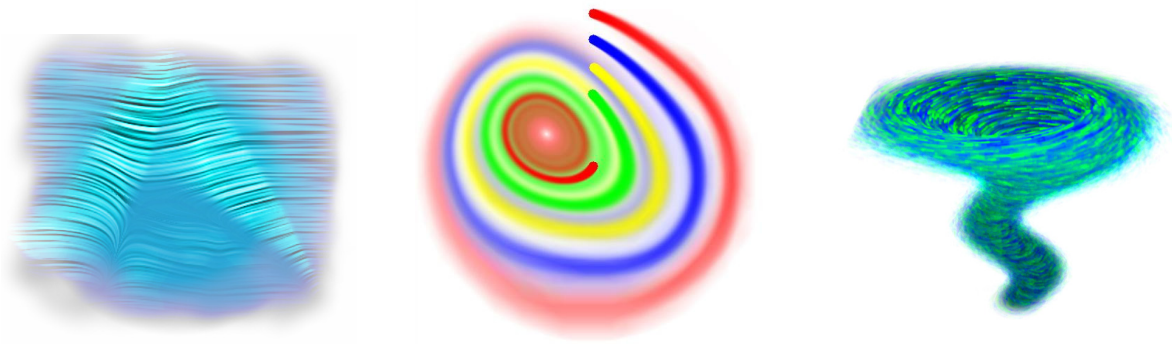


IEEE Visualization 2004 Tutorial



Interactive Texture-Based Flow Visualization

Organizer

- Daniel Weiskopf (University of Stuttgart)

Speakers

- Gordon Erlebacher (Florida State University)
- Robert S. Laramée (VRVis)
- Daniel Weiskopf (University of Stuttgart)

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Tutorial Description

Abstract

Interactive texture-based flow visualization has become an active field of research in the last three or four years. Recent progress in this field has led to efficient vector field visualization methods and, in particular, to improved techniques for time-dependent data. This tutorial covers approaches for vector fields given on 2D planes, on surfaces, and within 3D volumes. Both the theoretical background and the GPU-oriented implementations of many of these techniques are presented, along with a demonstration of their usefulness by means of typical applications.

Tutorial Web Page

http://www.vis.uni-stuttgart.de/vis04_tutorial

This web page contains example images, slides, and additional material.

Duration

Half-day.

Level of the Tutorial

Intermediate.

The tutorial is aimed at scientific researchers and developers of visualization tools. Participants should have basic programming skills and some background knowledge of flow visualization; they should be familiar with OpenGL and / or DirectX. Basic knowledge of graphics hardware and GPU programming is helpful, although a brief introduction to GPU programming will be given in the tutorial. Basic previous knowledge of flow visualization is recommended.

Organization and List of Topics

1. Introduction [15 min] (D. Weiskopf):
Introductory words; motivation; visualization pipeline; traditional flow visualization techniques (glyphs, geometric streamlines, feature-based approaches), overview of the course.
2. Basics of GPU-Based Programming [15 min] (D. Weiskopf):
Structure of modern GPUs (graphics processing units); rendering pipeline; low-level programming; shading languages.
3. 2D Texture-Based Flow Visualization [60 min] (G. Erlebacher):
Line integral convolution (LIC), texture advection, Lagrangian-Eulerian Advection (LEA), Image Based Flow Visualization (IBFV), dye advection, large data visualization via tiling, generalization of time-dependent 2D flow visualization within a generic framework, CPU vs. GPU implementations, applications (meteorology, CFD).
4. 2.5D Flow Visualization [40 min] (R. S. Laramée):
Object space vs. surface parameterization (e.g., on curvilinear grids) vs. image space approaches, Image-Space Advection (ISA), Image Based Flow Visualization on Surfaces (IBFVS), flow on isosurfaces, CPU vs. GPU implementations, applications (visualization of CFD simulation data, in-cylinder flow of automotive engines, oceanography).
5. 3D Texture-Based Flow Visualization [40 min] (D. Weiskopf):
3D LIC, 3D texture advection, 3D IBFV, preprocessing of streamlines in textures (Chameleon system), GPU implementations, perception issues.
6. Summary, Questions and Answers [10+ min] (all speakers)

Description of Topics

Introduction. The tutorial starts with a short introduction that contains an outline of the time schedule, some examples of areas of application for flow visualization, a few example images for alternative visualization approaches (streamlines or similar geometric objects, feature-based techniques), and the classification scheme that we follow to structure the topics of this tutorial. The following classification parameters are used: spatial dimension of the visualization domain (2D, 2.5D = on surfaces, and 3D), steady vs. unsteady flow, CPU vs. GPU-based approaches, and type of internal representation (object space vs. image space). Dimensionality serves as basis for the overall organization, the other aspects are indicated along the discussion of the corresponding visualization methods.

GPU Programming. A brief summary of some background of GPU programming is included to support participants that have some previous knowledge of GPU programming. A

comprehensive presentation of GPU programming, however, is beyond the scope of this tutorial.

2D Flow Visualization. This part deals with texture-based flow visualization techniques for 2D planar domains. We start with fundamental “classic” approaches like LIC and original texture advection. Subsequently, more recent techniques for time-dependent flow are explained in detail, ranging from LEA to IBFV and dye advection. Building on this algorithmic background, application, implementation, and large-data visualization topics are discussed for these techniques. Implementation issues are focused on details of GPU realizations. Finally, a generic framework is presented to compare the previously mentioned techniques and to relate them to each other.

2.5D Flow Visualization. This part focuses on recent developments for texture-based flow visualization on surfaces. Both ISA and IBFVS work on image space to avoid problems of older approaches that require a time-consuming computation in object space or a parameterization of the surface. A brief comparison between object-space, image-space, and parameterization approaches serves as introduction to this part. Special attention is paid to the application of these techniques to real-world examples from CFD because a good choice for the surface is essential to an intuitive and effective visualization.

3D Flow Visualization. We discuss 3D texture-based flow visualization in the last part. A brief presentation of 3D LIC is followed by an in-depth discussion of 3D texture advection. One major issue of dense 3D representations is the large amount of numerical operations involved. Therefore, efficient GPU implementations play an important role and are compared for 3D IBFV and GPU-based texture advection. As an alternative approach, a pre-computation of streamlines within a volumetric texture, as in the Chameleon system, overcomes some of these efficiency problems. Finally, some perception issues of visual clutter and spatial perception are mentioned and an outlook on possible future developments for perception-oriented interactive representations is given.

Summary. The tutorial closes with an overall questions & answers session.

Speakers' Background

Gordon Erlebacher

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Gordon Erlebacher currently works in the School of Computational Science & Information Technology at Florida State University. His fields of expertise span the intersection of numerical flow simulations, flow visualization, and Information Technology. He received his undergraduate degree at the Polytechnique Institute at the Free University of Brussels in 1979 and his Ph.D at Columbia University, both in the field of Plasma Physics. His work at NASA Langley Research Center (1983-1996) centered primarily on the simulation of compressible fluid transition and turbulence. During this time, he developed extensive graphical software to help better understand the massive datasets produced by the simulations. This included techniques to display particle paths, streamlines, and volume rendering. Early experiments with remote visualization were also performed during this period. He has been a Professor in the Department of Mathematics and Computer Science at Florida State University since 1996. He has taught several courses on flow visualization and feature extraction. He has contributed several papers and case studies to IEEE Visualization, TVCG, and two articles on vector field visualization (together with D. Weiskopf) in the upcoming Handbook of Visualization. His current research focuses on the use of modern graphics hardware to develop real-time algorithms for vector field visualization. Other interests include shape recognition, use and development of distributed visualization services across heterogeneous systems, fluid simulation, and geometric algebra.

More information on his research projects is available online at:
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Robert S. Laramee received a bachelors degree in physics, cum laude, from the University of Massachusetts, Amherst in 1997. In 2000, he received a masters degree in computer science from the University of New Hampshire, Durham. He is currently a PhD candidate

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For more detailed description of his research, please visit:
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Daniel Weiskopf is senior researcher and teacher of computer science at the Institute of Visualization and Interactive Systems at the University of Stuttgart (Germany). He studied physics at the University of Tübingen (Germany), San Francisco State University, and the University of California at Berkeley. He received a Diplom (Masters) of physics in 1997 and a PhD in theoretical astrophysics in 2001, both from the University of Tübingen. Daniel Weiskopf authored several articles on scientific visualization and computer graphics, and he is regularly teaching courses and seminars on computer graphics, visualization, geometric modeling, and computer animation. He was co-organizer of the SIGGRAPH 2001 Course on “Visualizing Relativity” and organizer of the IEEE Visualization 2003 Tutorial on “Interactive Visualization of Volumetric Data on Consumer PC Hardware”; and he participated in the Eurographics 2002 Tutorial “Programmable Graphics Hardware for Interactive Visualization” and the Eurographics 2003 Tutorial “Programming Graphics Hardware”. His research interests include scientific visualization, real-time graphics, virtual reality, interaction techniques, non-photorealistic rendering, computer animation, special and general relativity.

Detailed information about his research projects are available online at:
<http://www.vis.uni-stuttgart.de/~weiskopf>

Literature on Texture-Based Flow Visualization

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University of Stuttgart

R. S. Laramée
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Survey Papers and Course Notes

The goal of this short note is to provide references for further reading on flow visualization and, in particular, on texture-based flow visualization. Because of the large number of research papers in this field, we cannot include an exhaustive list of references here but rather point to corresponding survey papers and course notes.

An overview of flow visualization in general can be found in the state-of-the-art report by Post et al. [8] and a flow visualization chapter [13] in the forthcoming “Handbook on Visualization” [3].

According to one possible classification scheme (see the survey paper [4], which is included as a reprint in Section C), there are different approaches to flow visualization:

- *Direct flow visualization*: This category of techniques uses a translation that is as direct as possible for representing flow data in the resulting visualization. Common approaches are drawing arrows or color coding velocity (see [8, 13] for more details and references).
- *Dense, texture-based flow visualization*: A texture is computed that is used to generate a dense representation of the flow. A notion of where the flow moves is incorporated through correlated texture values along the vector field. In most cases this effect is achieved through filtering of texture values according to the local flow vector. This approach is the focus of this tutorial. A description of the state-of-the-art can be found in Section C (a reprint of [4]). Texture-based flow visualization is also covered in other surveys [1, 10].
- *Geometric flow visualization*: For a better communication of the long-term behavior induced by flow dynamics, integration-based approaches first integrate the flow data and use geometric objects as a basis for flow visualization. The resulting integrated objects have a geometry that reflects the properties of the flow. Examples include streamlines,

streaklines, and pathlines. A description of geometric techniques is presented by Post et al. [8].

- *Feature-based flow visualization*: Another approach makes use of an abstraction and/or extraction step that is performed before visualization. Special features are extracted from the original data set, such as important phenomena or topological information of the flow. Visualization is then based on these flow features. Feature-based flow visualization is covered in the state-of-the-art report by Post et al. [9], a chapter [2] in the “Handbook on Visualization” [3], and this year’s IEEE Visualization Tutorial on “Feature Oriented Methods in Flow Visualization”.

Recent Papers

In this section, some of the most recent papers on texture-based flow visualization (which are not contained in any of the aforementioned survey articles) are briefly described.

Laramee et al. [6] present a side-by-side analysis of two recent image space approaches for the visualization of vector fields on surfaces. The two methods, Image Space Advection (ISA) [5] and Image Based Flow Visualization for Curved Surfaces (IBFVS) [11] generate dense representations of time-dependent vector fields with high spatio-temporal correlation. While the 3D vector fields are associated with arbitrary surfaces represented by triangular meshes, the generation and advection of texture properties is confined to image space. Fast frame rates are achieved by exploiting frame-to-frame coherency and graphics hardware. In the comparison of ISA and IBFVS the authors point out the strengths and weaknesses of each approach and give recommendations as to when and where they are best applied.

In [14], the aforementioned approaches for a dense texture-based visualization of vector fields on curved surfaces are extended. The advection mechanism relies on a Lagrangian particle tracing that is simultaneously computed in the physical space of the object and in the device space of the image plane. This approach retains the benefits of previous image-space techniques [5, 11], such as output sensitivity, independence from surface parameterization or mesh connectivity, and support for dynamic surfaces. At the same time, frame-to-frame coherence is achieved even when the camera position is changed.

In [12], an approach for dye advection is proposed to avoid the artificial blurring that is present in previous texture-based implementations of dye advection that make use of permanent resampling by bilinear or trilinear interpolation. The interface between dye and background is modeled as a level-set within a signed distance field. The level-set evolution is governed by the underlying flow field and is computed by a semi-Lagrangian method. A reinitialization technique is used to counteract the distortions introduced by the level-set evolution and to maintain a level-set function that represents a local distance field.

An IEEE Visualization 2004 Application Paper [7] investigates two important, common fluid flow patterns from computational fluid dynamics (CFD) simulations, namely, swirl and tumble motion typical of automotive engines. The authors investigate and visualize swirl and tumble flow using three different flow visualization techniques: direct, geometric, and texture-based. When illustrating these methods side-by-side, they describe the relative strengths and weaknesses of each approach within a specific spatial dimension and across multiple spatial dimensions typical of an engineer's analysis. Based on this investigation perspectives are offered on where and when these techniques are best applied in order to visualize the behavior of swirl and tumble motion.

References

- [1] G. Erlebacher, B. Jobard, and D. Weiskopf. Flow textures: High-resolution flow visualization. In C. R. Johnson and C. D. Hansen, editors, *Visualization Handbook*, pages 271–285. Academic Press, 2004. In print.
- [2] M. Jiang, R. Machiraju, and D. S. Thompson. Detection and visualization of vortices. In C. R. Johnson and C. D. Hansen, editors, *Visualization Handbook*. Academic Press, 2004. In print.
- [3] C. R. Johnson and C. D. Hansen, editors. *Visualization Handbook*. Academic Press, 2004.
- [4] R. S. Laramee, H. Hauser, H. Doleisch, B. Vrolijk, F. H. Post, and D. Weiskopf. The state of the art in flow visualization: Dense and texture-based techniques. *Computer Graphics Forum*, 23(2):143–161, 2004.
- [5] R. S. Laramee, B. Jobard, and H. Hauser. Image space based visualization of unsteady flow on surfaces. In *IEEE Visualization '03*, pages 131–138, 2003.
- [6] R. S. Laramee, J. J. van Wijk, B. Jobard, and H. Hauser. ISA and IBFVS: Image space based visualization of flow on surfaces. *IEEE Transactions on Computer Graphics and Visualization*, 10(6), 2004. Forthcoming.
- [7] R. S. Laramee, D. Weiskopf, J. Schneider, and H. Hauser. Investigating swirl and tumble flow with a comparison of visualization techniques. In *IEEE Visualization '04*, 2004. Forthcoming.
- [8] F. H. Post, B. Vrolijk, H. Hauser, R. S. Laramee, and H. Doleisch. Feature extraction and visualization of flow fields. In *Eurographics 2002 State-of-the-Art Reports*, pages 69–100, 2002.

- [9] F. H. Post, B. Vrolijk, H. Hauser, R. S. Laramée, and H. Doleisch. The state of the art in flow visualization: Feature extraction and tracking. *Computer Graphics Forum*, 22(4):775–792, 2003.
- [10] A. Sanna, B. Montrucchio, and P. Montuschi. A survey on visualization of vector fields by texture-based methods. *Recent Res. Devel. Pattern Rec.*, 1:13–27, 2000.
- [11] J. J. van Wijk. Image based flow visualization for curved surfaces. In *IEEE Visualization '03*, pages 123–130, 2003.
- [12] D. Weiskopf. Dye advection without the blur: A level-set approach for texture-based visualization of unsteady flow. *Computer Graphics Forum (Proceedings of Eurographics 2004)*, 23(3), 2004.
- [13] D. Weiskopf and G. Erlebacher. Flow textures. In C. R. Johnson and C. D. Hansen, editors, *Visualization Handbook*, pages 253–270. Academic Press, 2004. In print.
- [14] D. Weiskopf and T. Ertl. A hybrid physical/device-space approach for spatio-temporally coherent interactive texture advection on curved surfaces. In *Proceedings of Graphics Interface*, pages 263–270, 2004.

Reprint

R.S. Laramee, H. Hauser, H. Doleisch, B. Vrolijk, F.H. Post, D. Weiskopf: The State of the Art in Flow Visualization: Dense and Texture-Based Techniques, Computer Graphics Forum (2)23, 203-221, 2004.

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The State of the Art in Flow Visualization: Dense and Texture-Based Techniques

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Abstract

Flow visualization has been a very attractive component of scientific visualization research for a long time. Usually very large multivariate datasets require processing. These datasets often consist of a large number of sample locations and several time steps. The steadily increasing performance of computers has recently become a driving factor for a reemergence in flow visualization research, especially in texture-based techniques. In this paper, dense, texture-based flow visualization techniques are discussed. This class of techniques attempts to provide a complete, dense representation of the flow field with high spatio-temporal coherency. An attempt of categorizing closely related solutions is incorporated and presented. Fundamentals are shortly addressed as well as advantages and disadvantages of the methods.

Keywords: visualization, flow visualization, vector field visualization, texture-based flow visualization.

ACM CCS: I.3 [Computer Graphics]: visualization, flow visualization, computational flow visualization

1. Introduction

Flow visualization (FlowVis) is one of the classic subfields of visualization, covering a rich variety of applications, from the automotive industry, aerodynamics, turbomachinery design, to weather simulation, meteorology, climate modeling, ground water flow and medical visualization. Consequently, the spectrum of FlowVis solutions is very rich, spanning multiple technical challenges: 2D versus 3D solutions and techniques for steady or time-dependent data.

Bringing many of those solutions in linear order (as necessary for a text like this) is neither easy nor intuitive. Several options of subdividing this broad field of literature are possible. Hesselink *et al.*, for example, addressed the problem of how to categorize techniques in their 1994 overview of research issues [24] and consider dimensionality as a means to classify the literature. In the following, several aspects are discussed on an abstract level before literature is addressed directly.

1.1. Classification

According to the different needs of the users, there are different approaches to flow visualization (cf. Figure 1):

- **Direct flow visualization:** This category of techniques uses a translation that is as direct as possible for representing flow data in the resulting visualization. The result is an overall picture of the flow. Common approaches are **drawing arrows** (Figure 2, left) or **color coding velocity**. Intuitive pictures can be provided, especially in the case of two dimensions. Solutions of this kind allow immediate investigation of the flow data.
- **Dense, texture-based flow visualization:** Similar to direct flow visualization, a texture is computed that is used to generate a dense representation of the flow (Figure 2, middle). A notion of where the flow moves is incorporated through correlated texture values along the vector field. In most cases this effect is achieved through filtering of texture values according to the local flow vector.

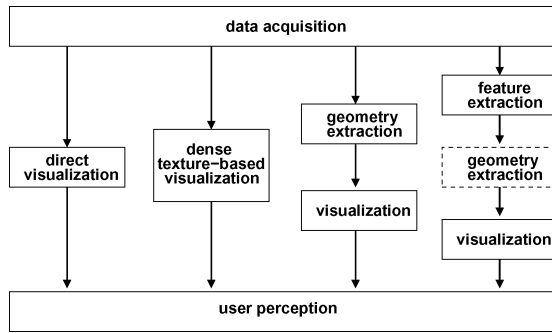


Figure 1: Classification of flow visualization techniques—(left) direct, (middle-left) texture-based, (middle-right) based on geometric objects and (right) feature-based.

- *Geometric flow visualization:* For a better communication of the long-term behavior induced by flow dynamics, *integration-based approaches* first integrate the flow data and use geometric objects as a basis for flow visualization. The resulting integral objects have a geometry that reflects the properties of the flow. Examples include streamlines (Figure 2, right), streaklines and pathlines. These geometric objects are based on integration as opposed to other geometric objects, like isosurfaces, that may also be useful for visualization. A description of geometric techniques is presented by Post *et al.* [55].
- *Feature-based flow visualization:* Another approach makes use of an abstraction and/or extraction step which is performed before visualization. Special features are extracted from the original dataset, such as important phenomena or topological information of the flow. Visualization is then based on these flow features (instead of the entire dataset), allowing for compact and efficient flow visualization, even of very large and/or time-dependent datasets. This can also be thought of as visualization of *derived* data. Post *et al.* [56] cover feature-based flow visualization in detail.

Figure 1 illustrates a classification of the aforementioned classes and Figure 2 shows three typical examples. Note that there are different amounts of computation associated with each category. In general, direct flow visualization techniques require less computation than the other three categories, whereas feature-based techniques require the most computation. This overview focuses on the body of research related to dense, texture-based techniques.

1.2. Spatial temporal and data dimensionality

Solutions in flow visualization differ with respect to the dimensionality of the flow data. Useful techniques for 2D flow data, like color coding or arrow plots, sometimes lack similar advantages in 3D. Here, the spatial dimensionality of the flow data is indicated as either 2D, 2.5D or 3D. In our classification the dimensionality of the results from each technique is

marked with a corresponding label indicating dimensionality (see Figure 4).

By 2.5D we mean flow visualization restricted to surfaces in 3D. We draw attention to the notion that in many cases like CFD, the simulation sets all velocities on a surface to zero. One way to approach this is to extrapolate the vector field just inside the surface to the boundary. In any case, the vector component normal to the surface is usually lost in the visualization. Furthermore, another vector field can be calculated on a surface, such as skin friction.

In addition to *spatial* dimension, *temporal* dimension (dimensionality with respect to time) is of great importance. Firstly, velocity incorporates a notion of time—flows are often interpreted as differential data with respect to time (cf. Equation 1), i.e. when integrating the data, instantaneous paths such as streamlines may be obtained (cf. Equation 3). We call this *steady velocity time*. Additionally, the flow data itself can change over time resulting in time-dependent (or unsteady) flow. We refer to this as *unsteady velocity time*. The visualization must carefully distinguish between both. Performing integration in the case of unsteady data results in pathlines or streaklines as opposed to streamlines.

The distinction between steady and unsteady velocity time is important especially when animation is used in the visualization. Then, even a third notion of time, i.e. animation time, may affect the visualization. Animation time can be an arbitrary feature added to the visualization in order to create motion. Sometimes, geometric objects like streamlines are animated in order to show flow orientation, e.g. the motion of color controlled by a color table [31]. Animation is also often added to texture-based methods with the same goal in mind. Special attention is required for correct interpretation of animation time.

In many cases, further *data* dimensions, i.e. attributes are supplied with the data, such as temperature, pressure or vorticity in addition to spatial and temporal dimensions. The dimension of the data values is also associated with the terms multivariate and multi-field data. Flow visualization may also take these values into account, e.g. by using color or isosurface extraction.

Although we do not have space to focus on experimental flow visualization, it is interesting to recognize that many computational solutions more or less mimic the visual appearance of well-accepted techniques in experimental visualization (cf. particle traces, dye injection or Schlieren techniques [77]).

1.3. Data sources

Computational flow visualization, in general, deals with data that exhibits temporal dynamics like the results from (a) *flow simulation* (e.g. the simulation of fluid flow through a turbine), (b) *flow measurements* (possibly acquired through

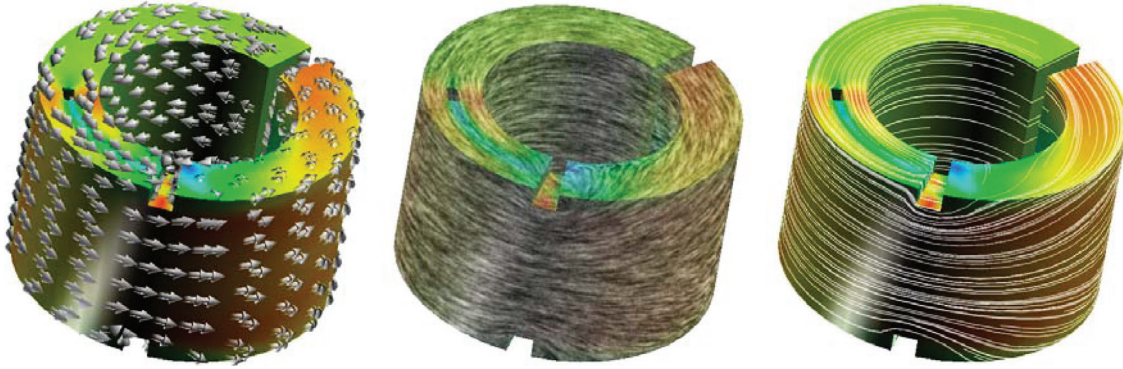


Figure 2: An example of circular flow at the surface of a ring to help illustrate our flow visualization classification: (left) direct visualization by the use of arrow glyphs, (middle) texture-based by the use of LIC and (right) visualization based on geometric objects, here streamlines.

laser-based technology) or (c) *analytic models* of flows (e.g. dynamical systems [1], given as set of differential equations).

We focus on visualization of data from computational flow simulation, i.e. flow data given as a set of samples on a grid. In many cases, the velocity information in a flow dataset (encoded as a set of velocity vectors) represents the focus. Therefore, flow visualization is strongly related to *vector field visualization*, which may also deal with vector fields other than velocity fields.

The relation of computational and experimental visualization is worthy of mention. Experimental flow visualization, as in a wind tunnel, is also used to validate computational flow simulation. In such a case the computational visualization needs to be set up in a way such that results can be easily compared.

2. Fundamentals

Before outlining some of the most important texture-based techniques, a short overview of common mathematics as well as some general concepts with regard to the computation of results are presented.

Flow simulations are often solutions to systems of PDEs, such as the Navier Stokes, Euler or Advection-Diffusion equations [82]. In general, discretized solution methods are used. Noteworthy are finite volume (FV) and finite element (FE) analysis, which subdivide the domain into small elements like hexahedral or tetrahedral cells. A solution is defined on the computation grid in physical space: unstructured for FE and structured curvilinear for FV solutions. In the discussion that follows, we assume that vector data are defined on the grid nodes (cell vertices).

2.1. Reconstruction of flow data

An inherent characteristic of flow data is that derivative information is given with respect to time, which is laid out with

respect to an n -dimensional spatial domain $\Omega \subseteq R^n$, e.g. $n = 3$ for representing 3D fluid flow. Temporal derivatives \mathbf{v} of nD locations \mathbf{p} within the flow domain Ω are n -dimensional vectors:

$$\mathbf{v} = d\mathbf{p}/dt, \quad \mathbf{p} \in \Omega \subseteq R^n, \mathbf{v} \in R^n, t \in R. \quad (1)$$

A general formulation of (possibly unsteady) flow data \mathbf{v} is

$$\mathbf{v}(\mathbf{p}, t) : \Omega \times \Pi \rightarrow R^n, \quad (2)$$

where $\mathbf{p} \in \Omega \subseteq R^n$ represents the spatial reference of the flow data and $t \in \Pi \subseteq R$ represents the system time. For steady flow data, the simpler case of $\mathbf{v}(\mathbf{p}) : \Omega \rightarrow R^n$ is given (\mathbf{v} not dependent on t).

In results from nD flow simulation, such as from automotive applications or airplane design, vector data \mathbf{v} is usually not given in analytic form, but requires reconstruction from the discrete simulation output. The numerical methods used for the flow simulation, such as finite element methods, output simulation values usually on large-sized grids of many sample vectors \mathbf{v}_i , which discretely represent the solution of the simulation process. Furthermore, it is assumed that the flow simulation is based on a continuous model of the flow allowing continuous reconstruction of the flow data \mathbf{v} . One option is to apply a reconstruction filter $h : R^n \rightarrow R$ to compute $\mathbf{v}(\mathbf{p}) = \sum_i h(\mathbf{p} - \mathbf{p}_i)\mathbf{v}_i$. For practical reasons, filter h usually has only local extent. Efficient procedures for finding flow samples \mathbf{v}_i , which are nearest to the query point \mathbf{p} , are needed to do proper reconstruction.

2.2. Grids

In flow simulation, the vector samples \mathbf{v}_i usually are laid out across the flow domain with respect to a certain type of grid. Grid types range from simple rectilinear or Cartesian grids to curvilinear grids to complex unstructured grids (cf. Figure 3). Typically, simulation grids exhibit large variations in cell sizes. This variety of cell sizes stems from the influence

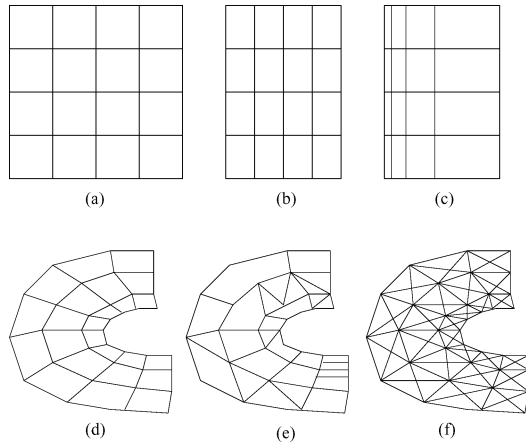


Figure 3: Grids involved in flow simulation—(a) Cartesian, (b) regular, (c) general rectilinear, (d) structured or curvilinear, (e) unstructured and (f) unstructured triangular [37,89].

of grid generation onto the flow simulation process. The quality of the grid model and its implementation impact the quality of the simulation results.

Although the principal theory of reconstruction from discrete samples does not exhibit many differences with respect to grid cell types, the practical handling does. While neighbor searching might be trivial in a rectilinear grid, it usually is not in a tetrahedral grid. Similar differences hold for the problems of point location and vector reconstruction. In the following we shortly describe some fundamental operations which form the basis for visualization computations on simulation grids.

Starting with *point location*, i.e. the problem of finding the grid cell in which a given nD -point lies, usually two cases are distinguished. For general point location, special data structures can be used that subdivide the spatial domain to speed up the search. For iterative point location, often needed during integral curve computation, algorithms are used that efficiently exploit spatial coherence during the search. One kind of such algorithms starts with an initial guess for the target cell, checks for point containment and refines accordingly afterward. This process is iterated until the target cell is found. More details can be found in text books about flow visualization fundamentals [53,68].

Beside point location, *flow reconstruction*, or interpolation, within a cell of the dataset is a crucial issue. Often, once the cell containing the query location is found, only the sample vectors at the cell's vertices are considered for reconstruction. The approach used most often is first-order reconstruction by performing linear interpolation within the cell. For example, trilinear flow reconstruction may be used within a 3D hexahedral cell.

After point location and flow reconstruction, visualization begins: vectors can be represented with glyphs; virtual particles can be injected and traced across the flow domain. Nevertheless, the *computation of derived data* may be necessary to do more sophisticated flow visualization. Usually, the first step is to request second-order gradient information for arbitrary points in the flow domain, i.e. $\nabla \mathbf{v}|_{\mathbf{p}}$, which gives information about local properties of the flow (at point \mathbf{p}) such as flow convergence and divergence, or flow rotation and shear. For feature extraction, flow vorticity $\omega = \nabla \times \mathbf{v}$ can be of high interest. Further details about local flow properties can be found in previous work [45,54].

2.3. Integration

Recalling that flow data in most cases is derivative information with respect to time, the idea of integrating flow data over time is natural to provide an intuitive notion of evolution induced by the flow. One example is visualization by the use of particle advection. A respective particle path $\mathbf{p}(t)$ —here through unsteady flow—can be defined by

$$\mathbf{p}(t) = \mathbf{p}_0 + \int_{\tau=0}^t \mathbf{v}(\mathbf{p}(\tau), \tau) d\tau, \quad (3)$$

where \mathbf{p}_0 represents the location of the particle path at seed time 0. Note that Equations 1 and 3 are complimentary to each other. For other types of integral curves, such as streaklines see previous work [36,68].

In addition to the theoretical specification of integral curves, it is important to note that respective integral equations like Equation 3 usually cannot be resolved for the curve function analytically, and thereby *numerical integration methods* are employed. The most simple approach is to use a first-order Euler method to compute an approximation $\mathbf{p}_E(t)$ —one iteration of the curve integration is specified by

$$\mathbf{p}_E(t + \Delta t) = \mathbf{p}(t) + \Delta t \cdot \mathbf{v}(\mathbf{p}(t), t), \quad (4)$$

where Δt usually is a very small step in time and $\mathbf{p}(t)$ denotes the location to start this Euler step from. A more accurate but also more costly technique is the second-order Runge-Kutta method [57], which uses the Euler approximation \mathbf{p}_E as a look-ahead to compute a better approximation $\mathbf{p}_{RK2}(t)$ of the integral curve:

$$\begin{aligned} \mathbf{p}_{RK2}(t + \Delta t) = & \mathbf{p}(t) + \Delta t \cdot (\mathbf{v}(\mathbf{p}(t), t) \\ & + \mathbf{v}(\mathbf{p}_E(t + \Delta t), t))/2. \end{aligned} \quad (5)$$

Higher-order methods like the often used fourth-order Runge-Kutta integrator utilize more such steps to better approximate the local behavior of the integral curve. Also, adaptive step sizes are used to compute smaller steps in regions of high curvature.

3. Dense and Texture-Based Flow Visualization

Dense, texture-based techniques in flow visualization generally provide full spatial coverage of the vector field. In our classification we group these methods into the following categories based on their respective *primitive*: the fundamental object upon which the algorithm is based. Our classification subdivides the techniques based on their similarity.

- *Spot Noise techniques*: These methods (Section 3.1) are based on a technique introduced by Van Wijk [78]. In this category, the basic primitive on which the algorithms operate is the so-called *spot*: an ellipse or other shape that is warped and distributed in order to reflect the characteristics of a vector field.
- *LIC techniques*: The methods in this category (Section 3.2) are derived from an algorithm introduced by Cabral and Leedom [8], namely, line integral convolution (LIC). The basic primitive here is a *noise texture*: the properties of texture are convolved, or smeared, using a kernel filter in the direction of the underlying vector field.
- *Texture advection and GPU-based techniques*: The primitive in this case (Section 3.3) is a *moving texel* [50]. Individual texels/texel properties, or groups of texels are advected in the direction of the vector field. Many of the techniques in this category utilize more computation on the GPU (Graphics Processing Unit)—rather than the CPU—in order to realize performance gains.
- *Related techniques*: Most of the dense, texture-based flow visualization research falls into one of the previous categories. Related research that does not fit cleanly into one of the previous classifications is discussed in Section 3.4.

We have included a section of meta-research papers in Section 4 after the individual research techniques. These papers attempt to provide an alternative, higher-level framework that incorporates many of the techniques discussed here.

3.1. Spot noise

Spot noise, introduced by Van Wijk [78], was one of the first dense, texture-based techniques for vector field visualization. Spot noise generates a texture by distributing a set of intensity functions, or spots, over the domain. Each spot represents a particle warped over a small step in time and results in a streak in the direction of the local flow from where the particle is seeded. A spot noise texture is defined by: [78]

$$f(\mathbf{x}) = \sum a_i h(\mathbf{x} - \mathbf{x}_i, \mathbf{v}(\mathbf{x}_i)) \quad (6)$$

in which $h()$ is called the intensity function, a_i is a scaling factor, and \mathbf{x}_i is a random position. A spot is a function with unity intensity value for the spot, e.g. a ellipse and its interior, and zero everywhere else. The summation denotes the

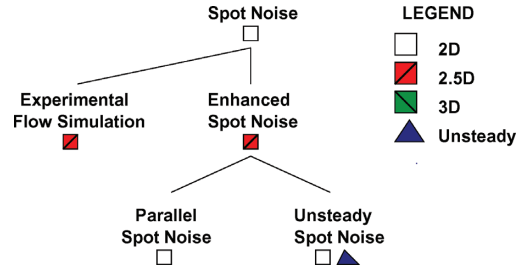


Figure 4: The spot noise hierarchy of related research. Children in the hierarchy build upon the work of their parent.

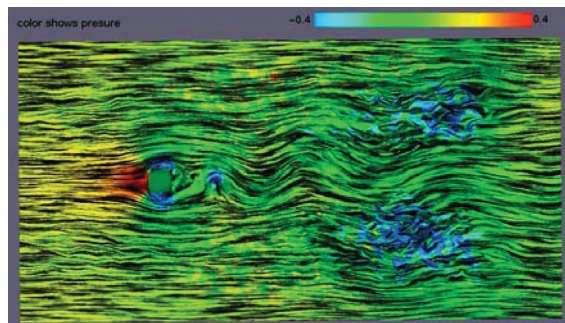


Figure 5: A snapshot of the unsteady spot noise algorithm [16]. Image courtesy of De Leeuw and Van Liere.

blending of each instance of the intensity function at random positions.

The hierarchy shown in Figure 4 illustrates the relationship amongst spot noise related methods. Follow-up research that builds upon a previous technique is shown as a child in the hierarchy. Children that share a common parent are presented in chronological order of appearance when reading from left to right. Each node in the hierarchy is labeled and the corresponding description can be matched in the text of this article. The dimensionality of the flow data used to generate the results is indicated for convenience. The time dimension label is given a different shape to distinguish it from the spatial dimensions. We believe the spot noise hierarchy (Figure 4) and the LIC hierarchy (Figure 7) will be valuable assets in helping the reader navigate the related research literature. In what follows, we visit each node in the hierarchy in depth-first-search order.

Comparative visualization: Spot noise has been used to simulate the results from the field of experimental flow visualization [14]. First, the parameters of the spot noise technique are tuned in order to simulate the smearing of oil on a surface. A postprocessing step is then added to enhance the visualization result such that it looks closer to the smearing of real oil from experimental flow visualization.

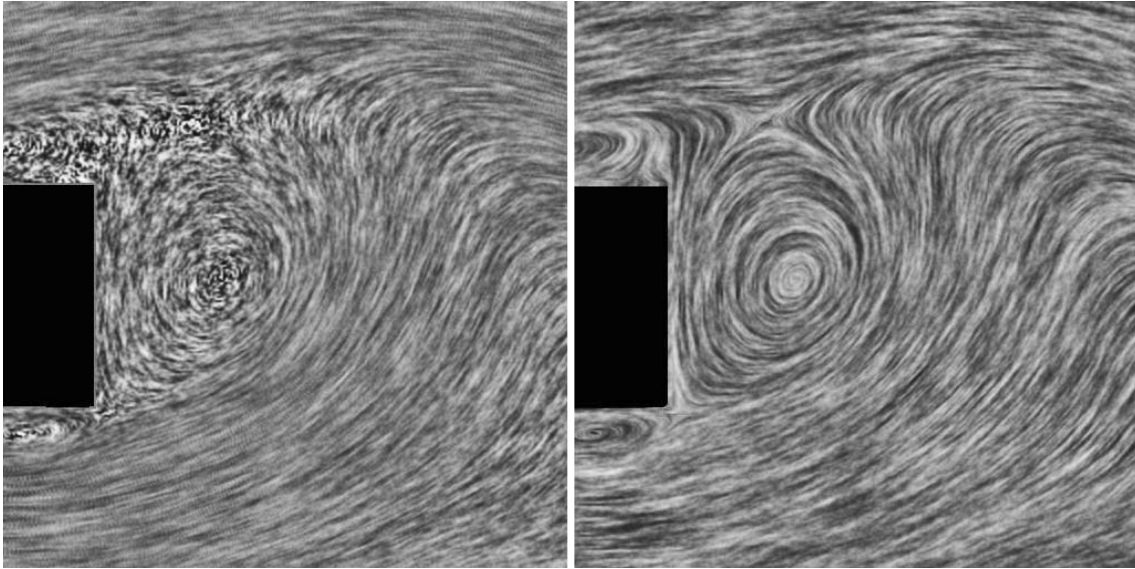


Figure 6: Visualization of flow past a box using (left) spot noise and (right) LIC.

Enhanced spot noise: One limitation of the original spot noise algorithm was the inability to represent high, local velocity curvature especially with high speeds. Enhanced spot noise [12] by De Leeuw and Van Wijk addresses these challenges through the use of bent spot primitives.

Parallel and unsteady spot noise: In order to accelerate the performance of enhanced spot noise towards interactive frame rates, a parallel implementation of the algorithm was introduced by De Leeuw [13]. The parallel implementation was applied to the steering of a smog prediction simulation and searching a very large data set resulting from a numerical simulation of turbulence.

The first application of spot noise to unsteady flow is presented by De Leeuw and Van Liere [16] (Figure 5). The motion of spots is modeled after particles in unsteady flow. In order to visualize unsteady flow, the distribution of spots with respect to the temporal domain is discussed. Unsteady spot noise also introduces support for zooming views of the vector field. Spot noise with zooming is also utilized by De Leeuw and Van Liere when visualizing topological features of 2D flow [10].

Spot noise related literature: A combination of both texture-based FlowVis on 2D slices and 3D arrows for 3D flow visualization is employed by Telea and Van Wijk [74]. Arrows denote the main characteristics of the 3D flow after clustering and a 2D slice with spot noise visualization serves as context. The focus of this work is on vector field clustering.

Löffelmann *et al.* [44] use anisotropic spot noise created from a grid-shaped spot to visualize streamlines and timelines concurrently on stream surfaces. Another interesting appli-

cation of spot noise is its use for the depiction of discrete maps (noncontinuous flow) [43].

Spot noise has also been applied to the visualization of turbulent flow [15] and in combination with the visualization of flow topology [10,11]. We refer the reader to Post *et al.* [55,56] for more on the subject of flow topology.

Spot noise versus LIC: A visual comparison of LIC (the focus of the next section) and spot noise is shown in Figure 6. Spot noise is capable of reflecting velocity magnitude within the amount of smearing in the texture, thus freeing up hue for the visualization of another attribute such as pressure, temperature, etc. On the other hand, LIC is more suited for the visualization of critical points which is a key element in conveying the flow topology. The vector magnitudes are normalized thus retaining lower spatial frequency texture in areas of low velocity magnitude. De Leeuw and Van Liere also compare spot noise to LIC [17]. They report that LIC is better at showing direction than spot noise, but it does not encode velocity magnitude. By flow direction, we refer to the path along which a massless particle follows when injected into the flow.

3.2. Line integral convolution

Line integral convolution (LIC), first introduced by Cabral and Leedom [8], has spawned a large collection of research as indicated in Figure 7. The original LIC method takes as input a vector field on a 2D, Cartesian grid and a white noise texture of the same size. Texels are *convolved* (or correlated) along the path of streamlines using a *filter kernel* in order to create a dense visualization of the flow field. More specifically, given a streamline σ , LIC consists of calculating the intensity I for

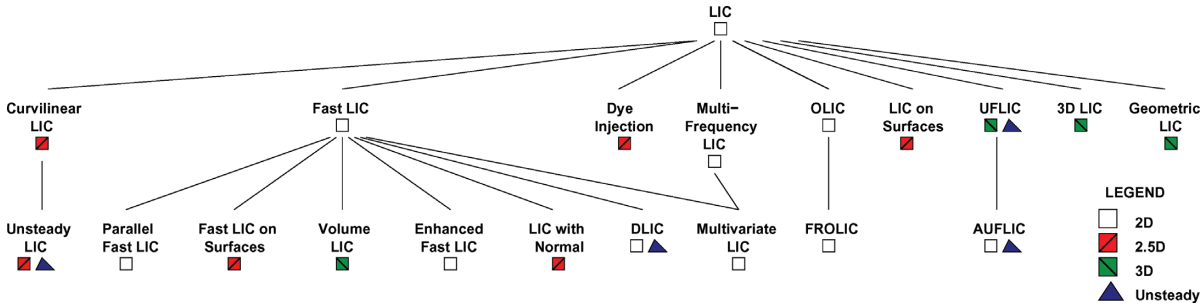


Figure 7: The LIC hierarchy of related research. Node labels correspond to paragraphs in the text, which then lead to specific entries in the bibliography.

a pixel located at $\mathbf{x}_0 = \sigma(s_0)$ by: [70]

$$I(\mathbf{x}_0) = \int_{s_0-L/2}^{s_0+L/2} k(s - s_0)T(\sigma(s)) ds \quad (7)$$

where T stands for an input noise texture, k denotes the filter kernel, s is an arc length used to parameterize the streamline curve and L represents the filter kernel length. See Figure 2 (middle) for a result. LIC was one of the first dense, texture-based algorithms able to accurately reflect velocity fields with high local curvature.

The research in LIC-based flow visualization described here extends LIC in several directions: (1) adding flow orientation cues, (2) showing local velocity magnitude, (3) adding support for nonrectilinear grids, (4) animating the resulting textures such that the animation shows the upstream and downstream flow direction, (4) allowing real-time and interactive exploration, (5) extending LIC to 3D and (6) extending LIC to unsteady vector fields. In the following, we visit the LIC hierarchy of Figure 7 in depth-first-search order.

Curvilinear grids and unsteady LIC: Forssell [20] was early to extend LIC to surfaces represented by curvilinear grids. The original LIC method portrays a vector field with uniform velocity magnitude. Forssell introduces a technique for displaying vector magnitude. She also describes one approach to animate the resulting LIC textures. Forssell and Cohen extend this work to visualize unsteady flow [21]. Their approach modifies the convolution such that the filter kernel operates on streaklines rather than streamlines. In other words, they modify the LIC algorithm to trace a path that incorporates multiple time steps.

Fast LIC: Many algorithms are built on fast LIC introduced by Stalling and Hege [70]. Fast LIC is approximately one order of magnitude faster than the original. The speedup is achieved through two key observations: (1) fast LIC minimizes the computation of redundant streamlines present in the original method and (2) fast LIC exploits similar convolution integrals along a single streamline and thus re-uses parts of the convolution computation from neighboring streamline

texels. They also introduce support for filtered images at arbitrary resolution.

Parallel fast LIC: Amongst the first parallel implementations of fast LIC is that of Zöckler *et al.* [90]. The proposed algorithm computes animation sequences on a massively parallel distributed memory computer. Parallelization is performed in image space rather than in time in order to take advantage of the strong temporal coherence between frames. Luckily, as we shall see later, flow visualization research in this area has evolved far enough such that expensive parallel processing hardware is not always necessary to achieve interactive visualization [28,29,38,79]. However, for 3D and unsteady flow there is still need for parallelization. For the sake of completeness, we also mention the work of Cabral and Leedom on parallelization of LIC [7] although this is a parallel processing version of the original LIC algorithm, not fast LIC.

Fast LIC on surfaces: Battke *et al.* [2] extend fast LIC to surfaces represented by arbitrary grids in 3D. The approach by Forssell and Cohen [21] was limited to surfaces represented by curvilinear grids. The method works by tessellating a given surface representation with triangles. The triangles are packed (or tiled) into texture memory and a local LIC texture is computed for each triangle. The results presented here are limited to relatively small simple surface representations composed of equilateral triangles (1,600–4,000 triangles).

Volume LIC: Interrante and Grosch [25,26] visualize true 3D flow using the fast LIC algorithm as a starting point. Clearly, there are perceptual challenges related to 3D flow visualization such as occlusion, depth perception and visual complexity. Volume LIC introduces the use of *halos* in order to enhance depth perception such that the user has a better chance at perceiving the 3D space covered in the visualization (Figure 8). Areas of higher velocity magnitude are mapped to higher texture opacity. It is interesting to note that with the introduction of halos, we are then able to identify distinct entities in the 3D field, a property generally not present in other LIC techniques. Thus, the 3D LIC takes a step in

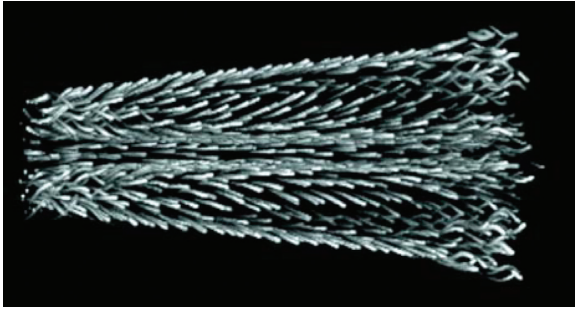


Figure 8: A result from the Volume LIC method [25,26]. Image courtesy of Interrante and Grosch.

the direction of being a geometric flow visualization technique where discrete integral objects such as streamlines can be distinguished. Without introducing some notion of sparseness into the visualization, the results would not be very useful. However, with the introduction of sparseness, a trade-off is made between flow field coverage and reducing occlusion.

Enhanced fast LIC and LIC with normal: Two useful extensions to the fast LIC algorithm are introduced by Hege and Stalling [22] and Scheuermann *et al.* [64]. Hege and Stalling [22] experiment with higher order filter kernels in order to enhance the quality of the resulting LIC textures.

In the case of slices, vector components orthogonal to the slice are removed when using texture-based and geometric methods for visualization results. Scheuermann *et al.* [64] address this missing orthogonal vector field component by extending fast LIC to incorporate a normal component into the visualization.

DLIC: Sundquist [71] presents an extension to fast LIC, DLIC (Dynamic LIC), in order to visualize time-dependent electromagnetic fields. According to Sundquist, the motion of the field is not necessarily along the direction of the field itself in the case of electromagnetic fields. The algorithm proposed here handles the case of when the vector field and the direction of the motion of the field lines are independent. Conceptually, there are two vector fields used in this approach: (1) the electromagnetic field itself and (2) the vector field that describes the evolution of streamlines as a function of time.

Multivariate LIC: Urness *et al.* [76] present an extension to fast LIC that incorporates a new coloring scheme that can be used to incorporate multiple 2D scalar and vector attributes. *Color weaving* assigns a specific attribute represented by a color to an individual streamline thread in the visualization. The streamline patterns may interweave and thus so may the color patterns. Using multiple colors allows visualization of more than one variate in the result. Their second contribution is called *texture stitching*: an extension to the idea presented by Kiu and Banks [34], namely multifrequency LIC. How-



Figure 9: Dye injection is used to highlight areas of the flow in combination on the boundary surface of an intake port and combustion chamber.

ever, in the case of Urness *et al.* [76] the multifrequency noise textures are used to highlight regions of interest as opposed to velocity magnitude as by Kiu and Banks [34].

Dye injection: Shen *et al.* address the problem of directional cues in LIC by incorporating animation and introducing dye advection into the computation [66]. The simulation of dye may be used to highlight features of the flow. In addition, they incorporate volume rendering methods that map a LIC texture onto a 3D surface. Thus the user is able to visualize the dye throughout the volume. We point out that the modeling of dye transport is not always physically correct since dye is dispersed not only by advection, but also by diffusion. Note that dye advection techniques can be classified differently. Dye injection can result in discrete geometric objects used to visualize the flow, and thus, could be classified as a group of geometric visualization techniques. Dye injection is also implemented by some of the texture advection and GPU-based techniques described in Section 3.3.

Again, in Shen *et al.* we see the notion of a sparser visualization in order to see into the 3D flow. The resulting 3D visualization approaches that of a geometric technique such as the use of streamsurfaces. And just as with the other geometric techniques, the notion of where to place or inject the dye into the flow becomes important. Figure 9 illustrates the use of dye injection.

Multifrequency LIC: Kiu and Banks propose to use a multifrequency noise for LIC [34]. The spatial frequency of the noise is a function of the magnitude of the local velocity. Long, fat streaks indicate regions of the flow with higher velocity magnitude.

One problem with many curvilinear grid LIC algorithms is that the resulting LIC textures may be distorted after being mapped onto the geometric surfaces, since a curvilinear grid usually consists of cells of different sizes. Mao *et al.* propose a solution to the problem by using multigranularity noise as the input image for LIC [46].

OLIC and FROLIC: Wegenkittl *et al.* address the problem of direction of flow in still images with their OLIC (Oriented LIC) approach [84]. By orientation, they mean the upstream and downstream directions of the flow, not visible in the original LIC implementation. Conceptually, the OLIC algorithm makes use of a sparse texture consisting of many separated spots that are smeared in the direction of the local vector field through integration. A fast version of OLIC, called FROLIC (Fast Rendering of OLIC), is achieved by Wegenkittl and Gröller [83] via a trade-off of accuracy for time. FROLIC approximates the simulated droplet trace resulting from OLIC with a sequence of disks of varying intensity, with disk intensity increasing towards the downstream direction.

Animated FROLIC [4] achieves animation of the result via a color-table and is based on the observation that only the colors of the FROLIC disks need to be changed. Each pixel is assigned a color-table index that points to a specific entry in the color-table. Color-table animation then changes the entries of the color-table itself rather than the pixels of the corresponding image.

LIC on surfaces: Mao *et al.* [47] extend the original LIC method by applying it to surfaces represented by arbitrary grids in 3D. Former LIC methods targeted at surfaces were restricted to structured grids [20,21,66]. Also, mapping a computed 2D LIC texture to a curvilinear grid may introduce distortions in the texture. Mao *et al.* propose solutions to overcome these limitations. The principle behind their algorithm relies on solid texturing [52]. The convolution of a 3D white noise image, with filter kernels defined along the local streamlines, is performed only at visible ray-surface intersections.

This idea has an advantage over that of Battke *et al.* [2] in that it avoids what can be a timely and complex assembly of triangles into texture space. However, ray-tracing is also costly. The method here is view-point dependent and required relatively lengthy processing time for an unstructured mesh composed of 10,000 triangles.

A significant body of research is dedicated to the extension of LIC onto boundary surfaces. Teitzel *et al.* [73] present an approach that works on both 2D unstructured grids and directly on triangulated grids in 3D space. This topic itself is the subject of a survey by Stalling [69].

UFLIC: Shen and Kao [67] extend the original LIC algorithm to handle unsteady flows. Their extension, called UFLIC (Unsteady Flow LIC), handles the case of unsteady flow fields by introducing a new convolution filter that better models

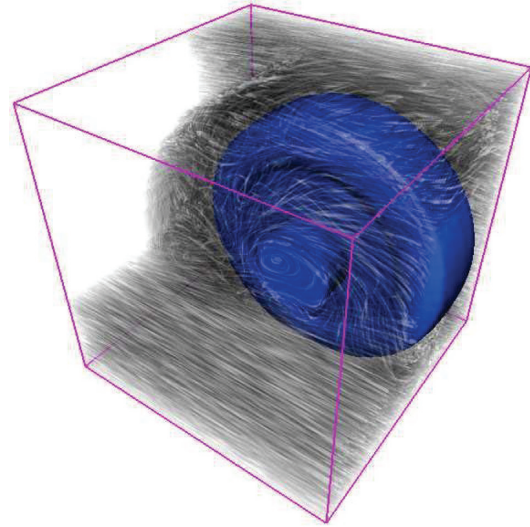


Figure 10: An LIC visualization showing a simulation of flow around a wheel [59]. The appropriate choice of transfer function results in a sparser noise texture. Image courtesy of Rezk-Salama *et al.* [59].

the nature of unsteady flow. The convolution is done along pathlines (as opposed to streamlines). They improve upon the shortcomings of the previous unsteady LIC attempt presented by Forssell and Cohen [21]. According to Shen and Kao, Forssell and Cohen's approach has multiple limitations including: (1) lack of clarity with respect to spatial coherence, (2) deriving current flow values from future flow values, (3) unclear exposition with respect to temporal coherence and (4) lack of accurate time stepping. All of these problems are addressed by UFLIC. Shen and Kao also apply UFLIC to the visualization of time-dependent flow to parameterized surfaces. UFLIC is also extended using a parallel implementation by Shen and Kao [65].

AUFLIC: AUFLIC (Accelerated UFLIC) is an extension to UFLIC that enhances performance times [41]. The principle behind AUFLIC is to save, reuse, and update pathlines in a vector field seeding strategy. AUFLIC requires approximately one half of the time required by UFLIC and generates similar results.

3D LIC: Rezk-Salama *et al.* [59] propose rendering methods to effectively display the results of 3D LIC computations. They utilize texture-based volume rendering in an effort to provide exploration of 3D LIC textures at interactive frame rates. Like Interrante [26], they address the perceptual problems posed by dense, 3D visualization. They approach these challenges through the use of transfer functions and clipping planes, as in Figure 10. Transfer functions allow the user to see through portions of the LIC textures deemed uninteresting by the user. In addition to conventional clipping planes,

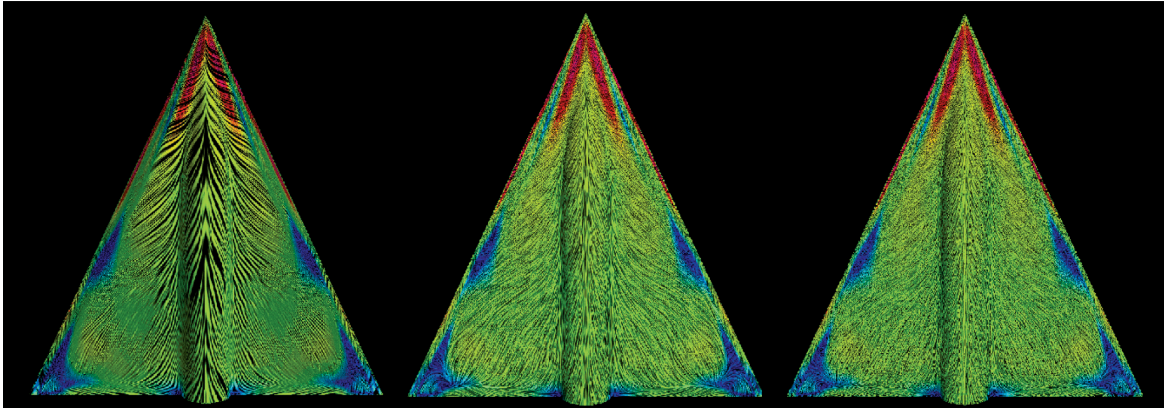


Figure 11: A comparison of 3 LIC techniques: (left) UFLIC [65], (middle) ELIC [51], and (right) PLIC [81]. Image courtesy of Verma et al. [81].

Rezk-Salama *et al.* also use clipping with arbitrary closed-surface geometries.

The use of transfer functions and geometric clipping objects are interesting choices for dealing with the perceptual problems associated with 3D. In some sense, these can be compared with the seeding problem of the geometric class of visualization techniques. Seeding strategies address where to start streamlines and other integration-based geometric objects. Selective seeding of geometric objects in 3D is often considered a key to successful visualization. However, knowledge of the proper seed locations is a requisite for this approach. And just as proper seed placement is a requisite when using geometric objects, knowledge of the transfer function(s) and closed-object clipping geometries is required in the case of 3D LIC.

Geometric LIC: We make a distinction between geometric flow visualization and dense, texture-based flow visualization. However, these two topics are closely coupled. Conceptually, the path from using geometric objects to texture-based visualization is obtained via a dense seeding strategy. That is, densely seeded geometric objects result in an image similar to that obtained by dense, texture-based techniques [30]. Likewise, the path from dense, texture-based visualization to visualization using geometric objects is obtained using something such as a sparse texture for texture advection [84].

Here we have grouped together techniques that synthesize LIC results by mapping a precomputed LIC texture onto geometric primitives such as streamlines. By using geometric primitives, researchers hope to speed up performance times of the LIC results. The drawback of these methods is that they require careful seeding strategies to gain the complete coverage of the flow field offered by traditional LIC techniques.

Motion map: Jobard and Lefer use a *motion map* [31] in order to animate 2D steady flows. First, the domain is covered

completely with streamlines. Next, a color is mapped to the streamlines and a color-table animation technique is used to animate the flow. It offers the advantage of saving memory and computation time since only one image of the flow has to be computed and stored in the motion map data structure. This technique is not applicable to unsteady flow however. It relies on a one-time cost of computing a set of streamlines.

PLIC: Verma *et al.* present a method for visual comparison of streamlines and LIC called PLIC [81] (Pseudo-LIC). They attempt to identify the relevant parameters to generate LIC-like images from a dense set of streamlines and for generating streamline-like images through the use of different filters used for convolution. By experimenting with different input textures for LIC, both streamline-like images and LIC-like results can be obtained. ELIC (enhanced LIC), placed here because of its visual comparison with PLIC, builds on the original LIC algorithm in four ways: (1) by incorporating an algorithm to improve the delineation of streamlines, (2) increasing the image contrast, (3) removing texture distortion introduced by applying LIC to curvilinear grids and (4) using color to highlight flow separation and reattachment boundaries. A visual comparison between UFLIC [65], ELIC [51], and PLIC is shown in Figure 11.

Hierarchical LIC: Bordoloi and Shen [5] introduce a hierarchical approach to LIC based on a quadtree data structure used to support level of detail (LOD). The idea is to replace portions of the vector field of lower complexity with rectangular LIC texture-mapped patches. The LIC texture is taken from a previously calculated LIC image of a straight vector field. Here, complexity is a direct function of the amount of curl in the local vector field.

Decoupled LIC: Li *et al.* [40] present a technique for the visualization of 3D flow based on texture mapped primitives, namely streamlines. They decouple the visualization into a

		Advection Primitive		LEGEND
		Texel	Textured Polygons	
Forward Advection			IBFV □ ▲	□ 2D ■ 2.5D ■ 3D ▲ Unsteady
Backward Advection	3D Texture Advection ■		Moving Textures ■ ▲	
	Texture Advection □ ▲		ISA and IBFVS ■ ▲	
	LEA □ ▲		3D IBFV ■	
	UFAC □ ▲			

Figure 12: The classification of texture advection and GPU-based techniques. The columns indicate the primitive used during advection while the rows indicate the advection scheme.

preprocessing type stage that computes the streamlines and a stage which maps various textures to the streamlines computed in the first stage. The result is volume rendered at interactive frame rates. To address the perceptual challenges posed by 3D visualization, depth cues, lighting effects, silhouettes, shading and interactive volume culling are described.

3.3. Texture advection and GPU-based techniques

In this section we describe research based on moving texels or moving groups of texels, i.e. texture-mapped polygons whose motion is directed by the vector field. Figure 12 shows an overview of the different techniques and classifies them according to two properties: (1) the advection scheme used and (2) the primitive used during advection. Some of the literature focuses mainly on the integration scheme used to advect textures or texels. By the term texel means texture element. Some methods focus on the mapping to advected primitives and some focus on both. Figure 12 also shows the dimensionality of the flow data. In our discussion, we visit the methods in clockwise order starting at 12 o'clock. Within each sub-block the methods are listed in chronological order. This is because the mapping of texel properties between two time steps in the visualization is not 1-to-1 in this case. For a more detailed discussion see Jobard *et al.* [28,29].

One characteristic common to many of the texture advection techniques in this section [28,29,38,48] is the use of *backward coordinate integration* (or backward advection). None of the methods described here use forward advection (i.e. forward integration) and individual texels as a primitive. This is because the combination of forward integration and texel primitives leaves holes in the visual domain after the forward integration computation [29]. Given a position, $\mathbf{x}_0(i, j) = (i, j)$ of each particle in a 2D flow, backward integration over a time interval h determines its position at a previous time step [28]:

$$\mathbf{x}_{-h}(i, j) = \mathbf{x}_0(i, j) + \int_{\tau=0}^h \mathbf{v}_{-\tau}(\mathbf{x}_{-\tau}(i, j)) d\tau \quad (8)$$

where h is the integration step, $\mathbf{x}_{-\tau}(i, j)$ represents intermediary positions along the pathline passing through $\mathbf{x}_0(i, j)$,

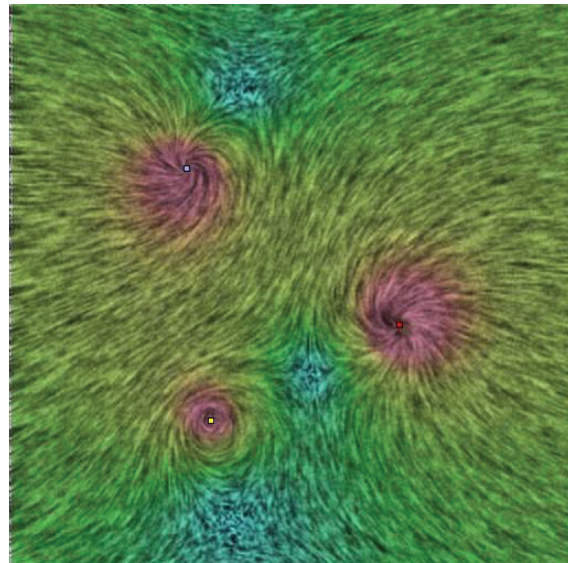


Figure 13: A screen shot from the image based flow visualization algorithm. Image courtesy of Van Wijk [79].

and \mathbf{v}_τ is the vector field at time τ . We note that the methods in this category are generally implemented in an *iterative* fashion. That is for each animated frame an integration is performed over a small time-step h , followed by an update of visual properties. This is opposed to geometric methods in which a longer particle path may be computed over several time steps before the results are displayed.

IBFV: Image based flow visualization (IBFV) by Van Wijk [79] is one of the fastest algorithms for dense, 2D, unsteady vector field representations (Figure 13). It is based on the advection and decay of textures in image space. Each frame of the visualization is defined as a blend between the previous image, warped according to the flow direction, and a number of background images composed of filtered white noise textures. One reason it is faster than many texture-based flow visualization methods is because it reduces the number of

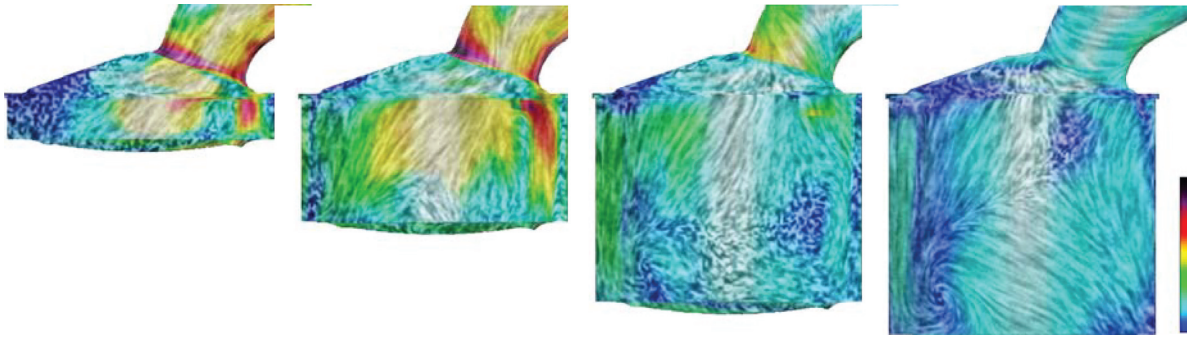


Figure 14: Snapshots from the visualization of a time-dependent surface mesh composed of 79 K polygons with dynamic geometry and topology [38].

integration computations that need to be performed via advecting small quadrilaterals rather than individual pixels.

Moving textures: Max and Becker were early to introduce the idea of moving textures in order to visualize vector fields [48]. One of the primary goals of this work was to use textures in motion to produce near-real-time animation of flow. Texture-mapped triangles are advected, or distorted, in the direction of the flow. Also, applying this technique to 3D flows with no modification provides results that are difficult to perceive, at least in the case of a still image.

ISA and IBFVS: IBFV has been extended to the visualization of flow on surfaces [38,80]. Van Wijk presents an extension called IBFVS, IBFV for Surfaces. Laramee et al. [38] present a similar dense, texture-based visualization technique on surfaces for unsteady flow called ISA (Image Space Advection). Both methods produce animated textures on arbitrary 3D triangle meshes in the same manner as the original IBFV method. Textures are generated, advected and blended in image space. The methods generate dense representations of time-dependent vector fields with high spatio-temporal correlation. While the 3D vector fields are associated with arbitrary triangular surface meshes, the generation and advection of texture properties is confined to image space. Both spot noise and LIC-like results can be attained. In both techniques, [38,40] fast frame rates are achieved in part by exploiting the GPU.

Van Wijk's method is applied to potential field visualization and surface visualization. Laramee et al.'s algorithm is applied to unsteady flow on boundary surfaces of large, complex meshes from computational fluid dynamics, dynamic meshes with time-dependent geometry and topology. It has also been applied to medical simulation data as well as isosurfaces [39]. Figure 14 shows the results applied to a time-dependent geometry and topology.

3D IBFV: IBFV has also been applied to the visualization of 3D flow [75]. The problem of how to see inside the flow

volume is addressed by varying both the noise sparsity, reminiscent of Interrante and Grosch [26], and through varying the opacity of the rendered volume similar to Rezk-Salama et al. [59]. In order to achieve sparseness, Telea and Van Wijk inject empty holes of noise into the 3D field, in addition to the noise described by the original IBFV. One important component of their method is to define a threshold value which eliminates all close-to-transparent texel values. One disadvantage of the method is that the range of velocity values it can display is limited: A texel property cannot be advected by more than one slice along the z axis of the volume in one animation frame. This problem is addressed by Weiskopf and Ertl [87].

3D Texture Advection: Kao et al. discuss the use of 3D and 4D texture advection for the visualization of 3D fluid flows [32]. The results show sparse texture noise in order to visualize inside the 3D vector field. Formidable challenges are introduced by the memory requirements involved in using 3D and 4D textures. The proposed method does not work well for the case of flows containing critical points for incoming flows from the grid boundary.

GPU-based LIC: Heidrich et al. [23] exploit pixel textures to accelerate LIC computation. Pixel textures are an OpenGL extension by SGI that provides the functionality of dependent textures in combination with multipass rendering. Heidrich et al.'s implementation supports 2D, steady vector fields only, and achieves sub-second computation times for LIC image generation. While this method could be categorized as a GPU-accelerated LIC technique, we position it here due to its comparability with the following texture advection techniques [27,88] that use the same proposed OpenGL extension, handle unsteady flow and thus can be considered an extension of this technique.

LEA: Jobard et al. [27] introduce a GPU-assisted texture advection technique for the dense visualization of 2D, unsteady flow. While the method of Max and Becker [49]

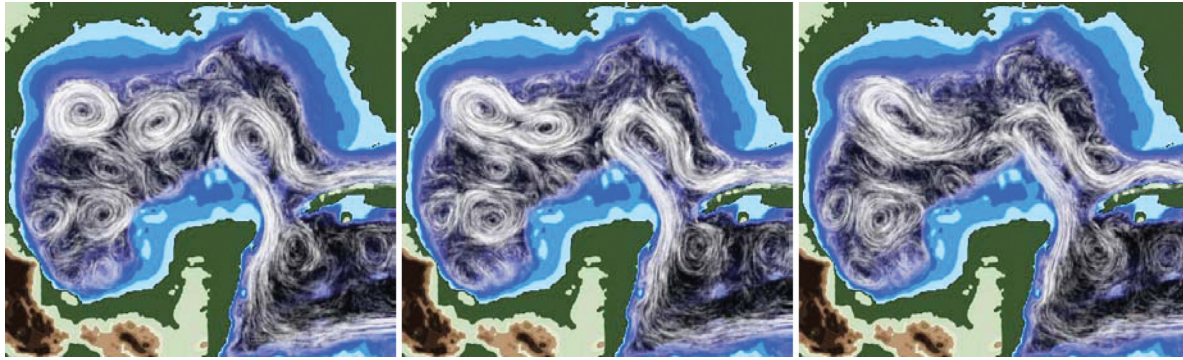


Figure 15: Three images taken from an animation of an unsteady vector field created with the Lagrangian-Eulerian advection algorithm. [28,29] Image courtesy of Jobard et al.

advects textures based on coarse triangular meshes, Jobard *et al.* advect textures on a per-pixel basis by means of pixel textures, which are used in a similar way as by Heidrich *et al.* [23]. The gray-scale texture from the previous time step is dragged along the flow field by modifying the texture coordinates for the dependent texture lookup according to the flow data. Nearest-neighbor sampling is combined with an update of fractional texture coordinates to represent subtexel motion and, at the same time, maintain a high contrast. An iterative injection of additional noise is used to compensate for a possible loss of contrast over time. Jobard *et al.* also discuss the treatment of inflow at boundaries, image enhancement by color masking and the use of dye advection. Because of the limited functionality of the graphics hardware that supports pixel textures, the implementation requires many rendering passes and advects a texture of size 256^2 at approximately two frames per second. Moreover, the maximum resolution of textures is restricted to 256^2 .

Jobard *et al.* extend this method to the more flexible Lagrangian-Eulerian Advection (LEA) scheme [28] for the visualization of unsteady, 2D flow. Here, they rely on a CPU implementation that leads to better advection quality, higher speed, and no limitations of the maximum flow size. Particle paths are integrated as a function of time, referred to as the Lagrangian step, while the color distribution of the image pixels is stored in a texture and updated in place (Eulerian step). The temporal coherence of the advected noise textures is transformed into spatial coherence by blending textures from subsequent time steps, i.e. each still frame depicts the instantaneous structure of the flow, whereas an animated sequence of frames still reveals the motion of the advected texture. Jobard *et al.* demonstrate that the combination of noise and dye advection is useful for an effective visualization and exploration of unsteady flow. Some results from the technique are shown in Figure 15. This work is extended by Jobard *et al.* [29] in order to improve the quality of dye advection.

Weiskopf *et al.* [86] present a GPU-accelerated version of the LEA algorithm using per-fragment operations. The

GPU-based texture advection by Weiskopf *et al.* [88] supports bilinear dependent texture lookups without taking into account the update of fractional coordinates. Therefore, this approach is mainly suitable for dye advection at high frame rates. Weiskopf *et al.* also demonstrate how GPU-accelerated visualization of unsteady, 3D flows can be implemented with pixel textures.

UFAC: Weiskopf *et al.* [85] introduce a generic texture-based framework for visualizing 2D, time-dependent vector fields. They propose unsteady flow advection convolution (UFAC) as an application of the framework for visualizing unsteady fluid flow. Also, their approach can reproduce other techniques such as LEA [29], IBFV [79], UFLIC [65], and DLIC [71]. Weiskopf *et al.* describe a GPU-accelerated implementation that, among other things, allows the user to trade-off quality for speed.

3.4. Related dense, texture-based methods

The literature described here is not, in general, as strongly interrelated as the literature in the spot noise, LIC, texture advection and GPU-based categories. For this reason we sought an alternative schema in order to relate the different techniques. Figure 16 shows the related methods and classifies them based on the density of their results. In this case each technique is given a subjective rating on a sparse-to-dense scale. Sparse results look more like the results from flow visualization using geometric objects whereas dense techniques produce results resembling spot noise or LIC. These methods do not fit cleanly into one of the previous categories; nonetheless, they are important to the dedicated topic and are briefly outlined here. Reading from top to bottom in Figure 16, we visit the techniques in chronological order.

Texture Splats: As an extension of the technique of splatting from volume rendering, Crawfis and Max [9] introduce the notion of *texture splats* for flow visualization. Being a volume rendering technique, it is targeted at the depiction of 3D vector fields. As with Rezk-Salama *et al.* [59], it is a selective

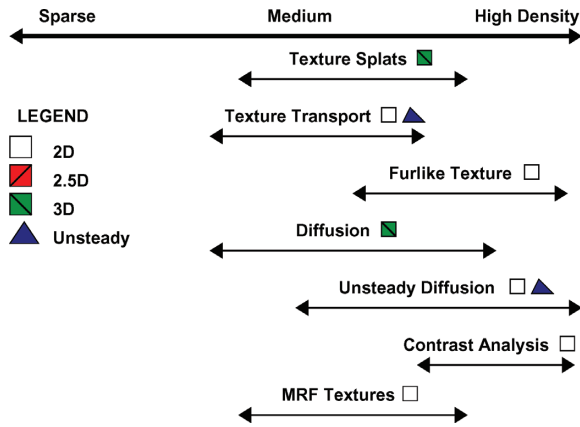


Figure 16: Related dense, texture-based flow visualization methods. Each method is compared with respect to the density of the resulting visualization.

transfer function that ultimately decides which subsets of the 3D data are shown and which are not. The transfer functions are used to emphasize or suppress spatial regions as opposed to ranges of data values.

Texture Transport: The texture transport method of Becker and Rumpf [3] introduces a mathematical framework based on the solution of a time-dependent transport equation. Lagrangian coordinates are computed from the transport equation and visualized using a texture mapping. The results in this case resemble those from the geometric class of solutions. Individual lines in the texture can be distinguished. The major drawback of this approach is the computation time required.

Furlike Texture: Khousa *et al.* synthesize LIC-like images in 2D with furlike textures [33]. Their technique is able to locally control attributes of the output texture such as orientation, length, density and color via a model based on filaments resembling fur.

Diffusion and Unsteady Diffusion: Preußer and Rumpf [58] as well as Diewald *et al.* [18] borrow a well known technique from image analysis for visualization of fluid flow. The non-linear, anisotropic diffusion equations from image analysis are adopted and applied to vector fields. A noisy texture covering the domain is strongly smoothed along integral lines while still retaining and enhancing edges in directions orthogonal to the flow, i.e. streamline-aligned diffusion. Successively coarse patterns representing the vector field can also be generated. It is applied to 2D, 2.5D, and 3D vector fields [18,58]. In the case of 3D, the resulting enhanced edges are discretized and resemble streamlines or streamribbons. In this case, occlusion becomes an important issue because the 3D results appear somewhat cluttered.

Bürkle *et al.* extend this technique to the case of time-dependent flow [6]. Instead of streamline-like patterns,

streakline patterns are generated. A blending strategy, comparable to noise or dye injection, is introduced in order to provide the new time-dependent texture necessary for the case of long-term flow evolution. They propose a solution based on the blending of different results from the transport diffusion evolution started at successively incremented times. Again, the disadvantage of this approach is the required computational time. Also, no attempt is made to apply this method to time-dependent 3D flow, a formidable challenge.

Contrast Analysis: Sanna *et al.* [63] focus on the issue of encoding another scalar value into the texture used to visualize the flow, in addition to flow direction, orientation and local magnitude of the field. It is an extension of a previous technique called TOSL—Thick Oriented Streamline Algorithm [62]. Areas of higher scalar values are characterized by higher contrast levels in the texture and streamline tones are generated in order to highlight these areas. The goal is to allow an additional variable into the visualization beyond previous techniques.

MRF: Taponecco and Alexa apply Markov Random Field (MRF) texture synthesis methods to vector fields [72]. The results resemble a mixture of traditional texture-based methods and geometric methods. In the resulting texture, distinct streamline patterns can be seen. One drawback to this method is performance. MRF texture synthesis methods may require hours of computation time. How it may be applied to unsteady flow is an open question.

4. Comparisons and Discussion

In this section we briefly introduce literature that compares and discusses dense, texture-based techniques at a meta-level. Sanna *et al.* also provide a summary of this area of research, with a different classification [61]. The methods are classified according to the dimensionality outlined here in Section 1.2.

Flow Textures: Erlebacher *et al.* [19] present a class of flow visualization algorithms called *flow textures* within a common conceptual framework. Flow textures are textures that encode dense, 2D, time-dependent representations of flow. The framework allows important ingredients of flow texture algorithms to be understood with respect to spatial and temporal correlation. A subset of the more recent visualization techniques is described.

User Studies: Laidlaw *et al.* [35] present one of the few findings related to human-computer interaction (HCI). They attempt to assess some different visualization techniques from the viewpoint of the user in terms of searching for and classifying critical points in the flow and predicting where a particle may end after advection. Error was highest for the LIC technique in conjunction with classifying critical points and the prediction of particle advection. This is probably due to the fact that LIC images do not distinguish between upstream and downstream flow. User error was higher than expected for all methods. Hedgehog techniques and LIC were also

associated with high error for locating critical points. The authors postulate that this was because in many cases critical points near the borders of the vector field were difficult to identify.

5. Conclusions and Future Prospects

Texture-based flow visualization algorithms are effective, versatile, and applicable to a wide spectrum of applications. A large number of techniques have been developed and refined. In general, which techniques are best depends strongly on the goal of the visualization, such as for exploration, detailed analysis, or presentation and on the kind of data involved. Therefore, we believe that a large variety of techniques should be available in order to allow researchers to choose the most suitable one.

The problem of dense, 2D, unsteady flow visualization is close to being solved [79]. And with recent follow-up work [38,80], unsteady flow visualization on surfaces is not far behind. However, the generalization to 3D flow fields is still unsolved, especially in the case of unsteady flow. Hardware, arguably, will not be the primary bottleneck to solving this challenge, but perceptual issues will. Perceiving three spatial and three data dimensions directly is a difficult job for the human eye and brain. So far, techniques based on geometric objects and particle animation generalize better to 3D fields.

The scale of numerical flow simulations, and thus the size of the resulting datasets, continues to grow rapidly—generally faster than the size of computer memory. For these reasons more simplification strategies must be conceived, such as spatial selection (slicing, regions of interest), geometry simplification and feature extraction.

Slicing in a 3D field reduces the problem to 2D, allowing use of good 2D techniques, but care must be taken with interpretation, as the loss of the third dimension may lead to physically irrelevant results and wrong interpretation. Taking a single 3D time slice from a 3D time-dependent dataset has similar dangers. Other spatial selections such as 3D region-of-interest selection are less risky, but may lead to loss of context. Reduction of data dimension, such as reducing vector quantities to scalars will give more freedom of choice in visualization techniques (such as using volume rendering), but will not lead to much data reduction. Geometry simplification techniques such as polygon mesh decimation, levels-of-detail or multiresolution techniques will be effective in managing very large datasets and interactive exploration, enabling users to trade accuracy with response time. Some areas that need additional work are:

- dense visualization techniques in 3D,
- multifield visualization with scalar, vector and tensor data,
- handling and exploring huge time-dependent flow datasets,

- user studies for evaluation, validation and field testing of flow visualization techniques,
- visualization of inaccuracy and uncertainty [42,60],
- more robust feature extraction techniques, especially in the case of 3D flow.

We also note that much of the research literature presented here demonstrates methods operating on structured, uniform resolution grids. However, the grids used in the private, commercial industry sector are often adaptive resolution and unstructured, especially in the case of CFD [37,38]. Thus, further research is necessary in order to integrate many of these methods into practical industrial applications.

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For supplementary material, including additional, higher resolution images and animations, please visit: <http://www.vrvis.at/ar3/pr2/star/>

References

1. D. Arrowsmith and C. Place. *An Introduction to Dynamical Systems*. Cambridge University Press, USA, 1990.
2. H. Battke, D. Stalling and H. Hege. Fast Line Integral Convolution for Arbitrary Surfaces in 3D. In *Visualization and Mathematics*, Springer-Verlag, Heidelberg, pp. 181–195. 1997.
3. J. Becker and M. Rumpf. Visualization of Time-Dependent Velocity Fields by Texture Transport. In *Visualization in Scientific Computing '98*, Eurographics, pp. 91–102, 1998.
4. S. Berger and E. Gröller. Color-Table Animation of Fast Oriented Line Integral Convolution for Vector Field Visualization. In *WSCG 2000 Conference Proceedings*, pp. 4–11, 2000.

5. U. Bordoloi and H. W. Shen. Hardware Accelerated Interactive Vector Field Visualization: A level of detail approach. In *Eurographics 2002 Proceedings*, volume 21(3) of *Computer Graphics Forum*, pp. 605–614, 2002.
6. D. Bürkle, T. Preußner and M. Rumpf. Transport and Anisotropic Diffusion in Time-Dependent Flow Visualization. In *Proceedings IEEE Visualization '01*, IEEE Computer Society, pp. 61–67, 2001.
7. B. Cabral and C. Leedom. Highly Parallel Vector Visualization Using Line Integral Convolution. In *Proceedings of the 27th Conference on Parallel Processing for Scientific Computing*, SIAM Press, USA, pp. 802–807, 1995.
8. B. Cabral and L. C. Leedom. Imaging Vector Fields Using Line Integral Convolution. In *Proceedings of ACM SIGGRAPH 1993*, Annual Conference Series, ACM Press/ACM SIGGRAPH, pp. 263–272, 1993.
9. R. A. Crawfis and N. Max. Texture Splats for 3D Scalar and Vector Field Visualization. In *Proceedings IEEE Visualization '93*, IEEE Computer Society, pp. 261–267, Oct. 1993.
10. W. de Leeuw and R. van Liere. Visualization of Global Flow Structures Using Multiple Levels of Topology. In *Data Visualization '99*, Eurographics, Springer-Verlag, pp. 45–52, May 1999.
11. W. de Leeuw and R. van Liere. Multi-Level Topology for Flow Visualization. *Computers and Graphics*, 24(3):325–331, June 2000.
12. W. de Leeuw and J. van Wijk. Enhanced Spot Noise for Vector Field Visualization. In *Proceedings IEEE Visualization '95*, IEEE Computer Society, pp. 233–239, Oct. 1995.
13. W. C. de Leeuw. Divide and Conquer Spot Noise. In *Proceedings of Supercomputing '97 (CD-ROM)*, ACM SIGARCH and IEEE, Nov. 1997.
14. W. C. de Leeuw, H. Pagendarm, F. H. Post and B. Waltzer. Visual Simulation of Experimental Oil-Flow Visualization by Spot Noise from Numerical Flow Simulation. In *Visualization in Scientific Computing '95*, Springer-Verlag, pp. 135–148, May 1995.
15. W. C. de Leeuw, F. H. Post and R. W. Vaatstra. Visualization of Turbulent Flow by Spot Noise. In *Virtual Environments and Scientific Visualization '96*, Springer-Verlag, pp. 286–295, Apr. 1996.
16. W. C. de Leeuw and R. van Liere. Spotting Structure in Complex Time Dependent Flow. In H. Hagen, G. M. Nielson and F. H. Post eds *Scientific Visualization*, IEEE, Dagstuhl Seminar 9724, pp. 9–13, June 1997.
17. W. C. de Leeuw and R. van Liere. Comparing LIC and Spot Noise. In *Proceedings IEEE Visualization '98*, IEEE Computer Society, pp. 359–366, 1998.
18. U. Diewald, T. Preußner and M. Rumpf. Anisotropic Diffusion in Vector Field Visualization on Euclidean Domains and Surfaces. In *IEEE Transactions on Visualization and Computer Graphics*, 6(2):139–149, 2000.
19. G. Erlebacher, B. Jobard and D. Weiskopf. Flow Textures. In C. R. Johnson and C. D. Hansen (eds), *The Visualization Handbook*. Academic Press, Oct. 2003.
20. L. K. Forssell. Visualizing Flow over Curvilinear Grid Surfaces Using Line Integral Convolution. In *Proceedings IEEE Visualization '94*, IEEE Computer Society, pp. 240–247, Oct. 1994.
21. L. K. Forssell and S. D. Cohen. Using Line Integral Convolution for Flow Visualization: Curvilinear Grids, Variable-Speed Animation, and Unsteady Flows. *IEEE Transactions on Visualization and Computer Graphics*, 1(2):133–141, June 1995.
22. H. Hege and D. Stalling. Fast LIC with Piecewise Polynomial Filter Kernels. In *Mathematical Visualization*, Springer Verlag, pp. 295–314, 1998.
23. W. Heidrich, R. Westermann, H.-P. Seidel and T. Ertl. Applications of Pixel Textures in Visualization and Realistic Image Synthesis. In *ACM Symposium on Interactive 3D Graphics*, pp. 127–134, 1999.
24. L. Hesselink, F. H. Post and J. van Wijk. Research Issues in Vector and Tensor Field Visualization. *IEEE Computer Graphics and Applications*, 14(2):76–79, Mar. 1994.
25. V. Interrante and C. Grosch. Strategies for Effectively Visualizing 3D Flow with Volume LIC. In *Proceedings IEEE Visualization '97*, pp. 421–424, 1997.
26. V. Interrante and C. Grosch. Visualizing 3D flow. *IEEE Computer Graphics & Applications*, 18(4):49–53, 1998.
27. B. Jobard, G. Erlebacher and M. Y. Hussaini. Hardware-Accelerated Texture Advection. In *Proceedings IEEE Visualization 2000*, IEEE Computer Society, pp. 155–162, 2000.
28. B. Jobard, G. Erlebacher and M. Y. Hussaini. Lagrangian-Eulerian Advection for Unsteady Flow Visualization. In *Proceedings IEEE Visualization '01*, IEEE, October 2001.


29. B. Jobard, G. Erlebacher and Y. Hussaini. Lagrangian-Eulerian Advection of Noise and Dye Textures for Unsteady Flow Visualization. *IEEE Transactions on Visualization and Computer Graphics*, 8(3):211–222, 2002.
30. B. Jobard and W. Lefer. Creating Evenly-Spaced Streamlines of Arbitrary Density. In *Proceedings of the Eurographics Workshop on Visualization in Scientific Computing '97*, volume 7, Eurographics, Springer-Verlag, April 28–30, 1997.
31. B. Jobard and W. Lefer. The Motion Map: Efficient Computation of Steady Flow Animations. In *Proceedings IEEE Visualization '97*, IEEE Computer Society, pp. 323–328, Oct. 19–24, 1997.
32. D. Kao, B. Zhang, K. Kim and A. Pang. 3D Flow Visualization Using Texture Advection. In *International Conference on Computer Graphics and Imaging '01*, August 2001.
33. L. Khouas, C. Odet and D. Friboulet. 2D Vector Field Visualization Using Furlike Texture. In *Joint Eurographics-IEEE TVCG Symposium on Visualization (VisSym '99)*, Eurographics, Springer-Verlag, pp. 35–44, May 1999.
34. M. Kiu and D. C. Banks. Multi-frequency Noise for LIC. In *Proceedings IEEE Visualization '96*, IEEE, pp. 121–126, Oct. 27–Nov. 1, 1996.
35. D. H. Laidlaw, R. M. Kirby, J. S. Davidson, T. S. Miller, M. da Silva, W. H. Warren and M. Tarr. Quantitative Comparative Evaluation of 2D Vector Field Visualization Methods. In *Proceedings IEEE Visualization 01*, IEEE Computer Society, pp. 143–150, October 2001.
36. D. A. Lane. Scientific Visualization of Large-Scale Unsteady Fluid Flows, *Scientific Visualization: Overviews, Methodologies, and Techniques*. IEEE Computer Science Press, Los Alamitos, chapter 5, pp. 125–145, 1997.
37. R. S. Laramée. FIRST: A Flexible and Interactive Resampling Tool for CFD Simulation Data. *Computers & Graphics*, 27(6):905–916, 2003.
38. R. S. Laramée, B. Jobard and H. Hauser. Image Space Based Visualization of Unsteady Flow on Surfaces. In *Proceedings IEEE Visualization '03*, IEEE Computer Society, pp. 131–138, 2003.
39. R. S. Laramée, J. Schneider and H. Hauser. Texture-Based Flow Visualization on Isosurfaces from Computational Fluid Dynamics. In *Joint Eurographics—IEEE TVCG Symposium on Visualization (VisSym '04)*, Konstanz, Germany, May 19–21, 2004, forthcoming.
40. G. S. Li, U. Bordoloi and H. W. Shen. Chameleon: An Interactive Texture-based Framework for Visualizing Three-dimensional Vector Fields. In *Proceedings IEEE Visualization '03*, IEEE Computer Society, pp. 241–248, 2003.
41. Z. P. Liu and R. J. Moorhead, II. AUFLIC: An Accelerated Algorithm for Unsteady Flow Line Integral Convolution. In *Proceedings of the Joint Eurographics—IEEE TVCG Symposium on Visualization (VisSym '02)*, pp. 43–52, 2002.
42. S. K. Lodha, A. Pang, R. E. Sheehan and C. M. Wittenbrink. UFLOW: Visualizing Uncertainty in Fluid Flow. In *Proceedings IEEE Visualization '96*, pp. 249–254, Oct. 27–Nov. 1, 1996.
43. H. Löffelmann, T. Kučera and E. Gröller. Visualizing Poincaré Maps Together with the Underlying Flow. In *Mathematical Visualization*, Springer Verlag, pp. 315–328, 1998.
44. H. Löffelmann, L. Mroz, E. Gröller and W. Purgathofer. Stream Arrows: Enhancing the Use of Streamsurfaces for the Visualization of Dynamical Systems. *The Visual Computer*, 13:359–369, 1997.
45. H. Löffelmann, Z. Szalavári and E. Gröller. Local Analysis of Dynamical Systems—Concepts and Interpretation. In *WSCG 1996 Conference Proceedings*, pp. 170–180, Feb. 1996.
46. X. Mao, L. Hong, A. Kaufman, N. Fujita and M. Kikukawa. Multi-Granularity Noise for Curvilinear Grid LIC. In *Graphics Interface*, pp. 193–200, June 1998.
47. X. Mao, M. Kikukawa, N. Fujita and A. Imamiya. Line Integral Convolution for 3D Surfaces. In *Visualization in Scientific Computing '97. Proceedings of the Eurographics Workshop*, pp. 57–70. Eurographics, 1997.
48. N. Max and B. Becker. Flow Visualization Using Moving Textures. In *Proceedings of the ICASW/LaRC Symposium on Visualizing Time-Varying Data*, pp. 77–87, Sept. 1995.
49. N. Max, B. Becker and R. Crawfis. Flow Volumes for Interactive Vector Field Visualization. In *Proceedings IEEE Visualization '93*, IEEE Computer Society, pp. 19–24, Oct. 1993.
50. N. Max, R. Crawfis and D. Williams. Visualizing Wind Velocities by Advecting Cloud Textures. In *Proceedings IEEE Visualization '92*, IEEE Computer Society, 1992.
51. A. Okada and D. L. Kao. Enhanced Line Integral Convolution with Flow Feature Detection. In *SPIE Vol. 3017*

- Visual Data Exploration and Analysis IV*, pp. 206–217, Feb. 1997.
52. D. R. Peachey. Solid Texturing of Complex Surfaces. *Computer Graphics (Proceedings of ACM SIGGRAPH 85)*, 19(3):279–286, 1985.
 53. F. H. Post and T. van Walsum. Fluid flow visualization. In *Focus on Scientific Visualization*, Springer, pp. 1–40, 1993.
 54. F. H. Post and J. van Wijk. Visual Representation of Vector Fields: Recent Developments and Research Directions. In L. Rosenblum et al. (eds), *Scientific Visualization: Advances and Challenges*. Springer, chapter 23, pp. 367–390, 1994.
 55. F. H. Post, B. Vrolijk, H. Hauser, R. S. Laramee and H. Doleisch. Feature Extraction and Visualization of Flow Fields. In *Eurographics 2002 State-of-the-Art Reports*, The Eurographics Association, pp. 69–100, 2–6, September 2002.
 56. F. H. Post, B. Vrolijk, H. Hauser, R. S. Laramee and H. Doleisch. The State of the Art in Flow Visualization: Feature Extraction and Tracking. *Computer Graphics Forum*, 22(4):775–792, Dec. 2003.
 57. W. H. Press, S. A. Teukolsky, W. T. Vetterling and B. P. Flannery. *Numerical Recipes in C++: The Art of Scientific Computing*. 2 edition, Cambridge University Press, Cambridge, 2002.
 58. T. Preußner and M. Rumpf. Anisotropic Nonlinear Diffusion in Flow Visualization. In *Proceedings IEEE Visualization '99*, IEEE Computer Society, pp. 325–332, Oct. 1999.
 59. C. Rezk-Salama, P. Hastreiter, C. Teitzel and T. Ertl. Interactive exploration of volume line integral convolution based on 3D-texture mapping. In *Proceedings IEEE Visualization '99*, IEEE Computer Society, pp. 233–240, 1999.
 60. P. J. Rhodes, R. S. Laramee, R. D. Bergeron and T. M. Sparr. Uncertainty Visualization Methods in Isosurface Rendering. In M. Chover, H. Hagen and D. Tost (eds), *Eurographics 2003, Short Papers*, The Eurographics Association, pp. 83–88, September 1–5, 2003.
 61. A. Sanna, B. Montrucchio and P. Montuschi. A survey on visualization of vector fields by texture-based methods. *Recent Research Developments in Pattern Recognition*, 1(1):13–27, 2000.
 62. A. Sanna, B. Montrucchio, P. Montuschi and A. Sparavigna. Visualizing Vector Fields: The Thick Oriented Stream-Line Algorithm (TOSL). *Computers and Graphics*, 25(5):847–855, Oct. 2001.
 63. A. Sanna, C. Zunino, B. Montucchio and P. Montuschi. Adding a Scalar Value to Texture-Based Vector Field Representations by local contrast analysis. In *Proceedings of the Joint Eurographics—IEEE TCVG Symposium on Visualization (VisSym '02)*, pp. 35–41, 2002.
 64. G. Scheuermann, H. Burbach and H. Hagen. Visualizing Planar Vector Fields with Normal Component Using Line Integral Convolution. In *Proceedings IEEE Visualization '99*, IEEE Computer Society, pp. 255–262, 1999.
 65. H. Shen and D. L. Kao. A New Line Integral Convolution Algorithm for Visualizing Time-Varying Flow Fields. *IEEE Transactions on Visualization and Computer Graphics*, 4(2), Apr.–June, pp. 98–108, 1998.
 66. H. W. Shen, C. R. Johnson and K. L. Ma. Visualizing Vector Fields Using Line Integral Convolution and Dye Advection. In *1996 Volume Visualization Symposium*, IEEE, pp. 63–70, Oct. 1996.
 67. H. W. Shen and D. L. Kao. UFLIC: A Line Integral Convolution Algorithm for Visualizing Unsteady Flows. In *Proceedings IEEE Visualization '97*, IEEE Computer Society, pp. 317–323, 1997.
 68. D. Silver, F. Post, and I. Sadarjoen. *Flow Visualization*, volume 7 of *Wiley Encyclopedia of Electrical and Electronics Engineering*, John Wiley & Sons, New York, pp. 640–652, 1999.
 69. D. Stalling. LIC on Surfaces. In *Texture Synthesis with Line Integral Convolution*, ACM SIGGRAPH 97, International Conference on Computer Graphics and Interactive Techniques, pp. 51–64, 1997.
 70. D. Stalling and H. Hege. Fast and Resolution Independent Line Integral Convolution. In *Proceedings of ACM SIGGRAPH 95*, Annual Conference Series, ACM SIGGRAPH, ACM Press/ACM SIGGRAPH, pp. 249–256, 1995.
 71. A. Sundquist. Dynamic Line Integral Convolution for Visualizing Streamline Evolution. *IEEE Transactions on Visualization and Computer Graphics*, 9(3):273–282, 2003.
 72. F. Taponecco and M. Alexa. Vector Field Visualization using Markov Random Field Texture Synthesis. In *Proceedings of the Joint Eurographics—IEEE TCVG Symposium on Visualization (VisSym '03)*, Springer-Verlag, pp. 195–202, May 2003.


73. C. Teitzel, R. Grosso and T. Ertl. Line Integral Convolution on Triangulated Surfaces. In *WSCG 1997 Conference Proceedings*, pp. 572–581, 1997.
74. A. Telea and J. van Wijk. Simplified Representation of Vector Fields. In *Proceedings IEEE Visualization '99*, IEEE Computer Society, pp. 35–42, 1999.
75. A. Telea and J. J. van Wijk. 3D IBFV: Hardware-Accelerated 3D Flow Visualization. In *Proceedings IEEE Visualization '03*, IEEE Computer Society, pp. 233–240, 2003.
76. T. Urness, V. Interrante, I. Marusic, E. Longmire, and B. Ganapathisubramani. Effectively Visualizing Multi-Valued Flow Data using Color and Texture. In *Proceedings IEEE Visualization '03*, IEEE Computer Society, pp. 115–122, 2003.
77. M. van Dyke. *An Album of Fluid Motion*. The Parabolic Press, 1982.
78. J. J. van Wijk. Spot noise-Texture Synthesis for Data Visualization. In T. W. Sederberg (ed), *Computer Graphics (Proceedings of ACM SIGGRAPH 91)*, ACM, volume 25, pp. 309–318, 1991.
79. J. J. van Wijk. Image Based Flow Visualization. *ACM Transactions on Graphics*, 21(3):745–754, 2002.
80. J. J. van Wijk. Image Based Flow Visualization for Curved Surfaces. In *Proceedings IEEE Visualization '03*, IEEE Computer Society, pp. 123–130, 2003.
81. V. Verma, D. Kao and A. Pang. PLIC: Bridging the Gap Between Streamlines and LIC. In *Proceedings IEEE Visualization '99*, N.Y., pp. 341–348, Oct. 25–29, 1999.
82. H. K. Versteeg and W. Malalasekera. Addison-Wesley, February 1996.
83. R. Wegenkittl and E. Gröller. Fast Oriented Line Integral Convolution for Vector Field Visualization via the Internet. In *Proceedings IEEE Visualization '97*, IEEE Computer Society, pp. 309–316, Oct. 19–24, 1997.
84. R. Wegenkittl, E. Gröller and W. Purgathofer. Animating Flow Fields: Rendering of Oriented Line Integral Convolution. In *Computer Animation '97 Proceedings*, IEEE Computer Society, pp. 15–21, June 1997.
85. D. Weiskopf, G. Erlebacher and T. Ertl. A Texture-Based Framework for Spacetime-Coherent Visualization of Time-Dependent Vector Fields. In *Proceedings IEEE Visualization '03*, IEEE Computer Society, pp. 107–114, 2003.
86. D. Weiskopf, G. Erlebacher, M. Hopf and T. Ertl. Hardware-Accelerated Lagrangian-Eulerian Texture Advection for 2D Flow Visualizations. In *Proceedings of the Vision Modeling and Visualization Conference 2002 (VMV-01)*, pp. 439–446, Nov. 21–23, 2002.
87. D. Weiskopf and T. Ertl. GPU-Based 3D Texture Advection for the Visualization of Unsteady Flow Fields. In *WSCG 2004 Conference Proceedings, Short Papers*, pp. 259–266, February 2004.
88. D. Weiskopf, M. Hopf and T. Ertl. Hardware-Accelerated Visualization of Time-Varying 2D and 3D Vector Fields by Texture Advection via Programmable Per-Pixel Operations. In *Proceedings of the Vision Modeling and Visualization Conference 2001 (VMV 01)*, pp. 439–446, Nov. 21–23, 2001.
89. R. Yagel, D. M. Reed, A. Law, P. Shih and N. Shareef. Hardware Assisted Volume Rendering of Unstructured Grids by Incremental Slicing. In *Proceedings 1996 Symposium on Volume Visualization*, pp. 55–62, Sept. 1996.
90. M. Zöckler, D. Stalling and H.-C. Hege. Parallel Line Integral Convolution. *Parallel Computing*, 23(7):975–989, 1997.

Tutorial Introduction


Interactive Texture-Based Flow Visualization



Gordon Erlebacher



Bob Laramée



Daniel Weiskopf

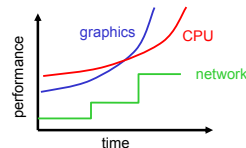
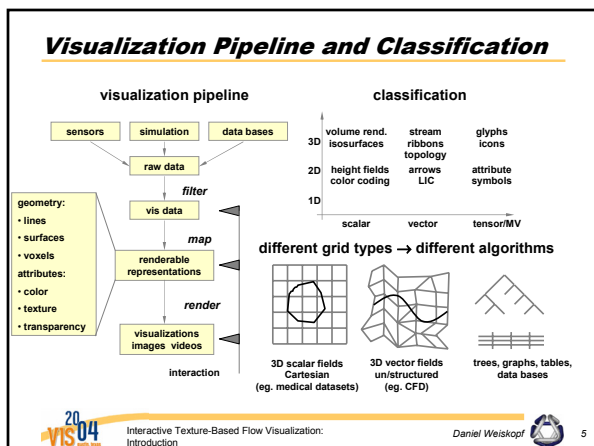
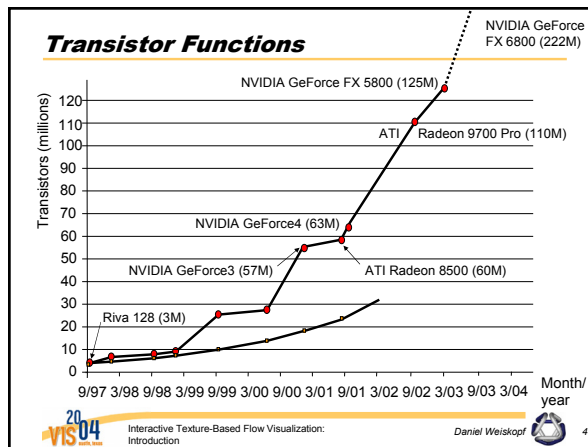
IEEE Visualization 2004 Tutorial: Interactive Texture-Based Flow Visualization

Schedule

8.30 – 9.00	Introduction to the Tutorial Intro to GPU Programming	Daniel Weiskopf
9.00 – 10.00	2D Texture-Based Flow Visualization	Gordon Erlebacher
10.00 – 10.30	<i>Coffee Break</i>	
10.30 – 11.10	Texture-Based Flow Visualization on Surfaces	Bob Laramée
11.10 – 11.50	3D Texture-Based Flow Visualization	Daniel Weiskopf
11.50 – 12.15	Summary, Questions & Answers	All speakers

Graphics Hardware Trends

- Faster development than Moore's law
 - Double transistor functions every 6-12 months
 - Driven by game industry
- Improvement of performance and functionality
 - Textures and multi-textures
 - Pixel operations (transparency, blending, pixel shaders)
 - Geometry and lighting modifications (vertex shaders)

GPU and Visualization Pipeline

- Filtering**
 - Data filtering in graphics memory
 - Compression/decompression (of textures)
- Mapping**
 - Integrate particle traces
 - Classification in volume rendering
- Rendering**
 - Texture-based techniques (e.g., for volume rendering)

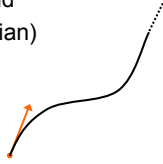
Tutorial Introduction

Flow Visualization

- Flow:
 - Vector field
 - Additional attributes: pressure, temperature, etc.
- Vector field = velocity field
- Particle tracing (Lagrangian)

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

- Initial value problem



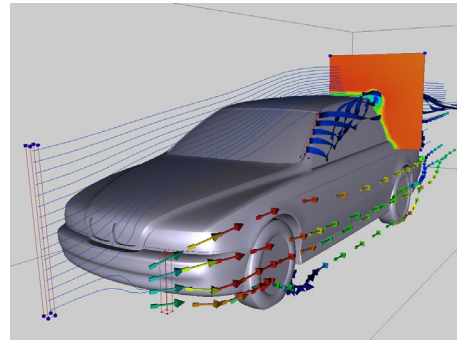
Interactive Texture-Based Flow Visualization:
Introduction

Daniel Weiskopf



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Flow Visualization



Interactive Texture-Based Flow Visualization:
Introduction

Daniel Weiskopf



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Classification: Level 1

- Direct flow visualization
 - Arrows, color coding, etc.
- Geometric flow visualization
 - Streamlines, streaklines, pathlines
 - Geometric objects
- Feature-based flow visualization
 - Topology, vortices, etc.
 - IEEE Visualization 2004 Tutorial
"Feature Oriented Methods in Flow Visualization"
- Dense, texture-based flow visualization



Interactive Texture-Based Flow Visualization:
Introduction

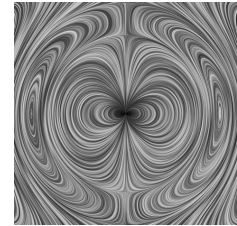
Daniel Weiskopf



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Texture-Based Flow Visualization

- Focus of this tutorial
- Dense representation
 - Cover domain "everywhere",
at each texel
 - Patterns through filtering
 - Overcomes seed-point
positioning problem
- Issues
 - Performance: Many texels, many computations
 - Interactivity?
 - Time-dependent flow?
 - Perception problems in 3D



Interactive Texture-Based Flow Visualization:
Introduction

Daniel Weiskopf



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Classification: Level 2 and Beyond

- Classification of texture-based techniques
- Dimensionality of the domain
 - 2D on planar surfaces
 - 2.5D on curved surfaces within 3D space
 - 3D in 3D volume
- Further categories
 - Steady vs. unsteady flow
 - Internal representation (grid type, scattered data,
image space vs. object space)
 - Implementation: CPU-based vs. GPU-based



Interactive Texture-Based Flow Visualization:
Introduction

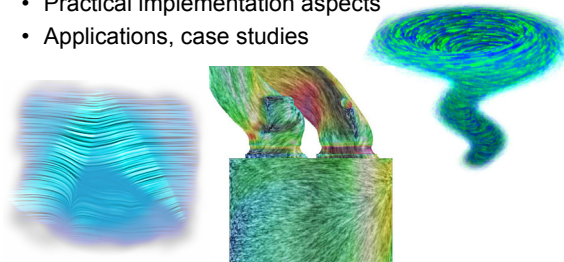
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Goals of this Tutorial

- Recent developments (last 3-5 years)
- Theoretical and algorithmic background
- Practical implementation aspects
- Applications, case studies



Interactive Texture-Based Flow Visualization:
Introduction

Daniel Weiskopf



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Tutorial Introduction

Tutorial Web Page

- Updated slides
- Additional images and material

http://www.vis.uni-stuttgart.de/vis04_tutorial



Basics of GPU-Based Programming

Basics of GPU-Based Programming



Daniel Weiskopf
Institute of Visualization and Interactive Systems
University of Stuttgart



IEEE Visualization 2004 Tutorial:
Interactive Texture-Based Flow Visualization

Overview

- Rendering pipeline on current GPUs
- Low-level languages
- High-level shading languages

- Also see tutorial
„GPGPU: General-Purpose Computation on Graphics Processors”



Interactive Texture-Based Flow Visualization:
Basics of GPU-Based Programming

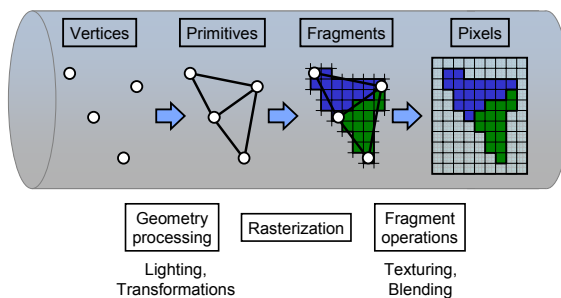
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2

Graphics Pipeline

Scene description



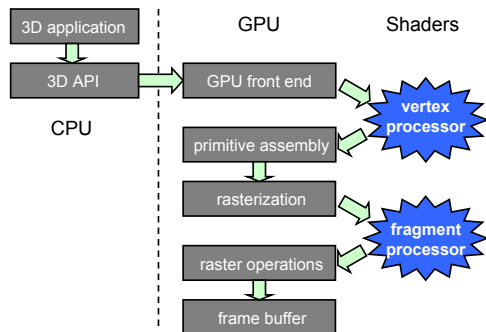
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Basics of GPU-Based Programming

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3

Programmable Pipeline



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Basics of GPU-Based Programming

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4

Issues

- How are vertex and pixel shaders specified?
 - Low-level, assembler-like
 - High-level language
- Data flow between components
 - Per-vertex data (for vertex shader)
 - Per-fragment data (for pixel shader)
 - Uniform (constant) data: e.g. model-view matrix, material parameters



Interactive Texture-Based Flow Visualization:
Basics of GPU-Based Programming

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What Are Low-Level APIs?

- Current low-level APIs:
 - OpenGL extensions: GL_ARB_vertex_program, GL_ARB_fragment_program
 - DirectX 9: Vertex Shader 2.0, Pixel Shader 2.0, Vertex Shader 3.0, Pixel Shader 3.0
- Older low-level APIs:
 - DirectX 8.x: Vertex Shader 1.x, Pixel Shader 1.x
 - OpenGL extensions: GL_ATI_fragment_shader, GL_NV_vertex_program, ...



Interactive Texture-Based Flow Visualization:
Basics of GPU-Based Programming

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Basics of GPU-Based Programming

Applications of Vertex Programming

- Customized computation of vertex attributes
- Computation of anything that can be interpolated linearly between vertices
- Limitations:
 - Vertices can neither be generated nor destroyed
 - No information about topology or ordering of vertices is available



Applications of Fragment Shaders

- Customized computation of fragment attributes
- Computation of anything that should be computed per **pixel**

→ Basis for texture-based flow visualization

- Limitations:
 - Fragments cannot be generated
 - Position of fragments cannot be changed
 - No information about geometric primitive is available

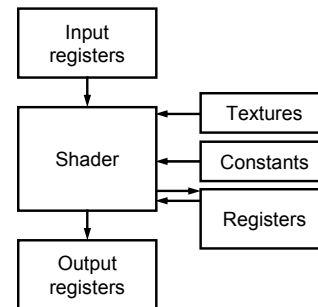


Fragment Shader

- Circumvents the traditional fragment pipeline
- What is not replaced?
 - Fragment tests (alpha, stencil, and depth tests)
 - Blending



Fragment Shader: Programming Model



DirectX 9: Pixel Shader 2.0

- Pixel Shader 2.0 introduced in DirectX 9.0
 - Syntax of Pixel Shader 3.0 is closely related
- Instruction set
 - Numerical operations
 - Texture operations (lookup)
- Similar functionality and limitations in GL_ARB_fragment_program
 - Similar registers and syntax



DirectX 9: Pixel Shader 2.0

- Declaration of texture samplers

```
dcl_type s*
```

- Examples:

```
dcl_2d s0  
dcl_volume s1
```

- Declaration of input color and texture coordinate

```
dcl v*[,mask]  
dcl t*[,mask]
```



Basics of GPU-Based Programming

Pixel Shader 2.0: Instructions

- Instruction set
 - Operate on floating-point scalars or 4-vectors
 - Basic syntax:

```
op destination [, source1 [, source2 [, source3]]]
```
 - Example:

```
mov oC0, v0; // sets resulting color oC0
```
- Texture sampling
 - Syntax:

```
op destination, source, sn
```
 - Example:

```
texld r2, t1, s0;
```

Pixel Shader 2.0: Simple Example

```
ps_2_0  
  
dcl_2d s0  
dcl t0.xy  
  
texld r1, t0, s0  
mov oC0, r1
```

High-Level Shading Languages

- Why?
 - Avoids programming, debugging, and maintenance of long assembly shaders
 - Easy to read
 - Easier to modify existing shaders
 - Automatic code optimization
 - Wide range of platforms

Assembler vs. High-Level Language

Assembler

High-level language

```
...  
dp3 r0, r0, r1  
max r1.x, c5.x, r0.x  
pow r0.x, r1.x, c4.x  
mul r0, c3.x, r0.x  
mov r1, c2  
add r1, c1, r1  
mad r0, c0.x, r1, r0  
...
```

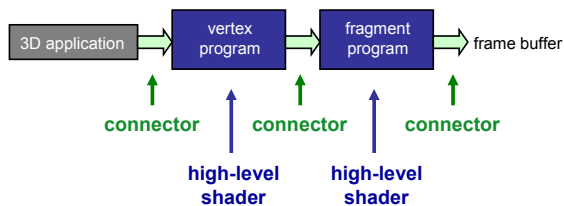
```
...  
float4 cSpec = pow(max(0, dot(Nf, H)), phongExp).xxx;  
float4 cPlastic = Cd * (cAmbi + cDiff) + Cs * cSpec;  
...
```

Blinn-Phong shader expressed in both assembler and high-level language



Data Flow through Pipeline

- Vertex shader program
- Fragment shader program
- Connectors



High-Level Shading Languages

- Cg
 - “C for Graphics”
 - By NVIDIA
- HLSL
 - “High-level shading language”
 - Part of DirectX 9 (Microsoft)
- OpenGL 2.0 Shading Language

Basics of GPU-Based Programming

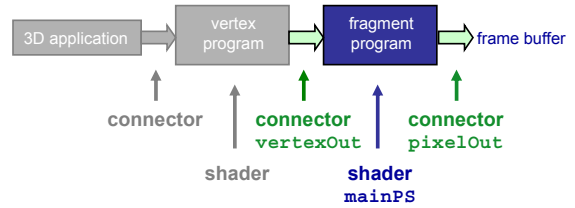
Cg

- Typical concepts for a high-level shading language
- Language is (almost) identical to DirectX HLSL
- Syntax, operators, functions from C/C++
- Conditionals and flow control



Cg: Pixel Shader

- Connectors: What kind of data is transferred to / from pixel program?
- Actual pixel shader



Cg: Pixel Shader Example

```
// vertex shader to pixel shader
struct vertexOut {
    float4 Position : POSITION;
    float4 Diffuse : COLOR;
    float4 TexCoord : TEXCOORD;
};

// final pixel output: data from pixel shader to frame buffer
struct pixelOut {
    float4 Col : COLOR;
};

// pixel shader
pixelOut mainPS(
    vertexOut IN, // input from vertex shader
    uniform float param, // constant parameter
) {
    pixelOut OUT;
    ... // more code
    OUT.Col = IN.Diffuse;
    return OUT; // output of pixel shader
}
```



What's Next?

- Usage of GPU and CPU for flow visualization



2D Texture-Based Flow Visualization



Gordon Erlebacher

School of Computational Science
Florida State University



IEEE Visualization 2004 Tutorial:
Interactive Texture-Based Flow Visualization

Overview

- Textures
 - Line Integral Convolution
 - Time-dependent flows
 - Lagrange-Eulerian Advection (LEA)
 - Image-Base Flow Visualization (IBFV)
 - Tiling (large datasets)
 - Generic Framework
 - Unsteady Flow Advection Code
 - Dye Advection
- Applications
- References



Interactive Texture-Based Flow Visualization:
2D Flow Visualization

2/73

Gordon Erlebacher



What are Textures?

- Textures = 1D, 2D, 3D arrays
- Texture array element = A_i , A_{ij} , A_{ijk}
 - A_{ij} : texel (2D texture element)
 - A_{ijk} : voxel (3D volume element)
- A texture can encode, 1, 2, 3, or 4 pieces of information
 - each piece can be a (u)byte, (u)int, or float
- n components and mD
 - byte: nm bytes per texture array element
 - int/float: 4nm bytes per texture array element



Interactive Texture-Based Flow Visualization:
2D Flow Visualization

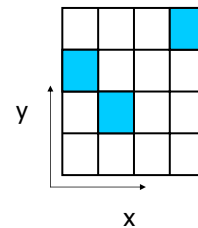
3/73

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Eulerian Approach

- Properties given on a grid, not wrt particles
- Position is implicit
- Sampling of particles on regular grid (=texture)



Interactive Texture-Based Flow Visualization:
2D Flow Visualization

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Gordon Erlebacher



Texture Encoding

- What to encode?
 - Color: any combination of RGBA
 - Normal vectors: n_x , n_y , n_z
 - Transparency/opacity: alpha
 - Any kind of information:
 - particle positions
 - velocity components
 - velocity magnitude
 - diffusivity
 - CFD simulation data attributes (P, T, ...)



Interactive Texture-Based Flow Visualization:
2D Flow Visualization

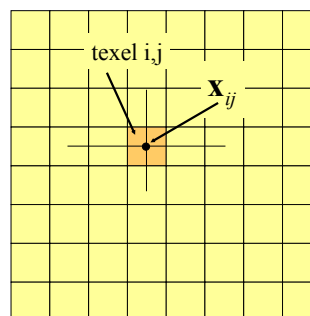
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Textures

Position encoding



2-component texture

$$\mathbf{x}_{ij} = (x_i, y_j)$$

$$x_i = x_{\min} + i\Delta x$$

$$y_j = y_{\min} + j\Delta y$$



Interactive Texture-Based Flow Visualization:
2D Flow Visualization

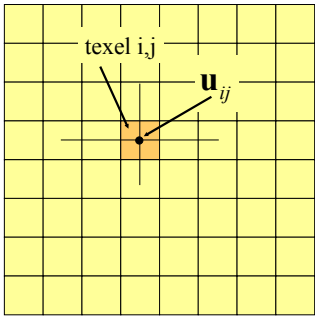
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Textures

Velocity encoding

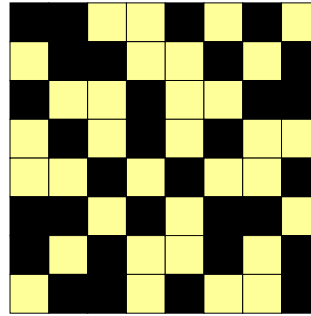


2-component texture
 $\mathbf{u}_{ij} = (u_{ij}, v_{ij})$



Textures

Noise encoding



1-component texture
 $N_{ij} = 0 \text{ or } 1$



Texture Initialization

- Executed on the CPU
- Textures are modified on the GPU during the advection process
- Each texel encodes a single particle
 - particle is treated as a point at position \mathbf{x}_{ij} within texel ij

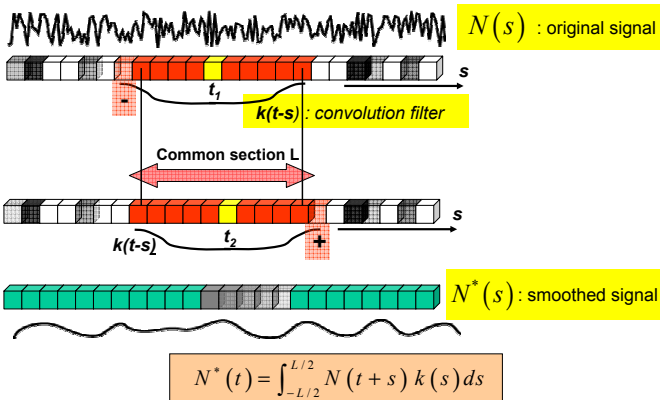


Overview

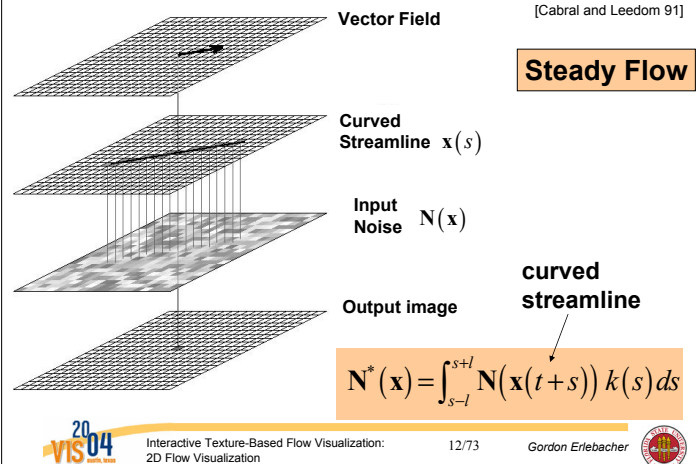
- Textures
- **Line Integral Convolution**
- Time-dependent flows
 - Lagrange-Eulerian Advection (LEA)
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1D Convolution



Line Integral Convolution (LIC)

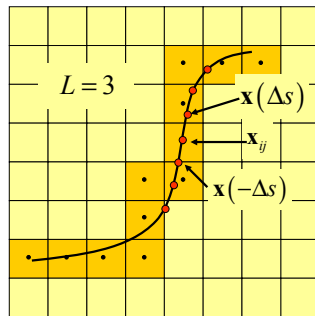


Discretization of Convolution Integral

$$N^*(\mathbf{x}) = \int N(\mathbf{x}(s)) ds$$

$$N(\mathbf{x}_{ij}) \approx \sum_{k=-L}^L N(\mathbf{x}(k\Delta s))$$

- $\mathbf{x}(s)$ is a streamline
- $\mathbf{x}_{ij} = \mathbf{x}(0)$



GPU Implementation (1)

$n = N, Ka = 0$

for $l = 1, L$

$$\mathbf{x} = \mathbf{x} + \mathbf{v}(\mathbf{x})\Delta t$$

$$\mathbf{n} = \mathbf{n} + \mathbf{v}(\mathbf{x})K(l\Delta s)\Delta s$$

$$Ka = Ka + K(l\Delta s)$$

end for

Dependent texture

Forward integration

.....

Backward integration

$$\mathbf{n}_{ij} = \mathbf{n}_{ij} / Ka$$

Filter normalization

Overview

- Textures
- Line Integral Convolution
- **Time-dependent flows**
 - Lagrange-Eulerian Advection (LEA)
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- References

Time-Dependent Flows

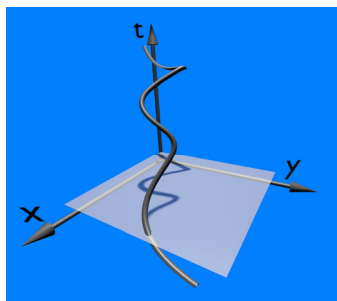
- Velocity field is a function of time: $\mathbf{v}(\mathbf{x}, t)$
- Several ways to visualize the vector field:
 - track a dense collection of particles
 - release (multi-)colored dye into the flow
 - track streaklines, pathlines, timelines
- Objectives
 - Visualize the “structure” of the flow
 - Visualize the motion of particles
 - Minimize numerical artifacts
 - Maintain uniform density of particles

Particle Path in Space-Time

A particle is at \mathbf{x} at $t=0$

The particle is transported according to the velocity field $\mathbf{v}(\mathbf{x}, t)$.

The particle follows the 3D path seen in the figure.



Curves of Interest

- **Particle path**
 - path followed by a particle immersed in a time-dependent velocity field
- **Streamline**
 - path followed by a particle when the velocity field is frozen at a *particular* time
- **Streakline**
 - locus of fluid particles that originate from a fixed point in space

Potential Problems

- Accumulation of particles in regions of flow convergence
- Dispersal of particles in regions of flow divergence (necessitates particle injection)
- Injection of particles at boundary inflow
- Treatment of particles at outflow regions

Particle Property P

- P remains constant over the lifetime of a particle

$$\frac{DP}{dt} = \frac{\partial P}{\partial t} + \mathbf{v} \cdot \nabla P = 0$$

- Equate property value of a given particle at times t and $t - h$

single particle $P(\mathbf{x}_{ij}, t) = P(\mathbf{x}_{ij} - h\mathbf{v}_{ij}, t - h)$

texture $P(\mathbf{x}^{n+1}, t^{n+1}) = P(\mathbf{x}^n, t^n)$

- P is often particle “color” (RGB)
- Particle property is encoded in a noise texture

Overview

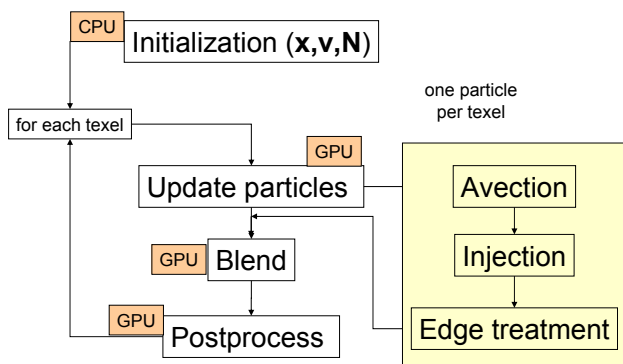
- Textures
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Lagrange-Euler Advection (LEA)

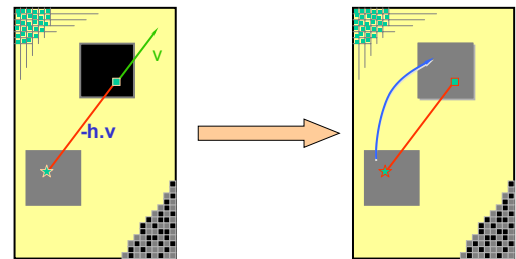
[Jobard et al. 00]

- Feedback algorithm
- Each texel encodes a single particle
- Particle property of each texel is computed from the particle position at some previous time
- Advect noise texture with *nearest neighbor* interpolation
- Alpha blend successive noise textures into the framebuffer
 - similar to long exposure photography

Flowchart



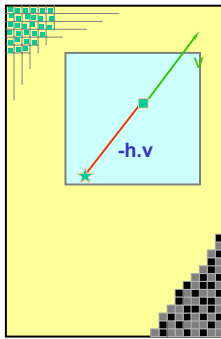
Property Assignment



Advection of noise texture $N(\mathbf{x}, t)$ for one time step

$$N(\mathbf{x}, t) = N(\mathbf{x} - \mathbf{v}^t, t - h)$$

Issue: Small Displacements



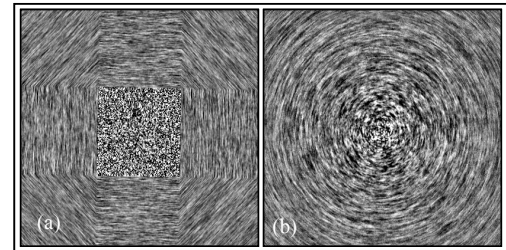
Problem

Particle remains in the texel
Particle property does not change

Solution

Keep track of explicit particle position within texel
Eventually, particle leaves texel

Solution: Fractional Correction



No fractional correction

Fractional correction

GPU Implementation

x : particle position texture
varies by one unit across one texel

$$x^* \leftarrow x - hv$$

$$N(x) \leftarrow N(x^*)$$

Dependent texture

$$x \leftarrow \text{frac}(x^*)$$

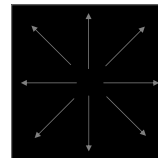
Fractional part

Render Buffer \leftarrow LIC ($N(x)$)

Noise Injection (1)

Problem: Noise frequency decreases in region of flow divergence

Vector Field



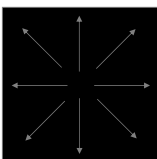
Advected Noise



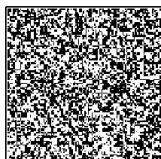
Noise Injection (2)

Solution: Maintain high frequency by swapping 2-3% of pixels

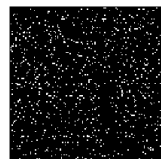
Vector Field



Advected Noise



Sparse Noise

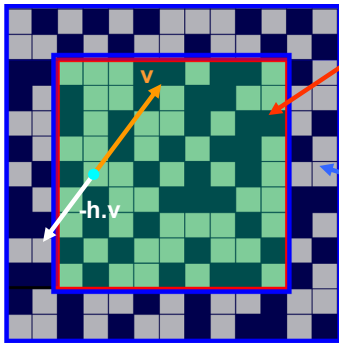


Blend, XOR

GPU Implementation

- Create sparse noise texture (2 percent black, 98 percent white texels) on CPU with GL_REPEAT
- Maintain texture on the GPU
- Every iteration, shift the texture randomly
 - (maintain list of random numbers on CPU)
- XOR advected noise and random noise

Edge Treatment



Physical domain

- Noise is advected according to $v(x,t)$
- Minimal spatial correlation

Buffer zone

- Noise has no spatial correlation
- Noise is time-dependent
- Width $< h |v|_{\max}$



GPU Implementation

$$\mathbf{x}^* \leftarrow \mathbf{x} - h\mathbf{v}$$

$$\mathbf{N}(\mathbf{x}) \leftarrow \mathbf{N}(\mathbf{x}^*)$$

$$\mathbf{x} \leftarrow \text{frac}(\mathbf{x}^*)$$

Noise advection

Fractional correction

$$\mathbf{F}_R(\mathbf{x}) \leftarrow \alpha(\mathbf{x}^*)\mathbf{N}(\mathbf{x}^*) + (1 - \alpha(\mathbf{x}^*))\mathbf{N}_B$$

Boundary treatment

\mathbf{N} : Advected noise

\mathbf{N}_B : Boundary buffer noise

\mathbf{F}_R : Render buffer

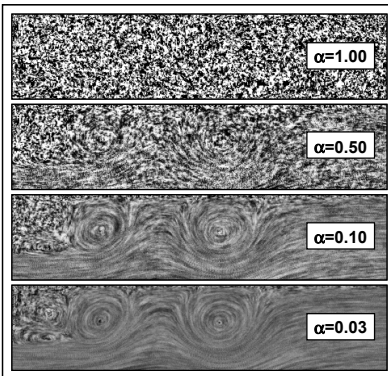
α : Transparency mask

$$\alpha(\mathbf{x}^*) = 0, \quad \mathbf{x}^* \in \text{buffer region}$$

$$= 1, \quad \mathbf{x}^* \in \text{physical domain}$$



LEA: α -blending



Introduces spatial correlation

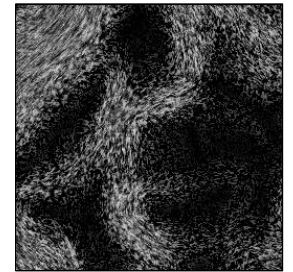
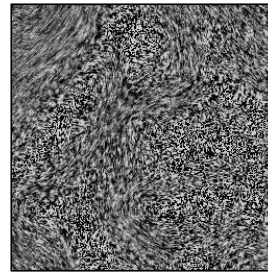
$$D(t + \Delta t) = \alpha \mathbf{N}(t + \Delta t) + (1 - \alpha) D(t)$$

$D(t)$: framebuffer at t



Velocity Mask

- Use of velocity textures to enhance regions of higher velocity magnitude



GPU Implementation

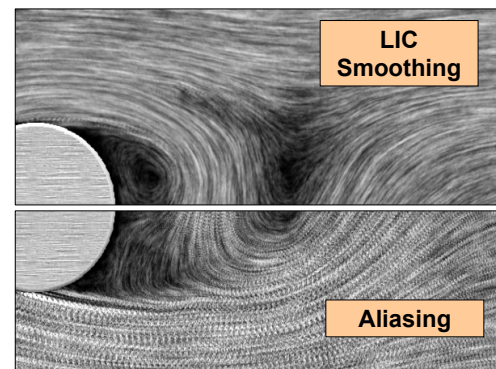
- \mathbf{D} : rendered framebuffer
- mask $\mathbf{M} = C|\mathbf{v}|^p$ in α channel

$$\mathbf{D}.xy = \alpha \mathbf{D}.xy + (1 - \alpha) \mathbf{N}.xy$$

$$\mathbf{D}.w = \text{mag}(\mathbf{v}.xy)$$

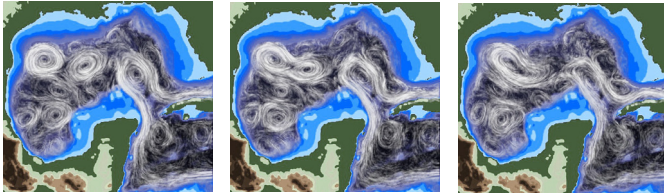


Post-processing



Ocean Circulation, Gulf of Mexico

- Background texture
- Masking to emphasize strong currents



Three frames in a time sequence



Overview

- Textures
- Line Integral Convolution
- Time-dependent flows
 - Lagrange-Eulerian Advection (LEA)
 - **Image-Base Flow Visualization (IBFV)**
 - Tiling (large datasets)
 - Generic Framework
 - Unsteady Flow Advection Code
 - Dye Advection
- Applications
- References



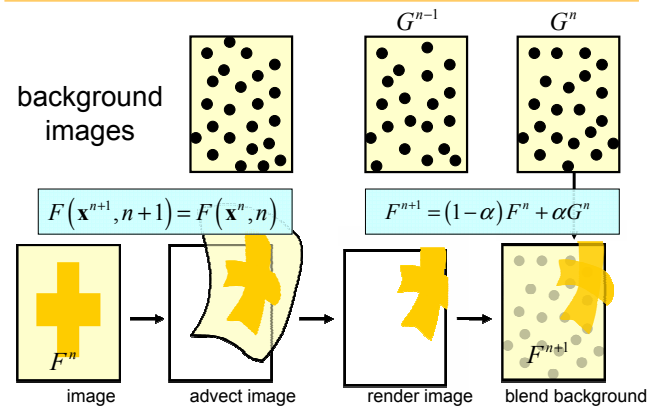
Image-Based Flow Visualization (IBFV)

[Van Wijk 02]

- Feedforward algorithm
- Advect a textured mesh
- Texture encodes particle properties
- Mesh nodes are advected according to $\mathbf{v}(\mathbf{x}, t)$
- Advect noise texture with *linear* interpolation
- Blend in a background image



Basic Idea

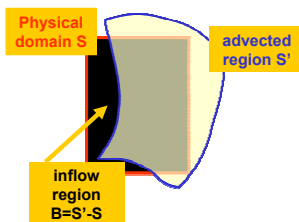


Practical Implementation

- Clear screen to black
- Render previous image onto a warped (i.e., advected) mesh
- Blend in a background image

ISSUE: Inflow boundaries

- inflow regions remain close to black



CPU/GPU Implementation

- Mesh-based so very efficient using fixed pipeline (no shaders)

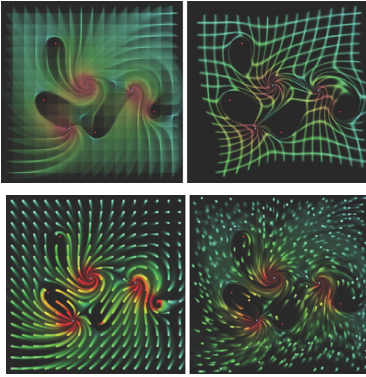
Initialize property texture \mathbf{N} (noise)

for each polygon P in mesh

- advect 4 vertices $\mathbf{x}^* = \mathbf{x} + h\mathbf{v}$
- draw polygon defined by \mathbf{x}^* using texture coordinates at \mathbf{x}
- α -blend background image



Samples from IBFV Demo Program



<http://www.win.tue.nl/~vanwijk/ibfv>

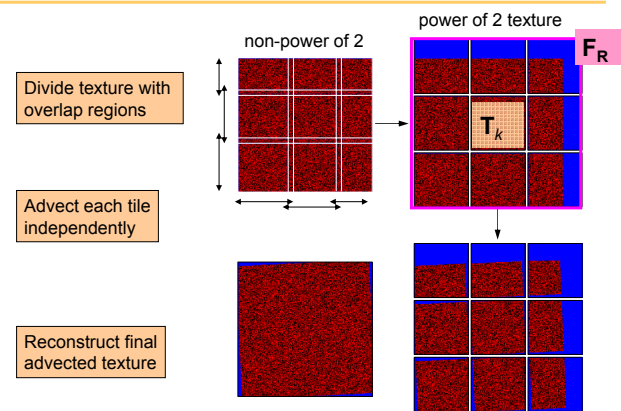
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Large Datasets: Tiling

- On older machines and cheaper graphics cards
 - depth of color channels: 8 or 12 bits
 - coordinate textures of 256x256: 4 remaining bits for fractional coordinates: minimum displacement: 1/16 texel
 - if texture is 1024x1024, particles can only advance in units of one texel
- **Solution:** simulate a 1024x1024 texture by 16 tiles of 256x256, leading to fractional displacements of 1/16 texel
- In practice, use texture with 16 bit channels (Radeon)
 - 32 bit textures on Radeon and Nvidia
 - 256x256 textures: minimum increment: 1/256
 - 1024x1024 texture: minimum increment :1/64

Tiled Texture Advection



GPU Implementation

- Global rendering texture F_R
- Loop over tiles T_k
 - standard LEA in each tile
 - composite T_k into F_R through blending

$$F_R \leftarrow (1 - \alpha(T_k)) F_R + \alpha(T_k) T_k$$

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Generic Framework

[Erlebacher et al. 02]

- All texture advection techniques for time-dependent flows depend on 4 elements:
 - spatial correlations
 - temporal correlations
 - a property texture (noise, dye, ...)
 - the shape of the convolution kernels
- Correlations occur along curves $\Gamma(t)$ in space-time and satisfy

$$N^*(\mathbf{x}) = \int N(\Gamma(s)) ds$$

$$N(\mathbf{x}_{ij}) \approx \sum_{k=L}^L N(\Gamma(k\Delta s))$$



Generic Framework

- Temporal correlations
 - Maintain particle identity along particle trajectories
 - Avoid Lagrangian tracking
 - Responsible for visual tracking of spatial structures
- Spatial correlations
 - Introduces spatial structures into an otherwise random collection of particles

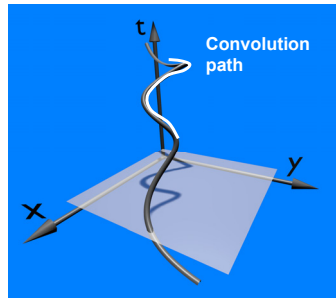


Noise Volume in Space-Time

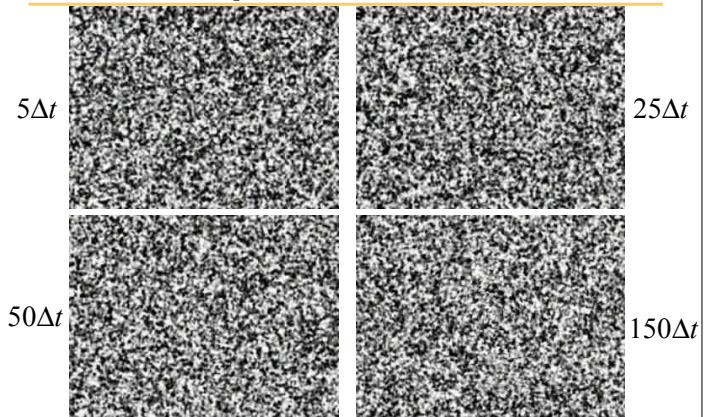
Fill space-time (x-y-t) volume with noise

Perform a temporal convolution of this noise (i.e., smoothing) operation along the pathlines of a field $\mathbf{V}_T(\mathbf{x}, t)$

Perform a spatial convolution of this noise (i.e., smoothing) operation along the pathlines of a field $\mathbf{V}_S(\mathbf{x}, t)$



Effect of Temporal Filter Width



Brute Force GPU Implementation

- Specify two vector fields: $\mathbf{V}_T(\mathbf{x}, t)$ and $\mathbf{V}_S(\mathbf{x}, t)$
- Temporal phase
 - For each time t_n
 - Convolution along pathlines of \mathbf{V}_T in 3D noise texture \mathbf{N}
 - Store resulting particle texture \mathbf{T}_n
- Spatial phase
 - For each time t_n
 - Convolution along pathlines of \mathbf{V}_S in 3D collection $\{\mathbf{T}_n\}$
 - Display result in framebuffer \mathbf{F}



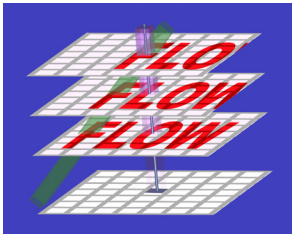
GPU Implementation

- **Problem:** In practice, cannot store full 3D textures in GPU memory
- **Solutions:**
 - Reduce width of temporal filter
 - LEA: width of $2h$
 - Freeze \mathbf{V}_S to perform spatial convolution at fixed time



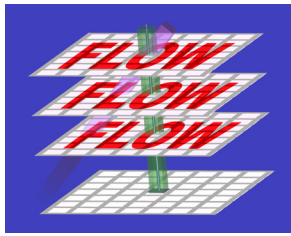
LEA versus IBFV: General Framework

LEA



Temporal convolution: **Vertical**
 Spatial conv.: **Streaklines**
 Constant Noise: **Pathlines**

IBFV



Temporal Convolution: **Pathlines**
 Spatial Conv.: **Streaklines**
 Constant Noise: **Vertical**

[Jobard et al. 01]

[Van Wijk 02]



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Unsteady Flow Advection-Convolution (UFAC)

- Temporal convolution along pathlines
- Spatial convolution along streamlines

Problem

- Pathlines and streamlines through a point x are tangent but different
- Resulting streamlines do not change smoothly

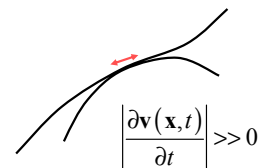
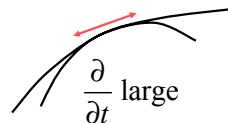
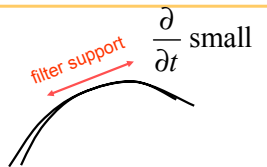
Solution

- Support of spatial convolution filter is proportional to degree of unsteadiness



UFAC

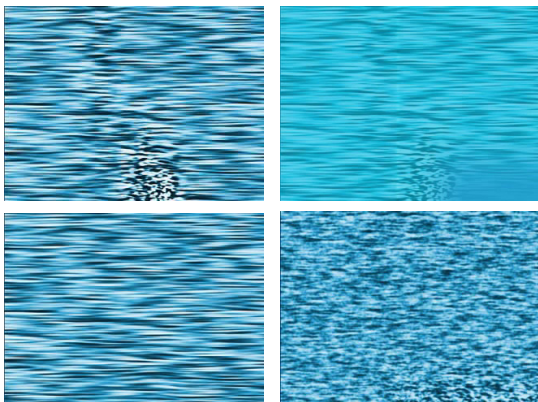
$$\frac{\partial}{\partial t} = 0$$



streamline \neq pathline



Comparison: UFAC, LIC, LEA



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Dye Advection

- Dye is a particle property
- A connected group of particles have the same property: dye color
- Noise initialization
 - Particles in a connected set have color A
 - Remainder of particles have color B
 - Apply LEA, IBFV or other texture advection method

LEA: Dye Advection

- Track noise texture \mathbf{N} (black and white) using nearest neighbor interpolation
- Track a dye texture \mathbf{D} using bilinear interpolation
- Add additional dye to the dye texture when dye is injected into the fluid

noise advection

$$\begin{aligned} \mathbf{x}^* &\leftarrow \mathbf{x} - h\mathbf{v} \\ \mathbf{N}(\mathbf{x}) &\leftarrow \mathbf{N}(\mathbf{x}^*) \\ \mathbf{F} &\leftarrow \alpha\mathbf{F} + (1-\alpha)\mathbf{N} \end{aligned}$$

dye advection

$$\begin{aligned} \mathbf{D}(\mathbf{x}) &\leftarrow \mathbf{D}(\mathbf{x}^*) \\ \mathbf{F}_R &\leftarrow \alpha_D\mathbf{F} + (1-\alpha_D)\mathbf{D} \\ \mathbf{x} &\leftarrow \mathbf{x}^* \end{aligned}$$

\mathbf{F} : intermediate buffer

\mathbf{F}_R : rendering buffer

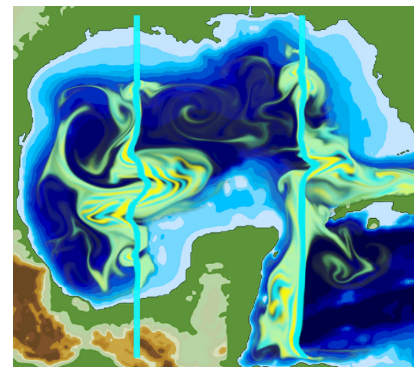
IBFV: Dye Advection

- Inject the dye into the current image
- Advect resulting image (with dye) at next iteration
- **Consequence:** diffusion of dye due to first order Euler integration scheme (numerical dissipation)

$$\begin{aligned} \mathbf{x}^* &\leftarrow \mathbf{x} - h\mathbf{v} \\ \mathbf{F}(\mathbf{x}) &\leftarrow (1-\alpha)\mathbf{F}(\mathbf{x}^*) + \alpha\mathbf{N}(\mathbf{x}) \\ \mathbf{F} &\leftarrow (1-\alpha_D)\mathbf{F} + (1-\alpha)\mathbf{D} \end{aligned}$$

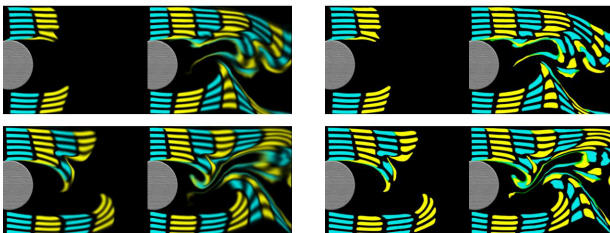
Image and dye advection are combined

Timelines (LEA)



Periodic dye injection from a fixed set of points

Circular Flow around a Cylinder (LEA)



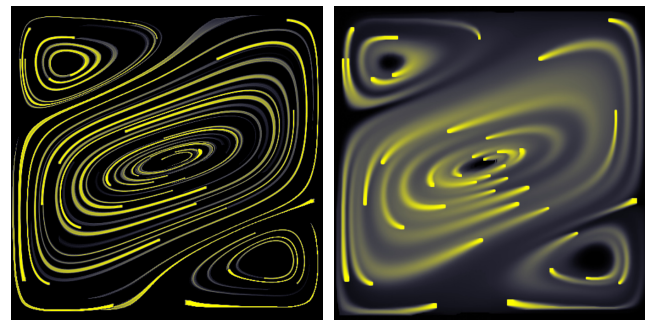
Diffusion of dye

Antidiffusive correction

[Jobard et al. 02]

Periodic release
Alternate coloring: better tracking
Maintain sharpness of dye boundaries: CHALLENGE!

Dye Advection: Numerical Diffusion



Framework

Bilinear resampling

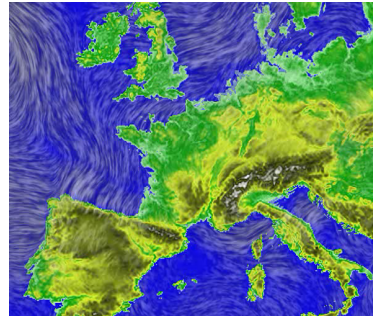
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Unsteady Flow-Animated Textures

[Jobard et al. 01]



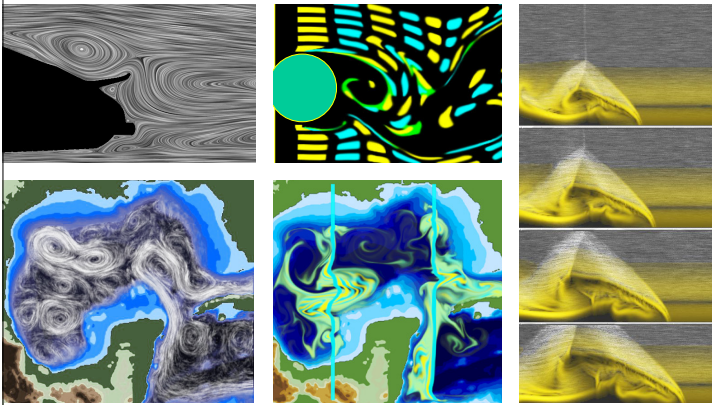
High spatial and temporal correlation

Natural interpretation of unsteady flows

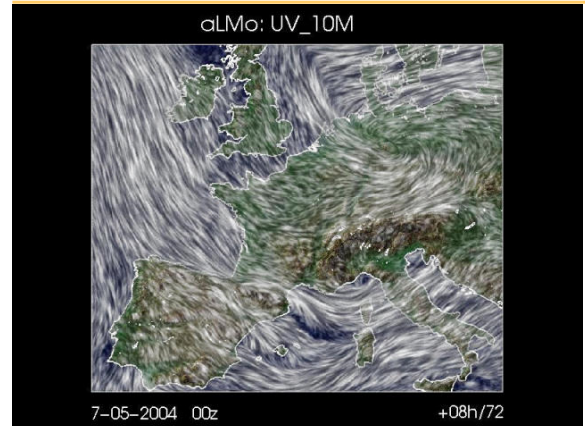
Motion follows **pathlines**, each frame depicts **streamlines**



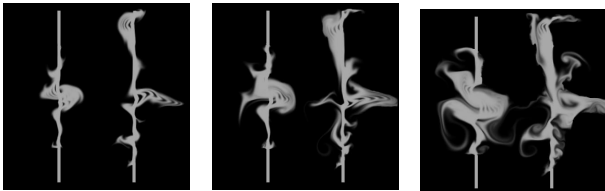
2D Vector Fields



http://www.cscs.ch/~bjobard/Projects/Meteo_Swiss/Forecast/forecast.html
http://lsrnp.cscs.ch/Gallery/texture_loop.html



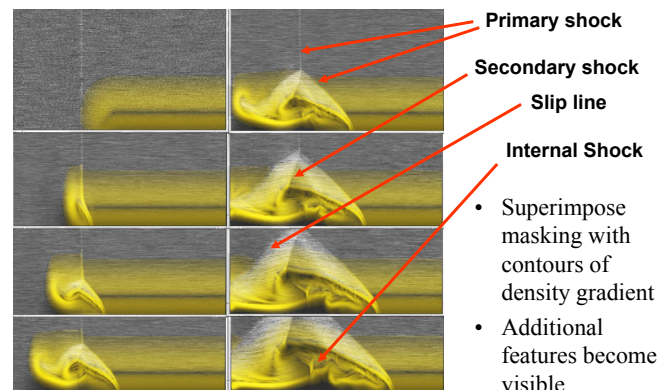
Gulf of Mexico: Timelines



- Grey dye is released (for short duration) along two vertical lines periodically in time
- Flow velocity: proportional to distance between two consecutive releases



Shock-Vortex Interaction



Primary shock

Secondary shock

Slip line

Internal Shock

- Superimpose masking with contours of density gradient
- Additional features become visible



References


- [Cabral and Leedom 93] B. Cabral and L. Leedom. Imaging vector fields using line integral convolution. In Proceedings of ACM SIGGRAPH 93, pages 263–272, 1993.
- [Erlebacher et al. 04] Erlebacher, G., Jobard, B., and Weiskopf, D., Flow Textures, Handbook of Visualization, Academic Press, (2004).
- [Jobard et al. 00] B. Jobard, G. Erlebacher, and M. Y. Hussaini. Tiled hardware-accelerated texture advection for unsteady flow visualization. In Proceedings of Graphicon 2000, pages 189–196, 2000.
- [Jobard et al. 02] B. Jobard, G. Erlebacher, and M. Hussaini. Lagrangian-Eulerian advection for unsteady flow visualization. IEEE Transactions on Visualization and Computer Graphics, 8(3):211–222, 2002.
- [Max and Becker 95] N. Max and B. Becker. Flow visualization using moving textures. In Proceedings of the ICASE/LaRC Symposium on Visualizing Time-Varying Data, pages 77–87, 1995.
- [Van Wijk et al. 02] J. J. van Wijk. Image based flow visualization. ACM Transactions on Graphics, 21(3):745–754, 2002.
- [Weiskopf et al. 02] D. Weiskopf, G. Erlebacher, M. Hopf, and T. Ertl. Hardware-accelerated Lagrangian-Eulerian texture advection for 2D flow visualization. In Vision, Modeling, and Visualization VMV '02 Conference, pages 439–446, 2002.
- [Weiskopf et al. 2003] Weiskopf, D., Erlebacher, G., and Ertl, T., "A Texture-Based Framework for Spacetime Coherent Visualization of Time-Dependent Vector Fields," IEEE Visualization 2003 Proceedings, October 2003, pp. 107-114.




2.5D Flow Visualization

2.5D Flow Visualization

Robert S. Laramée
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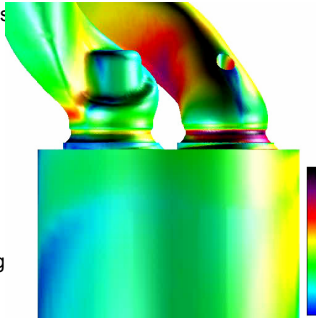





IEEE Visualization 2004 Tutorial:
Interactive Texture-Based Flow Visualization

Overview

- parameter vs object vs image space approaches
- Image Space Advection (ISA) [Laramée et al 03]
- Image Based Flow Visualization for Curved Surfaces (IBFVS) [Van Wijk 03]
- applications: including texture-based flow visualization on isosurfaces






Interactive Texture-Based Flow Visualization:
2.5D Flow Visualization

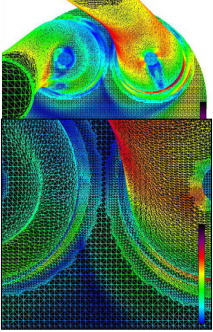
2


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Parameter vs Object vs Image Space

- parameter space: not all surfaces easily parameterized, e.g., isosurfaces
- parameter space: distortion introduced by 2D to 2.5D mapping
- object space: slow, too many polygons
- 3D textures: inefficient, problem with zooming, limited memory





Interactive Texture-Based Flow Visualization:
2.5D Flow Visualization

3

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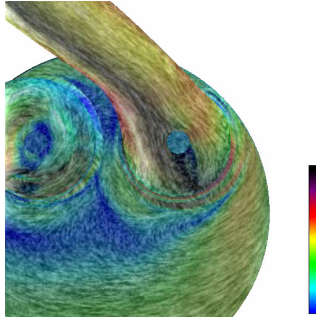



Image Space Advection (ISA)

supports [Laramée et al 03]:

- texture advection on surfaces
- unsteady flow
- fast frame rates
- user rotation, translation, zooming
- dynamic, unstructured, AR meshes






Interactive Texture-Based Flow Visualization:
2.5D Flow Visualization

4

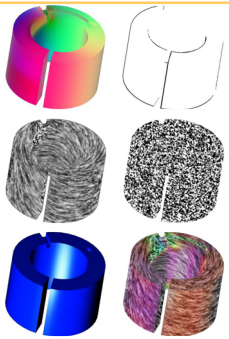
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ISA Method Overview

```

graph TD
    A[Vector Field Projection] --> B[Edge Detection]
    B --> C[Compute Advection Mesh]
    C --> D[Image Advection]
    D --> E[Noise Blending]
    E --> F[Edge Blending]
    F --> G[Image Overlay Application]
    
```






Interactive Texture-Based Flow Visualization:
2.5D Flow Visualization

5

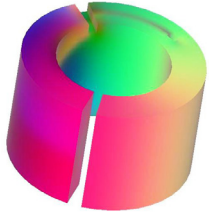
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ISA Vector Field Encoding

- assign colors to the mesh vertices as a function of velocity
- colored image used as the simplified (view dependent) 3D vector field
- 3D vectors are projected to image space transforming the computation from 3D to 2D
- no more computation time spent on occluded polygons

sample velocity image






Interactive Texture-Based Flow Visualization:
2.5D Flow Visualization

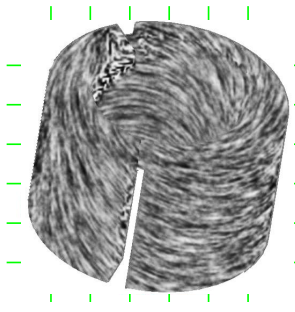
6

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2.5D Flow Visualization

ISA Advection Mesh Computation (1/2)



Euler approximation of a pathline

$$\mathbf{p}_{k+1} = \mathbf{p}_k + \mathbf{v}^p(\mathbf{p}_k; t) dt$$

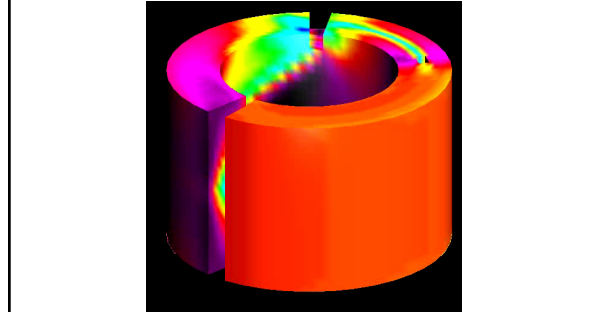
backward integration

$$\mathbf{p}_{k-1} = \mathbf{p}_k - \mathbf{v}^p(\mathbf{p}_{k-1}; t) dt$$

advect noise

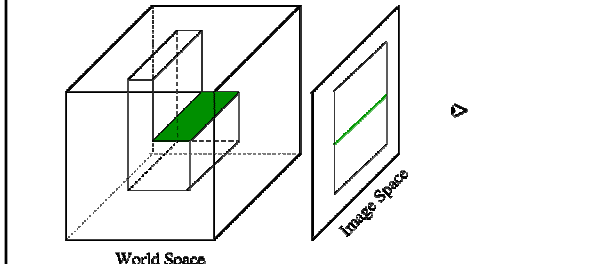
2004 VIS Interactive Texture-Based Flow Visualization: 2.5D Flow Visualization 7 Robert S. Laramée v r vis

ISA Advection Mesh Computation (2/2)



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Edge Detection and Blending (1/5)



World Space

Image Space

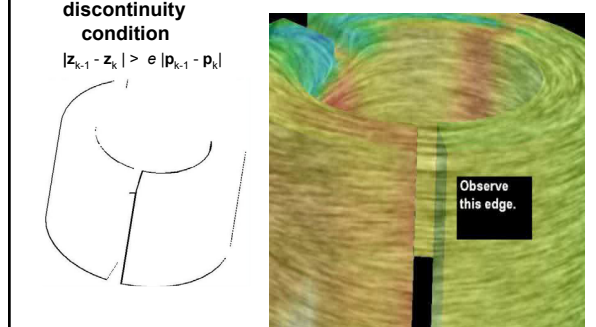
discontinuity condition

$$|z_{k-1} - z_k| > e |p_{k-1} - p_k|$$

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Edge Detection and Blending (2/5)

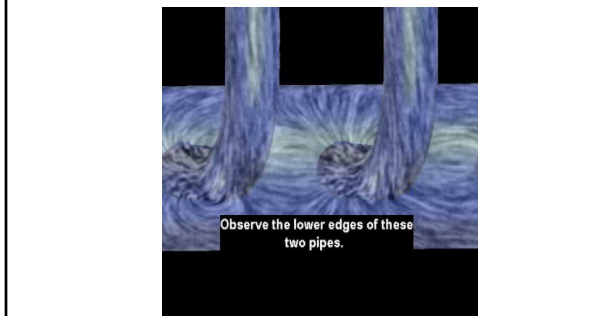
discontinuity condition

$$|z_{k-1} - z_k| > e |p_{k-1} - p_k|$$


Observe this edge.

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Edge Detection and Blending (3/5)

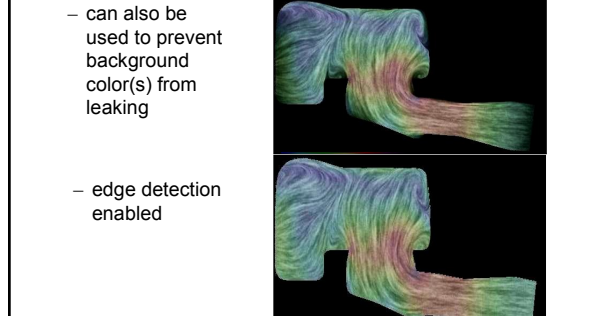


Observe the lower edges of these two pipes.

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Edge Detection and Blending (4/5)

- can also be used to prevent background color(s) from leaking
- edge detection enabled

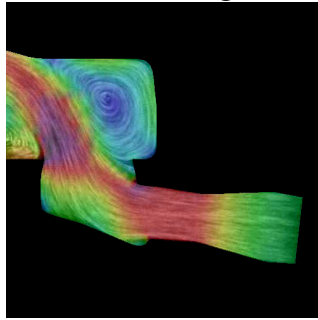


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2.5D Flow Visualization

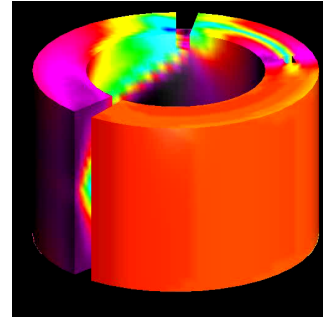
Edge Detection and Blending

- (5/5) 100 frames, edge detection disabled
- 2nd 100 frames, edge detection enabled



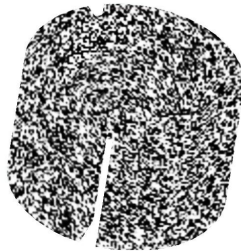
Noise Injection and Blending (1/3)

- why noise injection and blending?
- for full coverage



Noise Injection and Blending (2/3)

- both spatial and temporal characteristics
- spatial characteristic: linearly interpolated sequence of random values



Noise Injection and Blending (3/3)

- temporal characteristics: a black and white pulsing function
- can be implemented using pre-computed texture stack
- more textures, higher quality



Image Overlay Application

- final stage
- computed once for each dynamic case
- applied last for each animated frame

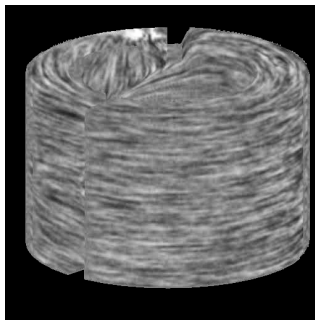
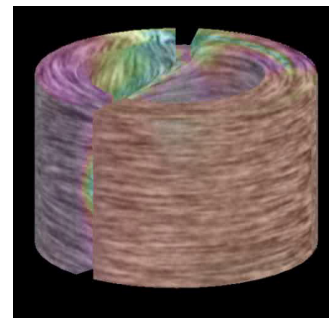


Image Overlay Application

- opacity of overlay is arbitrary
- therefore, user controlled



2.5D Flow Visualization

Putting Pieces Together

Dynamic Case

- Vector Field Projection
- Edge Detection
- Compute Advection Mesh
- Image Advection
- Noise Blending
- Edge Blending
- Image Overlay Application

Static Case

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Texture Clipping (1/2)

- texture clipped along edges to reduce artifacts resulting from rectilinear advection mesh
- (no texture clipping) (clipping enabled)

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Texture Clipping (2/2)

- illustration is exaggerated for exposition
- can be implemented trivially as part of image overlay

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IBFV for Curved Surfaces (IBFVS)

- IBFVS [Van Wijk 03], introduced at same time as ISA [Laramée et al 03]
- another image space based solution to the same problem
- comparison of ISA and IBFVS gives greater understanding of both algorithms [Laramée et al 04]

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Method Overview of ISA and IBFVS, Side-by-Side

Dynamic Case

Static Case

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- conceptually share several overlapping components
- differences stem from object vs image space implementations

Projection: Image vs Object space

<p>ISA</p> <ul style="list-style-type: none"> hardware based vector field projection implemented using velocity image <p>Advantage(s)</p> <ul style="list-style-type: none"> no further computation time for polygons smaller than one pixel HW accelerated occlusion culling 	<p>IBFVS</p> <ul style="list-style-type: none"> distorted vertices projected on per-mesh-vertex basis no actual vectors are projected (coords only) <p>Advantage(s)</p> <ul style="list-style-type: none"> avoids read-back of frame buffer no resampling or interpolation necessary
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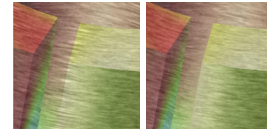
2.5D Flow Visualization

Advection: Image vs Object space

- | | |
|---|--|
| <p>ISA</p> <ul style="list-style-type: none"> - <i>distorts 2D, rectilinear mesh in image space</i> - vectors reconstructed using velocity image <p>Advantage(s)</p> <ul style="list-style-type: none"> - advection time independent of original mesh size - no advection for occluded polygons | <p>IBFVS</p> <ul style="list-style-type: none"> - <i>distorted vertices are computed in 3D object space</i> - distorted vertices projected to image plane <p>Advantage(s)</p> <ul style="list-style-type: none"> - resolution of polygonal advection mesh matches that of original mesh |
|---|--|

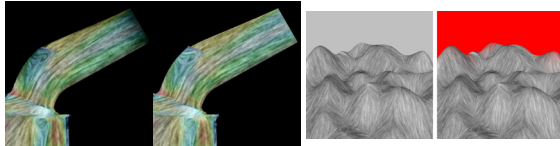
Edge Detection: Image vs Object space

- | | |
|---|--|
| <p>ISA</p> <ul style="list-style-type: none"> - compares spatially adjacent depth values - built into integration step <p>Advantage(s)</p> <ul style="list-style-type: none"> - takes advantage of information provided by graphics hardware | <p>IBFVS</p> <ul style="list-style-type: none"> - silhouette edges identified between front and back facing polygons - separate processing step <p>Advantage(s)</p> <ul style="list-style-type: none"> - avoids read-back of depth buffer |
|---|--|



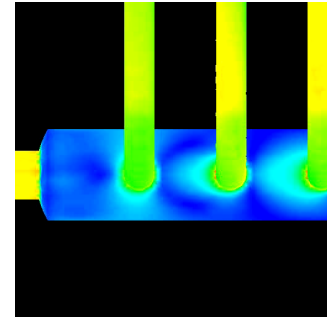
Edge Detection: Boundaries

- | | |
|--|---|
| <p>ISA</p> <ul style="list-style-type: none"> - edge detection blends in extra noise at inlets | <p>IBFVS</p> <ul style="list-style-type: none"> - use gray background - implement object space based silhouette edge detection |
|--|---|

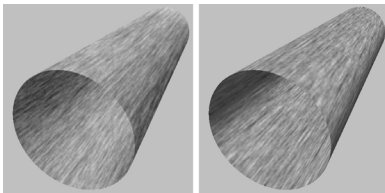


Noise Injection and Image Overlay

- The same for both ISA and IBFVS:
- noise injection and blending, from original IBFV
 - application of image overlay with arbitrary opacity



A Perceptual Consequence



- For both ISA and IBFVS**
- density of texture constant in image space
 - may appear unnatural, but does avoid aliasing artifacts

ISA and IBFVS, Performance

	no. of polys	IBFVS FPS	ISA adv. mesh res.	ISA FPS
- Nvidia 980XGL Quadro	10K	64 (49)	64 ²	64 (38)
			128 ²	64 (20)
			256 ²	31 (7.5)
			512 ²	14 (2.7)
- 2.8 GHz dual processor	79K	56 (38)	64 ²	64 (38)
			128 ²	64 (18)
			256 ²	30 (7.5)
			512 ²	15 (2.7)
	221K	13 (3.0)	64 ²	64 (13)
			128 ²	64 (10)
			256 ²	30 (5.3)
			512 ²	15 (1.9)
	228K	13 (2.7)	64 ²	64 (15)
			128 ²	64 (13)
			256 ²	47 (8.0)
			512 ²	20 (3.1)

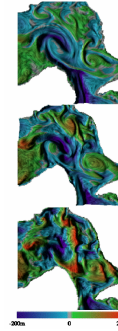
2.5D Flow Visualization

ISA and IBFVS, Which One?

- | ISA | IBFVS |
|--|---|
| <ul style="list-style-type: none">- good for large meshes (polygons > 200,000)- good for complex, adaptive resolution meshes | <ul style="list-style-type: none">- faster for smaller meshes- easier to implement |
| <ul style="list-style-type: none">- both are much faster than previous attempts in this area- UFLIC was last attempt at unsteady flow [Shen and Kao 1998] | |

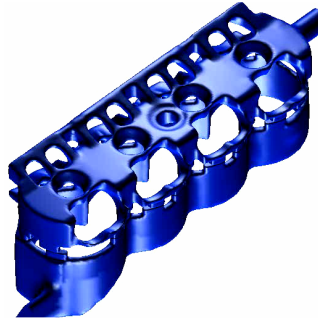
Applications: Oceanography

- LEA originally 2D, extended to time surfaces, 2.5D [Grant et al. 02]
- surfaces used to study thermocline movement (layer with high temperature gradient)
- goal: gain better understanding of vertical movement
- three time surfaces at 200, 400, and 800 meter depth (top to bottom)



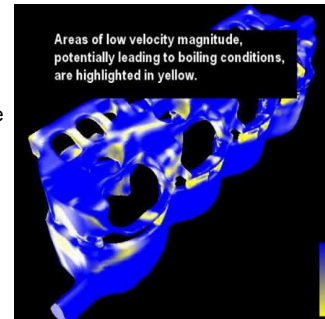
Applications: Complex, AR Data

- cooling jacket
- 228,000 unstructured, adaptive resolution polygons



Applications: CFD

- can be used to highlight *undesirable* properties of the flow



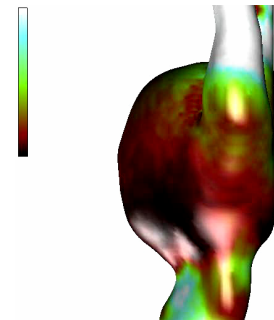
Applications: Surface Vis

- texture, aligned with principle directions, aids in understanding surface shape



Applications: Medical Data

- visualization of blood flow through an aneurysm



2.5D Flow Visualization

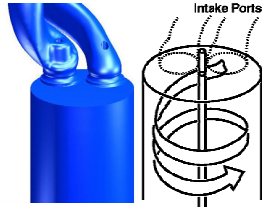
Applications: Swirl Flow

Hi Bob,

...

• "I hope many people from the CFD side will read it [case study paper]. I think it is not only to have something for papers, I think it is very useful in CFD engineer's daily work. This feature really makes sense!" ...

Keep in touch, Jürgen [AVL engineer]



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Interactive Texture-Based Flow Visualization: 2.5D Flow Visualization 37

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Application to Isosurfaces

- why isosurfaces?
 - show 3D characteristics that slices and boundary surfaces alone cannot
- why texture-based flow visualization?
 - provides even more insight into flow motion
 - highlights non-ideal flow motion
 - only recently feasible [Laramée et al 04]



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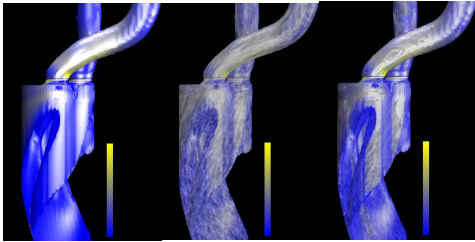
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Applying a Normal Mask (1/2)

- flow may be characterized by a strong component normal to the surface



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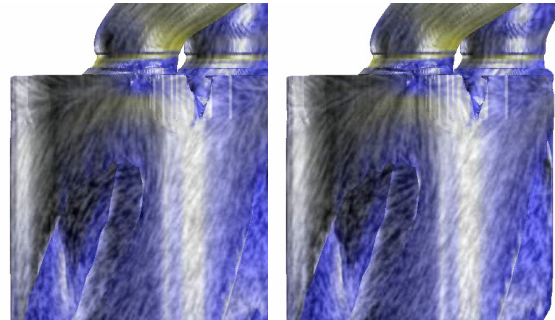
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Applying a Normal Mask (2/2)

- a closer look



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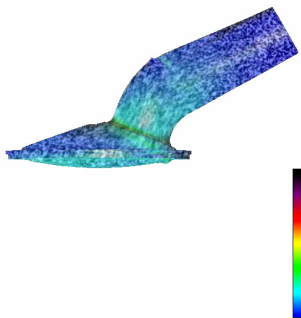
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Applications: Time-Dependent Meshes

- meshes with time-dependent geometry and topology
- mesh is both unstructured and adaptive resolution
- one half of a valve-cycle visualized



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Summary of 2.5D Flow Visualization

- a lot of progress has been made w.r.t. the dense representation of unsteady flow on surfaces
- we can now visualize flow on large surfaces, independent of surface's complexity and resolution
- current methods support user-interaction
- current methods fast
- ISA and IBFVS can visualize flow on dynamic meshes
- surface parameterization is not a requirement

Now onto the 3D portion of the tutorial!

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2.5D Flow Visualization

Acknowledgements

Thanks to:

- Jürgen Schneider
- Jarke van Wijk
- Austrian national research program, Kplus
(www.kplus.at)
- AVL (www.avl.com)



Interactive Texture-Based Flow Visualization:
2.5D Flow Visualization

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3D Texture-Based Flow Visualization

3D Texture-Based Flow Visualization



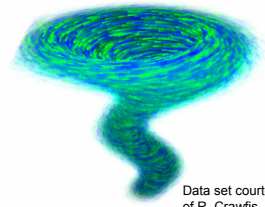
Daniel Weiskopf
Institute of Visualization and Interactive Systems
University of Stuttgart



IEEE Visualization 2004 Tutorial:
Interactive Texture-Based Flow Visualization

Overview

- 3D LIC
- 3D texture advection
- Injection mechanisms (dye, noise)
- Perception issues



Data set courtesy of R. Crawfis



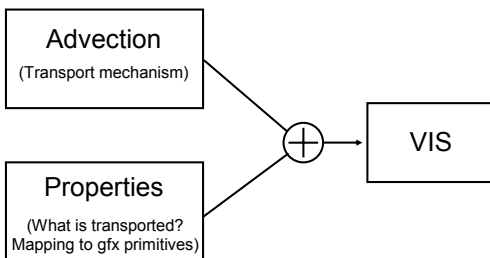
Interactive Texture-Based Flow Visualization:
3D Flow Visualization

Daniel Weiskopf



2

Ingredients



Interactive Texture-Based Flow Visualization:
3D Flow Visualization

Daniel Weiskopf



3

3D Flow Visualization

- Goals
 - Show 3D flow structures, not just 2D slices
 - Interactivity
 - Steady and unsteady flow fields



Interactive Texture-Based Flow Visualization:
3D Flow Visualization

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3D LIC

- Line integral convolution

$$T(\mathbf{x}) = \int_{s-l}^{s+l} k(t-s)N(\mathbf{x}(t))dt$$

- Independent of dimension: $\mathbf{x} \in \mathbb{R}^2$ or $\mathbf{x} \in \mathbb{R}^3$
 - straightforward extension to 3D
 - 3D noise field $N(\mathbf{x})$
 - 3D property field $T(\mathbf{x})$
 - Computation of streamlines in 3D



Interactive Texture-Based Flow Visualization:
3D Flow Visualization

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3D LIC

- Issues
 - Computation time
 - Unsteady flow
 - Perception: Occlusion etc.

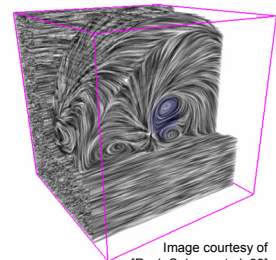


Image courtesy of [Rezki-Salama et al. 99]



Interactive Texture-Based Flow Visualization:
3D Flow Visualization

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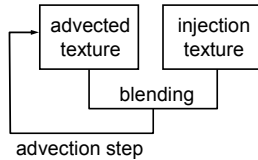


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3D Texture-Based Flow Visualization

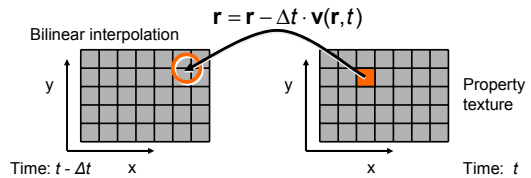
Texture Advection

- Basic idea:
 - Advection of particle field
 - Blending of particle injection texture (at each time step)
 - Based on Image-Based Flow Visualization (IBFV) [Van Wijk 02]



2D Texture Advection

- Particle tracing $\frac{dr}{dt} = \mathbf{v}(\mathbf{r}, t)$
- Euler integration
- Uniform grid \rightarrow texture
- Semi-Lagrangian approach:

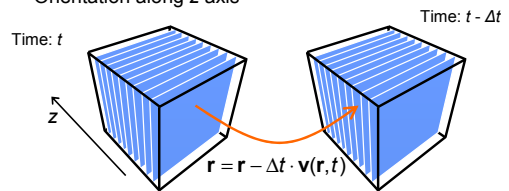


3D Texture Advection

- Extension of 2D dye advection / IBFV [Weiskopf & Ertl 04]
- Advection process is similar
- Straightforward changes:
 - From two-component to three-component vector field
 - From 2-vector to 3-vector for (texture) coordinates
 - From 2D domain to 3D domain: from 2D texture to 3D texture
- Structural differences:
 - Update 3D property texture slice by slice
 - Volume rendering for property field

3D Texture Advection

- Slice-by-slice update
 - Orientation along z axis



- Update of a single slice
 - Standard: `glCopyTexSubImage3D`
 - ARB_superbuffer extension

Fragment Program for 3D Advection

```

!!ARBfp1.0
PARAM  stepSize   = program.local[0];
ATTRIB iTexCoord  = fragment.texcoord[0];
OUTPUT  oColor    = result.color;
TEMP   velocity;
TEMP   oldPos;

# Fetch flow field
TXP velocity, iTexCoord, texture[0], 3D;
# Compute previous position (Euler integration)
MAD oldPos, velocity, stepSize, iTexCoord;
# Dependent texture lookup:
# Property value from previous time step
TEX oColor, oldPos, texture[1], 3D;
END
    
```

Performance

- 3D advection speed in FPS:

Domain	64 ³	128 ³	256 ³
Steady Flow	106.3	40.9	10.2
Unsteady Flow	50.3	9.8	1.7

- Measured on an ATI Radeon 9800 Pro (256 MB)
- Same sizes of property and flow fields

3D Texture-Based Flow Visualization

3D IBFV

- 3D Image-Based Flow Visualization [Telea & Van Wijk 03]
- Difference to 3D texture advection
 - Stack of 2D textures along z axis
 - Standard OpenGL texturing and blending
 - Gathering data from two neighboring slices

z axis

1 slice

Lookup vector

Missing data

Possible

Time: t

Time: t - Δt

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Comparison

- 3D IBFV
 - + Standard OpenGL
 - + Fast due to bilinear interpolation
 - No large z velocity component
 - Problems with volume rendering for arbitrary viewing directions
- 3D texture advection
 - + Velocity is not restricted
 - + Constructs 3D texture for correct volume rendering
 - Needs fragment shaders
 - Slower: trilinear interpolation, update of 3D texture slices

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Material Injection

advection texture

injection texture

compositing

advection step

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Material Injection

$$T_t = W_t \circ T_{t-\Delta t} + V_t \circ I_t$$

advection texture

injection texture

compositing

advection step

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Material Injection

$$T_t = W_t \circ T_{t-\Delta t} + V_t \circ I_t$$

advection texture

injection texture

compositing

advection step

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Material Injection

$$T_t = W_t \circ T_{t-\Delta t} + V_t \circ I_t$$

advection texture

injection texture

compositing

advection step

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3D Texture-Based Flow Visualization

Material Injection

$$T_t = W_t \circ T_{t-\Delta t} + V_t \circ I_t$$

- Space-variant weights
- Component-wise multiplication
- Different materials

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Dye and Noise Injection

Data set courtesy of R. Crawfis

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Volume Rendering

- Final display of property fields

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Texture-Based Volume Rendering

- Slices through 3D texture
 - Proxy geometry

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Complete Visualization Process

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Dense 3D Representations: Issues

- Perceptual issues
 - Clutter
 - Occlusion
 - Depth perception

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3D Texture-Based Flow Visualization

Clipping and Semi-Transparency

Images courtesy of [Rezki-Salama et al. 99]

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Clipping and Semi-Transparency

- Semi-transparency
 - Choose transfer function carefully
- Clipping
 - Clip planes (directly supported by OpenGL)
 - Object-space approach for complex clip geometries
 - Alternative image-space approach

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Clipping with Clip Plane

With clip plane

Original

Data set courtesy of R. Crawfis

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Image-Space Clipping

Image plane

Ray

Pixel

Depth structure

z value

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Image-Space Clipping

- 3D texture slicing
- Fragment shader: [Weiskopf et al. 03]
 - Compares current depth with depth structure of the clip geometry
- Depth structure in n textures

Fragment

Comparison

Pixel

Store depth values in 2D textures

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Object-Space Clipping

- Additional clipping texture [Weiskopf et al. 03]
 - Voxelized representation of clip geometry
 - Binary or distance volume
- Fragment shader removes invisible fragments

Clipping texture

Data set

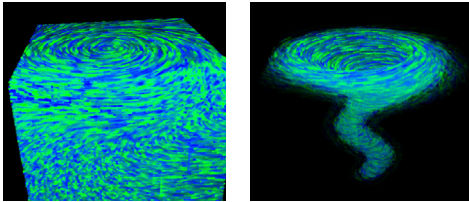
Combined rendering

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3D Texture-Based Flow Visualization

Smooth Selection of Flow Regions

- Extension of clipping
- Smooth transition between opaque and invisible
- Based on “feature” or regions of interest



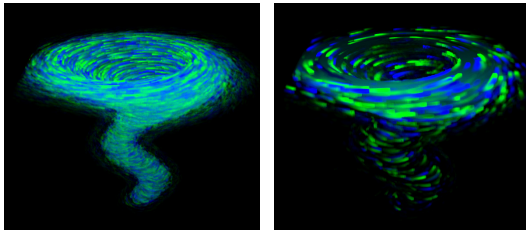
Original Velocity magnitude

Smooth Selection of Flow Regions

- Implemented via enriched transfer functions
- Additional feature field
- Examples
 - Velocity magnitude
 - Vortex criteria (e.g. λ_2)
 - User-defined features

Change Density of Representation

- Modify noise injection texture



Dense Sparse

Improved Rendering

- Improve spatial perception [Interrante & Grosch 97]
 - Illumination
 - Halos
 - Depth cues

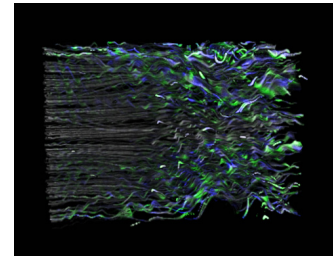
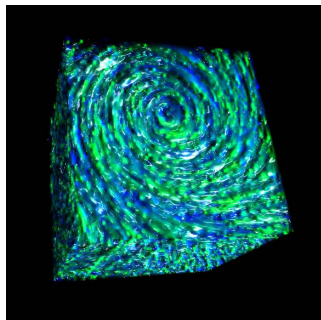


Image by Victoria Interrante

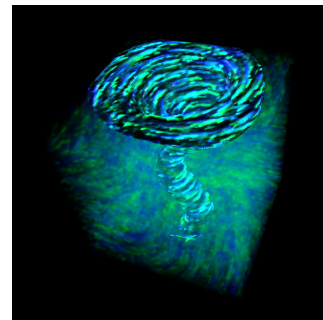
Improved Rendering

- Illumination
 - Specular highlights



Improved Rendering

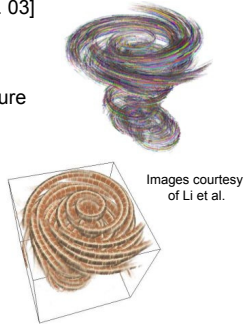
- In combination with region of interest
 - Focus and context



3D Texture-Based Flow Visualization

Chameleon: Advanced Rendering

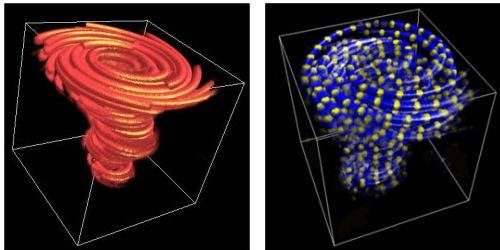
- Chameleon system [Li et al. 03]
- Idea:
 - Precompute 3D streamlines
 - Store streamlines in 3D texture
 - Change rendering style (appearance) on-the-fly



Chameleon: Program Structure

- Preprocessing
 - Evenly space streamlines with controlled density
 - Voxelized streamlines in *trace volume*
 - Scan conversion by sequence of slices with a pair of moving clip planes
 - Each texel: ID for streamline & parameterization
- During rendering:
 - Dependent lookup in appearance texture
 - Additional lighting and depth cueing

Chameleon: Example Images



With lighting

Color tubes

Summary

- GPU needed for on-the-fly computation of dense 3D representations
- Efficiency still a problem
- Perception issues are even more crucial
 - Starting point for future work

References

- [Interrante & Grosch 97] V. Interrante, C. Grosch. Strategies for effectively visualizing 3D flow with volume LIC. In *IEEE Visualization '97*, 421-424, 1997.
- [Li et al. 03] G.-S. Li, U.D. Bordoloi, H.-W. Shen. Chameleon: An interactive texture-based rendering framework for visualizing three-dimensional vector fields. In *IEEE Visualization '03*, 241-248, 2003.
- [Rezk-Salama et al. 99] C. Rezk-Salama, P. Hastreiter, C. Teitzel, T. Ertl, T. Interactive exploration of volume line integral convolution based on 3D-texture mapping. In *IEEE Visualization '99*, 233-240, 1999.
- [Telea & Van Wijk 03] A. Telea, J. van Wijk. 3D IBFV: Hardware-accelerated 3D flow visualization. In *IEEE Visualization '03*, 233-240, 2003.
- [Van Wijk 02] J. van Wijk. Image based flow visualization. *ACM Transactions on Graphics* 21 (3), 745-754, 2002.

References

- [Weiskopf et al. 03] D. Weiskopf, K. Engel, T. Ertl. Interactive clipping techniques for texture-based volume visualization and volume shading. *IEEE Transactions on Visualization and Computer Graphics* 9(3), 298-312, 2003.
- [Weiskopf & Ertl 04] D. Weiskopf, T. Ertl. GPU-based 3D texture advection for the visualization of unsteady flow fields. In *Proceedings of WSCG 2004 Short Papers*, 259-266, 2004.