Lesson 1

- Objectives
  - Properties of solids, liquids and gases
  - Continuum hypothesis
  - Volume and Surface force
  - Relative motion near a point

State Properties

- Solid
  - Rigid system with definite shape and volume
    - Desk, chair, book, brick
    - Maintain their identity
  - Molecules are not free to move around
  - Nearly incompressible
    - If you apply a moderate shear stress, you may deform the solid slightly - if the force is significant you could break the solid

State Properties

- Liquids
  - Nearly incompressible (assumed incompressible)
  - Deforms to fit container
- Gases
  - Molecules are free to move around
  - Compressible

State Properties

- Fluid
  - A material whose molecules change position significantly when suitable forces are applied
- Liquids and gasses are fluids as neither are rigid
  - Deforms continuously when acted on by a shearing stress of any magnitude
  - Need different magnitudes of force to deform
- Fluid vs. Solid
  - The deformation (strain) of a solid is linearly proportional to the stress

Continuum Hypothesis

- Fluid dynamics - the concern is with large scale motion (scales of weather and climate)
  - For these motions the discrete molecular nature of the atm/ocean can be ignored
- Useful to assume that the atmosphere/ocean is a continuous fluid - the molecular structure can be ignored and can treat it as a continuous fluid entity
- Formally:
  - The macroscopic behavior of a fluid is the same as if it was perfectly continuous in structure
    - Locally homogeneous

Continuum Hypothesis

- Allows us to:
  - Treat all physical properties as continuous variables
    - Allowing a clear understanding of that property at a point
  - Establish equations that are independent of the molecular structure
  - Derive the Navier-Stokes (equations of motion (EOM)) equations

Continuum Hypothesis

- Falls apart when we:
  - Examine quantum mechanical scales of materials
  - Consider fluids with significant concentrations of particles or sediments
  - Consider extremely low density environments or rapid spatial variations

Fluid Behavior

- Surface Force
  - Act on a thin layer adjacent to the fluid boundary
  - Short range
  - Direct contact is needed
    - Friction (wind stress)
- Volume (body) Force
  - Acts on **all** elements of a fluid
  - Long range
  - Direct contact is not needed
    - Gravity

Fluid Behavior

- Stress
  - A measure of the internal forces in a body between its constituents as they resist tension and compression or sliding in response to external forces
  - Shear Stress
    - Sliding
  - Normal Stress
    - Compression

Material Derivative

- We will use the Eulerian framework for this course
- Recall, the material derivative represents the change of a fluid parcel as it travels through the domain
  - It considers the time and space dependence

$$\boxed{\frac{D}{Dt}} = \boxed{\frac{\partial}{\partial t}} + \boxed{u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial z}}$$

Following Air parcel

Fixed Location

Advective terms: rate of importation by movement of air

Material Detivative

- Imagine this past weekend in Annapolis, with a **cold** northwesterly. Standing in T-court, the temperature dropped with time. If we rode along with the the air, we'd observe a constant temperature with time.
- A parcel with T = 270K passed us in T-court at 0800L still has T = 270K at 1400L even thought is out over the Atlantic.
- The drop in temp we observe in T-court is due to the continuous import of an Artic air mass

Material Derivative

- Example
  - A car is driving straight southward, past a service station at 100 km/h. The surface pressure is decreasing toward the southeast at 1 Pa/km. What is the pressure tendency at the service station if the pressure measured by the car is decreasing at a rate of 50 Pa/3 h?

Relative Motion

- We know that the flow field varies in x and y directions (u and v velocity components)

$$\frac{\partial u}{\partial x} \pm \frac{\partial v}{\partial y} \qquad \frac{\partial v}{\partial x} \pm \frac{\partial u}{\partial y}$$

- These four equations can describe fluid flow - each combination has a name

Relative Motion

- Divergence (D) $$D = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}$$
- Stretching deformation (F_{str}) $$F_{str} = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}$$
- Shearing deformation (F_{shr}) $$F_{shr} = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}$$
- Vorticity (ζ) $$\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$$

Relative Motion

- $\zeta = 1$; D, F_{str}, $F_{shr} = 0$
- Pure Vorticity

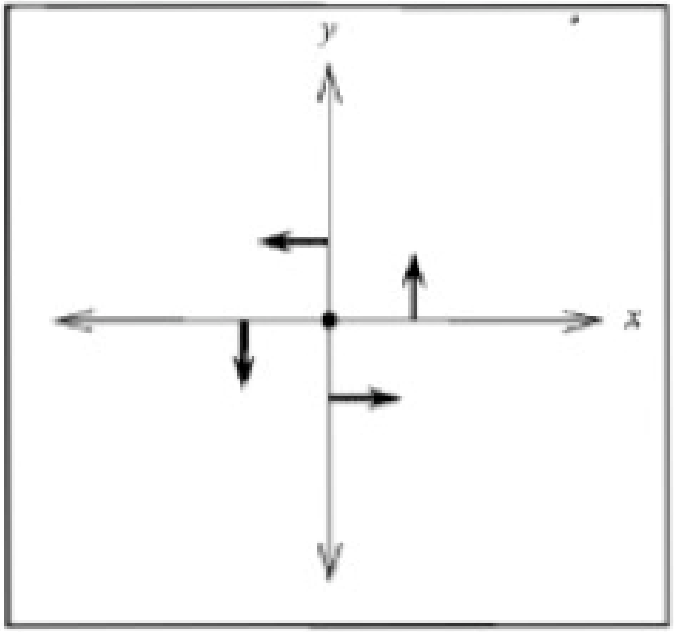

Figure 1.8 A field of pure, positive vorticity ($\zeta = 1$)

Relative Motion

- $D = 1$; ζ , F_{str}, $F_{shr} = 0$
- Pure Divergence

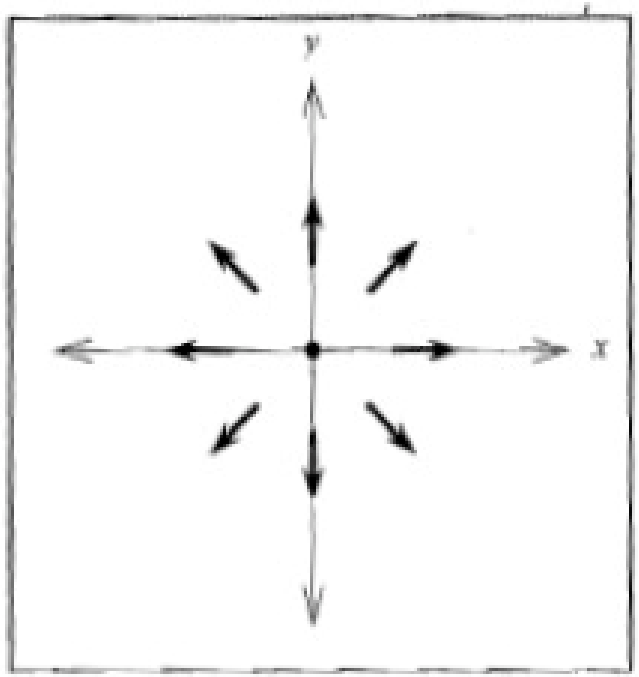

Figure 1.9 A field of pure, positive divergence ($D = 1$)

Relative Motion

- $F_{str} = 1$; D, ζ, $F_{shr} = 0$
- Stretching Deformation

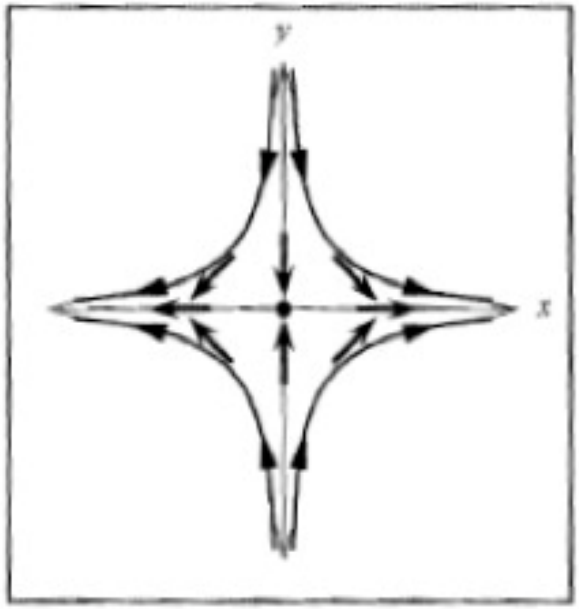

Figure 1.10 A field of pure, positive stretching deformation ($F_1 = 1$). The dark solid lines are streamlines of the deformation field. The x-axis serves as the axis of dilatation and the y-axis is the axis of contraction

Relative Motion

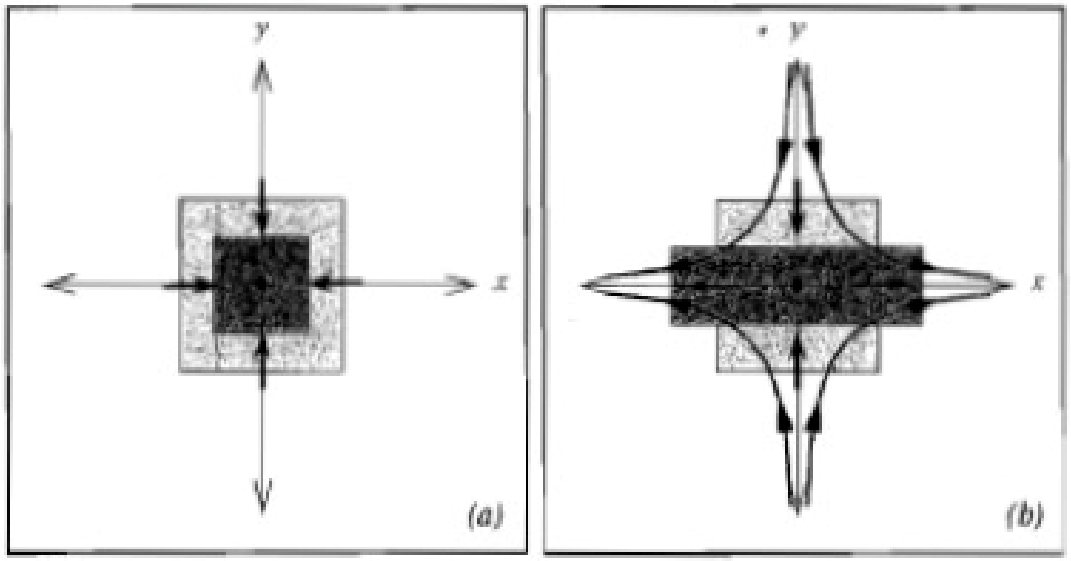

Figure 1.11 (a) A fluid element in a field of pure convergence. The lighter square represents the initially square element. Note that the area of the fluid element is decreased in a field of convergence. (b) A fluid element in a field of pure stretching deformation. The original square is deformed into a rectangle whose area is the same as that of the square

Relative Motion

- $F_{shr} = 1$; D, F_{str}, $\zeta = 0$
- Shearing Deformation

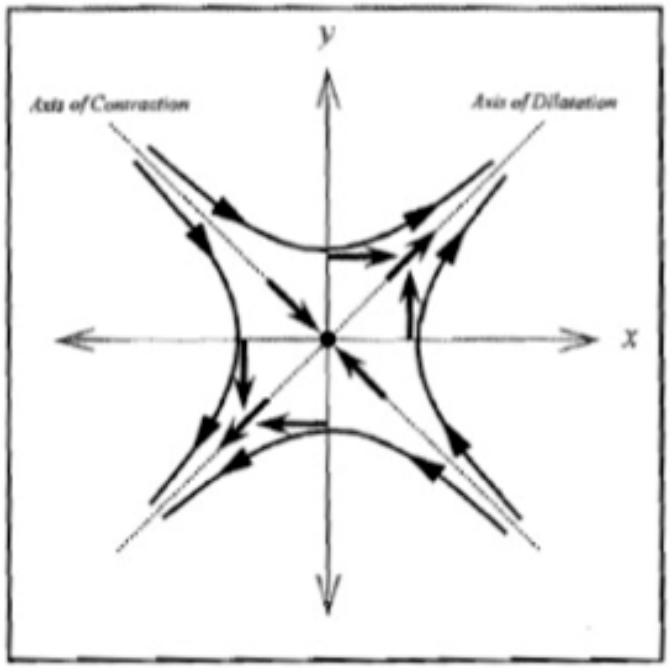

Figure 1.12 A field of pure, positive shearing deformation ($F_2 = 1$). The dark solid lines are streamlines of the deformation field. The axes of dilatation and contraction are indicated by the dashed lines

Relative Motion

- Total Deformation

$$F = (F_{str}^2 + F_{shr}^2)^{1/2}$$

  - Resultant deformation has axis of dilatation at an angle counterclockwise to the original x-axis
    - Rotation has no effect on vorticity or divergence - rotationally invariant
    - Enables vorticity and divergence to explain the behavior of fluids