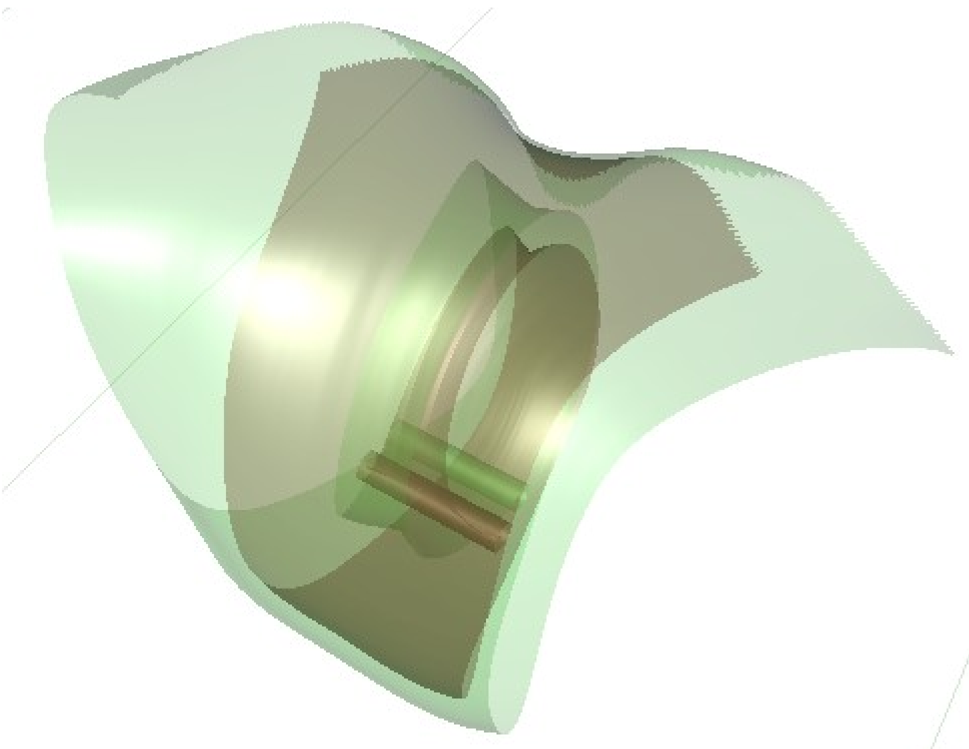
Flow Visualization with Integral Surfaces



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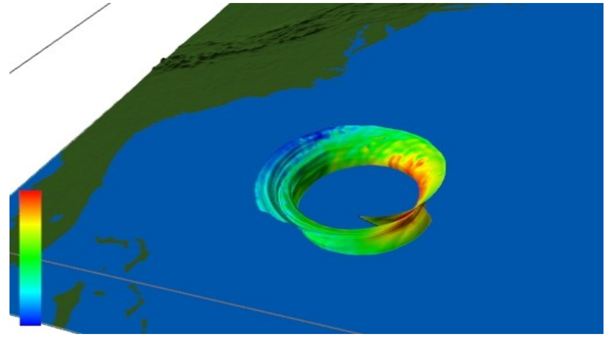
Overview

Flow Visualization with Integral Surfaces:

- Introduction to flow visualization
- Flow data and applications
- Stream, path, and streaklines
- Integral surface-based flow visualization
- Advantages of surfaces over curves
- Stream and path surfaces
- Stream and path surface construction
- Stream and path surface demo
- Streak surfaces and construction
- Streak surface demo
- Conclusions and Acknowledgments



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What is Flow Visualization?

- A classic topic within scientific visualization
- The depiction of vector quantities (as opposed to scalar quantities)
- Applications include: aerodynamics, astronomy, automotive simulation, chemistry, computational fluid dynamics (CFD), engineering, medicine, meteorology, oceanography, **physics**, turbo-machinery design

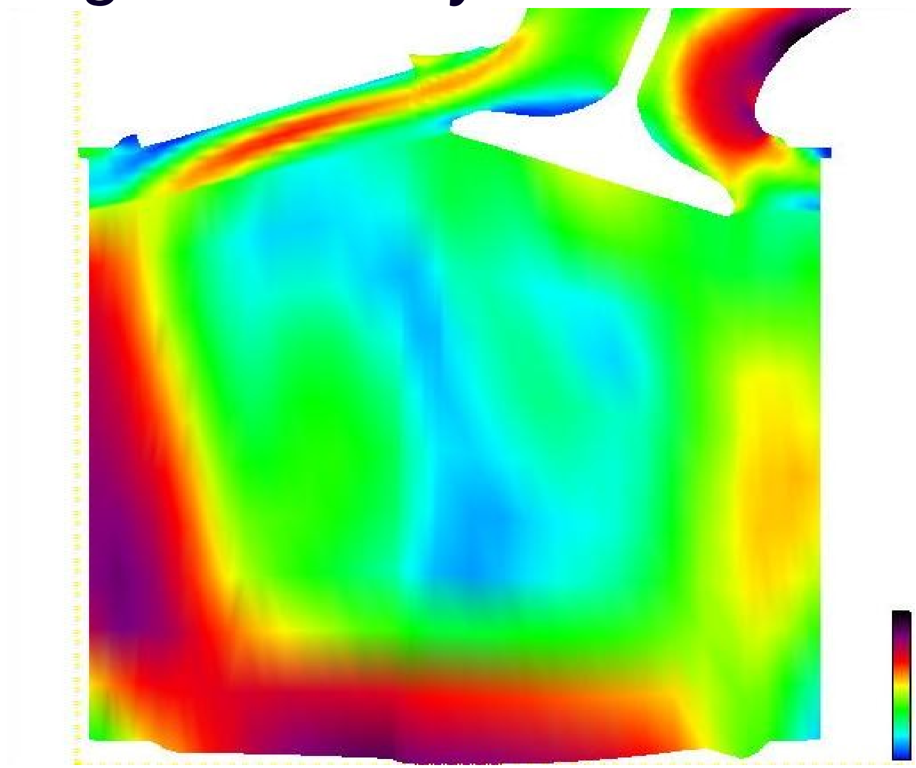
Challenges:

- to effectively visualize both *magnitude* + *direction,* often simultaneously
- large data sets
- time-dependent data
- What should be visualized? (data filtering/feature extraction)

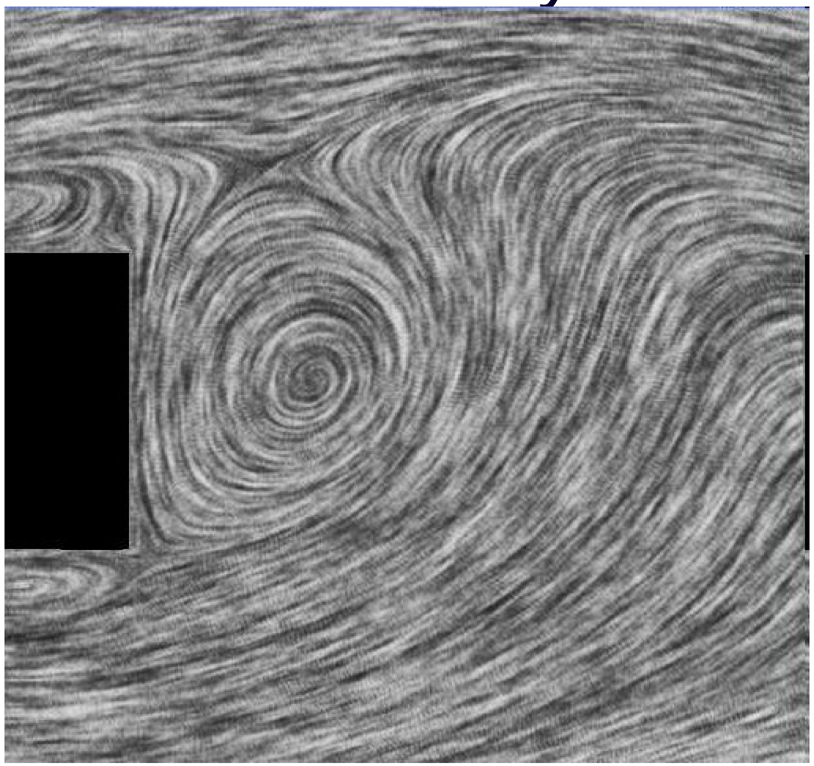
What is Flow Visualization?

Challenge: to effectively visualize both *magnitude* + *direction* often simultaneously

magnitude only

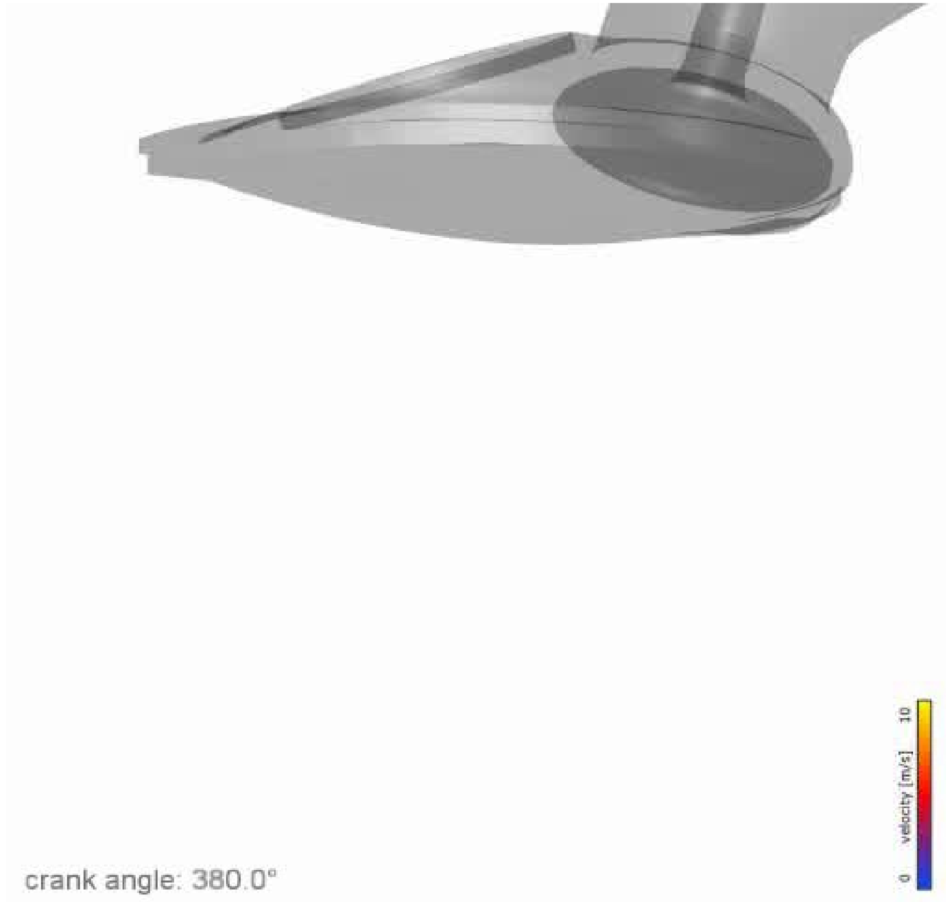


orientation only



Note on Computational Fluid Dynamics

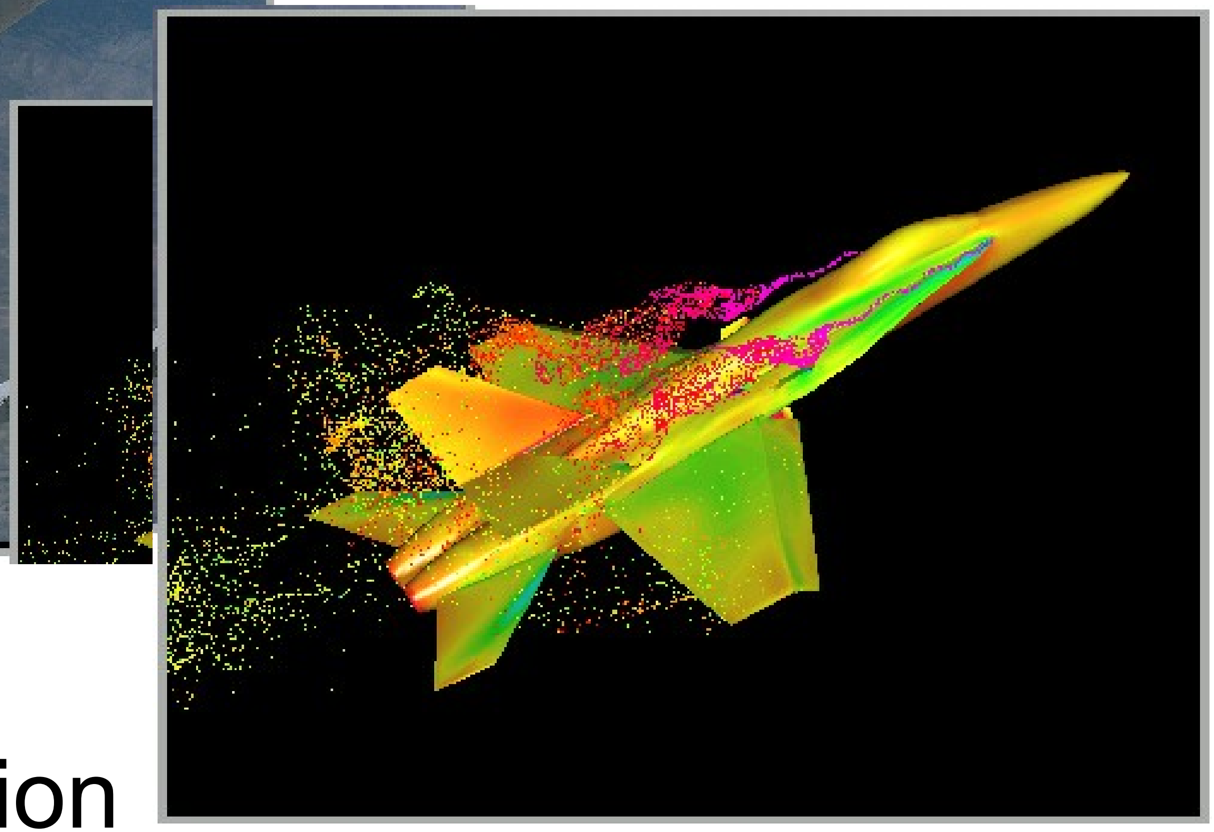
- We often visualize Computational Fluid Dynamics (CFD) simulation data
- CFD: discipline of predicting flow behavior, quantitatively
- data is (often) result of a simulation of flow through or around an object of interest



- some characteristics of CFD data:
  - large, often gigabytes
  - unsteady, time-dependent
  - unstructured, adaptive resolution grids
  - smooth

Comparison with Reality

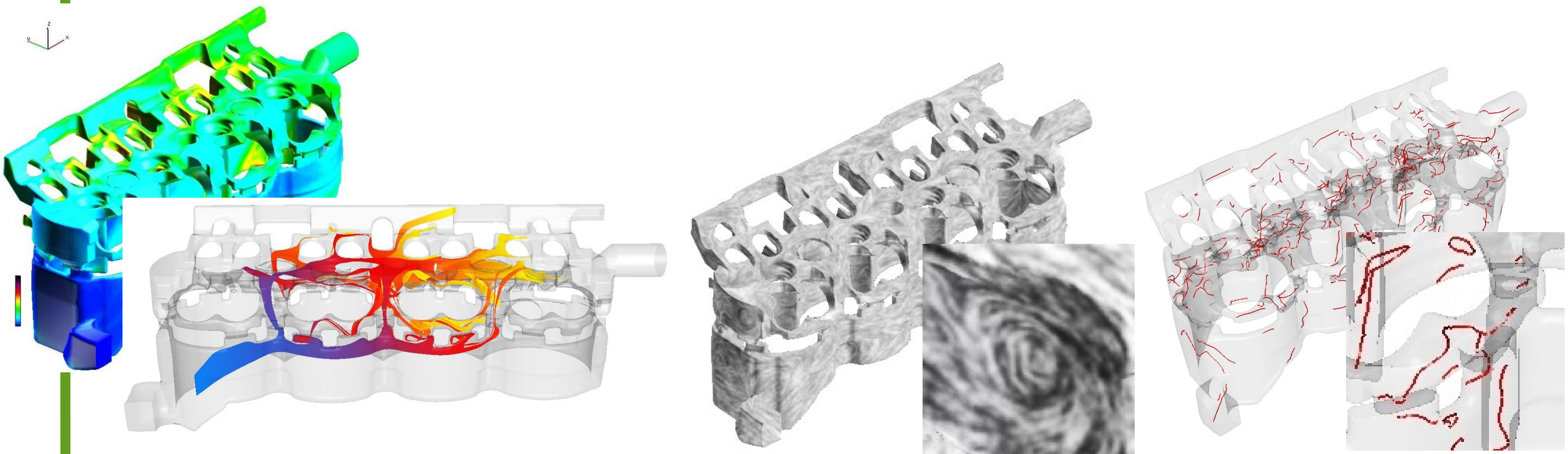
Experiment



Simulation

Flow Visualization Classification

1. **direct:** overview of vector field, minimal computation, e.g. glyphs, color mapping
2. **texture-based:** covers domain with a convolved texture, e.g., Spot Noise, LIC, ISA, IBFV(S)
3. **geometric:** a discrete object(s) whose geometry reflects flow characteristics, e.g. streamlines
4. **feature-based:** both automatic and interactive feature-based techniques, e.g. flow topology



Steady vs. Time-dependent

Steady (time-independent) flows:

- flow itself constant over time
- **v**(**x**), e.g., laminar flows
- simpler case for visualization

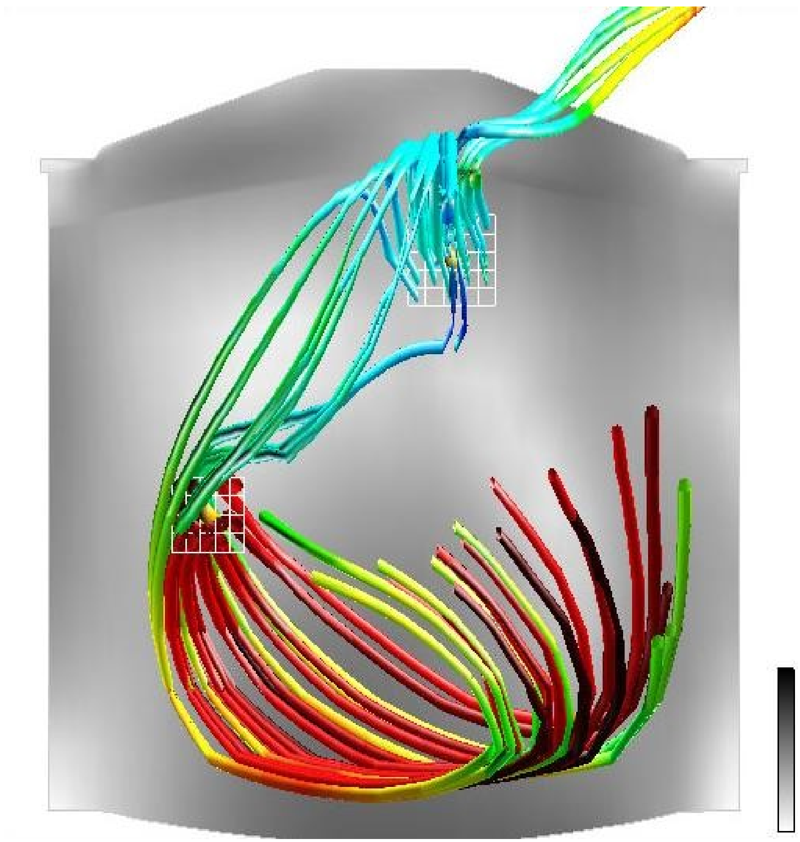
Time-dependent (unsteady) flows:

- flow itself changes over time
- **v**(**x**,*t*), e.g., turbulent flow
- more complex case

Stream, Path, and Streaklines

Terminology:

- **Streamline**: a curve that is everywhere tangent to the flow (release 1 massless particle)
- **Pathline**: a curve that is everywhere tangent to an unsteady flow field (release 1 massless particle)
- **Streakline**: a curve traced by the continues release of particles in unsteady flow from the same position in space (release infinitely many massless particles)



Each is equivalent in steady-state flow

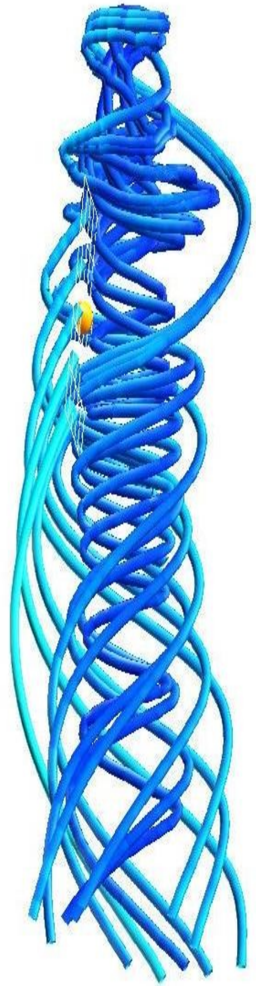
Characteristics of Integral Lines

Advantages:

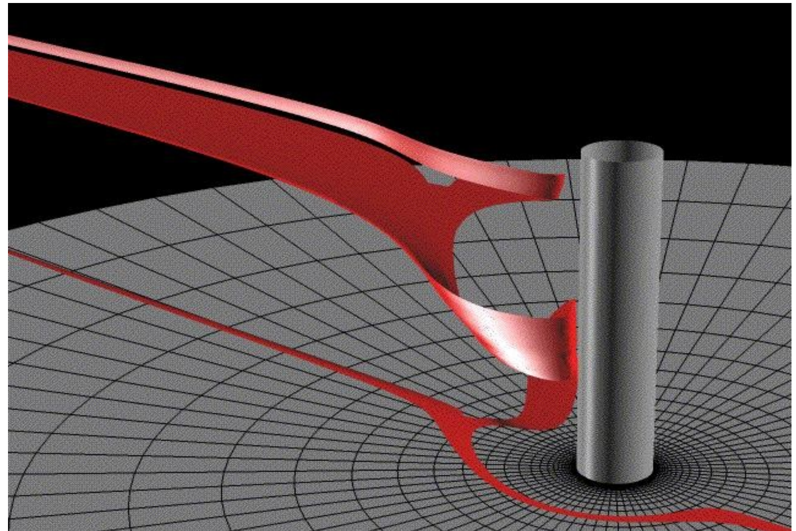
- **Implementation:** various easy-to-implement streamline tracing algorithms (integration)
- **Intuitive**: interpretation is not difficult
- **Applicability**: generally applicable to all vector fields, also in three-dimensions

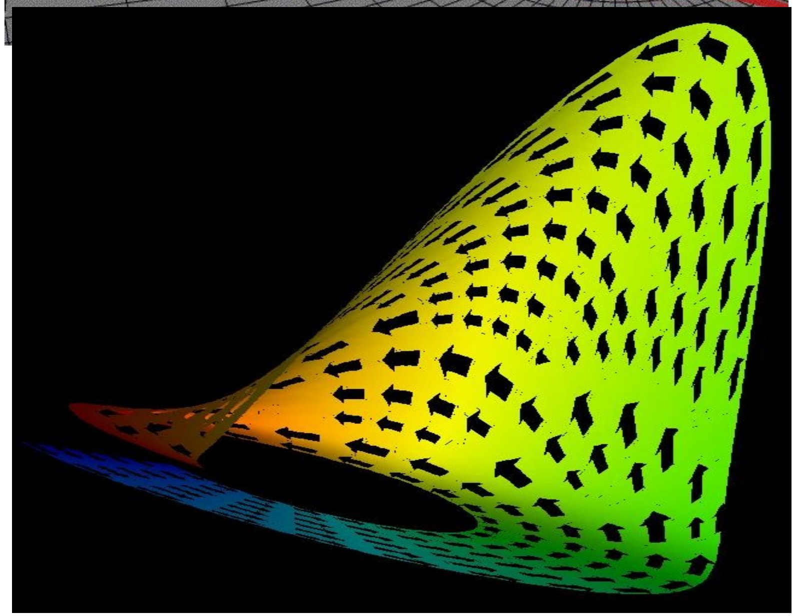
Disadvantages:

- **Perception:** too many lines can lead to clutter and visual complexity
- **Perception:** depth is difficult to perceive, no well-defined normal vector
- **Seeding:** optimal placement is very challenging (unsolved problem)



Stream Surfaces





Terminology:

- **Stream surface**: a surface that is everywhere tangent to flow
- **Stream surface**: the union of stream lines seeded at all points of a curve (the seed curve)
- Next higher dimensional equivalent to a streamline
- Unsteady flow can be visualized with a **path surface** or **streak surface**

Stream Surfaces

First stream surface computation

- Introduced before SciVis existed
- Early use in flow visualization (Helman and Hesselink 1990) for flow separation

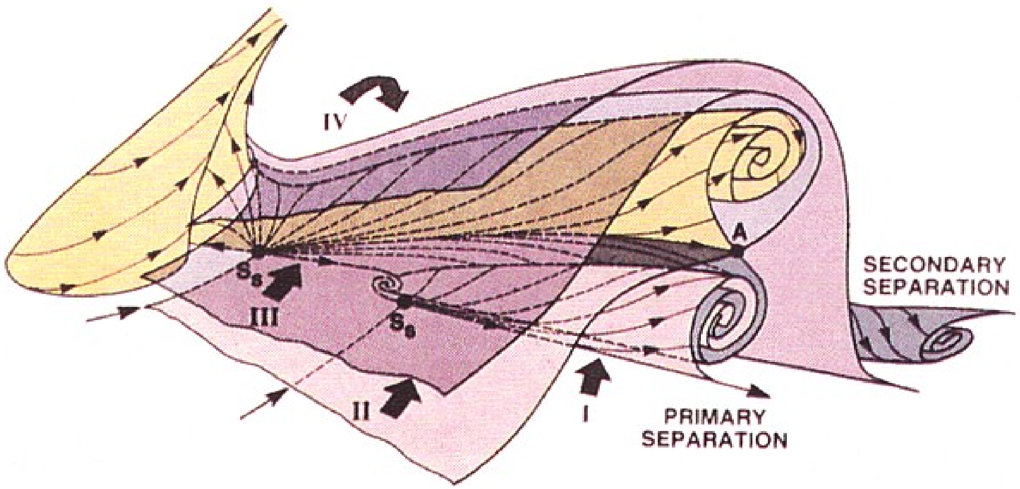
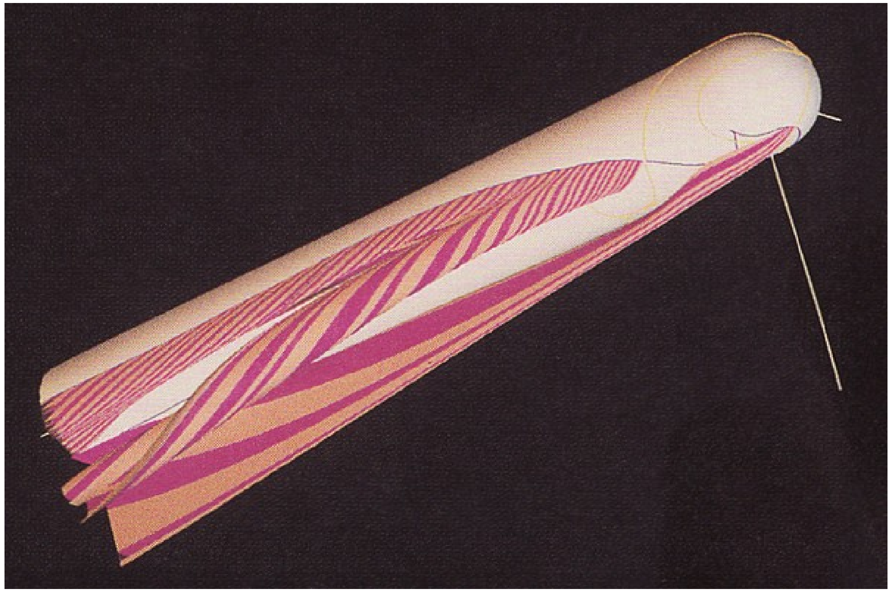


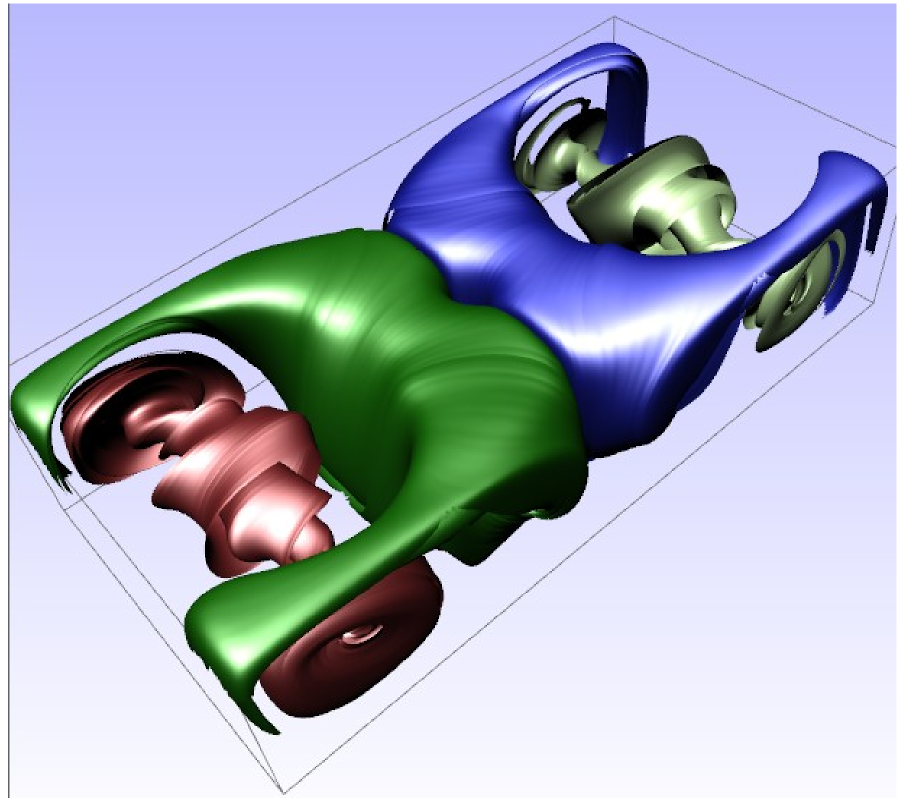
Image: Ying et al.



Stream Surfaces: Advantages

Motivation:

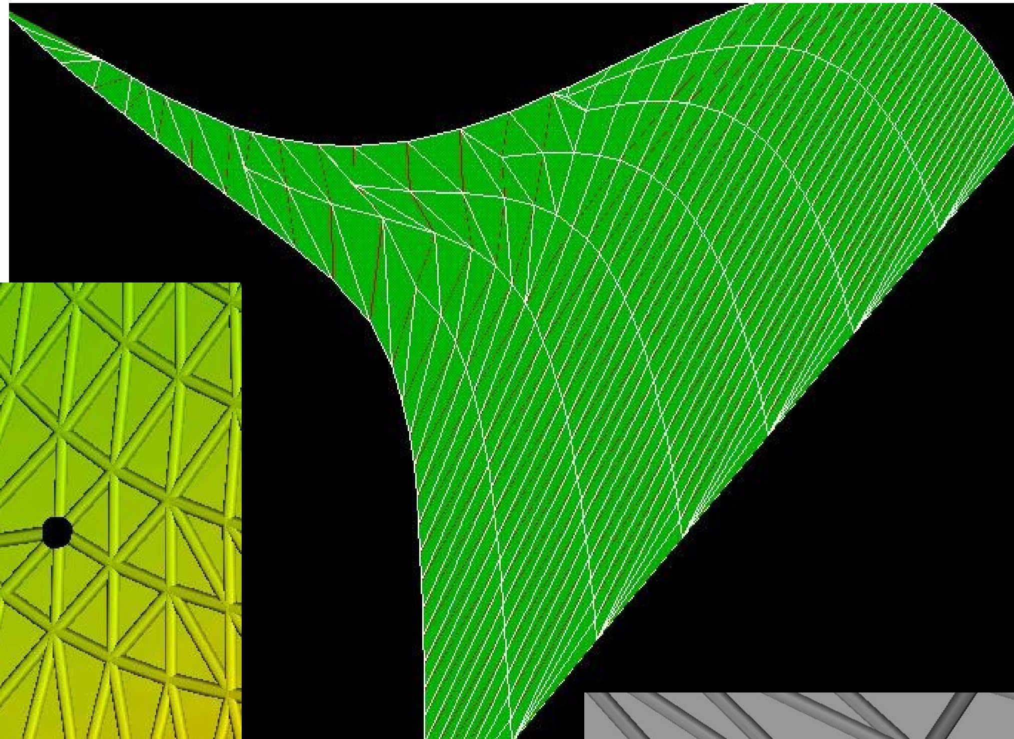
- **Separates (steady) flow:** flow cannot cross surface (stream surfaces only)
- **Perception:** Less visual clutter and complexity than many lines/curves
- **Perception:** well-defined normal vectors make shading easy, improving depth perception
- **Rendering:** surfaces provide more rendering options than lines: e.g., shading and texture-mapping etc.

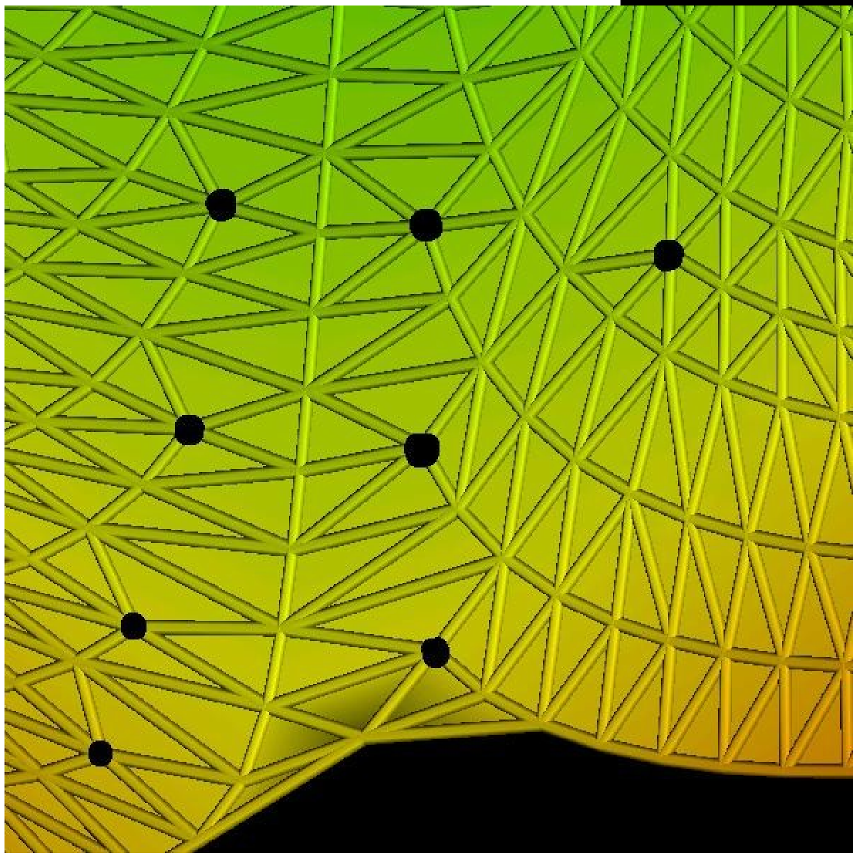


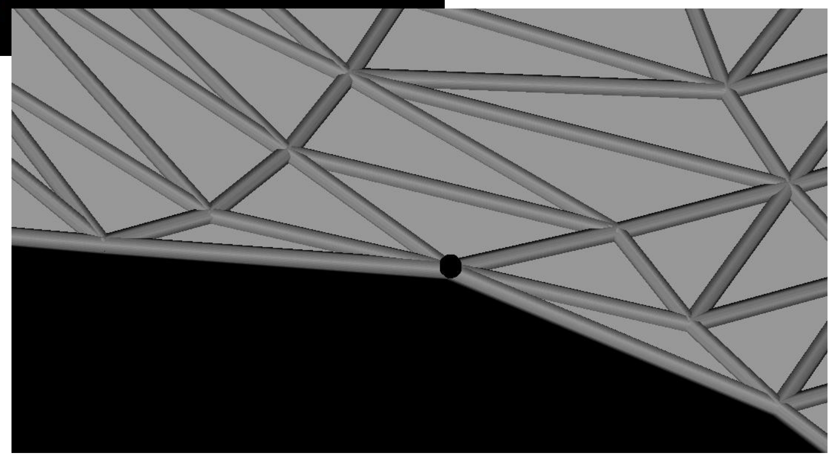
Disadvantages:

- **Construction/Implementation:** *more complicated algorithms are required to construct integral surfaces*
- **Occlusion:** multiple surfaces hide one another
- **Placement:** placement of surfaces is still and unsolved problem

Stream Surfaces – Split / Merge







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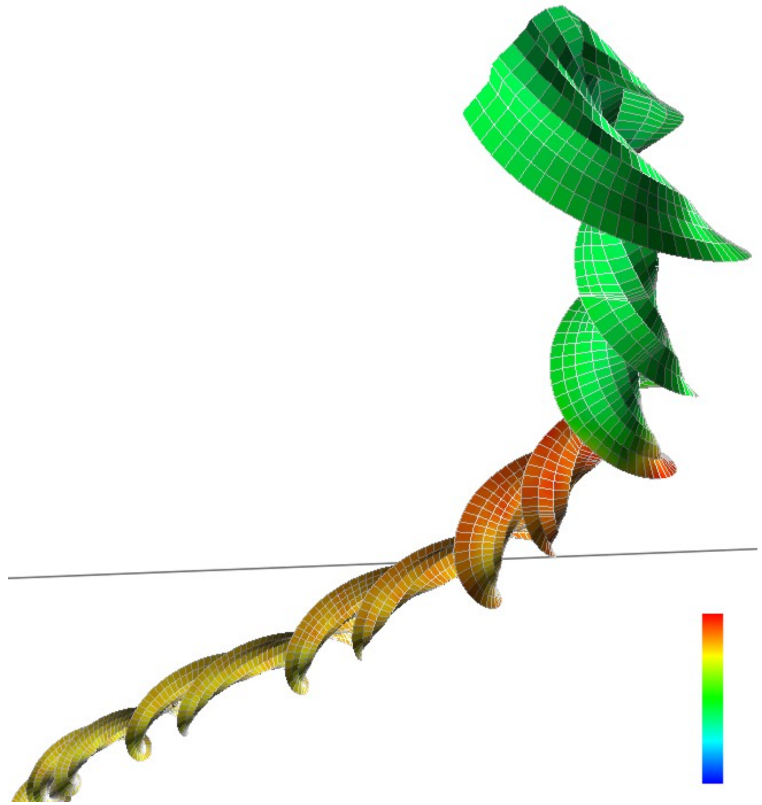
Easy Integral Surfaces

- Relies on use of quad primitives
- Use of local operations (per quad).
- Simple data structure
- Implicit parameterization
- Formulated as a reconstructive sampling of the vector field
  - `d_sample`
  - `d_advance`
  - `d_sep`



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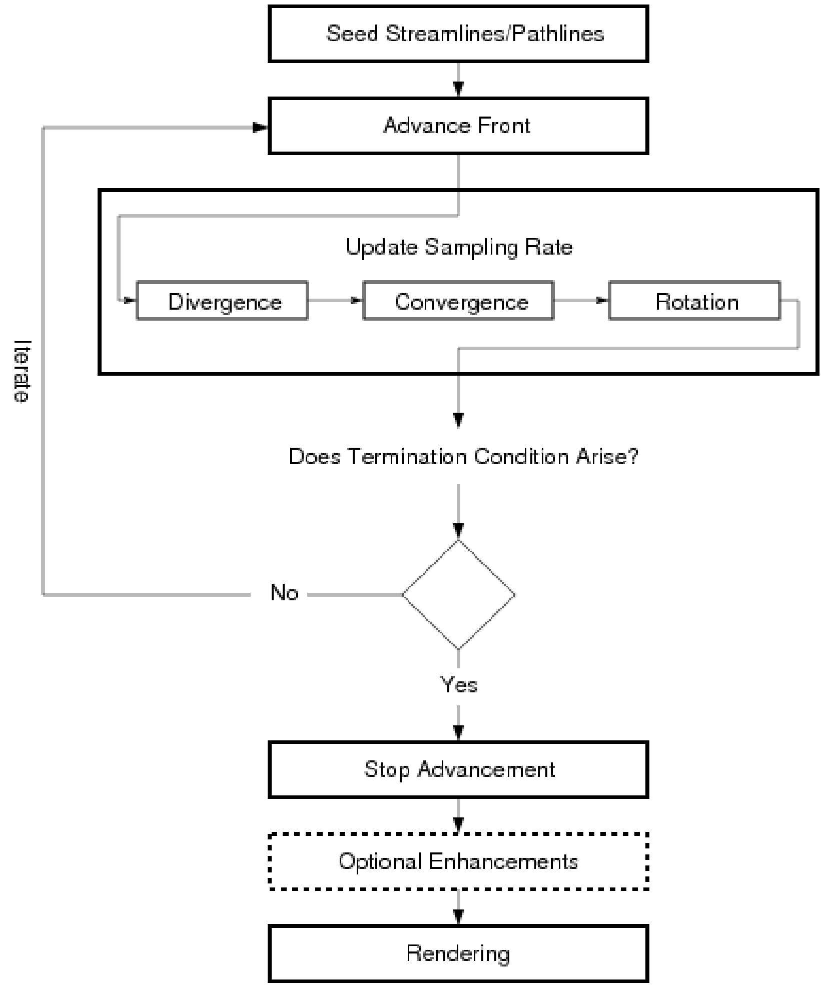
Algorithm Overview

```
Seed;
While(not terminated)
   Advance front;
   Update Sampling Rate;
End While
Render;
```



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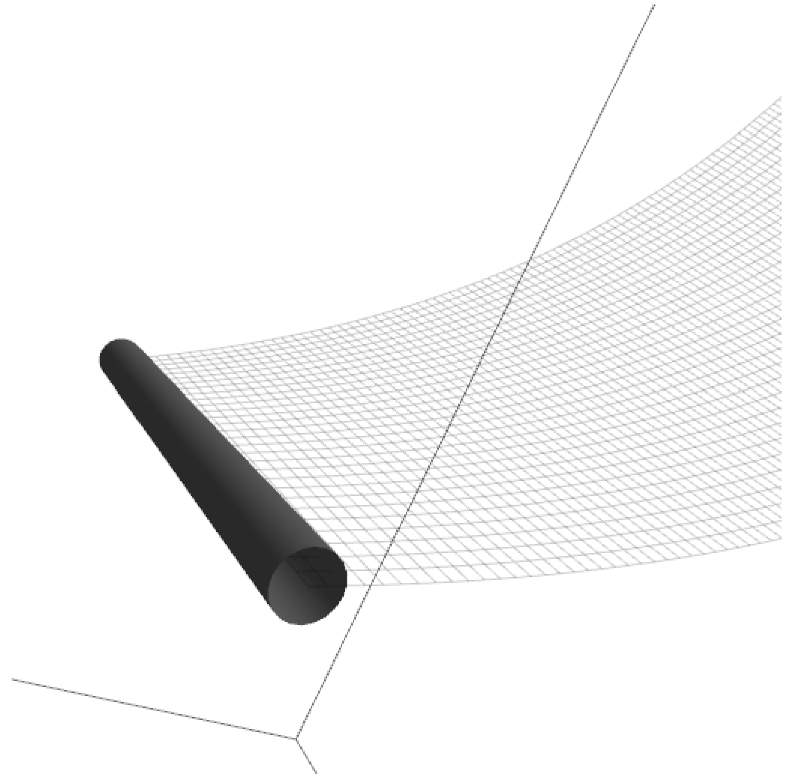
Seeding and Advancement

- Interactive seeding curve:
  - Position and orientation
  - Length
  - Prongs/number of seeds
- Integral surface front advance distance guided by
  - Nyquist rate
  - 0.5 d_sample



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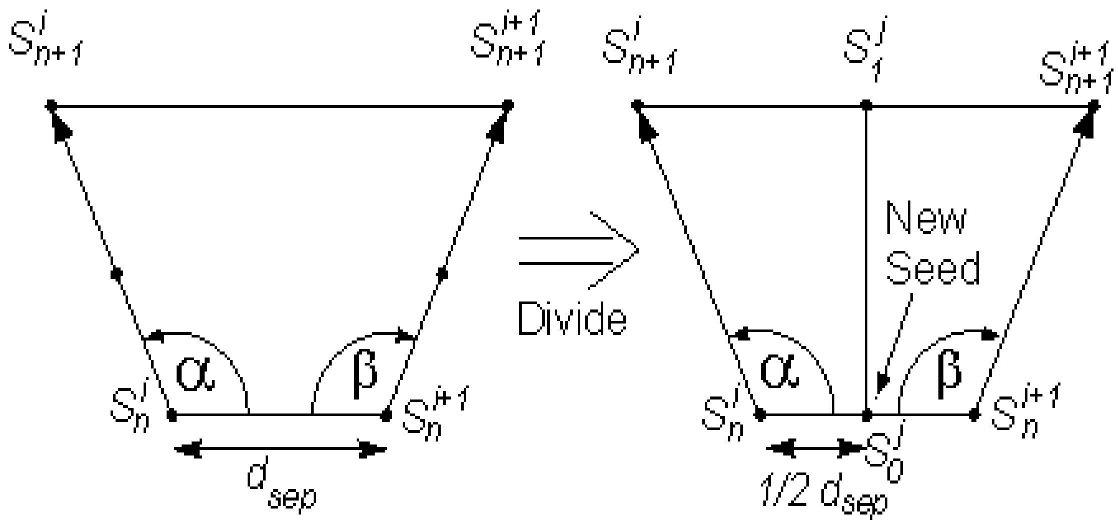
Divergence

- Leads to undersampling
- Depicted by surface widening
- Detected: (α > 90 AND β > 90) AND d_sep > d_sample.
- Solution: Introduce new vertices into surface.
- Split quad in two



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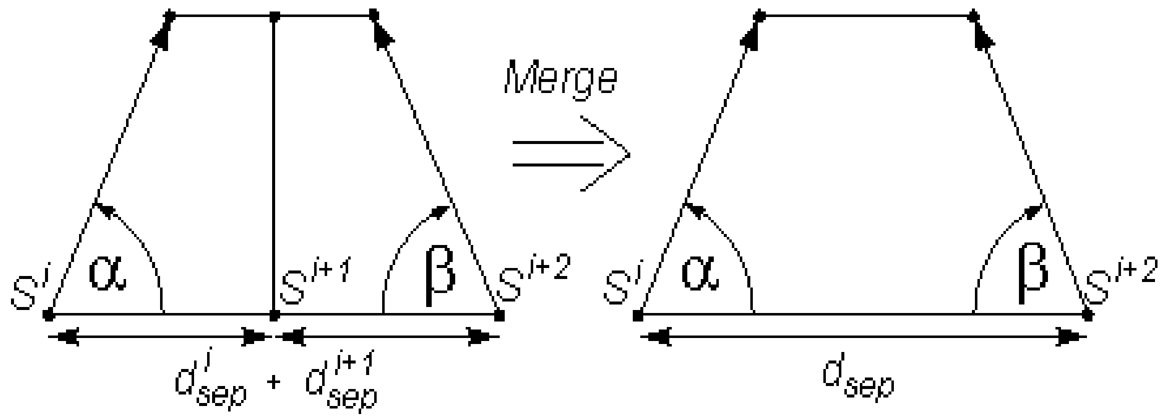
Convergence

- Results in oversampling.
- Surface narrows
- Detected: (α < 90 AND β < 90) AND edge length < 0.5 d_sample
- Solution: Remove vertices from surface
- Merge two quads into a single one



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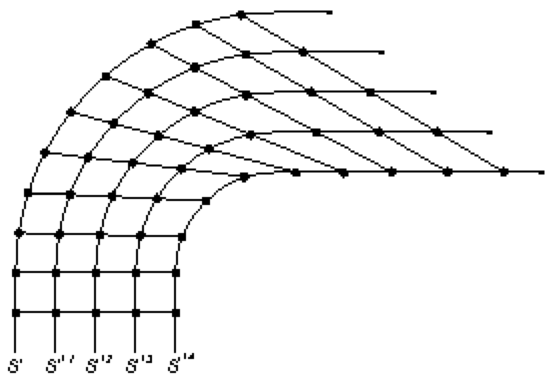
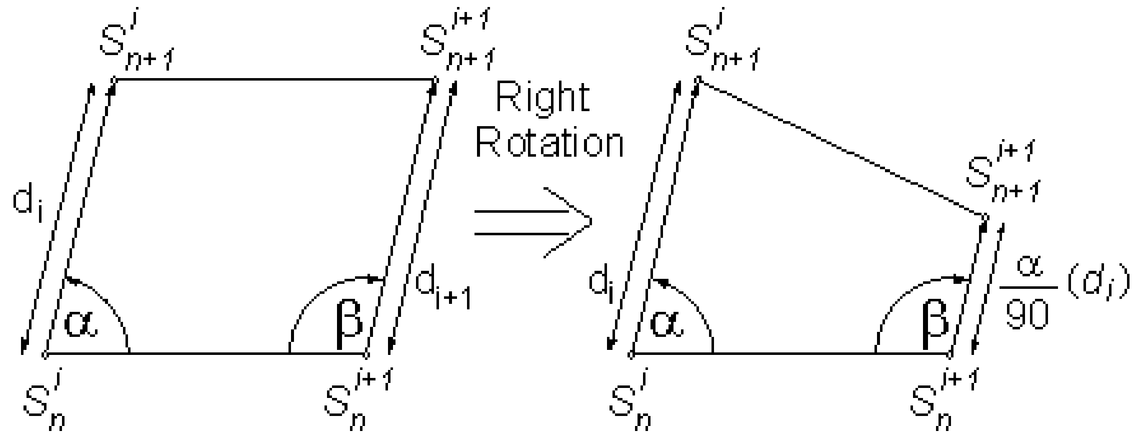
Curvature

- Produces irregular quads.
  - Detected: (α < 90 AND β < 90) OR (α > 90 AND β < 90).
  - Solution: Adjust step-size according to angle between segments
- Groups of quads may have to be processed together





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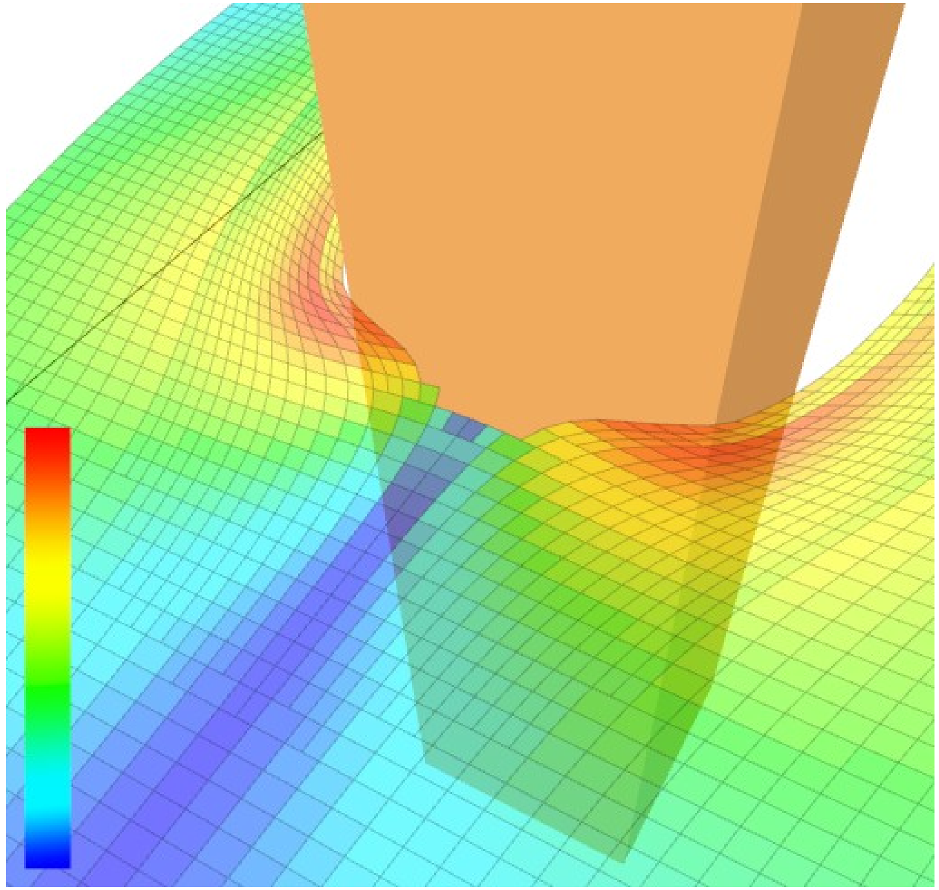
Splitting and Termination

- Surface may split when object boundary encountered
- Separate portions computed independently
- Terminating Conditions:
  - Critical Point (Zero Velocity)
  - Object Intersection
  - Leave Domain
  - Desired geodesic length reached



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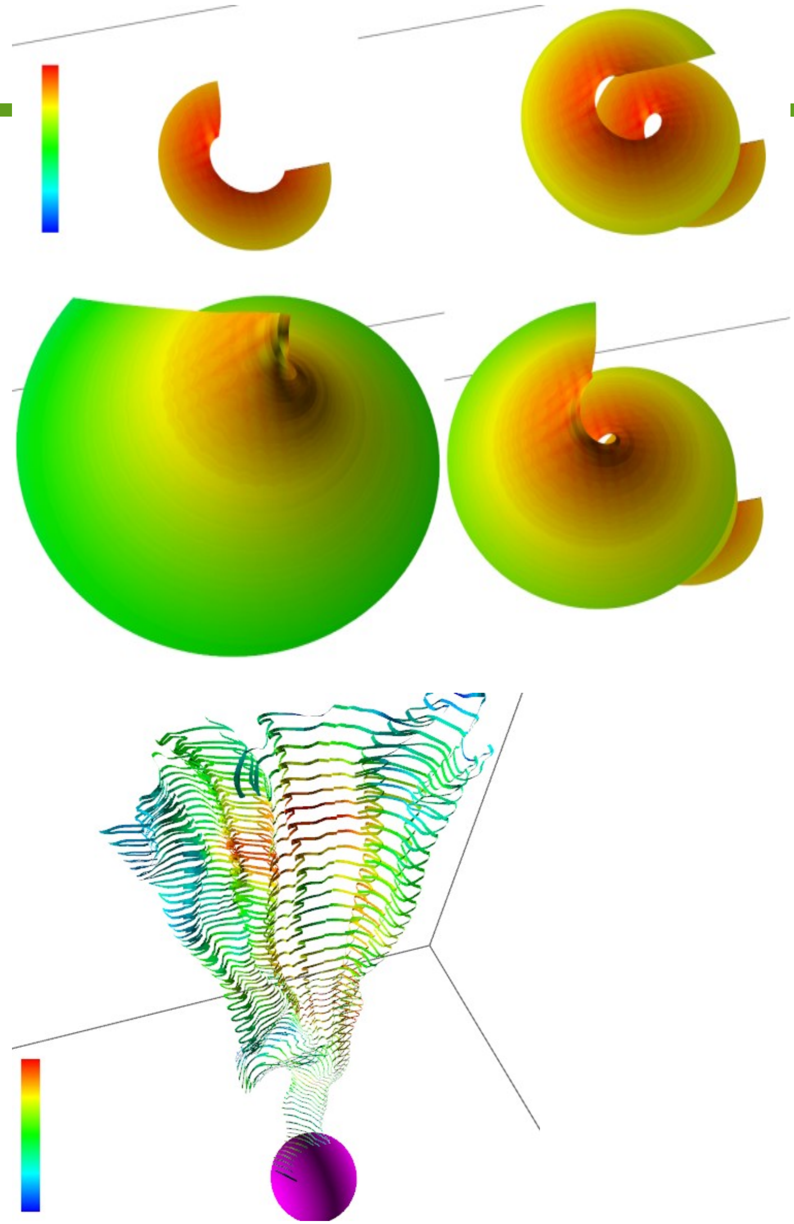
Enhancements

- Surface Painter
  - Helps reduce occlusion
  - User controls the length of surface

- Timelines and Timeribbons
  - Formed from the surface front
  - Turn off the shear operation
  - Velocity magnitude is required



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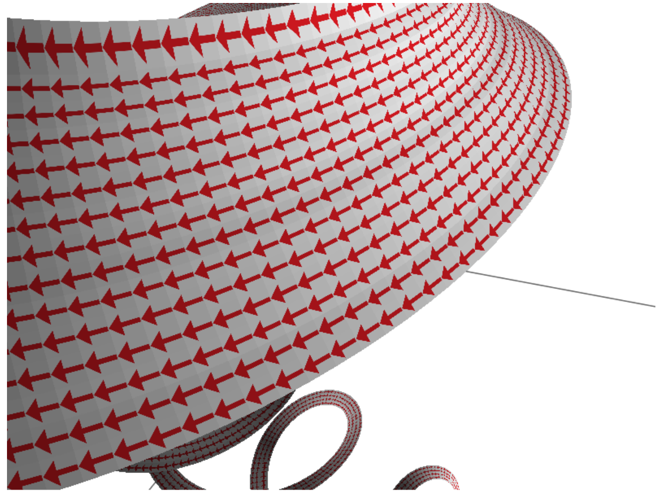
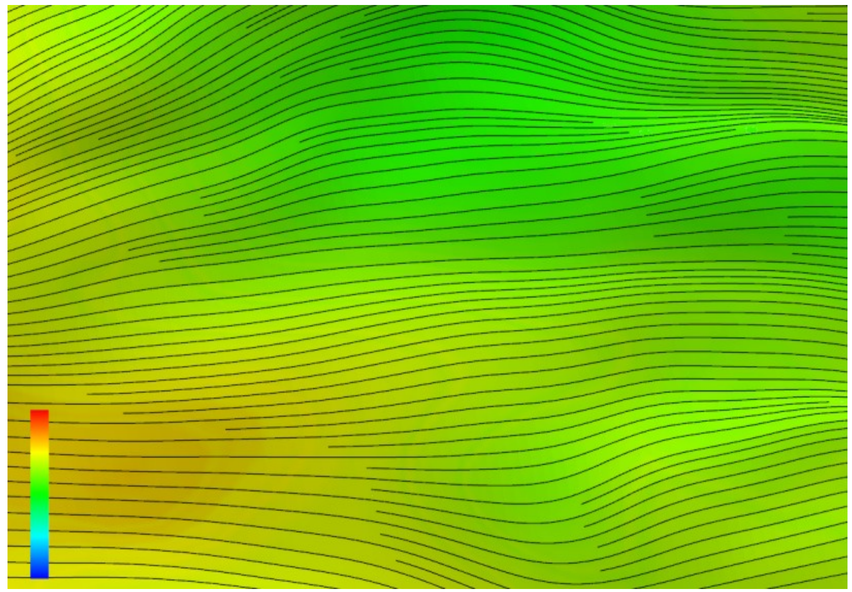
Enhancements

- Stream and Path Arrows
  - Provide information on internal surface structure.
  - Clearly show downstream direction.



- Evenly-spaced flow lines.
  - Stems naturally from convergence and divergence operations.
  - Render flow lines on top of surface.



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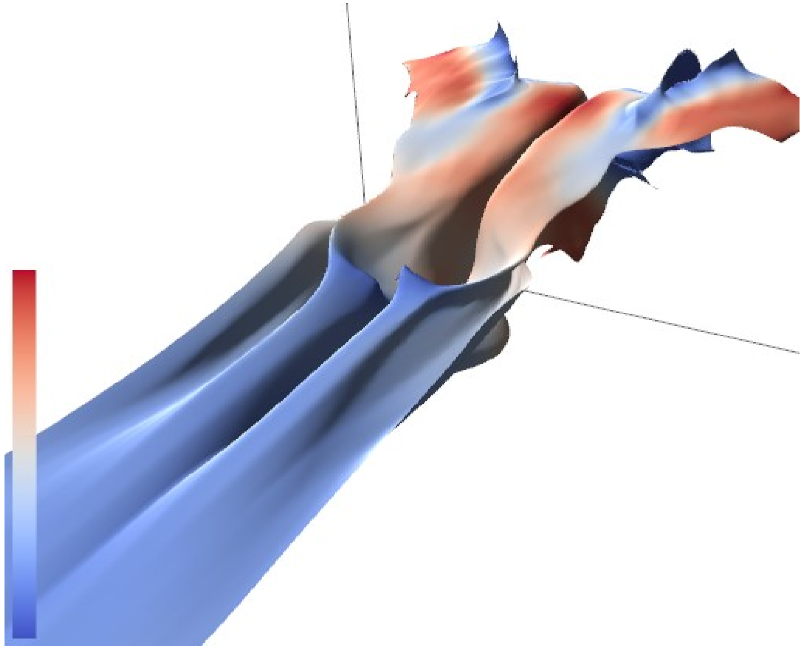
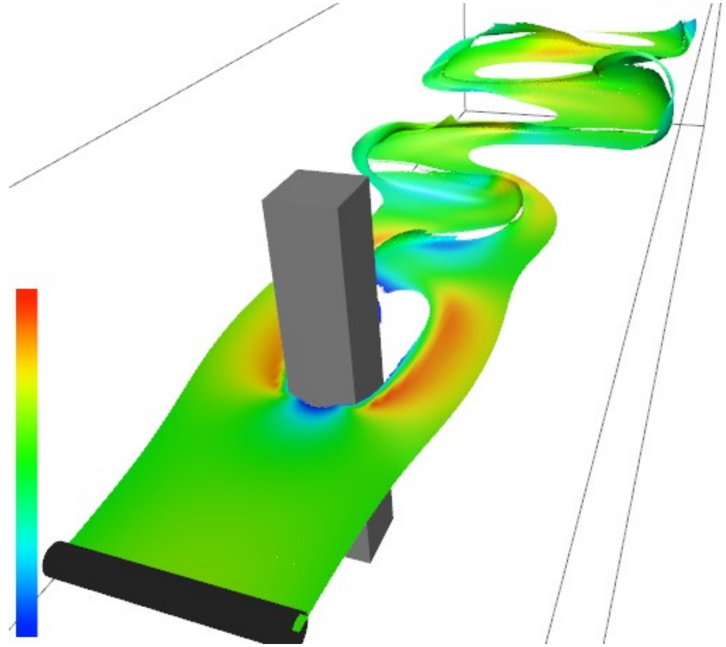
Stream and Path Surface Results: Video(s)

Constructing Streak Surfaces in 3D Unsteady Vector Fields





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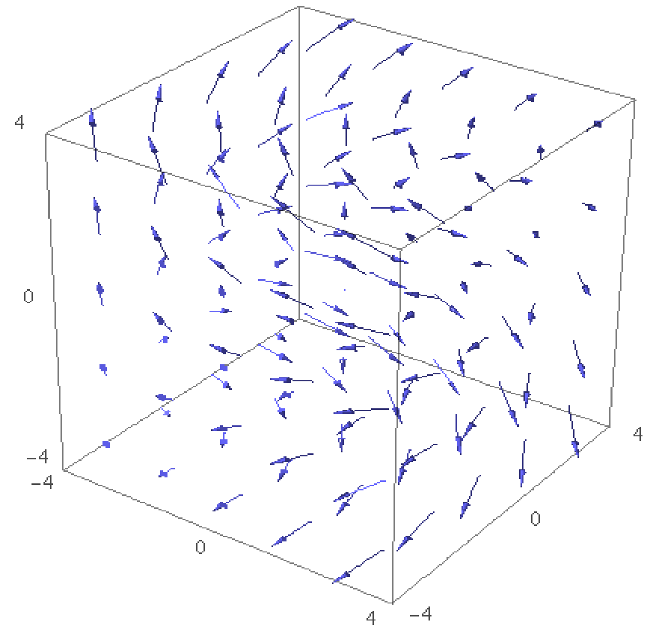
3D, Unsteady Vector Fields

Discrete locations in 3D space

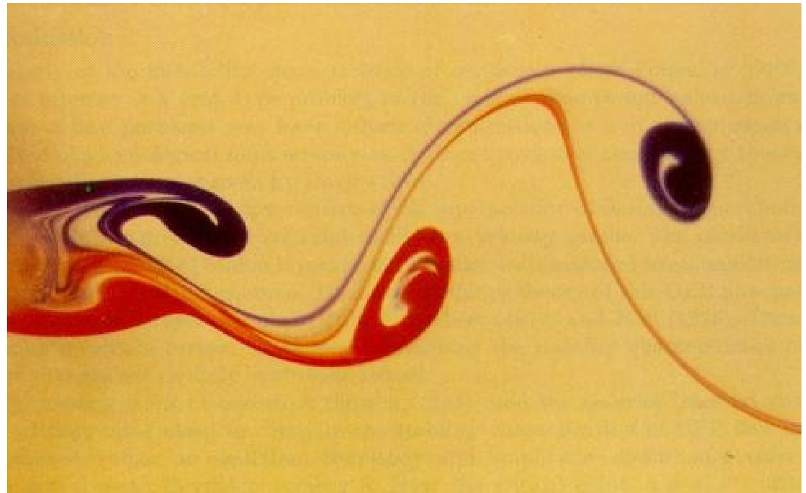
- 4-tuple (4D vector) for each sample
- x-, y-, z-, t- components
- Direction
- Magnitude
- Velocity field when describing the motion of a fluid
- Obtained from CFD simulations or constructed from empirical data
- Unsteady vector fields vary over time

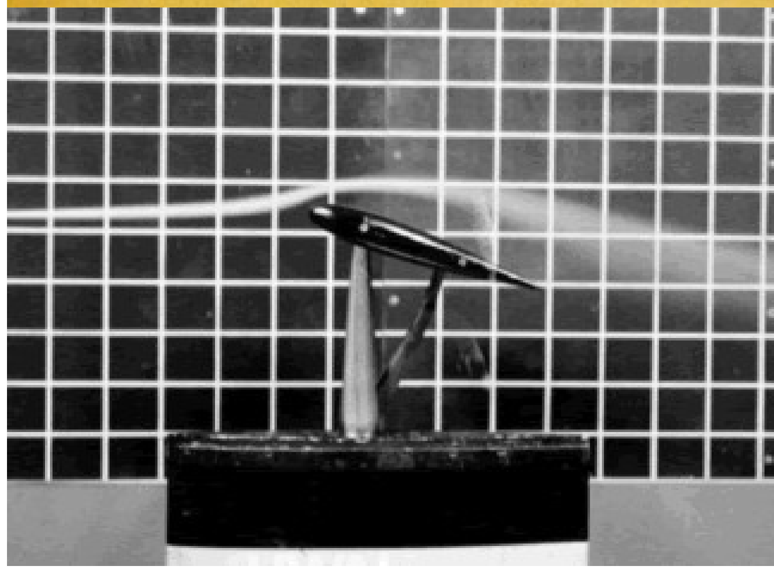


What are Streak Surfaces? Recall:

Terminology

- **Streaklines**: curved formed by joining all particles passing through same point in space (at different times)
- Strong relation to smoke/dye injection from experimental flow visualization.
- **Streak surfaces** are an extension of streak lines (next higher dimension)

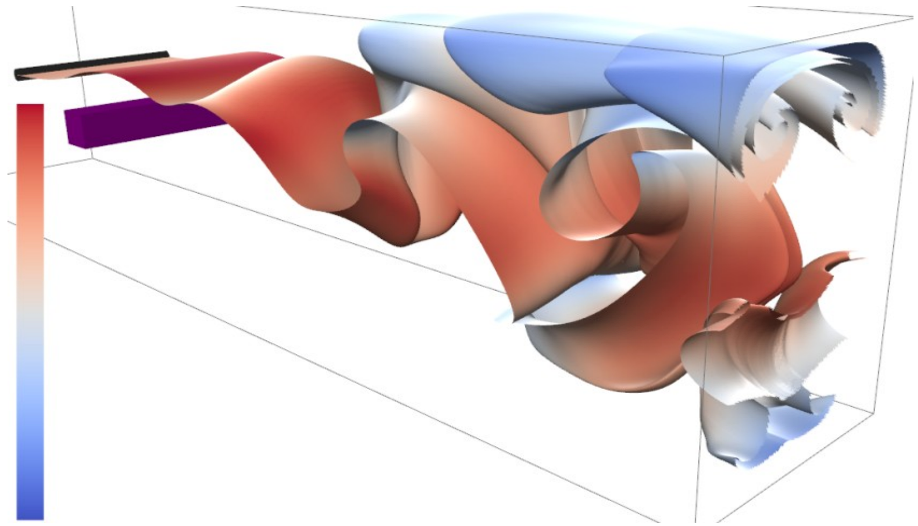




Streak Surfaces: Challenges

Challenges:

- Computational cost: surface advection is **<u>very</u>** expensive
- Surface completely dynamic: entire surface (all vertices) advect at each time-step
- Mesh quality and maintaining an adequate sampling of the field.
  - Divergence
  - Convergence
  - Shear
- Objects in domain and critical points
- Large size of time-dependent (unsteady) vector field data, out-of-core techniques



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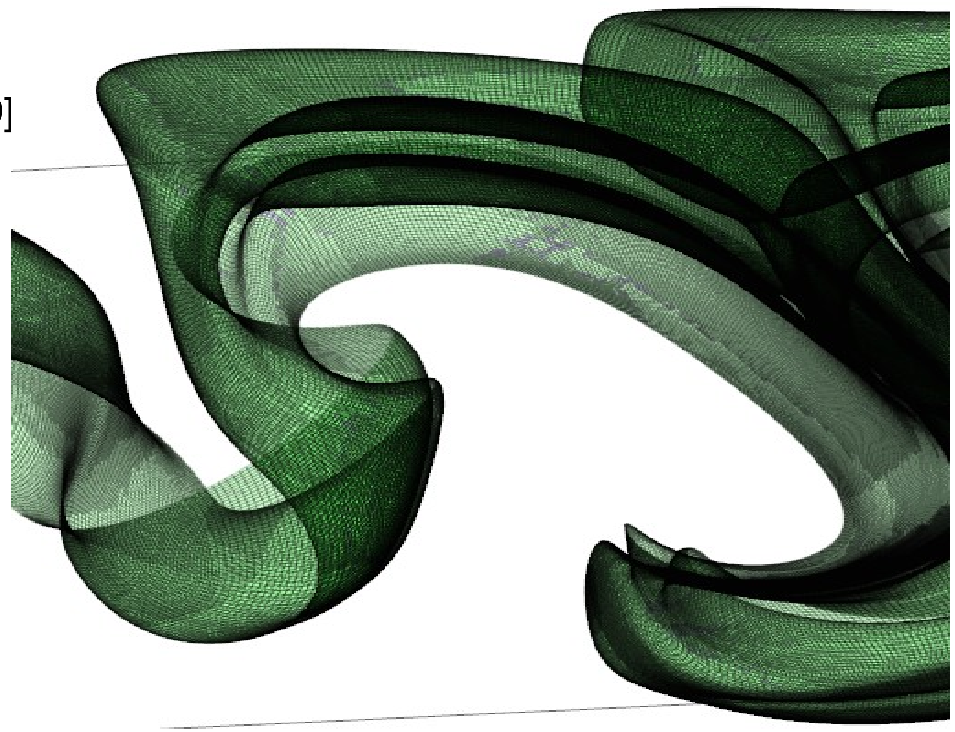
Our Method

Properties:

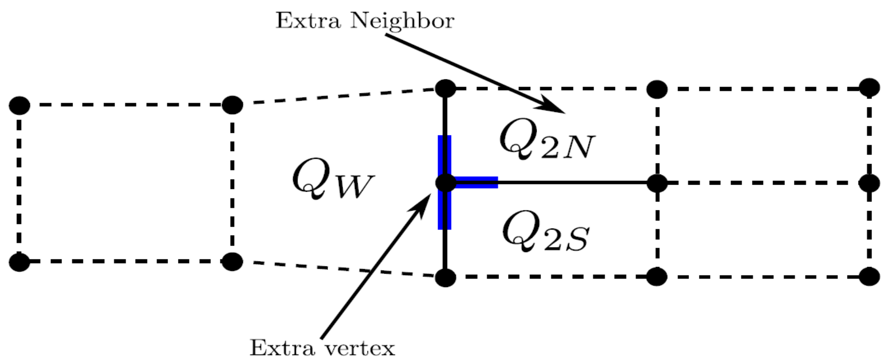
- Surface constructed using quad primitives (as opposed to triangles)
- Local operations for surface refinement performed on a quad-by-quad basis
- No global optimization required
- Allows the construction of large surfaces
- CPU-based for easier implementation
- Fills the gap between methods of Burger et al. [2009] and Krishnan et al. [2009]
  - Not as fast as GPU but interactive
  - Less constraints than GPU implementation – does not need to fit into GPU memory
- Good quality surfaces



Algorithm Data Structures

Data Structures:

- Maintain list of particles
- Particles form vertices that create mesh
- Maintain list of quads
  - Store pointers to vertices
  - Store pointers to all (Quad) neighbors
  - Store T-Junction objects
- Test edge lengths after each integration
- T-junction objects store extra vertex and neighbor information
- Only one T-junction allowed per edge



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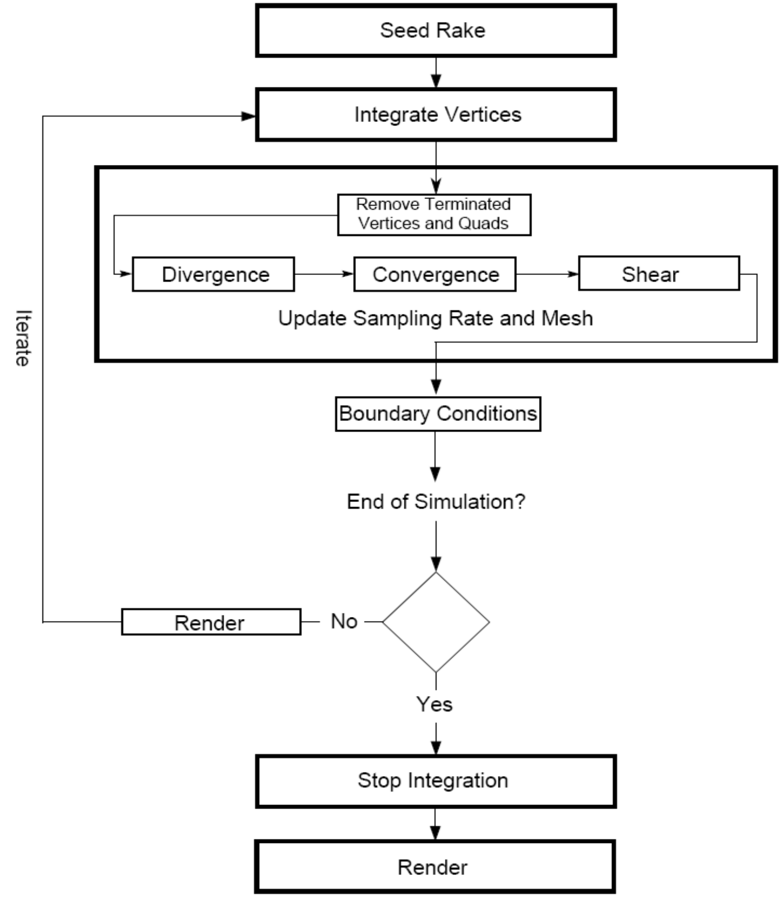
Streak Surface Algorithm Overview

Do:

Position seed with interactive rake

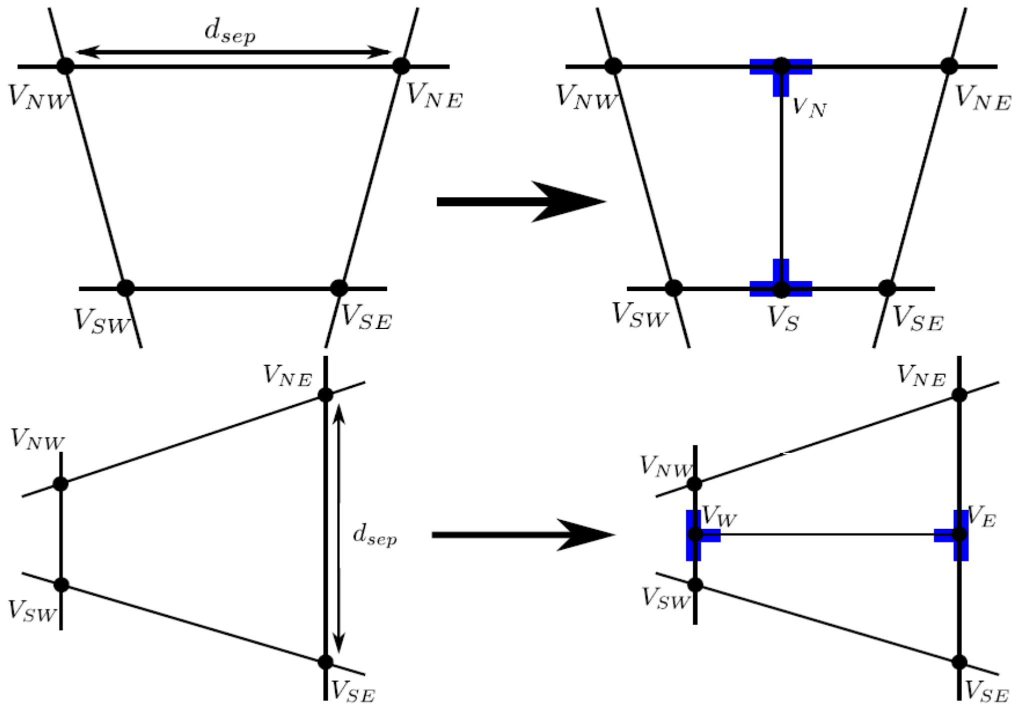
- Iteratively construct surface:
  - Advect surface
  - Refine Surface
  - Test for boundary conditions
  - Update
  - Test for termination criteria
- Final rendering



Divergence

Quad Splitting:

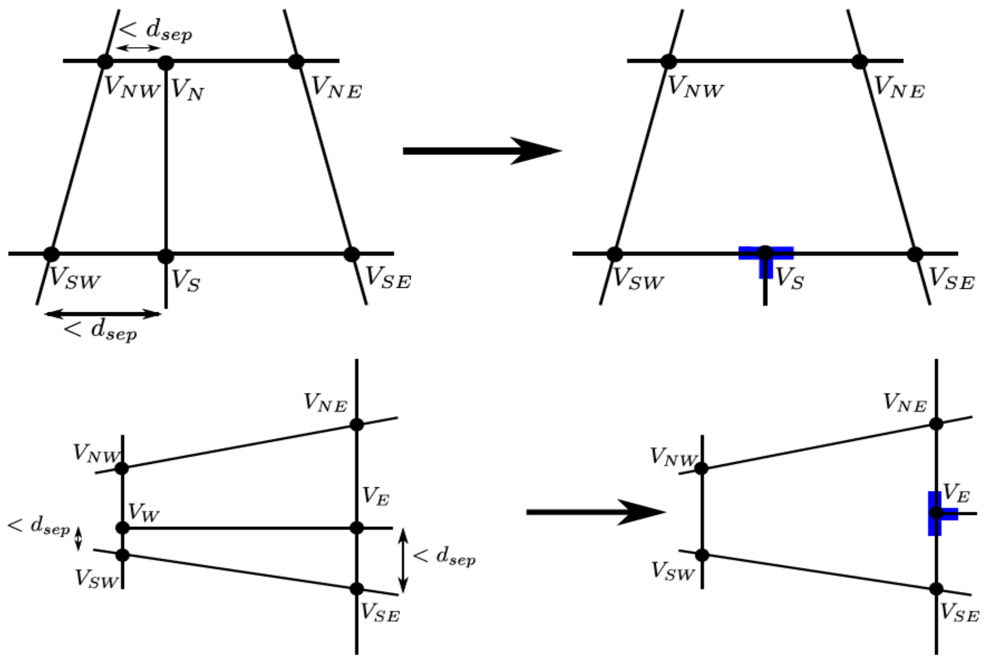
- Occurs when distance between neighbouring particles increases.
- Reduces the sampling of the vector field – may miss features.
- Introduce new particles – divide the quad.

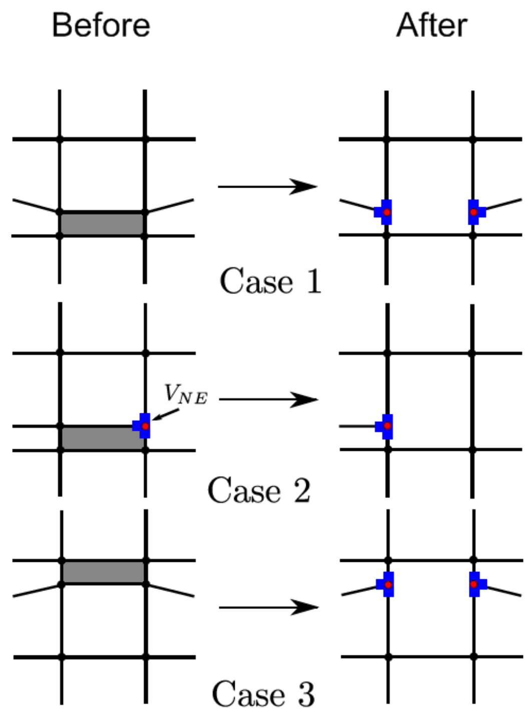


Convergence

Quad Collapse:

- Occurs when neighbouring particles move closer together.
- Leads to over-sampling, redundant particles and extra computation.
- Test distance between neighboring particles
- Remove particles from the surface – merge the quad with neighbor.

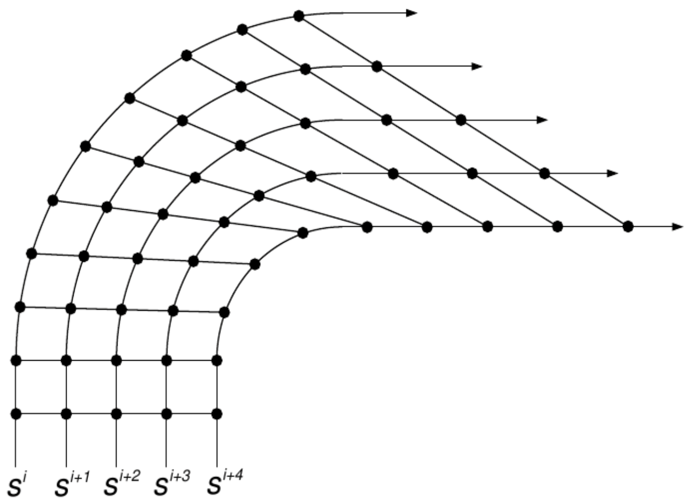


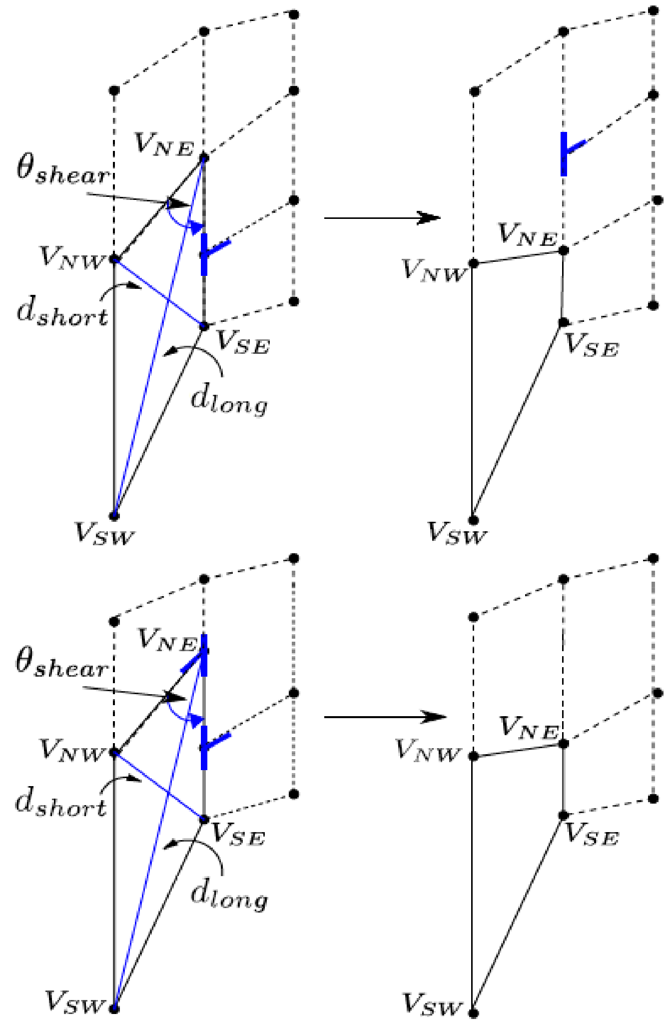


Shear

Shear Update:

- Can lead to heavily deformed quads
- May lead to errors in checking sampling frequency
- Test the ratio between the quad diagonals
- Update the mesh connectivity





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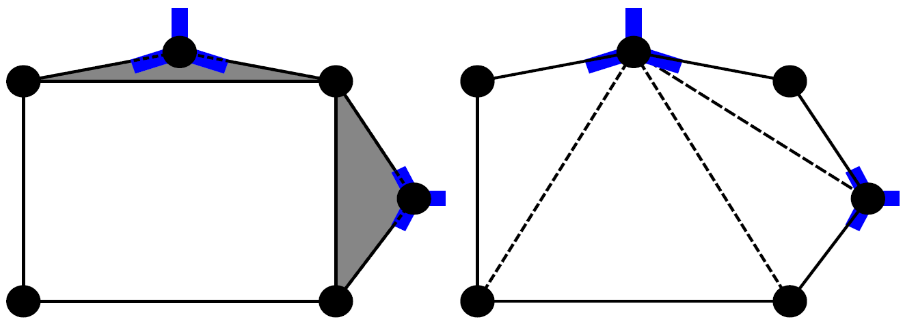
T-Junctions and Surface Discontinuities

Create Temporary Triangle Fan:

- Store T-Junction object explicitly
- T-junction vertices may not necessarily lie on neighboring quads edge
- If ignored cracks can form in the surface
- Render the quad using a triangle fan
    - Ensures whole surface is tesselated



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Streak Surface Results: Video

Summary and Conclusions

- We claim surfaces offer advantages over traditional curves when visualizing 3D and 4D flow
- We present interactive algorithms for construction of stream, path and streak surfaces
- Algorithms are based on local operations performed on quads for mesh refinement
- Technique handles divergence, convergence and shear flow
- Splitting of surface to adapt to flow around object boundaries
- Demonstrated on a variety of data sets

Acknowledgements

Thank you for your attention! Any questions?

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