# Flow Visualization and Analysis: From Geometry to Physics

Lei Zhang

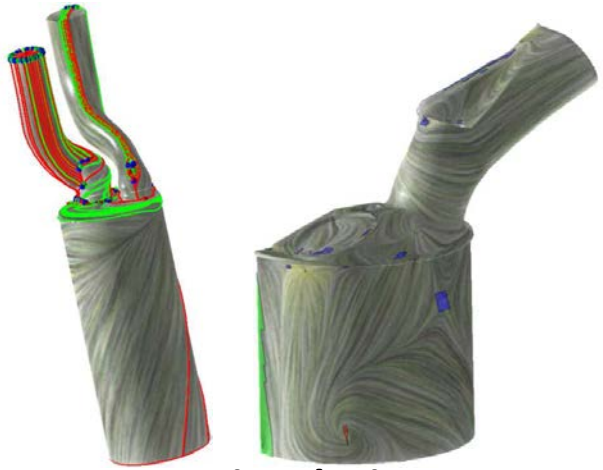
Advisor: Guoning Chen

# Outline

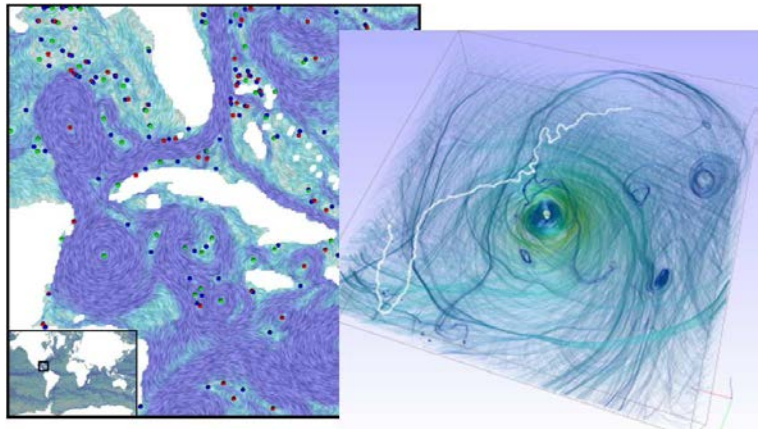
- ❑Problem Definition
- ❑**Lagrangian Accumulation Framework (done)**
- ❑**TAC and Multi-TAC based Framework (on-going)**
- ❑Future Work & Questions

# Why Vector Fields are Important?

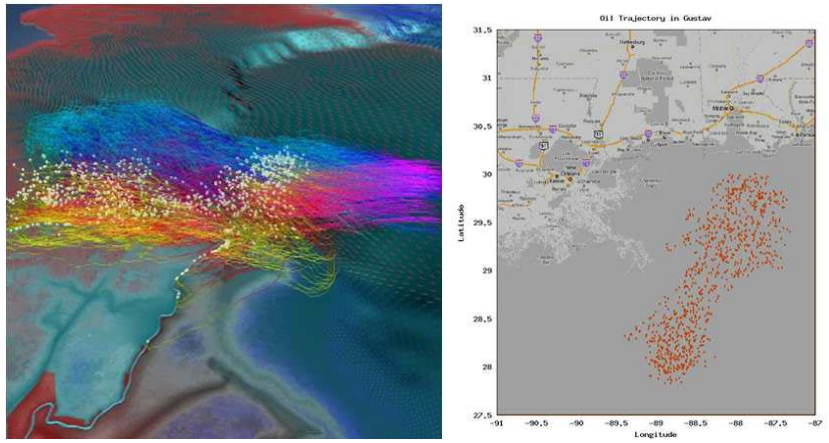
# Vector Fields in Engineering and Science



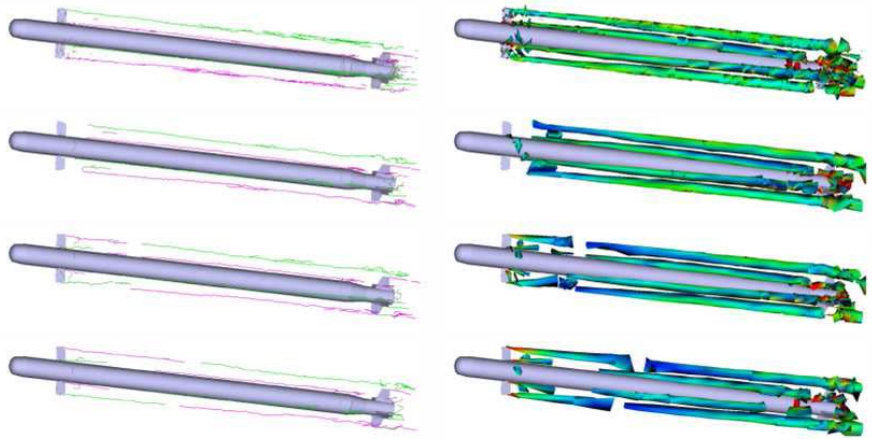
**Automotive design** [Chen et al. TVCG07,TVCG08]



**Weather study** [Bhatia and Chen et al. TVCG11]

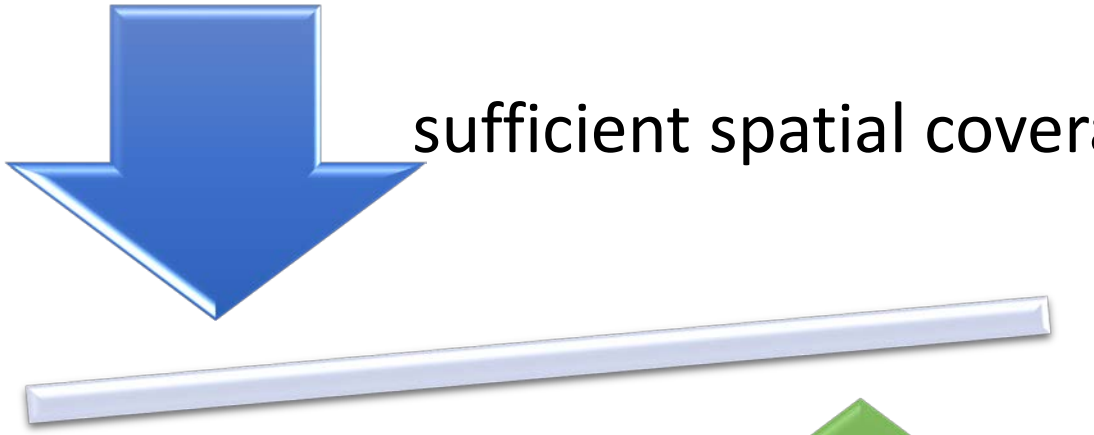



**Oil spill trajectories** [Tao et al. EMI10]



**Aerodynamics around missiles** [Kelly et al. Vis06]

# What are we looking for from vector fields?

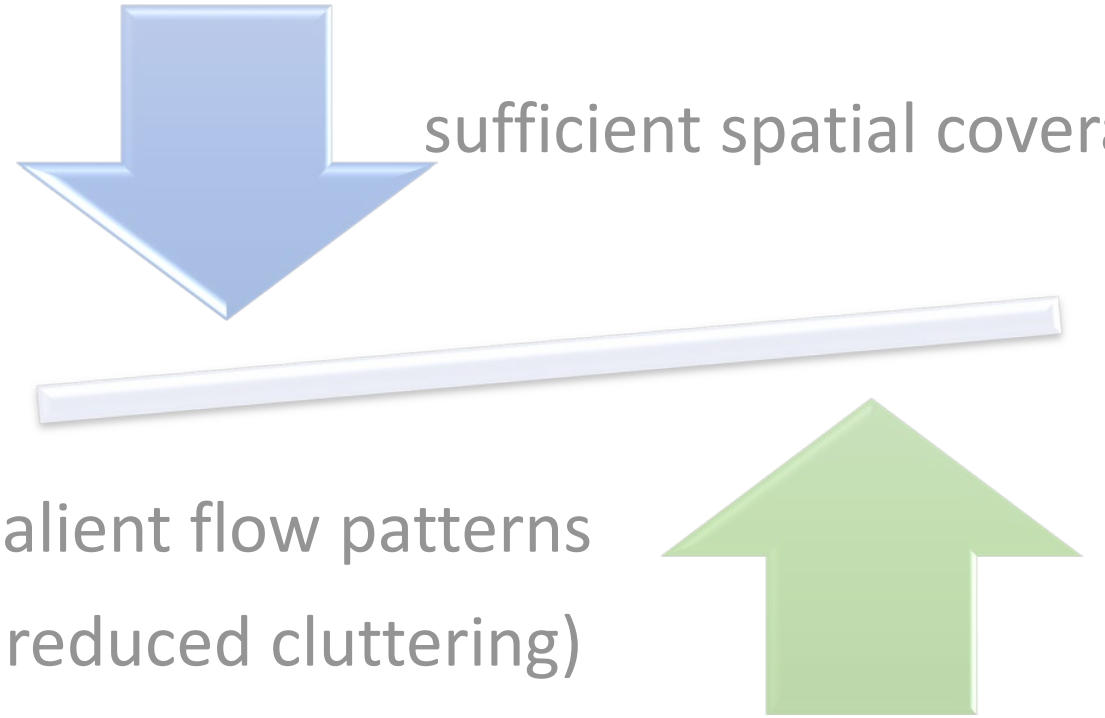


sufficient spatial coverage

salient flow patterns

(reduced cluttering)

# What are we looking for from vector fields?




An abstract representation is strongly need!

# Related Work - Vector Field Topology

- Goal

  Obtaining a compact representation of a vector

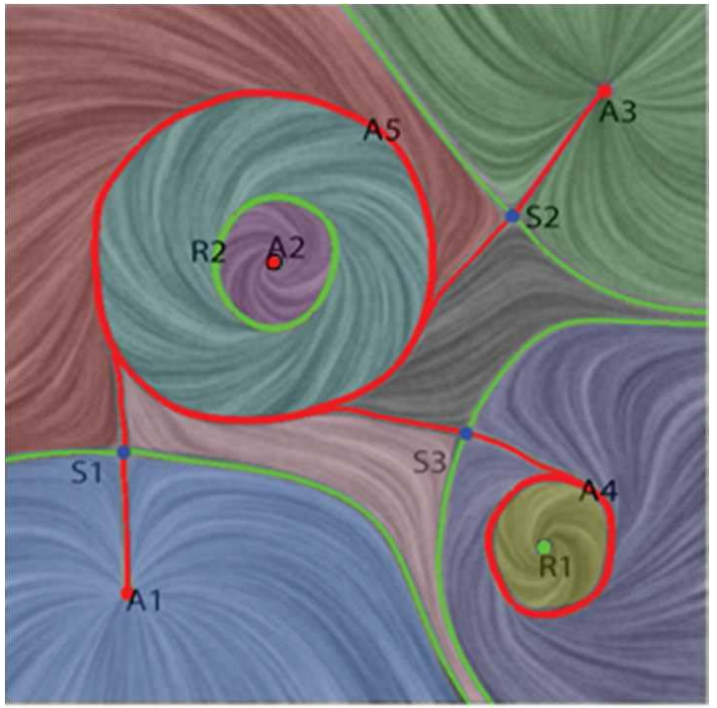
- Pros

  Providing a holistic understanding of the flow in a more semantic level

- Cons

  Challenges in unsteady flow

  Pure geometry, no physical info




Entity Connection Graph [Chen et al. TVCG07]

[Chen et al. TVCG07, TVCG08, TVCG11a; Szymaczak et al. TVCG12, TVCG13; Haller 2001]

# Related Work – Geometric-based Flow Visualization

- Goal

  Extracting representative geometric objects: streamlines, pathlines, surfaces ect.

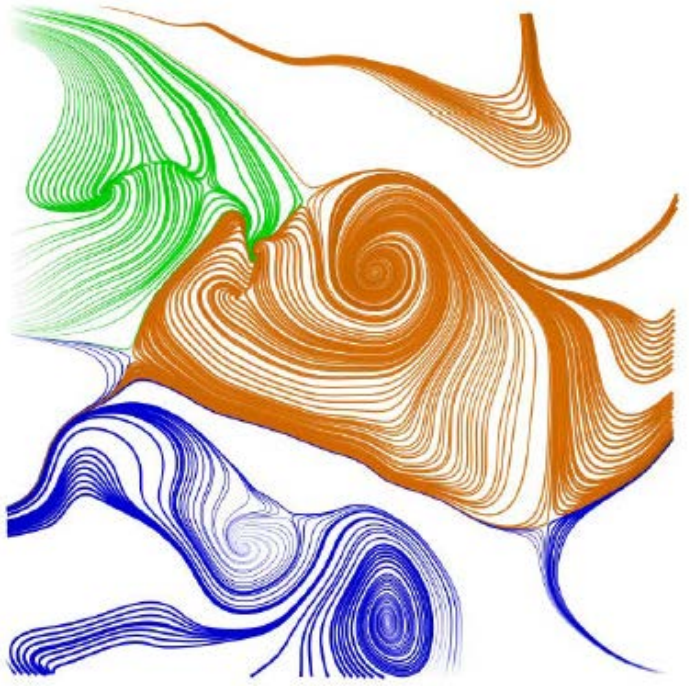
- Pros

  Data compressed

  Intuitive visualization

- Cons

  May loose some important features



Streamline clustering [[Yu et al. 2012]

Salzbrunn et al. TVCG06, 2008; Shi et al. TVCG08; Weinkauf et al. TVCG10, TVCG12; McLoughlin et al. TVCG13.

# Related Work – Attributes-based Flow Visualization

- Goal

  Extracting local/global attributes of integral curves

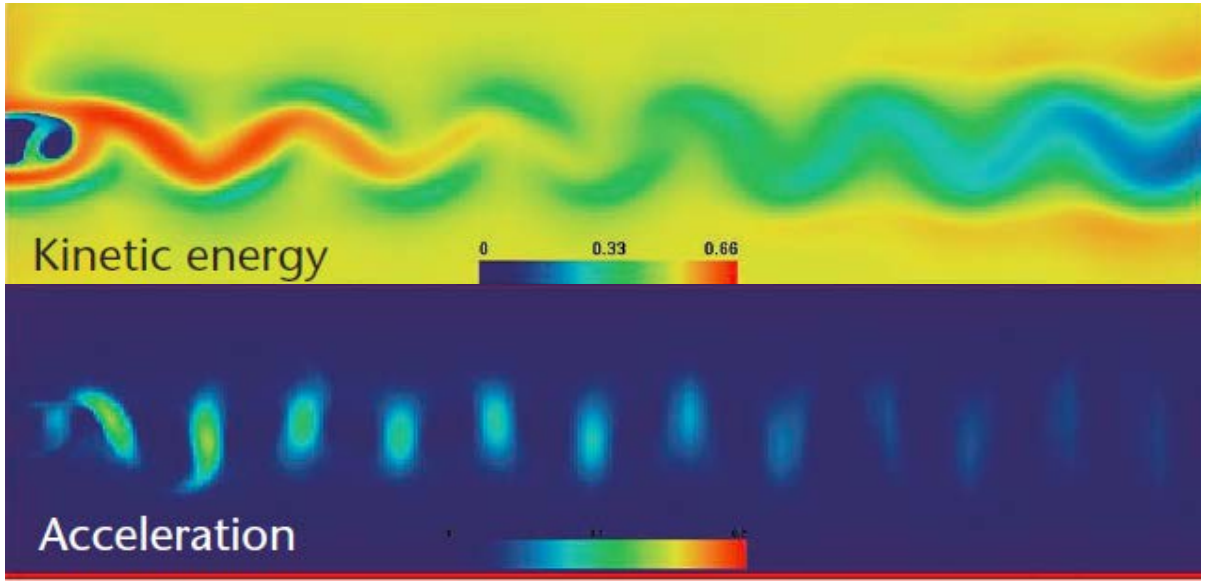
- Pros

  information visualization

- Cons

  Additional efforts needed to interpret the result

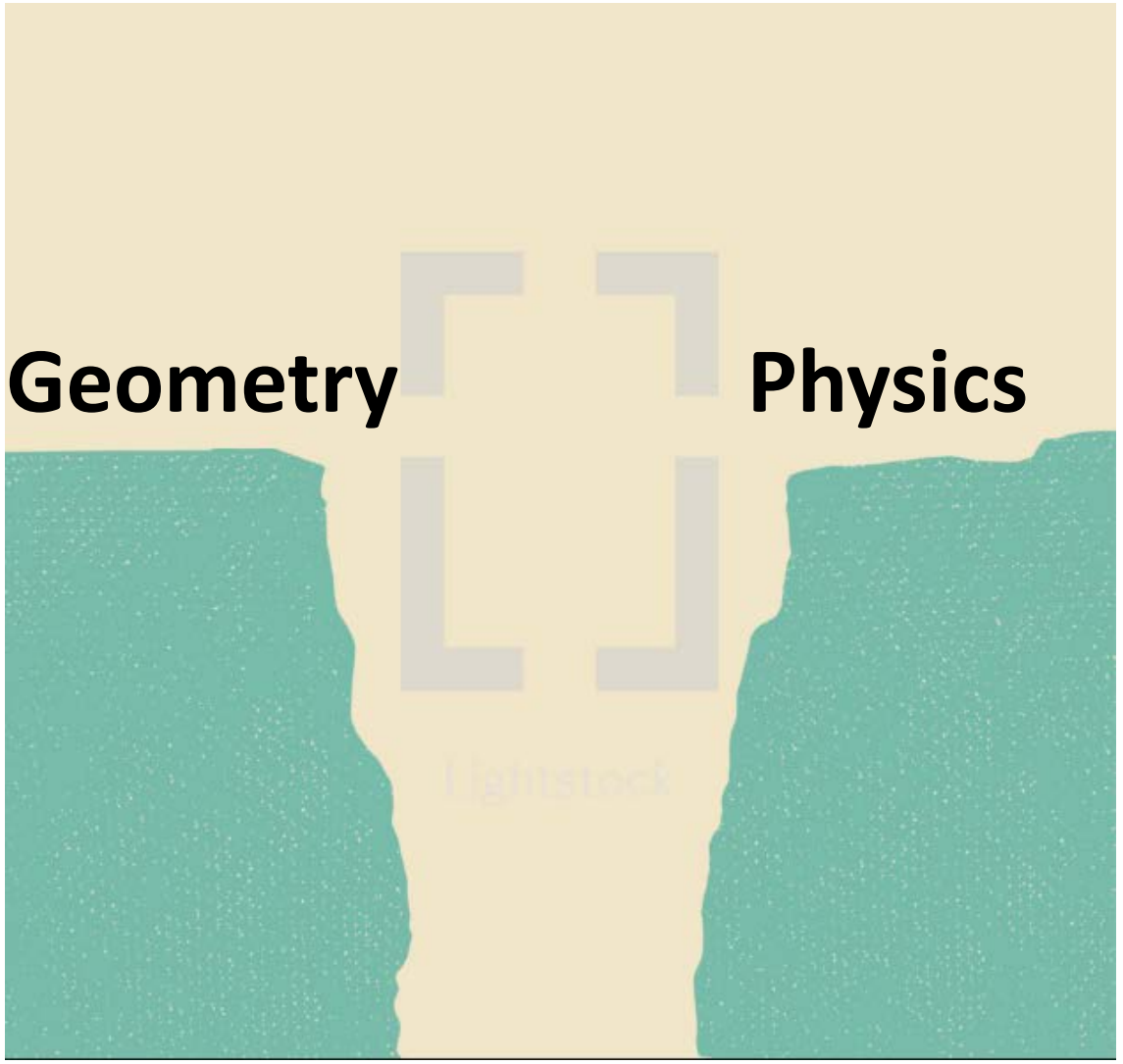
  Lack of details




Local Attributes. [Shi et al. CGA08]

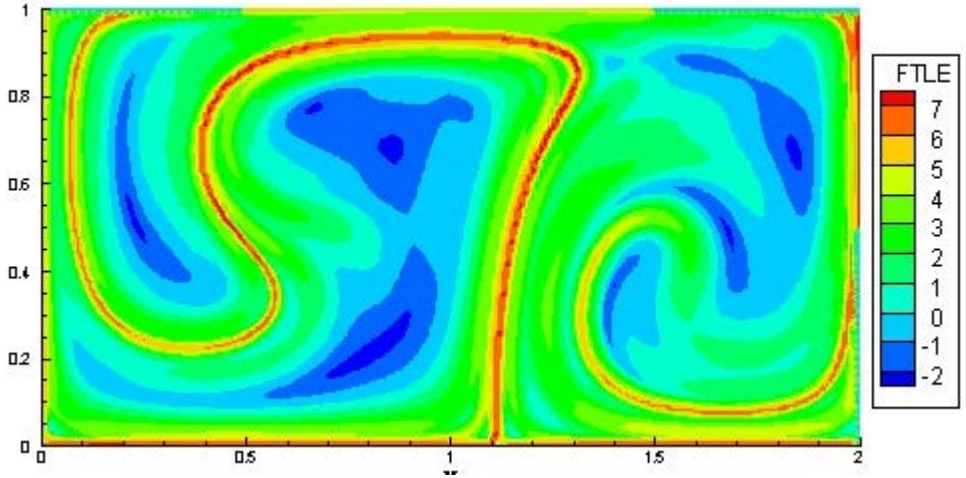
Pobitzer et al. PacificVis12, 2008; Guo et al. PacificVis14; Shi et al. CGA08, TopoInVis09.

# Motivation



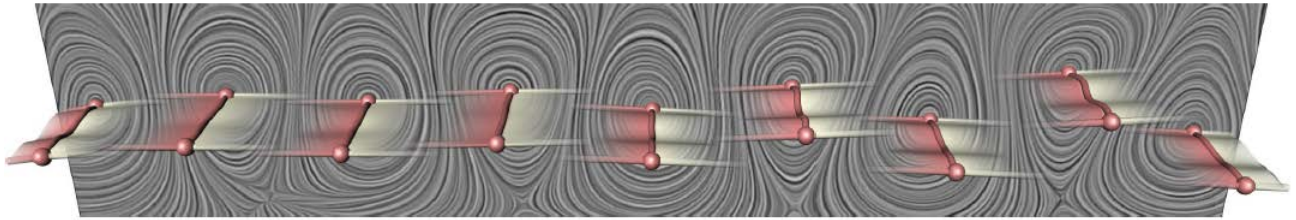
# Physical Features

- Flow separation
  - FTLE/LCS
- Vortex
  - $Q$-criterion and $\lambda_2$-criterion




FTLE of Double Gyre flow at t=0 and T=15.

- **Dissipation and Diffusion**
- **Dispersion**
  - **Dispersive mass transfer**
  - **Atmospheric dispersion**

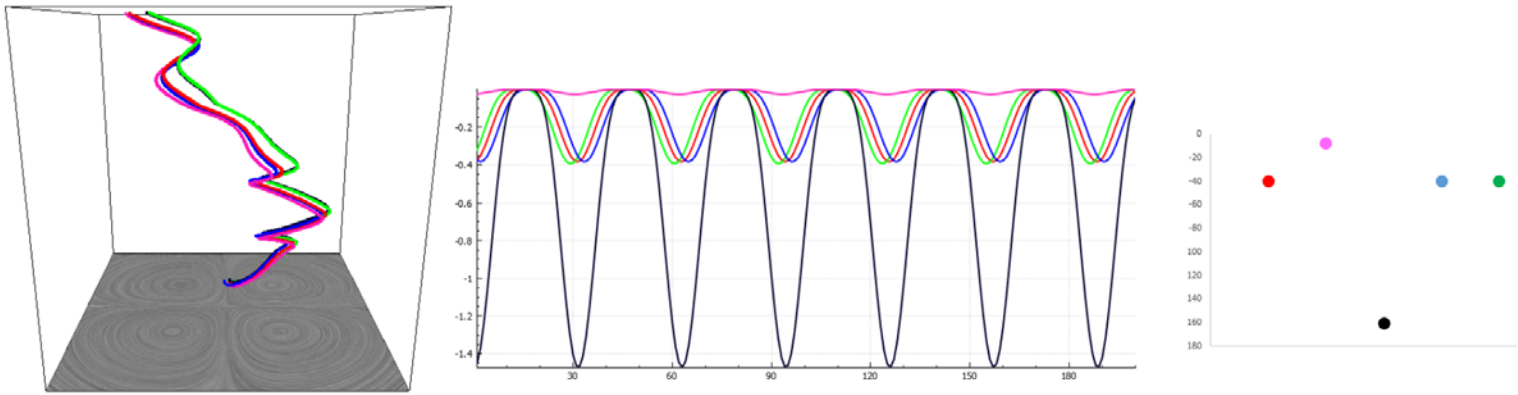


Evolution of the vortices core lines over time of a 3D unsteady flow behind a cylinder. [Weinkauf et al. TVCG07]

*Is it possible to make a theoretical model to describe the behavior of a turbulent flow — in particular, its internal structures? (unsolved problem in Physics)*

# Problem Definition

- A Physics-based Flow Exploration Framework
  - Apply to different categories of Physical feature
  - Achieve a level-of-detail flow exploration




(a) (b) (c)

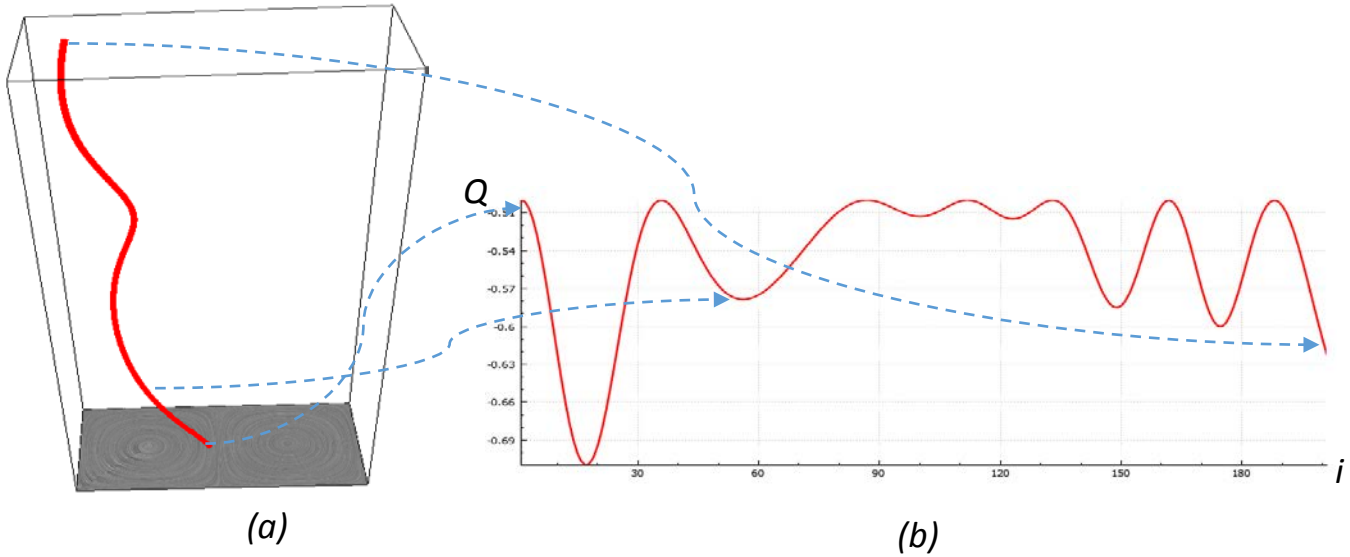
The illustration of the gap between geometrics representation and physical interpretation. (a) A number of pathlines with homogeneous behaviors. (b) The time activity curves of the physical attribute ***Q***. (c) Accumulated ***Q*** field values of each corresponding pathines in (a).

# Time Activity Curve (TAC)

- Definition

  Given an integral curve $C_{\mathbf{x},t}$ seeded at $(\mathbf{x}, t)$, computing a local attribute **A** along the curve gives rise to a time series data, which we refer as a Time Activity Curve (TAC) of$C_{\mathbf{x},t}$ on the attribute **A**.

$$\Gamma_{\mathbf{A},\mathscr{C}}[i] = \mathbf{A}(\mathscr{C}(\mathbf{x}, t_i), t_i) | i = 1, 2 \ldots n$$




(a) A pathline. (b) TAC of the pathline on physical attribute ***Q***.

# Expected Contributions

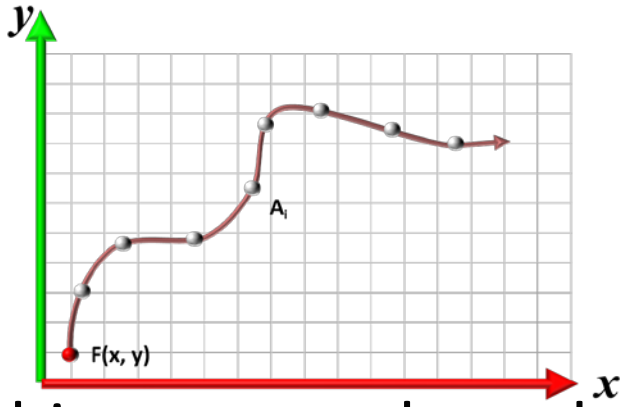
- ❑A Lagrangian accumulation framework (done)
  - ❑Derived attribute fields
  - ❑Properties study
  - ❑Integral seeding
  - ❑Flow segmentation
  - ❑Discontinuity study
- ❑TAC and Multi-TAC (on-going)
  - ❑Event detection
  - ❑Hierarchical clustering based on TAC
  - ❑ Stable set analysis
  - ❑Correlation study

# Outline

- ❑ Problem Definition
- ❑ Lagrangian Accumulation Framework (done)
  - ❑ Definition
  - ❑ Properties
  - ❑ Exploration framework
  - ❑ Applications
- ❑ **TAC and Multi-TAC based Framework (on-going)**
- ❑ Future Work

# L.A. - Definition

- Consider an integral curve C, starting from a given point ***(x, t),*** the Lagrangian accumulation can be formulated as:




$$A_g(\mathbf{x},t) = \int_{T_1}^{T_2} k(\tau) A_l(\mathscr{C}_{\mathbf{x},t}(\tau),\tau) d\tau$$

- Similarly, the accumulation can also be done within a range along the integral curves with a specified length

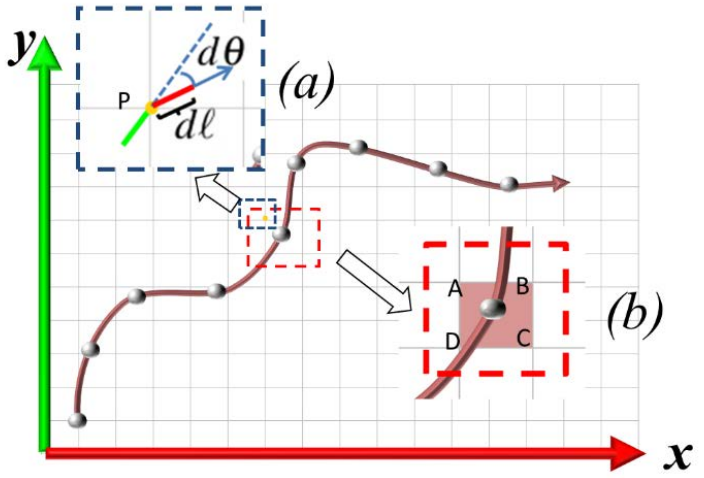
$$A_g(\mathbf{x},t) = \int_{s_1}^{s_2} k(s) A_l(\mathscr{C}_{\mathbf{x},t}(s),s) ds$$

- $\mathcal{A}$ Field: a derived **scalar** field obtained from the above convolution.

# L.A. - Definition

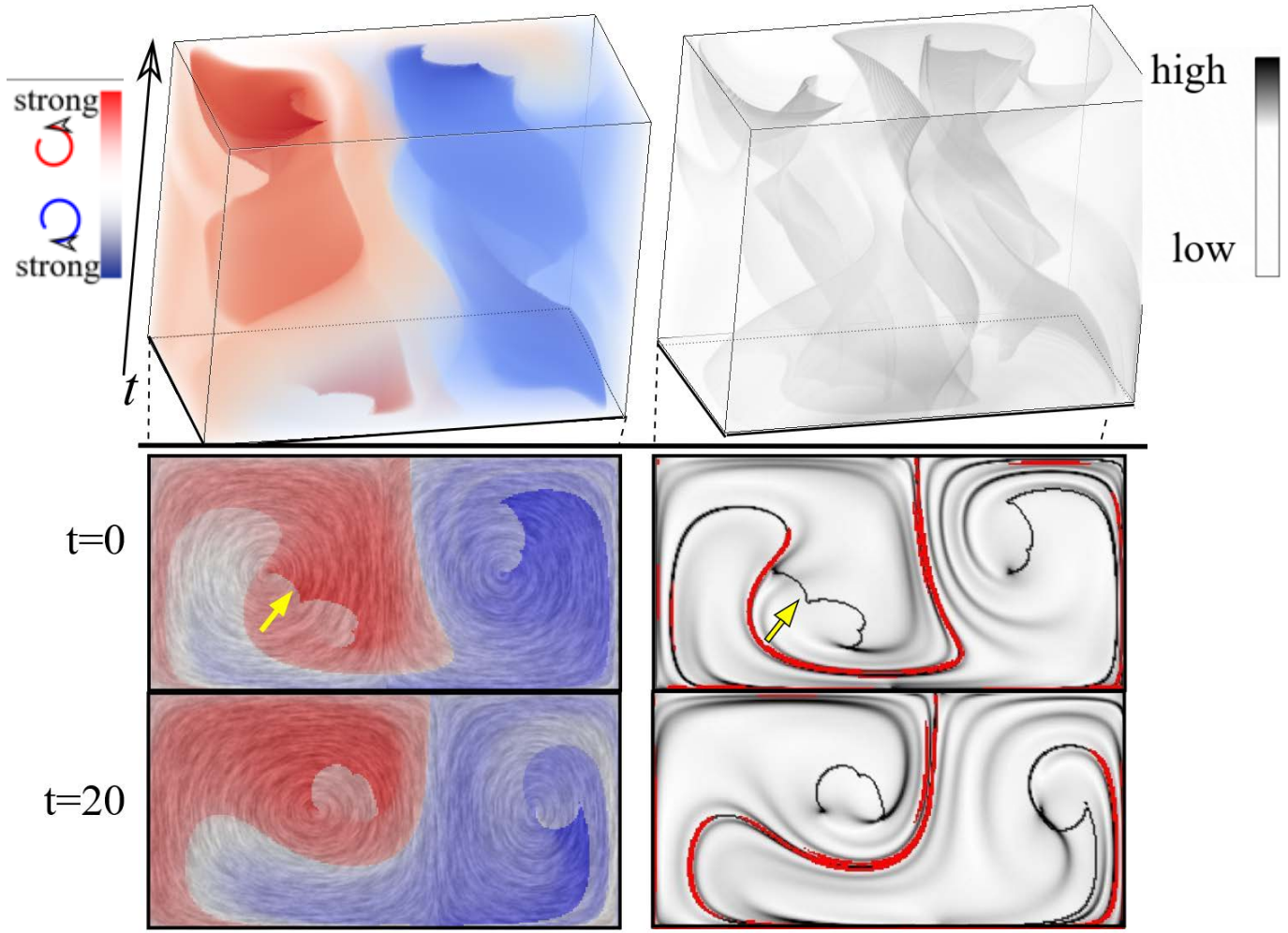
- An example of the Rotation field - $\Phi$

$$\Phi = \sum_{i=0}^{N} d\theta_i \qquad \nabla\Phi = \left(\frac{\partial\Phi}{\partial x}, \frac{\partial\Phi}{\partial y}, \frac{\partial\Phi}{\partial z}\right)$$




Assuming the integral curve $C$ is represented by $N$ integration points $P_i$,
$d\theta_i$ represents the angle difference between two consecutive line segments on an integral curve.
We use box-filter for all the examples, therefore, the kernel function $k_i = 1$

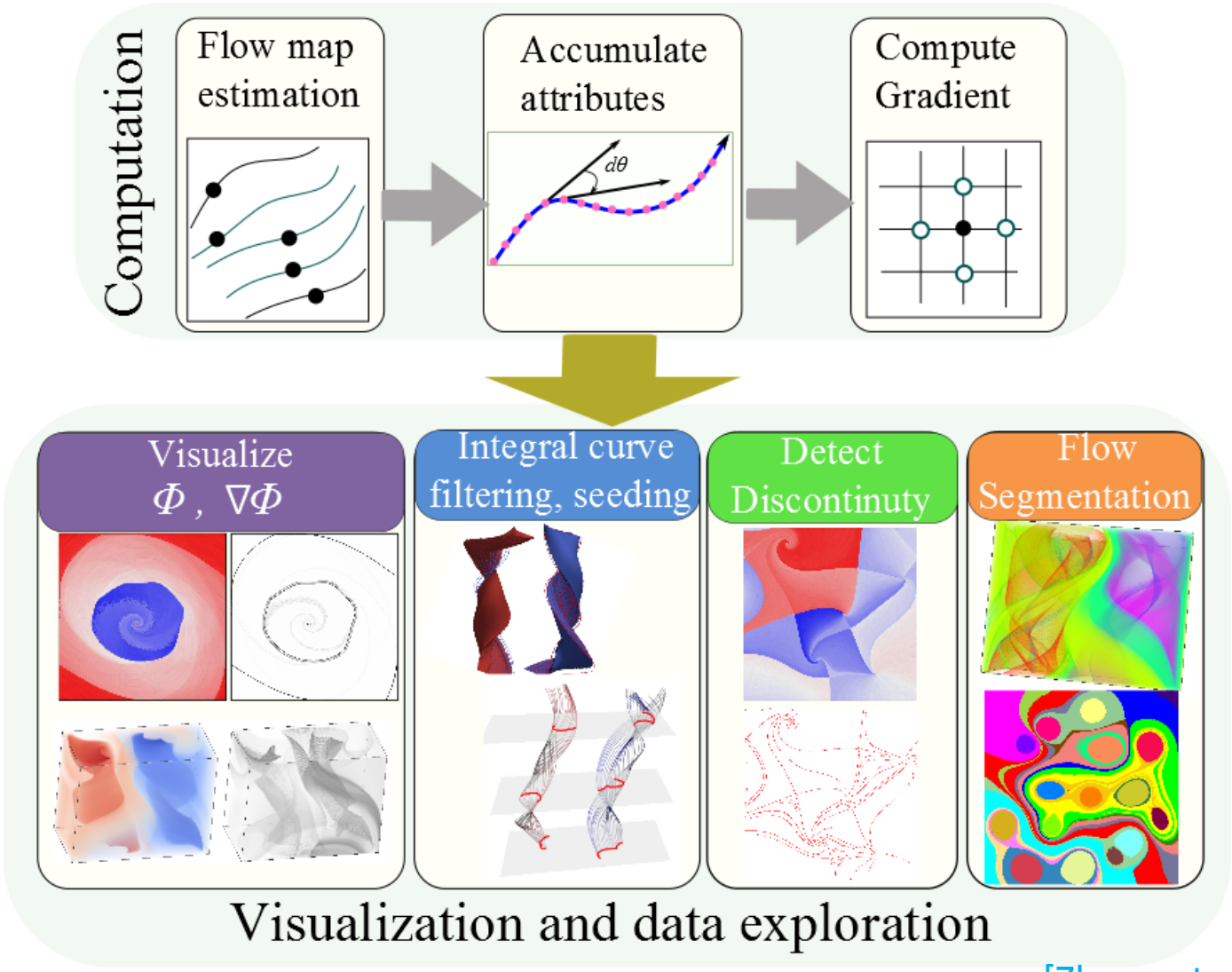
# An Attribute Field




The result of the double gyre flow with T = 10.

[Zhang et al. VDA2016].

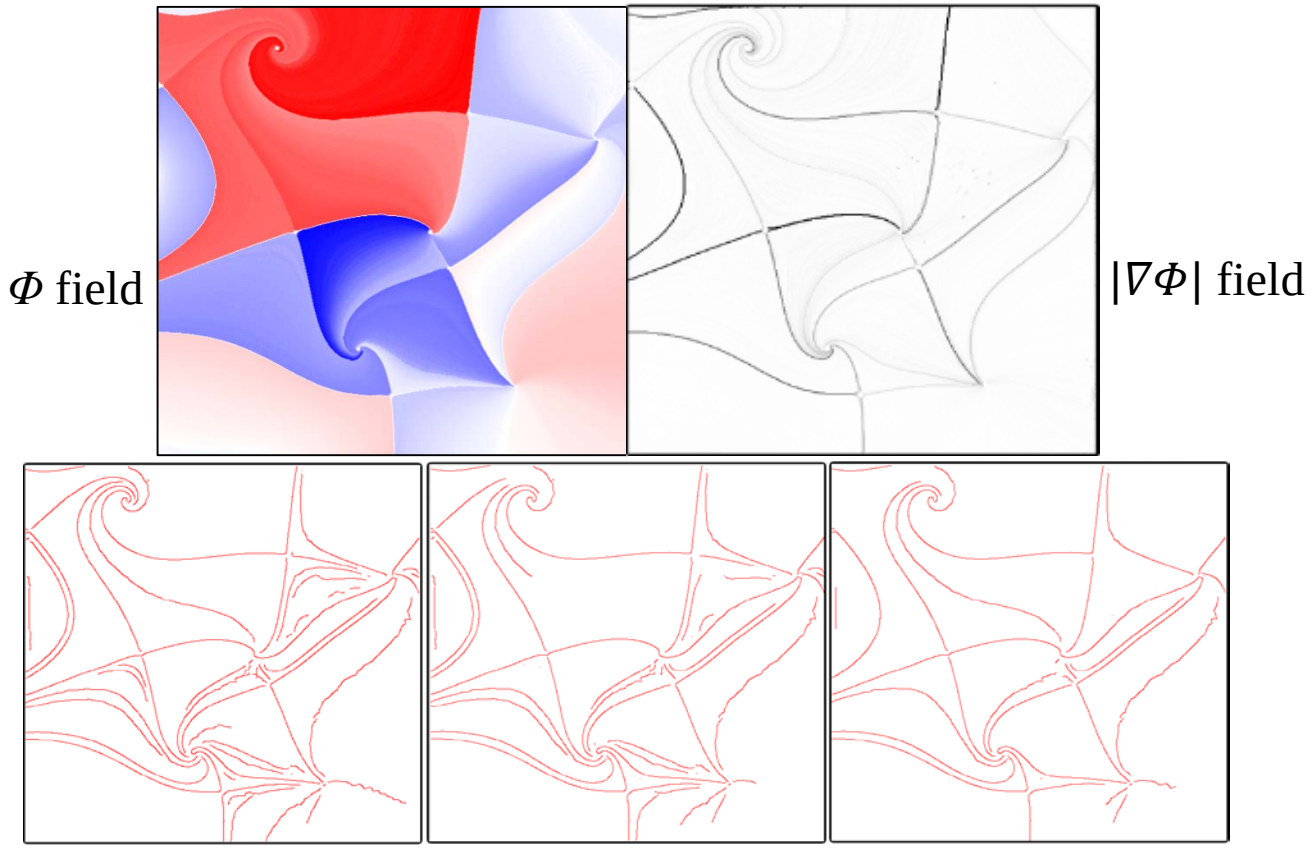
# L.A. – Exploration Framework




[Zhang et al. VDA2016].

# L.A. – Application

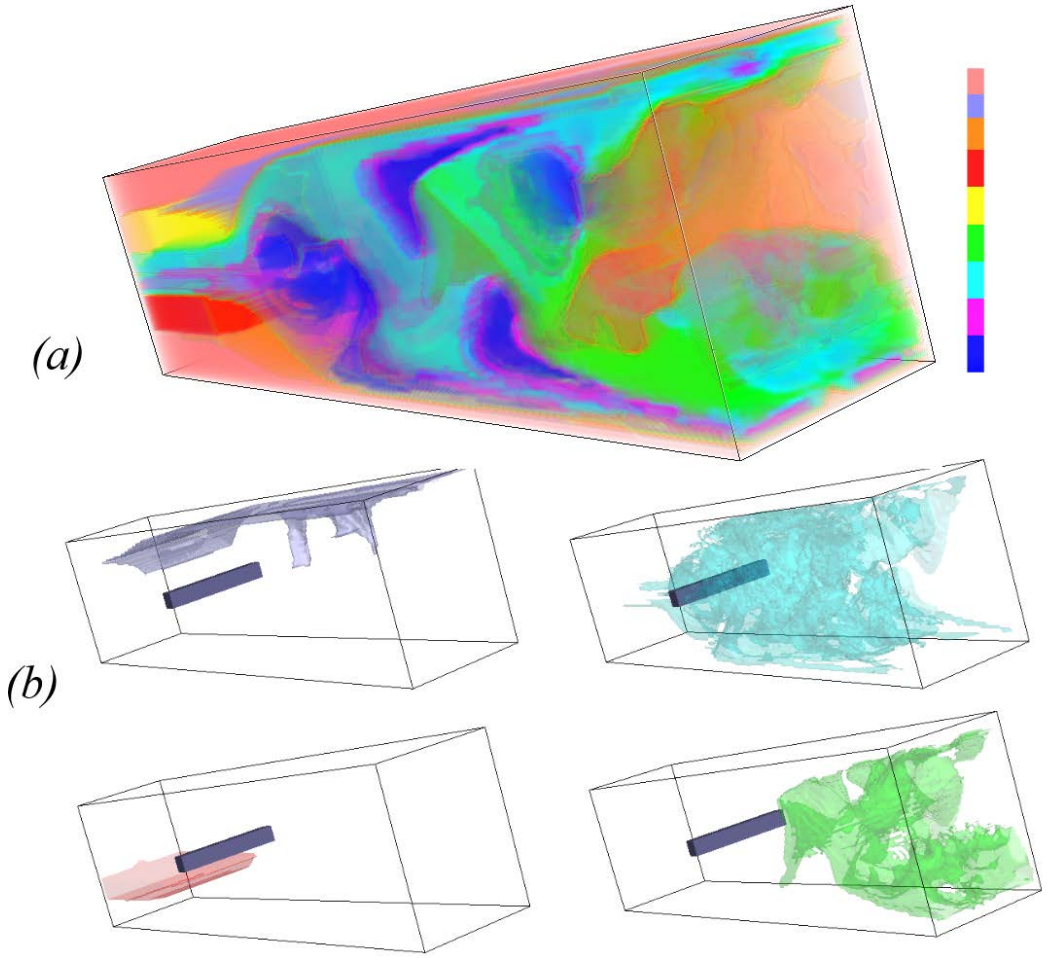
- Discontinuity Study




Discontinuity detection using the Canny edge detector with different combinations of parameters [Zhang et al. TopoInVis2015].

# L.A. – Application

- Flow Segmentation

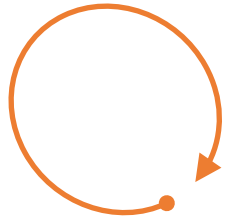


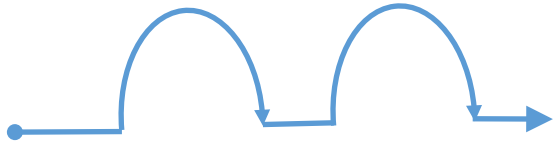

Segmentation and estimated boundaries of a 3D steady flow behind cylinder. [Zhang et al. JofVis2016].

# Where, when and how long the events of interest occur?

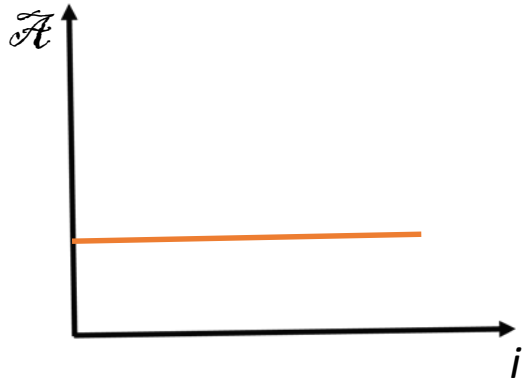
- Limitation of Lagrangian Accumulation

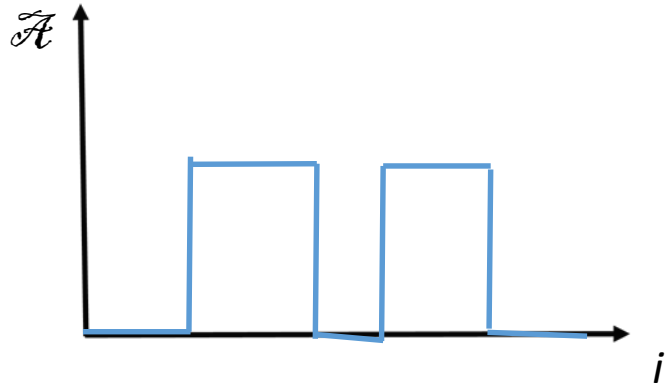
Integral curves





TACs



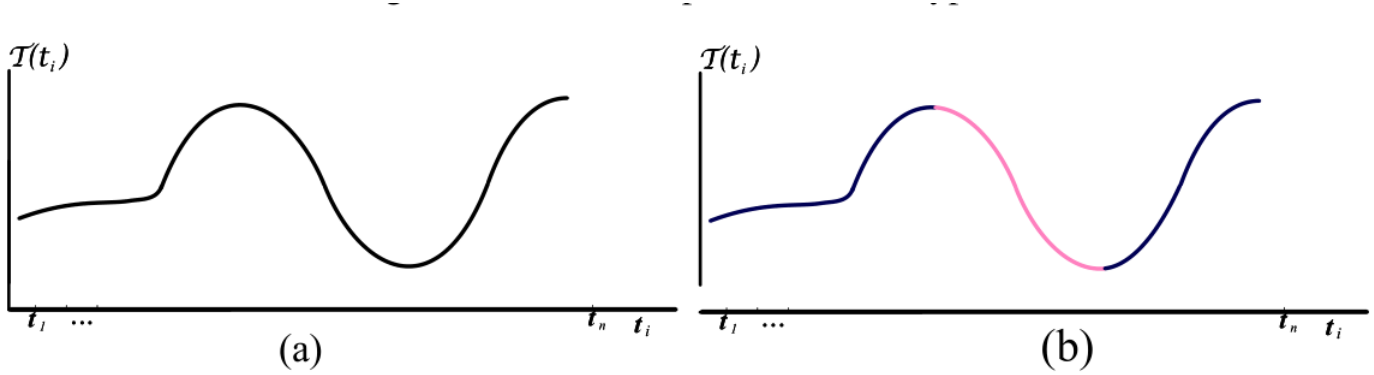
# Outline

- ❑Problem Definition
- ❑Lagrangian Accumulation Framework (done)
- ❑TAC and Multi-TAC based Framework (on-going)
  - ❑Definition
  - ❑TAC decomposition
  - ❑A Hierarchical Clustering Framework
  - ❑Applications
- ❑Future Work

# TAC and Multi-TAC

- Single TAC
- Event Definition

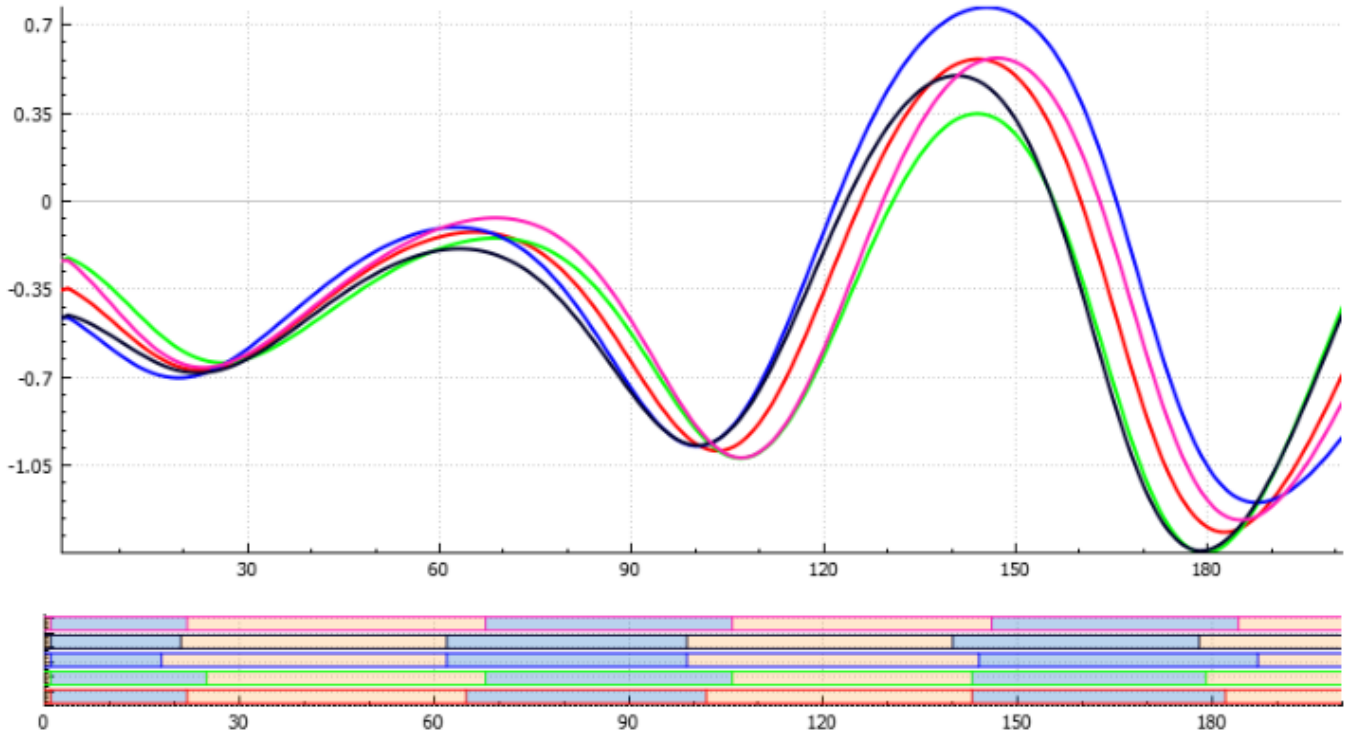
$$\forall k \in (i,j], E = \begin{cases} Increasing & \Gamma[k] > \Gamma[k-1] \\ Stable & \Gamma[k] = \Gamma[k-1] \\ Decreasing & \Gamma[k] < \Gamma[k-1] \end{cases}$$




An example of an event (b) detected by a given TAC (a).

# TAC and Multi-TAC

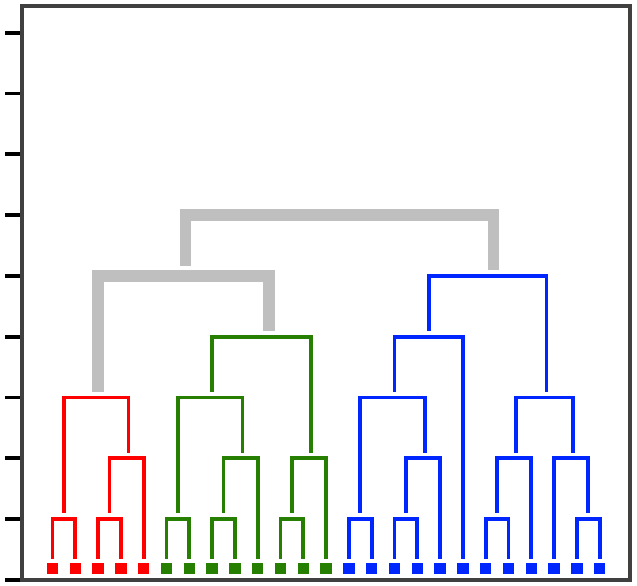
- Multi-TAC
- TAC Decomposition



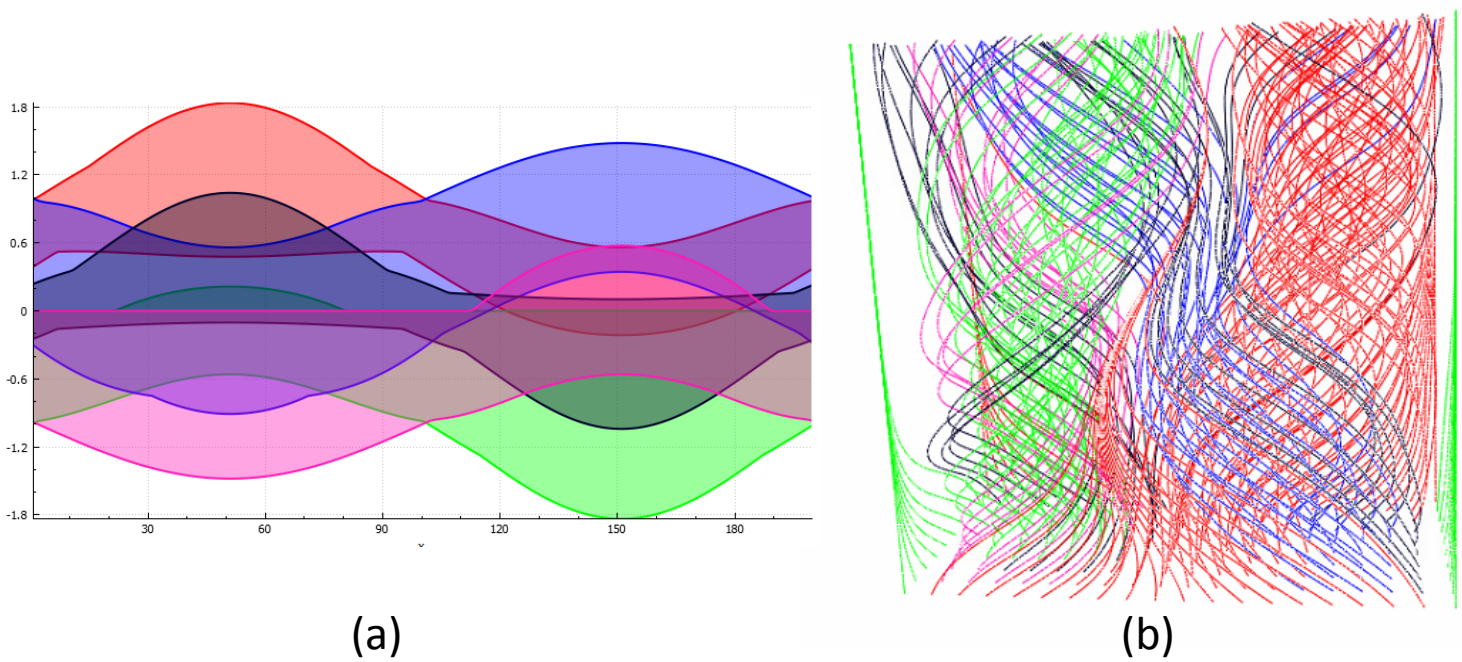

An example of multi-TAC and its decomposition.

# TAC and Multi-TAC

- Hierarchical Clustering based on TAC



An illustration of agglomerative hierarchical clustering (AHC) algorithm.

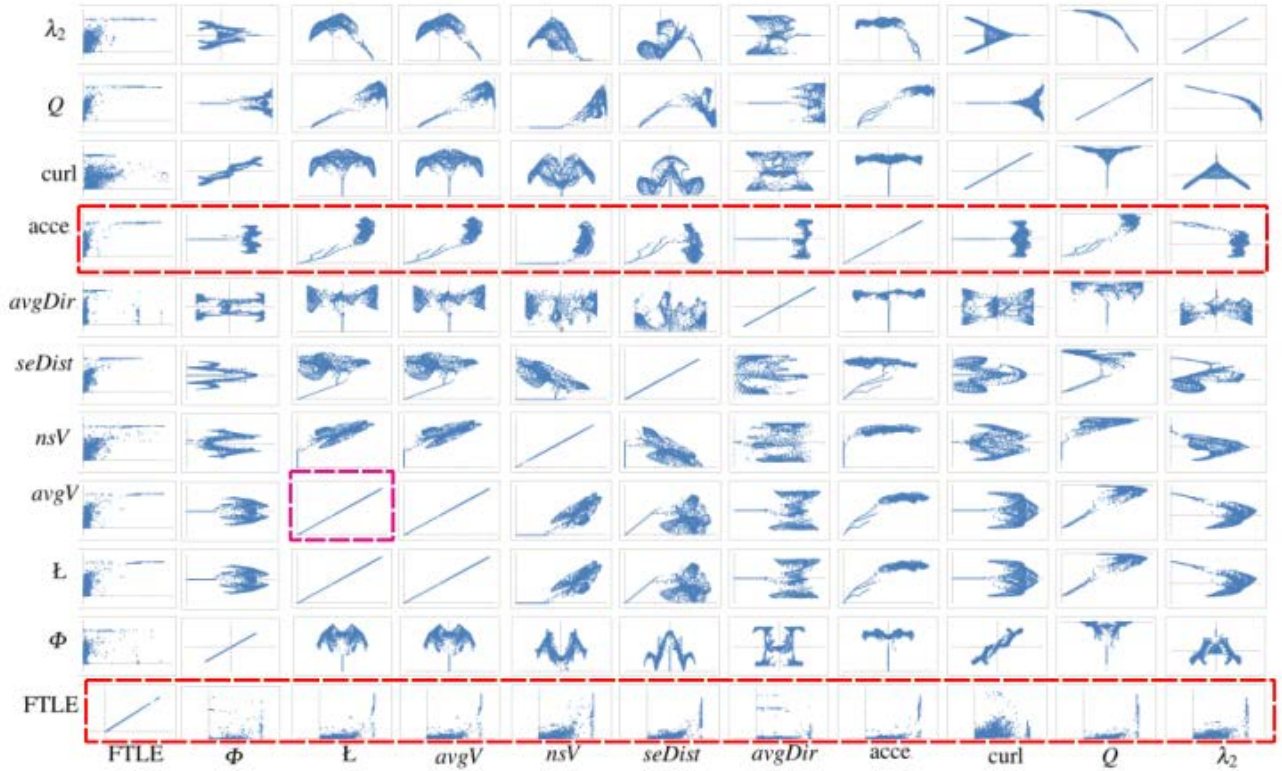



(a) (b)

AHC result of Double Gyre flow based on TAC of curl field. Five clusters are displayed. (a) TAC-clusters. (b) Pathline clusters.

# TAC and Multi-TAC - Applications

- Correlation Study




The scatter plot matrix of different attribute fields of the Double Gyre flow.

# TAC and Multi-TAC – Future Work

- TAC related similarity metric
  - Study classic Euclidean distance, Manhattan distance and Pearson correlation
  - Propose a new TAC-based metric
  - Define distance of multi-TAC
- Stable set analysis
  - Study geometrically neighboring particles with high similarity to a given TAC of interest
  - Reveal relations between geometrics attributes and physical attributes

# TAC and Multi-TAC – Future Work

- An extended descriptor
  - Introduce some statistical metrics
- New applications
  - Vortices related attributes study under the new framework
  - Time-varying multi-fields correlation study based on TAC

# Questions

- The motivation of our work is to bridge the gap between the geometric representation and the physical interpretation of the flow behaviors that are of interest to the experts. Is the motivation strong enough for the proposed dissertation work?
- We try to use the accumulation framework and TAC-based framework to provide two levels of flow visualization (global v.s. detailed information). In the perspective view of visualization, does the proposed work has potential impact to the visualization community?
- TAC-based similarity metric encoding events(trend) difference?
- What Physical features people care about?

# Thank you!