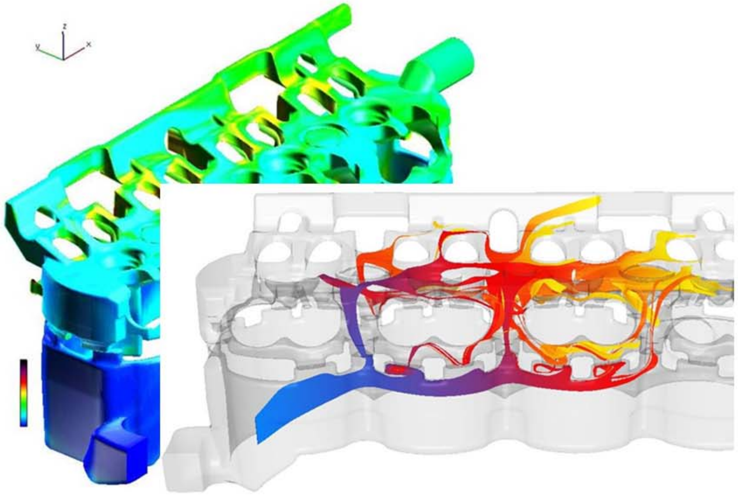
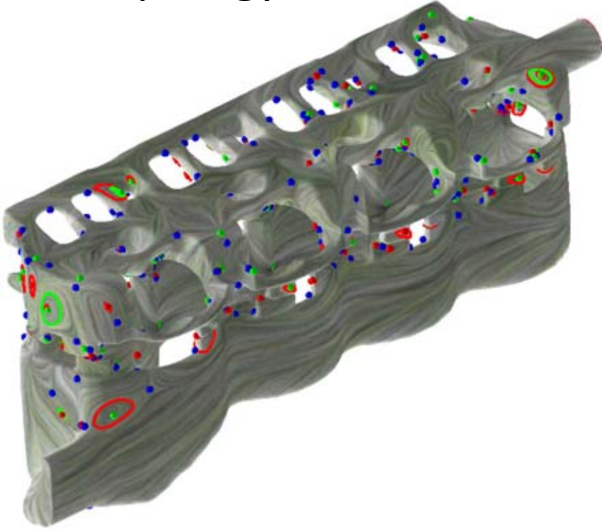
Review of Flow Vis for Lower Dimensional (2D) Flow Data

- **Direct:** overview of vector field, minimal computation, e.g., glyphs (arrows), color mapping
- **Texture-based:** covers domain with a convolved texture, e.g., Spot Noise, LIC, ISA, IBFV(S), and many more
- **Geometric-based:** a discrete object(s) whose geometry reflects flow characteristics, e.g., streamlines
- **Feature-based:** both automatic and interactive feature-based techniques, e.g., vortices, separation/attachment lines, vector field topology

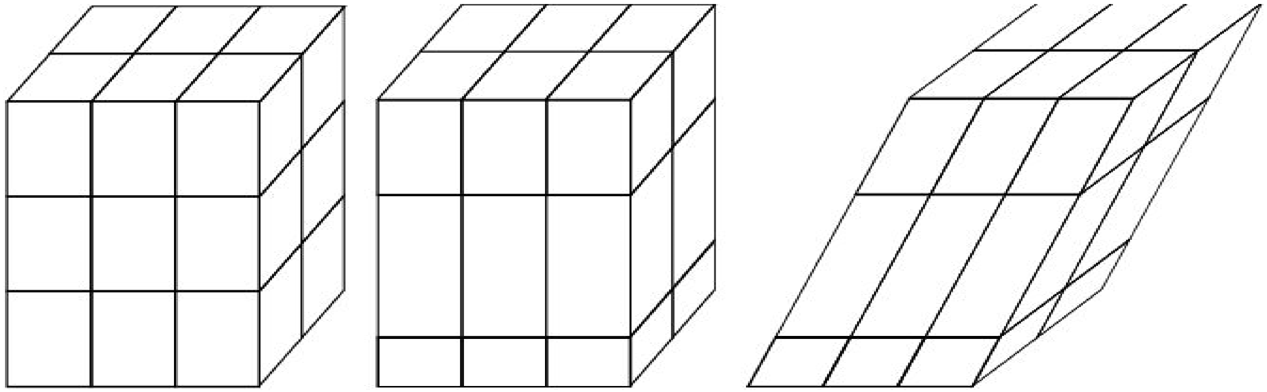




Vector Field Visualization in 3D

Goal: understand the challenges of visualizing 3D vector fields; know a few standard techniques

Review of Data Structure

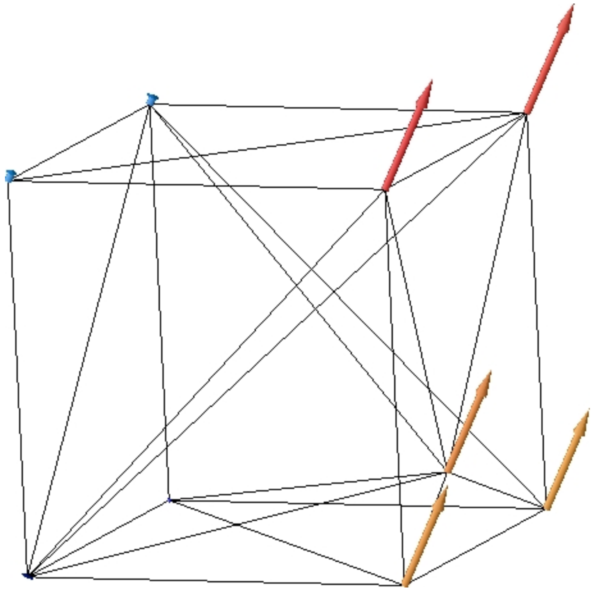


Regular (uniform), rectilinear, and structured grids

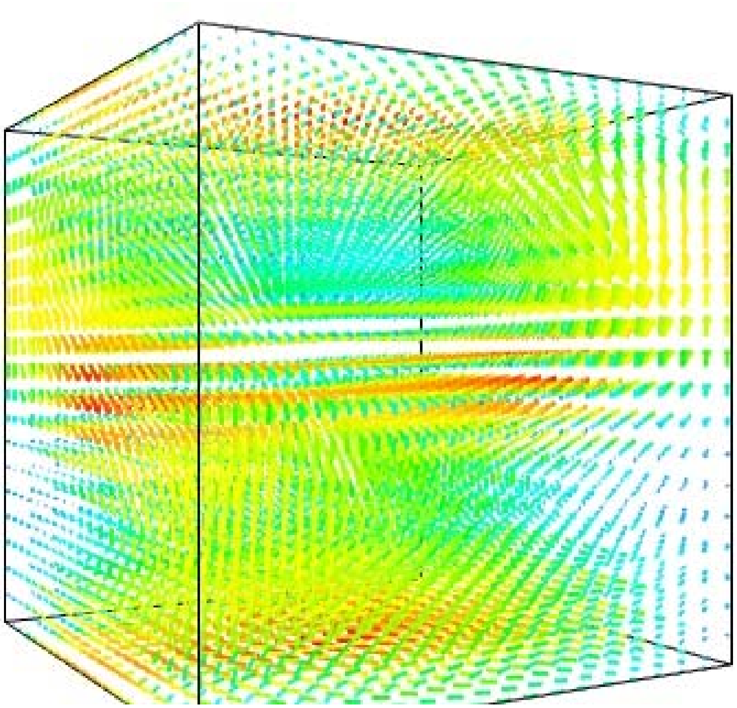
Alternative:

tetrahedral volume elements:

unstructured

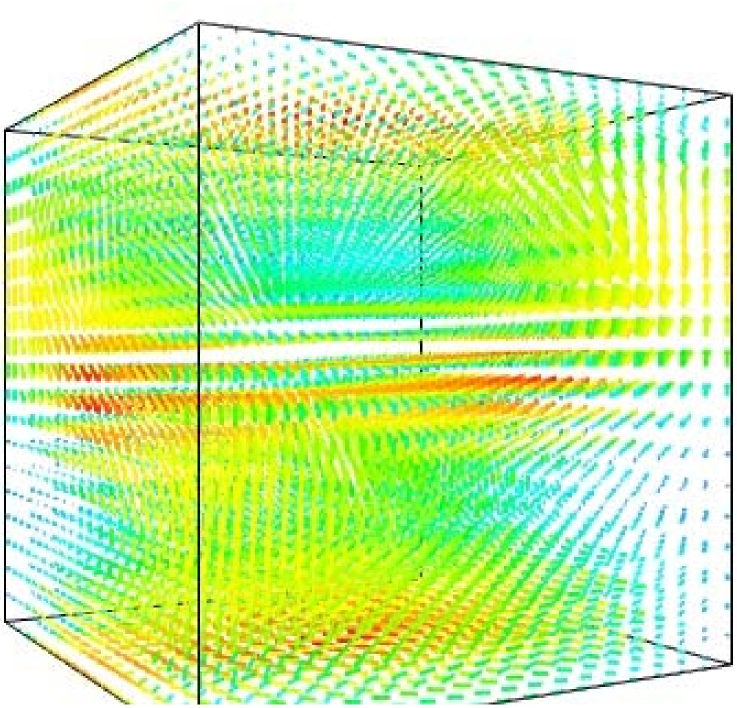


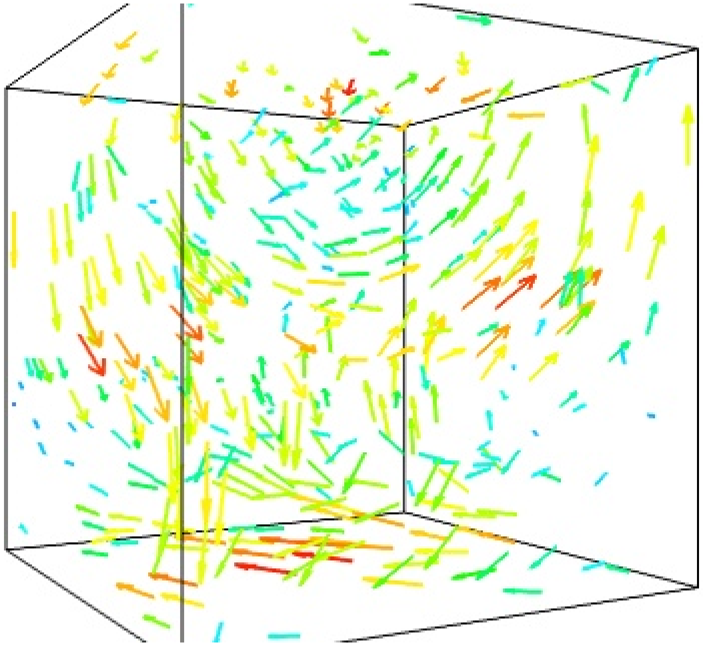
Direct Method (Arrow Plot)



Source:
http://docs.enthought.com/mayavi/mayavi/mlab.html

Direct Method (Arrow Plot)

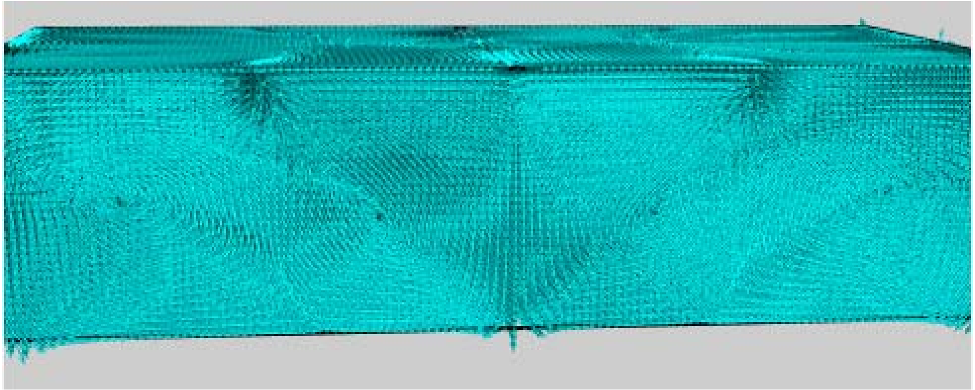




Sparse and random

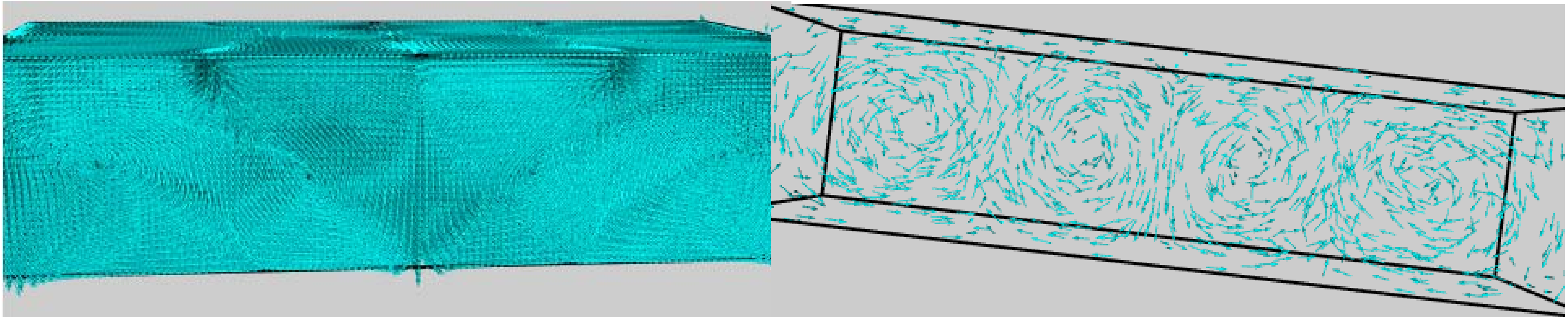
Source:
http://docs.enthought.com/mayavi/mayavi/mlab.html

For Assignment 4



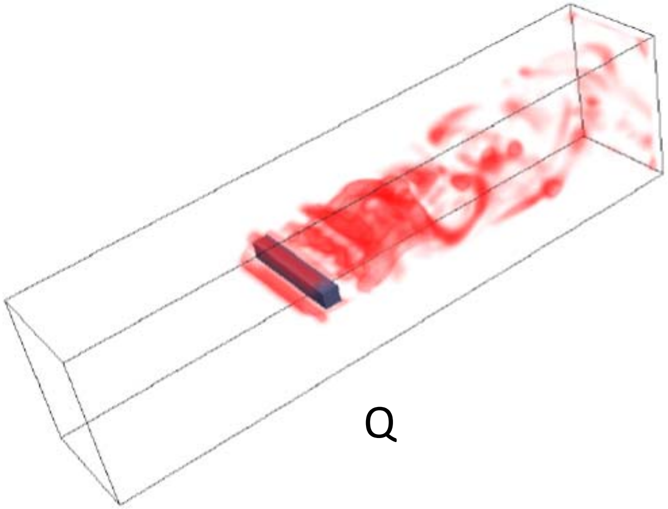
Bernard Flow

For assignment 5

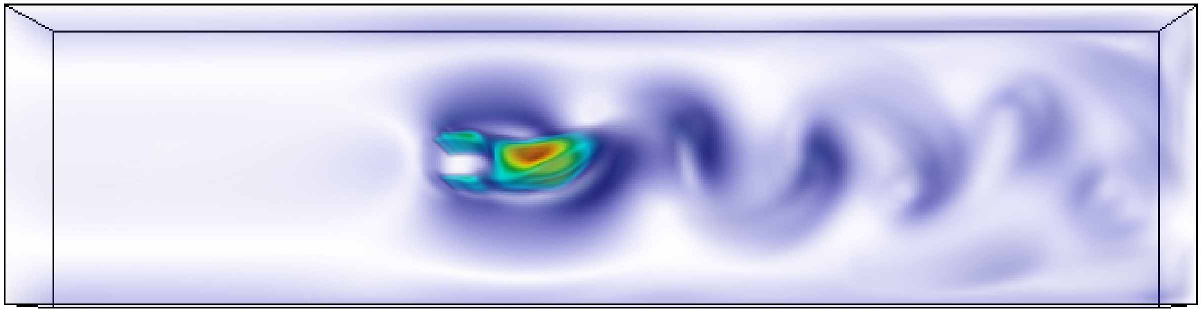


Bernard Flow

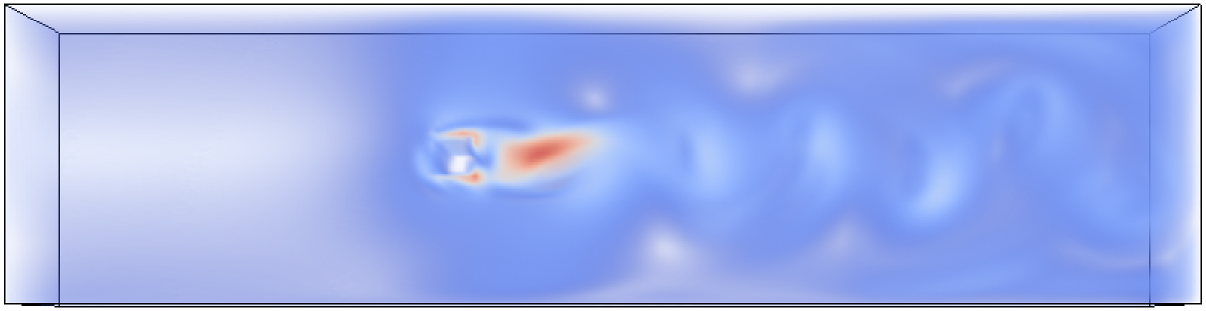
Direct Method – Volume Rendering of Certain Scalar Characteristics



Q



Acceleration



Local shearing

Flow behind a cylinder

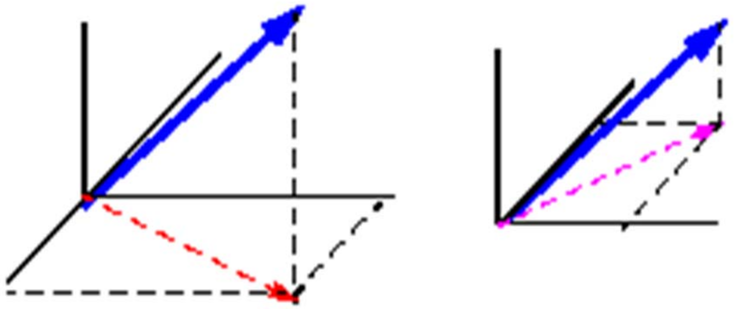
Issues of Arrows in 3D

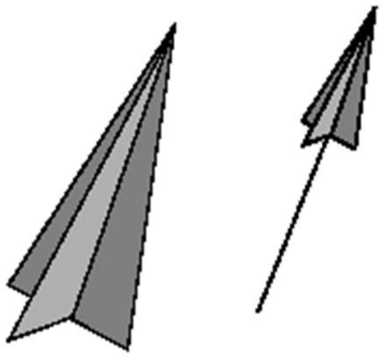
Common problems:

- Ambiguity
- Perspective shortening
- 1D objects generally difficult to grasp in 3D

Remedy:

- **3D**-Arrows
  (are of some help)



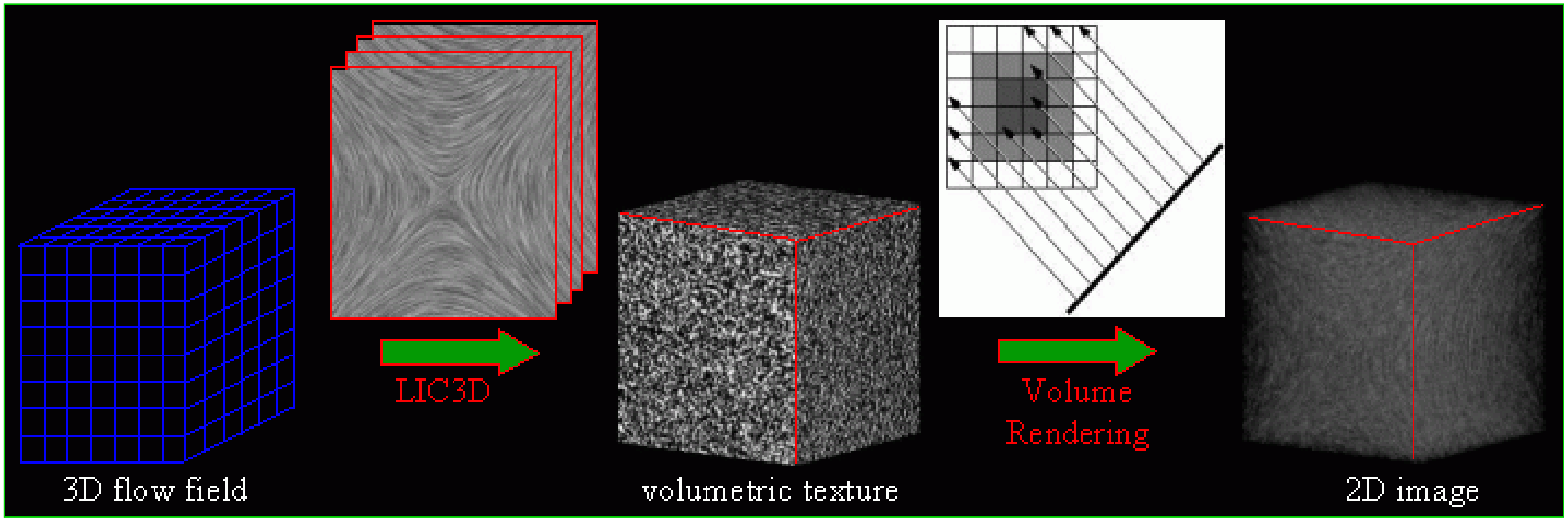


Texture-Based Method

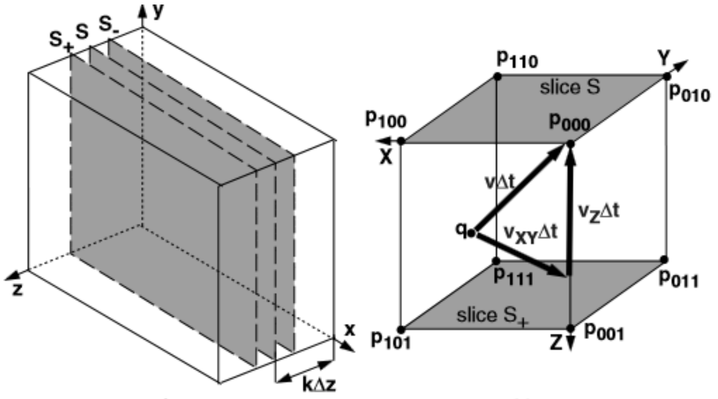
Volume LIC

- Victoria Interrante and Chester Grosch (*IEEE Visualization 97*).
- A straightforward extension of LIC to 3D flow fields.
- Low-pass filters *volumetric noise* along 3D streamlines.
- Uses *volume rendering* to display resulting 3D LIC textures.
- Very time-consuming to generate 3D LIC textures.
- Texture values offer no useful guidance for transfer function design due to *lack of intrinsic physical info* that can be exploited to distinguish components.

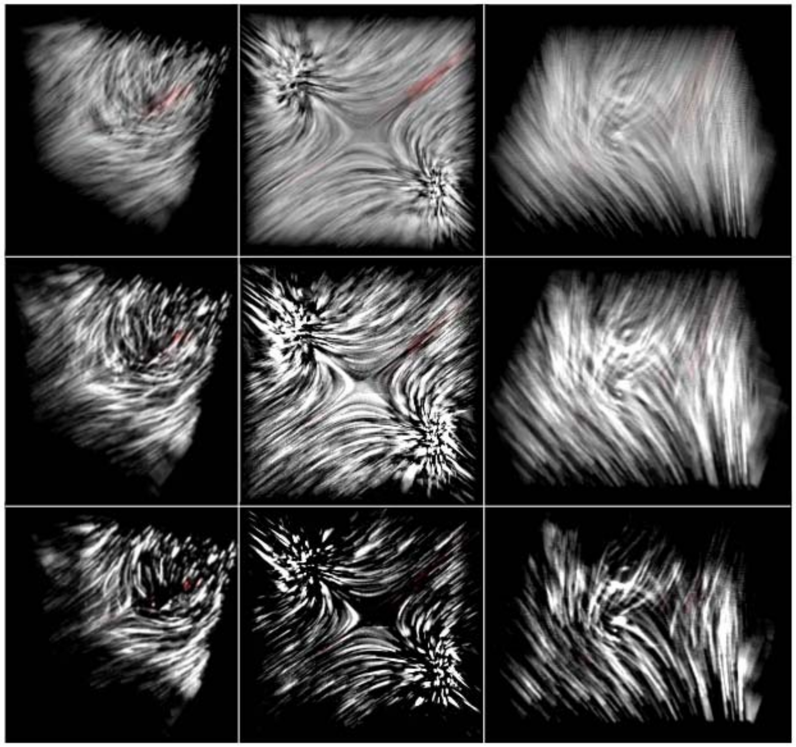
⇨ Very challenging to clearly show *flow directions and interior structures through a dense texture volume.*

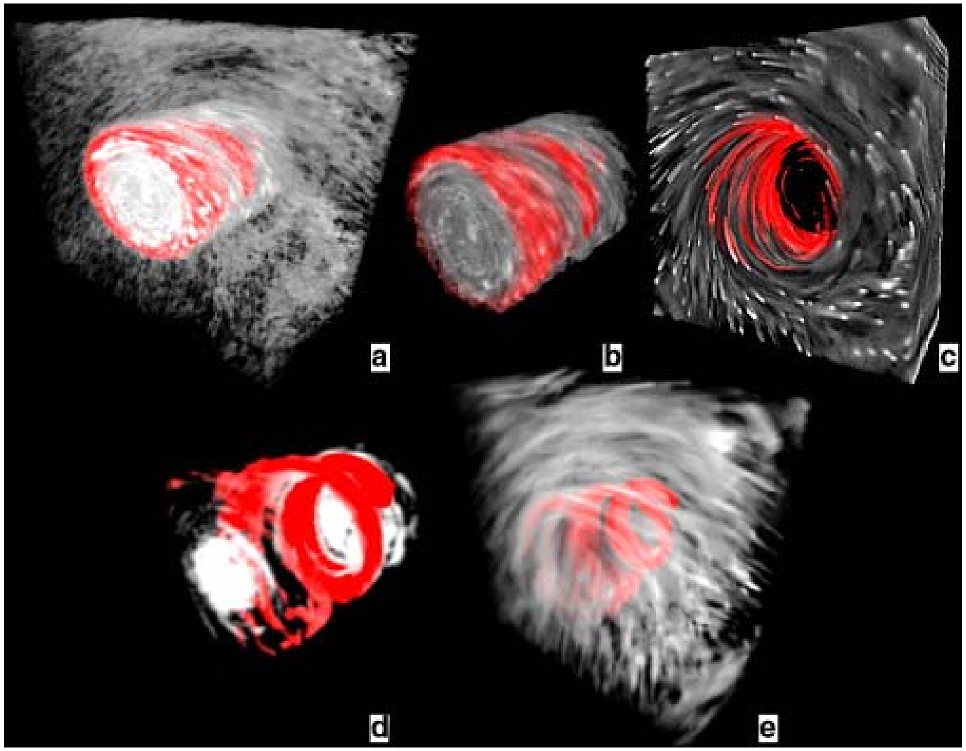


3D IBFV



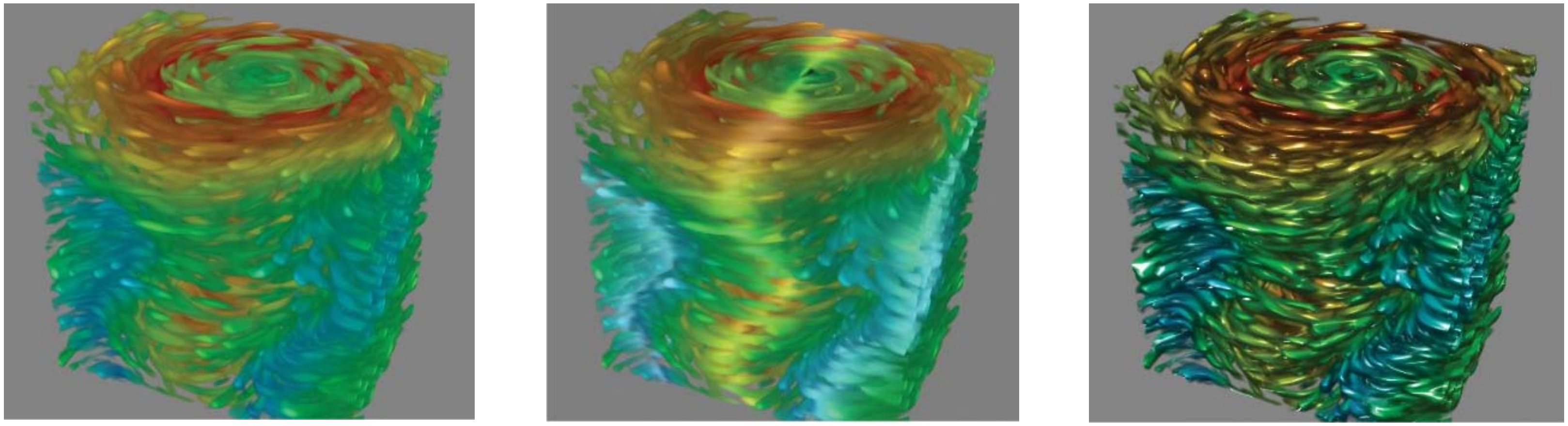
```
for i = 0 to N-1
{
  if (i>0)                                                    (1)
     do 1D Z-axis advection from $S_{i-1}$ to $S_i$
  if (i<N-1)                                                  (2)
     do 1D Z-axis advection from $S_{i+1}$ to $S_i$
  do 2D IBFV-based advection in the slice $S_i$               (3)
}
```





[Telea and van Wijk Vis03]

Improvement in 3D Texture-based Method

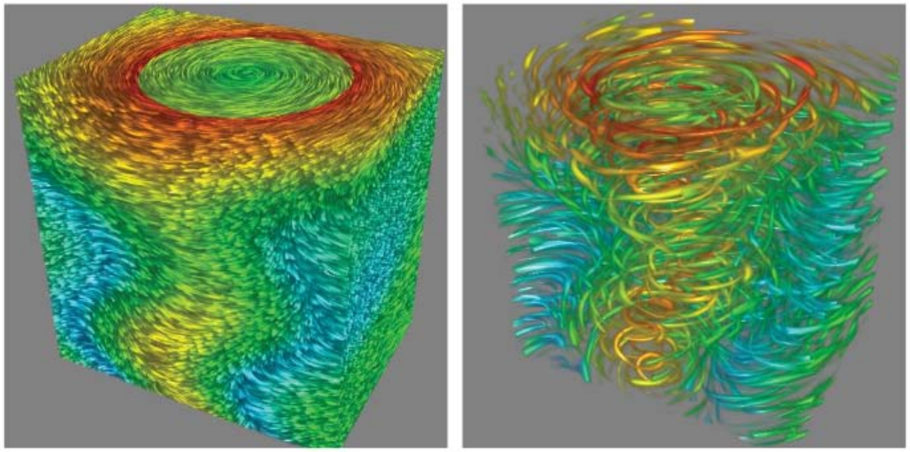


without illumination

with illumination

Gradient-based illumination

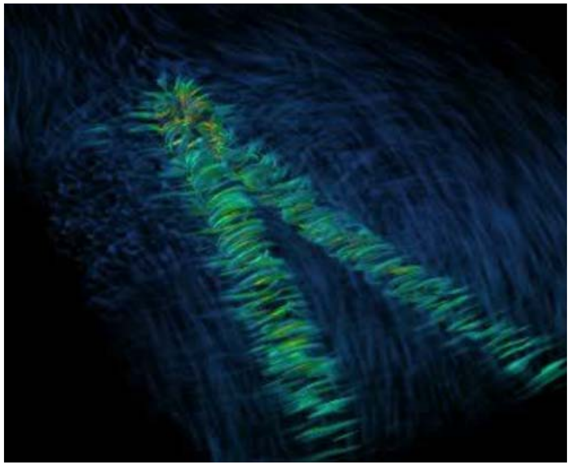
Codimension-2 illumination



Dense (white noise)

Sparse noise

Different seeding strategies



Feature enhancement

[Falk and Weikopf 2008]

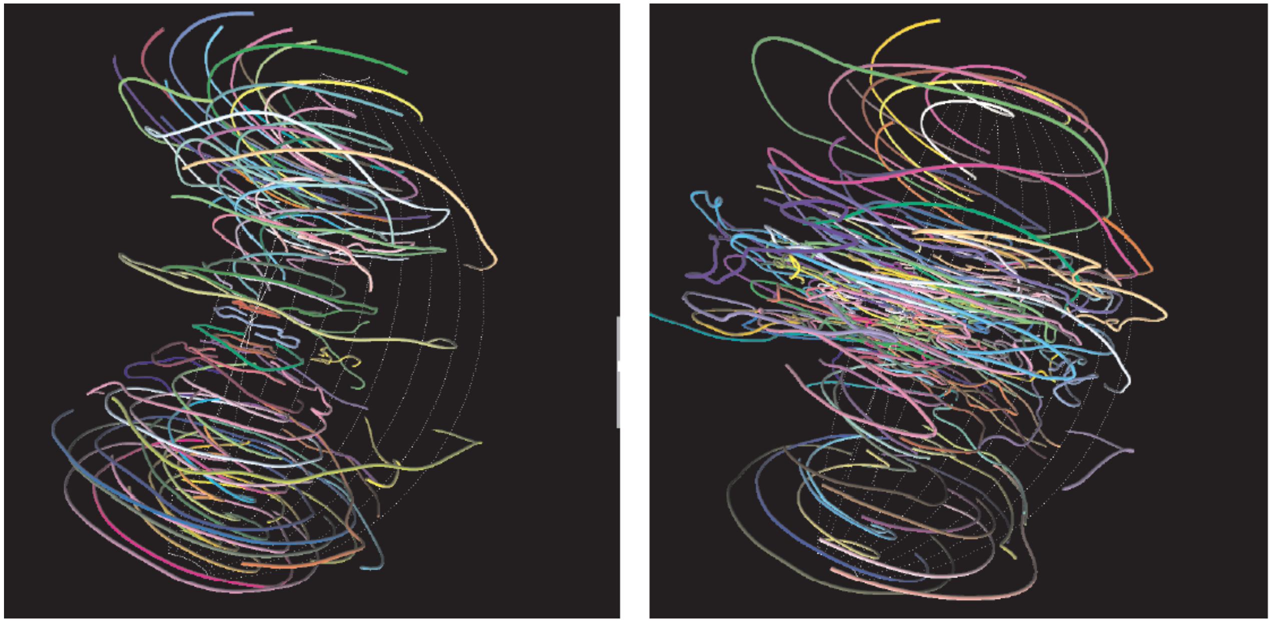
People's choice ✓

Geometric-Based Methods

Streamlines:

Theory $\mathbf{s}(t) = \mathbf{s}_0 + \int_{0 \le u \le t} \mathbf{v}(\mathbf{s}(u))\, \mathrm{d}u$

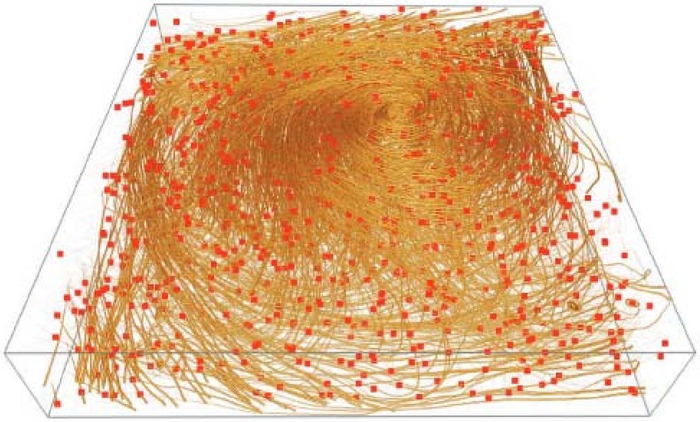
Practice: Numerical integration such as **Euler, RK2, RK4**, etc.



Chen et al. Vis 2007

3D Seed Placement

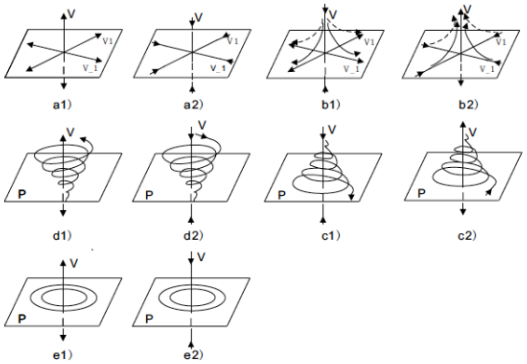
- The placement of seeds **and** the number of seeds directly determine the visualization quality
  - Too many: scene cluttering
  - Too little: no pattern formed
- It has to be in the right place and in the right amount



A bad seeding example

Some Existing Work

- 3D flow topology-guided [Ye et al. 2005]



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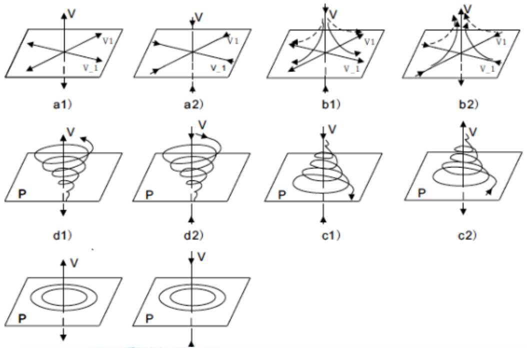
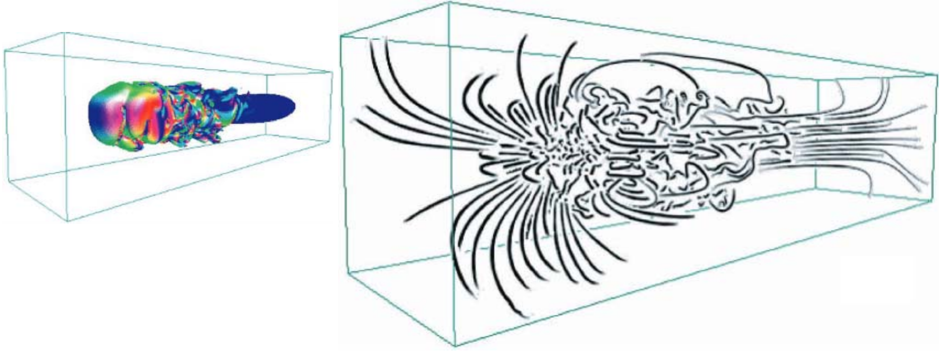


- Image-based streamline placement [Li and Shen 2007]



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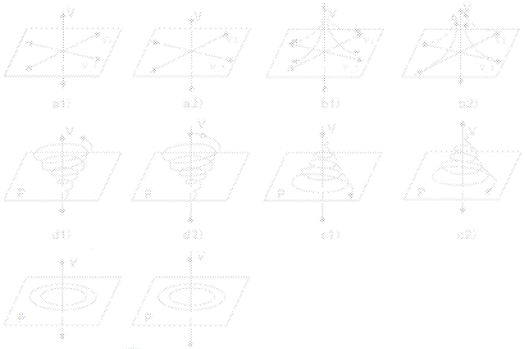

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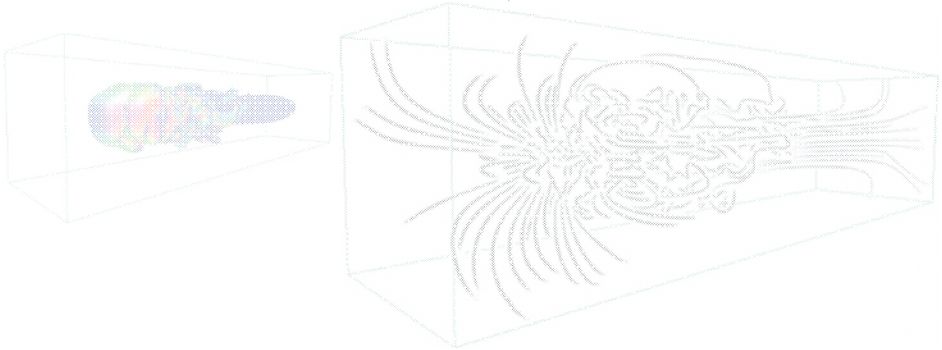
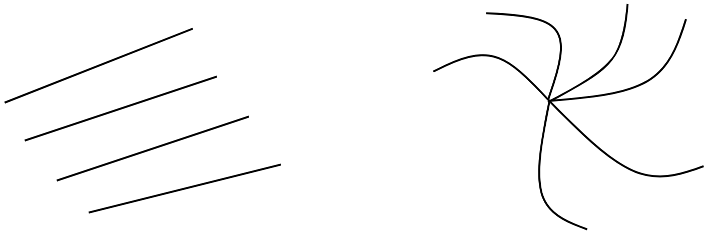
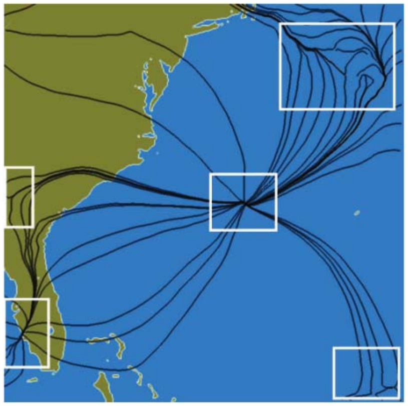


- Entropy-guided seed placement [Xu et al. 2010]



which one has higher entropy?

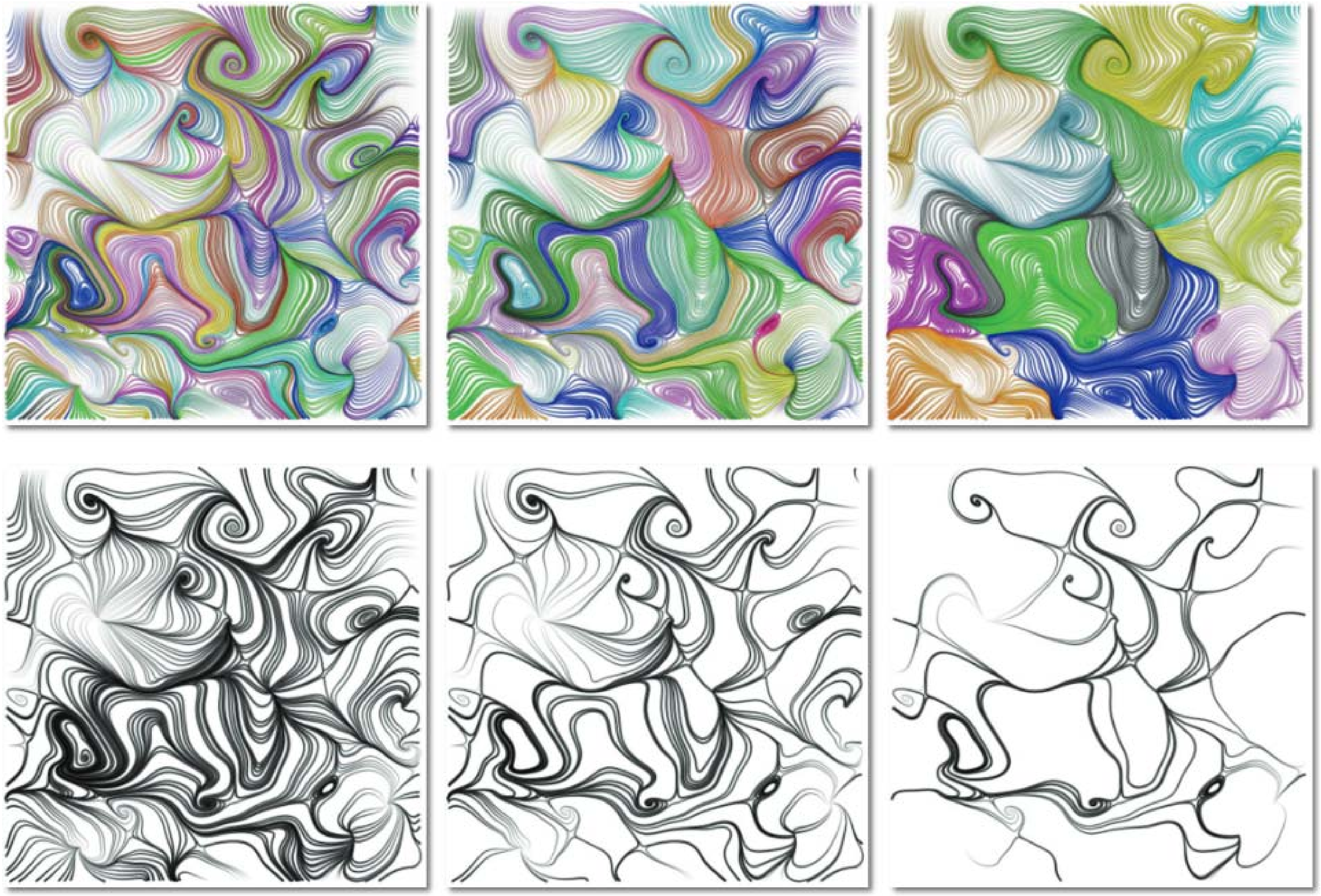


Open Issues

- Seed placement in 3D (to address occlusion and clarity)
- Techniques for handling big data
- Flow field navigation and interaction
- *Human perception and user evaluation*

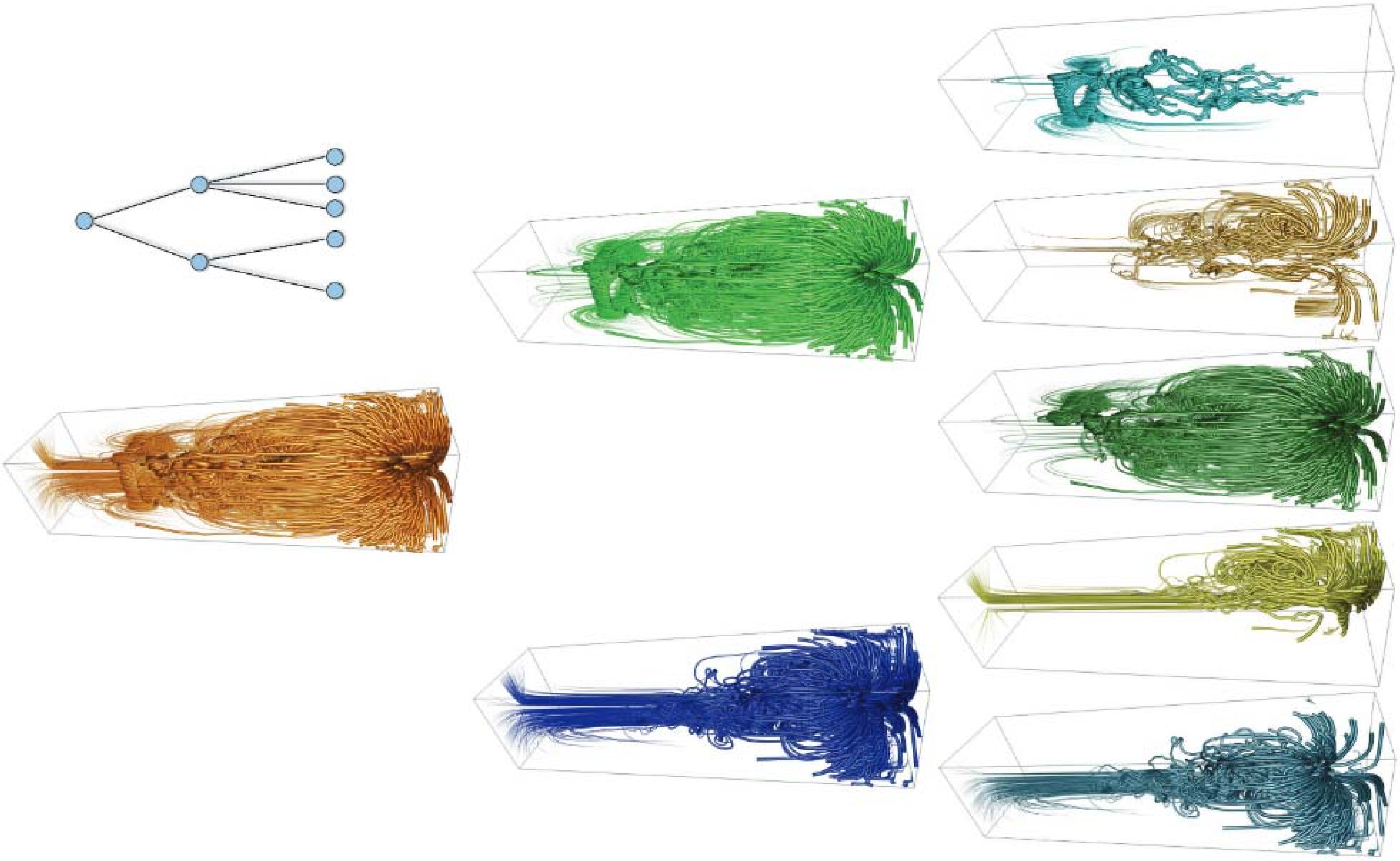
Streamline filtering and/or selection techniques

Streamline Bundling



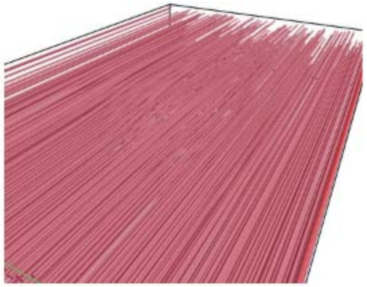
[Yu et al. 2012]

Streamline Bundling

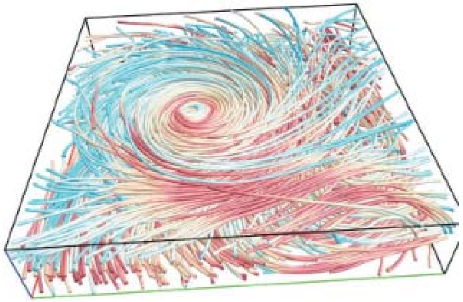


[Yu et al. 2012]

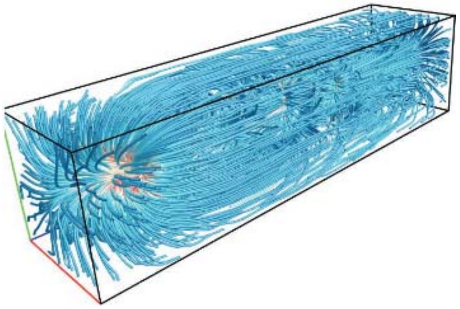
View-dependent streamline selection



initial pool



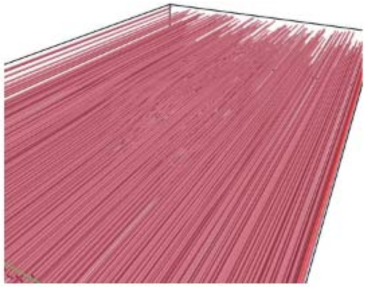
initial pool



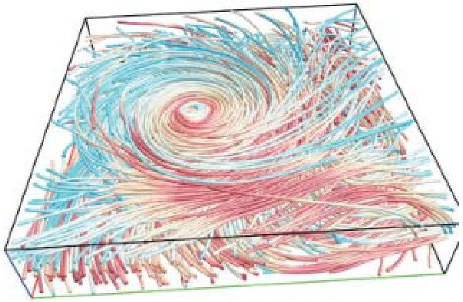
initial pool

[Tao et al. 2013]

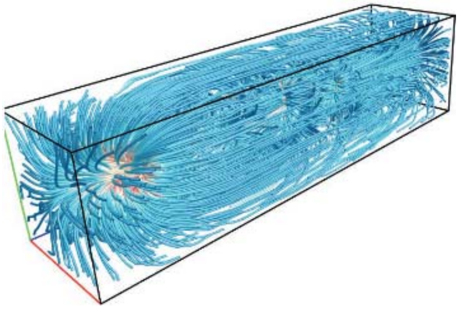
View-dependent streamline selection



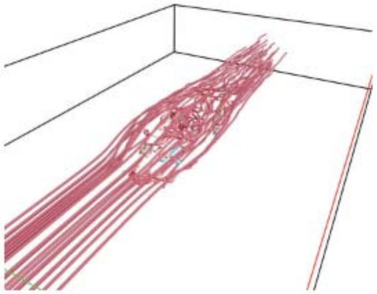
initial pool



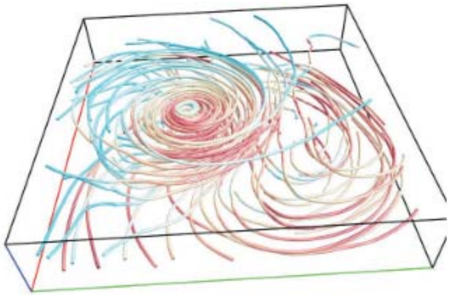
initial pool



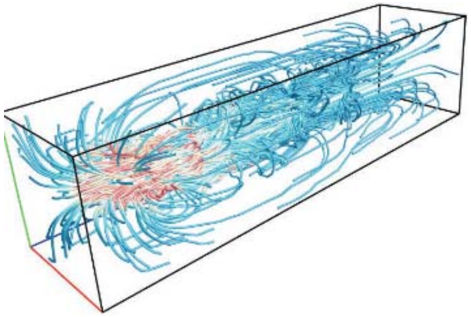
initial pool



selected streamlines



selected streamlines

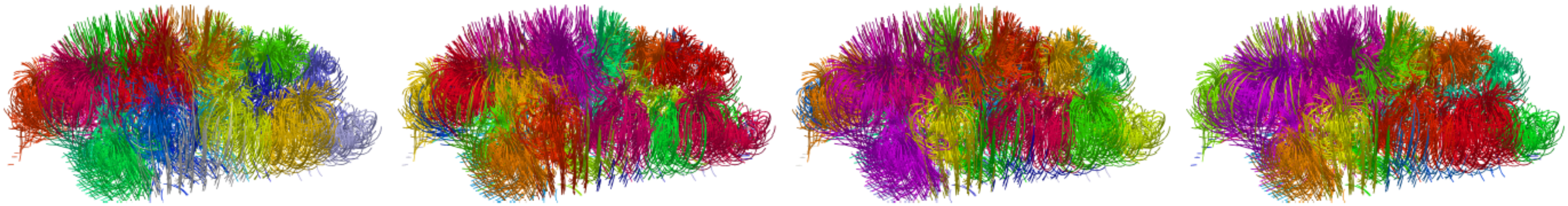


selected streamlines

[Tao et al. 2013]

Clustering-based Streamline selection

First, perform streamline clustering using a selected clustering algorithm and distance measures.



[Shi et al., TVCG 2021]

Clustering-based Streamline selection

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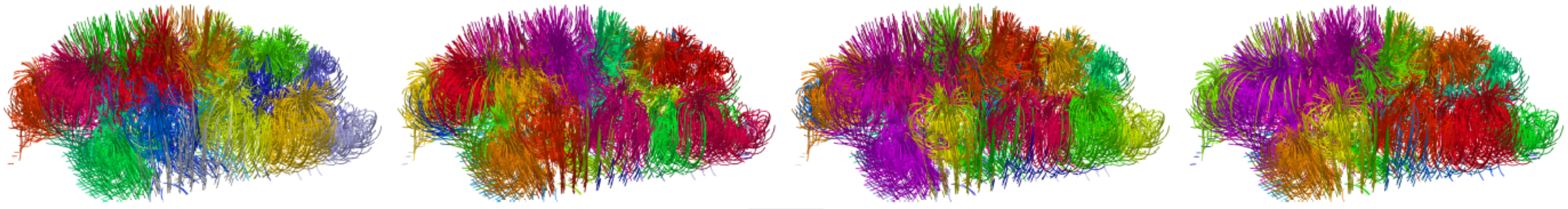
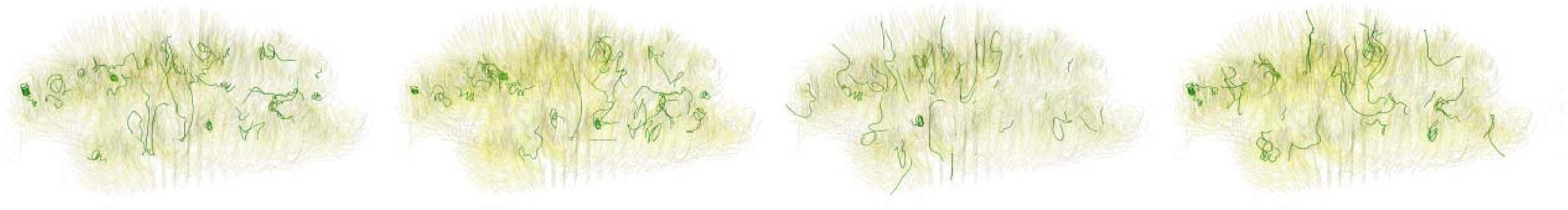


Second, from each obtained cluster, select one (or a few) representative streamlines.



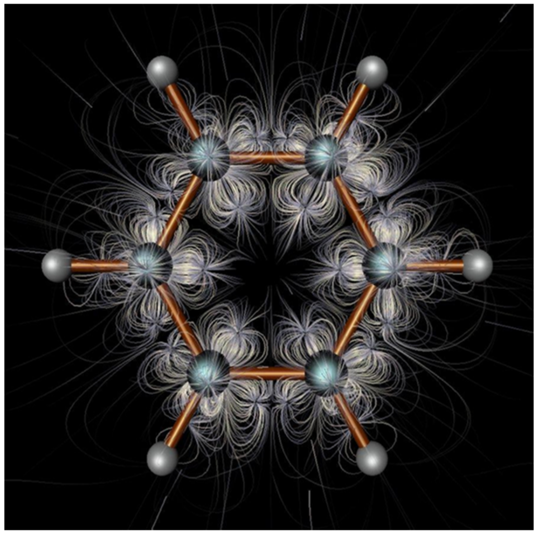
[Shi et al., TVCG 2021]

Streamline rendering techniques

Illuminated Streamlines

Use lighting to improve spatial perception of lines in 3D.

This can to some extend reduce the 3D cluttering issue.



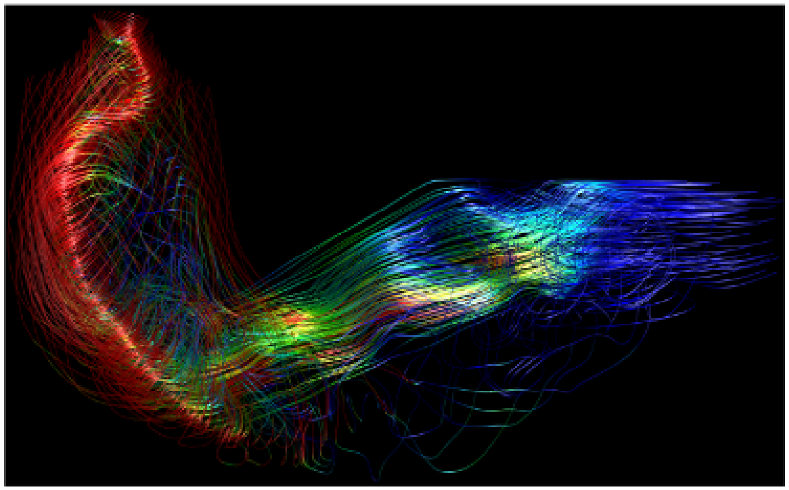
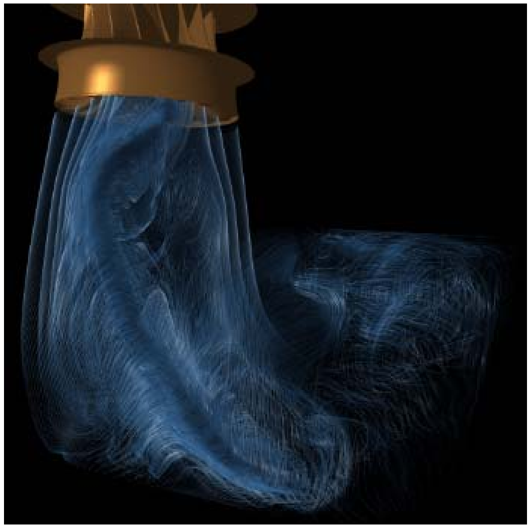


Figure 1: Flow in a Francis draft tube visualized by streamlines regularly seeded on a cone and colored by speed. Streamlines are illuminated based on cylinder averaging. In the vertical part of the tube, a vortex rope is visible.



Open Source: http://www.scivis.ethz.ch/research/projects/illuminated_streamlines

[Zockler et al. 96, Mallo et al. 2005]

Opacity Optimization for 3D Line Fields

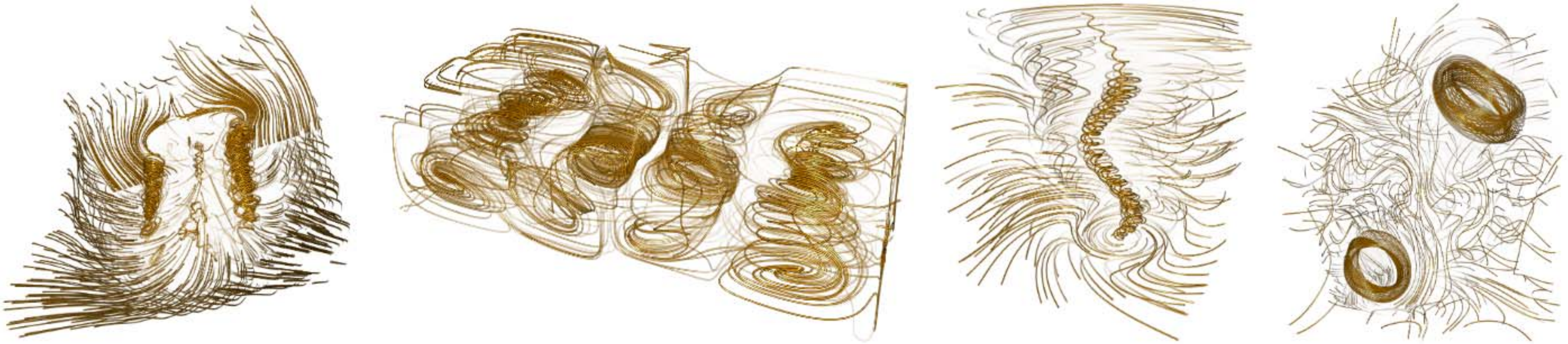
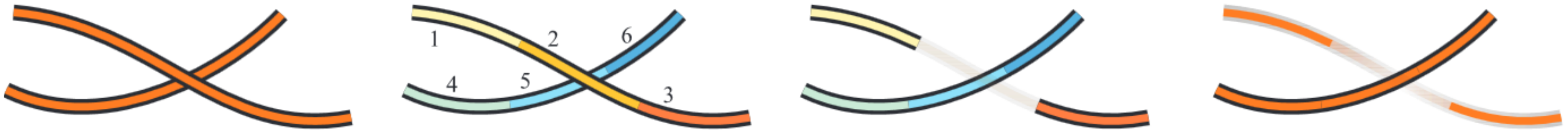


Figure 1: *Applications of our interactive, global line selection algorithm. Our bounded linear optimization for the opacities reveals user-defined important features, e.g., vortices in rotorcraft flow data, convection cells in heating processes (Rayleigh-Bénard cells), the vortex core of a tornado and field lines of decaying magnetic knots (from left to right).*



(a) Given is a set of polylines.

(b) Discretize polylines into n segments (here: $n = 6$).

(c) Compute per-segment opacity α_i by energy minimization.

(d) Interpolate opacities between adjacent segments for final rendering.

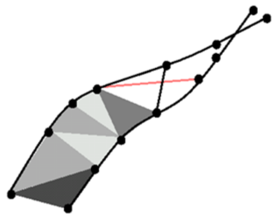
[Gunthe et al. 2013]

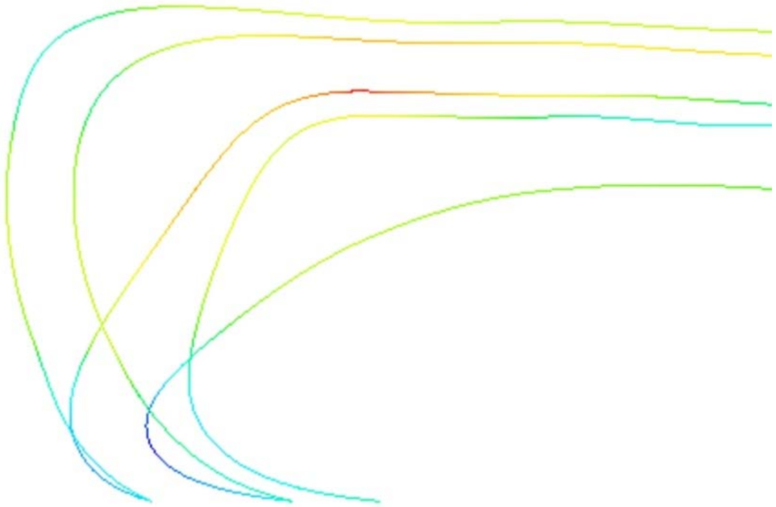
Other Geometric-Based Methods

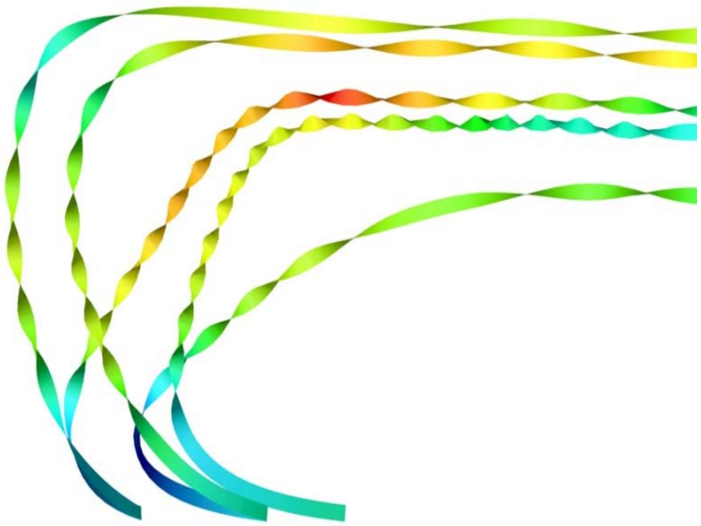
✓ Streamribbons, Streamtubes, Stream surfaces, ✓ Flow volumes

streamribbon:

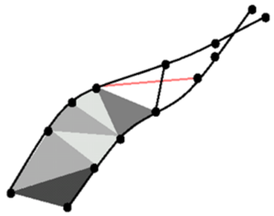
a ribbon (surface of fixed width) always tangent to the vector field
shows rotational (or twist) properties of the 3D flow



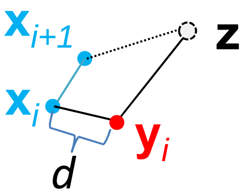




Streamribbon generation:

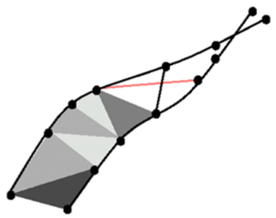


- Start with a 3D point $\mathbf{x}_{i=0}$ and a 2nd one $\mathbf{y}_{i=0}$ in a particular dist. *d*, i.e. $|\mathbf{x}_i - \mathbf{y}_i|^2 = d^2$
- Loop:
  - Integrate from $\mathbf{x}_i$ to yield $\mathbf{x}_{i+1}$
  - Do an integration step from $\mathbf{y}_i$ to yield $\mathbf{z}$ renormalize the distance between $\mathbf{x}_{i+1}$ & $\mathbf{z}$ to *d*, i.e. $\mathbf{y}_{i+1} = \mathbf{x}_{i+1} + d \cdot (\mathbf{z} - \mathbf{x}_{i+1}) / |\mathbf{z} - \mathbf{x}_{i+1}|$
  - Connect the integration points to form 2D cells (a quad or two triangles)



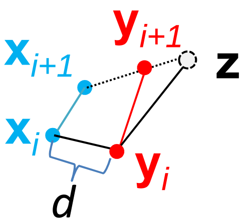
- End streamribbon integration if necessary

Streamribbon generation:



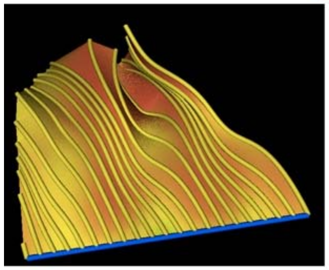
- Start with a 3D point $\mathbf{x}_{i=0}$ and a 2nd one $\mathbf{y}_{i=0}$ in a particular dist. d, i.e. $|\mathbf{x}_i-\mathbf{y}_i|^2 = d^2$
- Loop:
  - Integrate from $\mathbf{x}_i$ to yield $\mathbf{x}_{i+1}$
  - Do an integration step from $\mathbf{y}_i$ to yield $\mathbf{z}$

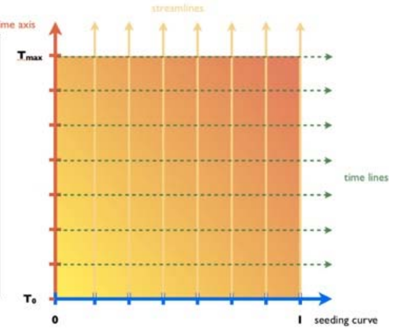
    renormalize the distance between $\mathbf{x}_{i+1}$ & $\mathbf{z}$ to d, i.e. $\mathbf{y}_{i+1} = \mathbf{x}_{i+1} + d\cdot(\mathbf{z}-\mathbf{x}_{i+1})/|\mathbf{z}-\mathbf{x}_{i+1}|$
  - Connect the integration points to form 2D cells (a quad or two triangles)
- End streamribbon integration if necessary



What about Stream Surfaces?

- The computation of stream surfaces is similar to streamribbon.
- However, now the seeding points are typically **more than two**.





What about Stream Surfaces?

- The computation of stream surfaces is similar to streamribbon.
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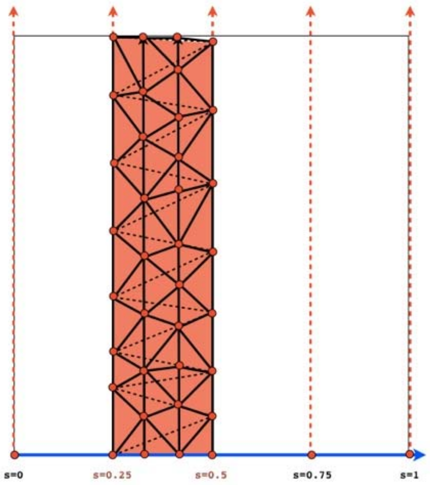

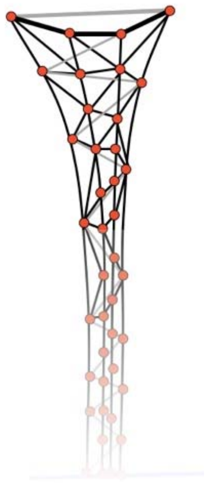

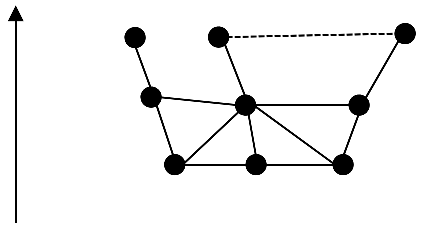

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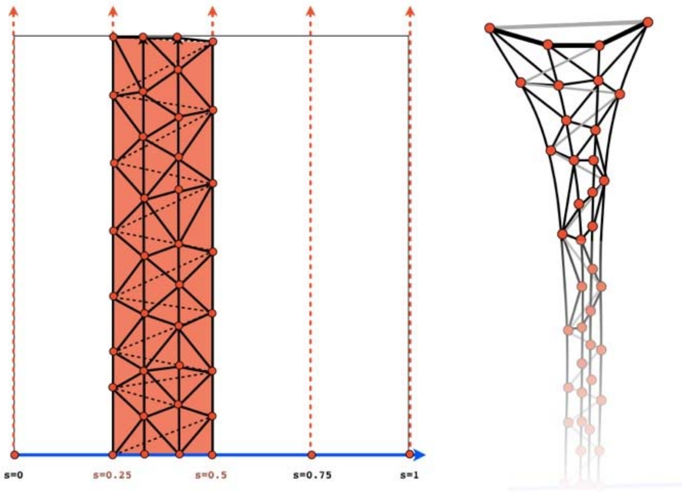

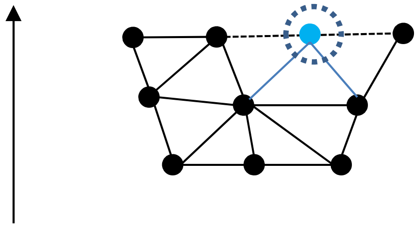

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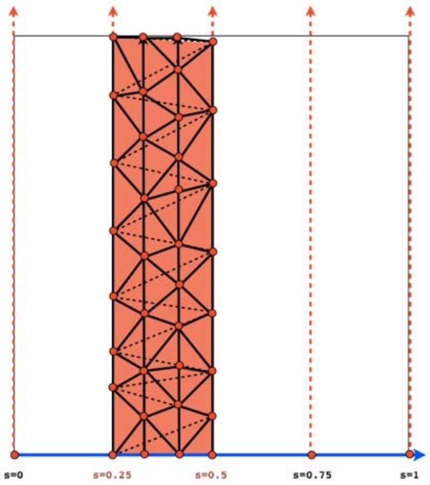

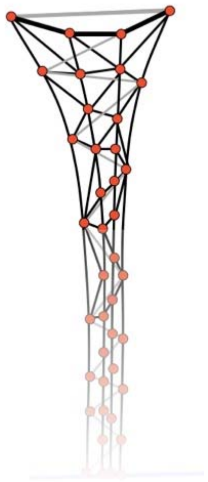

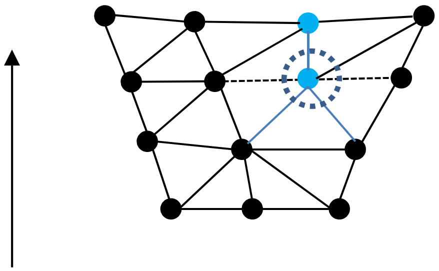

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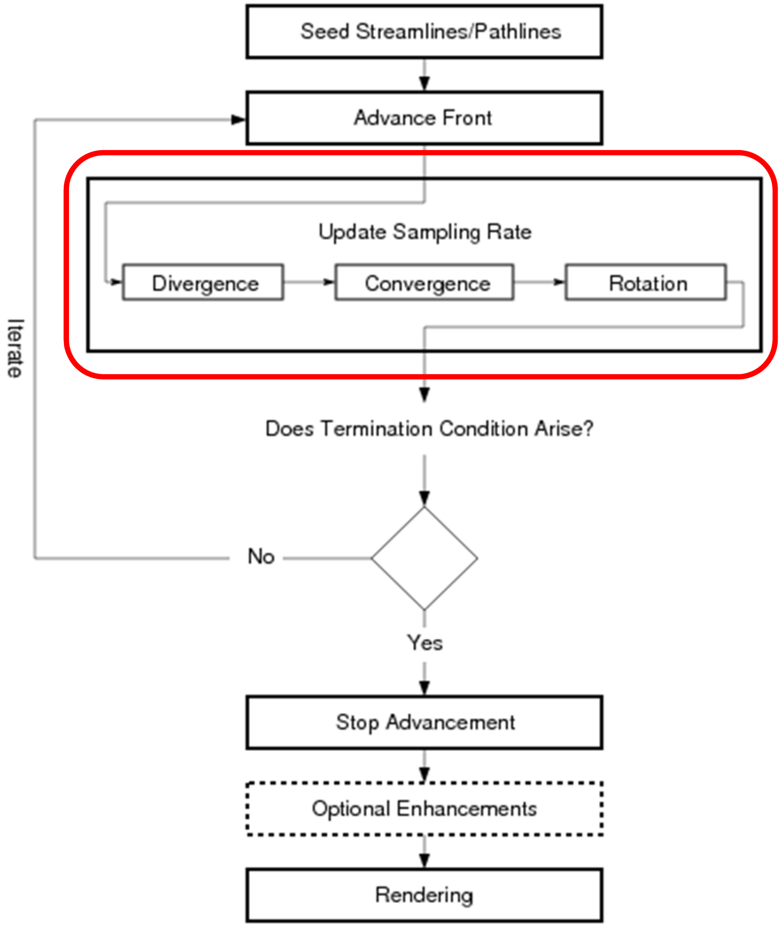
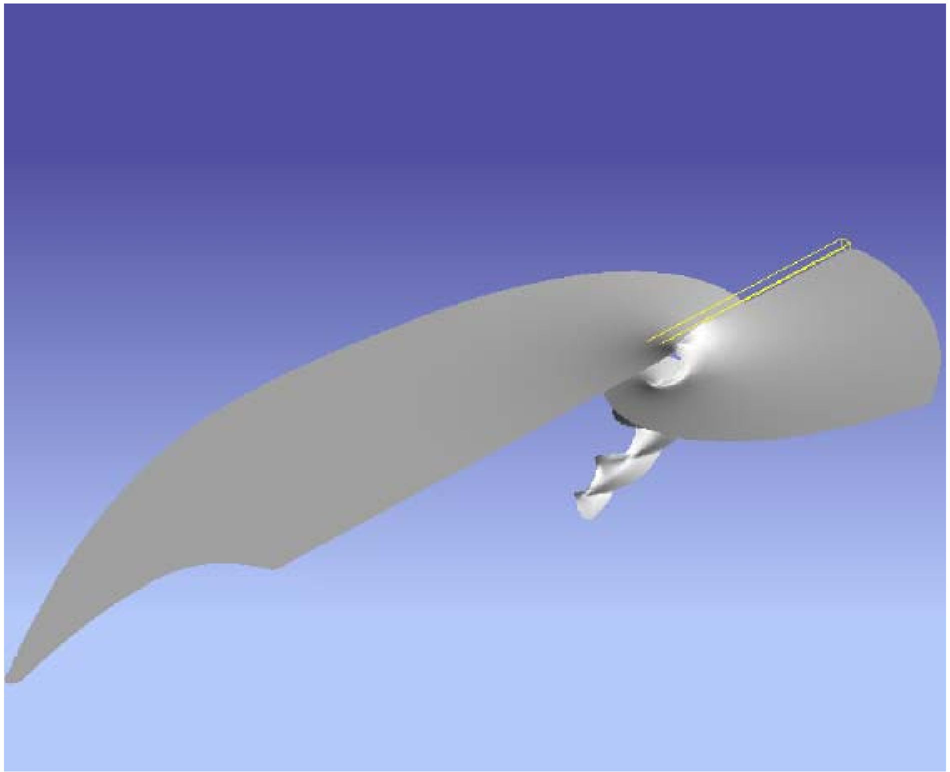
- ***What is the other challenge?***



Where to put seeds to start the integration?

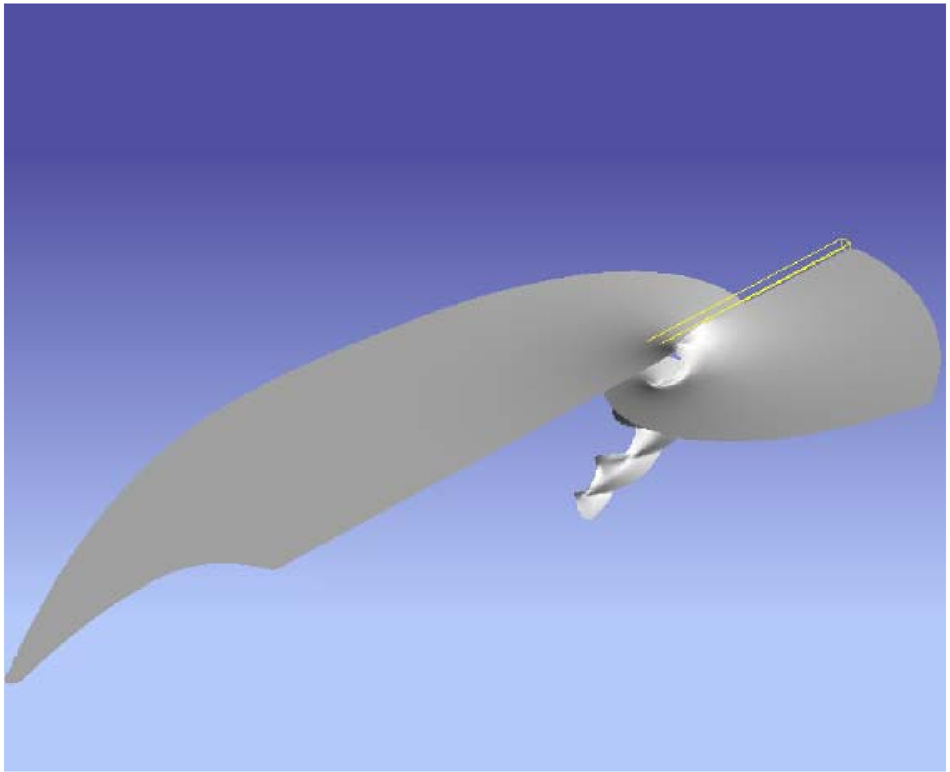


Seeding along a straight-line

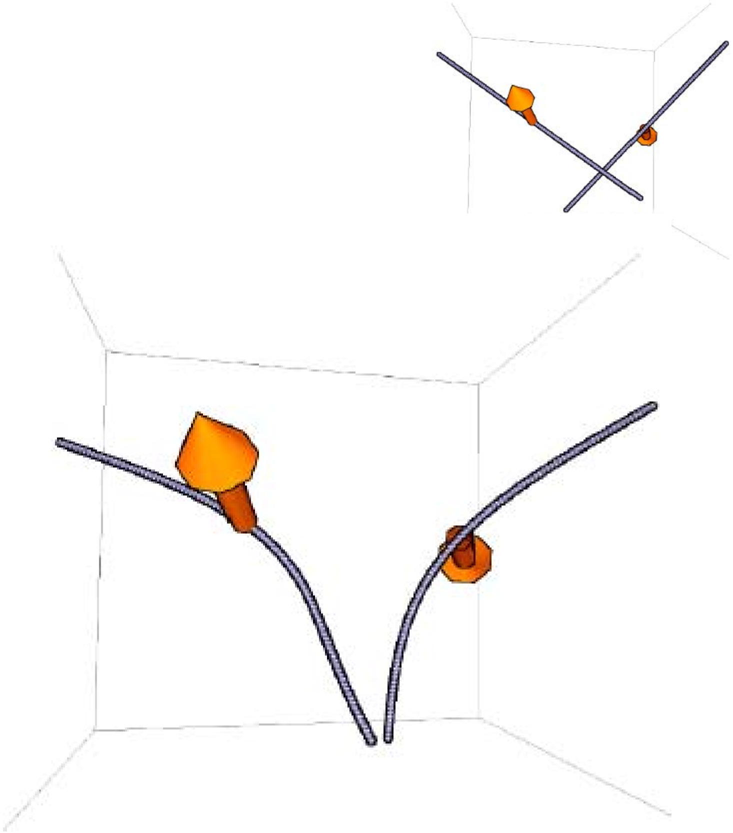
Allow user exploration

[Weiskopf et al. 2007]

Where to put seeds to start the integration?



Seeding along a straight-line
Allow user exploration
[Weiskopf et al. 2007]



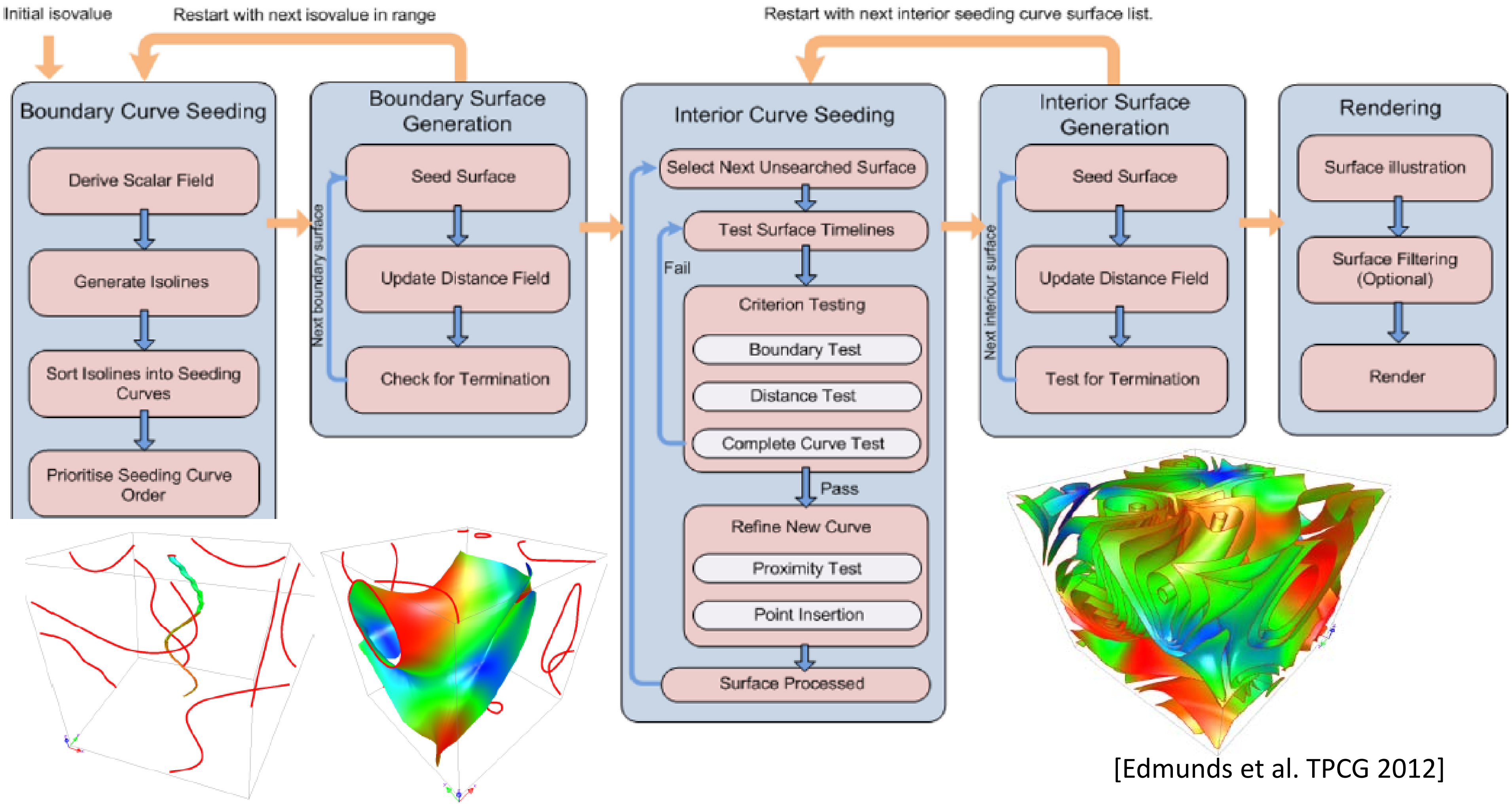
Seeding along the direction that is perpendicular to the flow leads to stream surface with large coverage
[Edmunds et al. EuroVis2012]

How about automatic evenly-spaced stream surface placement (i.e., placing multiple surfaces)?

Where to start?

How to proceed?

Render



Initial isovalue

Restart with next isovalue in range

Restart with next interior seeding curve surface list.

Boundary Curve Seeding
- Derive Scalar Field
- Generate Isolines
- Sort Isolines into Seeding Curves
- Prioritise Seeding Curve Order

Boundary Surface Generation
- Seed Surface
- Update Distance Field
- Check for Termination

Next boundary surface

Interior Curve Seeding
- Select Next Unsearched Surface
- Test Surface Timelines
- Criterion Testing
  - Boundary Test
  - Distance Test
  - Complete Curve Test
- Refine New Curve
  - Proximity Test
  - Point Insertion
- Surface Processed

Fail

Pass

Interior Surface Generation
- Seed Surface
- Update Distance Field
- Test for Termination

Next interior surface

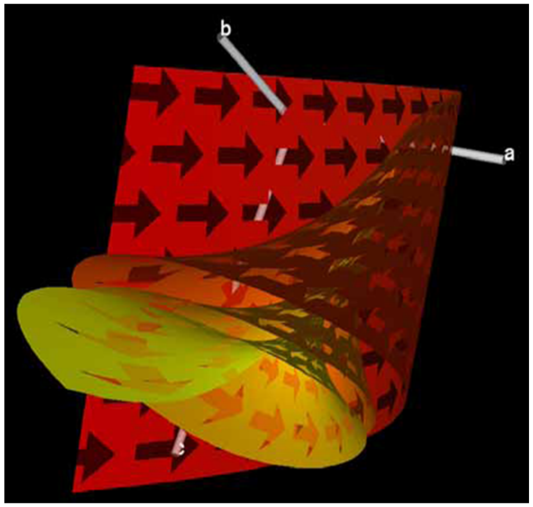
Rendering
- Surface illustration
- Surface Filtering (Optional)
- Render

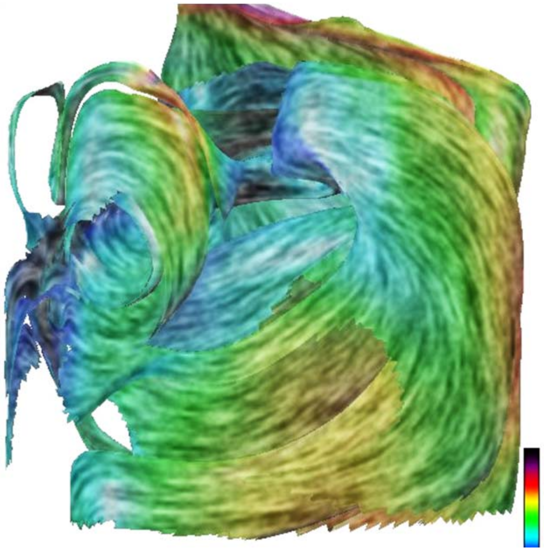
[Edmunds et al. TPCG 2012]

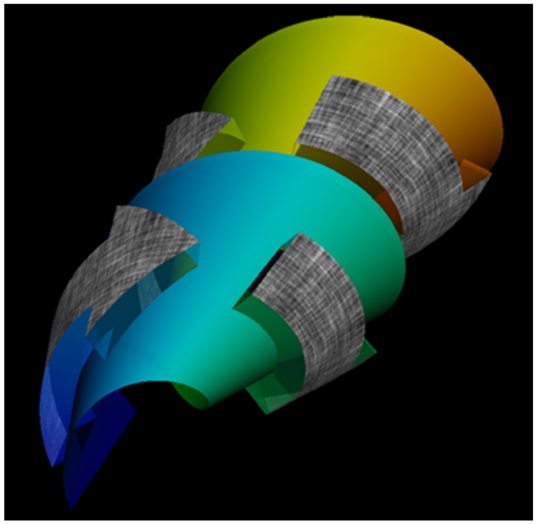
Rendering of stream surfaces

- Stream arrows
  (Löffelmann et al. 1997)

- Texture advection on stream surfaces (Laramee et al. 2006)



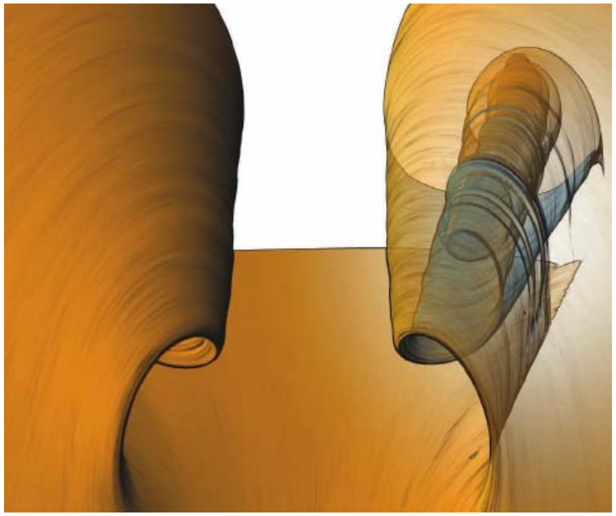




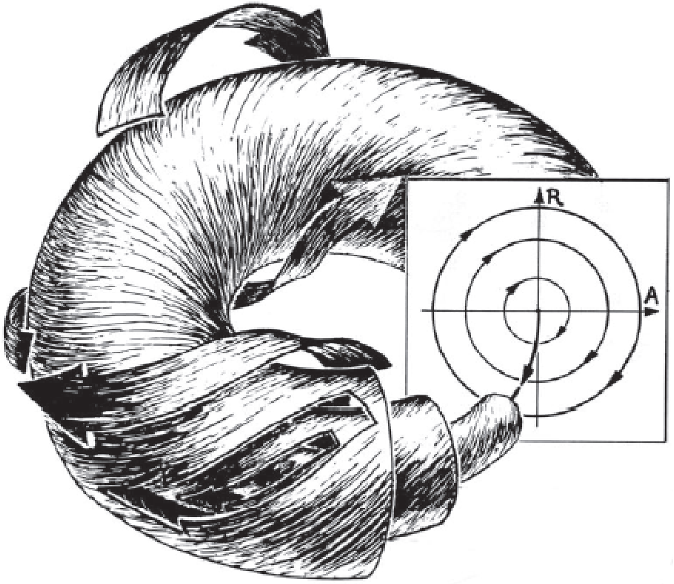
Rendering of stream surfaces

Illustrative visualization

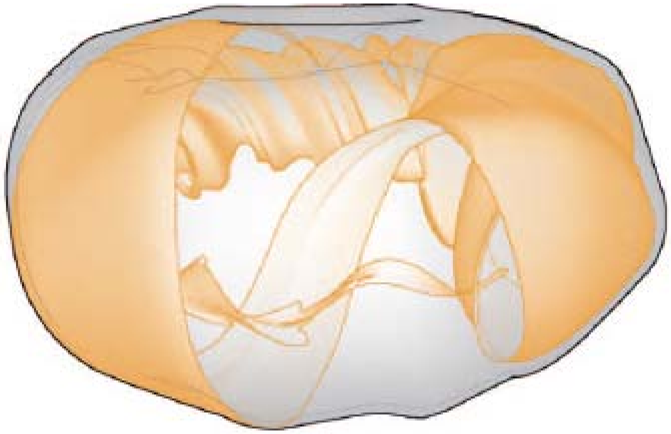
- Using transparency and surface features such as silhouette and feature curves.



[Hummel et al. 2010]



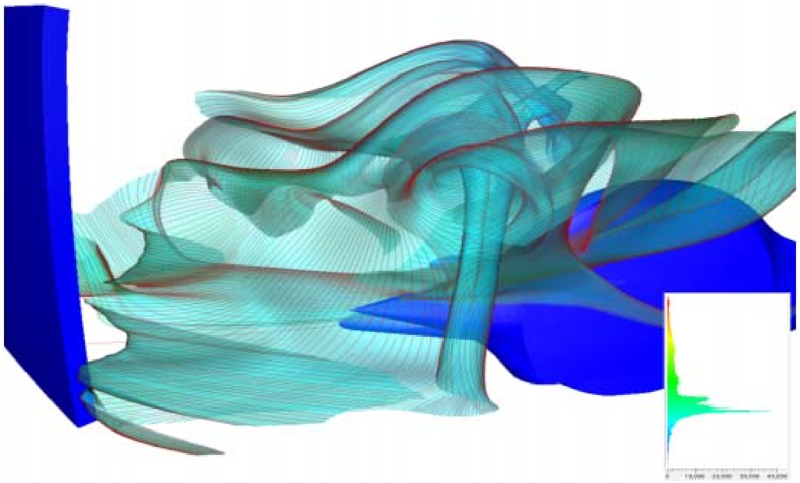
Abraham/Shaw’s illustration, 1984



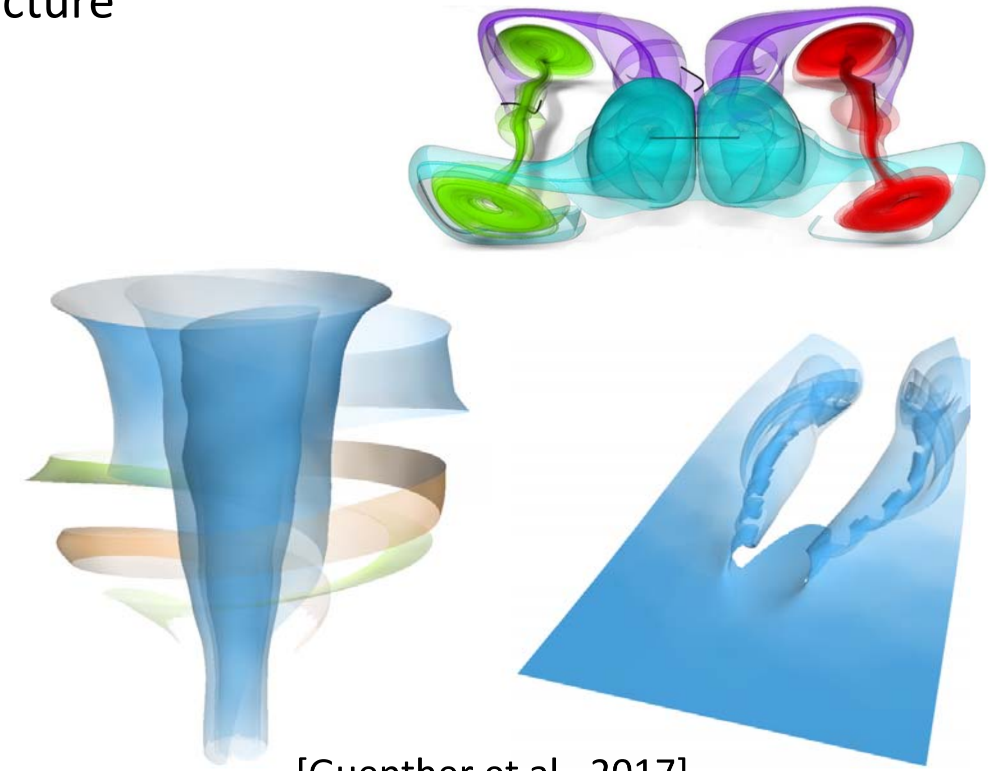
[Born et al. Vis2010]

Rendering of stream surfaces

Set the proper opacity values for surfaces to reduce occlusion and reveal important interior flow structure



[Edmunds et al., 2015]

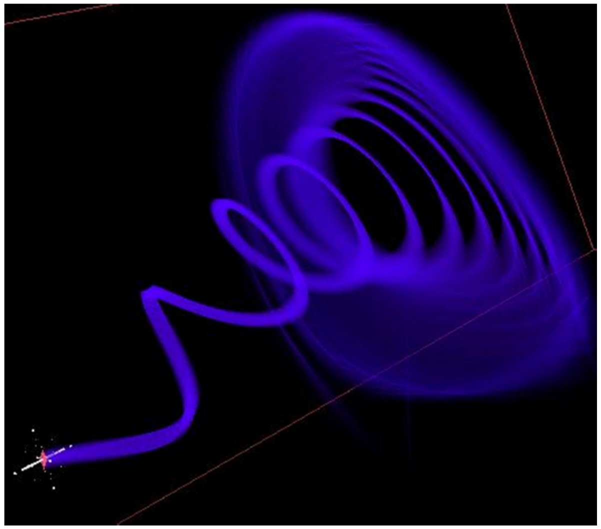


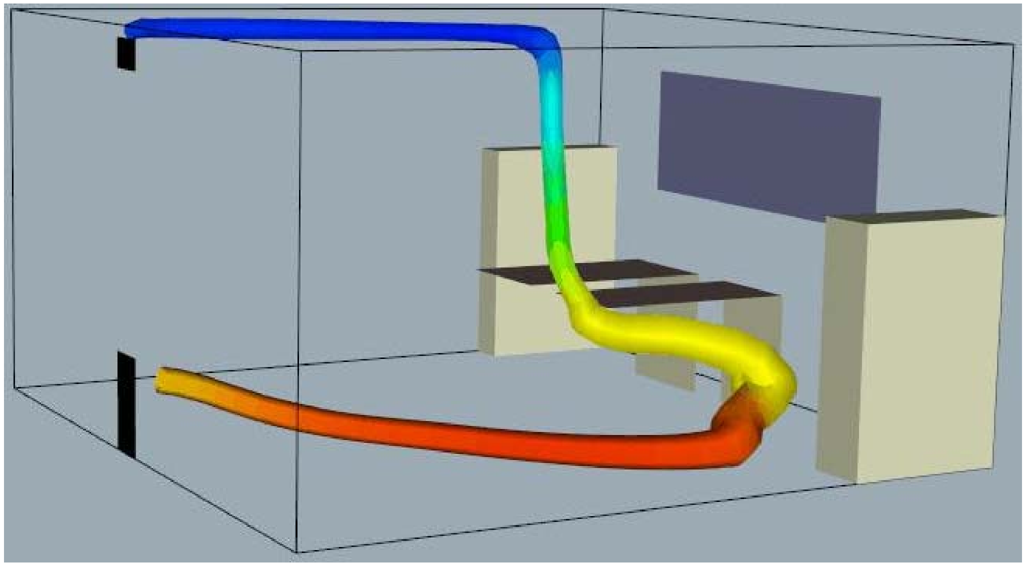
[Guenther et al., 2017]

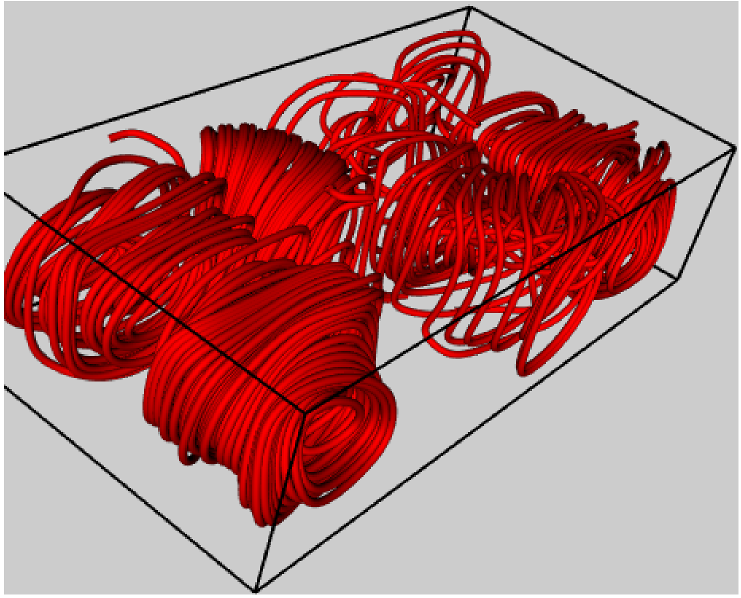
Geometric FlowVis in 3D

flow volume: a volume whose surface is everywhere tangent to the flow

streamtube: shows convergence and divergence of flow (similar to streamribbon)





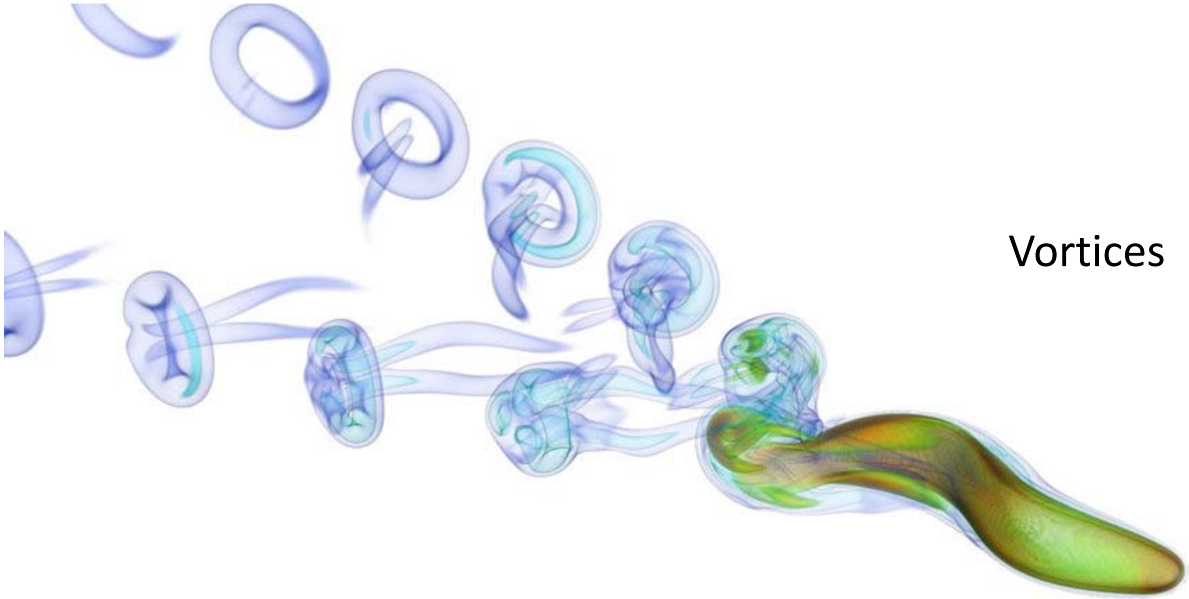


Relation to Seed Objects

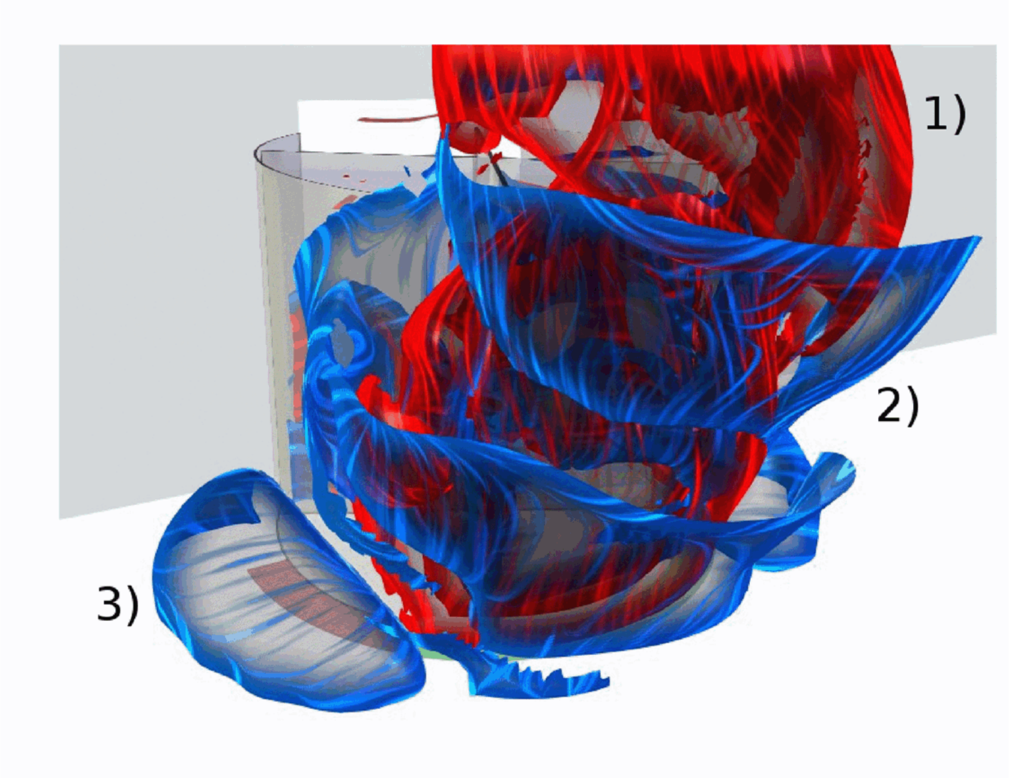
	Object Dimensionality	Seed Object Dimensionality
Streamline,…	1D	0D (point)
Streamribbon	2.5D	1D (line segment)
Streamtube	2.5D	1D (circle)
Stream surface	2.5D	1D (curve)
Flow volume	3D	2D (patch)

Feature-Based Methods

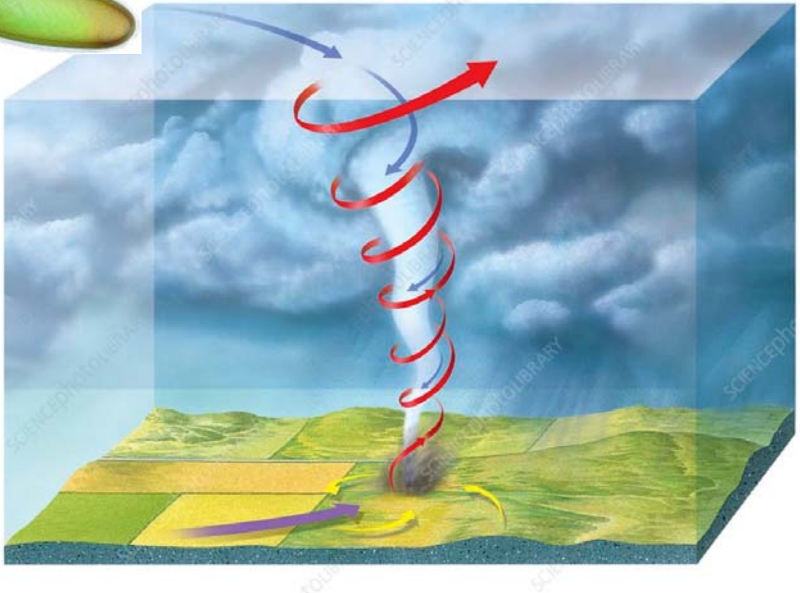
Physics-relevant features



Vortices



Flow separation

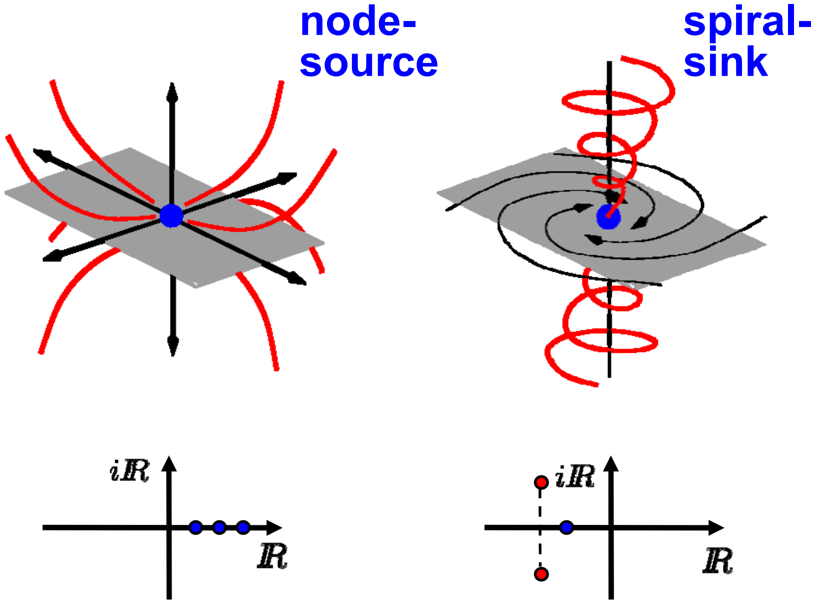


Feature-Based Methods

Topology of 3D **Steady** Flows

3D Flow Topology

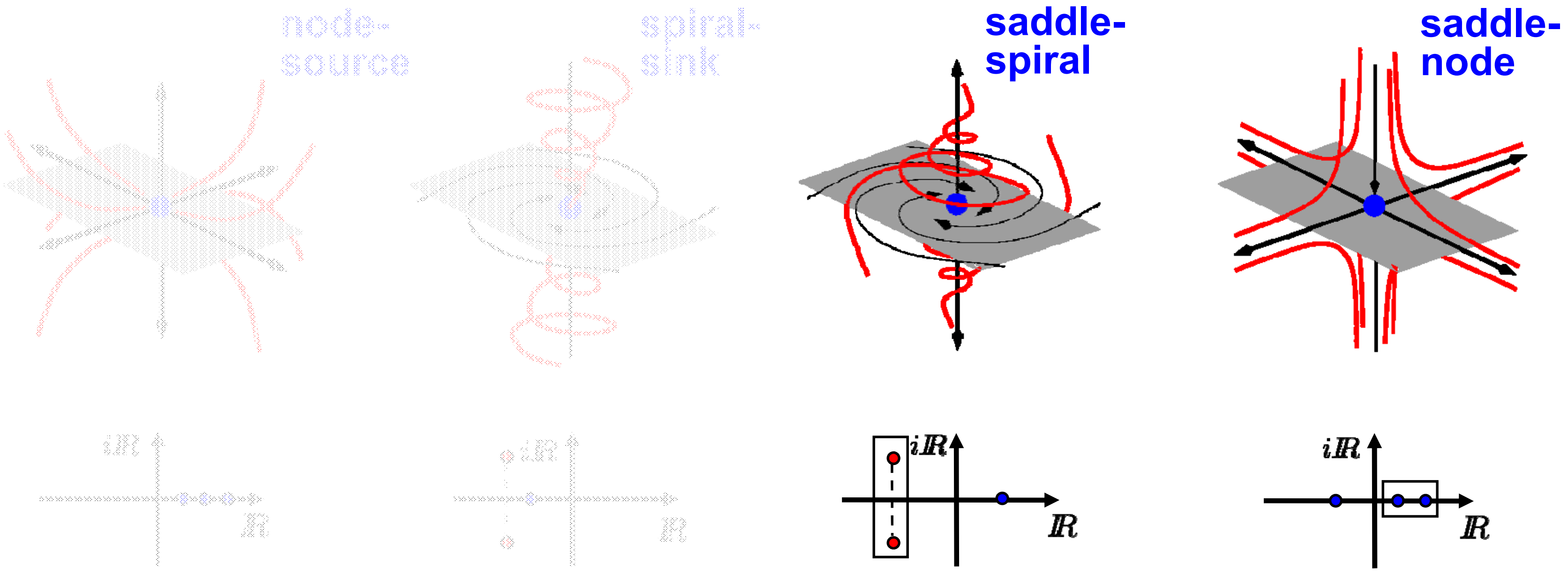
- Fixed points



- Can be characterized using 3D Poincaré index

3D Flow Topology

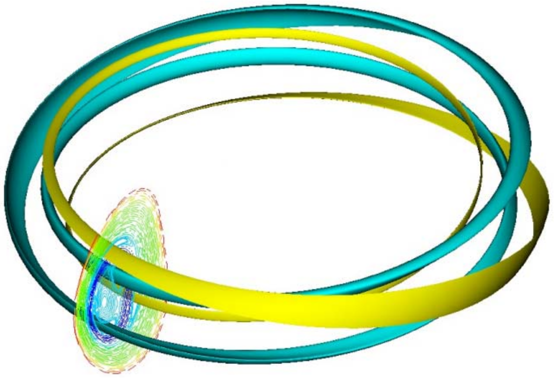
- Fixed points



- Can be characterized using 3D Poincaré index
- Both line and surface separatrices exist

3D Cycles

- Similar principle as in 2D
  - Isolate closed cell chain in which streamline integration appears captured
  - Start stream surface integration along boundary of cell-wise region
  - Use flow continuity to exclude re-entry cases

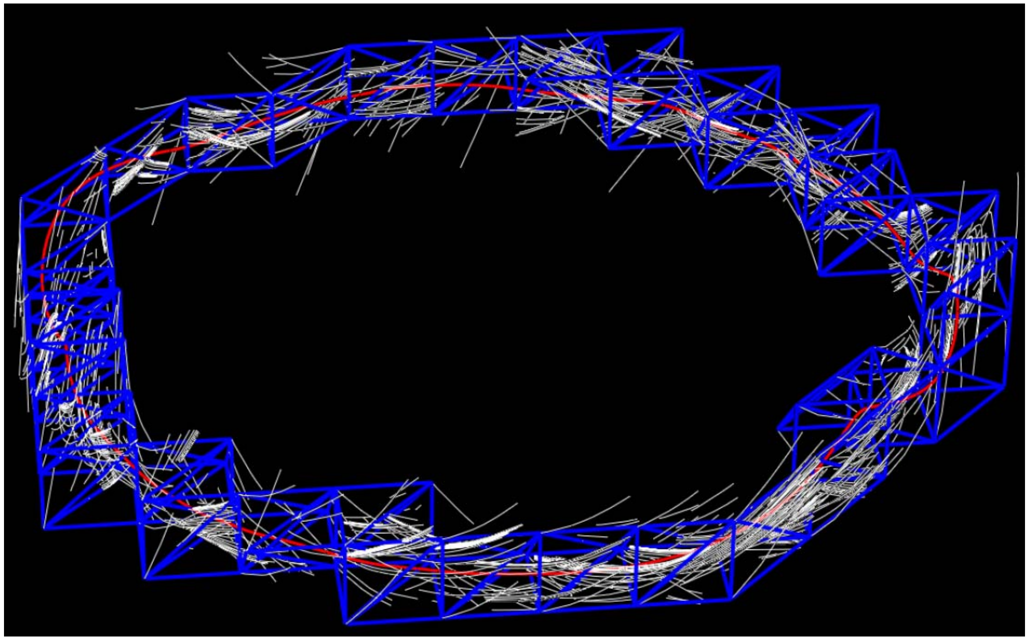


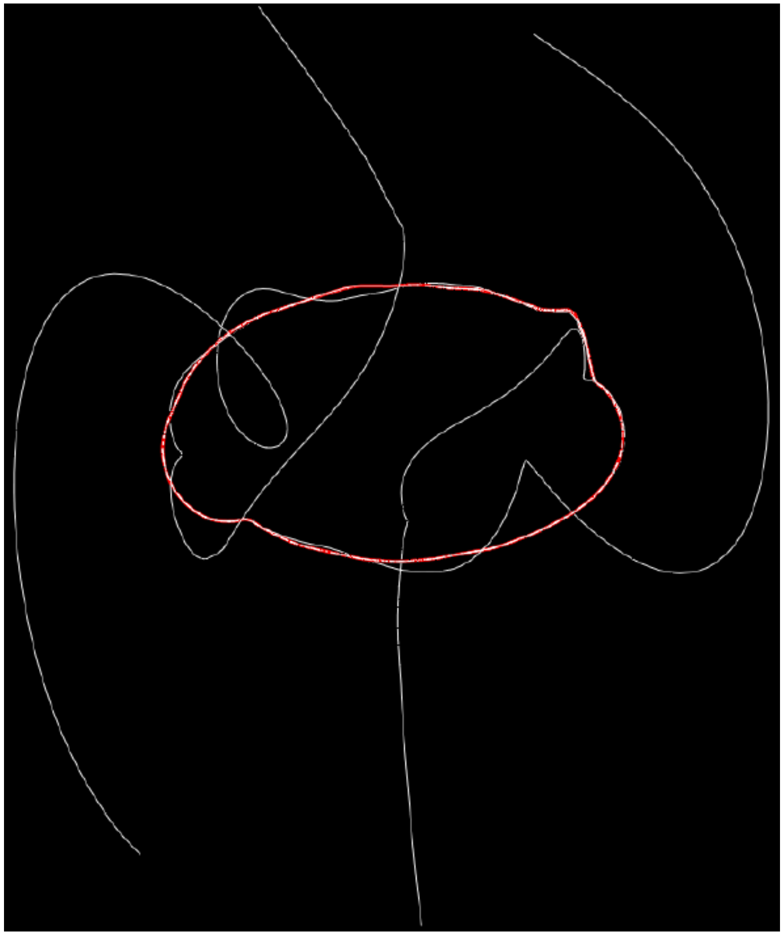
[Sanderson et al., IEEE VIS 2010]

Challenging to **strange attractor**

https://en.wikipedia.org/wiki/Lorenz_system

3D Cycles



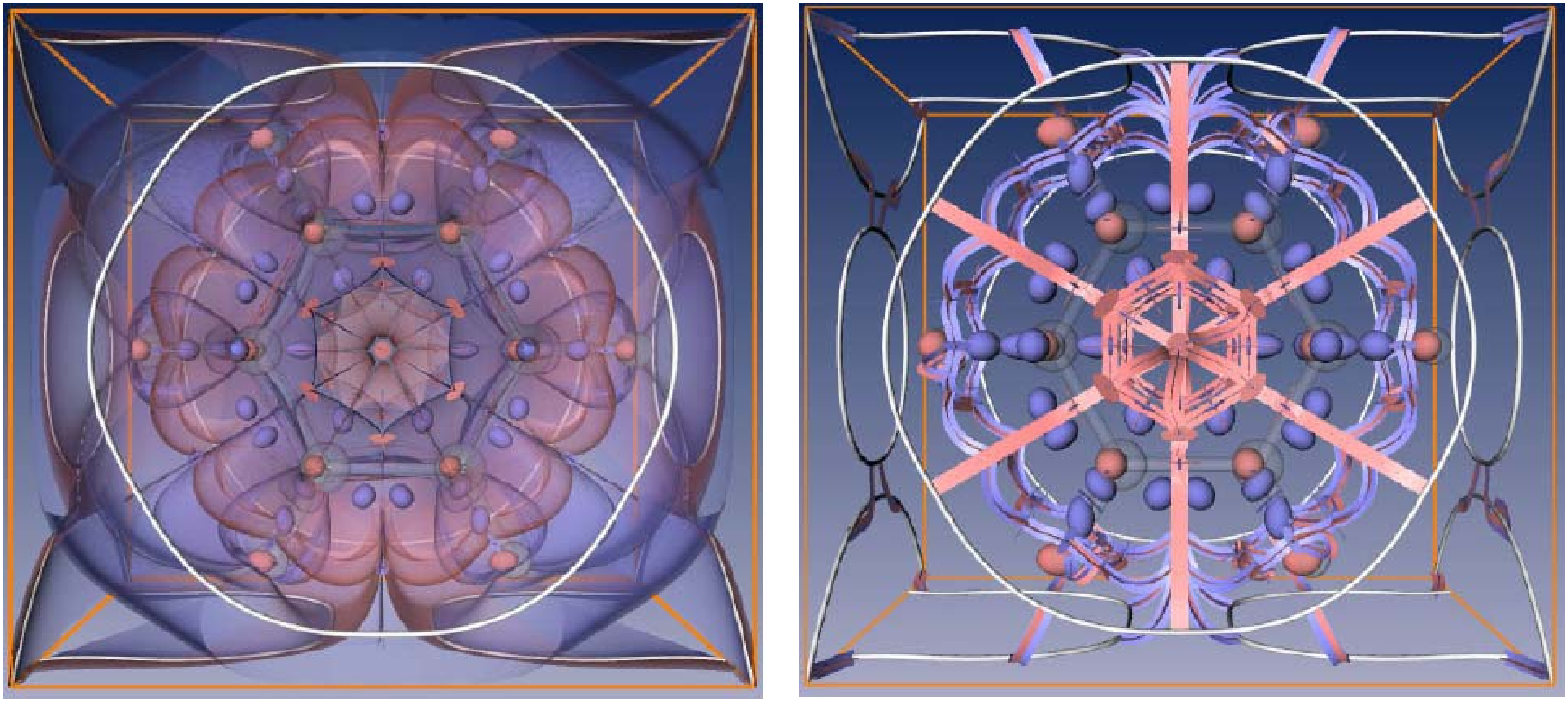


3D Topology Extraction

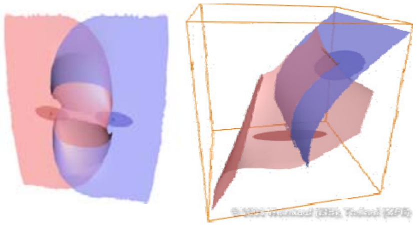
- Cell-wise fixed point extraction:
  - Compute root of linear / trilinear expression
  - Compute Jacobian at found position and compute its eigenvalues for classification
  - If type is saddle compute eigenvectors
- Extract closed streamlines

- Integrate line-type separatrices
- Integrate surface separatrices as stream surfaces

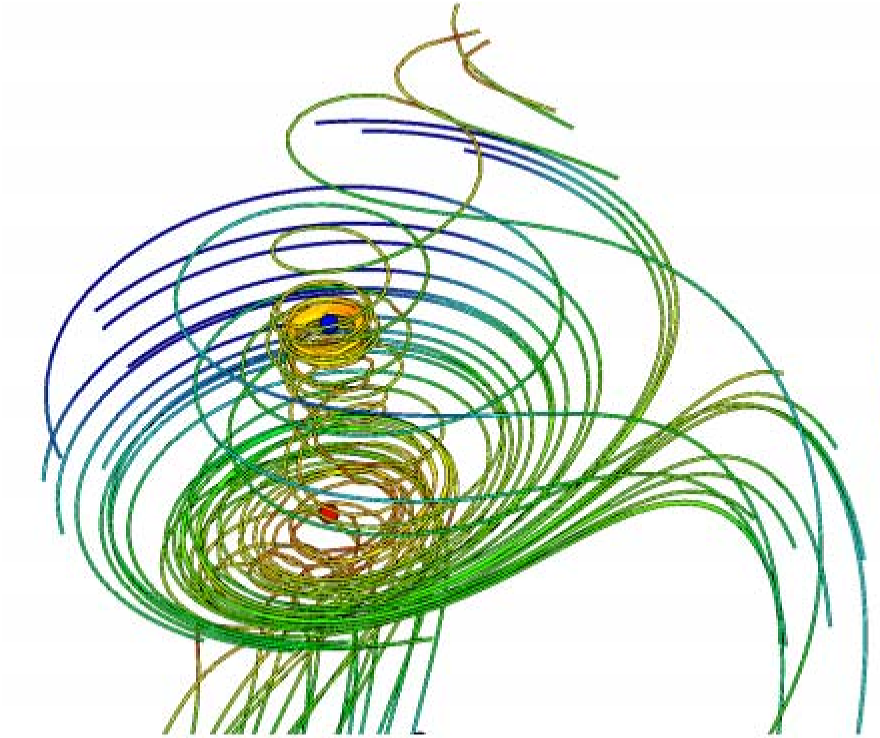
Saddle Connectors



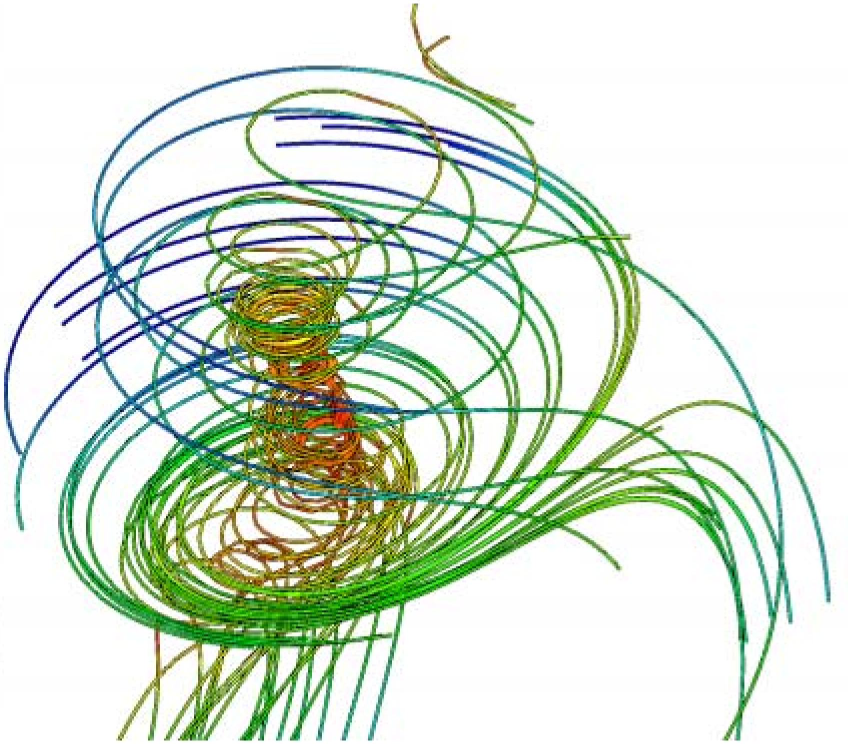
Topological representations of the Benzene data set.
(left) The topological skeleton looks visually cluttered due to the shown separation surfaces.
(right) Visualization of the topological skeleton using connectors.
Source: Weinkauf et al. VisSym 2004



Vector field topology simplification



Before



After

[Skraba et al. 2016 TVCG]

Additional Readings

- Matthew Edumunds, Robert S. Laramee, Guoning Chen, Nelson Max, Eugene Zhang, and Colin Ware, **Surface Based Flow Visualization**, *Computers & Graphics*, *forthcoming.*
- Tony McLoughlin, Robert S. Laramee, Ronald Peikert, Frits H. Post, and Min Chen, **Over Two Decades of Integration-Based, Geometric Flow Visualization** in *Computer Graphics Forum (CGF)* , Vol. 29, No. 6, September 2010, pages 1807-1829.
- Tino Weinkauf and Holger Theisel. **Streak Lines as Tangent Curves of a Derived Vector Field**. IEEE Visualization 2010.

Acknowledgment

Thanks for the materials

- Prof. Robert S. Laramee, Swansea University, UK
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