The State of the Art in Flow Visualization

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NCE Subsea Theme Meeting - Visualization for Industrial Applications

Visualization – What for?

- The data shows details, but (usually) fails to convey overview
- **To visualize:** to form a mental image of s.th. (from Oxford dictionary)
- Aims at insight, not pictures!
- Used for
  - Exploration
  - Analysis
  - Presentation

Visualization – What for?

Example: algebraic equations

- Data:

$$x^2 + y^2 z - z^2 = 0$$

- Questions:
  - Surface?
  - Self intersections?
  - Singularities?

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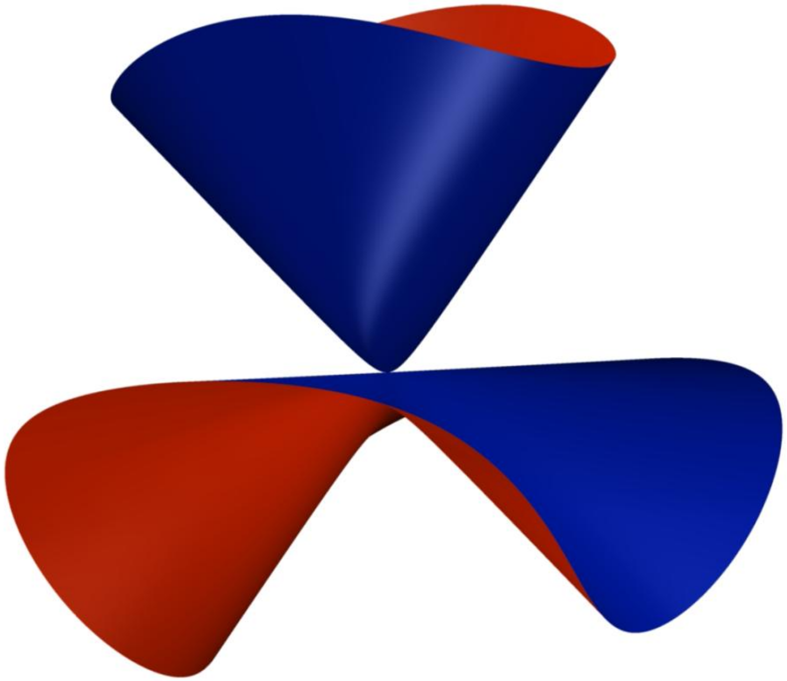

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Visualization – What for?

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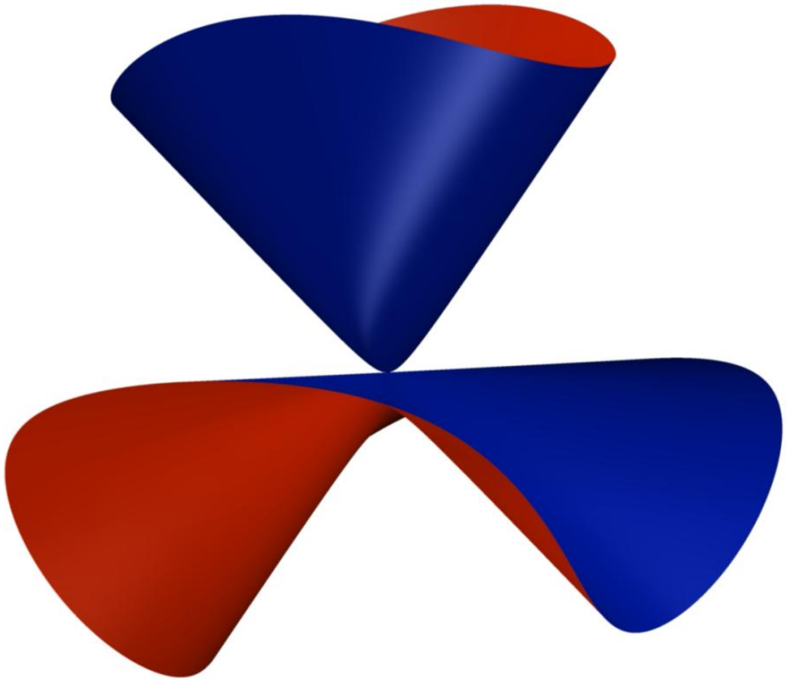
  - Surface ✓
  - Self intersections ✗
  - Singularities ✓

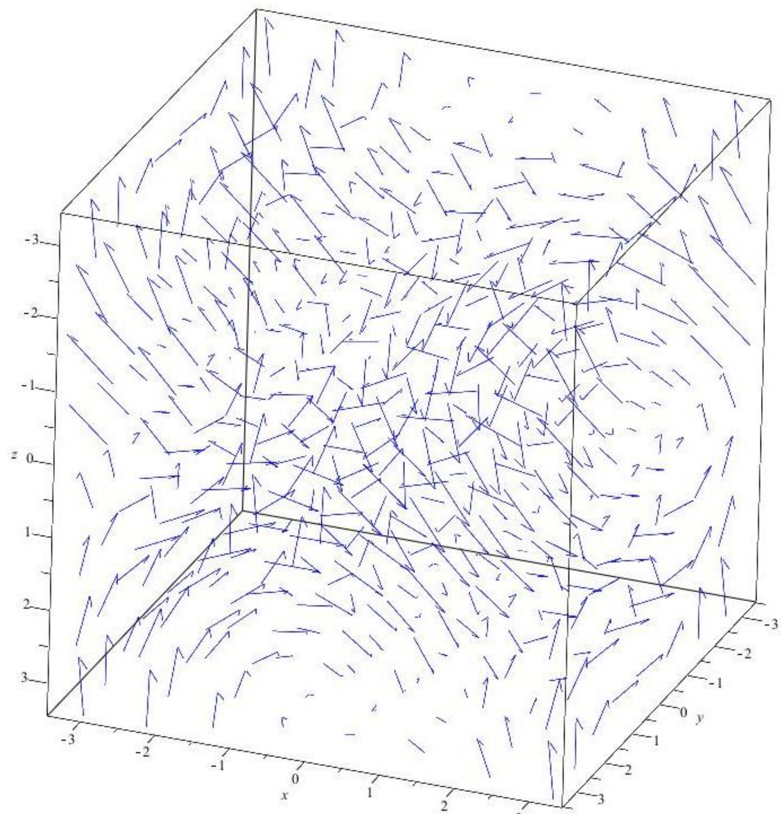


Flow visualization – Beyond vectors

- Usually velocity vectors on discrete grid (possibly time dependent)
  - Direct visualization usually fails to convey insight
    Example: Arnold-Beltrami-Childress flow

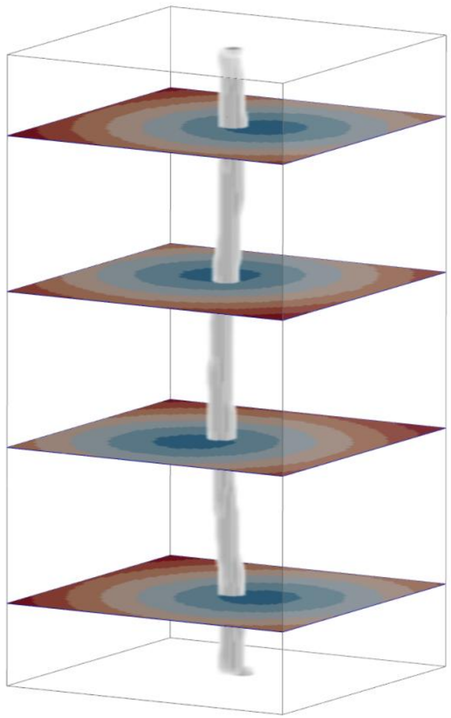
$$
\begin{aligned}
\dot{x} &= A\sin(z) + C\cos(y) \\
\dot{y} &= B\sin(x) + A\cos(z) \\
\dot{z} &= C\sin(y) + B\cos(x)
\end{aligned}
$$

$$A = B = \sqrt{3}, \quad C = 1$$



Flow Visualization – Classical approaches

- Feature extraction: derivation of a characteristic numerical value, based on local velocities

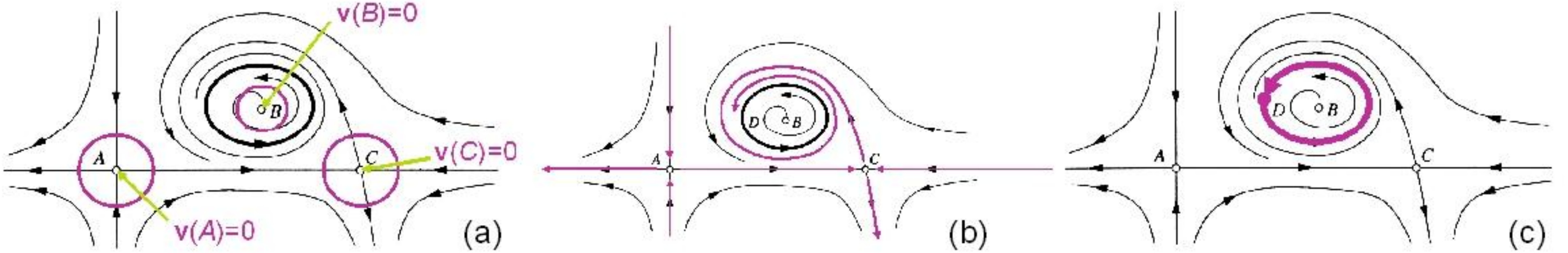


Vortex core +
velocity magnitude

- Limitations to “local” phenomena

Flow Visualization – Classical approaches

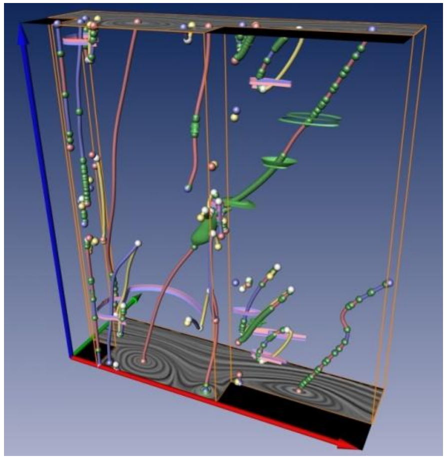
- Vector field topology: segmentation of flow in regions of different behavior



- Limitations: only for steady velocity field!

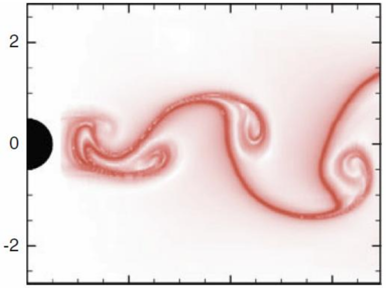
Flow Visualization – New Directions

- Reformulation of theory for unsteady vector fields
  - E.g., for tracking of features over time



[Theisel et al., 2005]

- Alternatives for transport barriers in unsteady flow
  - Finite-time Lyapunov exponents



[Kourentis and Konstantinidis, 2011]

Flow Visualization – in Bergen

- UiB involved in an European project in Flow visualization:
  SemSeg - 4D Space-Time Topology for Semantic Flow Segmentation
- A collaboration with:
  - ETH Zürich, Switzerland
  - University of Magdeburg, Germany
  - VRVis research center Vienna, Austria

Research directions

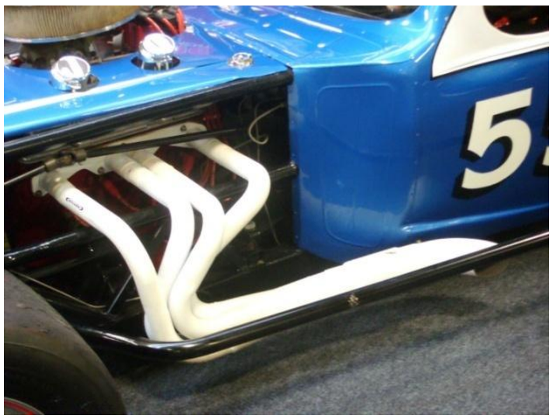
- Interactive Visual Analysis for flow visualization: framework to incorporate domain experts more closely
- Feature extraction on different scales: method to distinguish between features that act at different scales of motion/energy
- Lagrangian Methods: based on particle movement, related to investigation of transport, mixing,…
- Incorporation of uncertainty: vector field topology-like segmentation for uncertain velocity data

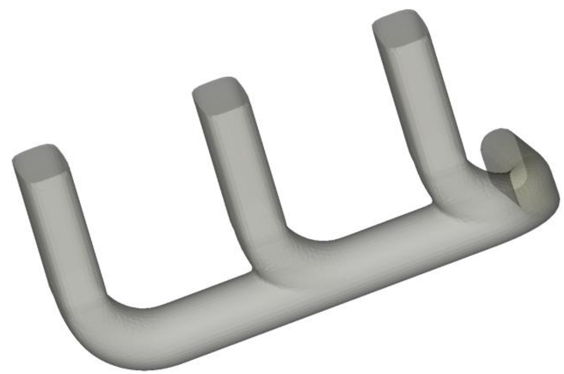
IVA for flow visualization

- Large number of measured or computable variables to describe the flow
  - e.g., λ_2, vorticity, …
  - both on grid or particle
- Depict multiple dimensions in multiple views
  - e.g., scatter plots, histograms, function plots,…
- Views are linked to each other and a 3D view of the flow domain
  - Highlighting interesting data ranges can reveal correlation of different fields and the spatial location of this interplay

Example: exhaust manifold (Lež et al., Pobitzer et al.)

- Examination of exhaust gas flow
  - Design goal: higher power/less fuel consumption
  - Analysis goal: Detect back pressure

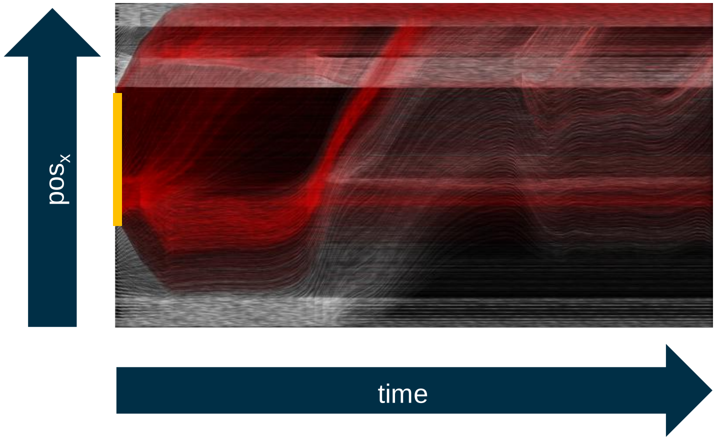




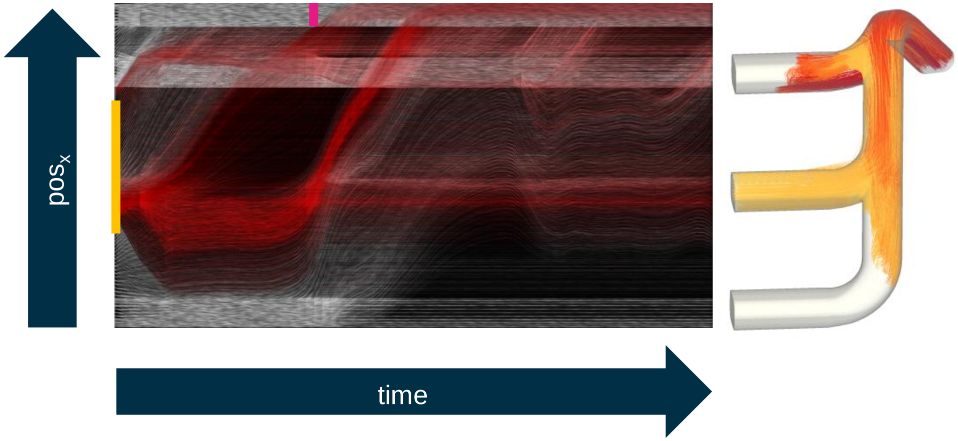
- Compute path lines and descriptors of their behavior (curvature, torsion, average velocity,…)

Example: exhaust manifold (Lež et al., Pobitzer et al.)

- Examine particles that originate in or close to middle pipe

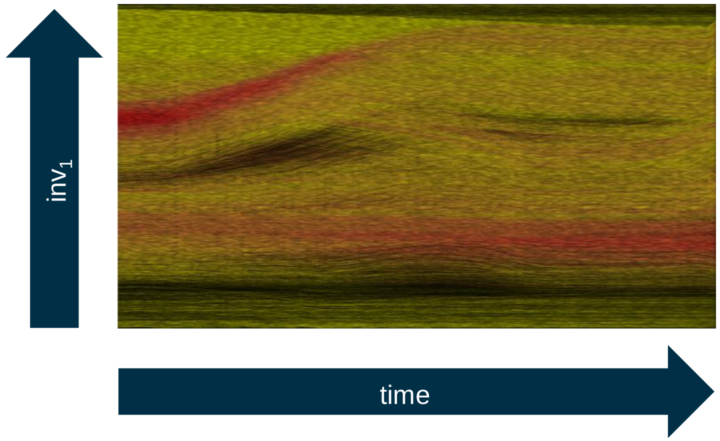


- Discard particles that leave domain immediately



Example: exhaust manifold (Lež et al., Pobitzer et al.)

- Look at shape descriptors



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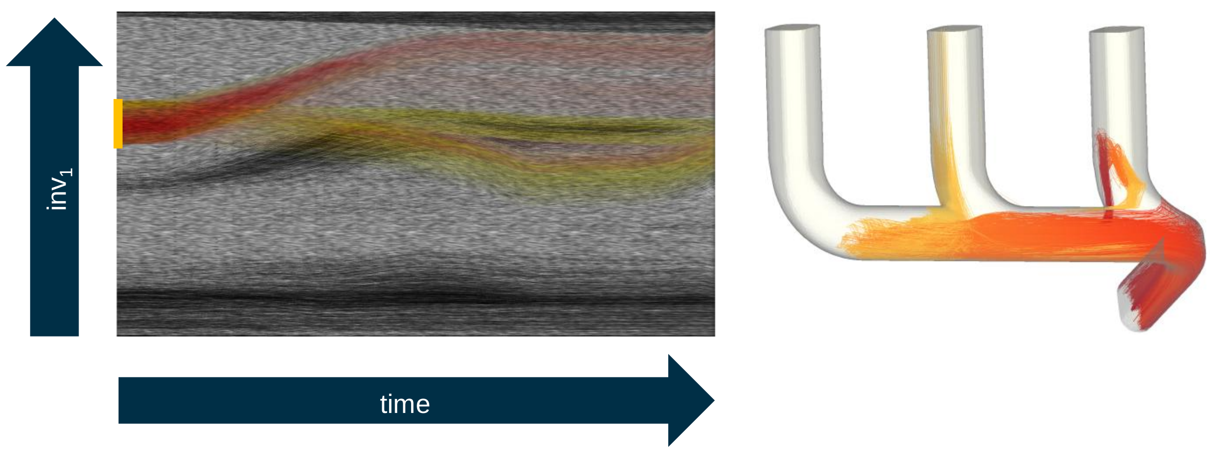
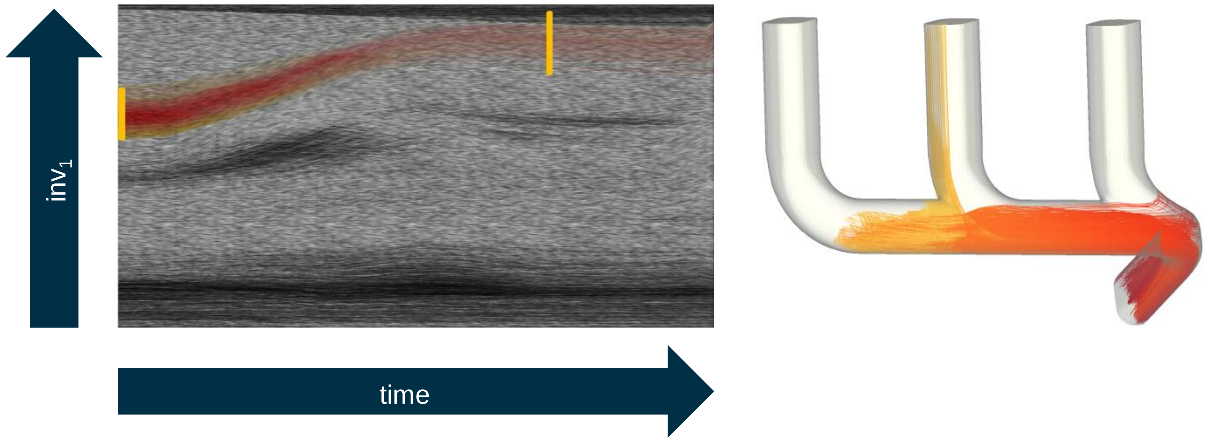
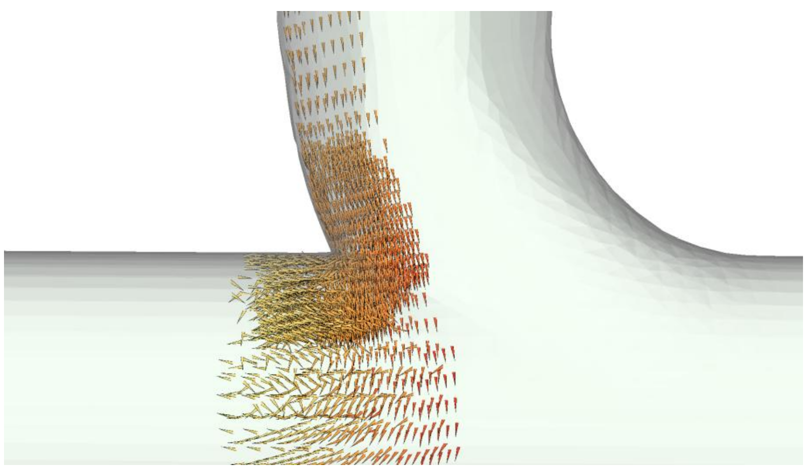


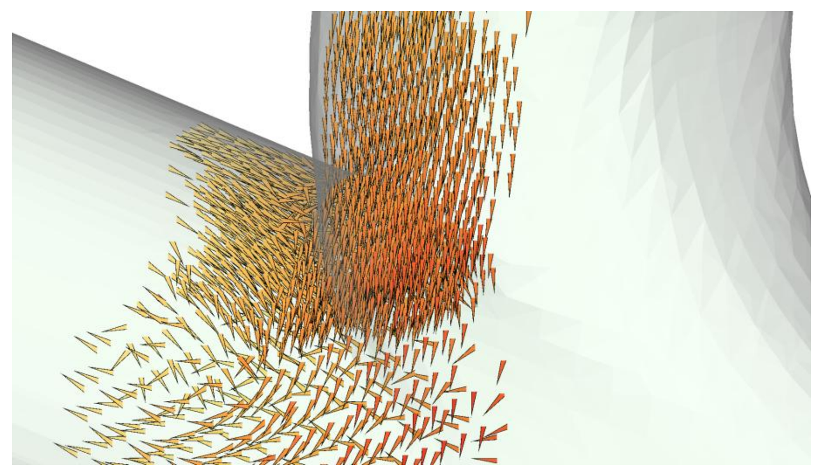
Example: exhaust manifold (Lež et al., Pobitzer et al.)

- Investigate different branches



- Change 3D view from path lines to particles



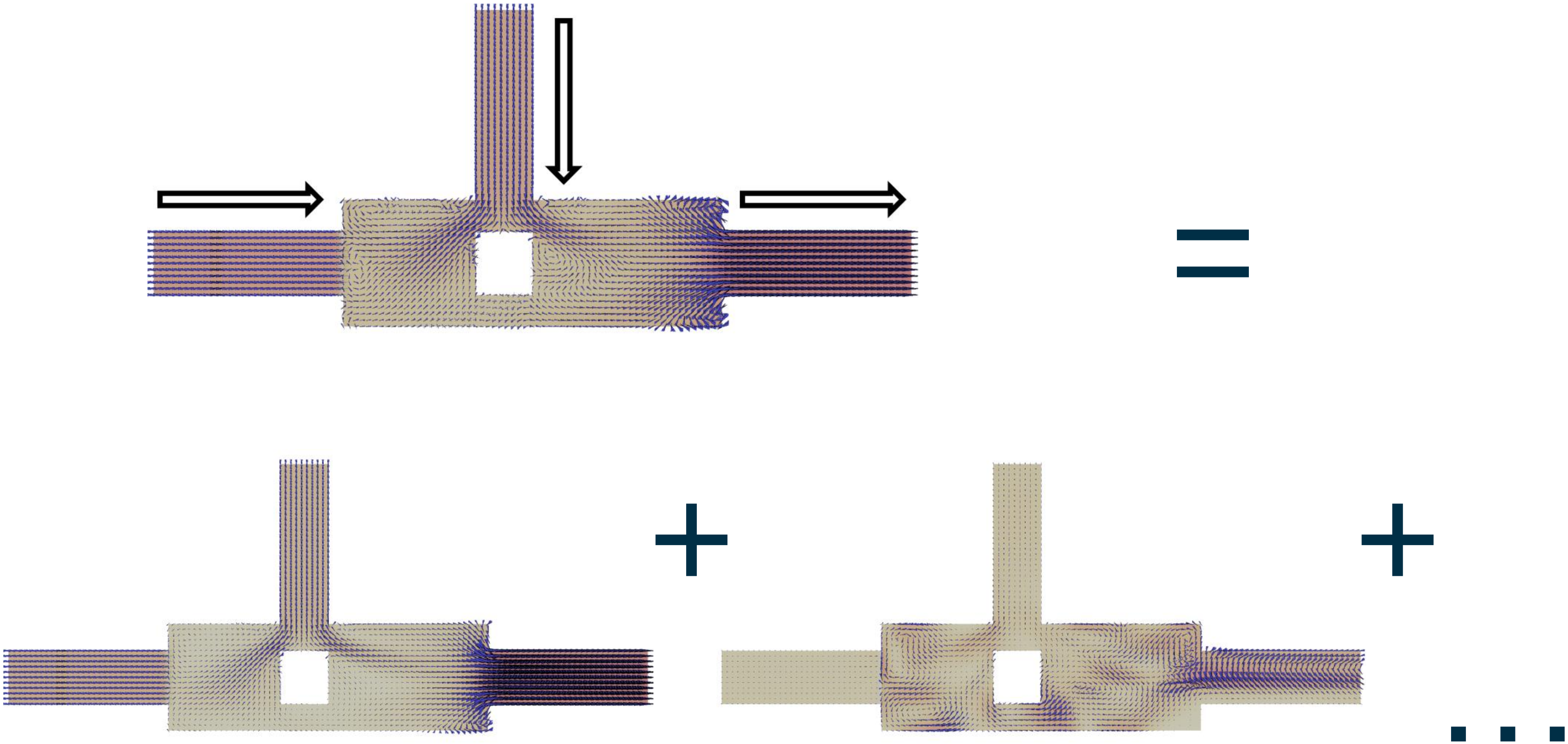


IVA in other settings

- simulations: detection of bugs
  - areas with wrong gridding
  - problems with boundary conditions
  - …
- tool for the expert to detect undesired / unexpected flow behavior

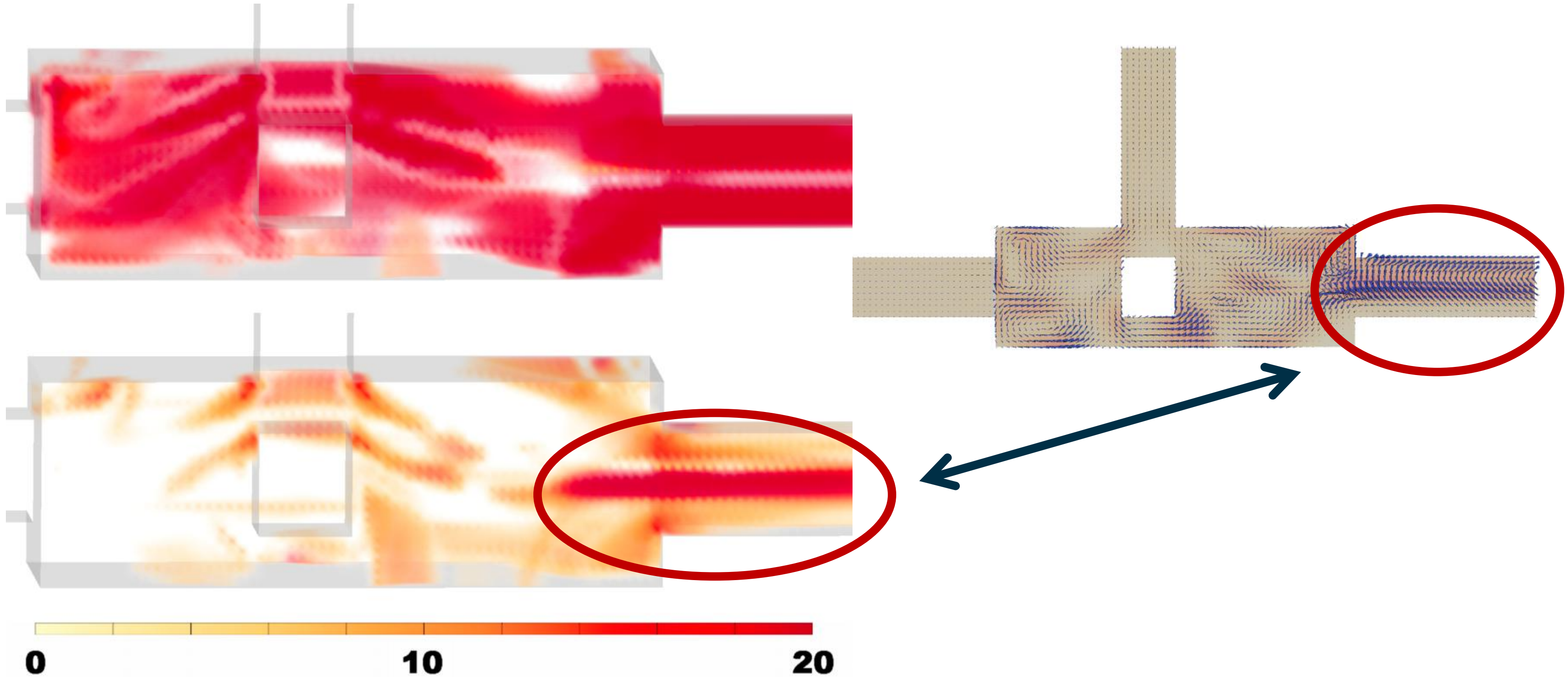
Feature extraction on different scales (Pobitzer et al.)

- Velocity fields are composed of different energy scales (turbulence cascade)



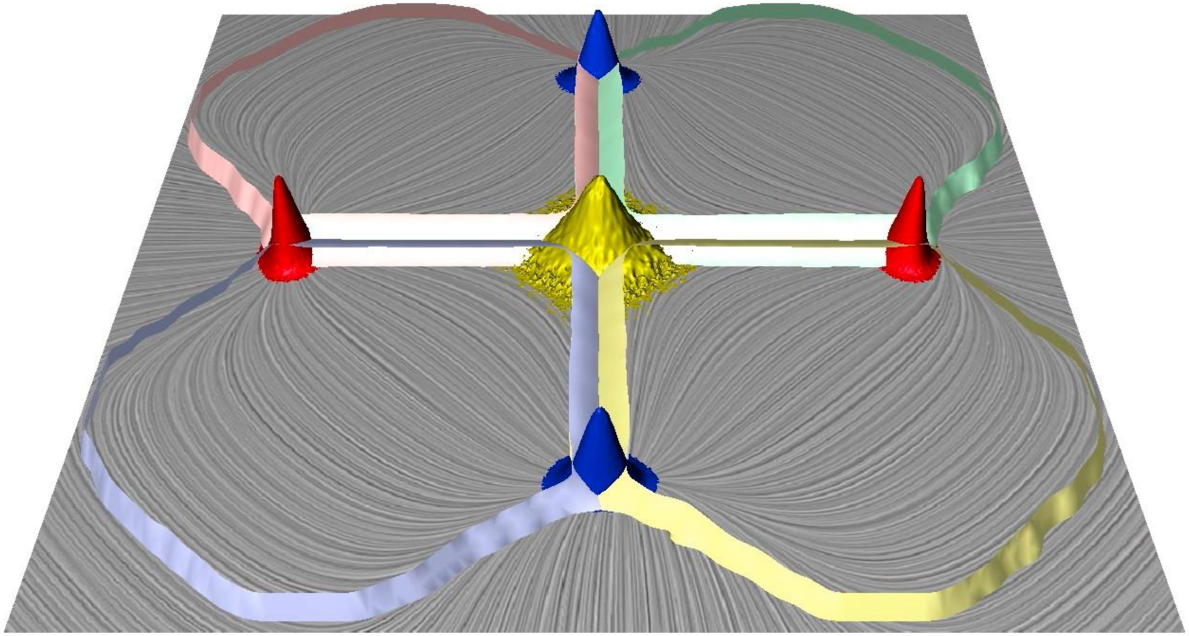
Feature extraction on different scales (Pobitzer et al.)

- The scales can be calculated by *proper orthogonal decomposition*
- Extracting features at different scales gives physically correct simplification



Uncertain vector fields (Otto et al.)

- Velocity fields can be affected by uncertainty, e.g., multiple samples, measurement accuracy,…
- Uncertainty is accumulated along particle paths
- New method to compute stream lines taking uncertainty in account



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Further information…

- All discussed papers can be found at www.SemSeg.eu

- Two survey articles (http://www.ii.uib.no/vis/publications)

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The State of the Art in Topology-Based Visualization of Unsteady Flow

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Abstract
Vector fields are a common concept for the representation of many different kinds of flow phenomena in science and engineering. Methods based on vector field topology are known for their convenience for visualizing and analysing steady flows, but a counterpart for unsteady flows is still missing. However, a lot of good and relevant work aiming at such a solution is available. We give an overview of previous research leading towards topology-based and topology-inspired visualization of unsteady flow, pointing out the different approaches and methodologies involved as well as their relation to each other, taking classical (i.e. steady) vector field topology as our starting point. Particularly, we focus on Lagrangian methods, space–time domain approaches, local methods and stochastic and multifield approaches. Furthermore, we illustrate our review with practical examples for the different approaches.

Keywords: flow visualization, topology, unsteady flow, State of the art report

ACM CCS: I.3.6 [Computer Graphics]: Methodology and Techniques; I.3.3 [Computer Graphics]: Picture/Image Generation.

1. Introduction

The concept of *flow* plays a central role in many fields of science. Classical application fields are, for example, the automotive and aviation industry, where the investigation of air flow around vehicles is an important task. However, the same concepts are used in the simulation and analysis of water flow in turbines of power plants, of blood flow in vessels, the propagation of smoke in buildings, and weather simulations, to mention just a few. The visualization of data gained from the simulation/measurement of such processes is relevant for the domain users as visualization has the potential to ease the understanding of such complex flow phenomena. In this context, topological flow visualization methods have been developed, with the aim to give insight into the overall behaviour of the flow. A characteristic of this class of methods is the segmentation of the flow domain into regions of substantially different flow behaviour, providing a topology of the flow domain.

Topological methods for flow visualization have been researched over recent decades and a specific conference, called *Topological Methods in Visualization* (TopoInVis), has recently been established [HHT07, HPS08].

The overall setting for topological methods is more general than described above. Namely, any vector field , interpreting it as the rate of change of a certain quantity, might

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The SemSeg project and recent developments in flow visualization

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Summary The present paper discusses recent efforts to develop semantic segmentation of space-time flow domains for visualization purposes, taking the work of the “SemSeg” project as a starting point. In particular we address separation structures based on *Finite-time Lyapunov exponents* and their extraction, the incorporation of uncertainty, and the application of *Interactive Visual Analysis* in the context of flow visualization.

Introduction

The aim of visualization is to convey a mental image of a phenomenon of interest by means of a visual representation and appropriate mechanisms of interaction. Although direct visualization of all data might be possible in some cases, the level of detail in such a visualization easily distracts form the actually important information. This is especially true in the case of flow visualization, where single vectors carry little information about the overall behavior. It is often more informative to identify and segment regions of “coherent behavior”. For steady velocity fields, an elegant mathematical theory, yielding such a segmentation, is available. In the flow visualization community this theory is usually referred to as *vector field topology* (VFT) [13].

VFT is based on the analysis of equilibrium points (here: critical points), as known from dynamical systems theory. The analysis of critical points is based on the assumption of isolated critical points in systems of autonomous ODEs, e.g., the equations defining trajectories in flow fields. These assumptions make it unfortunately inapplicable to time-dependent velocity fields, since they are non-autonomous, or, when looking at the problem in $(n+1)$ dimensions (the spatial dimensions + time), have no isolated critical points. Hence, finding a comparably elegant solution to the segmentation of flow domains in a time-varying setting can not be obtained by straight-forward extension of the existing VFT theory.

Nevertheless, VFT is an important inspiration since an optimal solution for unsteady flow fields should lead to comparable results. One of the most prominent properties of the segmentation obtained from VFT is the extraction of lines or surfaces representing the stable and unstable manifolds, so-called separatrices. These separatices confine regions of phase curves with homogeneous properties with respect to their asymptotic behavior. The analogous structures for non-autonomous dynamical systems are referred to as *Lagrangian coherent structures* (LCS) [8].

Although the concept of LCS as boundaries of particle groups with similar behavior is rather intuitive, no strict mathematical definition is available. One of the most prominent ways to define LCS is related to *finite-time Lyaponov exponents* (FTLE), a separation measure inspired by stability theory [7]. More precisely, ridges of this scalar separation measure have been proposed as LCS [10, 33].

In other cases, we have the situation that the velocity fields at different time instances represent different measurements of the same field and a more probabilistic view point needs to be taken, yielding the notion of *uncertain VFT* [23].

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