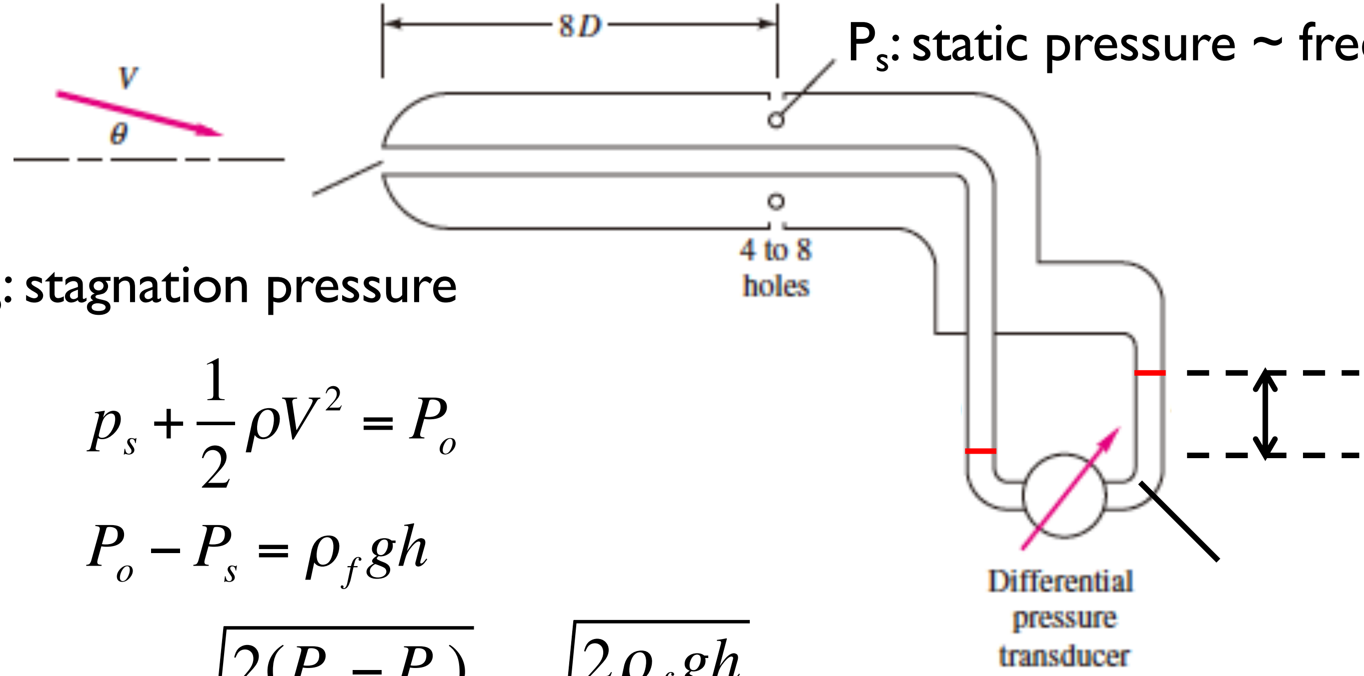
Local velocity measurements

❑ Pitot tube

P_s: static pressure ~ free stream



P_o: stagnation pressure

$$p_s + \frac{1}{2}\rho V^2 = P_o$$

$$P_o - P_s = \rho_f g h$$

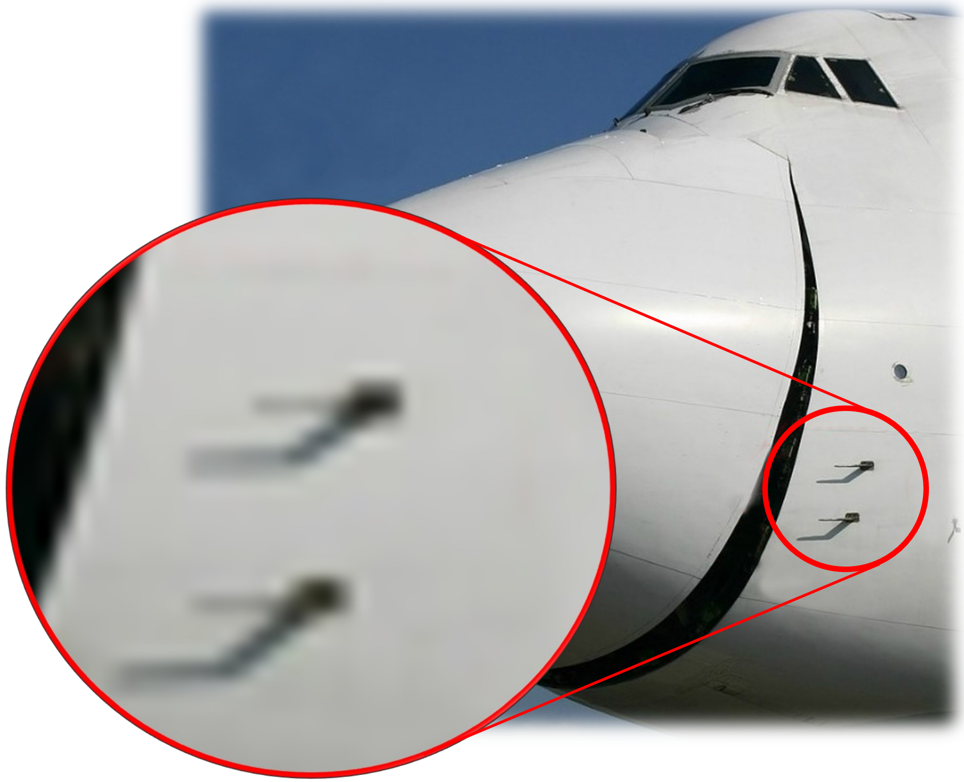
$$V = \sqrt{\frac{2(P_o - P_s)}{\rho}} = \sqrt{\frac{2\rho_f g h}{\rho}}$$

- ϑ: should be aligned with flow direction (small)
- not suitable for low-velocity measurement
- poor temporal and spatial resolution (compared to hot-wire)

Local velocity measurements

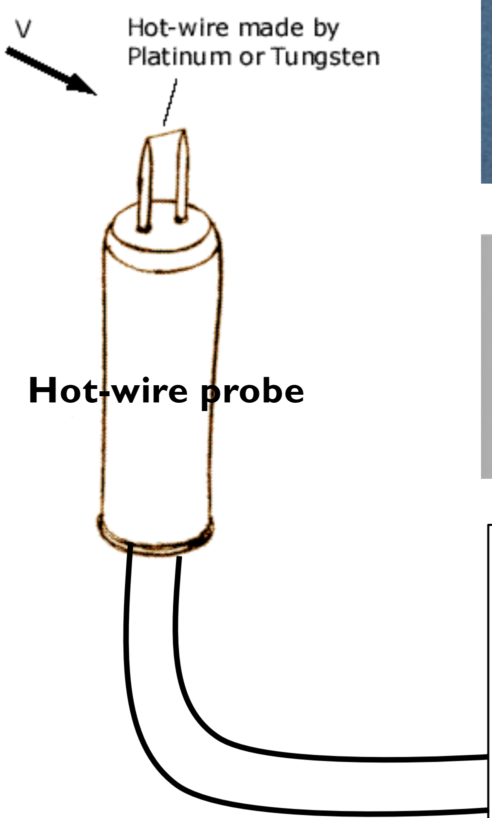
❑ Pitot tube

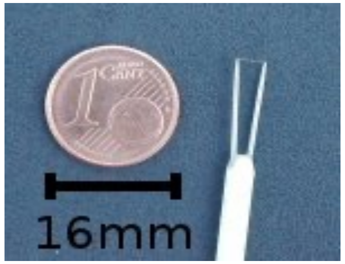
Pitot tube mounted on an airplane

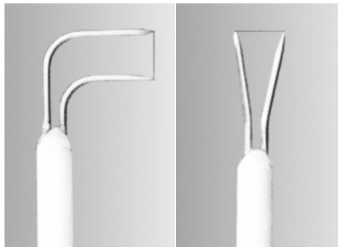


Local velocity measurements

❑ Hot-wire anemometer





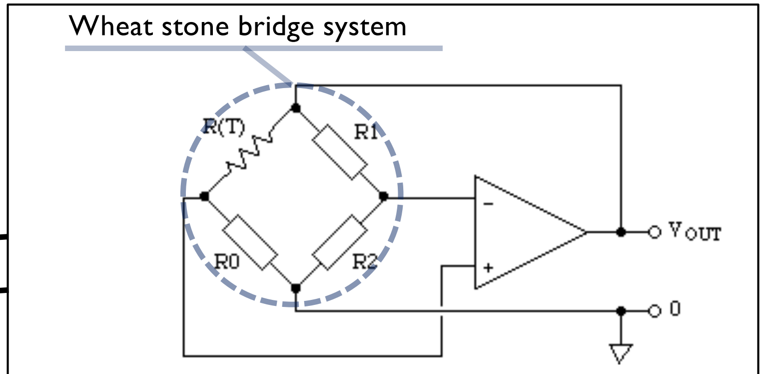


Flow velocity (V) → Temperature T decreases
Current (or voltage) to increase T and maintain the constant temperature

→ voltage vs. V (calibration)

Good temporal and spatial resolution

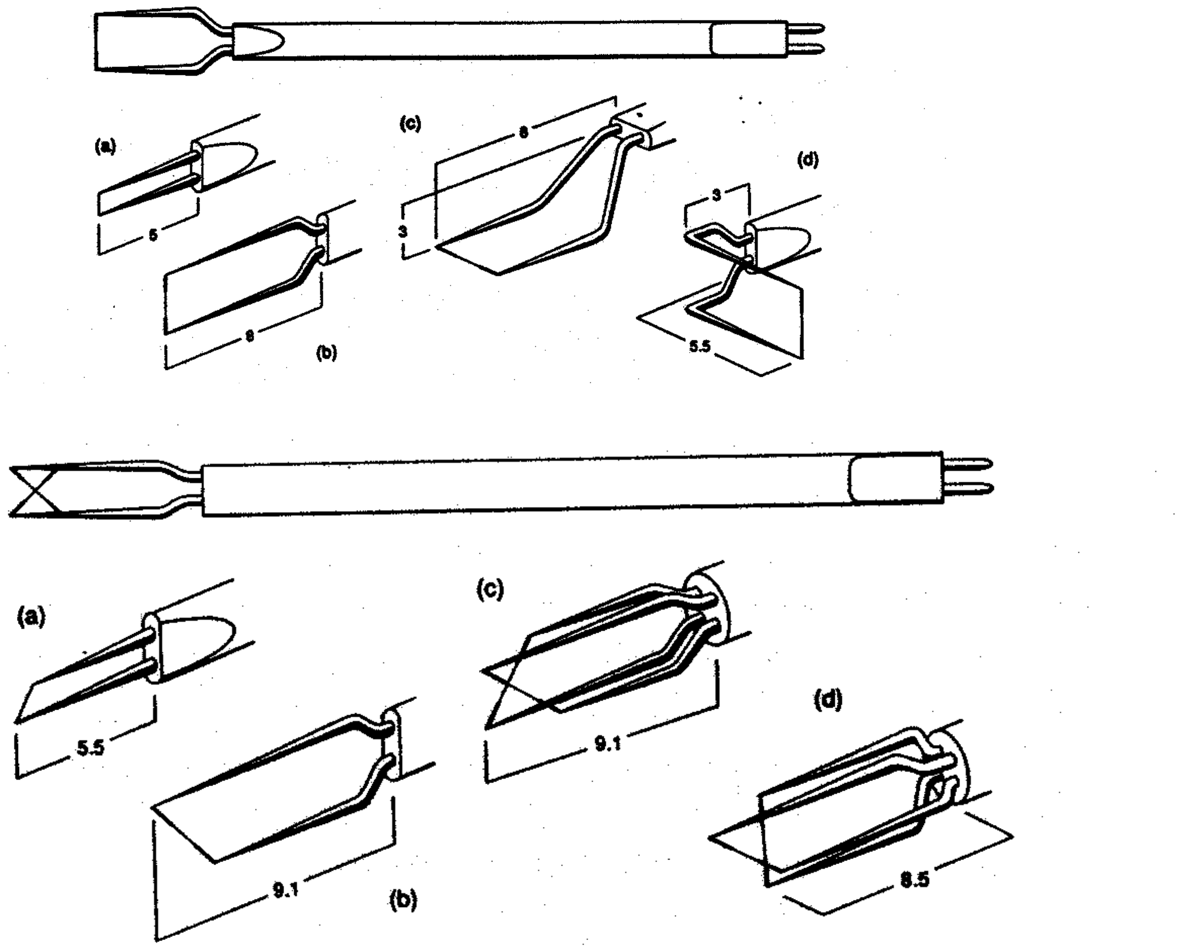
anemometry



Hot-wire Constant Temperature circuit

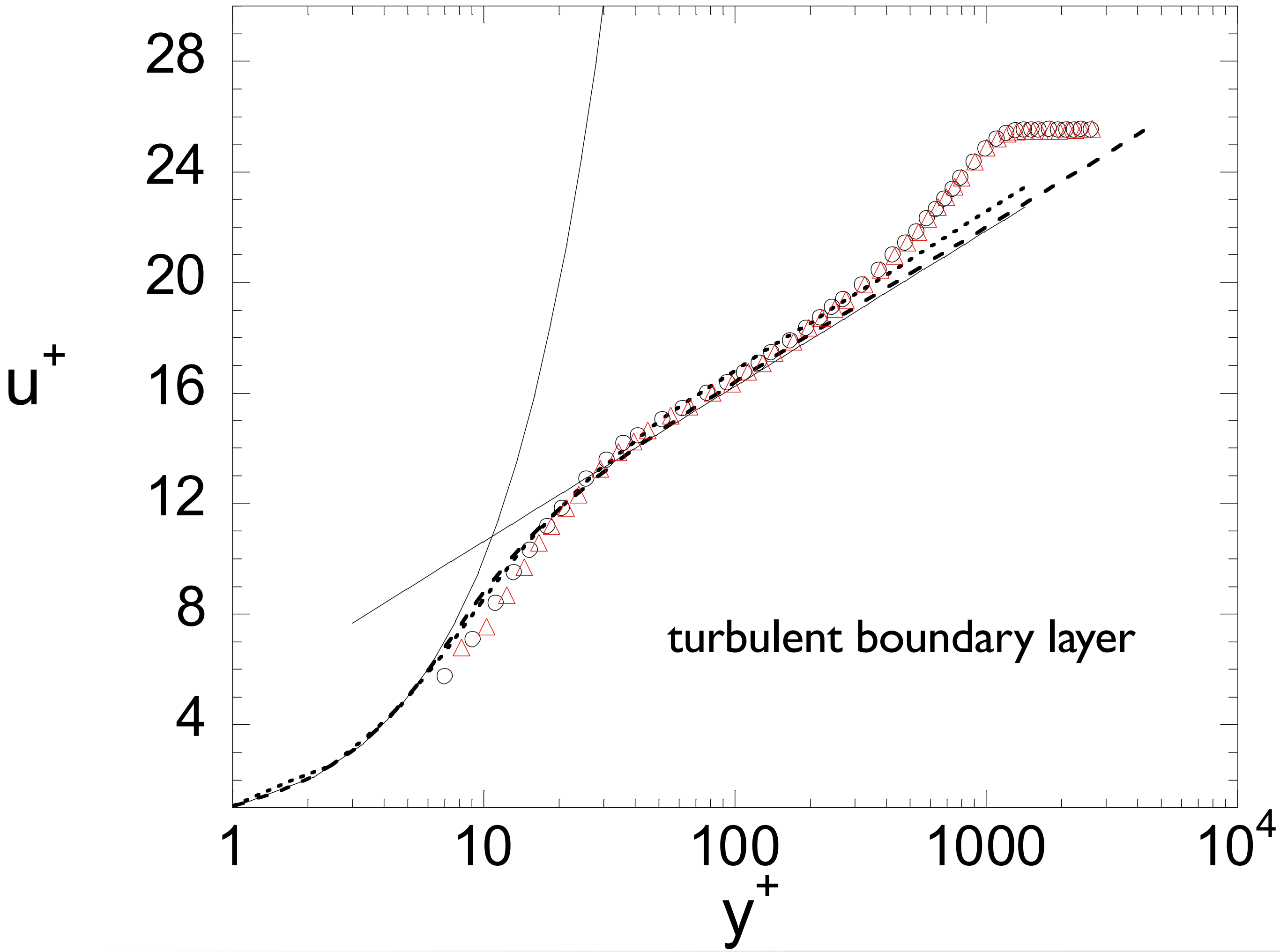
Local velocity measurements

- Hot-wire anemometer



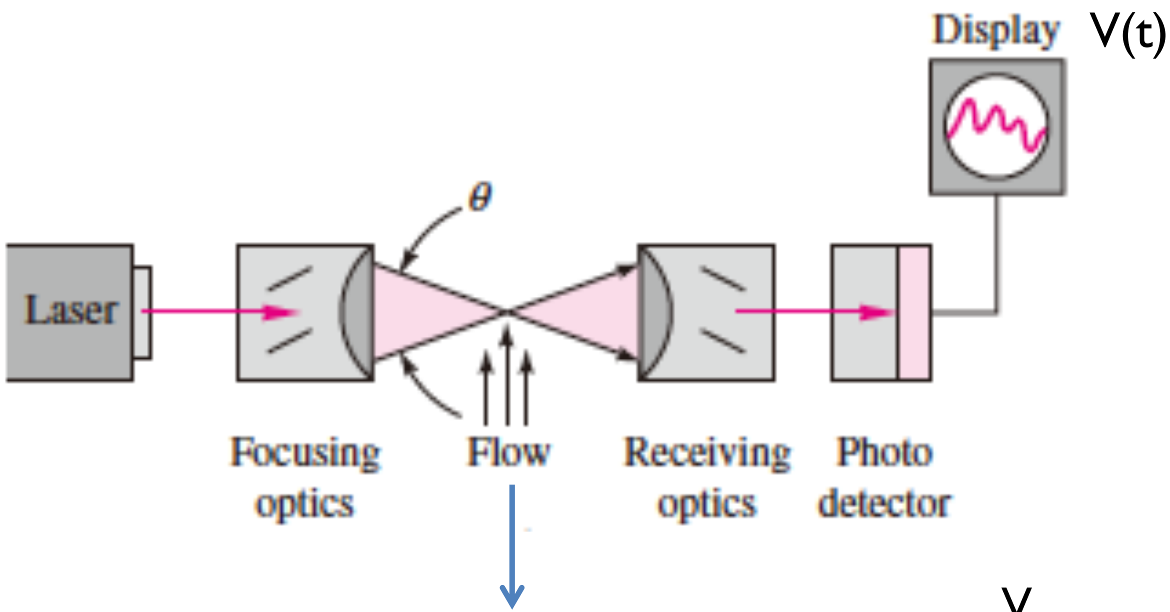
Local velocity measurements

- Hot-wire anemometer



Local velocity measurements

- Laser-Doppler anemometer (LDA or LDV)



Particles scatter lights: $f \xrightarrow{V} f + \Delta f$ (Doppler effect)

$$V = \frac{\lambda \Delta f}{2\sin(\theta/2)}$$ (λ: wavelength of laser light)

Very good spatial resolution

Local velocity measurements

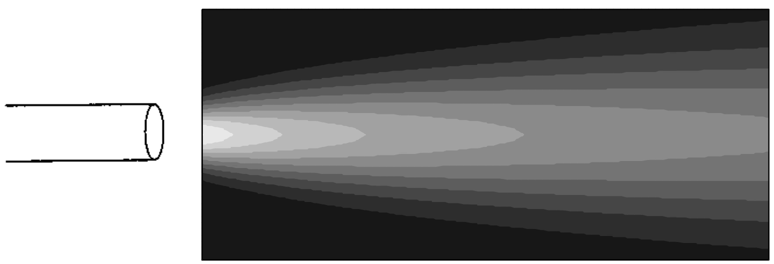
- Particle image velocimetry (PIV)

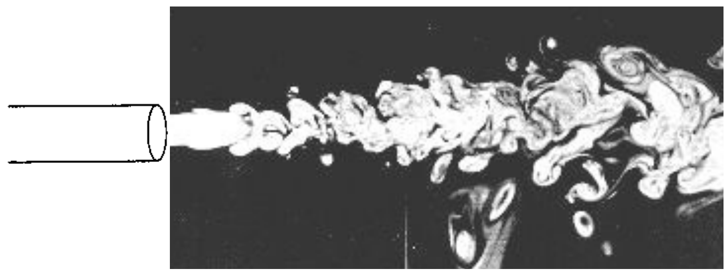
Conventional methods
(HWA, LDV)

- Single-point measurement
- Traversing of flow domain
- Time consuming
- Only turbulence statistics

Particle image velocimetry

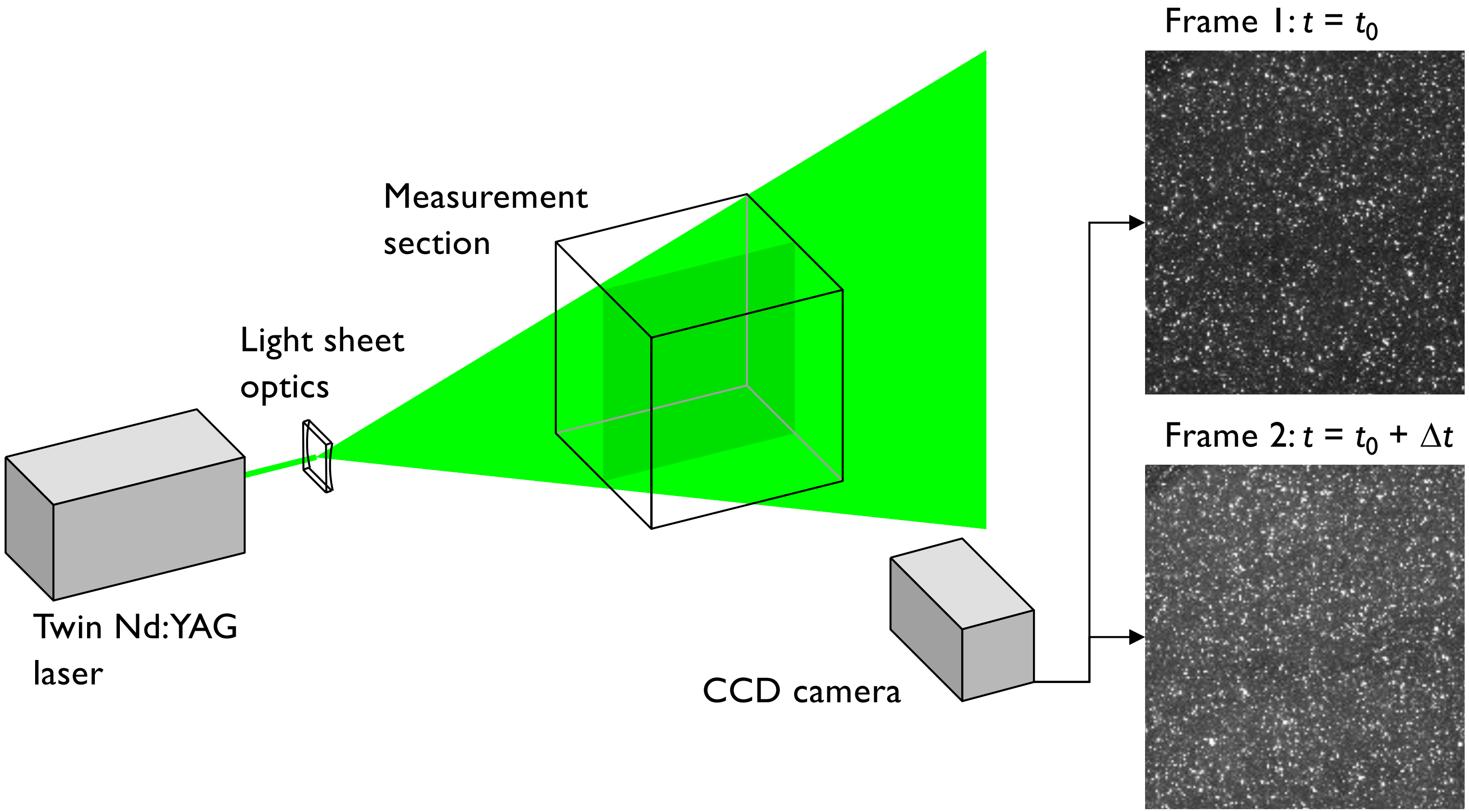
- Whole-field method
- Non-intrusive (seeding)
- Instantaneous flow field





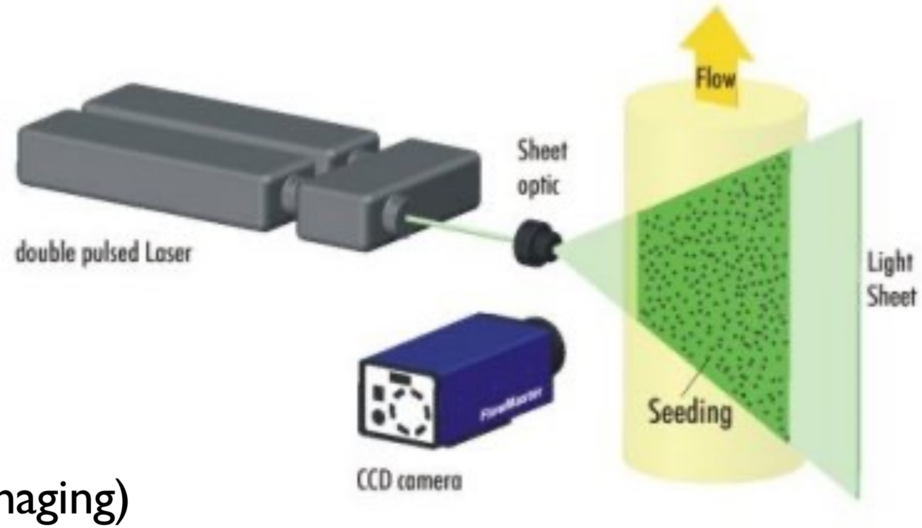
Local velocity measurements

- Particle image velocimetry (PIV)



Local velocity measurements

❑ Particle image velocimetry (PIV)



PIV components:

- tracer particles
- light source
- light sheet optics
- camera

Hardware (imaging)

- measurement settings

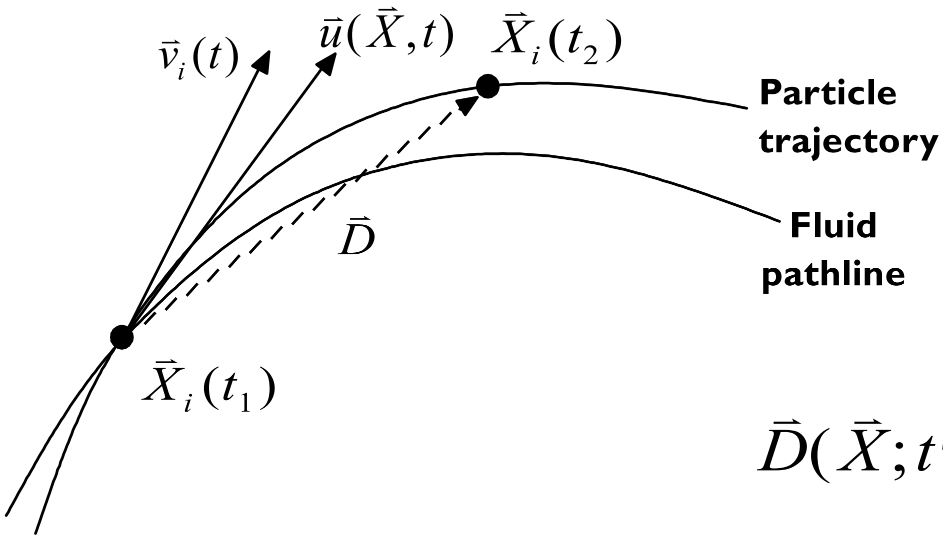
- interrogation
- post-processing

Software (image analysis)

Local velocity measurements

- Particle image velocimetry (PIV)

  - The fluid motion is represented as a displacement field



$$\vec{D}(\vec{X};t',t'') \approx \int_{t'}^{t''} \vec{u}[\vec{X}(t),t]\,dt$$

After: Adrian, *Adv. Turb. Res.* (1995) 1-19

Local velocity measurements

❑ Particle image velocimetry (PIV)

Inherent assumptions

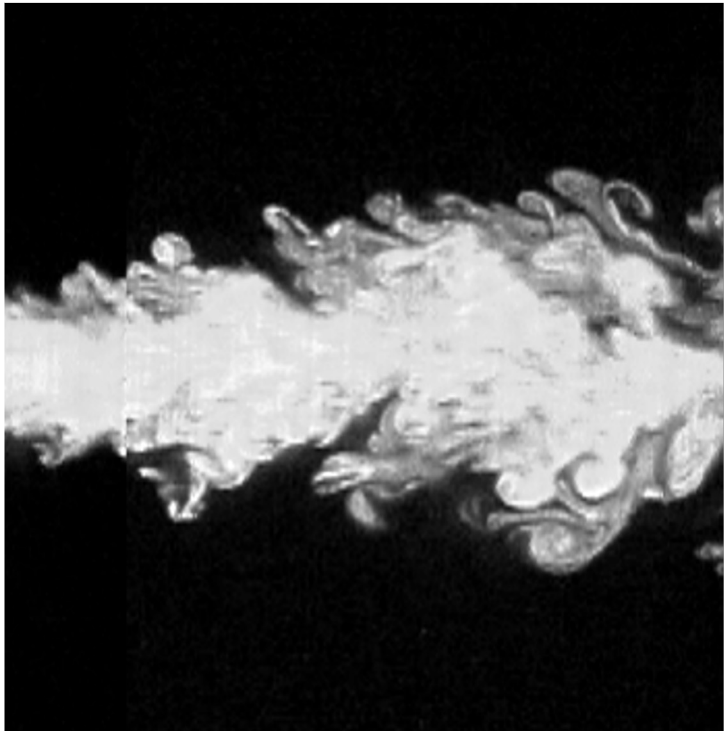
- **Tracer particles follow the fluid motion**
- **Tracer particles are distributed homogeneously**
- **Uniform displacement within interrogation region**

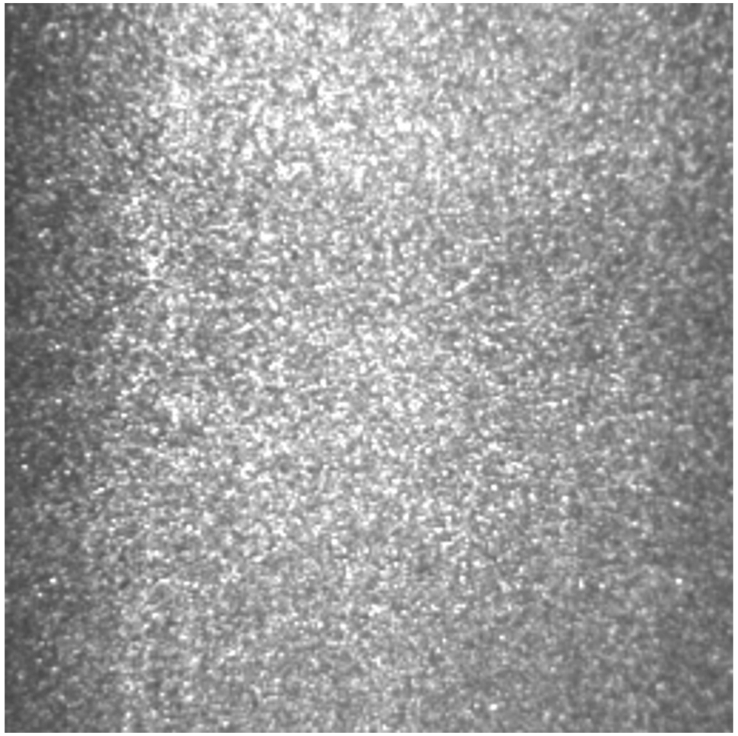
Local velocity measurements

❑ Particle image velocimetry (PIV)

Visualization vs. Measurement

inhomogeneous vs. homogeneous seeding

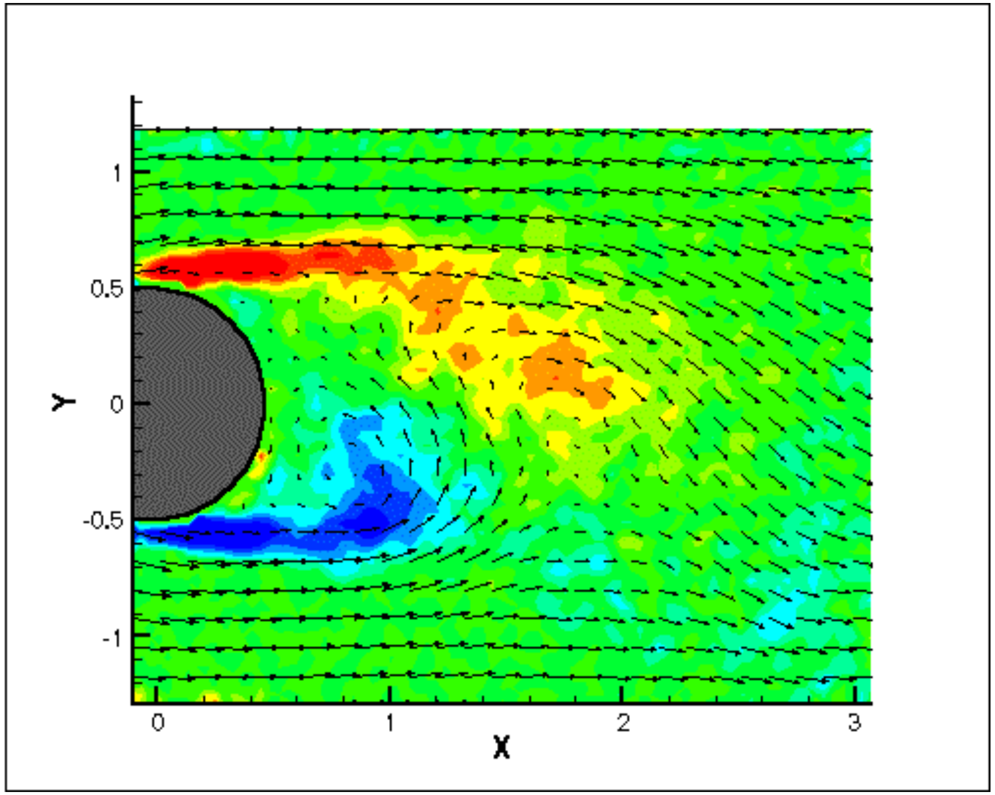


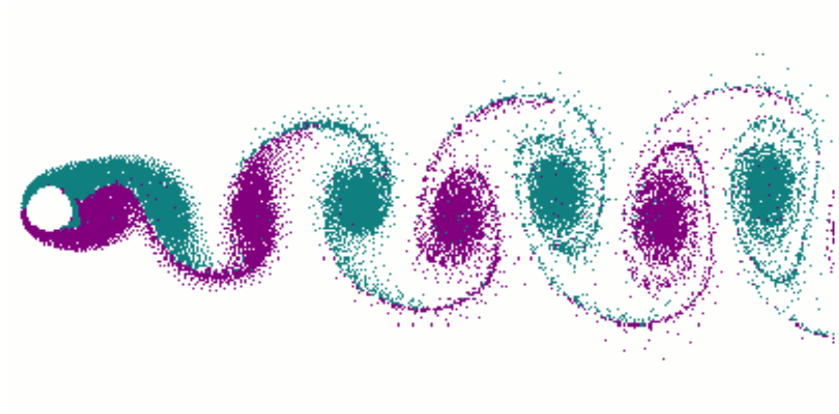


Local velocity measurements

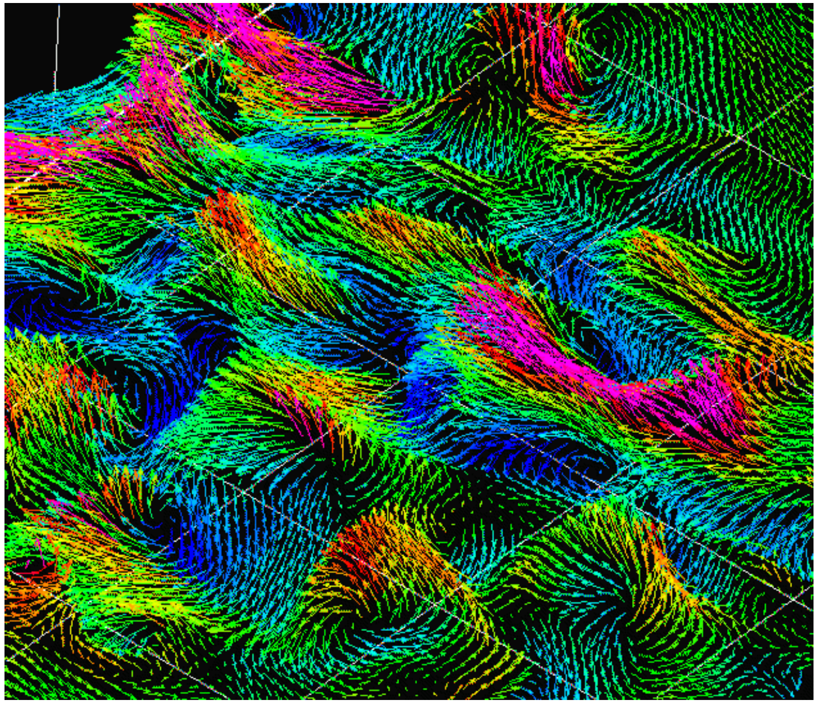
Local velocity measurements

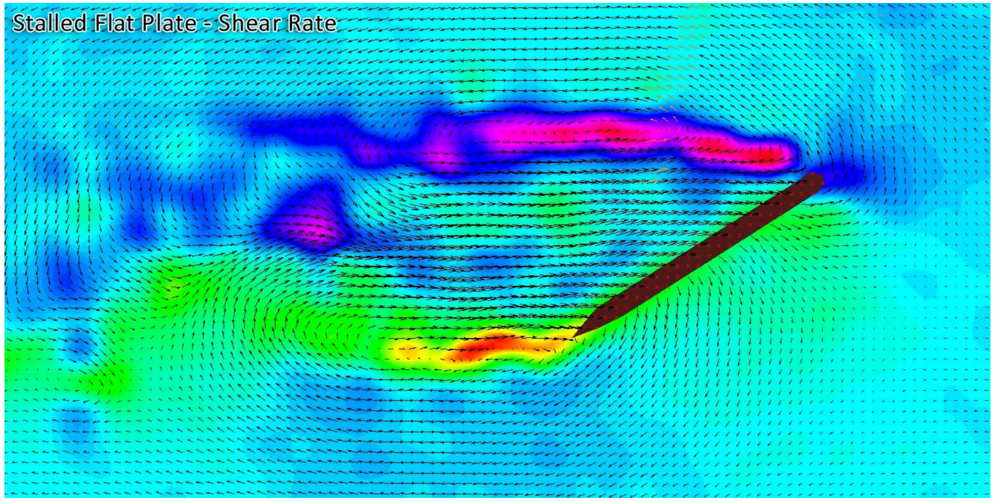
Karman Vortex (Shedding, Street)

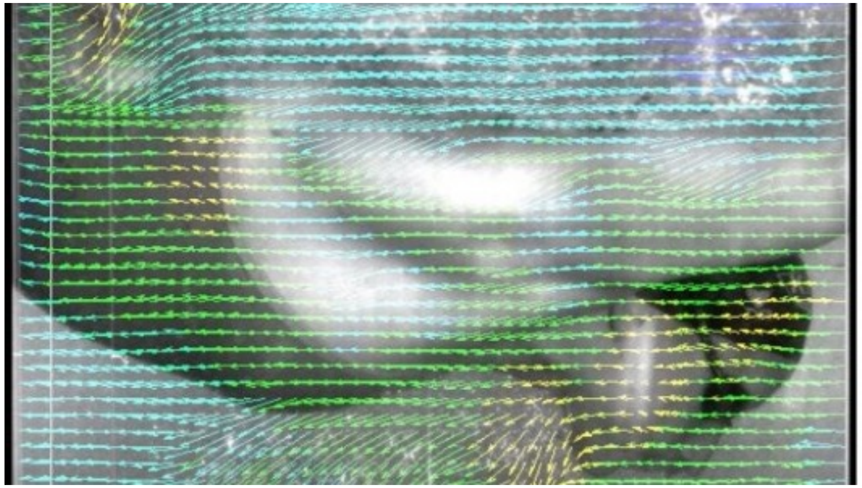




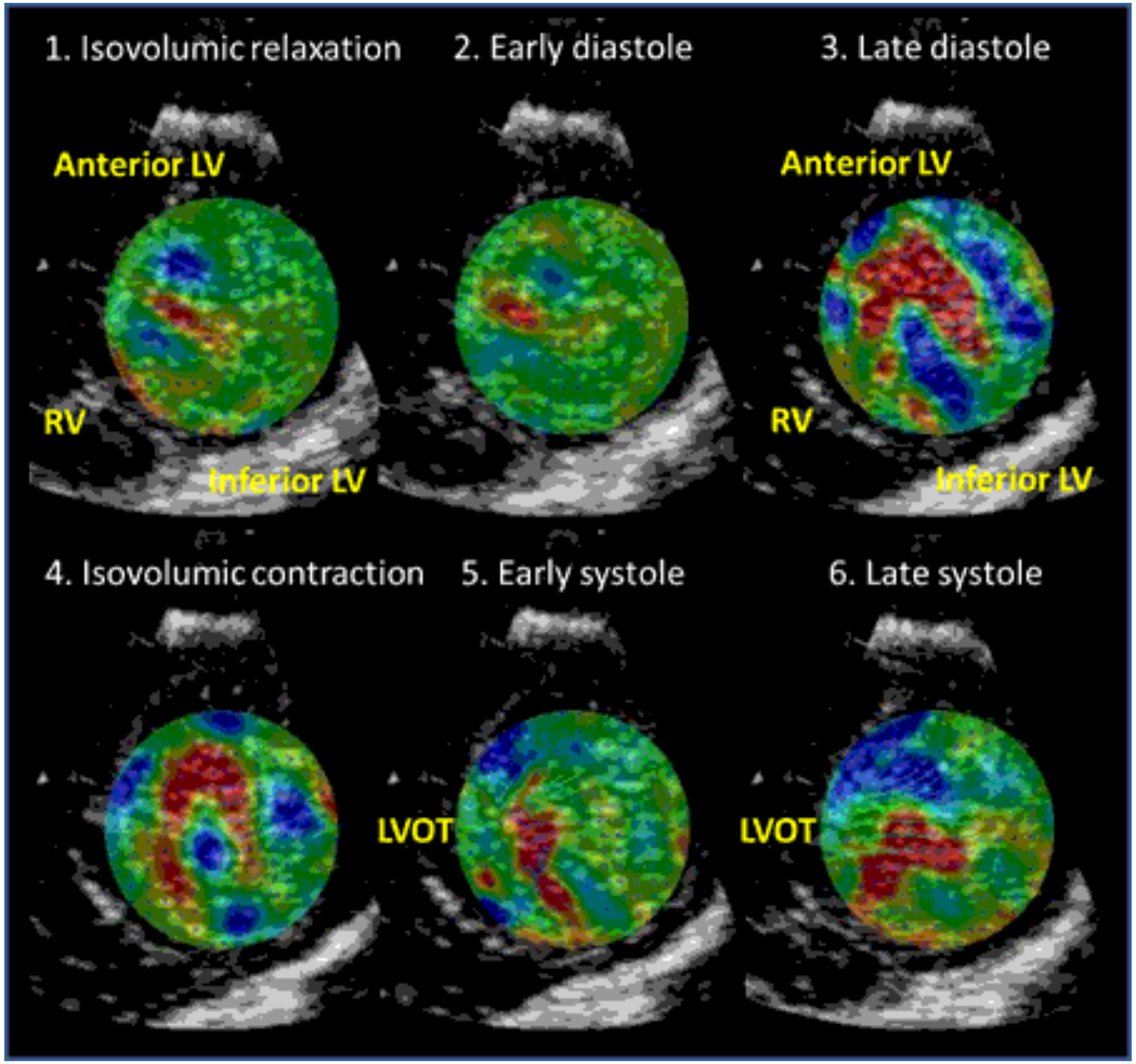
Local velocity measurements



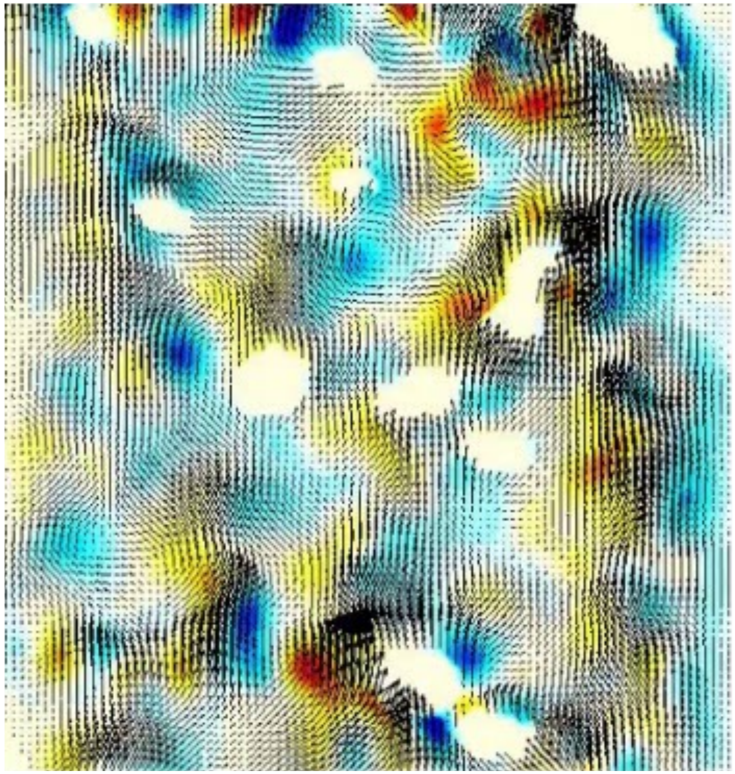


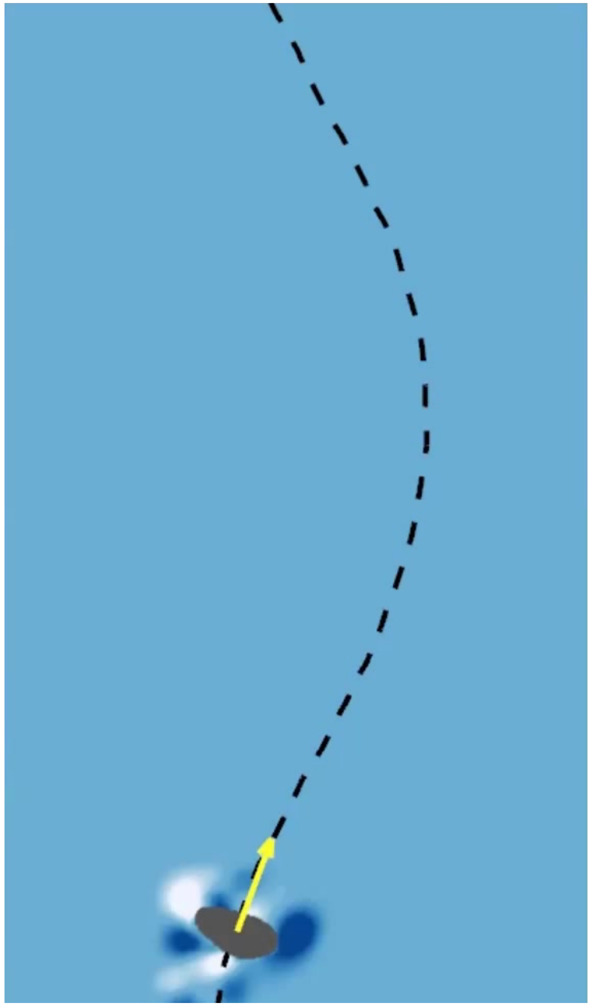


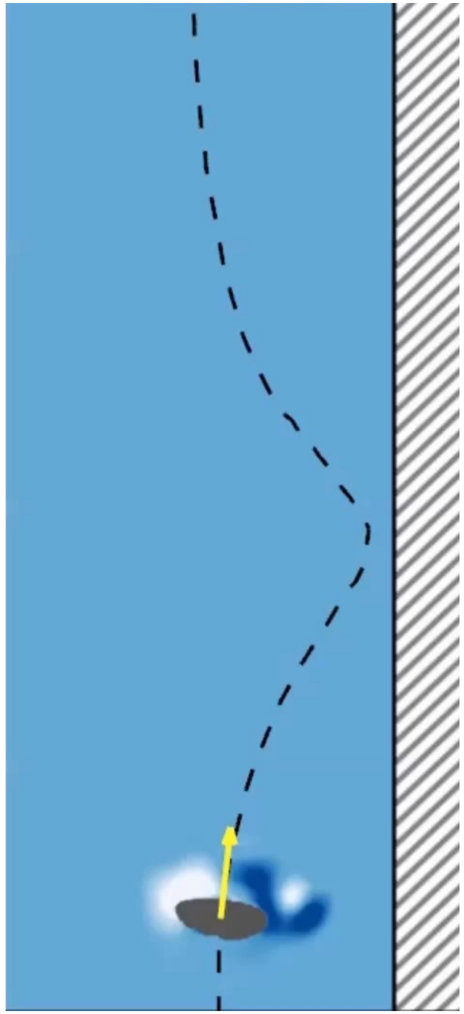
Local velocity measurements



Local velocity measurements

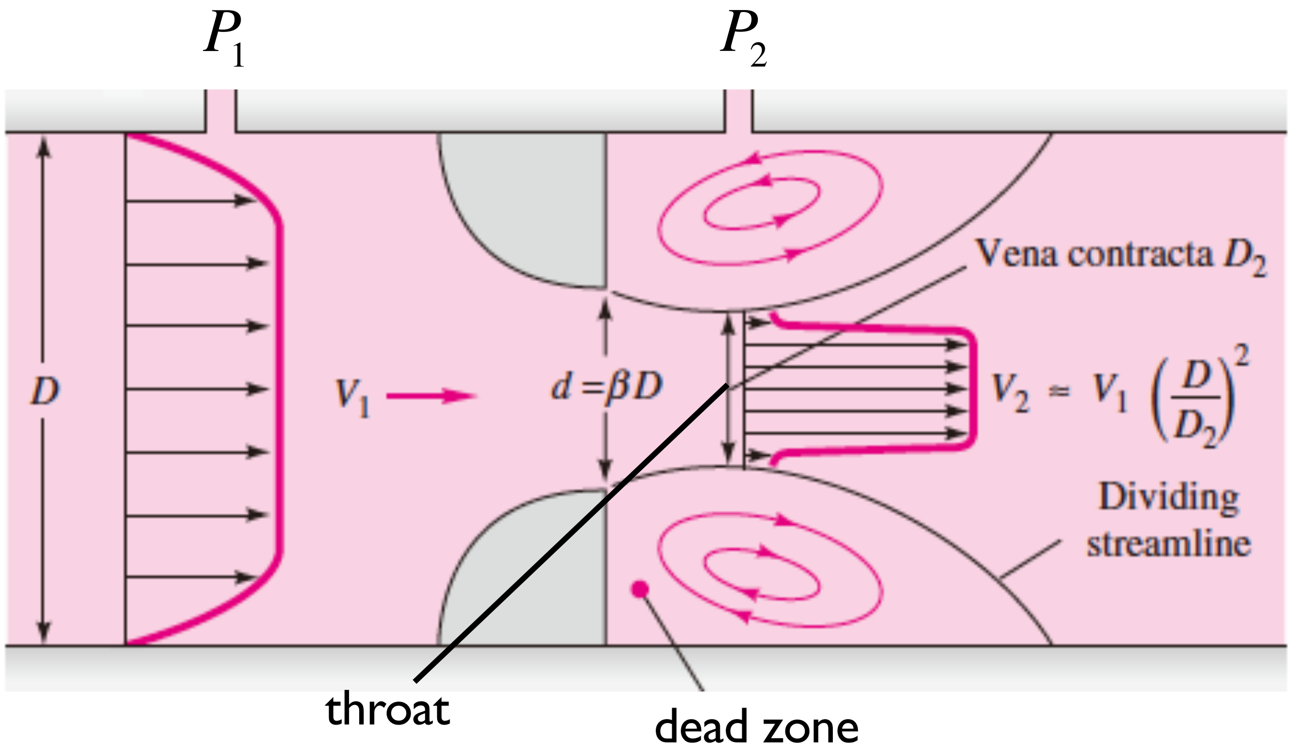






Volume-flow measurement

- Bernoulli obstruction theory



continuity: $Q = \frac{\pi}{4} D^2 V_1 = \frac{\pi}{4} D_2^2 V_2$

Bernoulli eq: $P_o = P_1 + \frac{1}{2}\rho V_1^2 = P_2 + \frac{1}{2}\rho V_2^2$

Volume-flow measurement

❑ Bernoulli obstruction theory

$$\frac{Q}{A_2} = V_2 \simeq \left[\frac{2(P_1 - P_2)}{\rho\left(1 - D_2^4 / D^4\right)} \right]^{1/2}$$

: inaccurate due to neglected friction and we don't want to measure D_2.

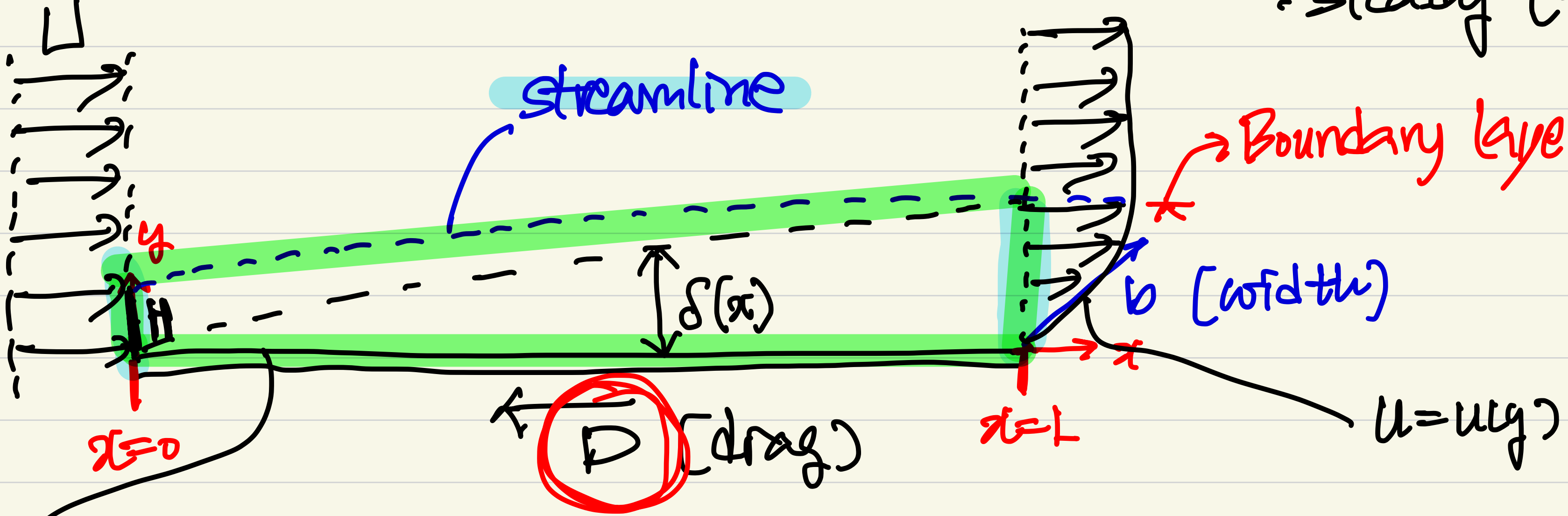
$$\rightarrow \text{ assume}, D_2 / D = \beta \text{ (i.e., } d = D_2\text{)}$$

$$Q = A_t V_t = c_d A_t \left[\frac{2(P_1 - P_2)/\rho}{1 - \beta^4} \right]^{1/2}$$

$c_d = f(\beta, \mathrm{Re}_D)$: dimensionless discharge coefficient

- Momentum integral relation (BL)

. steady ($\partial/\partial t = 0$)



→ CV analysis

$$UH = \int_0^\delta u\,dy \quad : \text{mass conservation} \quad ①$$

$$\Sigma \bar{F} = \frac{d}{dt}\int_{CV} \rho \bar{v}\, d\forall + \int_{CS} \rho \bar{v}(\bar{v}\cdot\bar{n})\, dA$$

$$-D = \int_0^\delta \rho u^2\, dy \cdot b - \rho U^2 H b \quad : \text{m'tm conservation} \quad ②$$

area.

① + ②

$$D = \rho b\left[-\int_0^\delta u^2\,dy + U^2 H\right]$$

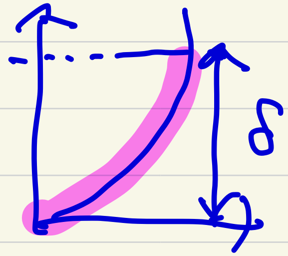
$U^2H = U\cdot UH = U\cdot\int_0^\delta u\,dy$

$$= \rho b\int_0^\delta u(U-u)\,dy \quad ☆$$

$$= \rho b U^2\int_0^\delta \frac{u}{U}\left(1-\frac{u}{U}\right)dy.$$

$= \theta$ (momentum thickness, 운동량두께)

Ⓢ $\underline{\underline{\delta}}$



loss
↑

$$\rightarrow \underline{D} = \rho b U^2 \underline{\theta(x)} = \int_0^x \tau_w(x)\,dx\cdot b$$

$$\Rightarrow \frac{dD}{dx} = \tau_w(x)\cdot b = \rho b U^2\cdot\frac{d\theta}{dx} \quad ③$$

$$\hookrightarrow \tau_w(x) = \rho U^2\frac{d\theta}{dx}$$

let $C_f \equiv \dfrac{\tau_w}{\frac{1}{2}\rho U^2}$ (skin-friction coefficient) ④

③ + ④ : $$\frac{1}{2} C_f = \frac{d\theta}{dx}$$

momentum integral relation for flat-plate BL

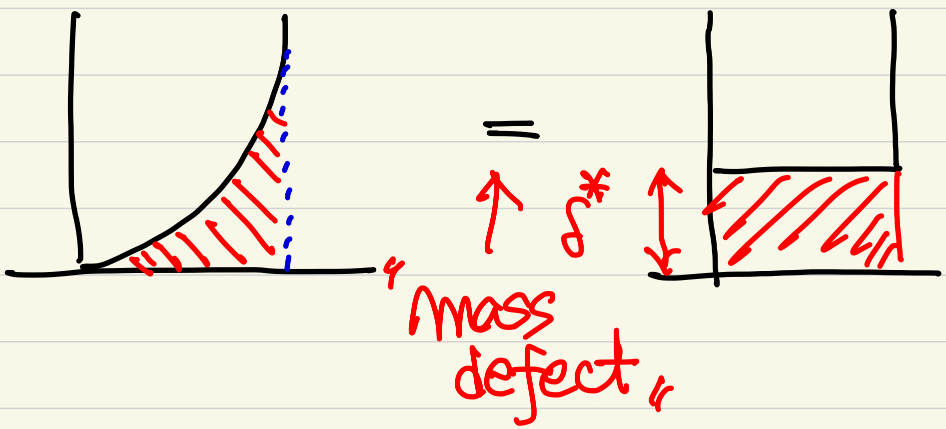
velocity profile $u(y)$ should be known!

→ use assumed profile!

δ, θ, δ^*

- Displacement thickness (배제두께)

↳ loss of mass



→ $$\delta^* = \int_0^{\delta} \left(1 - \frac{u}{U}\right) dy$$

- Shape factor, $H = \delta^* / \theta$ = 2.5 (laminar)

  = 1.3 (turbulent)

  → large H → susceptible to flow separation!

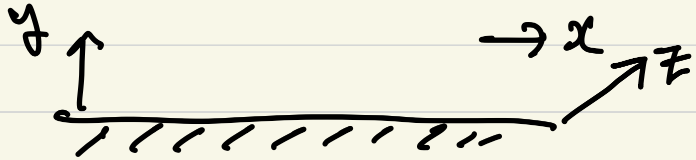
※ Flow separation (유동박리)

- pressure gradient.
  - adverse pressure gradient (역압력구배)

    $$\frac{\partial p}{\partial x} > 0$$

  - favorable pressure gradient (순압력구배)

    $$\frac{\partial p}{\partial x} < 0$$



$u = v = w = 0$

N-S eq at the wall ($y=0$), no-slip condition

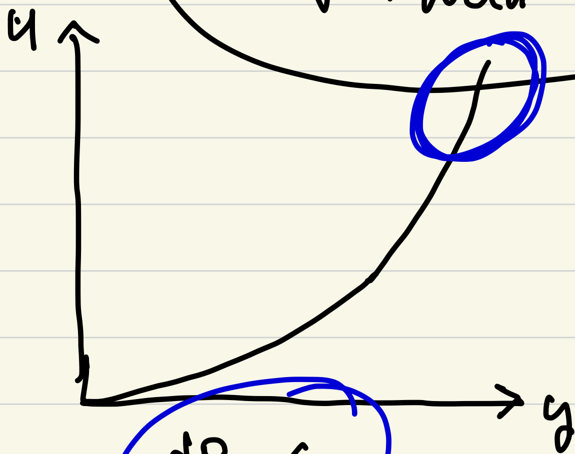
$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right)$$

$\frac{\partial^2 u}{\partial y^2} \Leftarrow \frac{\partial}{\partial y}\left(\frac{\partial u}{\partial y}\right)$

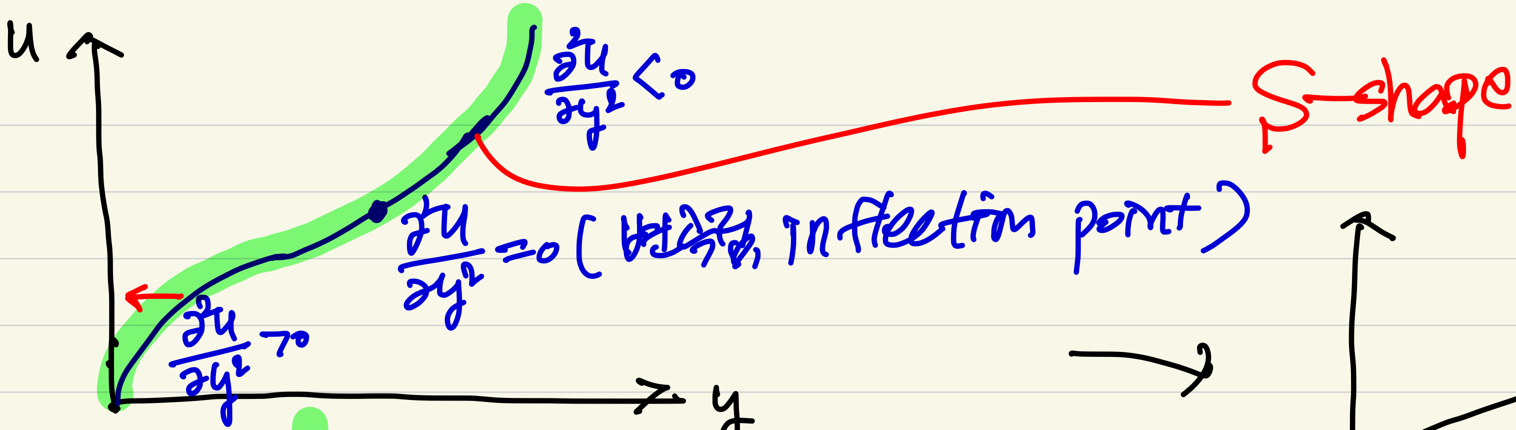
$\frac{\partial^2 u}{\partial x^2} = \frac{\partial}{\partial x}\left(\frac{\partial u}{\partial x}\right) \to 0$

$\frac{\partial^2 u}{\partial z^2} = \frac{\partial}{\partial z}\left(\frac{\partial u}{\partial z}\right) \to 0$

$$\therefore \left(\frac{\partial^2 u}{\partial y^2}\right)_{wall} \sim \frac{\partial p}{\partial x}.$$



$\frac{dp}{dx} \leq 0$ (no-separation)

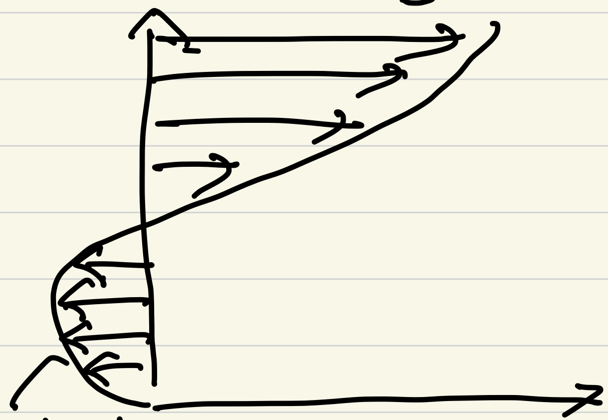


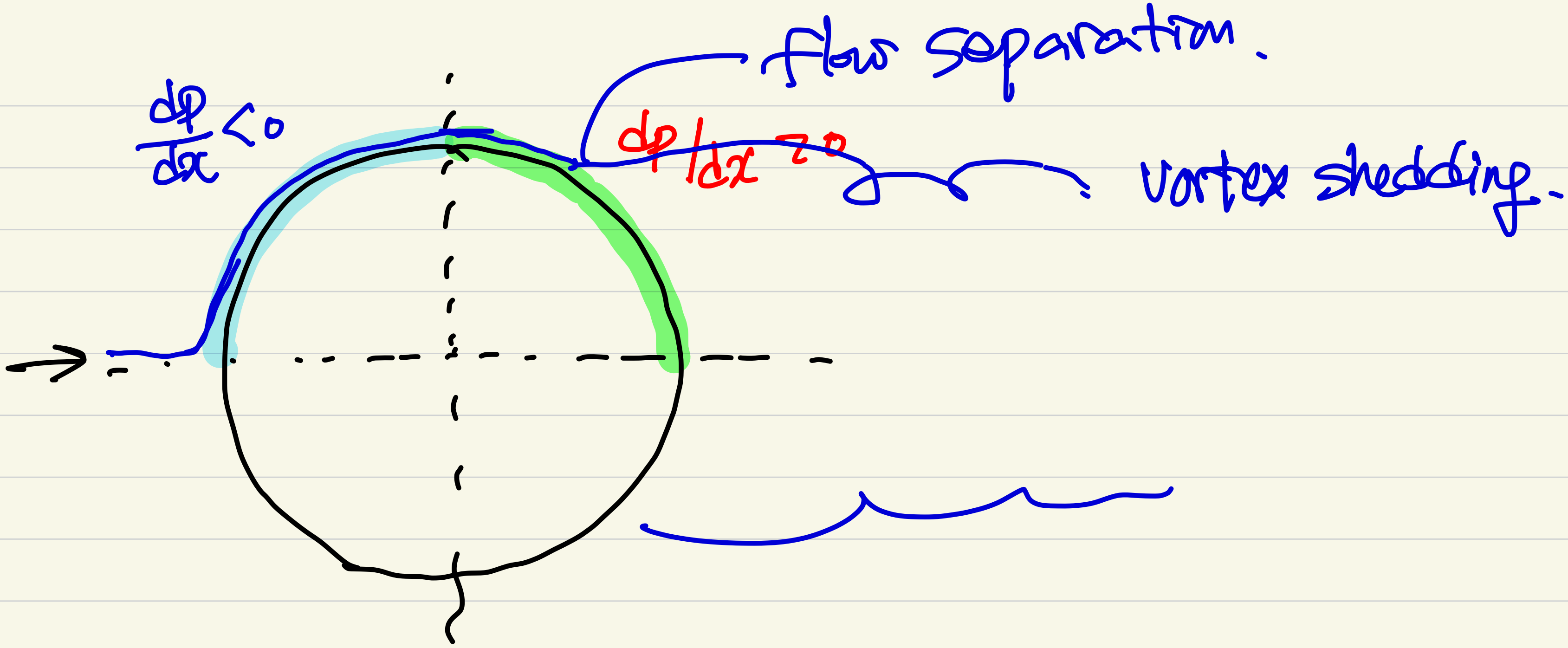
$$\frac{dp}{dx} > 0 \Rightarrow \frac{\partial^2 u}{\partial y^2} > 0 \text{ (wall)}$$

↳ curvature

→

separation occurs.





dp/dx < 0
dp/dx > 0
flow separation.
vortex shedding.