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:
  - due to the data\(\rightarrow\)information\(\rightarrow\)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.**

- IVA, in general, is a loop (**interactive & iterative**),
  1. usually starting with **some data visualization first**,
  2. followed by **user inspection** and **certain interaction**
  3. the user interaction causes a **new visualization**, \(\Rightarrow\) 2.
  4. user-induced **computations** lead to vis., again, \(\Rightarrow\) 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 columns),
  - 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)

- 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)
  - 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 $d_i$ 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** $d_t \frac{d}{dt}$ // Eularian view
    - **spatial derivatives** $\nabla d_x \frac{d}{dx}$, in particular also the spatial velocity gradient $J=\nabla v (dv/dx)$
  - **vector calculus** based on —"—, inc.
    - divergence $\nabla \cdot v$ ($\nabla \cdot v$)
    - rate of strain $S = (J + J^T)/2$
    - curl (vorticity) $\omega$ ($\nabla \times v$)
  - **local feature detectors**, e.g., based on —"— [Bürger et al., 2007]
    - vorticity magnitude $|\omega|$ [Strawn et al., 1998]
    - normalized helicity [Levy et al., 1990]
    - 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** $P_r(x) = \{ y \mid |x-y|<r \}$
  - **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 $\epsilon_r||v$ (eigenvector corresponding to the only real eigenvalue of $\nabla v$),
  - and a re-formulation [Peikert & Roth, 1999] as $a_E||v$
    (with $a_E=(\nabla v)v$, only for $\nabla v$ with only one real eigenvalue),
  - we can now search for all places with $a_L||v$
    (with $a_L=Du/dt$, i.e., the particle acceleration $(\nabla v)v+dv/dt$)
  - higher-order [Roth & Peikert, 1998] $b_E||v \Rightarrow b_L||v$
    ($b_L=D^2u/dt^2$)

Time-related Derivations in IVA

- To access unsteady aspects of flows, [Doleisch et al., 2006]
  - we look at temporal changes $dd_i/dt$, 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 $\epsilon$-neighborhood)
  - we provide a measure to capture local extrema (both maxima of $d_i$ as well as minima of $d_i$)
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 Langrangian data for IVA

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  Question?

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