Interactive Visual Analysis of Time-Dependent Flows

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Context

- This talk:
  - about **Interactive Visual Analysis** (IVA) in general and the **IVA of simulation data** in particular,
  - and specifically **IVA of time-dep. flow data**

- In general:
  - IVA is one **methodology within visualization**
  - to **facilitate insight** into **large and/or complex data**
  - via **interactive exploration** and **analysis**

Interactive Visual Analysis – main idea

- On top level: [Chen et al., 2009]
  - due to the *data→information→knowledge* cascade (knowledge/insight being implicitly coded within data), we need **means to abstract insight from data**
  - integrating the *best from "two worlds"*, we combine
    - data **exploration**/analysis by the **user**, based on **interactive visualization**
    - and data **analysis** by the **computer**, based on **statistics**, **machine learning**, etc. [Hauser et al., 2000–]
  - IVA, in general, is a loop (*interactive & iterative*),
    show / brush
    1. usually starting with **some data visualization first**,
    2. followed by **user inspection** and **certain interaction**
    3. the user interaction causes a **new visualization**, ⇨ 2.
    4. user-induced **computations** lead to vis., again, ⇨ 2.
- IVA works for engineers, bioinformaticians, climatologists, …

Basis of IVA

- Given some data, *e.g.*,
  - a (large) bunch of time series,
  - some (larger) tables of numbers (usually multiple colums),
  - spatiotemporal data that is multivariate (like here!),
  - *etc.* (*yes, it's really that general!*),
- IVA is
  - a flexible exploration & analysis methodology
  - that utilizes a variety of **different views on the data**
  - and **feature extraction** (interactively & computationally)
- IVA enables
  - interactive **information drill-down**, while navigating between *overview & detail*, **seeing the unexpected**, *e.g., for hypothesis generation*, **steering the analysis**
  - IVA **bridges the gap between the data & the user**

Level 1: KISS-principle IVA

- **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)*

Getting more out of IVA (advanced IVA)

level 2

- 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*

level 3

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

Flow Simulation Data and IVA

- Data from computational simulation, *e.g.*, CFD, is
  - usually given on (large & interesting) **spatial grids** (often also **time-dependent** *← special focus here!*)
  - 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 $\mathbf{d}_i$ **and** $\mathbf{d}_j$ (multivariate analysis)
  - we consider **δ**(**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

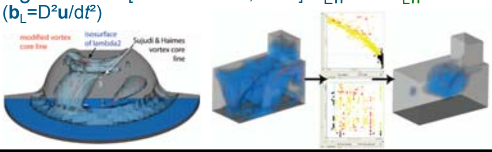
- **Local** [vs. non-local (semi-local, global)] derivations
  - considering **derivatives**, e.g., wrt. space/time, incl.
    - **temporal derivatives** $\mathbf{d}_i'$ ($d\mathbf{d}_i/dt$) // Eularian view
    - **spatial derivatives** $\nabla\mathbf{d}_i$ ($d\mathbf{d}_i/d\mathbf{x}$), in particular also the spatial velocity gradient $\mathbf{J}=\nabla\mathbf{v}$ ($d\mathbf{v}/d\mathbf{x}$)
  - **vector calculus** based on —"—, inc.
    - **divergence** div**v** ($\nabla\cdot\mathbf{v}$)
    - **rate of strain** $\mathbf{S} = (\mathbf{J} + \mathbf{J}^{\mathsf{T}})/2$
    - **curl** (vorticity) **ω** ($\nabla\times\mathbf{v}$)
    - rate of rotation $\mathbf{\Omega} = (\mathbf{J} - \mathbf{J}^{\mathsf{T}})/2$
  - **local feature detectors**, *e.g.*, based on —"— [Bürger et al., 2007]
    - **vorticity magnitude** |**ω**| [Strawn et al., 1998]
    - **normalized helicity** [Levy et al., 1990] $H_n = \dfrac{\mathbf{v}\cdot\omega}{|\mathbf{v}|\cdot|\omega|}$
    - **Hunt's Q** [Hunt et al., 1988] $Q = \|\mathbf{\Omega}\|^2 - \|\mathbf{S}\|^2$
    - **kinematic vorticity number** [Truesdell, '54] $N_k = \|\mathbf{\Omega}\| \,/\, \|\mathbf{S}\|$
    - λ_2 according to Jeong & Hussain (1995) $\lambda_2(\mathbf{\Omega}^2 + \mathbf{S}^2)$

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

- **Non-local** (semi-local, global) **derivations**
  - **local neighborhoods** $\mathbf{P}_r(\mathbf{x})$ = { **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

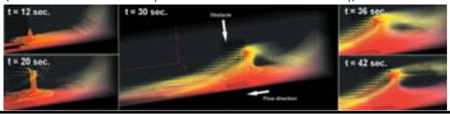
Unsteady Vortex Extraction with IVA

- Going unsteady in vortex extraction: [Fuchs et al., 2008]
  - Based on the approach by Sujudi & Haimes (1995), *i.e.*, to search where $\boldsymbol{\varepsilon}_r || \mathbf{v}$ (eigenvector corresponding to the only real eigenvalue of $\nabla\mathbf{v}$),
  - and a re-formulation [Peikert & Roth, 1999] as $\mathbf{a}_E || \mathbf{v}$ (with $\mathbf{a}_E = (\nabla\mathbf{v})\mathbf{v}$, only for $\nabla\mathbf{v}$ with only one real eigenvalue),
  - we can now search for all places with $\mathbf{a}_L || \mathbf{v}$ (with $\mathbf{a}_L = D\mathbf{u}/dt$, i.e., the particle acceleration $(\nabla\mathbf{v})\mathbf{v} + d\mathbf{v}/dt$)
  - higher-order [Roth & Peikert, 1998] $\mathbf{b}_E || \mathbf{v} \Rightarrow \mathbf{b}_L || \mathbf{v}$ ($\mathbf{b}_L = D^2\mathbf{u}/dt^2$)



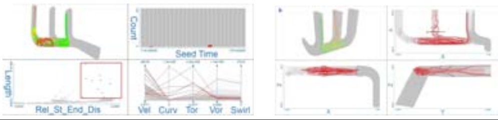
Time-related Derivations in IVA

- To access unsteady aspects of flows, [Doleisch et al., 2006]
  - we look at temporal changes $d\mathbf{d}_i/dt$, for ex., approximated by central differences, possibly computed after some temporal smoothing
  - we derive time-step-relative normalization ($\mathbf{d}_i$ 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 $\mathbf{d}_i$ is (for how long it stays within an ε-neighborhood)
  - we provide a measure to capture local extrema (both maxima of $\mathbf{d}_i$ as well as minima of $\mathbf{d}_i$)



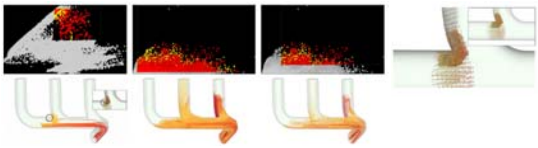
Pathline Attributes and IVA

- Getting insight into flow via pathlines and their attributes [Shi et al. 2009] [Lež et al., 2011]
  - 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 [Pobitzer et al. 2012]
  - 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 Eularian and Langrangian data for IVA

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