Tutorial: State-of-the-Art Flow Field Analysis and Visualization

Texture-Based Flow Visualization

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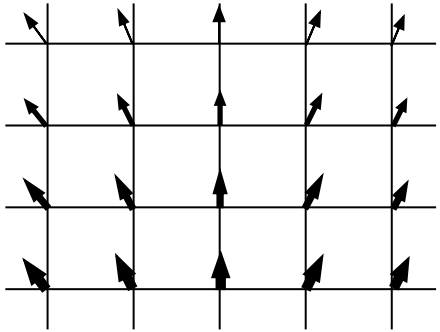
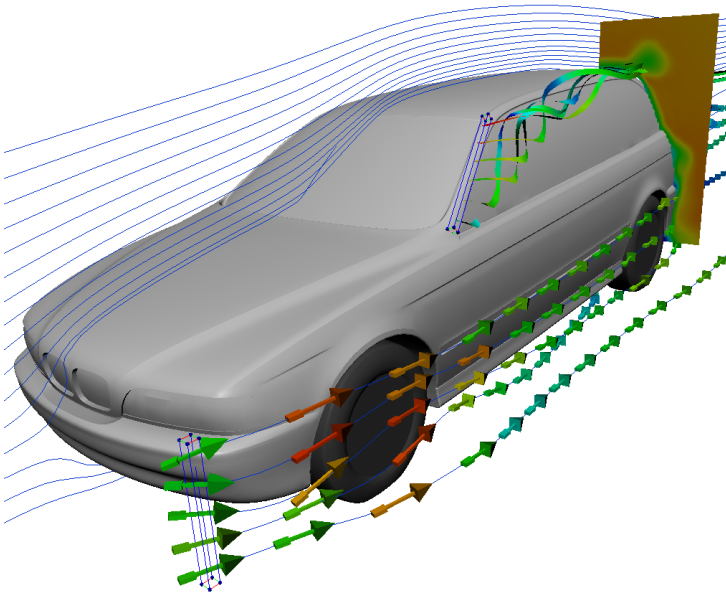
Overview

- Background
- Line integral convolution and texture advection
- Hierarchical line integration
- Effective rendering and feature extraction
- Outlook and conclusion

Flow Visualization Approaches

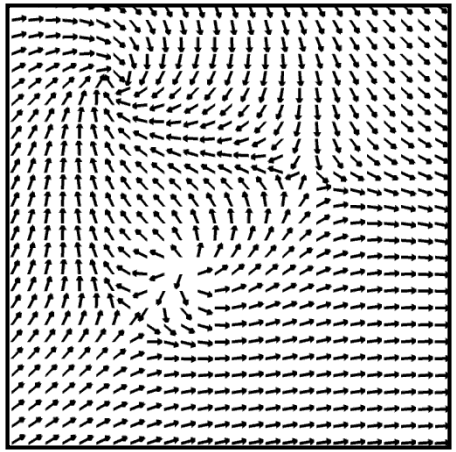


- Direct approaches
  - Glyphs, arrows
  - Color coding
- Sparse, line-like representations
- Dense, line-like representations
- Characteristic lines
  - Streamlines
  - Pathlines
  - Streaklines

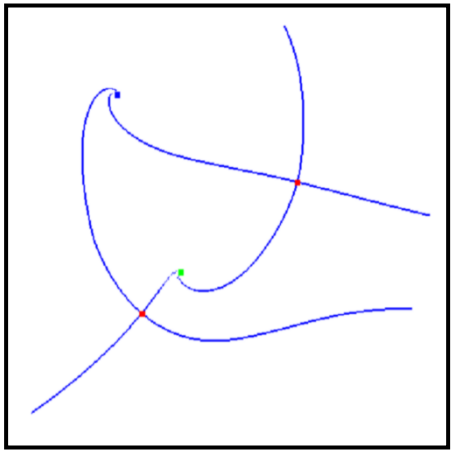


[courtesy of BMW Group and Martin Schulz]

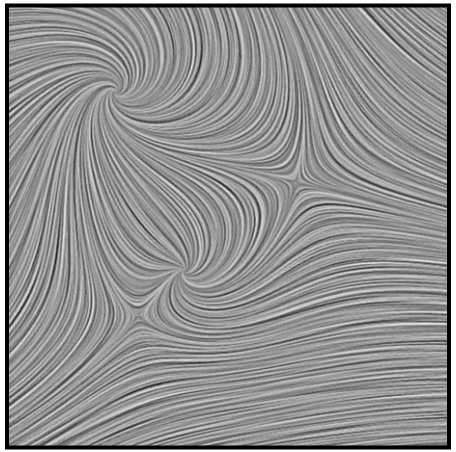
Visualization Approaches



Arrows



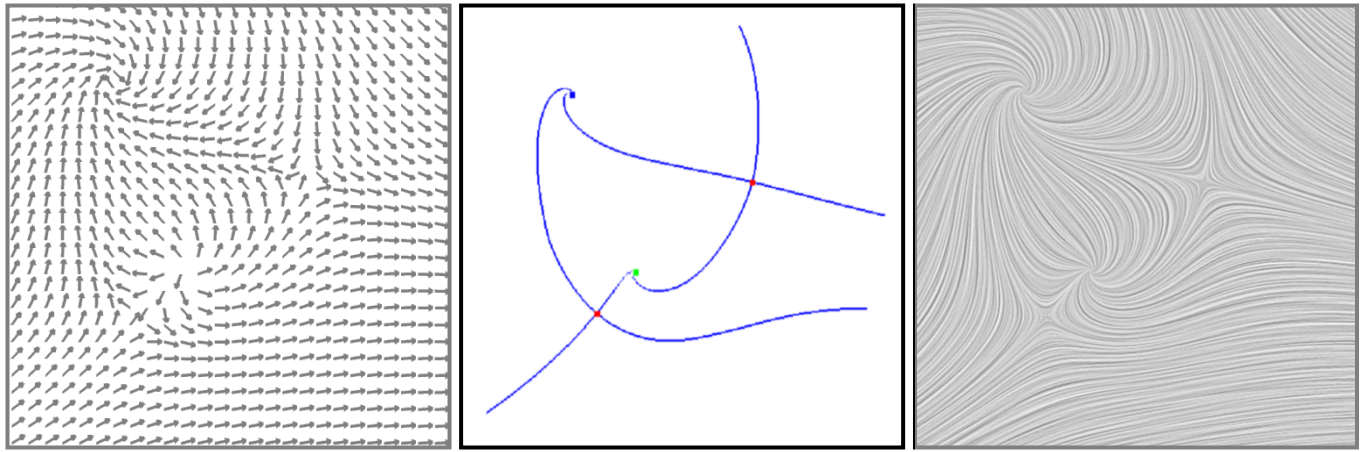
Sparse (topology)
[Source: G. Scheuermann]



Dense (texture-based)

[Weiskopf, Erlebacher 2005]

Visualization Approaches



Arrows

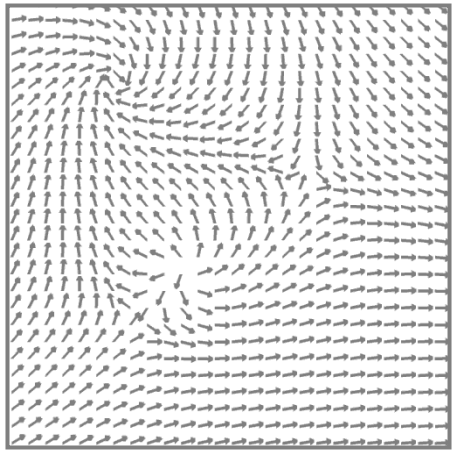
Sparse (topology)
[Source: G. Scheuermann]

Dense (texture-based)

see later: Vector Field Topology in Flow Analysis and Visualization

[Weiskopf, Erlebacher 2005]

Visualization Approaches



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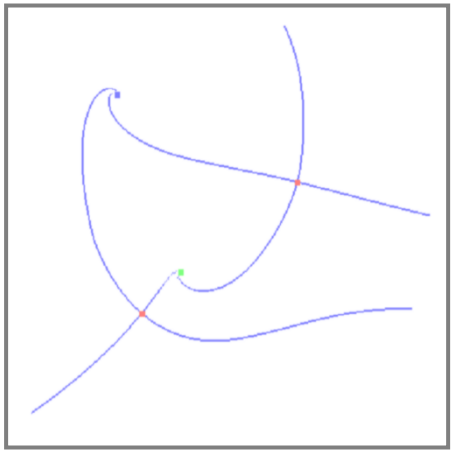

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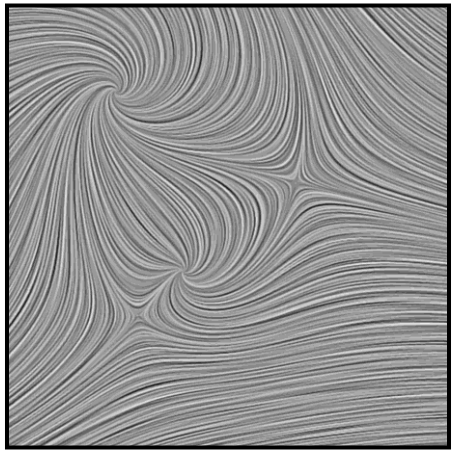


Dense (texture-based)

[Weiskopf, Erlebacher 2005]

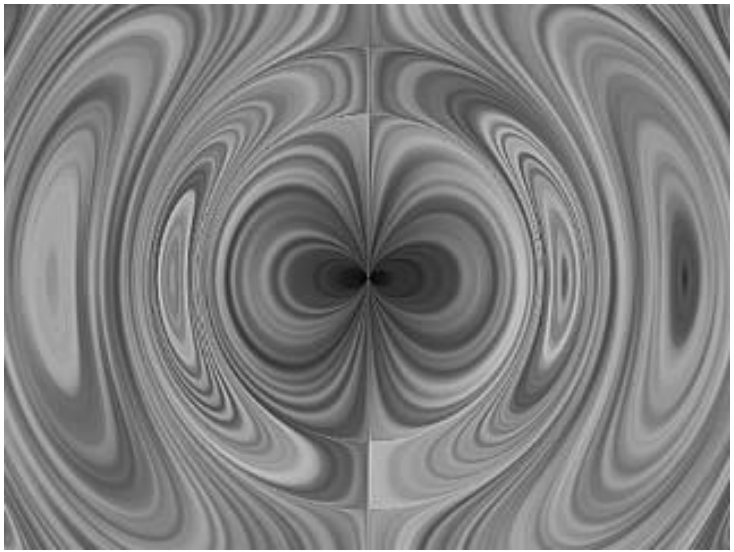
Why Texture-Based Flow Visualization?

- Dense sampling
  - Better coverage of information
  - (Partially) solved problem of seeding
- Flexibility in visual representation
  - Good controllability of visual style
  - From line-like (crisp) all the way to fuzzy

Dense Vector Field Visualization

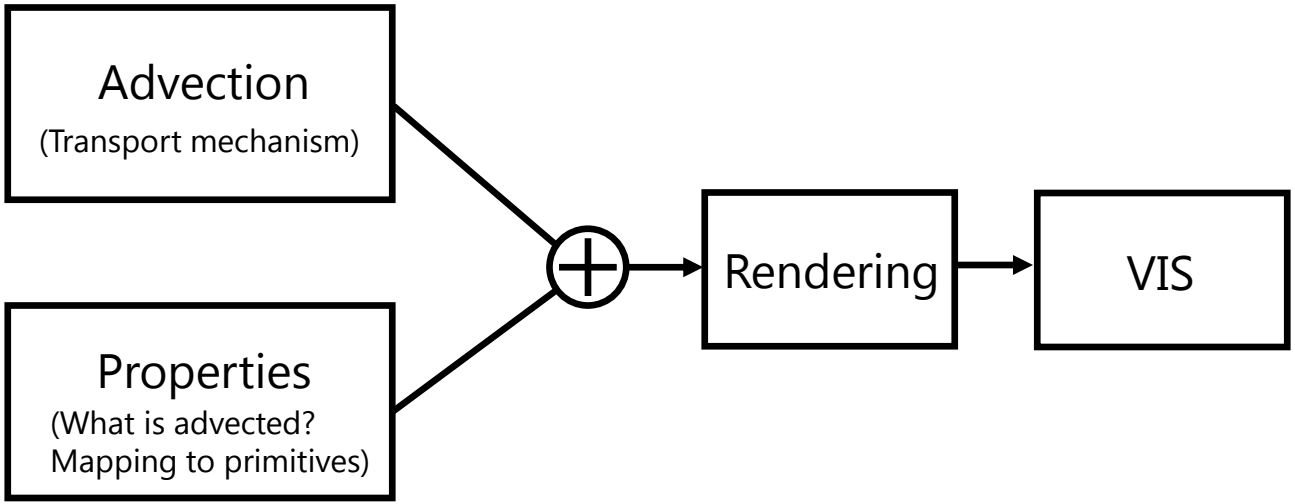
- Characteristic lines
- Challenges
  - Visualization speed
  - Quality
  - Effectiveness

- Interactive GPU methods
- Hierarchical computation
- Facilitate good visual perception
- Combine with feature extraction

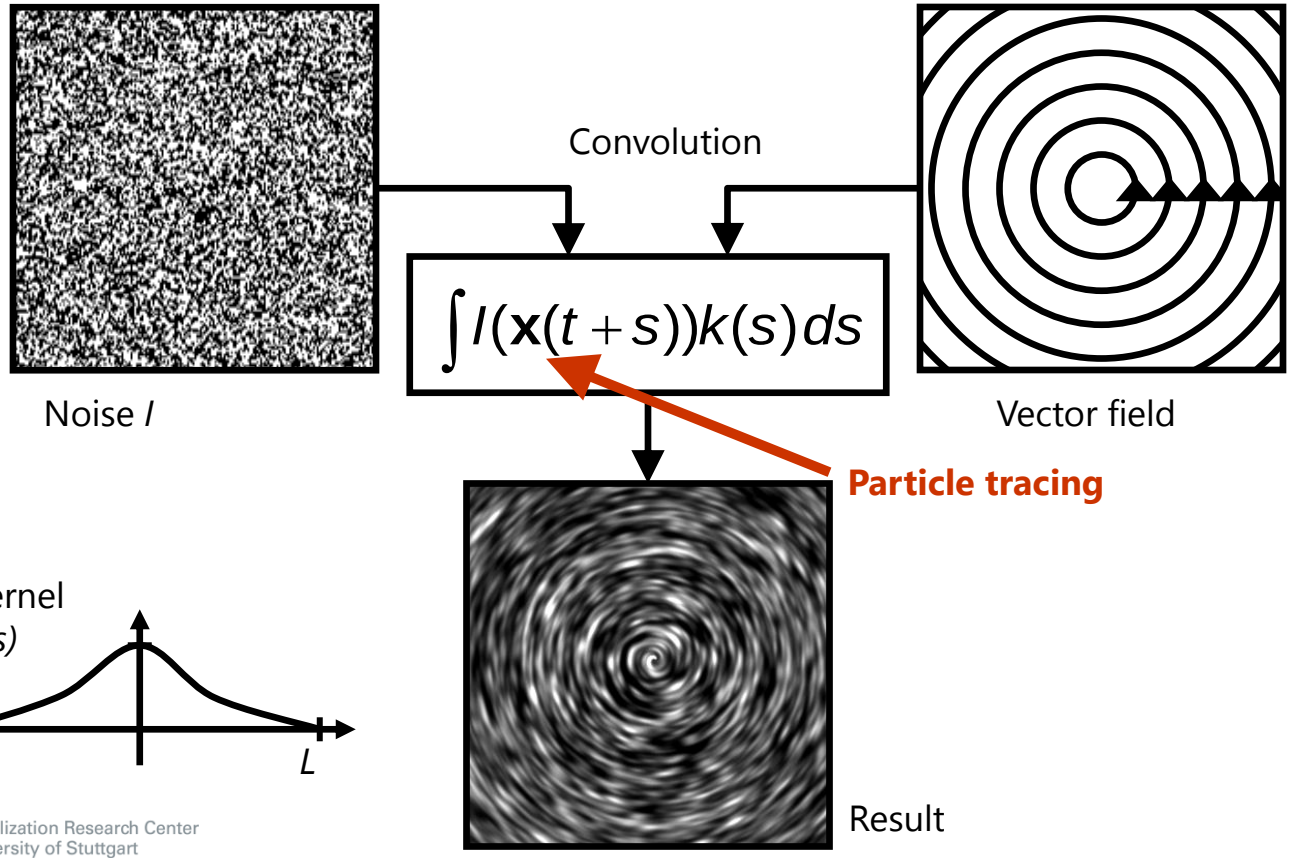


[Weiskopf et al. 2003]

Ingredients of Vector Field Visualization



Line Integral Convolution (LIC)



Lagrangian Particle Tracing

- Velocity vector **v**
- Trace massless particles
- Equation of motion:

$$\frac{d\mathbf{r}}{dt} = \mathbf{v}(\mathbf{r}, t)$$

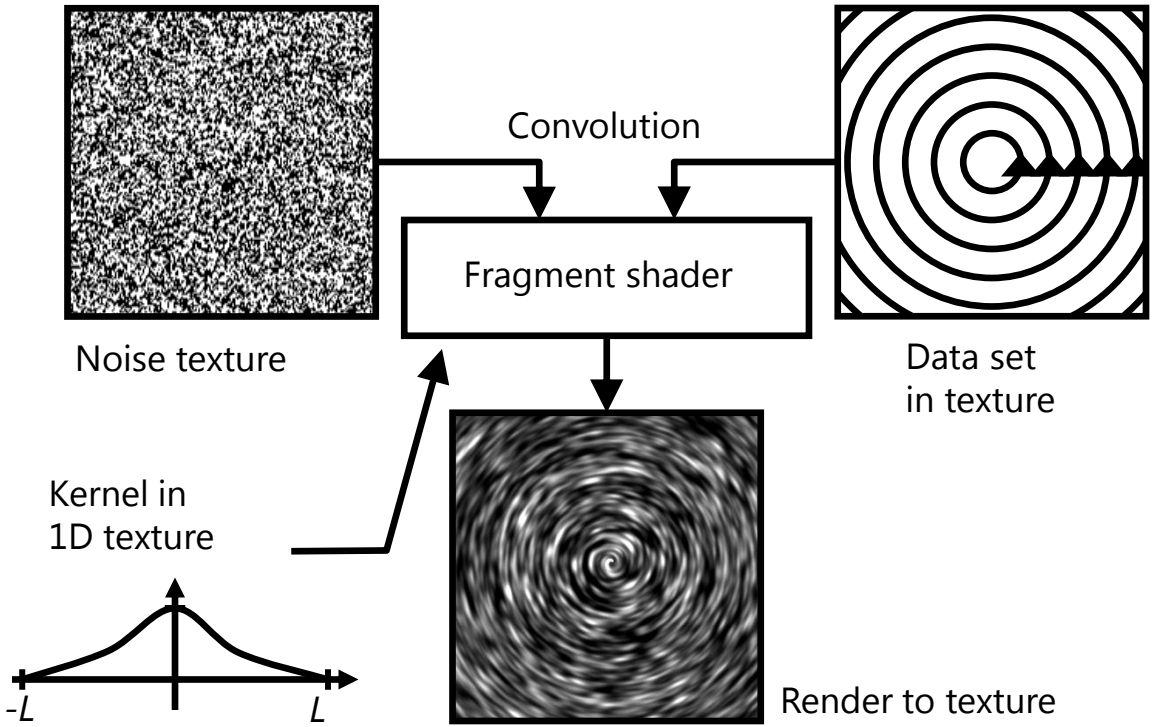
- Explicit integration
  - Step-by-step
  - Possible in GPU fragment shaders

see later: Foundations of Data-Parallel Particle Advection

Convolution

- Discretization of the convolution integral
- Integration simultaneously with particle tracing
- Accumulate noise values

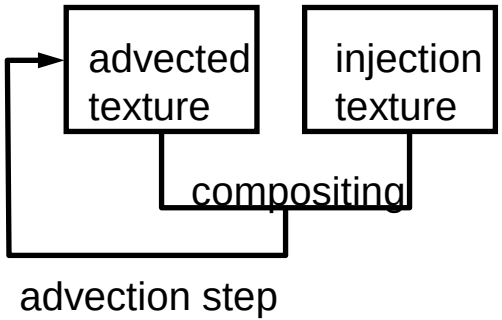
Mapping to GPU: Parallel Computation

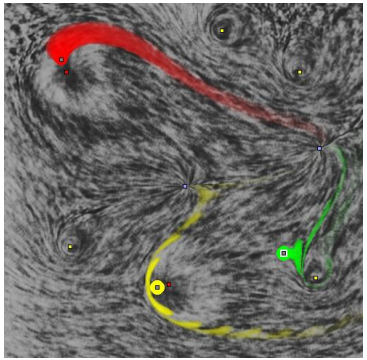


Incremental LIC: Texture Advection

- Injection of new material
  - IBFV idea
  - Injection texture
- Alpha blending
  - Exponential filter kernel (steady case)
  - Streaklets (unsteady)

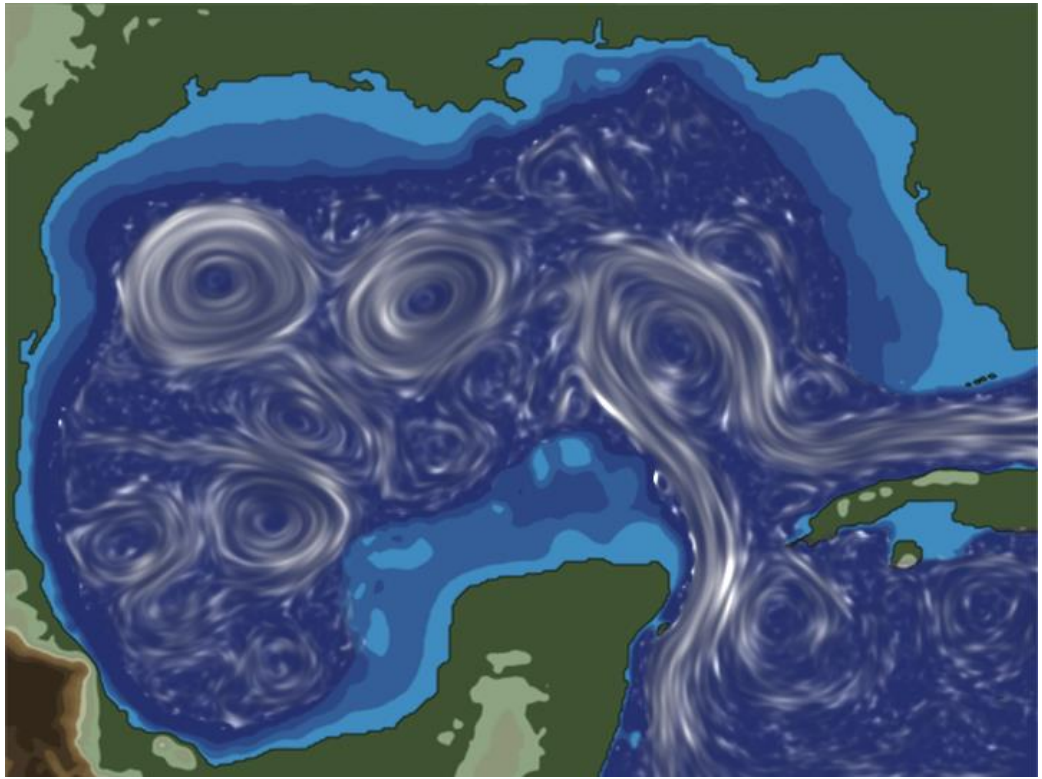
[Van Wijk 2002]





[generated by Van Wijk's demo program]

Golf of Mexico

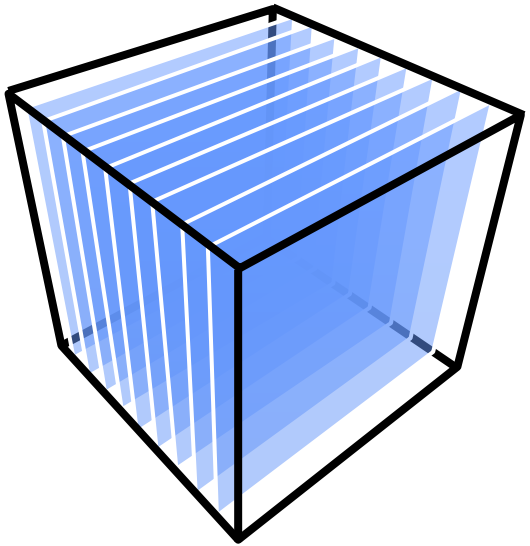


Data set: 352 x 320, 183 time steps [Data courtesy of O'Brien, FSU]

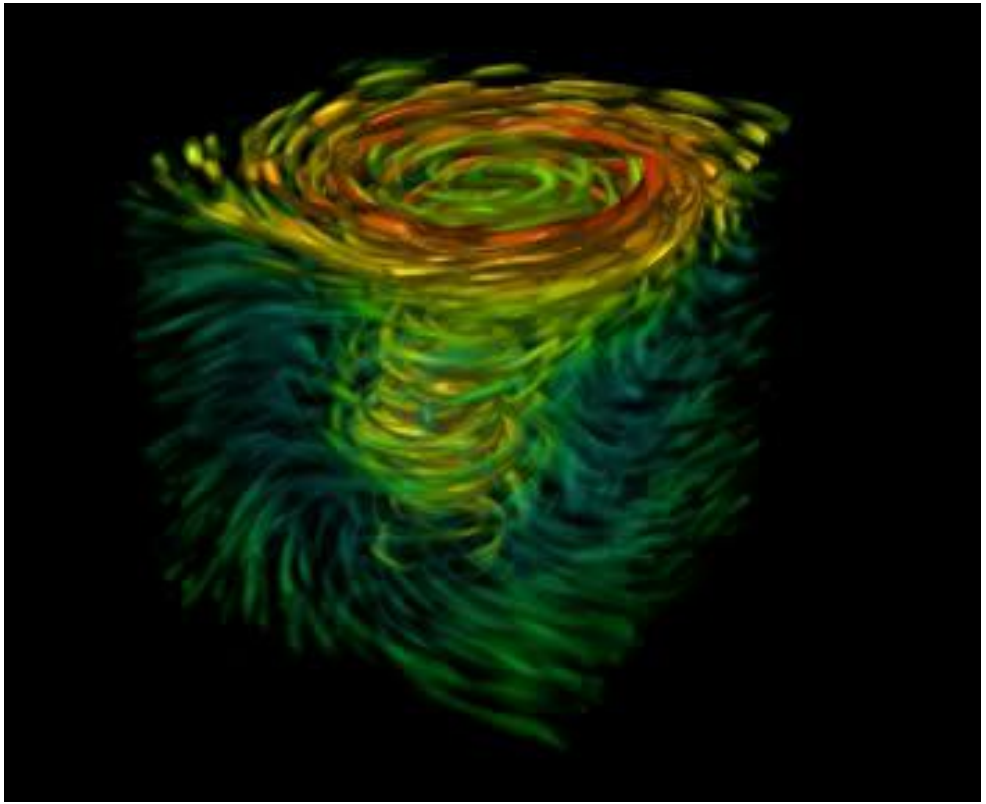
[Weiskopf et al. 2005]

2D and 3D LIC

- 2D case:
  - Only 2D textures (vector field, noise, result)
  - Rendering is trivial: just 2D image
- 3D case:
  - 3D textures for vector field and noise
  - Slice-by-slice output
  - Volume rendering
- 3D alternative:
  - On-the-fly computation [Falk, Weiskopf 2008]
  - Integrated within GPU ray casting
  - Lazy evaluation: output sensitivity

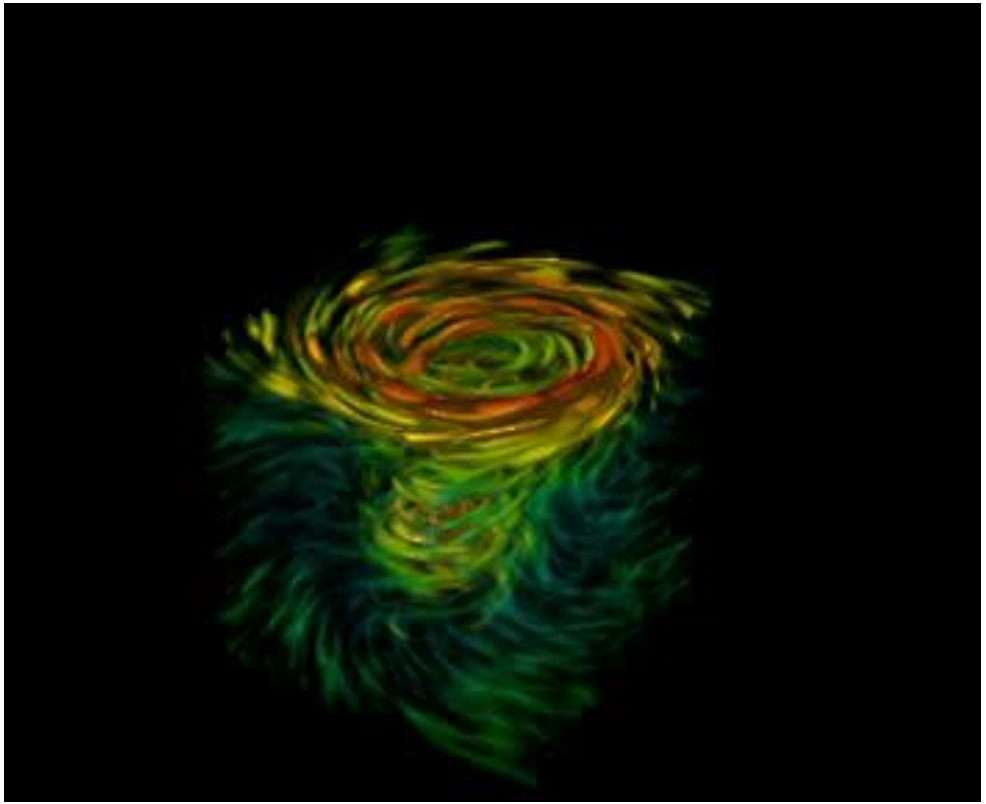


3D LIC On-the-Fly



[Falk, Weiskopf 2008]

3D LIC On-the-Fly



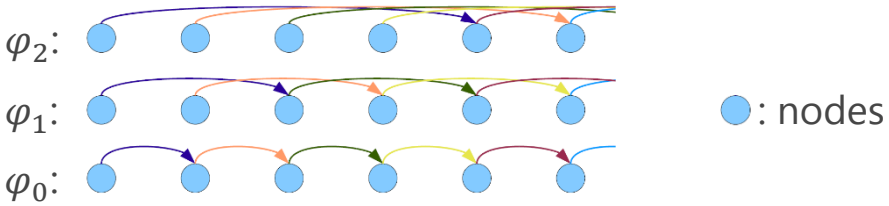
[Falk, Weiskopf 2008]

Hierarchical Line Integration

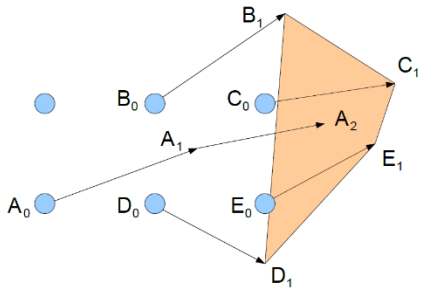
[Hlawatsch et al. 2011]

- Coordinate maps

φ_i	$: D \to D\ ,\ D \subseteq \mathbb{R}^n$
x	: start point of traj.
$\varphi_i(x)$	: end point of traj.
i	: hierarchy level



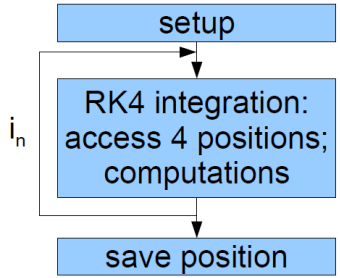
  - φ_0 obtained, e.g., by integration
  - $\varphi_{>0}$ constructed by "concatenation"
  - All levels have same resolution (no pyramid)
  - Overwrite (store only highest level)



- general case: end points not at nodes → interpolation

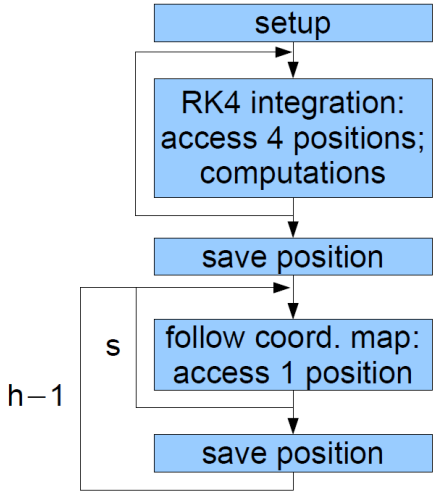
Hierarchical Line Integration: Procedure

traditional approach
(*n* integration steps)



O(*n*)

hierarchical approach
(*h* levels)



O(h) = O(log *n*)

integration of initial trajectories

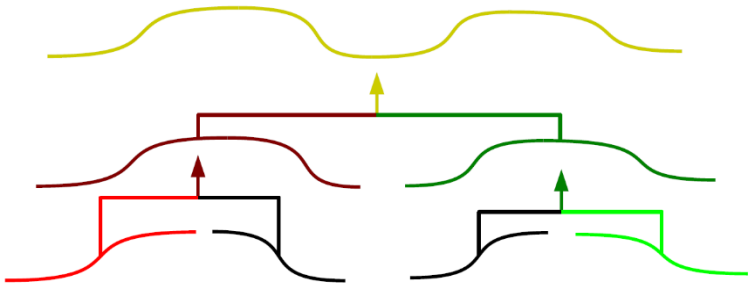
$\rightarrow \varphi_0$

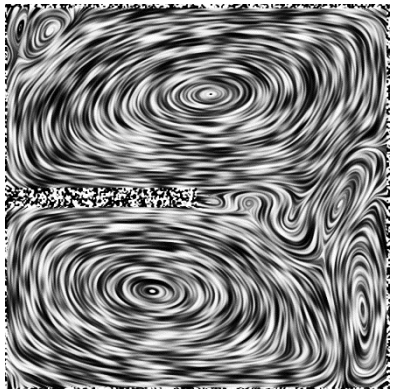
one catenation (s = 2) for next level

$\rightarrow \varphi_{+1}$

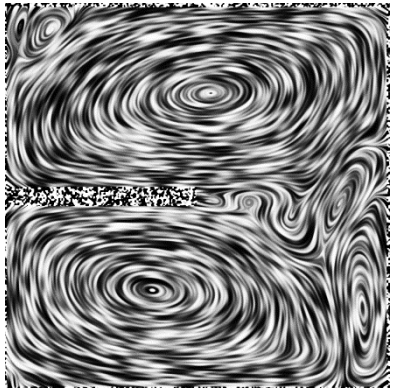
Hierarchical Convolution

- Perform LIC operations inside hierarchical scheme
  - Combine intermediate quantities from integration
  - Convolution of Gaussian with Gaussian is Gaussian





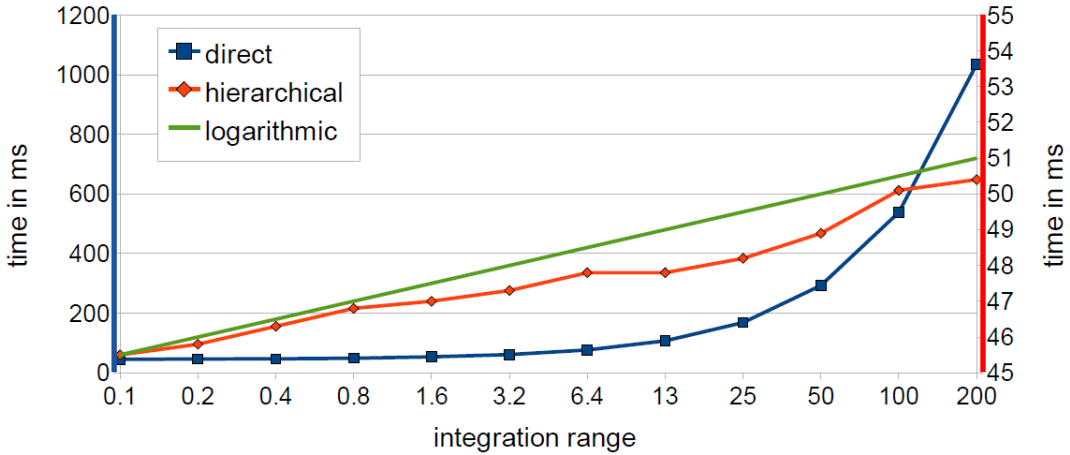
straightforward



hierarchical

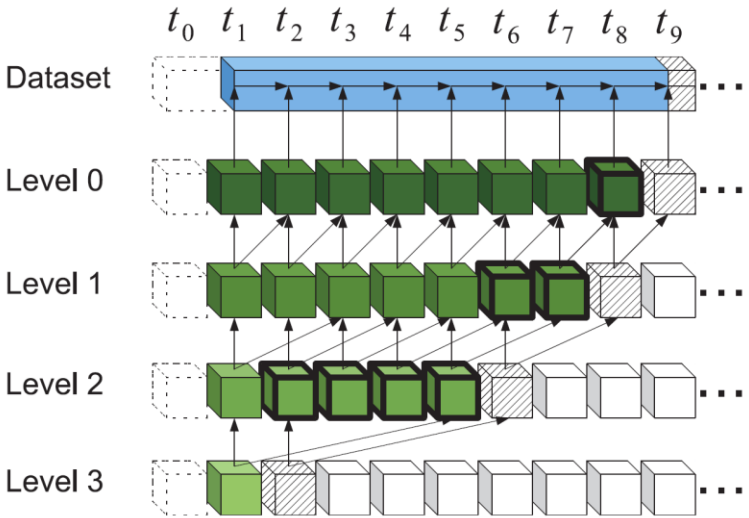
[Hlawatsch et al. 2011]

Performance of Hierarchical Integration



[Hlawatsch et al. 2011]

Time-Dependent Hierarchical Integration



- level 0: from data set (by integration, blue)
- green: required for result at time t_1 (at level 3)
- bold outlines: blocks kept in memory (overwrite)
- hatched: next time blocks

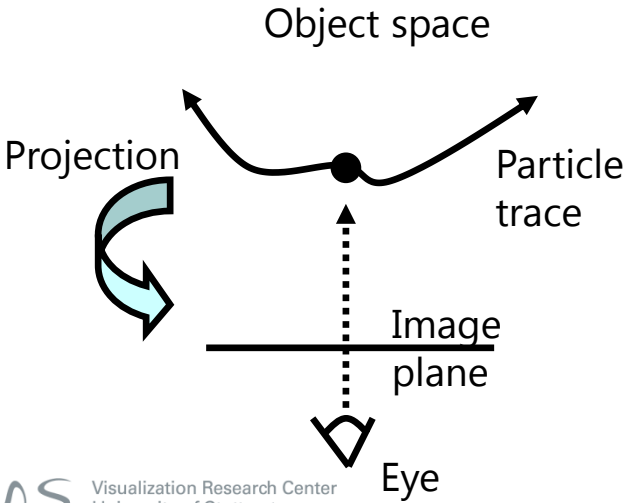
- integration range → number of blocks in memory
- scheme pays off for time series, i.e., dense trajectory seeding in time

- no temporal interpolation needed

[Hlawatsch et al. 2011]

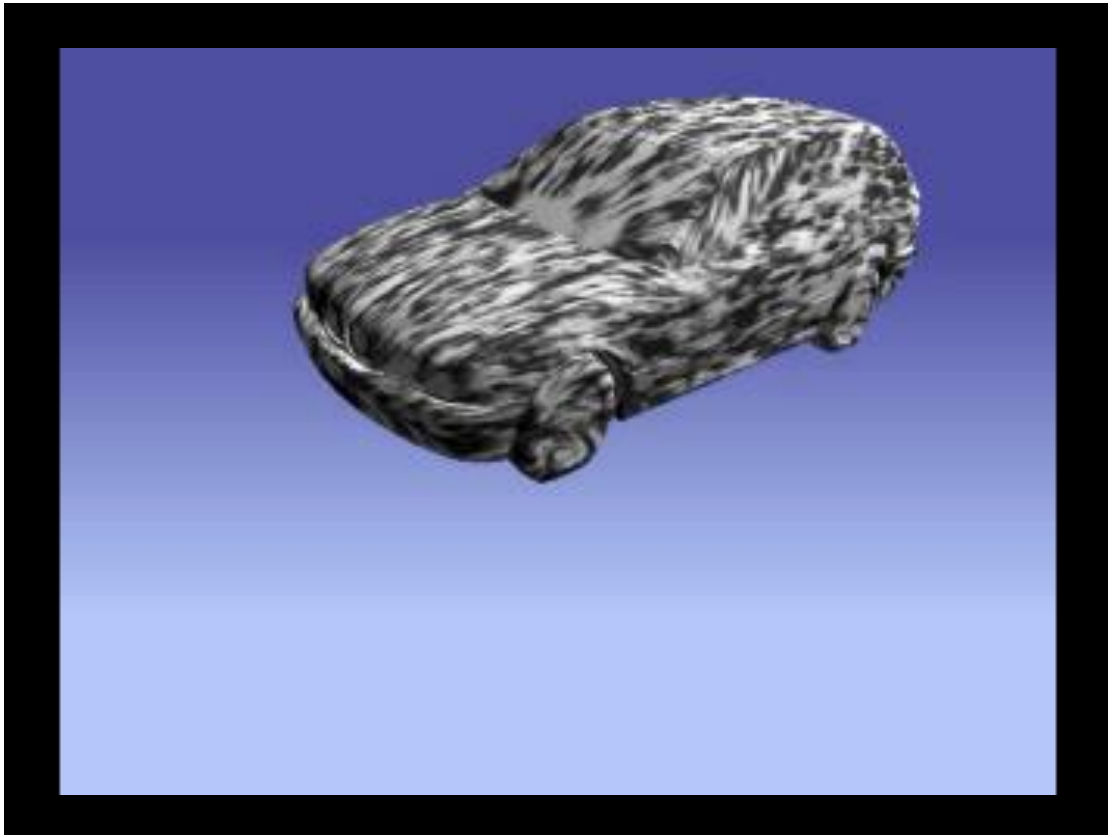
2.5D LIC

- Adapted to flow on boundaries
- Image-space methods
  [Van Wijk 2003], [Laramee et al. 2003], [Weiskopf, Ertl 2004b]



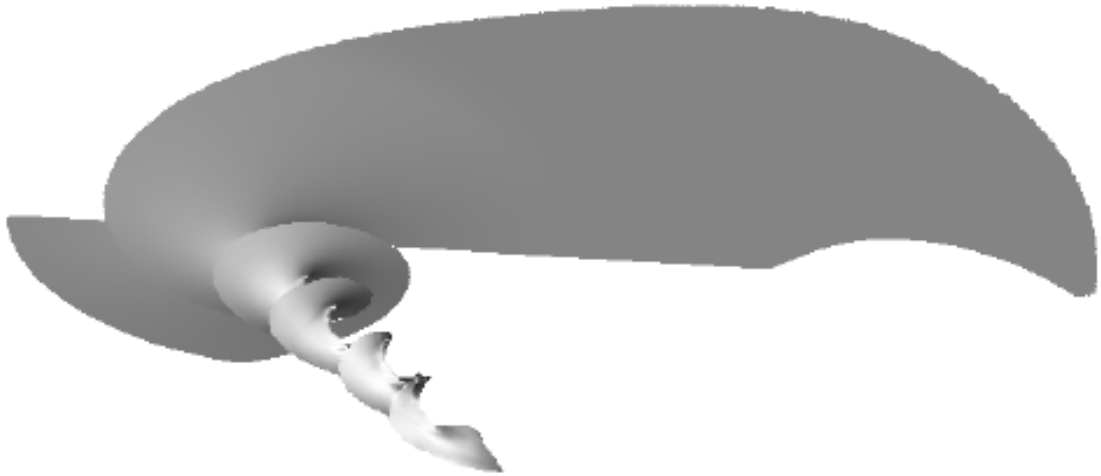
[Weiskopf, Ertl 2004b]

2.5D LIC



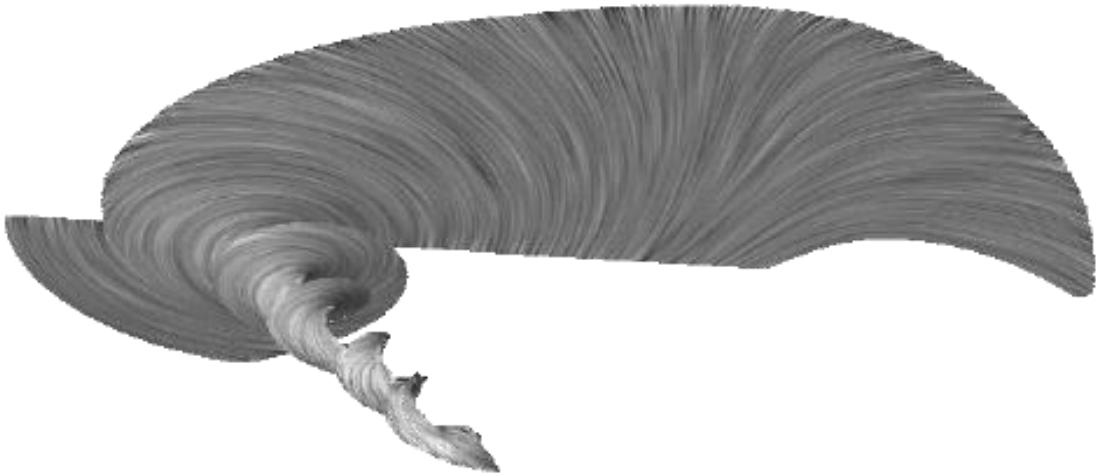
[Weiskopf, Ertl 2004b]

On Pathsurfaces



[Schafhitzel et al. 2007]

On Pathsurfaces



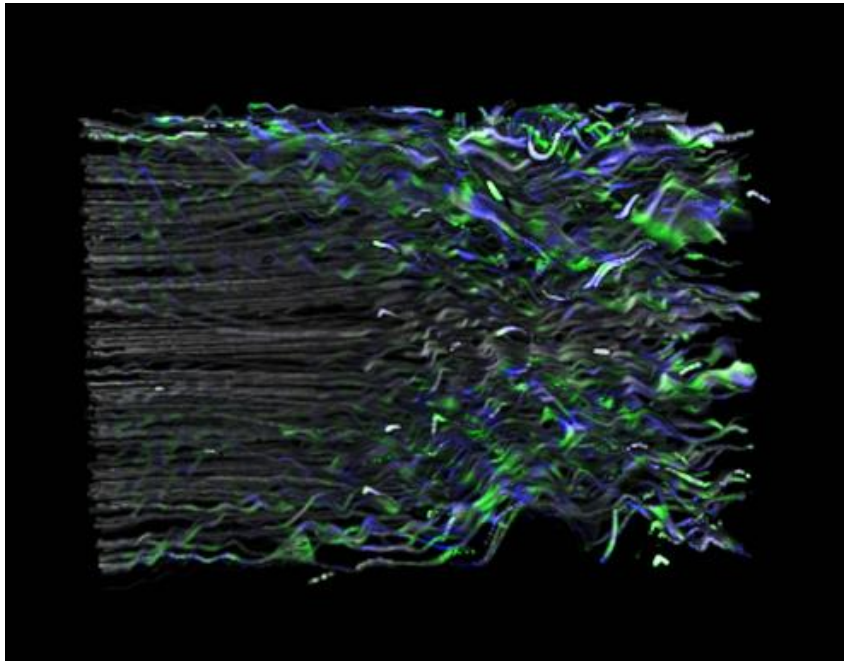
[Schafhitzel et al. 2007]

Effective Visual Representation

- Perceptual issues for 3D LIC and texture advection
  - Spatial perception: Orientation, depth
  - Clutter
  - Occlusion

Improved Rendering

- Improve spatial perception [Interrante, Grosch 1997]
  - Illumination
  - Halos
  - Depth cues
  - Line continuity



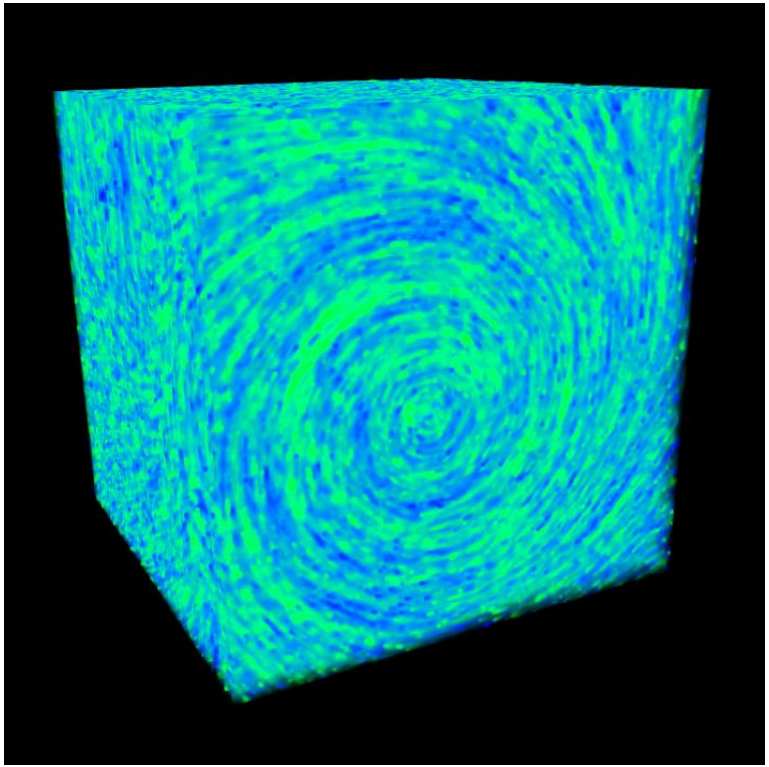
[Courtesy of Interrante, image reprinted from Weiskopf, Erlebacher 2005]

Spatial Perception

- Technical solution:
  Real-time volumetric illumination
  [Weiskopf et al. 2007], [Falk, Weiskopf 2008]
  - On-the-fly computation of gradients
  - Various illumination models (Phong, cool/warm, halos)
  - Tangent-based illumination

Spatial Perception

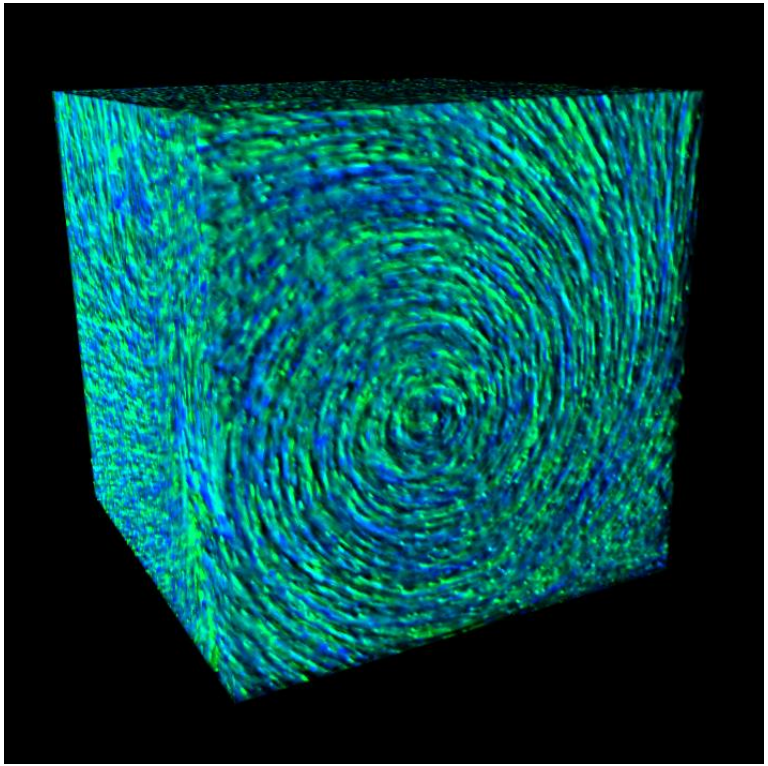
- No illumination



[Weiskopf et al. 2007]

Spatial Perception

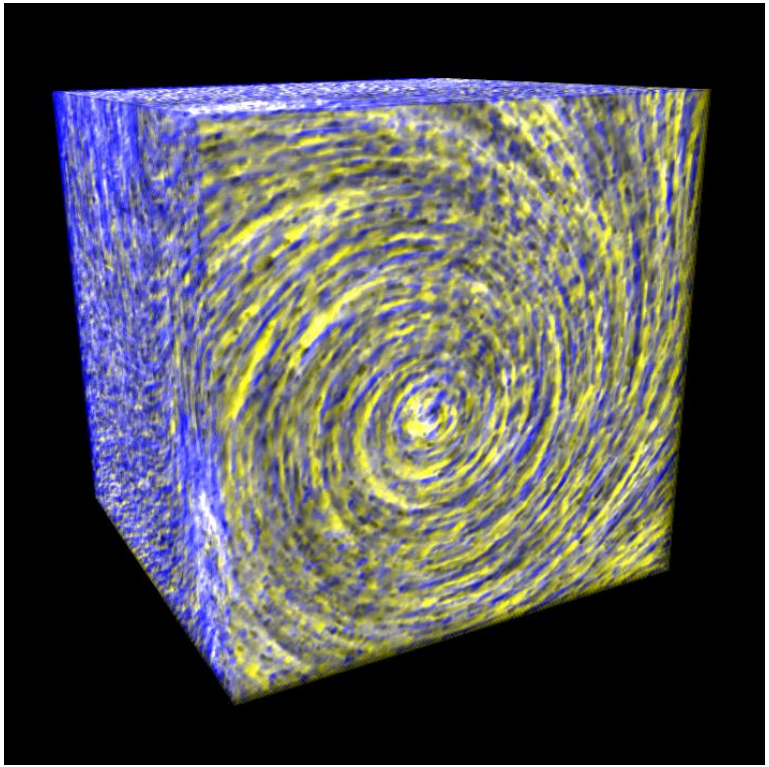
- Phong illumination



[Weiskopf et al. 2007]

Spatial Perception

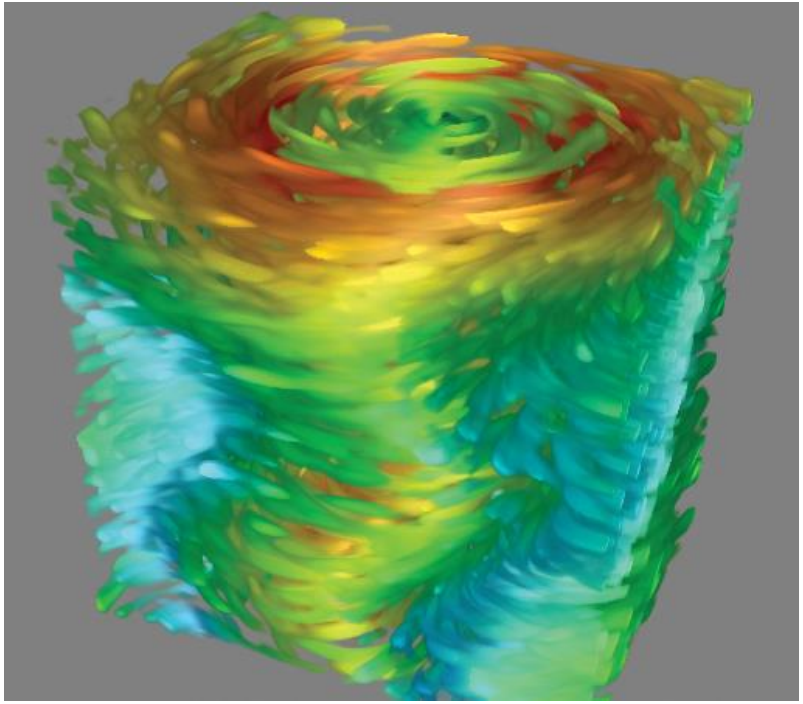
- Cool/warm



[Weiskopf et al. 2007]

Codimension-2 Illumination

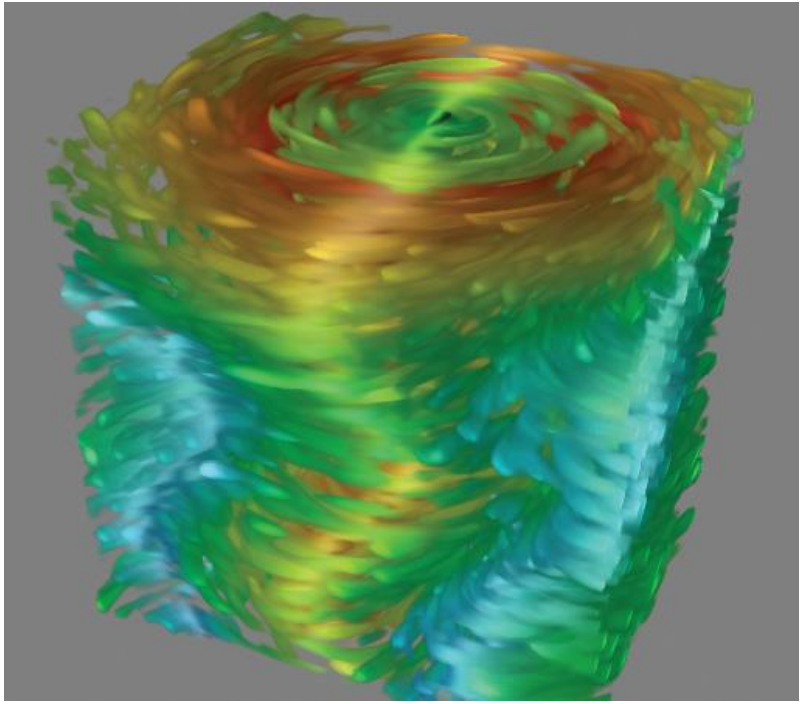
- Illuminated streamlines: no gradients computed



[Falk, Weiskopf 2008]

Codimension-2 Illumination

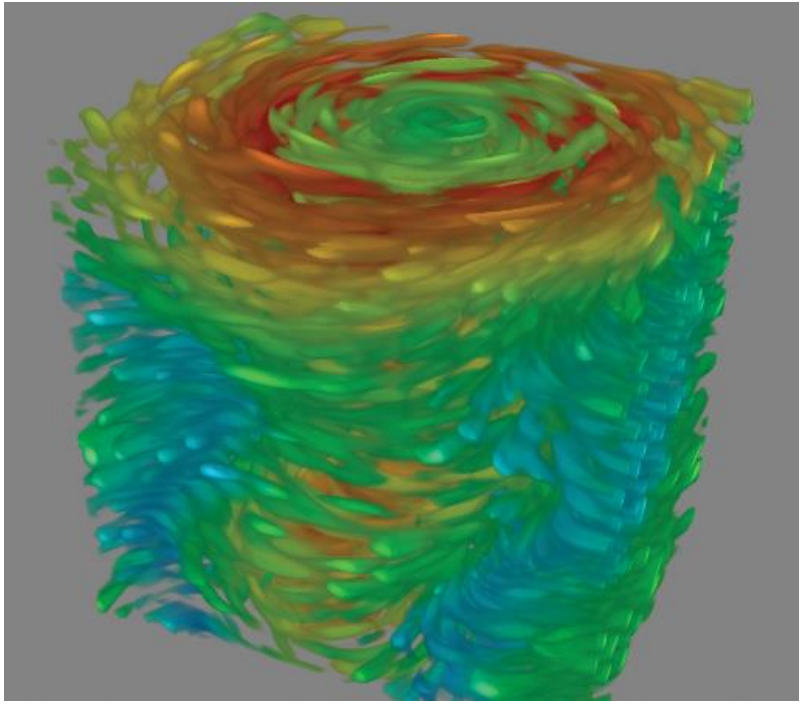
- Alternative codimension-2 illumination model (Mallo)



[Falk, Weiskopf 2008]

Codimension-2 Illumination

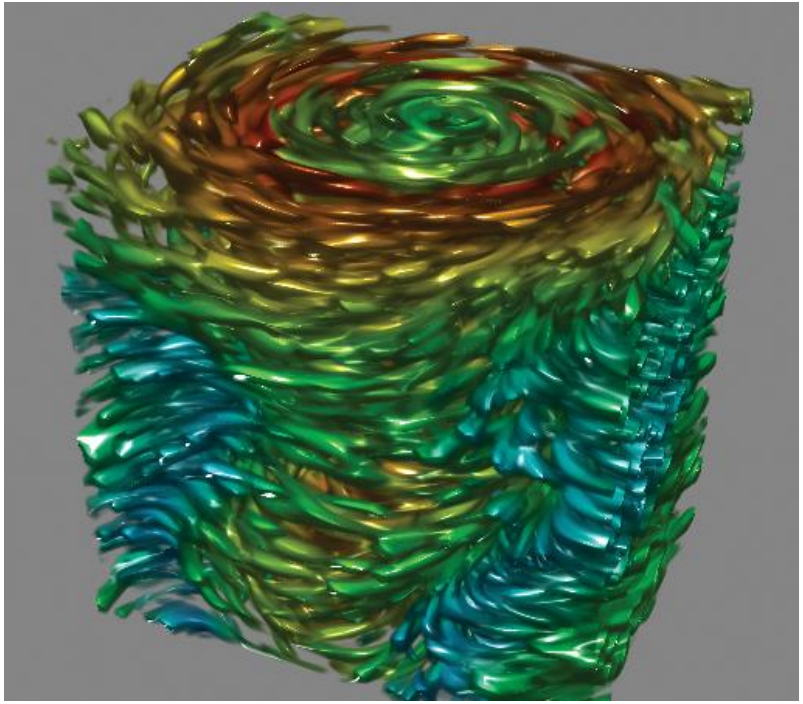
- Comparison:
  without illumination



[Falk, Weiskopf 2008]

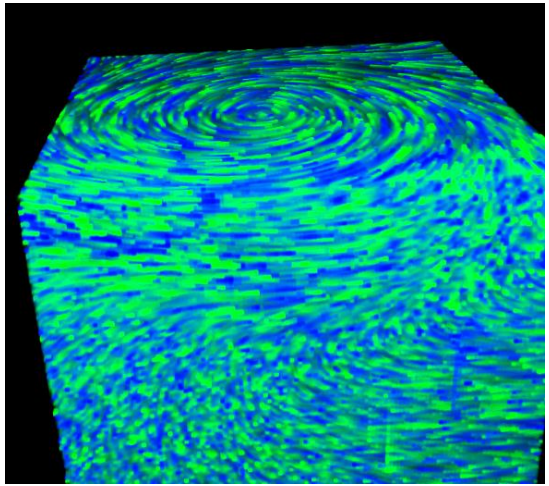
Codimension-2 Illumination

- Comparison:
  gradient-based illumination



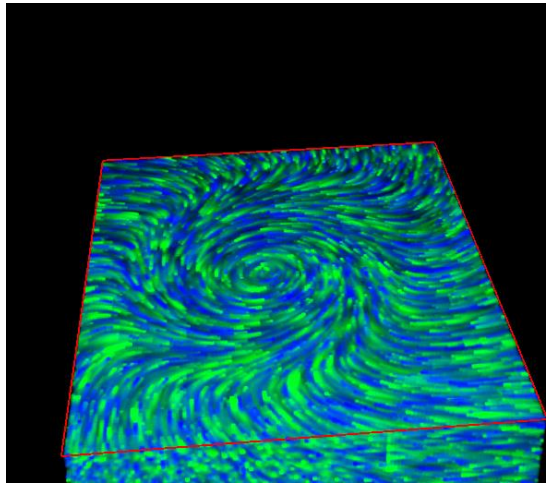
[Falk, Weiskopf 2008]

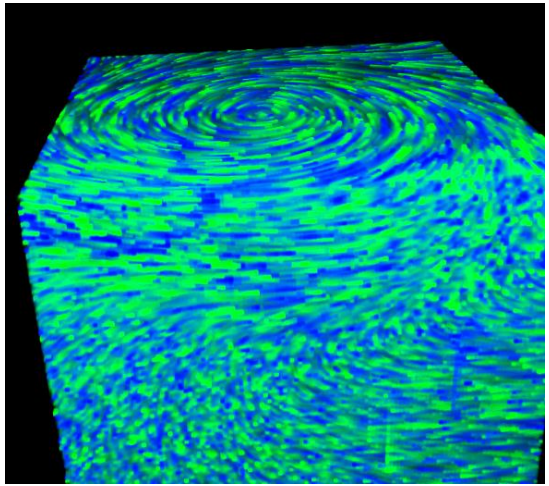
Clutter and Occlusion



[Weiskopf, Ertl 2004a]

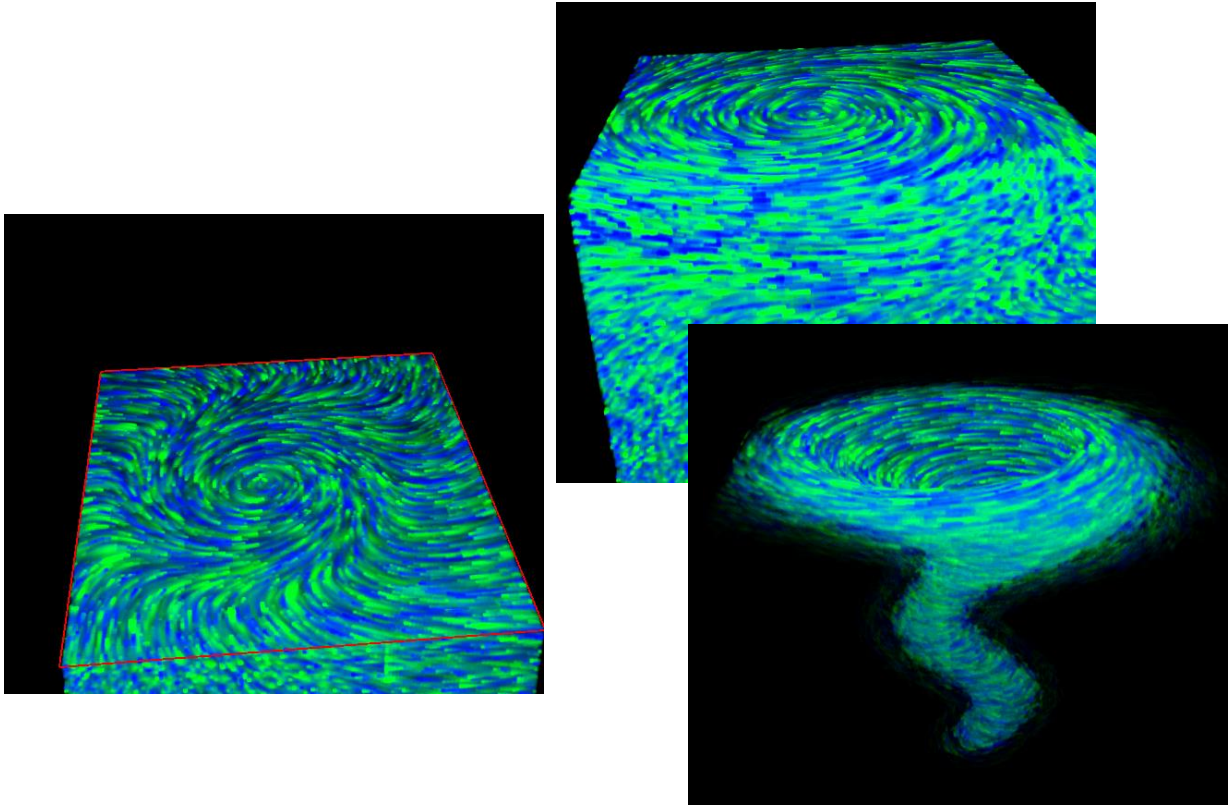
Clutter and Occlusion





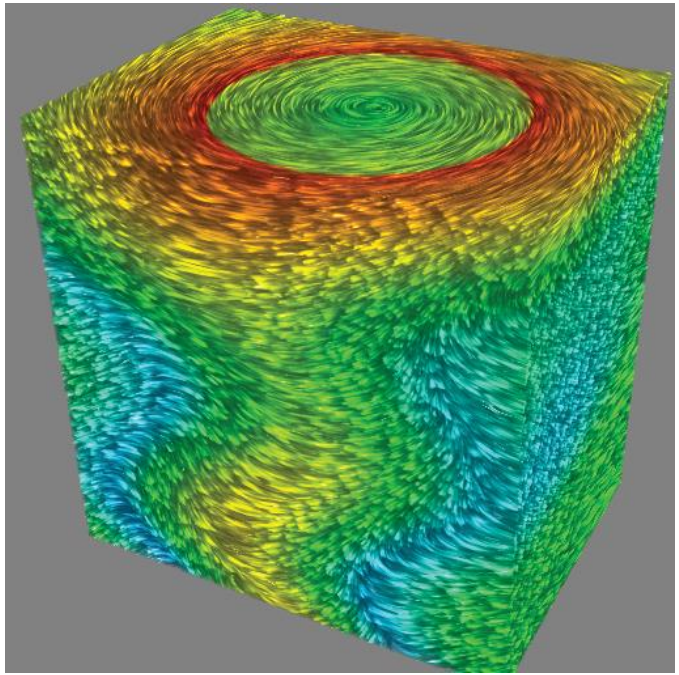
[Weiskopf, Ertl 2004a]

Clutter and Occlusion

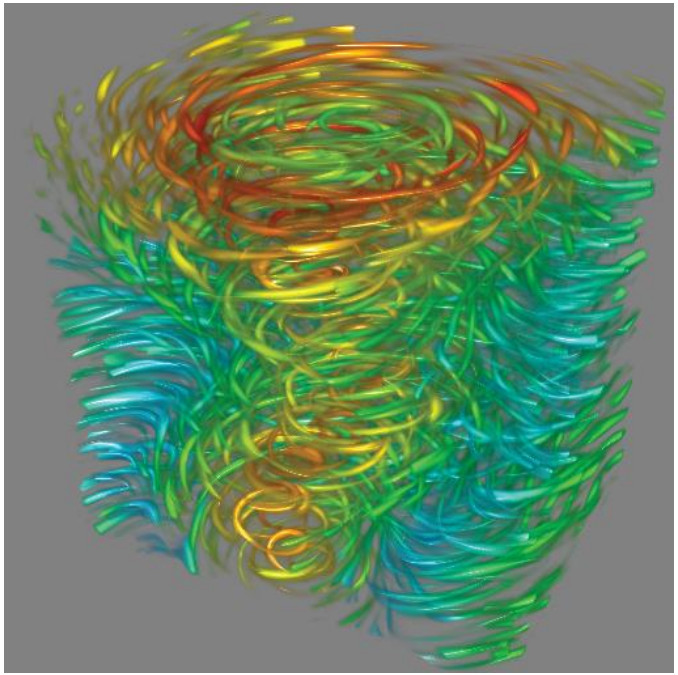


[Weiskopf, Ertl 2004a]

Different Noise Models: “Seeding”



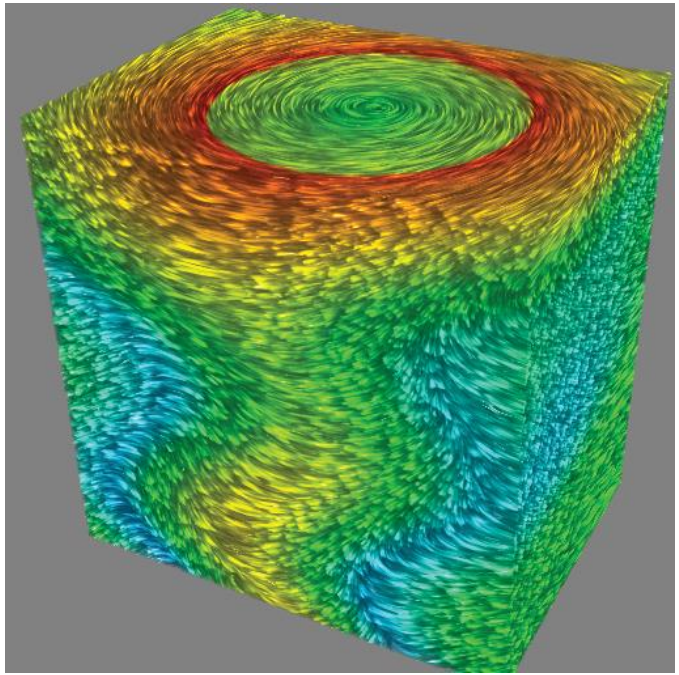
Dense (white noise)



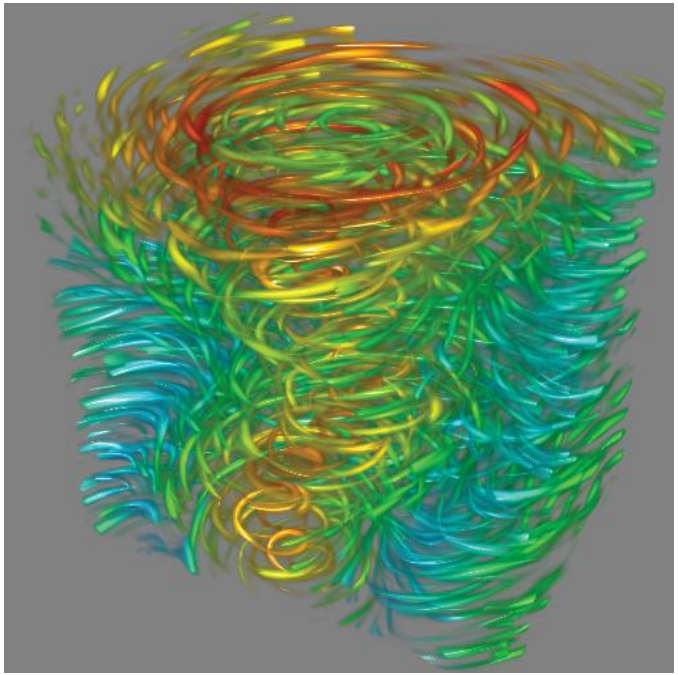
Sparse noise

[Falk, Weiskopf 2008]

Different Noise Models: “Seeding”



Dense (white noise)



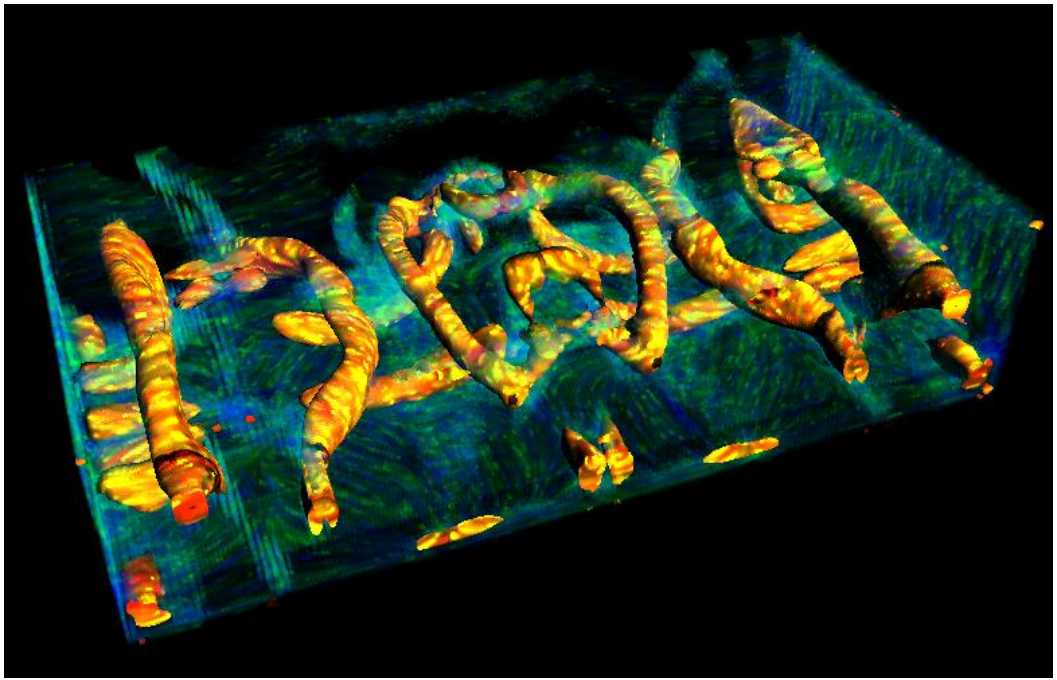
Sparse noise

see from before: Streamlines in 3D: Techniques beyond Seed Placement

[Falk, Weiskopf 2008]

Flow Feature Extraction

- 3D interest function
  - Domain knowledge
  - Interactive exploration

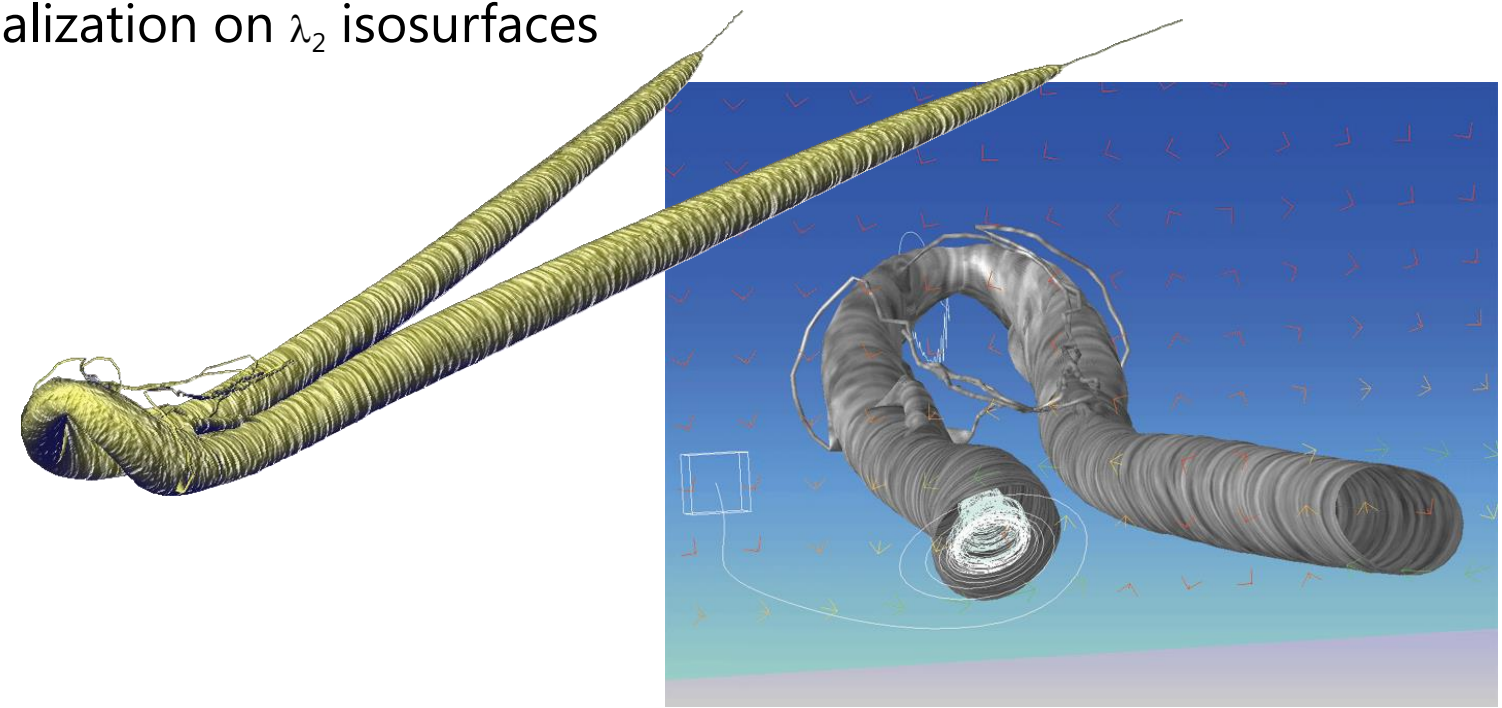


Vortex extraction with λ_2

[Weiskopf et al. 2007]

Flow Feature Extraction

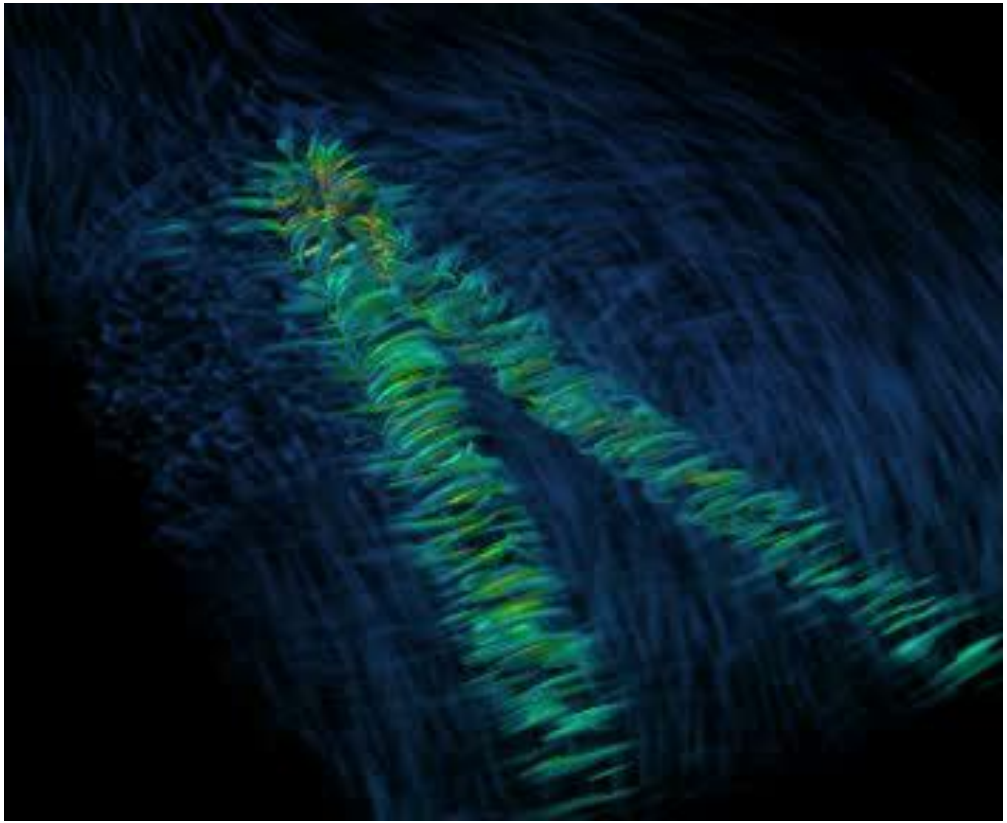
- 2.5D visualization on λ_2 isosurfaces



[Schafhitzel et al. 2006]

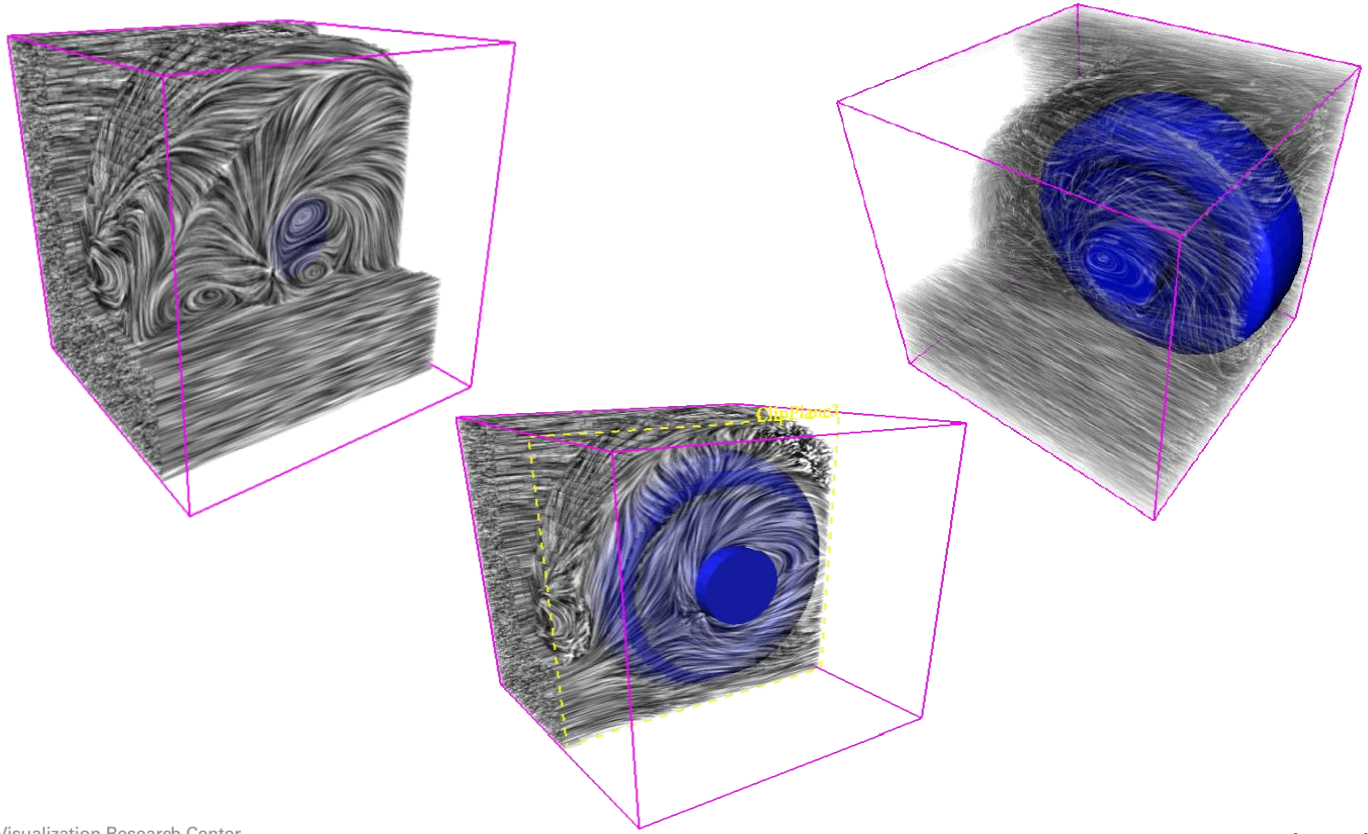
Flow Feature Extraction

- 3D LIC with λ_2 feature enhancement



[Falk, Weiskopf 2008]

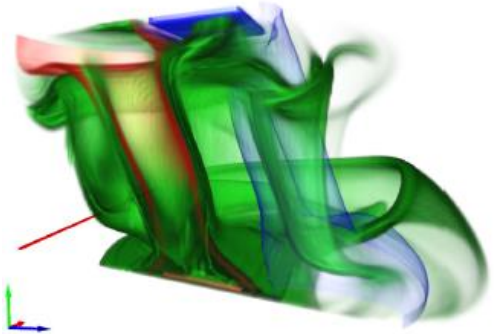
Clipping and Semi-Transparency



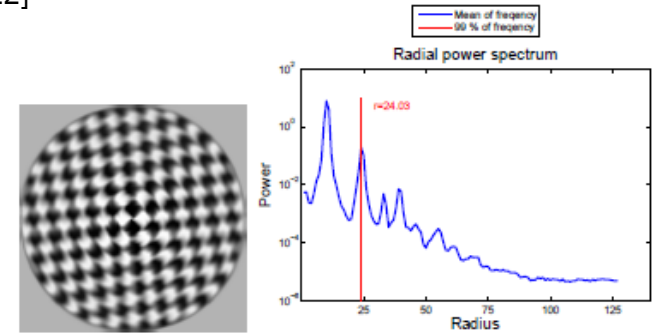
[Rezk-Salama et al. 1999]

Outlook: Topics Not Covered Here

- Physically oriented dye advection
  - Advection and diffusion [Karch et al. 2012]
- Numerical quality of dye and texture advection
  - Level-set and particle level-sets
    [Weiskopf 2004b], [Cuntz et al. 2008]
  - WENO schemes [Karch et al. 2012]
  - Higher-order and BFECC advection [Netzel et al. 2012]
- Quality of filtering
  - Frequency analysis: low-pass filter characteristics [Netzel et al. 2012] , [Weiskopf 2009]



[Karch et al. 2012]

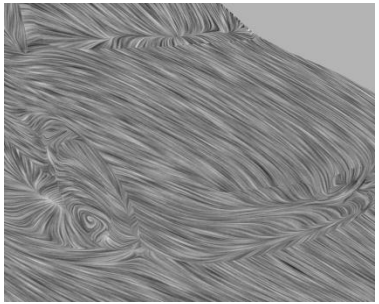


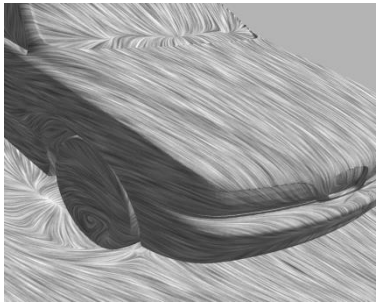
[Netzel et al. 2012]

Outlook: Topics Not Covered Here

- Relationship to dense geometric curves and hybrid techniques [Verma et al. 1999], [Weiskopf et al. 2005]
- Control of rendering styles
  - Chameleon system [Li et al. 2003]
- Non-uniform grids and higher-order reconstruction
- Perceptual graphics
  - Texture, color, motion perception
    [Bachthaler, Weiskopf 2008], [Weiskopf 2004a]

[Li et al. 2003]





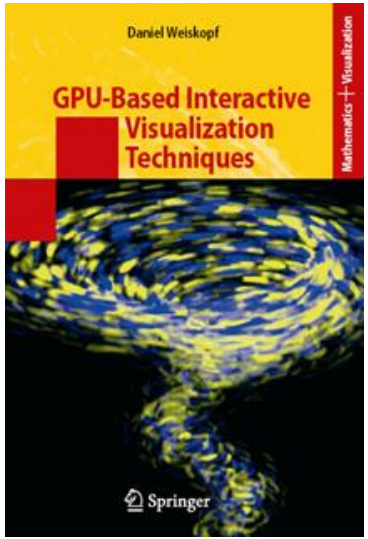
[Weiskopf 2004a]

Conclusion

- Texture-based vector field visualization
  - Flexible, widely applicable
  - Fast
- Components
  - Transport mechanism
  - Visual representation and rendering
  - Visualization quality

Further Material

www.vis.uni-stuttgart.de/texflowvis



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