Flow Field Visualization

- Traditional wind/water tunnels
  - experimental flow visualization techniques
- Computational Fluid Dynamics (CFD)
  - numerical solution to partial diff eqns for fluid flow
  - cheaper than building physical models
  - more visualization options
- Computer-aided flow visualization

Experimental Flow Visualization

- Inject foreign mattter (dye, bubbles, smoke) and/or use optical techniques
- Experimental visualization options
  - *path line*: path traversed by a particle in the flow - bubble injection
  - *streak line*: locus of particles that previously passed through each point - dye injection
  - *time line*: advected image of a *rake* - row of bubbles perpendicular to flow
- Injection can change the field

Computational Fluid Dynamics

- Scalar fields: temperature, pressure et al.
- Vector field: direction of fluid flow
- Steady state: no change in field over time
  - flow still occurs, but same field defines it over time
  - visualization uses time, but field is constant
- Unsteady state: flow field changes over time
  - need separate field for each time step
- visualization time need not match simulation time, so may need to access 2 or more fields

Indirect Flow Visualization

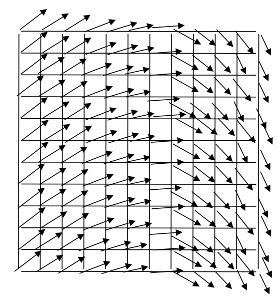
- Derive scalar values from vector field
  - velocity magnitude
  - vorticity
  - helicity
  - Reynolds number
- Render using volume rendering techniques

Direct Flow Visualization

- Vector plots
- Traditional: path, streak, and time lines
- *streamlines*: tangent to the velocity vector
- *stream ribbons*: tiling of two adjacent streamlines
- *stream surfaces*: connecting stream ribbons
- *stream polygons*: polygon normal to vector flow
- *stream tube*: connect stream polys
- *surface particles*: model particle as small polygon
- *flow topology*: find critical points

Vector Plots

- Display vectors in a flow field
  - too cluttered if do every vector
  - especially hard in 3d
  - how to render vectors?
    - direction only?
    - also length?
    - as lines or solids



Path Lines

- Path traversed by a particle, also called *particle traces*
- Need set of initial particle positions (*seeds*): random placed, user specified, or program specified
- At each new time step:
  - $x(t+\Delta t) = x(t) + \text{Integral}(v(x(t)))\,dt$ from t to $t+\Delta t$
- Path line: at time t_n
  - connect points from t_0 through t_n
  - connect points from t_{n-k} through t_n for some k

Streak Lines

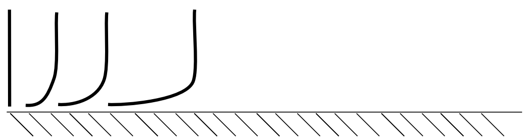
- The locus of particles that have previously passed through a given point in space.
- Same as a path line in steady state flow
- For unsteady state

  for every t from t=0 to end time

  solve integral from t to end time with initial condition x(t) = point in space

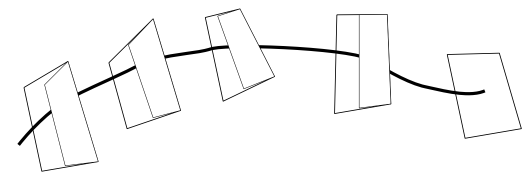
Time Lines

- Rake: a line of points (particles) usually perpendicular to the flow at some initial position
- Show position of rake in each time step



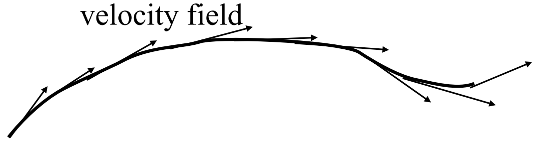
Stream Polygons

- *Strain* causes distortion in fluid elements in a flow - not representable in other visualizations
- Polygons can be oriented along stream normal to local velocity. Local rotation is applied to polygon and local strain causes distortion.



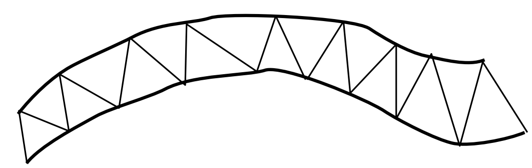
Streamlines

- Streamlines are curves in the field that are everywhere tangent to the velocity field
- Same as streakline and path line for steady state
- Solution to $dx/u = dy/v = dz/w$
  - where x,y,z are spatial position and u,v,w is velocity field



Stream Ribbons

- Connect 2 adjacent streamlines by triangulation
  - In 3D streamlines are hard to follow; can't see "twisting" very well
  - Stream ribbons show flow direction and twisting and curvature
  - polygons can be colored based on some other attribute



Stream Surfaces

- Connect many stream ribbons
- Problems
  - Efficient step sizes: also problem for stream ribbon
    - not too small (too many triangles)
    - not too large (course surface)
  - Determining when surface should be split or joined

Stream Tubes

- By connecting stream polygons together can get get "tubes" that bend, twist, and deform through space
- Can map textures to surface of the tubes to help show flow or other attributes.

Surface Particles

- Rather than drawing *path lines*, can generate small solid particles at each time step (not connected)
- Particles
  - have surface area, so can reflect light
  - can be colored to represent some value
  - can have a "life time" to simulate the "history" that is inherent in a path line: if particles are close enough over time, will see equivalent of path lines

Flow Topology

- *Critical points*: magnitude of field is zero
  - streamline slope is undefined and streamlines only cross at critical points. Can represent entire field by its critical points
  - eigenvalues of gradient: positive correspond to velocities away from critical point (*repelling*); negative towards (*attracting*). Complex eigenvalues result in a *focus*. Real part = 0 yield ellipses; non-zero are spirals. Examples: