Photo: A. Christen

15 Laminar and turbulent flow.

▲ Color schlieren image of a coughing person (Garry Settles, University of Pennsylvania)

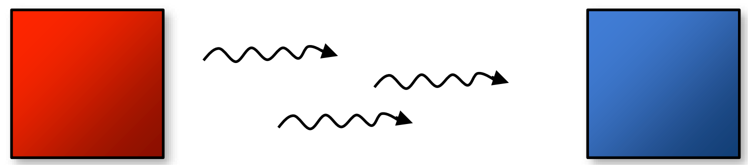
Learning objectives

- Define turbulence, and how a turbulent flow differs from a laminar (non-turbulent) one.
- Give examples where flow in the atmosphere is purely laminar.
- Describe how we can describe mass and heat exchange in a laminar flow.

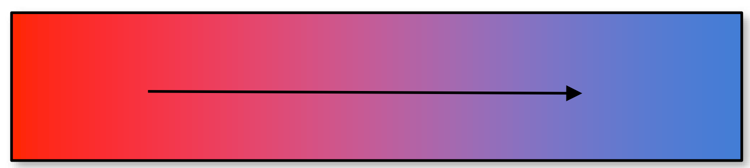
▲ Color schlieren image of a coughing person (Garry Settles, University of Pennsylvania)

Mechanisms of energy transfer

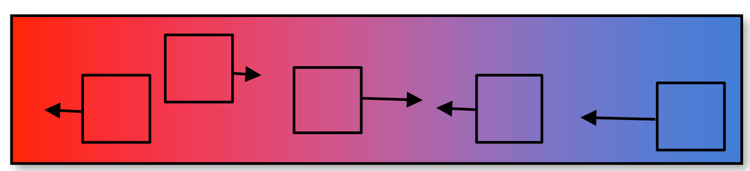
Radiation - electromagnetic waves



Conduction - molecular motion



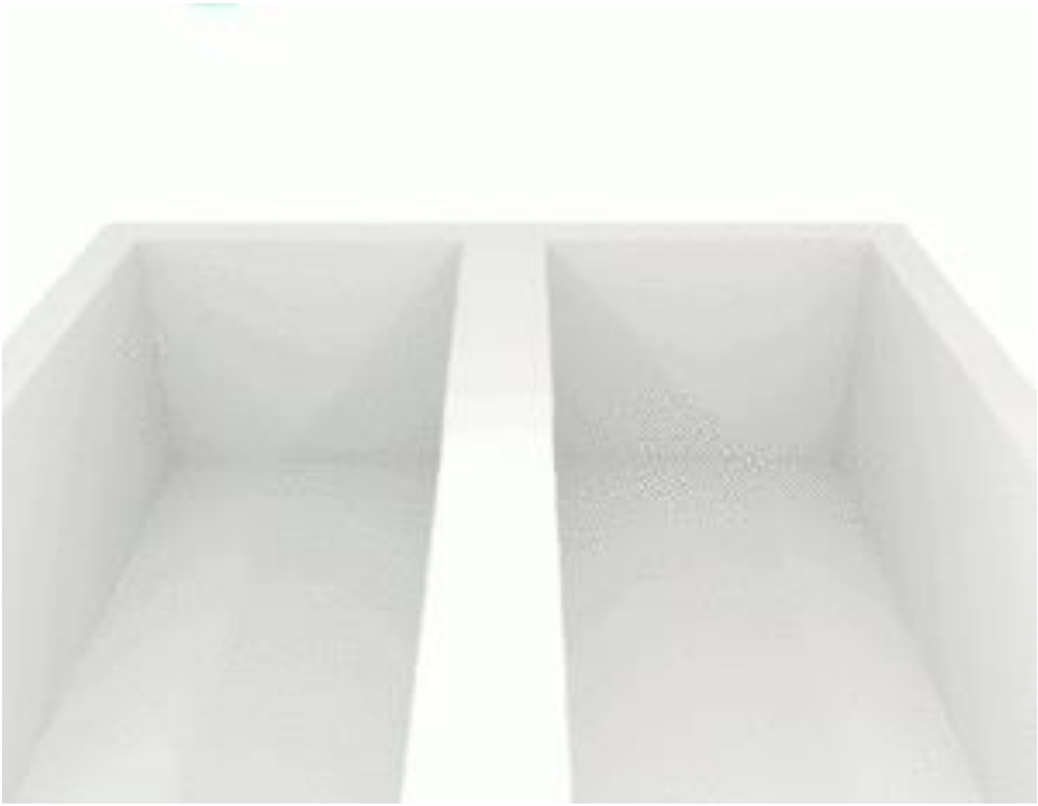
Convection - mass movement in a fluid



Viscosity

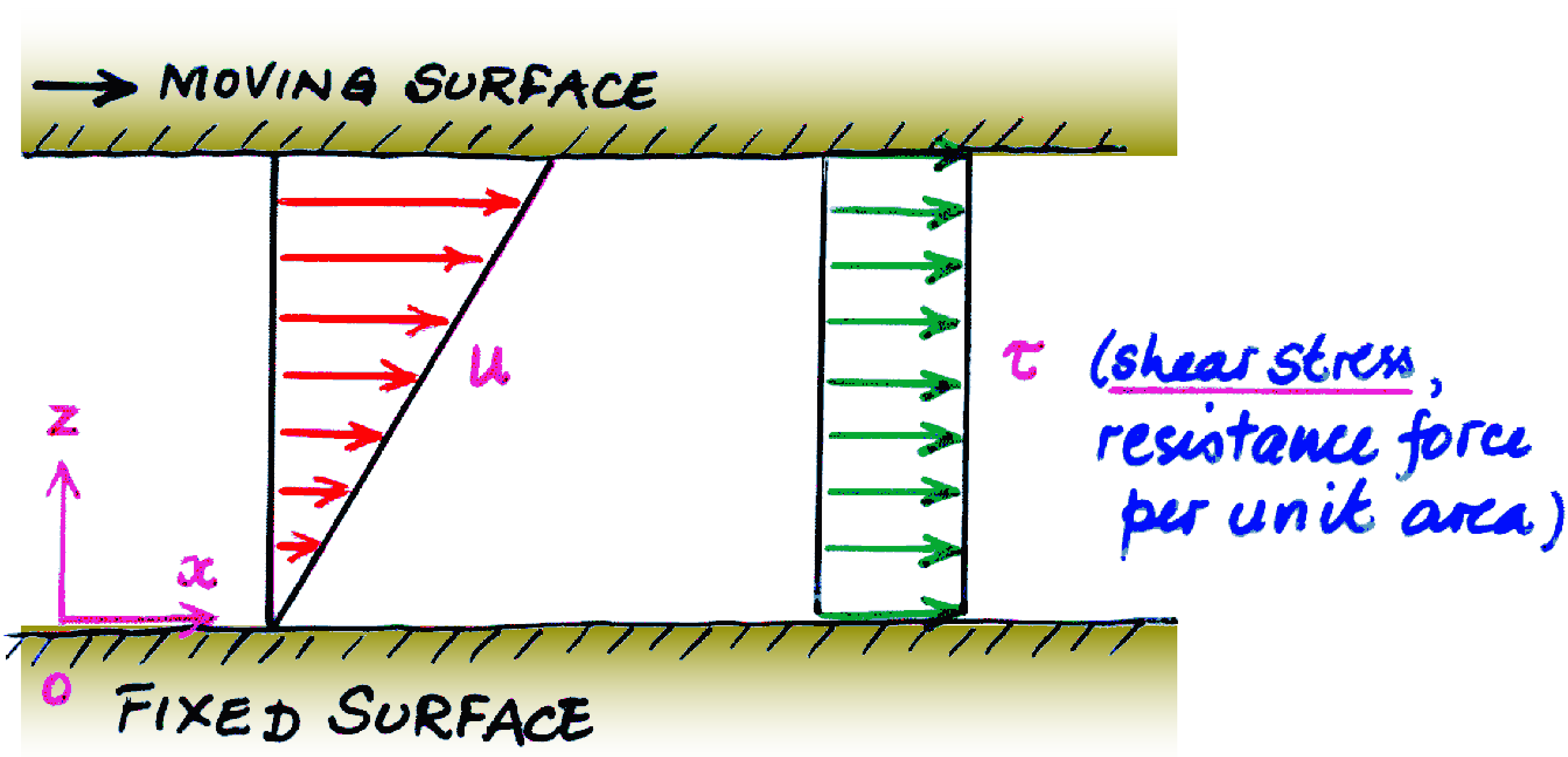
Viscosity – internal resistance of fluid to **deformation**.

Can be also interpreted as internal ‘friction’ between adjacent fluid layers or particles.



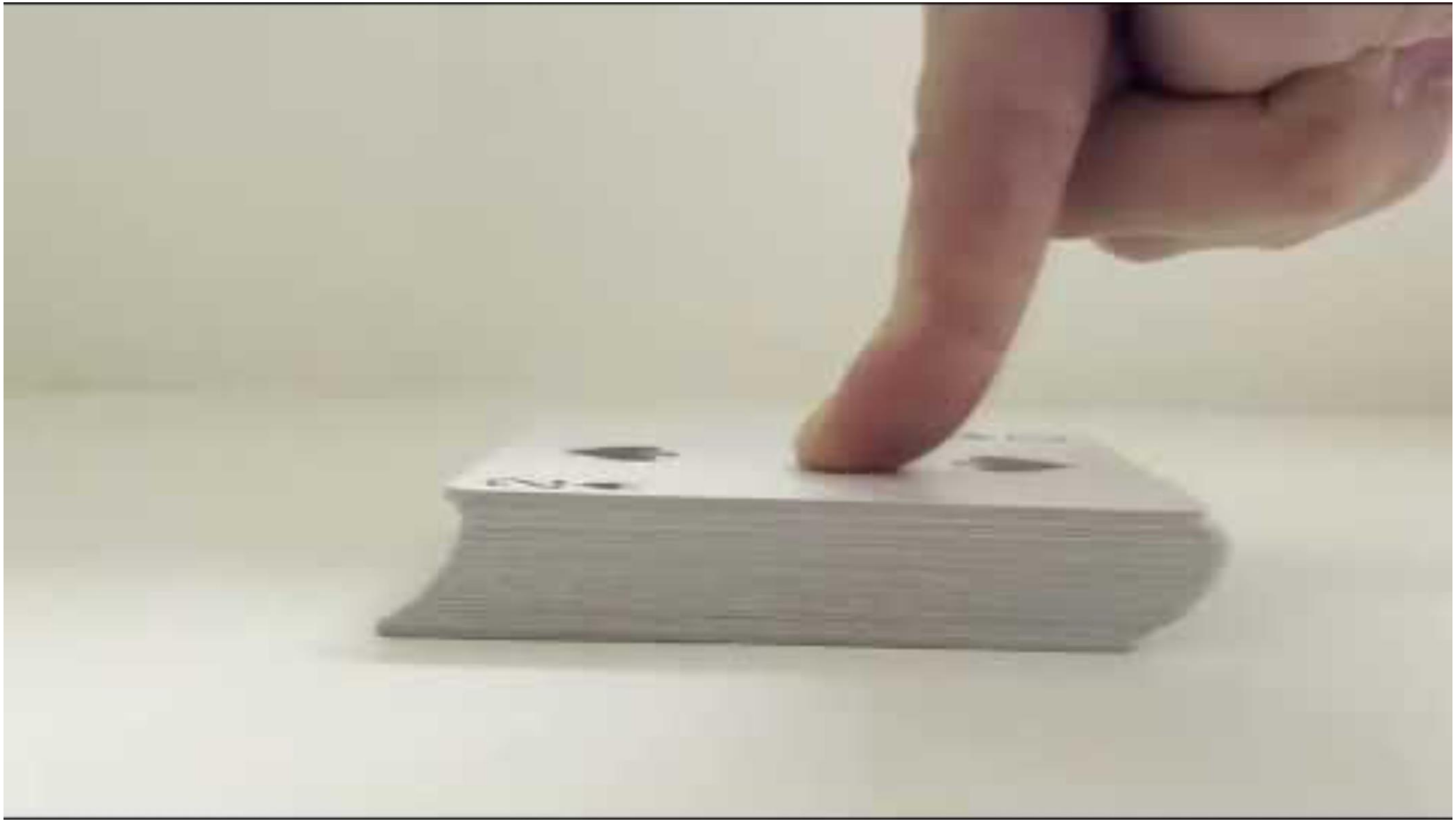
Source: https://en.wikipedia.org/wiki/Viscosity

Viscosity



no-slip condition applies to the fixed surface

Shear Force/Stress



https://youtu.be/CVno4aJjMuc?si=Zd8Jjco1-wetxJ3y

Force vs. stress

- **Force** (N) is an external push or pull acting on an object, causing motion or deformation
- **Stress** is the internal resistance per unit area (force/area; N/m^2 or Pa)
- While force is total load, stress determines if the material will fail.
- **Normal Stress**: Force acting perpendicular to the cross-sectional area (tension or compression).
- **Shear Stress**: Force acting parallel to the surface.

Inviscid and viscous flows

Inviscid fluid (ideal fluid) – is assumed to have no viscosity.

Effects of viscosity and turbulence are neglected. As a consequence there is is no transport of momentum, energy and mass except in form of advection along the streamlines.

In most applications, the atmosphere needs to be modelled as a viscous flow.

Inviscid and viscous flows

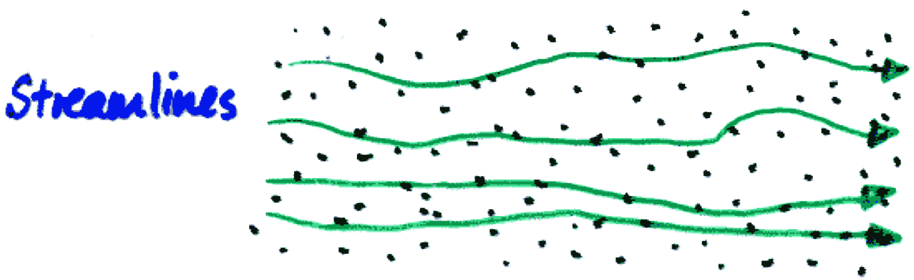
Viscous flow - Closer to surfaces, the flow is always viscous and viscosity plays an important role in boundary layers. In a viscous flow, **shear stress** τ is proportional to the velocity gradient (linearly proportional in a Newtonian fluid):

$$\tau = \mu \frac{\partial u}{\partial z}$$

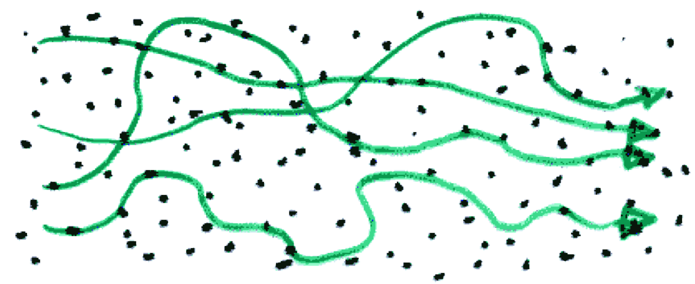
where μ is the **dynamic viscosity** (kg s^{-1} m^{-1}) and $\upsilon = \mu / \rho$ is the **kinematic viscosity** (m^2 s^{-1}) and ρ is fluid density (kg m^{-3}). In laminar flows, μ and υ are molecular properties of the fluid.

Laminar and turbulent flow

Laminar flow



Turbulent flow



Flow with approximately **parallel streamlines**. Layers glide by. Little mixing or transport across, exchange only occurs by molecular diffusion.

Flow is is regular and predictable.

Highly **irregular**, almost random flow that is very diffusive (mixing), with 3D curved streamlines. Can apply over large time and space scales. Dissipative in nature.

Turbulent flow cannot be predicted deterministically in time or space → statistics.

http://boojum.as.arizona.edu/~jill/NS102_2006/Lectures/Lecture12/turb03.jpg

Laminar or turbulent? Effect of flow velocity.

Source: https://www.youtube.com/watch?v=y0WRJtXvpSo

Laminar or turbulent? Effect of viscosity.

Laminar or turbulent? Effect of differential forces

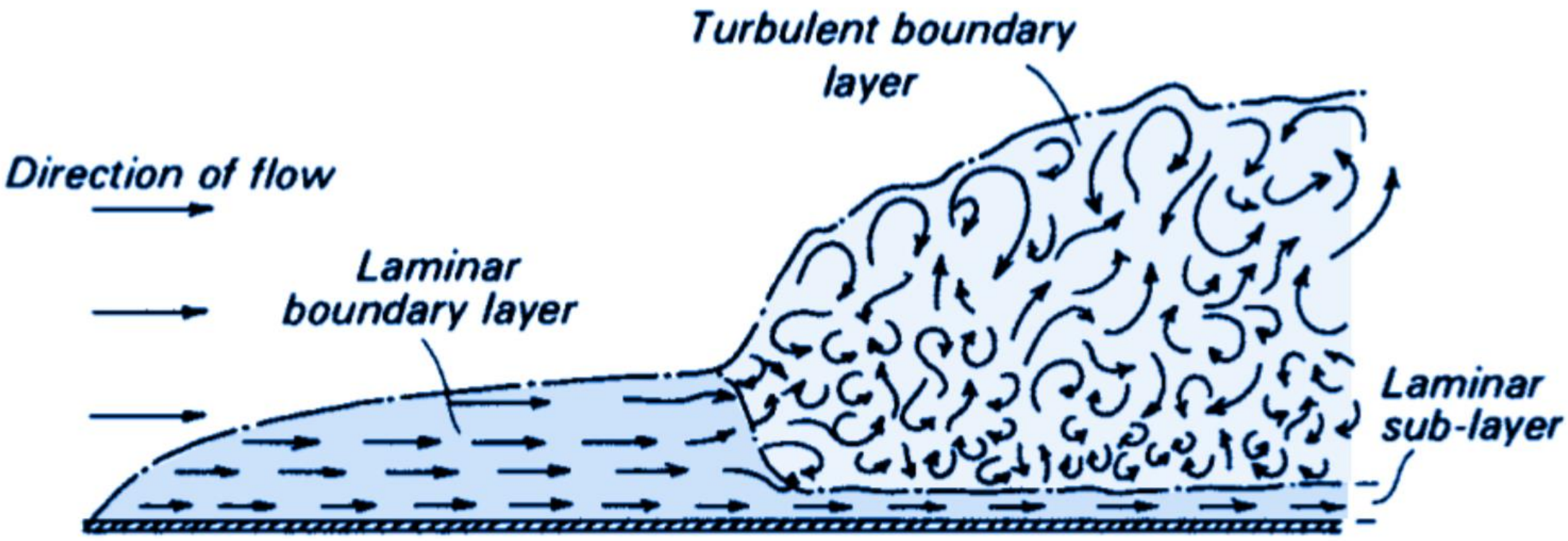


Figure 1: Development of a laminar boundary layer over a flat plate and its transition to turbulent flow.

Turbulence

Turbulence is a feature of flows, not fluids.

Turbulent flows are **very efficient** in equalizing temperature and concentration gradients: In the Atmosphere, turbulent flows are 10^5 times faster than molecular diffusion.

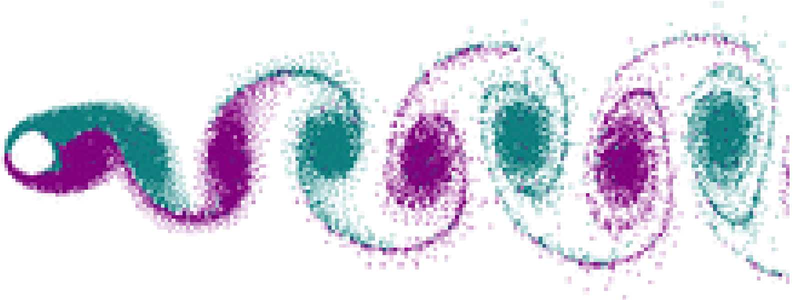
A. Christen

Turbulence

Eddies are coherent parts within the moving fluid.

Eddies exist in a wide range of different sizes.

The smallest eddies **dissipate** to heat.



Leonardo da Vinci's famous drawing of water poured into a pot: His turbulent flow superimposes different scales of eddies.

Properties of turbulence

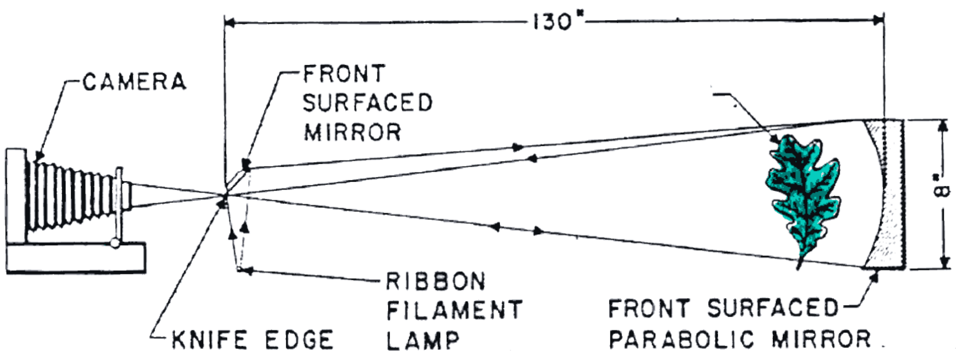
Turbulence is:

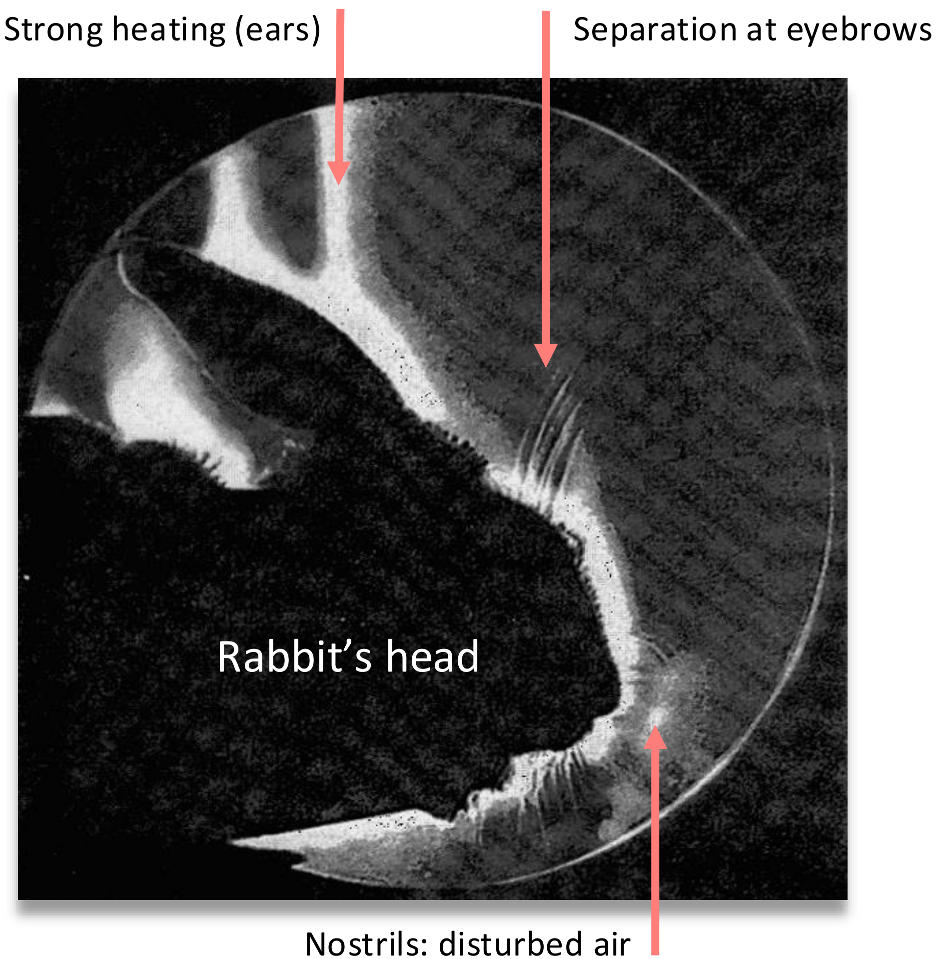
- Irregular/random
- Three-dimensional
  - Motions are rotational and anisotropic
- Diffusive
  - Ability to mix properties
- Dissipative
  - Energy of motion is degraded into heat
- Consists of multiple length scales
  - Large scales of energy input break down into smaller and smaller scales

Leonardo da Vinci's famous drawing of water poured into a pot: His turbulent flow superimposes different scales of eddies.

Visualizing the LBL

The LBL can be made visible using the Schlieren photography. This technique uses the temperature dependence of the **index of refraction** of air.





Legend - cooler air: dark, warmer air: light

The laminar boundary layer (LBL)

- This thin layer (5 to 50 mm) is very important.
- It adheres to all objects and because diffusion is very poor (molecular) it provides a buffer between the object and the turbulent air above.

Measurements in the LBL of leaves with a hotwire probe (Photo: A. Black, UBC).

Importance of the LBL

The principles we'll learn about the LBL are important in developing formulae for calculating:

- rates of transpiration and evaporation from leaves
- rates of CO_2 uptake by leaves (plant growth),
- rates of pollutant (O_3, SO_2) deposition on leaves,
- rates of heat loss from buildings, humans, animals.

Describing exchange in the LBL

Fluxes that pass through the LBL (**molecular transport**) are proportional to gradients between surface and turbulent atmosphere.

Sensible heat

$$Q_H \propto K_H \frac{\partial T}{\partial z}$$

K_H molecular diffusivity for heat

Latent heat

$$Q_E \propto K_E \frac{\partial q}{\partial z}$$

K_E molecular diffusivity for water vapour

Momentum

$$\tau \propto K_M \frac{\partial u}{\partial z}$$

K_M molecular diffusivity for momentum

Describing heat exchange in the LBL

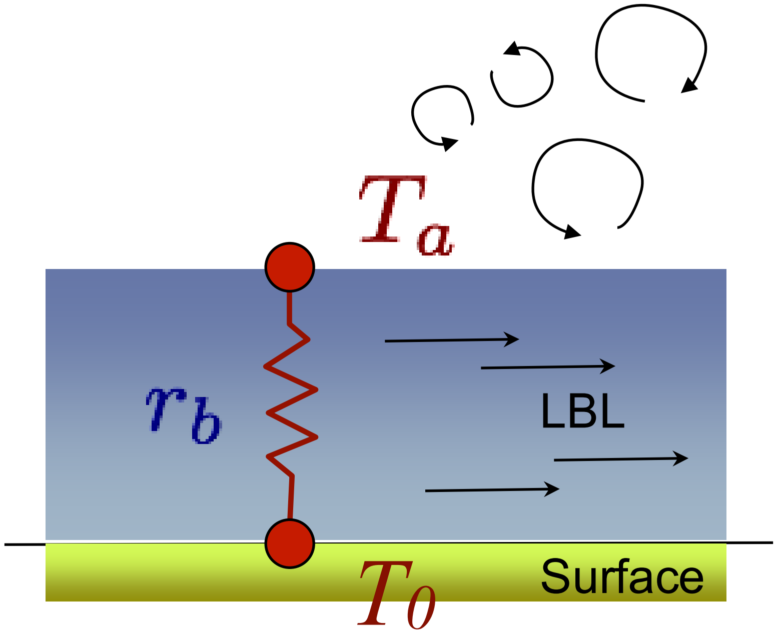
Ohm's law (resistance) format very useful:

Heat capacity of air

Temperature difference

$$Q_H = \frac{C_a(T_0 - T_a)}{r_b}$$ ★

Where r_b is the boundary layer resistance in s m^{-1} which mainly depends on thickness of the LBL.



Characteristics of the LBL

Why this temperature distribution?

Thickness of LBL depends on:

- wind speed (inversely)
- turbulence intensity (inversely)
- buoyancy
- object size
- object's shape, orientation, roughness

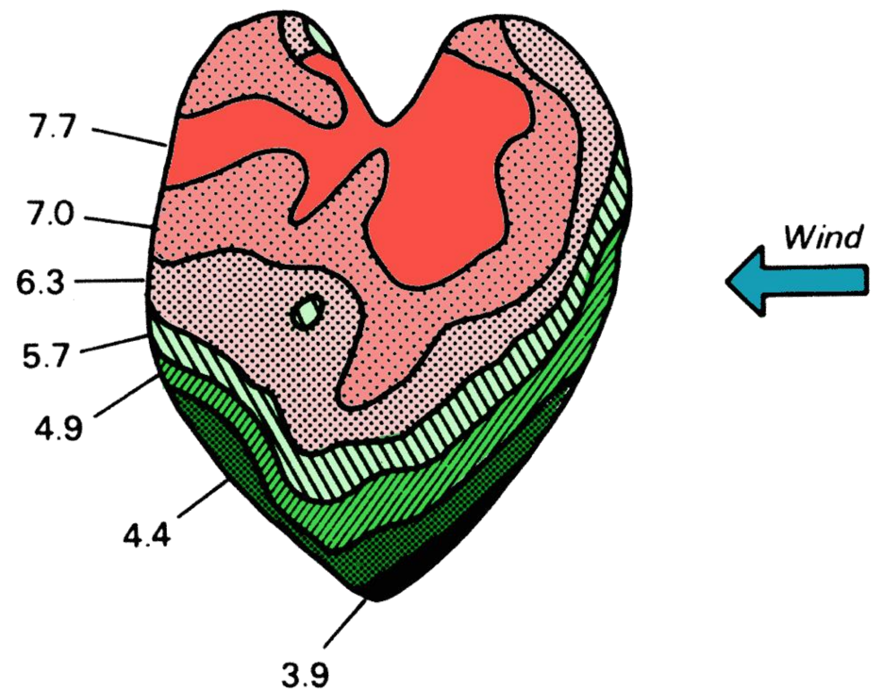


Figure 4.8 Variation of temperature over the surface of a bean leaf with a wind speed of $0{\cdot}7\ \mathrm{m\ s^{-1}}$. Values are the amount by which the leaf *exceeds* the air temperature (°C). Other conditions: T_a = 25·6°C, Q^* = 150 W $\mathrm{m^{-2}}$, r_b = 400 to 1300 s $\mathrm{m^{-1}}$ (after Clark and Wigley, 1975).

T.R. Oke (1987): 'Boundary Layer Climates' 2nd Edition, with permission.

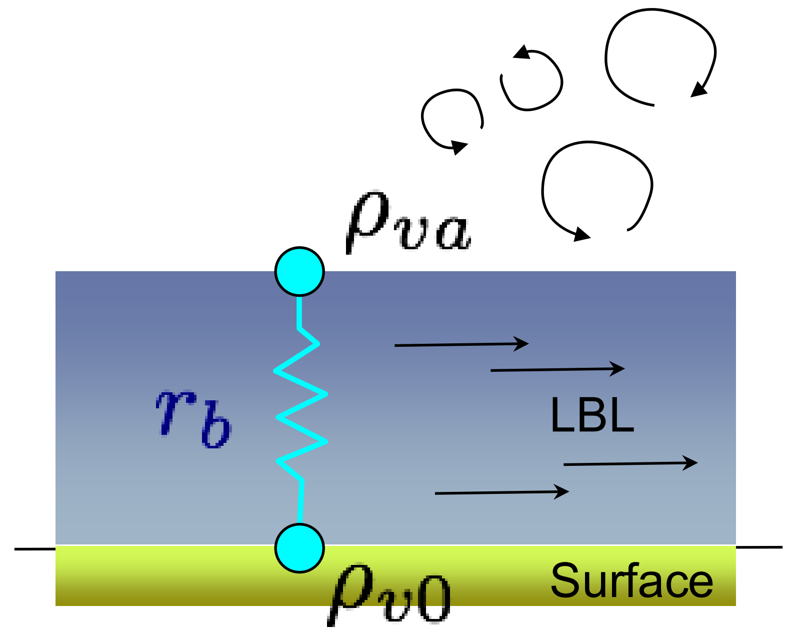
Latent heat exchange in the LBL

Fick's Law of diffusion can be written in resistance form for the transfer of water vapour (latent heat) in the LBL:

Latent heat of vaporization

Absolute humidity difference

$$Q_E = \frac{L_v(\rho_{v0} - \rho_{va})}{r_b}$$



Where r_b is again the boundary layer resistance for water vapour in s m^{-1}

Why does the frost accumulate at the edge of the leaf?

Hoar frost

The thinner LBL at the edge accumulates more frost because of a better Q_E exchange (lower r_b)

Photo by A. Christen

Take home points

- A **laminar flow** has approximately parallel streamlines. Layers glide by. A **turbulent flow** is highly irregular, and contains many scales of eddies.
- Turbulent and laminar are **properties of the flow**, not the fluid.
- Within millimetres of the surface of objects, the flow is always laminar - this is the **laminar boundary layer** (LBL)
- Molecular transfer of energy (heat) and mass in the LBL can be described using **resistances** in analogy to **Ohm's law**.