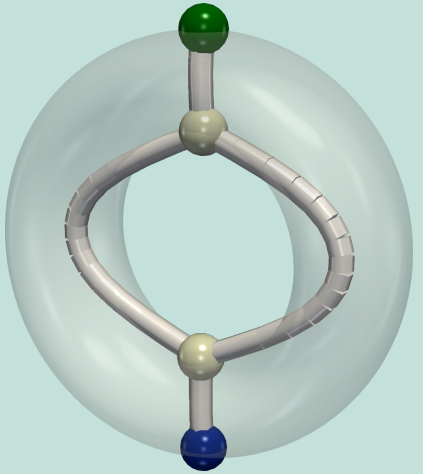
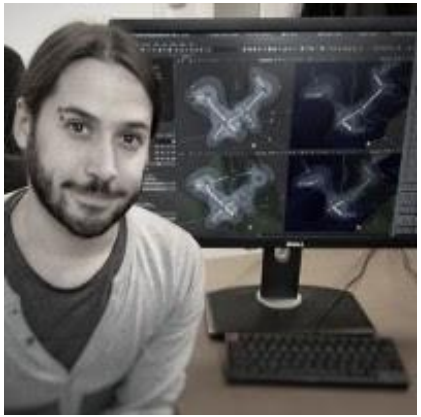


Visual data analysis

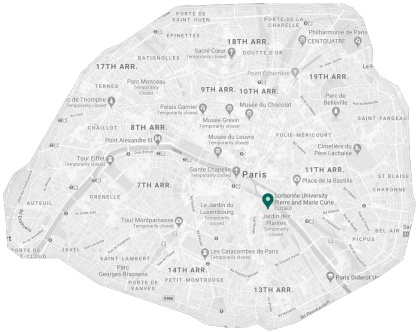
Julien Tierny

About me



- **Institutions**
  - CNRS researcher (DR)
  - Sorbonne University

- **Expertise**
  - **Topological data analysis**
    - For interactive visual data analysis & visualization
    - Papers, code, videos, demos, slides, exercises:
    - **http://julien-tierny.github.io**



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  - *“Data analysis is a process of inspecting, cleansing, transforming, and modeling data with the goal of discovering useful information, informing conclusions, and supporting decision-making.”*

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What is data analysis?

- **Simple classification**
  - Predictive data analysis
  - Exploratory data analysis

Why *visual* data analysis?

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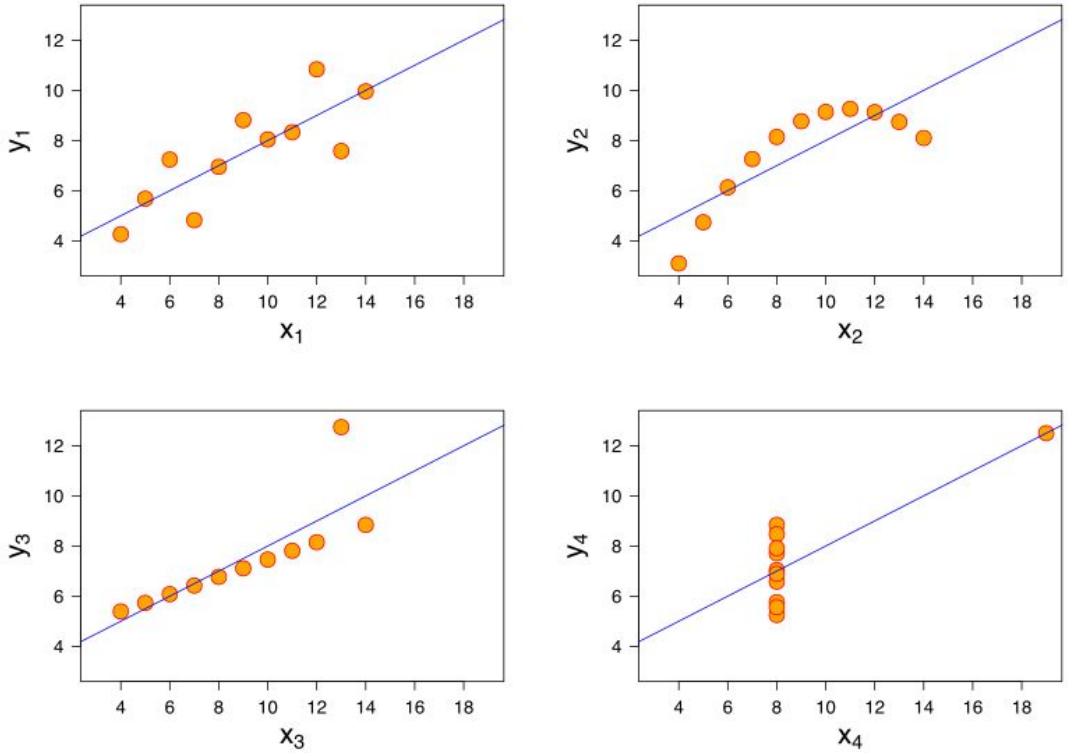

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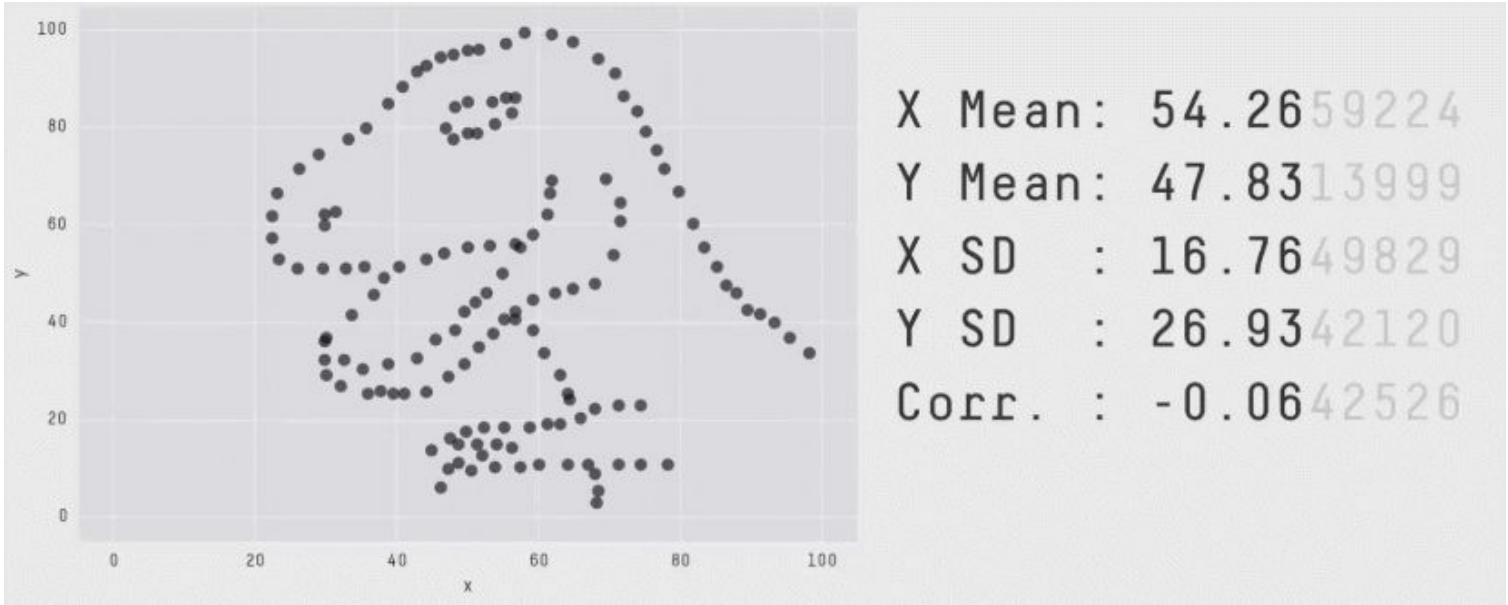

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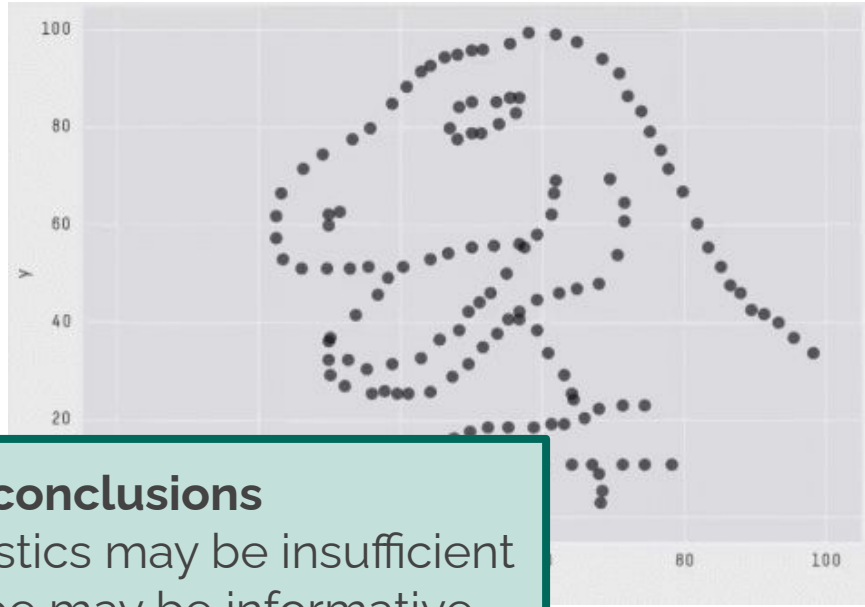

X Mean: 54.2659224
Y Mean: 47.8313999
X SD : 16.7649829
Y SD : 26.9342120
Corr. : -0.0642526

- **First conclusions**
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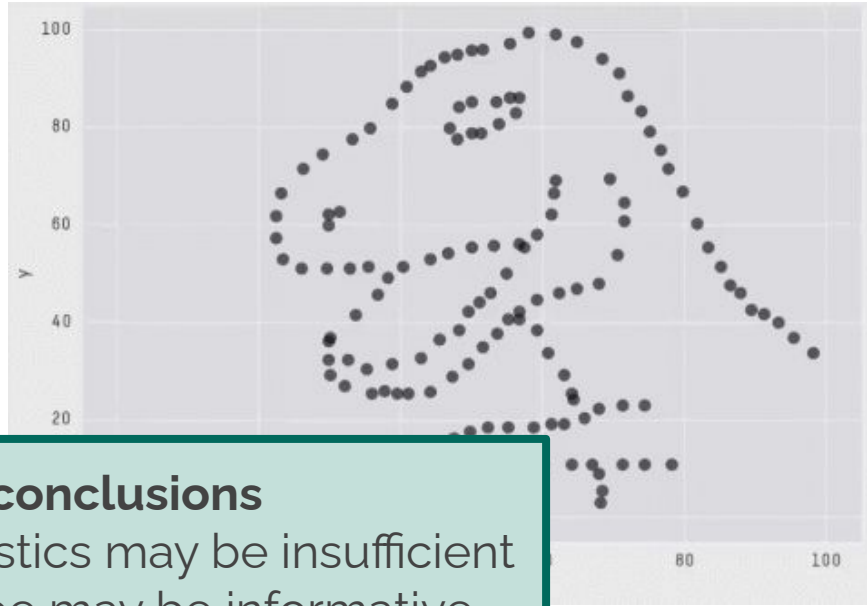

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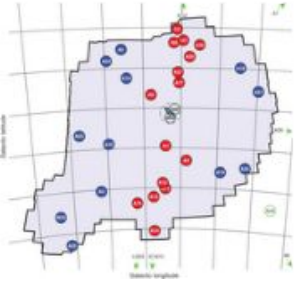
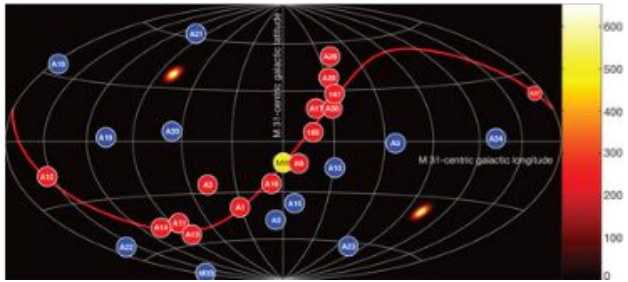
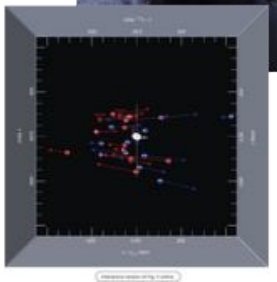
- **Data visualization**
  - Essential part of data analysis

Visual exploratory analysis

- **Goals**
  - Fast hypothesis verification
  - **Novel** hypothesis formulation







Dwarf galaxies orbiting the
Andromeda Galaxy
Nature, January 3rd, 2013

What is visual data analysis?

- Tentative definition

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- **Tentative definition**
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What is visual data analysis?

- **Tentative definition**
  - Integration of a *visual* component in data analysis
    - Process of generating interactive graphical data representations
  - Integration of *visual* descriptors in data analysis
    - Capture the visual characteristics of data
      - Shape, topology

What data?

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- Alphabetical data: texts, arrays, etc.

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- Numerical data

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- **Alphabetical data: texts, arrays, etc.**
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  - On points (i.e. arrays)

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0	0	-1.21168	-1.24689
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2	2	0.979093	-0.00958214
3	3	1.55889	0.670995
4	4	0.777461	-0.525246
5	5	-0.958449	-0.29081
6	6	1.6709	-0.123773
7	7	0.284015	1.73621
8	8	-1.09296	1.34327
9	9	0.755332	-0.477734
10	10	0.308896	-0.817517
11	11	-0.391899	-0.71122
12	12	0.171268	-0.926897
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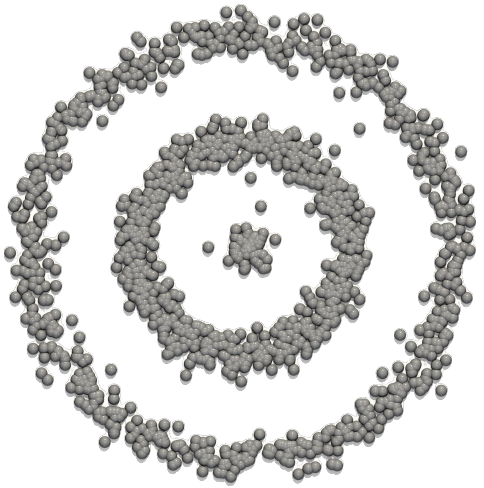

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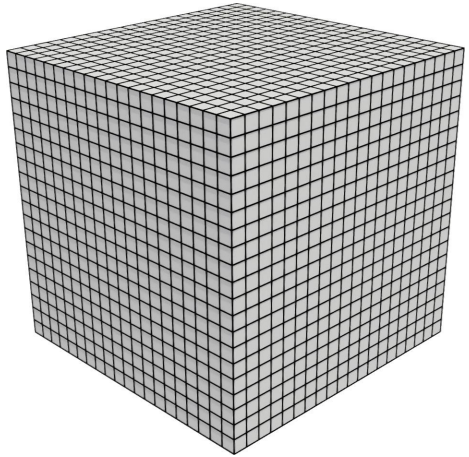

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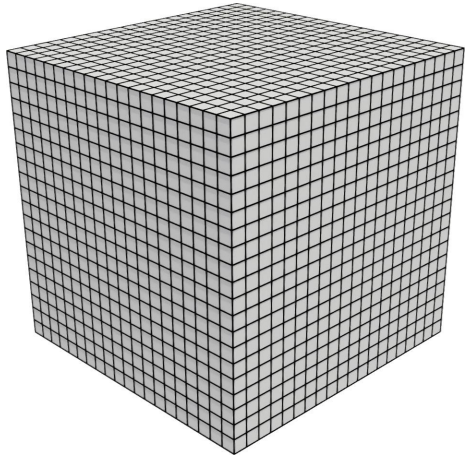

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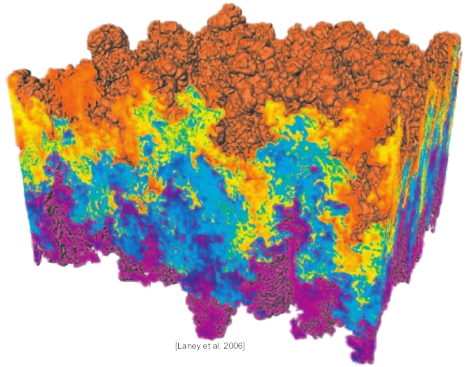

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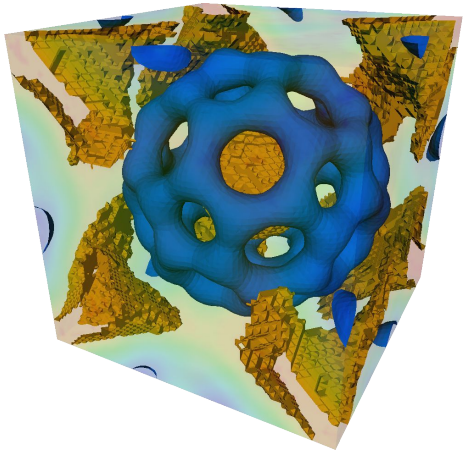

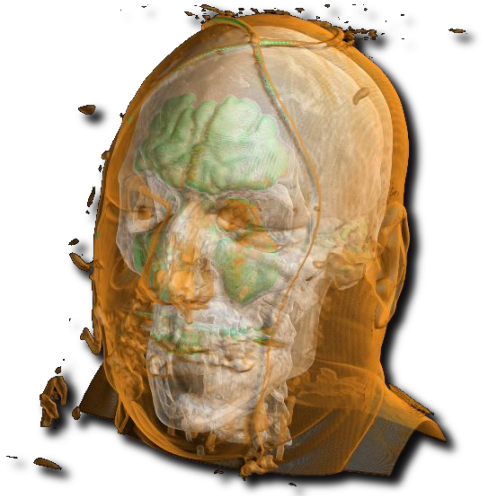

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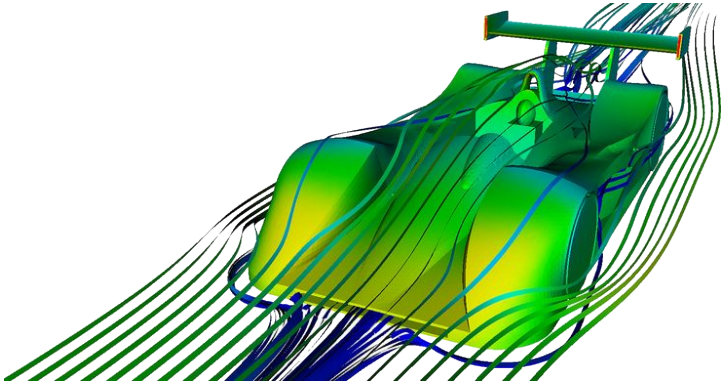

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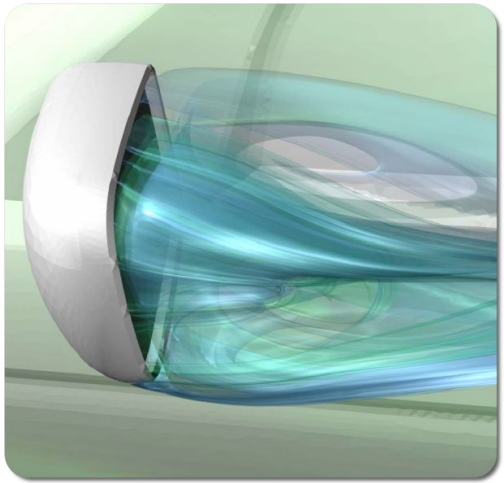

[GarthVIS08]

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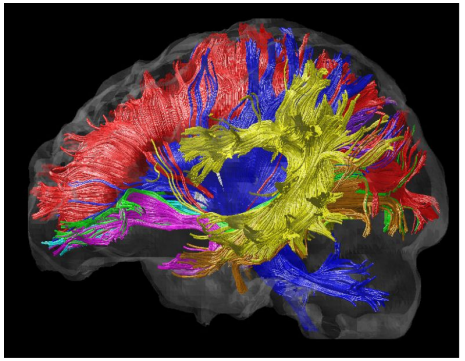

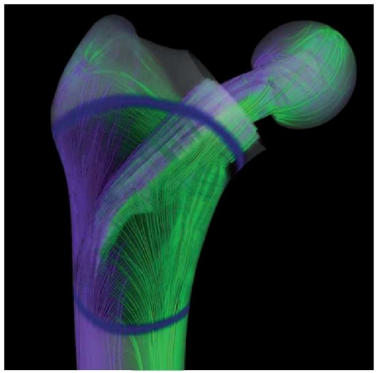

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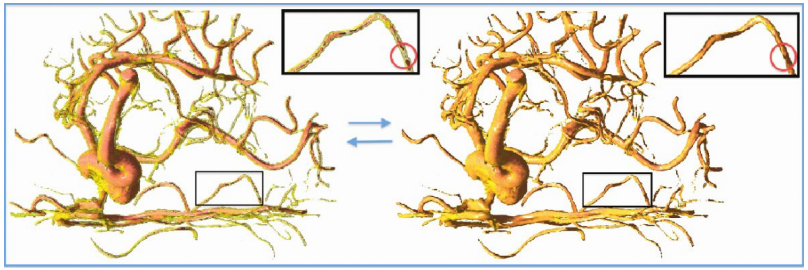

[Fout]

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    - Emerging types:
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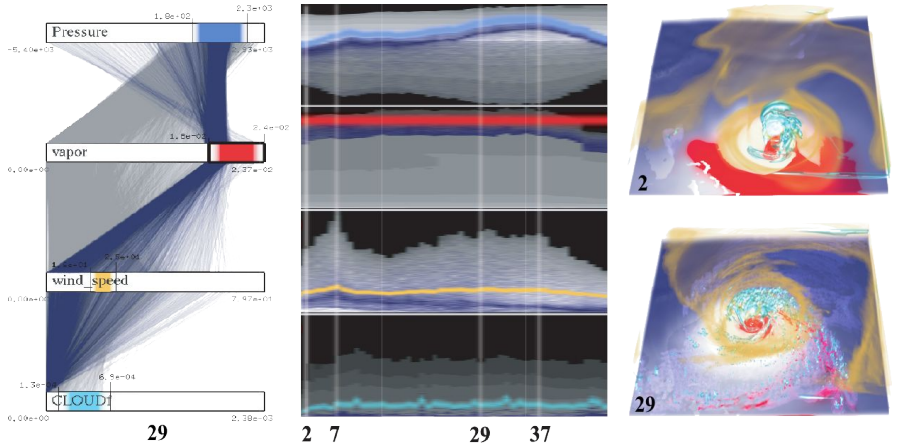


Core topics

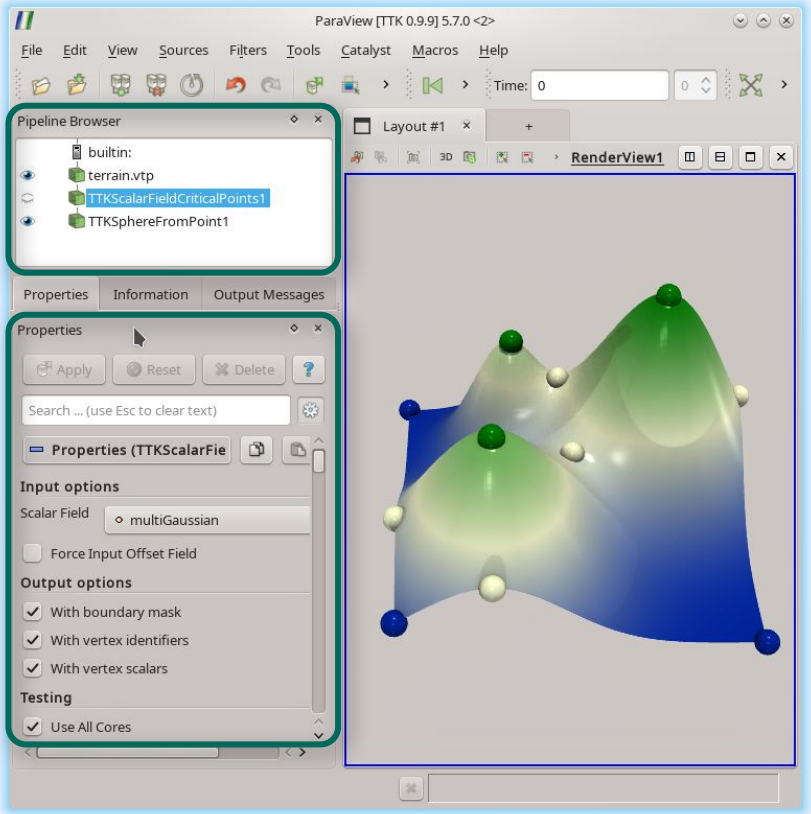
- **Rendering**
  - From geometry to pixels

- **Data transformation**
  - Not all datasets are directly visualizable
  - From data to visualizable geometry
    - Interactive process

Visualization as a pipeline

- **Overview**
  - Data analysis pipeline
  - Rendering

- **ParaView**
  - Open-source
  - De-facto standard
  - Visual programming
  - MPI support
  - **http://www.paraview.org**



Live demo

A quick tour of visualization classics

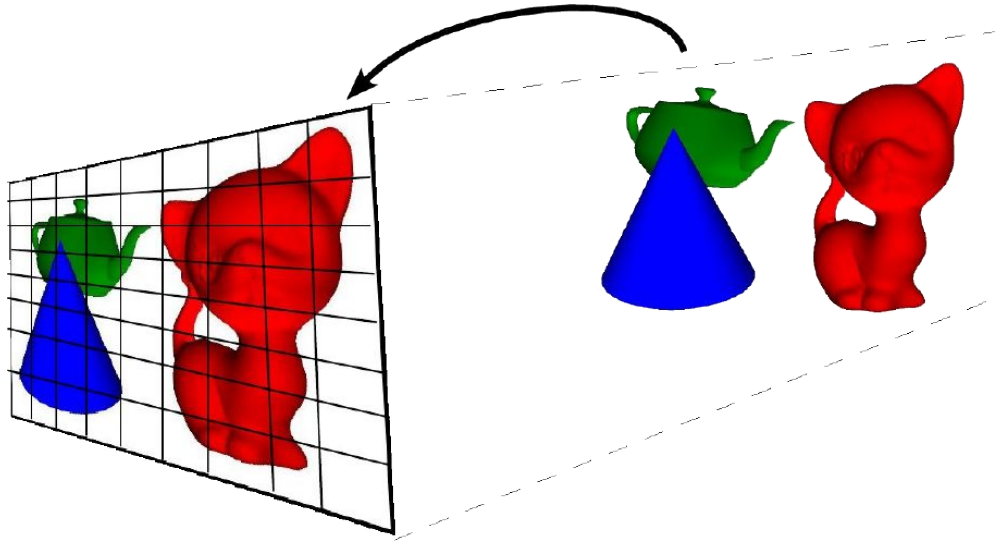
- **Class summary**
  - The classics
    - Rendering classics
    - Data manipulation classics
  - An introduction to Topological Data Analysis

Visualization classics

Rendering classics (1)

Rendering classics (1)

- **Projective rendering**
  - Position matrices
  - Color + Light model
  - Projection matrix
  - Screen space processing



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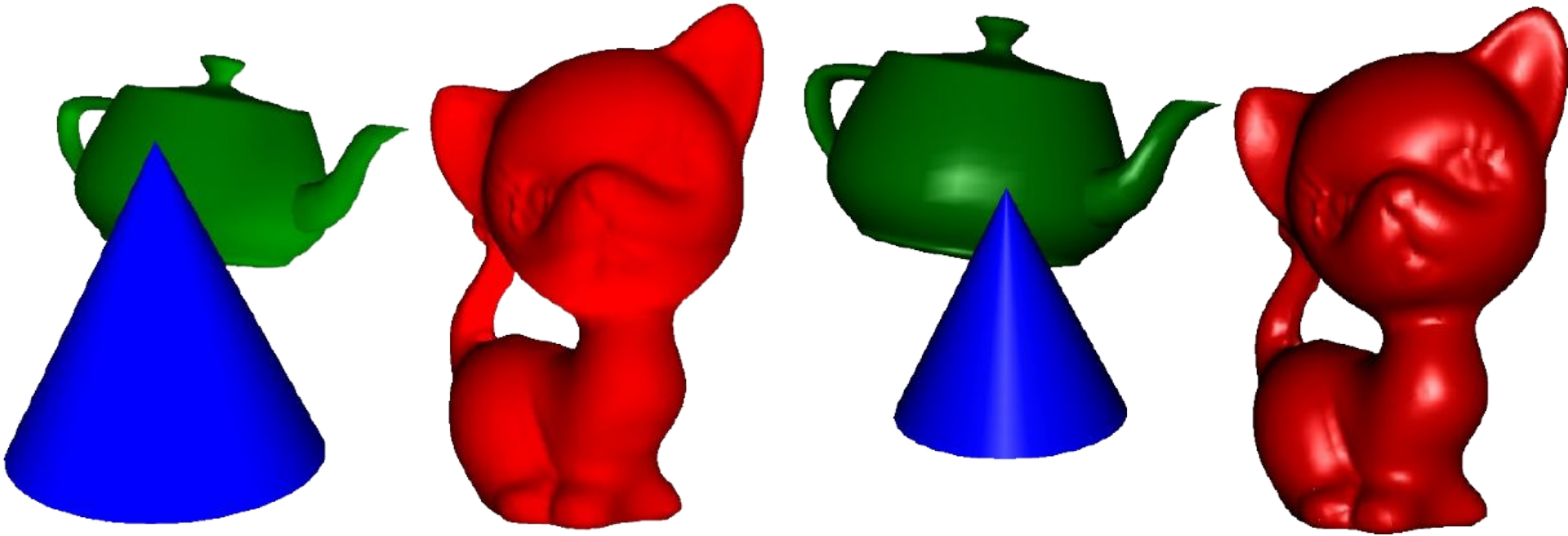

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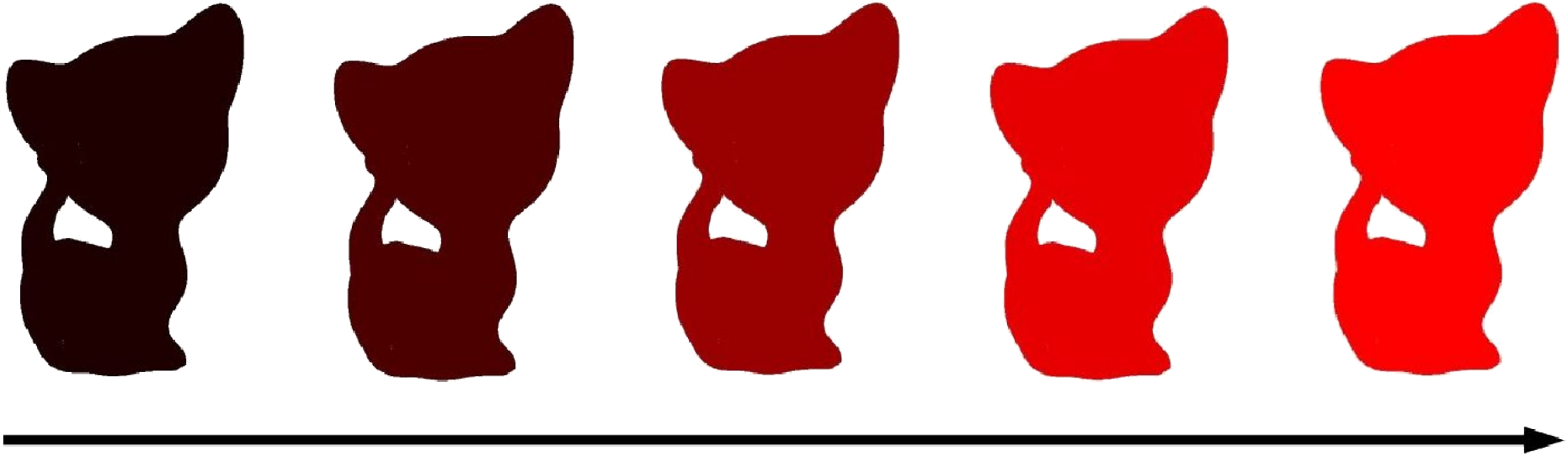

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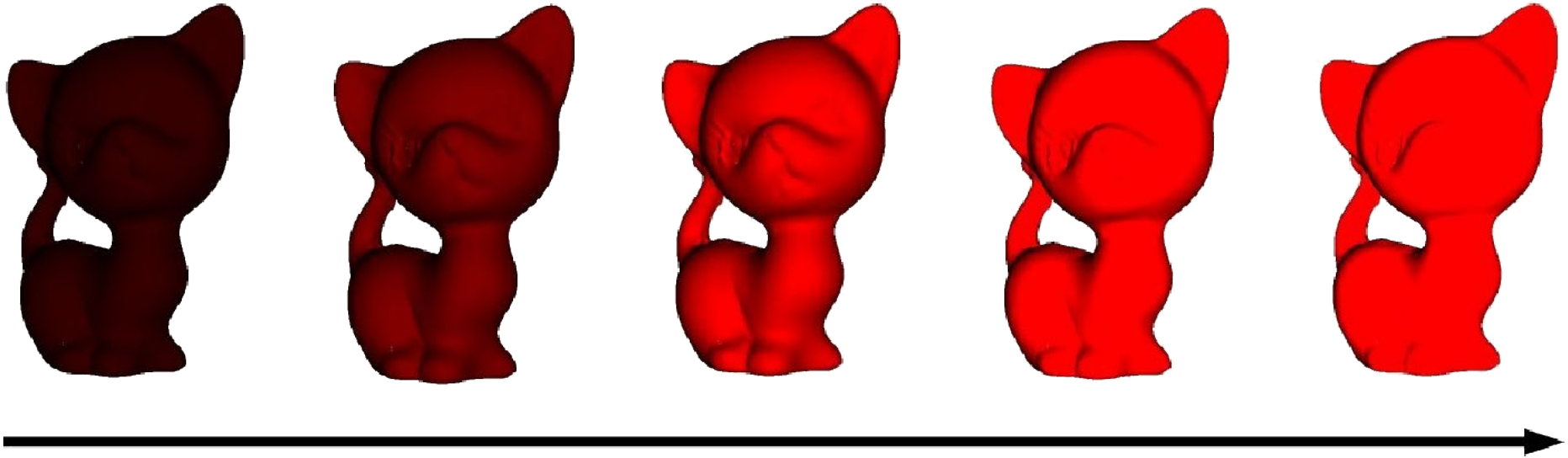

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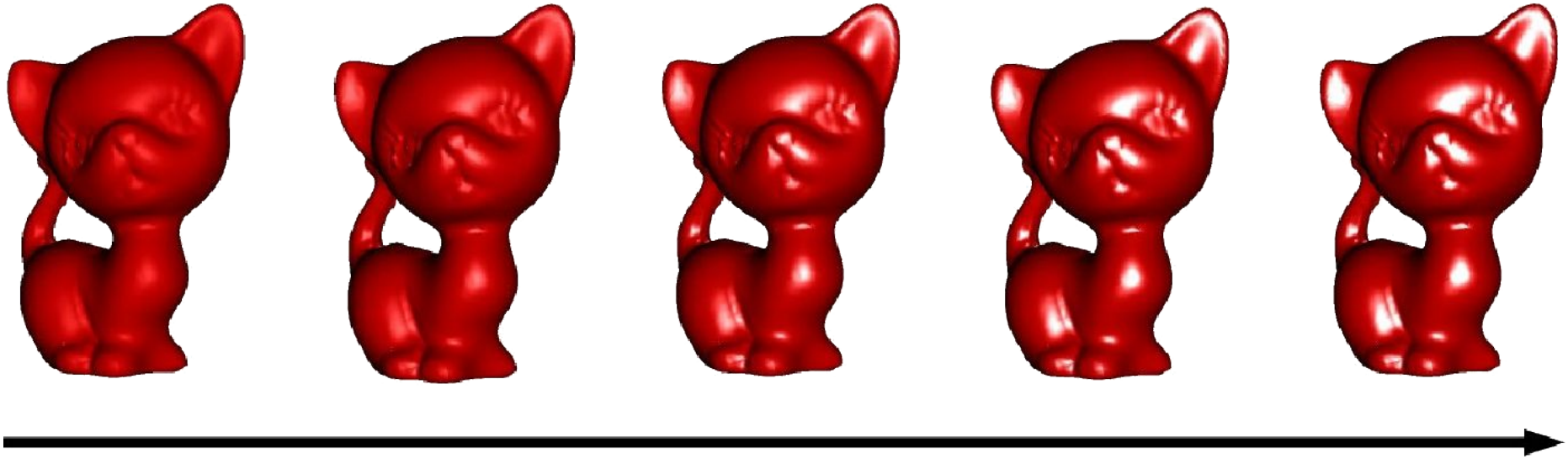

Rendering classics (2)

- Graph of a function

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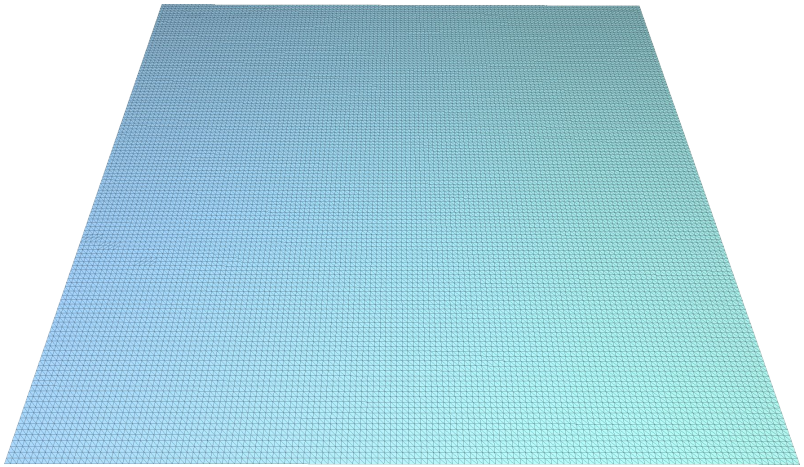

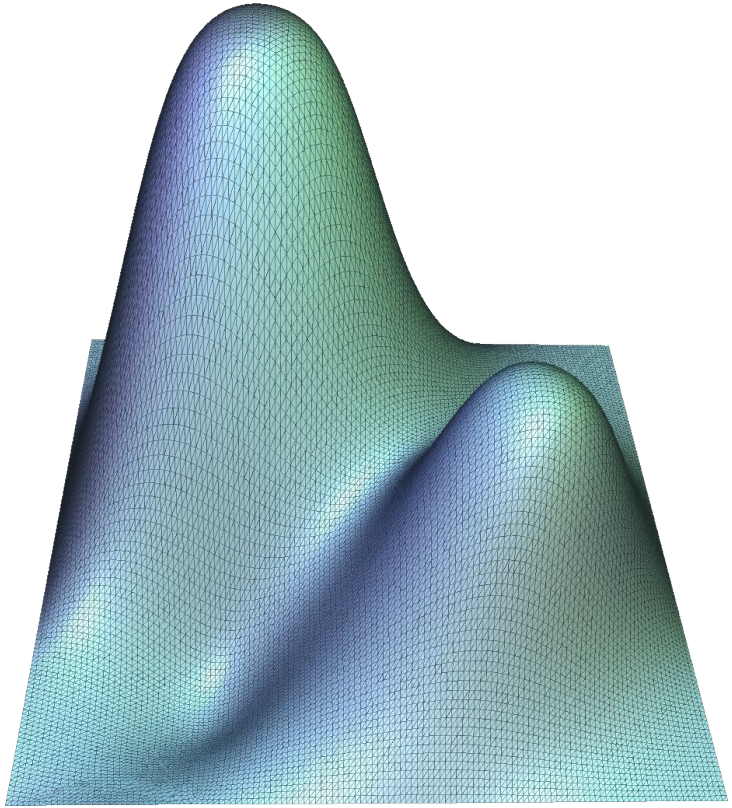

Rendering classics (3)

- Glyphs

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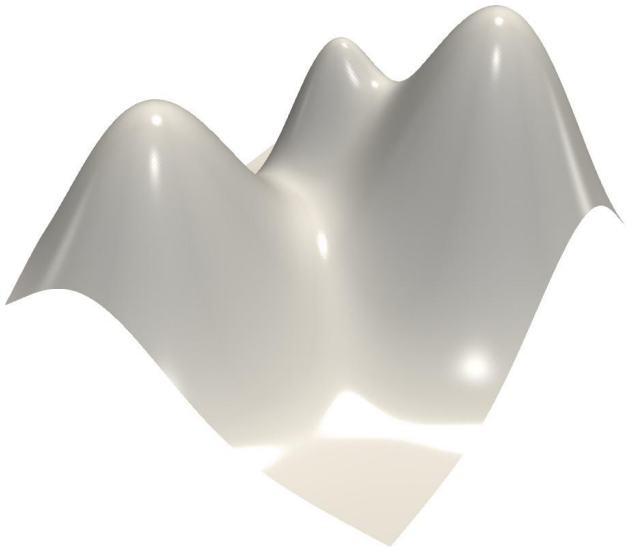

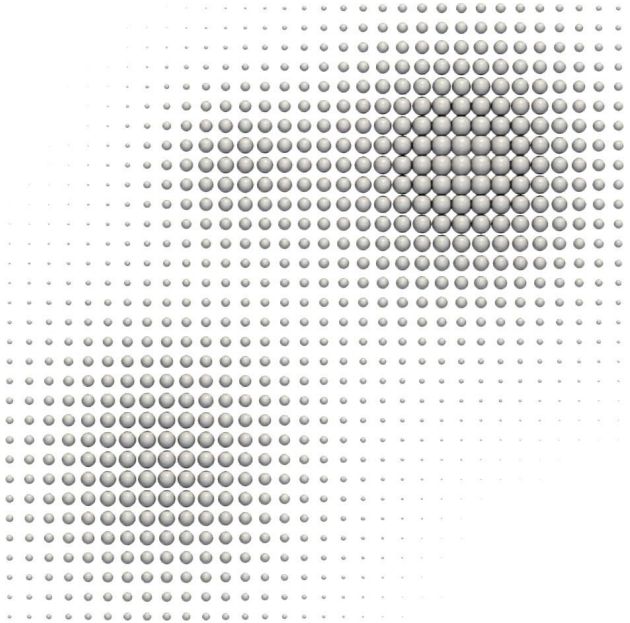

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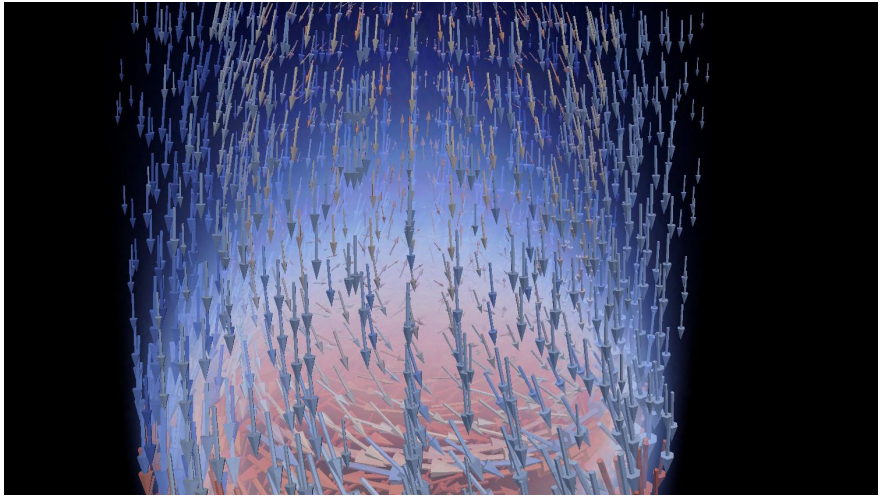

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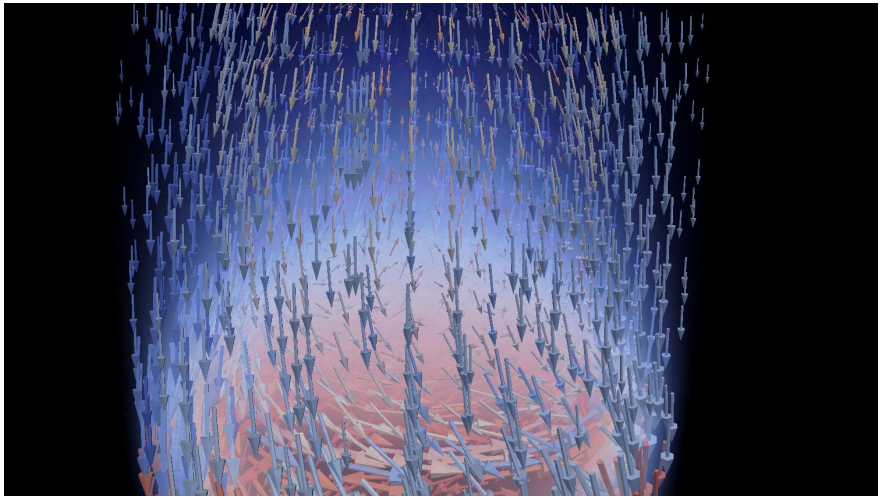

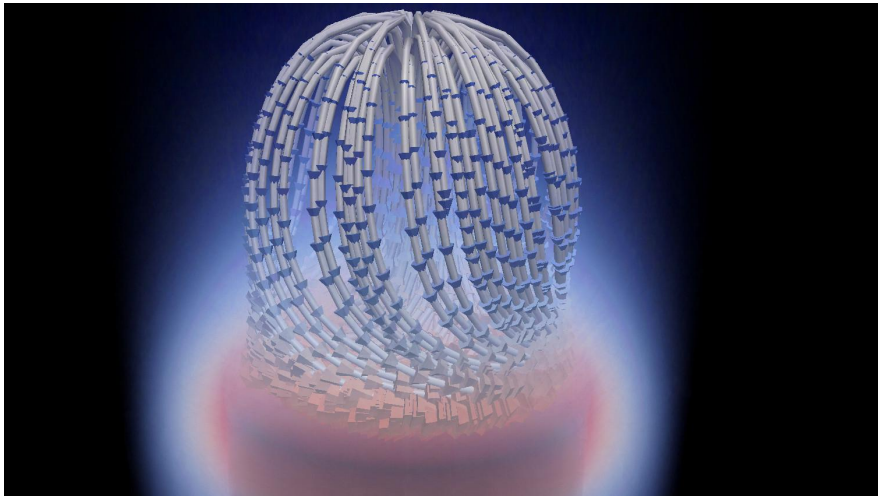

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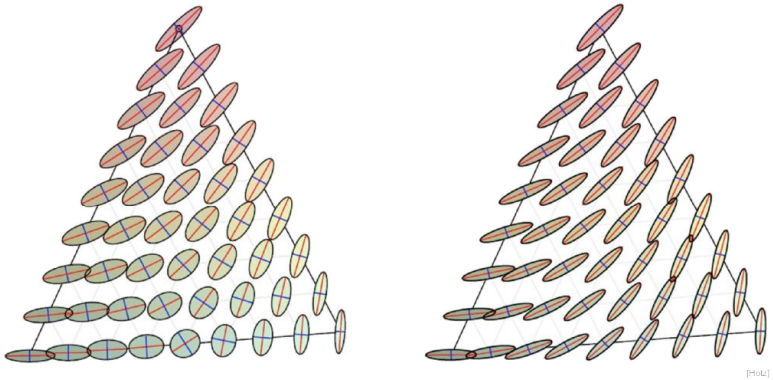

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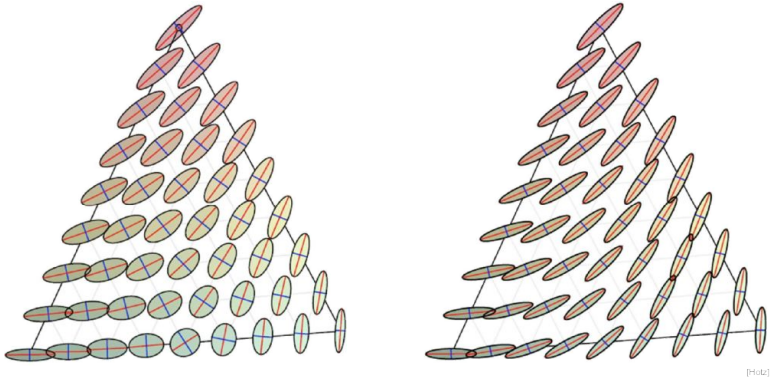

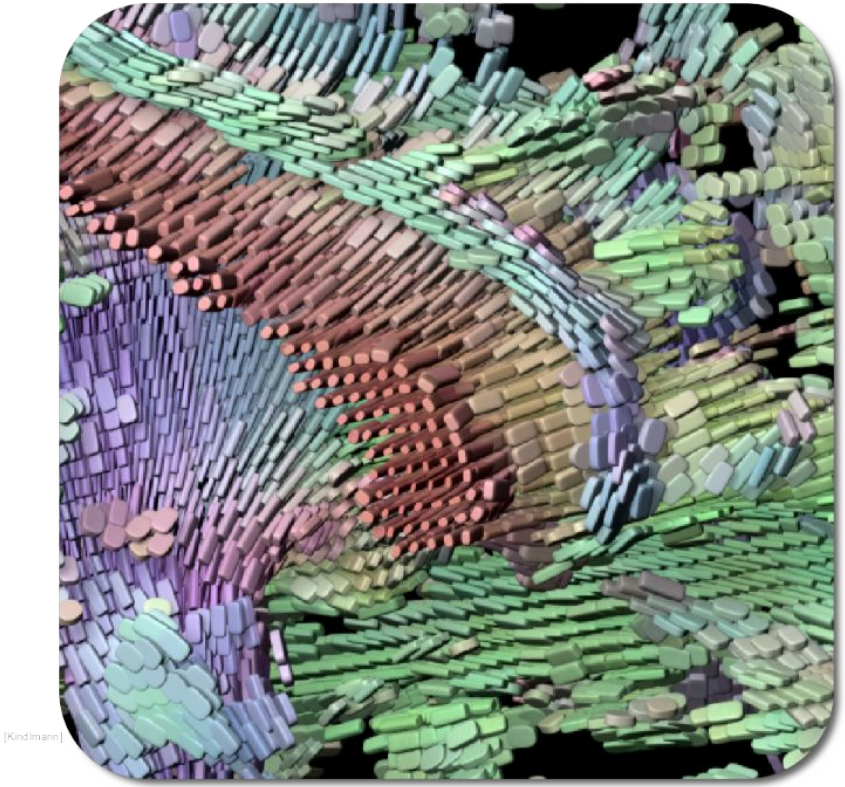

Rendering classics (4)

- **Perceptual channels**
  - Color maps

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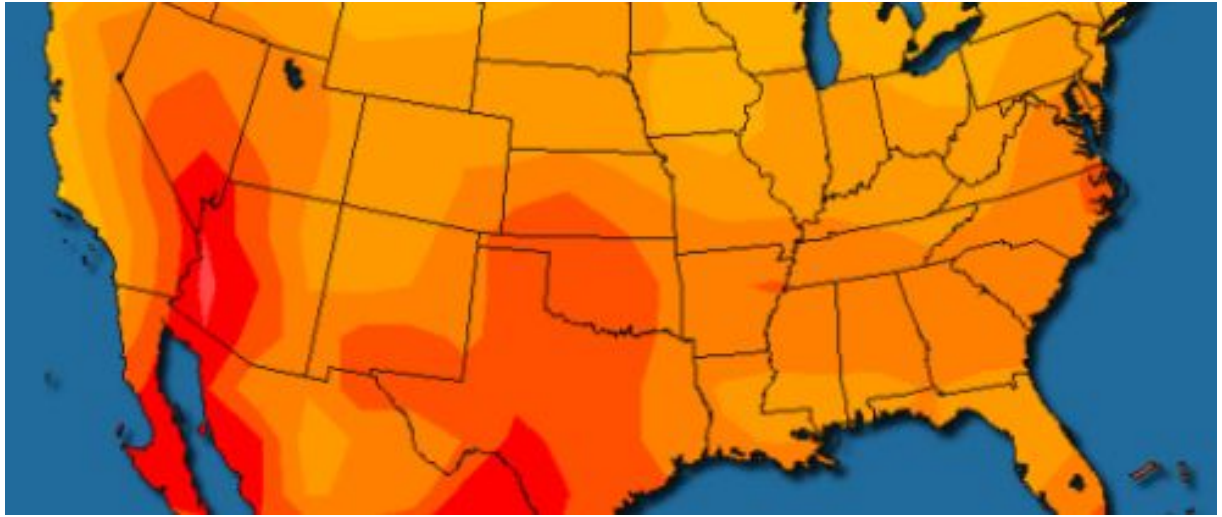

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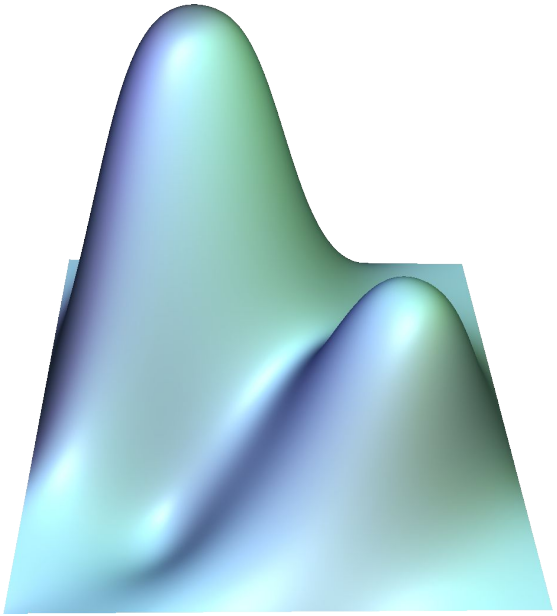
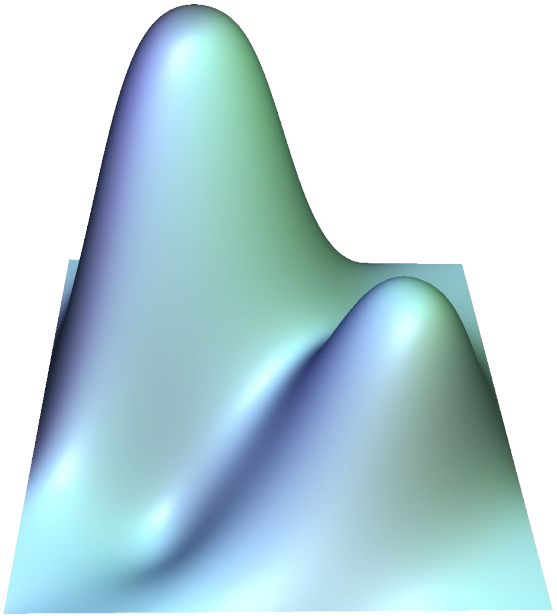


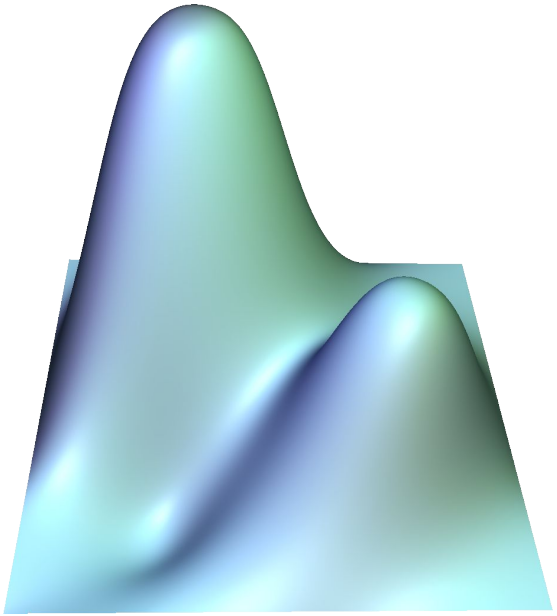
Rendering classics (4)

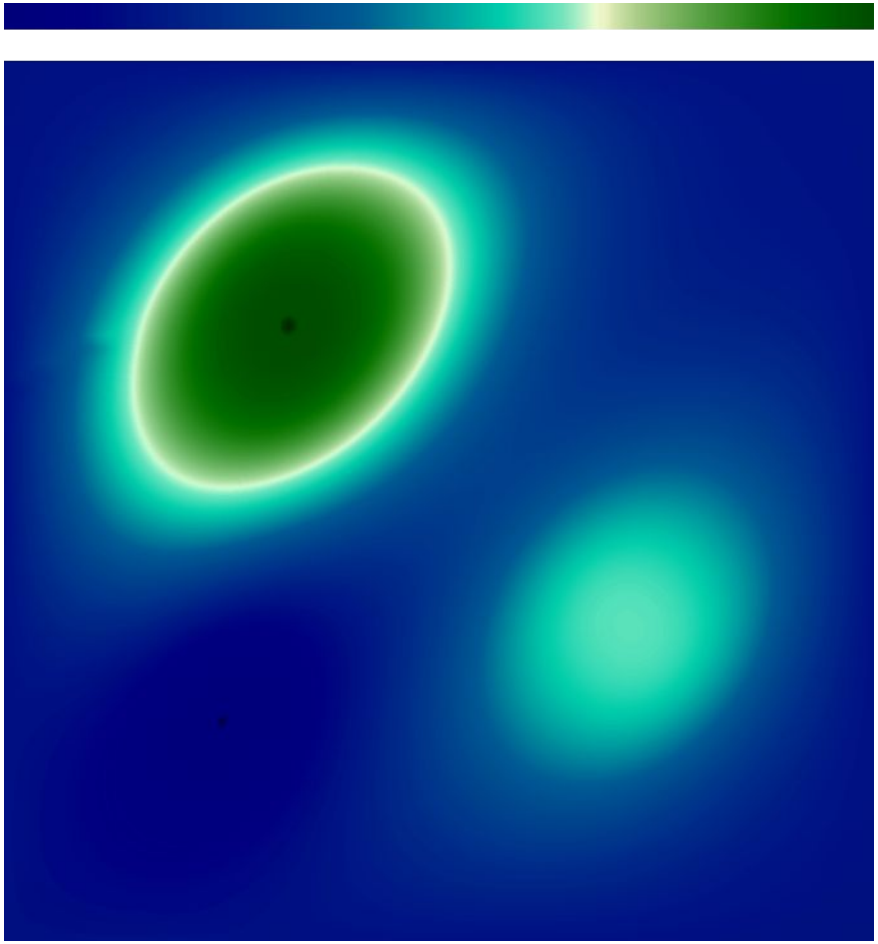


- **Perceptual channels**
  - Color maps

Rendering classics

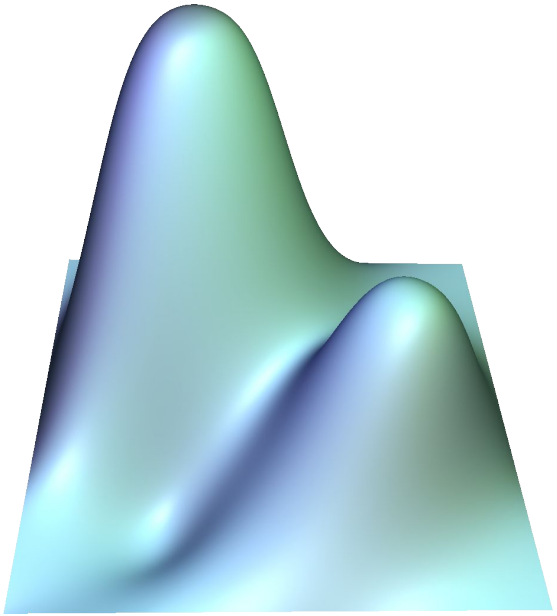
- **Perceptual channels**
  - Color maps

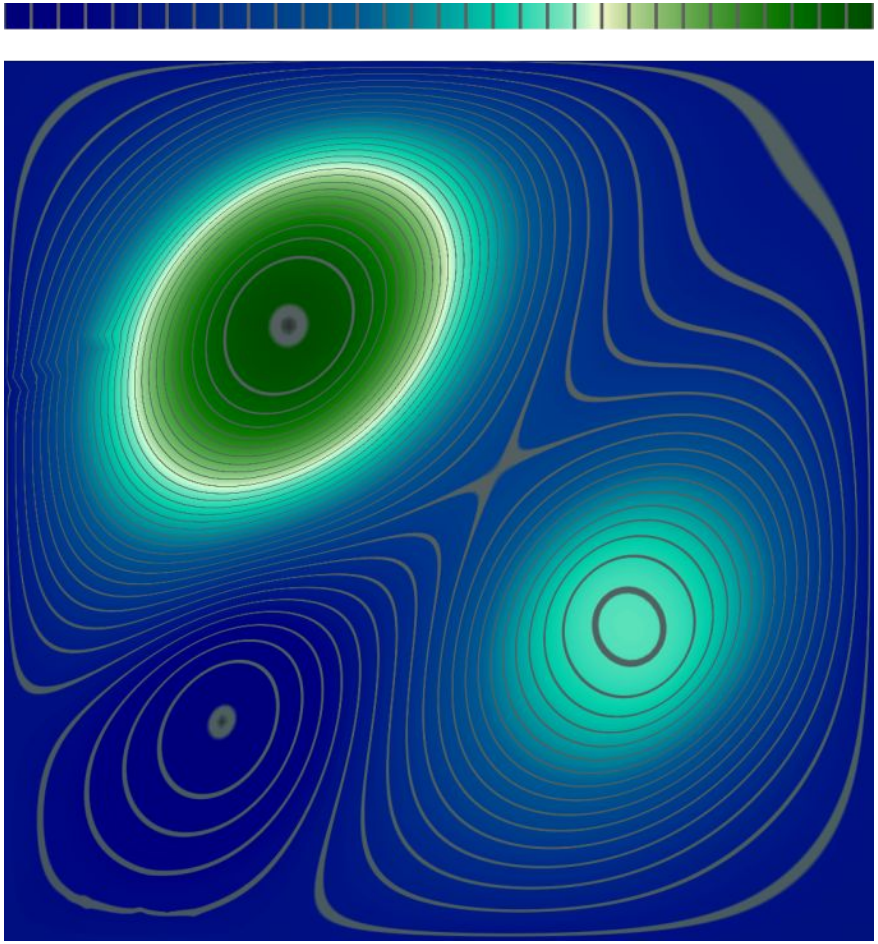




Rendering classics (4)

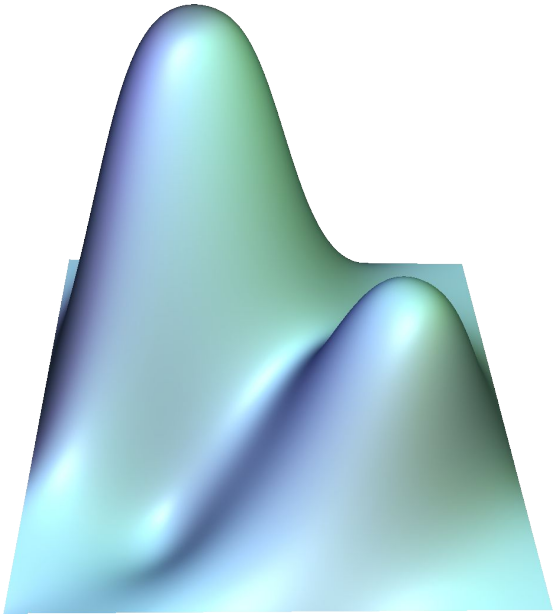
- **Perceptual channels**
  - Color maps

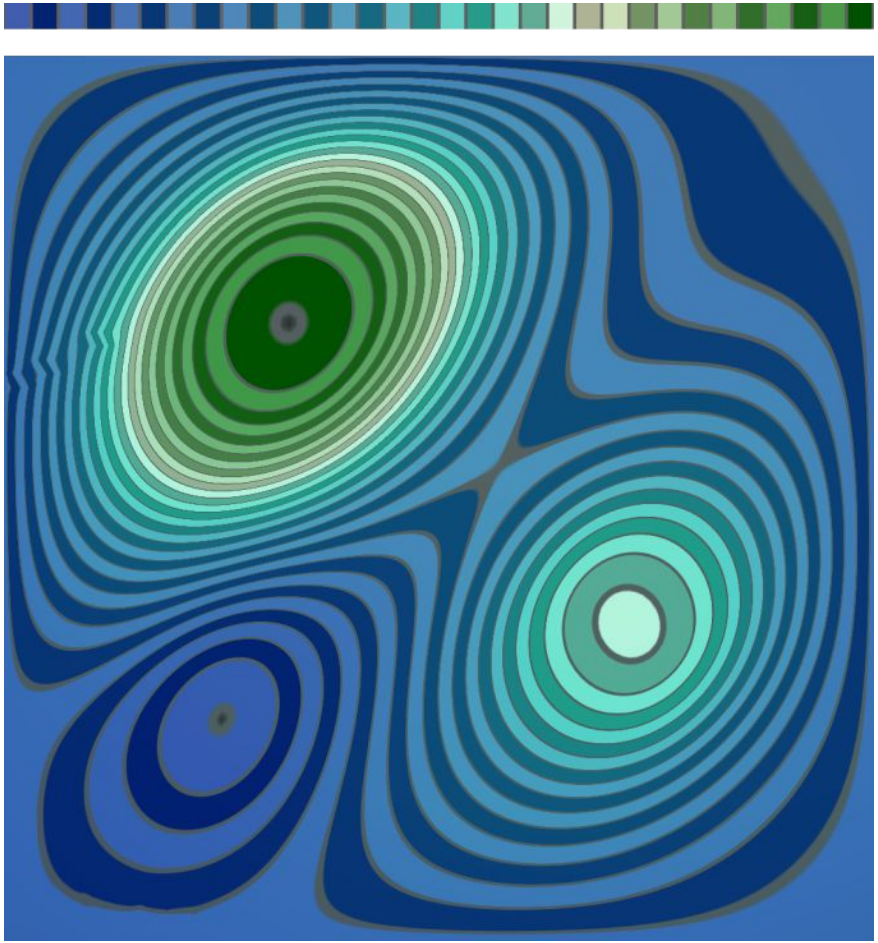




Rendering classics (4)

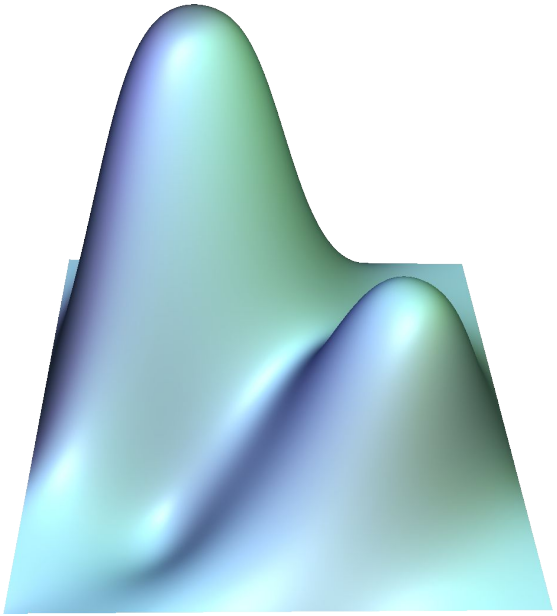
- **Perceptual channels**
  - Color maps

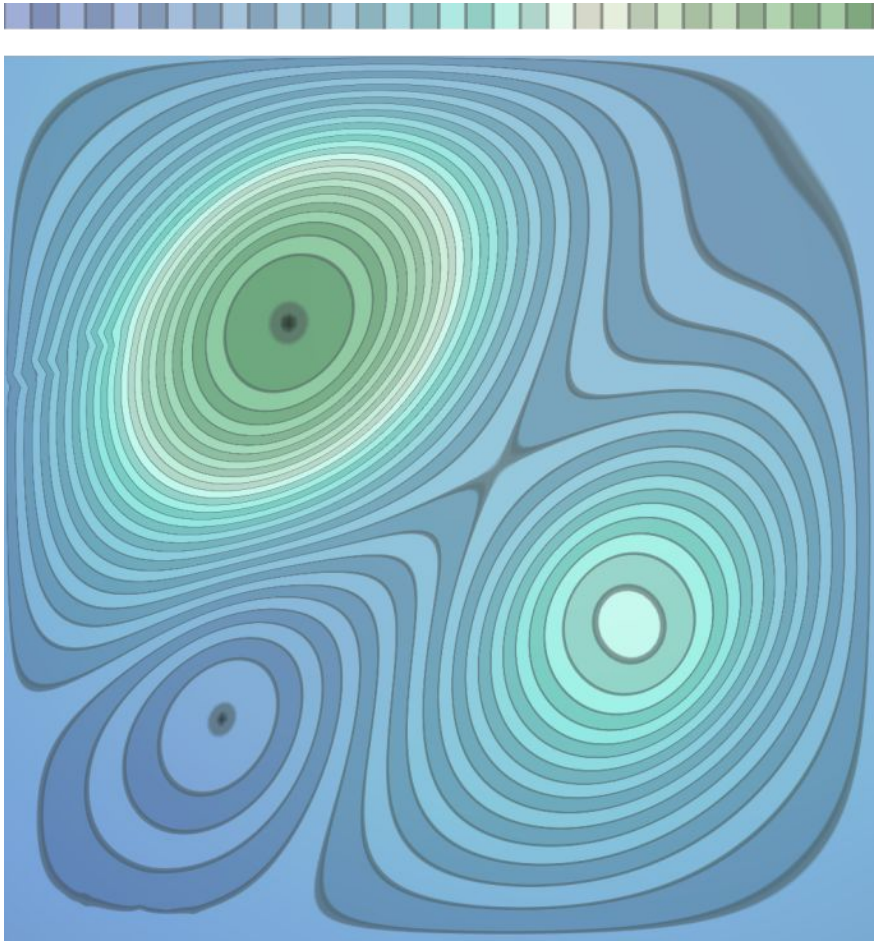




Rendering classics (4)

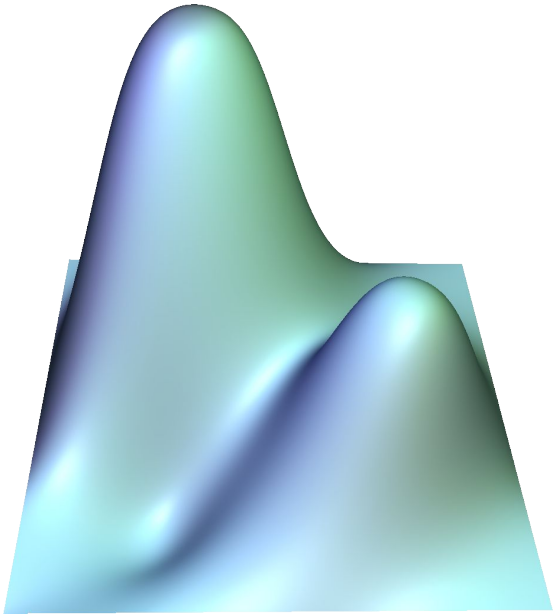
- **Perceptual channels**
  - Color maps

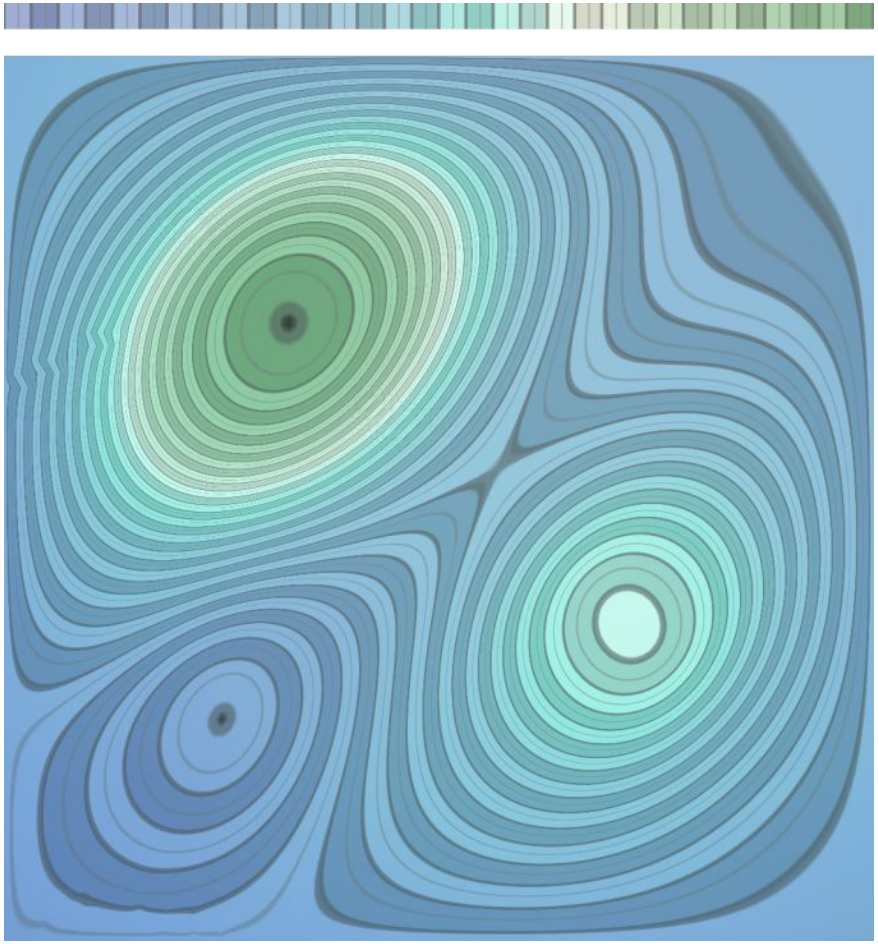




Rendering classics (4)

- **Perceptual channels**
  - Color maps





Rendering classics (5)

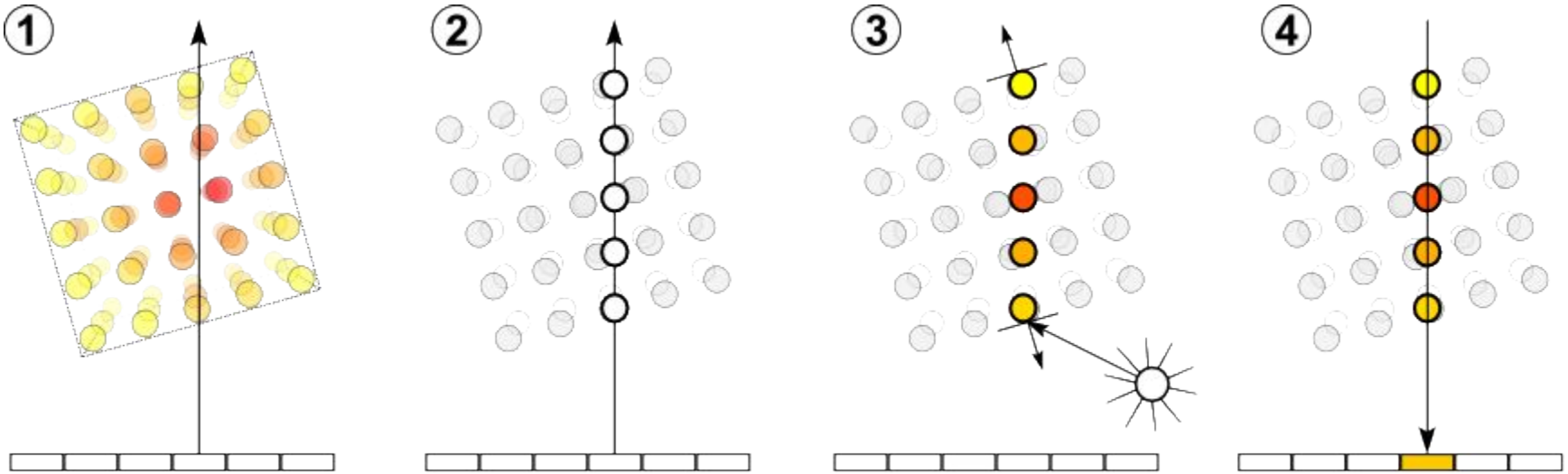
- **Perceptual channels**
  - Volume rendering

Rendering classics (5)

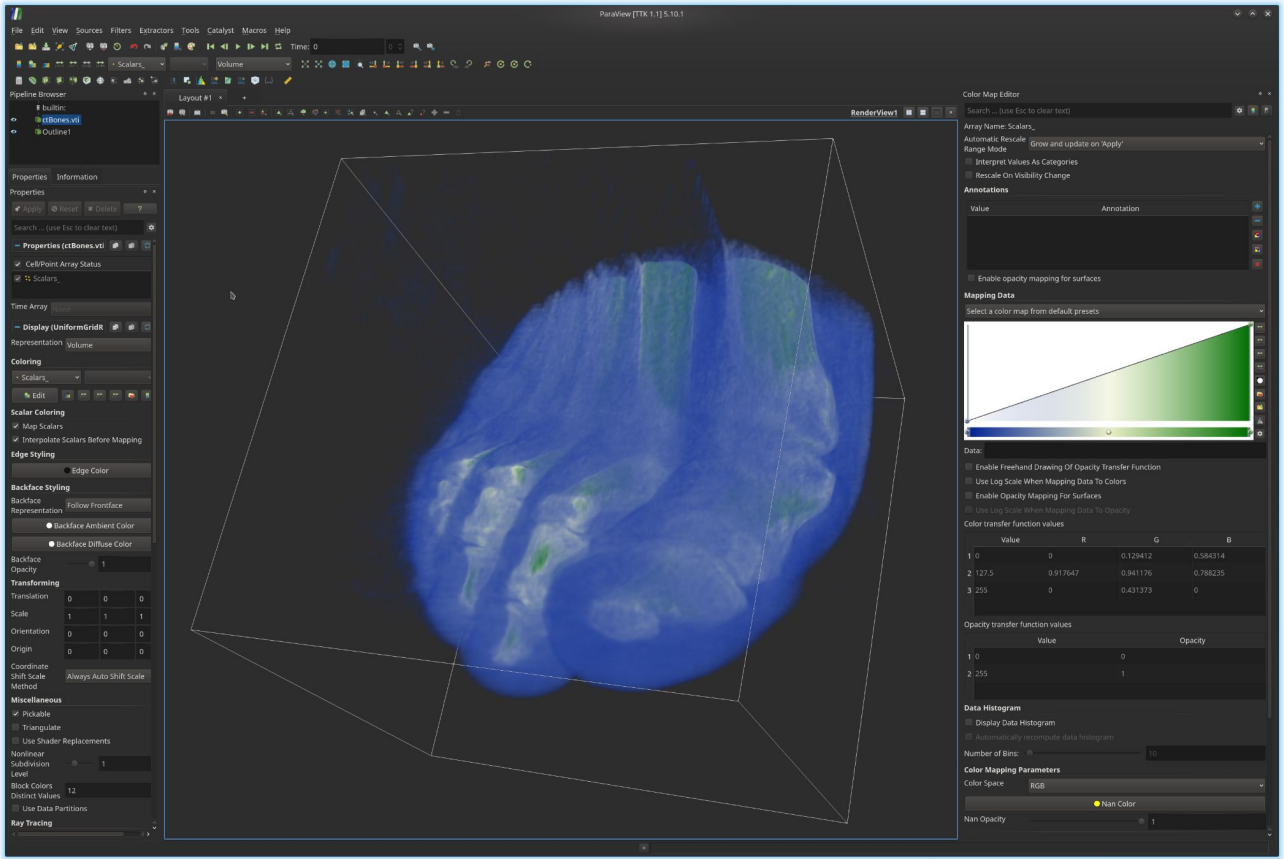
- **Perceptual channels**
  - Volume rendering

Rendering classics (5)

- **Perceptual channels**
  - Volume rendering



Rendering classics (5)



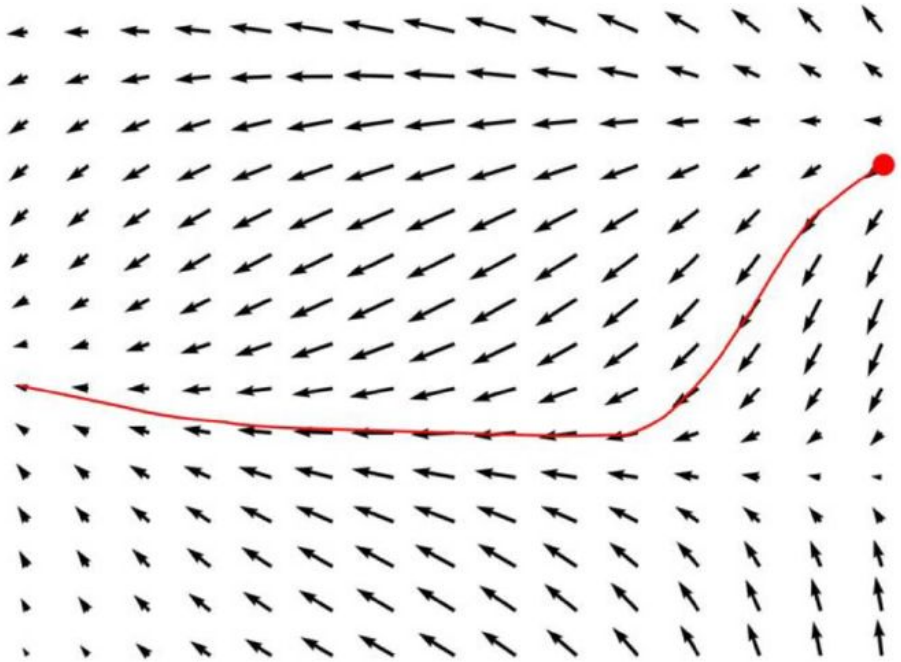
Live demo

Rendering classics (6)

- **Towards feature visualization**
  - Line integral convolution

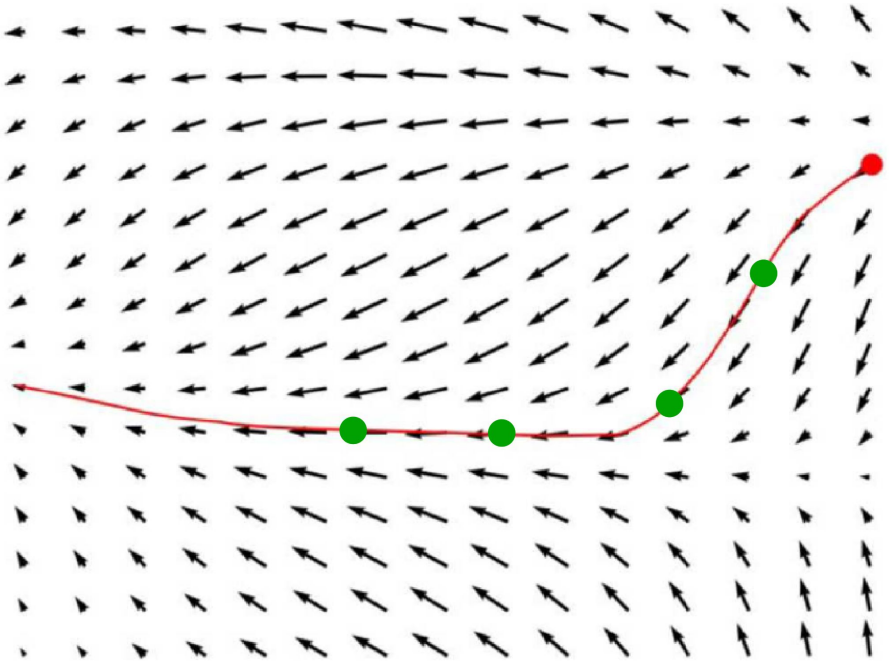
Rendering classics (6)

- **Towards feature visualization**
  - Line integral convolution



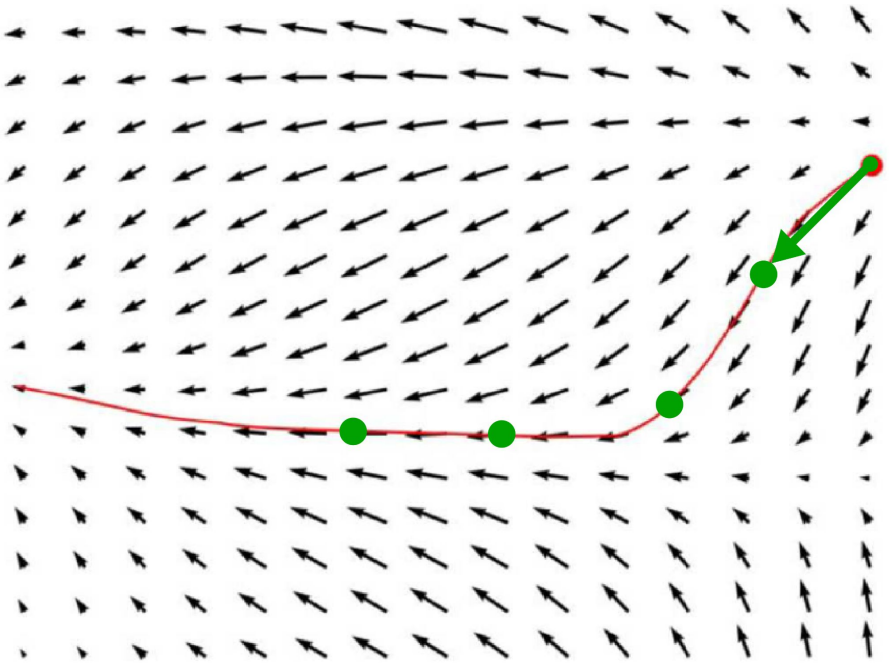
Rendering classics (6)

- **Towards feature visualization**
  - Line integral convolution



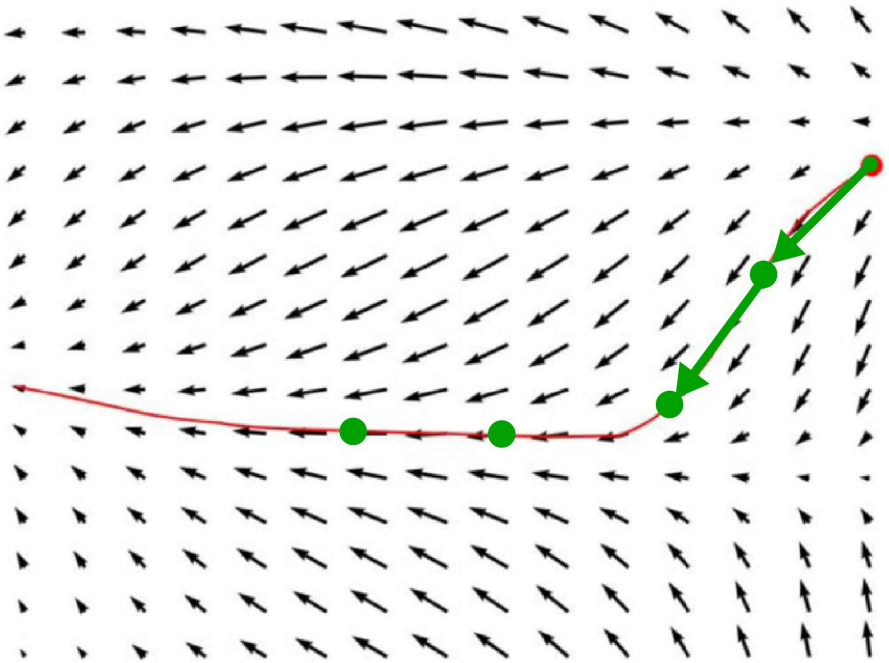
Rendering classics (6)

- **Towards feature visualization**
  - Line integral convolution



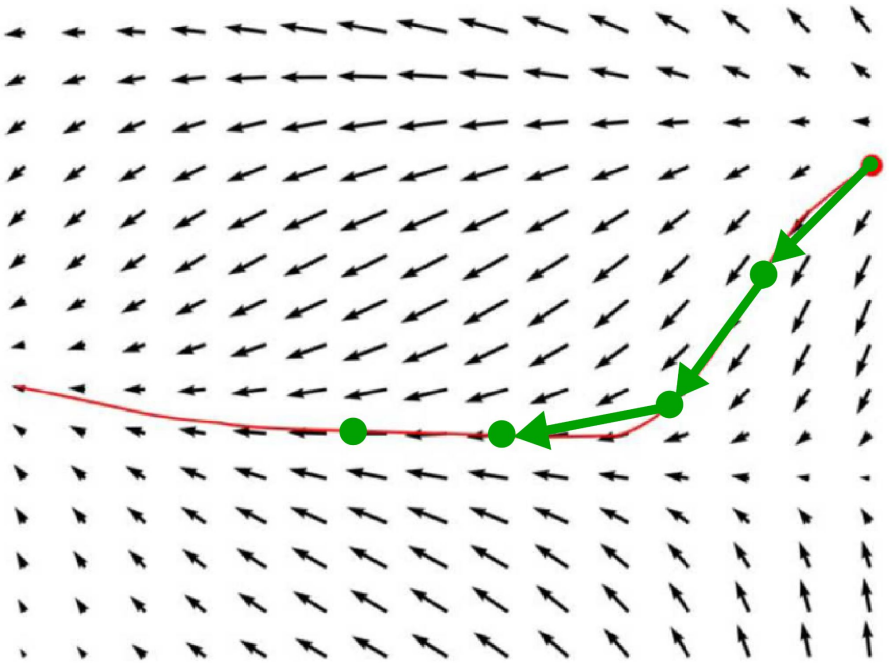
Rendering classics (6)

- **Towards feature visualization**
  - Line integral convolution



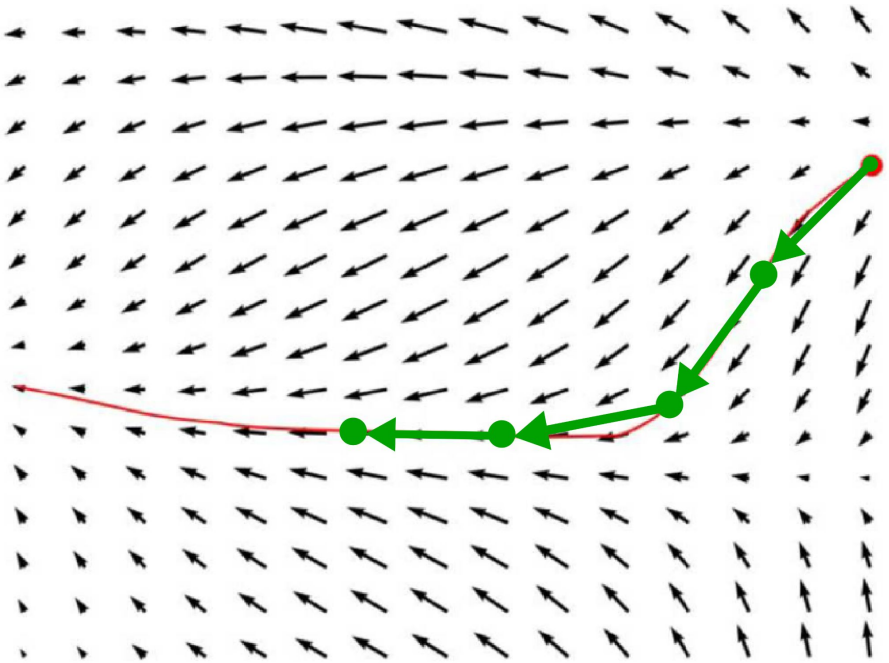
Rendering classics (6)

- **Towards feature visualization**
  - Line integral convolution



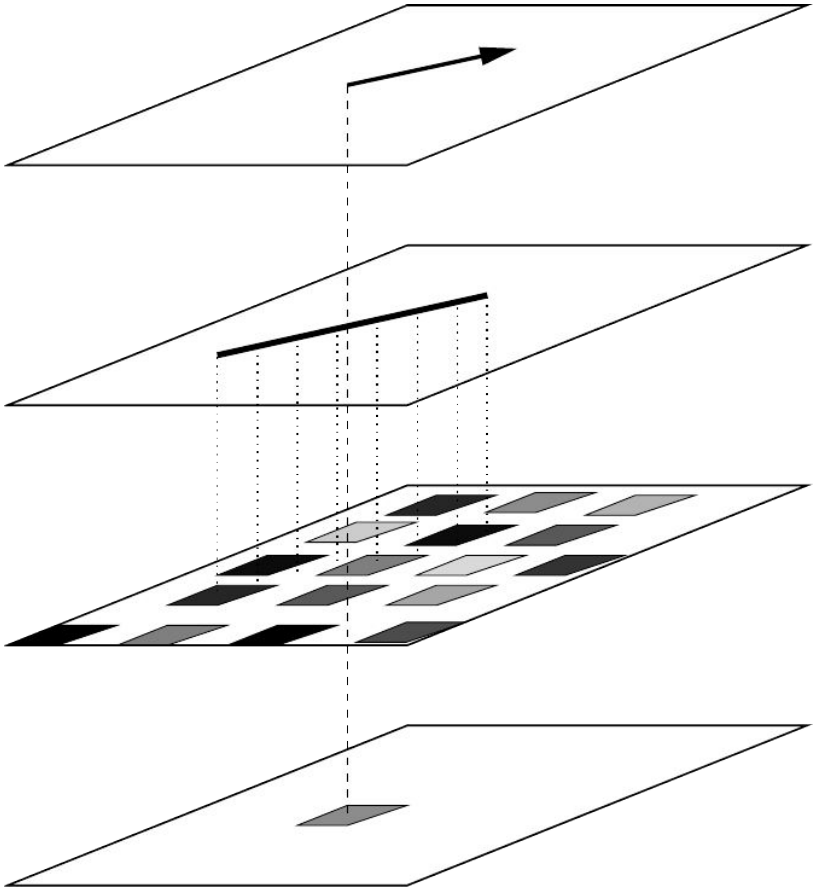
Rendering classics (6)

- **Towards feature visualization**
  - Line integral convolution



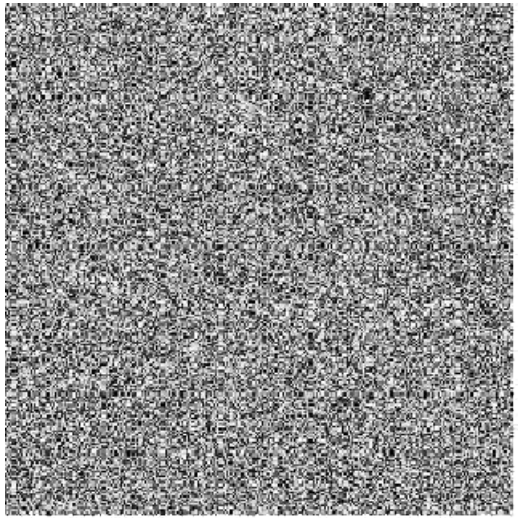
Rendering classics (6)

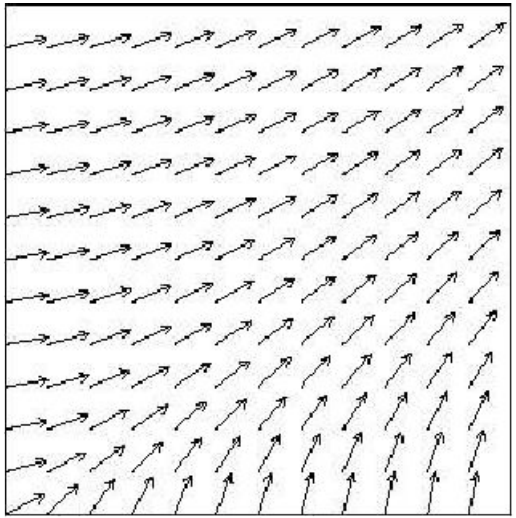
- **Towards feature visualization**
  - Line integral convolution



Rendering classics (6)

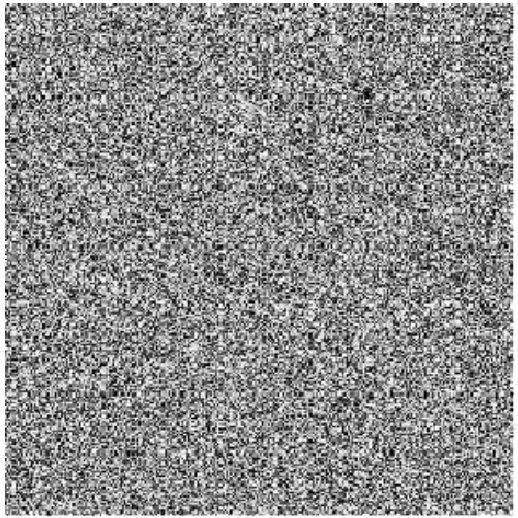
- **Towards feature visualization**
  - Line integral convolution

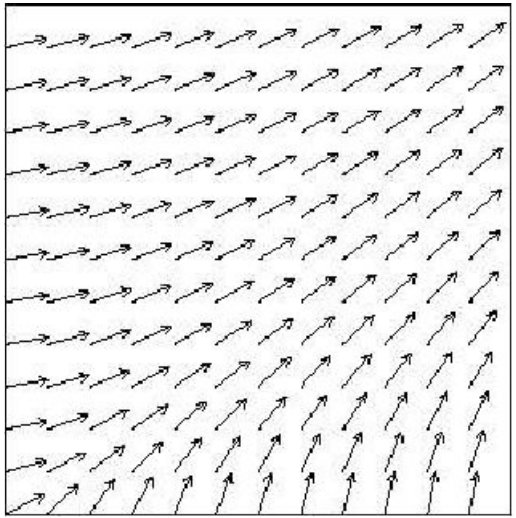




Rendering classics (6)

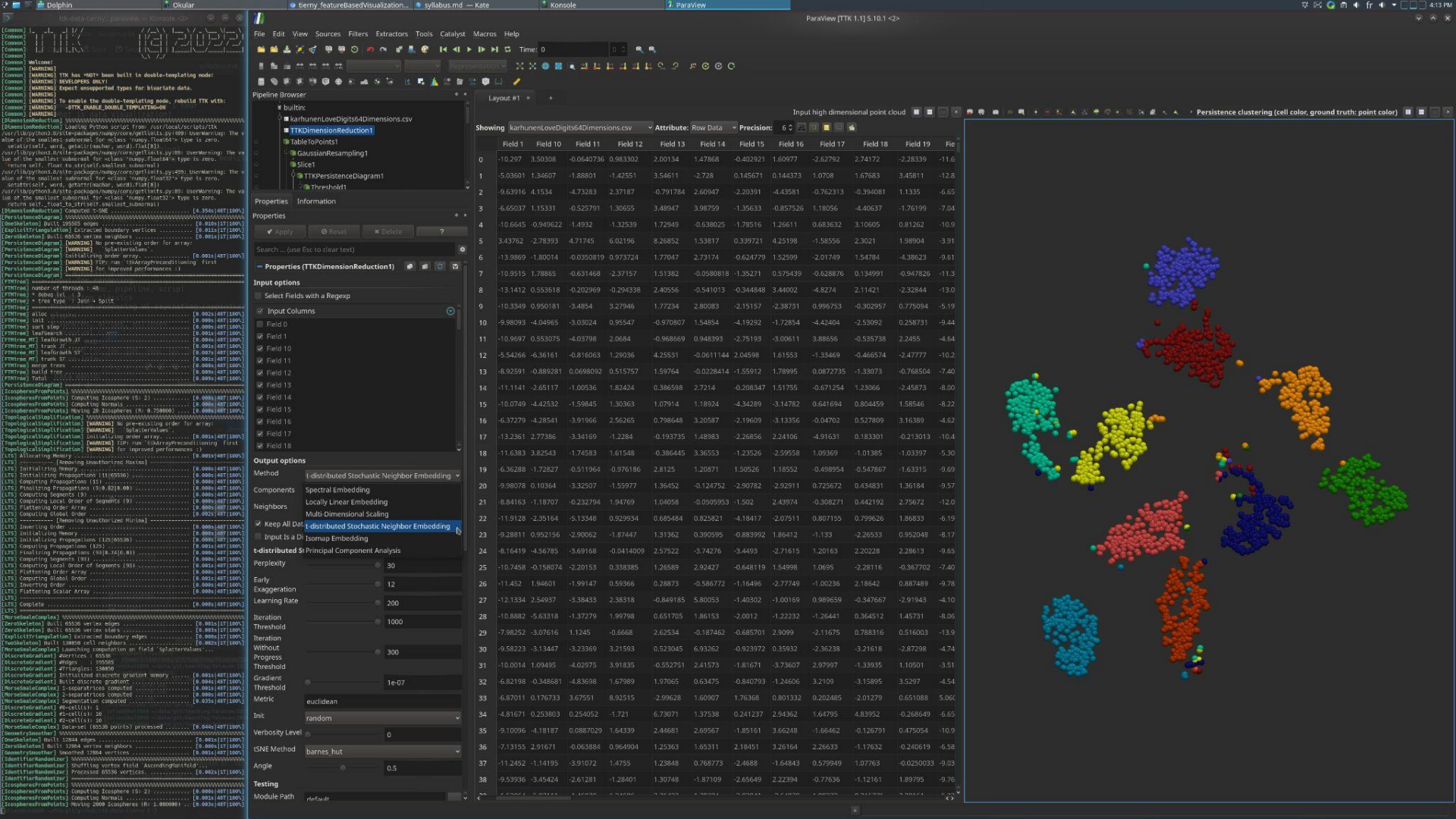
- **Towards feature visualization**
  - Line integral convolution





Data manipulation classics (1)

- Dimensionality reduction


Dolphin
Okular
tierny_featureBasedVisualization...
syllabus.md — Kate
Konsole
ParaView
ParaView [TTK 1.1] 5.10.1 <2>
File Edit View Sources Filters Extractors Tools Catalyst Macros Help
Time: 0
Pipeline Browser
builtin:
karhunenLoveDigits64Dimensions.csv
TTKDimensionReduction1
TableToPoints1
GaussianResampling1
Slice1
TTKPersistenceDiagram1
Threshold1
Properties Information
Properties
Apply Reset Delete ?
Search ... (use Esc to clear text)
Properties (TTKDimensionReduction1)
Input options
Select Fields with a Regexp
Input Columns
Field 0
Field 1
Field 10
Field 11
Field 12
Field 13
Field 14
Field 15
Field 16
Field 17
Field 18
Output options
Method
t-distributed Stochastic Neighbor Embedding
Components
Spectral Embedding
Neighbors
Locally Linear Embedding
Multi-Dimensional Scaling
t-distributed Stochastic Neighbor Embedding
Isomap Embedding
Principal Component Analysis
Perplexity 30
Early Exaggeration 12
Learning Rate 200
Iteration Threshold 1000
Iteration Without Progress Threshold 300
Gradient Threshold 1e-07
Metric euclidean
Init random
Verbosity Level 0
tSNE Method barnes_hut
Angle 0.5
Testing
Module Path default
Layout #1
Input high dimensional point cloud
Persistence clustering (cell color, ground truth: point color)
Showing karhunenLoveDigits64Dimensions.csv
Attribute: Row Data
Precision: 6
Field 1 Field 10 Field 11 Field 12 Field 13 Field 14 Field 15 Field 16 Field 17 Field 18 Field 19
0 -10.297 3.50308 -0.0640736 0.983302 2.00134 1.47868 -0.402921 1.60977 -2.62792 2.74172 -2.28339
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5 3.43762 -2.78393 4.71745 6.02196 8.26852 1.53817 0.339721 4.25198 -1.58556 2.3021 1.98904
6 -13.9869 -1.80014 -0.0350819 0.973724 1.77047 2.73174 -0.624779 1.52599 -2.01749 1.54784 -4.38623
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11 -10.9697 0.553075 -4.03798 2.0684 -0.968669 0.948393 -2.75193 -3.00611 3.88656 -0.535738 2.2455
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Data manipulation classics (2)

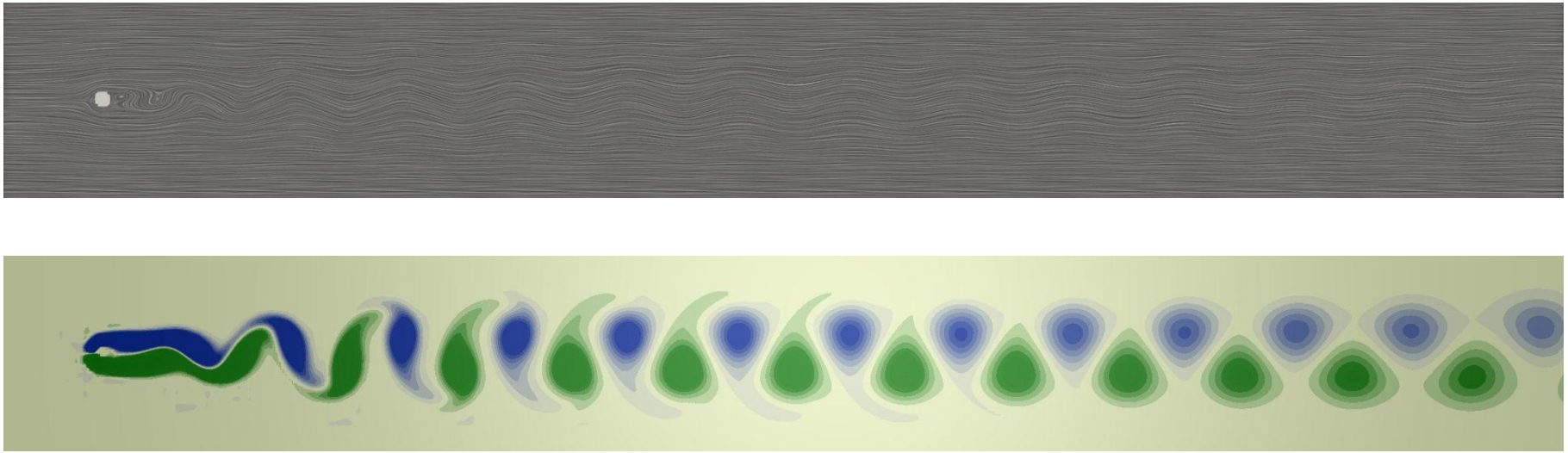
- Derived descriptors

Data manipulation classics (2)

- Derived descriptors

Data manipulation classics (2)

- Derived descriptors

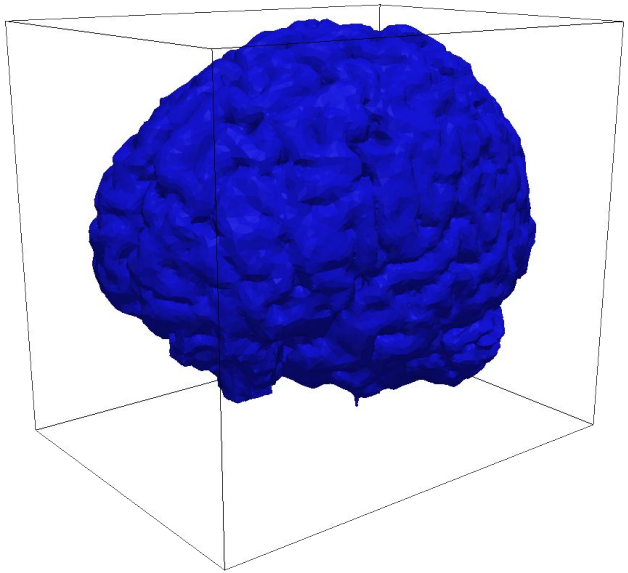


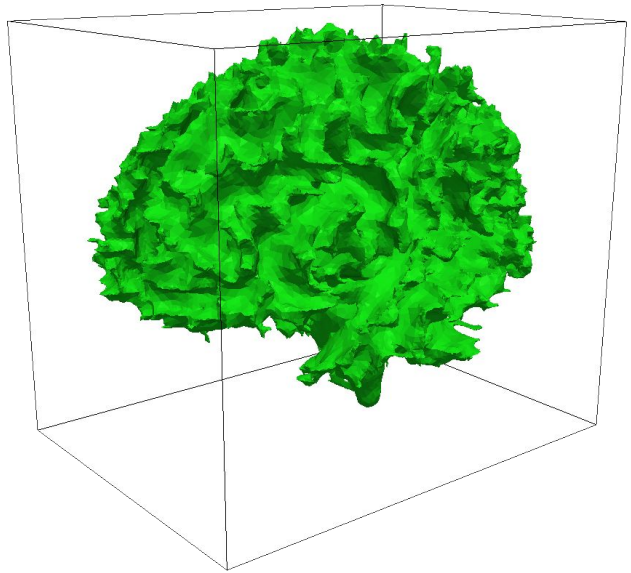
Data manipulation classics (3)

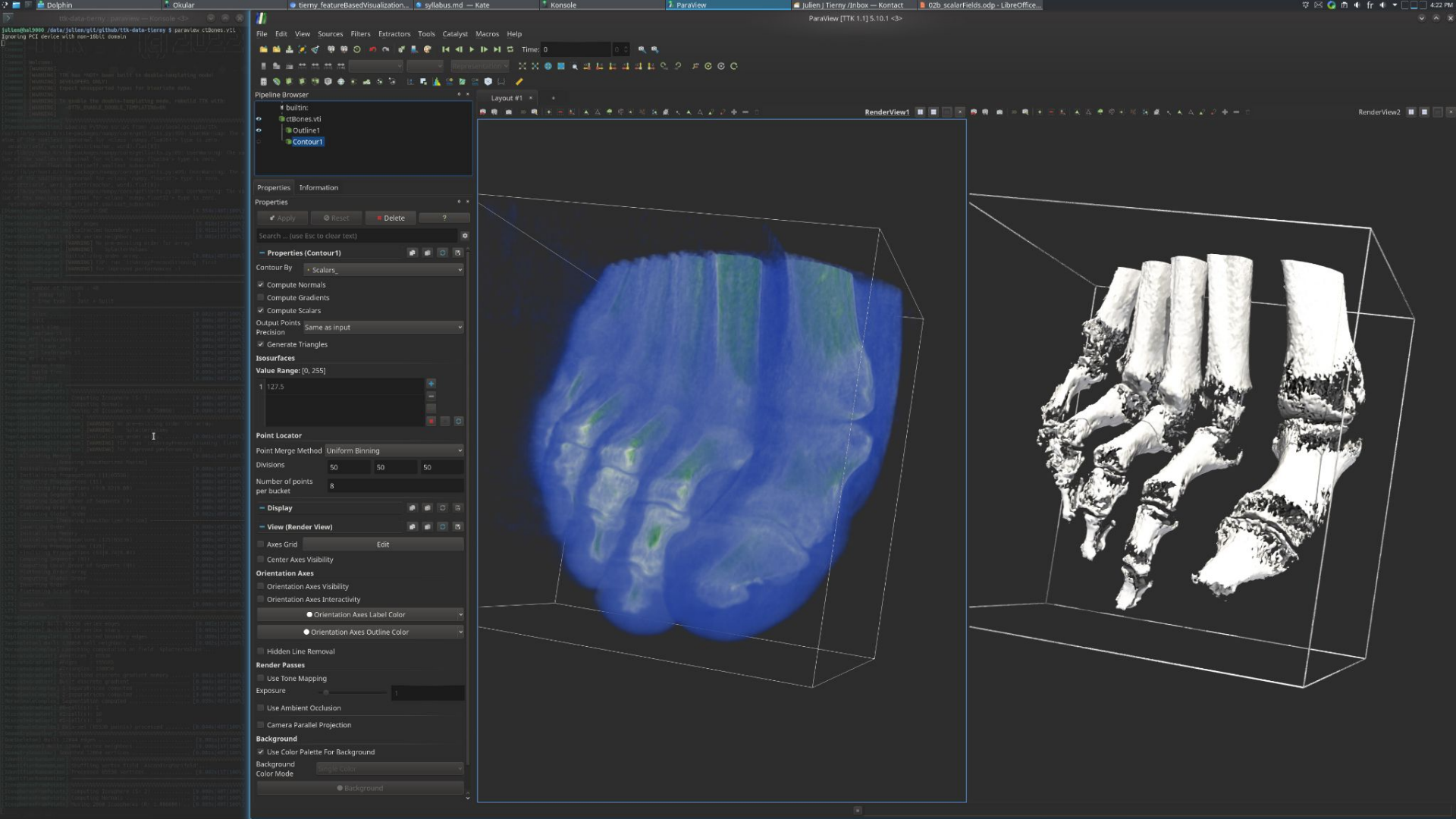
- Level sets

Data manipulation classics (3)

- Level sets






Dolphin
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Konsole
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Ignoring PCI device with non-16bit domain
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Pipeline Browser
builtin:
ctBones.vti
Outline1
Contour1
Properties Information
Properties
Apply Reset Delete ?
Search ... (use Esc to clear text)
Properties (Contour1)
Contour By Scalars_
Compute Normals
Compute Gradients
Compute Scalars
Output Points Precision Same as input
Generate Triangles
Isosurfaces
Value Range: [0, 255]
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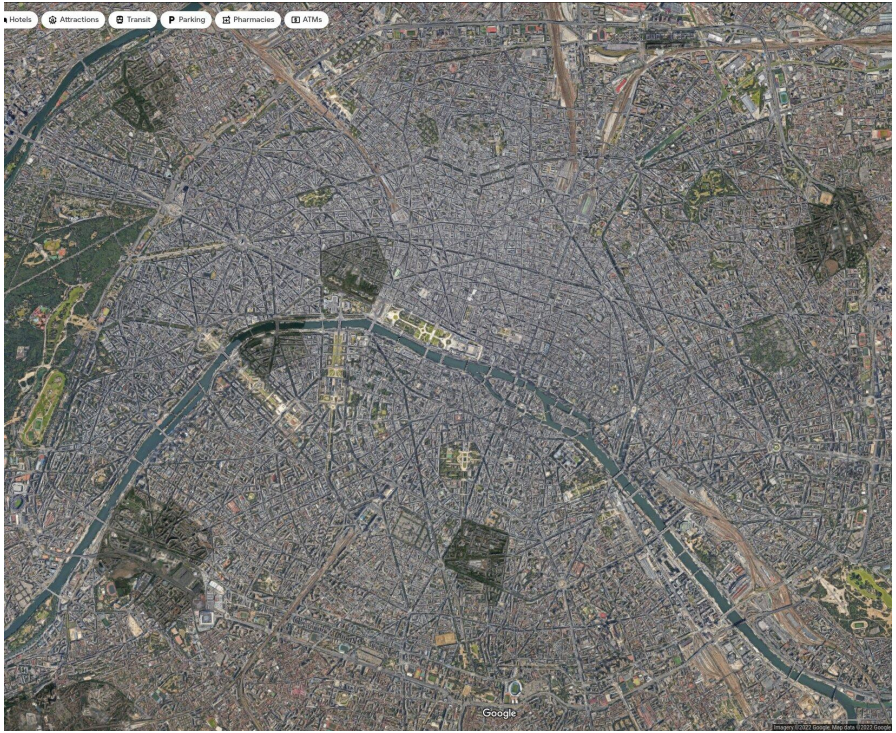
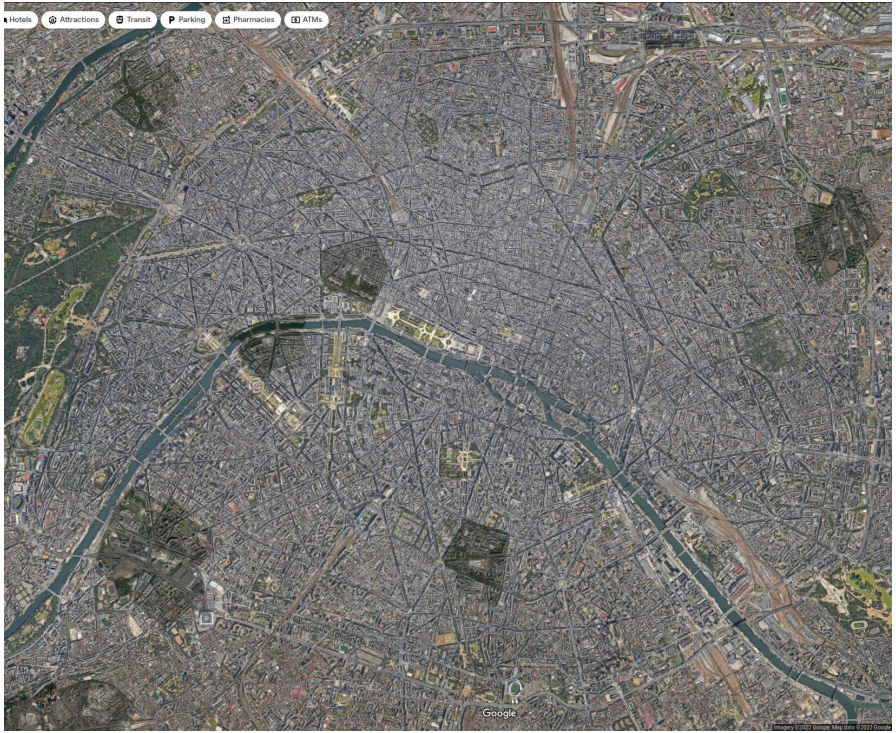
Point Locator
Point Merge Method Uniform Binning
Divisions 50 50 50
Number of points per bucket 8
Display
View (Render View)
Axes Grid Edit
Center Axes Visibility
Orientation Axes
Orientation Axes Visibility
Orientation Axes Interactivity
Orientation Axes Label Color
Orientation Axes Outline Color
Hidden Line Removal
Render Passes
Use Tone Mapping
Exposure 1
Use Ambient Occlusion
Camera Parallel Projection
Background
Use Color Palette For Background
Background Color Mode Single Color
Background
Layout #1
RenderView1
RenderView2

Towards a “data map”

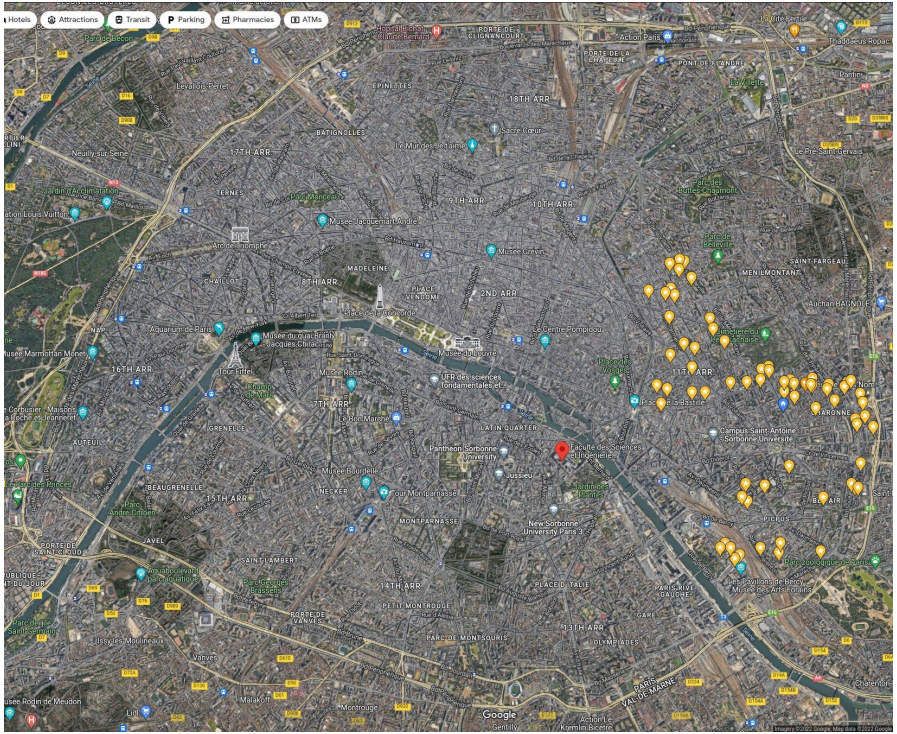


Raw data

Towards a “data map”

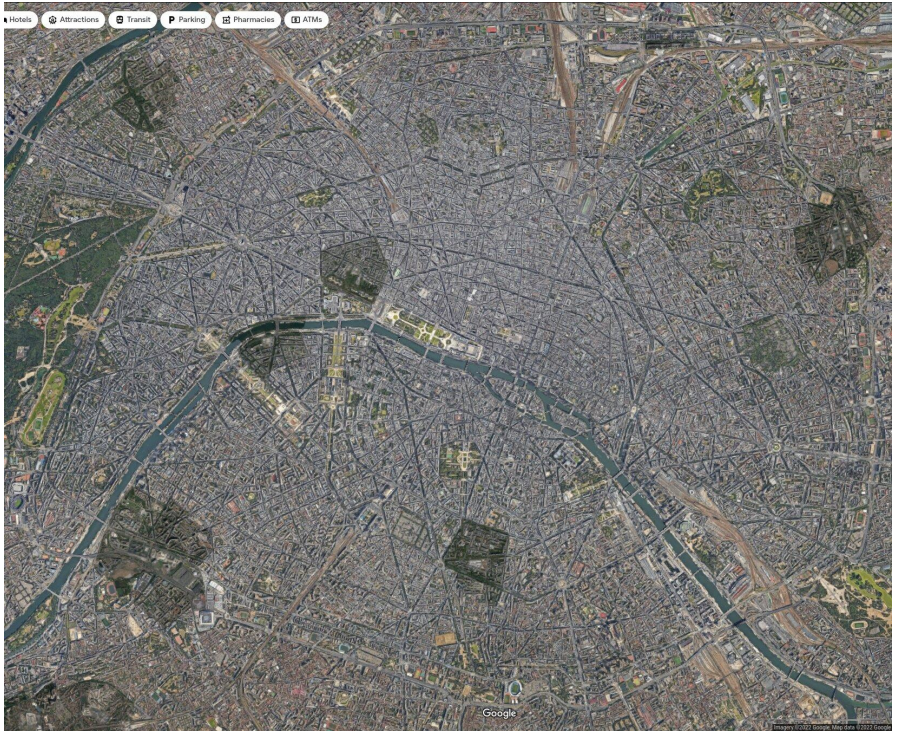


Raw data

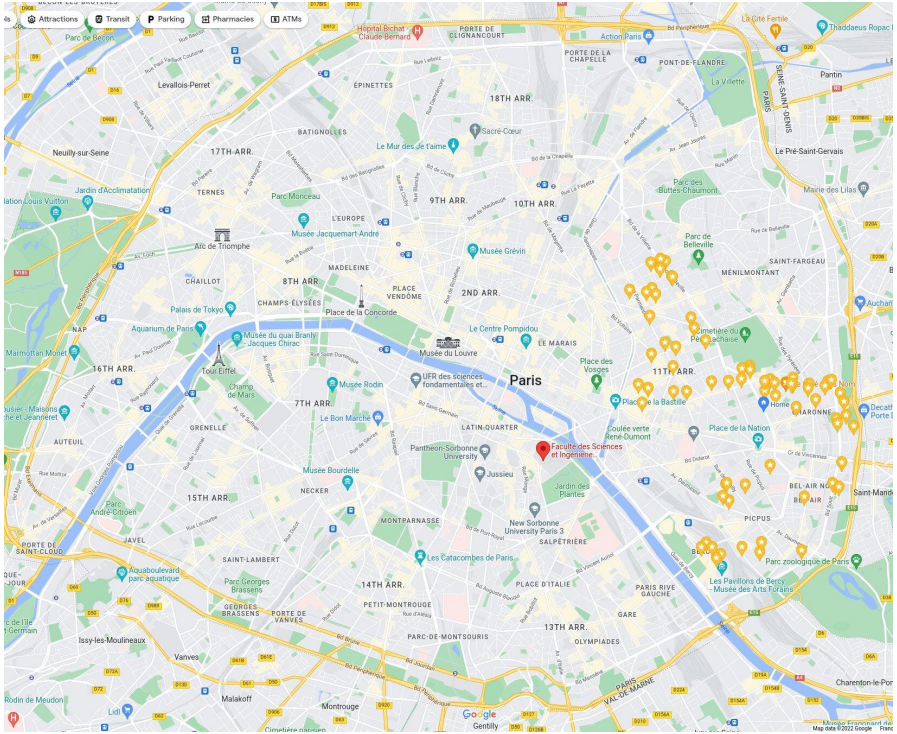


Feature extraction

Towards a “data map”

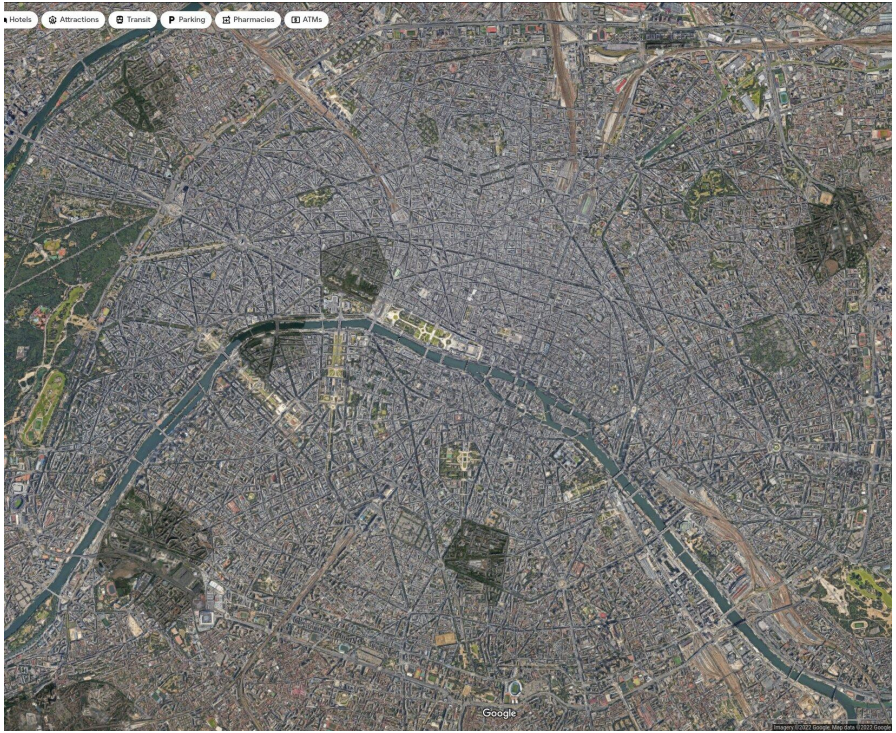


Raw data



Structural data representation

Towards a “data map”



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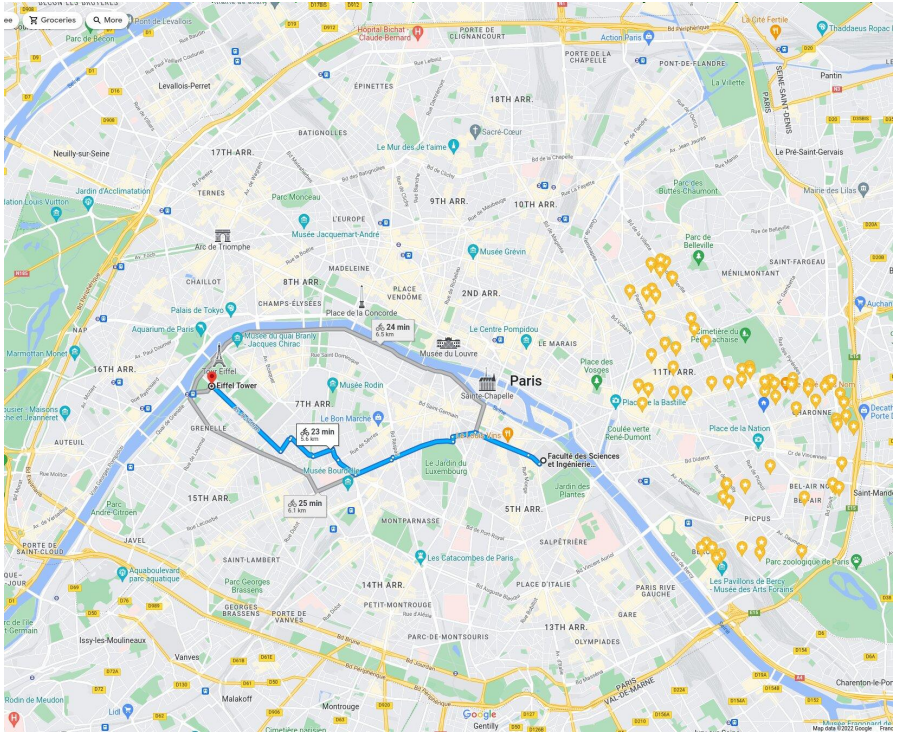
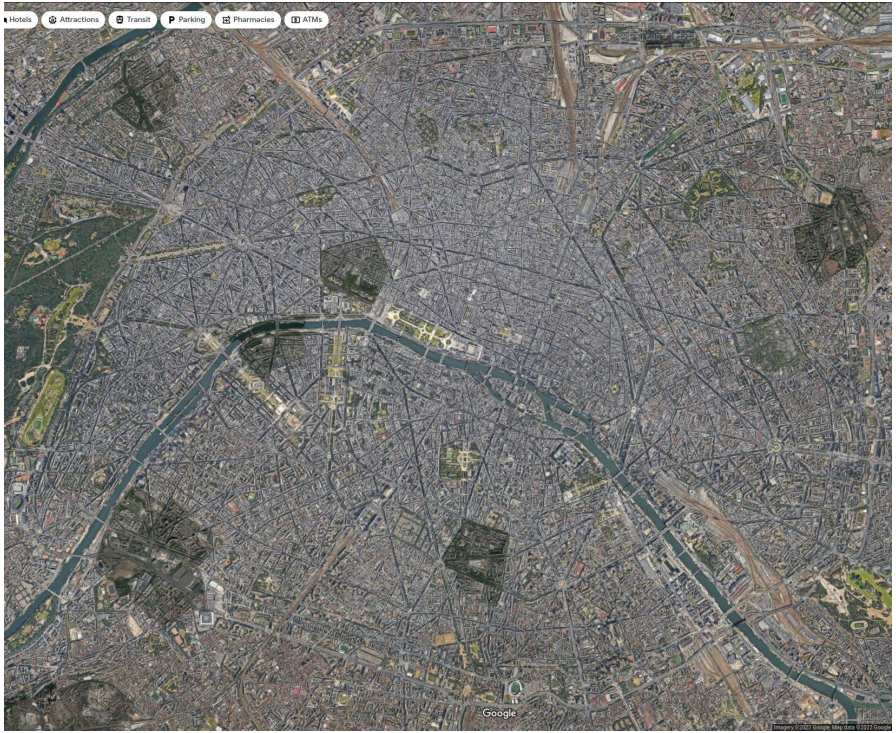


Structure extraction

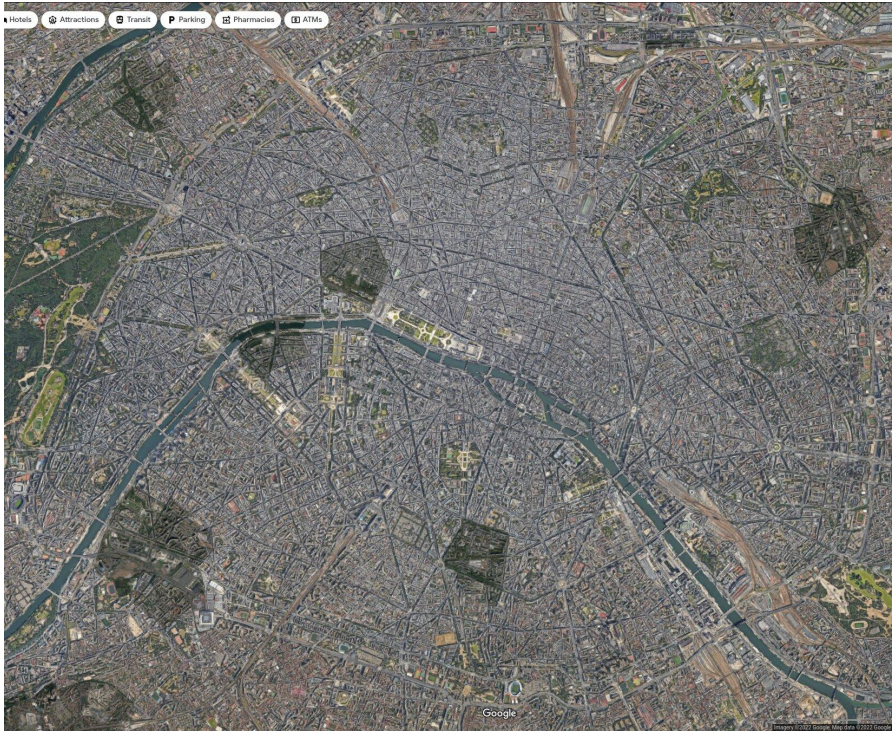
Towards a “data map”



Raw data

Structure extraction & selection

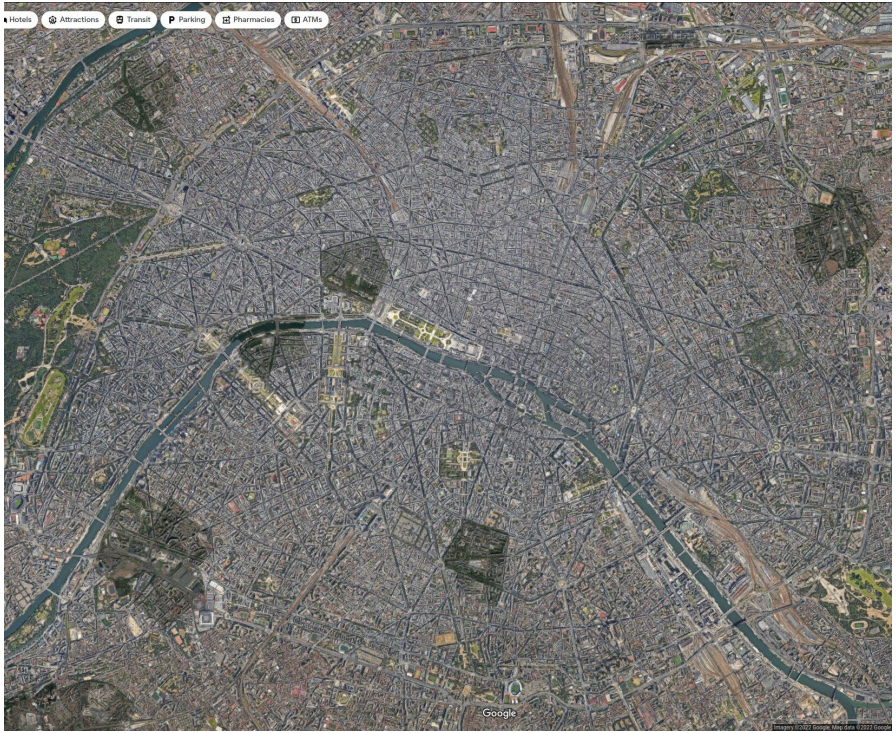
Towards a “data map”



Raw data

Structure extraction & derived indicator

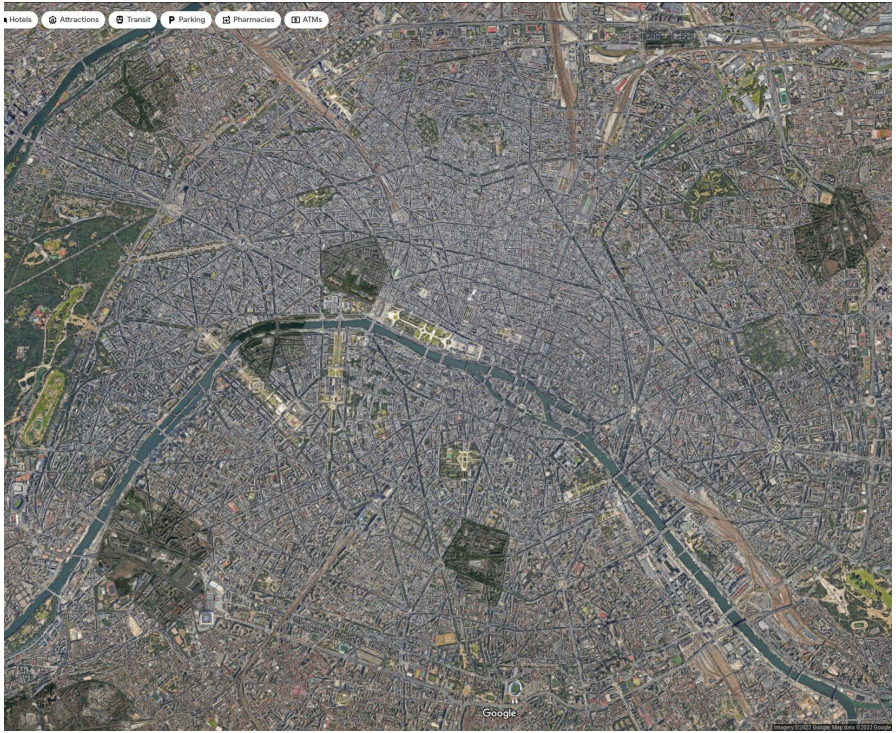
Towards a “data map”



Raw data

Structure comparison

Towards a “data map”

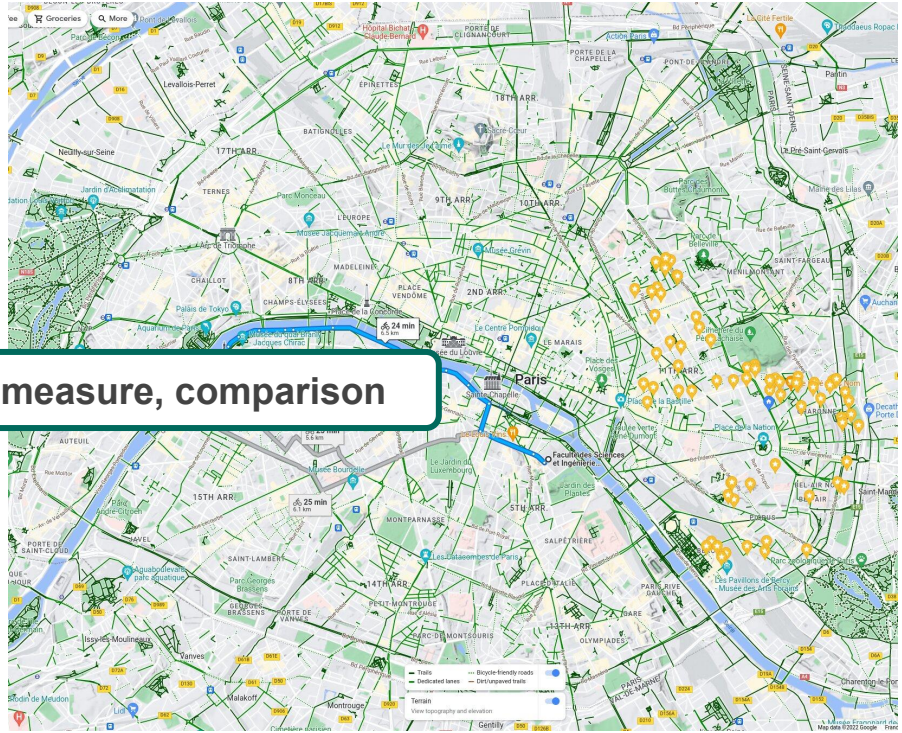


Raw data

Structure comparison

Towards a “data map”

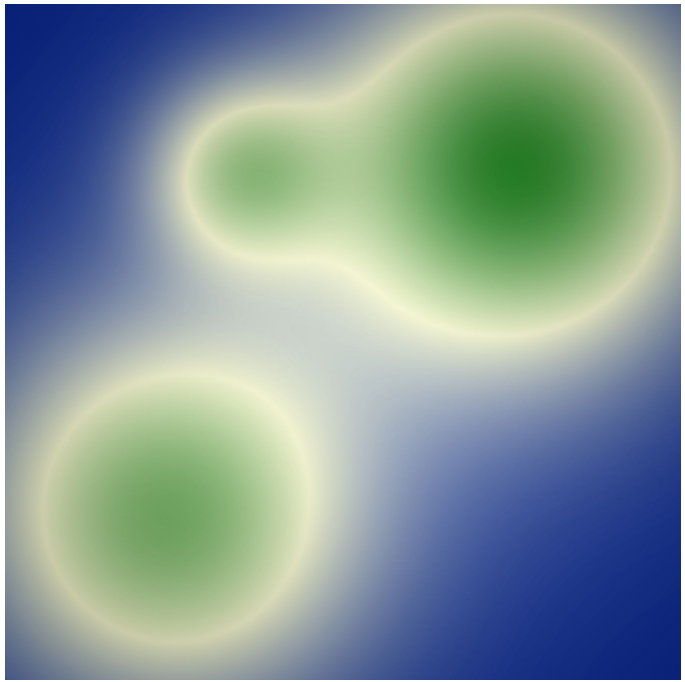
Raw data



Structure comparison

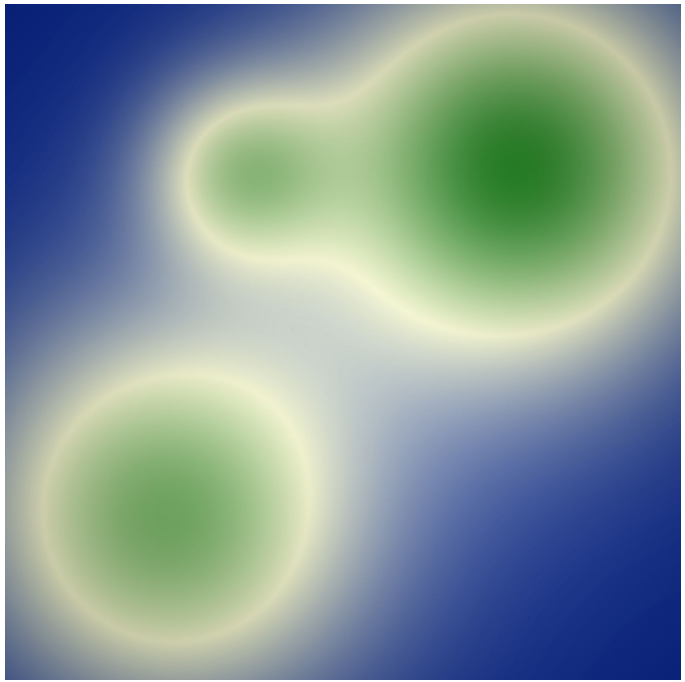
Interpretation, selection, measure, comparison

Towards a “data map”



Raw data

Towards a “data map”



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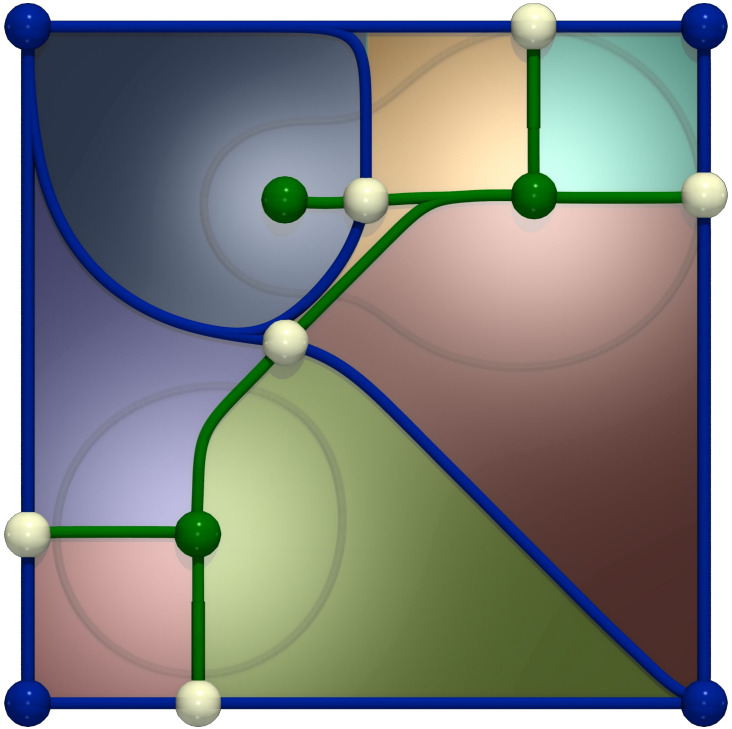
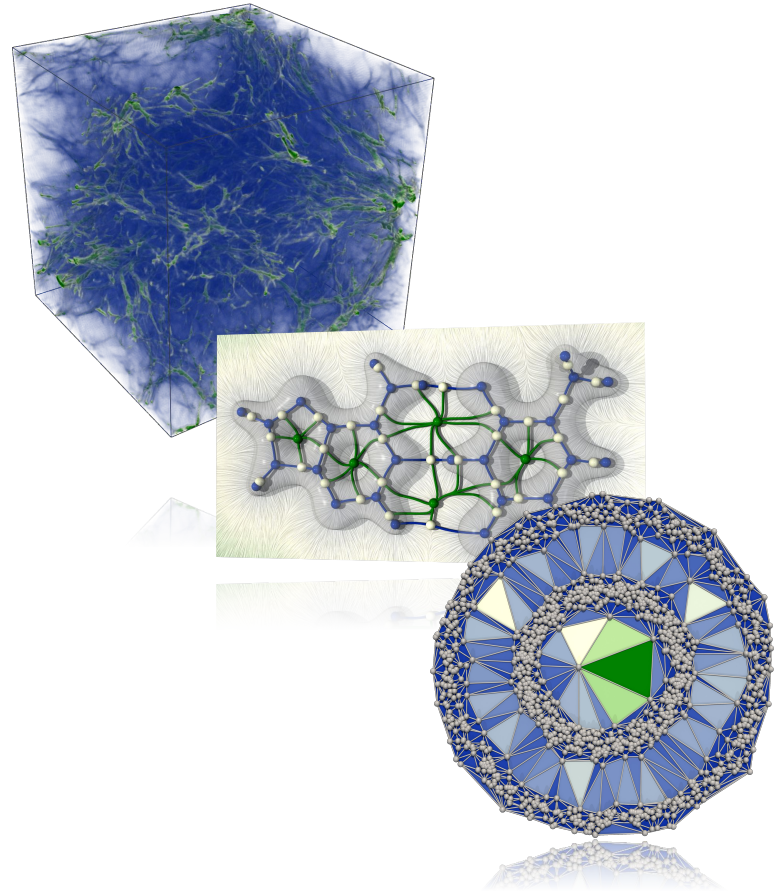


Structural representation

What is Topological Data Analysis?

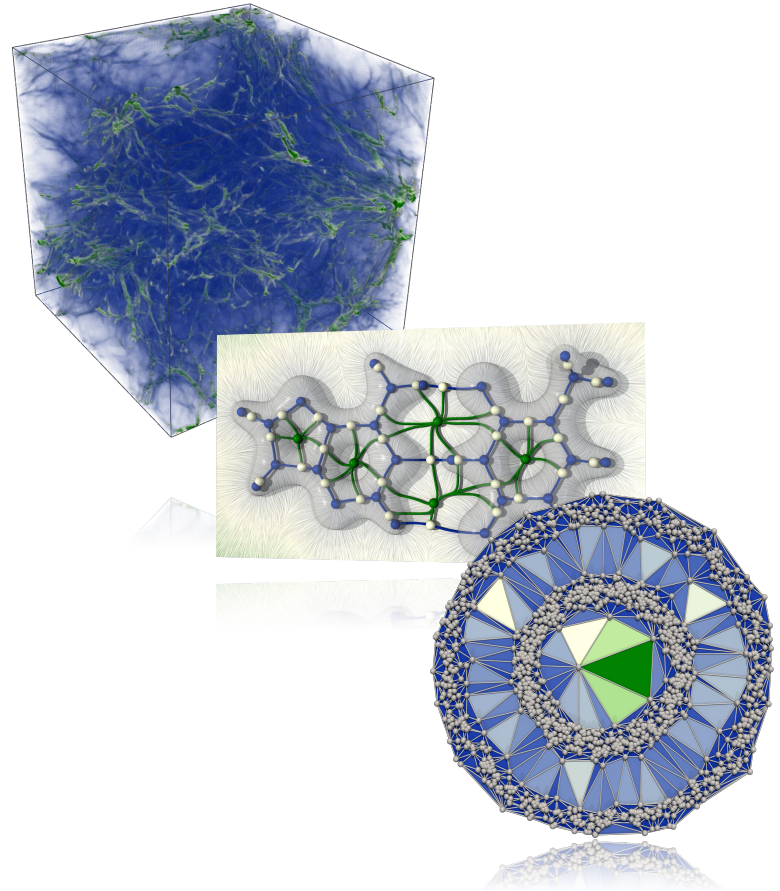
- **Context**
  - Data
  - On “meshes”, or “meshable” things



What is Topological Data Analysis?

- **Context**
  - Data
  - On “meshes”, or “meshable” things

- **Swiss-army knife for feature extraction**
  - Points, curves, surfaces, volumes, …
  - Robustness
  - Multi-scale nature
  - From raw data to features of interest

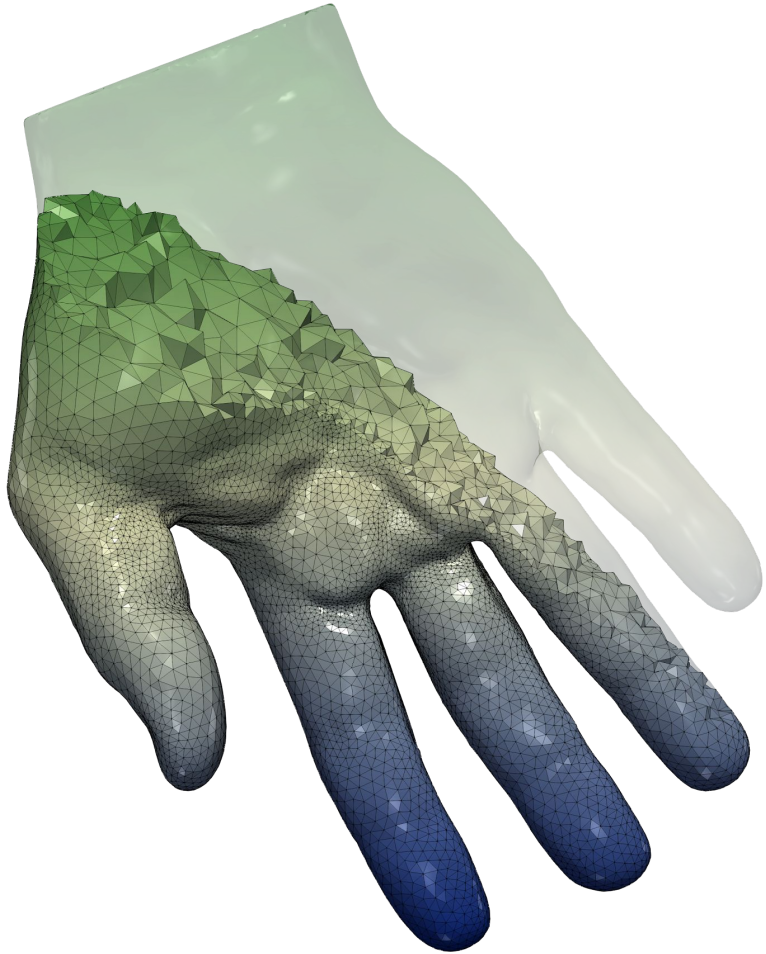


Piecewise linear setting

- Input PL scalar data
  - $f : \mathcal{M} \to \mathbb{R}$

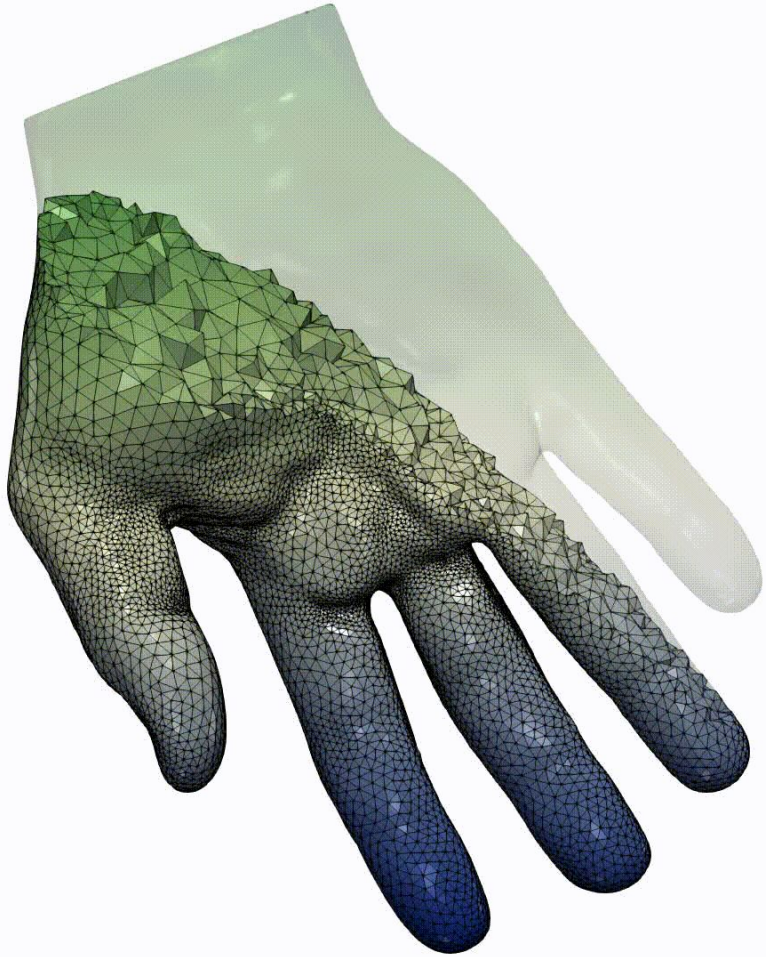
Piecewise linear setting

- **Input PL scalar data**
  - $f : \mathcal{M} \to \mathbb{R}$
  - $\mathcal{M}$: simplicial complex



Piecewise linear setting

- **Input PL scalar data**
  - $f : \mathcal{M} \to \mathbb{R}$
  - $\mathcal{M}$: simplicial complex
    - Triangulated surface
    - Tetrahedral volume
    - 2D pixel image
    - 3D voxel image
    - Point cloud data



Piecewise linear setting

- **Input PL scalar data**
  - $f : \mathcal{M} \to \mathbb{R}$
  - $\mathcal{M}$: simplicial complex
    - Triangulated surface
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    - 2D pixel image
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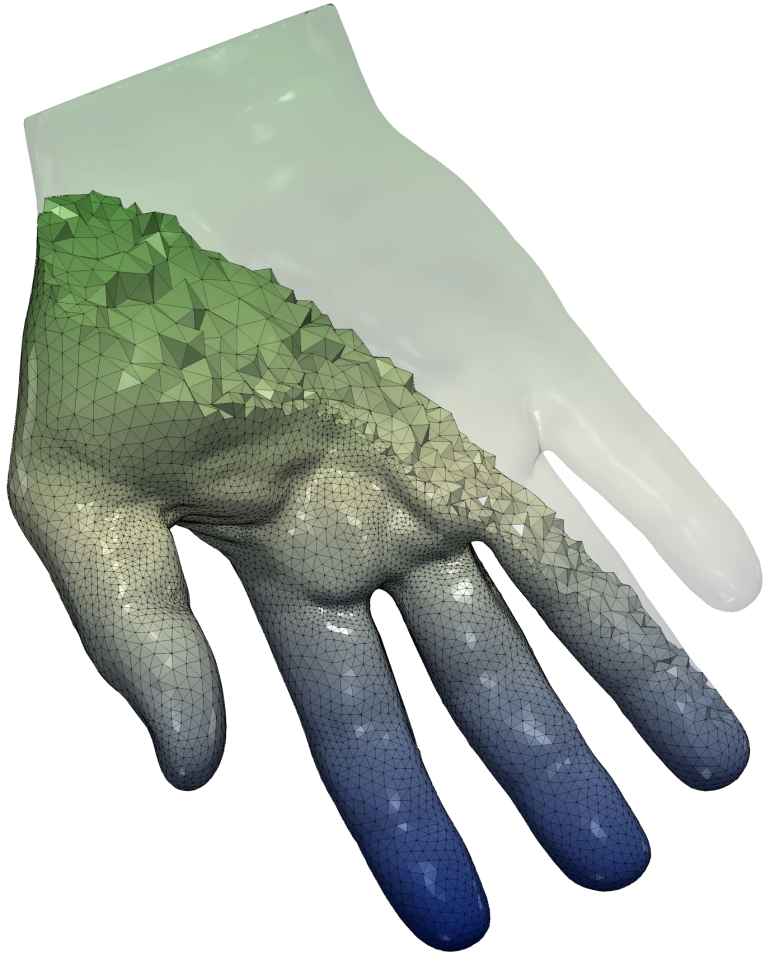


Piecewise linear setting

- Input PL scalar data
  - $f : \mathcal{M} \to \mathbb{R}$

- Topological abstractions

Piecewise linear setting

- Input PL scalar data
  - $f : \mathcal{M} \to \mathbb{R}$
- Topological abstractions

Piecewise linear setting

- Input PL scalar data
  - $f : \mathcal{M} \to \mathbb{R}$

- Topological abstractions

Piecewise linear setting

- Input PL scalar data
  - $f : \mathcal{M} \to \mathbb{R}$

- Topological abstractions

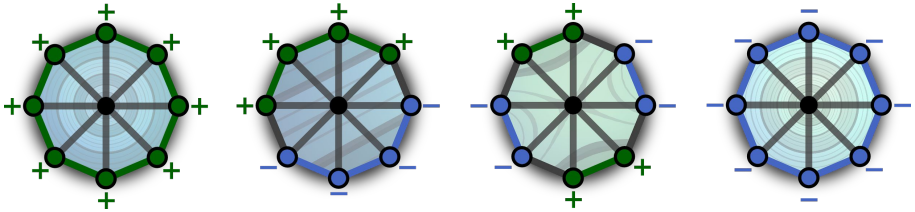
Piecewise linear setting

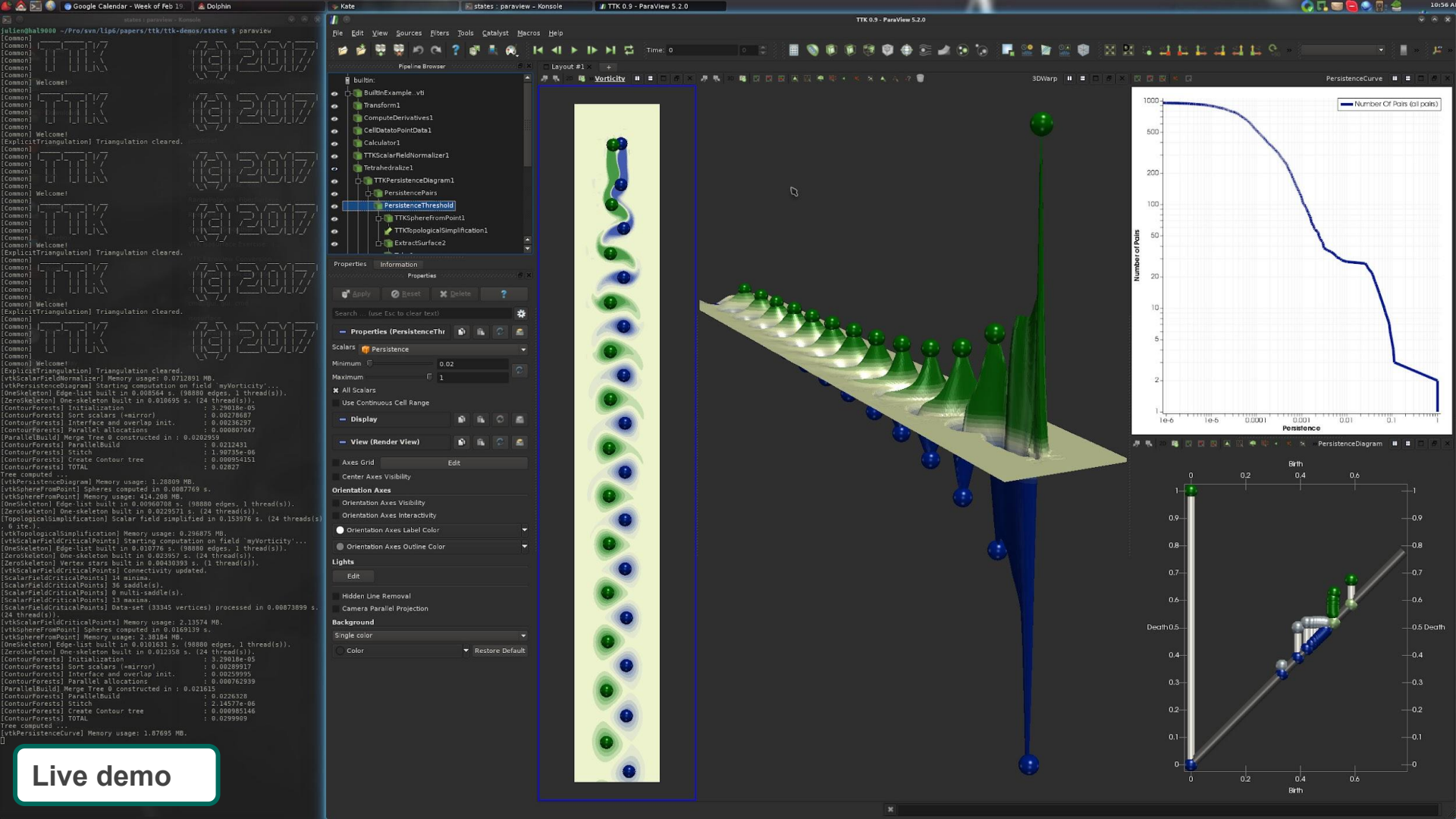
- **Input PL scalar data**
  - $f : \mathcal{M} \to \mathbb{R}$

- **Topological abstractions**
  - Critical points

Critical point extraction

- **Local link inspection**
  - Banchoff 1970




Live demo

Persistence diagram

- **Input PL scalar data**
  - $f : \mathcal{M} \to \mathbb{R}$

- **Topological abstractions**
  - Critical points

Persistence diagram

- **Input PL scalar data**
  - $f : \mathcal{M} \to \mathbb{R}$

- **Topological abstractions**
  - Critical points

Persistence diagram

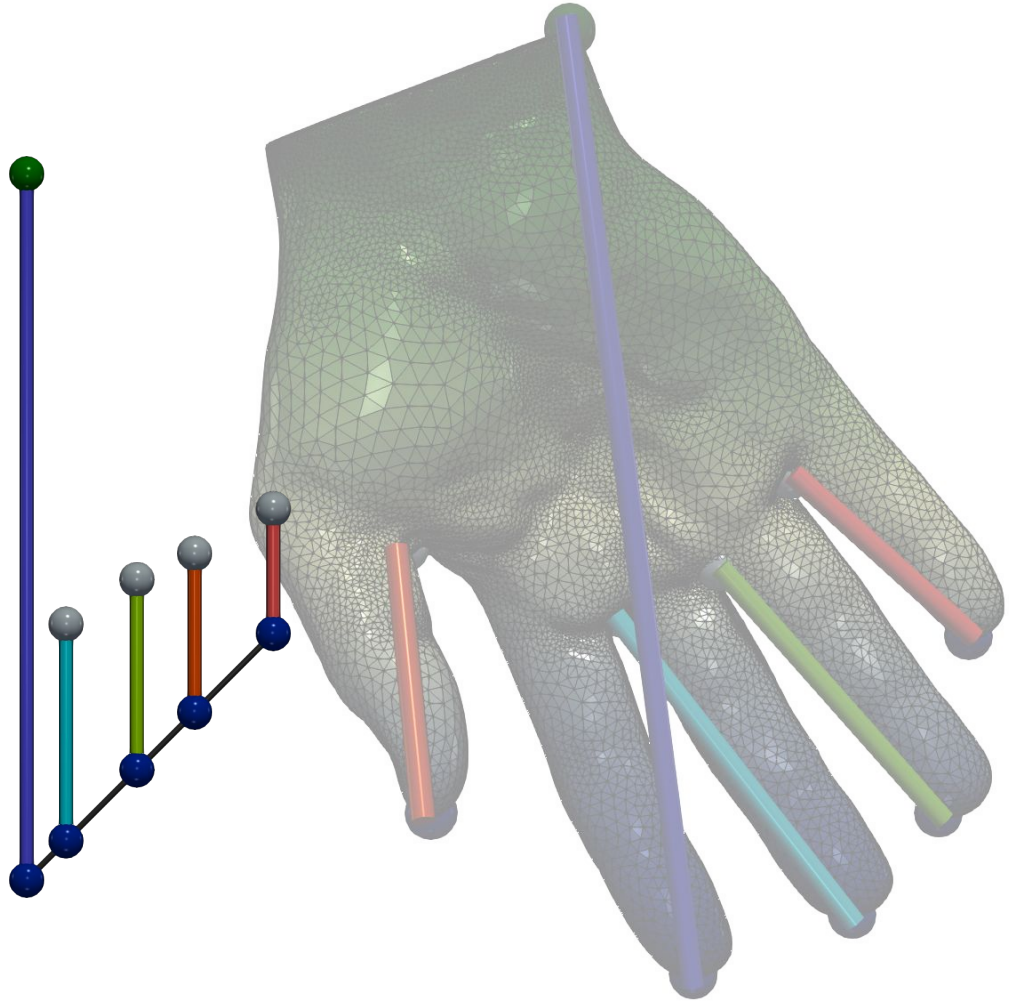
- **Input PL scalar data**
  - $f : \mathcal{M} \to \mathbb{R}$

- **Topological abstractions**
  - Critical points

Persistence diagram

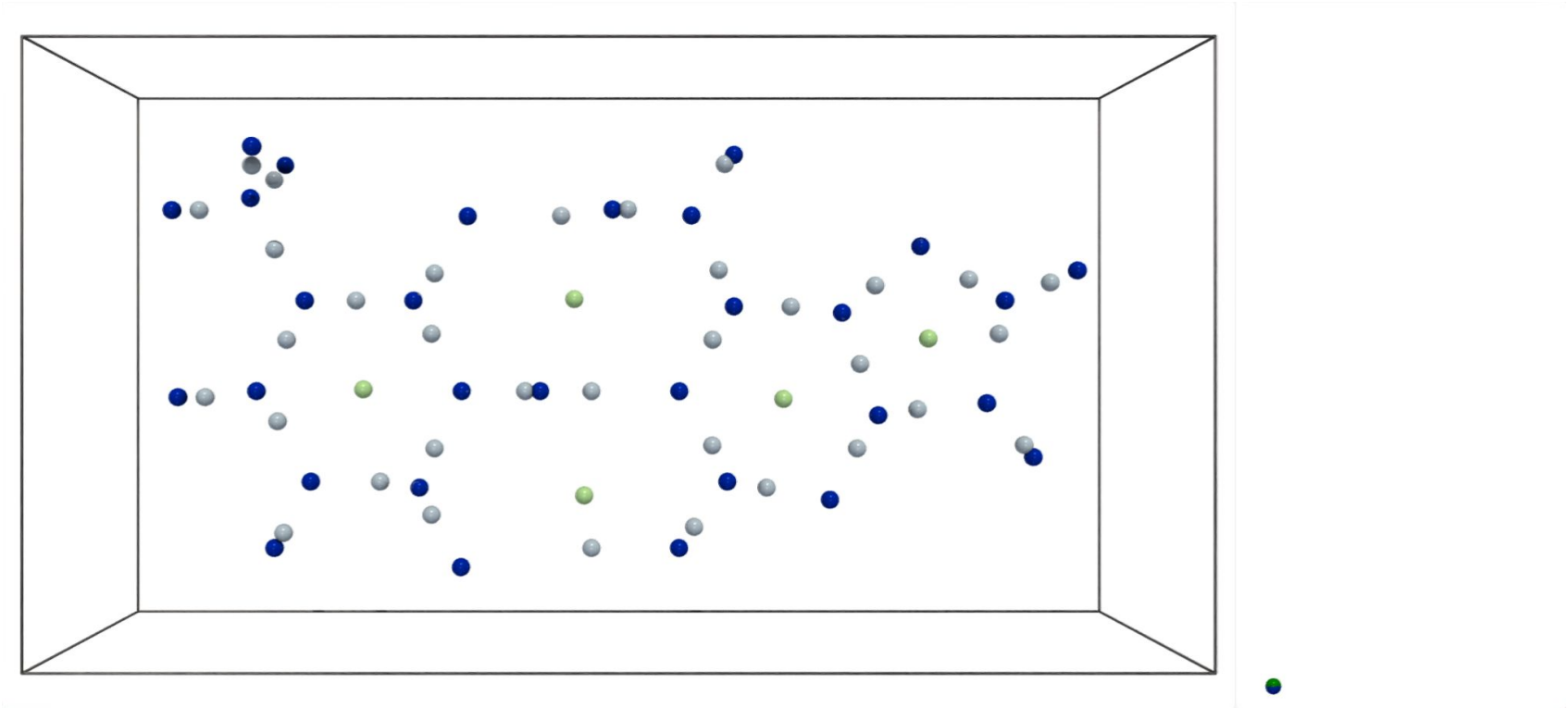
- **Input PL scalar data**
  - $f : \mathcal{M} \to \mathbb{R}$

- **Topological abstractions**
  - Critical points
  - Persistence diagrams



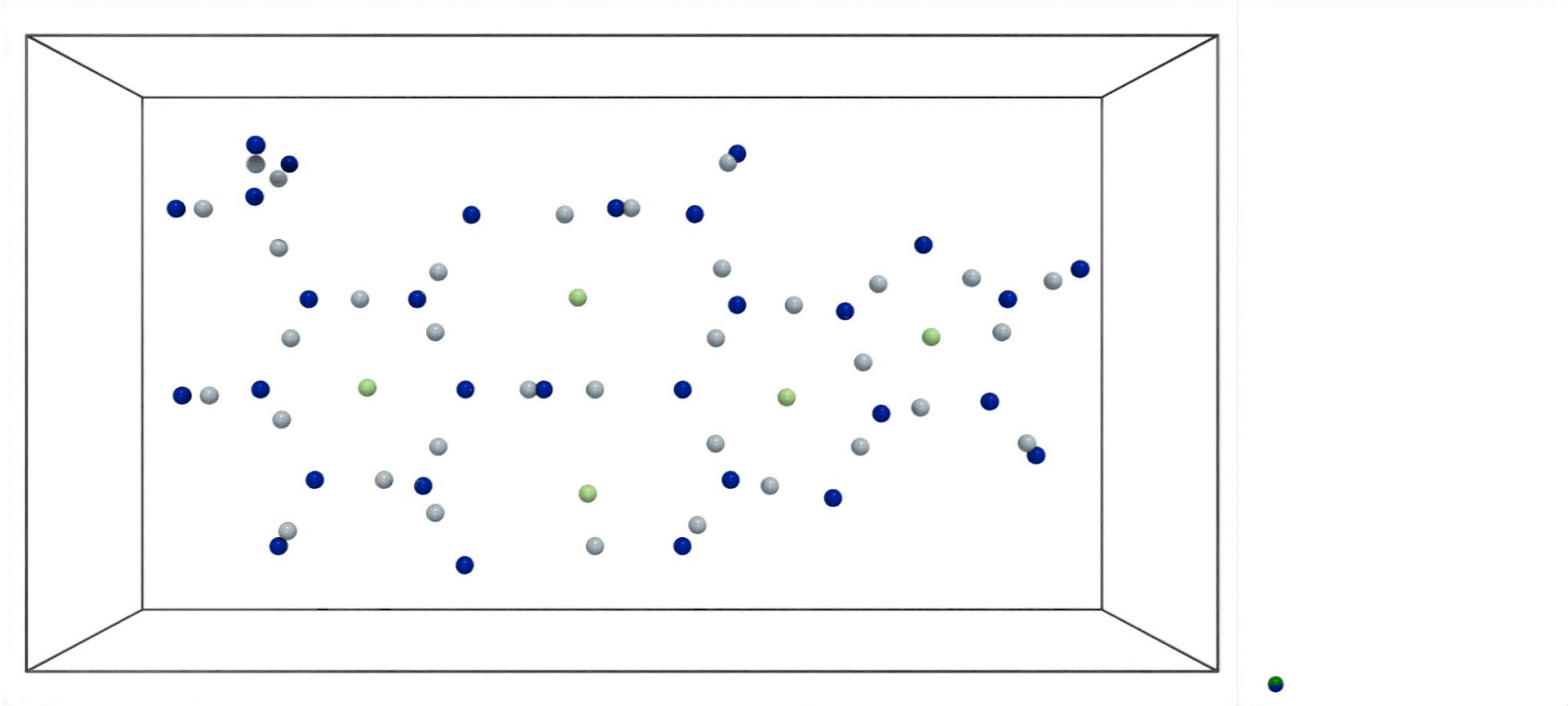
Persistence diagram

- Beyond connected components



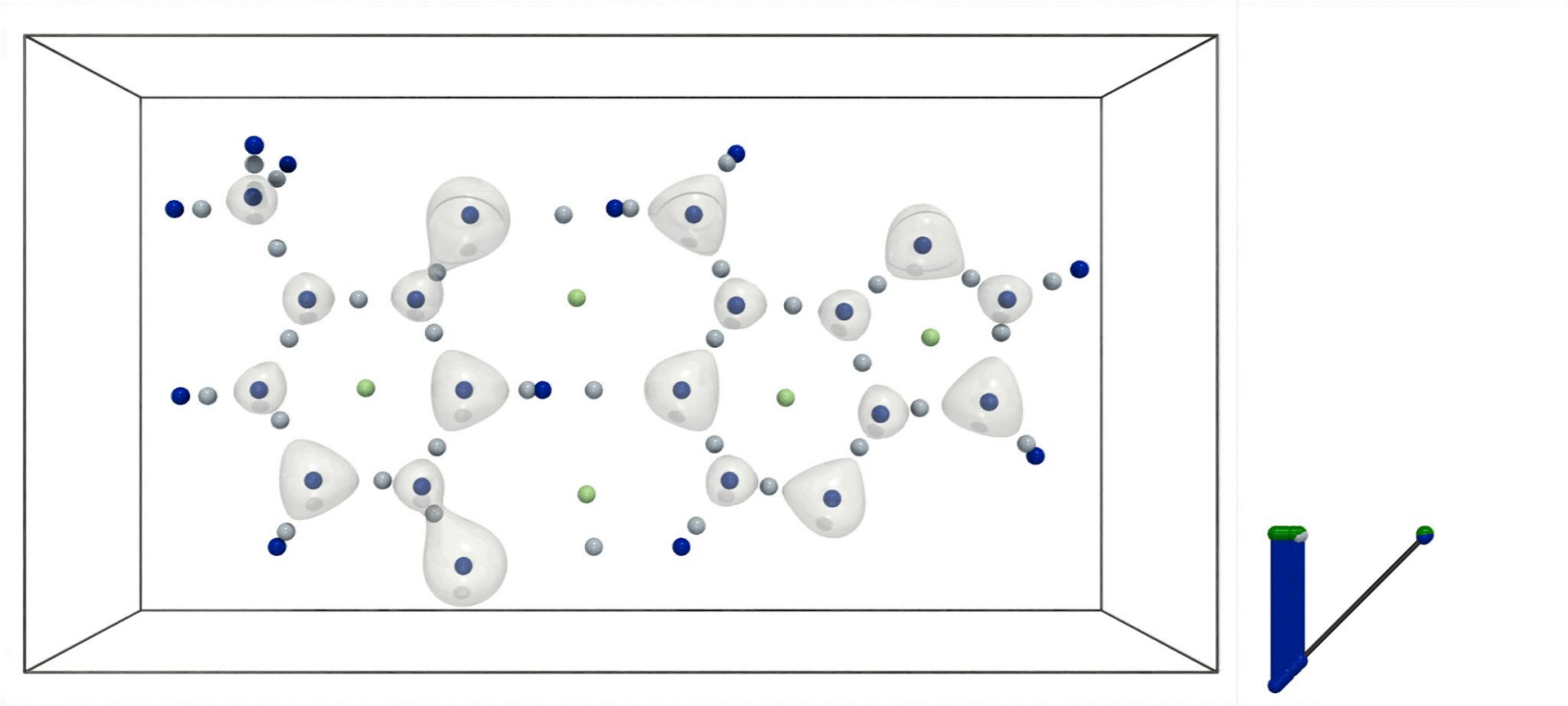
Persistence diagram

- Beyond connected components



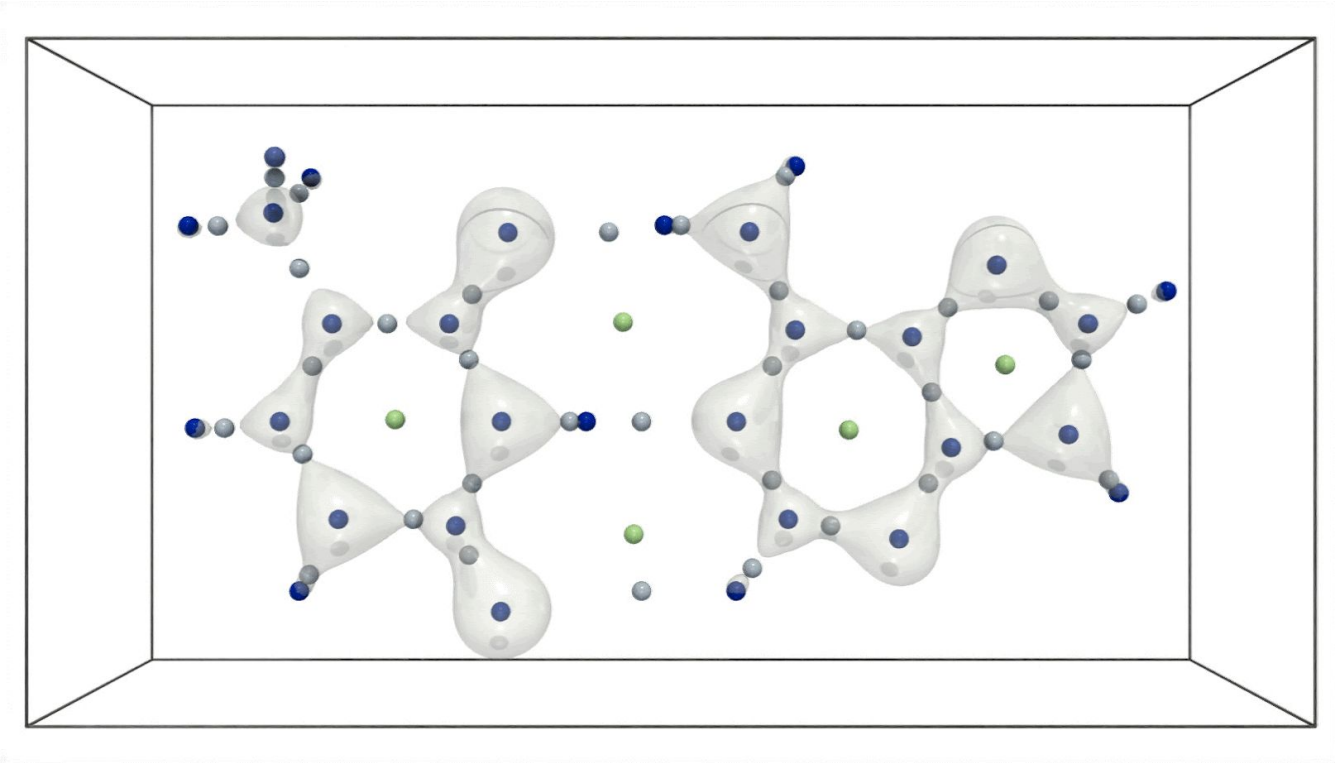
Persistence diagram

- Beyond connected components



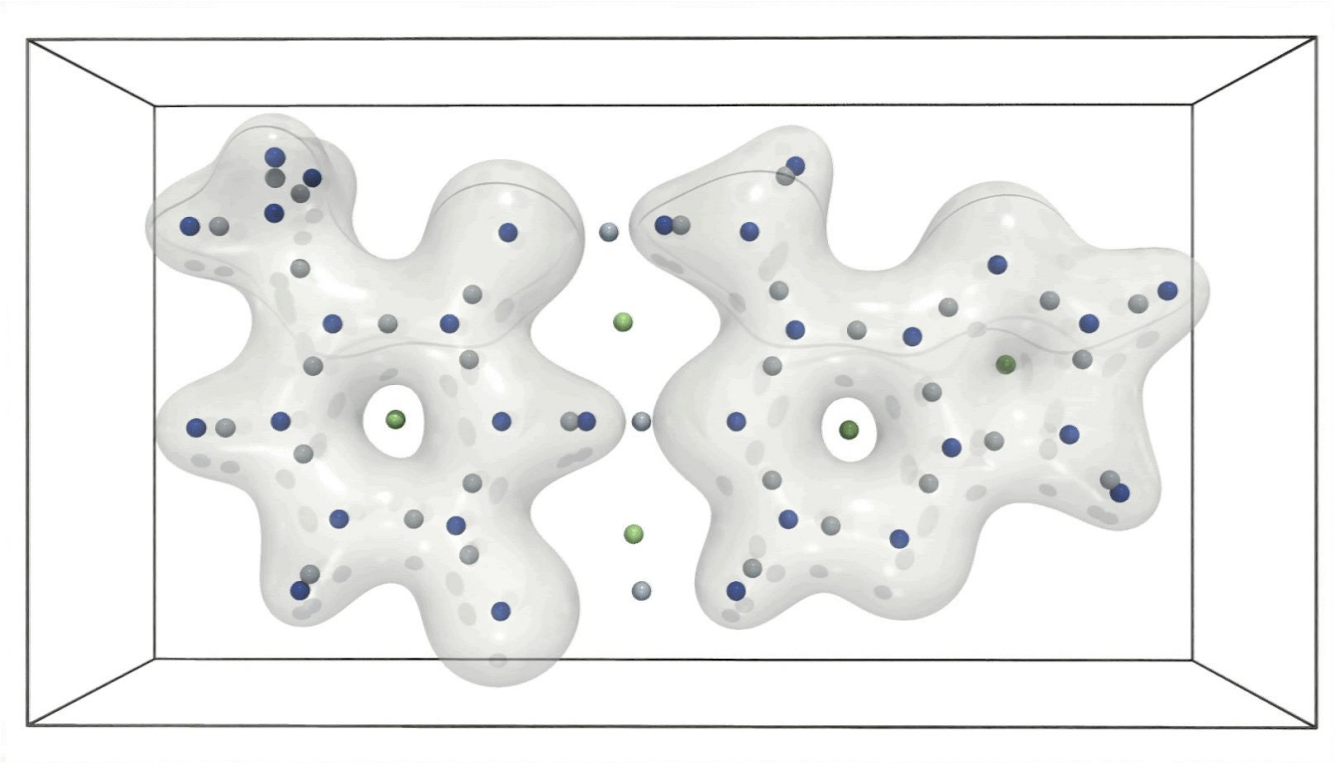
Persistence diagram

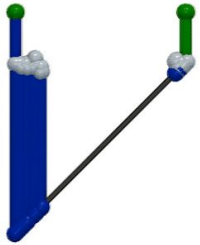
- Beyond connected components



Persistence diagram

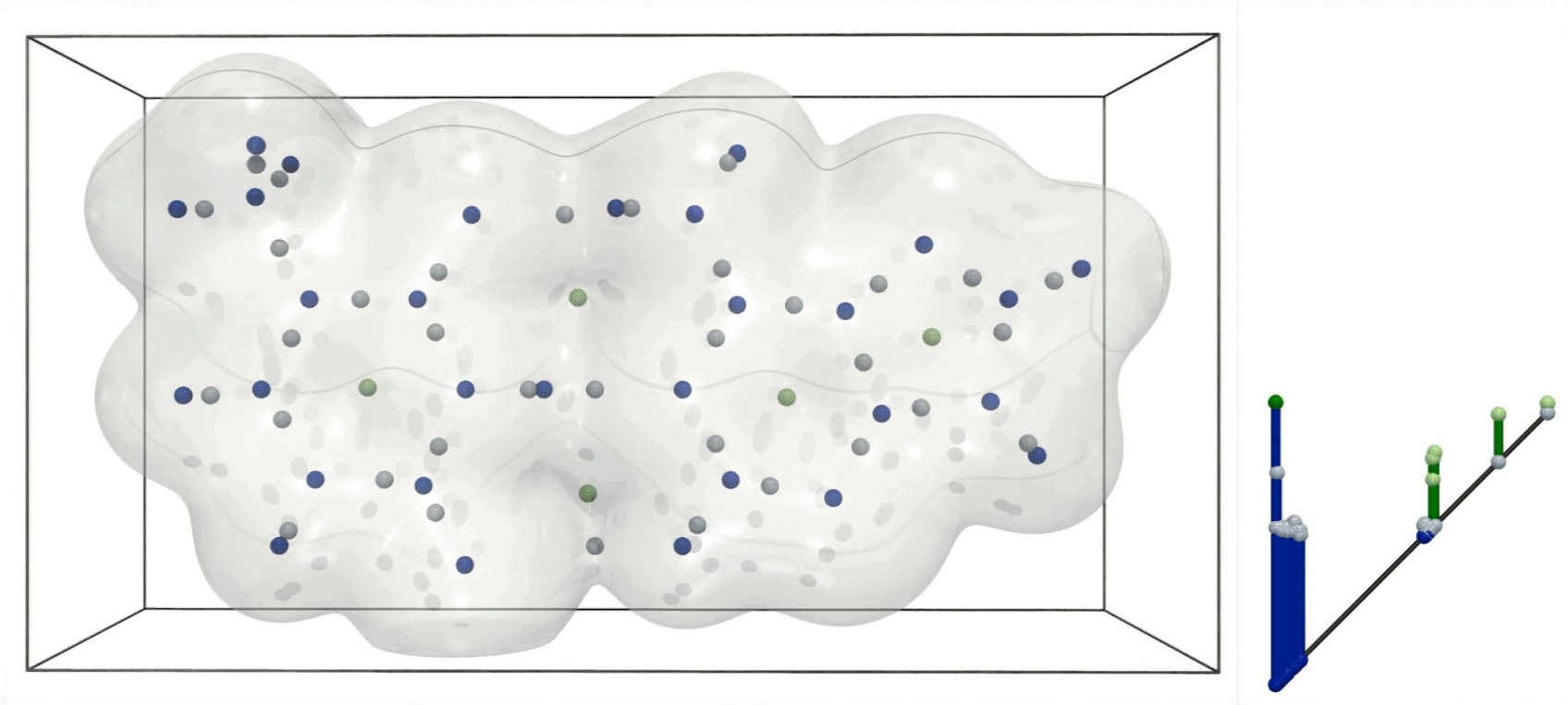
- Beyond connected components





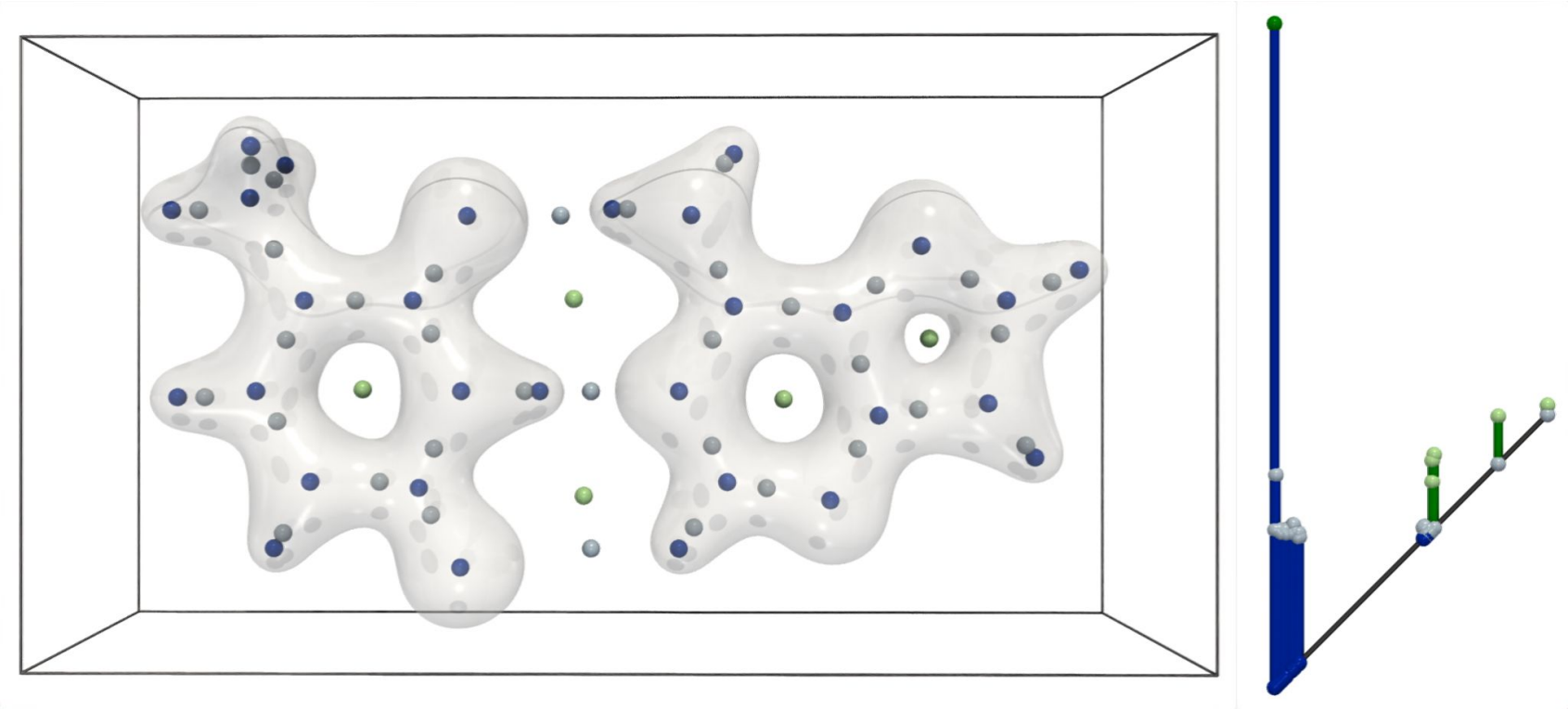
Persistence diagram

- Beyond connected components



Persistence diagram

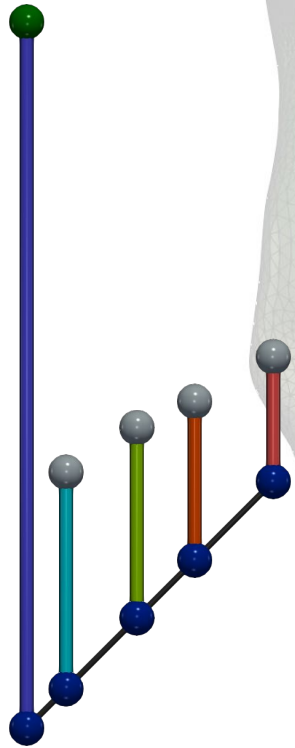
- Beyond connected components

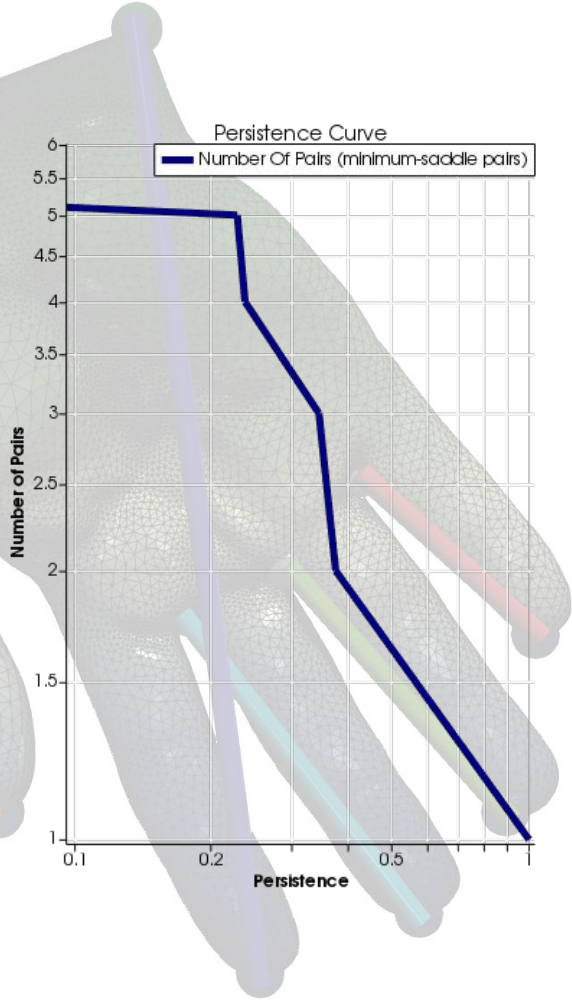


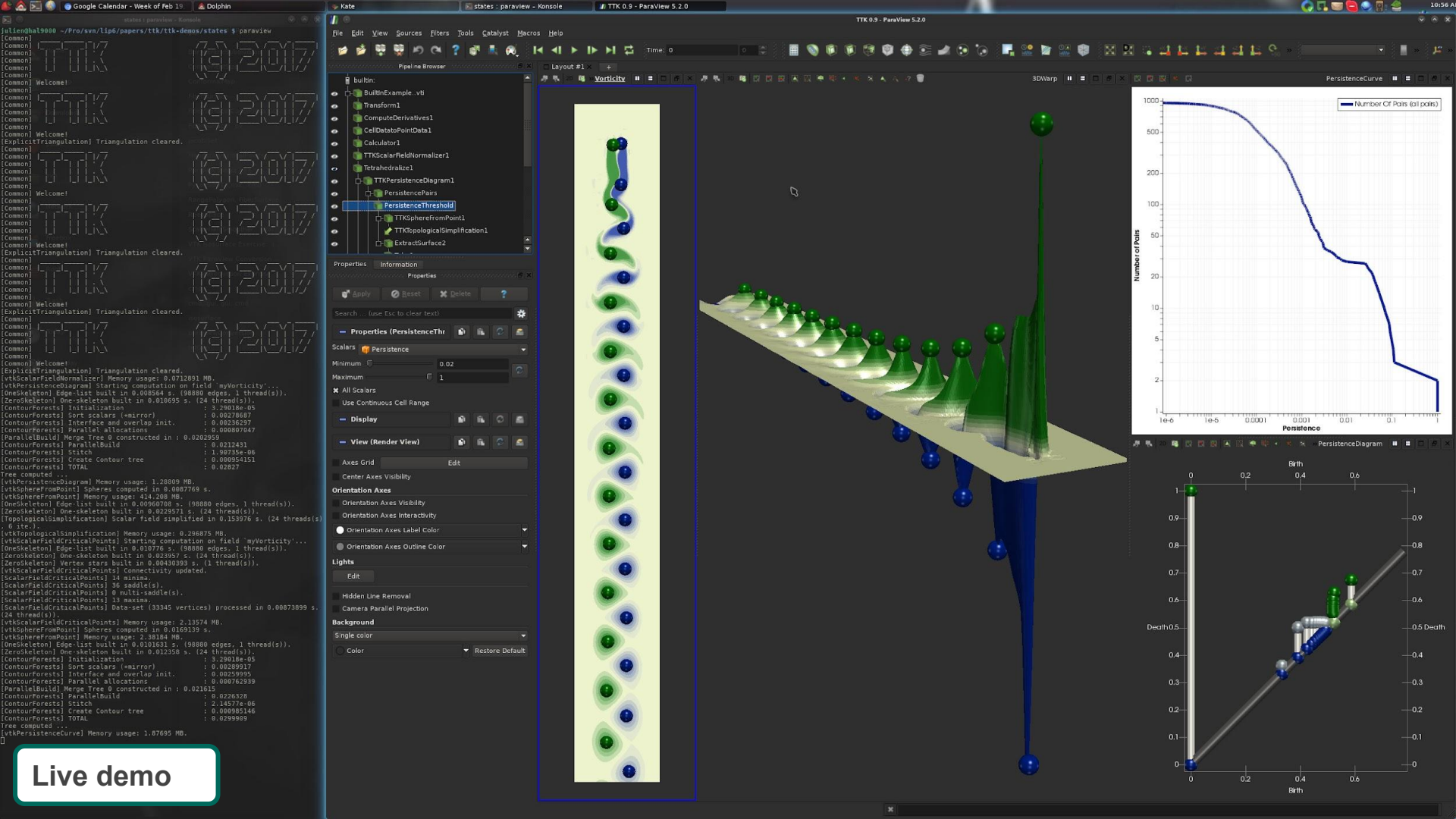
Persistence diagram

- **Input PL scalar data**
  - $f : \mathcal{M} \to \mathbb{R}$

- **Topological abstractions**
  - Critical points
  - Persistence diagrams
  - Persistence curves



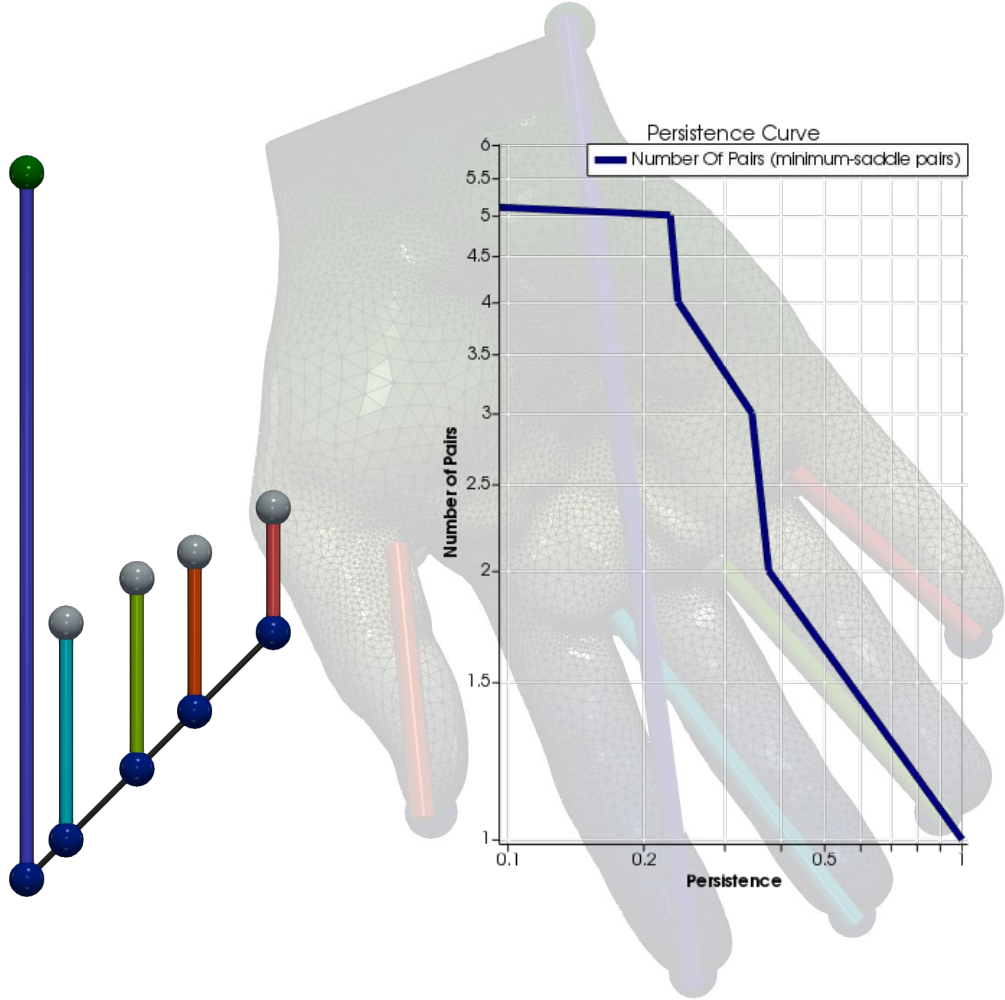



Live demo

Persistence diagram

- **Arbitrary dimension**
  - Boundary matrix reduction
  - Edelsbrunner et al. 2002

- **Low-dimensions**
  - Union-Find data structures
    - *Gueunet et al. 2017*
  - Discrete Morse Theory
    - *Guillou et al. 2023*



Persistence diagram

- **Latest backend!**
  - *“Discrete Morse Sandwich”*
    - **https://arxiv.org/abs/2206.13932**

JOURNAL OF LATEX CLASS FILES, VOL. 14, NO. 8, MAY 2021 1

arXiv:2206.13932v1 [cs.LG] 27 Jun 2022

Discrete Morse Sandwich: Fast Computation of Persistence Diagrams for Scalar Data – An Algorithm and A Benchmark

Pierre Guillou, Jules Vidal, and Julien Tierny

Abstract—This paper introduces an efficient algorithm for persistence diagram computation, given an input piecewise linear scalar field f defined on a d-dimensional simplicial complex $\mathcal{K}$, with $d \leq 3$. Our method extends the seminal *“PairCells”* algorithm [102] by introducing three main accelerations. *(i)* First, we express this algorithm within the setting of discrete Morse theory [32], which considerably reduces the number of input simplices to consider. *(ii)* Second, we introduce a stratification approach to the problem, that we call *sandwiching*. Specifically, minima-saddle persistence pairs ($\mathcal{D}_0(f)$) and saddle-maximum persistence pairs ($\mathcal{D}_{d-1}(f)$) are efficiently computed by respectively processing with a Union-Find the unstable sets of 1-saddles and the stable sets of $(d-1)$-saddles. Additionally, we provide a detailed description of the (optional) handling of the boundary components of $\mathcal{K}$ when processing $(d-1)$-saddles. This fast processing of the dimensions 0 and $(d-1)$ further reduces, and drastically, the number of critical simplices to consider for the computation of $\mathcal{D}_1(f)$, the intermediate layer of the *sandwich*. *(iii)* Third, we document several performance improvements via shared-memory parallelism. We provide an open-source implementation of our algorithm for reproducibility purposes. We also contribute a reproducible benchmark package, which exploits three-dimensional data from a public repository and compares our algorithm to a variety of publicly available implementations. Extensive experiments indicate that our algorithm improves by two orders of magnitude the time performance of the seminal *“PairCells”* algorithm it extends. Moreover, it also improves memory footprint and time performance over a selection of 14 competing approaches, with a substantial gain over the fastest available approaches, while producing a strictly identical output. We illustrate the utility of our contributions with an application to the fast and robust extraction of persistent 1-dimensional generators on surfaces, volume data and high-dimensional point clouds.

Index Terms—Topological data analysis, scalar data, persistence diagrams, discrete Morse theory.

1 Introduction

SCALAR data is central to many fields of science and engineering. It can be the result of an *(i)* acquisition process (examples include CT-scans produced in medical imaging or one-dimensional time-series produced by punctual sensors) or it can be the result of a *(ii)* numerical computation (examples include simulations in computational fluid dynamics, material sciences, etc). In both cases, the data is typically provided as a low-dimensional scalar field (1D, 2D, or 3D) defined on the vertices of either *(i)* a regular grid (e.g. pixel or voxel images) or *(ii)* a mesh (e.g. polyhedral surfaces and volumes, AMR grids, etc.). An established strategy to generically process either cases of data provenance is to subdivide each cell of the input domain into simplices [48], [53], hence converting the input data into a generic representation that facilitates subsequent processing, namely a piecewise linear scalar field defined over a simplicial complex (i.e. poly-lines in 1D, triangulated surfaces in 2D and tetrahedral meshes in 3D). However, such scalar fields are provided in the applications with an ever-increasing size and geometrical complexity, which significantly challenges their interpretation by human users. This motivates the design of advanced data analysis tools, to support the interactive exploration and analysis of the features of interest present in large datasets. This is precisely the purpose of Topological Data Analysis (TDA) [28], which provides a toolbox of techniques for the generic, robust, and efficient extraction of structural features in data.

Topological methods have been investigated by the visualization community for more than twenty years [50], with applications to a variety of domains, including combustion [14], [41], [60] fluid dynamics [19], [56] material sciences [45], [61], chemistry [6], [35], [74], or astrophysics [82], [87] to name a few. Several topological data representations studied in TDA (such as the persistence diagram [28], the contour tree [15], [37], [89], the Reeb graph [7], [38], [75], [76], [77] or the Morse-Smale complex [13], [22], [42], [44], [46], [81]) have been specialized and used successfully in visualization, in particular for the explicit extraction and visual representation of structural patterns hidden in the data. An important aspect of TDA is its ability to provide multi-scale hierarchies of the above topological data representations, which consequently enables multi-scale visualization, exploration and analysis. In that setting, *Topological Persistence* [28] is an established importance measure which enables to distinguish the most salient topological structures present in the data from those corresponding to noise. In typical analysis pipelines (as shown in Fig. 1), this importance measure drives the simplification of the above topological representations, resulting in interactive, multi-scale data explorations. In practice, topological persistence can be obtained by computing *Persistence Diagrams* [28]. Several algorithms have been proposed for their computation (see Sec. 1.1) and

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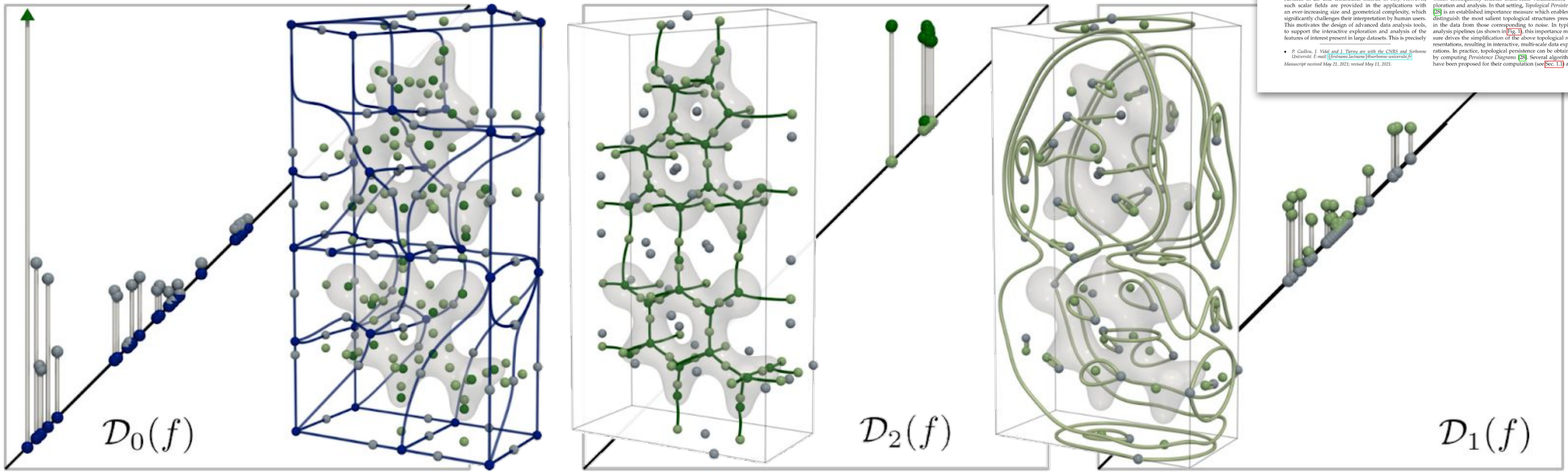
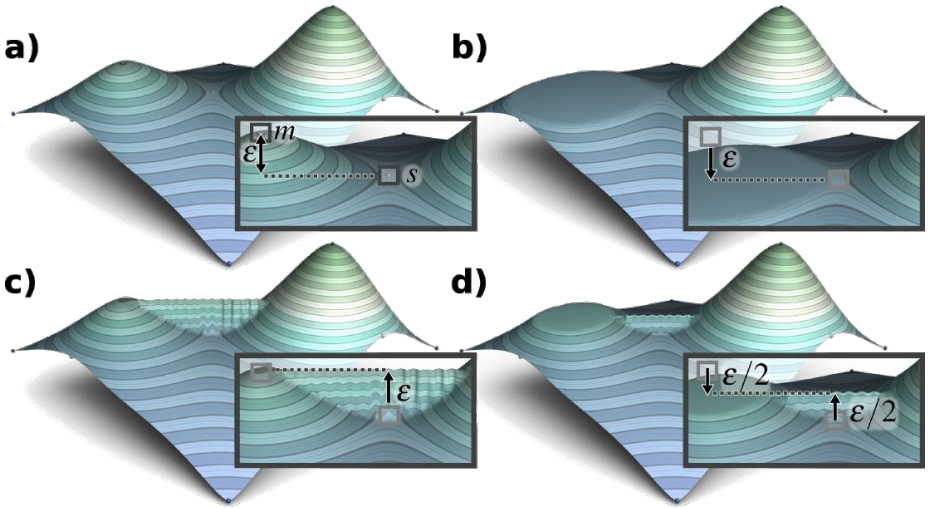
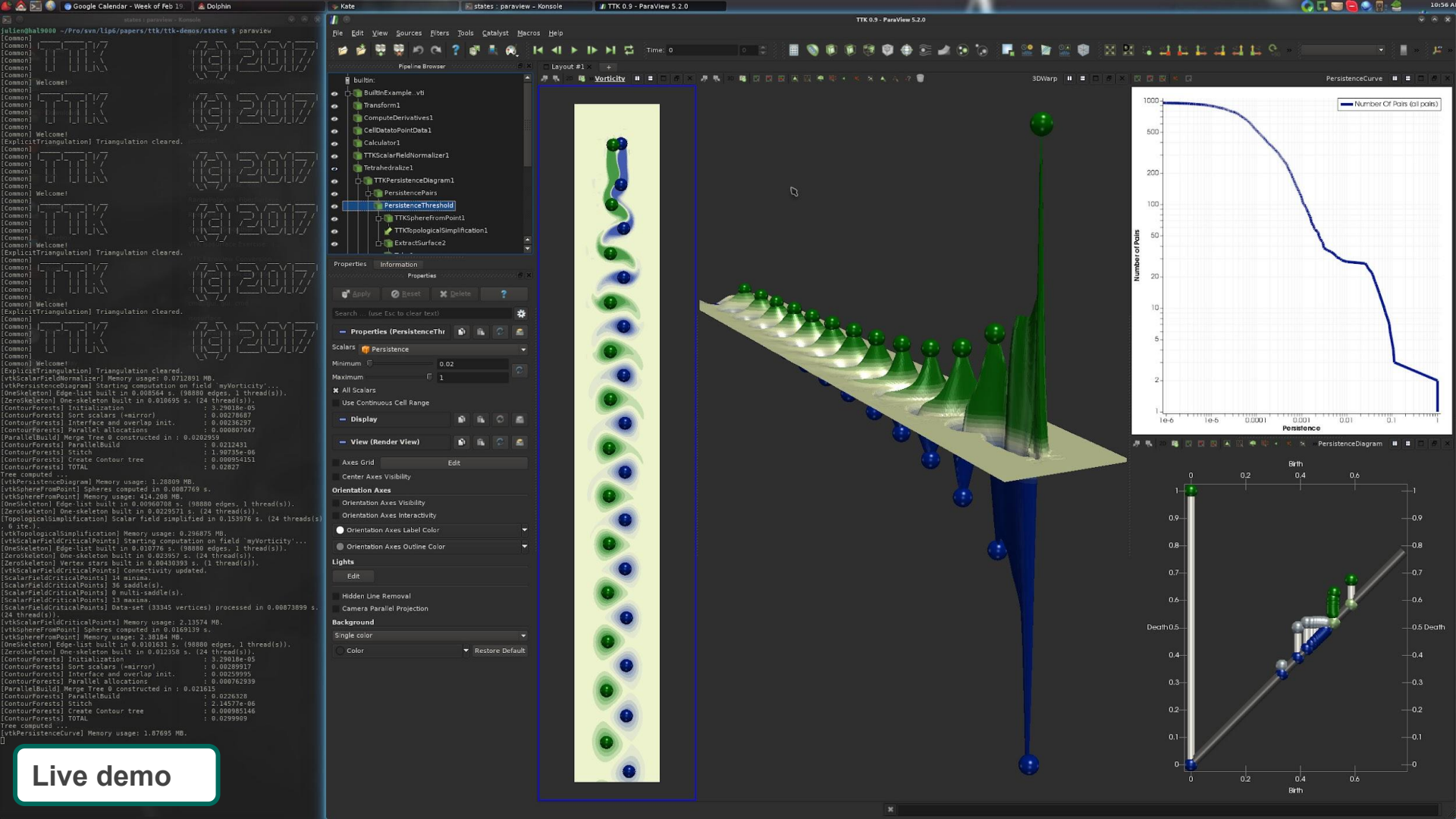


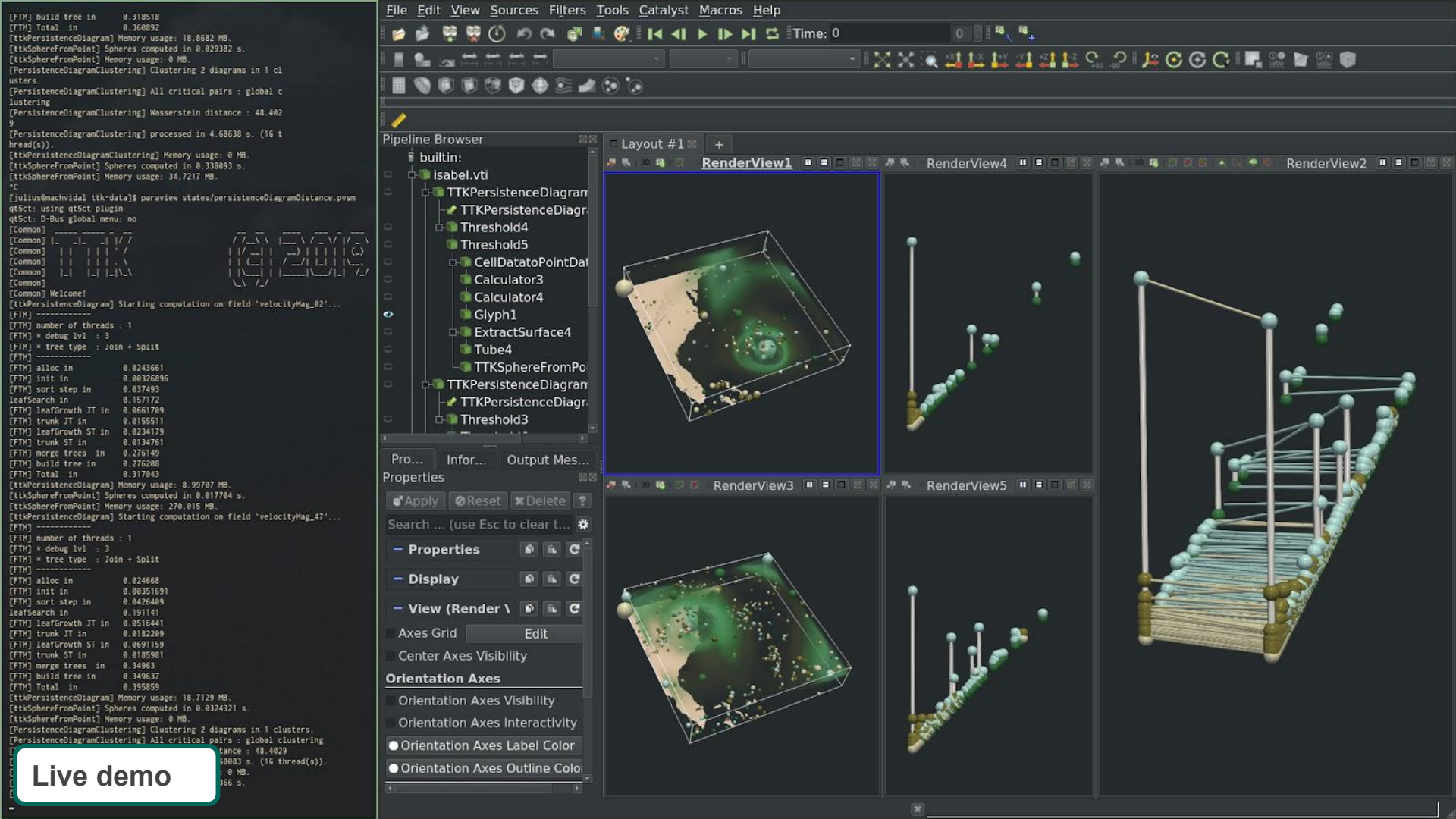
Persistence simplification

- **Simplify the data**
  - Retain only persistent features

- **Algorithms**
  - Edelsbrunner et al. 2006, Attali et al. 2009, *Tierny and Pascucci 2012*, Bauer et al. 2012, *Lukasczyk et al. 2020*.




Live demo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[FTM] Total in 0.360892
[ttkPersistenceDiagram] Memory usage: 18.8682 MB.
[ttkSphereFromPoint] Spheres computed in 0.029382 s.
[ttkSphereFromPoint] Memory usage: 0 MB.
[PersistenceDiagramClustering] Clustering 2 diagrams in 1 clusters.
[PersistenceDiagramClustering] All critical pairs : global clustering
[PersistenceDiagramClustering] Wasserstein distance : 48.4029
[PersistenceDiagramClustering] processed in 4.68638 s. (16 thread(s)).
[ttkPersistenceDiagramClustering] Memory usage: 0 MB.
[ttkSphereFromPoint] Spheres computed in 0.338093 s.
[ttkSphereFromPoint] Memory usage: 34.7217 MB.
[julius@machvidal ttk-data]$ paraview states/persistenceDiagramDistance.pvsm
qt5ct: using qt5ct plugin
qt5ct: D-Bus global menu: no
[Common] Welcome!
[ttkPersistenceDiagram] Starting computation on field 'velocityMag_02'...
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[FTM] * debug lvl : 3
[FTM] * tree type : Join + Split
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[FTM] trunk ST in 0.0134761
[FTM] merge trees in 0.276149
[FTM] build tree in 0.276208
[FTM] Total in 0.317043
[ttkPersistenceDiagram] Memory usage: 8.99707 MB.
[ttkSphereFromPoint] Spheres computed in 0.017704 s.
[ttkSphereFromPoint] Memory usage: 270.015 MB.
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[ttkSphereFromPoint] Memory usage: 0 MB.
[PersistenceDiagramClustering] Clustering 2 diagrams in 1 clusters.
[PersistenceDiagramClustering] All critical pairs : global clustering
Live demo
File Edit View Sources Filters Tools Catalyst Macros Help
Time: 0
Pipeline Browser
builtin:
isabel.vti
TTKPersistenceDiagram
TTKPersistenceDiagr
Threshold4
Threshold5
CellDatatoPointDat
Calculator3
Calculator4
Glyph1
ExtractSurface4
Tube4
TTKSphereFromPo
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Layout #1
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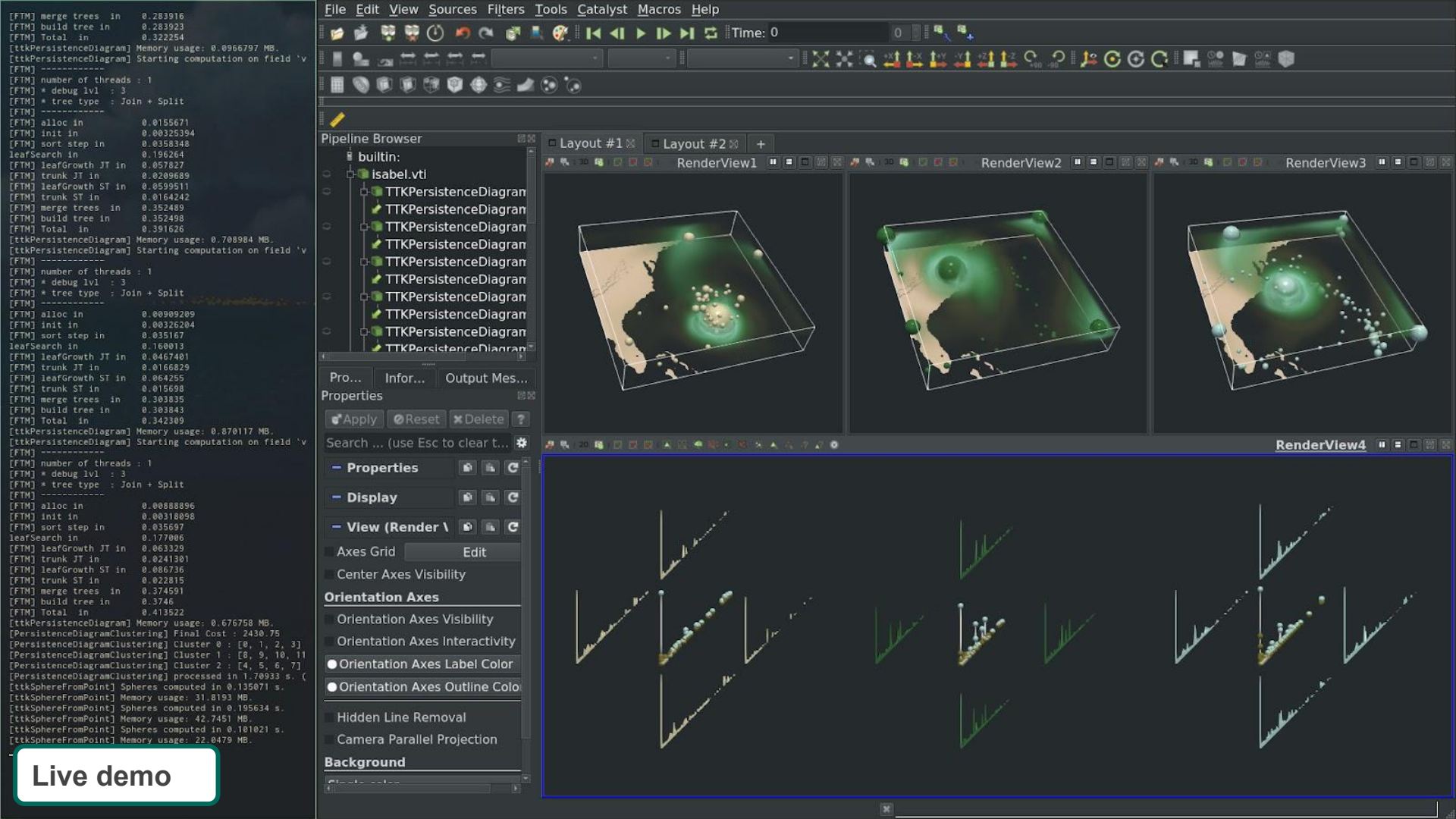
RenderView2
RenderView3
RenderView5


[FTM] merge trees in 0.283916
[FTM] build tree in 0.283923
[FTM] Total in 0.322254
[ttkPersistenceDiagram] Memory usage: 0.0966797 MB.
[ttkPersistenceDiagram] Starting computation on field 'v
[FTM] ------------
[FTM] number of threads : 1
[FTM] * debug lvl : 3
[FTM] * tree type : Join + Split
[FTM] ------------
[FTM] alloc in 0.0155671
[FTM] init in 0.00325394
[FTM] sort step in 0.0358348
leafSearch in 0.196264
[FTM] leafGrowth JT in 0.057827
[FTM] trunk JT in 0.0209689
[FTM] leafGrowth ST in 0.0599511
[FTM] trunk ST in 0.0164242
[FTM] merge trees in 0.352489
[FTM] build tree in 0.352498
[FTM] Total in 0.391626
[ttkPersistenceDiagram] Memory usage: 0.708984 MB.
[ttkPersistenceDiagram] Starting computation on field 'v
[FTM] ------------
[FTM] number of threads : 1
[FTM] * debug lvl : 3
[FTM] * tree type : Join + Split
[FTM] ------------
[FTM] alloc in 0.00909209
[FTM] init in 0.00326204
[FTM] sort step in 0.035167
leafSearch in 0.160013
[FTM] leafGrowth JT in 0.0467401
[FTM] trunk JT in 0.0166829
[FTM] leafGrowth ST in 0.064255
[FTM] trunk ST in 0.015698
[FTM] merge trees in 0.303835
[FTM] build tree in 0.303843
[FTM] Total in 0.342309
[ttkPersistenceDiagram] Memory usage: 0.870117 MB.
[ttkPersistenceDiagram] Starting computation on field 'v
[FTM] ------------
[FTM] number of threads : 1
[FTM] * debug lvl : 3
[FTM] * tree type : Join + Split
[FTM] ------------
[FTM] alloc in 0.00888896
[FTM] init in 0.00318098
[FTM] sort step in 0.035697
leafSearch in 0.177006
[FTM] leafGrowth JT in 0.063329
[FTM] trunk JT in 0.0241301
[FTM] leafGrowth ST in 0.086736
[FTM] trunk ST in 0.022815
[FTM] merge trees in 0.374591
[FTM] build tree in 0.3746
[FTM] Total in 0.413522
[ttkPersistenceDiagram] Memory usage: 0.676758 MB.
[PersistenceDiagramClustering] Final Cost : 2430.75
[PersistenceDiagramClustering] Cluster 0 : [0, 1, 2, 3]
[PersistenceDiagramClustering] Cluster 1 : [8, 9, 10, 11
[PersistenceDiagramClustering] Cluster 2 : [4, 5, 6, 7]
[PersistenceDiagramClustering] processed in 1.70933 s. (
[ttkSphereFromPoint] Spheres computed in 0.135071 s.
[ttkSphereFromPoint] Memory usage: 31.8193 MB.
[ttkSphereFromPoint] Spheres computed in 0.195634 s.
[ttkSphereFromPoint] Memory usage: 42.7451 MB.
[ttkSphereFromPoint] Spheres computed in 0.101021 s.
[ttkSphereFromPoint] Memory usage: 22.0479 MB.
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TTKPersistenceDiagram
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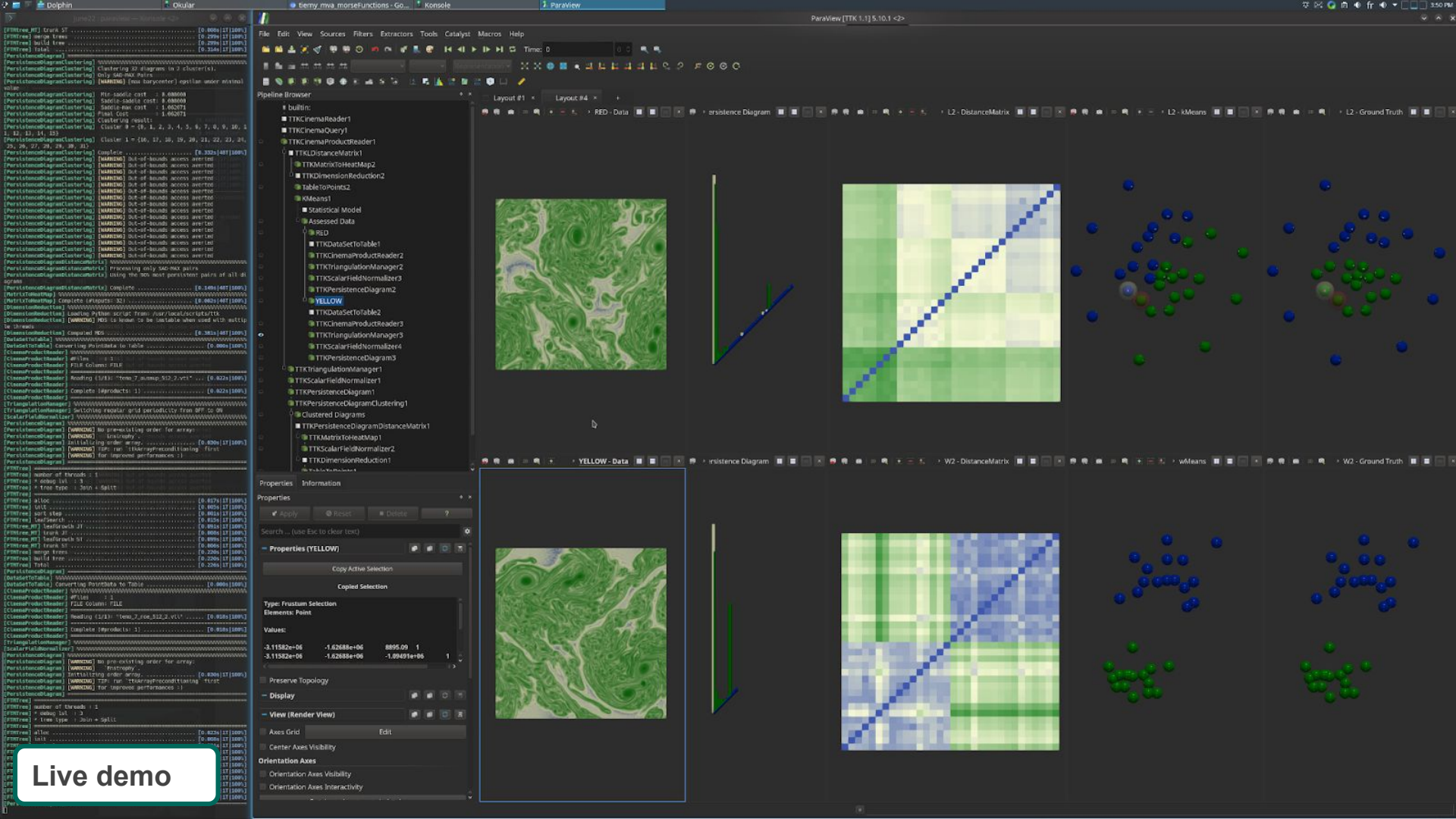
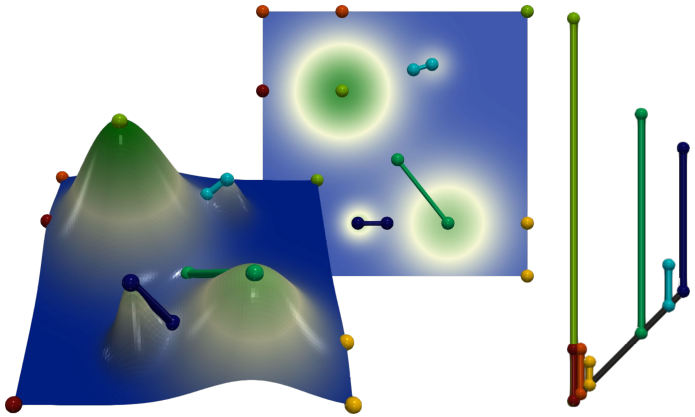
Layout #1
Layout #2
RenderView1
RenderView2
RenderView3
RenderView4
Live demo


Live demo

Piecewise linear setting

- **Input PL scalar data**
  - $f : \mathcal{M} \to \mathbb{R}$



- **Topological abstractions**
  - Critical points
  - Persistence diagrams
  - Persistence curves

Piecewise linear setting

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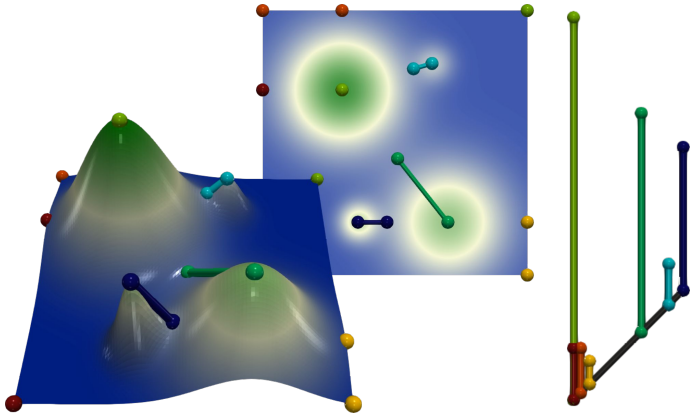
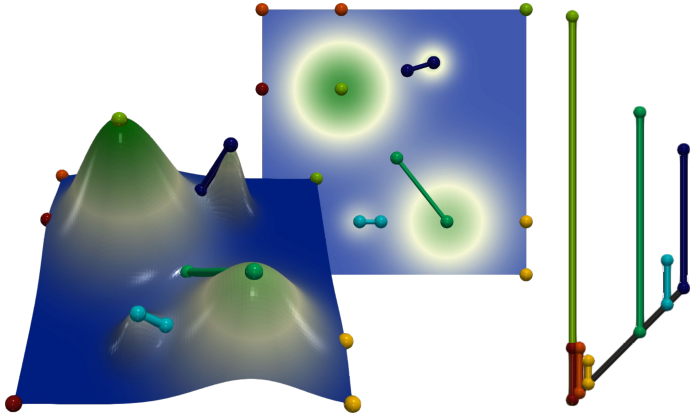
  - $f : \mathcal{M} \to \mathbb{R}$



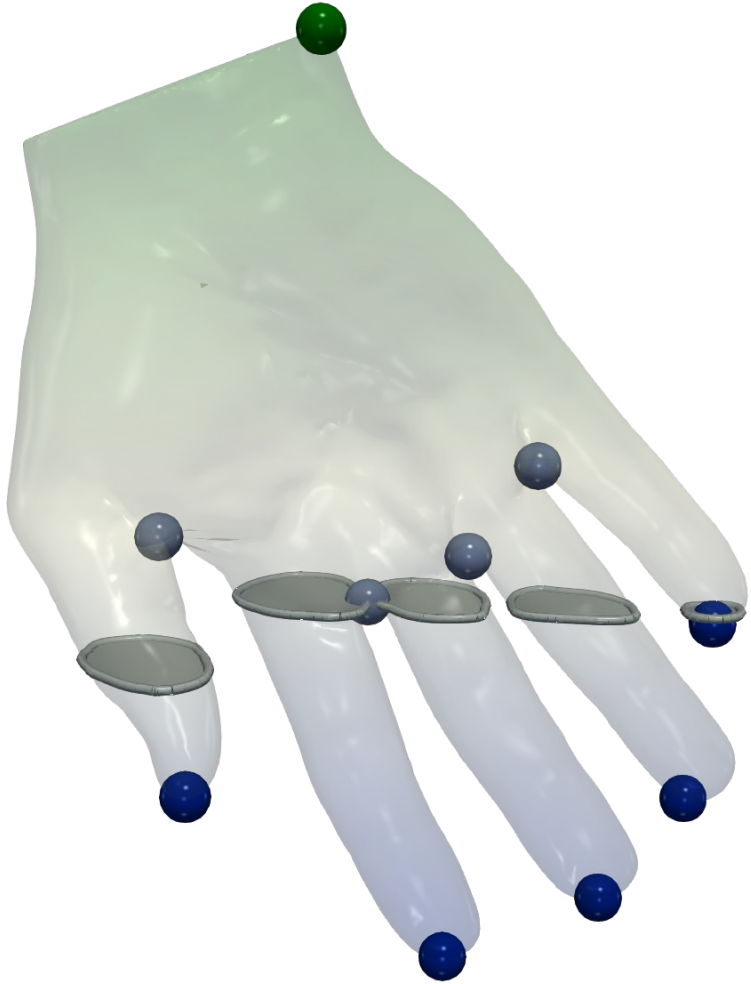
- **Topological abstractions**
  - Critical points
  - Persistence diagrams
  - Persistence curves



Piecewise linear setting

- **Input PL scalar data**
  - $f : \mathcal{M} \to \mathbb{R}$

- **Topological abstractions**
  - Critical points
  - Persistence diagrams
  - Persistence curves
  - Reeb graphs



Piecewise linear setting

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  - $f : \mathcal{M} \to \mathbb{R}$

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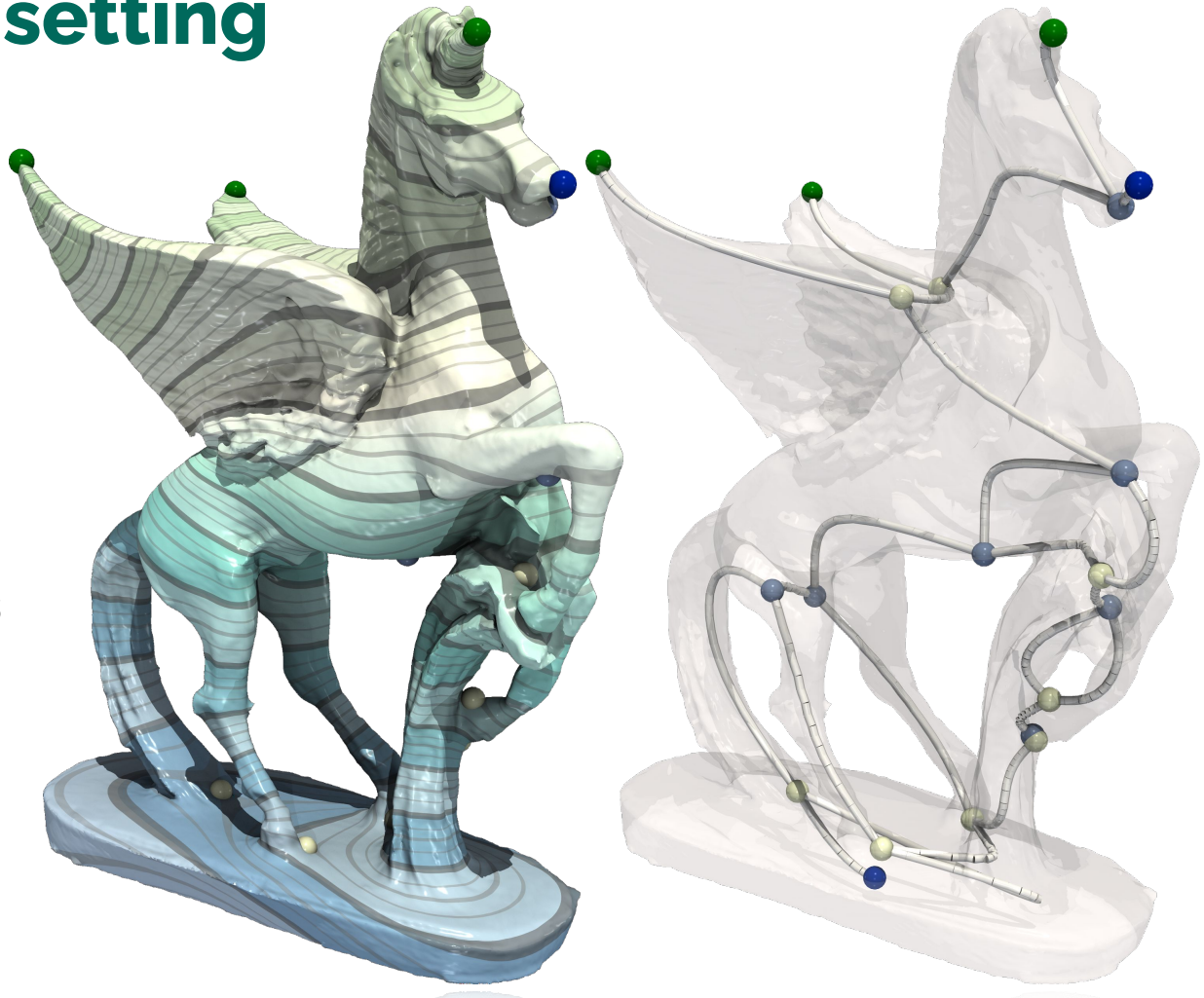
  - Persistence diagrams
  - Persistence curves
  - Reeb graphs

Piecewise linear setting

- **Input PL scalar data**
  - $f : \mathcal{M} \rightarrow \mathbb{R}$

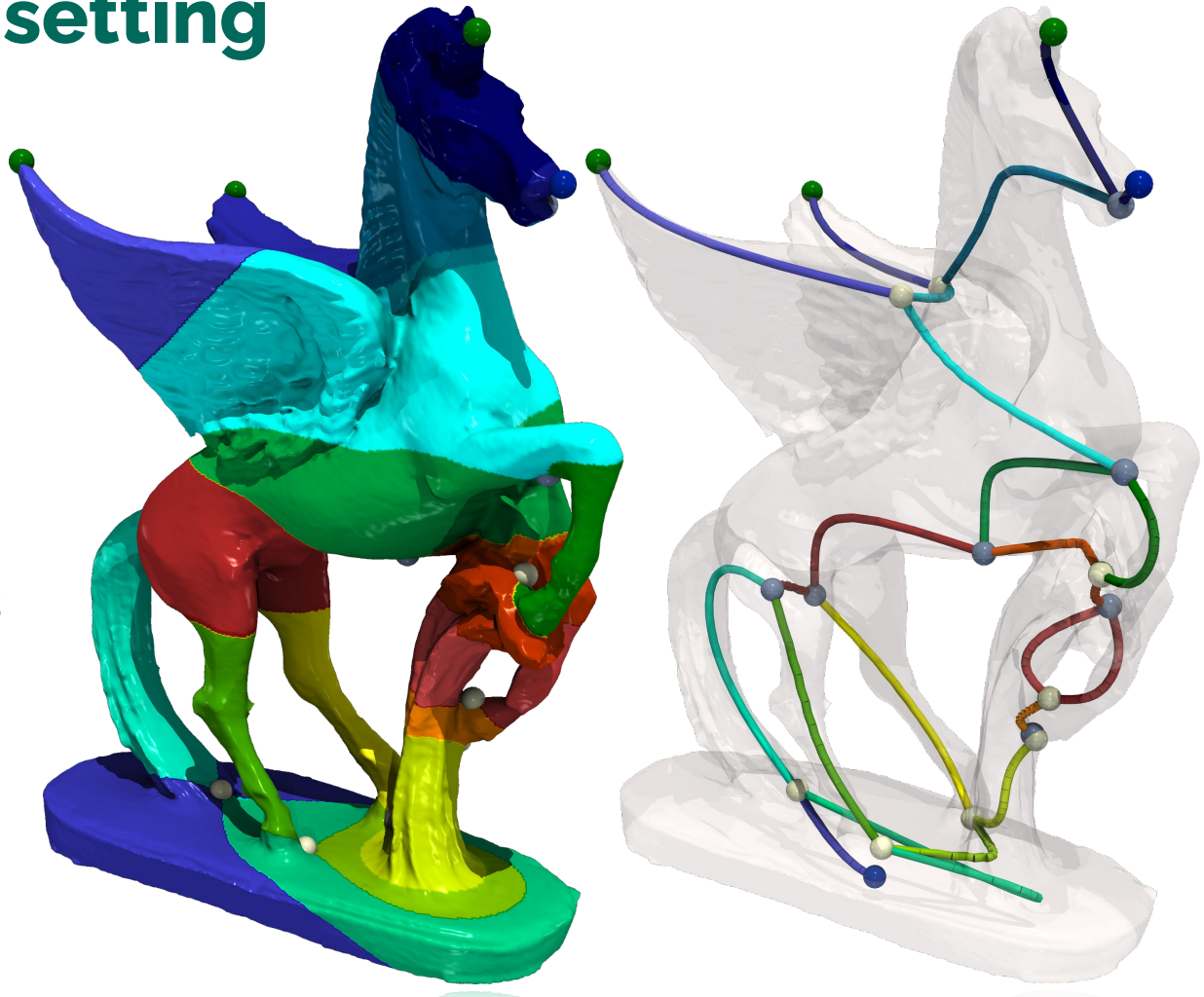
- **Topological abstractions**
  - Critical points
  - Persistence diagrams
  - Persistence curves
  - Reeb graphs

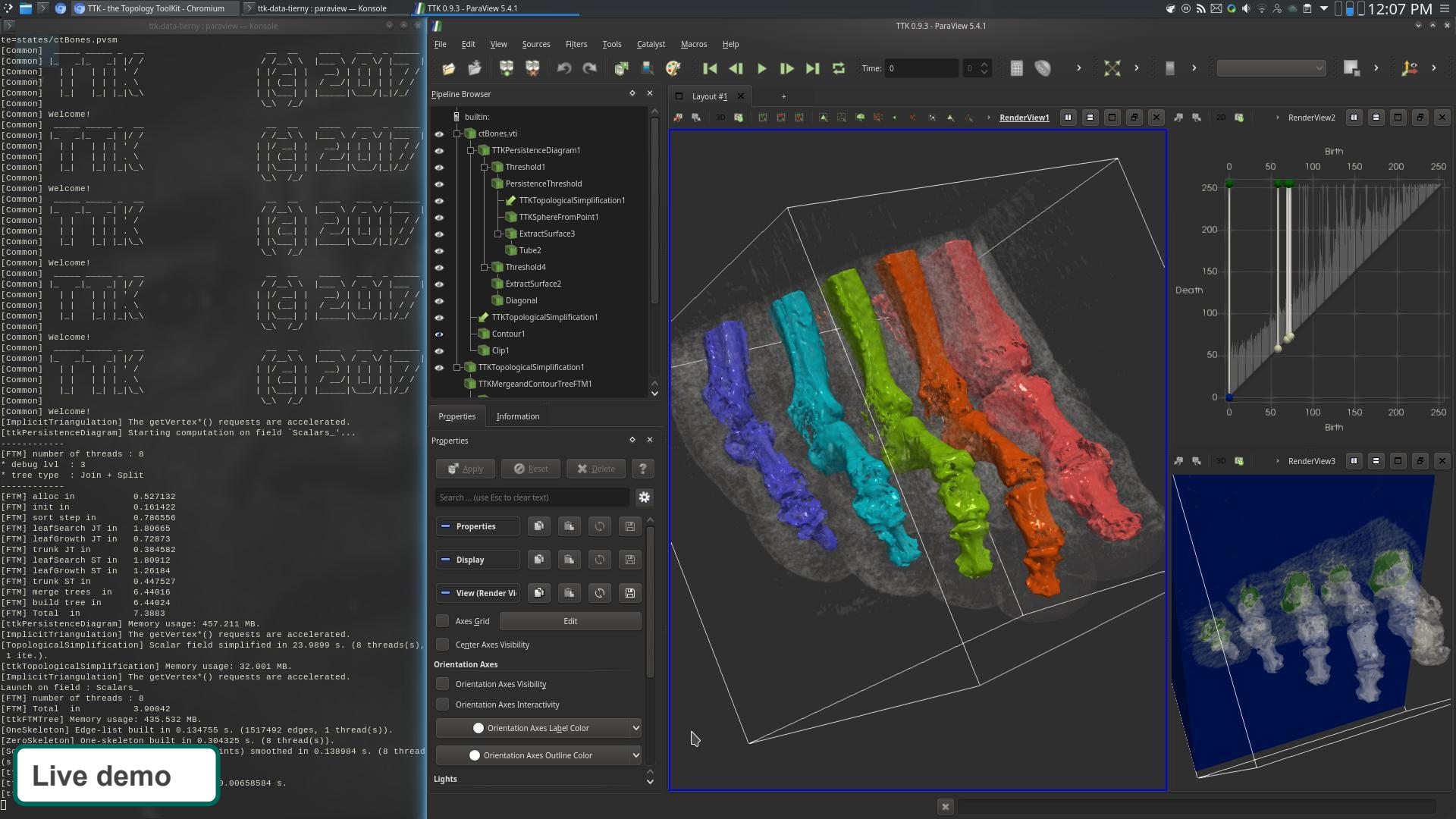


Piecewise linear setting

- **Input PL scalar data**
  - $f : \mathcal{M} \to \mathbb{R}$

- **Topological abstractions**
  - Critical points
  - Persistence diagrams
  - Persistence curves
  - Reeb graphs

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TTK 0.9.3 - ParaView 5.4.1
12:07 PM
ttk-data-tierny : paraview — Konsole
te=states/ctBones.pvsm
[Common] Welcome!
[ImplicitTriangulation] The getVertex*() requests are accelerated.
[ttkPersistenceDiagram] Starting computation on field `Scalars_'...
[FTM] number of threads : 8
* debug lvl : 3
* tree type : Join + Split
[FTM] alloc in 0.527132
[FTM] init in 0.161422
[FTM] sort step in 0.786556
[FTM] leafSearch JT in 1.80665
[FTM] leafGrowth JT in 0.72873
[FTM] trunk JT in 0.384582
[FTM] leafSearch ST in 1.80912
[FTM] leafGrowth ST in 1.26184
[FTM] trunk ST in 0.447527
[FTM] merge trees in 6.44016
[FTM] build tree in 6.44024
[FTM] Total in 7.3883
[ttkPersistenceDiagram] Memory usage: 457.211 MB.
[ImplicitTriangulation] The getVertex*() requests are accelerated.
[TopologicalSimplification] Scalar field simplified in 23.9899 s. (8 threads(s), 1 ite.).
[ttkTopologicalSimplification] Memory usage: 32.001 MB.
[ImplicitTriangulation] The getVertex*() requests are accelerated.
Launch on field : Scalars_
[FTM] number of threads : 8
[FTM] Total in 3.90042
[ttkFTMTree] Memory usage: 435.532 MB.
[OneSkeleton] Edge-list built in 0.134755 s. (1517492 edges, 1 thread(s)).
[ZeroSkeleton] One-skeleton built in 0.304325 s. (8 thread(s)).
Live demo
TTK 0.9.3 - ParaView 5.4.1
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TTKPersistenceDiagram1
Threshold1
PersistenceThreshold
TTKTopologicalSimplification1
TTKSphereFromPoint1
ExtractSurface3
Tube2
Threshold4
ExtractSurface2
Diagonal
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Center Axes Visibility
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Lights
Layout #1
RenderView1
RenderView2
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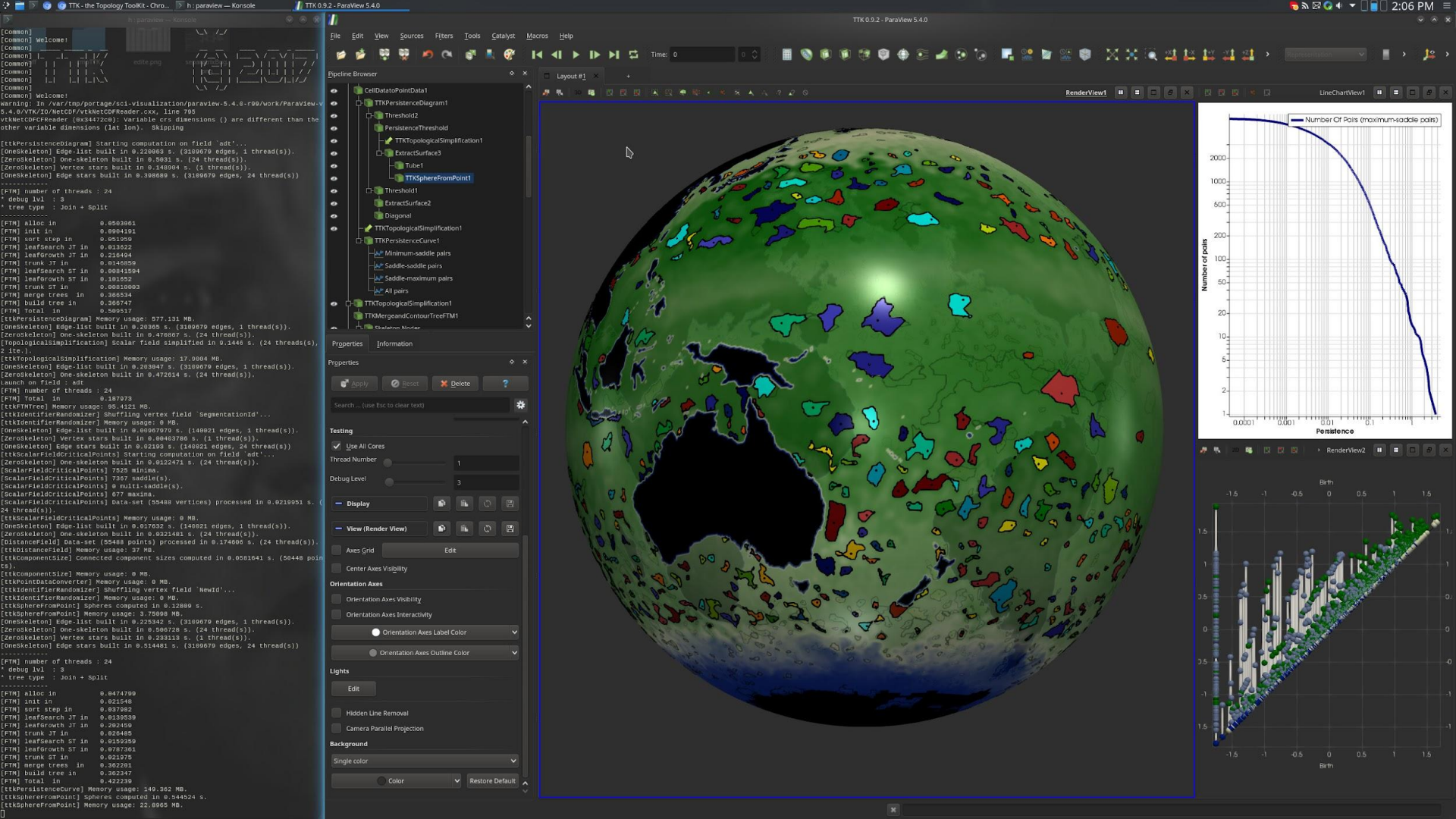
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TTKPersistenceDiagram1
Threshold2
PersistenceThreshold
TTKTopologicalSimplification1
ExtractSurface3
Tube1
TTKSphereFromPoint1
Threshold1
ExtractSurface2
Diagonal
TTKTopologicalSimplification1
TTKPersistenceCurve1
Minimum-saddle pairs
Saddle-saddle pairs
Saddle-maximum pairs
All pairs
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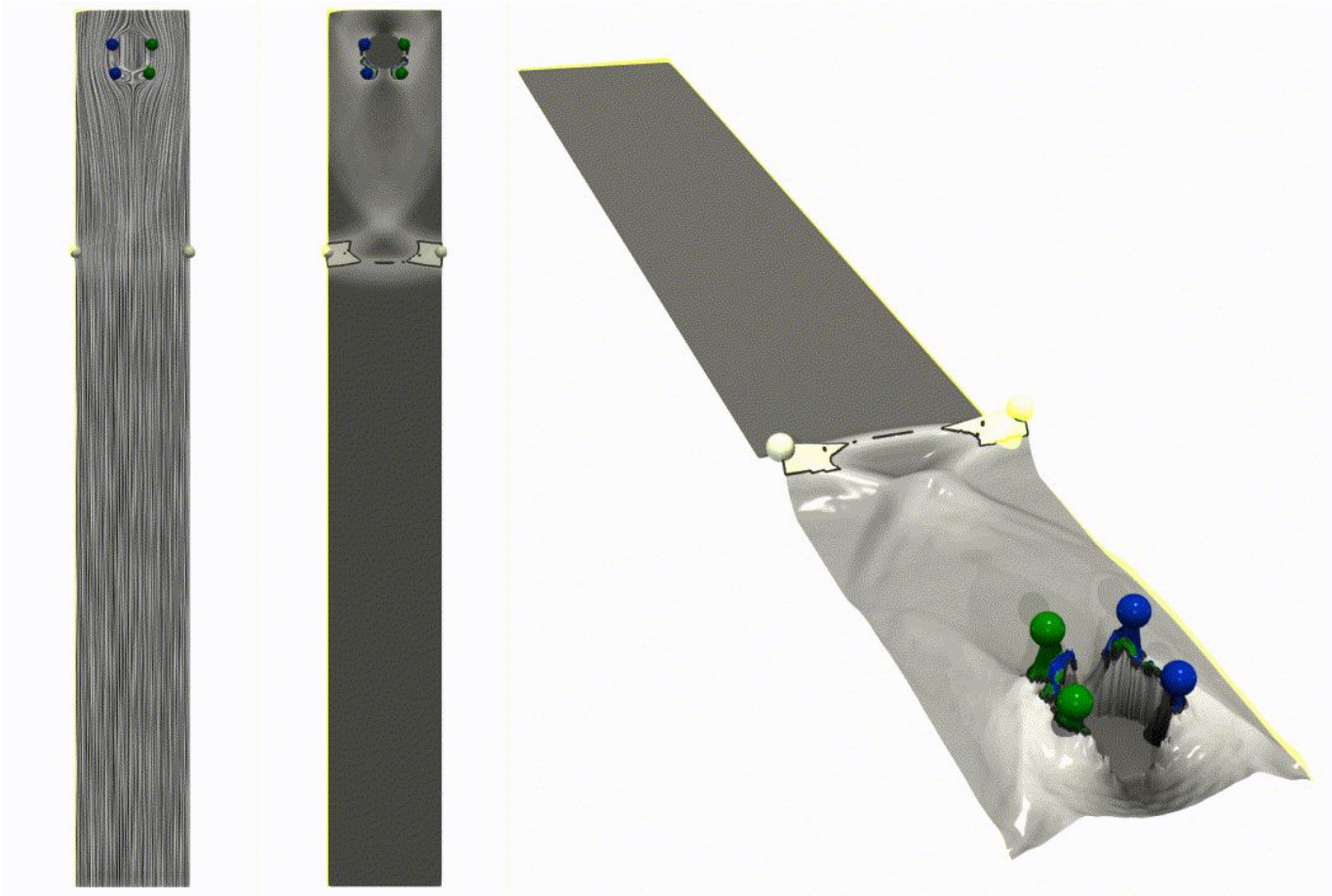
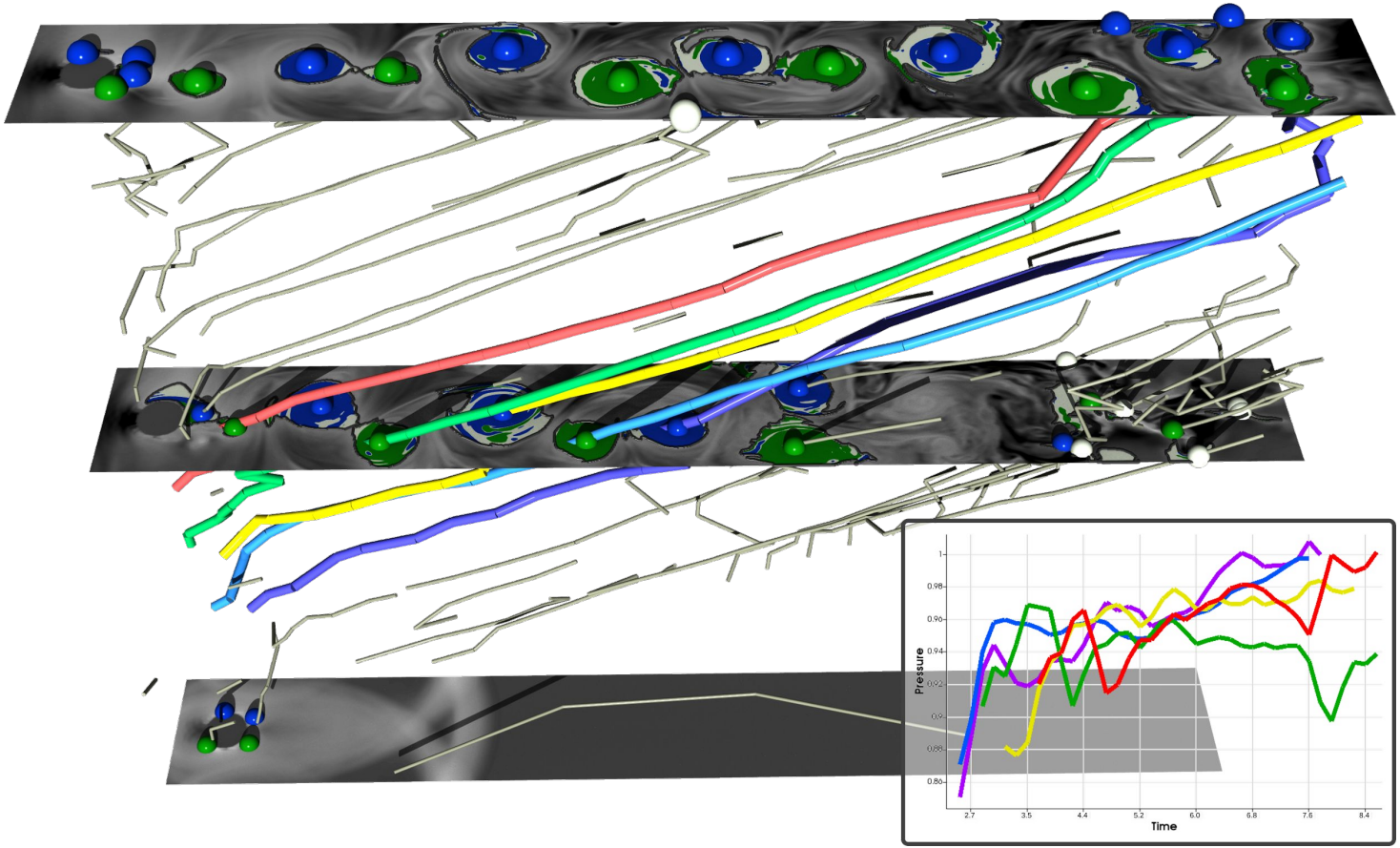
Restore Default
Layout #1
RenderView1
LineChartView1
Number Of Pairs (maximum-saddle pairs)
Number of pairs
Persistence
RenderView2
Birth

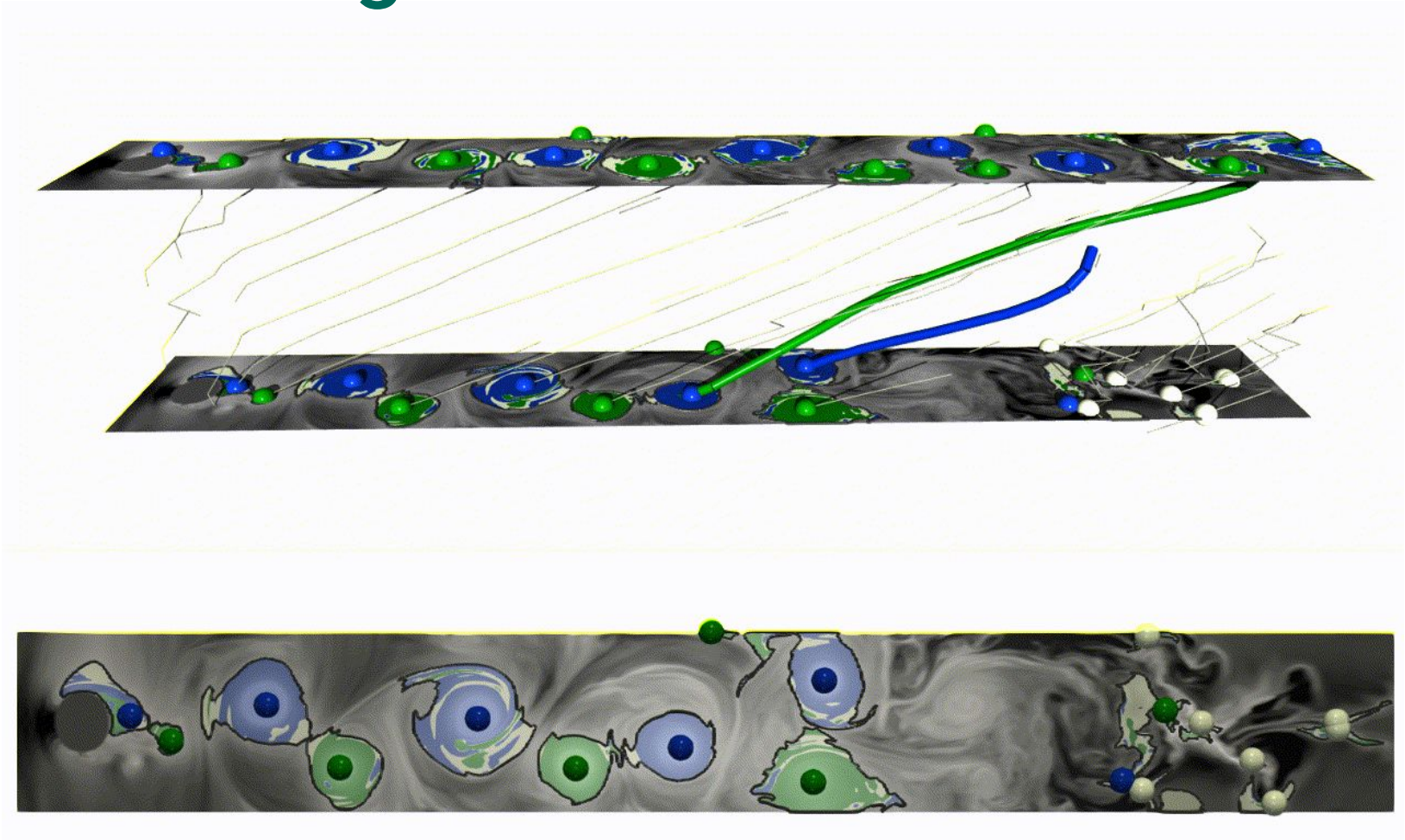
Vortex extraction



Vortex trajectory analysis

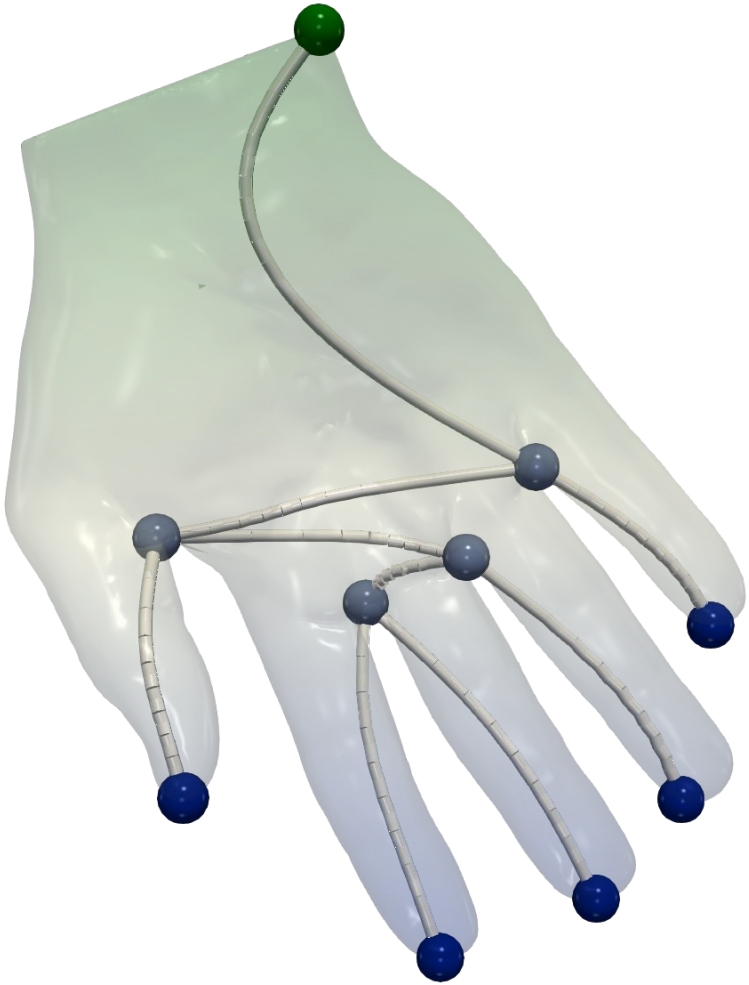


Vortex tracking



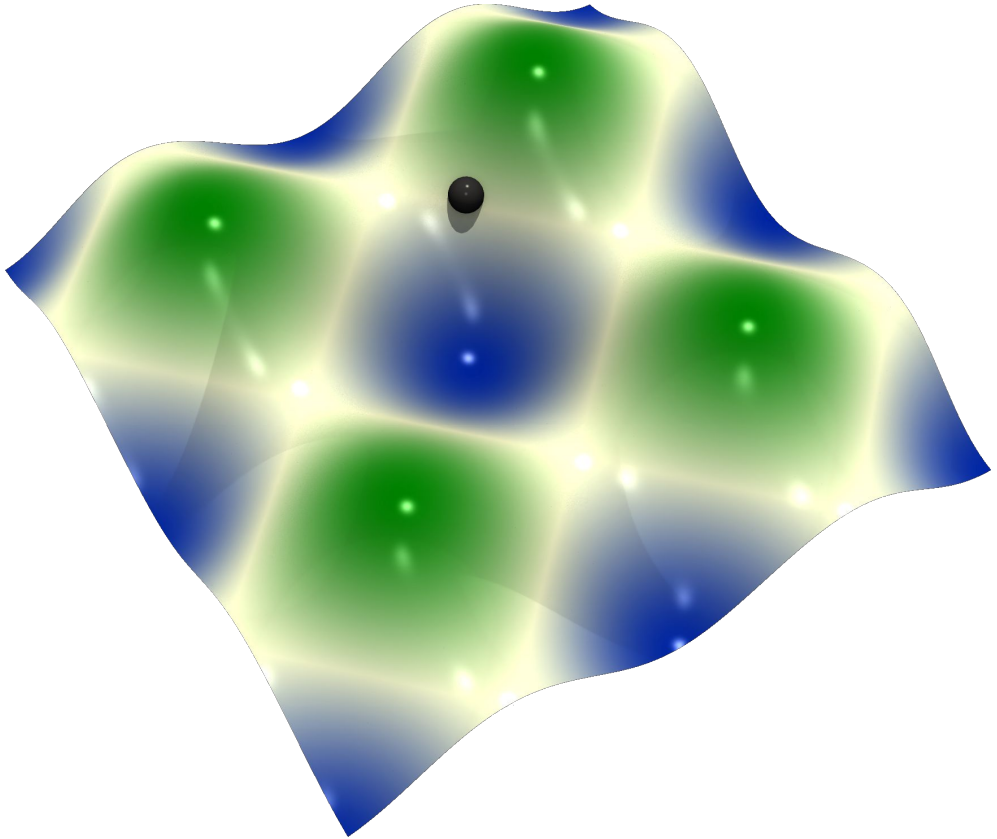
Reeb graphs

- **Vertex based contouring**
  - Shinagawa and Kunii 1991
- **Quantized range contouring**
  - Biasotti et al. 2000, Hilaga et al. 2001, Wood et al. 2004
- **Critical contouring**
  - Patane et al. 2008, *Tierny et al. 2009*, Doraiswamy and Natarajan 2013, Hajij and Rosen 2018
- **Dynamic connectivity**
  - Cole-McLaughlin et al. 2003, Pascucci et al. 2007, Doraiswamy and Natarajan 2009, Parsa 2013, *Gueunet et al. 2019*



Discrete Morse Theory

- **Morse-Smale complex**
  - Integration equivalence
  - Challenging PL computation



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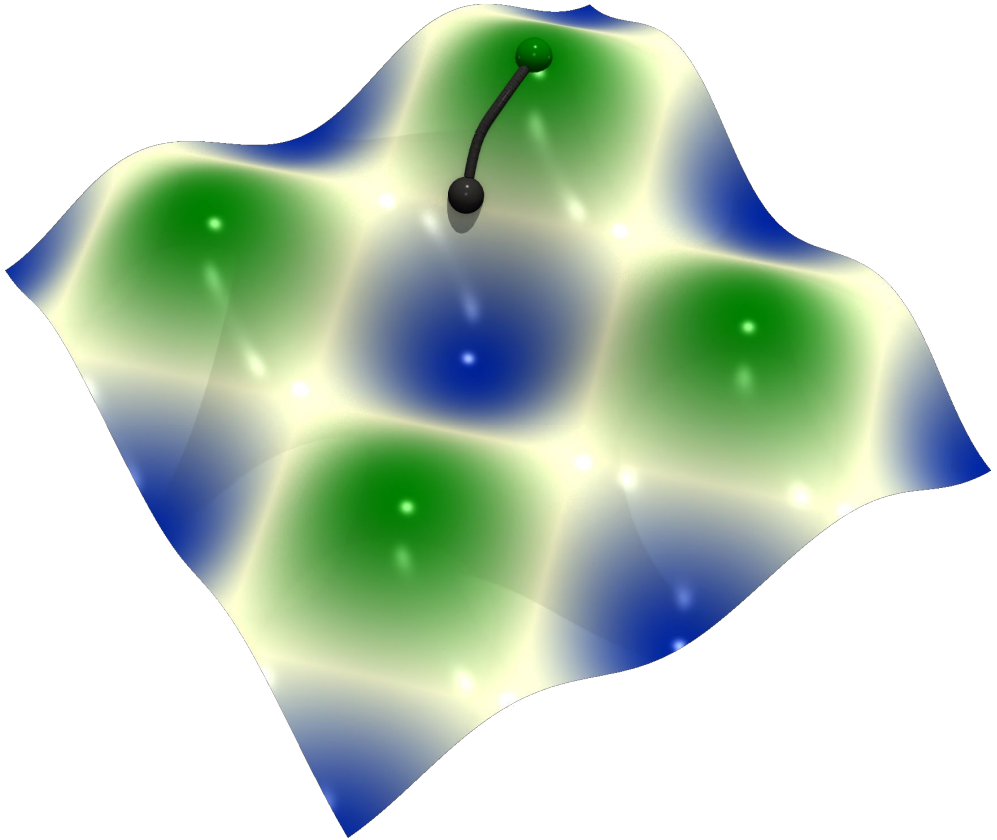

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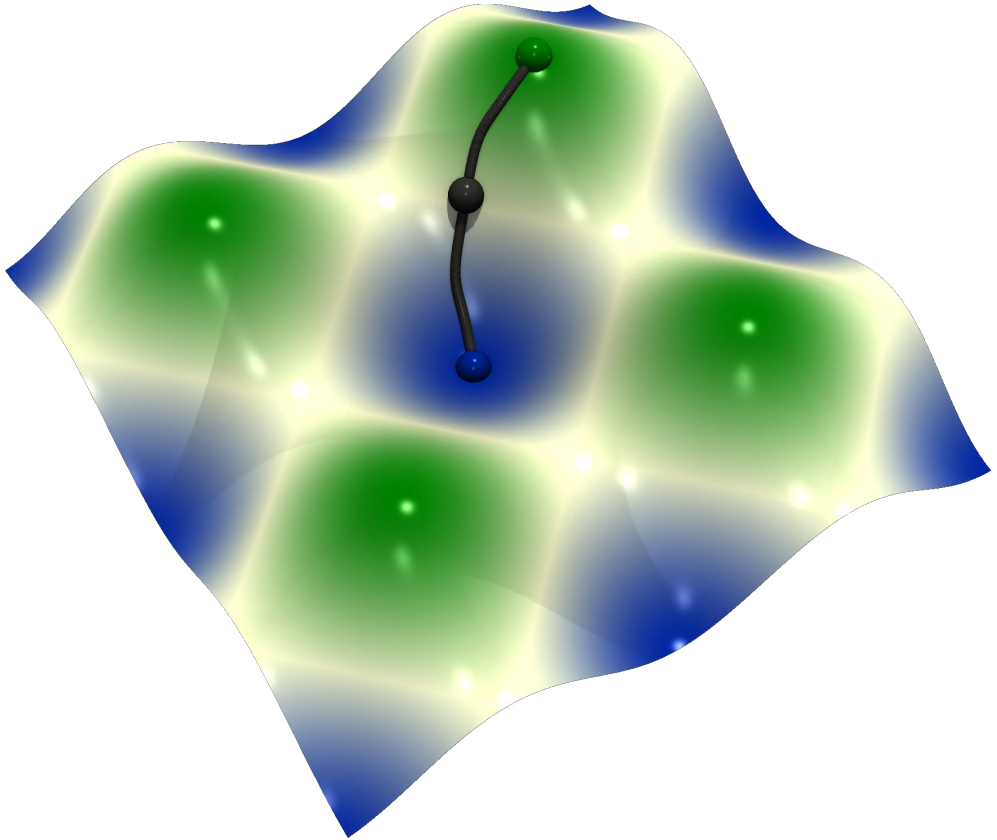

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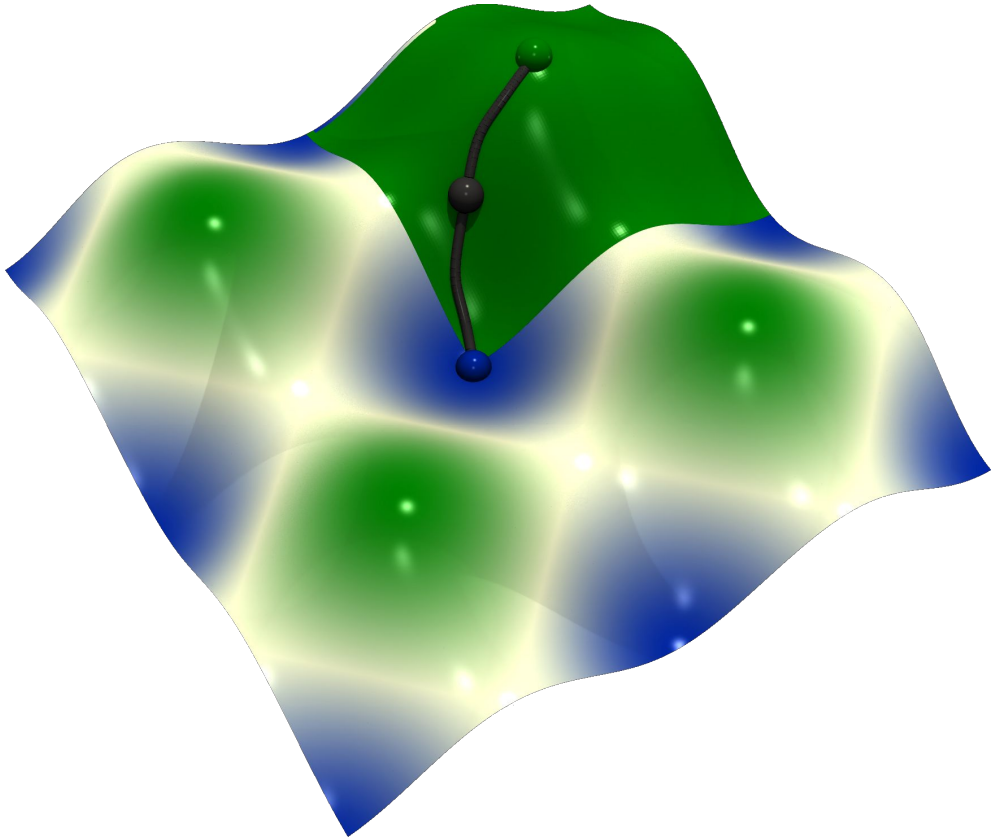

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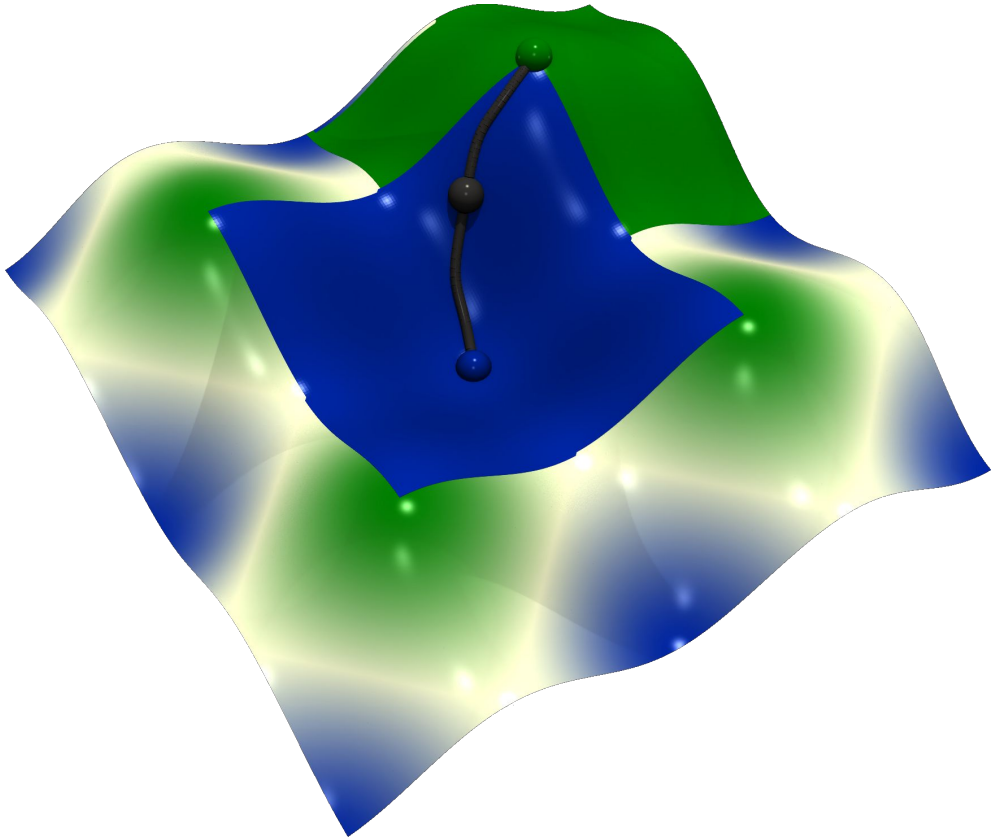

Discrete Morse Theory

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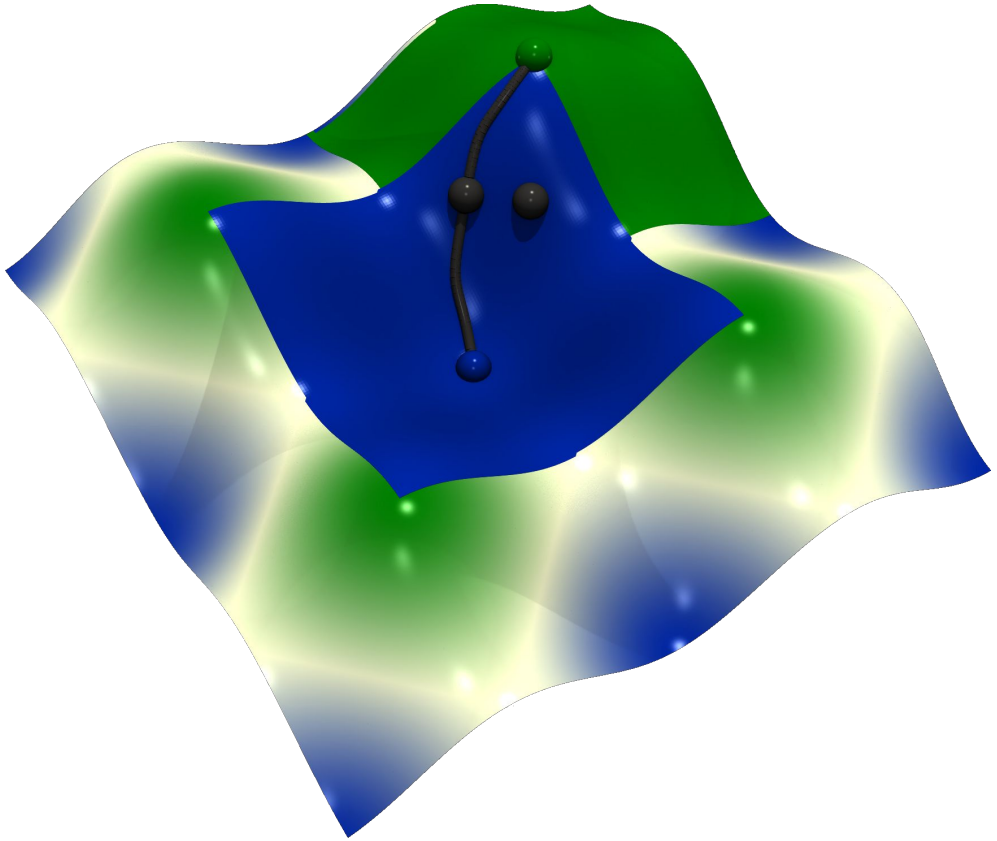

Discrete Morse Theory

- **Morse-Smale complex**
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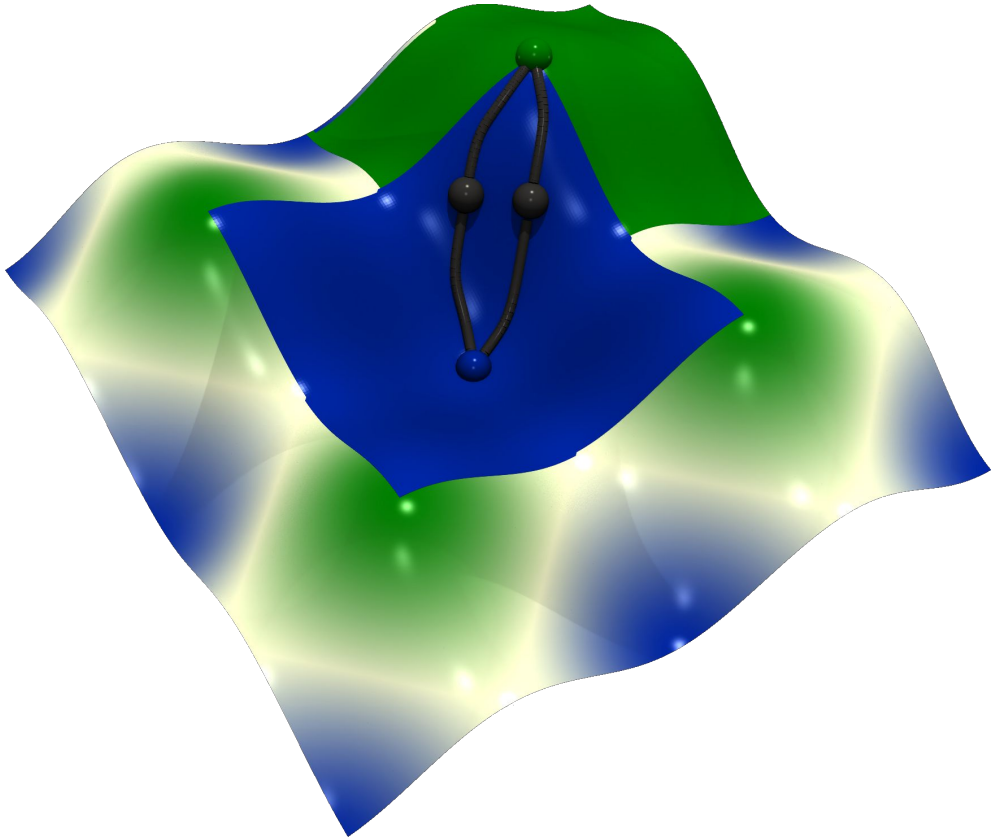
  - Challenging PL computation



Discrete Morse Theory

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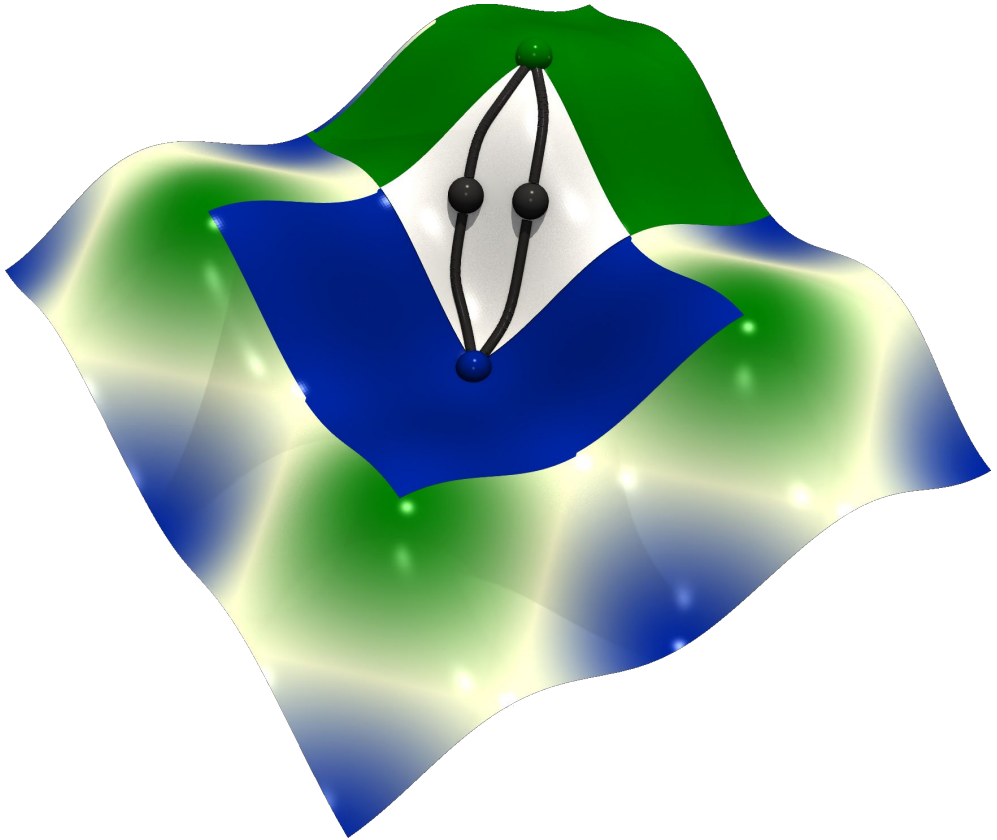

Discrete Morse Theory

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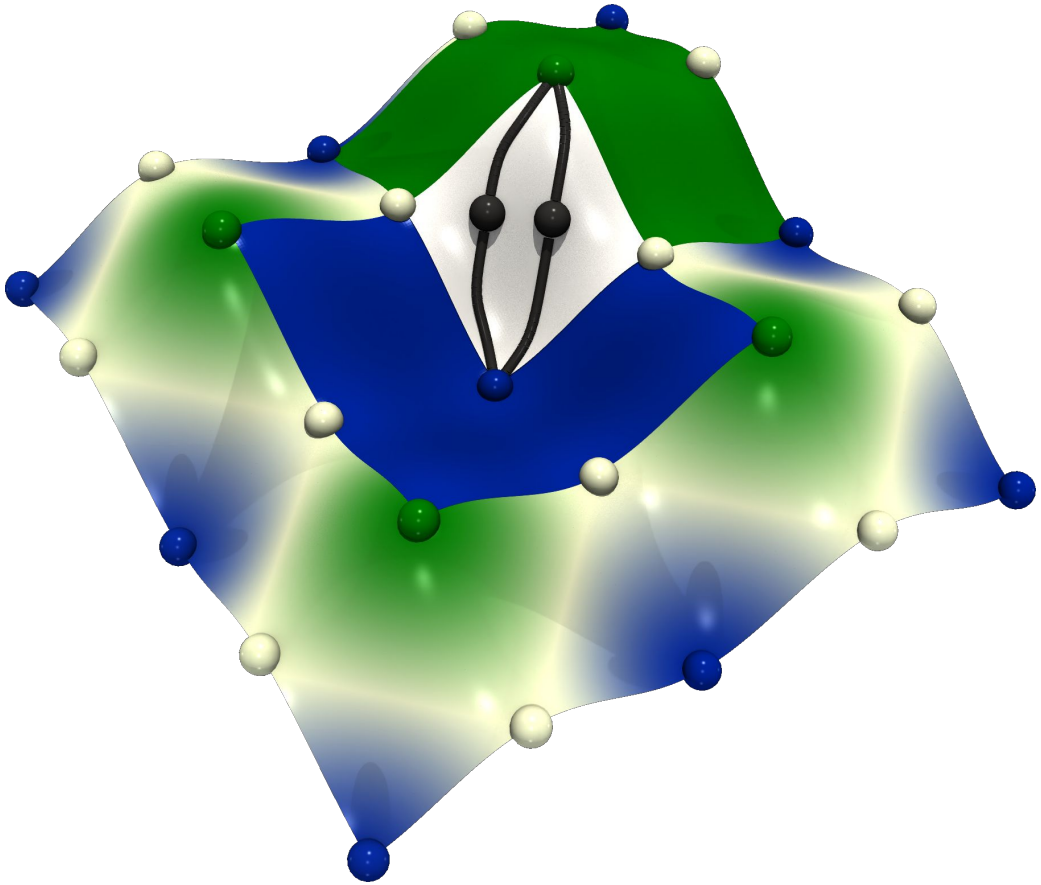

Discrete Morse Theory

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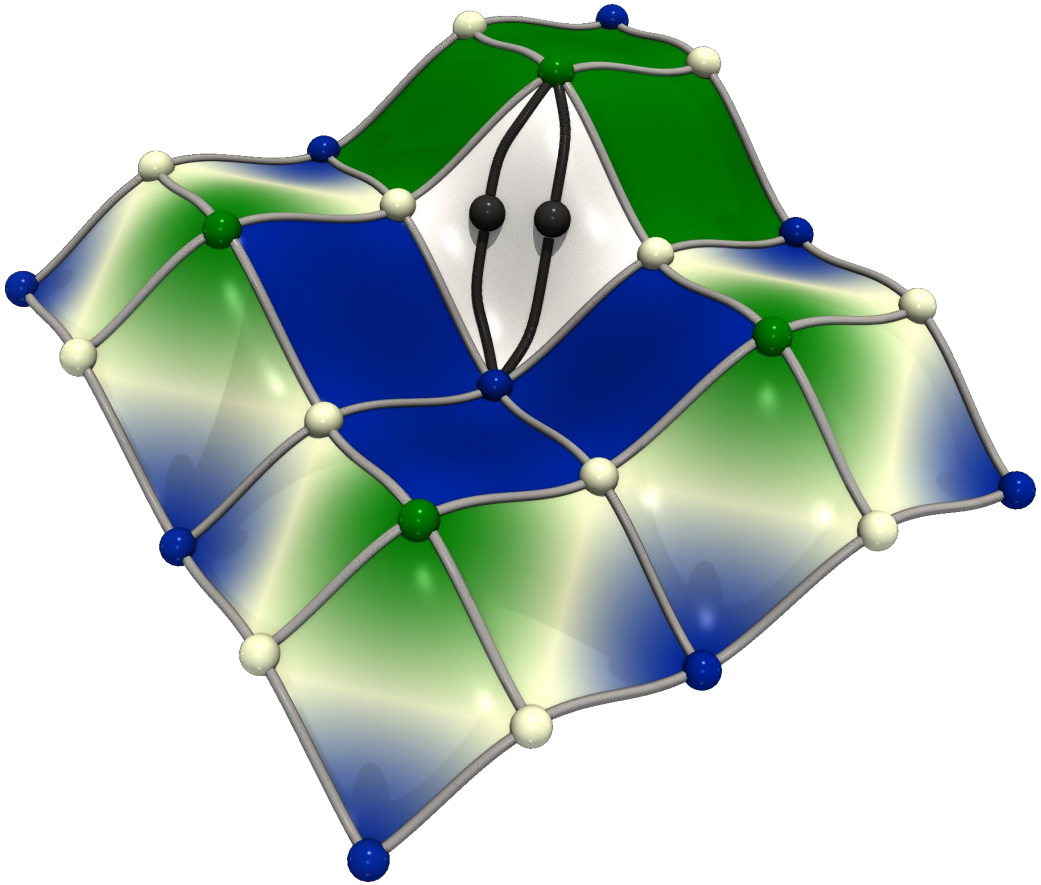

Discrete Morse Theory

- **Morse-Smale complex**
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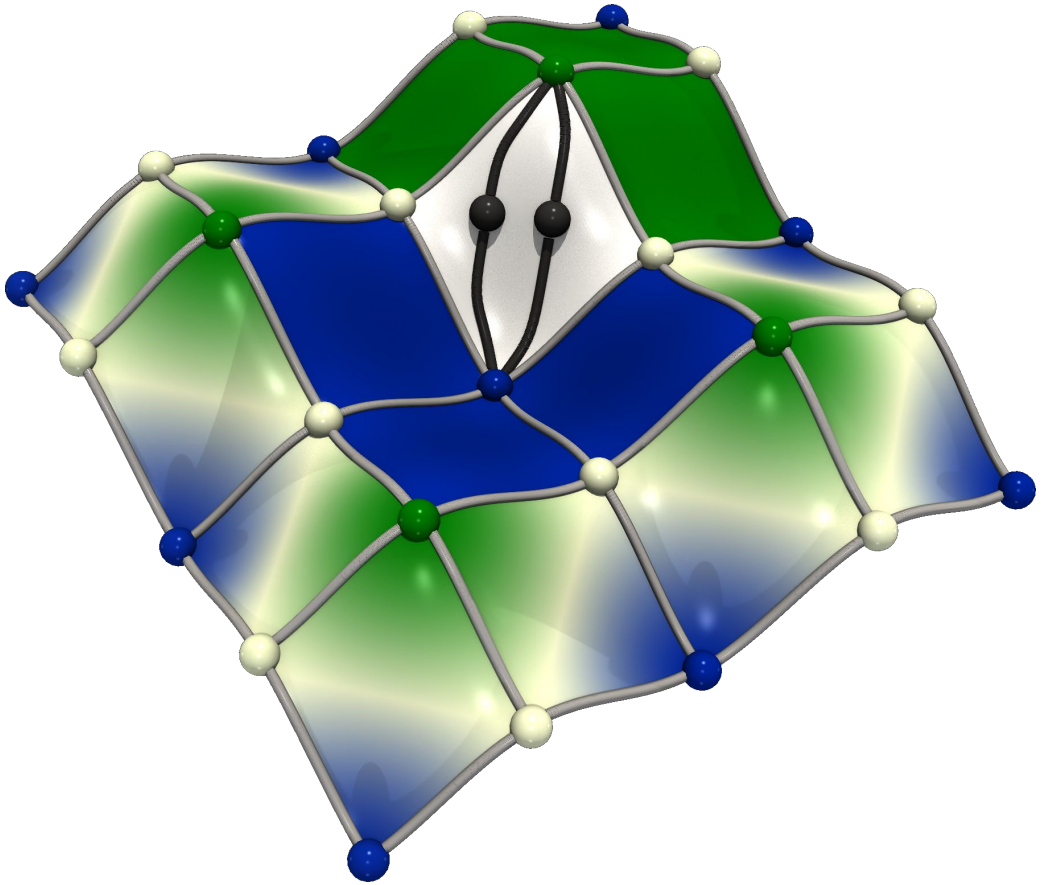
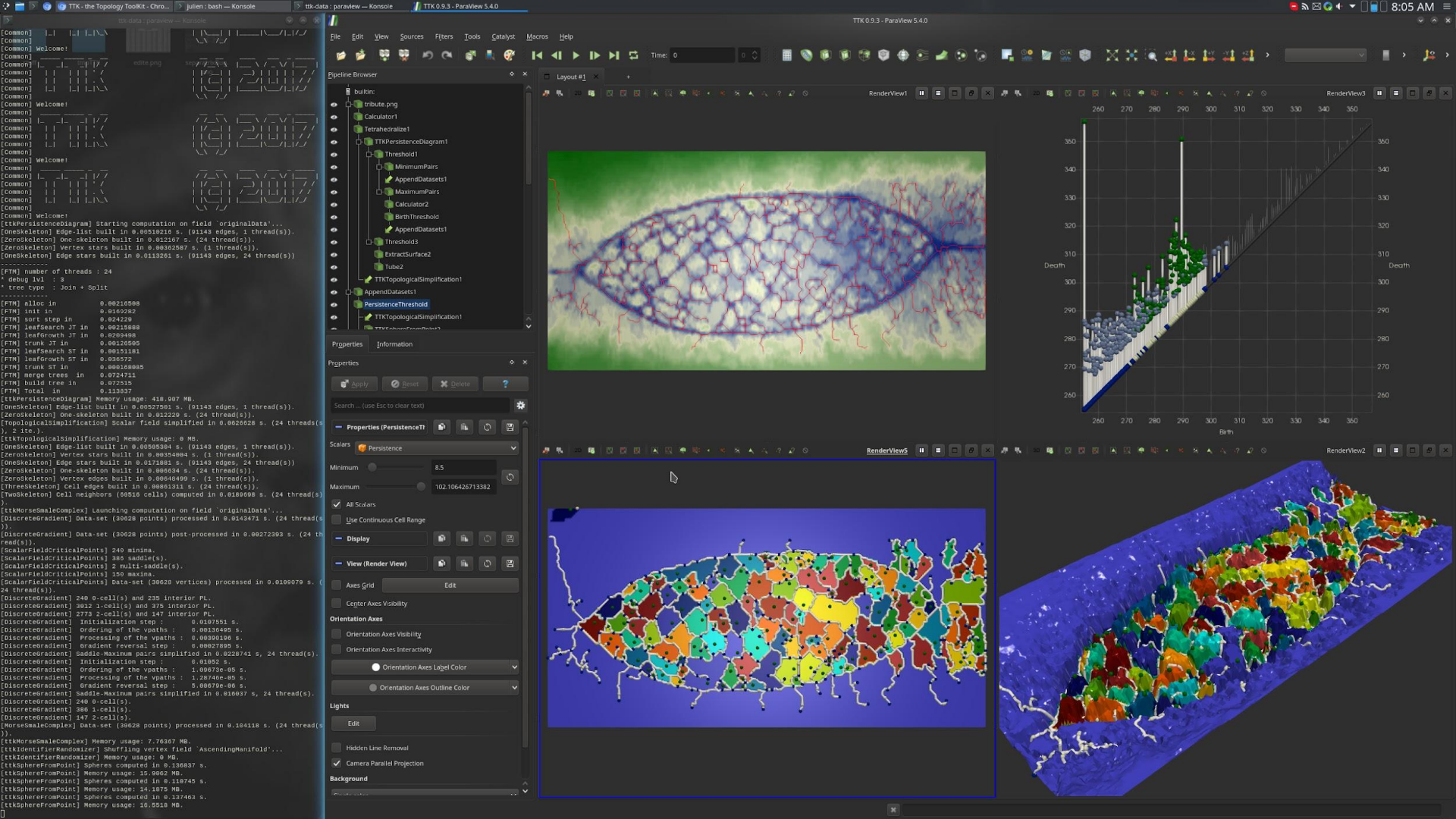
- **Discrete Morse theory**
  - Forman 1998
  - Algorithms
  - Gyulassy 2008, Robins 2011, Shivashankar and Natarajan 2012, *Tierny et al. 2017*




TTK - the Topology ToolKit - Chro...
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Threshold1
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AppendDatasets1
MaximumPairs
Calculator2
BirthThreshold
AppendDatasets1
Threshold3
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TTKTopologicalSimplification1
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Background
Layout #1
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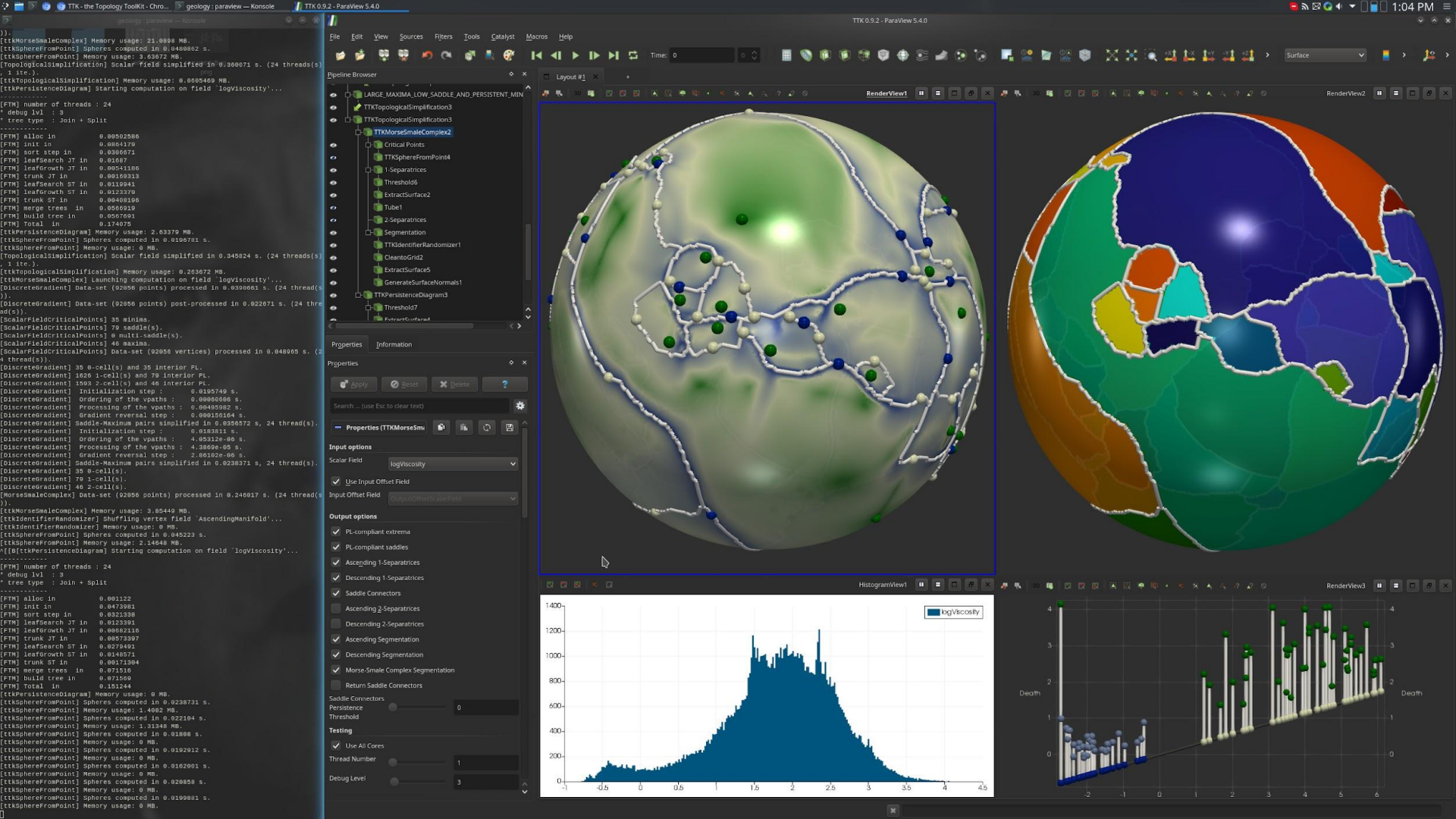
RenderView5
RenderView2
Death
Birth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1:04 PM
TTK 0.9.2 - ParaView 5.4.0
File Edit View Sources Filters Tools Catalyst Macros Help
Pipeline Browser
LARGE_MAXIMA_LOW_SADDLE_AND_PERSISTENT_MIN
TTKTopologicalSimplification3
TTKTopologicalSimplification3
TTKMorseSmaleComplex2
Critical Points
TTKSphereFromPoint4
1-Separatrices
Threshold6
ExtractSurface2
Tube1
2-Separatrices
Segmentation
TTKIdentifierRandomizer1
CleantoGrid2
ExtractSurface5
GenerateSurfaceNormals1
TTKPersistenceDiagram3
Threshold7
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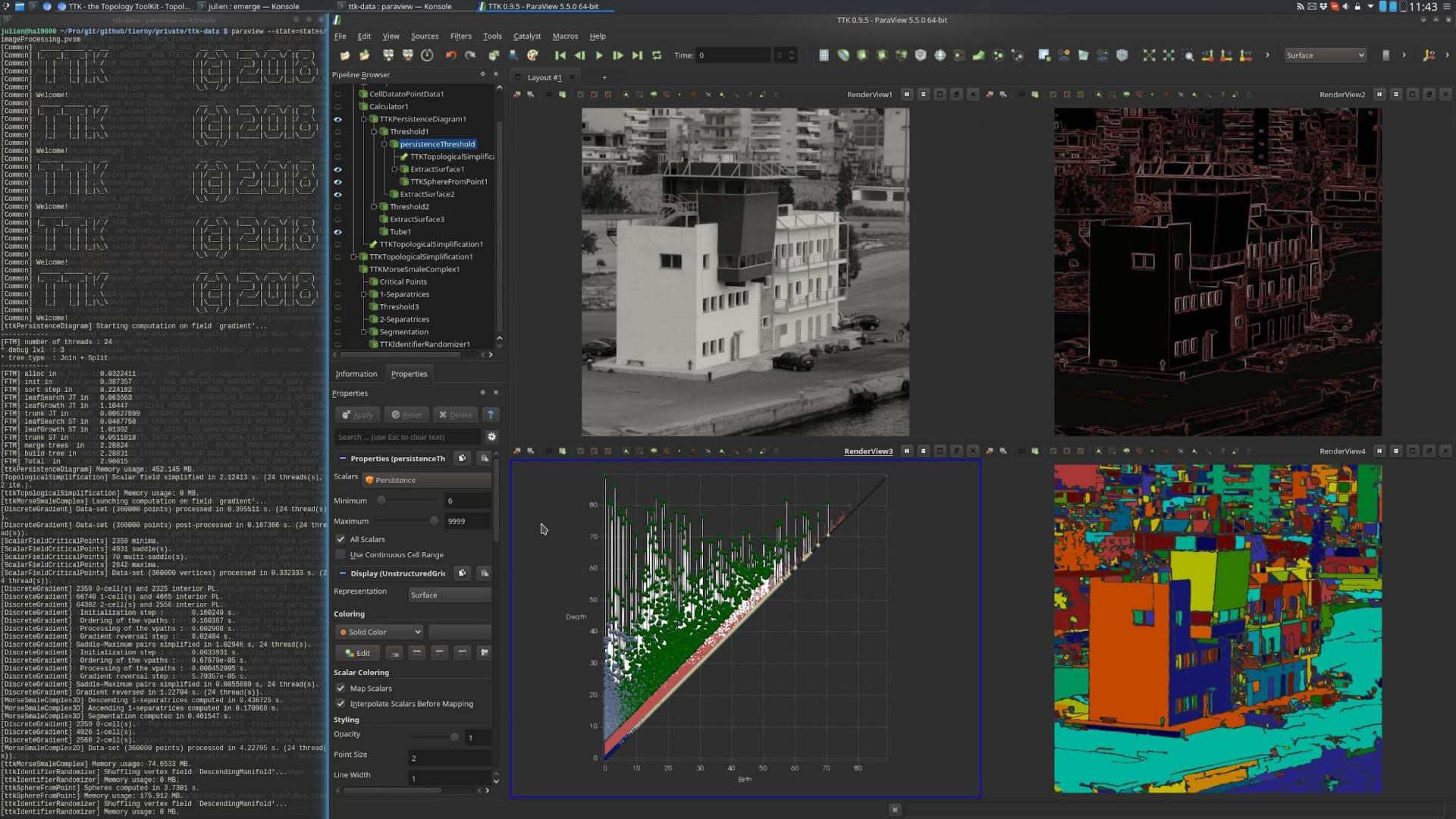
Input options
Scalar Field
logViscosity
Use Input Offset Field
Input Offset Field
Output options
PL-compliant extrema
PL-compliant saddles
Ascending 1-Separatrices
Descending 1-Separatrices
Saddle Connectors
Ascending 2-Separatrices
Descending 2-Separatrices
Ascending Segmentation
Descending Segmentation
Morse-Smale Complex Segmentation
Return Saddle Connectors
Saddle Connectors Persistence Threshold
Testing
Use All Cores
Thread Number
Debug Level
Layout #1
RenderView1
RenderView2
HistogramView1
RenderView3
logViscosity
Death
Death


TTK - the Topology ToolKit - Topol...
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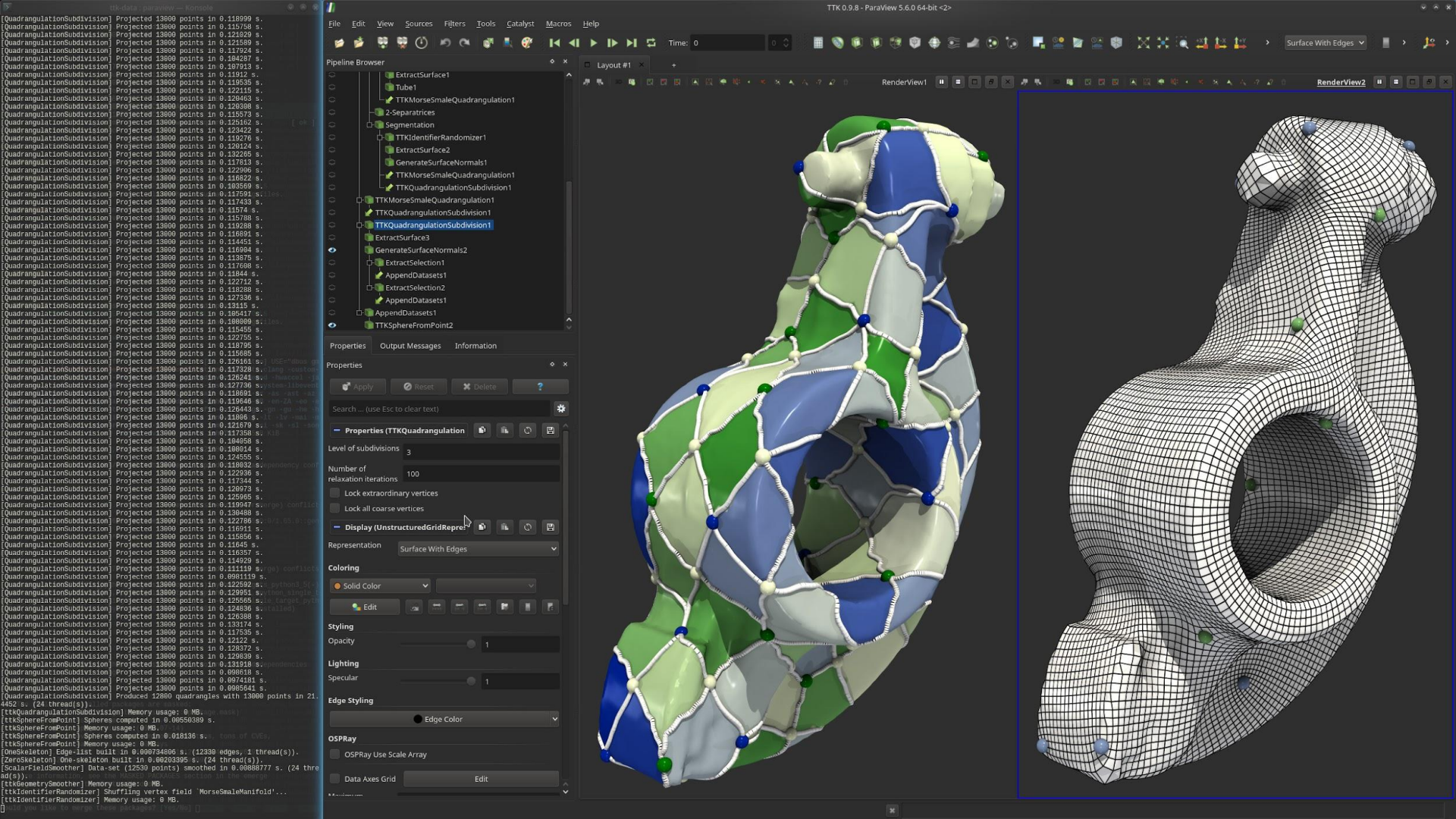
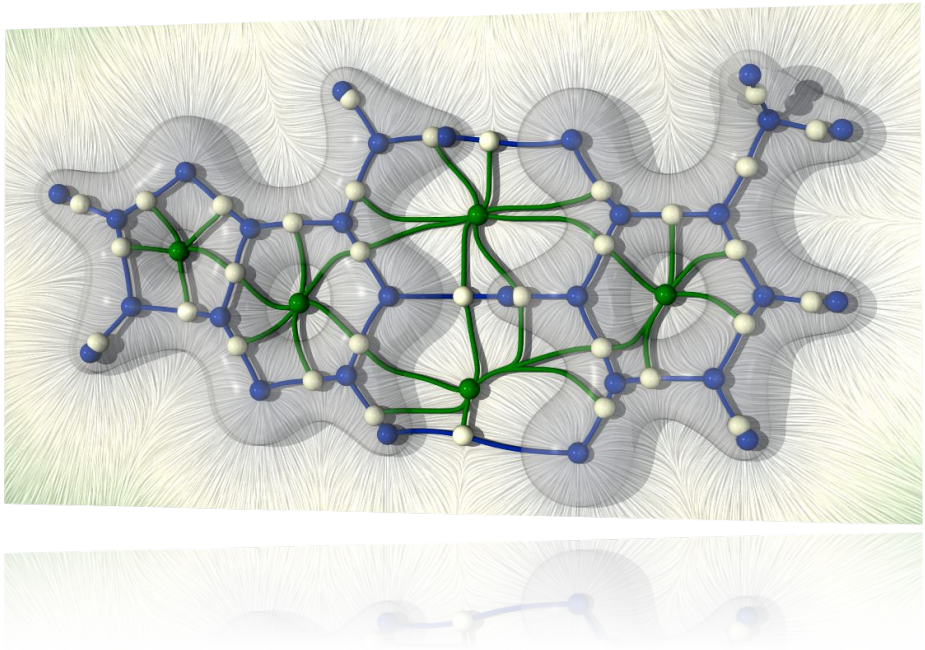
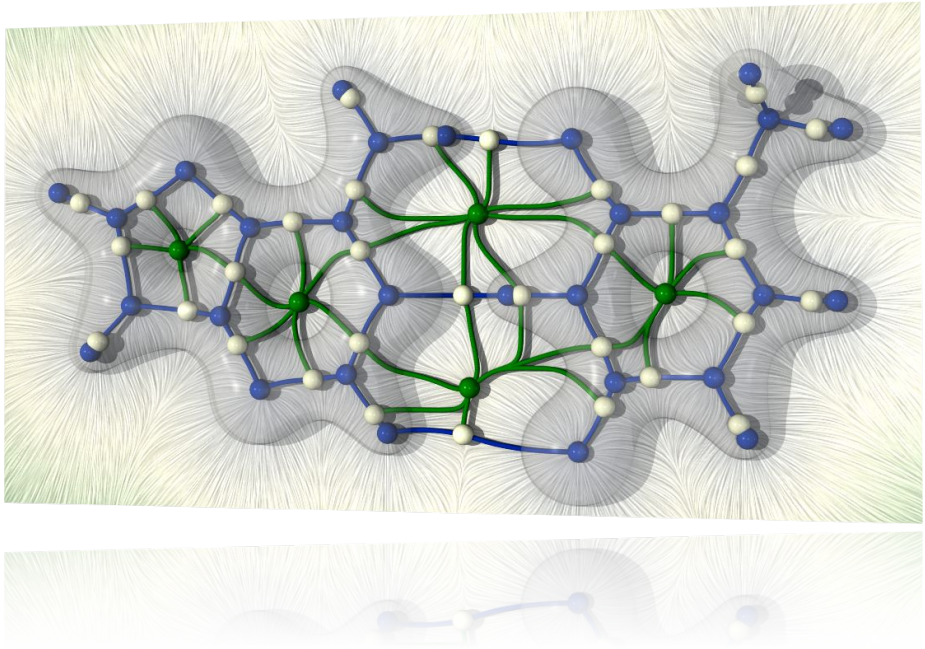
ttk-data : paraview — Konsole
TTK 0.9.5 - ParaView 5.5.0 64-bit
11:43
TTK 0.9.5 - ParaView 5.5.0 64-bit
File Edit View Sources Filters Tools Catalyst Macros Help
Time: 0
Surface
Pipeline Browser
CellDatatoPointData1
Calculator1
TTKPersistenceDiagram1
Threshold1
persistenceThreshold
TTKTopologicalSimplifica
ExtractSurface1
TTKSphereFromPoint1
ExtractSurface2
Threshold2
ExtractSurface3
Tube1
TTKTopologicalSimplification1
TTKTopologicalSimplification1
TTKMorseSmaleComplex1
Critical Points
1-Separatrices
Threshold3
2-Separatrices
Segmentation
TTKIdentifierRandomizer1
Information
Properties
Properties
Apply
Reset
Delete
Search ... (use Esc to clear text)
Properties (persistenceTh
Scalars
Persistence
Minimum
6
Maximum
9999
All Scalars
Use Continuous Cell Range
Display (UnstructuredGric
Representation
Surface
Coloring
Solid Color
Edit
Scalar Coloring
Map Scalars
Interpolate Scalars Before Mapping
Styling
Opacity
1
Point Size
2
Line Width
1
Layout #1
RenderView1
RenderView2
RenderView3
RenderView4
Death
Birth
0
10
20
30
40
50
60
70
80
julien@hal9000 ~/Pro/git/github/tierny/private/ttk-data $ paraview --state=states/imageProcessing.pvsm
[ttkPersistenceDiagram] Starting computation on field 'gradient'...
[FTM] number of threads : 24
* debug lvl : 3
* tree type : Join + Split
[FTM] alloc in 0.0322411
[FTM] init in 0.387357
[FTM] sort step in 0.224182
[FTM] leafSearch JT in 0.063663
[FTM] leafGrowth JT in 1.10447
[FTM] trunk JT in 0.00627899
[FTM] leafSearch ST in 0.0467758
[FTM] leafGrowth ST in 1.01302
[FTM] trunk ST in 0.0511818
[FTM] merge trees in 2.28824
[FTM] build tree in 2.28831
[FTM] Total in 2.90015
[ttkPersistenceDiagram] Memory usage: 452.145 MB.
[TopologicalSimplification] Scalar field simplified in 2.12413 s. (24 threads(s), 2 ite.).
[ttkTopologicalSimplification] Memory usage: 0 MB.
[ttkMorseSmaleComplex] Launching computation on field 'gradient'...
[DiscreteGradient] Data-set (360000 points) processed in 0.395511 s. (24 thread(s)).
[DiscreteGradient] Data-set (360000 points) post-processed in 0.167366 s. (24 thread(s)).
[ScalarFieldCriticalPoints] 2359 minima.
[ScalarFieldCriticalPoints] 4931 saddle(s).
[ScalarFieldCriticalPoints] 70 multi-saddle(s).
[ScalarFieldCriticalPoints] 2642 maxima.
[ScalarFieldCriticalPoints] Data-set (360000 vertices) processed in 0.332333 s. (24 thread(s)).
[DiscreteGradient] 2359 0-cell(s) and 2325 interior PL.
[DiscreteGradient] 66740 1-cell(s) and 4665 interior PL.
[DiscreteGradient] 64302 2-cell(s) and 2550 interior PL.
[DiscreteGradient] Initialization step : 0.160249 s.
[DiscreteGradient] Ordering of the vpaths : 0.160387 s.
[DiscreteGradient] Processing of the vpaths : 0.602908 s.
[DiscreteGradient] Gradient reversal step : 0.02404 s.
[DiscreteGradient] Saddle-Maximum pairs simplified in 1.02946 s, 24 thread(s).
[DiscreteGradient] Initialization step : 0.0633931 s.
[DiscreteGradient] Ordering of the vpaths : 9.67979e-05 s.
[DiscreteGradient] Processing of the vpaths : 0.000452995 s.
[DiscreteGradient] Gradient reversal step : 5.79357e-05 s.
[DiscreteGradient] Saddle-Maximum pairs simplified in 0.0855689 s, 24 thread(s).
[DiscreteGradient] Gradient reversed in 1.22704 s. (24 thread(s)).
[MorseSmaleComplex3D] Descending 1-separatrices computed in 0.436725 s.
[MorseSmaleComplex3D] Ascending 1-separatrices computed in 0.170968 s.
[MorseSmaleComplex3D] Segmentation computed in 0.461547 s.
[DiscreteGradient] 2359 0-cell(s).
[DiscreteGradient] 4926 1-cell(s).
[DiscreteGradient] 2568 2-cell(s).
[MorseSmaleComplex2D] Data-set (360000 points) processed in 4.22795 s. (24 thread(s)).
[ttkMorseSmaleComplex] Memory usage: 74.6533 MB.
[ttkIdentifierRandomizer] Shuffling vertex field 'DescendingManifold'...
[ttkIdentifierRandomizer] Memory usage: 0 MB.
[ttkSphereFromPoint] Spheres computed in 3.7301 s.
[ttkSphereFromPoint] Memory usage: 175.912 MB.
[ttkIdentifierRandomizer] Shuffling vertex field 'DescendingManifold'...
[ttkIdentifierRandomizer] Memory usage: 0 MB.

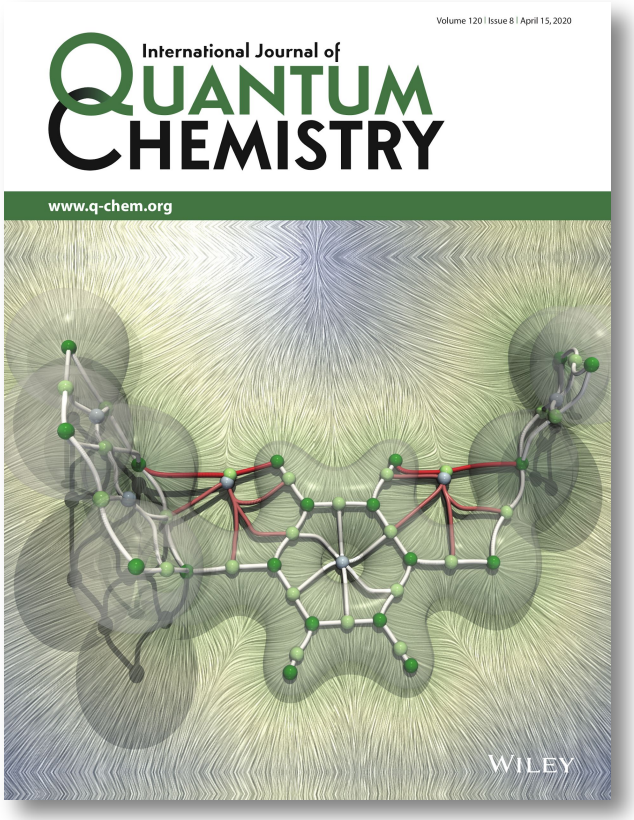

TTK 0.9.8 - ParaView 5.6.0 64-bit <2>
File Edit View Sources Filters Tools Catalyst Macros Help
Time: 0
Surface With Edges
Pipeline Browser
ExtractSurface1
Tube1
TTKMorseSmaleQuadrangulation1
2-Separatrices
Segmentation
TTKIdentifierRandomizer1
ExtractSurface2
GenerateSurfaceNormals1
TTKMorseSmaleQuadrangulation1
TTKQuadrangulationSubdivision1
TTKMorseSmaleQuadrangulation1
TTKQuadrangulationSubdivision1
TTKQuadrangulationSubdivision1
ExtractSurface3
GenerateSurfaceNormals2
ExtractSelection1
AppendDatasets1
ExtractSelection2
AppendDatasets1
AppendDatasets1
TTKSphereFromPoint2
Properties
Output Messages
Information
Properties
Apply
Reset
Delete
Search ... (use Esc to clear text)
Properties (TTKQuadrangulation
Level of subdivisions
3
Number of relaxation iterations
100
Lock extraordinary vertices
Lock all coarse vertices
Display (UnstructuredGridRepres
Representation
Surface With Edges
Coloring
Solid Color
Edit
Styling
Opacity
1
Lighting
Specular
1
Edge Styling
Edge Color
OSPRay
OSPRay Use Scale Array
Data Axes Grid
Edit
Layout #1
RenderView1
RenderView2

Application of the Morse-Smale complex



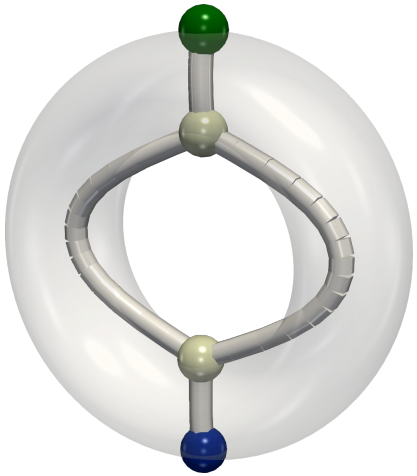
Application of the Morse-Smale complex





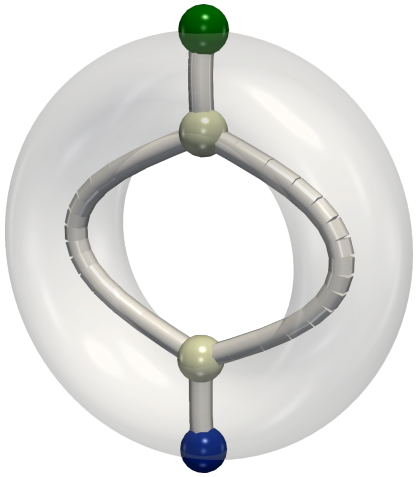
So far

- **TDA for low dimensional fields**
  - Data reduction by feature extraction



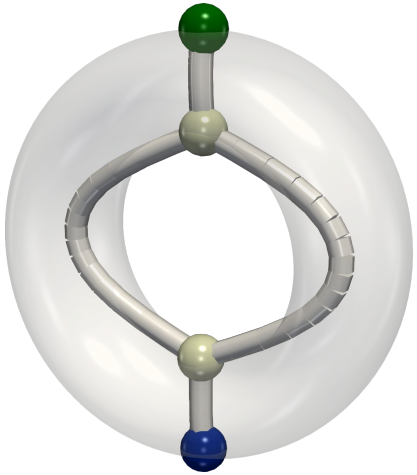
So far

- **TDA for low dimensional fields**
  - Data reduction by feature extraction
    - Critical points (vortices)
    - 1-Separatrices (filament structures)
    - 2-Separatrices (walls)
    - Regions of interest



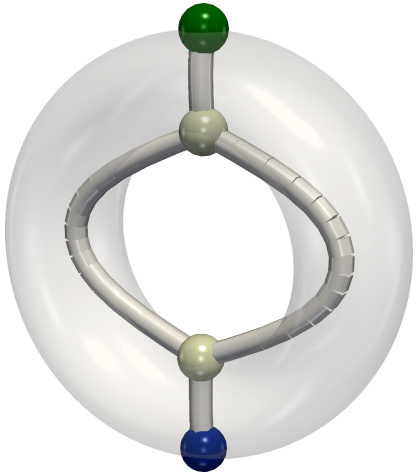
So far

- **TDA for low dimensional fields**
  - Data reduction by feature extraction
    - Critical points (vortices)
    - 1-Separatrices (filament structures)
    - 2-Separatrices (walls)
    - Regions of interest
  - Only store topological information
    - Further analysis, measure, comparison
    - TDA driven lossy compression (*Soler et al. 2018*)



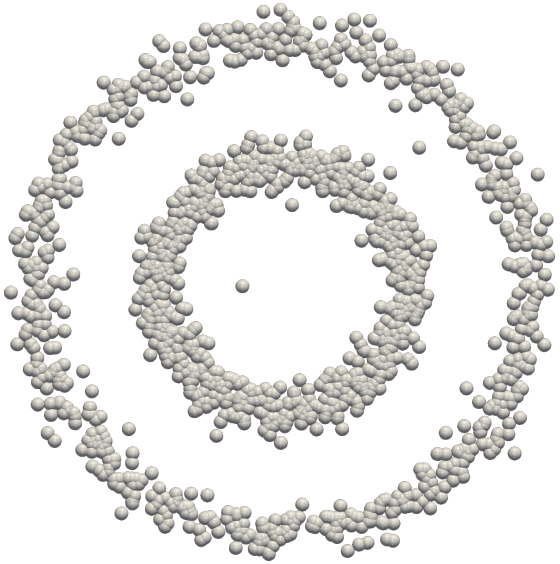
So far

- **TDA for low dimensional fields**
  - Data reduction by feature extraction
    - Critical points (vortices)
    - 1-Separatrices (filament structures)
    - 2-Separatrices (walls)
    - Regions of interest
  - Only store topological information
    - Further analysis, measure, comparison
    - TDA driven lossy compression (*Soler et al. 2018*)

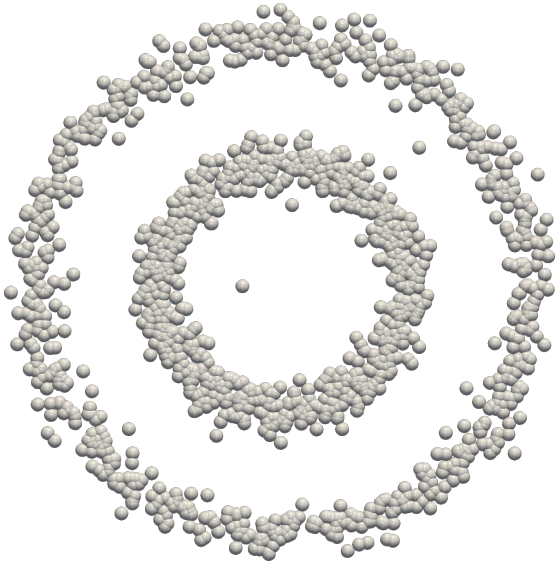


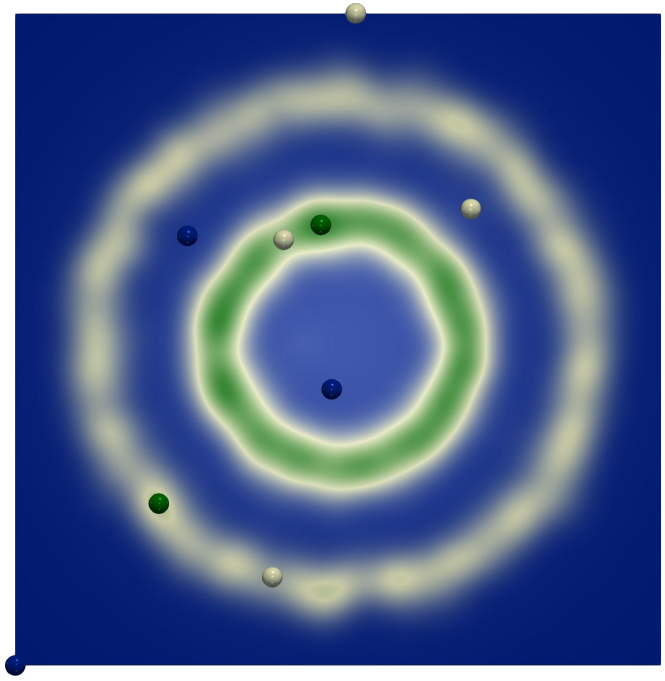
- **How about point cloud data?**

What about point cloud data?

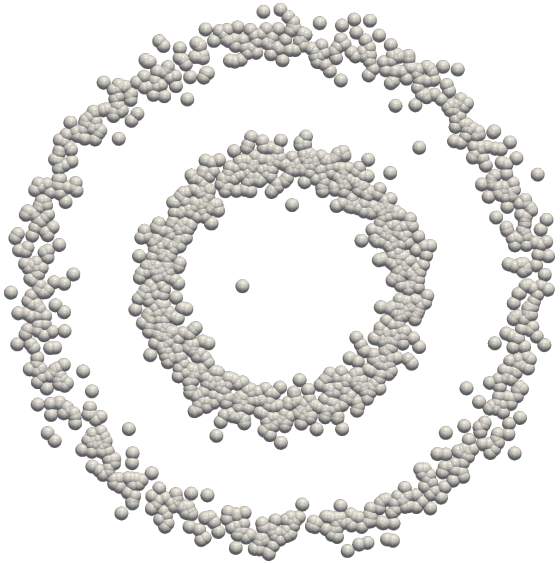


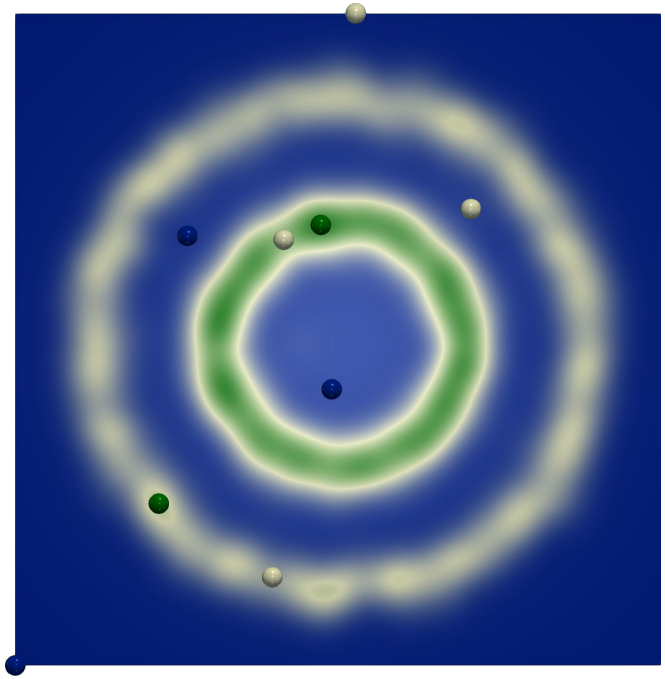
What about point cloud data?

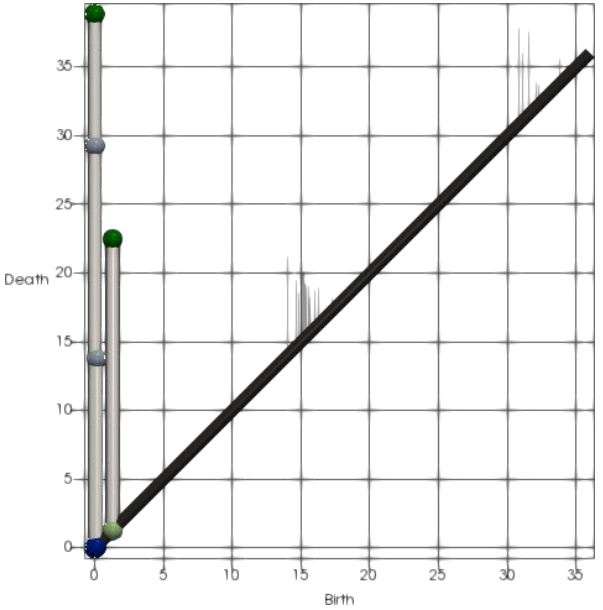




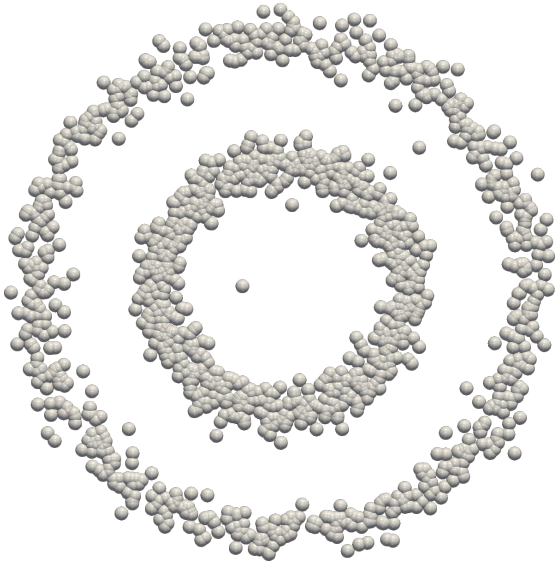
What about point cloud data?

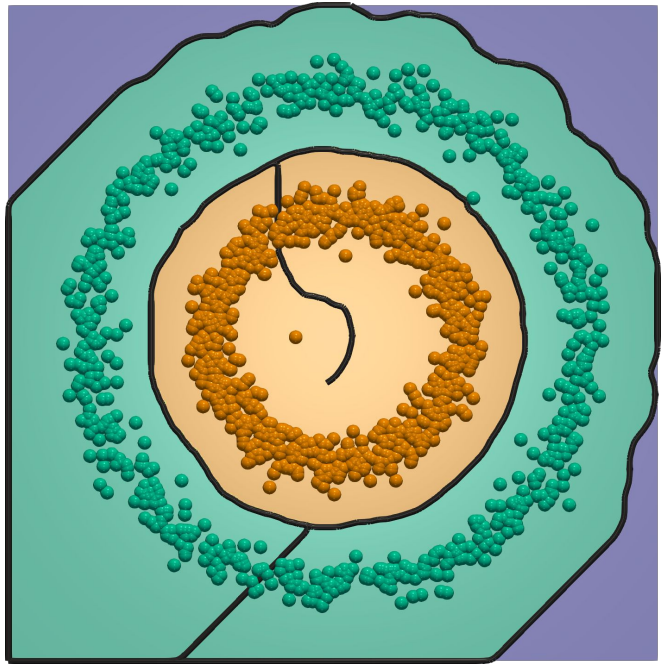


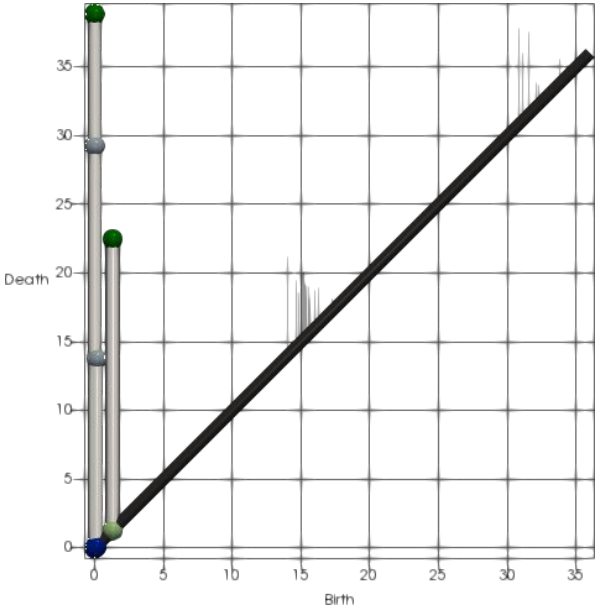




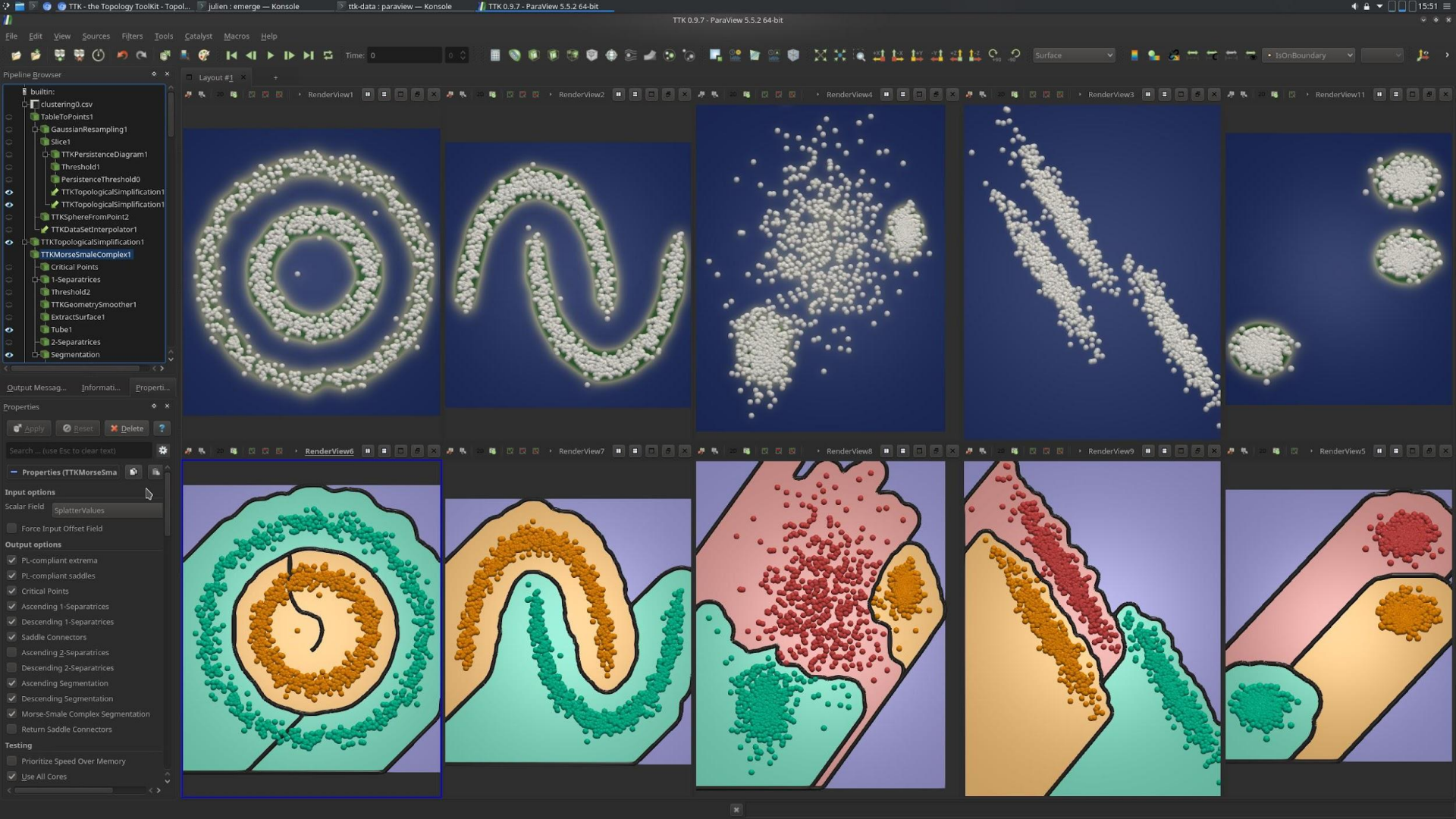
What about point cloud data?

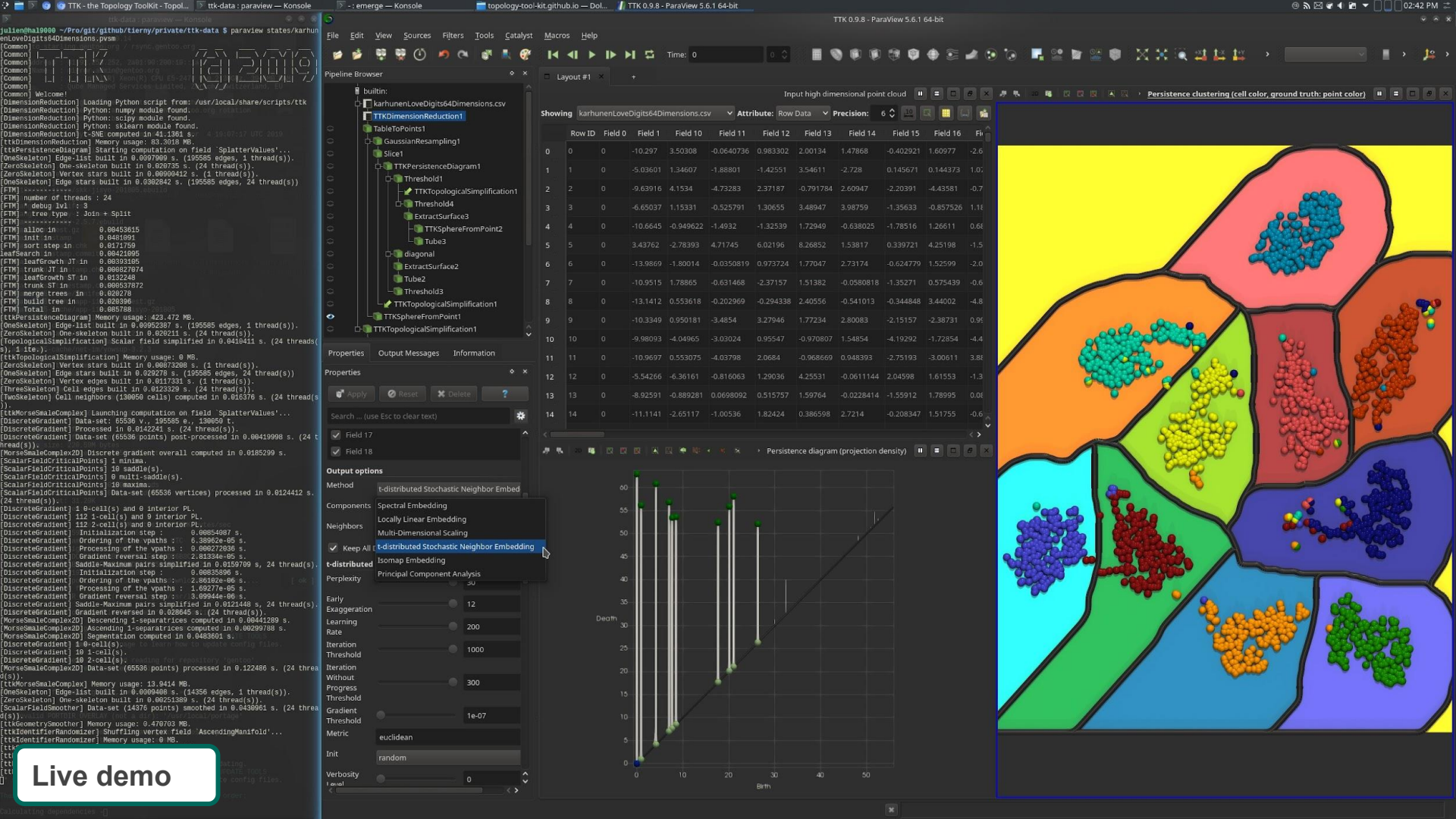




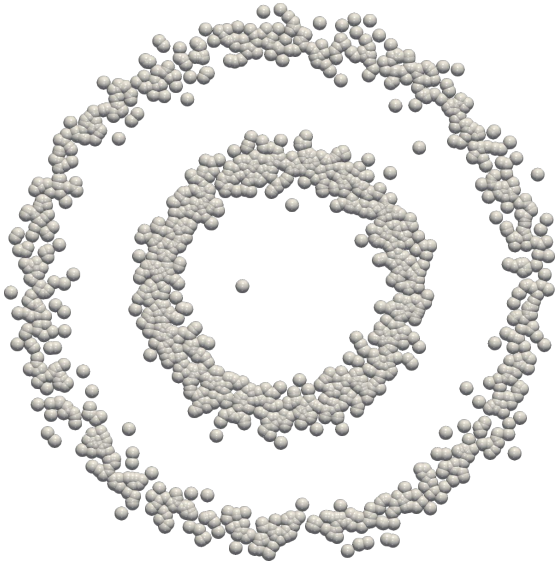


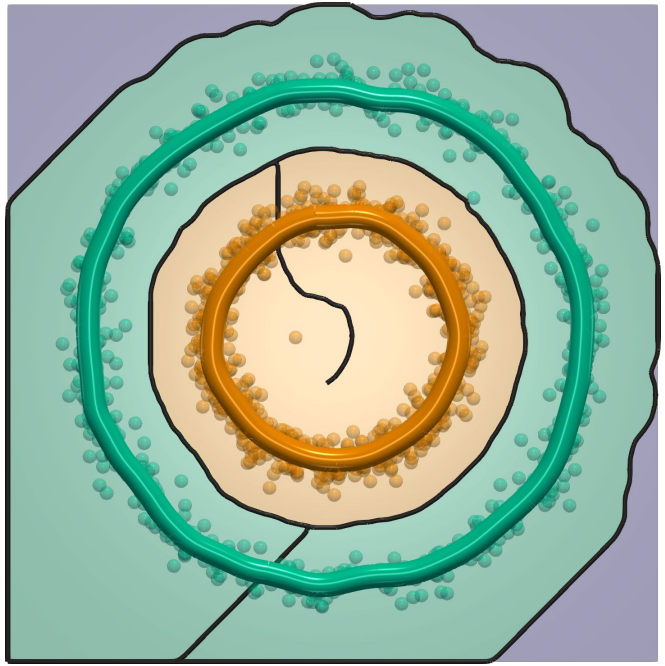
- Chazal et al. 2013

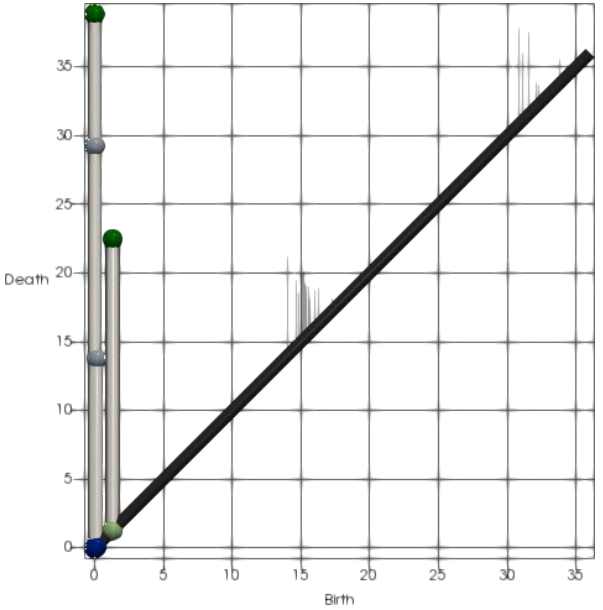

TTK - the Topology ToolKit - Topol...
julien : emerge — Konsole
ttk-data : paraview — Konsole
TTK 0.9.7 - ParaView 5.5.2 64-bit
15:51
TTK 0.9.7 - ParaView 5.5.2 64-bit
File Edit View Sources Filters Tools Catalyst Macros Help
Time: 0
Surface
IsOnBoundary
Pipeline Browser
builtin:
clustering0.csv
TableToPoints1
GaussianResampling1
Slice1
TTKPersistenceDiagram1
Threshold1
PersistenceThreshold0
TTKTopologicalSimplification1
TTKTopologicalSimplification1
TTKSphereFromPoint2
TTKDataSetInterpolator1
TTKTopologicalSimplification1
TTKMorseSmaleComplex1
Critical Points
1-Separatrices
Threshold2
TTKGeometrySmoother1
ExtractSurface1
Tube1
2-Separatrices
Segmentation
Output Messag...
Informati...
Properti...
Properties
Apply
Reset
Delete
Search ... (use Esc to clear text)
Properties (TTKMorseSma
Input options
Scalar Field
SplatterValues
Force Input Offset Field
Output options
PL-compliant extrema
PL-compliant saddles
Critical Points
Ascending 1-Separatrices
Descending 1-Separatrices
Saddle Connectors
Ascending 2-Separatrices
Descending 2-Separatrices
Ascending Segmentation
Descending Segmentation
Morse-Smale Complex Segmentation
Return Saddle Connectors
Testing
Prioritize Speed Over Memory
Use All Cores
Layout #1
RenderView1
RenderView2
RenderView4
RenderView3
RenderView11
RenderView6
RenderView7
RenderView8
RenderView9
RenderView5

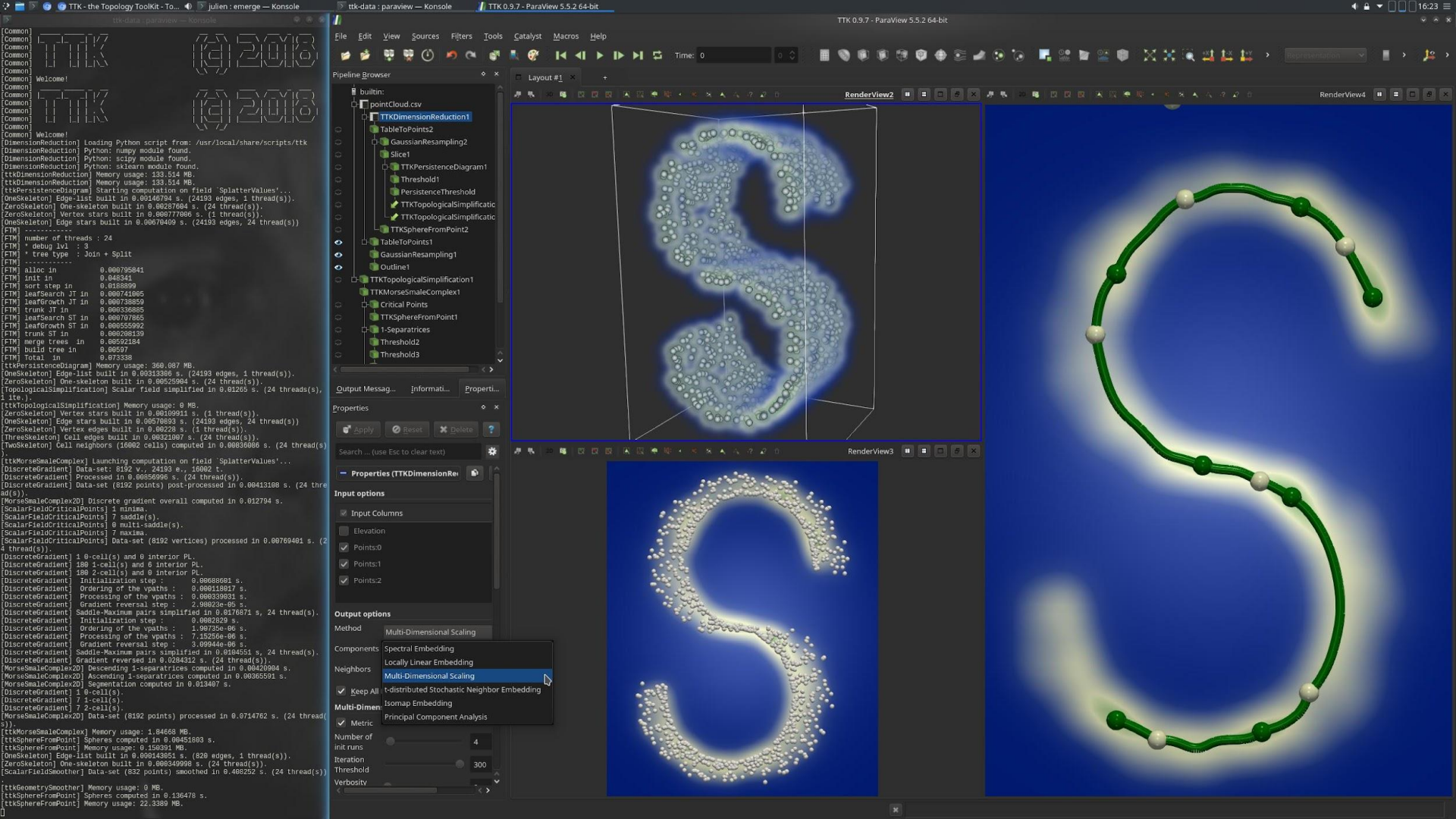

TTK 0.9.8 - ParaView 5.6.1 64-bit
File Edit View Sources Filters Tools Catalyst Macros Help
Pipeline Browser
builtin:
karhunenLoveDigits64Dimensions.csv
TTKDimensionReduction1
TableToPoints1
GaussianResampling1
Slice1
TTKPersistenceDiagram1
Threshold1
TTKTopologicalSimplification1
Threshold4
ExtractSurface3
TTKSphereFromPoint2
Tube3
diagonal
ExtractSurface2
Tube2
Threshold3
TTKTopologicalSimplification1
TTKSphereFromPoint1
TTKTopologicalSimplification1
Properties
Output Messages
Information
Apply
Reset
Delete
Search ... (use Esc to clear text)
Field 17
Field 18
Output options
Method
t-distributed Stochastic Neighbor Embed
Components
Neighbors
Keep All
Spectral Embedding
Locally Linear Embedding
Multi-Dimensional Scaling
t-distributed Stochastic Neighbor Embedding
Isomap Embedding
Principal Component Analysis
Perplexity
Early Exaggeration
Learning Rate
Iteration Threshold
Iteration Without Progress Threshold
Gradient Threshold
Metric
euclidean
Init
random
Verbosity
Layout #1
Input high dimensional point cloud
Showing
karhunenLoveDigits64Dimensions.csv
Attribute:
Row Data
Precision:
Row ID Field 0 Field 1 Field 10 Field 11 Field 12 Field 13 Field 14 Field 15 Field 16
Persistence diagram (projection density)
Death
Birth
Persistence clustering (cell color, ground truth: point color)
Live demo

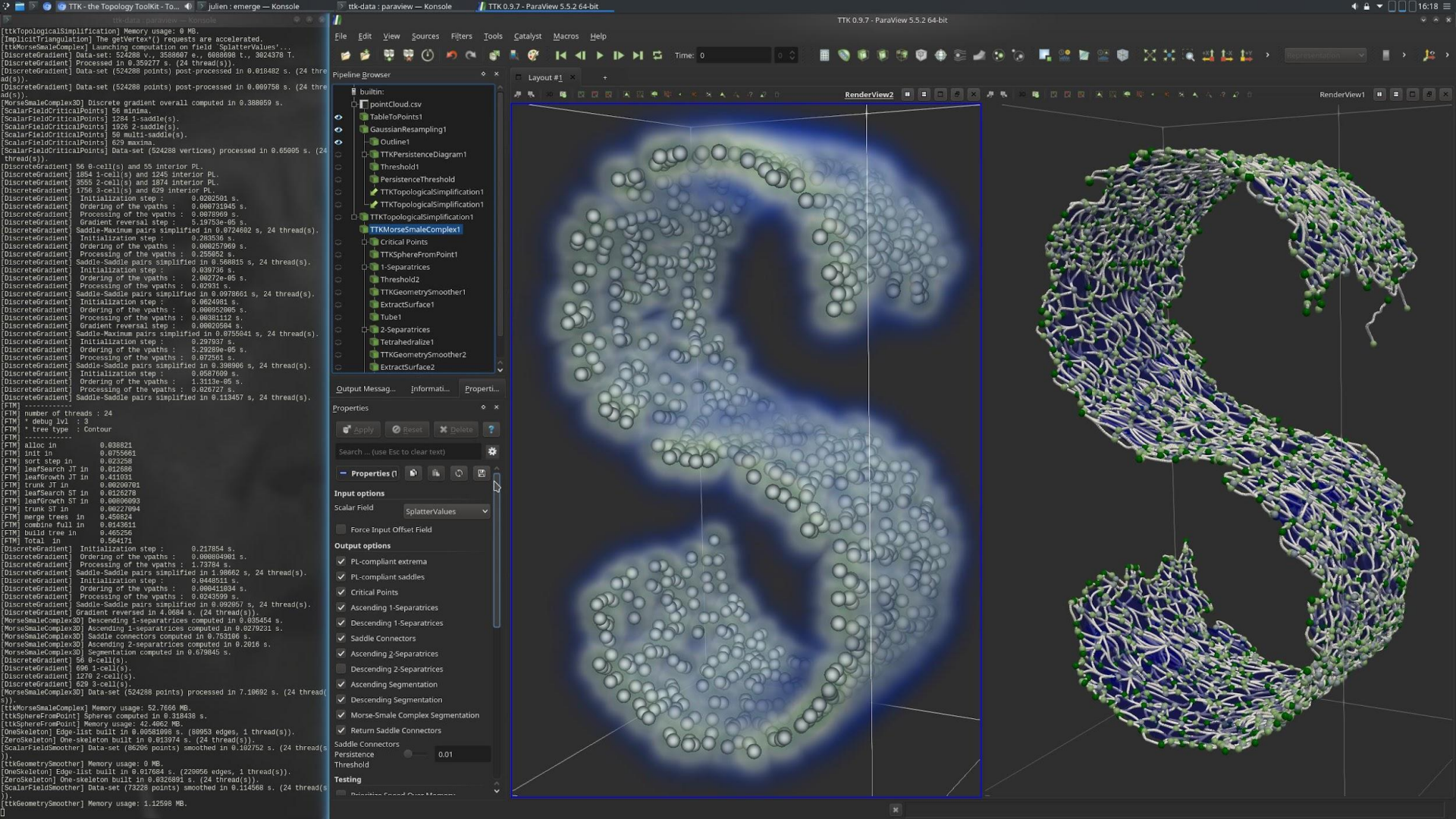
What about point cloud data?



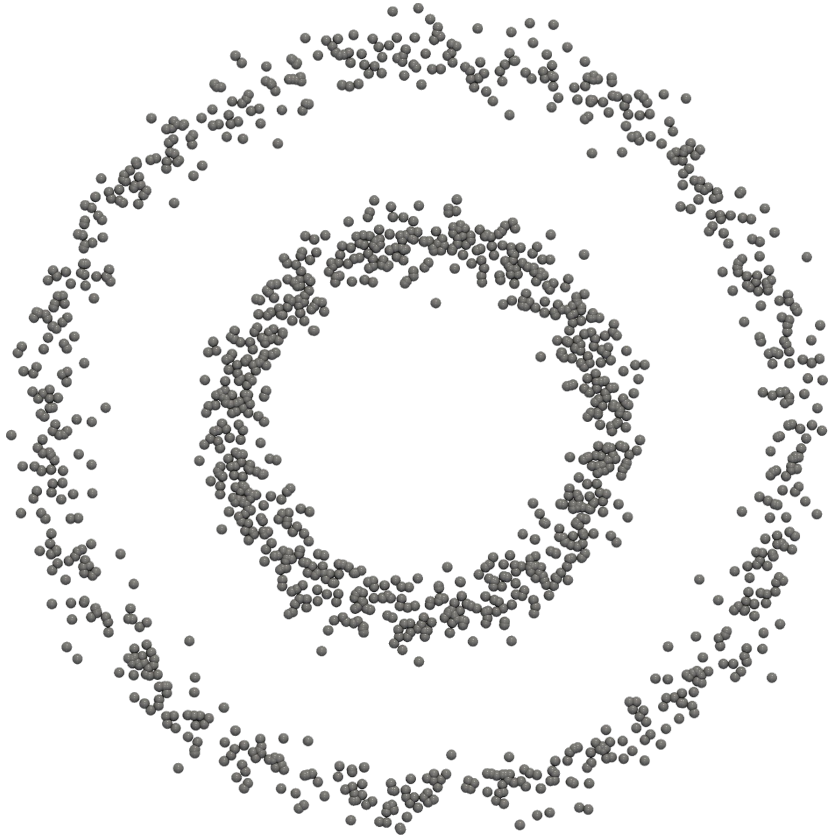




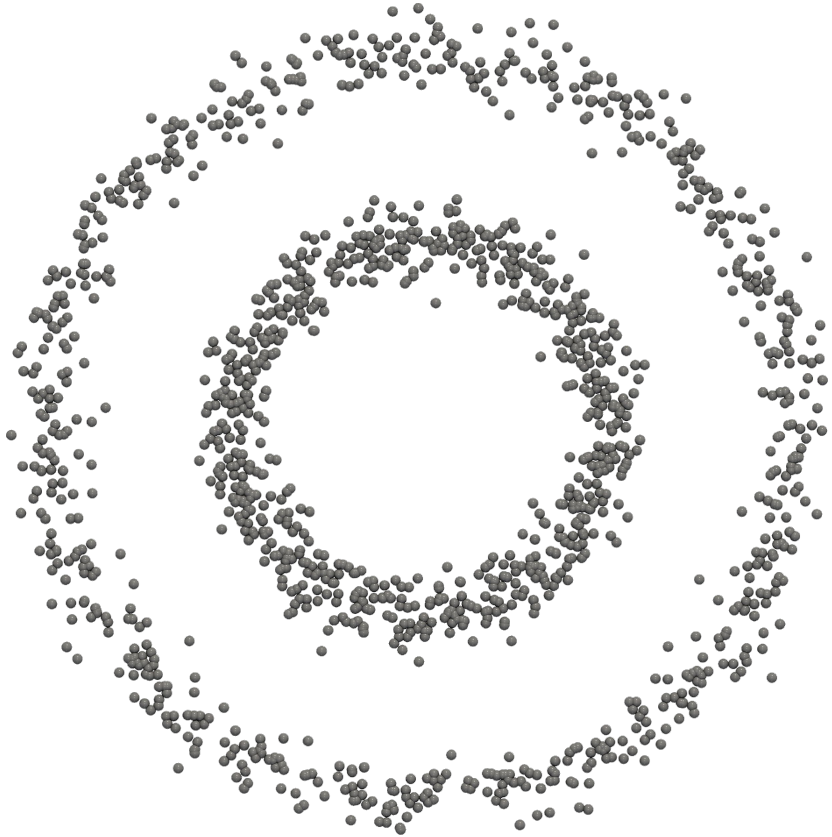

TTK - the Topology ToolKit - To...
julien : emerge — Konsole
ttk-data : paraview — Konsole
TTK 0.9.7 - ParaView 5.5.2 64-bit
16:23
TTK 0.9.7 - ParaView 5.5.2 64-bit
File Edit View Sources Filters Tools Catalyst Macros Help
Time: 0
Pipeline Browser
builtin:
pointCloud.csv
TTKDimensionReduction1
TableToPoints2
GaussianResampling2
Slice1
TTKPersistenceDiagram1
Threshold1
PersistenceThreshold
TTKTopologicalSimplificatic
TTKTopologicalSimplificatic
TTKSphereFromPoint2
TableToPoints1
GaussianResampling1
Outline1
TTKTopologicalSimplification1
TTKMorseSmaleComplex1
Critical Points
TTKSphereFromPoint1
1-Separatrices
Threshold2
Threshold3
Output Messag...
Informati...
Properti...
Properties
Apply
Reset
Delete
Search ... (use Esc to clear text)
Properties (TTKDimensionRe
Input options
Input Columns
Elevation
Points:0
Points:1
Points:2
Output options
Method
Multi-Dimensional Scaling
Components
Neighbors
Keep All
Multi-Dimen
Metric
Number of init runs
4
Iteration Threshold
300
Verbosity
Spectral Embedding
Locally Linear Embedding
Multi-Dimensional Scaling
t-distributed Stochastic Neighbor Embedding
Isomap Embedding
Principal Component Analysis
Layout #1
RenderView2
RenderView4
RenderView3

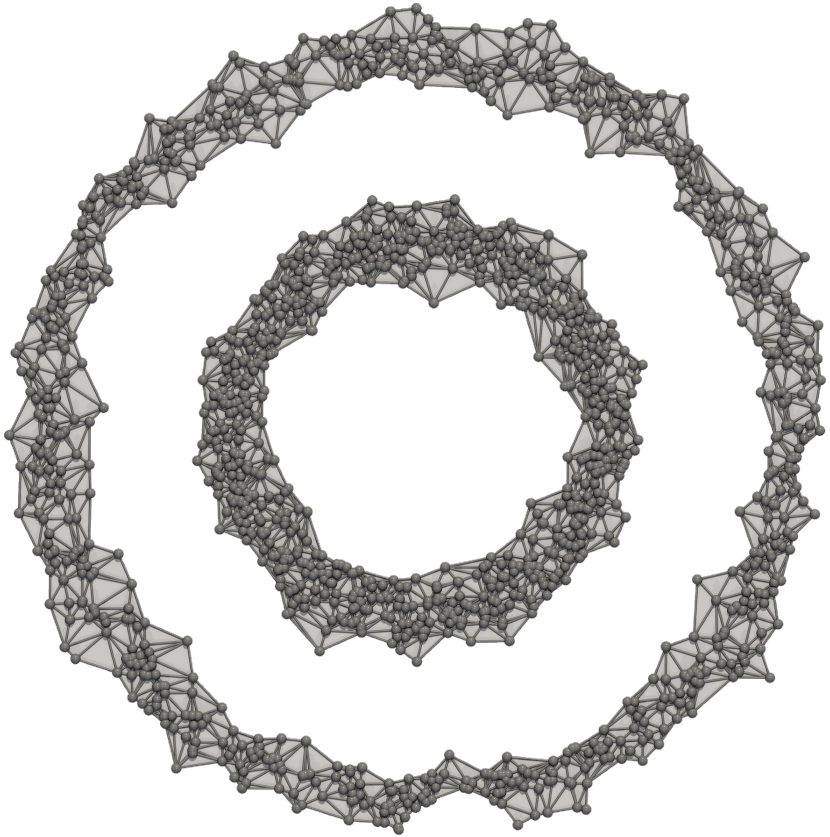

TTK - the Topology ToolKit - To...
julien : emerge — Konsole
ttk-data : paraview — Konsole
TTK 0.9.7 - ParaView 5.5.2 64-bit
16:18
ttk-data : paraview — Konsole
[ttkTopologicalSimplification] Memory usage: 0 MB.
[ImplicitTriangulation] The getVertex*() requests are accelerated.
[ttkMorseSmaleComplex] Launching computation on field 'SplatterValues'...
[DiscreteGradient] Data-set: 524288 v., 3588607 e., 6088698 t., 3024378 T.
[DiscreteGradient] Processed in 0.359277 s. (24 thread(s)).
[DiscreteGradient] Data-set (524288 points) post-processed in 0.018482 s. (24 thread(s)).
[DiscreteGradient] Data-set (524288 points) post-processed in 0.009758 s. (24 thread(s)).
[MorseSmaleComplex3D] Discrete gradient overall computed in 0.388059 s.
[ScalarFieldCriticalPoints] 56 minima.
[ScalarFieldCriticalPoints] 1284 1-saddle(s).
[ScalarFieldCriticalPoints] 1926 2-saddle(s).
[ScalarFieldCriticalPoints] 50 multi-saddle(s).
[ScalarFieldCriticalPoints] 629 maxima.
[ScalarFieldCriticalPoints] Data-set (524288 vertices) processed in 0.65005 s. (24 thread(s)).
[DiscreteGradient] 56 0-cell(s) and 55 interior PL.
[DiscreteGradient] 1854 1-cell(s) and 1245 interior PL.
[DiscreteGradient] 3555 2-cell(s) and 1874 interior PL.
[DiscreteGradient] 1756 3-cell(s) and 629 interior PL.
[DiscreteGradient] Initialization step : 0.0202501 s.
[DiscreteGradient] Ordering of the vpaths : 0.000731945 s.
[DiscreteGradient] Processing of the vpaths : 0.0078969 s.
[DiscreteGradient] Gradient reversal step : 5.19753e-05 s.
[DiscreteGradient] Saddle-Maximum pairs simplified in 0.0724602 s, 24 thread(s).
[DiscreteGradient] Initialization step : 0.283536 s.
[DiscreteGradient] Ordering of the vpaths : 0.000257969 s.
[DiscreteGradient] Processing of the vpaths : 0.255053 s.
[DiscreteGradient] Saddle-Saddle pairs simplified in 0.568815 s, 24 thread(s).
[DiscreteGradient] Initialization step : 0.039736 s.
[DiscreteGradient] Ordering of the vpaths : 2.00272e-05 s.
[DiscreteGradient] Processing of the vpaths : 0.02931 s.
[DiscreteGradient] Saddle-Saddle pairs simplified in 0.0978661 s, 24 thread(s).
[DiscreteGradient] Initialization step : 0.0624981 s.
[DiscreteGradient] Ordering of the vpaths : 0.000952005 s.
[DiscreteGradient] Processing of the vpaths : 0.00381112 s.
[DiscreteGradient] Gradient reversal step : 0.00020504 s.
[DiscreteGradient] Saddle-Maximum pairs simplified in 0.0755041 s, 24 thread(s).
[DiscreteGradient] Initialization step : 0.297937 s.
[DiscreteGradient] Ordering of the vpaths : 5.39289e-05 s.
[DiscreteGradient] Processing of the vpaths : 0.072561 s.
[DiscreteGradient] Saddle-Saddle pairs simplified in 0.398906 s, 24 thread(s).
[DiscreteGradient] Initialization step : 0.0587609 s.
[DiscreteGradient] Ordering of the vpaths : 1.3113e-05 s.
[DiscreteGradient] Processing of the vpaths : 0.026727 s.
[DiscreteGradient] Saddle-Saddle pairs simplified in 0.113457 s, 24 thread(s).
[FTM] ------------
[FTM] number of threads : 24
[FTM] * debug lvl : 3
[FTM] * tree type : Contour
[FTM] ------------
[FTM] alloc in 0.038821
[FTM] init in 0.0755661
[FTM] sort step in 0.023258
[FTM] leafSearch JT in 0.012686
[FTM] leafGrowth JT in 0.411031
[FTM] trunk JT in 0.00200701
[FTM] leafSearch ST in 0.0126278
[FTM] leafGrowth ST in 0.00806093
[FTM] trunk ST in 0.00222094
[FTM] merge trees in 0.450824
[FTM] combine full in 0.0143611
[FTM] build tree in 0.465256
[FTM] Total in 0.564171
[DiscreteGradient] Initialization step : 0.217854 s.
[DiscreteGradient] Ordering of the vpaths : 0.000804901 s.
[DiscreteGradient] Processing of the vpaths : 1.73784 s.
[DiscreteGradient] Saddle-Saddle pairs simplified in 1.98662 s, 24 thread(s).
[DiscreteGradient] Initialization step : 0.0448511 s.
[DiscreteGradient] Ordering of the vpaths : 0.000411034 s.
[DiscreteGradient] Processing of the vpaths : 0.0243599 s.
[DiscreteGradient] Saddle-Saddle pairs simplified in 0.092057 s, 24 thread(s).
[DiscreteGradient] Gradient reversed in 4.0684 s. (24 thread(s)).
[MorseSmaleComplex3D] Descending 1-separatrices computed in 0.035454 s.
[MorseSmaleComplex3D] Ascending 1-separatrices computed in 0.0279231 s.
[MorseSmaleComplex3D] Saddle connectors computed in 0.753106 s.
[MorseSmaleComplex3D] Ascending 2-separatrices computed in 0.2016 s.
[MorseSmaleComplex3D] Segmentation computed in 0.679845 s.
[DiscreteGradient] 56 0-cell(s).
[DiscreteGradient] 696 1-cell(s).
[DiscreteGradient] 1270 2-cell(s).
[DiscreteGradient] 629 3-cell(s).
[MorseSmaleComplex3D] Data-set (524288 points) processed in 7.10692 s. (24 thread(s)).
[ttkMorseSmaleComplex] Memory usage: 52.7666 MB.
[ttkSphereFromPoint] Spheres computed in 0.318438 s.
[ttkSphereFromPoint] Memory usage: 42.4062 MB.
[OneSkeleton] Edge-list built in 0.0958098 s. (80953 edges, 1 thread(s)).
[ZeroSkeleton] One-skeleton built in 0.013974 s. (24 thread(s)).
[ScalarFieldSmoother] Data-set (86206 points) smoothed in 0.102752 s. (24 thread(s)).
[ttkGeometrySmoother] Memory usage: 0 MB.
[OneSkeleton] Edge-list built in 0.017684 s. (220056 edges, 1 thread(s)).
[ZeroSkeleton] One-skeleton built in 0.0326891 s. (24 thread(s)).
[ScalarFieldSmoother] Data-set (73228 points) smoothed in 0.114568 s. (24 thread(s)).
[ttkGeometrySmoother] Memory usage: 1.12598 MB.
TTK 0.9.7 - ParaView 5.5.2 64-bit
File Edit View Sources Filters Tools Catalyst Macros Help
Time: 0
Pipeline Browser
builtin:
pointCloud.csv
TableToPoints1
GaussianResampling1
Outline1
TTKPersistenceDiagram1
Threshold1
PersistenceThreshold
TTKTopologicalSimplification1
TTKTopologicalSimplification1
TTKTopologicalSimplification1
TTKMorseSmaleComplex1
Critical Points
TTKSphereFromPoint1
1-Separatrices
Threshold2
TTKGeometrySmoother1
ExtractSurface1
Tube1
2-Separatrices
Tetrahedralize1
TTKGeometrySmoother2
ExtractSurface2
Output Messag...
Informati...
Properti...
Properties
Apply
Reset
Delete
Search ... (use Esc to clear text)
Properties (1
Input options
Scalar Field
SplatterValues
Force Input Offset Field
Output options
PL-compliant extrema
PL-compliant saddles
Critical Points
Ascending 1-Separatrices
Descending 1-Separatrices
Saddle Connectors
Ascending 2-Separatrices
Descending 2-Separatrices
Ascending Segmentation
Descending Segmentation
Morse-Smale Complex Segmentation
Return Saddle Connectors
Saddle Connectors Persistence Threshold
0.01
Testing
Layout #1
RenderView2
RenderView1

Mapper

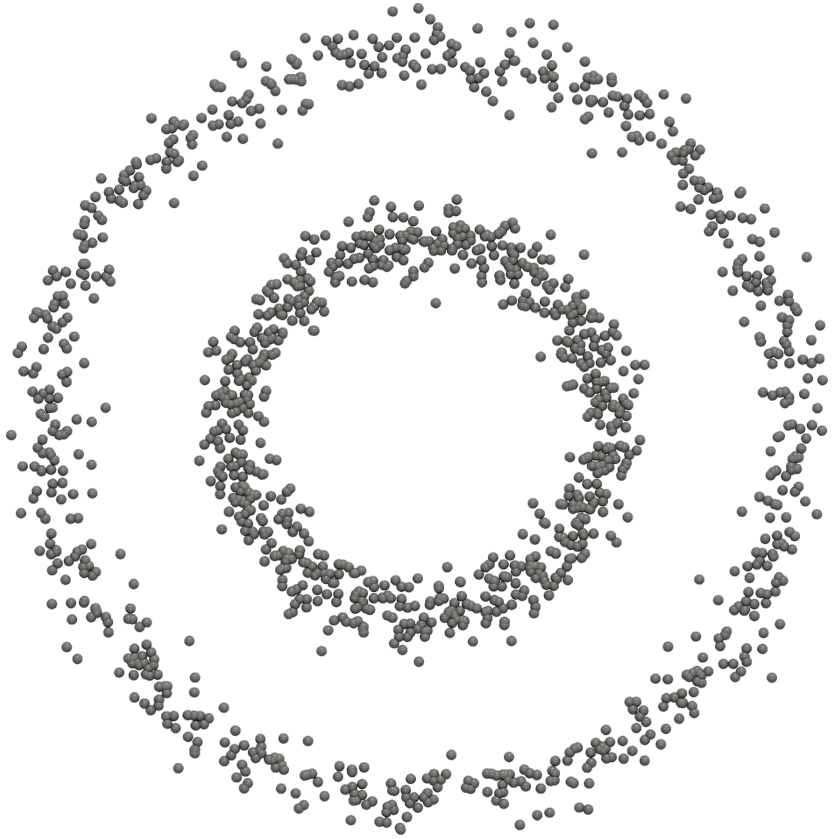


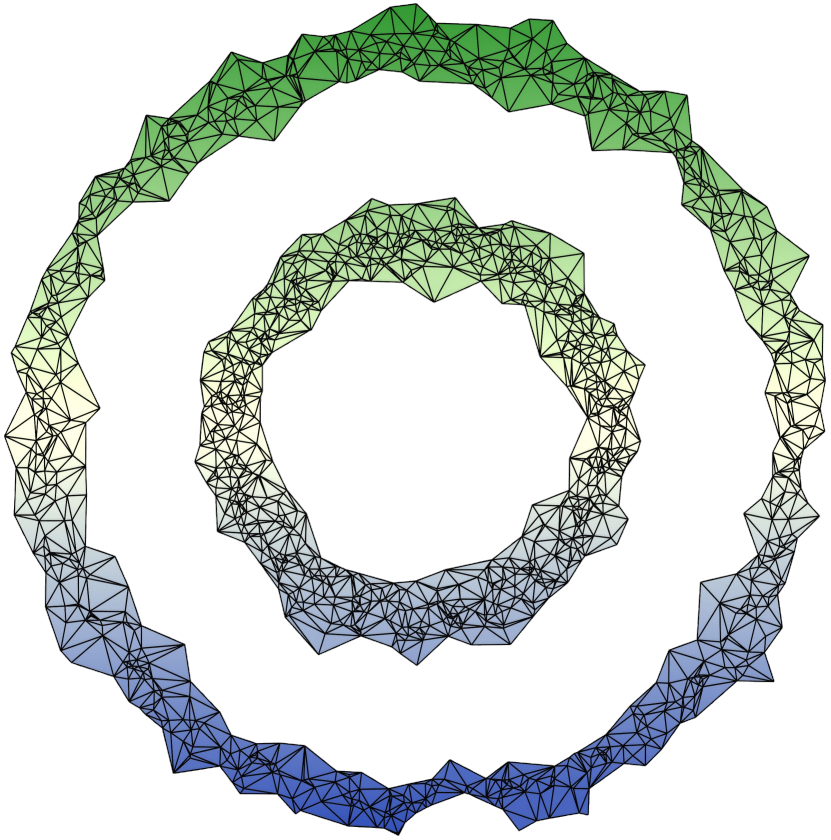
Mapper



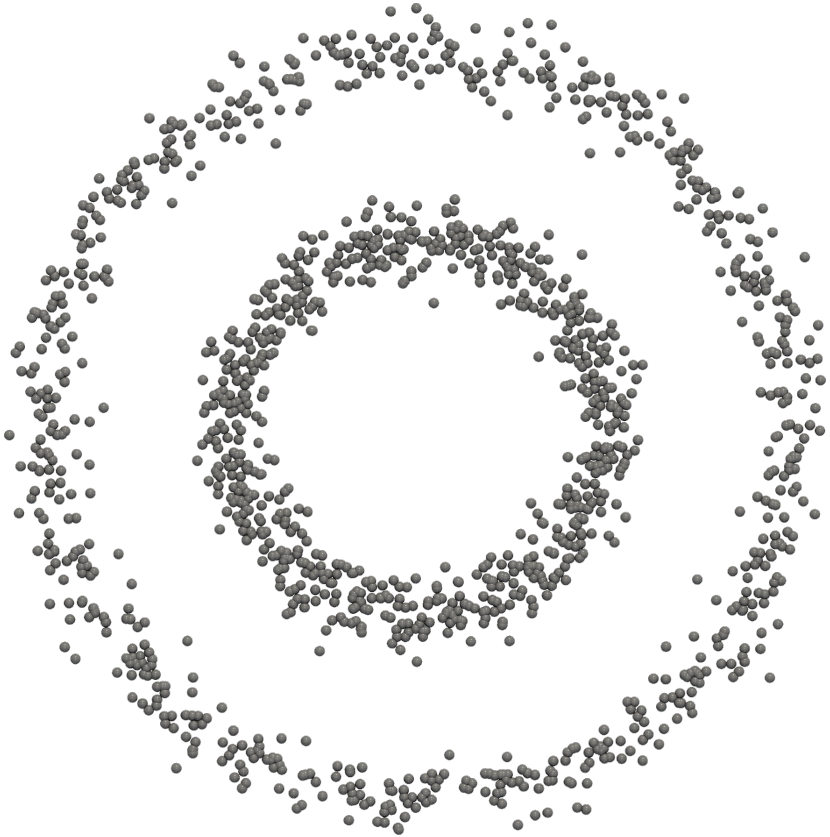


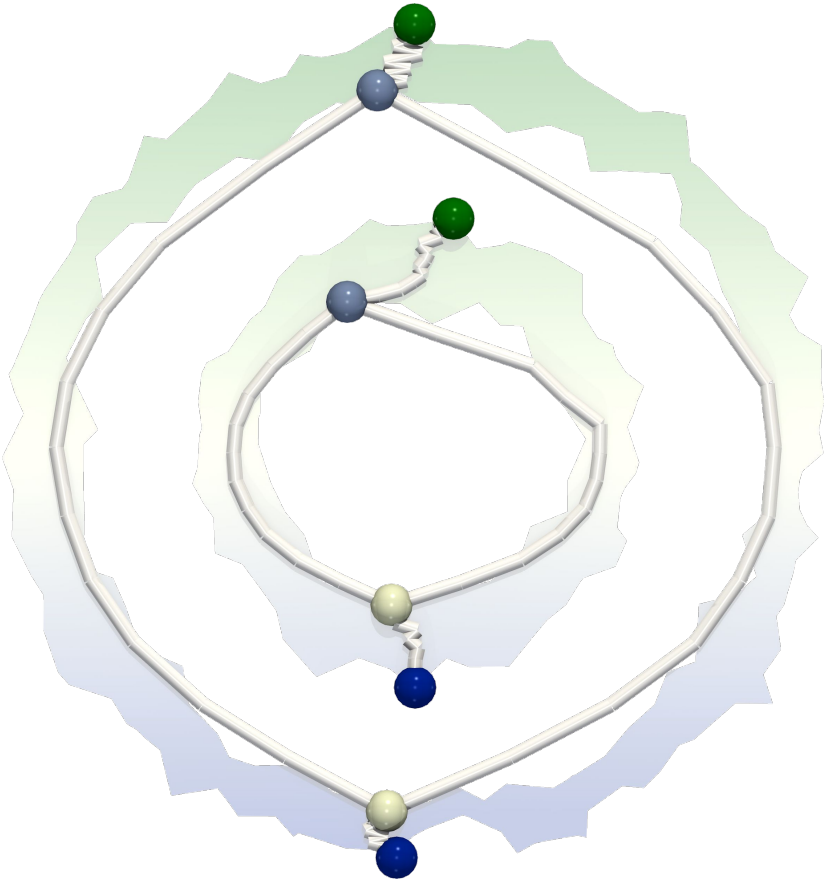
Mapper



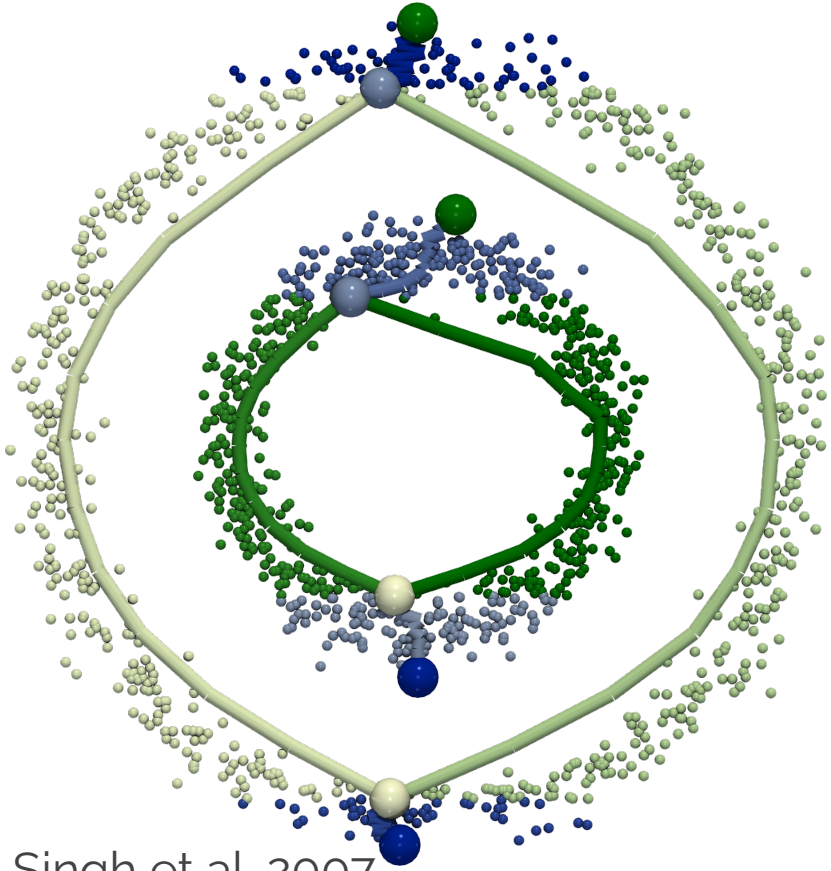


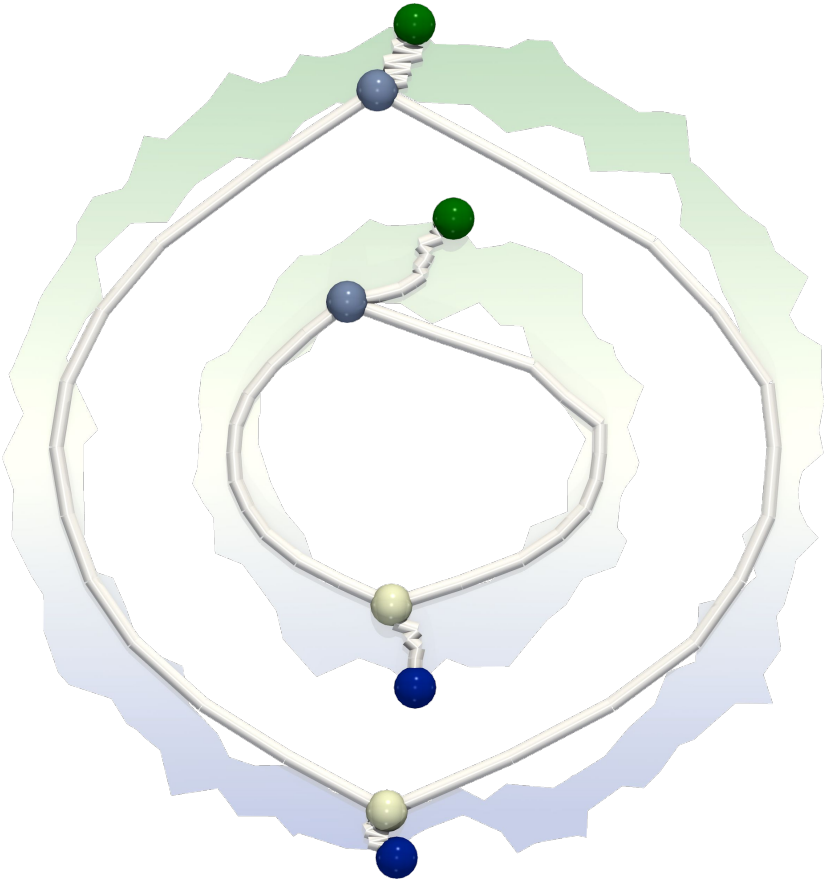
Mapper





Mapper

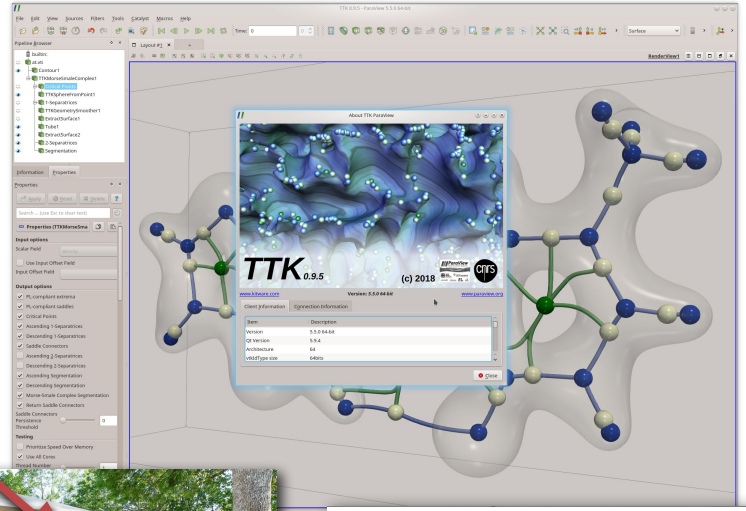




- Singh et al. 2007

The Topology ToolKit (TTK)

- **Open-source TDA library**
  - ~120k lines in C++, BSD license
  - Python bindings, binary packages
    - **Officially integrated in ParaView (5.10)**
  - **http://topology-tool-kit.github.io**
  - Best paper honorable mention IEEE VIS'17



- **Structuring research receptacle**
  - 17 contributing institutions
    - 14 universities, 3 companies
  - Mini-symposia:
    - IEEE VIS'18-22
    - Hackathons

Interested?

- **Interests**
  - Data, Code
  - Topology, Visualization

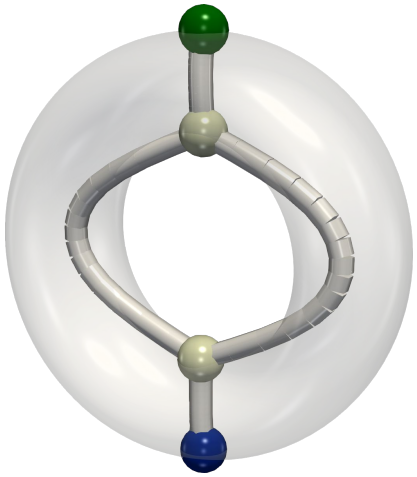
- **Academic opportunities**
  - We are recruiting **a lot**
    - **https://erc-tori.github.io/jobs/**
  - Internships
  - Ph.D. Thesis
  - Research engineers

Take-home messages

- **Data on meshes, or meshable data?**
  - Features of interest?
  - Recover ‘structural’ information

⇨ Topological Data Analysis

- Robust, multiscale
- Successful in applications
- Software available



Thanks!

- Papers, video, code, teaching material, exercise packages, tutorials...
  - http://lip6.fr/Julien.Tierny, https://twitter.com/JulienTierny
  - http://topology-tool-kit.github.io

- I'm hiring!
  - 1 Ph.D. student, 1 post-doc, 1 engineer

- Thanks to all my co-authors!
  - Roberto Alvarez-Boto, John Bell, Timo Bremer, Bert Buchholz, Joseph Budin, Hamish Carr, Amit Chattopadhyay, Fang Chen, Bruno Conche, Julia Contreras, Joel Daniels, Mohamed Daoudi, Marcus Day, Julie Delon, Harish Doraiswamy, Florent Dupont, Tiago Etiene, Noura Faraj, Guillaume Favelier, Tarik Filali, Pierre Fortin, Juliana Freire, Mariem Gargouri, Christoph Garth, Zhao Geng, Brad Grimm, Charles Gueunet, Pierre Guillou, Attila Gyulassy, Hans Hagen, Bernd Hamann, Mike Kirby, Pavol Klacansky, Scott Klasky, Aaron Knoll, Erwan Jolivet, Julien Jomier, Ayla Khan, Guillaume Lavoue, Josh Levine, Lauro Lins, Jonas Lukasczyk, Pooran Memari, Michael Michaux, Gustavo Nonato, Małgorzata Olejniczak, Valerio Pascucci, Philippe Petit, Sujin Philip, Jean-Philip Piquemal, Melanie Plainchault, Norbet Podhorszki, Mathieu Pont, Daisuke Sakurai, Joseph Salmon, Emanuele Santos, Carlos Scheidegger, Claudio Silva, Eddie Simon, Maxime Soler, Brian Summa, Roselyne Tchoua, Jean-Marc Thiery, Will Usher, Jean-Philippe Vandeborre, Jules Vidal, Ana Vintescu, Gunther Weber, Qi Wu

- Questions?

Main publications

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- V. Pascucci, X. Tricoche, H. Hagen, **J. Tierny**, "Topological methods in data analysis and visualization, Springer 2010.
- Jules Vidal, Joseph Budin, Julien Tierny, "Progressive Wasserstein Barycenters of Persistence Diagrams", IEEE Trans. On Visualization and Computer Graphics (Proc. of IEEE VIS 2019), **Best paper honorable mention.**
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- C. Gueunet, P. Fortin, J. Jomier, **J. Tierny**, "Task-based Augmented Reeb Graphs with Dynamic ST-Trees", Proc. of EGPGV 2019.
- C. Gueunet, P. Fortin, J. Jomier, **J. Tierny**, "Task-based Augmented Contour Trees with Fibonacci Heaps", IEEE Trans. On Parallel and Distributed Systems, 2019.
- G. Favelier, N. Faraj, B. Summa, **J. Tierny**, "Persistence Atlas for Critical Point Variability in Ensembles", IEEE Trans. On Visualization and Computer Graphics (Proc. of IEEE VIS 2018)
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- C. Gueunet, P. Fortin, J. Jomier, **J. Tierny**, "Task-based Augmented Merge Trees with Fibonacci Heaps", Proc. of IEEE LDAV 2017
- **J. Tierny**, H. Carr, "Jacobi Fiber Surfaces for Bivariate Reeb Space Computation", IEEE Trans. On Visualization and Computer Graphics (Proc. of IEEE VIS 2016), **Best paper award.**
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- C. Gueunet, P. Fortin, J. Jomier, **J. Tierny**, "Contour Forests: Fast Multi-threaded Augmented Contour Trees ", Proc. of IEEE LDAV 2016
- S. Philip, B. Summa, **J. Tierny**, T. Bremer, V. Pascucci, "Distributed Seams for Gigapixel Panoramas", IEEE Trans. On Visualization and Computer Graphics 2015
- H. Carr, Z. Geng, **J. Tierny**, A. Chattopadhyay, A. Knoll, "Fiber Surfaces: Generalizing Isosurfaces to Bivariate Data", Computer Graphics Forum Journal (Proc. of EuroVis 2015)
- A. Gyulassy, D. Guenther, J. Levine, **J. Tierny**, V. Pascucci, "Conforming Morse-Smale Complexes", IEEE Trans. On Visualization and Computer Graphics (Proc. of IEEE VIS 2014)
- D. Guenther, R. Alvarez-Boto, J. Contreras, J.P. Piquemal, **J. Tierny**, "Characterizing Molecular Interactions in Chemical Systems", IEEE Trans. On Visualization and Computer Graphics (Proc. of IEEE VIS 2014)
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- **J. Tierny** and V. Pasucci, "Generalized Topological Simplification of Scalar Fields on Surfaces, IEEE Trans. On Visualization and Computer Graphics (Proc. of IEEE VIS 2012)
- T. Etiene, G. Nonato, C. Scheidegger, **J. Tierny**, T. Peters, V. Pascucci, M. Kirby, C. Silva, "Topology verification for isosurface extraction", IEEE Trans. On Visualization and Computer Graphics 2012
- **J. Tierny**, J. Daniels, G. Nonato, V. Pascucci, C. Silva, "Interactive quadrangulation with Reeb atlases and connectivity textures", IEEE Trans. On Visualization and Computer Graphics 2012
- T. Bremer, G. Weber, **J. Tierny**, V. Pascucci, M. Day, J. Bell, "Interactive exploration and analysis of large scale simulations using topology-based data segmentation", IEEE Trans. On Visualization and Computer Graphics 2011
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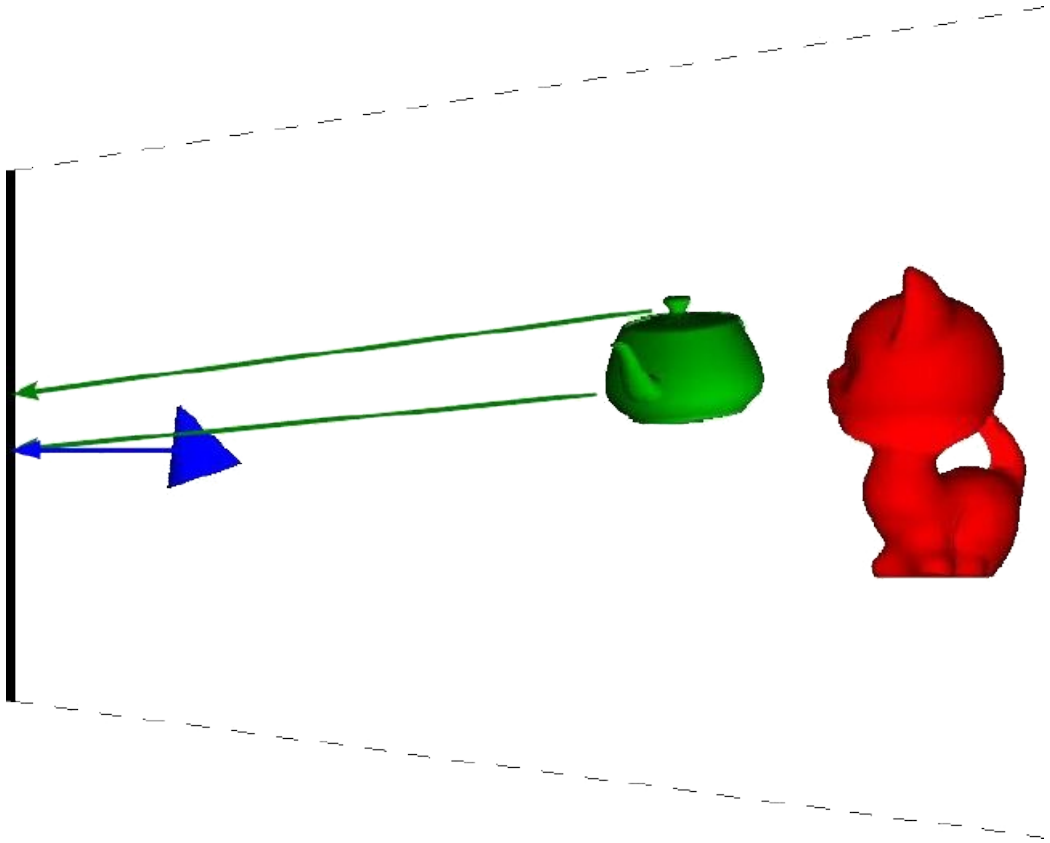
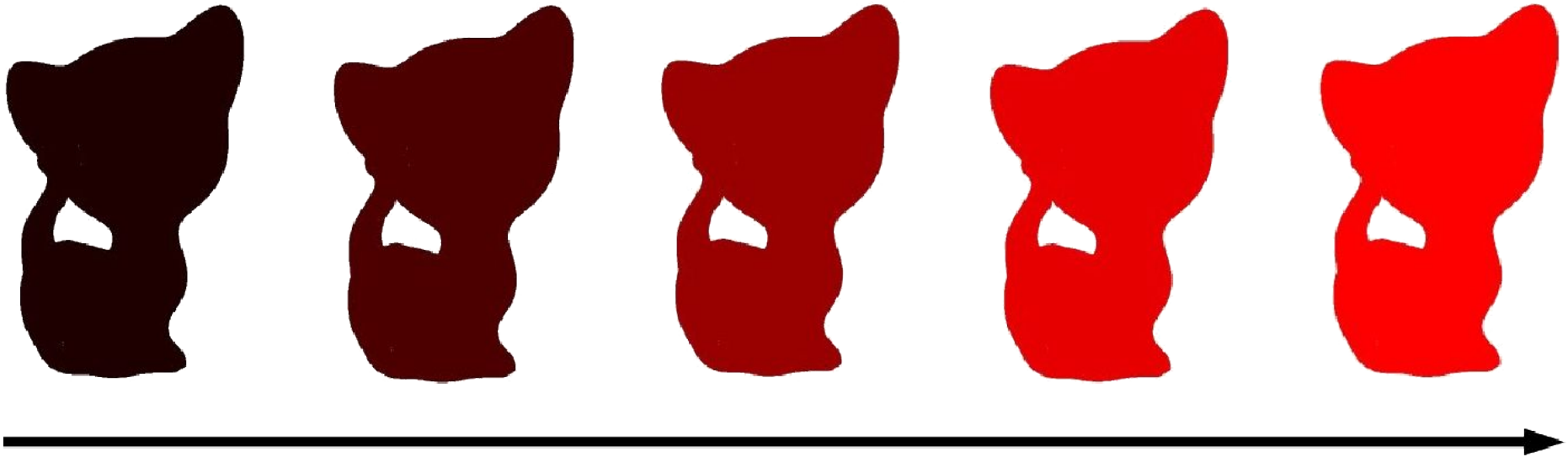
Appendix

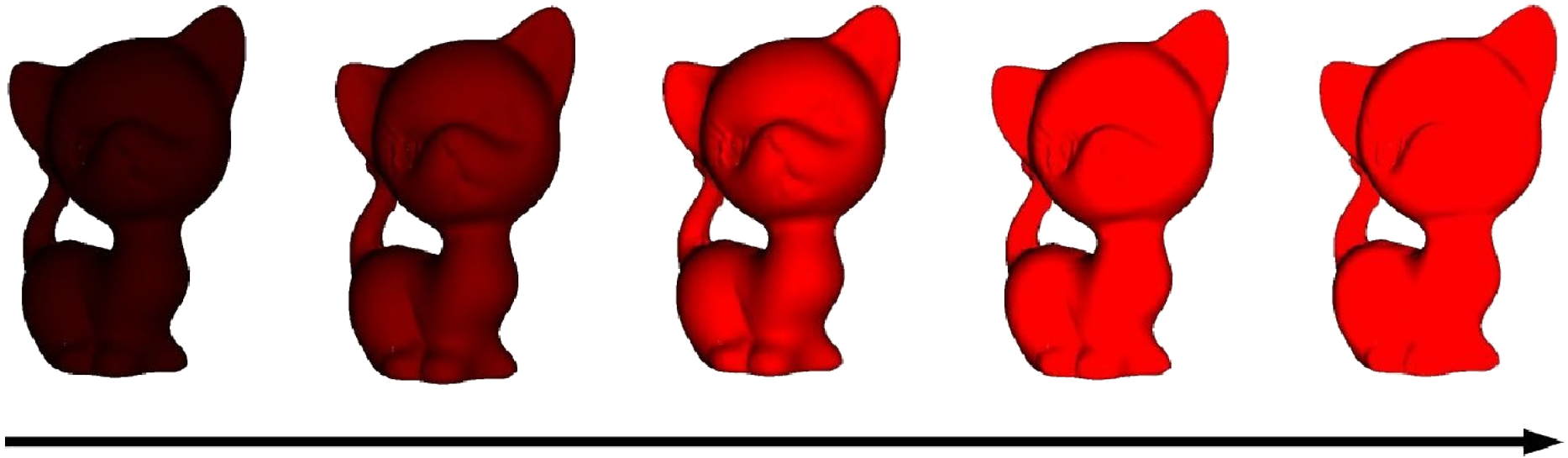
Projective rendering: depth test



Projective rendering: ambient contribution



Projective rendering: diffuse contribution



Projective rendering: specular contribution