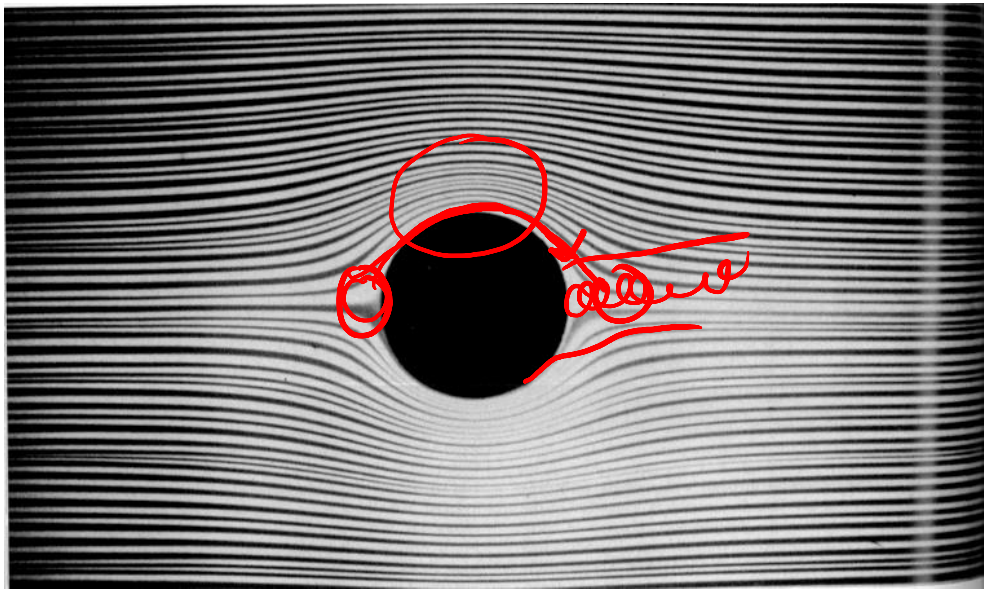
Some Questions

- Why are golf balls dimpled but ping pong balls are smooth?
- Why are cars streamlined?
- How and why does shape matter?
- What is separation and how does it form?
- What happens to the velocity of falling objects?



- What is drag
- Where does it come from?
- What affects it?
- …
- Some pictures…





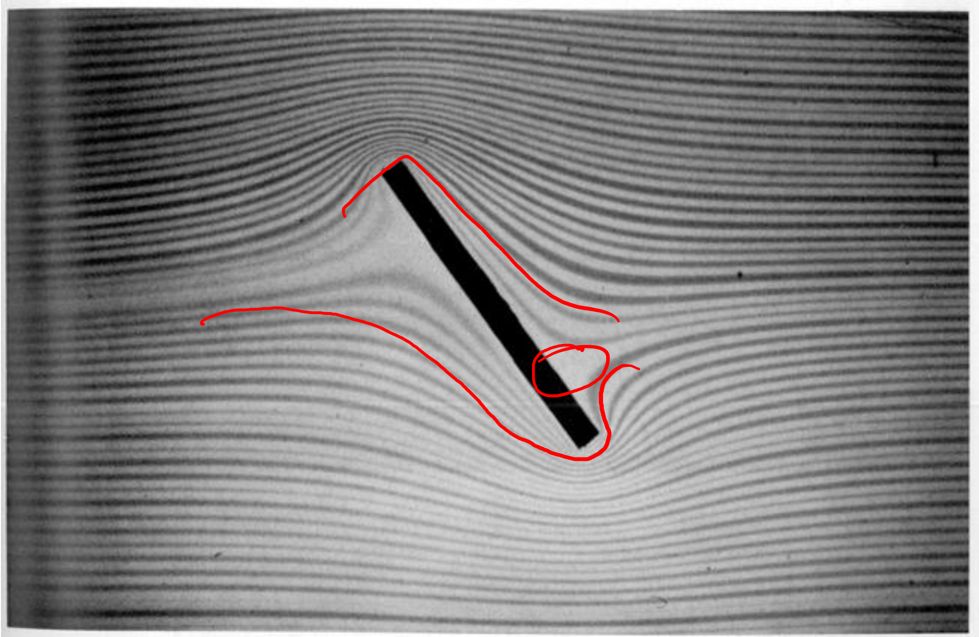
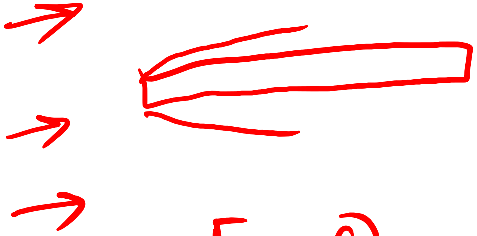
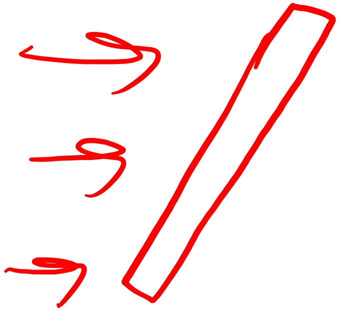


Plate Orientation



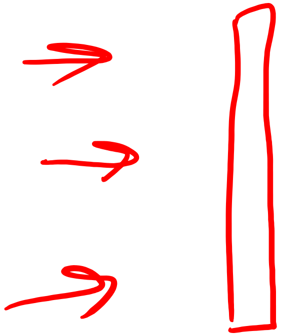
$F_p = 0$

$F_f = b$



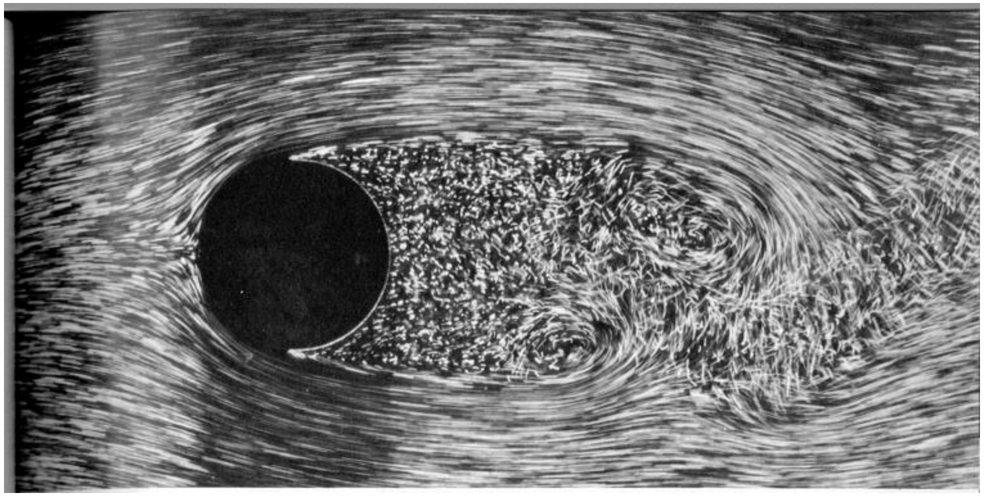
$F_p = a$

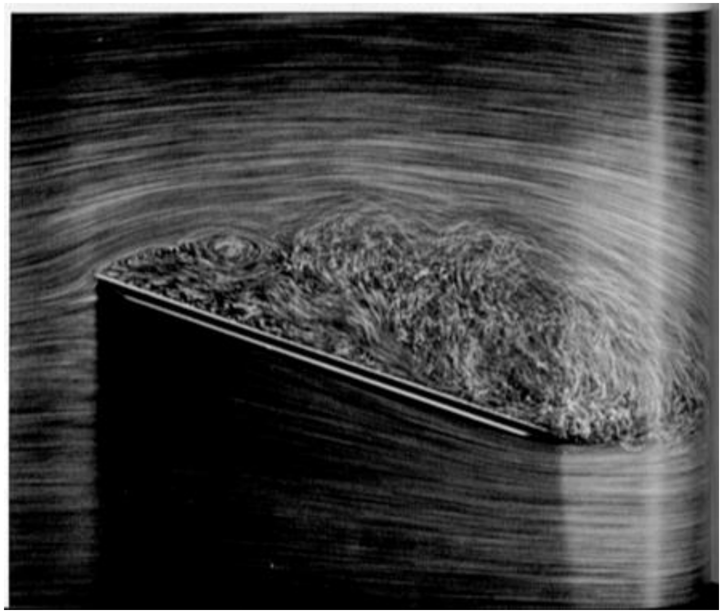
$F_f = c$

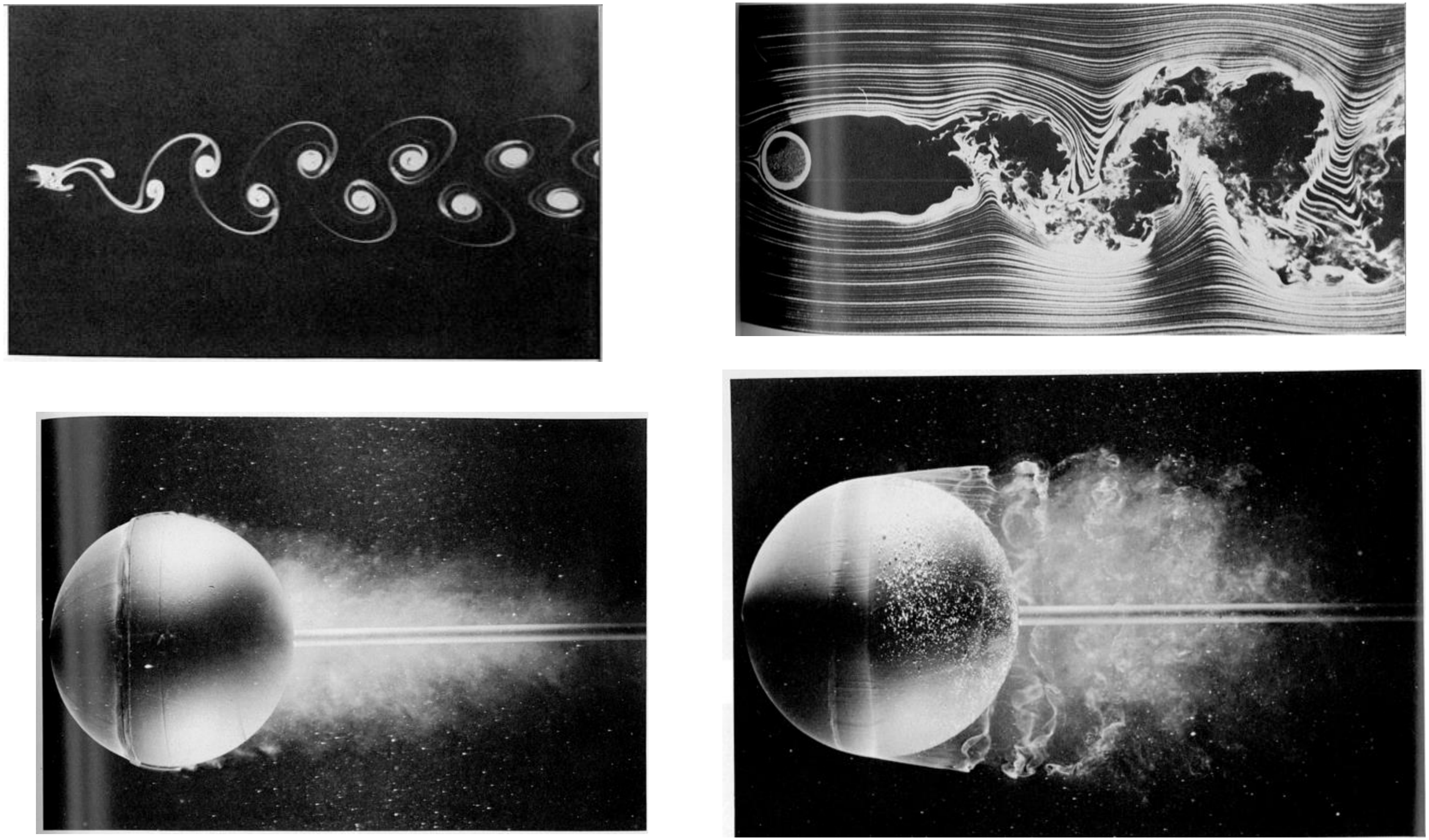


$F = d$

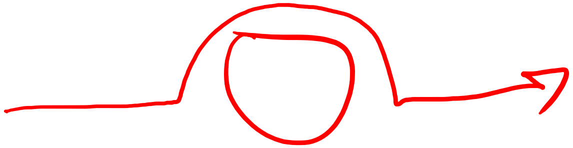
$F_f = 0$







Streamlining

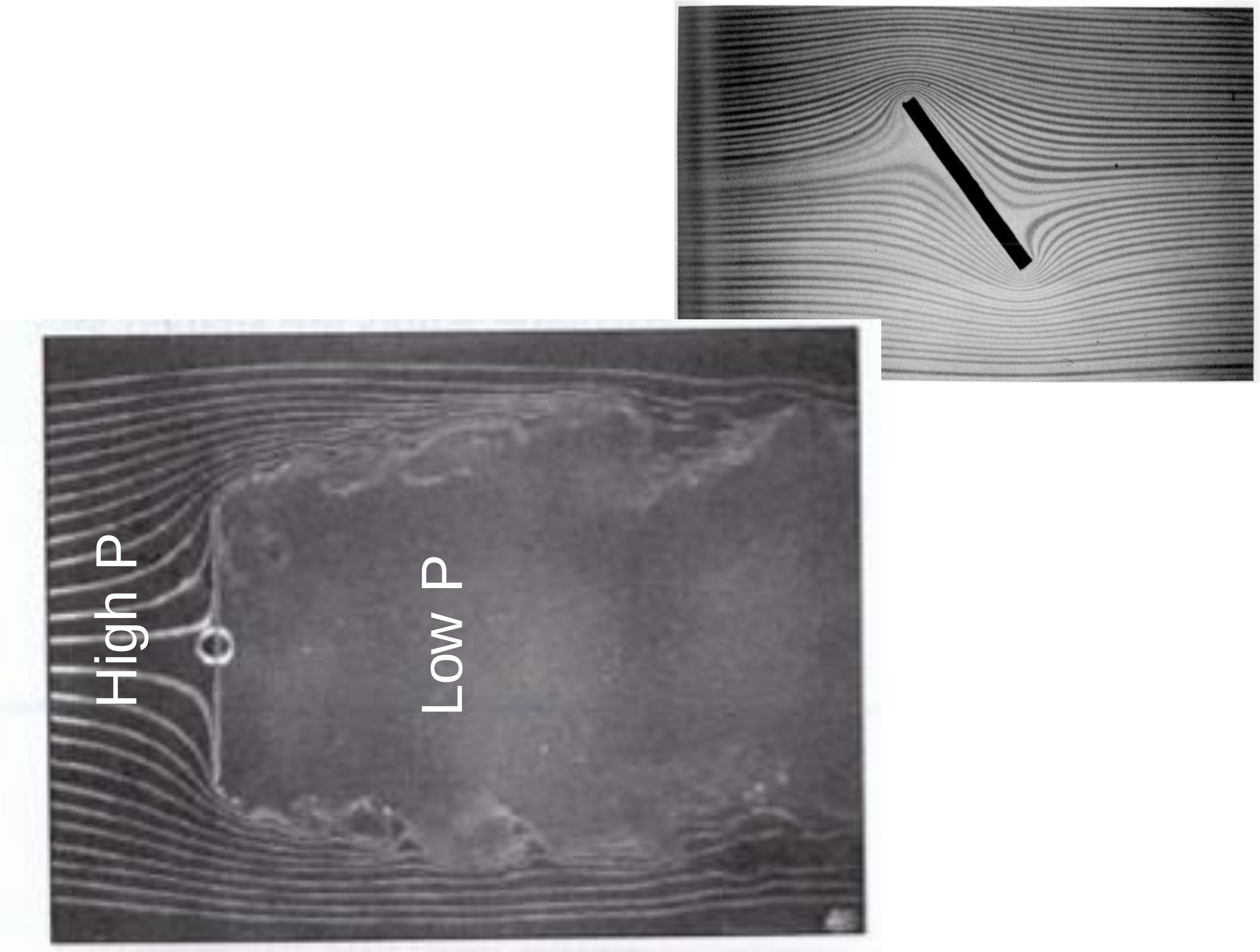


- Streamlines get closer, v increases
  - * fluid squeezed between smaller channels

Bernoulli Eq. for frictionless flow:

$$\frac{P}{\rho} + \frac{v^2}{2} = C$$

Forces, Separation

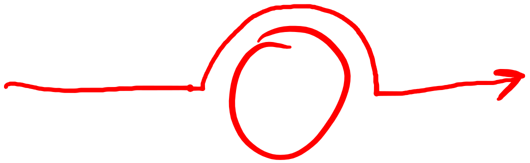


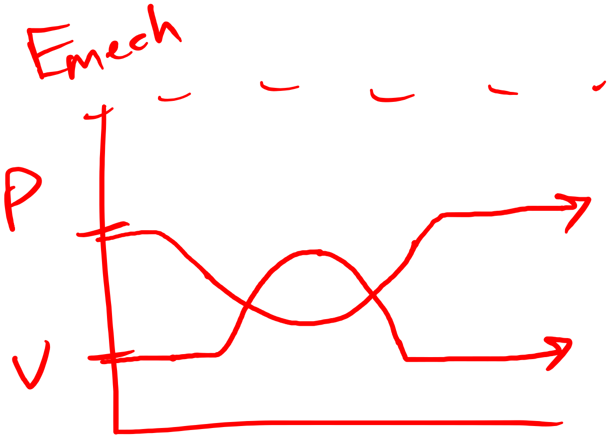
Net Force →

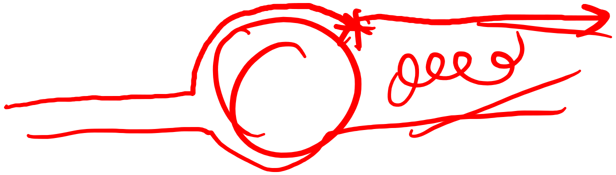
Separation

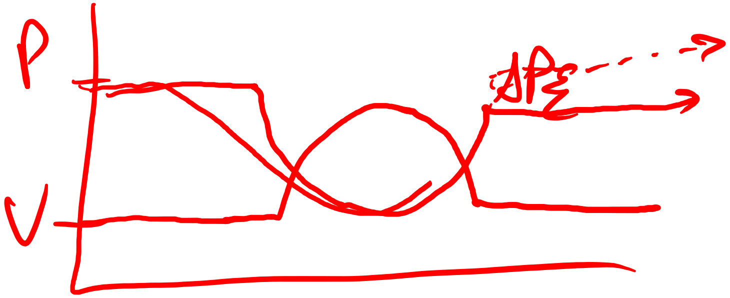
No friction

Friction





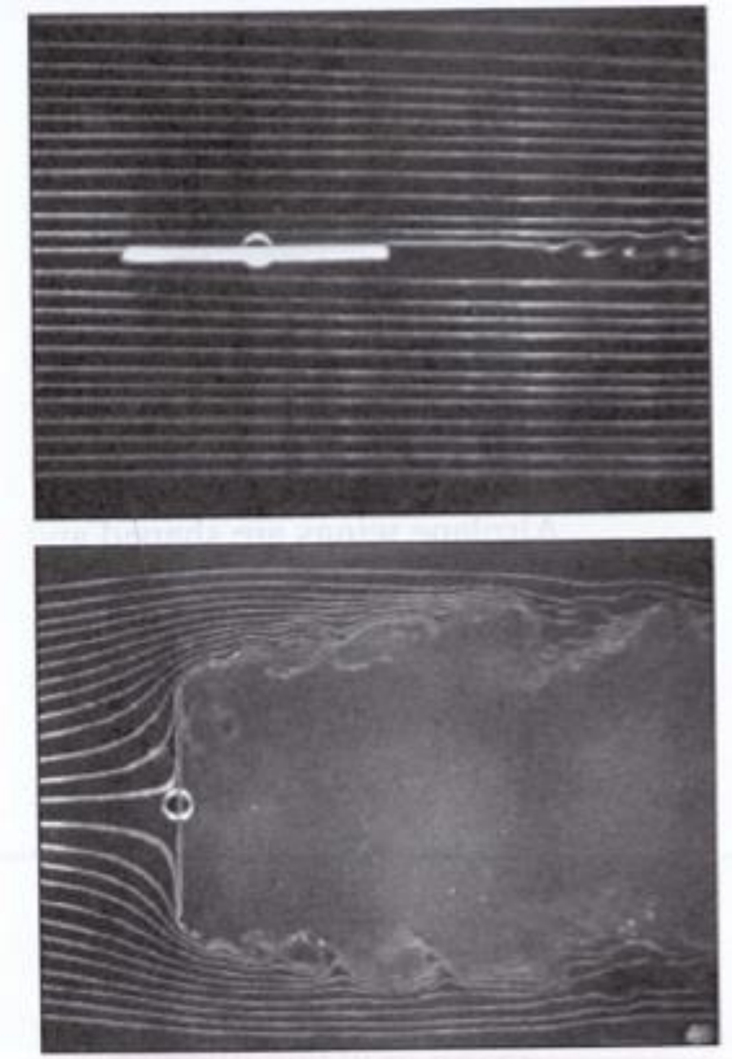




Drag

- What is drag
- Where does it come from?
- What affects it?

- "Drag is the net force a fluid exerts on a body in the flow direction"
- Two types:
  - –Friction drag
    - Along the surface
    - Dominates at low speeds (lower Re)
  - –Pressure drag
    - Normal to the surface
    - "Form drag"
    - Dominates at higher speeds (higher Re)
    - Primarily due to flow separation / wakes



Drag Evaluation

F_D, ρ, μ, V, L (or A), ε

6 parameters
− 3 dimensions
3 π's

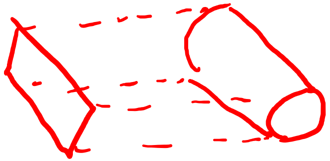
Pipes: $f = \overset{\text{Lam}}{\overline{f(Re)}}$ or $\overset{\text{turb.}}{\overline{f(Re, \varepsilon/D)}}$ → $f \sim \frac{\Delta P}{\rho V^2} \cdot \frac{D}{2}$

Here: $C_d = C_d(Re, \varepsilon/L)$

$$f \sim \frac{F/A}{\rho V^2}$$

$$C_d = \frac{F}{A \rho_f V^2/2}$$

A is the projected frontal Area



Drag Coefficients

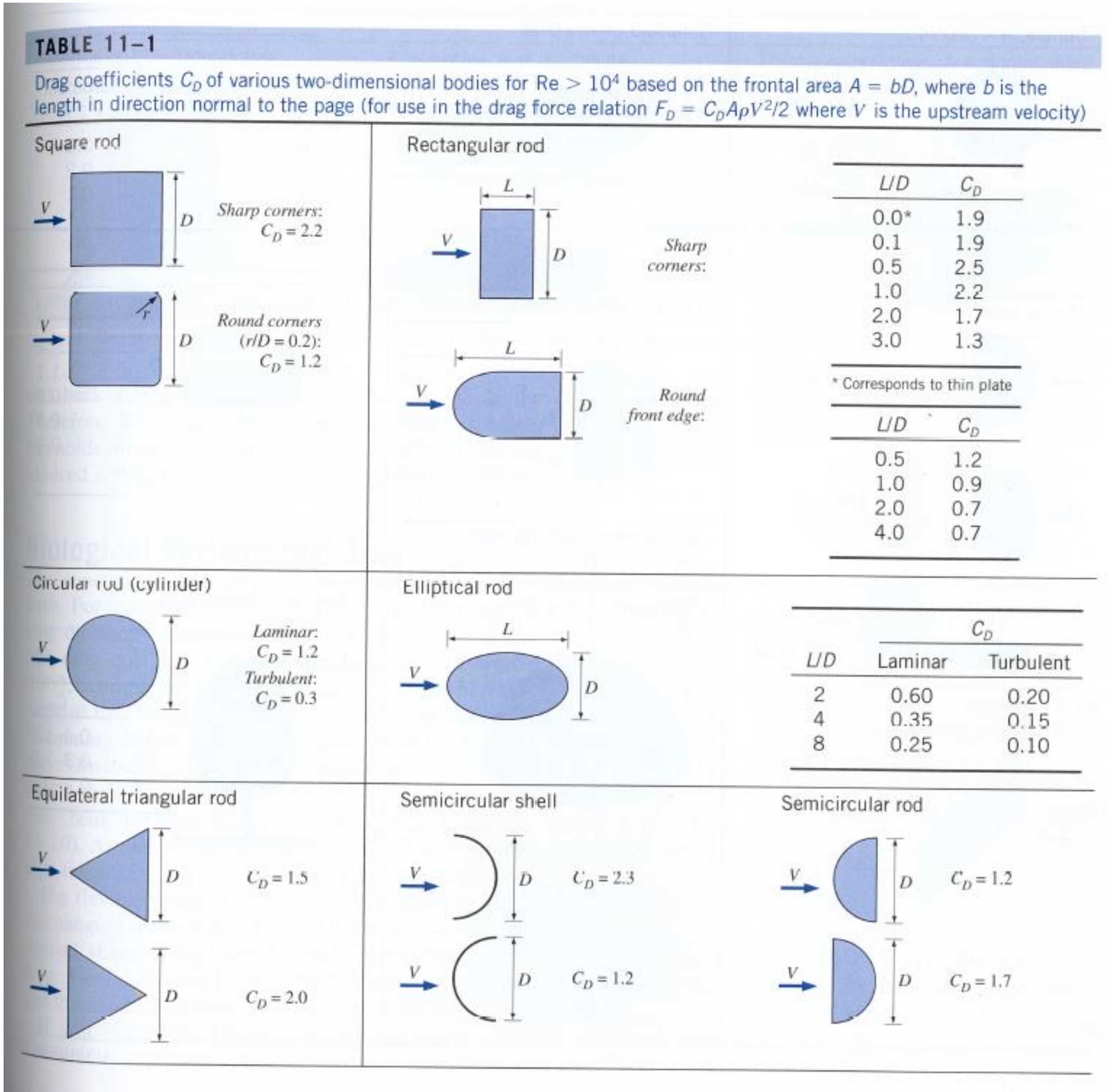


TABLE 11–1

Drag coefficients C_D of various two-dimensional bodies for Re $> 10^4$ based on the frontal area $A = bD$, where b is the length in direction normal to the page (for use in the drag force relation $F_D = C_D A \rho V^2/2$ where V is the upstream velocity)

Square rod

Sharp corners: $C_D = 2.2$

Round corners ($r/D = 0.2$): $C_D = 1.2$

Rectangular rod

Sharp corners:

L/D	C_D
0.0*	1.9
0.1	1.9
0.5	2.5
1.0	2.2
2.0	1.7
3.0	1.3

* Corresponds to thin plate

Round front edge:

L/D	C_D
0.5	1.2
1.0	0.9
2.0	0.7
4.0	0.7

Circular rod (cylinder)

Laminar: $C_D = 1.2$

Turbulent: $C_D = 0.3$

Elliptical rod

	C_D	
L/D	Laminar	Turbulent
2	0.60	0.20
4	0.35	0.15
8	0.25	0.10

Equilateral triangular rod

$C_D = 1.5$

$C_D = 2.0$

Semicircular shell

$C_D = 2.3$

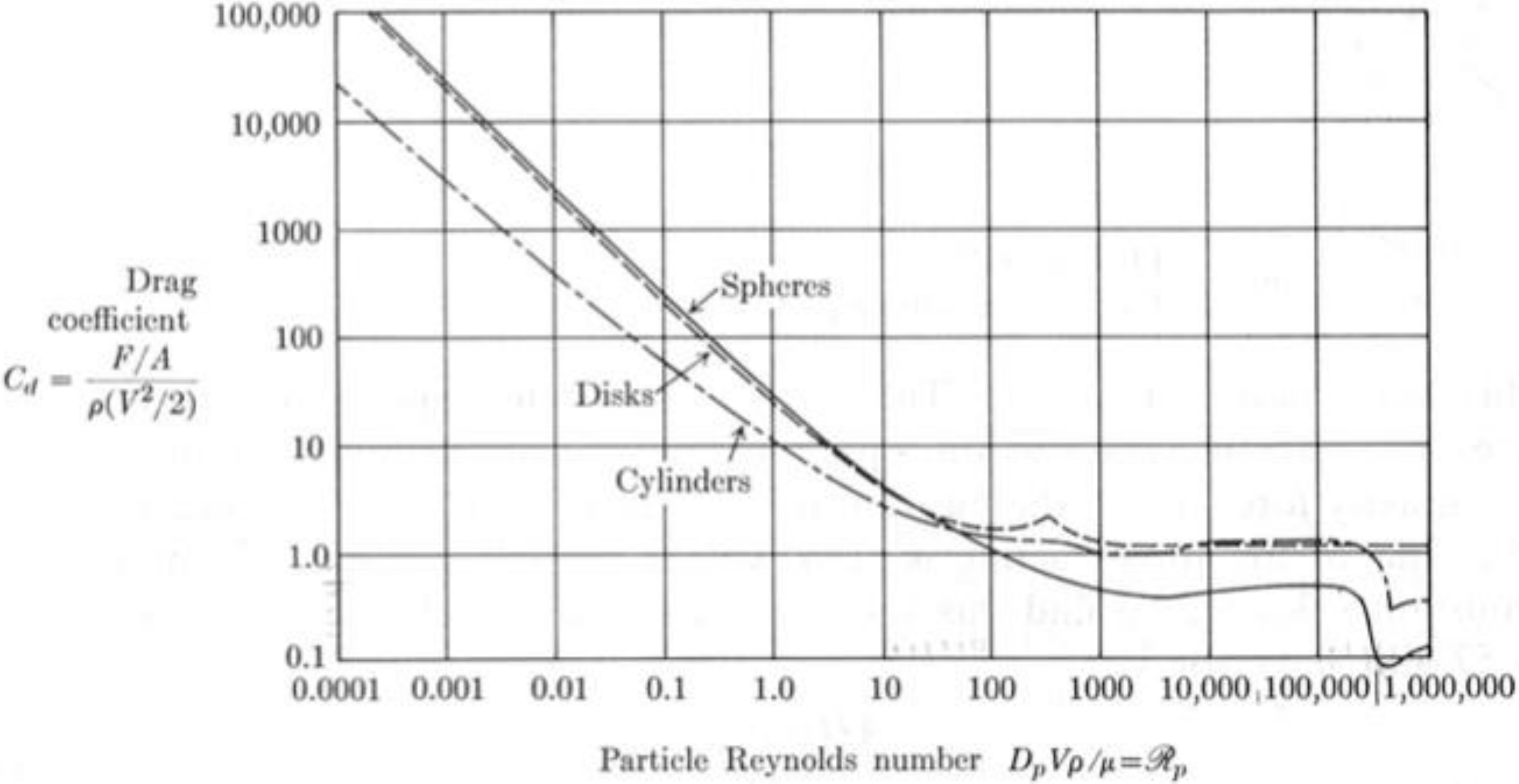
$C_D = 1.2$

Semicircular rod

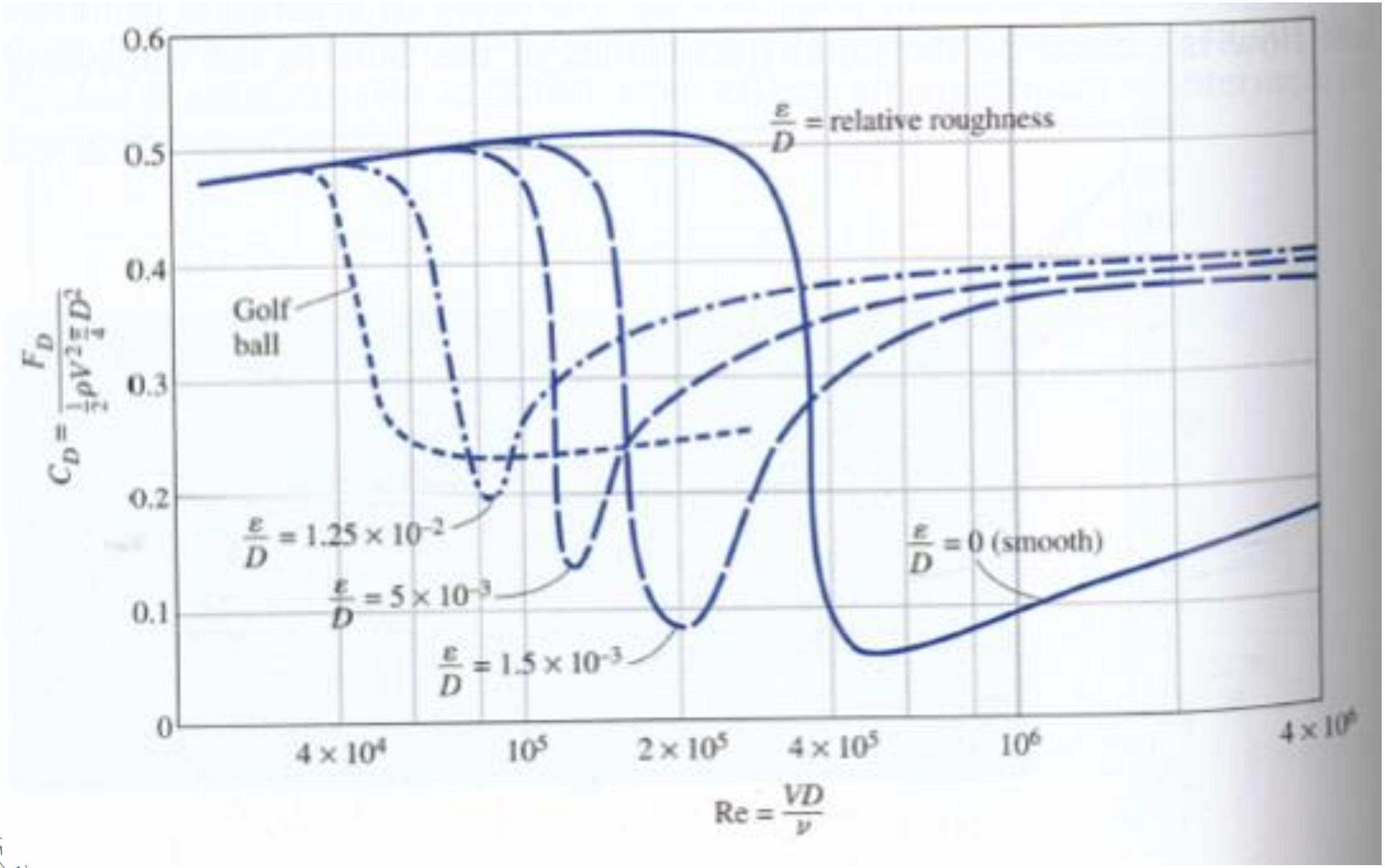
$C_D = 1.2$

$C_D = 1.7$

Drag vs. Re


100,000
10,000
1000
100
10
1.0
0.1
Drag coefficient
$C_d = \frac{F/A}{\rho(V^2/2)}$
Spheres
Disks
Cylinders
0.0001
0.001
0.01
0.1
1.0
10
100
1000
10,000
100,000
1,000,000
Particle Reynolds number $D_pV\rho/\mu = \mathscr{R}_p$

Drag on Spheres with Roughness



Example

- Question:
- If you drop a droplet of water in air, what happens to its velocity?
  - Starts at 0.
  - Gravity accelerates it: v increases
  - As v increases, drag increases until gravity matches drag.
  - → $v = v_{term}$
- Problem
  - Find v_{term} of a water droplet in air
  - D = 1 mm
  - ☐ ρ_f=1.2 kg/m^3
  - ☐ $\nu=\mu/\rho$ = 1.5E-5 m^2/s
  - C_d = 0.5

$$C_d = \frac{F}{A\rho f \frac{1}{2} v^2}$$

$$\Downarrow$$

$$F = A\rho f \frac{1}{4} v^2$$

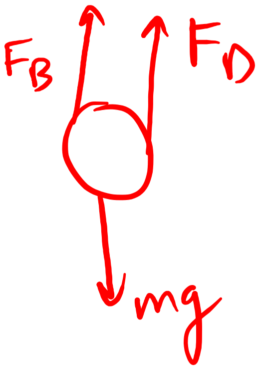
- Q: What if $C_d = C_d(Re)$ instead?

Terminal Velocity Example

$\rho_f = \rho_{air}$

- Find the terminal velocity of a 1 mm water droplet falling through air:

D



$$(\rho_D - \rho_f) V_D \cdot g = F_D = \tfrac{1}{2} \rho_f V^2 A C_D$$

$$V = \sqrt{\frac{2(\rho_D - \rho_f) V_D g}{\rho_f A C_D}} = \left(\frac{2(1000 - 1.2)\frac{\pi}{6}(.001)^3 (9.81)}{(1.2)\left(\frac{\pi}{4}\right)(.001)^2 \cdot C_D} \right)^{1/2}$$

$$V = \frac{3.3}{\sqrt{C_D}} \qquad Re = \frac{\rho V_D D_D}{\mu} = 54794 V_D$$

Guess $C_d = 2 \rightarrow V = 2.33 \rightarrow Re = 1.3 \times 10^5 \rightarrow$ (use chart or correlation)

$C_d = 0.5 \rightarrow V = 4.667 \rightarrow Re = 2.6 \times 10^5 \rightarrow Cd = 0.5 \rightarrow$

$$\boxed{V = 4.667 \ m/s}$$

What about a Balrog?

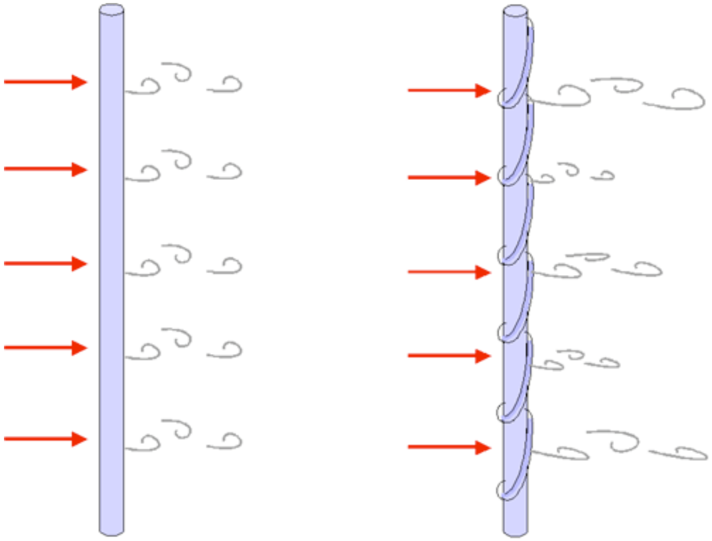
$$\Sigma \vec{F} = \frac{m\,d\vec{v}}{dt} + \cancel{\dot{m}\vec{v}}_{out} - \cancel{\dot{m}\vec{v}}_{in}$$

$$\downarrow$$

$$-mg + F_D = \frac{m\,d\vec{v}}{dt}$$

For mitigation of vortex-shedding induced vibration :

Eliminates cross-wind vibration, but increases drag coefficient and along-wind vibration



- Helical strakes