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)

<table>
<thead>
<tr>
<th>Region</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Stable laminar flow ( \text{Re}<em>x &lt; \text{Re}</em>{x \text{crit}} ) (BLWJ)</td>
</tr>
<tr>
<td>2</td>
<td>First instability appear @ ( \text{Re}<em>x = \text{Re}</em>{x \text{crit}} ) 2-0 Ti/S waves appear &amp; grow ( \leq 1% ) of ( U_0 )</td>
</tr>
<tr>
<td>3</td>
<td>3-0 waves appear on these 2-0 Ti/S waves (secondary instability)</td>
</tr>
<tr>
<td>4</td>
<td>3-0 &quot;hairpin eddy&quot; form</td>
</tr>
<tr>
<td>5</td>
<td>3-0 vortex breakdown – hairpin eddy pinch off ( \text{[no longer a continuous identifiable vortex line]} )</td>
</tr>
</tbody>
</table>
6. Fully unsteady 3-D fluctuation - But still not turbulent

Turbulent spots appear → patches of fully turbulent flow

Front moves faster than rear, so they stretch

8. Turbulent spots coalesce → merge together

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

9. Fully turbulent flow - Typ. \( \text{Re}_{x_{out}} \approx 3 \times 10^6 \) for a clean flow on a very smooth flat plate.

Comment:
- Above description is ideal (smooth plate, very clean flow no vibration, etc.)
- If grow 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

\[ L_{turb} \quad \text{Re}_{x_{out}} = 1 \times 10^5 \quad \text{TURB. FRONT of 30} \quad \text{Re}_{x_{out}} = 3 \times 10^6 \]
Addition of roughness on the plate or trip wire cause transition to occur much more rapidly.

\[ \text{or simply e.g., golf balls} \]

Vibration i.e., free stream noise (fluctuations) cause faster transition.

Transition is very hard to predict with CFD!

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**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".

      \[ \text{NOT GAUSSIAN} \]
b. Nonlinearity
- 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. Diffusivity (Mixing)
- Rapid mixing, churning.
  - Much faster momentum transfer, heat transfer, mass transfer.
  - Why? Large scale turbulent eddies.

- Laminar BL
- Turbulent BL

Macroscopic mixing + microscopic mixing

Microscopic mixing (Molecular) dominates.
1) 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 larger & smaller eddies

- Three-D interaction \( \rightarrow \) vortex stretching & deformation
  - eddy coalescence (merge)
  - eddy breakup

Vorticity is a measure of fluid rotation
- turbulent flows are by nature rotational

[ e.g. random surface waves in the ocean, but largely irrotational ]

\[ \text{very little mixing} \rightarrow \text{not turbulent} \]

Larger eddies can be more organized (not as random) - "predictable"
Smaller eddies are very unpredictable & "random"

- e.g. wake
- large-scale coherent structures or eddies
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)).