Flow Visualization: The State-of-the-Art

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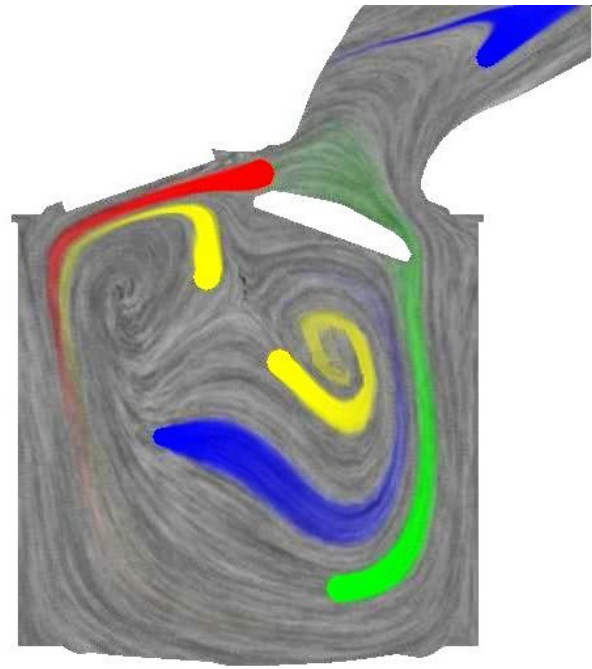
Overview

- Introduction to Flow Visualization (FlowViz)
- What is Flow Visualization? A Brief Introduction
- What approaches have been developed?
  - Classification:
  - Direct
  - Texture-based
  - Geometric
  - Feature-based flow visualization
- Applications
- Conclusions and Future Work



A note on scope: An overview is provided with references to more depth.

What is Flow Visualization?

- a classic topic within scientific visualization
- depiction of vector quantities (as opposed to scalar quantities)
- applications include automotive simulation, aerodynamics, turbomachinery, meteorology, oceanography, medical visualization

Challenges:

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

Computational vs. Experimental FlowVis

Computational FlowVis -using computers for FlowVis

- data resulting from flow *simulation*, *measurements*, or flow *modelling,* e.g., computational fluid dynamics (CFD)
- computer-generated images and animations, often mimicking experimental FlowVis

Visualization of actual fluids, e.g. water and air

- dye injection
- interferometry
- Schlieren/shadows
- flow topology graphs
- etc.

Data Characterized by Many Dimensions

Spatial dimensions:

- 2D (planar flow, simplified or synthetic)
- 2.5D (boundary flow, flow on surface)
- 3D (real-world flow)

Temporal dimension:

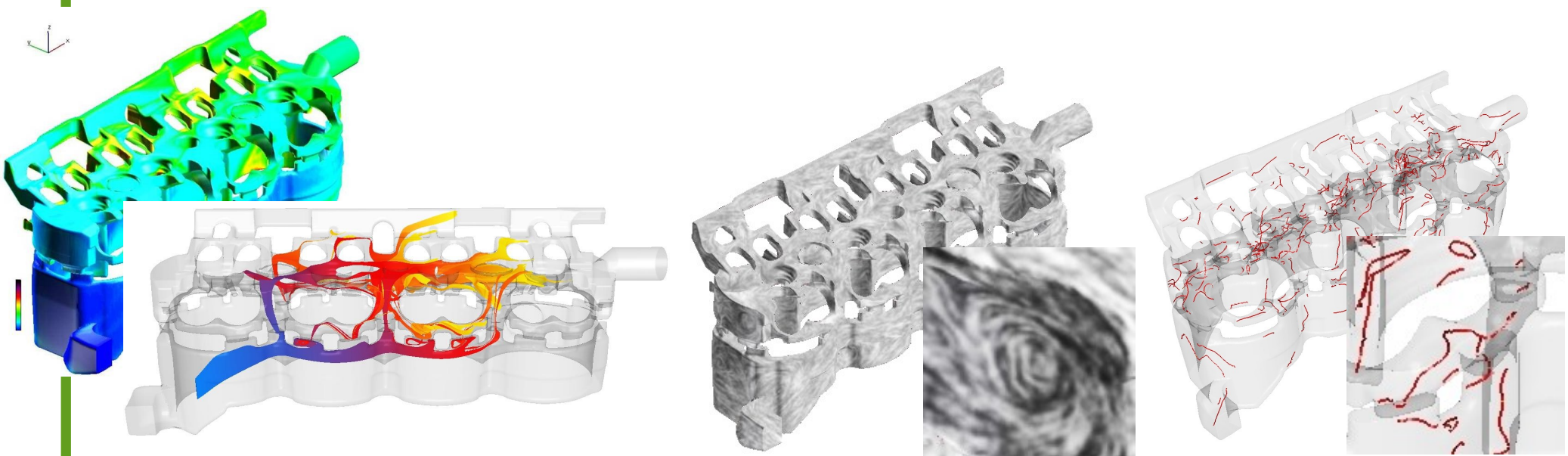
- steady flow -1 time step (or instantaneous or static flow)
- time-dependent flow -multiple time steps (or unsteady or transient, real-world)
- ***caution*** is advised in the context of animation

Simulation Data Attributes a.k.a. Data Dimensions:

- velocity
- temperature
- pressure
- and many more...

Flow Visualization Classification

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

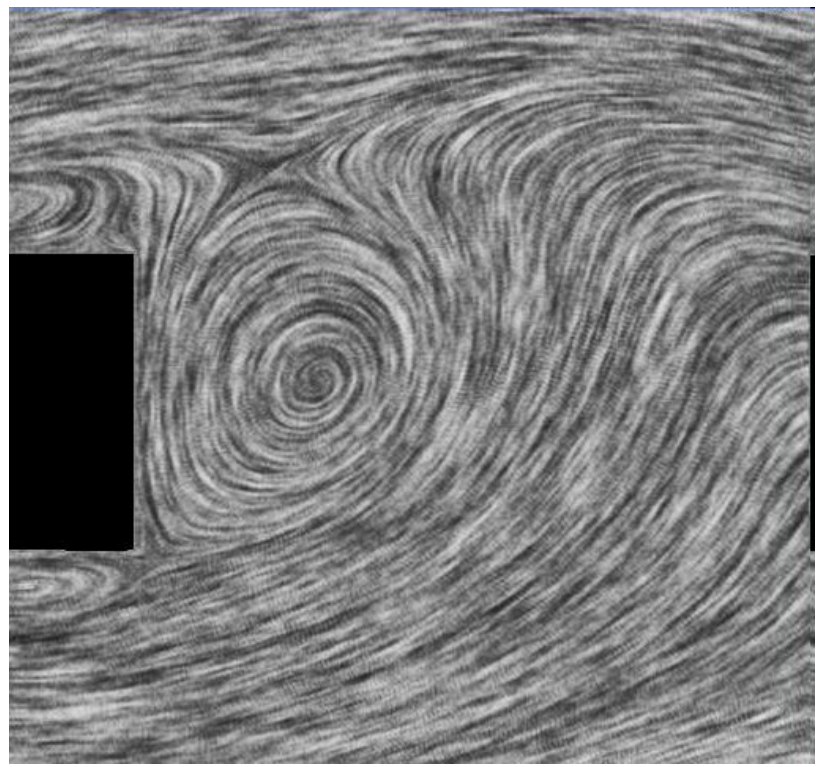


Texture-Based Flow Visualization

Computing textures that provide a dense coverage/visualization of a vector field.

Advantages:

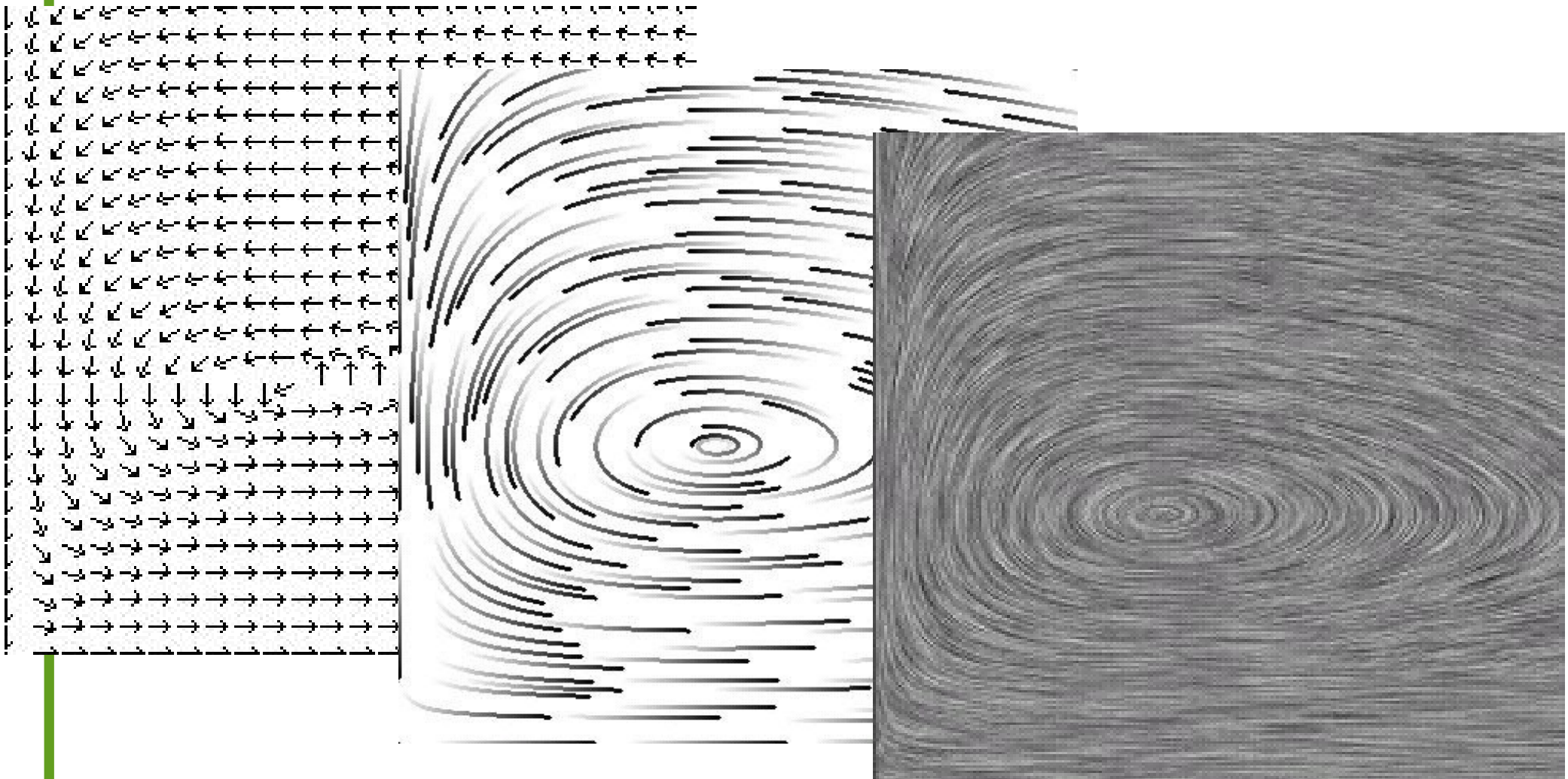
- detailed view of vector field
- clearer perception of characteristics
- contains elements of direct + geometric FlowViz



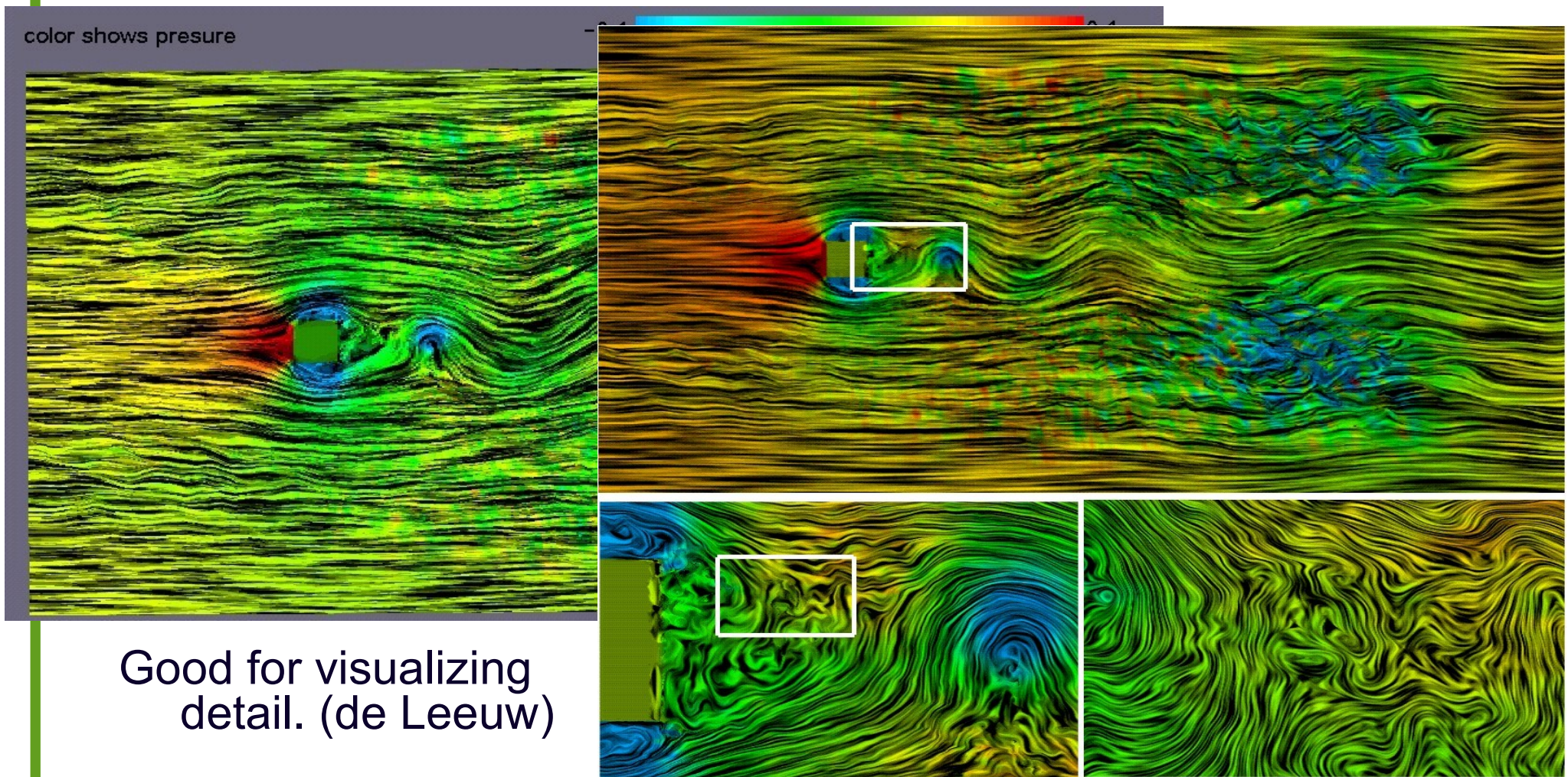
Disadvantages:

- computation time
- perception in 3D
- aliasing

Texture-Based FlowViz: LIC (Cabral and Leedom) in 2D, Instantaneous

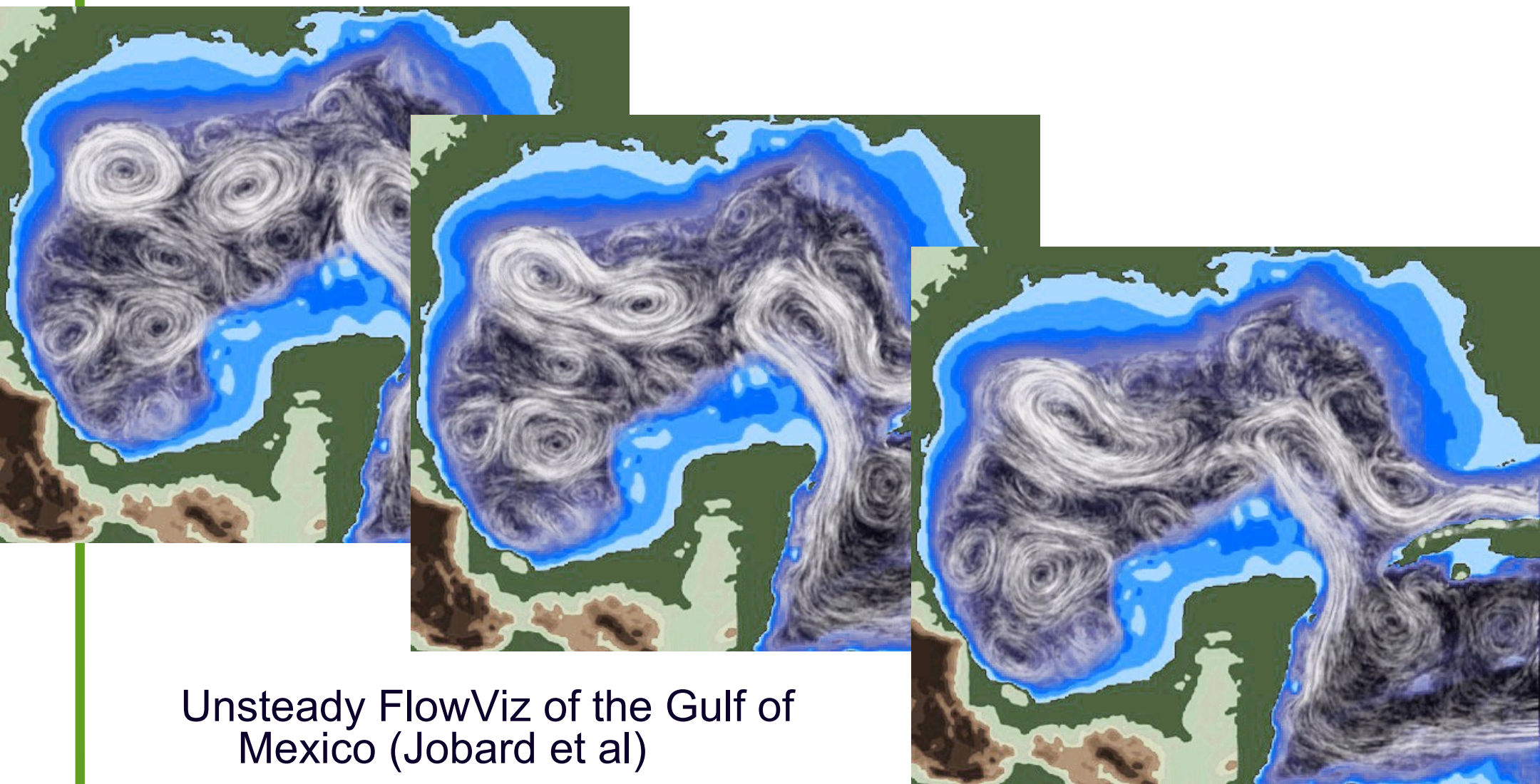


Texture-Based FlowViz: Spot Noise in 2D, Instantaneous with Color Coding



Good for visualizing detail. (de Leeuw)

Texture-Based FlowViz: Time-Dependent Texture Advection in 2D



Unsteady FlowViz of the Gulf of Mexico (Jobard et al)

Texture-Based FlowViz: 2D Unsteady Flow

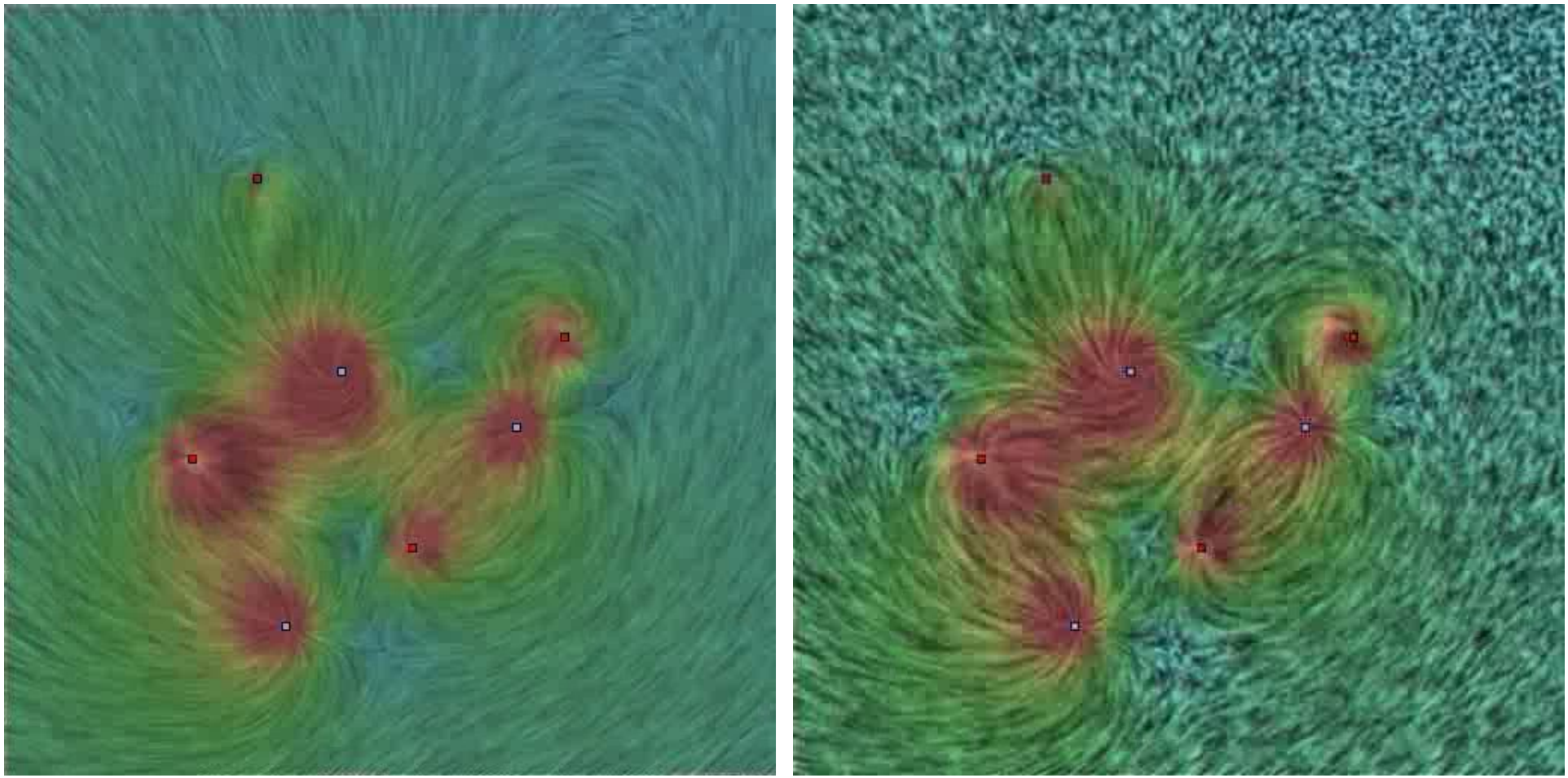
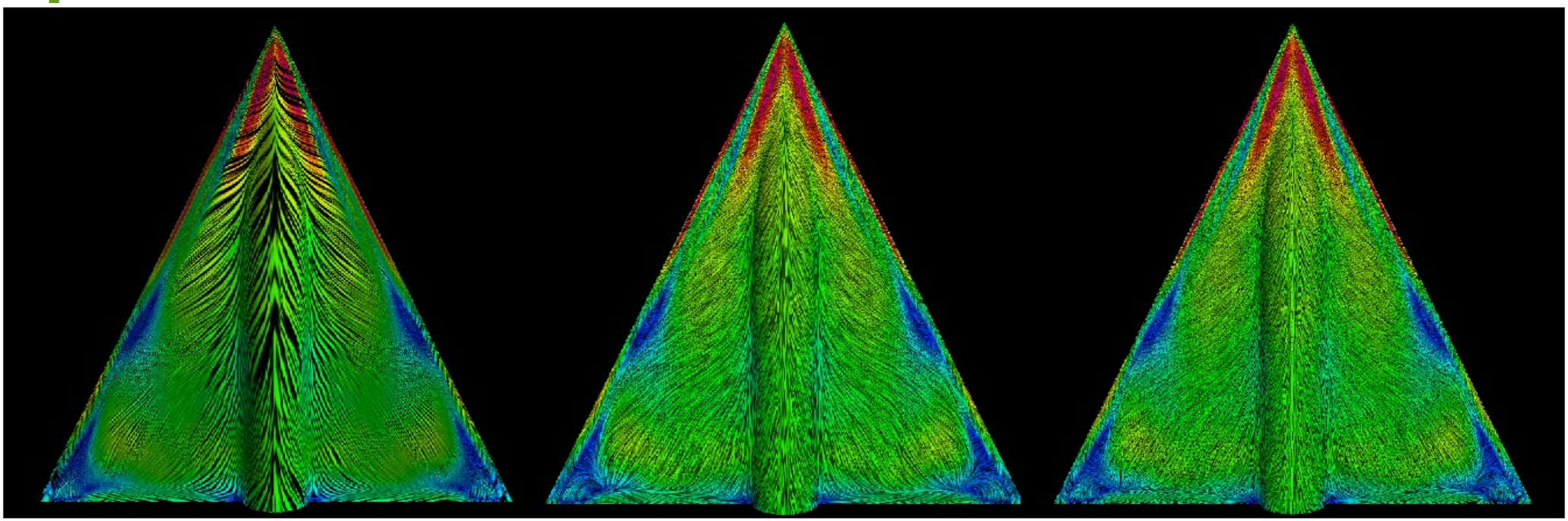


Image Based Flow Visualization (IBFV, Van Wijk)

Texture-Based FlowViz: LIC on Surfaces, Unsteady



A comparison of 3 LIC techniques (left) UFLIC, (middle) ELIC, and (right) PLIC (Verma et. al.)

Texture-Based FlowViz: Texture-Advection on Surfaces, Unsteady

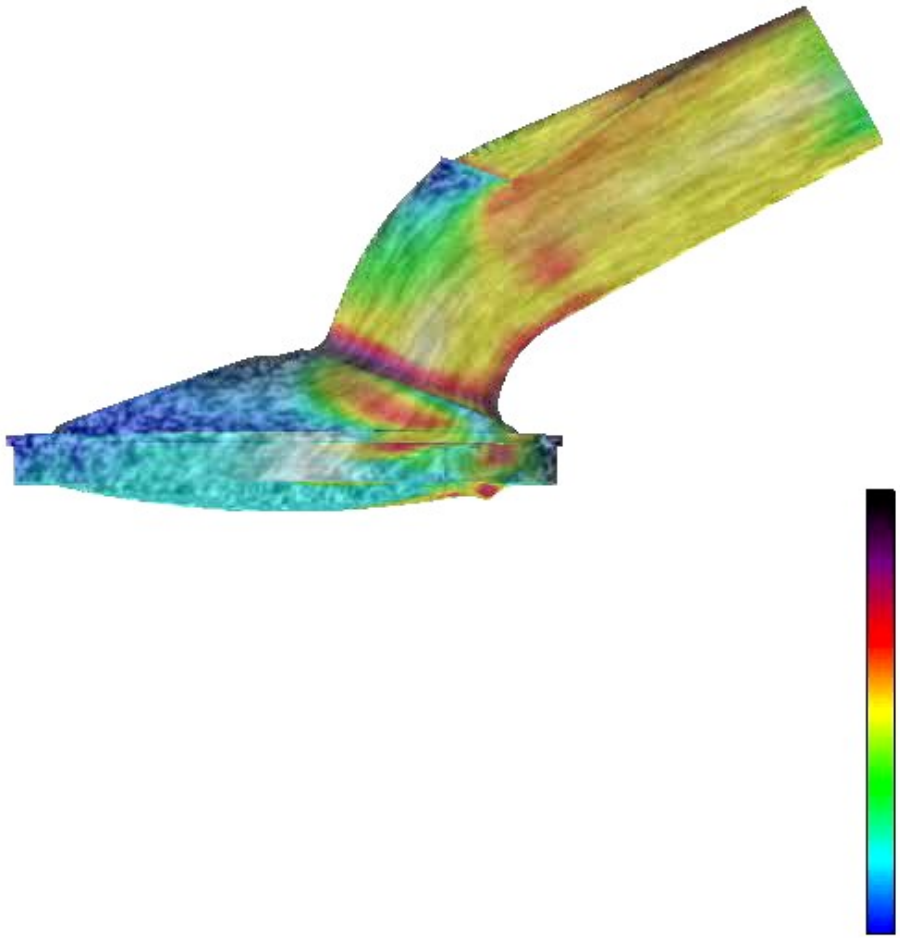
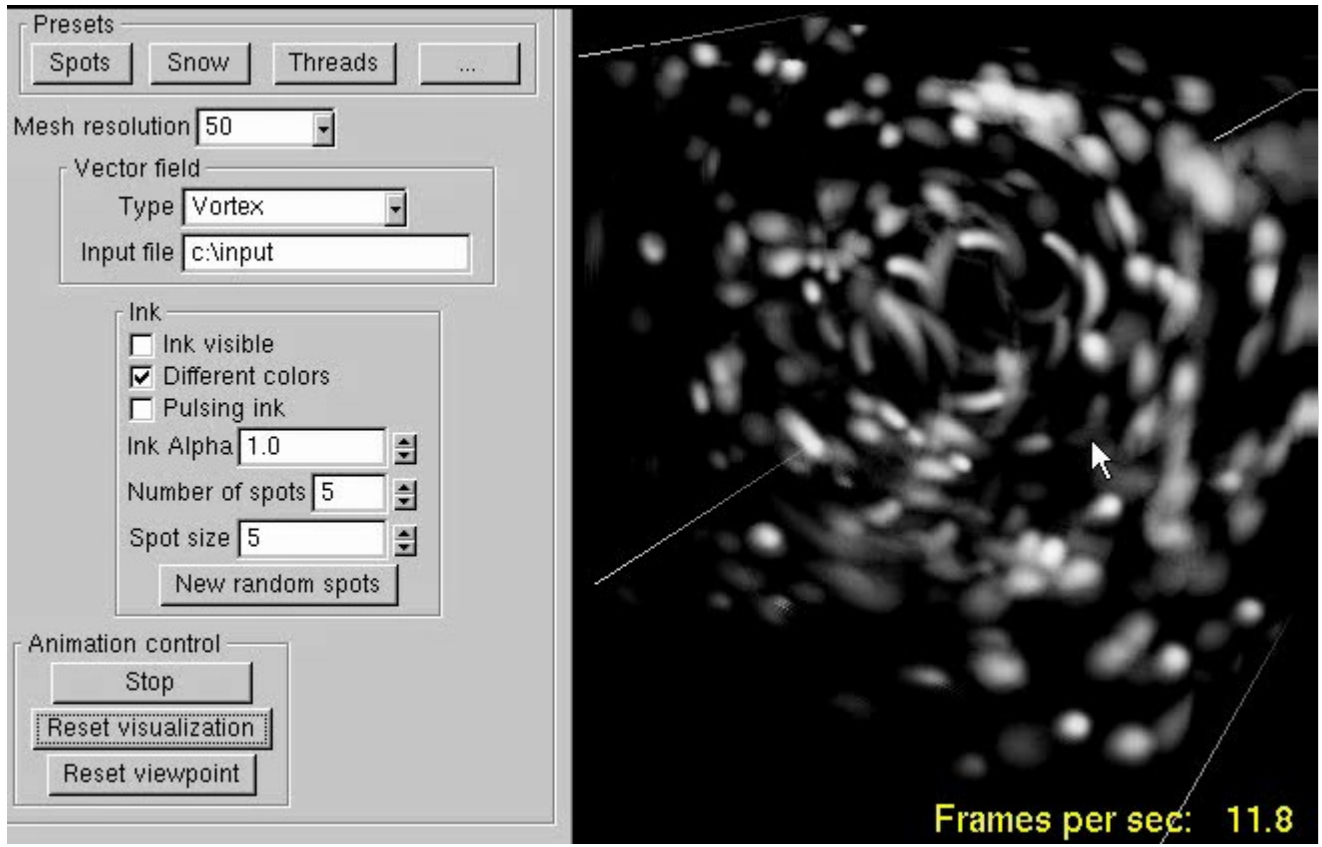


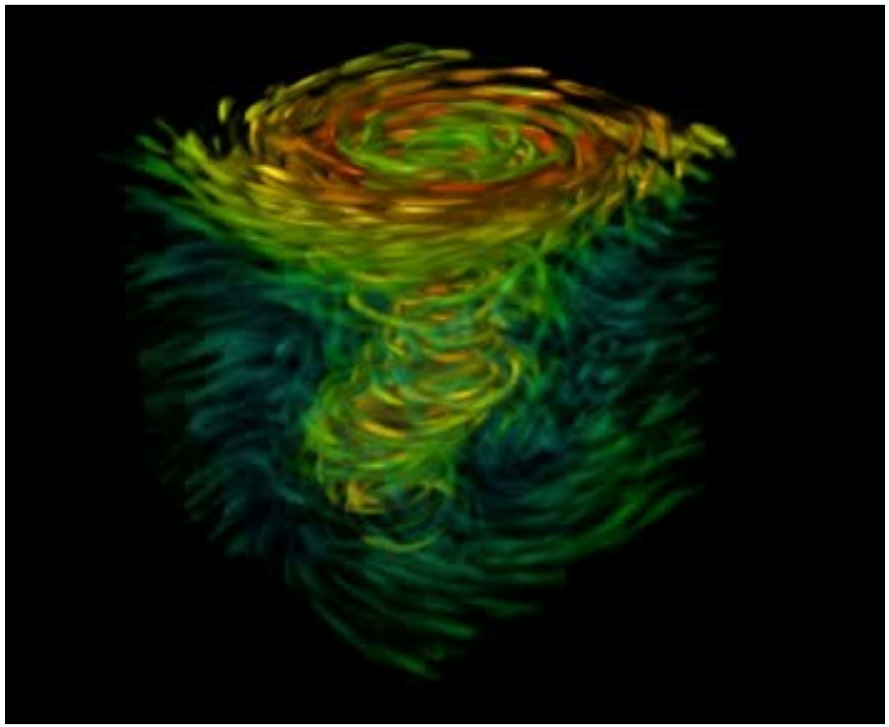
Image Space Advection (ISA, Laramee et al.) and Image Based Flow Visualization for Curved Surfaces (IBFVS, van Wijk)

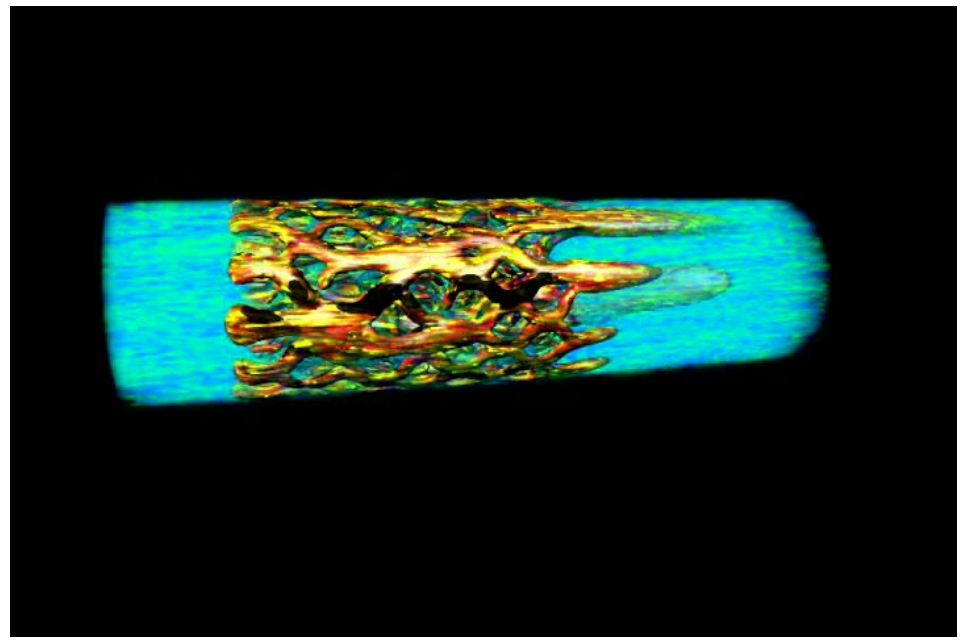
Texture-Based FlowViz: Texture Advection in 3D, Unsteady



3D IBFV (Telea and Van Wijk)

Texture-Based FlowViz: Texture Advection in 3D, Unsteady





3D texture-based flow vis with illumination, velocity masking, and focus+context (Weiskopf et al.)

Texture-Based Flow Visualization

For more information on texture-based flow visualization techniques, please see:

Robert S. Laramee, Helwig Hauser, Helmut Doleisch, Benjamin Vrolijk, Frits H. Post, and Daniel Weiskopf, **The State of the Art in Flow Visualization: Dense and Texture-Based Techniques** in *Computer Graphics Forum*, Vol. 23, No. 2, 2004, pages 203-221

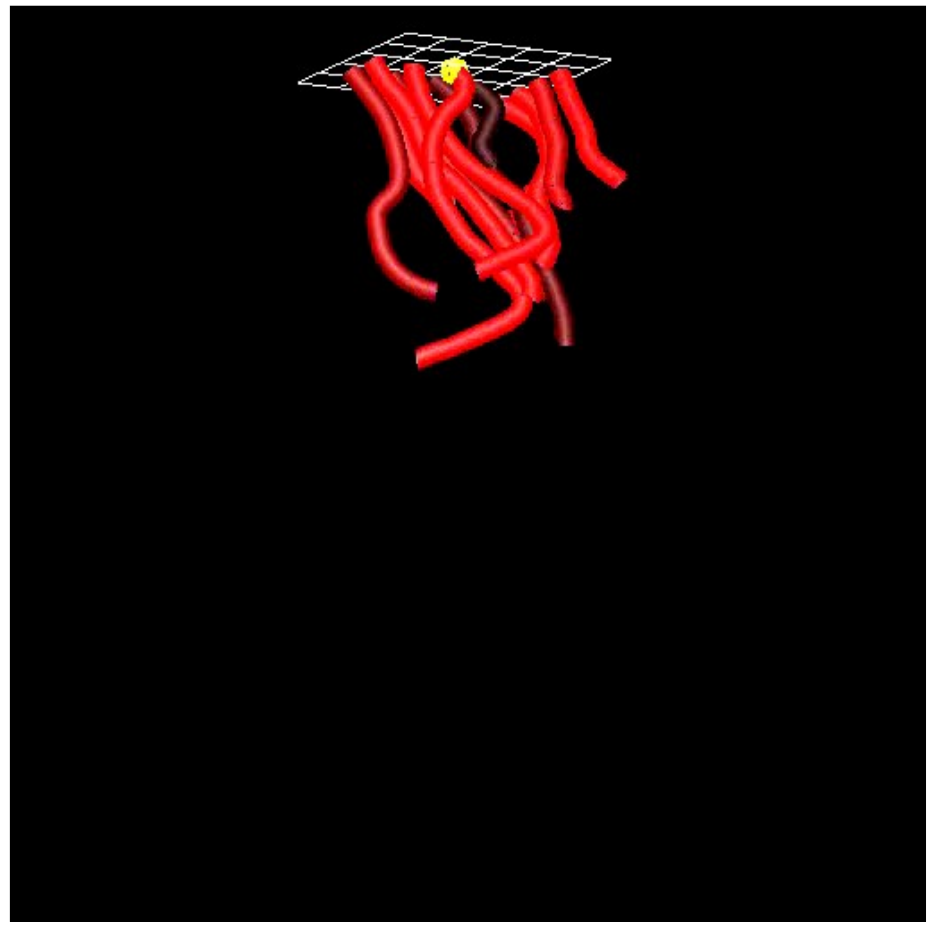
(1st STAR)

Geometric Flow Visualization

The computation of discrete objects whose shape is directly related to underlying geometry

Advantages:

- intuitive
- clearer perception of characteristics



Disadvantages:

- placement
- visual complexity in 3D

Geometric FlowViz: Some Terminology

Stream vs. Path vs Streak vs Time lines

Streamline

- everywhere tangent to flow at instantaneous time, t_0 (blue/aqua)

Pathline

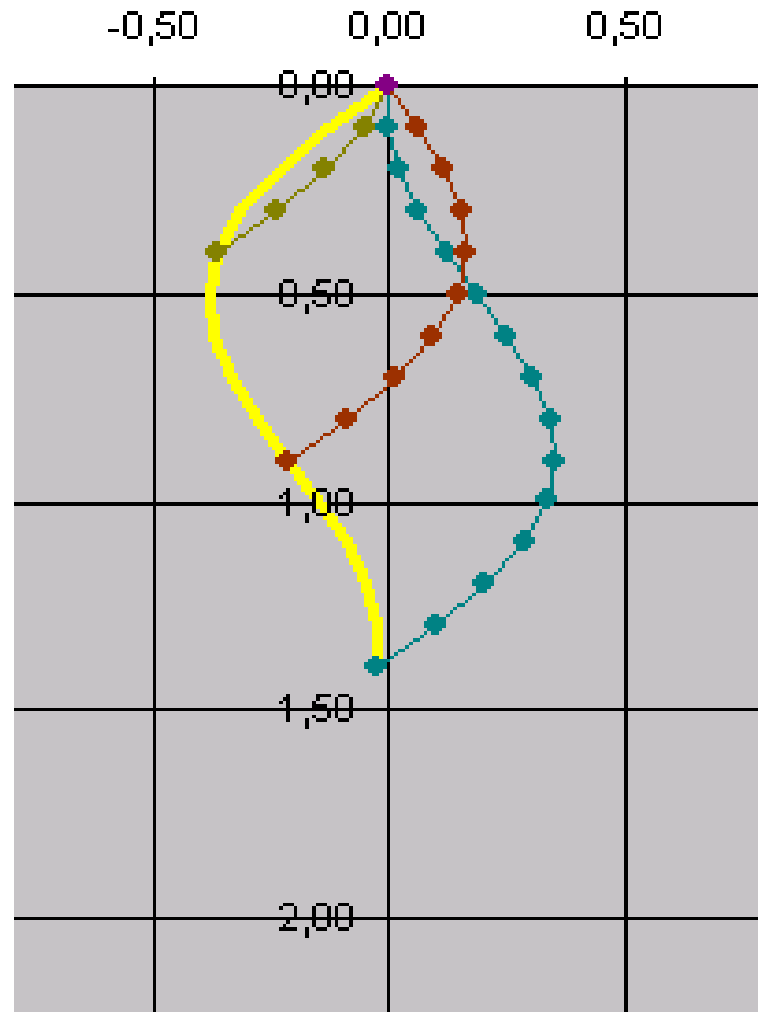
- path traced by a particle over time, t (red/maroon)

Streakline

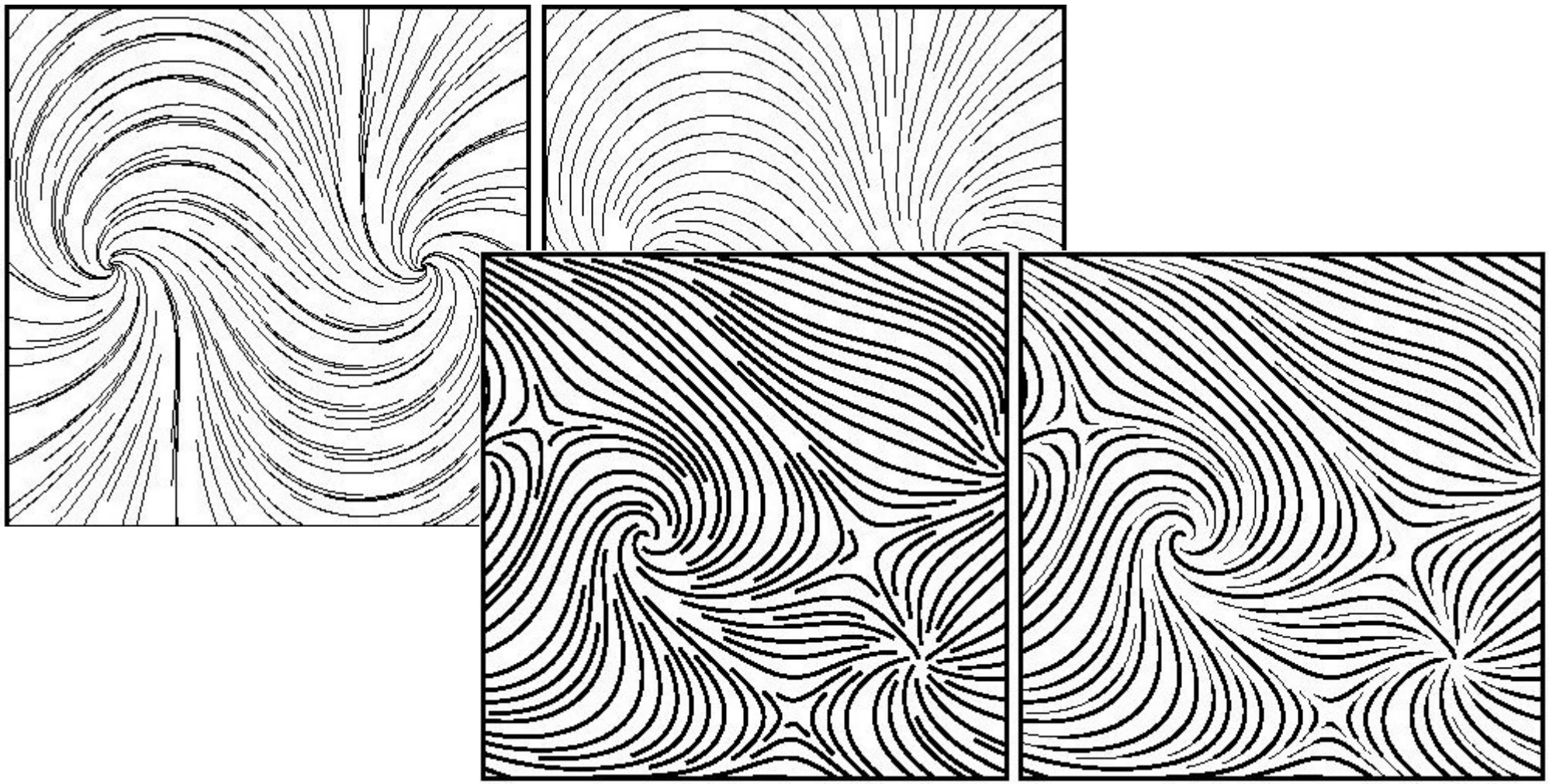
- line traced by continuous injection at location, x_0 (light green)

Timeline

- temporal evolution of initial line, l_0 (yellow)

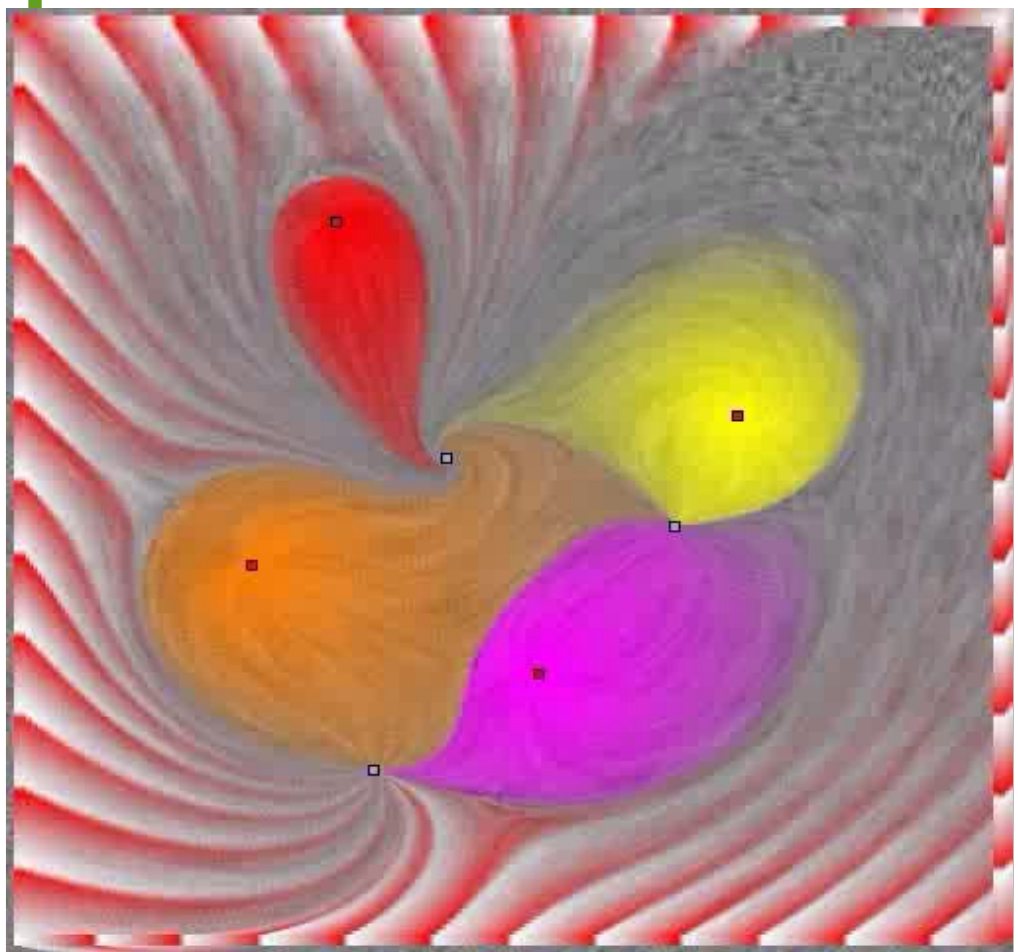


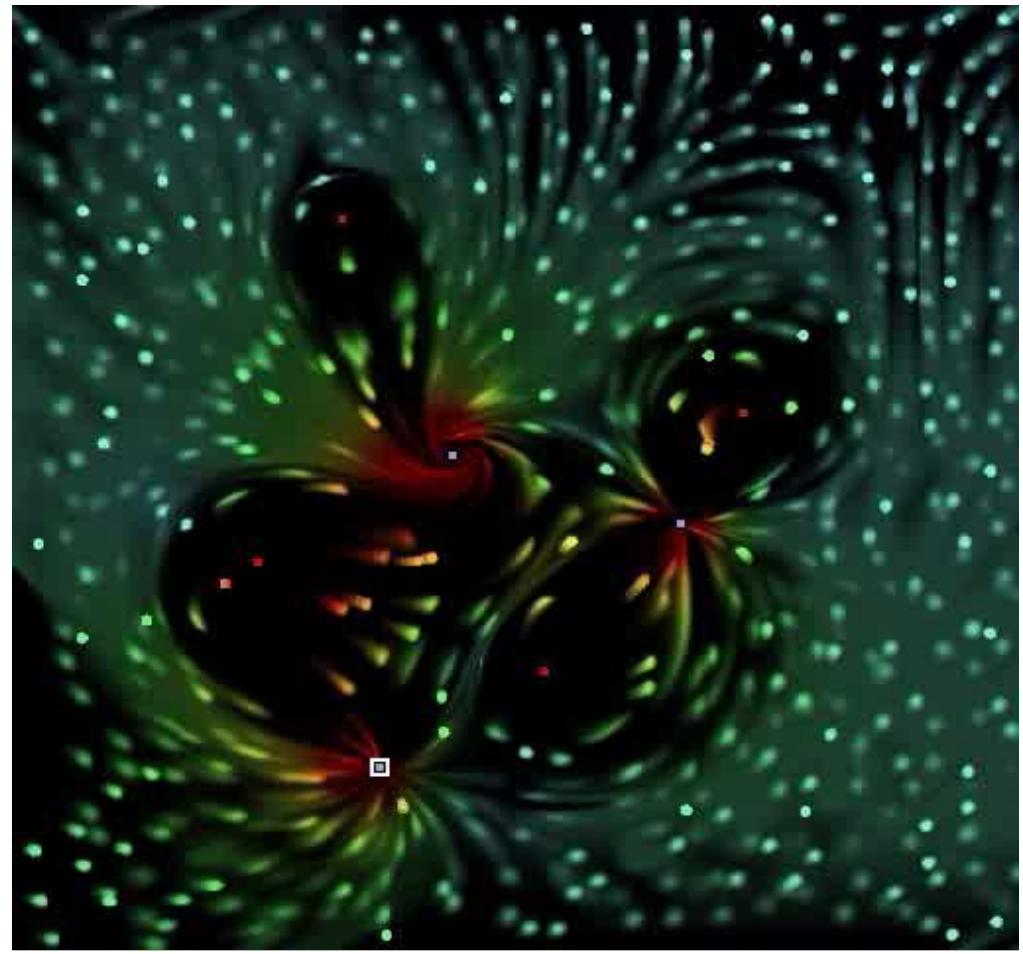
Geometric FlowViz: Streamlines and Streamlets in 2D, Steady-State



Evenly Space Streamlines (Jobard and Lefer)

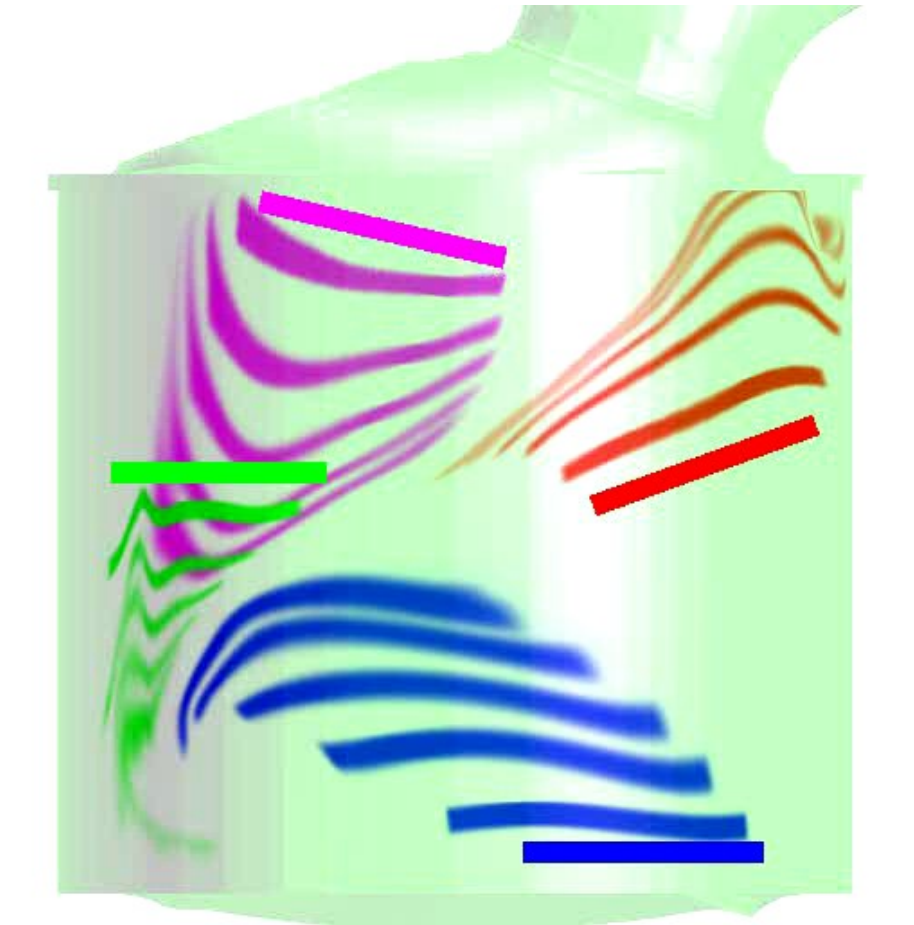
Geometric FlowViz: Pathlines and Streamlets in 2D, Unsteady

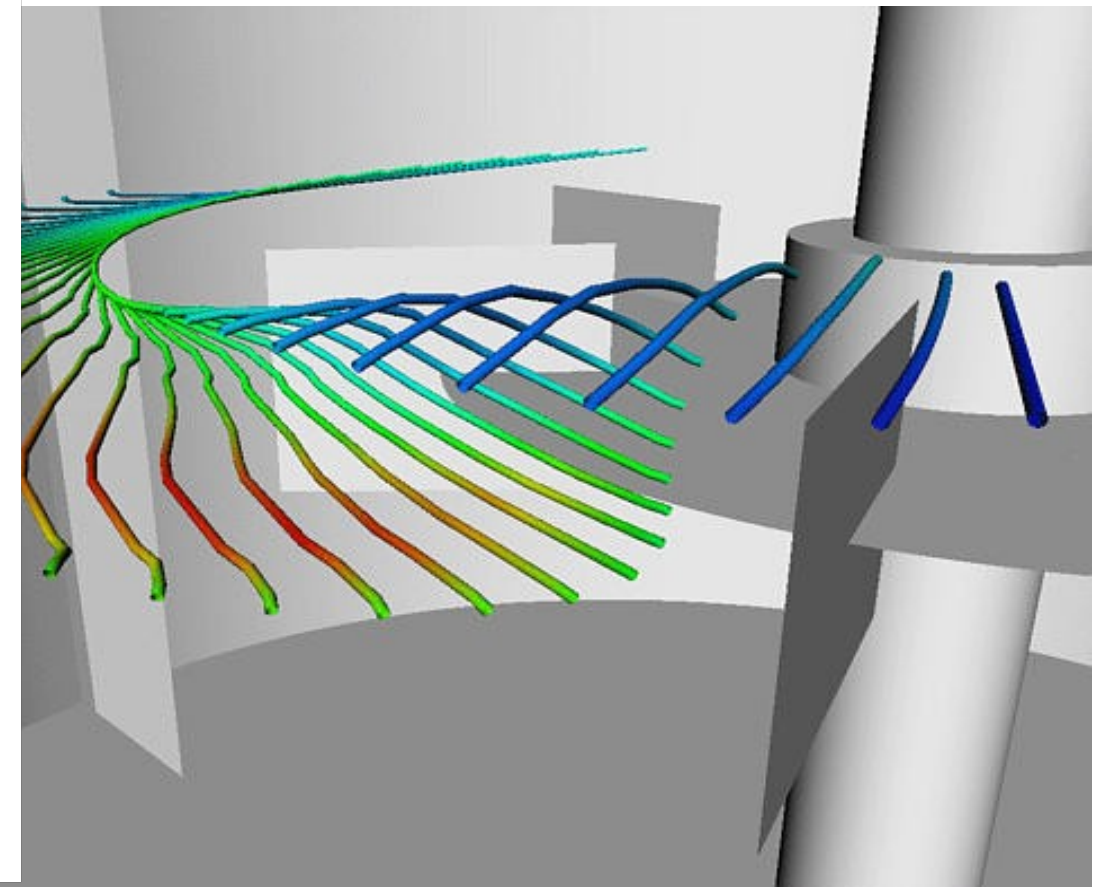




Pathlines and particles using textures (Van Wik)

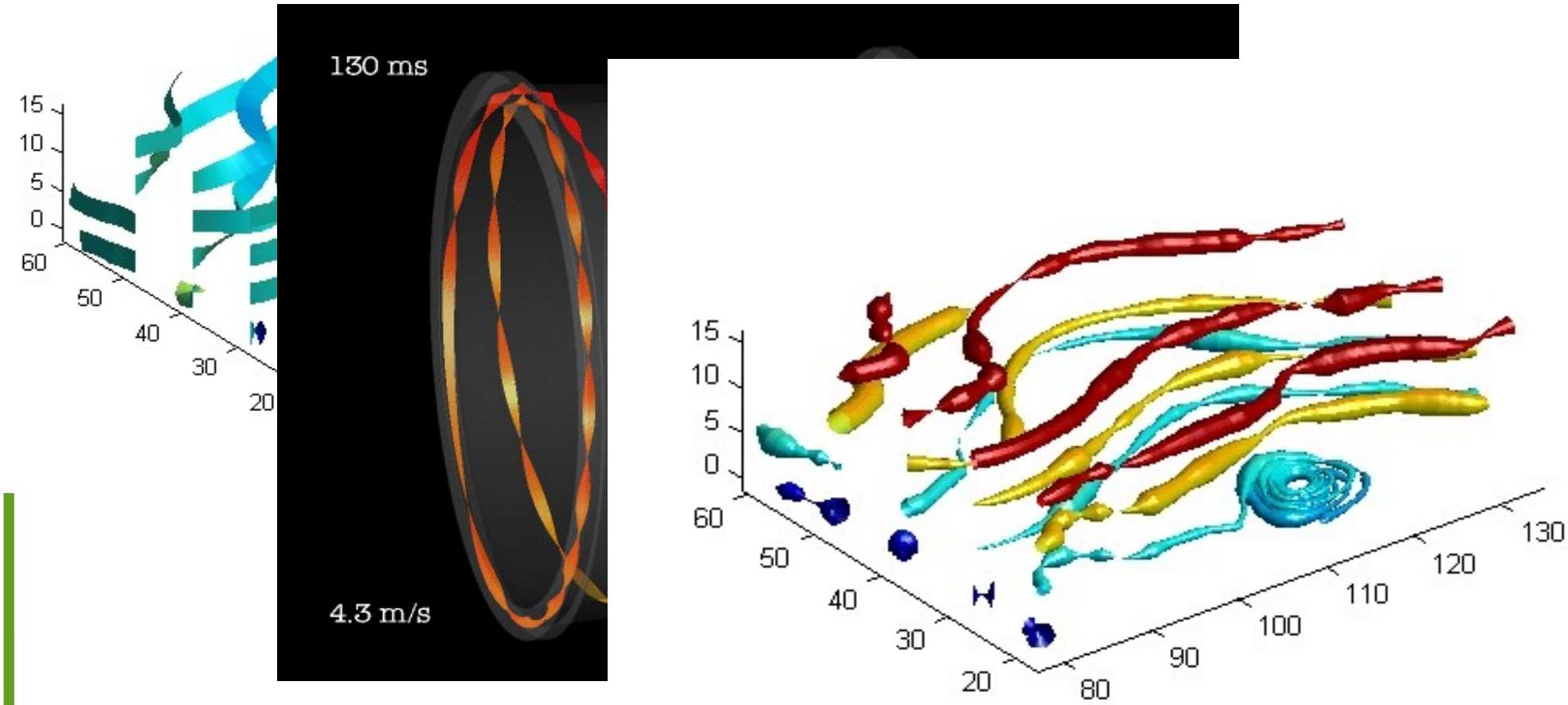
Geometric FlowViz: Timelines in 2.5D and 3D (B. Girod) (unsteady)





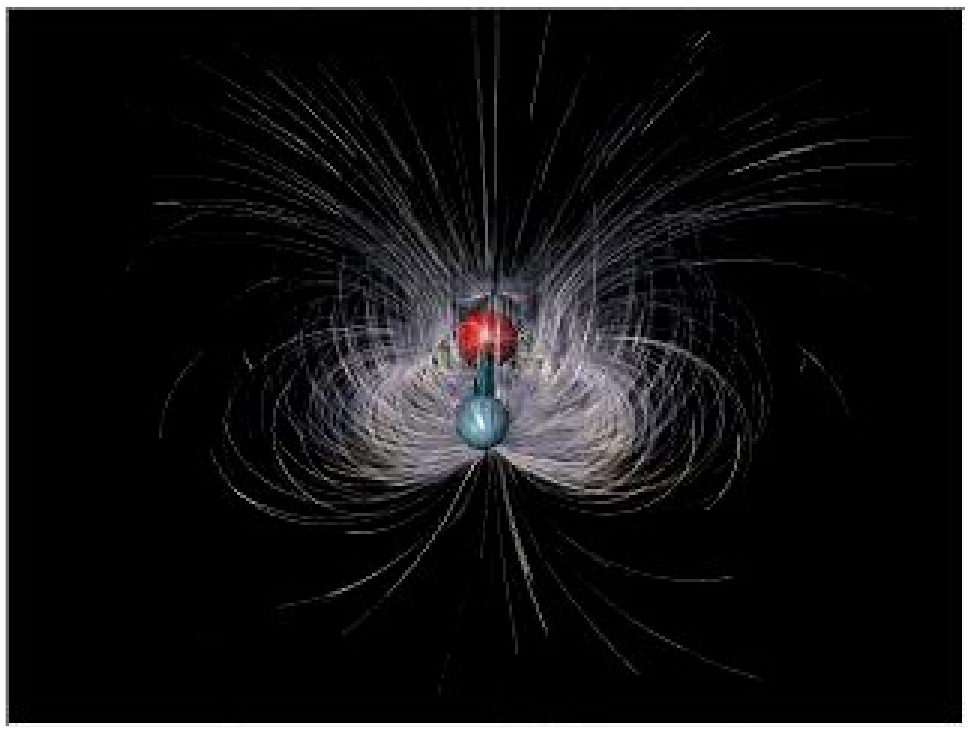
2.5D timelines using textures (Laramee et al.) and 3D timelines as discrete objects (B. Girod)

Geometric FlowViz: Streamribbons and Streamtubes, 3D, Steady-state

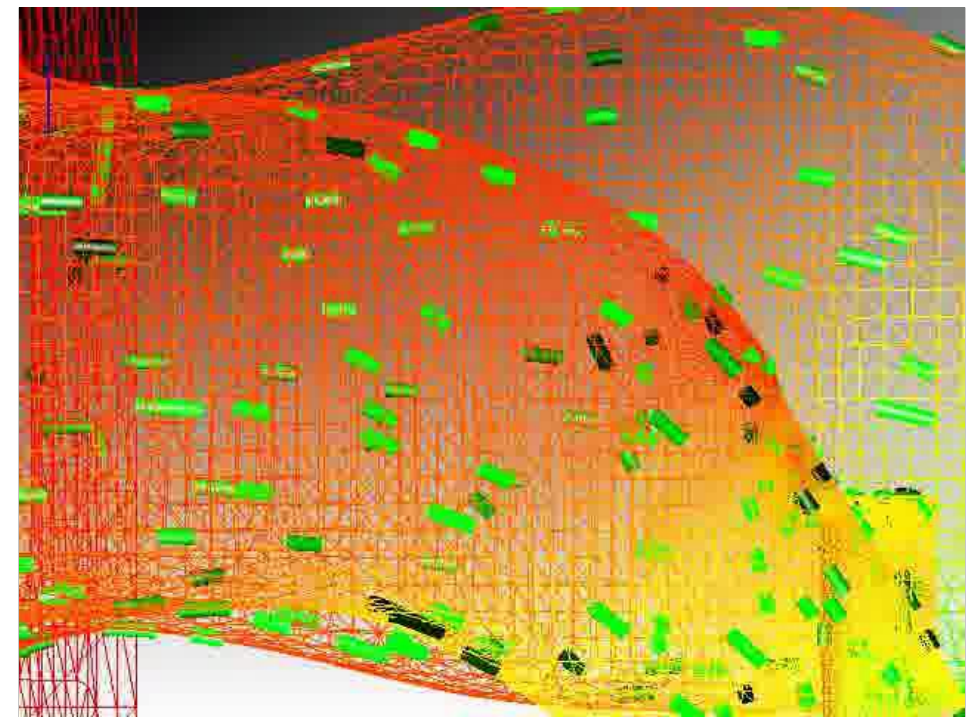


Geometric FlowViz: Perceptual Issues in 3D, Steady-State

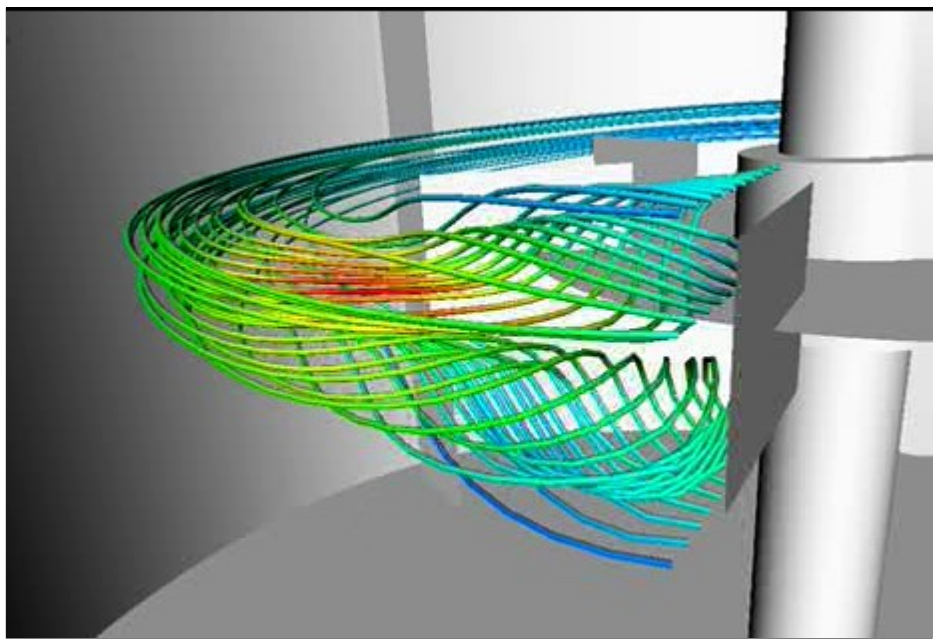
Illuminated Streamlines (Zoeckler et al)

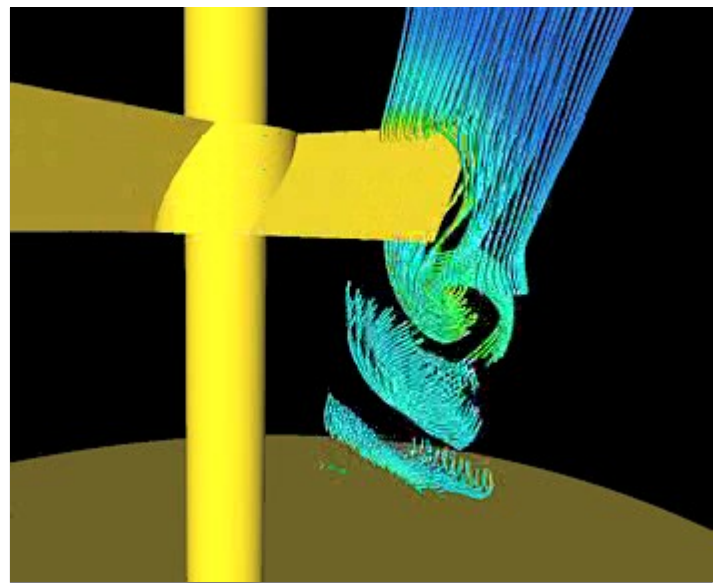


StreamRunner (Laramee)



Geometric FlowViz: Streaklines in 3D

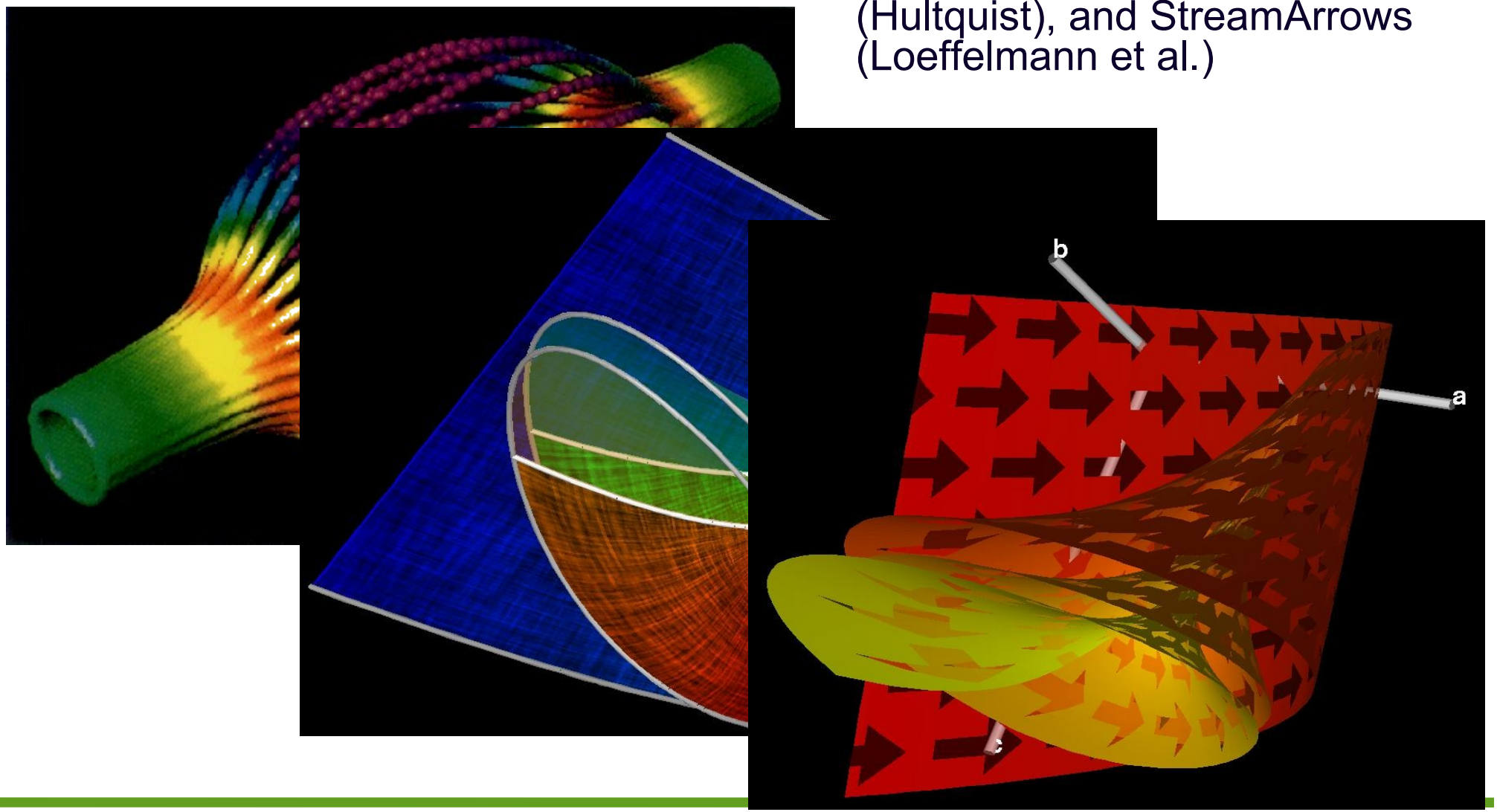




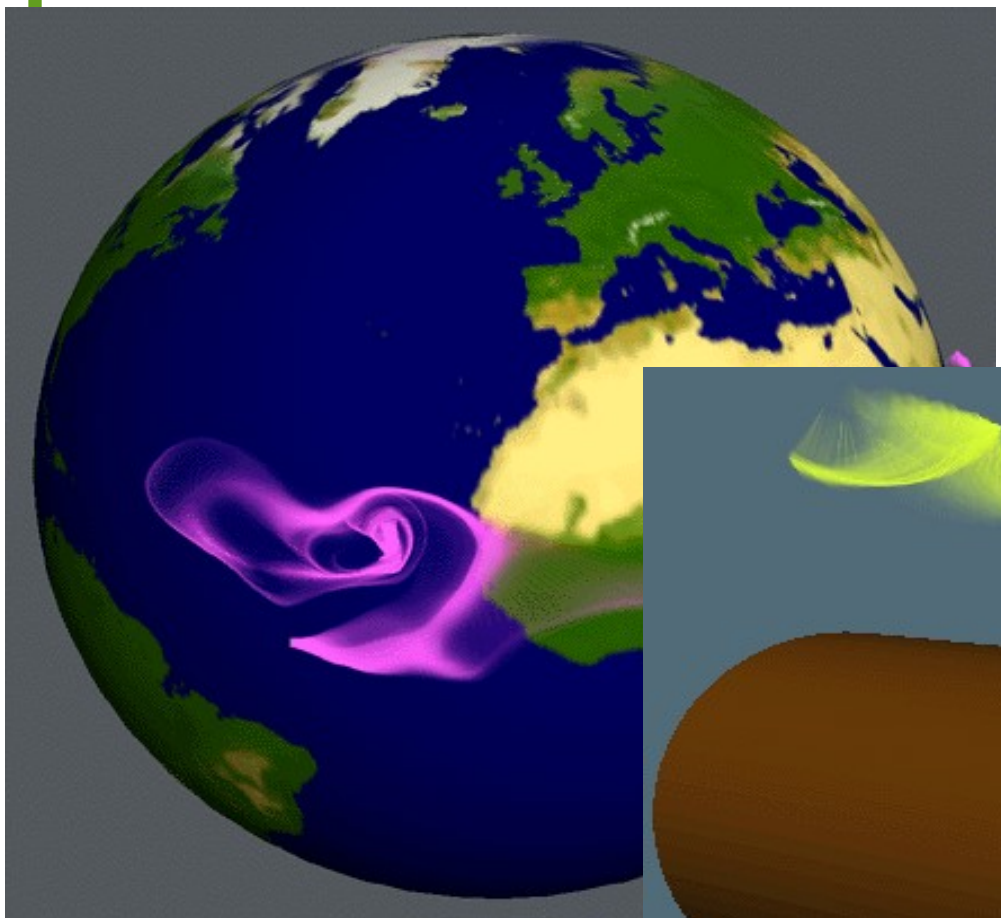
Streaklines in 3D as discrete objects (B. Girod)

Geometric FlowViz: StreamBalls, StreamSurfaces, StreamArrows, 3D, Steady-State

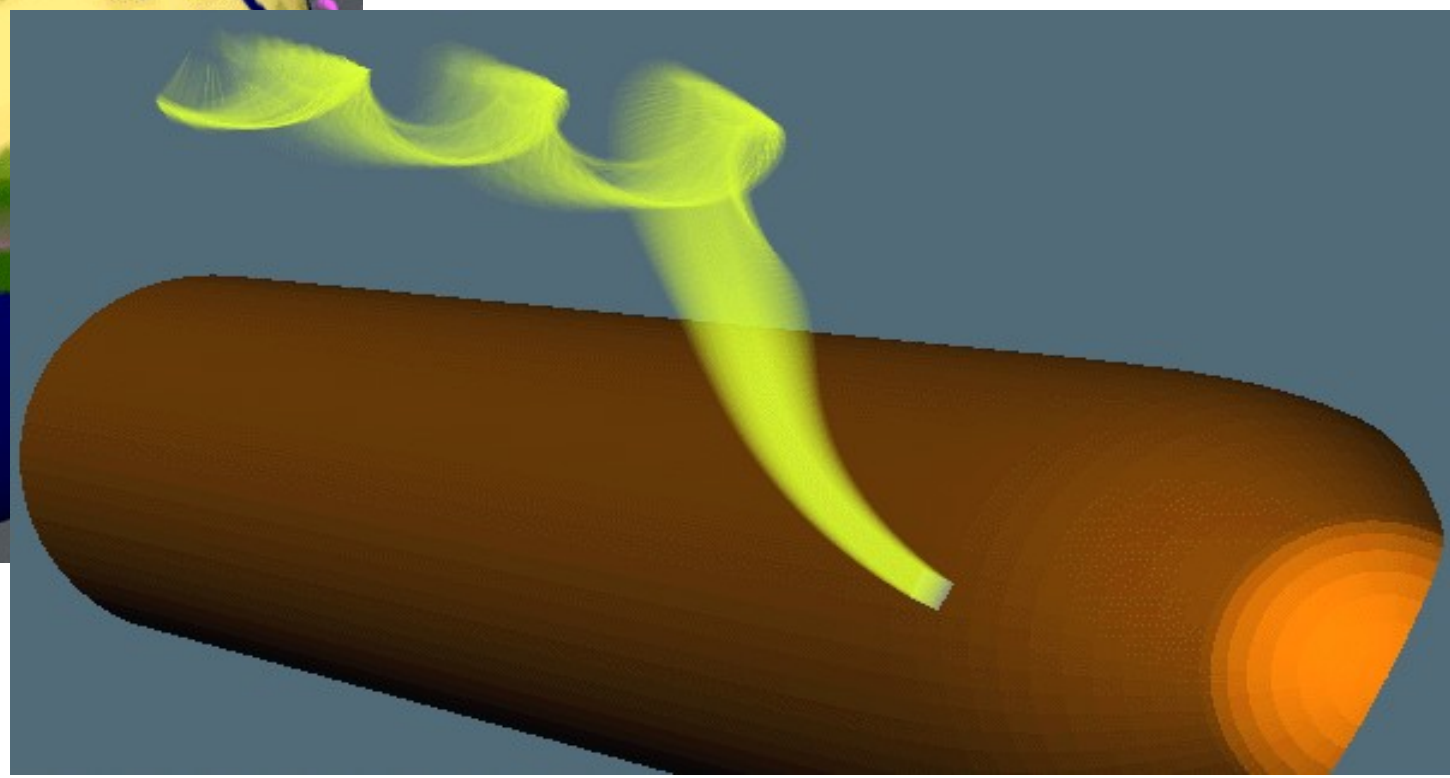
Streamballs (Brill et a), Streamsurfaces (Hultquist), and StreamArrows (Loeffelmann et al.)



Geometric FlowViz: Flow Volumes (3D), Steady and Unsteady

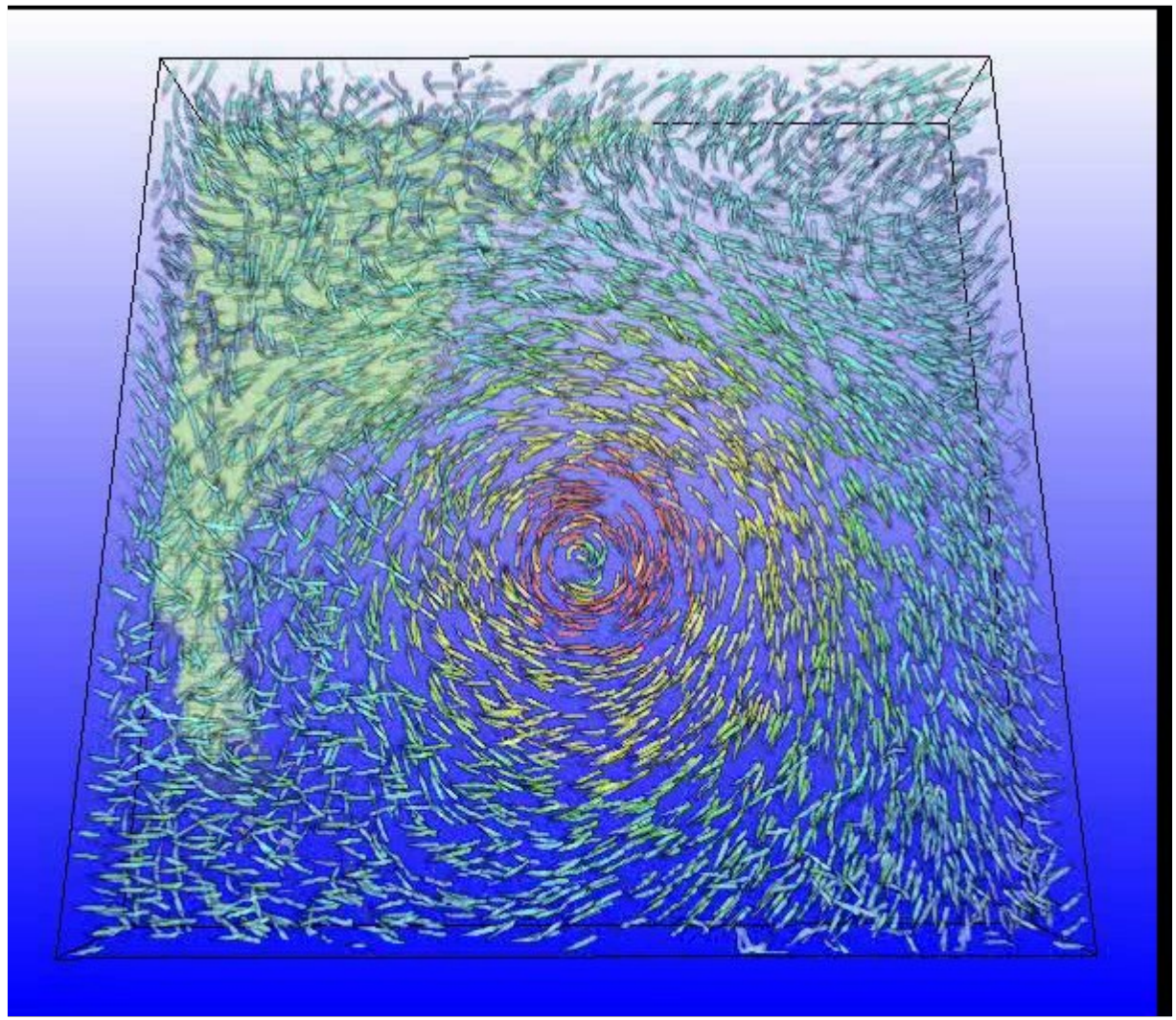


A subset of 3D flow domain specified by initial 2D patch (Crawfis)



Geometric FlowViz: High Quality Animation, 3D, Unsteady

Visualization of
Hurricane Isabel
(Helgeland et al.)



Geometric Flow Visualization

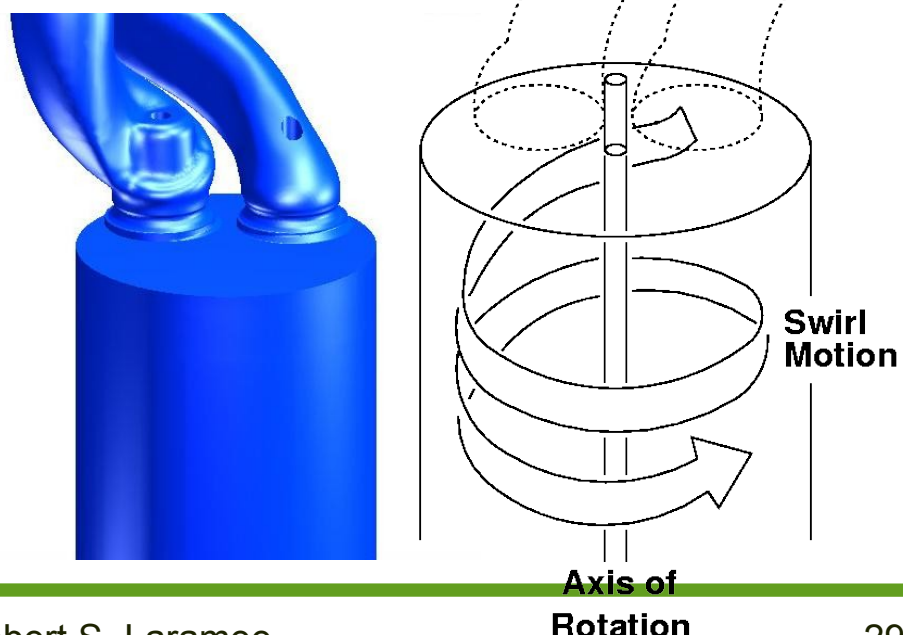
For more information on geometric flow visualization techniques, please see:

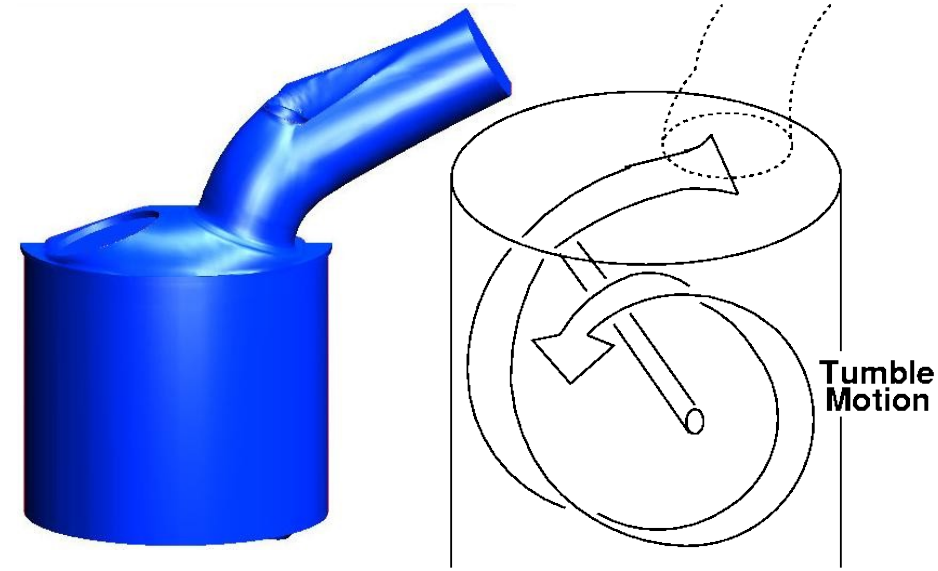
Frits H. Post, Benjamin Vrolijk, Helwig Hauser, Robert S. Laramee, and Helmut Doleisch, **Feature Extraction and Visualization of Flow Fields** in *EUROGRAPHICS 2002, State of the Art Reports*, pages 69-100, September 4-6 2002, Saarbruecken, Germany

(2nd STAR)

Flow Visualization: An Application

- **swirl motion:** characterized by motion about cylinder-aligned axis
- more stable (easier)





- **tumble motion:** characterized by motion about axis orthogonal to cylinder
- unstable, more difficult

Flow Visualization: An Application

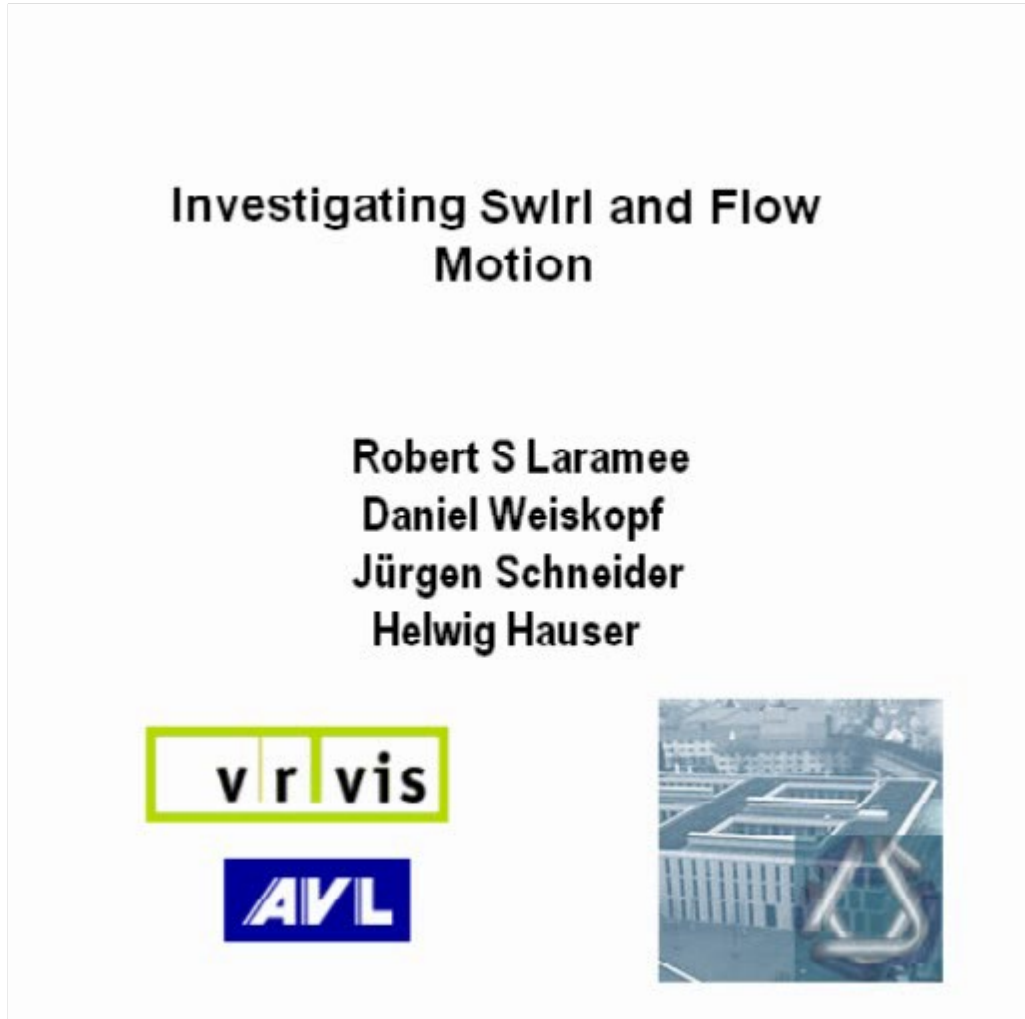
Achieving ideal patterns of motion leads to optimal mixing (of air and fuel) conditions

- e.g., higher exhaust/gas ratio (EGR)
- decrease in fuel consumption
- lower emissions

- Can visualization provide insight into or verify characteristic shape/behavior of flow?
- What tools help to visualize swirl/tumble motion?
- Where (in the combustion chamber) are ideal ideal flow pattern ***not*** being realized?

Flow Visualization: An Application

Direct, geometric, and texture-based flow visualization methods are used in 2D, 2.5D, and 3D.



Feature-Based Flow Visualization

What is Feature-Based Flow Visualization?
Recall: What is Flow Visualization?

- a classic topic within scientific visualization
- depiction of vector quantities (as opposed to scalar quantities)

Challenges:

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

What is Feature-Based Flow Visualization?

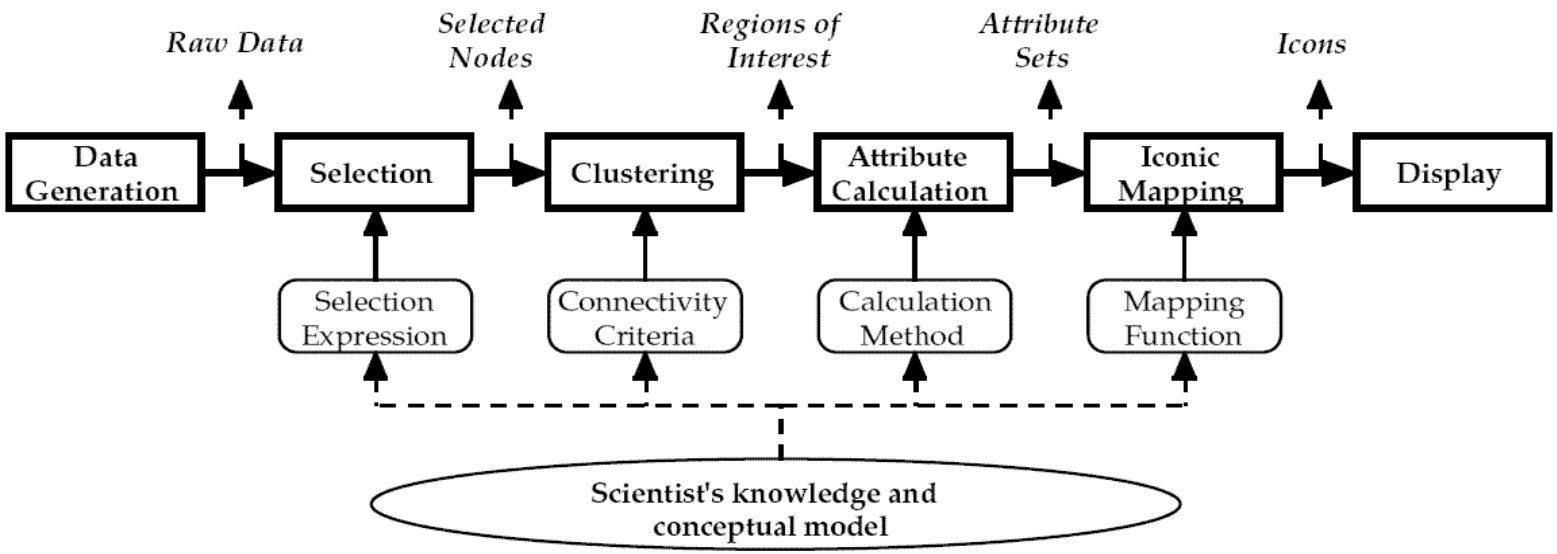
What is a feature?

- feature: “A prominent or distinctive aspect, quality, or characteristic”, from dictionary.com
- feature: any subset of the flow domain deemed interesting by an onlooker, i.e., the viewer (Bob’s definition)

What is feature-based flow visualization?

- feature-based flow visualization: the focus on and resulting depiction of a subset of the flow domain. (Bob’s definition)

Feature-Based Flow Visualization Pipeline



Feature-Based flow visualization involves extracting features from the vector field domain.

- selection: conceptually, filtering the data
- clustering: coherency is established from point selection
- attribute calculation: quantification, e.g., position, volume, orientation --> leads to features

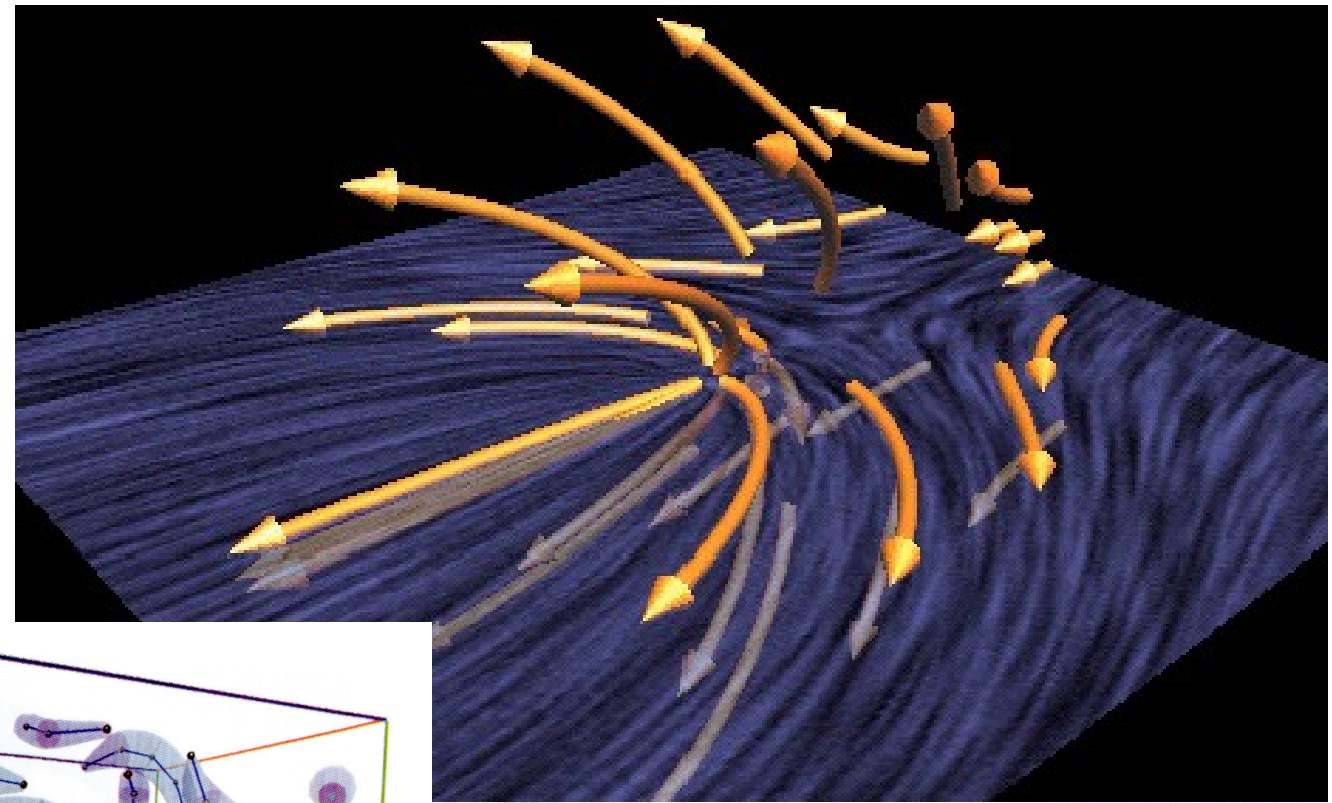
Feature-Based Flow Visualization: Motivation

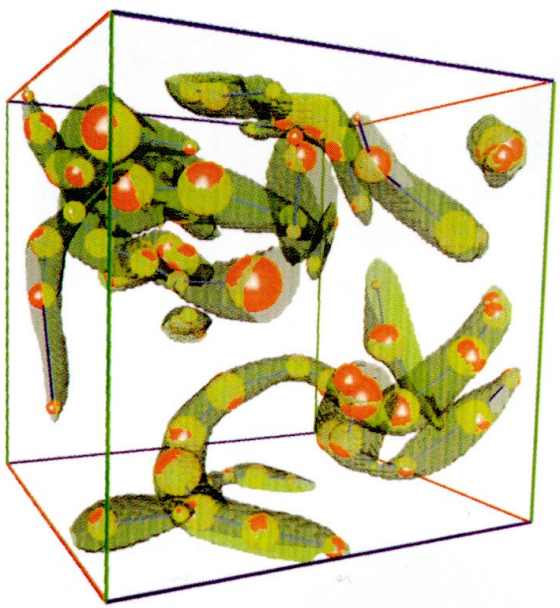
Why?

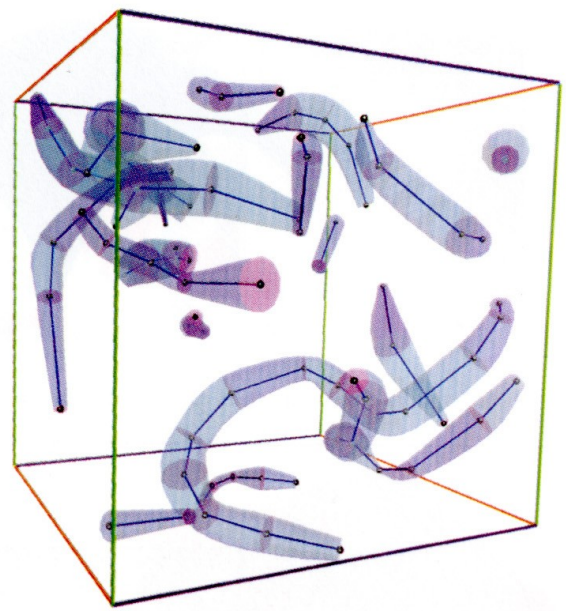
- **data reduction**: original data set is represented with important features
- **perception**: visualization of 3D and 4D flow is problematic in the absence of feature-based techniques
- **new insight**: “new” characteristics of the flow can be observed
- **technical advantages**: less memory consumption, faster interaction and rendering

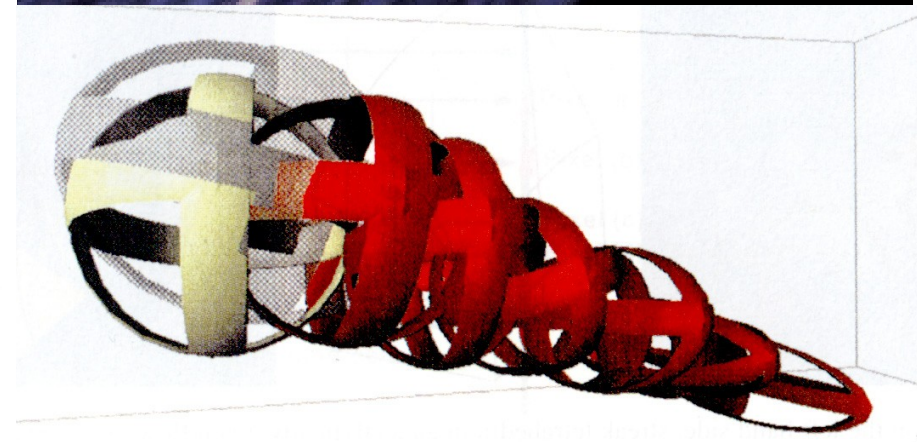
Feature Based Flow Visualization: 3D Steady and Unsteady

- Vector field clustering (Telea and Van Wijk)
- Vortex extraction (Post et al.)



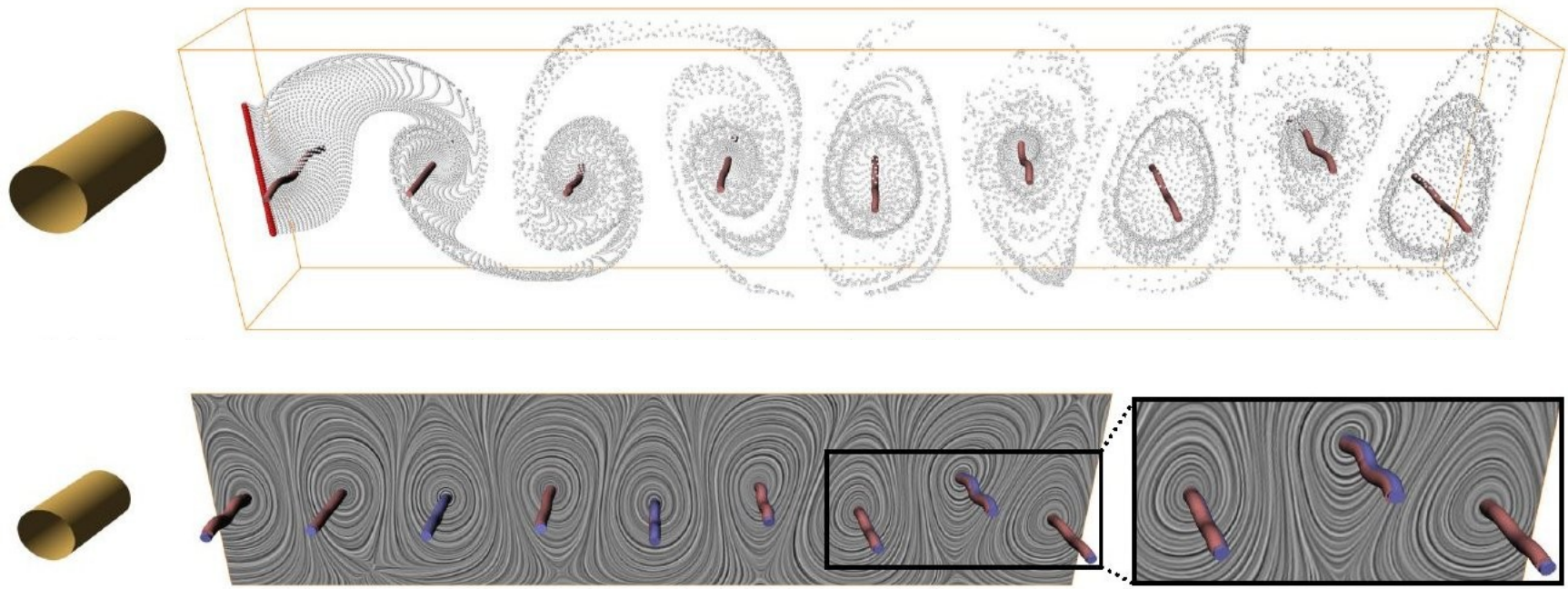






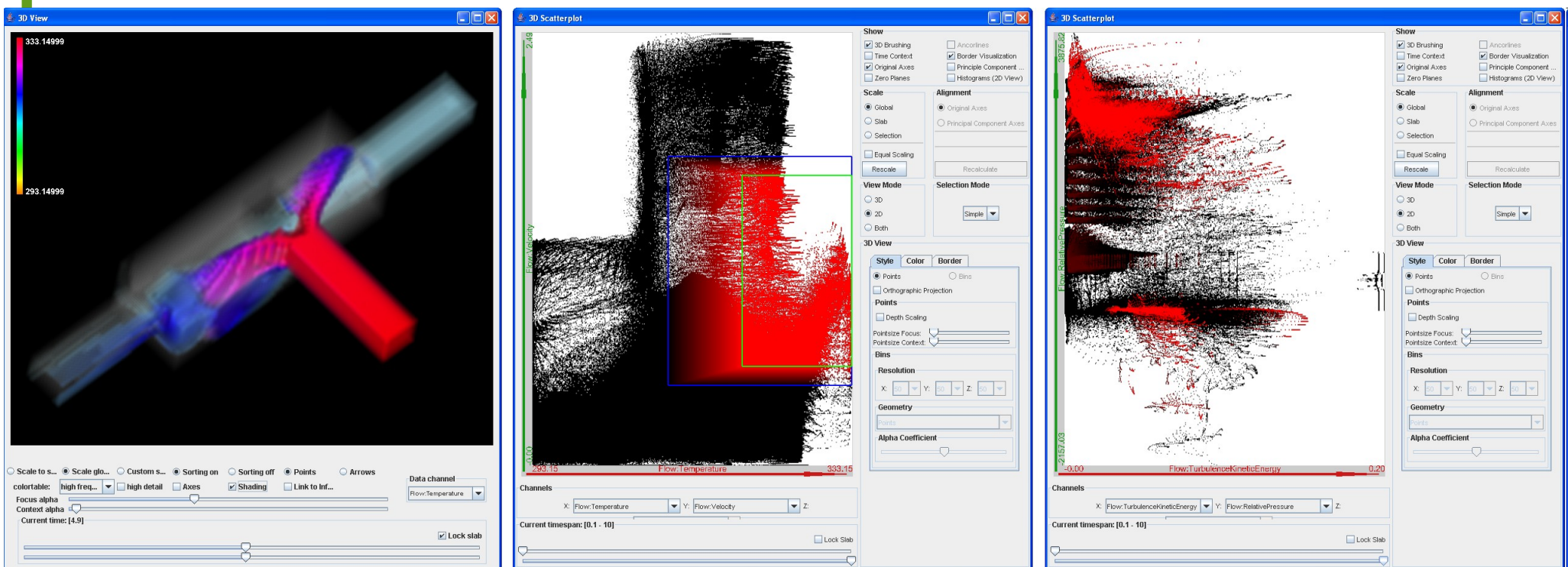
Feature Based Flow Visualization: 3D Unsteady

- Cores of swirling particle motion in unsteady flow, extraction based on pathlines (Wienkauf et al.)



Feature Based Flow Visualization: 3D, Unsteady, Interactive

- SimVis: interactive, multiple connected views (Doleisch et al.)



Feature-Based Flow Visualization

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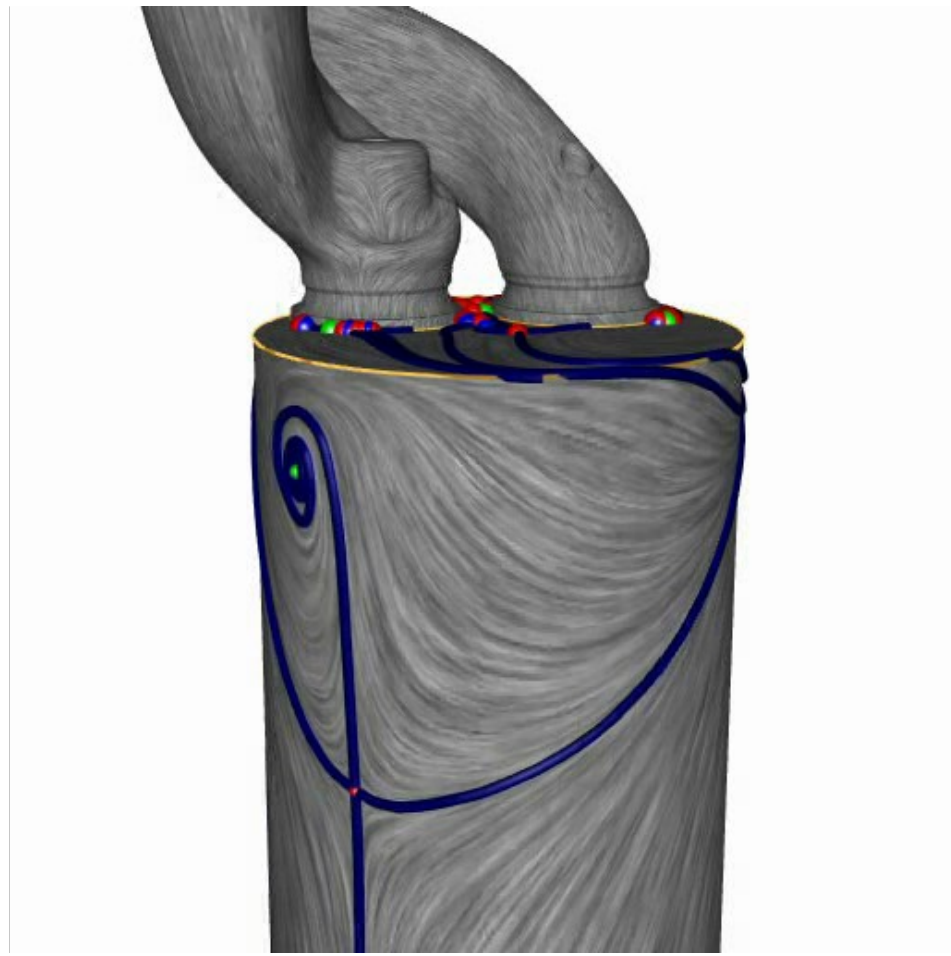
Frits H. Post, Benjamin Vrolijk, Helwig Hauser, Robert S. Laramee, and Helmut Doleisch, **The State of the Art in Flow Visualisation: Feature Extraction and Tracking** in *Computer Graphics Forum*, Vol. 22, No. 4, 2003, pages 775-792

(3rd STAR)

Topology-Based Flow Visualization

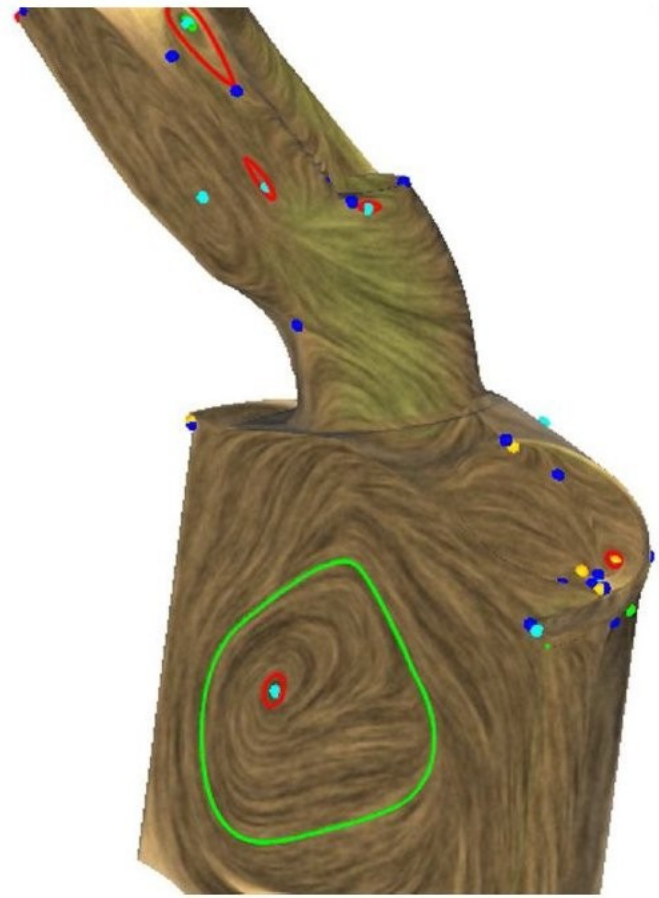
Can be considered a sub-field of feature-based flow visualization:

- **singularities** in flow field are extracted, loosely: locations where flow velocity approaches zero, e.g., sources, sinks, etc.
- the relationship, connectivity, or *topology* between singularities is then analyzed and visualized
- the topology of vector field is often called “skeleton” of the flow



Topology-Based Flow Visualization, 2.5D Steady

- a single framework can be used to extract sources, sinks, saddle points, and periodic orbits
- uncertainty due to discrete nature of simulation, interpolation, and integration can be factored into extraction and visualization
- (Chen et al.)



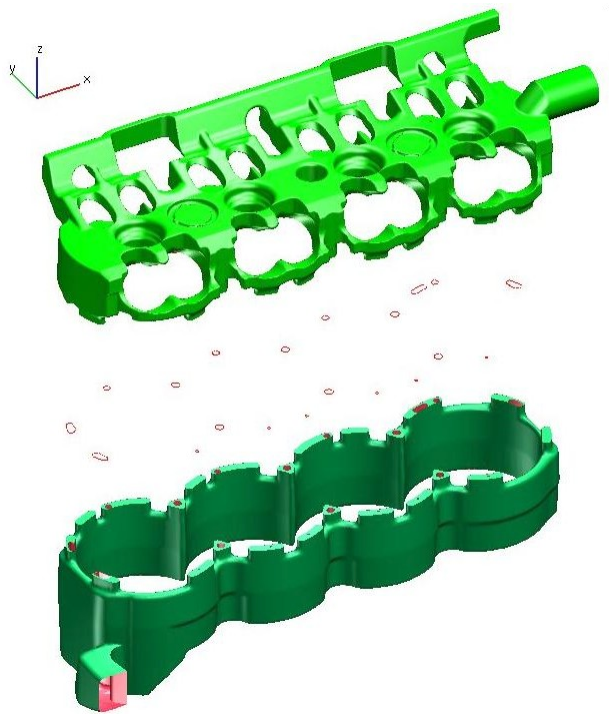
Topology-Based Flow Visualization

For more information on topology-based flow visualization techniques, please see:

Robert S. Laramee, Helwig Hauser, Lingxiao Zhao, and Frits H. Post, **Topology-Based Flow Visualization, The State of the Art**, in *Topology-Based Methods in Visualization (Proceedings of Topo-In-Vis 2005)*, Visualization and Mathematics, pages 1-19, 2007, Springer-Verlag

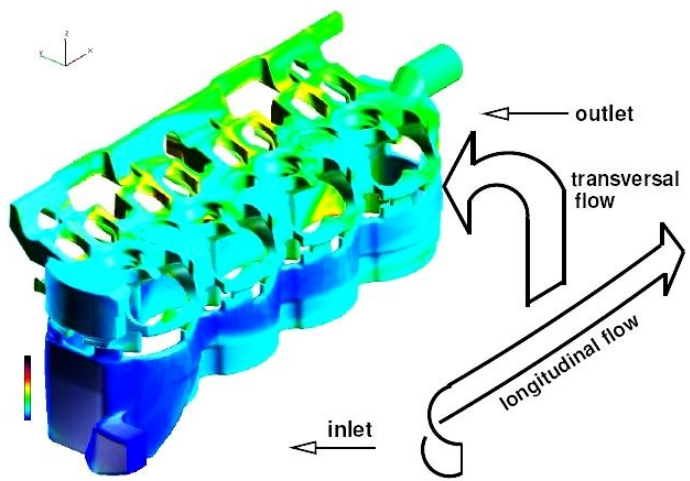
(4th! STAR)

Feature-Based Flow Visualization: An Application



Four major design goals:

- an even distribution of flow to each engine cylinder
- avoid regions of stagnant flow
- avoid very high velocity flow
- minimize fluid pressure loss between inlet and outlet



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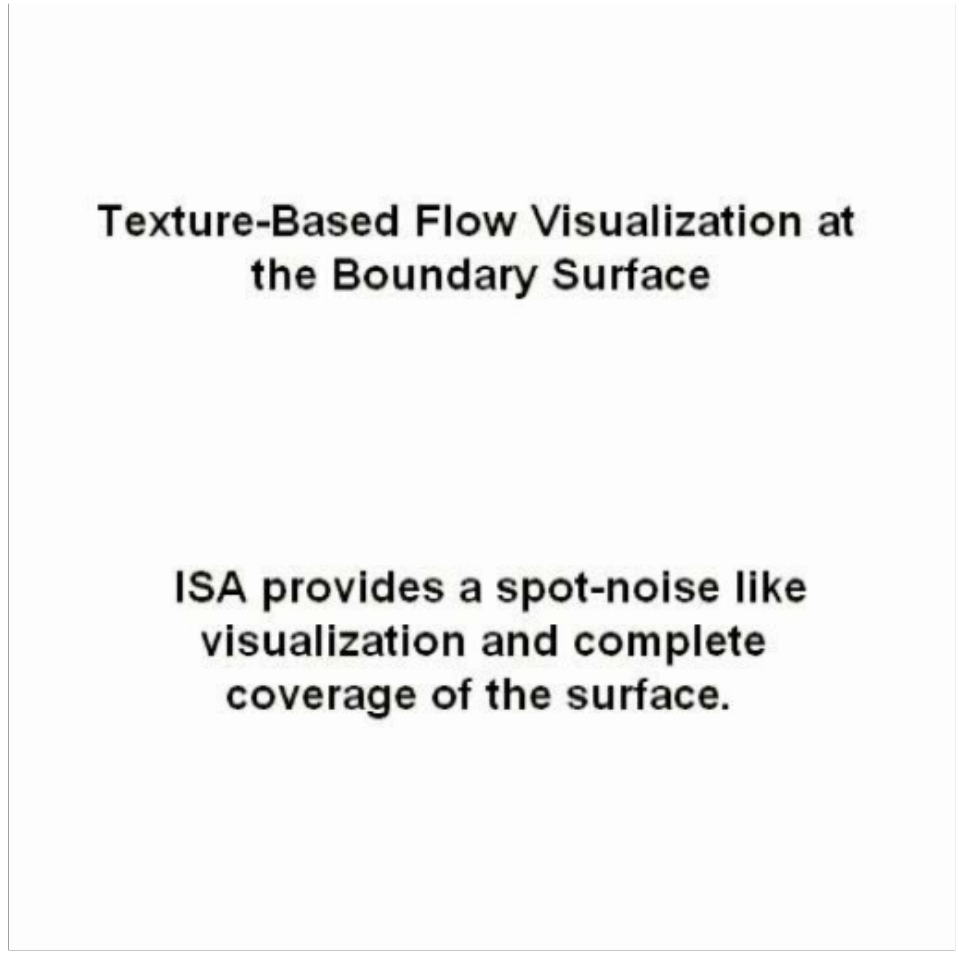
- A range of direct, texture-based, geometric, feature-based, and topology-based visualization methods are applied



Flow Visualization: Challenges

- FlowViz in 3D -perceptual issues, seeding strategies
- Unsteady FlowViz in 3D -computation time
- What should be extracted and visualized?
- How can features be extracted and visualized? e.g. vortices
- costly in terms of processing time
- interpretation can be challenging
- correctness: verification of result (sometimes ignored)

An area still rich in unsolved problems.

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- Thank you for your attention! Any questions?

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- PDF versions of STARS 1-4 and MPEG movies available at:

http://cs.swan.ac.uk/~csbob