Visualizing the Long-term Behavior of 3D Fluid Flows

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University of Bergen (Norway)

Introduction

- My supervisors

Helwig Hauser
(Univ of Bergen)

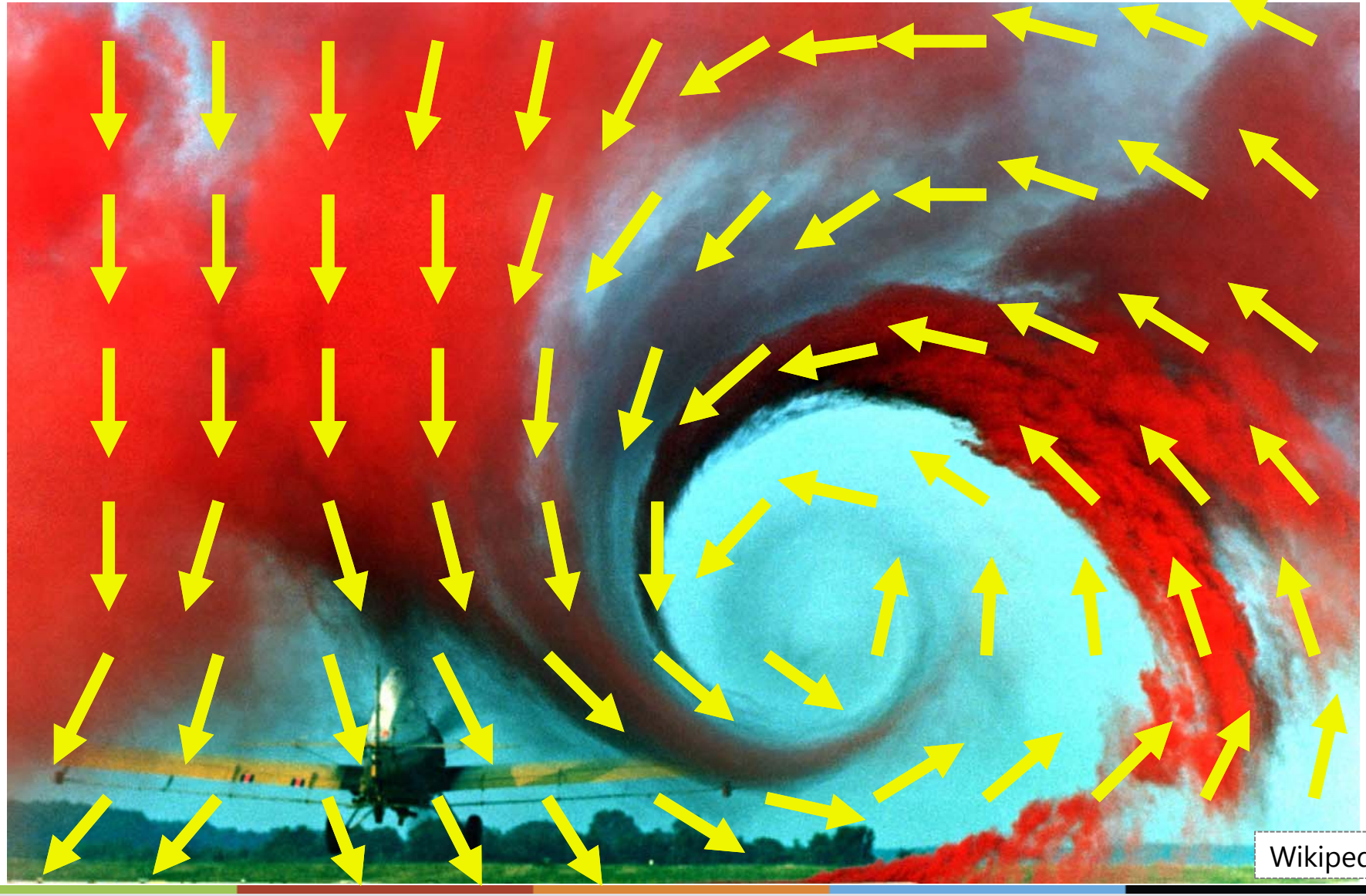
Ivan Viola
(TU Wien)

Øyvind Andreassen
(Norwegian Defence Research Council)

Fluid Flows

Wikipedia

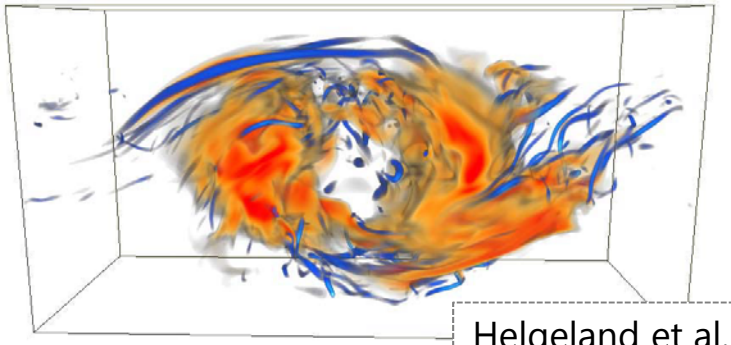
Fluid Flows



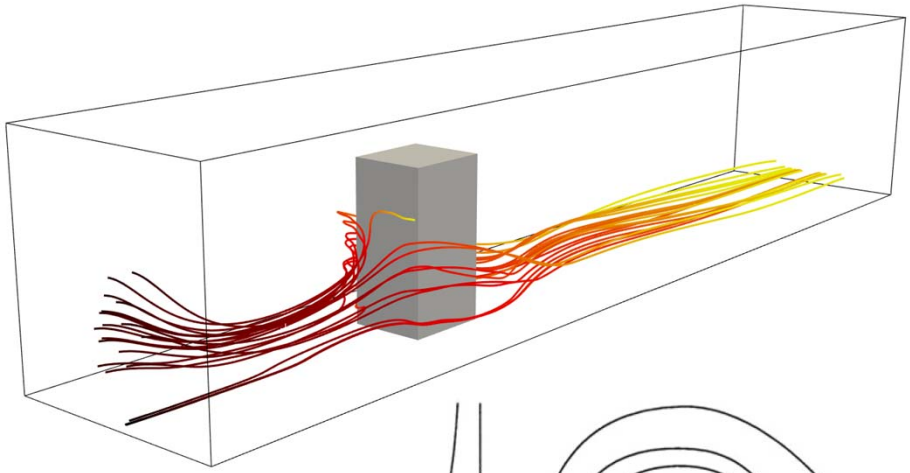
Wikipedia

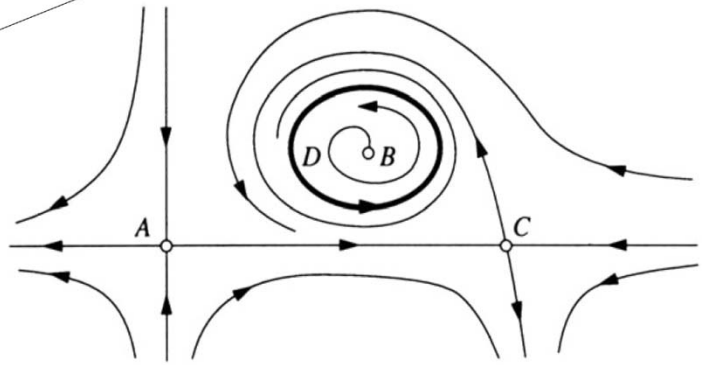
Multiple points-of-view

- Local
  - Turbulence
  - Shock waves
  - …
- Semi-global
  - Transport phenomena
  - Particle trajectories
  - …
- Global
  - VFT & LCS
  - Ensemble analysis
  - …



Helgeland et al. '04





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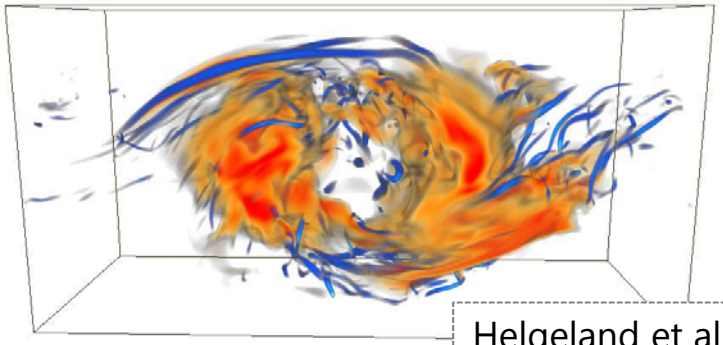

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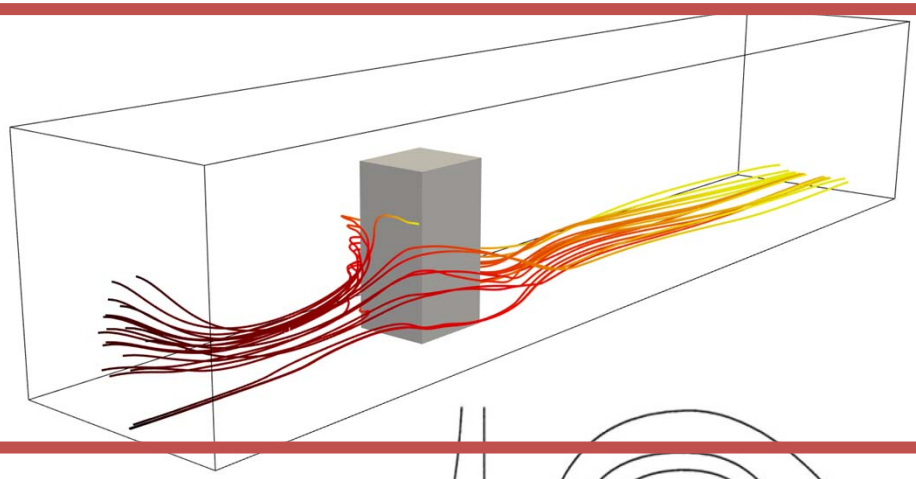

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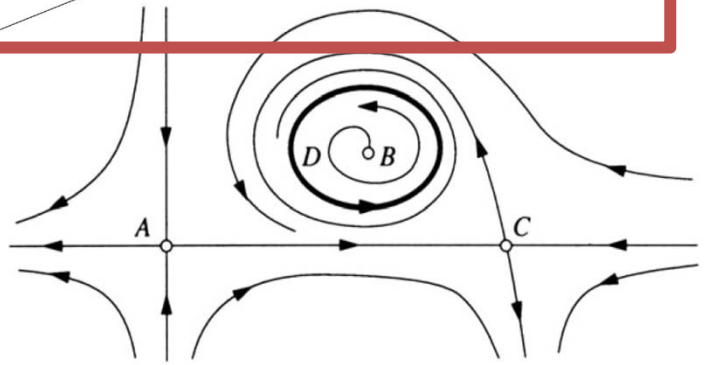
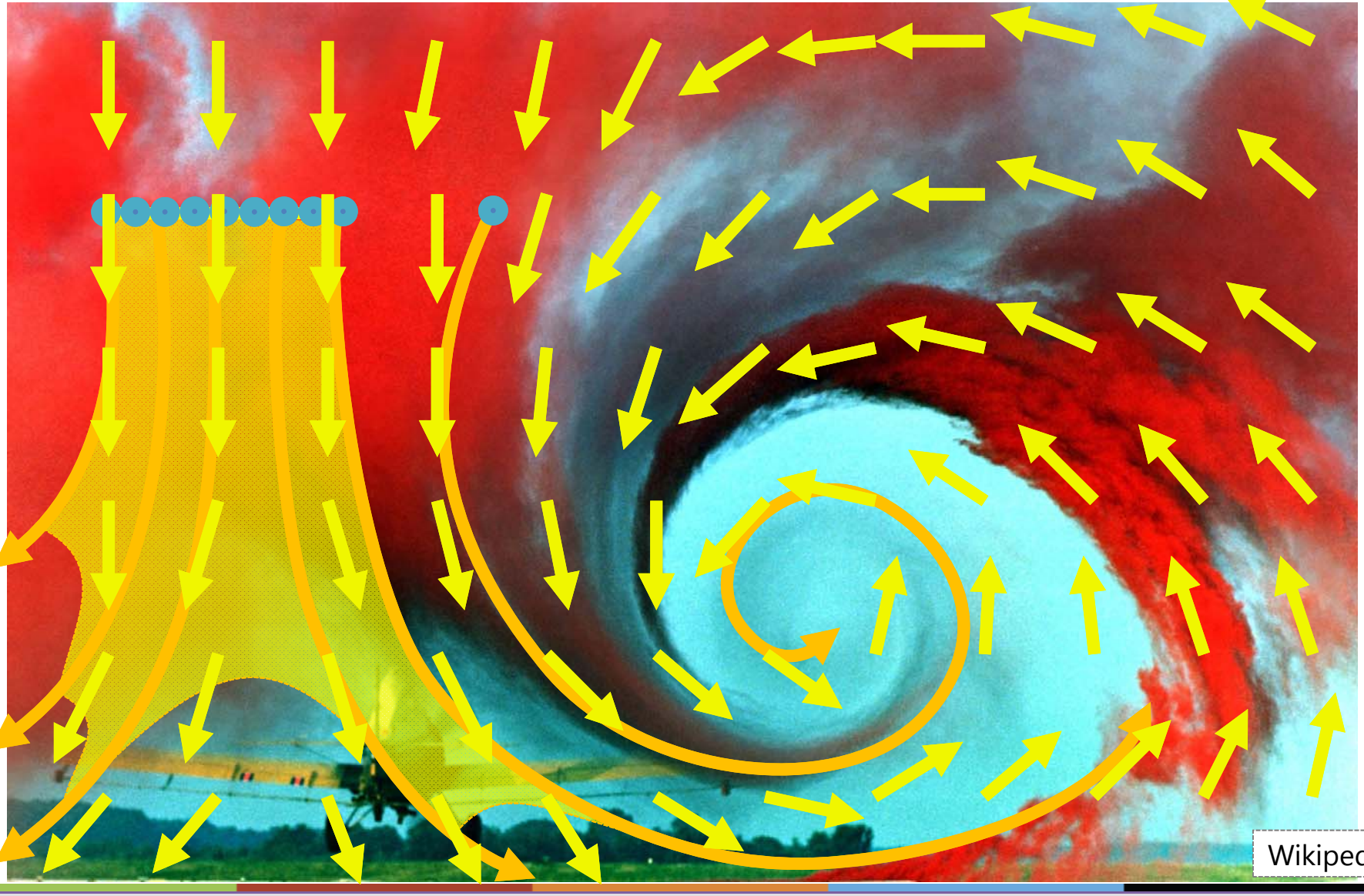


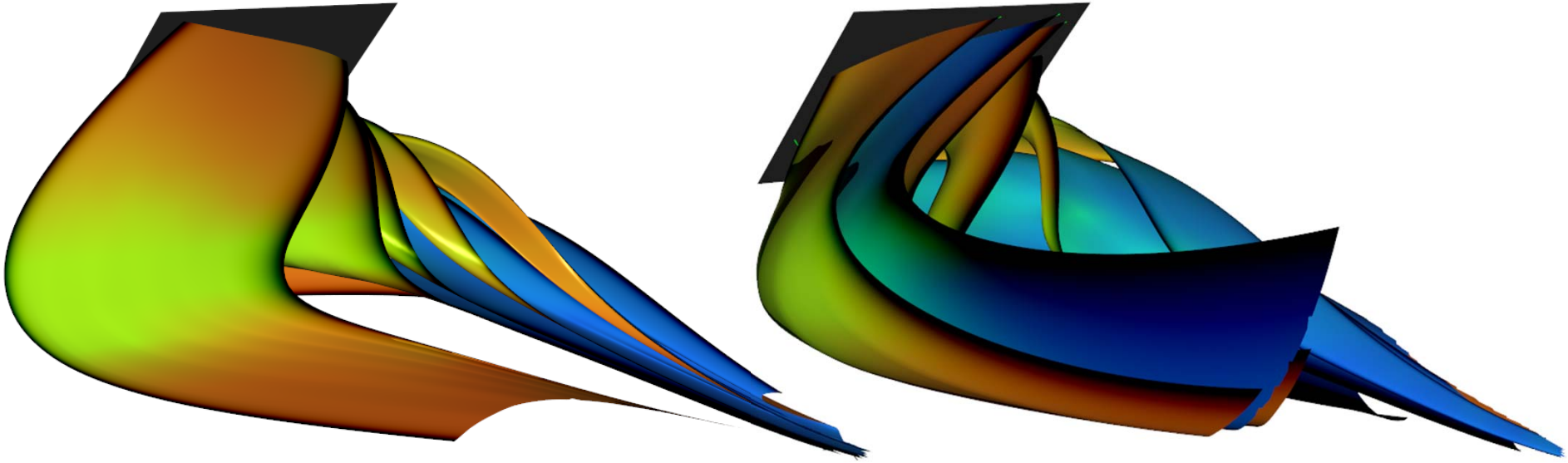
Integral structures



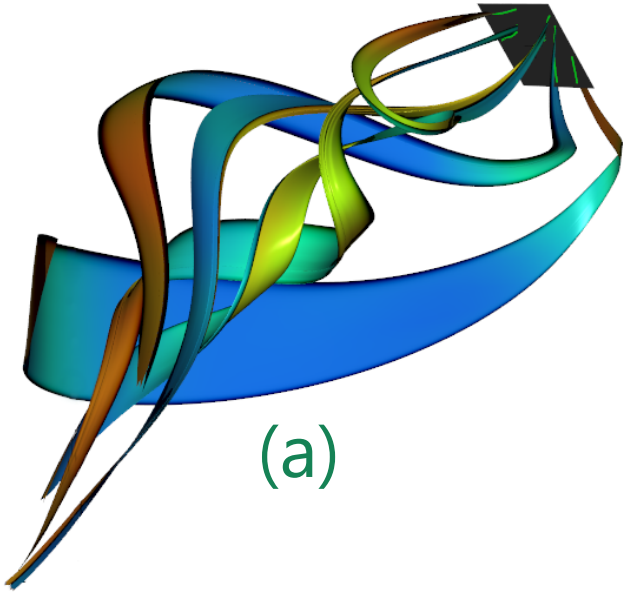
Wikipedia

Challenges

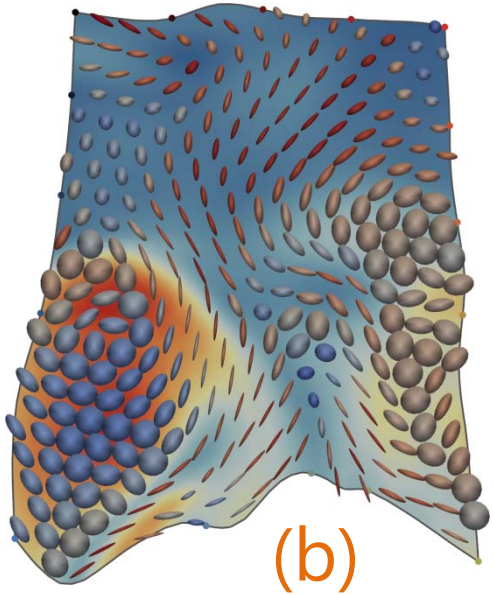
- Selection / Placement of seeding curves
- Cluttering and occlusion
- Amount of information conveyed
- Quantification of flow properties



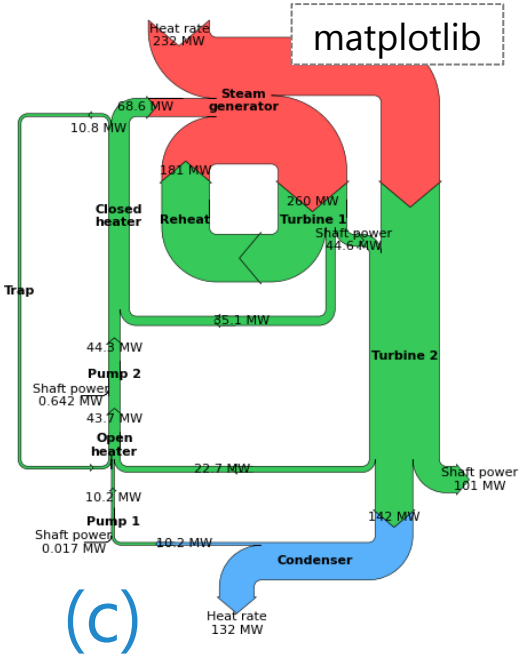
Projects



(a)



(b)



(c)

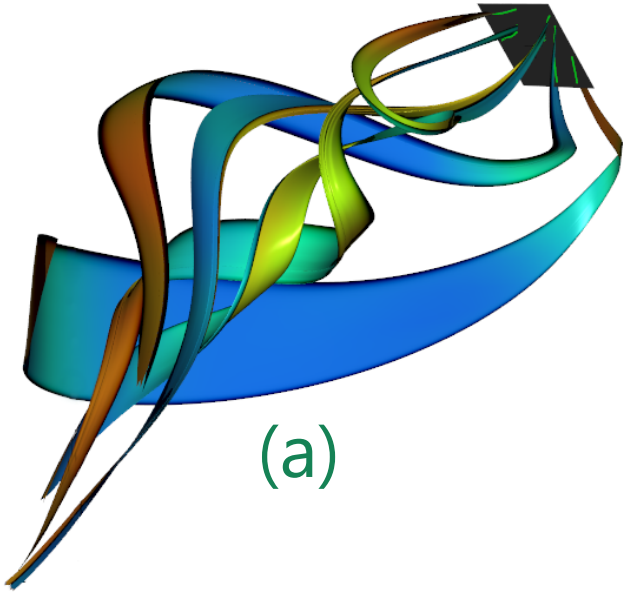
Seeding ....(a) .....

Visibility .....(b) .....

Expressiveness ....(a) .....(c)

Quantification .....(b) .....(c)

Projects



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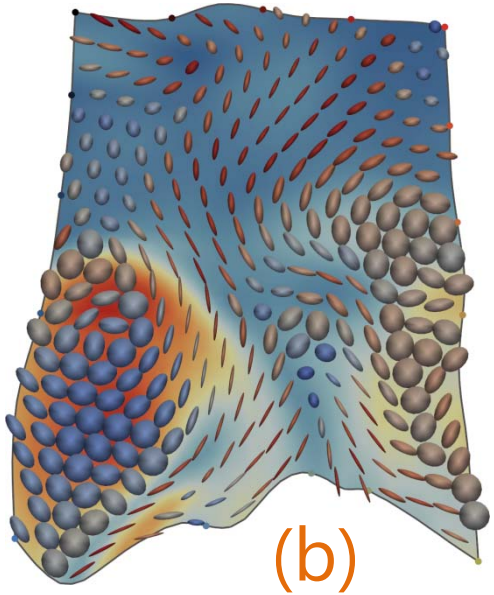
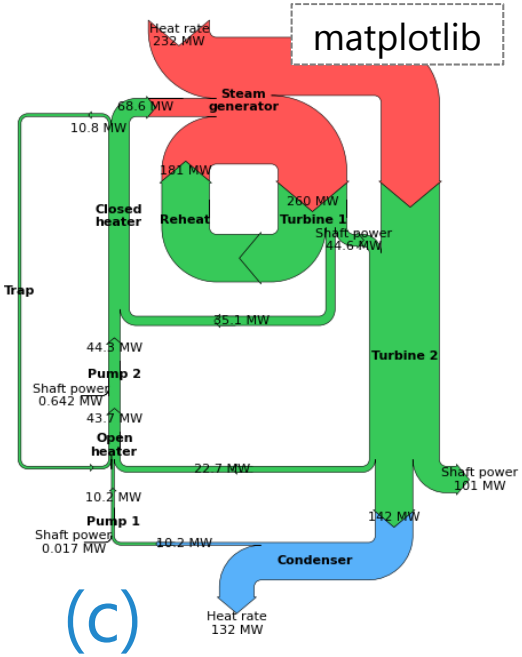


(b)

matplotlib

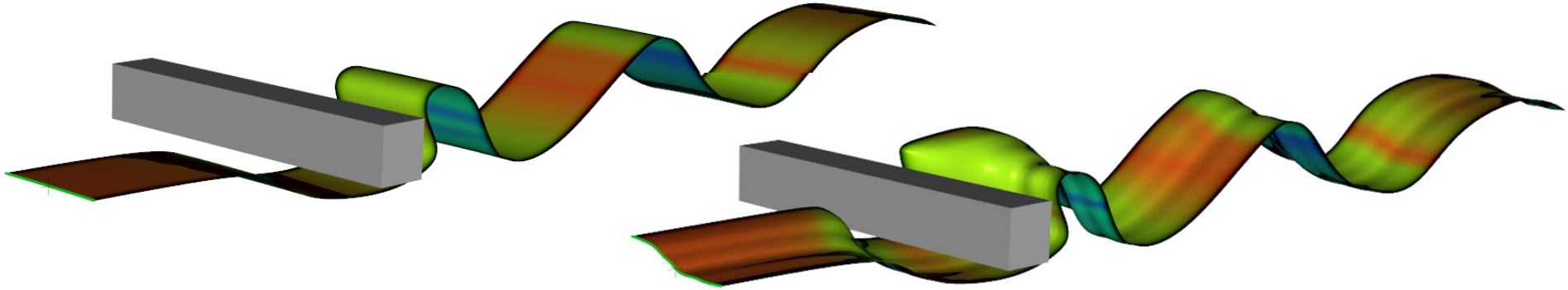


(c)

Seeding	(a)
Visibility	(b)
Expressiveness	(a) (c)
Quantification	(b) (c)

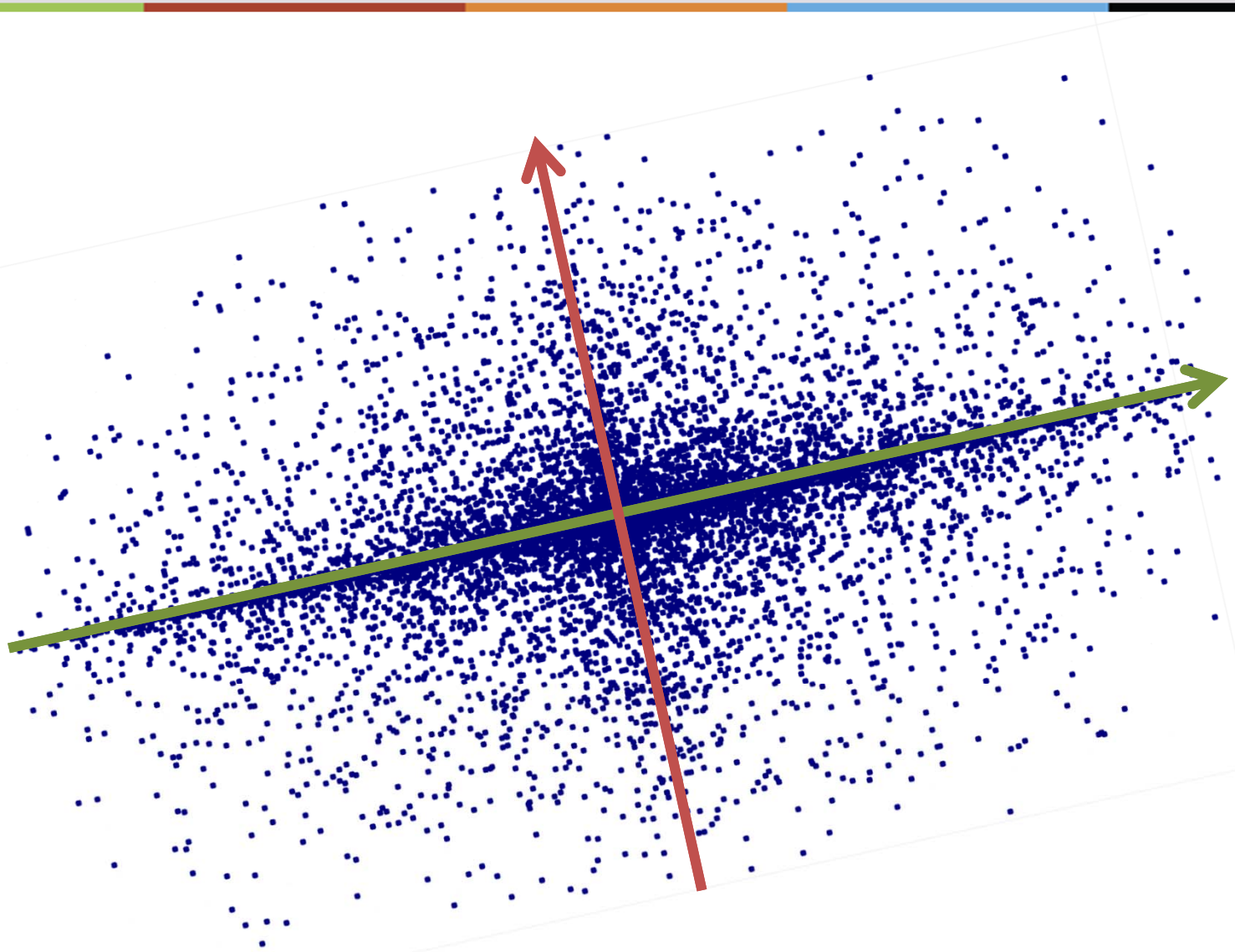
Integral Surface Placement

- How can we define a proper seeding structure?
  - Use a line segment -> 6 degrees of freedom
  - Use an arbitrary curve -> ... a lot
  - Seed multiple surfaces -> even more!

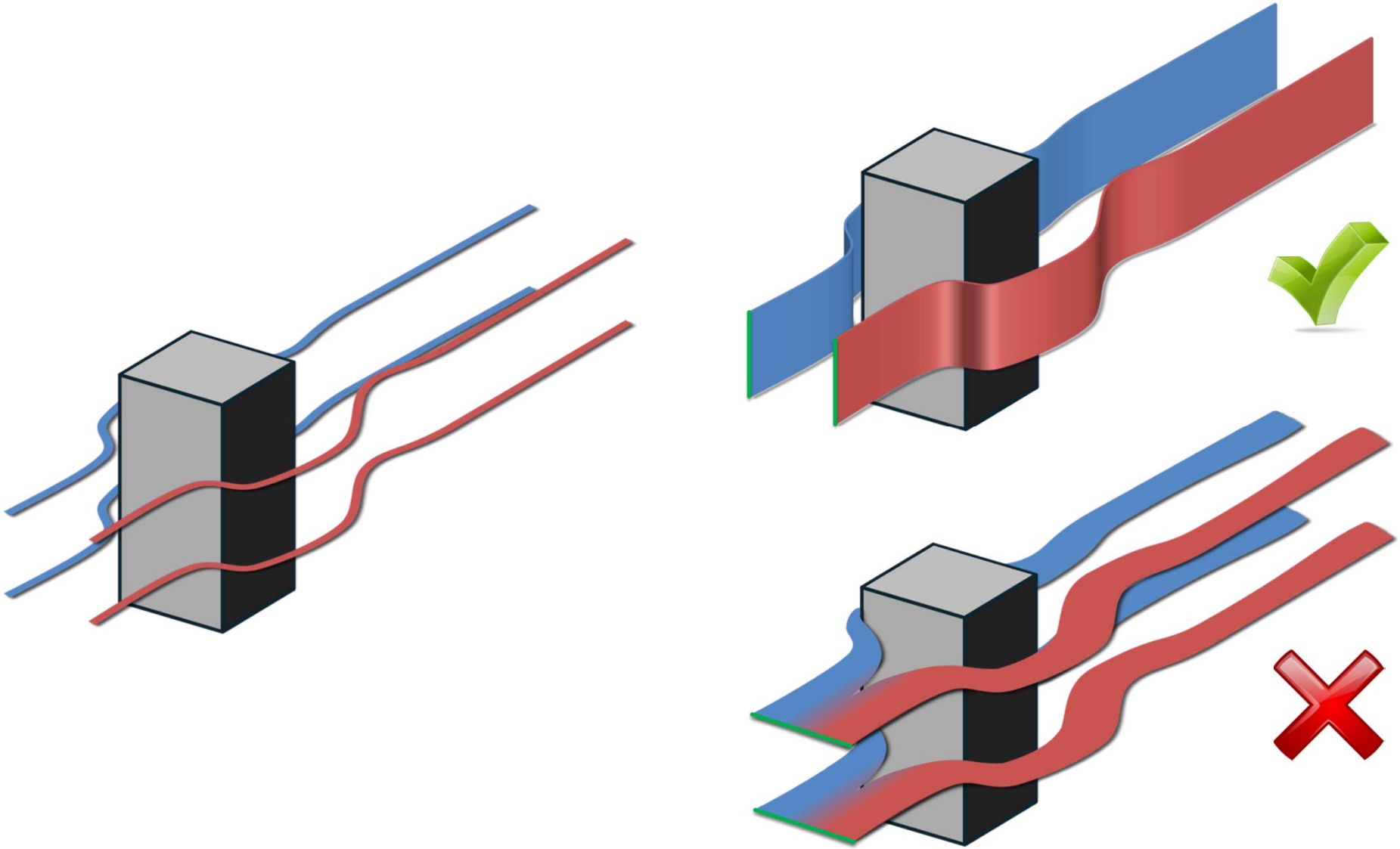


- Goal: define a semi-automatic seeding strategy s.t.:
  - Handle multiple surfaces
  - Captures the most prominent aspects of the flow
  - Each surface capture a single aspect of the flow

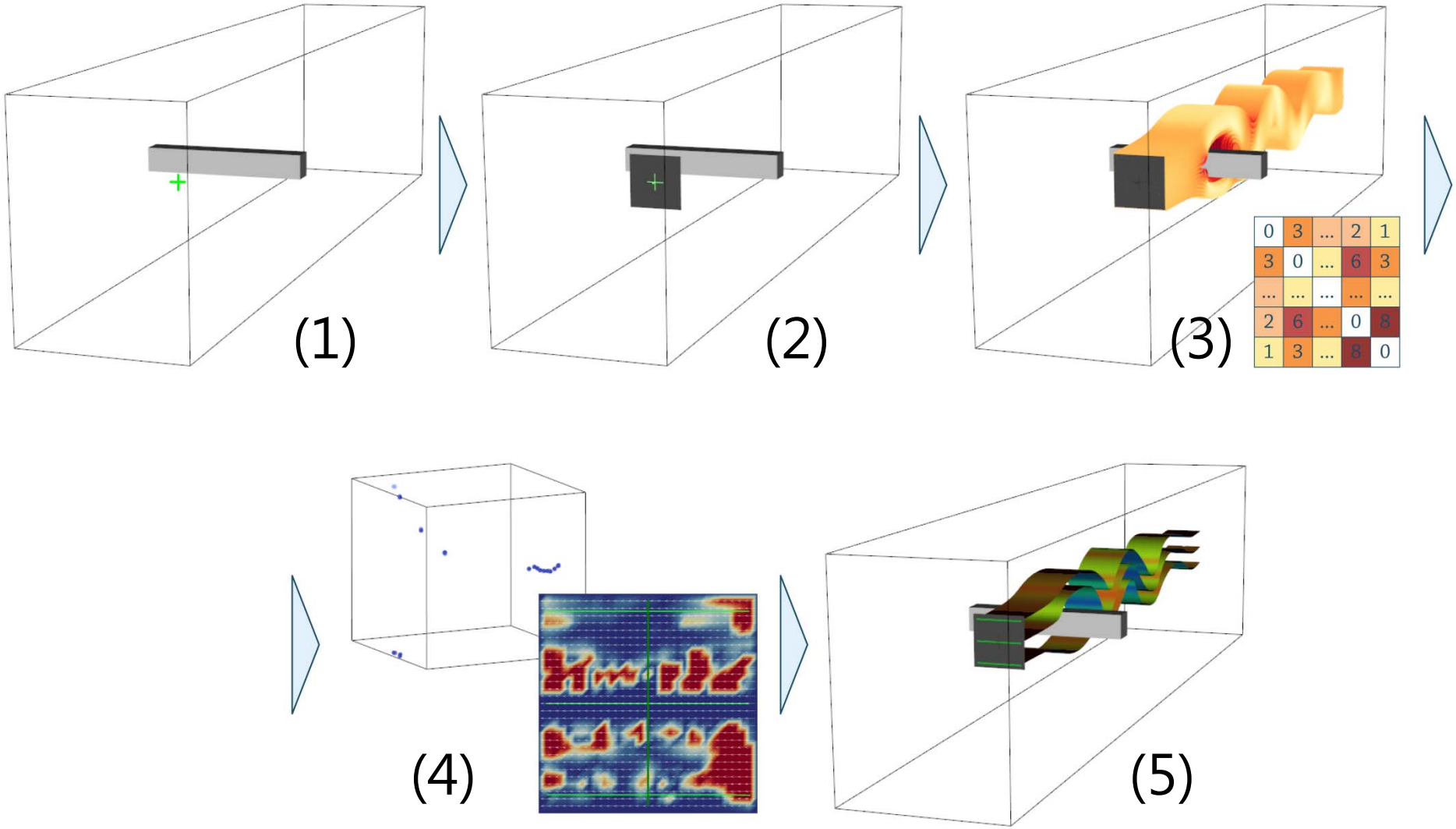
Multiple Aspects of a Flow



Multiple Aspects of a Flow

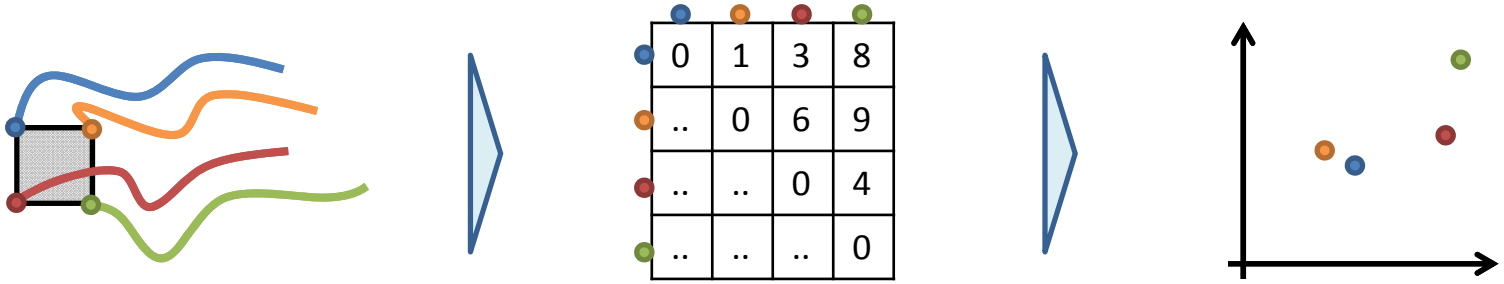


Placement Pipeline



Dissimilarity and MDS

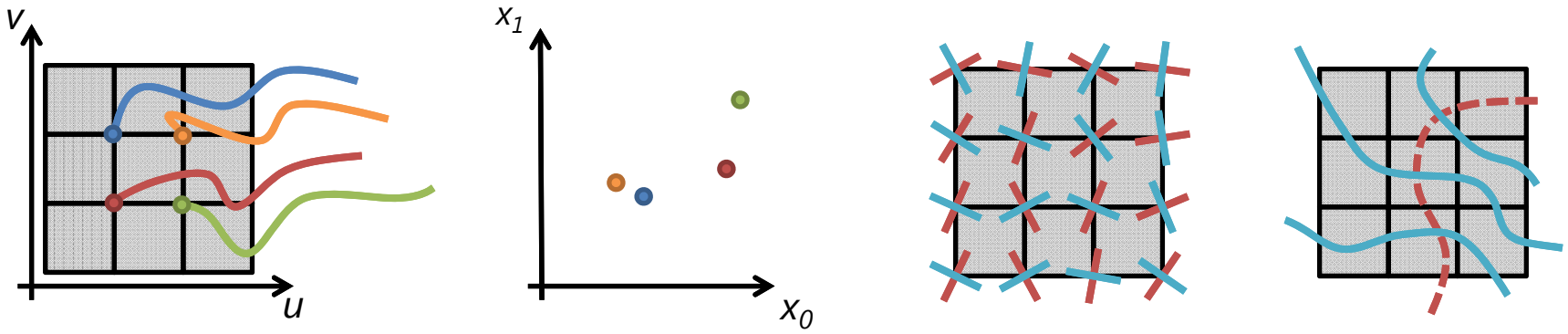
- Dissimilarity given by the Hausdorff distance
  - Expensive, so compute it on the GPU
  - Other dissimilarity measures can be used



- Multi Dimensional Scaling: embed points in R^N according to their reciprocal similarity
- Computed on the GPU using CFMDS (Park et al '12)

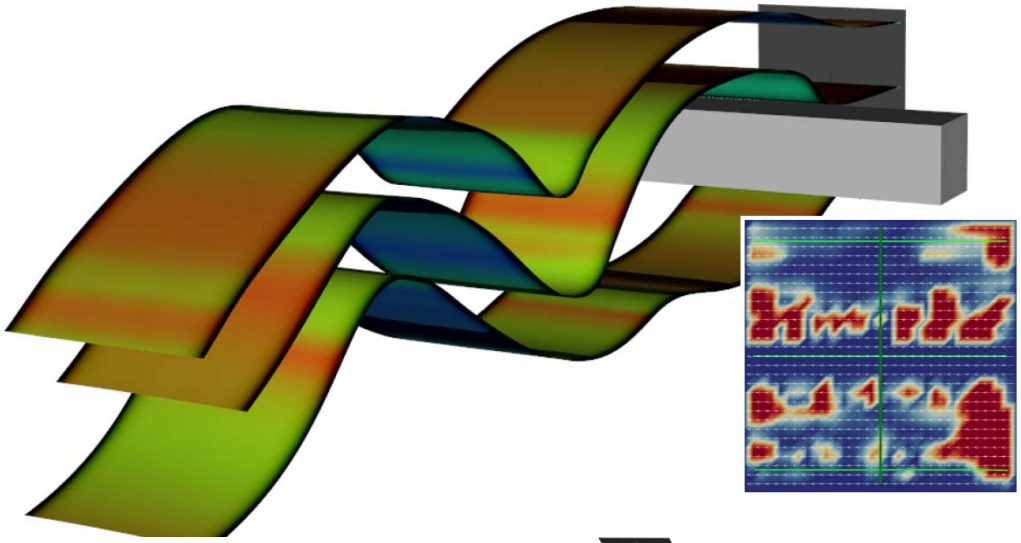
Derivatives and Seeding

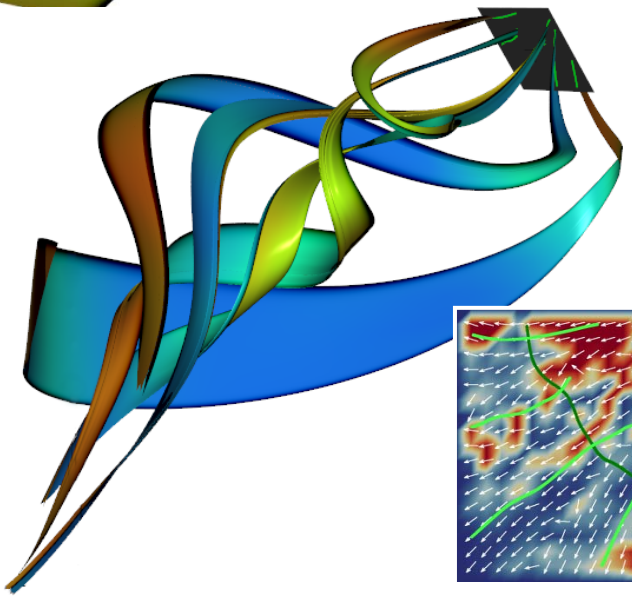
- Each point $\boldsymbol{P} = (u, v)$ is mapped by the MDS to a point $\boldsymbol{X} = (x_0, x_1, \ldots, x_N)$ in the embedding space

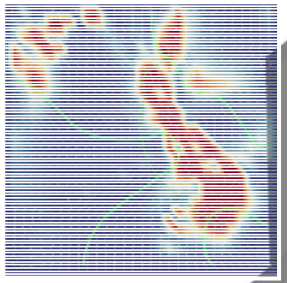


- The derivative $\boldsymbol{J} = d\boldsymbol{X} / d\boldsymbol{P}$ is a $Nx2$ matrix
- We compute the eigendecomposition of $\boldsymbol{J}^T\boldsymbol{J}$
- Eigenvectors are the directions of max/min similarity
- We use tensor lines of the min eigenvector field as seeding curves

Results







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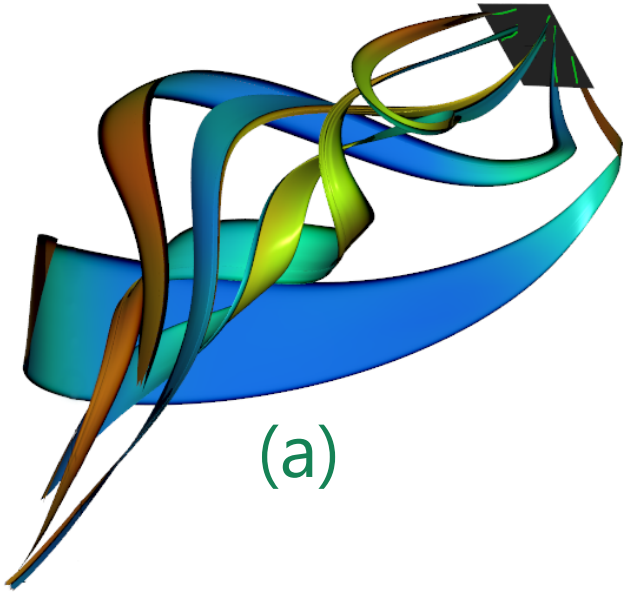

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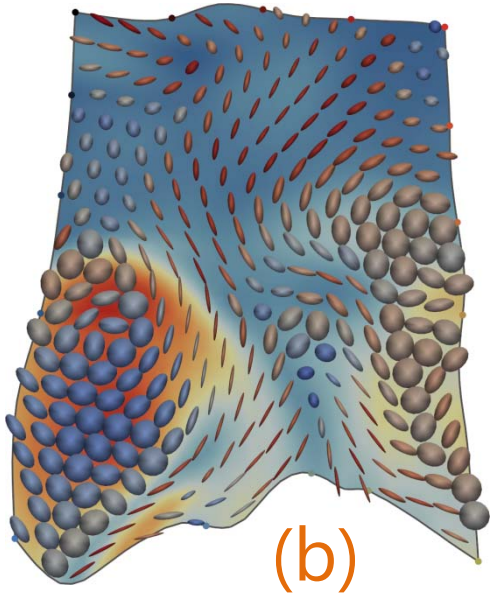

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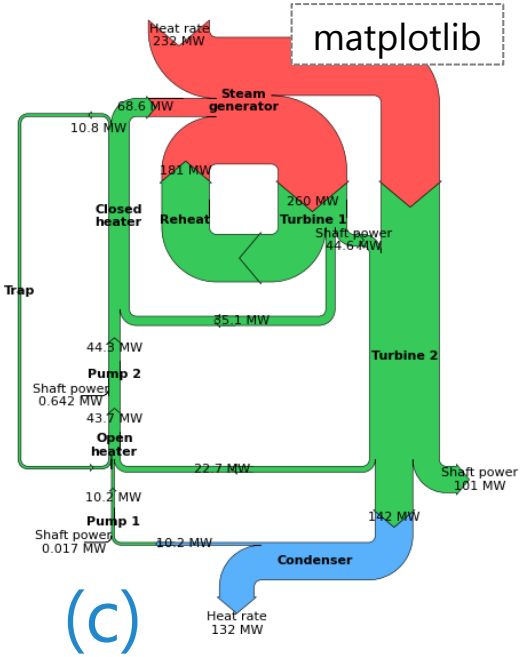


(c)

Seeding ....(a) .....

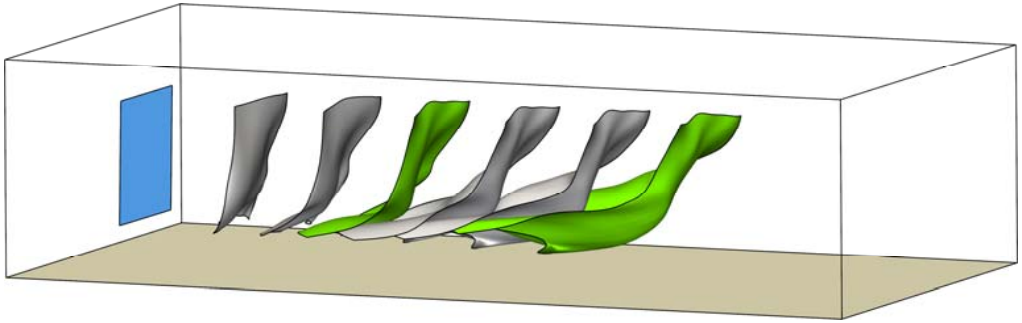
Visibility .....(b) .....

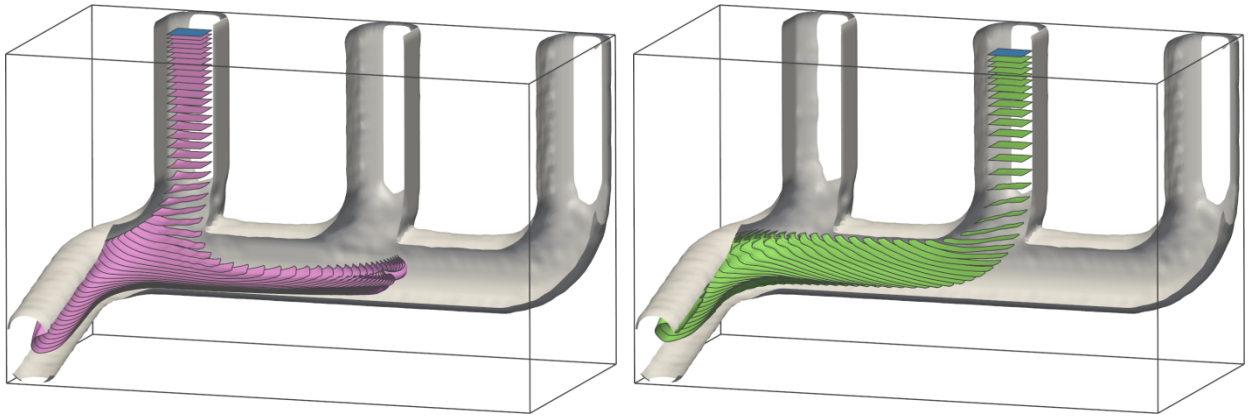
Expressiveness ....(a) .....(c)

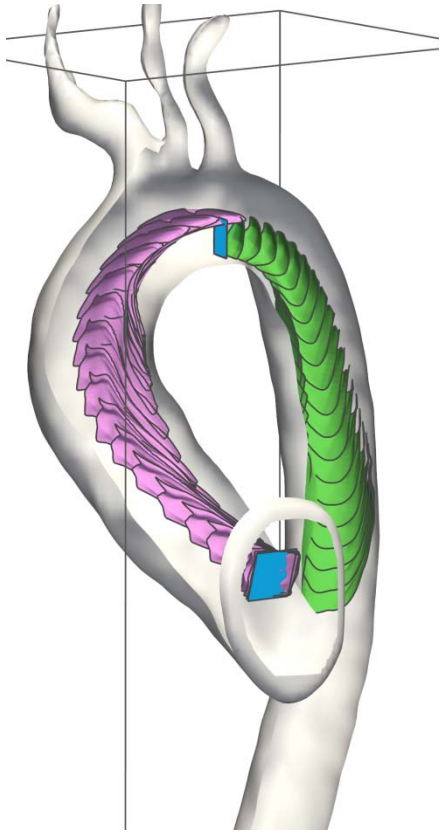
Quantification .....(b) .....(c)

Integral Surface Analysis

- We want to investigate the long-term flow behavior
- We adopted (families of) integral surfaces as a tool



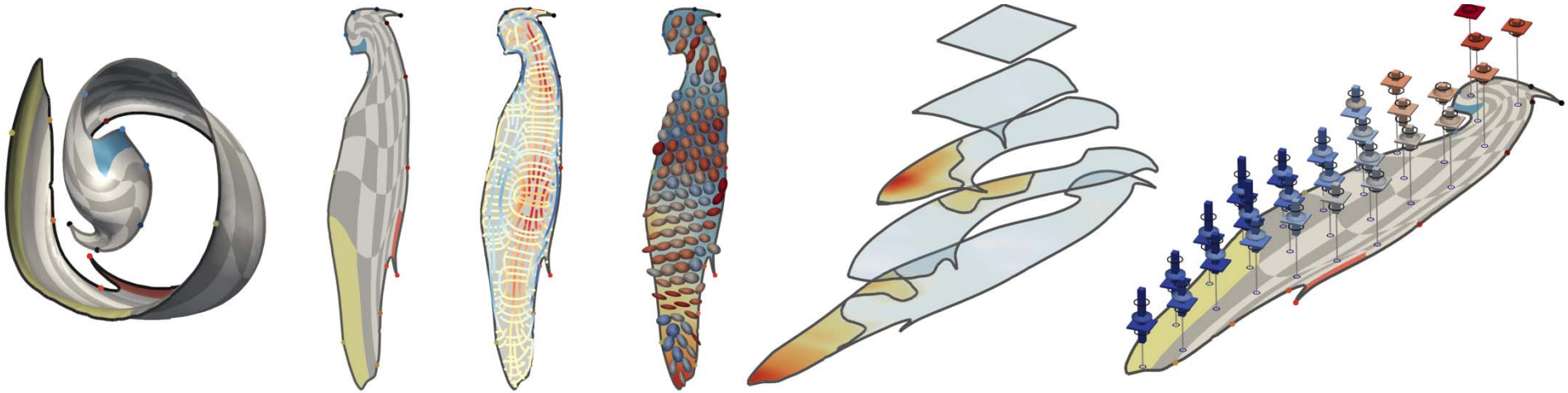




- Now we aim at easing their analysis

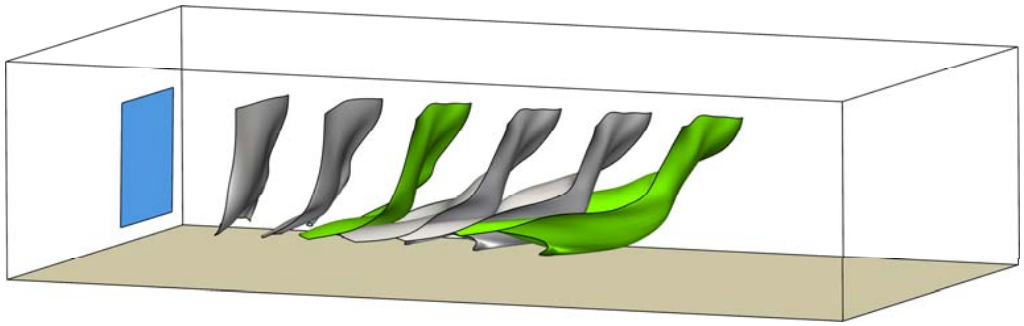
Integral Surface Analysis

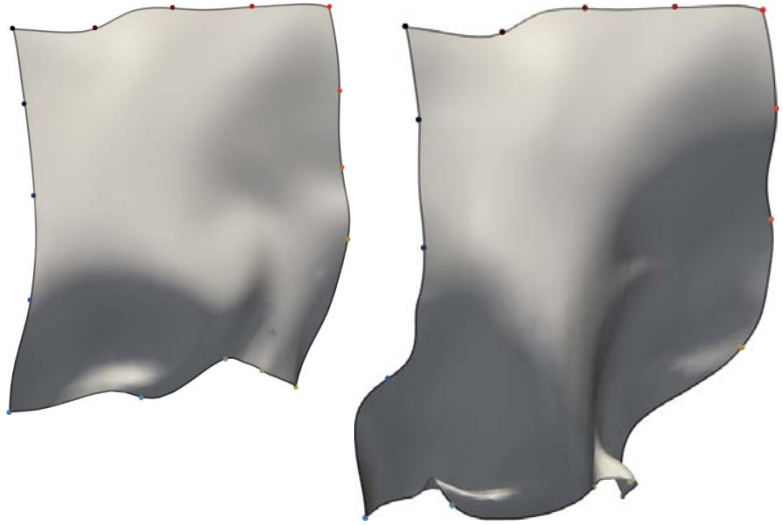
- Surfaces can have intricate shapes
  - Analysis of one surface at a time
  - Extensive user interaction / manipulation
  - Flow properties not easily conveyed
- We take advantage of **surface reformation**
- Ad-hoc visualizations in the reformed space



Surface Reformation

- As-Rigid-As-Possible flattening (Liu et al. '08)
- Maps surface points $\boldsymbol{X} = (x, y, z)$ to points $\boldsymbol{P} = (u, v)$ in the 2D reformed space
- The original shape should be still conveyed!

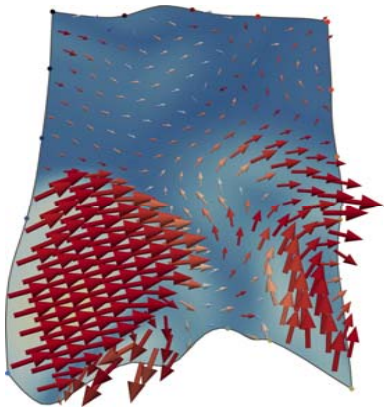




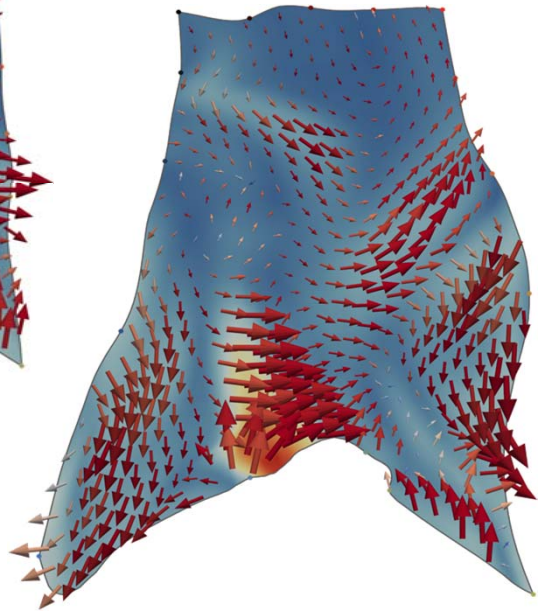
- Compute the matrix $\boldsymbol{J} = d\boldsymbol{X} / d\boldsymbol{P}$
- Compute the eigendecomposition of $\boldsymbol{J}^T\boldsymbol{J}$

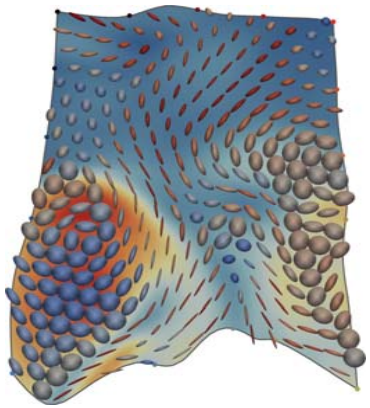
Flow Attributes on Surfaces

- Scalar attributes can be directly mapped to colors
- Vectors and tensors needs to:
  - be projected on the surface $\boldsymbol{S}_\psi = (\boldsymbol{I} - \boldsymbol{n}\boldsymbol{n}^T)\,\boldsymbol{S}\,(\boldsymbol{I} - \boldsymbol{n}\boldsymbol{n}^T)^T$
  - take flattening into account $\boldsymbol{S}_2 = \boldsymbol{J}^{-1}\,\boldsymbol{S}_\psi\,\boldsymbol{J}$

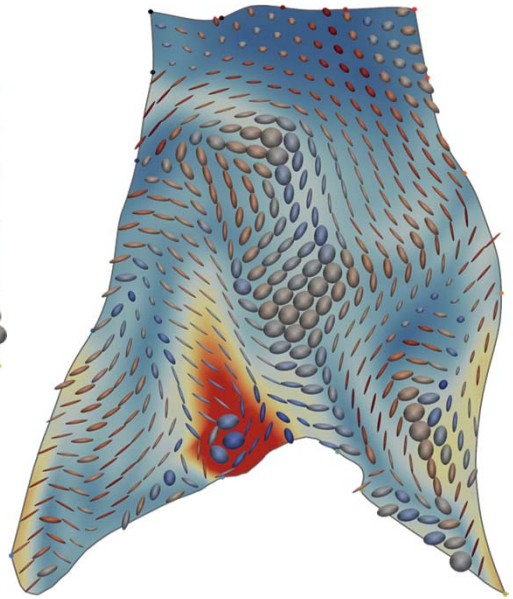


Vorticity



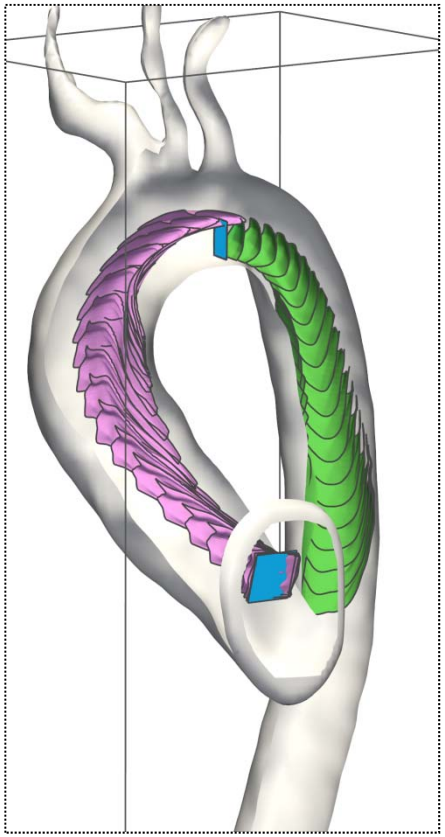


Strain rate



- Size <-> $\| \boldsymbol{S}_\psi \|$ Color <-> $\| \boldsymbol{S}_\psi \| / \| \boldsymbol{S} \|$

Families of Time Surfaces



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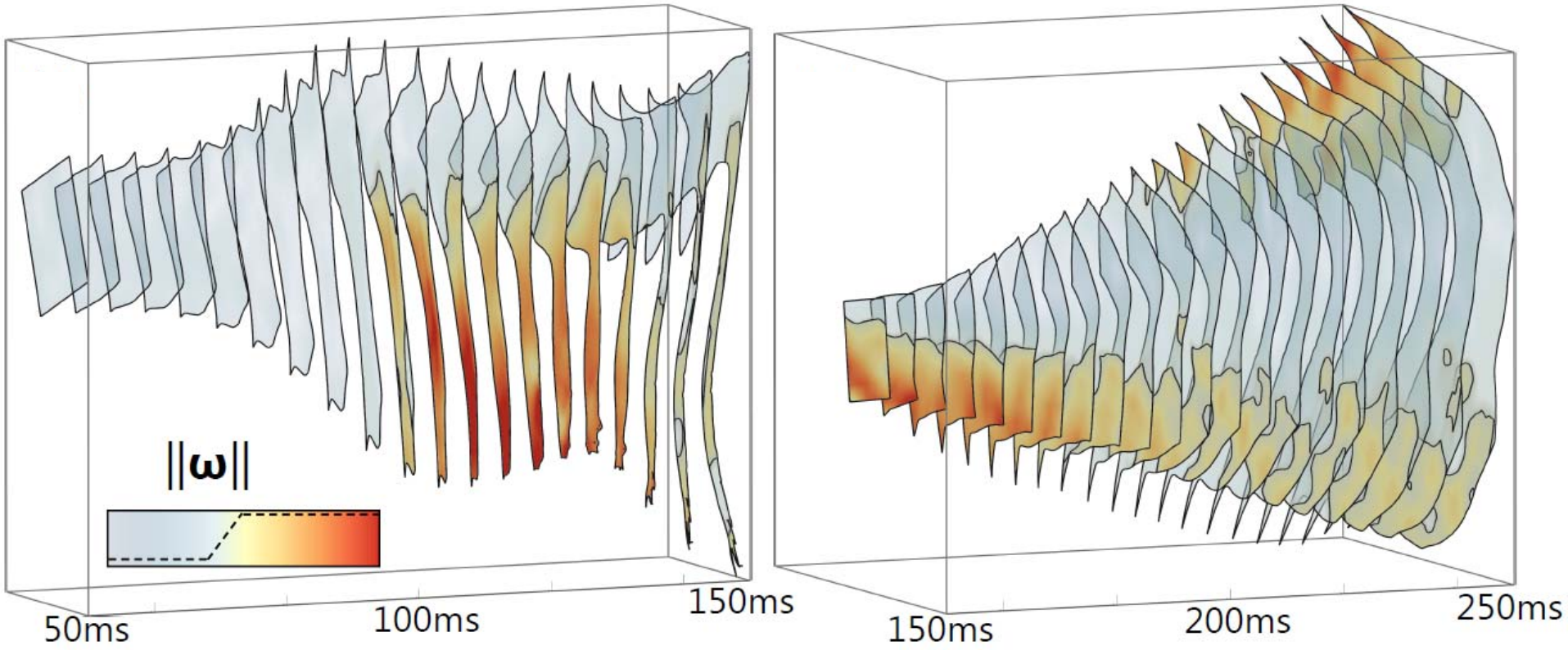
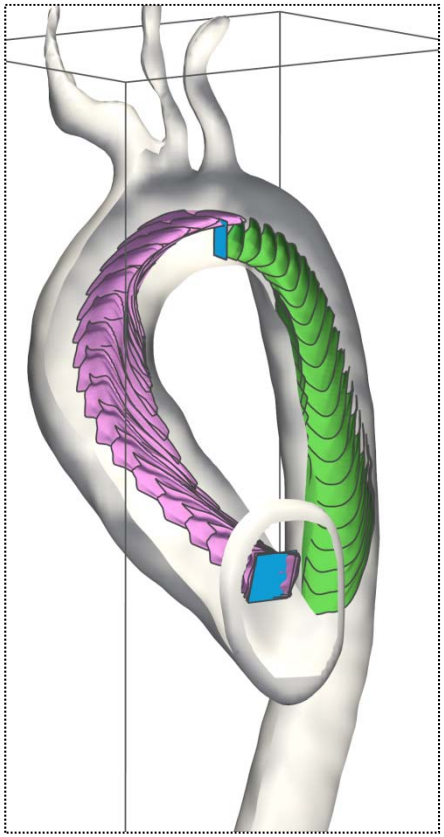
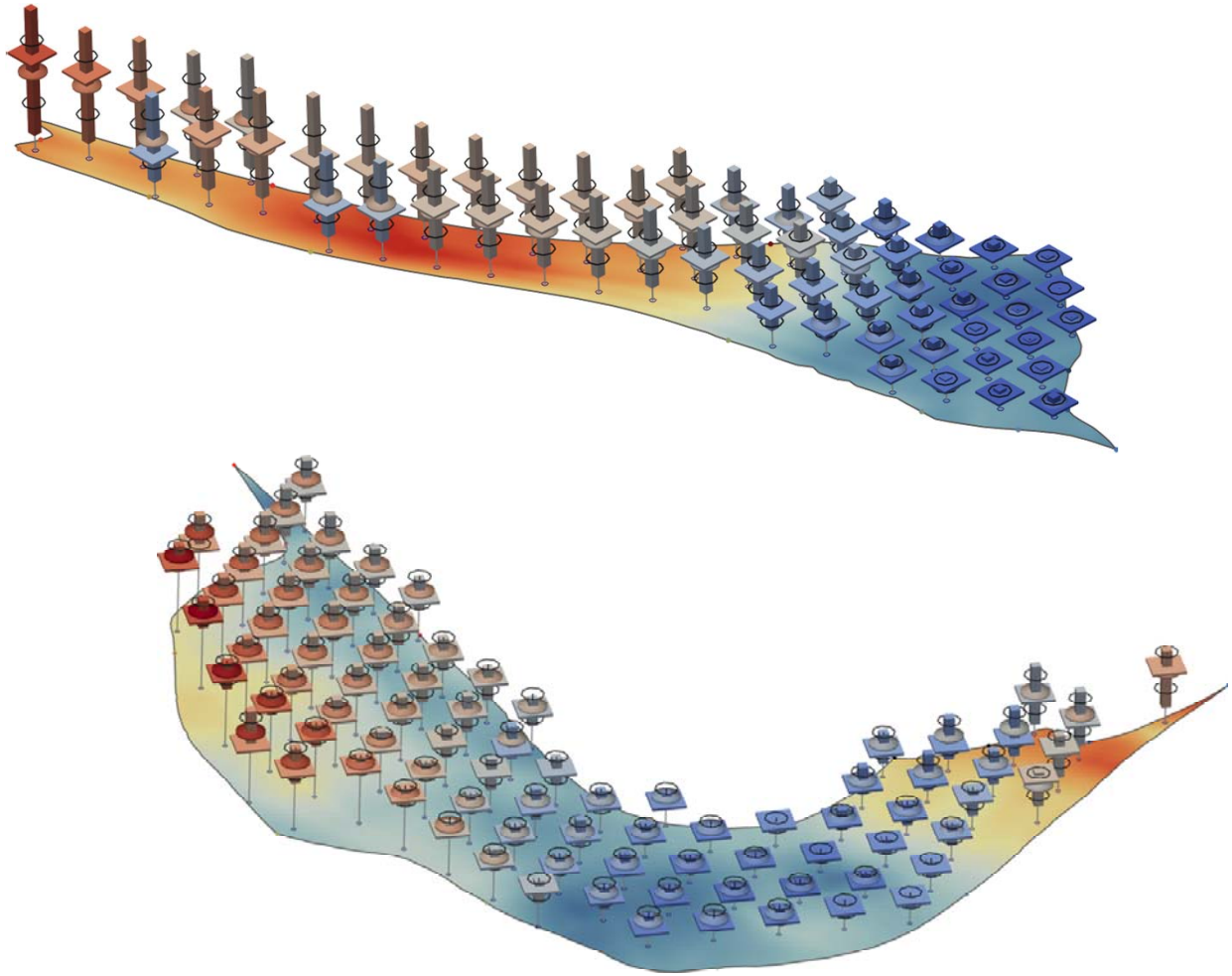


- Alignment by least square optimization
- Color & transparency depending on scalar attribute

Multiple Surface Families





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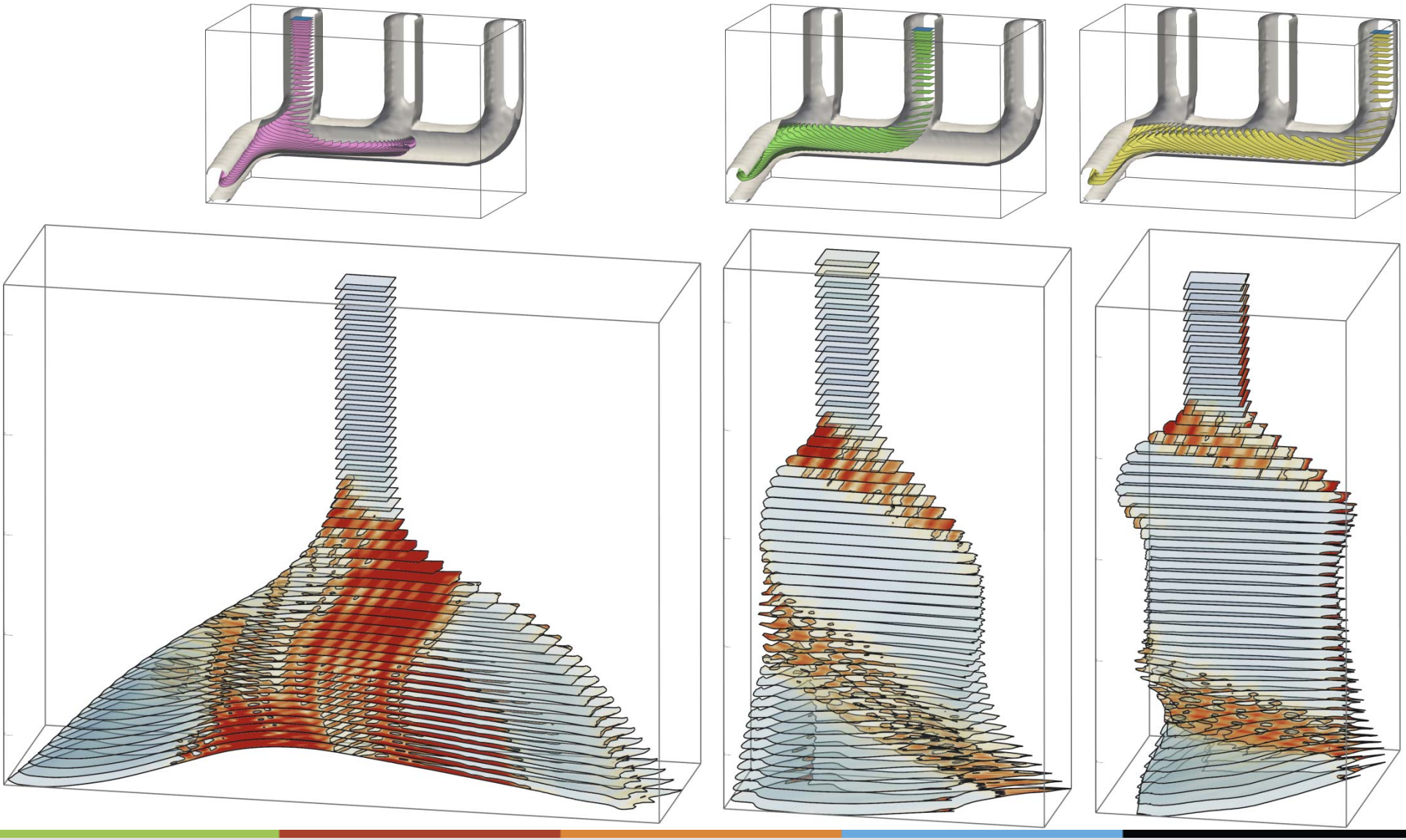

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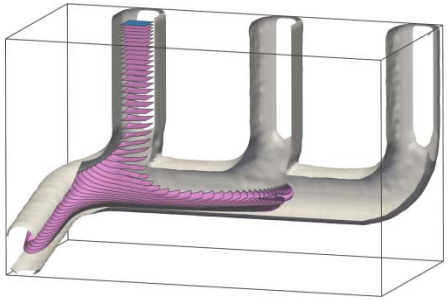
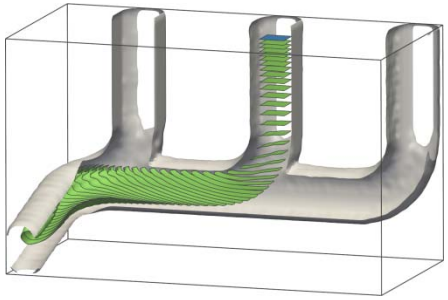
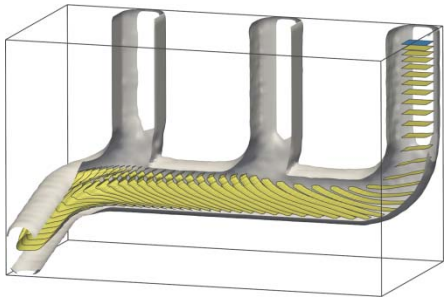
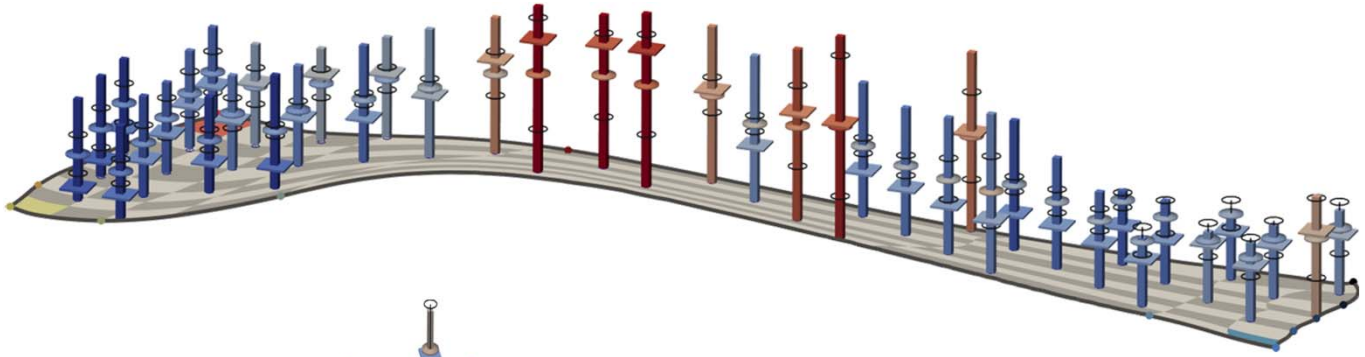
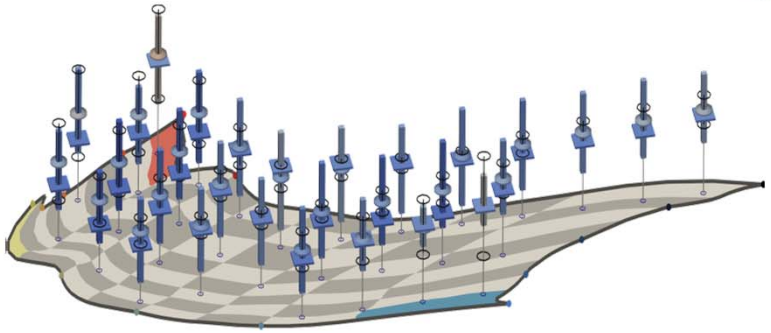
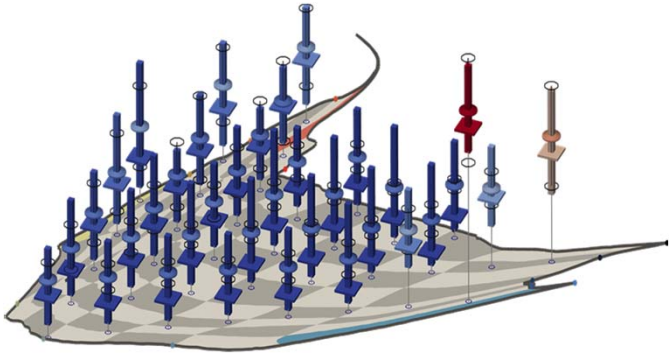




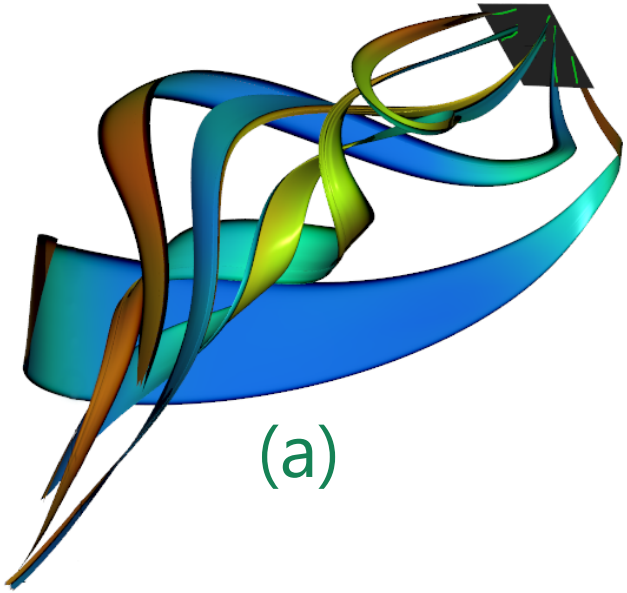








Projects



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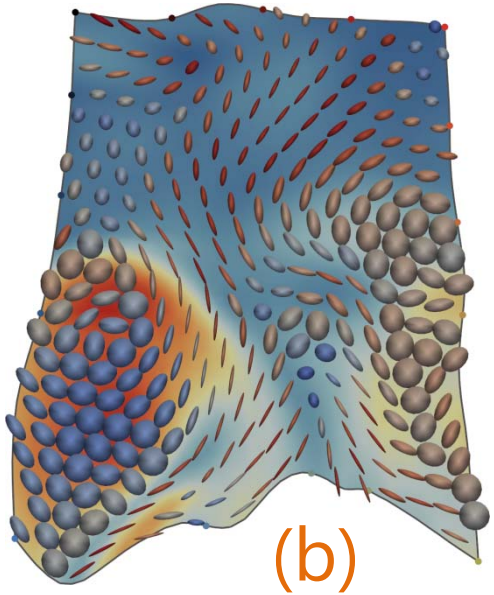

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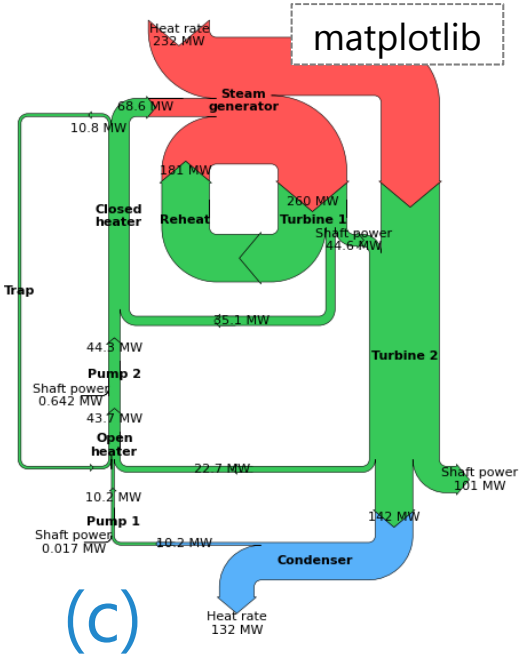
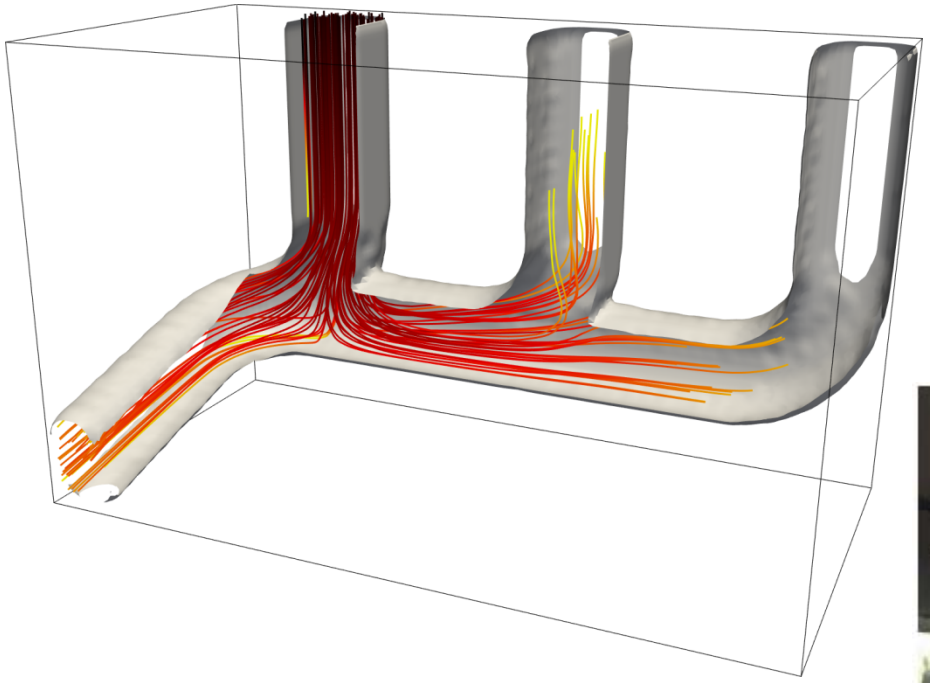


(c)

Seeding	(a)	
Visibility	(b)	
Expressiveness	(a)	(c)
Quantification	(b)	(c)

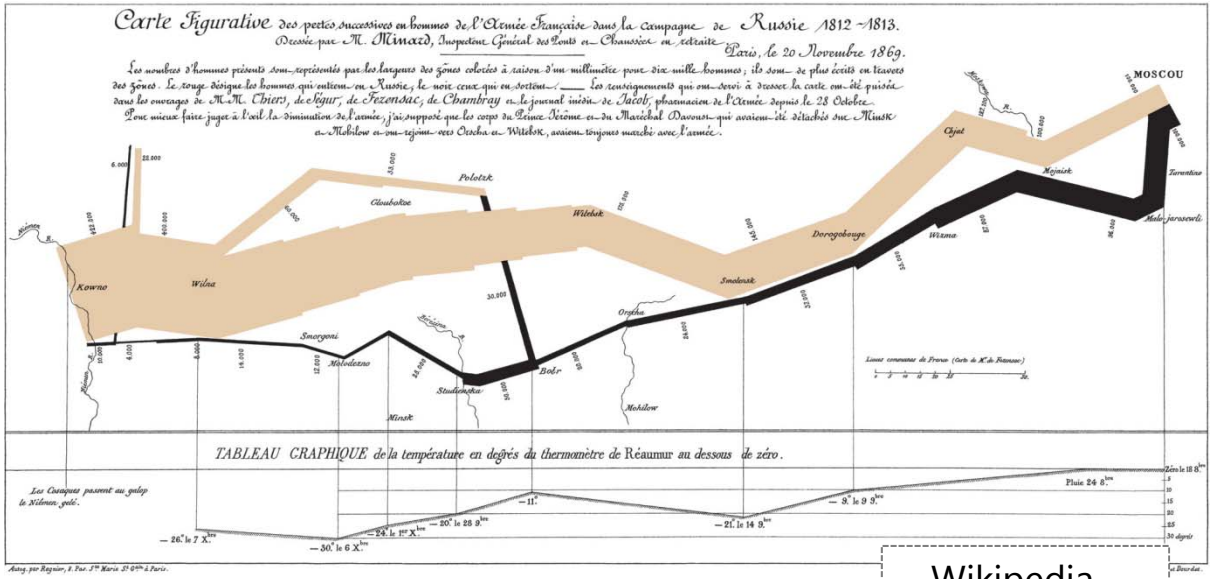
Application Scenarios



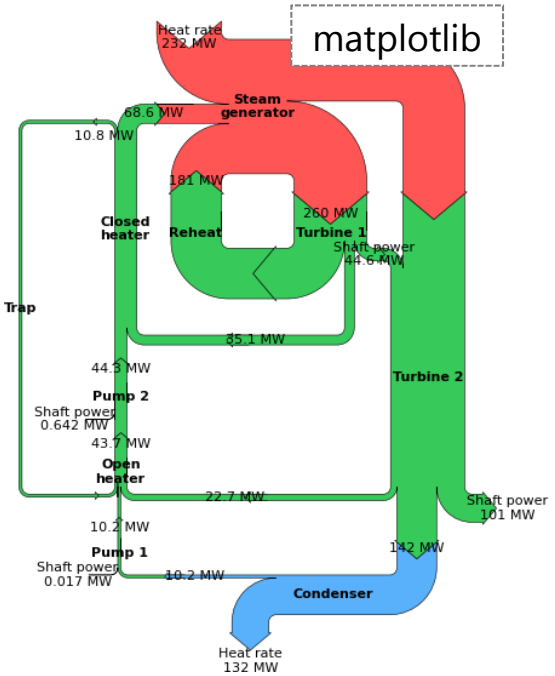
Schindler et al. '12

Sankey Diagrams

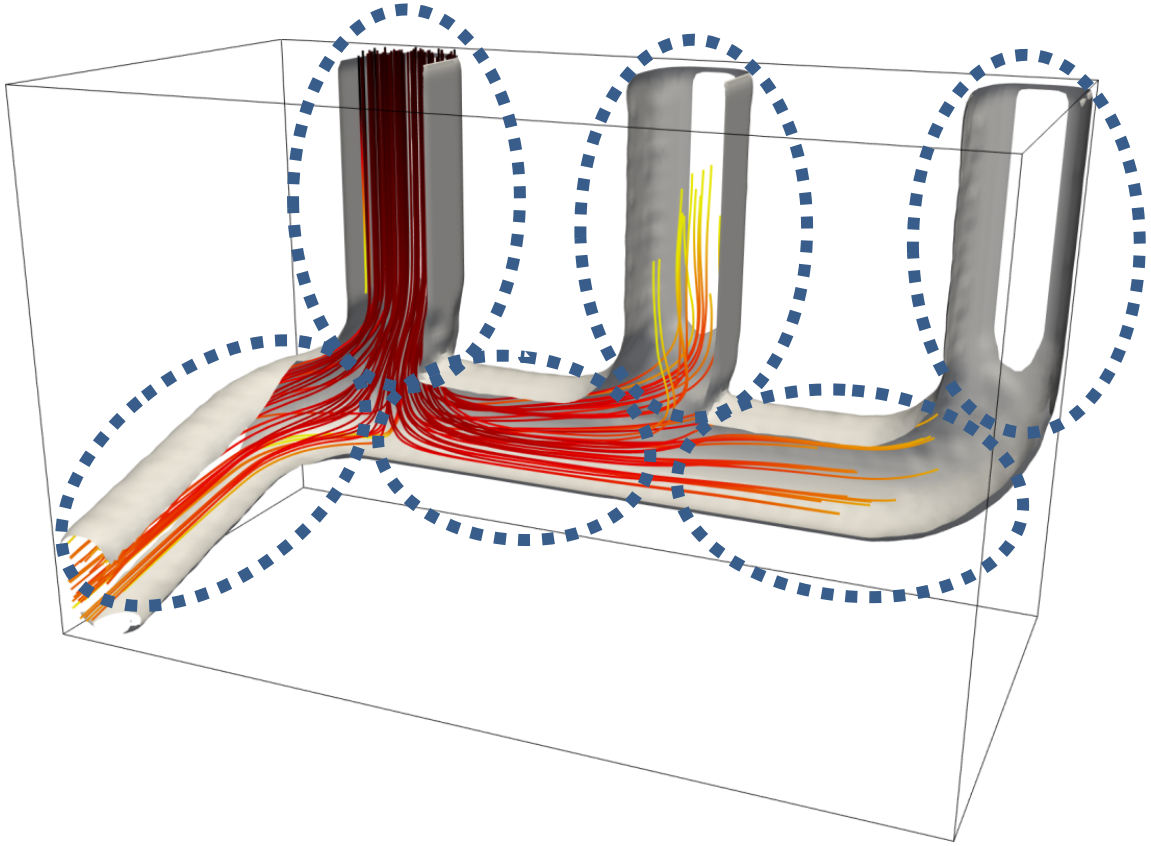
- Representation of a weighted graph
- Width proportional to the flow quantity

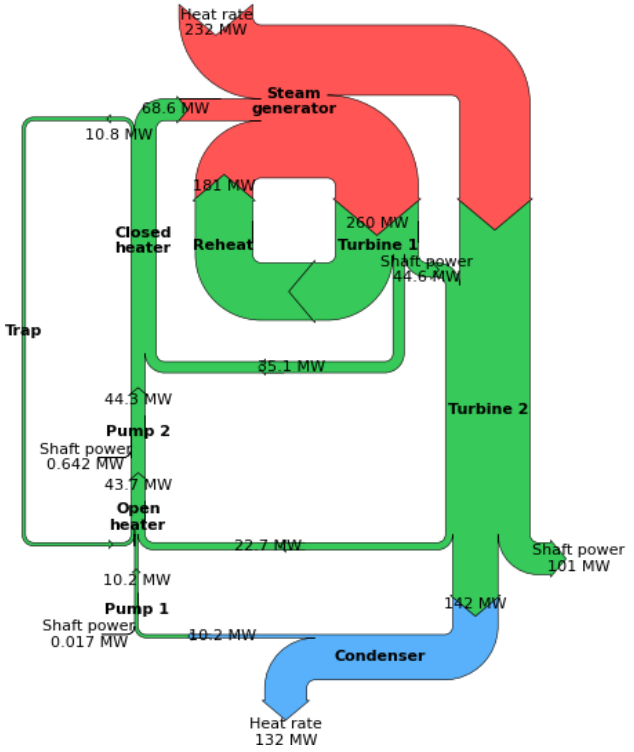


Wikipedia - Charles Joseph Minard

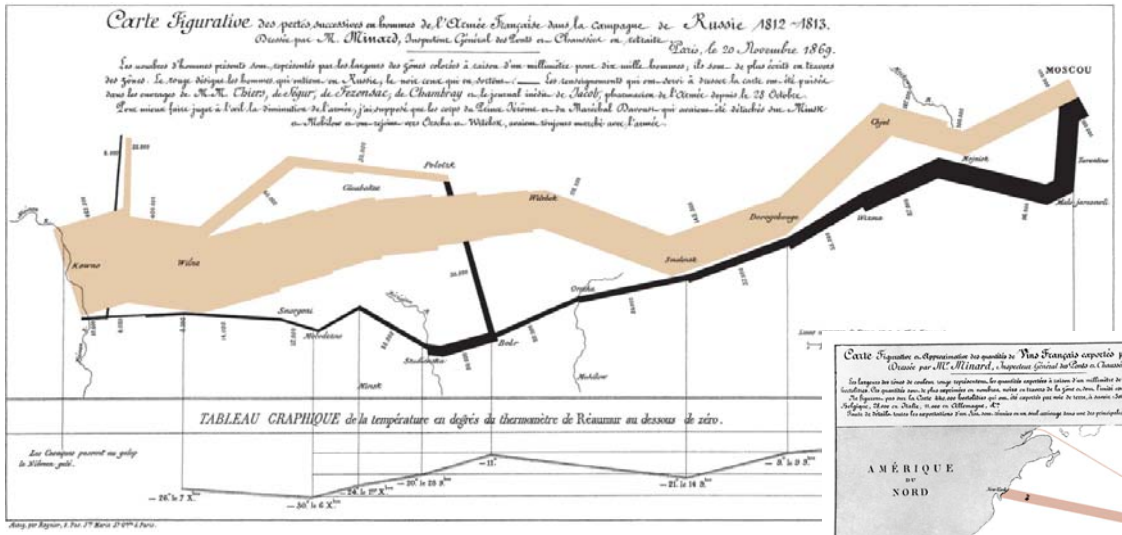


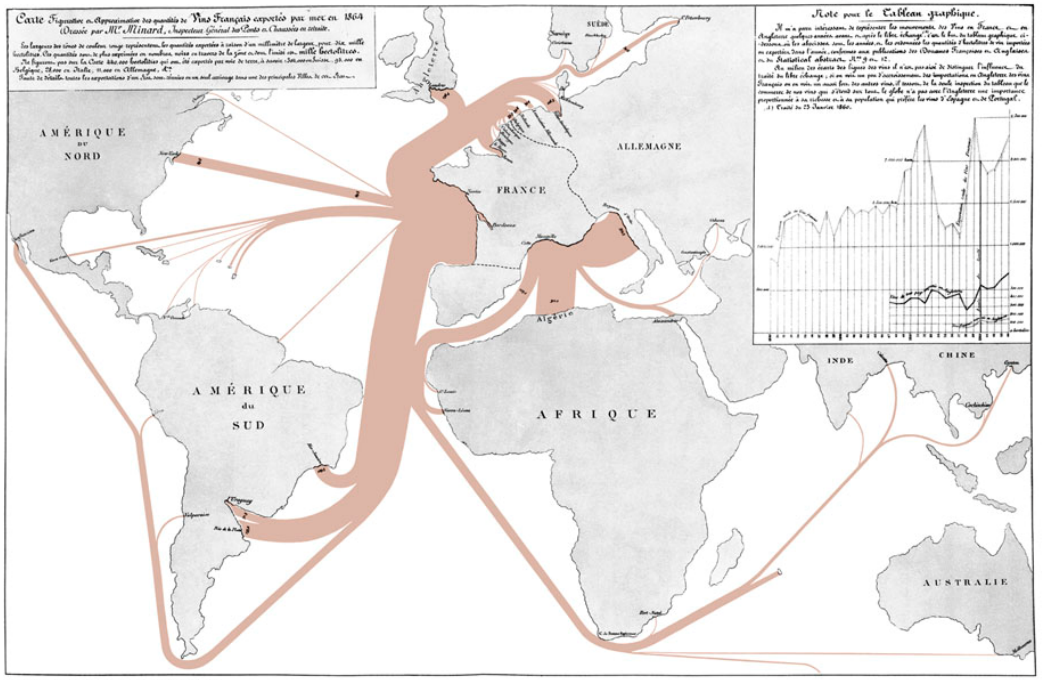
Putting Things together





Spatial Structure

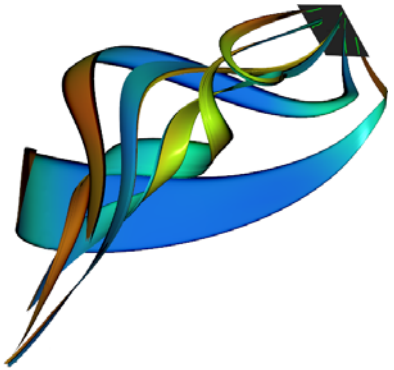




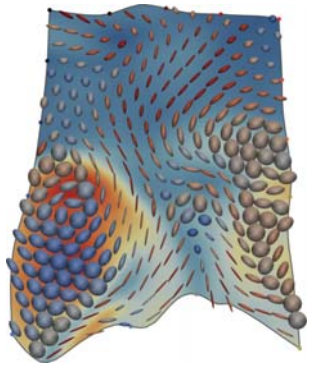
Charles Joseph Minard, *Tableaux Graphiques et Cartes Figuratives de M. Minard*, 1845-1869, a portfolio of his work held by the Bibliothèque de l'École Nationale des Ponts et Chaussées, Paris.

Final Remarks

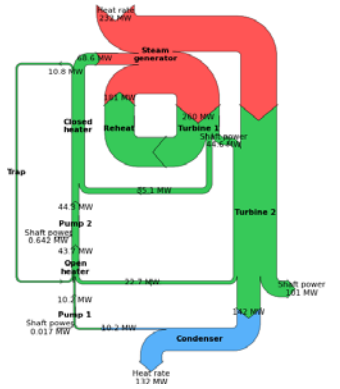
- Analyzing the long-term behavior of fluid flows is challenging



- We have made the task easier, wrt
  Seeding, Visibility, Expressiveness, Quantification



- There is still a lot to do!
  - Single approach that solves all the issues
  - Integration of different analysis tools
  - Multiple spatial scales
  - …



Acknowledgements

- The Institute of Computer Graphics and Algorithms, TU Wien

- Helwig Hauser
- Ivan Viola
- Øyvind Andreassen
- Visualization Group in Bergen

- Datasets:
  - AVL Gmbh (Graz)
  - Cardiovascular MRI Group, University Medical Center (Freiburg)
  - Tino Weinkauf
  - GexCon AS (Bergen)