Aquatic Botball

Basic Hydrodynamics

Fluid Forces

- Gravity
  - The weight of the water in the ocean produces pressure. Changes in gravity, due to the motion of sun and moon relative to Earth produces tides, tidal currents, and tidal mixing in the interior of the ocean.
- Buoyancy
  - The upward or downward force due to gravity.
- Friction
  - The force acting on a body as it moves past another body while in contact with that body.
- Pressure-induced forces
  - Forces created from adverse pressure gradients induced from movement or other stressors.

Basic Concepts in Fluid Statics

- Fluid statics - refers to the state of a fluid where its velocity is zero, hydrostatic.

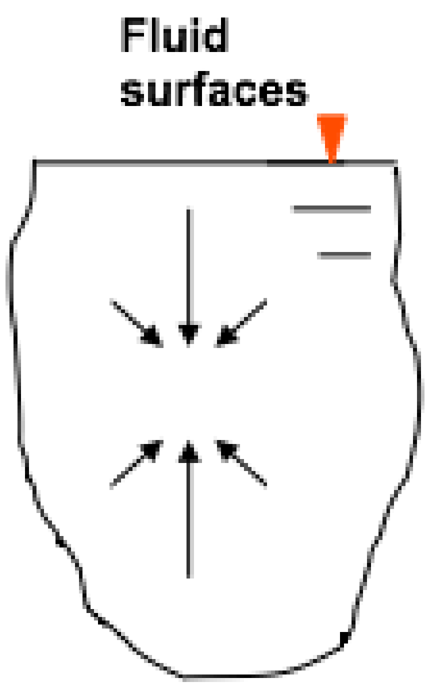
- In a static fluid, pressure the most important variable

- Pressure is the same in all directions.

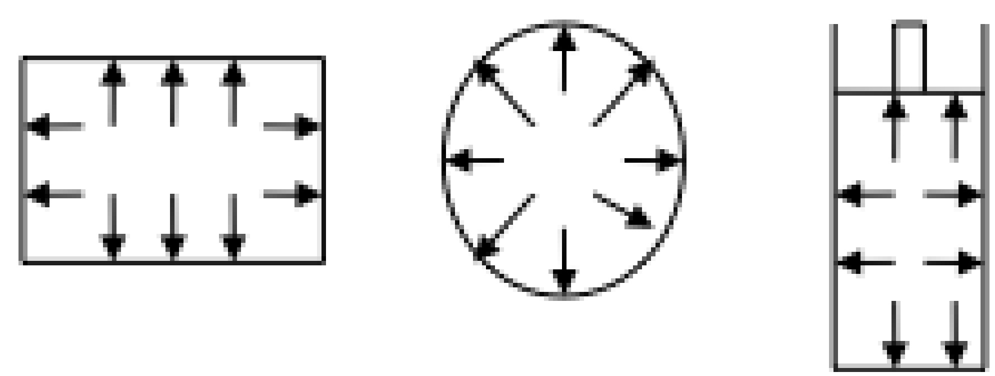
  - Pascal's law: "pressure exerted anywhere in a confined incompressible fluid is transmitted equally in all directions"

Force Equilibrium

- Pressure acts uniformly in all directions - whether inward or outward
- Pressure - surface force per unit area exerted by a fluid on a boundary
- P=F/A, Units: N/m^2 (Pascal, Pa) lb/in^2 (psi), Bar (1 bar = 105 Pa)



Pressure acting uniformly in all directions



Direction of fluid pressures on boundaries

Pressure Gradient

- Hydrostatic Pressure Controlling Equation: $p = p_o + \rho g h$
  - p - absolute pressure
  - p_0 - Initial pressure at free surface
  - ρgh - pressure produced by the column of water above the sensor
    - ρ - density of water: 1000 kg/m^3
    - g - Acceleration due to gravity: 9.81 m/s^2
    - h - height of the water column
  - Solve this equation for h to get depth

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Free Body Diagrams

- ✓ What is a free body Diagram
- ✓ Coordinate frame
- ✓ Object - geometry
- ✓ Forces

Buoyancy

- Buoyancy force – the upwared force experinced by a submerged body due to the diffence in pressure from the top of the body to the bottom

$$F_{buoyancy} = \rho g V$$

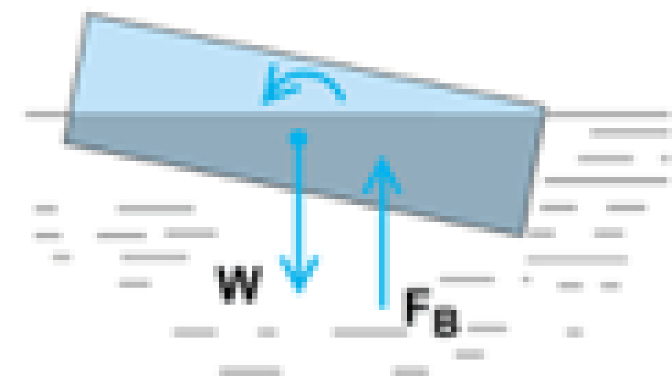
- ρ – Density of water, 1000 kg/m^3
- g – Acceleration due to gravity, 9.81 m/s^2
- V – Volume of submerged object

Force equilibrium:

- If the weight of the body is less than the buoyancy force then it will float
- If the weight of the body is greater than the buoyancy force then it will sink

Buoyancy and Stability of Floating Bodies

- Buoyant force is equal to the weight of the volume of fluid which is displaced by the body.
- Buoyant force acts at the centroid of the displaced fluid - center of buoyancy (CB).
- The difference between the center of buoyancy and the center of gravity of the floating body CG may lead to stability issue.
- In general, a body in equilibrium may be in two possible positions.



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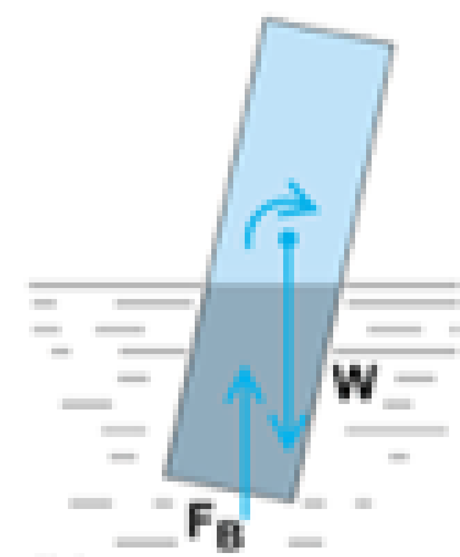

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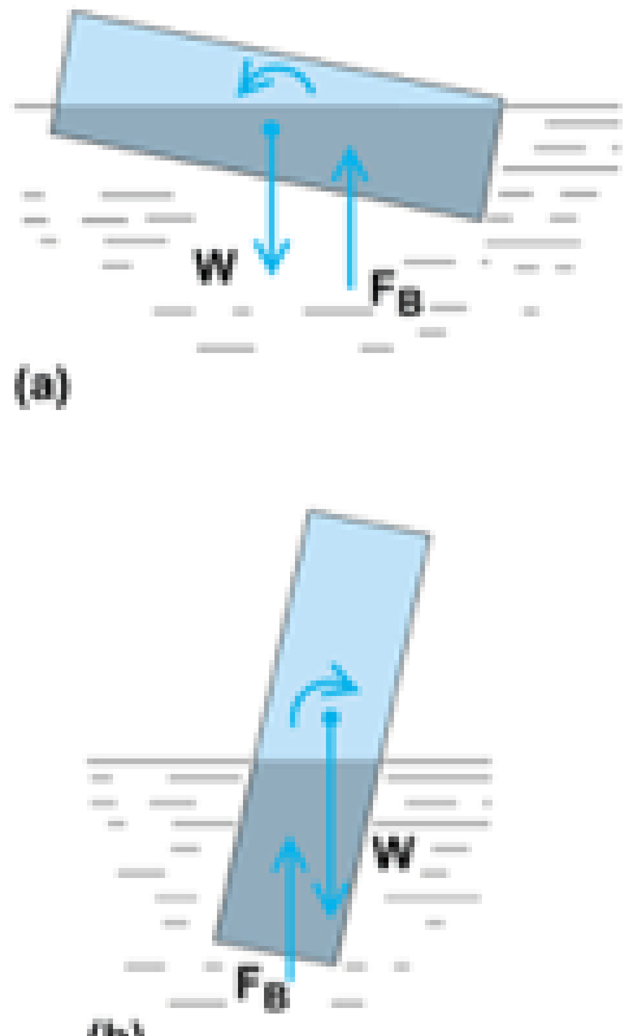
Buoyancy and Stability

- Stable equilibrium — a small displacement will result in the body returning to its original position.
- Unstable equilibrium — a small displacement results in the body moving to another position.

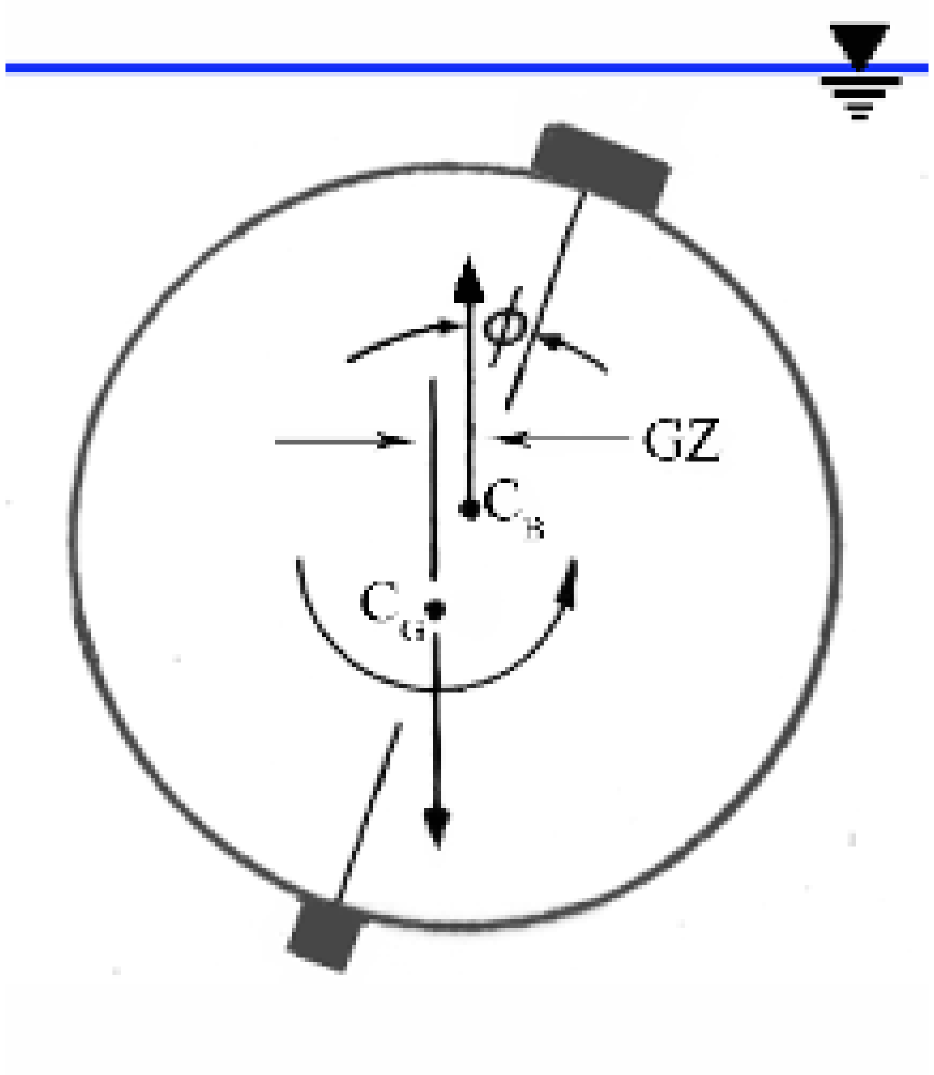


Stability for an Underwater Vehicle

The CG must be bellow the CB

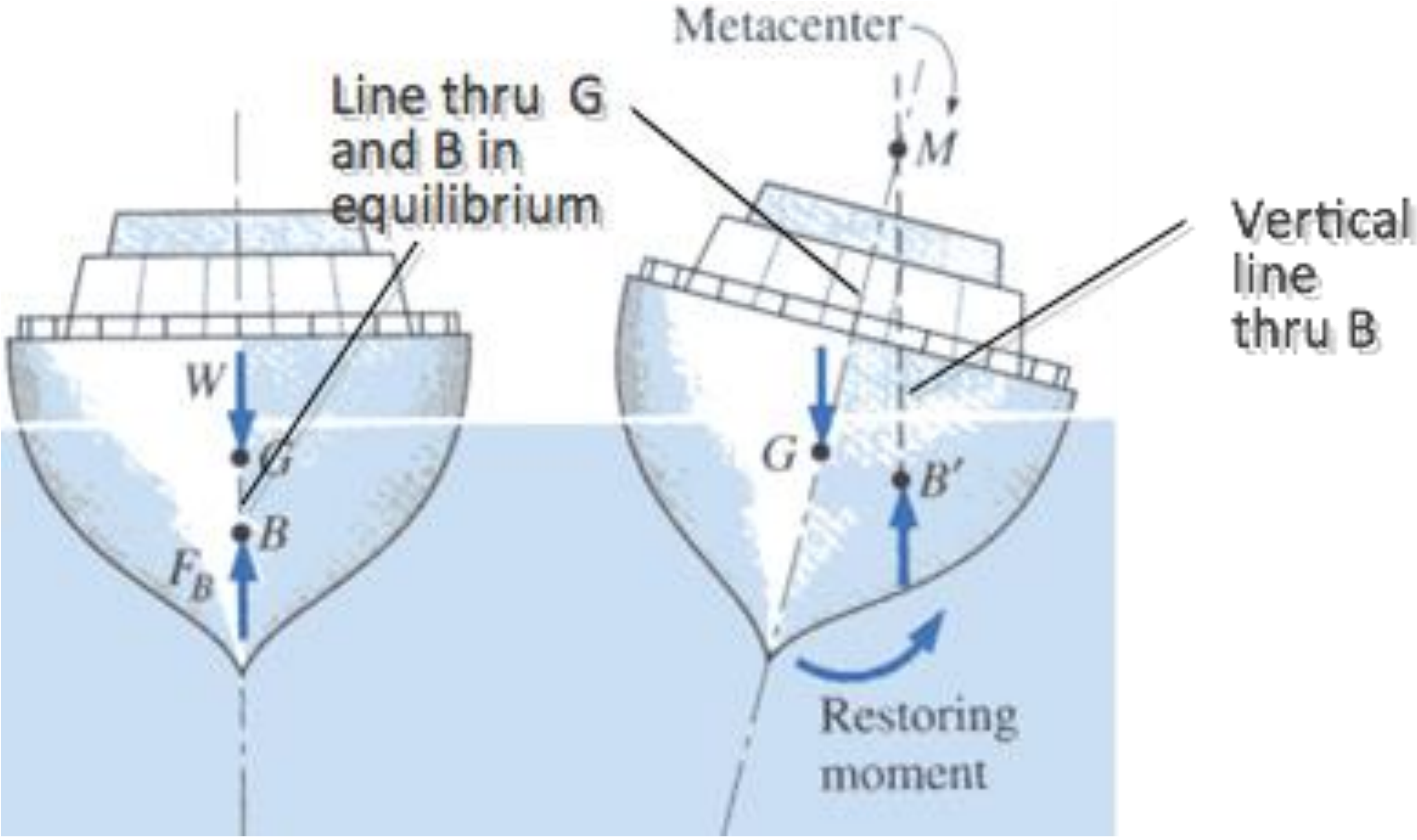
The Greater the distance between the CG and CB
 the more stable the vehicle will be

Start with a longer distance between CG and CB and gradually shorten this distance as you become better at controlling underwater vehicles



Interesting side note: Stability - Metacentric Height

- Metacenter or Metacentric Height (M):
  - Intersection of a vertical line through the center of buoyancy with a line connecting the center of gravity and the equilibrium center of buoyancy
  - A floating body is stable if the metacenter lies above the center of gravity
  - The restoring moment is called the Righting Arm (GZ)



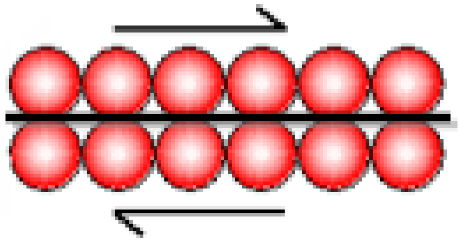
Drag Force

Drag force is the component of force on a body that acts parallel to the body's direction of motion.

- Drag has TWO major components
  - ➞Friction (viscous) drag
    - Produced by the tangential shear stresses acting on the object.
  - ➞Pressure or form drag
    - Results from variations in the normal pressure around the object

Friction Drag: Shear Force and Stress

Think about the effect of shear on the molecular layers immediately above and below the object



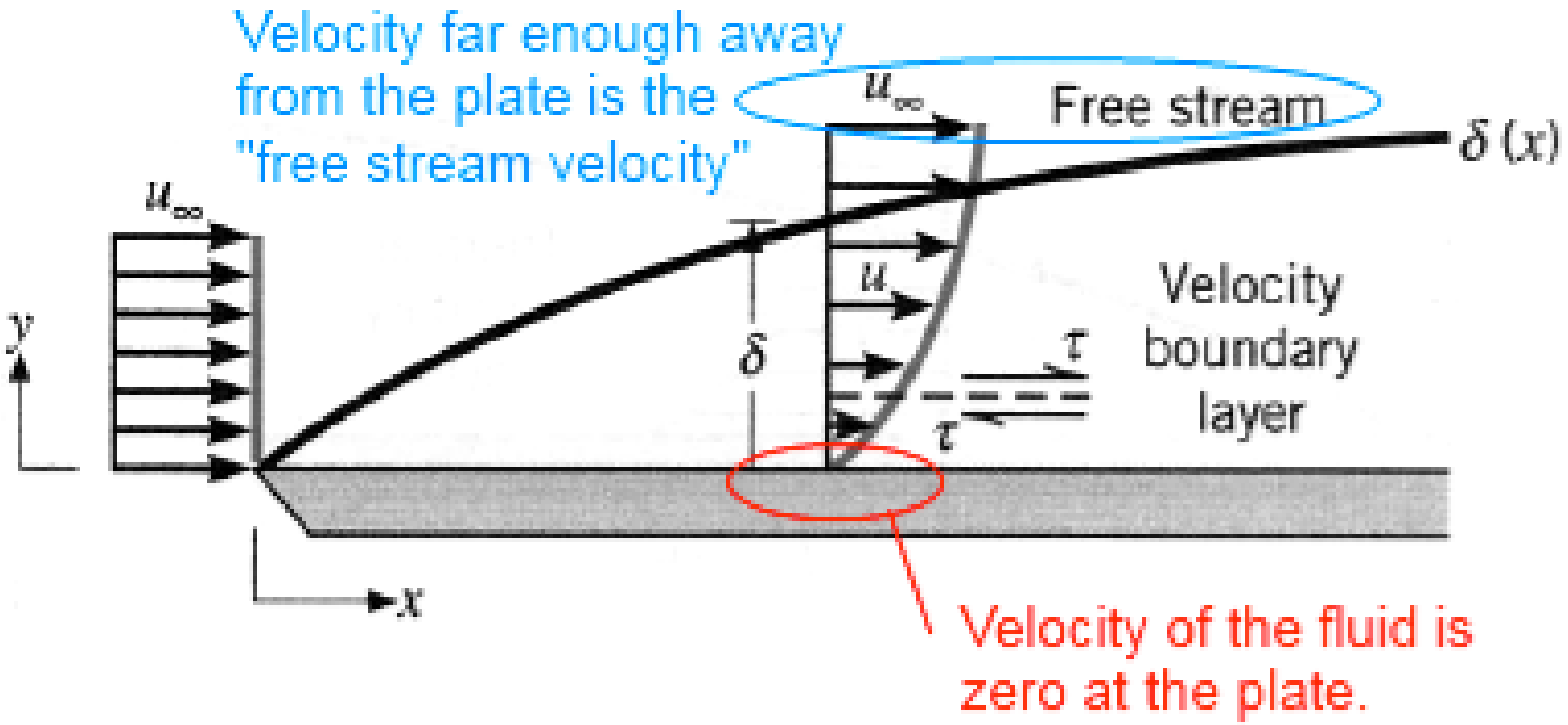
- Shear tends to cause slipping
- Note that the orientation of the surface is irrelevant
- Shear exists along all directions except normal

A no-slip condition exists at the surface of a submerged object

- Fluid in contact with the object will not move relative to the object
- Fluid at some distance away from the object will be stationary
- This creates a boundary layer

Boundary Layer

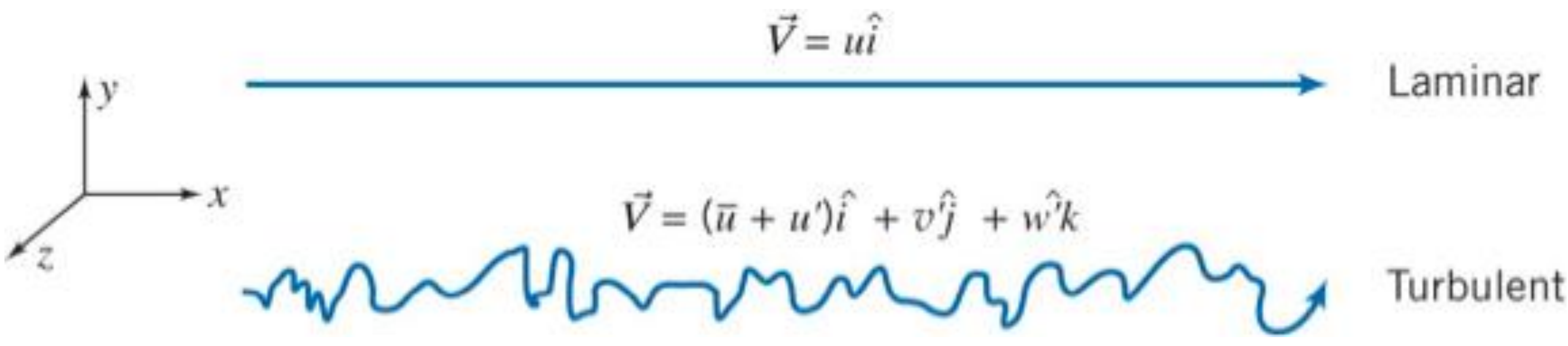
- BL grows thicker as x increases
- BL will eventually stop growing or reach the depth (or radius) of the flow



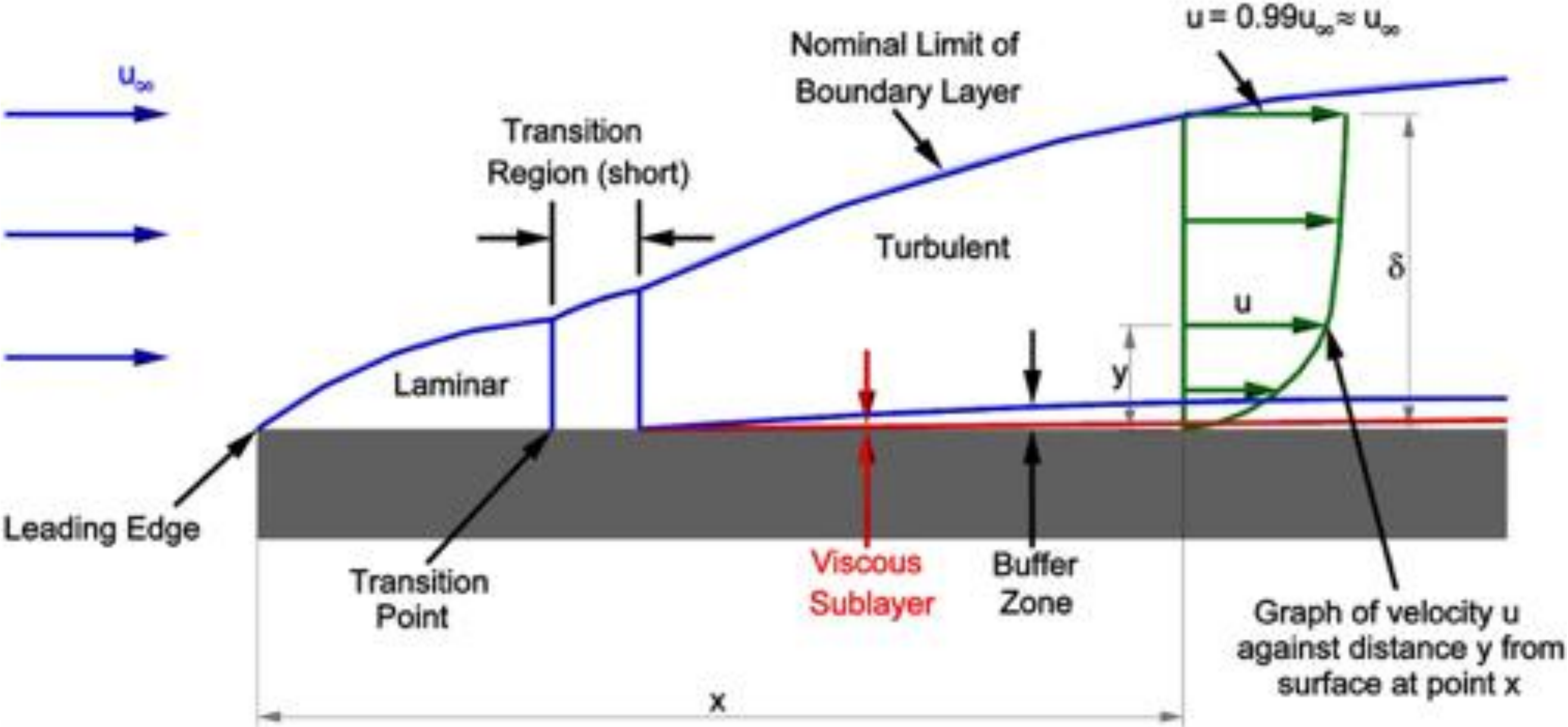
Laminar vs. Turbulent Flow

- Laminar:
  - Smooth motion
  - No macroscopic mixing between adjacent layers
  - Momentum transfer by molecular activity

- Turbulent:
  - Random 3-D motion within flow
  - Macroscopic mixing between adjacent layers
  - Very difficult to model / predict



Boundary Layer with Turbulent Flow



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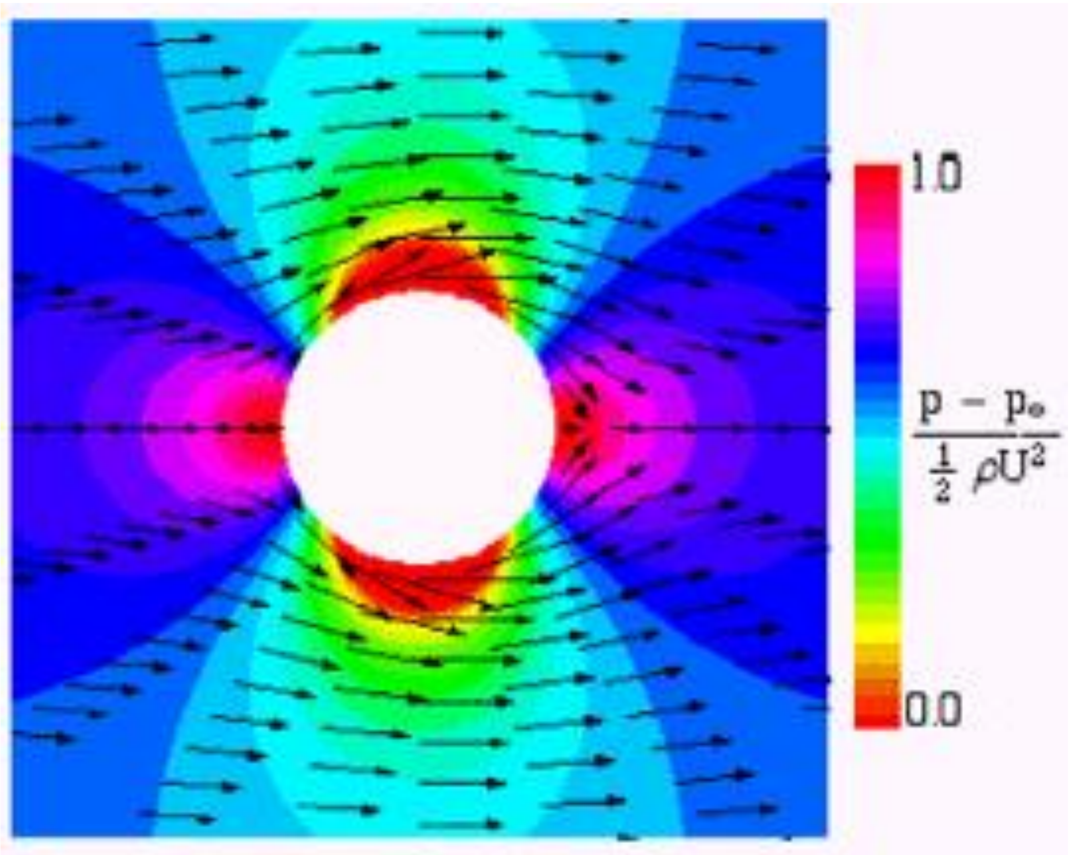
Pressure or Form Drag

Example: Inviscid flow around a cylinder

- The image shows the predictions of inviscid, irrotational flow around a cylinder, with the arrows representing velocity and the color map representing pressure.

1. The flow decelerates and stagnates upstream of the cylinder (high pressure zone).
2. It then accelerates to the top of the cylinder (lowest pressure).
3. Next it must decelerate against a high pressure at the rear stagnation point.



- The origins of the flow separation from a surface are associated with the pressure gradients impressed on the boundary layer by the external flow.

Reynolds Number

Ratio of inertial forces to viscous forces

- Laminar Flow - viscous forces dominate inertial forces
- Turbulent Flow - inertial forces dominate viscous forces

$$\mathrm{Re} = \frac{\rho v L}{\mu} = \frac{v L}{\nu}$$

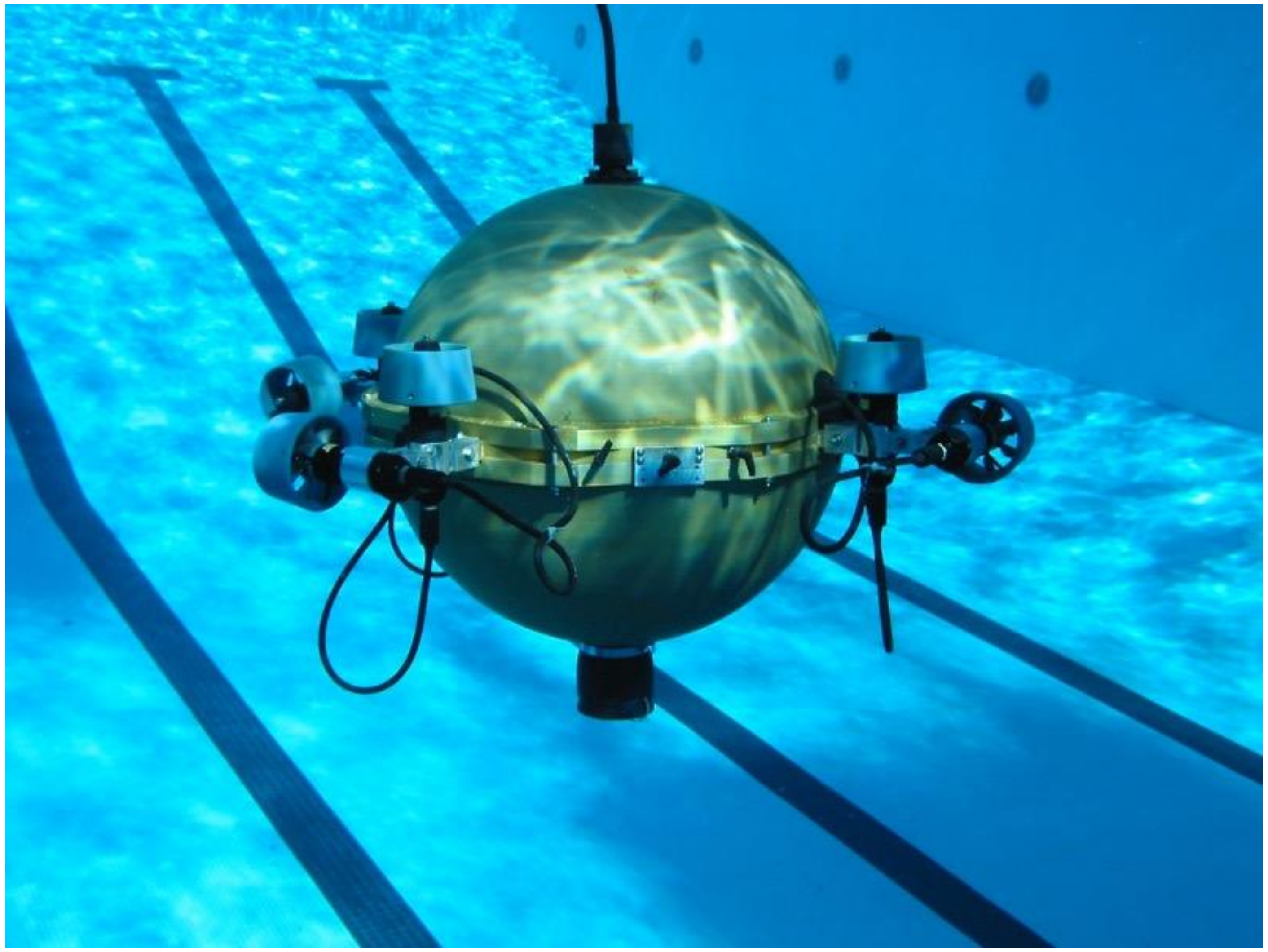
- ρ – Density: 1000 [kg/m^3]- water
- μ- Viscosity: $1x10^{-3}$ [Pa s N s / m^2
- v – velocity
- L – Length of vehicle

Example

- The Omni-Directional Intelligent Navigator (ODIN) is an autonomous underwater vehicle (AUV) that operates in the swimming pool at the University of Hawai`i. Given that ODIN has a diameter of 0.7 m, typical velocity of 0.5 m/s, and the water temperature is 77 degrees Fahrenheit, calculate the Reynolds number for the flow around ODIN while she is moving through the pool.

$$\rho = 1000 \frac{\mathrm{kg}}{\mathrm{m}^3}$$

$$\nu = 0.365 \times 10^{-6} \frac{\mathrm{m}^2}{s}$$



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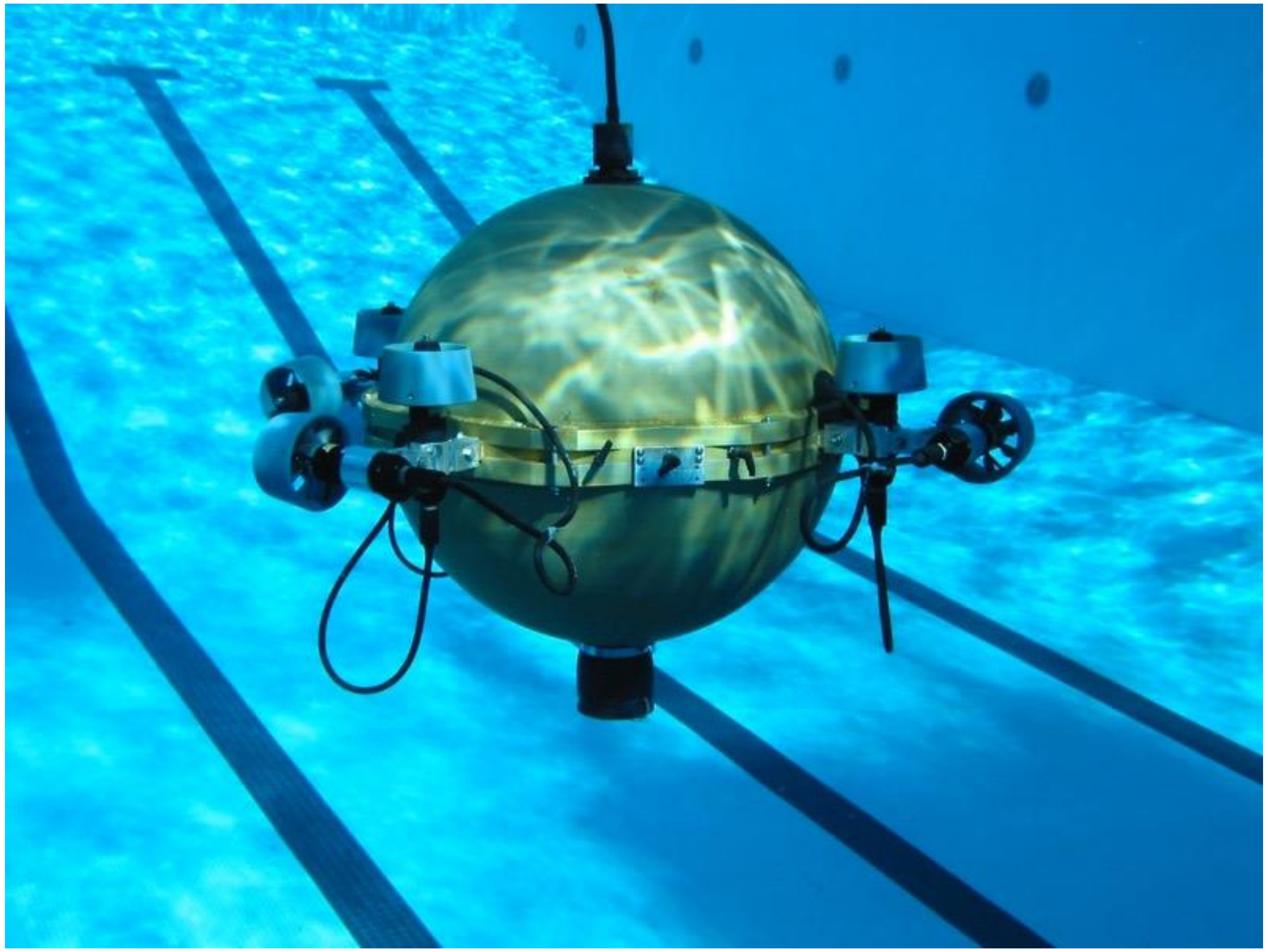
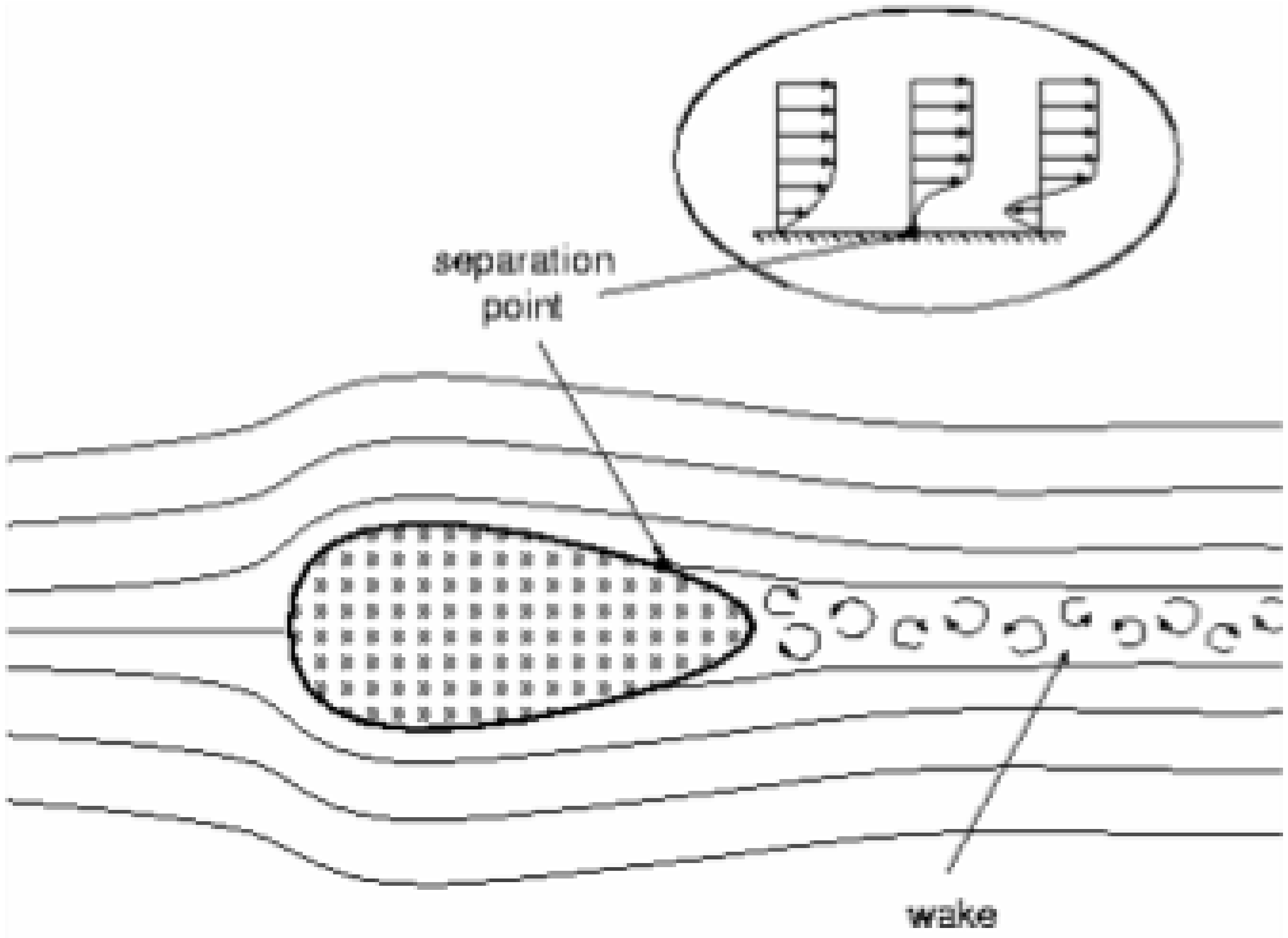


- $\mathrm{Re} = 10^5$

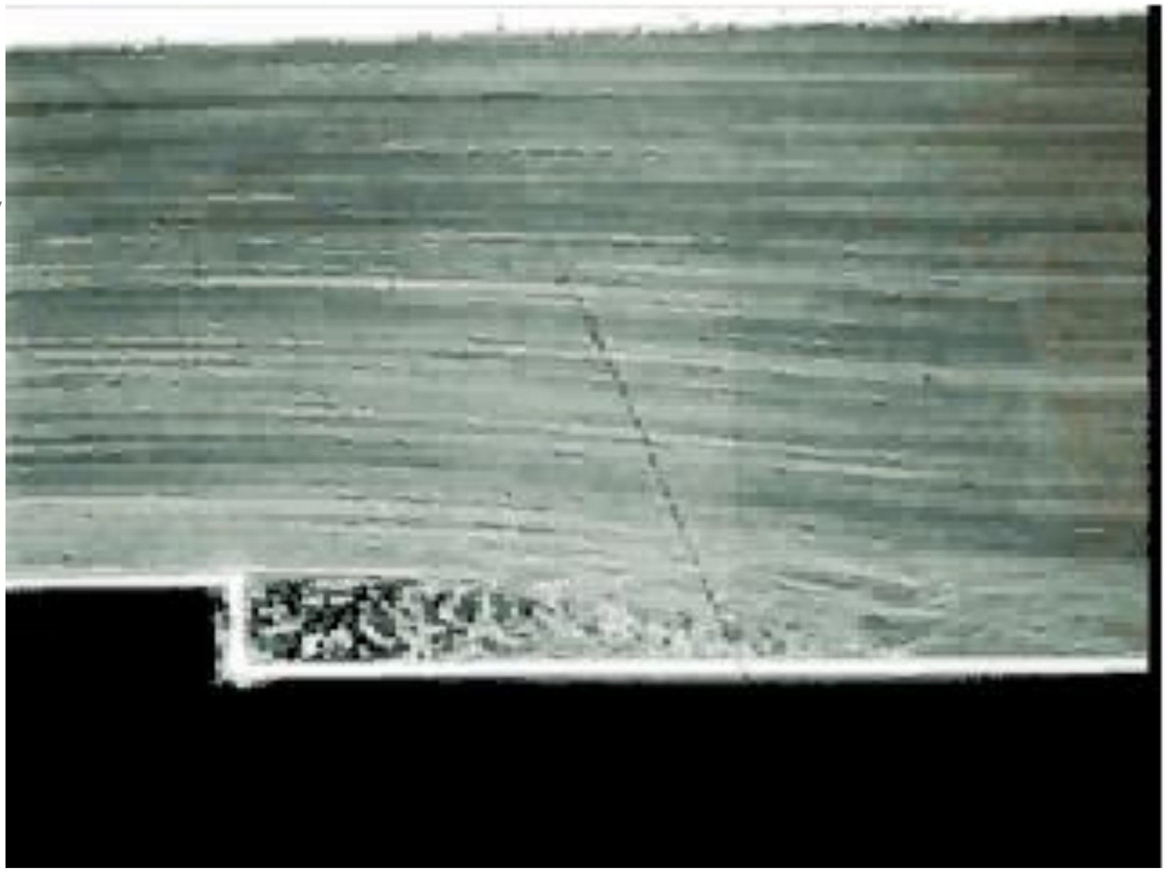
Flow Separation

- The velocity near the wall is zero or negative, which leads to the existence of an inflection point in the velocity profile, thus producing a positive or adverse pressure gradient in the direction of flow.



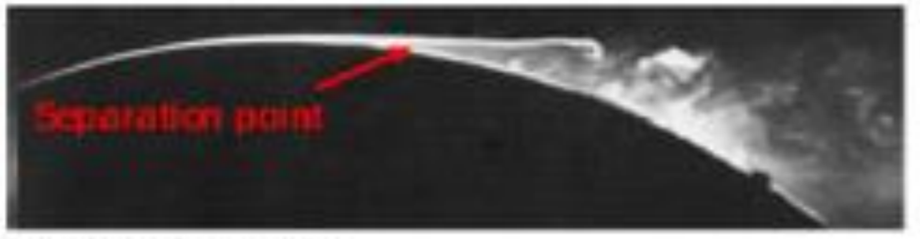
Flow Separation

- Sharp Corners
  - Sharp turns and high angles of attack represent sharply decelerating flow where the loss in energy in the boundary layer ends up leading to separation.
  - Flow (BL) is unable to follow the turn in the sharp corner (which would require a very rapid acceleration)
  - Separation at the edge and recirculation in the aft region of the backward facing step.



Separation

- Turbulent Boundary Layer Delays Separation
  - Photographs depict the flow over a strongly curved surface with a strong adverse pressure gradient.



Laminar Separation

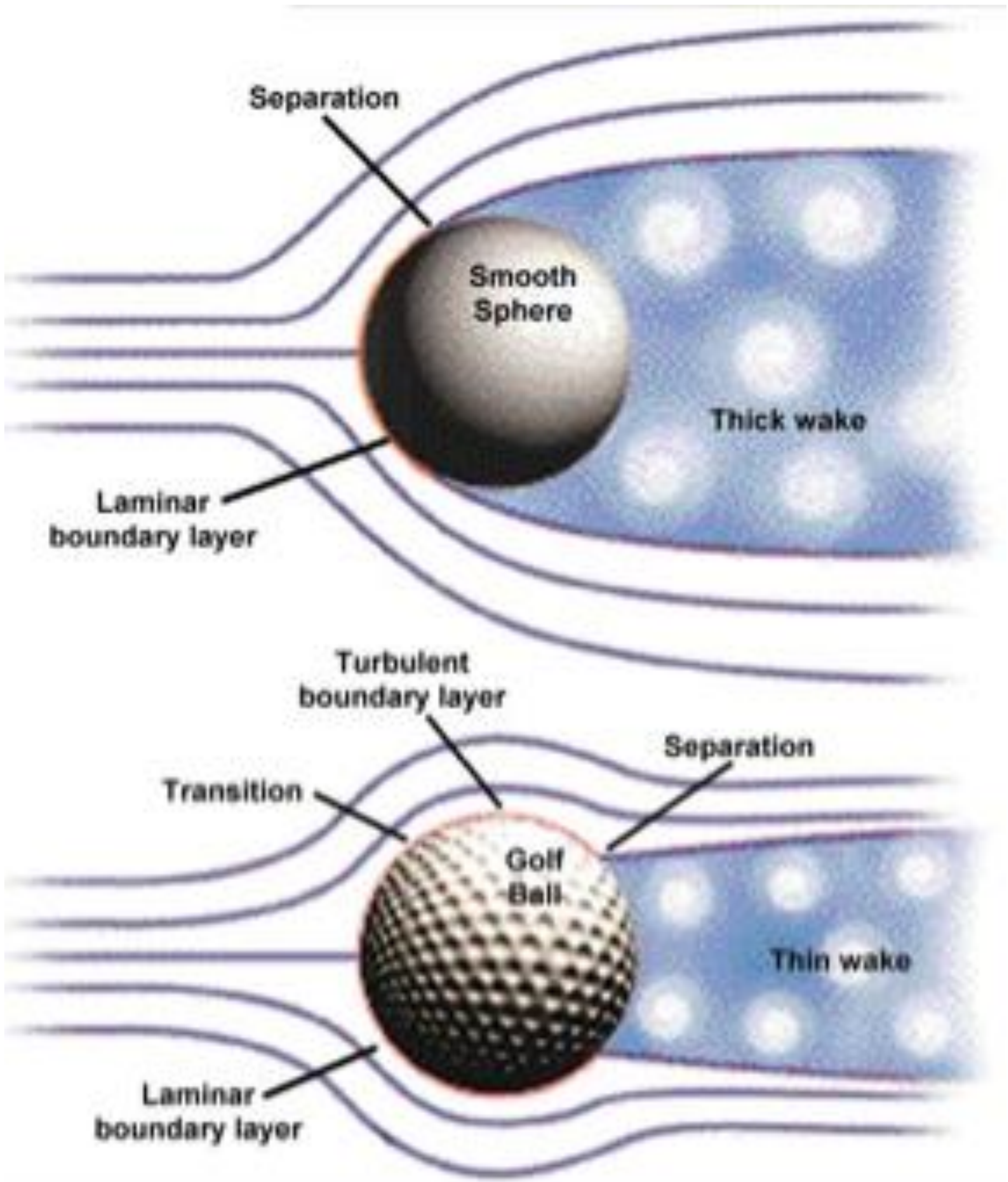
Turbulent Separation

  - The boundary layer has a high momentum deficit and wants to separate.
  - Increased momentum transport due to turbulence from the free stream flow to the flow near the wall makes turbulent boundary layers more resistant to flow separation.

- Laminar BL - insufficient momentum exchange takes place and the flow is unable to adjust to the increasing pressure and separates.

- Turbulent BL - the increased transport of momentum from the free-stream to the wall increases the stream-wise momentum in the boundary layer. This allows the flow to overcome the adverse pressure gradient. It eventually does separate but much further downstream.

Separation



Separation
Smooth Sphere
Thick wake
Laminar boundary layer
Turbulent boundary layer
Separation
Transition
Golf Ball
Thin wake
Laminar boundary layer

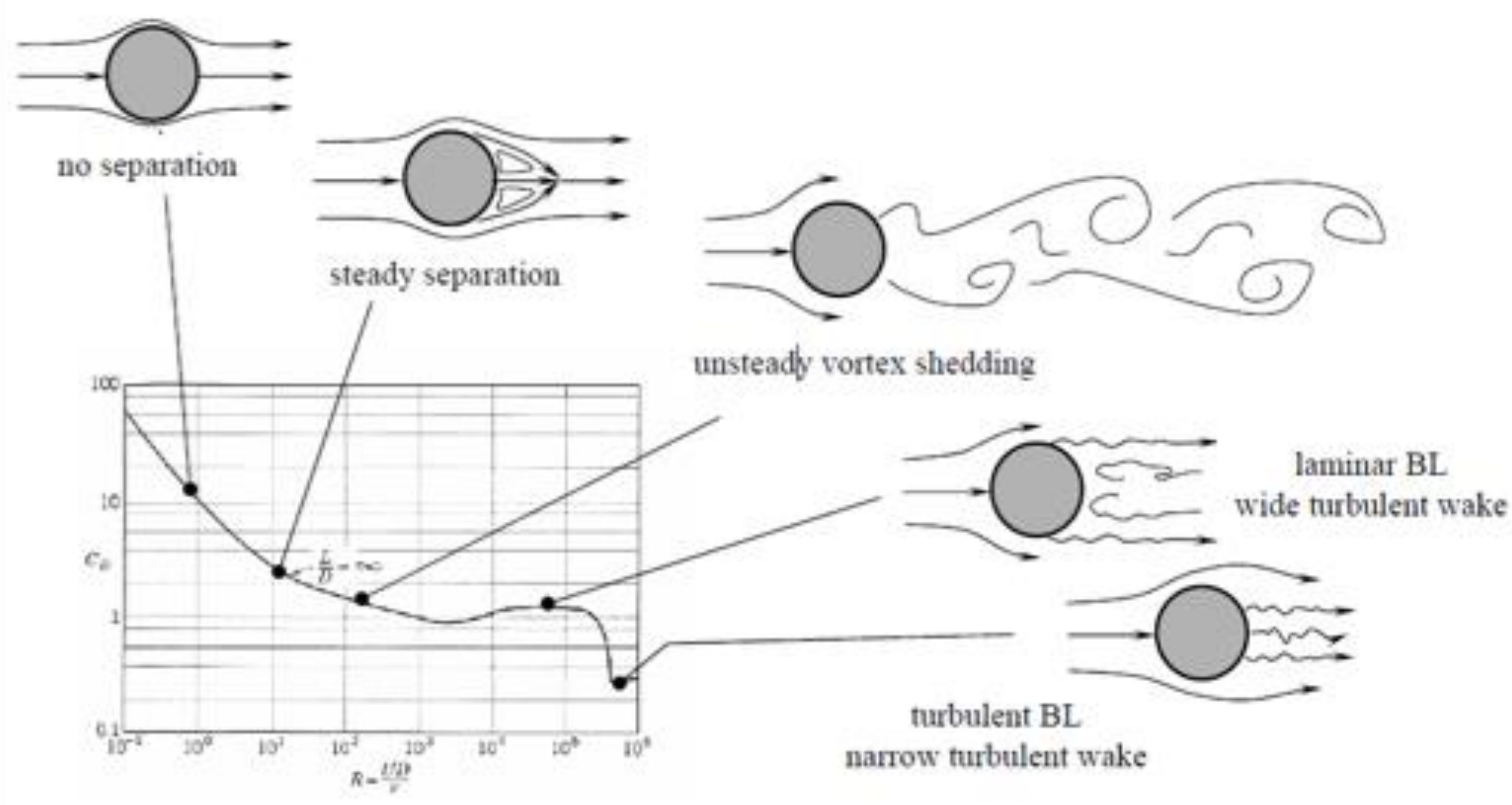
Drag and Separation

- Drag on a smooth circular cylinder

  ➞The drag coefficient is defined as follows:

  ➞$F_D = C_D \frac{1}{2} \rho v^2 A_n$

- Stages of separation vary with Re.



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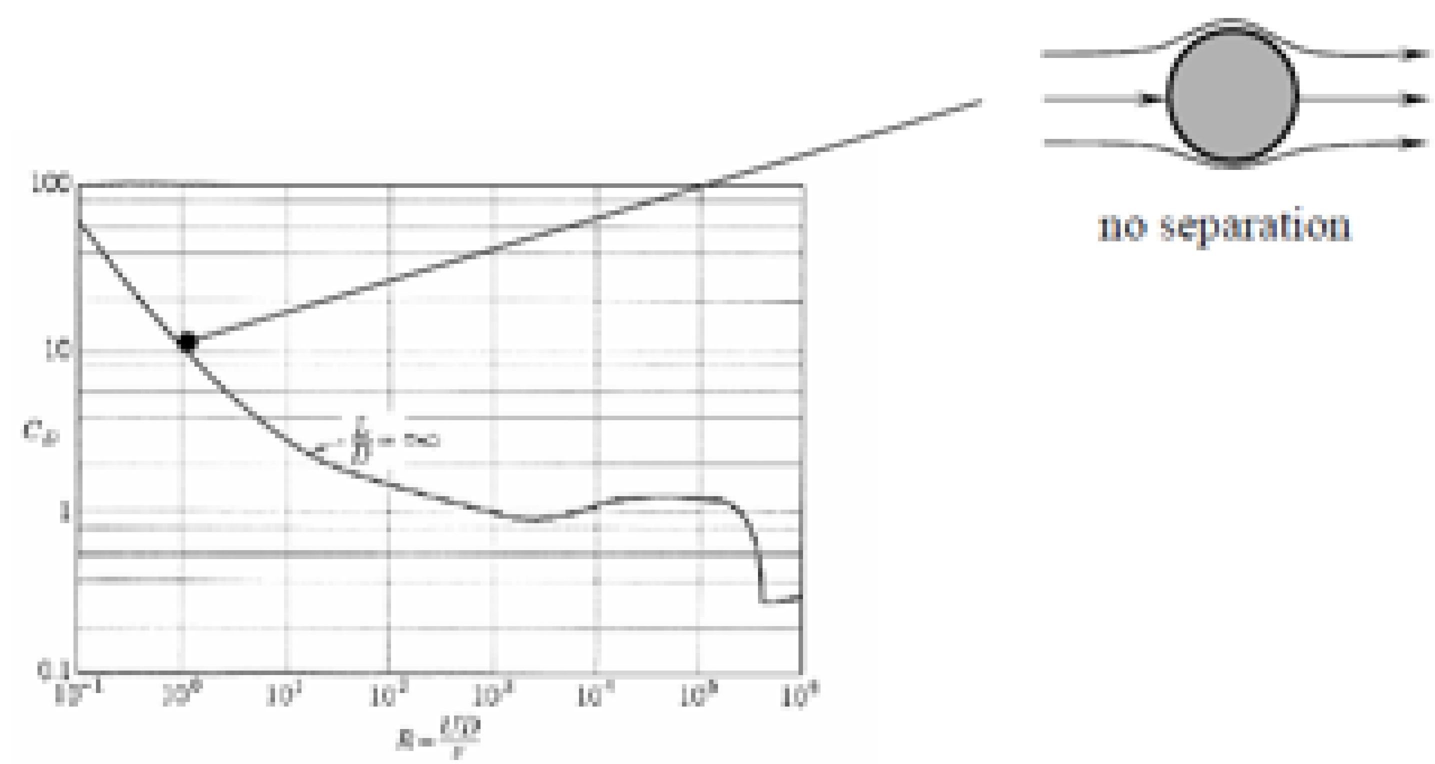
Drag on a Smooth Cylinder

- Stages of separation:

  ➡ <u>Low Re (Re < 1)</u> - Inertial effects are small relative to the viscous and pressure forces.

    - Drag coefficient varies inversely with the Reynolds number. For example, $C_D = 24/Re$ (sphere)



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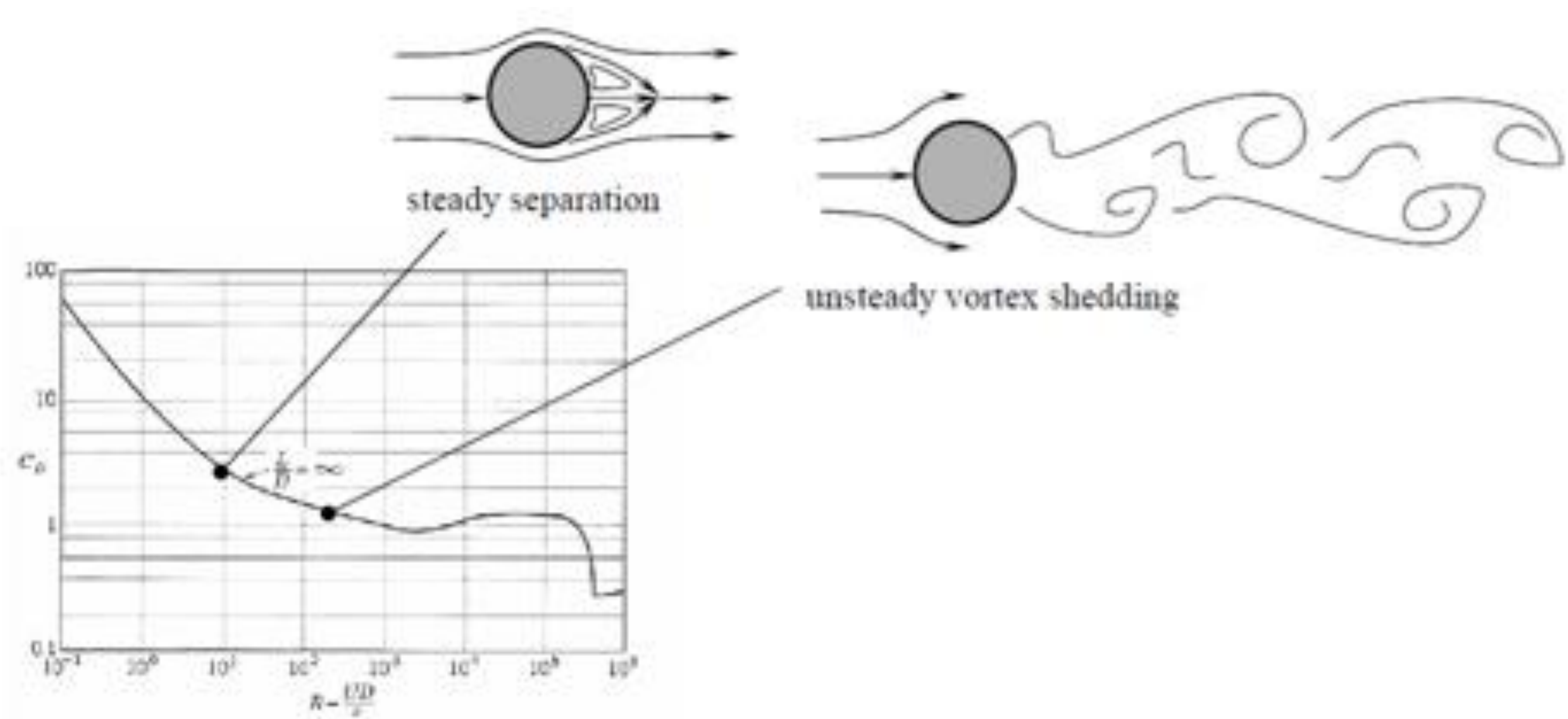
Drag on a Smooth Cylinder

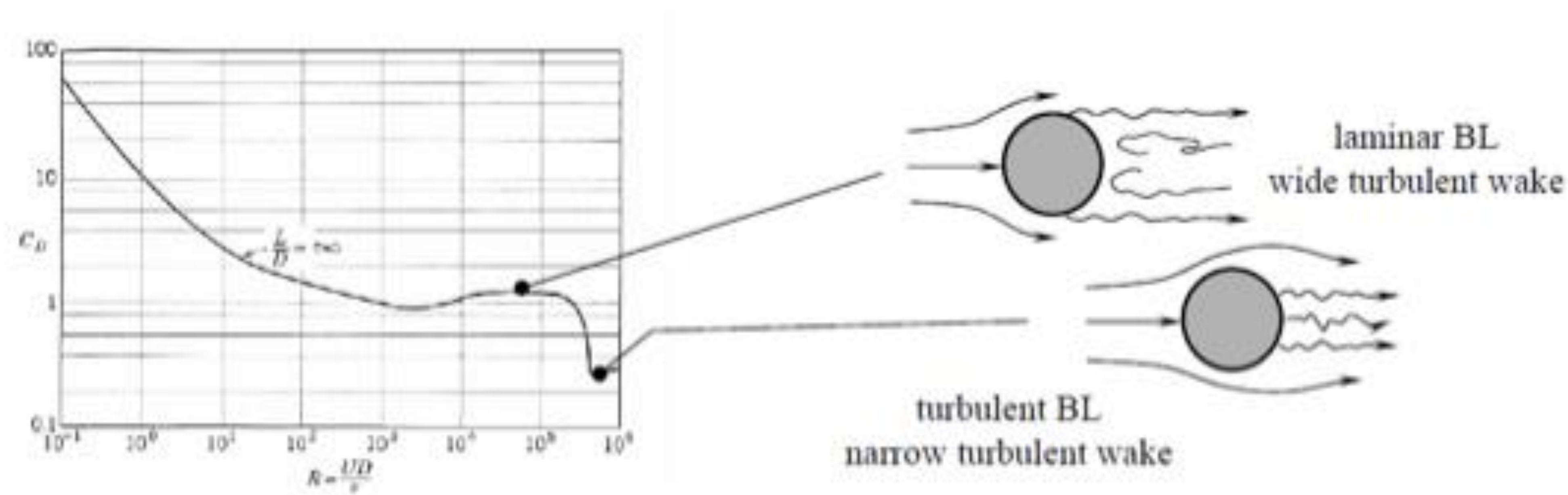
➞ <u>Moderate Re ($1<Re<10^3$) –</u> Inertial effects are similar to viscous forces and flow begins to separate in a periodic fashion in the form of Karman vortices.



Drag on a Smooth Cylinder

➞ Higher Re ($10^3 < Re < 10^5$) – Flow fully separates.

- An adverse pressure gradient exists over the rear portion of the cylinder resulting in a rapid growth of the laminar boundary layer and separation.
- As the Reynolds number increases, the boundary layer transitions to turbulent, delaying separation and resulting in a sudden decrease in the drag coefficient.

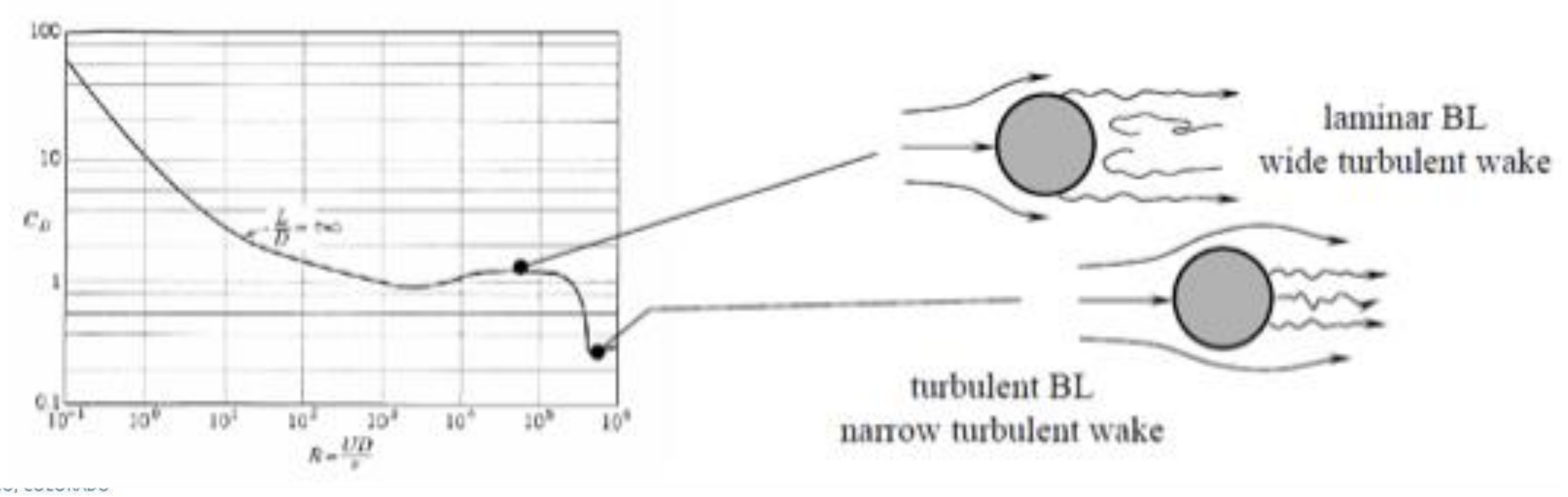


Drag on a Smooth Cylinder

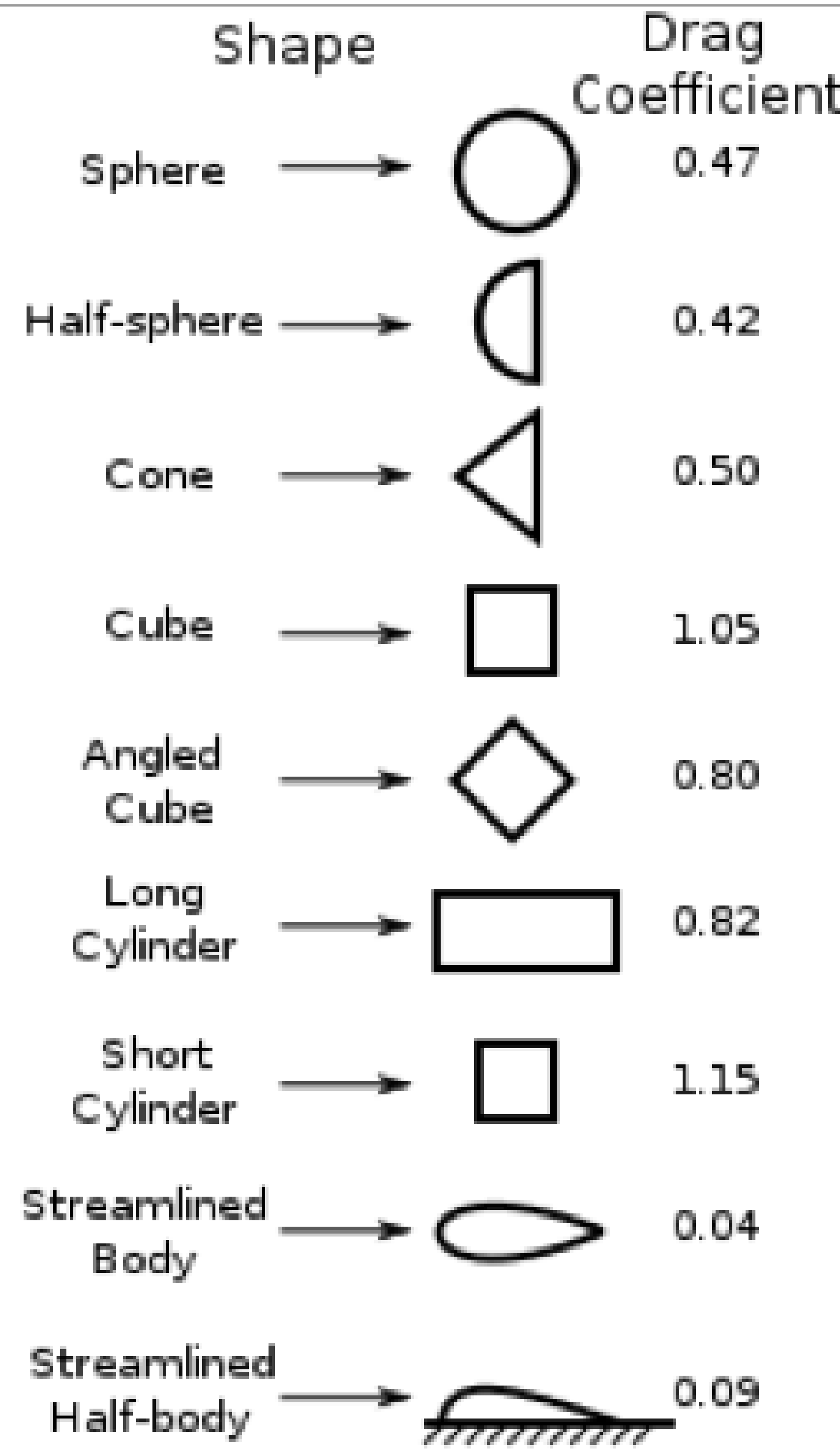
- Explanations:

  ➞Adverse pressure gradient (past midpoint) -streamlines diverge, velocity drops, pressure increases (Bernoulli principle).

  ➞Turbulence delays separation – turbulence means more momentum transfer into BL which "holds" the flow to the body surface.



Measured Drag Coefficients



Measured Drag Coefficients

Questions?