Interactive Visual Analysis of Flow Data

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*et al.*
Flows

- **Something moving**, usually some matter (a liquid or gas), but also dynamical systems, *etc*.

- **Usefully understood as differential wrt. time**
  \[
  \mathbf{v} = \frac{d \mathbf{p}}{dt} \quad \mathbf{p} \in \Omega \subseteq \mathbb{R}^n, \quad \mathbf{v} \in \mathbb{R}^n, \quad t \in \mathcal{R}
  \]

- Often represented as a **vector field**, *i.e.*, as set of vector samples \( \mathbf{v}(\mathbf{p}_i) \) over a certain grid \( \{\mathbf{p}_i\} \)

- Special challenge: unsteady flows \( \mathbf{v}(\mathbf{x},t) : \mathbb{R}^n \times \mathbb{R} \rightarrow \mathbb{R}^n \)

- **Flow data** origin in
  - **measurements**, *e.g.*, with PIV (particle image velocimetry)
  - **simulation**, *e.g.*, from CFD (computational fluid dynamics)
  - **modeling**, *e.g.*, as ODEs (ordinary differential equations)

Flow Visualization Methods

- From Post *et al.*:
  - Direct flow visualization
  - Texture-based flow visualization
  - Integration-based flow visualization
  - Feature-based / topological FlowViz
Direct Flow Visualization (1)

- One-to-one mapping of \( \mathbf{v} \) into vis. space

- Classical approaches:
  - arrows (hedgehog plot)
  - color coding

Texture-based FlowVis (2)

- Space-filling vis. of instantaneous flow \( \mathbf{v} \)

- Classical approaches:
  - line integral convolution (LIC) & spot noise
  - texture advection
Integration-based FlowVis (3)

- Utilization of integration paths
  \[ \mathbf{p}(s) = \mathbf{p}_0 + \int_{\tau=0}^{s} \mathbf{v}(\mathbf{p}(\tau), t_0+\tau) \, d\tau \]
- Classical approaches:
  - streamlines
  - streamsurfaces

Feature-based / Topological FlowVis (4)

- Computational analysis, then vis.
- Approaches:
  - topology-based FlowVis
  - utilization of vortex extraction for FlowVis
Interactive Visual Analysis of Flow Data

- **Base-level IVA** *(solves many problems, already!)*
  - bring up at **least two different views** on the data
  - allow to **mark up interesting data parts** *(brushing)*
  - utilize **focus+context visualization** to highlight the user selection **consistently(!)** in all views *(linking)*

- Example (interactively?)...

- With base-level IVA, you can already do
  - **feature localization** – *brush high temperatures in a histogram, for ex., and see where they are in spacetime*
  - **local investigation** – *for ex., select from spacetime and see how attributes are there (compared to all the domain)*
  - **multivariate analysis** – *brushing vorticity values and studying related pressure values (selection compared to all)*

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**Base-level IVA of Flow Data**

At least one **spatial view** & at least one **attribute view**
→ **studying different aspects of flow data**

[Hauser, 2006]
Getting more out of IVA (advanced IVA)

- Starting from base-level IVA,
  - we enable the **identification of complex features**, for ex., by exploiting a **feature definition language**
  - we realize **advanced brushing schemes**, e.g., by realizing a **similarity brush**
  - we facilitate **interactive attribute derivation**, e.g., by means of a **formula editor**
  - we **integrate statistics/ML on demand**, e.g., by linking to R

- With advanced IVA,
  - we **drill deeper** (data→selections→features→…)
  - we **read between the lines** (semantic relations)
  - we **answer complex questions** about the data

Low-level IVA of Flow Sim. Data

Multiple selections in parallel coordinates plus a time-histogram and linked volume rendering (colors according to the selections) [Akiba & Ma, 2007]
Flow Simulation Data and IVA

Data from computational simulation, e.g., CFD, is
- usually given on (large & interesting) spatial grids
  (often also time-dependent)
- often multivariate in terms of the simulated values
- based on a continuous model

Considering such data in the \( d(x) \) form
- with \( d \) being the dependent variables (the simulated variates), for ex., velocities, pressure, temperature, ...
- and \( x \) representing the independent variables, i.e., the domain of the data (usually space and time)

With IVA,
- we relate \( x \) and \( d \) (feature localization, local investigation) as well as \( d_i \) and \( d_j \) (multivariate analysis)
- we consider \( \delta(d) \), i.e., derived “views” on the data
  - either explicitly (by attribute derivation)
  - or implicitly (by advanced interaction mechanisms)
Derived “Views” (higher-level IVA) – local

- **Local** [vs. non-local (semi-local, global)] derivations
  - considering **derivatives**, e.g., wrt. space/time, incl.
    - **temporal derivatives** $d_i$ $(dd_i/dt)$ // Eularian view
    - **spatial derivatives** $\nabla d_i$ $(dd_i/dx)$, in particular also the spatial velocity gradient $J=\nabla v$ $(dv/dx)$
  - **vector calculus** based on —", inc.
    - **divergence** $\text{div} \ v$ $(\nabla \cdot v)$
    - **rate of strain** $S = (J + J^T)/2$
    - **curl (vorticity)** $\omega$ $(\nabla \times v)$
    - **rate of rotation** $\Omega = (J - J^T)/2$
  - **local feature detectors**, e.g., based on —" [Bürger et al., 2007]
    - **vorticity magnitude** $|\omega|$ [Strawn et al., 1998]
    - **normalized helicity** [Levy et al., 1990] $H_n = \frac{\text{v} \cdot \omega}{|\text{v}| \cdot |\omega|}$
    - **Hunt’s Q** [Hunt et al., 1988] $Q = ||\Omega||^2 - ||S||^2$
    - **kinematic vorticity number** [Truesdell, '54] $N_k = ||\Omega|| / ||S||$
    - **$\lambda_2$** according to Jeong & Hussain (1995) $\lambda_2(\Omega^2 + S^2)$

Derived “Views” (higher-level IVA) – non-local

- **Non-local** (semi-local, global) derivations
  - **local neighborhoods** $P_r(x) = \{ y | |x-y|<r \}$
    - **local neighborhood statistics** [Angelelli et al., 2011], like also moving averages, for ex.
    - **stream-/streak-/pathlet statistics** (e.g., averages)
    - **local normalization**
    - **etc.**
  - **global methods**
    - **reconstructions from scale-space representation**, e.g., POD-based reconstruction [Pobitzer et al., 2011]
    - **topology-based approaches**, e.g., uncertain vector field topology [Otto et al., 2010 & 2011]
    - **integration-based approaches**, e.g., FTLE computation
Analyzing the Change over Time

To access unsteady aspects of flows, we look at **temporal changes** \( \frac{d^2 d_i}{dt^2} \), for ex., approximated by central differences, possibly computed after some temporal smoothing.

- We derive **time-step-relative normalization** (\( d_i \) normalized to \([0,1]\) per time-step, also zero-preserving).
- We allow the **interpolation of selections over time** (like in keyframe animation).
- We provide a **measure of how stationary a \( d_i \) is** (for how long it stays within an \( \varepsilon \)-neighborhood).
- We provide a **measure to capture local extrema** (both maxima of \( d_i \) as well as minima of \( d_i \)).

Unsteady Vortex Extraction with IVA

- **Going unsteady in vortex extraction:**
  - Based on the approach by Sujudi & Haimes (1995), *i.e.*, to search where \( \varepsilon \| \nabla v \) (eigenvector corresponding to the only real eigenvalue of \( \nabla v \)),
  - and a **re-formulation** [Peikert & Roth, 1999] as \( a_E \| v \) (with \( a_E = (\nabla v) \), only for \( \nabla v \) with only one real eigenvalue),
  - we can now search for all places with \( a_L \| v \) (with \( a_L = \frac{Dv}{dt} \), *i.e.*, the particle acceleration \( (\nabla v)v + \frac{dv}{dt} \))
  - higher-order [Roth & Peikert, 1998] \( b_E \| v \Rightarrow b_L \| v \) \( (b_L = D^2 u/dt^2) \)
Pathline Attributes and IVA

- Getting insight into flow via pathlines and their attributes
  - we compute pathlines and various pathline attributes describing their local and global behavior
  - we use IVA to explore the attribute space
  - many parameters computed – scalar and time dep.
  - multi-step analysis introduced – start with coarse pathlines, refine where necessary
  - projections of pathlines to 2D planes used for interaction

Factor Analysis of Pathline Attributes IVA

- Main problem with parameters – parameter selection
  - statistical analysis in order to select relevant parameters
  - find an universal starting set of parameters
  - six data sets analyzed (5 simulated, 1 analytical)
  - six attributes identified (1 related to shape, 1 to vortices, 4 to motion) which for a common expressive set for analysis of all data sets
Conclusions

- IVA helps to integrate the user’s and the computer’s strengths to enable exploration and analysis
- IVA is interactive and iterative
- An approach to realize semantic abstraction from data (to features, insight)
- Enables the joint analysis based on multiple perspectives, e.g., several feature detectors
- Helps with questions of different character (physical, geometric, statistical, …)
- Non-trivial integration of Eulerian and Lagrangian data for IVA

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