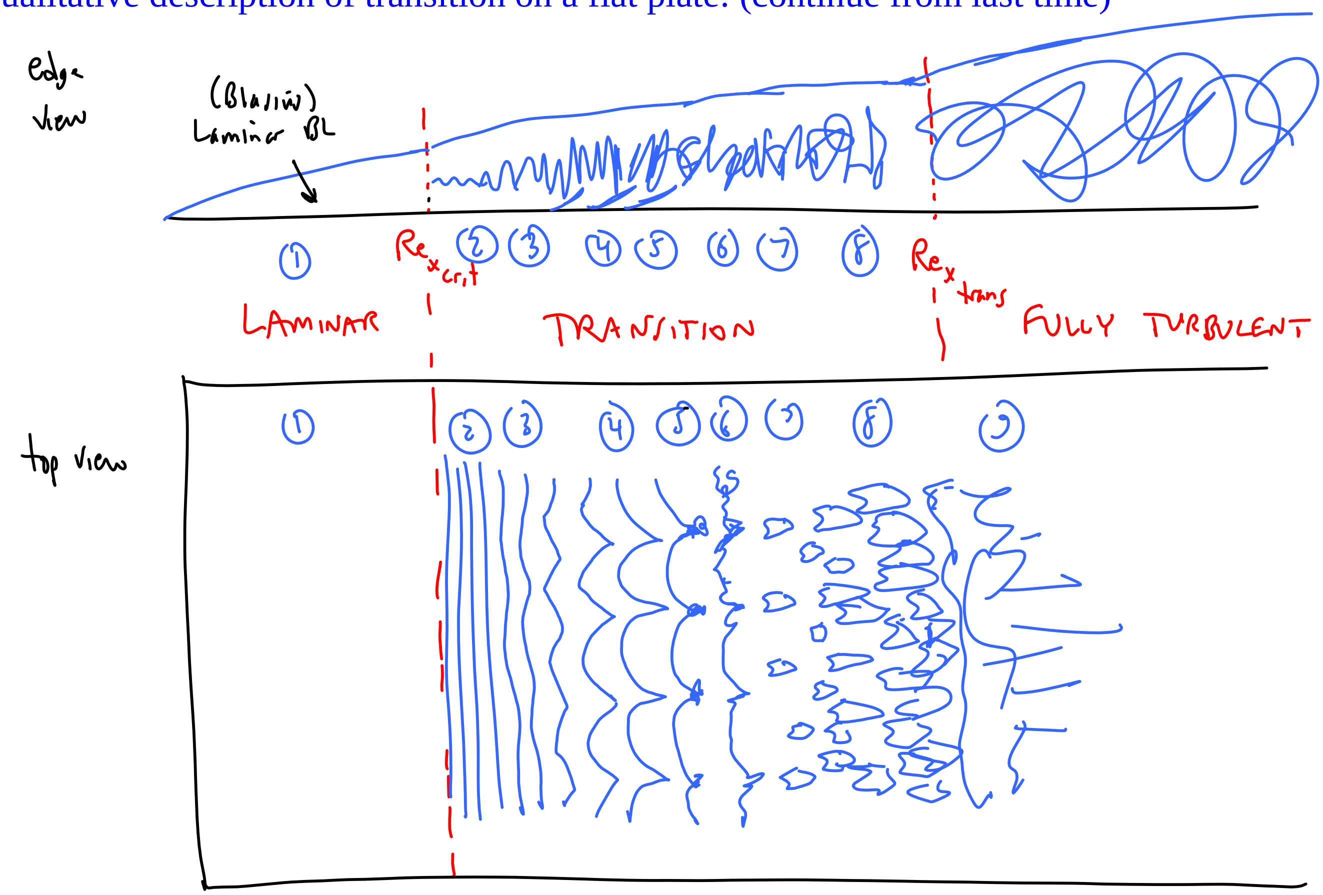
M E 522 Spring 2008 Professor John M. Cimbala Lecture 21 03/03/2008

Today, we will:

- Continue to discuss transition in a flat plate boundary layer
- Start discussing **Turbulence – The Final Frontier**

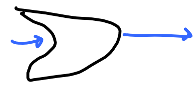
Qualitative description of transition on a flat plate: (continue from last time)



Region	Description
1	stable laminar flow $Re_x < Re_{x_{crit}}$ (Blasius)
2	First instability appears @ $Re_x = Re_{x_{crit}}$ 2-D T-S waves appear & grow [$\cong$ 1% of U_∞]
3	3-D waves appear on these 2-D T-S waves (secondary instability)
4	3-D "hairpin eddies" form
5	3-D vortex breakdown – hairpin eddies pinch off [no longer a continuous identifiable vortex line]

⑥ Fully unsteady 3-D fluctuations — But still not turbulent

⑦ Turbulent spots appear → patches of fully turbulent flow


Front moves faster than rear, so they stretch

⑧ turbulent spots coelesce — merge together

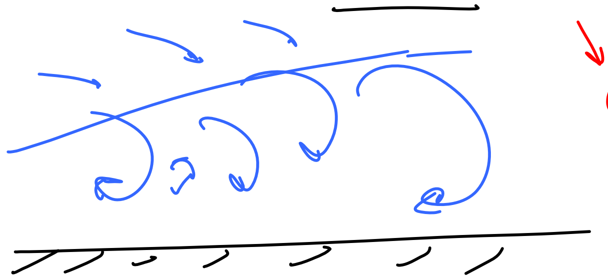
[Now we have mostly turbulence — some "pockets" of laminar flow in between the spots

⑨ Fully turbulent flow — Typ. $Re_{x_{tran}} \approx 3.0 \times 10^6$ for a clean flow & a very smooth flat plate.

Comments:

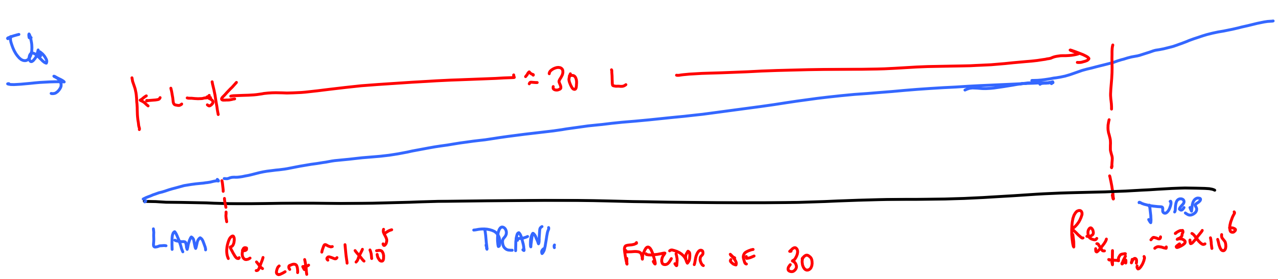
- Above description is ideal [smooth plate, very clean flow no vibrations, etc.]
- δ grows much faster in turbulent BL than in a laminar BL

Entrainment is a key mechanism for BL growth



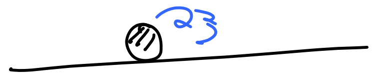
Greatly increased mixing due to the large vortices in turbulent flow

- Transition region for this idealized case is actually quite long



- Addition of roughness on the plate or trip wires causes transition to occur much more rapidly

or



[or dimples e.g., golf balls]

- Vibration & free stream noise (fluctuations) cause faster transition
- Transition is very hard to predict with CFD !

END OF EXAM I MATERIAL

IX TURBULENCE, THE FINAL FRONTIER!

References:
- Kundu, Ch. 13
- Tennekes & Lumley - A First Course in Turbulence

1. Definition of Turbulence

- No simple definition is possible
- So - we list its characteristics

2. Characteristics of Turbulence

a. "Randomness" or Irregularity

Turbulent flows are
- always unsteady
- unpredictable or "chaotic"

NOT GAUSSIAN

b. <u>Nonlinearity</u> → nonlinear terms in the fluctuations cannot be neglected

u, v, w → all interact nonlinearly

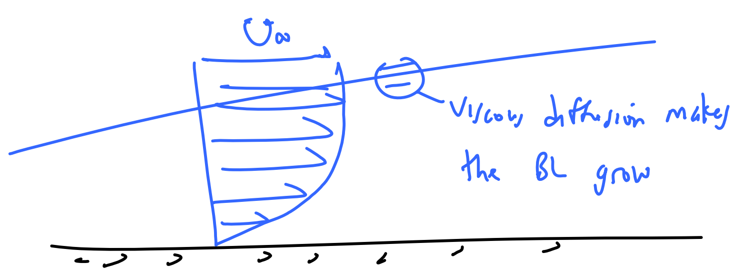
The nonlinearity makes the eqs for turbulence very hard to solve!

c. <u>Diffusivity</u> (Mixing)

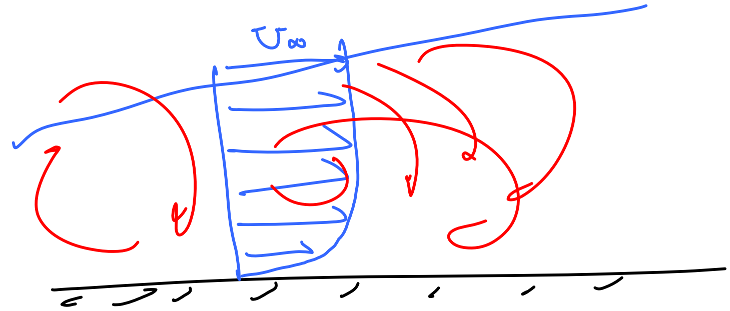
- Rapid mixing, churning
- Much faster momentum transfer, heat transfer, mass transfer

Why? <u>Large scale turbulent eddies</u>

– <u>Laminar BL</u>



<u>Turbulent BL</u>



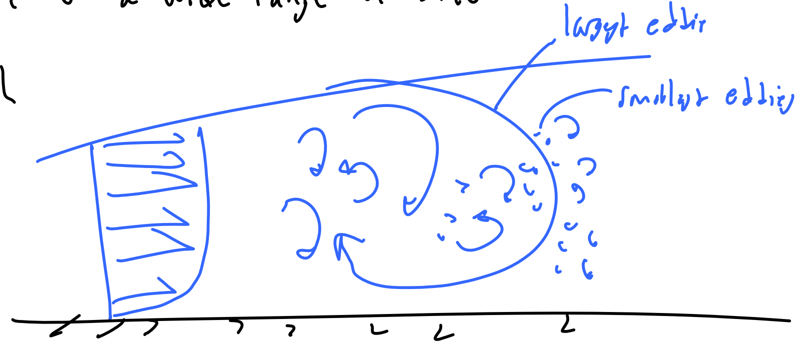
<u>MACROSCOPIC MIXING</u> + MICROSCOPIC MIXING

DOMINATES

MICROSCOPIC MIXING
(MOLECULAR)

d) 3-D Fluctuating vorticity (at a wide range of scales)

- Lots of spinning "eddies" (vortices)
- Eddies are of a wide range of size
- e.g., BL



- The larger the Reynolds #, the bigger the gap between largest & smallest eddies

- <u>Three-D interaction</u> → vortex stretching & distortion
  - eddy coalescence (merge)
  - eddy breakup

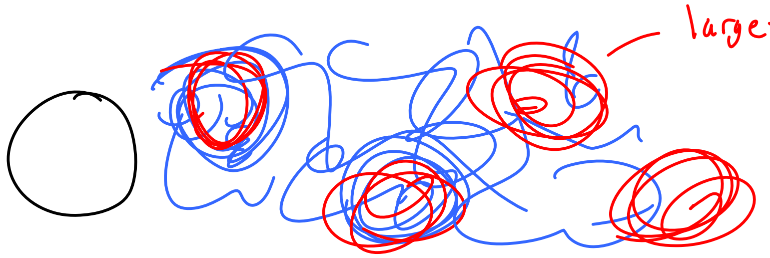
Recall
<u>Vorticity is a measure of fluid rotation</u>

∴ turbulent flows are by nature <u>rotational</u>

[e.g. random surface waves on the ocean, but largely <u>irrotational</u>
& very little mixing → ∴ <u>NOT TURBULENT</u>]

Largest eddies can be more organized (not as random) – "predictable"
Smallest eddies are very unpredictable & "random"

e.g. Wake



e) Dissipation — Turbulence needs a continuous supply of energy to maintain itself

The eddies have kinetic energy → this energy must come from the mean flow

— All of this kinetic energy in the eddies is ultimately dissipated as heat (due to friction (viscosity))