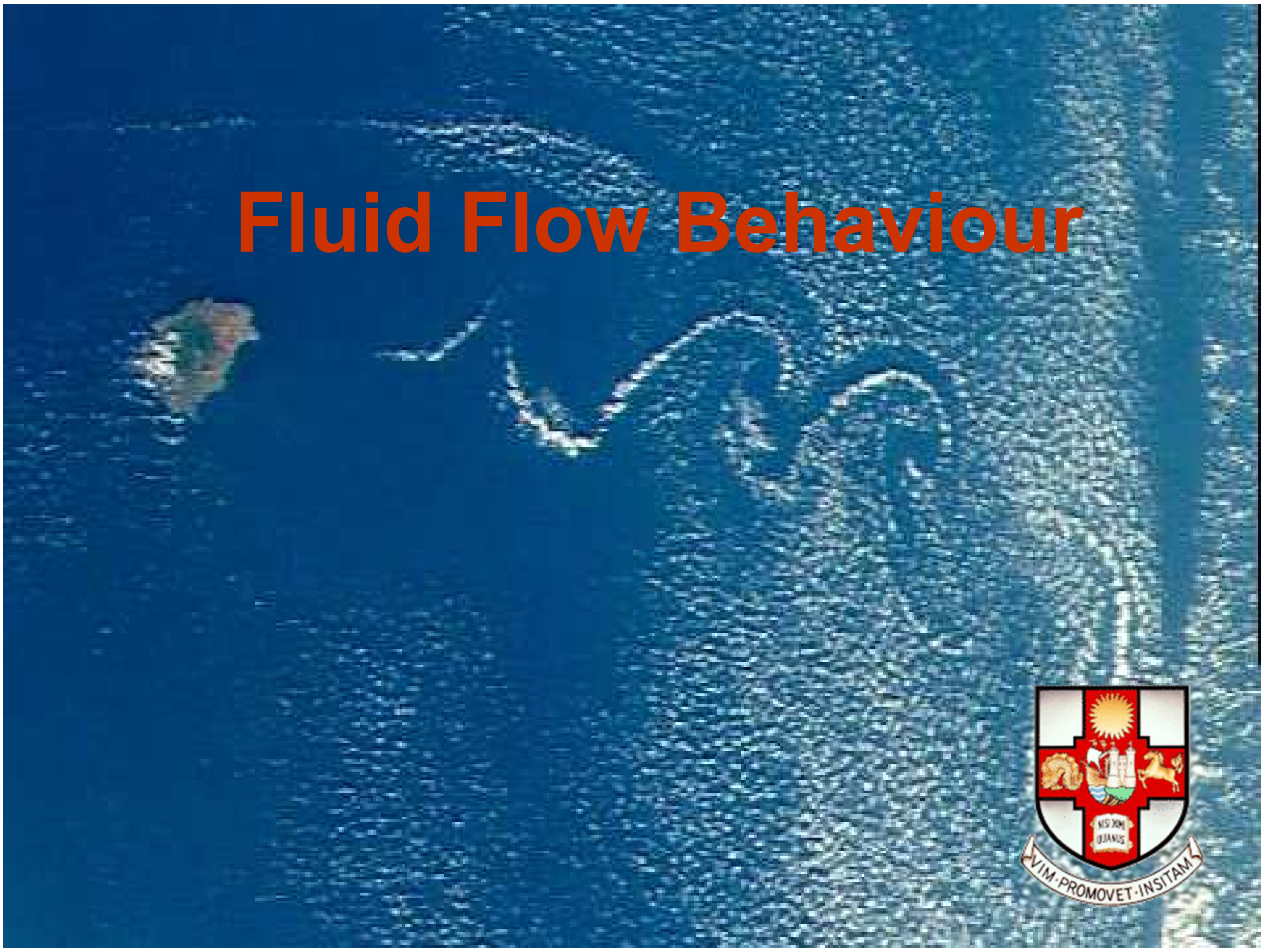
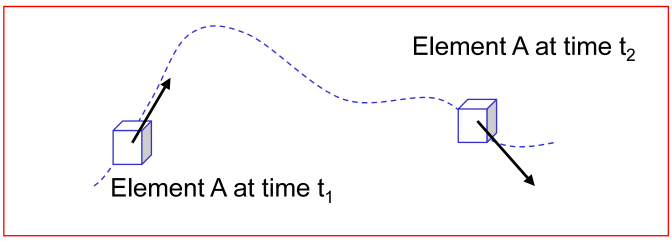
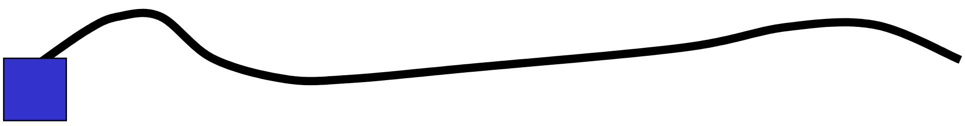


Flow Pictures

- It is useful to be able to visualise the physics of a fluid flow i.e. to understand “where the flow is going”.
- Common ways that are used are:
  - Pathlines
  - Streaklines
  - Streamlines

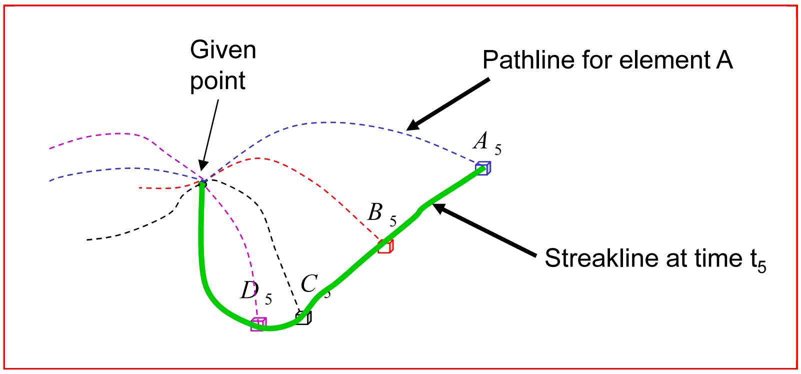
<u>Pathline:</u> the path traced by an element of fluid over an interval in time

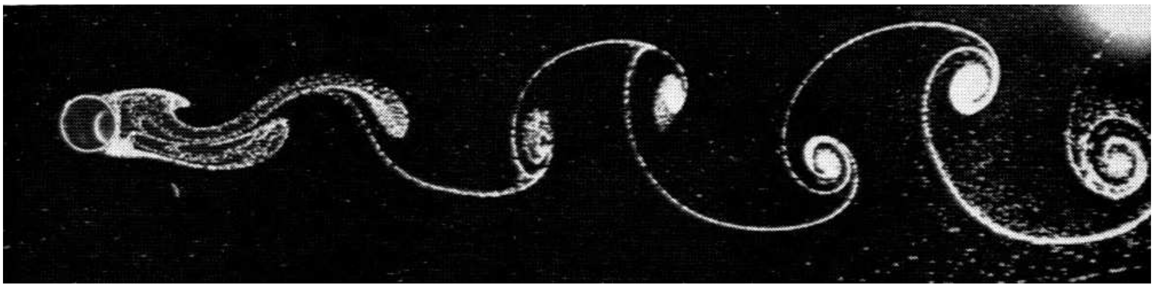




Flow Pictures 2

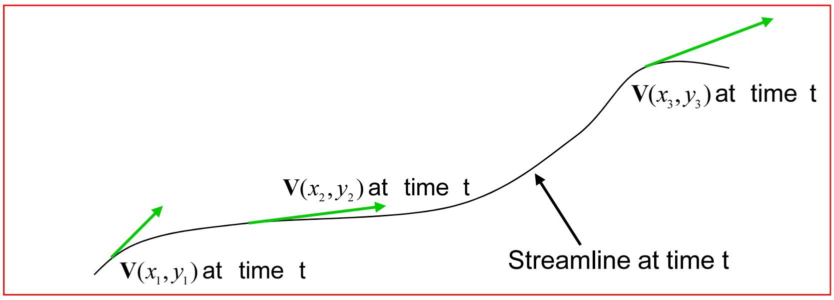
<u>Streakline</u>: the trace joining the instantaneous positions of fluid elements which have passed through a given point i.e. shown by smoke or dye injection





Flow Pictures 3

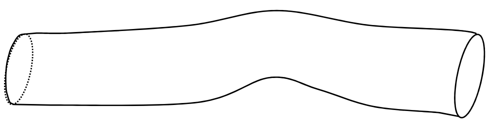
<u>Streamline</u>: The curve drawn from the flow field at an instant in time, whose tangent at any point is in the direction of the velocity vector at that point



Hence: no flow perpendicular to a streamline; streamlines can only cross at stagnation points (where velocity is zero) as the velocity at any point has only one value or direction

Pathlines, streaklines and streamlines are identical in **steady** flow but in general unsteady flows are different.

Streamtube is the 3D equivalent of the streamline



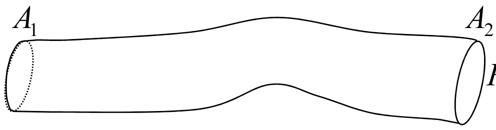
Steady Inviscid incompressible flow

We will see later in the course: Along a streamline in steady inviscid incompressible flow the total pressure, P_o, defined by Bernoulli's equation, is constant

$$\underbrace{P_0}_{\text{Total pressure}} = \underbrace{p}_{\text{Static pressure}} + \underbrace{\tfrac{1}{2}\rho V^2}_{\text{Dynamic pressure}} + \underbrace{\rho g z}_{\text{Hydrostatic pressure}} = \text{constant}$$

Hence fluid velocity and static pressure simply related along a streamline:

$$P_0 = p_1 + \tfrac{1}{2}\rho V_1^2 + \rho g z_1$$



$$P_0 = p_2 + \tfrac{1}{2}\rho V_2^2 + \rho g z_2$$

If height unchanged (hydrostatic term unchanged) $p_2 - p_1 = \tfrac{1}{2}\rho\left(V_1^2 - V_2^2\right)$

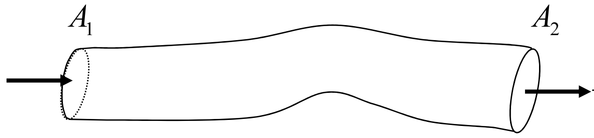
$V\uparrow\ p\downarrow$ *and* $V\downarrow\ p\uparrow$

For compressible flow we still have the idea of total pressure which is of the same form as the incompressible equation above. However the dynamic & hydrostatic pressure changes

Steady Inviscid incompressible flow (2)

As no flow across streamlines (and streamtubes) then mass flow rate in must equal mass flow rate out.

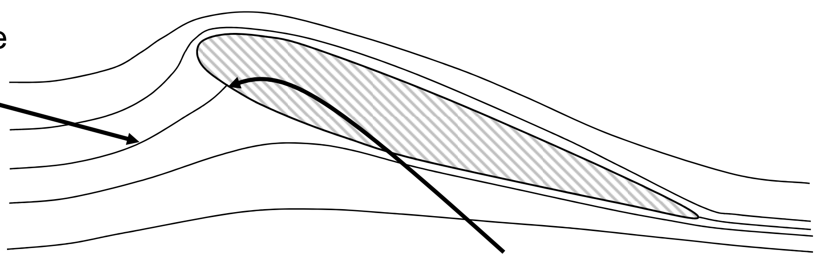
$$\frac{dm_1}{dt} = \rho A_1 V_1$$



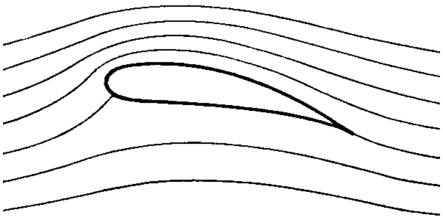
$$\frac{dm_2}{dt} = \rho A_2 V_2$$

$$\frac{dm_1}{dt} = \frac{dm_2}{dt} \quad \rightarrow \quad \rho A_1 V_1 = \rho A_2 V_2 \quad \rightarrow \quad A_1 V_1 = A_2 V_2$$

Hence, streamlines getting closer together implies a flow velocity increase and streamlines getting further apart implies the flow slows down

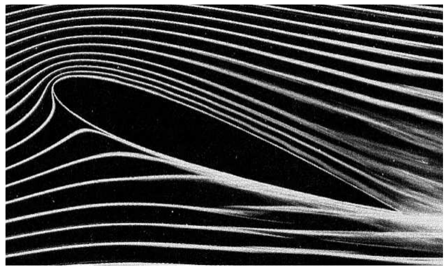


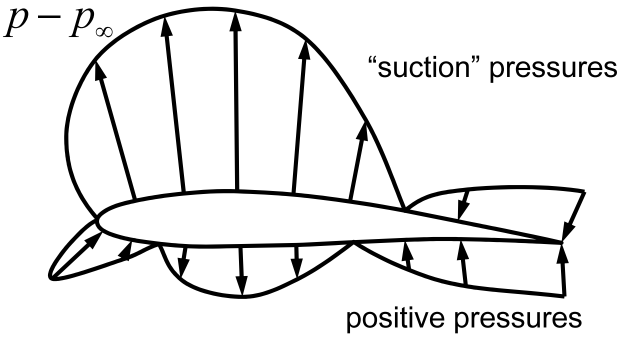
Pressure over streamlined bodies



Flow visualisation using smoke injection to show streaklines (equivalent to streamlines if flow steady)

Idealised streamlines for a 2D streamlined body where the effect of viscosity is neglected.

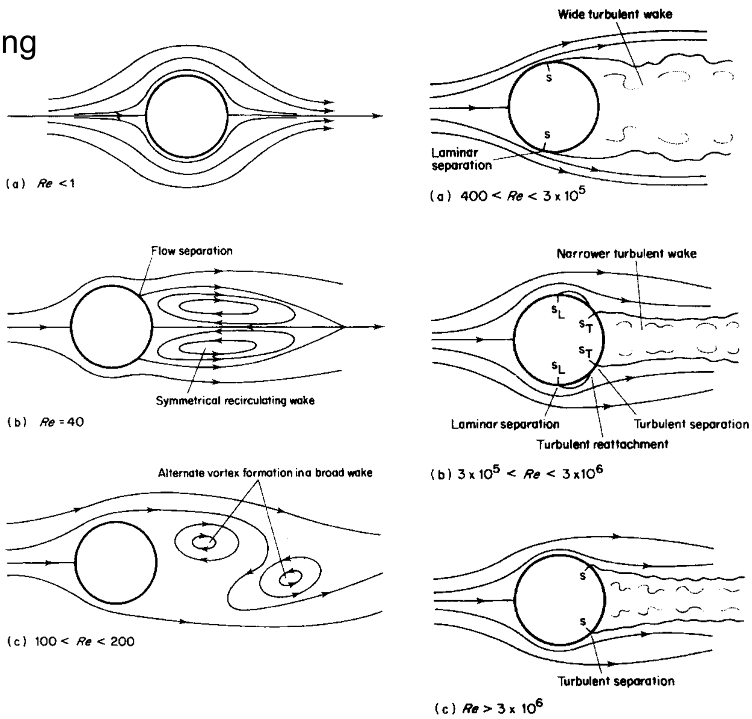




The lift and drag are functions of both pressure and the viscous shear stress but for streamlined bodies the viscous stress can be small and occasionally ignored when calculating lift.

Streamlines over smooth bluff bodies (eg sphere)

Creeping flow

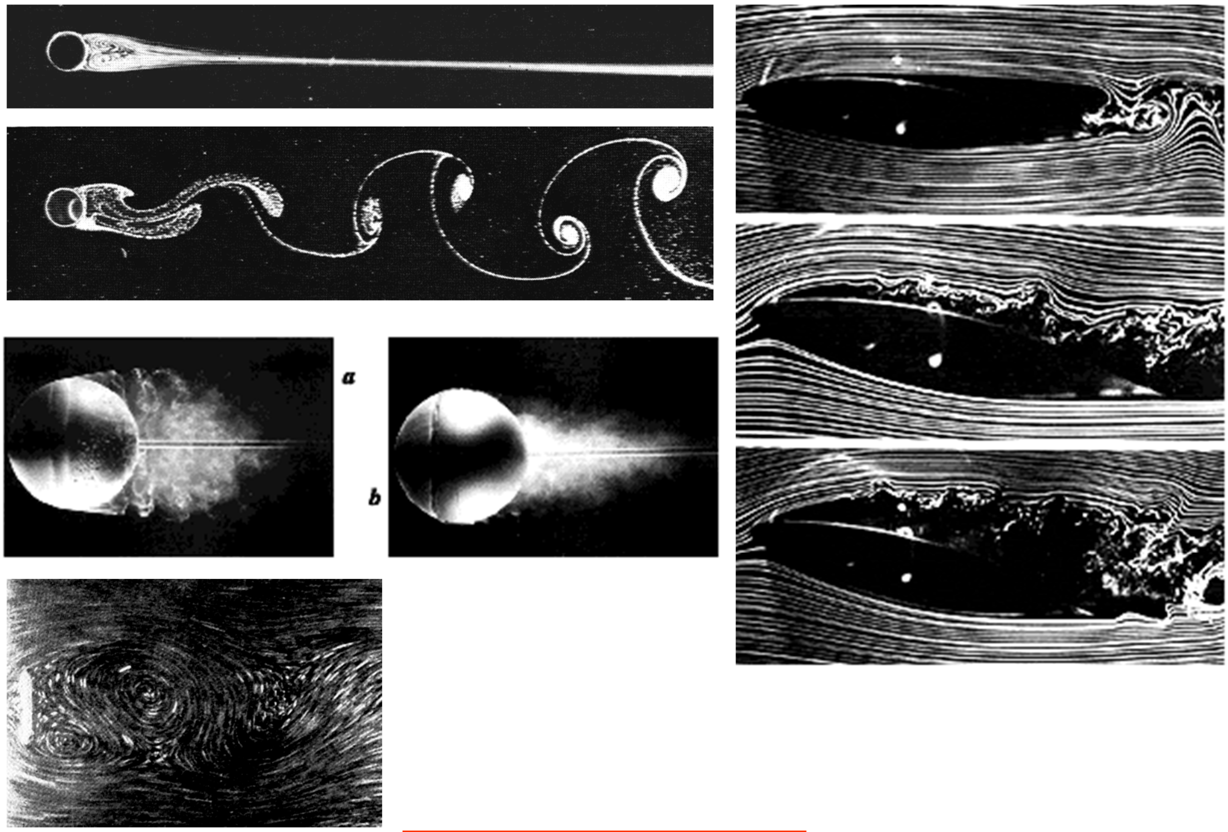


Velocity increasing

See later definition of Reynolds Number

Obviously significantly more complex than the previous streamlined body.To understand what is happening we must appreciate the effect of viscosity.

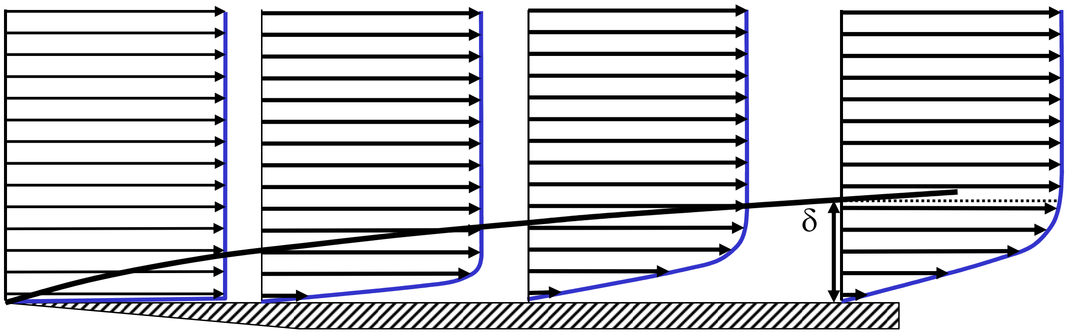
Streaklines over real bodies



Background, not in exam

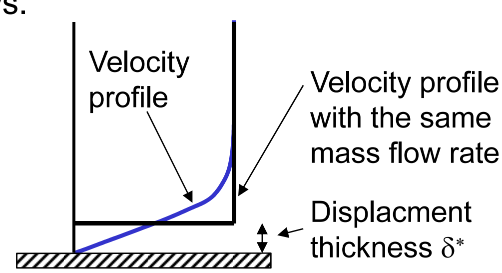
Flow over a flat plate: Laminar viscous flow

Consider a smooth steady uniform flow as it reaches the leading edge of a flat plate. Viscosity means the flow will be zero at the surface and the resulting shear stress will cause a region of smoothly retarded flow to develop (the boundary layer)



The boundary layer thickness (usually δ) is defined as the height above the surface where the velocity is 99% of the free stream value. Simple here, but can be very difficult to work out in complex flows.

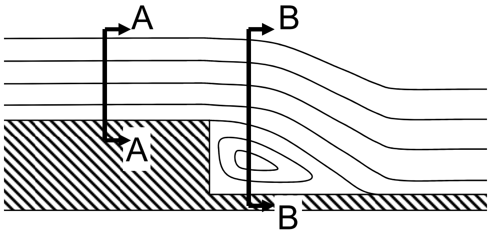
More useful definitions of the boundary layer height include the "displacement thickness", which represents the displacement of a uniform flow with the same mass flow rate.

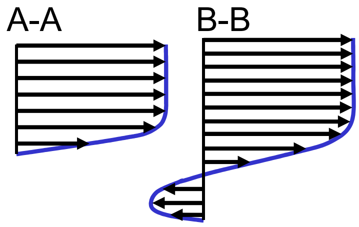


Practical Consequences of Viscosity

- leads to ‘no-slip’ velocity condition at surfaces
- → ‘skin friction’ drag
- → formation of ‘boundary layer’ adjacent to surface
- effectively ‘prohibits’ flow around sharp corners

- → flow separation at sharp edges





- Viscosity damps out flow instabilities
- → transition from laminar to <u>turbulent</u> flow

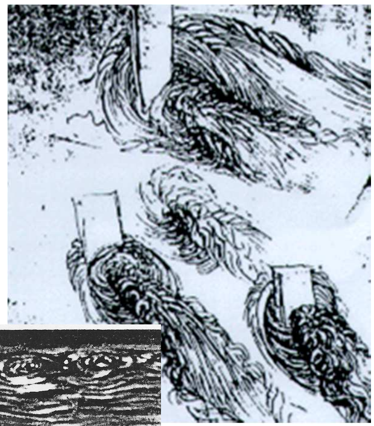
Viscous Effects & Reynolds Number

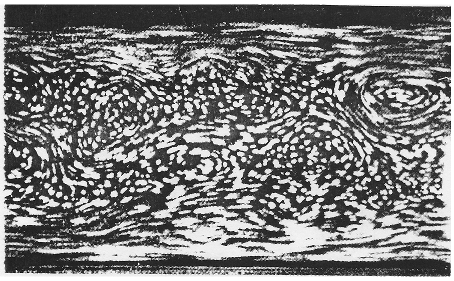
$$\boxed{Re = \frac{\rho V L}{\mu} = \frac{VL}{\nu} = \frac{inertia\ force}{viscous\ force}}$$

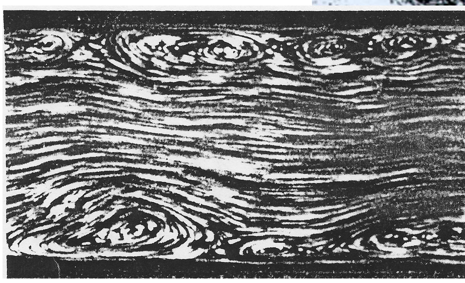
- *L* is an arbitrary (but usually physically significant) reference length, eg
  - diameter d for pipe flows
  - distance from the leading edge, x, for flows along surfaces
  - chord c for aerofoils and wings
  - depth δ for boundary layer flows
  - length scale used often indicated by subscript, eg Re_x
- low Re – viscous forces are important over entire flow
- high Re – significant viscous effects confined to thin region near body
- Transition Re – For any Re above some critical value viscous forces are no longer sufficient to damp disturbances and the flow becomes turbulent

Turbulent Flow – Basic Concepts

- turbulent flow can be considered to consist of a large number of *eddies* of varying sizes and frequencies, flowing with the stream and interacting with each other as they do so
  - analysis of turbulent motion remains *the* outstanding problem in fluid dynamics (indeed in all of applied mathematics) today



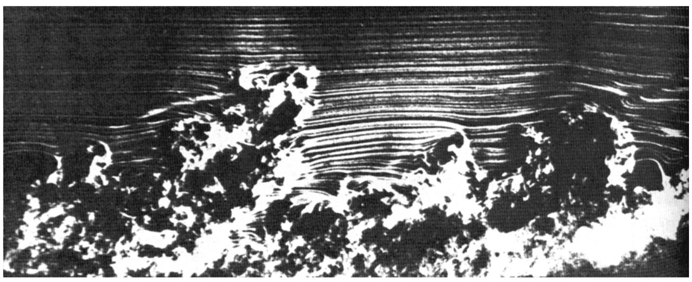




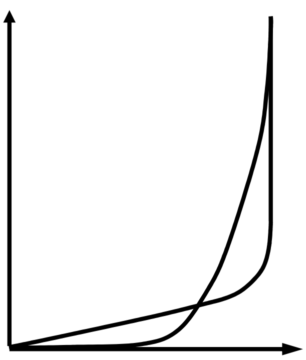
- in detail, turbulent flow is *unsteady, 3D* and (apparently) *random*
- when *time-averaged*, flow becomes *steady*

Turbulent Boundary Layer

- in *laminar* flow shear stress (viscosity) is due to lateral momentum transfer at the molecular level
- in *turbulent* flow 'large-scale' mixing provides an additional mechanism for lateral momentum transfer
  - effective shear stress greatly increased



instantaneous boundary layer



- Most analysis of turbulent boundary layers involves analysis of the time average flow.
- Boundary layer growth rate faster for turbulent flow