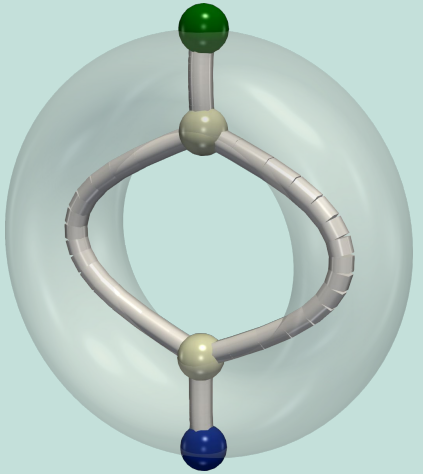
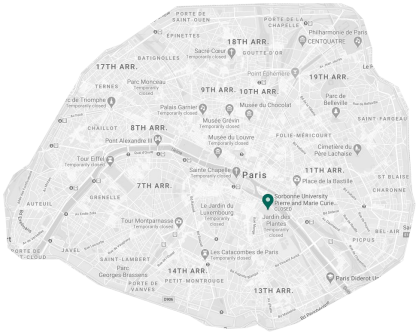


Topological Data Analysis with the Topology ToolKit

Julien Tierny

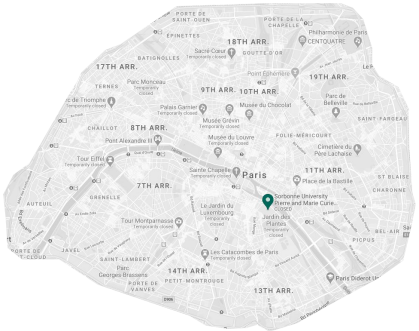
About our research

- **TDA @ Sorbonne**
  - Topological data analysis and visualization
    - Interactive data analysis
    - Data from engineering & science
  - Computational aspects
    - Practical algorithms
    - Emerging data types



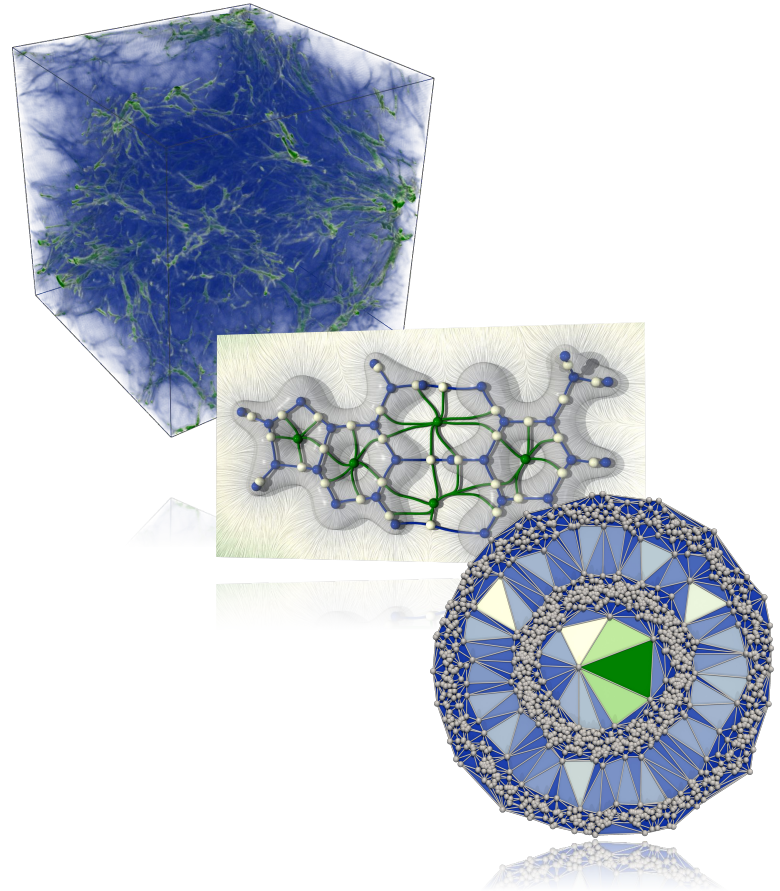
About our research

- **TDA @ Sorbonne**
  - Topological data analysis and visualization
    - Interactive data analysis
    - Data from engineering & science
  - Computational aspects
    - Practical algorithms
    - Emerging data types
  - Main venues
    - IEEE VIS, EuroVis, IEEE LDAV, TopoInVis



What is Topological Data Analysis?

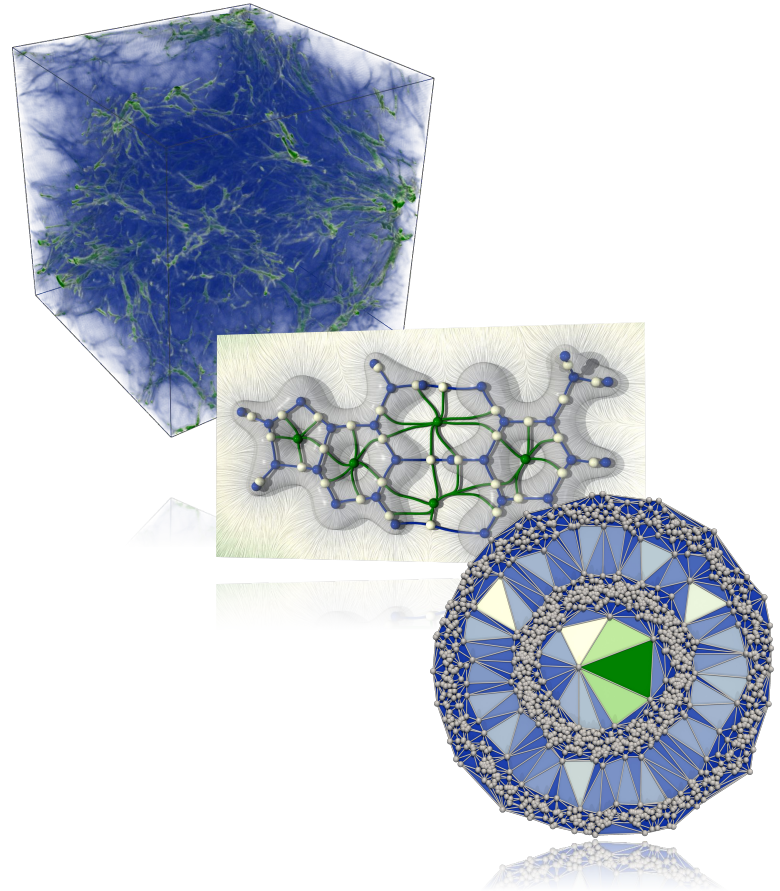
- **Context**
  - Data
  - On “meshes”, or “meshable” things



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

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- **Input PL scalar data**
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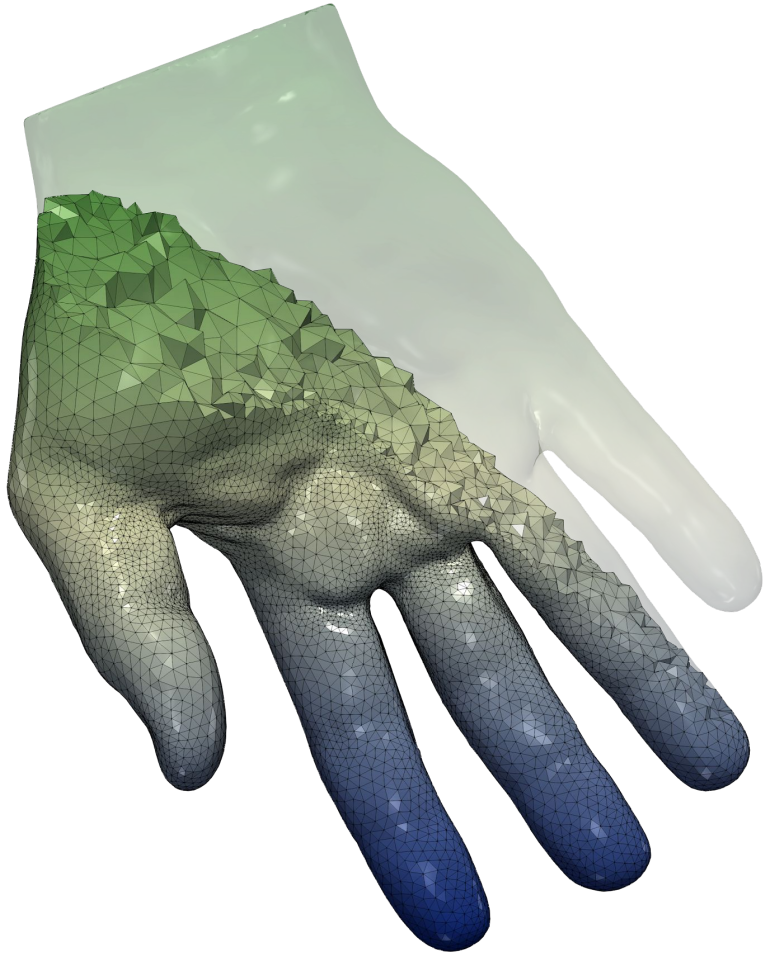
  - $\mathcal{M}$: simplicial complex



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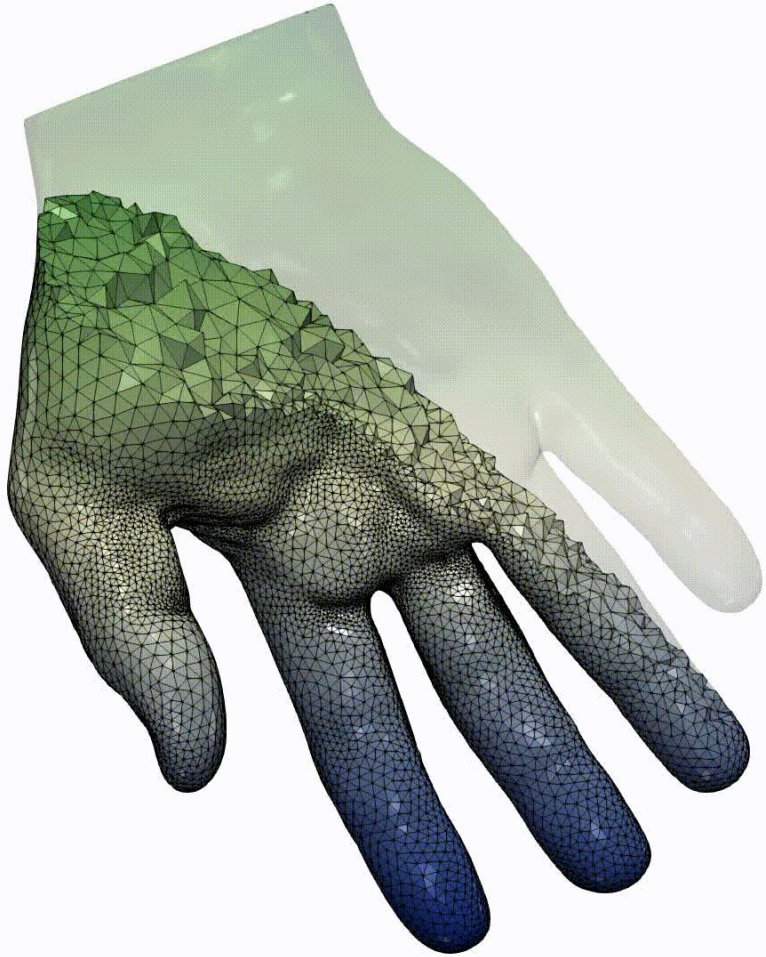
    - Triangulated surface
    - Tetrahedral volume
    - 2D pixel image
    - 3D voxel image
    - Point cloud data



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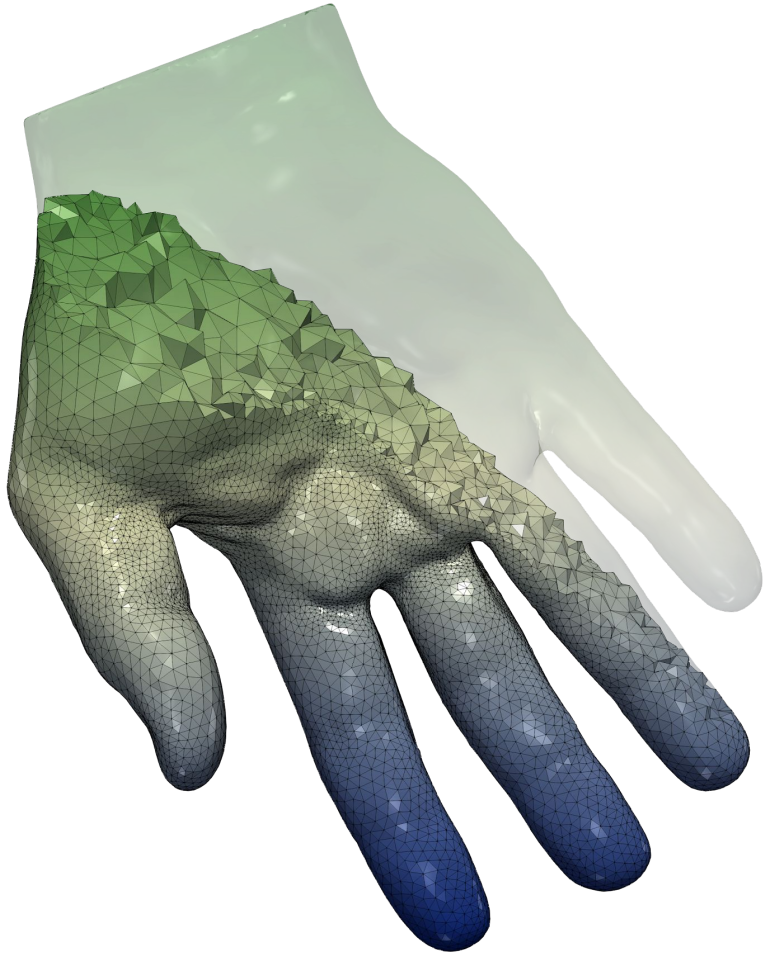

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- Topological abstractions

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Piecewise linear setting

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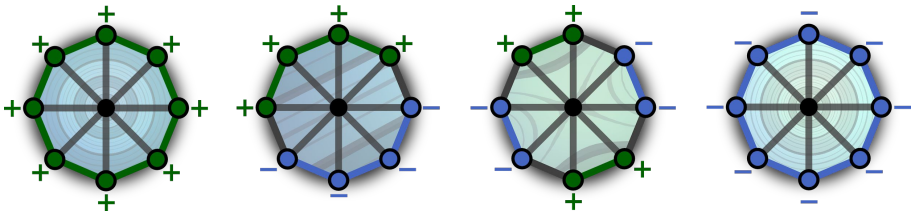
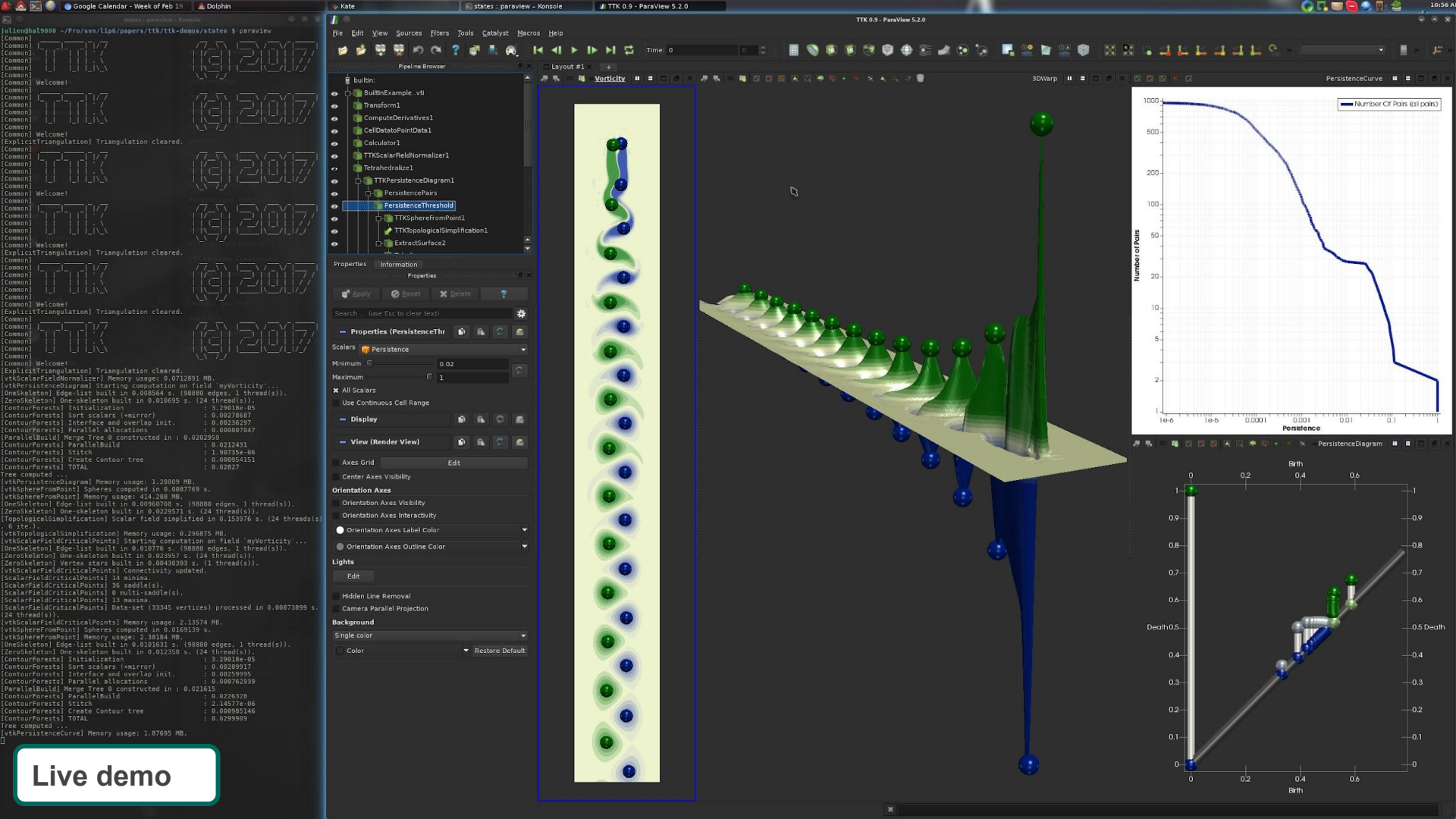
- **Topological abstractions**
  - Critical points

Critical point extraction

- **Local link inspection**
  - Banchoff 1970




Live demo

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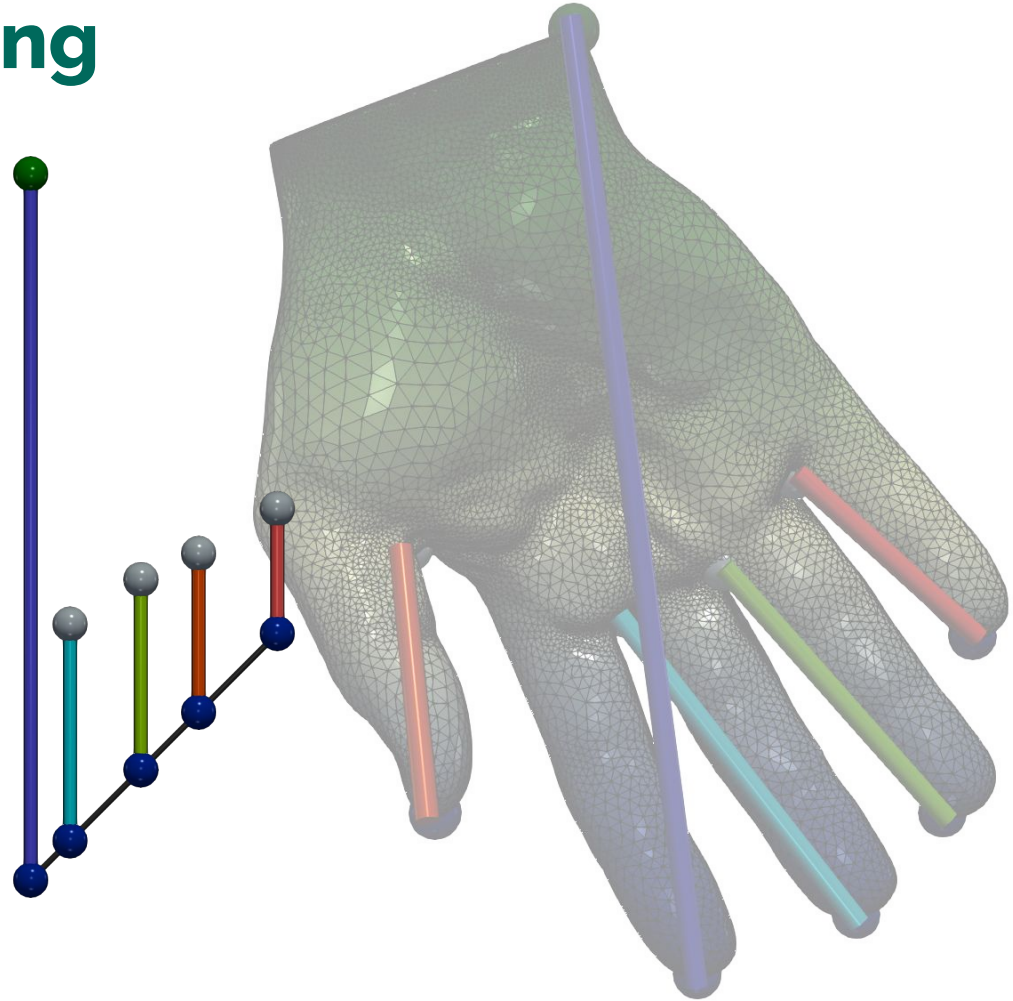
  - Persistence diagrams



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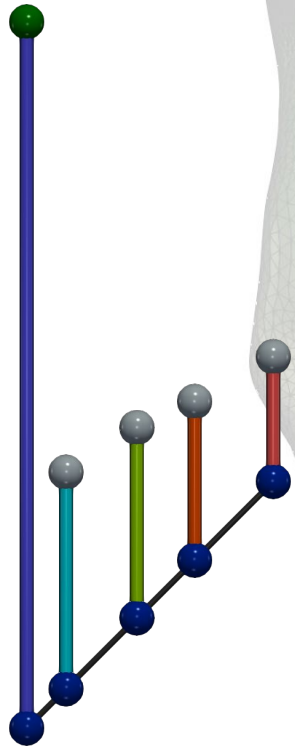
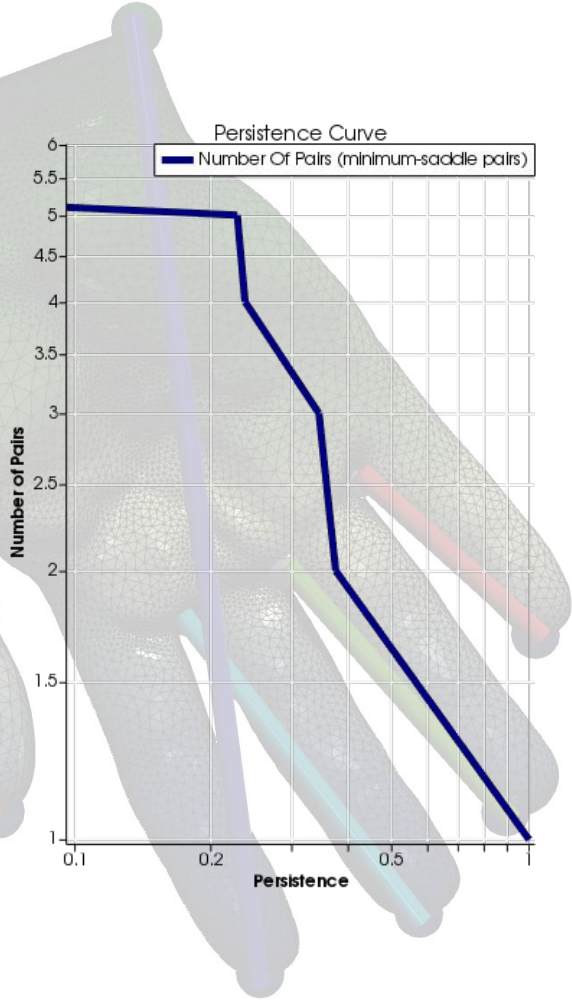
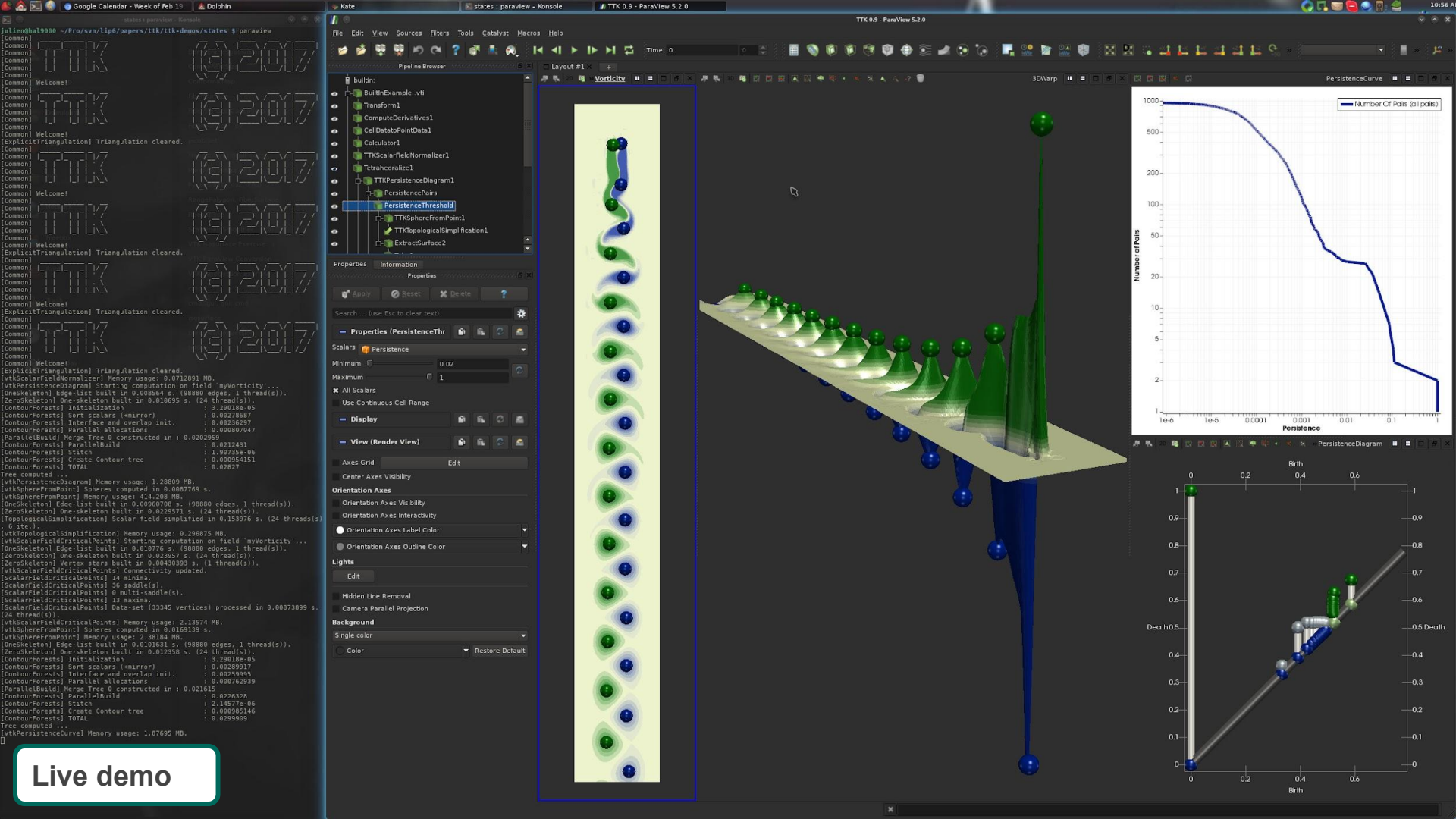


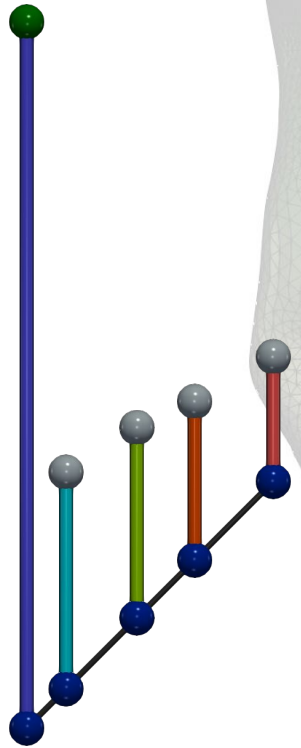


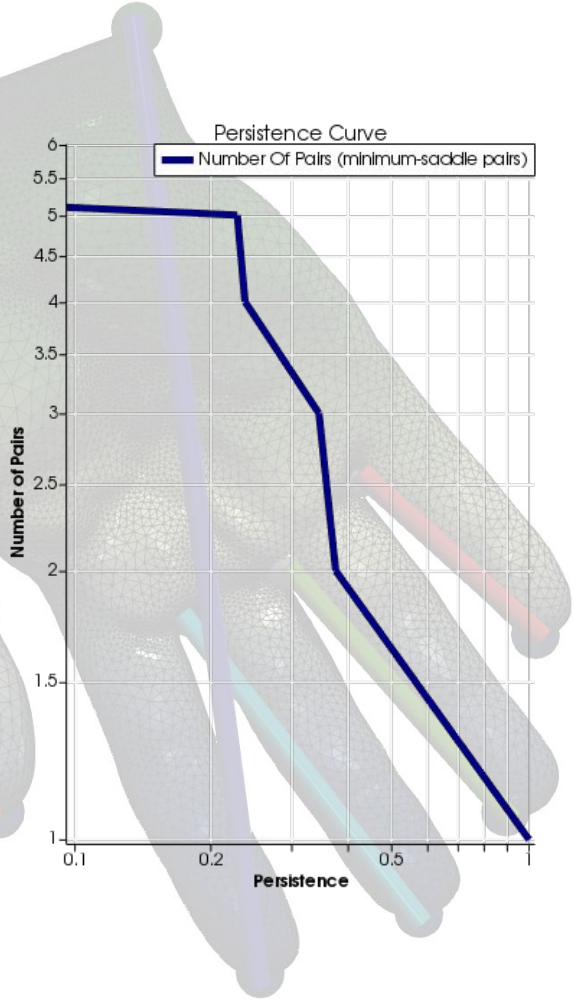

Live demo

Persistence diagrams/curves

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

- **Low-dimensions**
  - Union-Find data structures
    - Min-saddle pairs
    - Saddle-max pairs
    - *Gueunet et al. 2017*
  - Saddle connectors
    - Saddle-saddle pairs

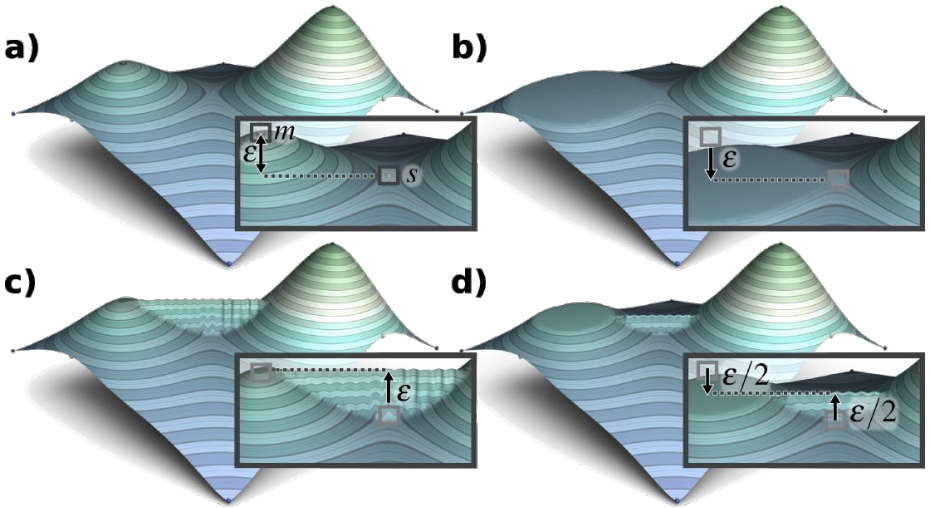


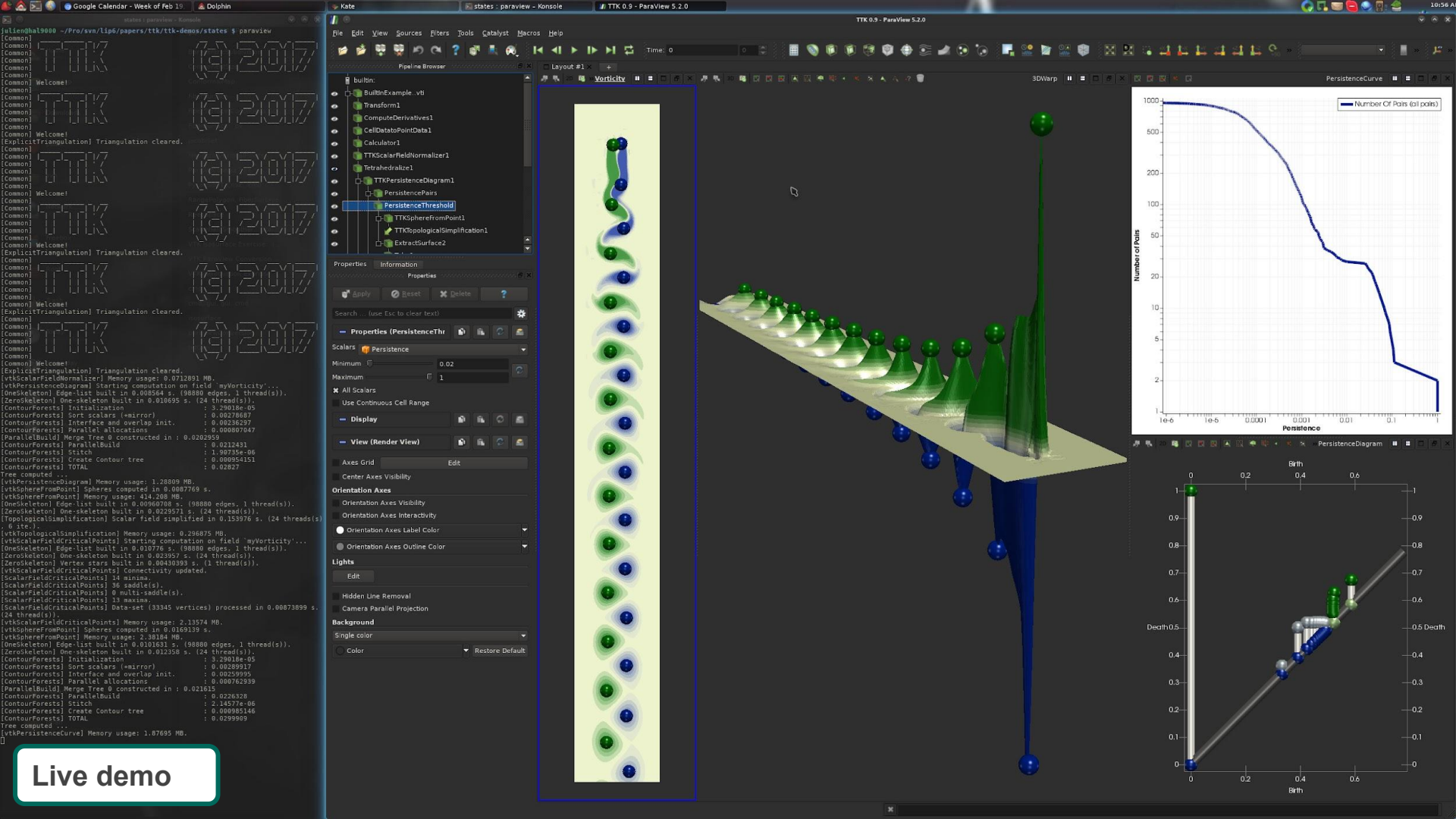


Persistence simplification

- **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*

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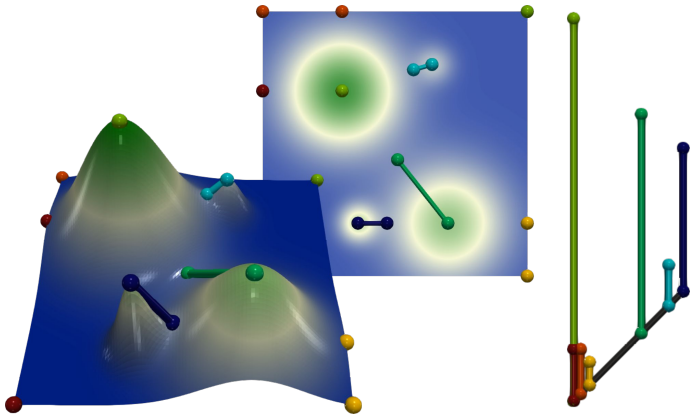

- **Topological abstractions**
  - Critical points
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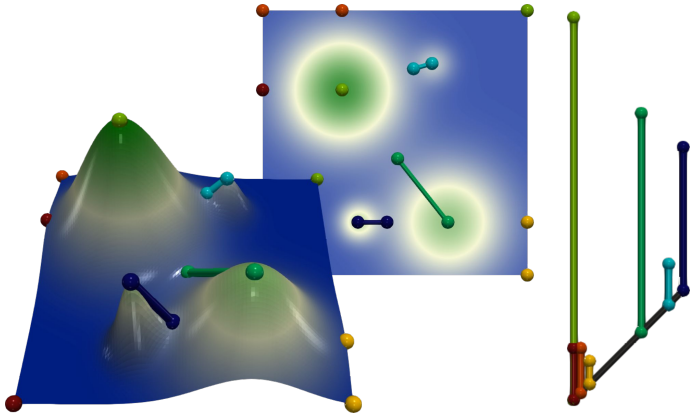

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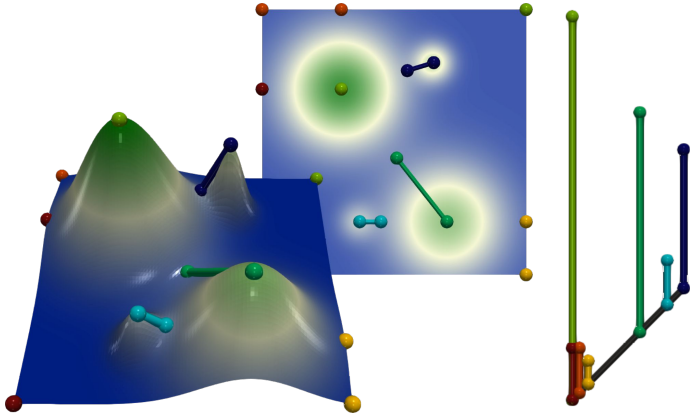

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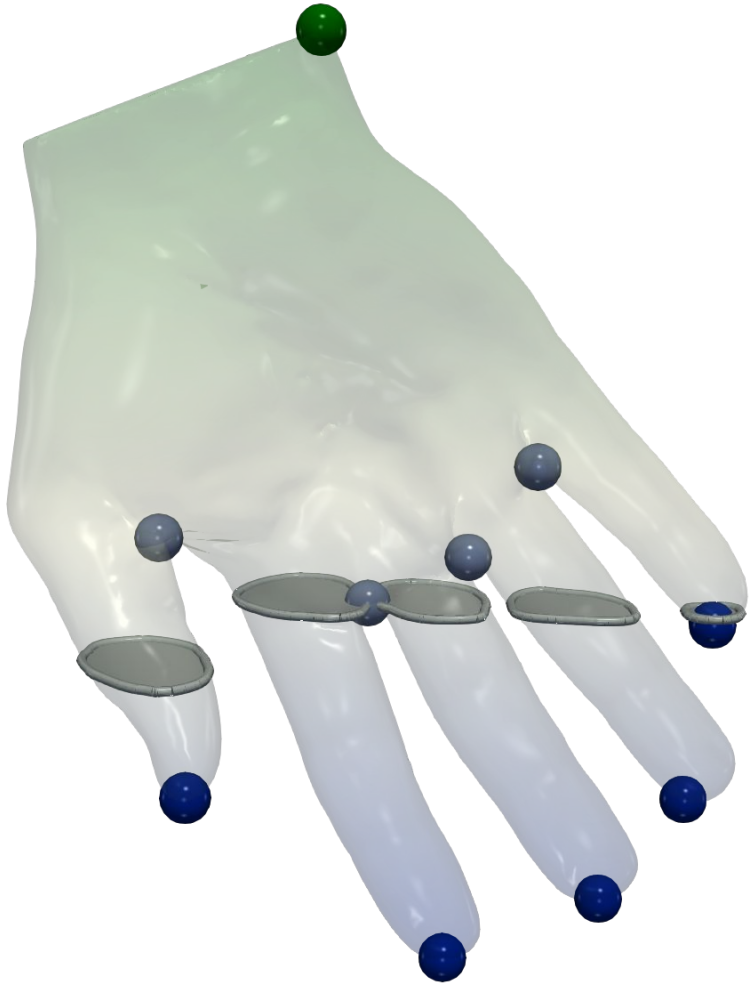

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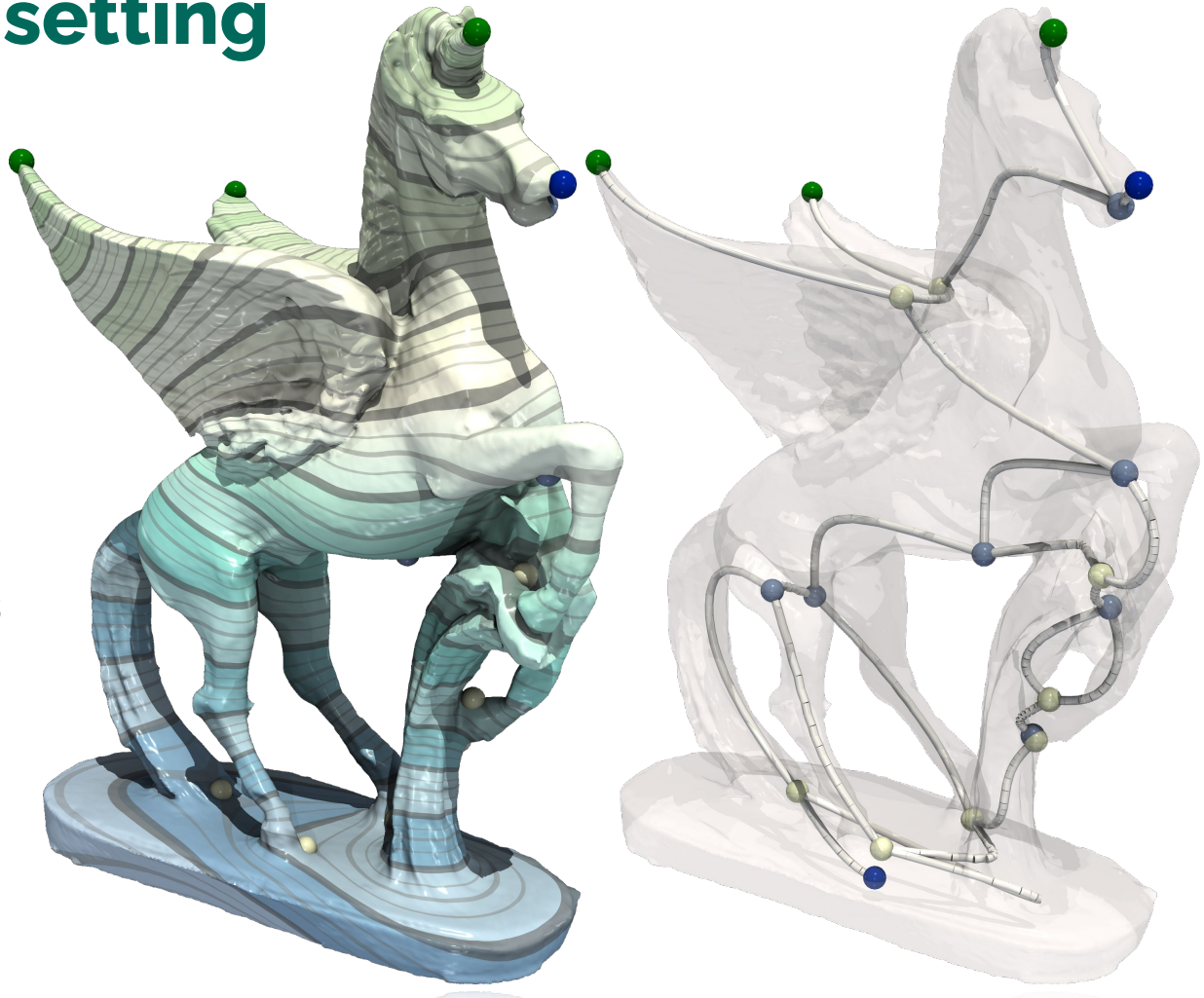

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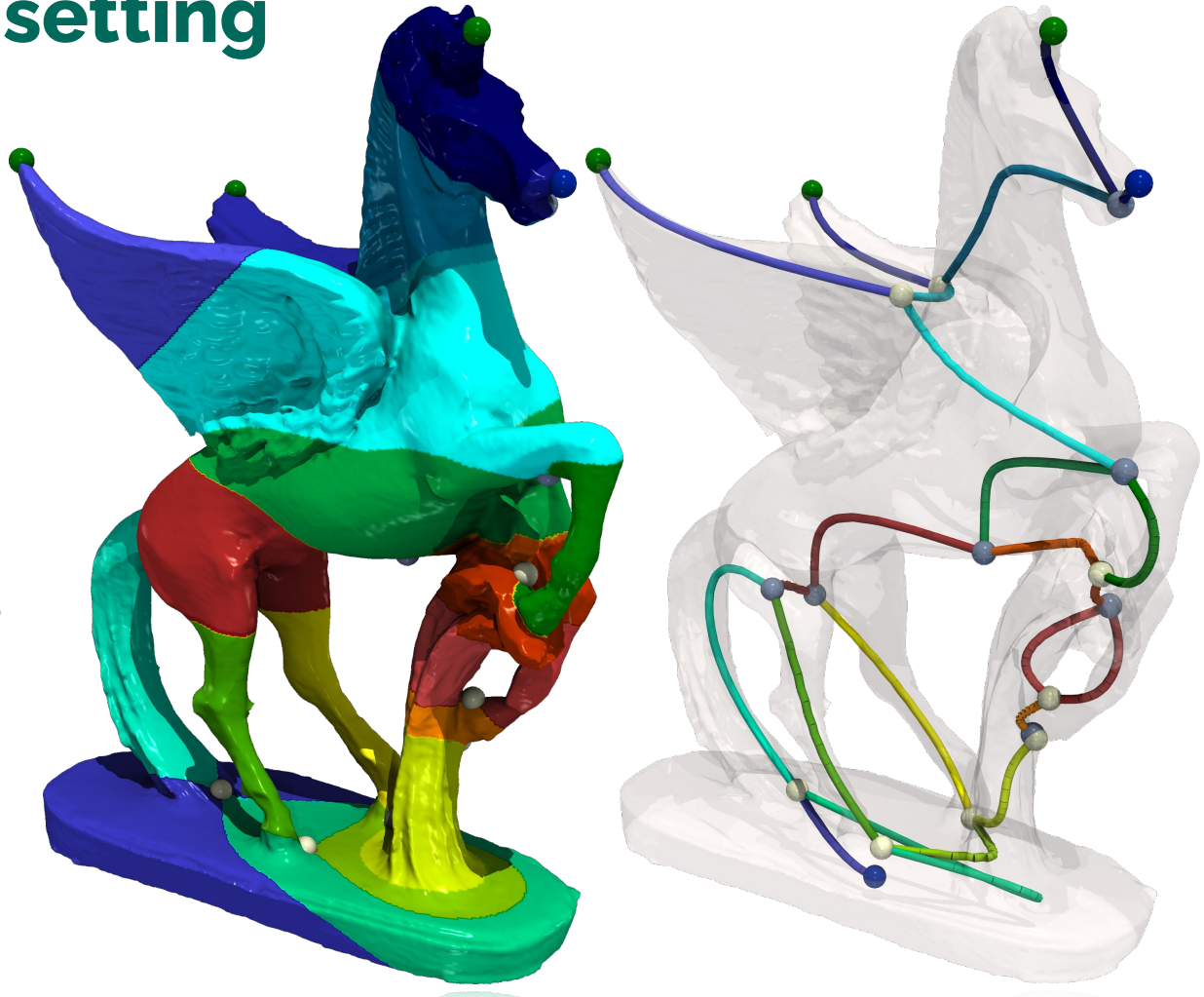
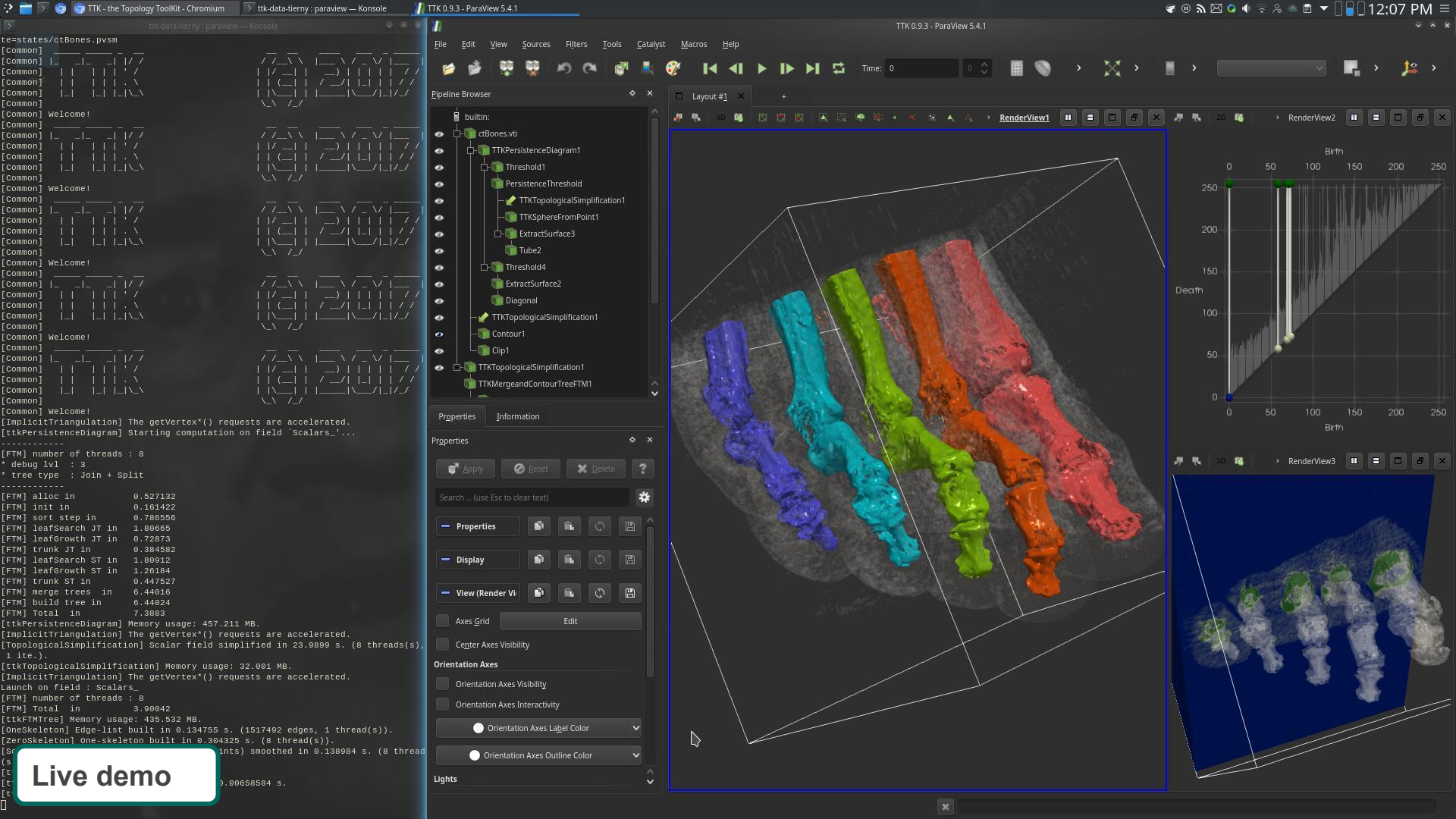
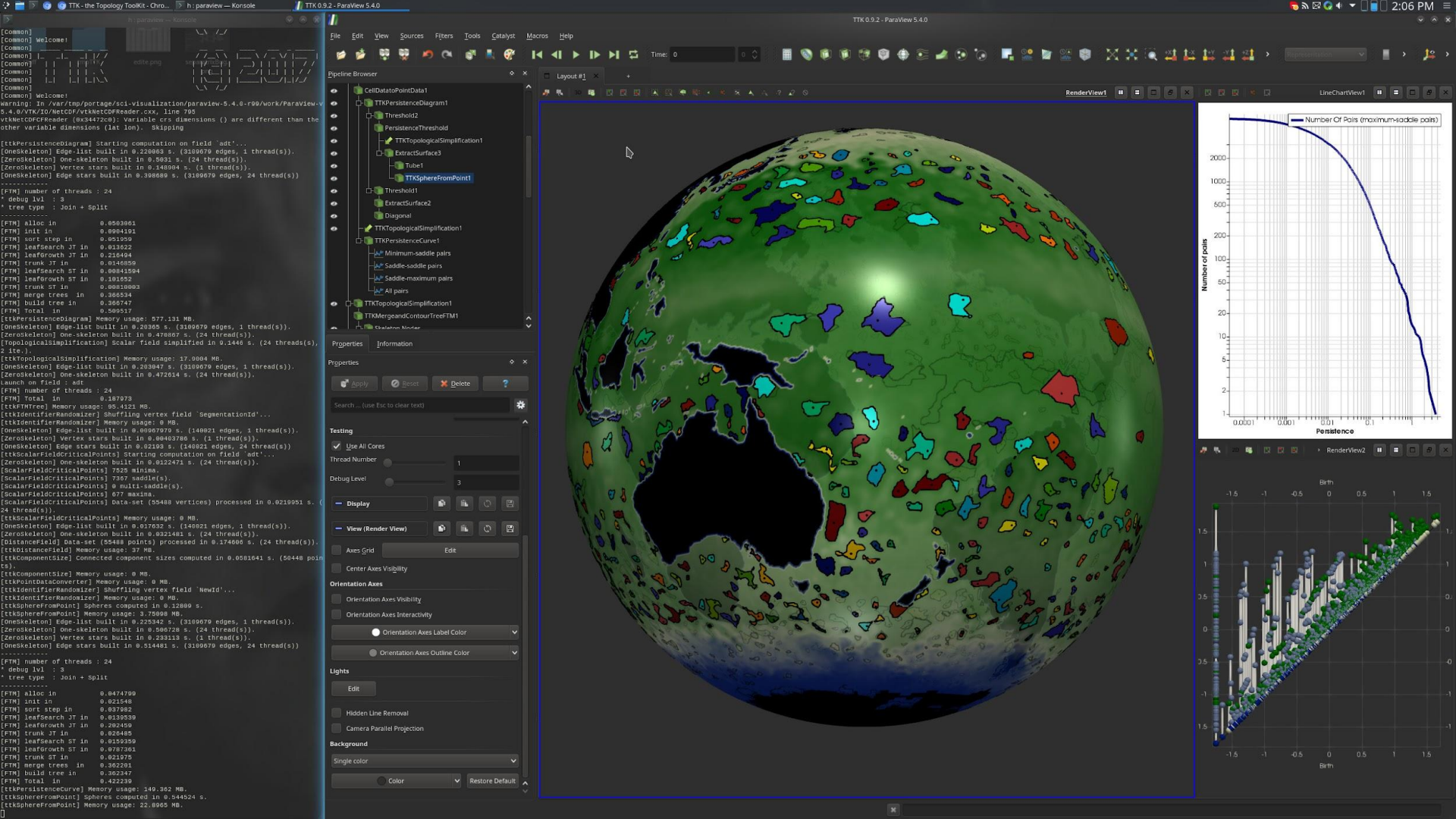



TTK - the Topology ToolKit - Chromium
ttk-data-tierny : paraview — Konsole
TTK 0.9.3 - ParaView 5.4.1
12:07 PM
ttk-data-tierny : paraview — Konsole
te=states/ctBones.pvsm
[Common] Welcome!
[ImplicitTriangulation] The getVertex*() requests are accelerated.
[ttkPersistenceDiagram] Starting computation 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
File Edit View Sources Filters Tools Catalyst Macros Help
Time: 0
Pipeline Browser
builtin:
ctBones.vti
TTKPersistenceDiagram1
Threshold1
PersistenceThreshold
TTKTopologicalSimplification1
TTKSphereFromPoint1
ExtractSurface3
Tube2
Threshold4
ExtractSurface2
Diagonal
TTKTopologicalSimplification1
Contour1
Clip1
TTKTopologicalSimplification1
TTKMergeandContourTreeFTM1
Properties
Information
Properties
Apply
Reset
Delete
Search ... (use Esc to clear text)
Properties
Display
View (Render Vi
Axes Grid
Edit
Center Axes Visibility
Orientation Axes
Orientation Axes Visibility
Orientation Axes Interactivity
Orientation Axes Label Color
Orientation Axes Outline Color
Lights
Layout #1
RenderView1
RenderView2
RenderView3
Birth
Death
0
50
100
150
200
250


TTK - the Topology ToolKit - Chro...
h : paraview — Konsole
TTK 0.9.2 - ParaView 5.4.0
2:06 PM
File Edit View Sources Filters Tools Catalyst Macros Help
Pipeline Browser
CellDatatoPointData1
TTKPersistenceDiagram1
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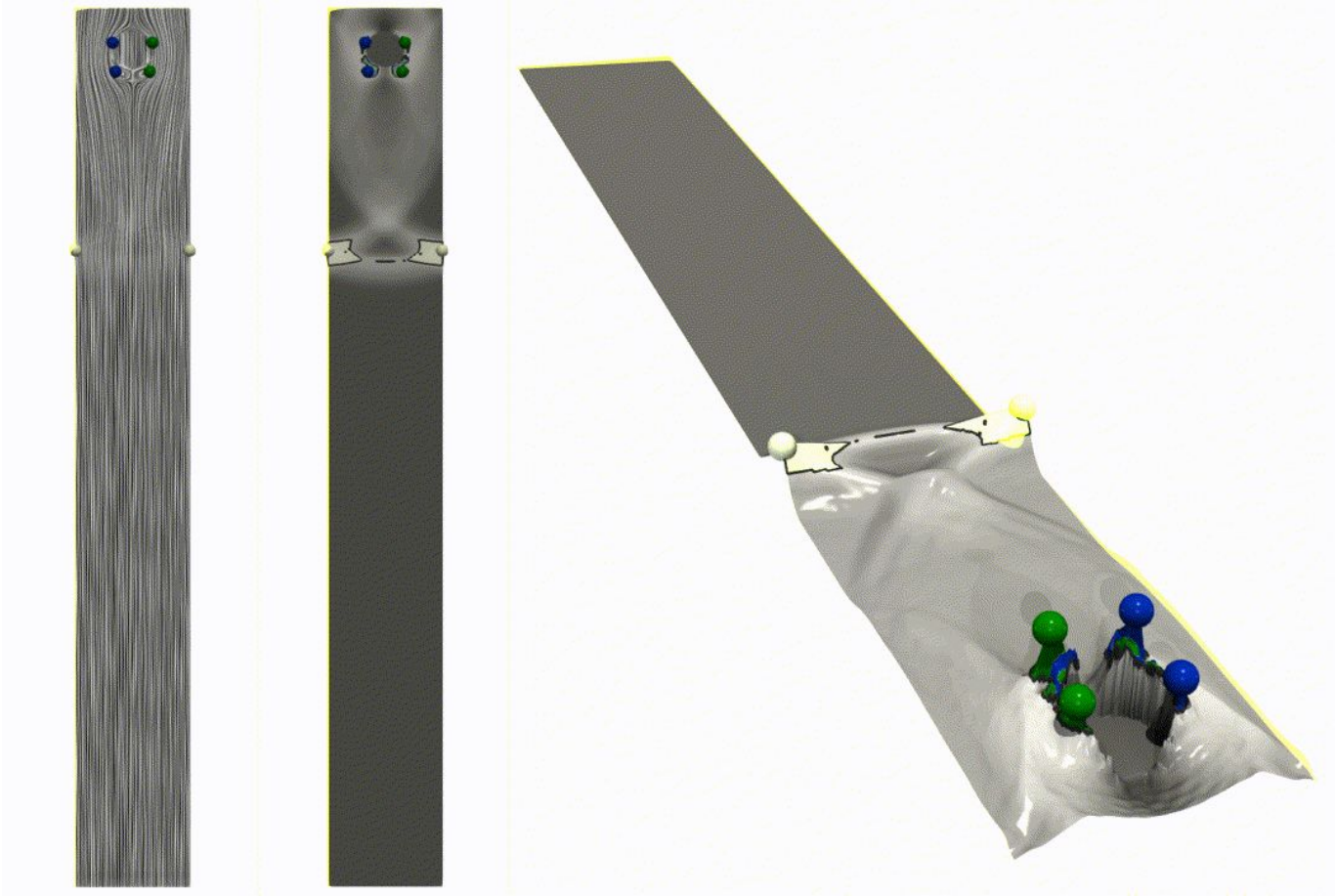
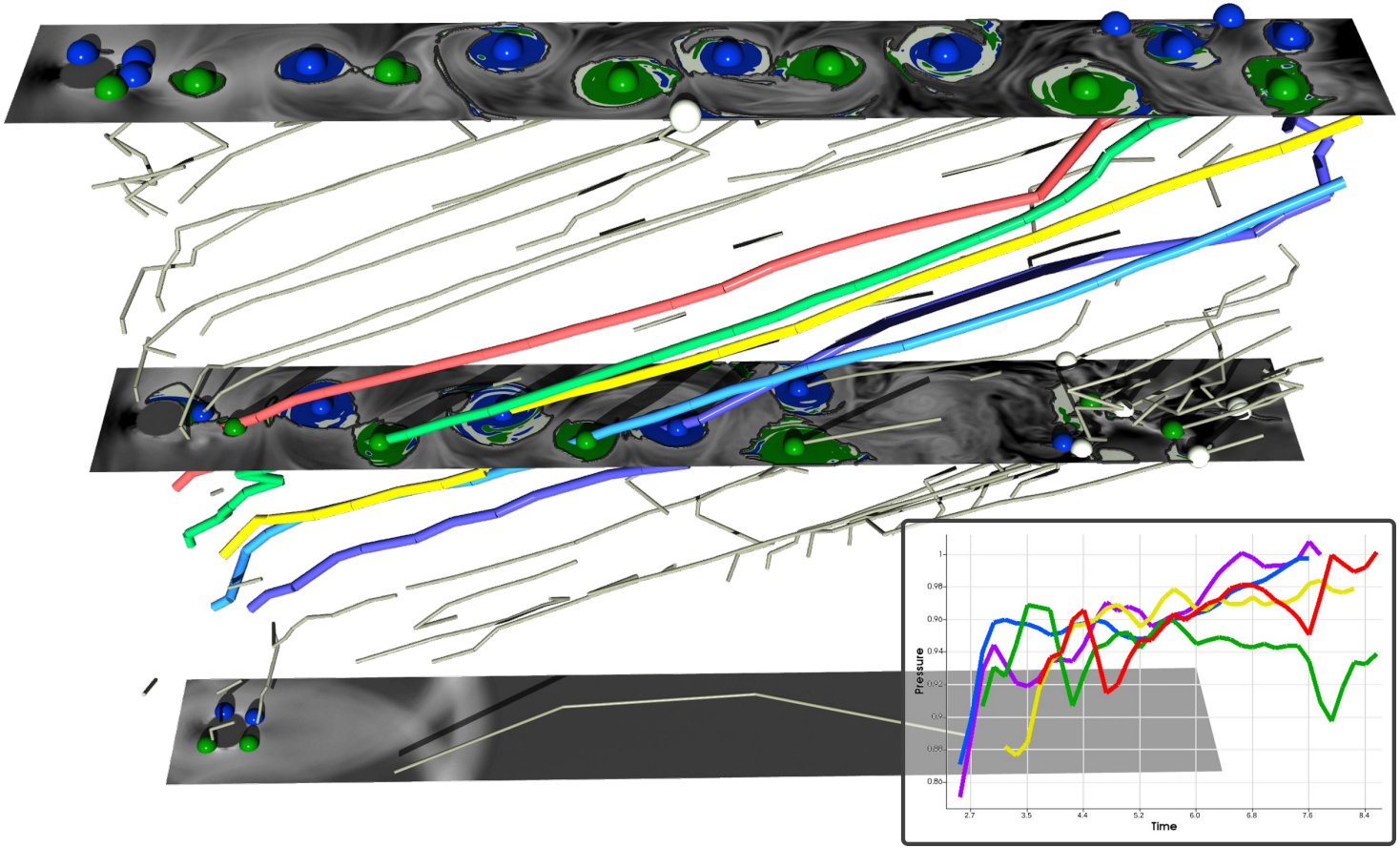
TTKSphereFromPoint1
Threshold1
ExtractSurface2
Diagonal
TTKTopologicalSimplification1
TTKPersistenceCurve1
Minimum-saddle pairs
Saddle-saddle pairs
Saddle-maximum pairs
All pairs
TTKTopologicalSimplification1
TTKMergeandContourTreeFTM1
Properties
Information
Apply
Reset
Delete
Testing
Use All Cores
Thread Number
Debug Level
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
Lights
Edit
Hidden Line Removal
Camera Parallel Projection
Background
Single color
Color
Restore Default
Layout #1
RenderView1
LineChartView1
Number Of Pairs (maximum-saddle pairs)
Number of pairs
Persistence
RenderView2
Birth

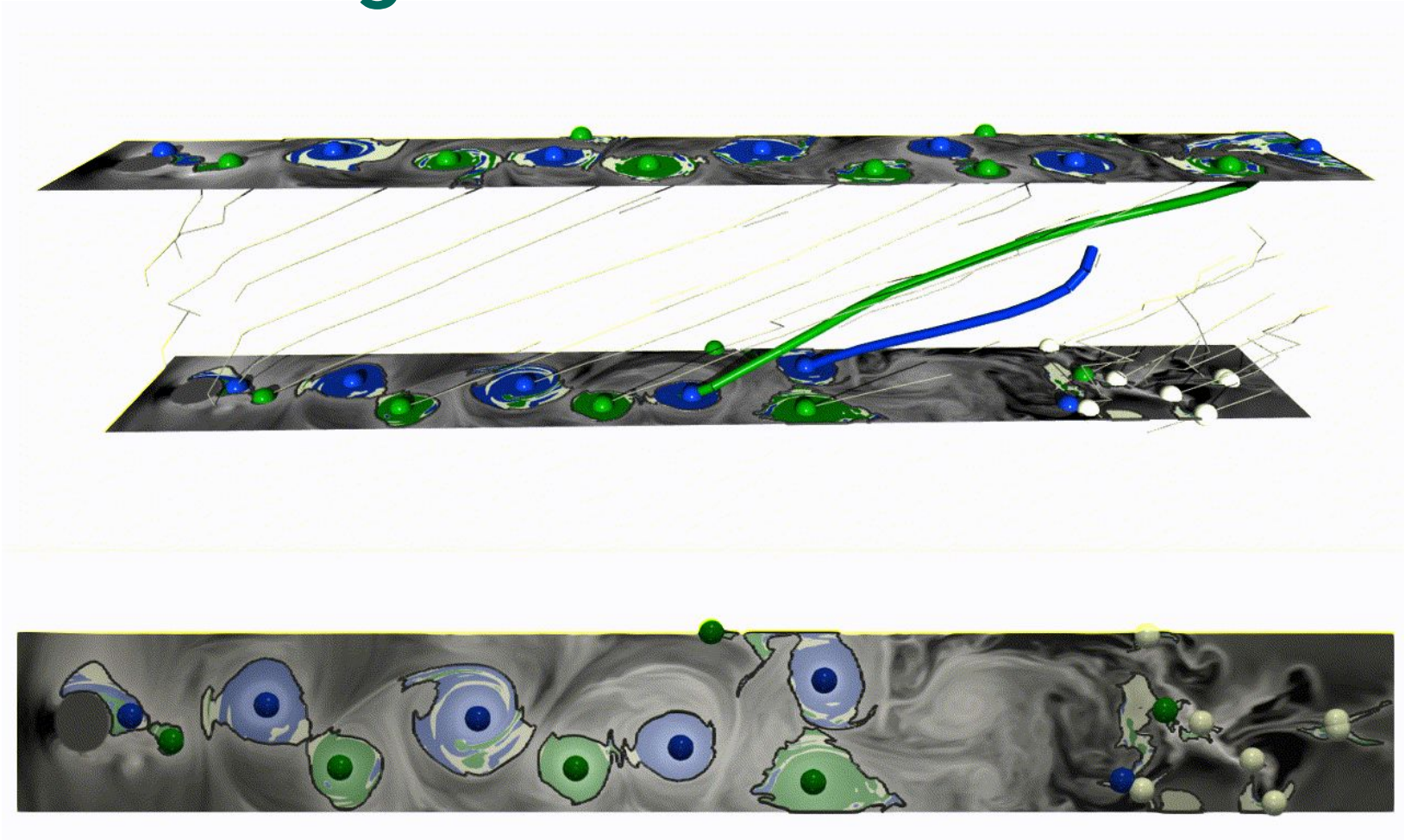
Vortex extraction



Vortex trajectory analysis

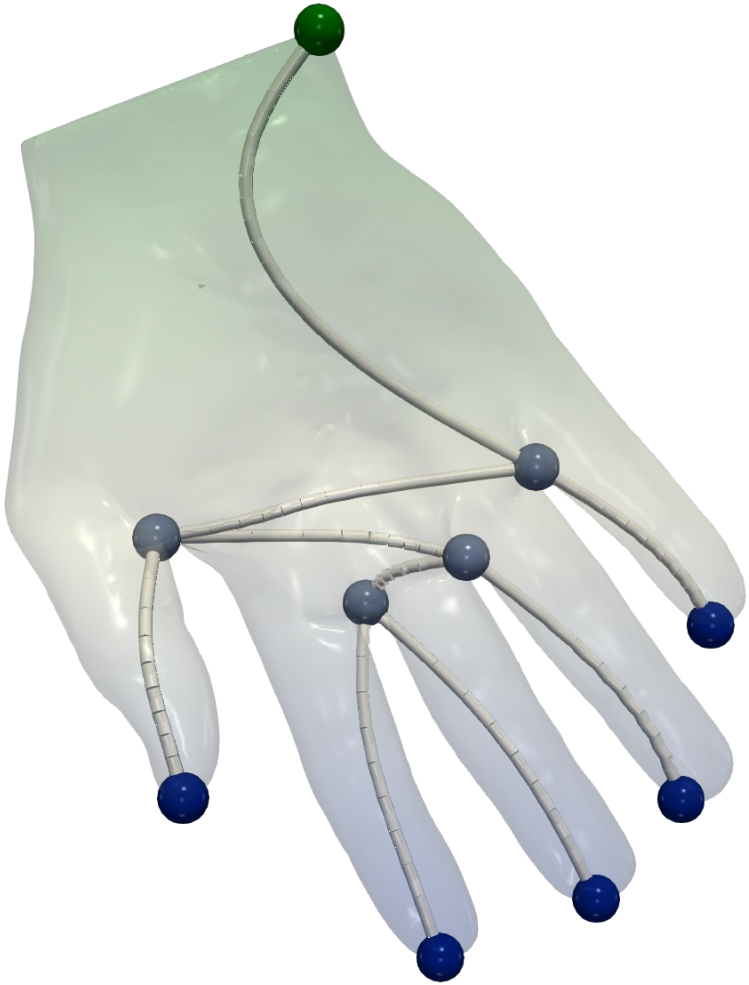


Vortex tracking



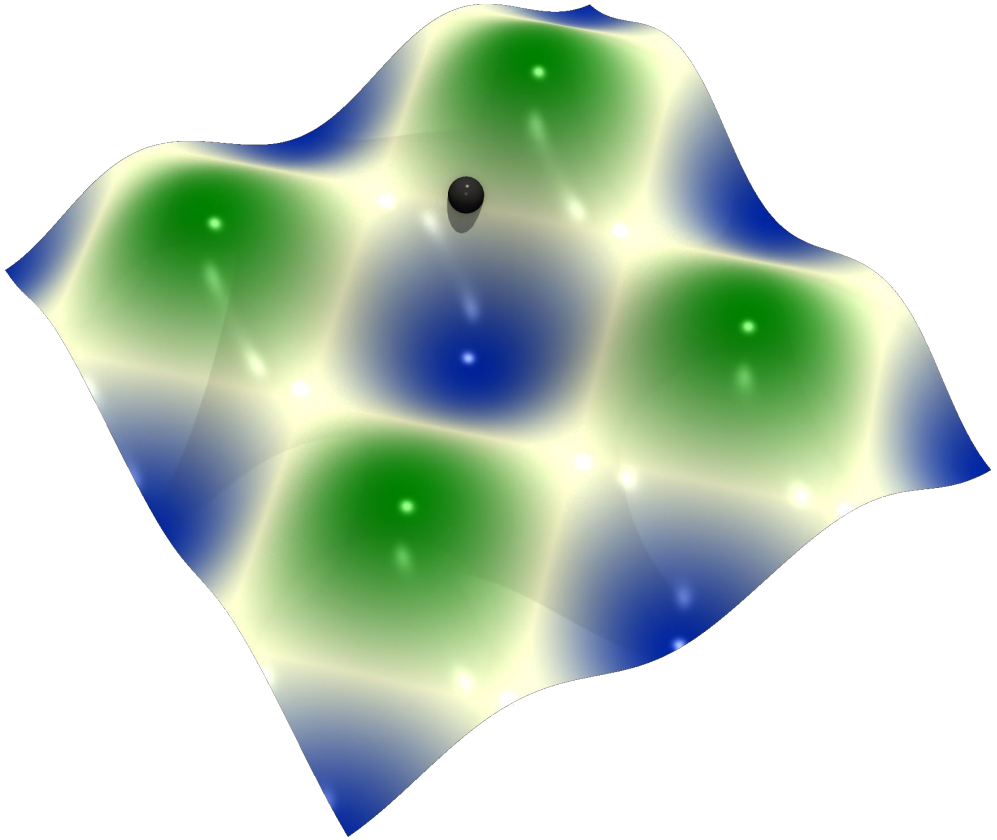
Reeb graphs

- **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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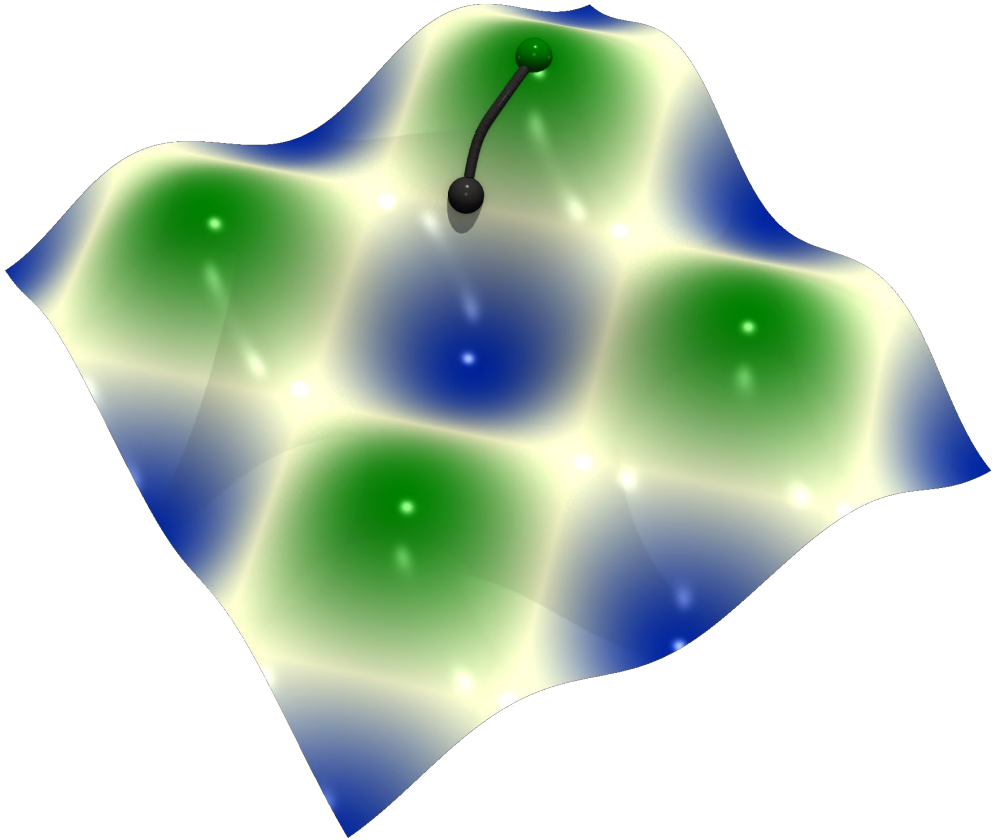

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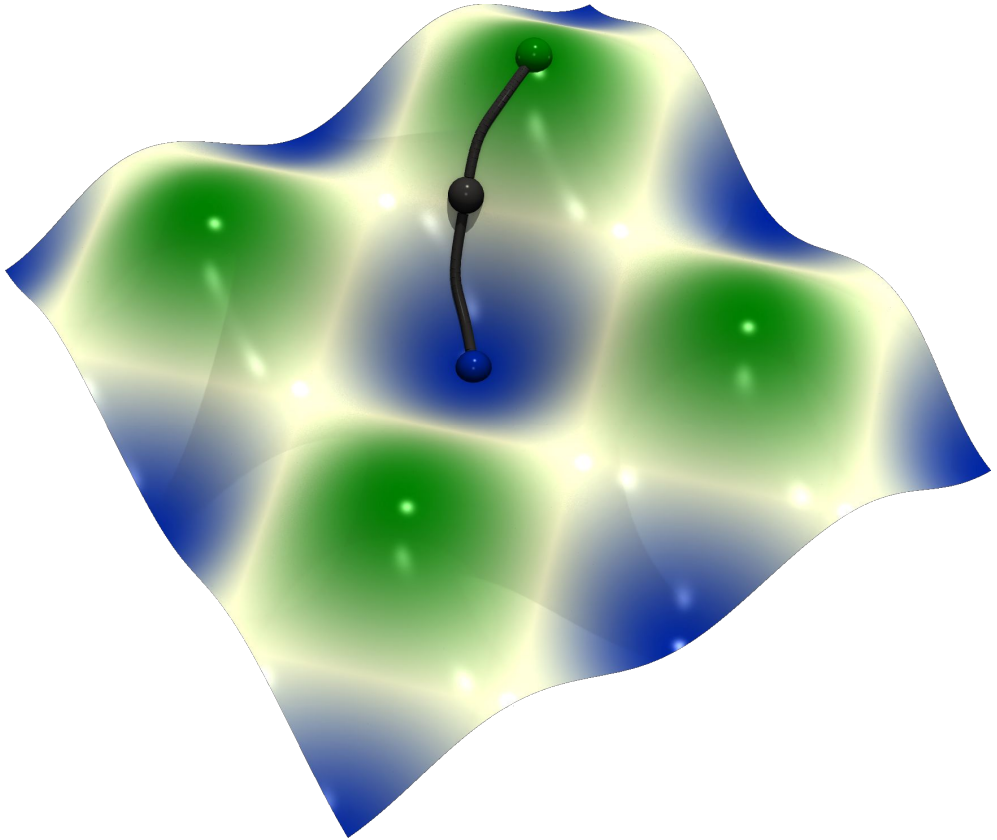

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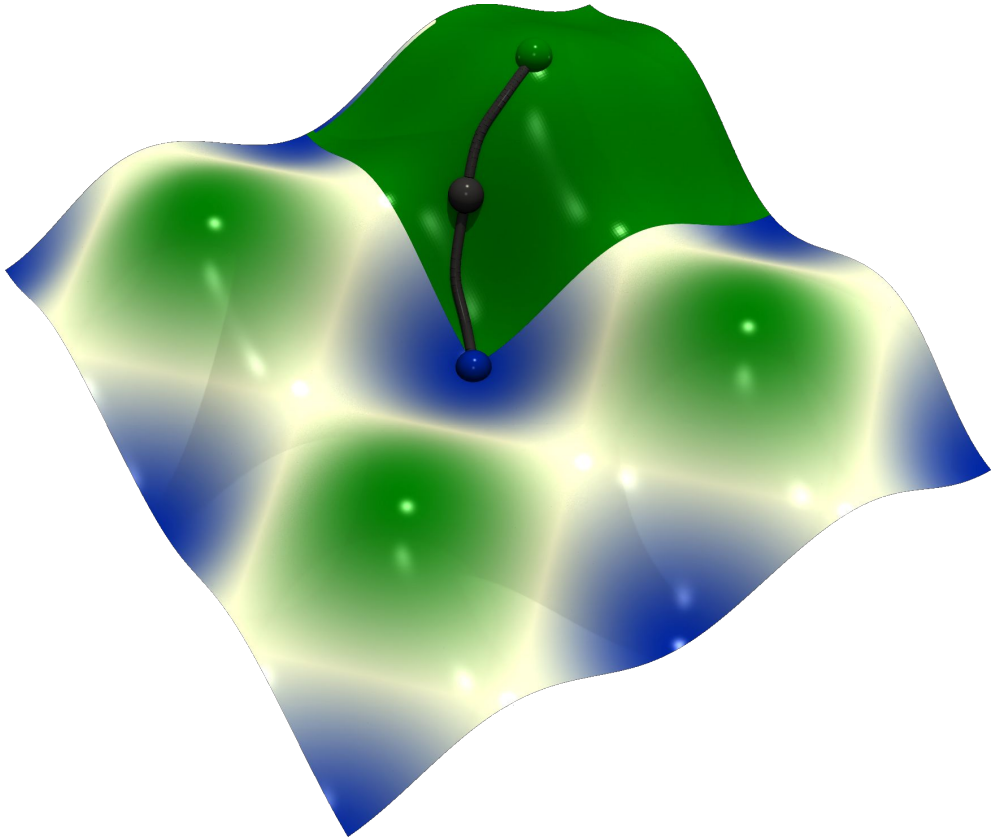

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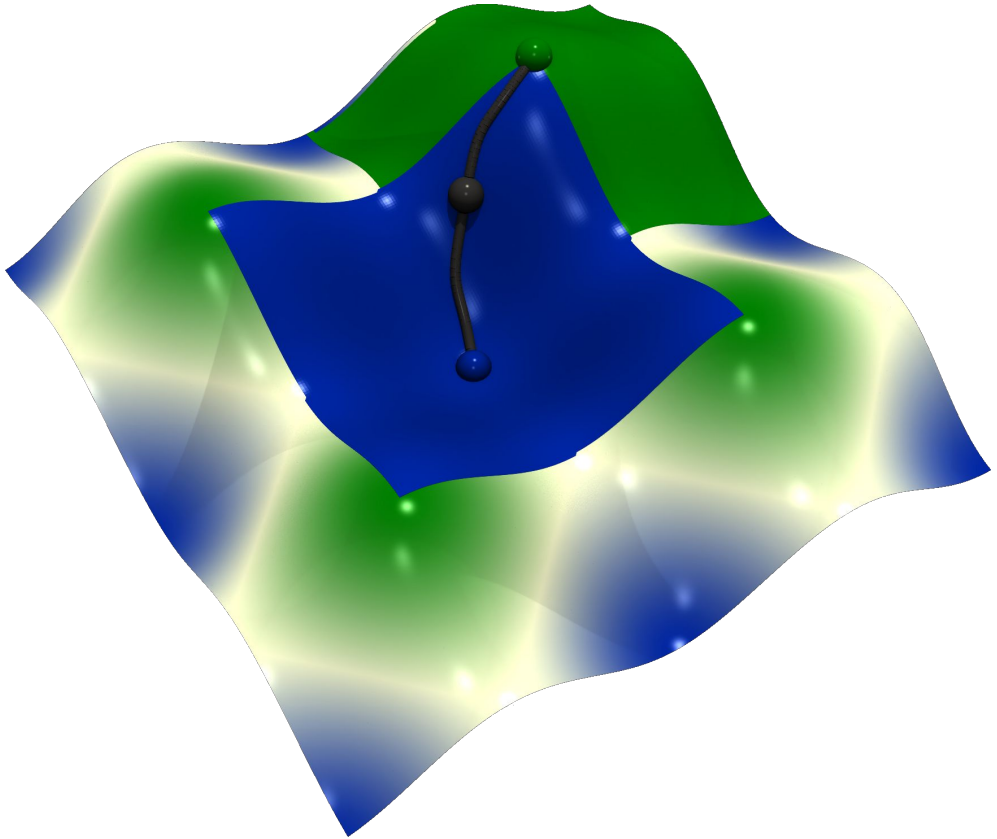

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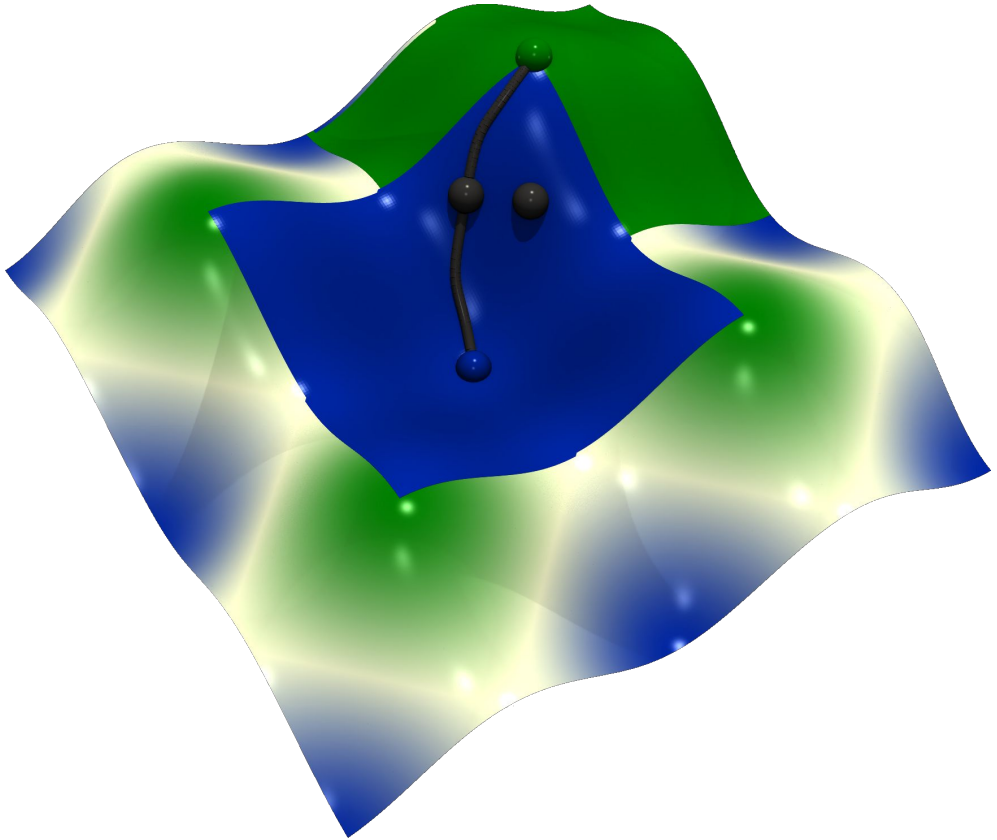

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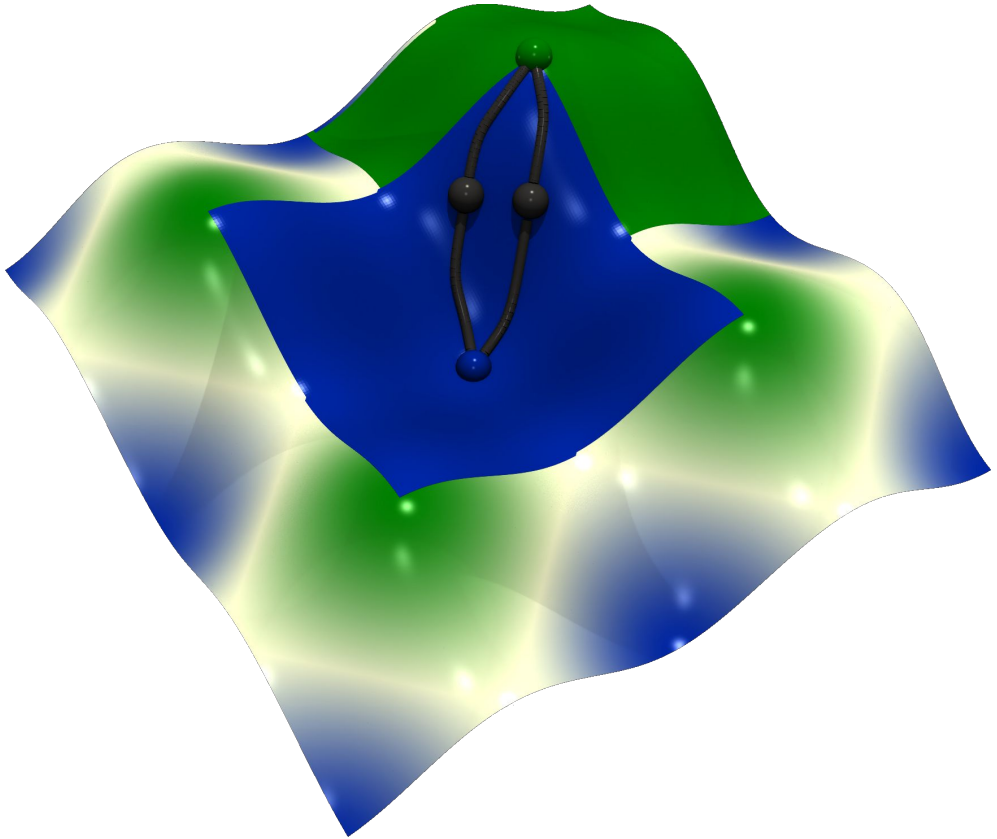

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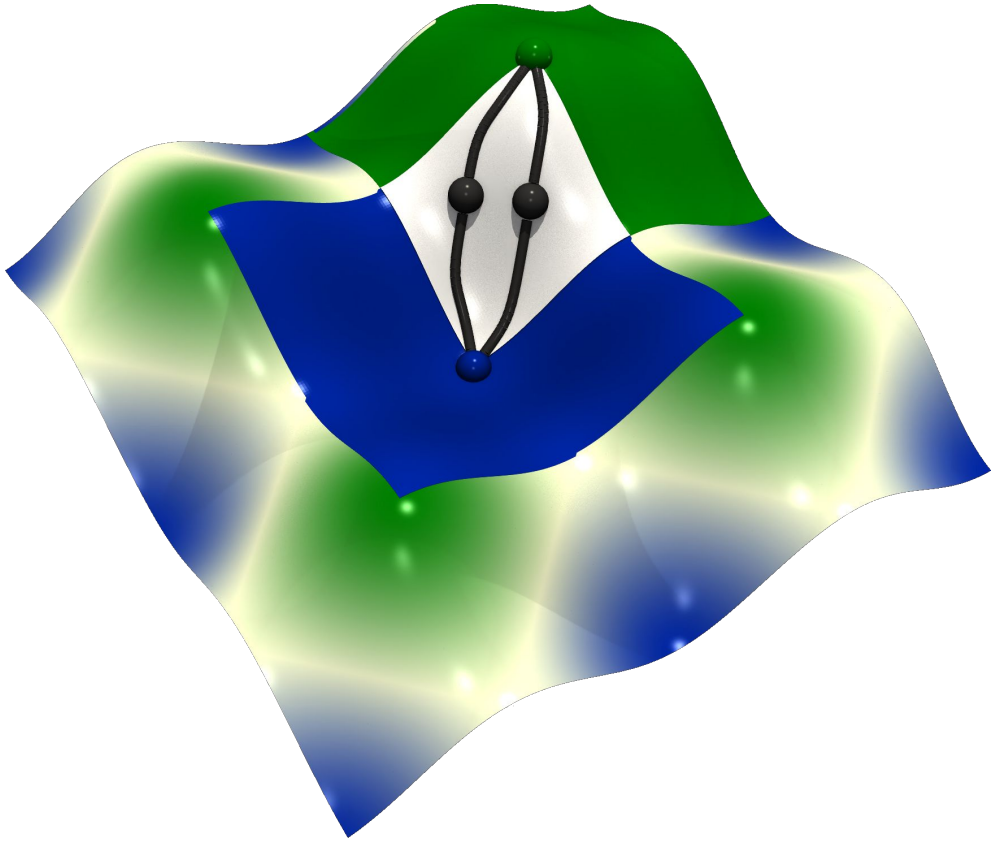
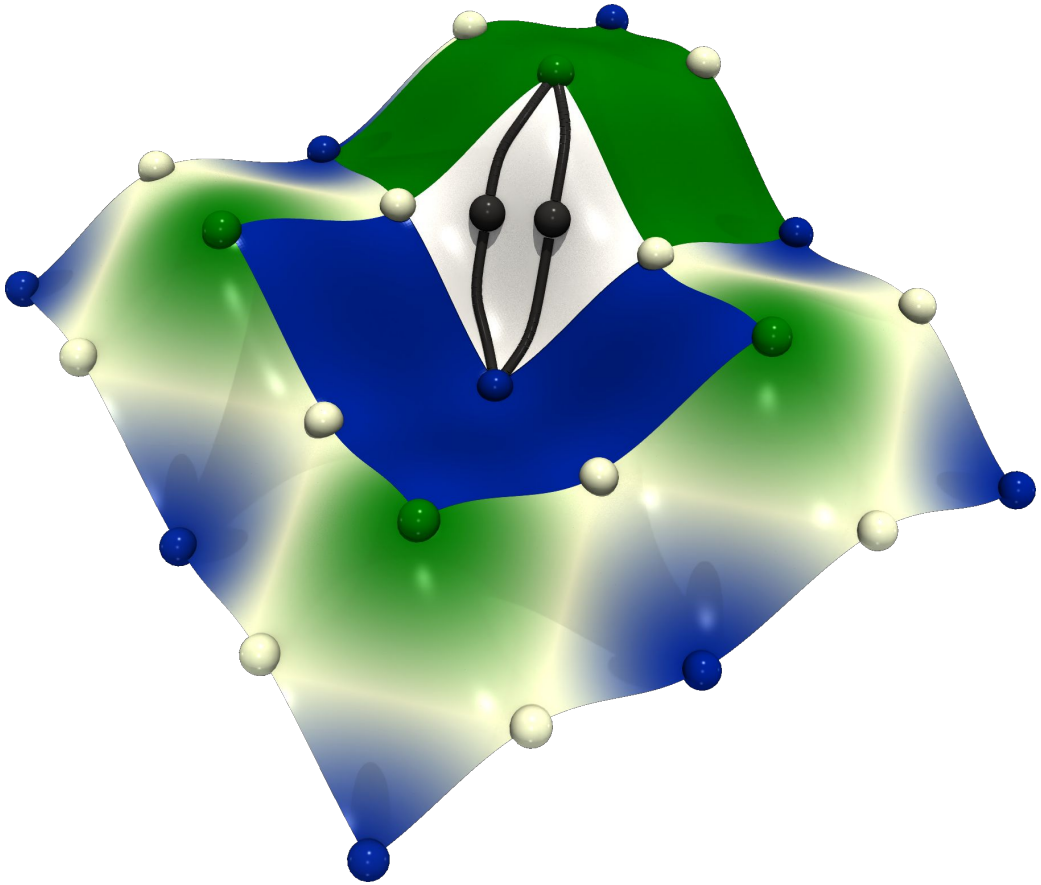
  - Challenging PL computation



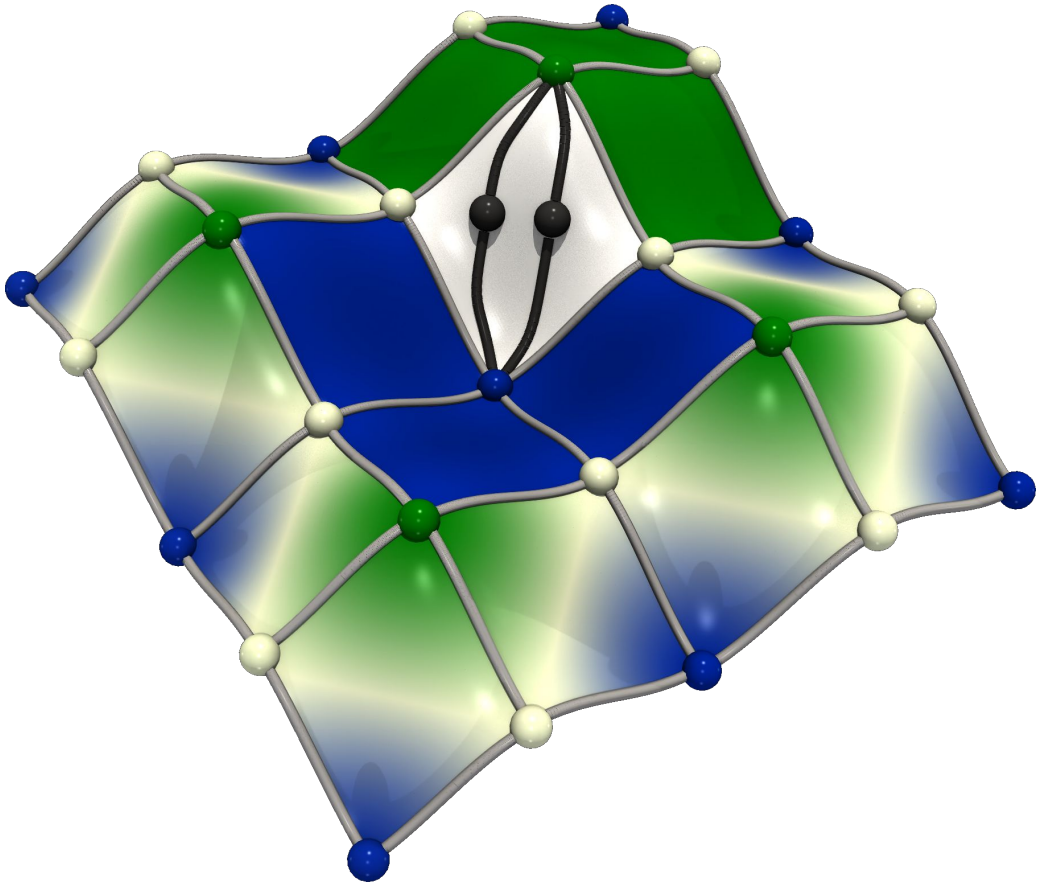
Discrete Morse Theory

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



Discrete Morse Theory

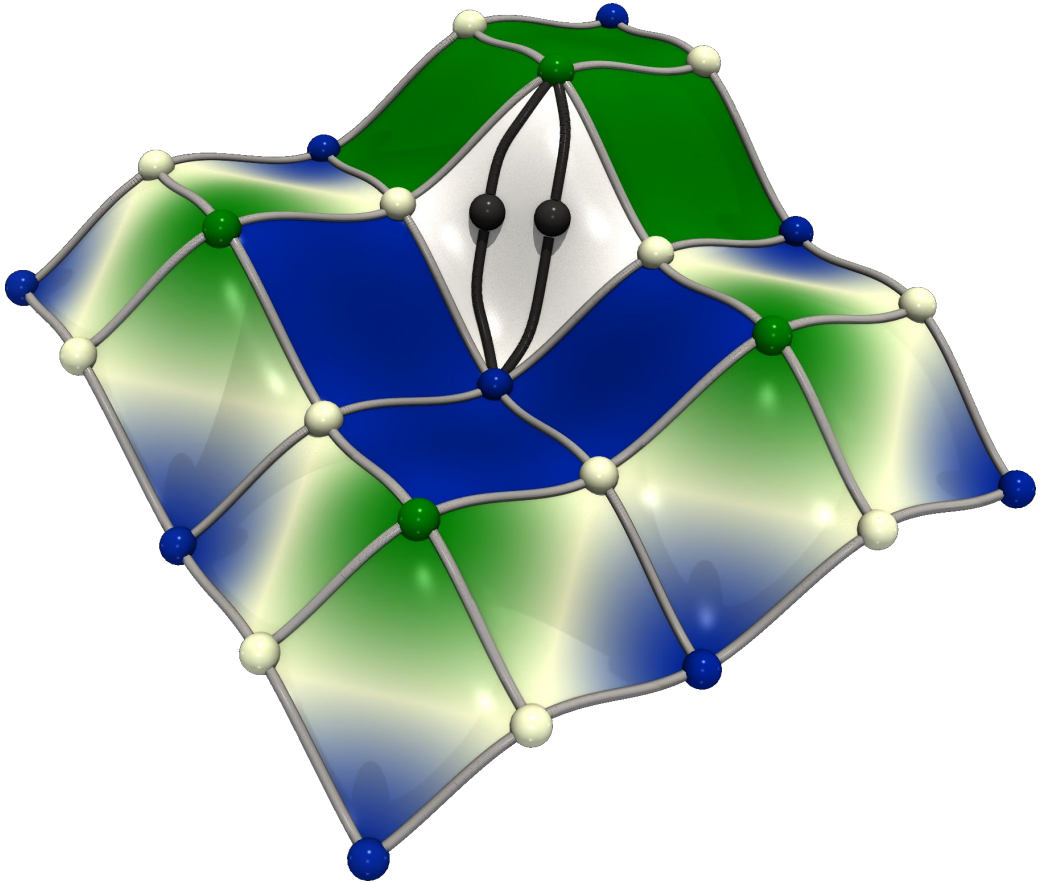
- **Morse-Smale complex**
  - Integration equivalence
  - Challenging PL computation

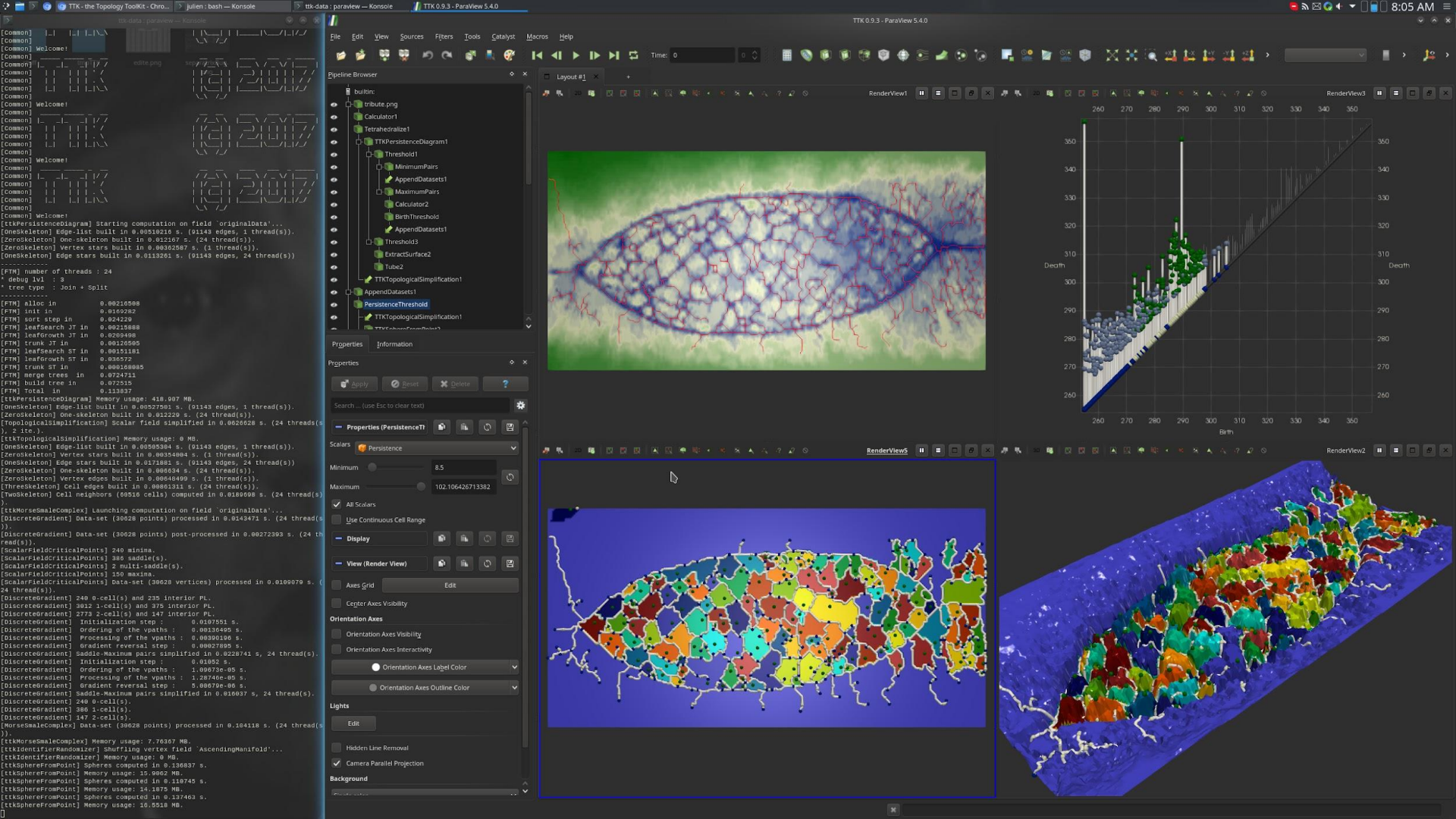


Discrete Morse Theory

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

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




TTK - the Topology ToolKit - Chro...
julien : bash — Konsole
ttk-data : paraview — Konsole
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8:05 AM
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Threshold1
MinimumPairs
AppendDatasets1
MaximumPairs
Calculator2
BirthThreshold
AppendDatasets1
Threshold3
ExtractSurface2
Tube2
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AppendDatasets1
PersistenceThreshold
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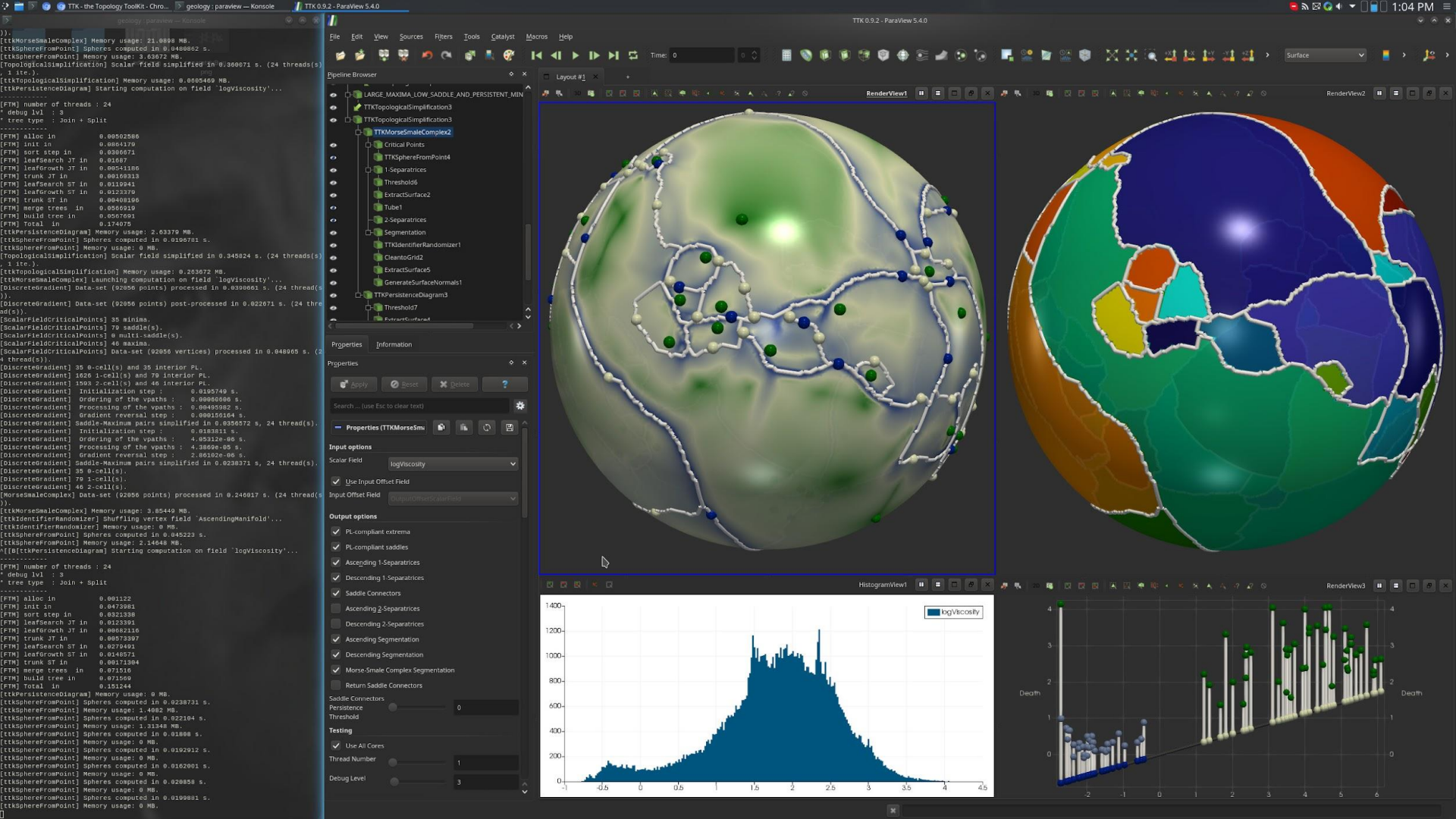
Center Axes Visibility
Orientation Axes
Orientation Axes Visibility
Orientation Axes Interactivity
Orientation Axes Label Color
Orientation Axes Outline Color
Lights
Edit
Hidden Line Removal
Camera Parallel Projection
Background
Layout #1
RenderView1
RenderView3
RenderView5
RenderView2
Death
Birth


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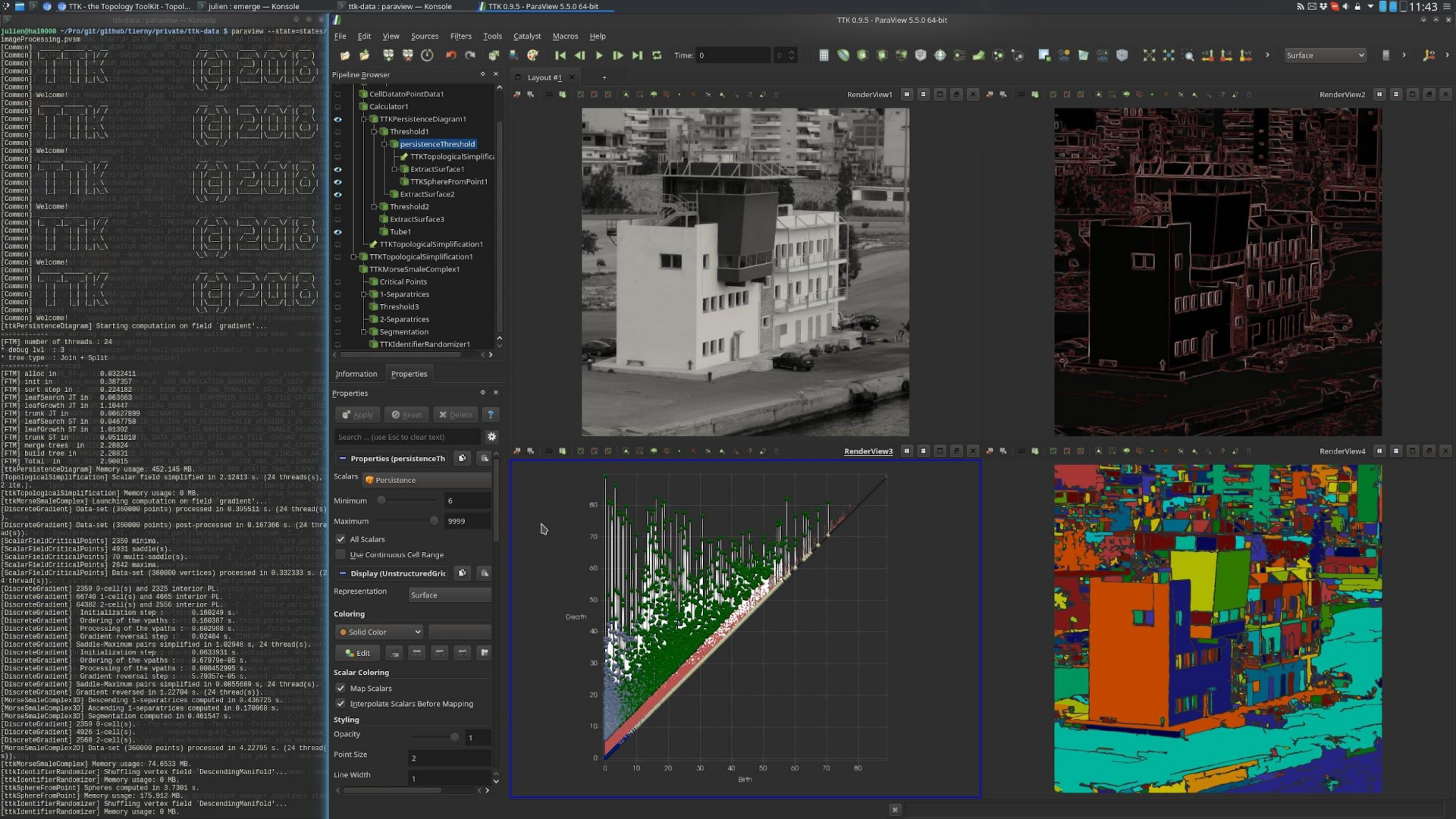
Descending 1-Separatrices
Saddle Connectors
Ascending 2-Separatrices
Descending 2-Separatrices
Ascending Segmentation
Descending Segmentation
Morse-Smale Complex Segmentation
Return Saddle Connectors
Saddle Connectors Persistence Threshold
Testing
Use All Cores
Thread Number
Debug Level
Layout #1
RenderView1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


TTK - the Topology ToolKit - Topol...
julien : emerge — Konsole
ttk-data : paraview — Konsole
TTK 0.9.5 - ParaView 5.5.0 64-bit
11:43
julien@hal9000 ~/Pro/git/github/tierny/private/ttk-data $ paraview --state=states/imageProcessing.pvsm
TTK 0.9.5 - ParaView 5.5.0 64-bit
File Edit View Sources Filters Tools Catalyst Macros Help
Time: 0
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Pipeline Browser
CellDatatoPointData1
Calculator1
TTKPersistenceDiagram1
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ExtractSurface1
TTKSphereFromPoint1
ExtractSurface2
Threshold2
ExtractSurface3
Tube1
TTKTopologicalSimplification1
TTKTopologicalSimplification1
TTKMorseSmaleComplex1
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2-Separatrices
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Scalar Coloring
Map Scalars
Interpolate Scalars Before Mapping
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2
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Layout #1
RenderView1
RenderView2
RenderView3
RenderView4
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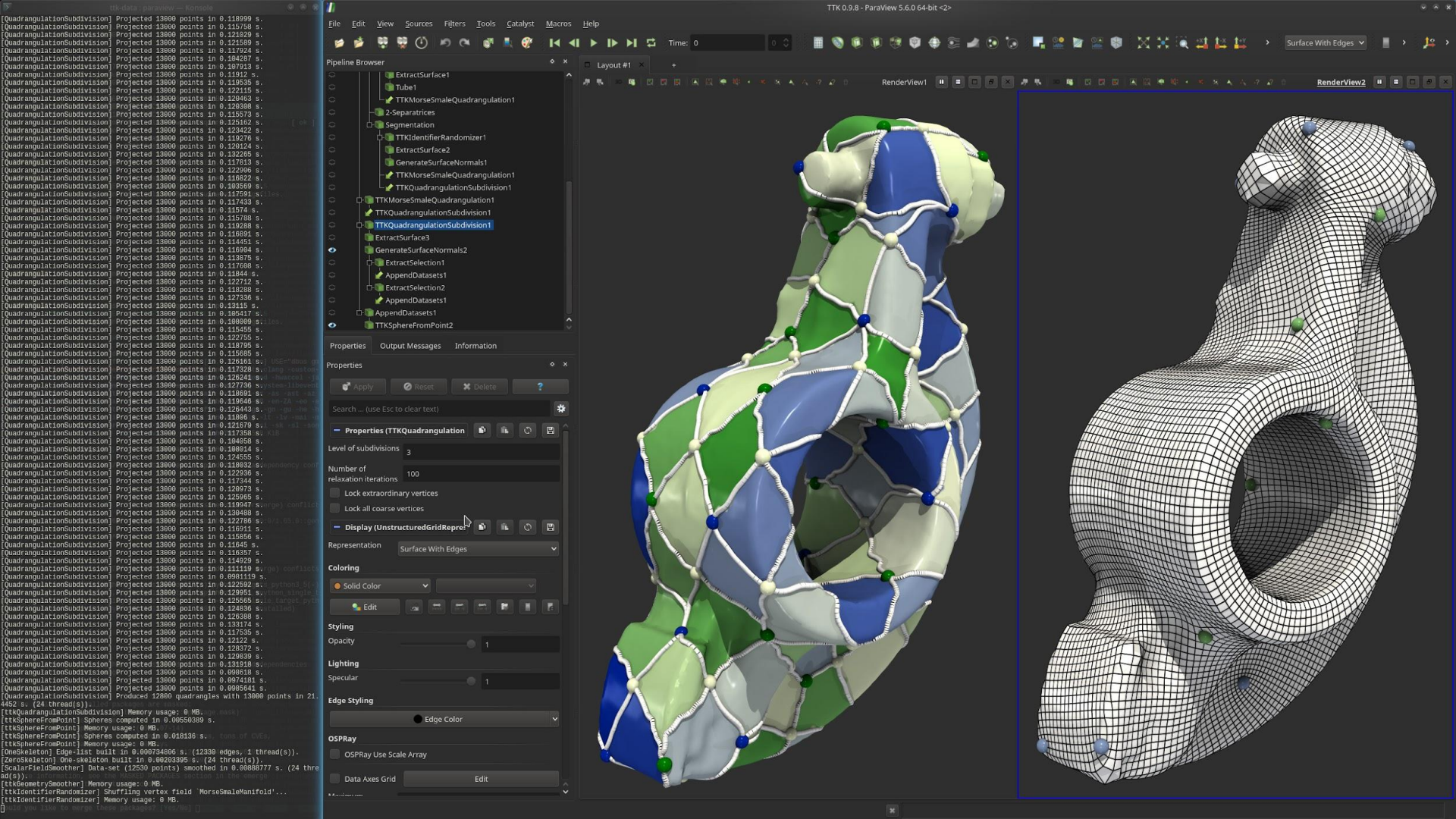
TTK 0.9.8 - ParaView 5.6.0 64-bit <2>
File Edit View Sources Filters Tools Catalyst Macros Help
Time: 0
Surface With Edges
Pipeline Browser
ExtractSurface1
Tube1
TTKMorseSmaleQuadrangulation1
2-Separatrices
Segmentation
TTKIdentifierRandomizer1
ExtractSurface2
GenerateSurfaceNormals1
TTKMorseSmaleQuadrangulation1
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)
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Level of subdivisions
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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
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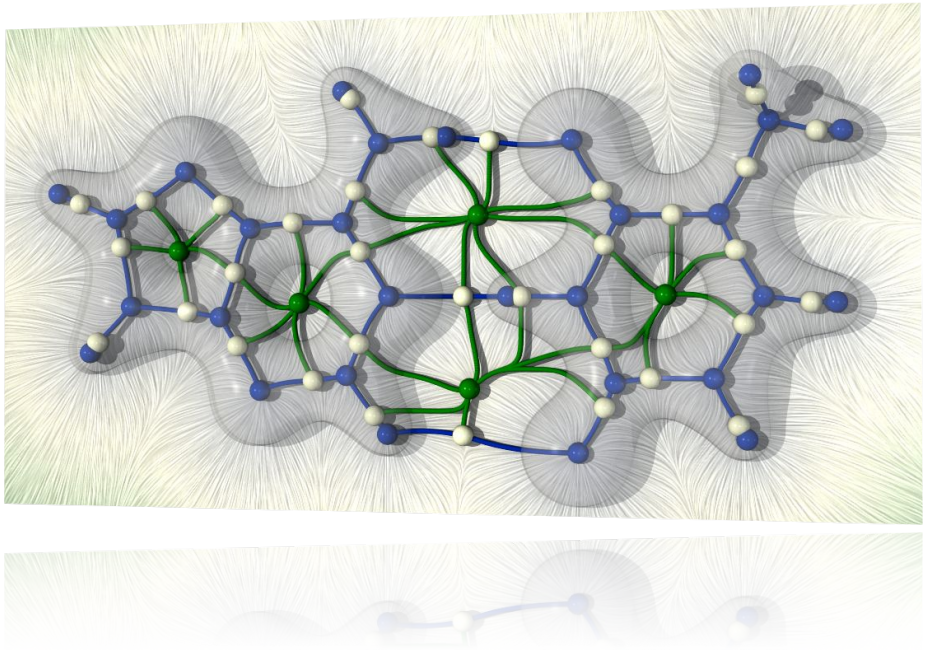
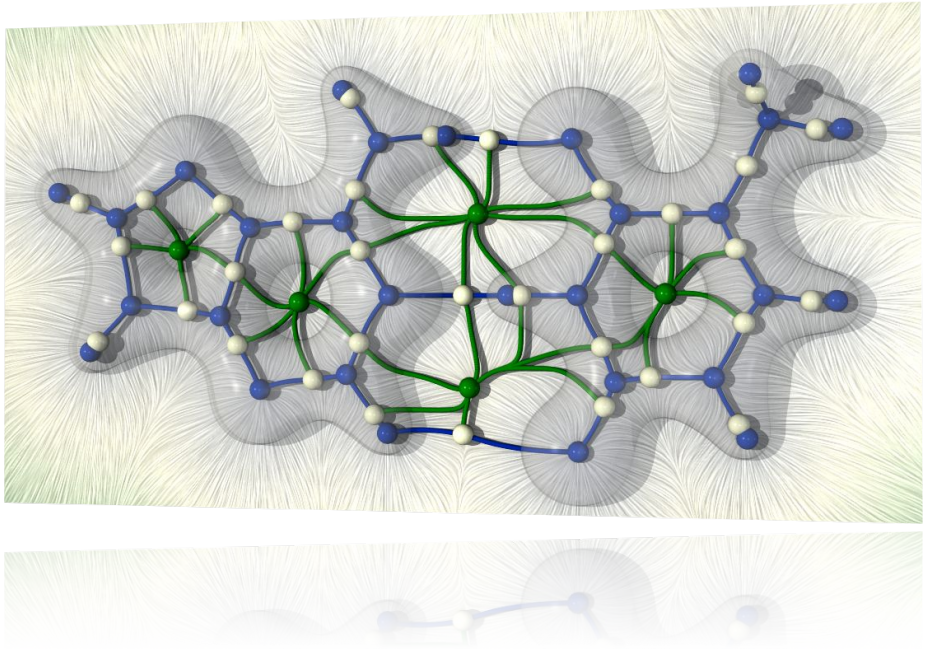
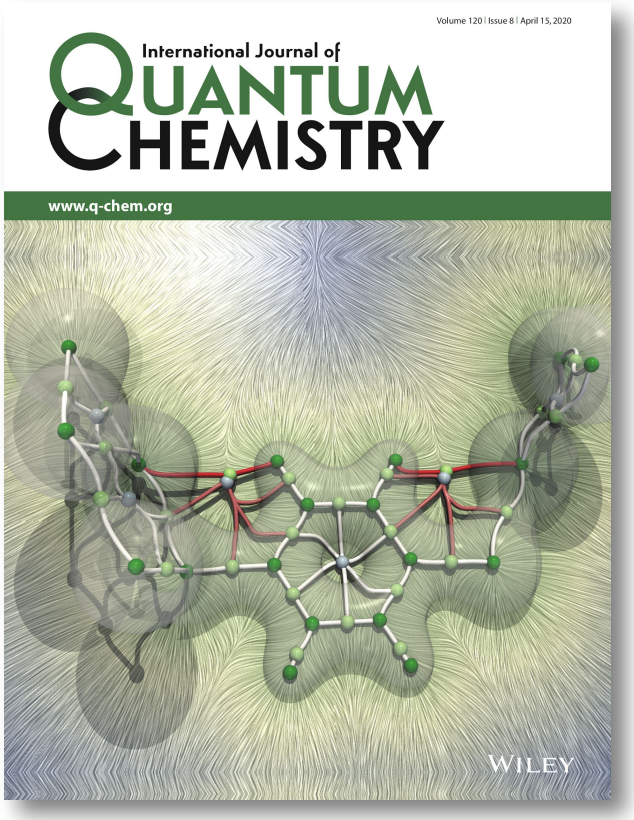
Data Axes Grid
Edit
Layout #1
RenderView1
RenderView2

Application of the Morse-Smale complex



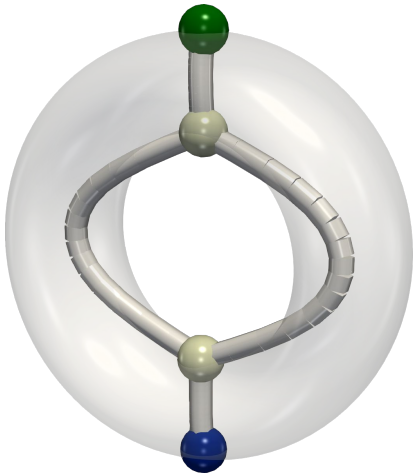
Application of the Morse-Smale complex





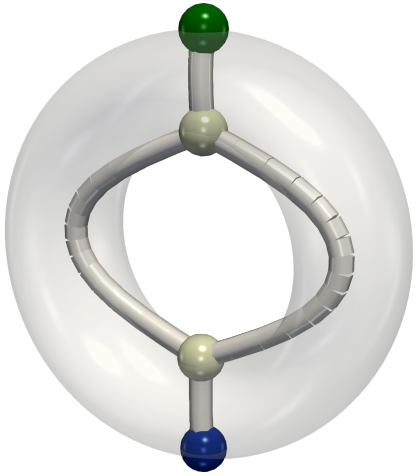
So far

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



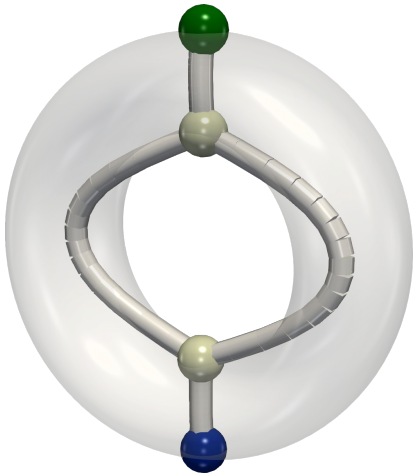
So far

- **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**
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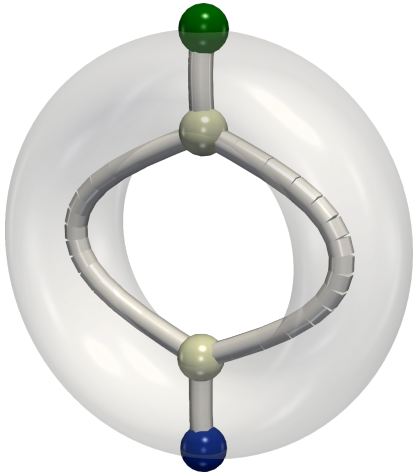
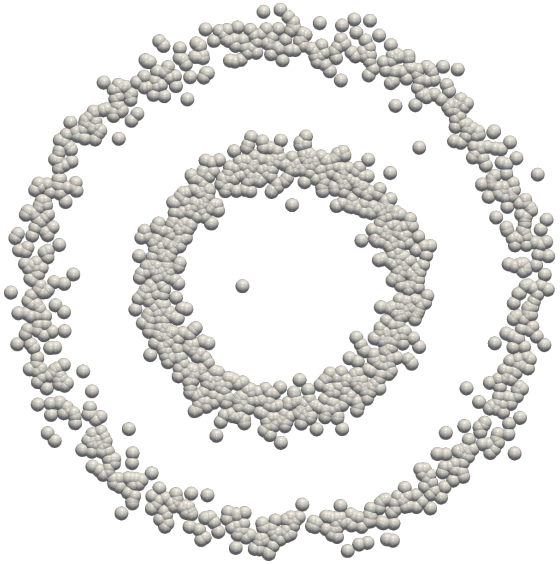
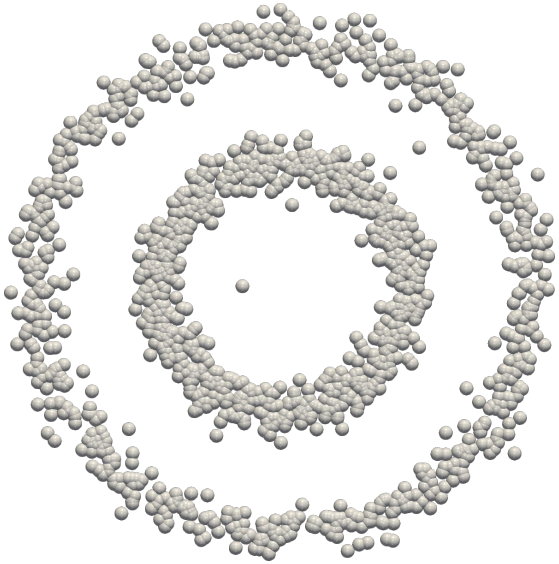


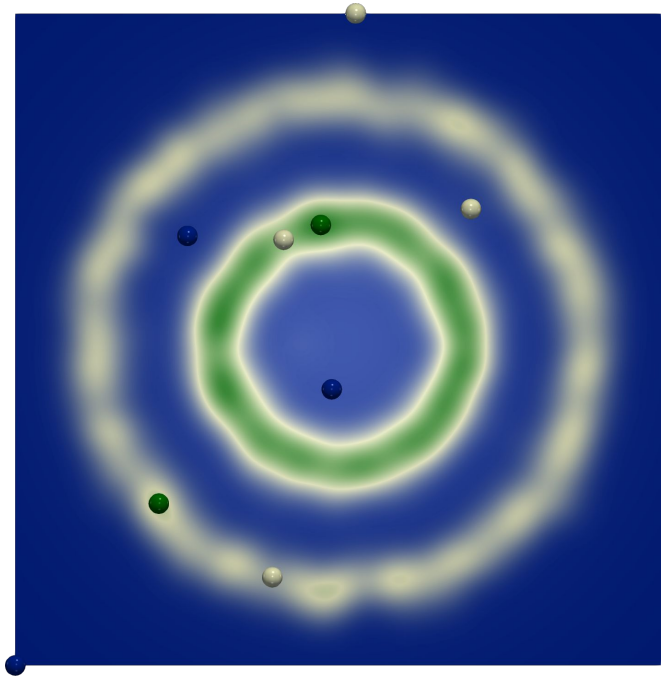
- **How about point cloud data?**

What about point cloud data?

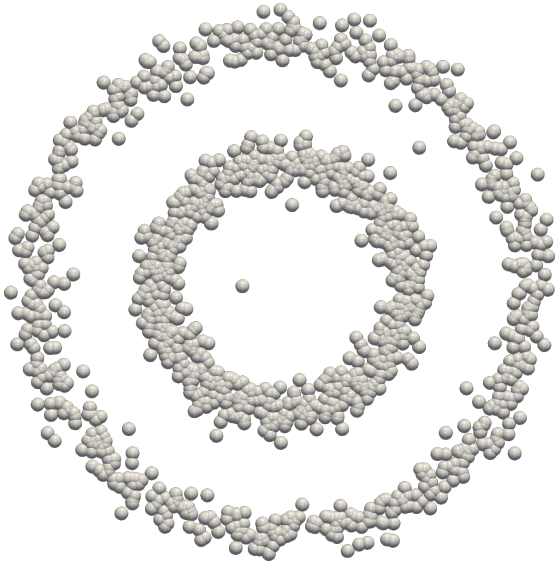


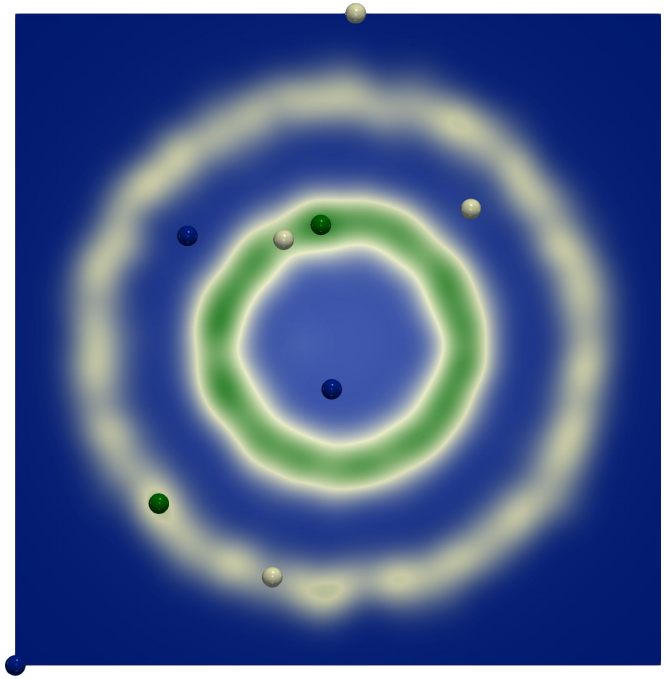
What about point cloud data?

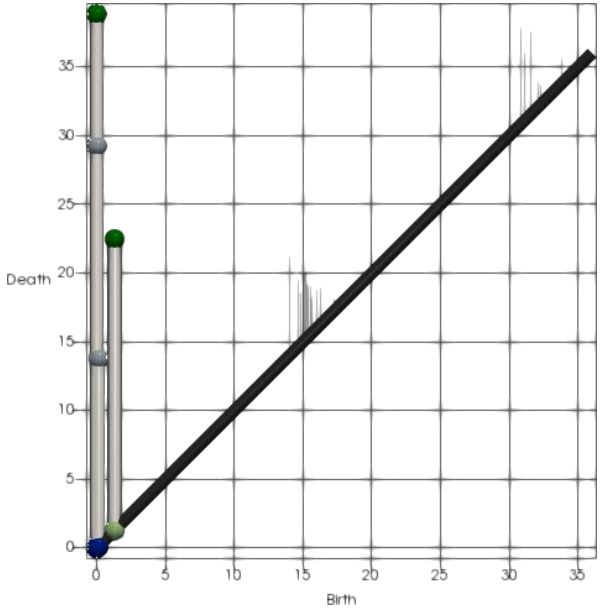




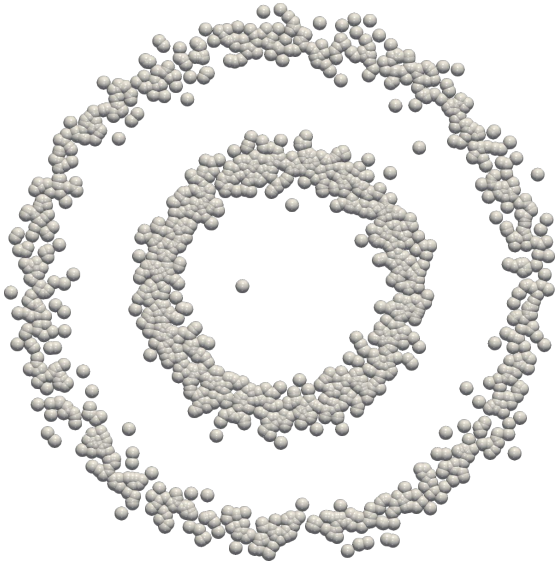
What about point cloud data?

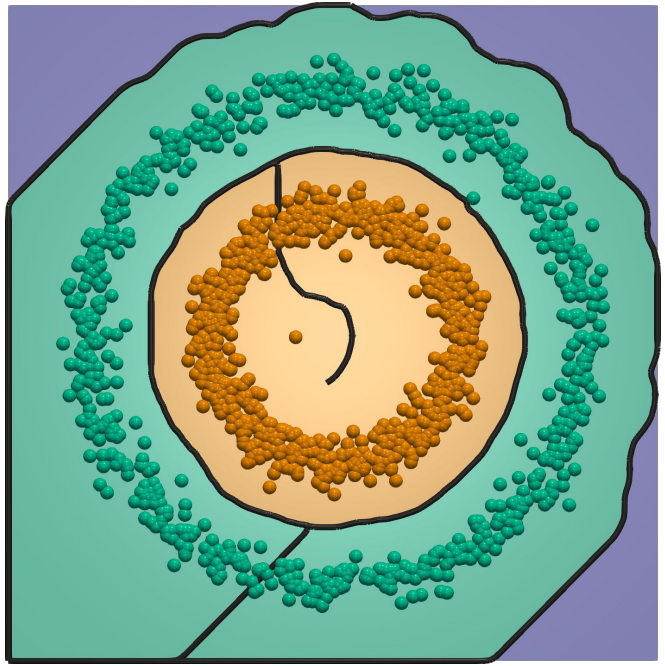


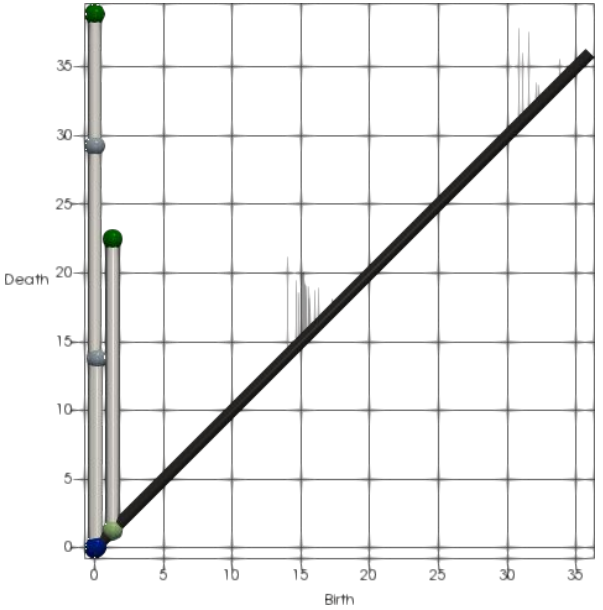




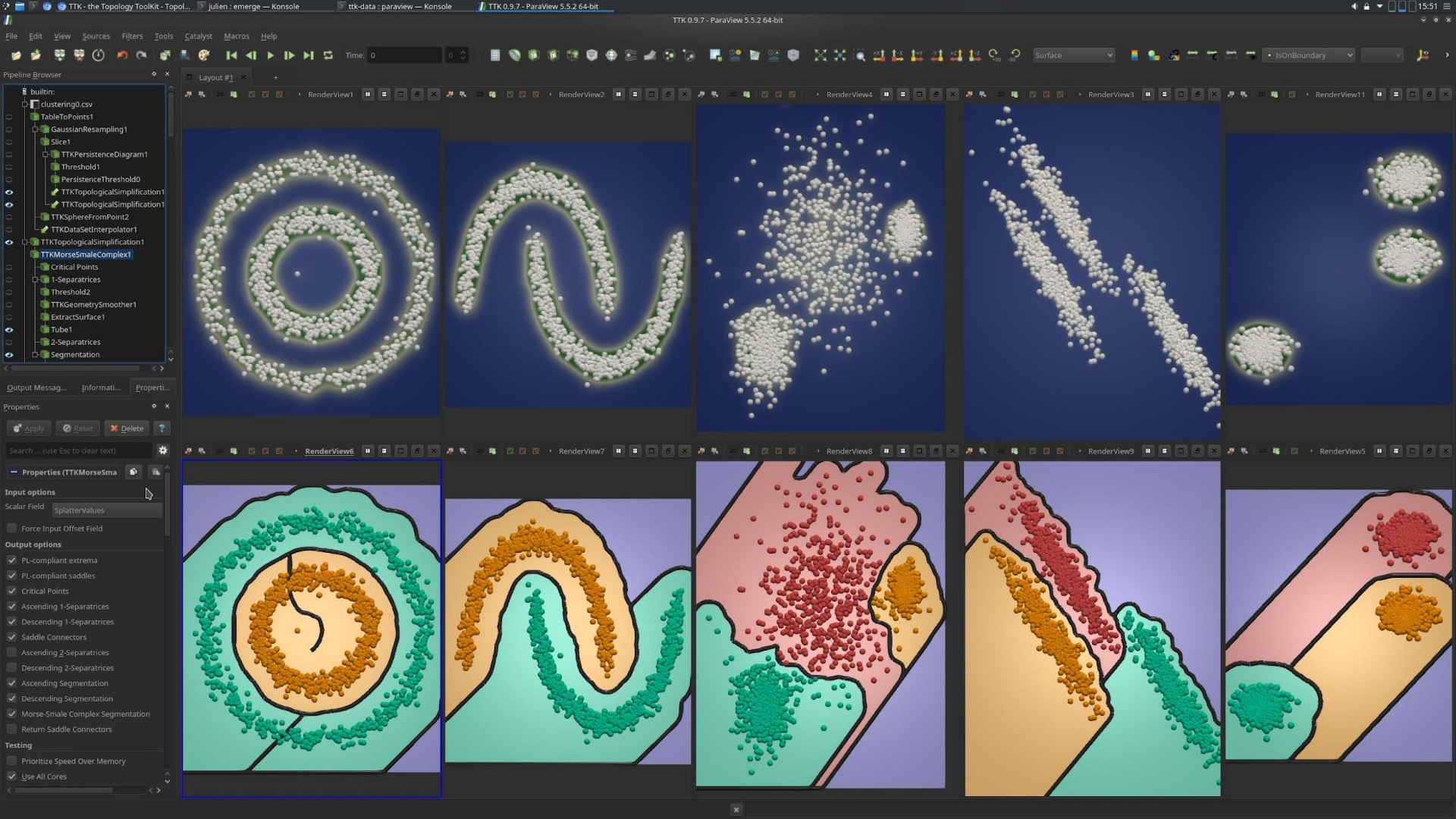
What about point cloud data?







- 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
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clustering0.csv
TableToPoints1
GaussianResampling1
Slice1
TTKPersistenceDiagram1
Threshold1
PersistenceThreshold0
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TTKTopologicalSimplification1
TTKSphereFromPoint2
TTKDataSetInterpolator1
TTKTopologicalSimplification1
TTKMorseSmaleComplex1
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TTKGeometrySmoother1
ExtractSurface1
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2-Separatrices
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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
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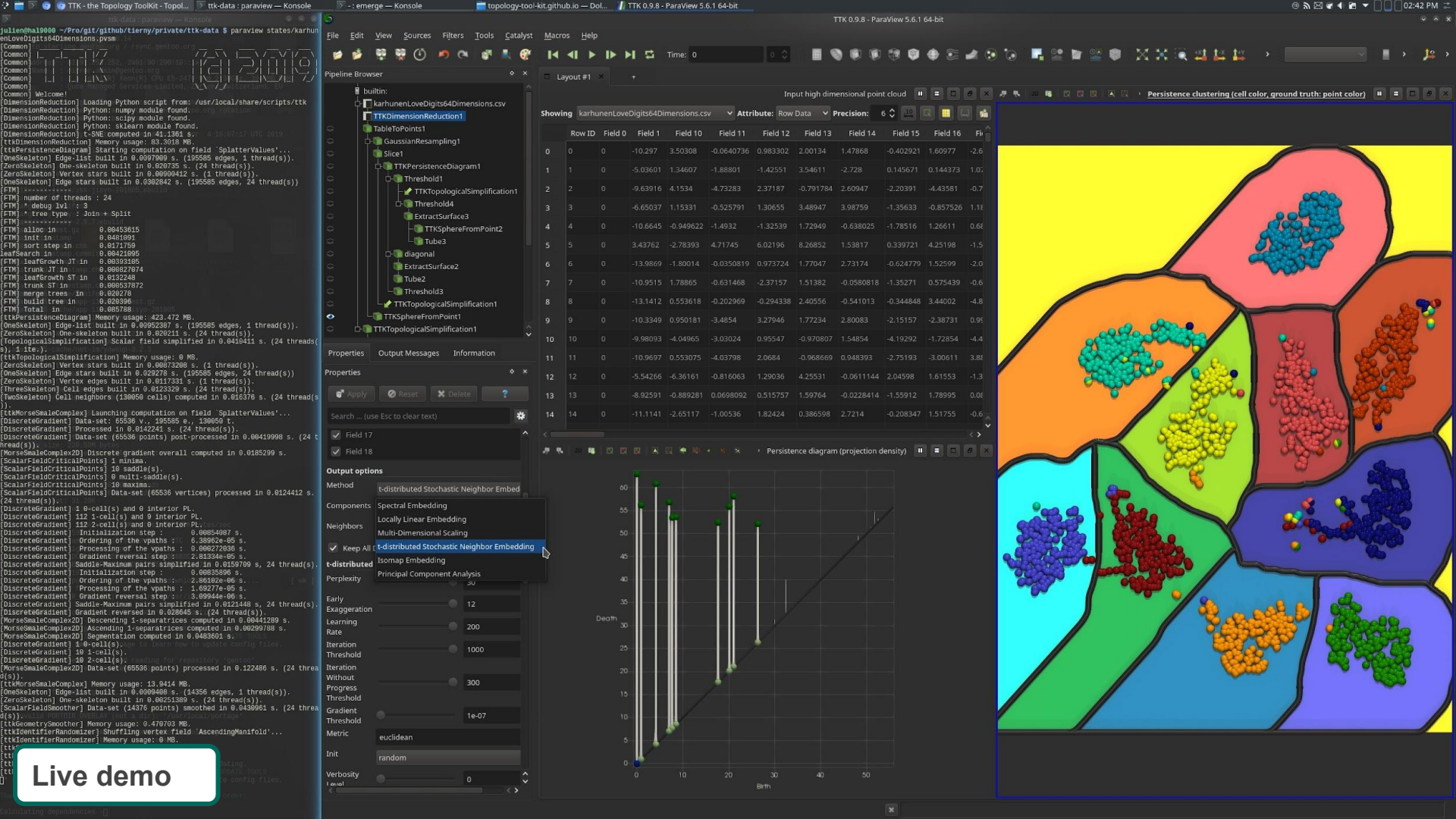
RenderView6
RenderView7
RenderView8
RenderView9
RenderView5


TTK 0.9.8 - ParaView 5.6.1 64-bit
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TableToPoints1
GaussianResampling1
Slice1
TTKPersistenceDiagram1
Threshold1
TTKTopologicalSimplification1
Threshold4
ExtractSurface3
TTKSphereFromPoint2
Tube3
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ExtractSurface2
Tube2
Threshold3
TTKTopologicalSimplification1
TTKSphereFromPoint1
TTKTopologicalSimplification1
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Information
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Reset
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Field 18
Output options
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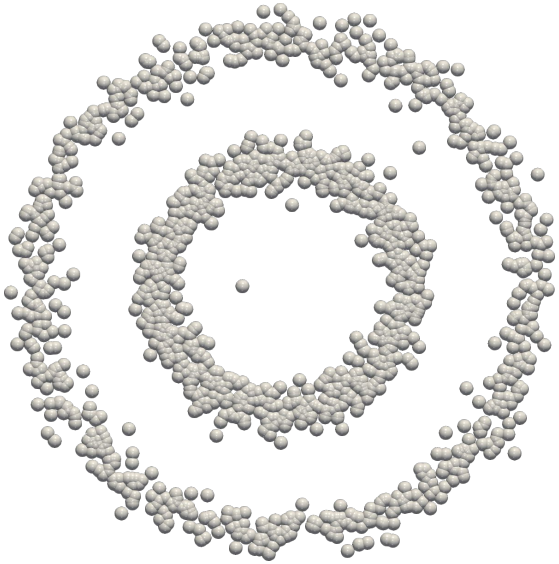
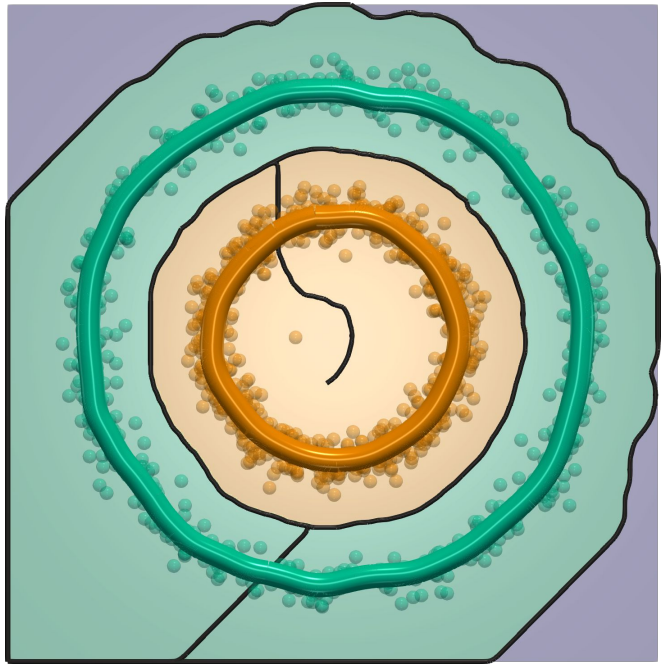
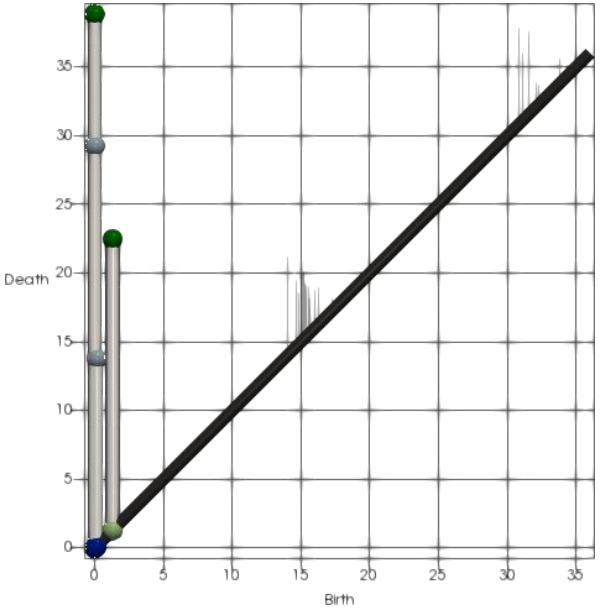
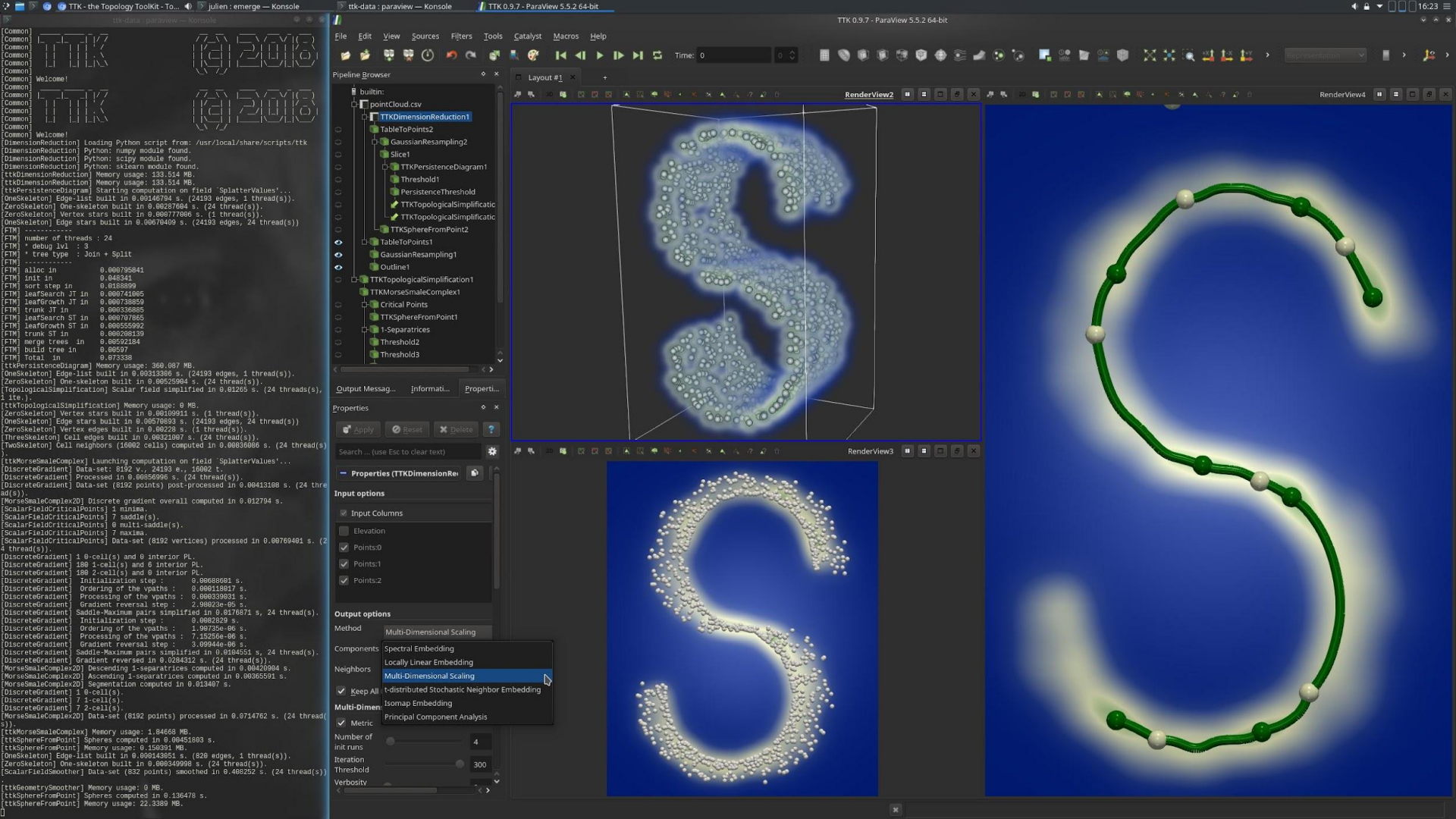
t-distributed Stochastic Neighbor Embed
Components
Neighbors
Keep All
Spectral Embedding
Locally Linear Embedding
Multi-Dimensional Scaling
t-distributed Stochastic Neighbor Embedding
Isomap Embedding
Principal Component Analysis
Perplexity
Early Exaggeration
Learning Rate
Iteration Threshold
Iteration 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...
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Search ... (use Esc to clear text)
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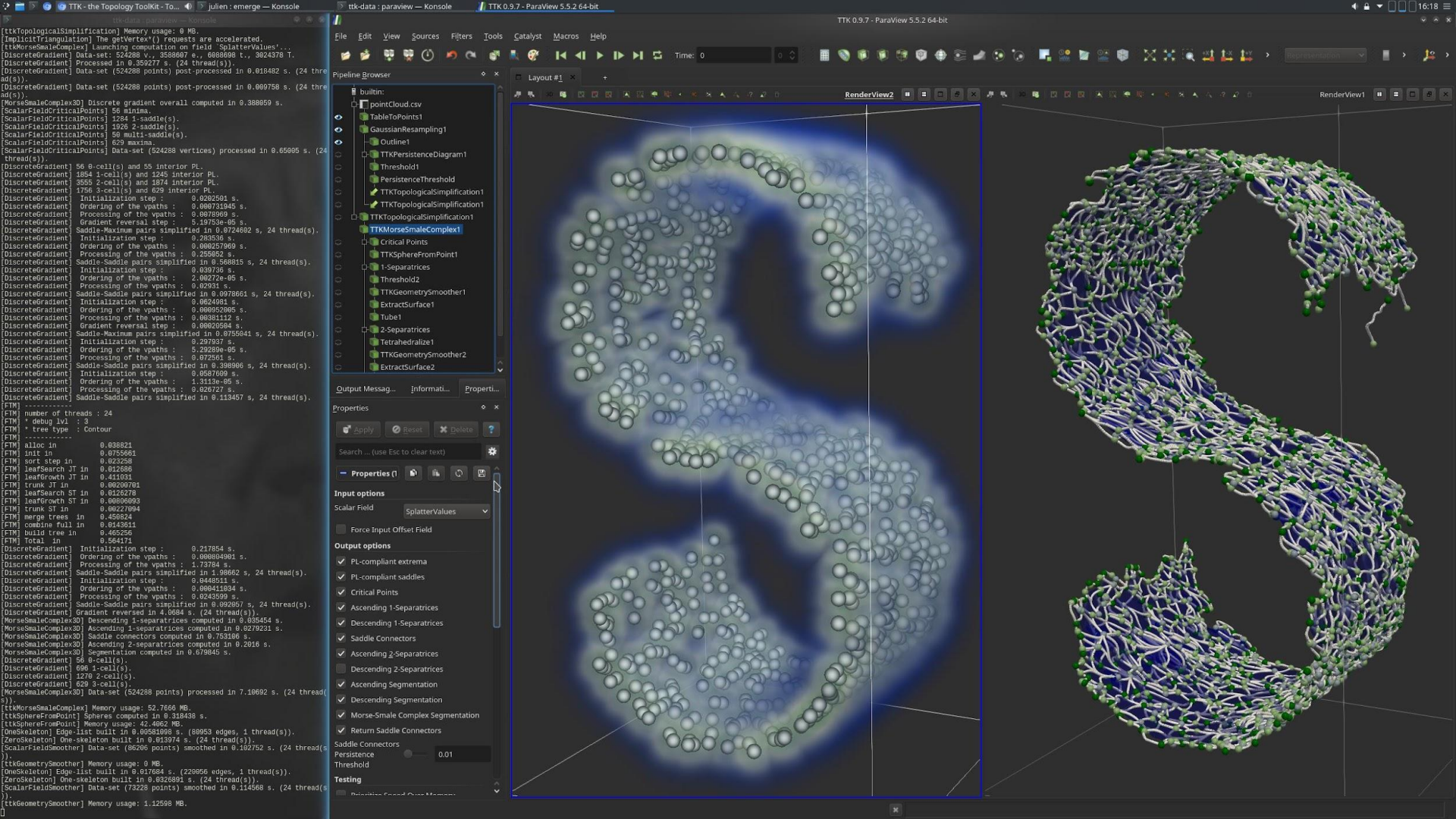
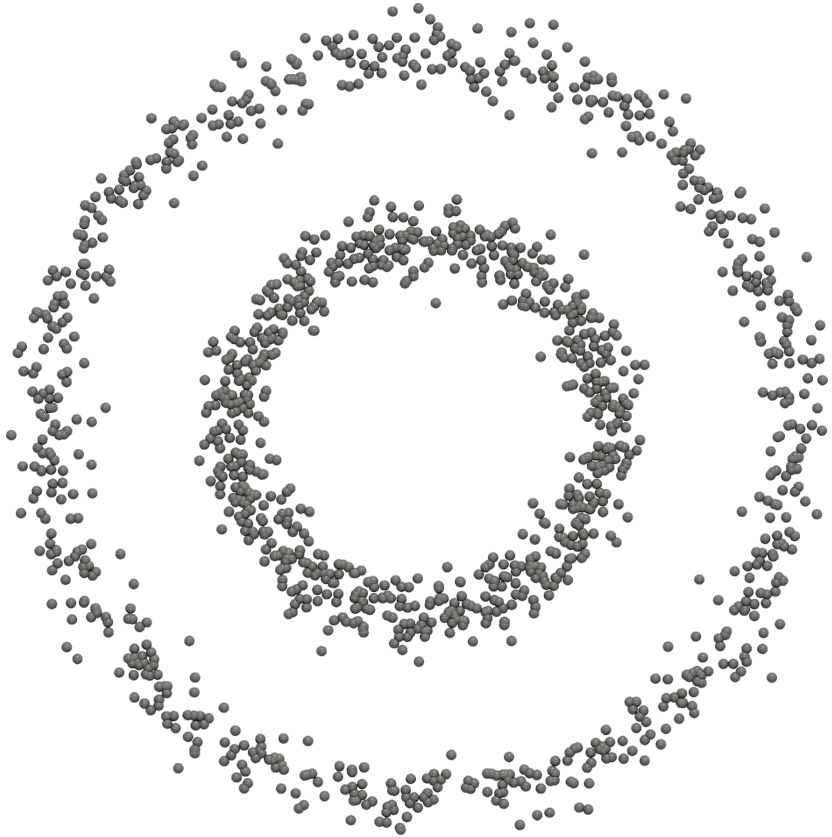
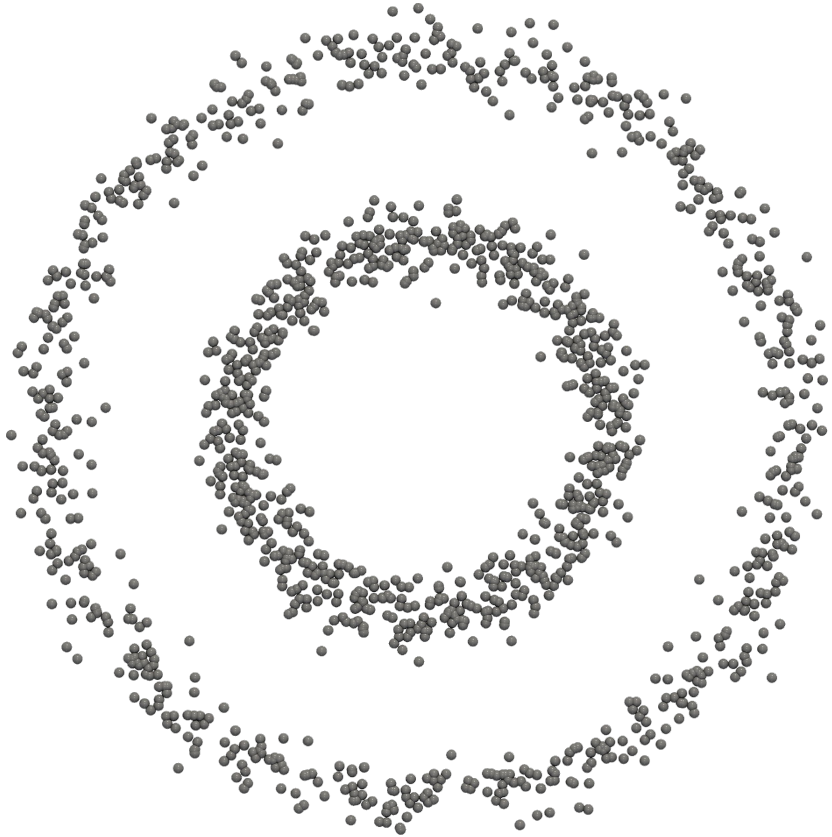
Input Columns
Elevation
Points:0
Points:1
Points:2
Output options
Method
Multi-Dimensional Scaling
Components
Neighbors
Keep All
Multi-Dimen
Metric
Number of init runs
4
Iteration Threshold
300
Verbosity
Spectral Embedding
Locally Linear Embedding
Multi-Dimensional Scaling
t-distributed Stochastic Neighbor Embedding
Isomap Embedding
Principal Component Analysis
Layout #1
RenderView2
RenderView4
RenderView3

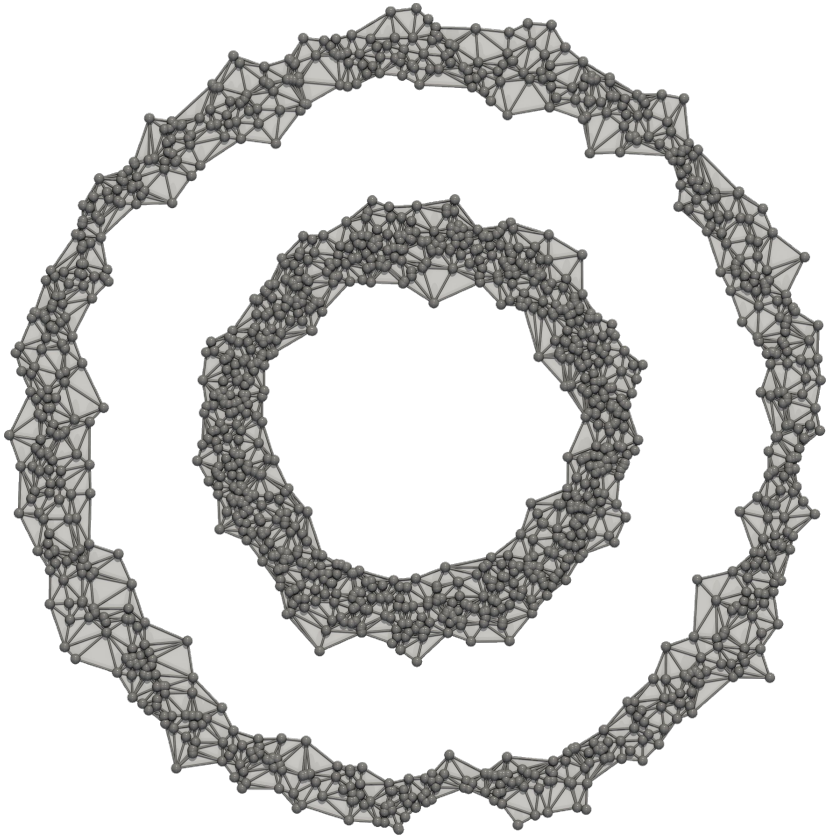

TTK - the Topology ToolKit - To...
julien : emerge — Konsole
ttk-data : paraview — Konsole
TTK 0.9.7 - ParaView 5.5.2 64-bit
16:18
ttk-data : paraview — Konsole
[ttkTopologicalSimplification] Memory usage: 0 MB.
[ImplicitTriangulation] The getVertex*() requests are accelerated.
[ttkMorseSmaleComplex] 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

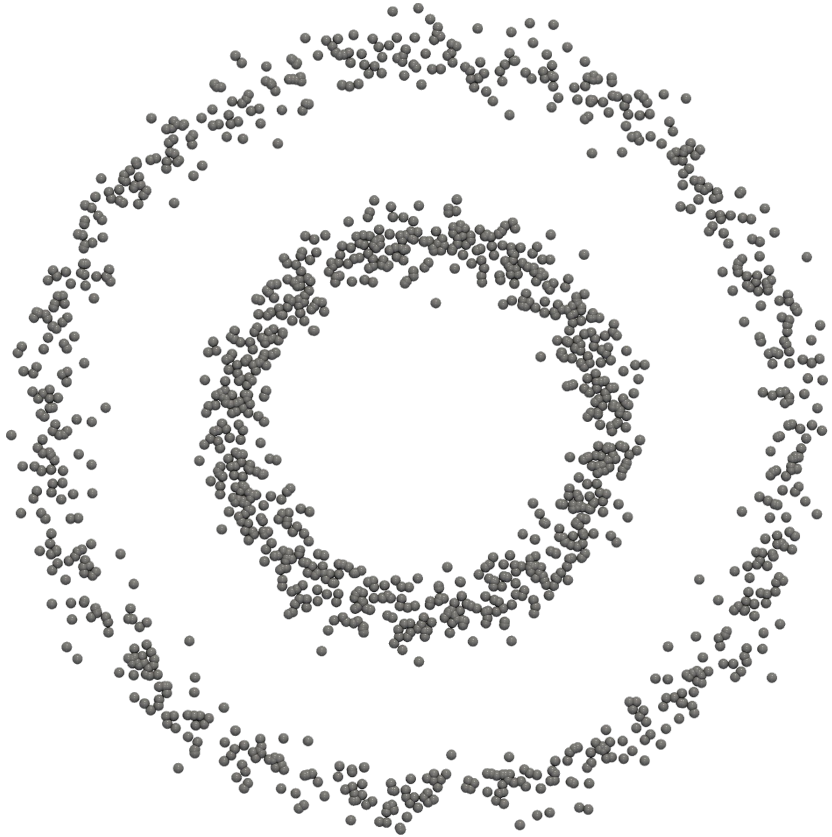


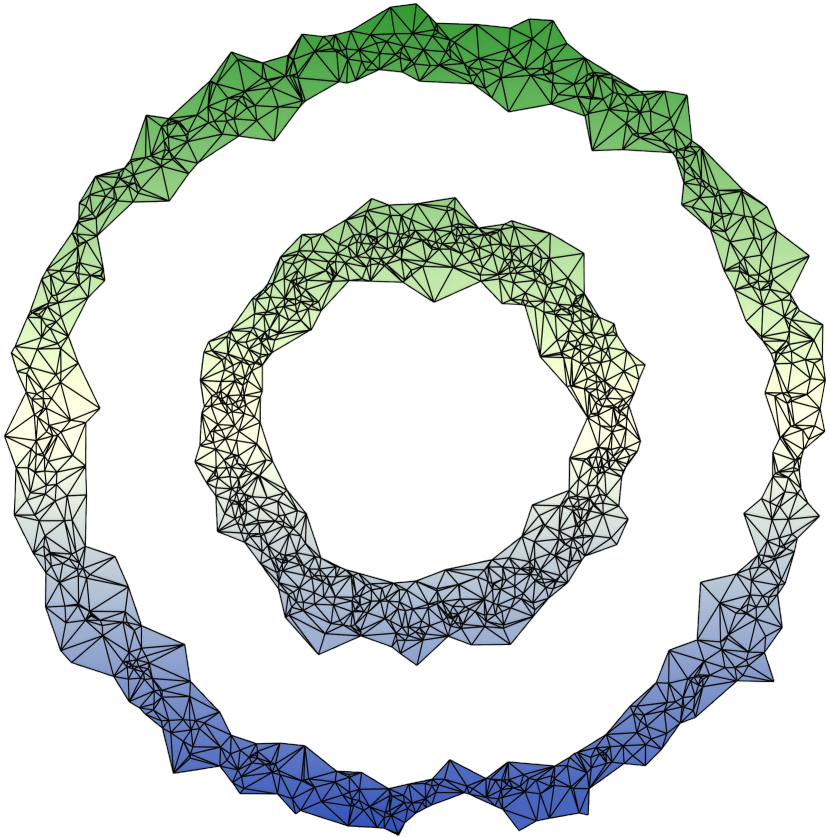
Mapper



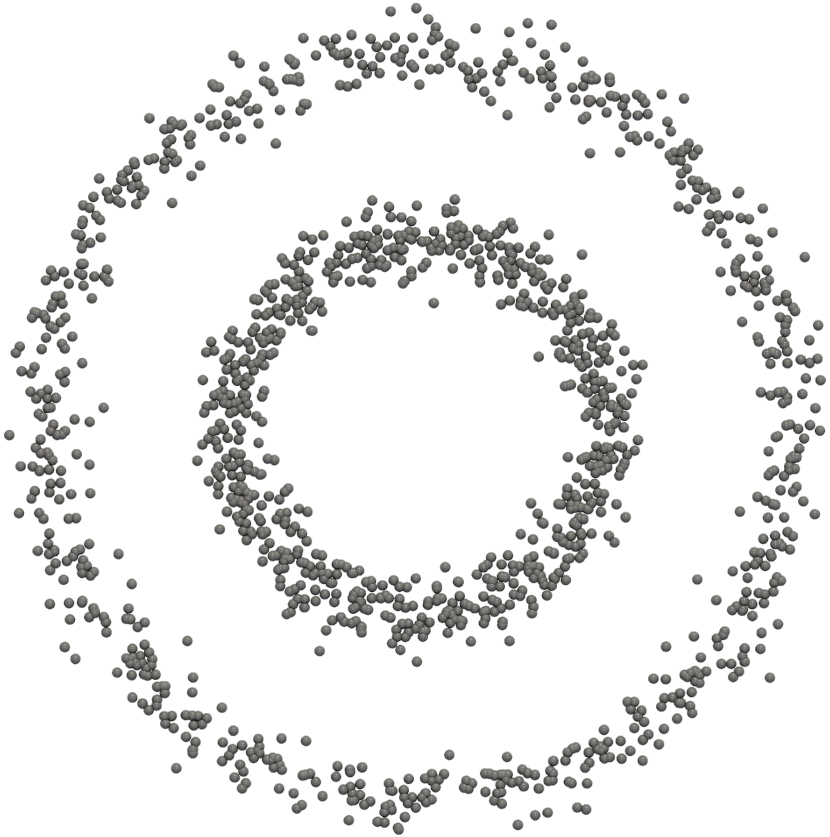


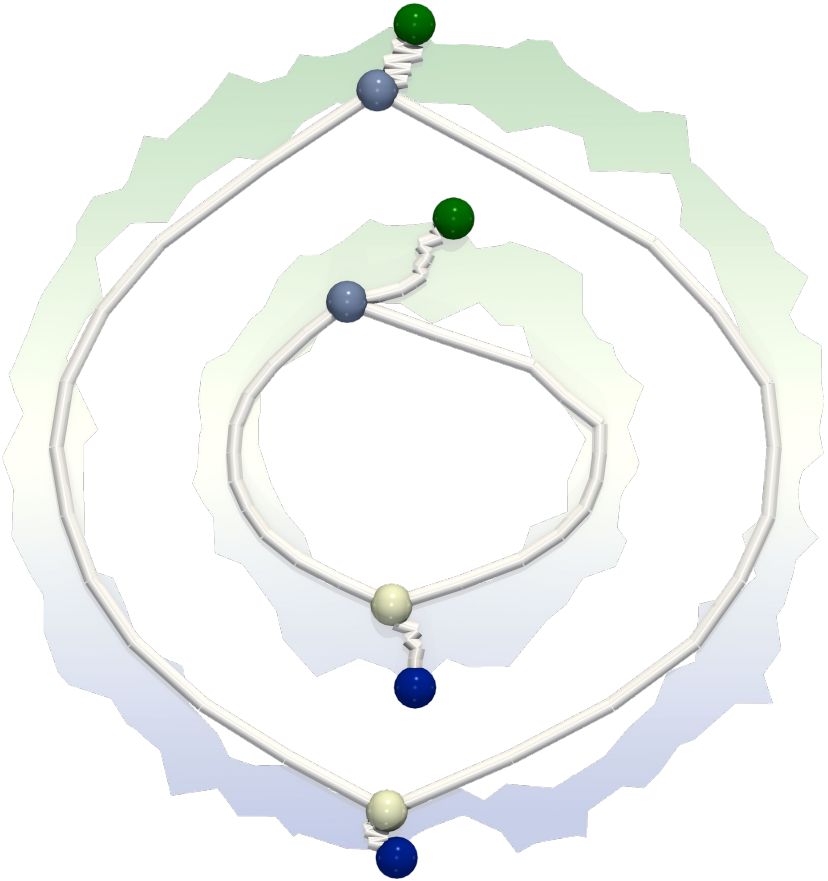
Mapper



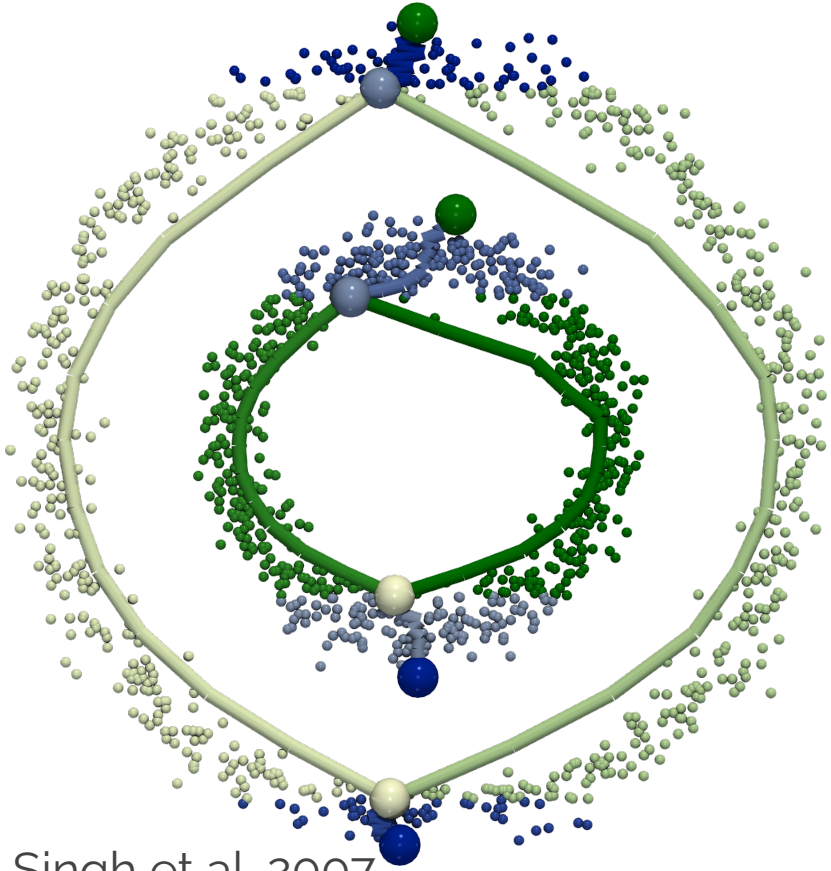


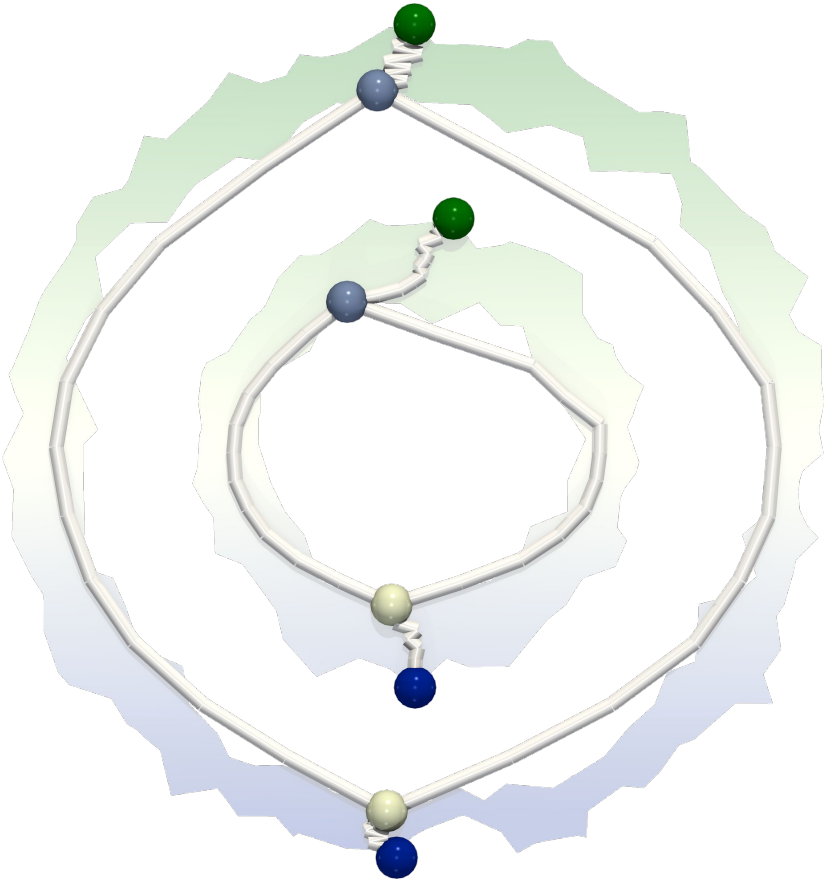
Mapper





Mapper

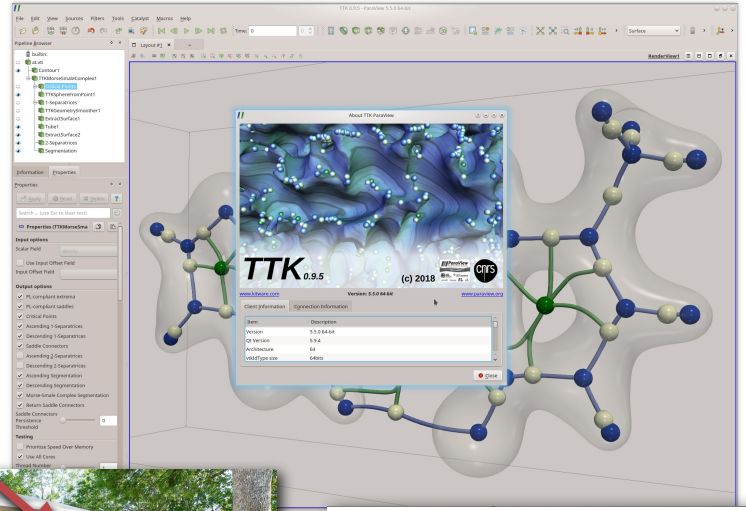




- Singh et al. 2007

The Topology ToolKit (TTK)

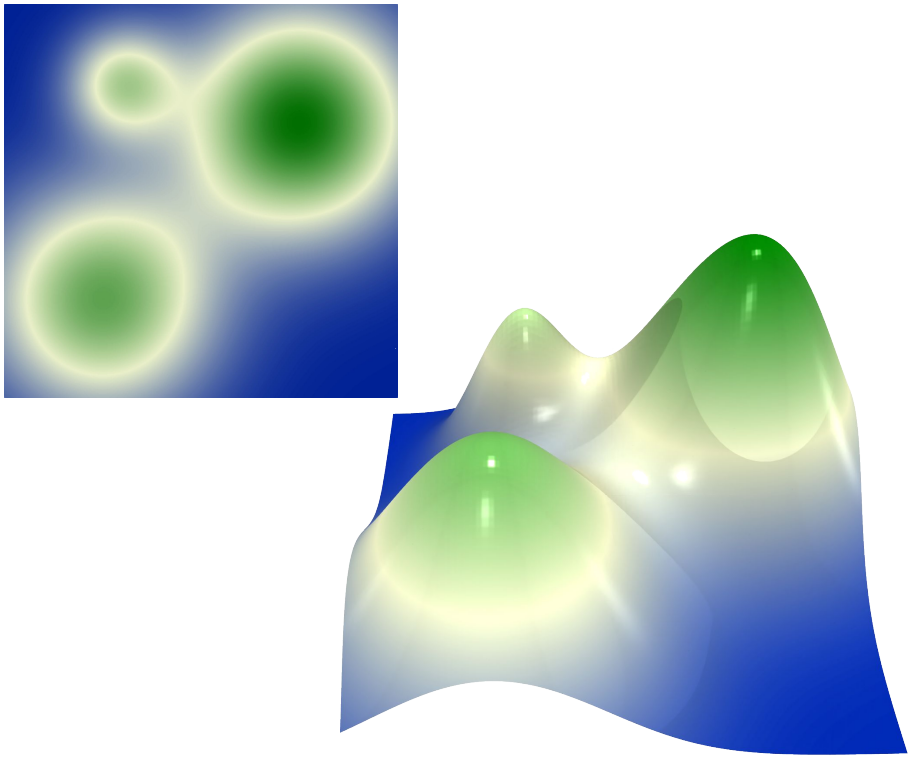
- **Open-source TDA library**
  - ~120k lines in C++, BSD license
  - Python bindings, binary packages
    - **Officially integrated in ParaView (5.10)**
  - **http://topology-tool-kit.github.io**
  - Best paper honorable mention IEEE VIS'17



- **Structuring research receptacle**
  - 17 contributing institutions
    - 14 universities, 3 companies
  - Mini-symposia:
    - IEEE VIS'18-19-20-21 (2020-1: online)
    - Hackathons

Why using TTK?

- **What is it good for?**
  - Low dimensional data
  - Continuous scalar fields
  - Science & engineering
    - Astrophysics, biological imaging, quantum chemistry, fluid dynamics, material sciences
- **What is it not good for? (yet)**
  - Vector / tensor data
  - High dimensional data



Online resources

- **https://topology-tool-kit.github.io/**
  - Installation instructions
  - Gallery
  - Data and examples
  - Video tutorials
  - Documentation
  - Exercises
  - Mailing lists
    - **ttk-users@googlegroups.com**

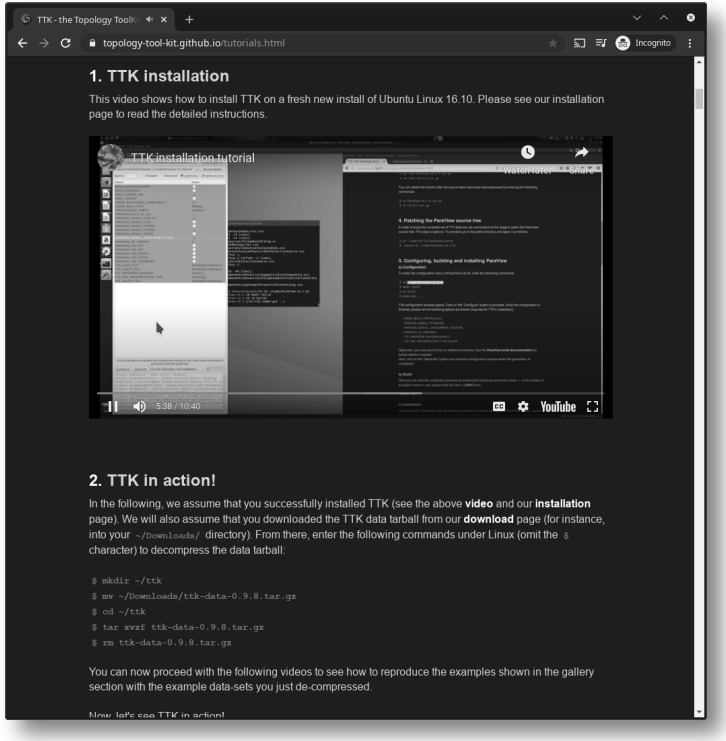
Installation

- **http://topology-tool-kit.github.io/installation.html**

- **Easy installation**
  - Officially integrated in ParaView 5.10
    - **http://www.paraview.org/download**
  - Binary packages
    - Linux (Ubuntu), MacOS, Windows
  - Anaconda package
    - `conda install -c conda-forge topologytoolkit`

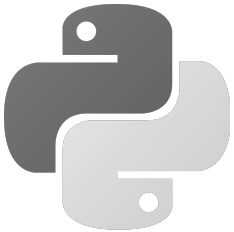
- **Virtualization images**
  - Virtualbox & docker

- **For the latest features**
  - Github repository
    - **https://github.com/topology-tool-kit/ttk**



How should I interact with TTK?

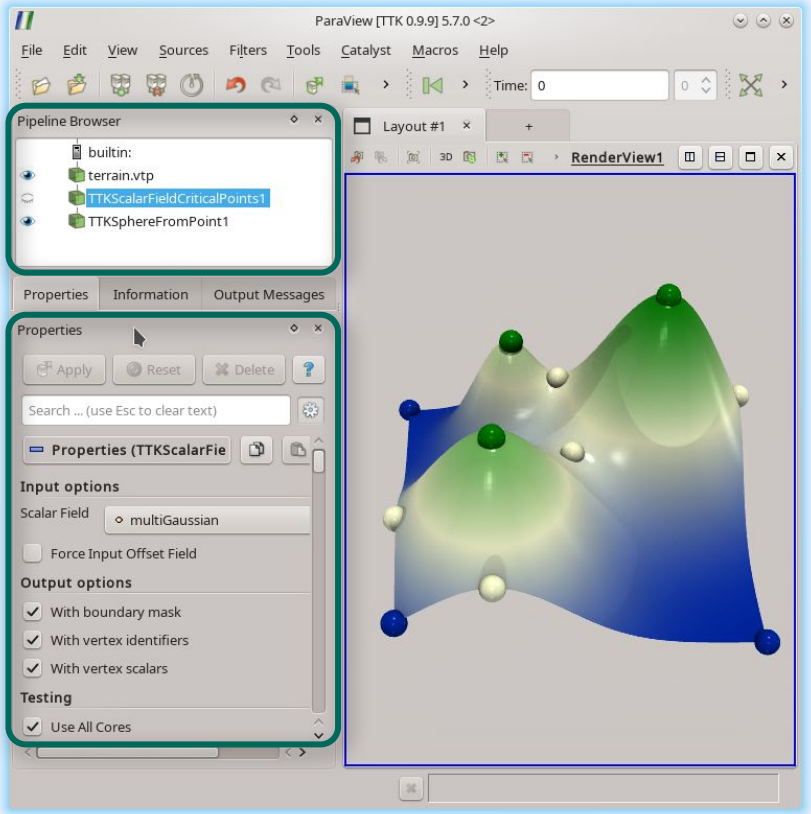
- **End users**
  - Plugins for ParaView
    - De-facto standard in scientific computing
  - Light Python API
    - Fast scripting
  - Inviwo environment
    - **https://inviwo.org/**



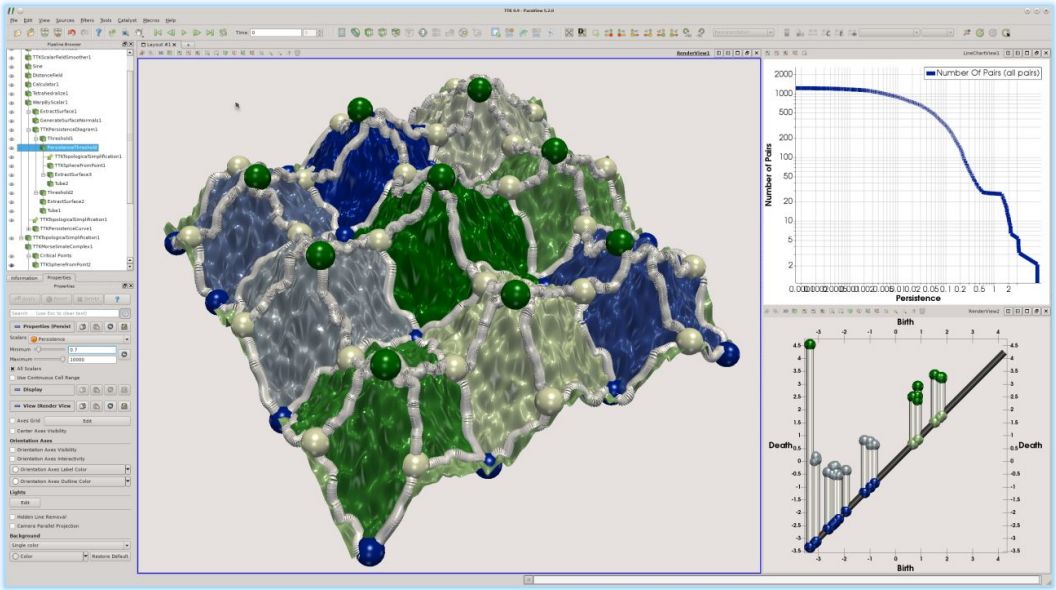
- **Developers**
  - Recommended
    - VTK-based APIs: C++ & Python
  - Advanced
    - Dependency-free plain C++ API

About ParaView

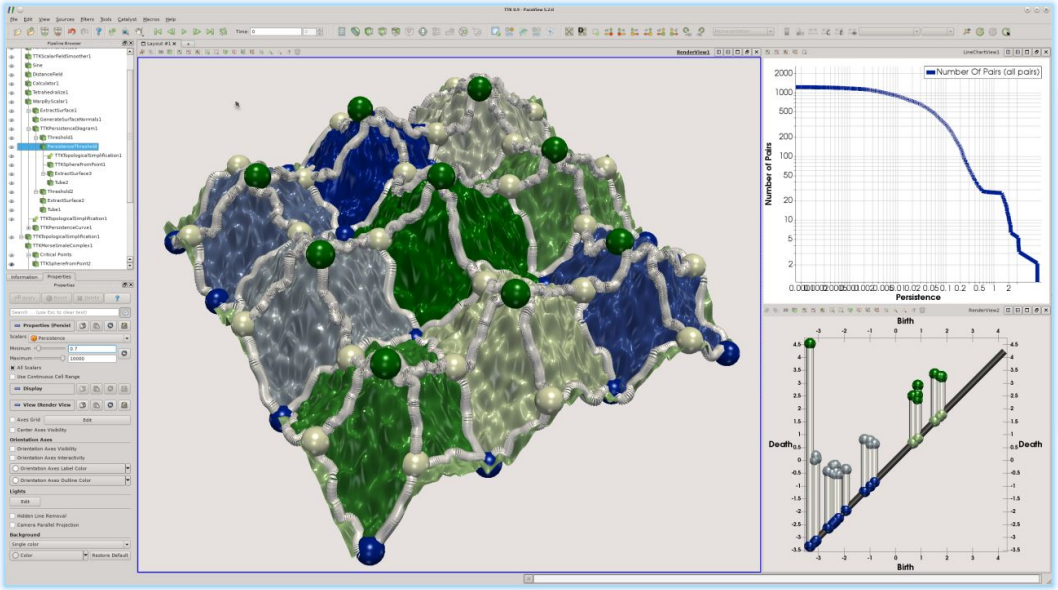
- **Interesting features**
  - Rich IO support
  - Modern rendering
    - OpenGL, OSPRay, Optix
  - Advanced user interface
  - “Visual” programming
    - Pipeline philosophy
  - Python scripting

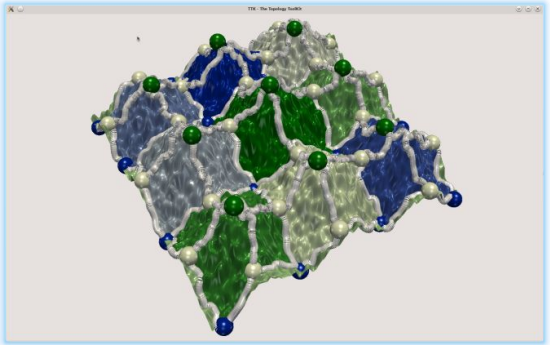


User experience

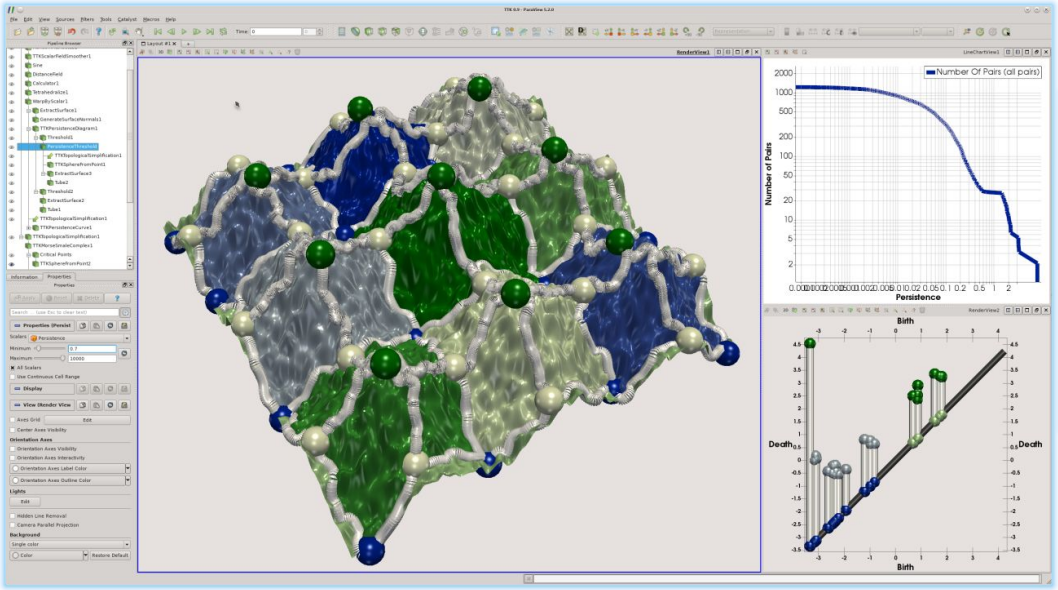


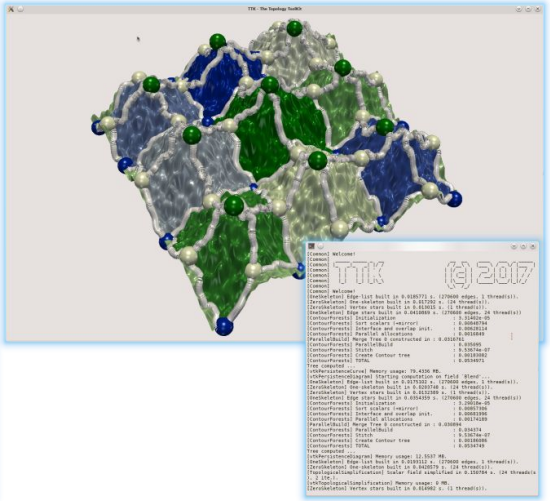
User experience



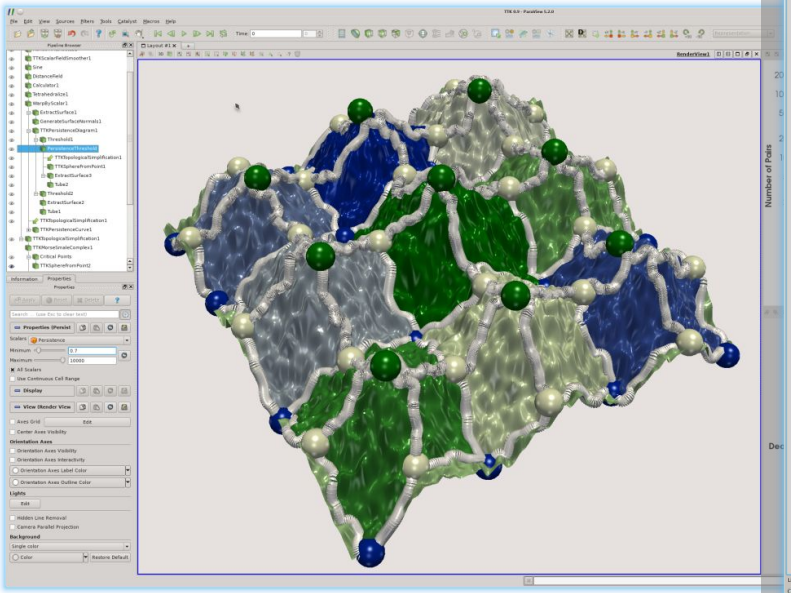


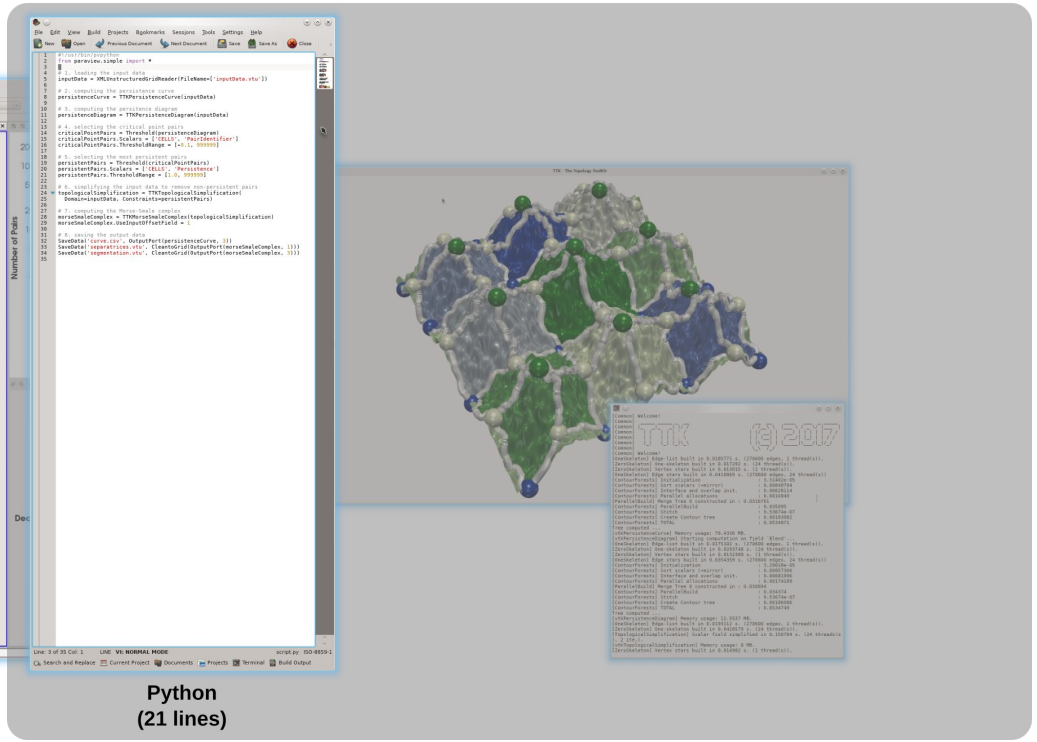
User experience





User experience

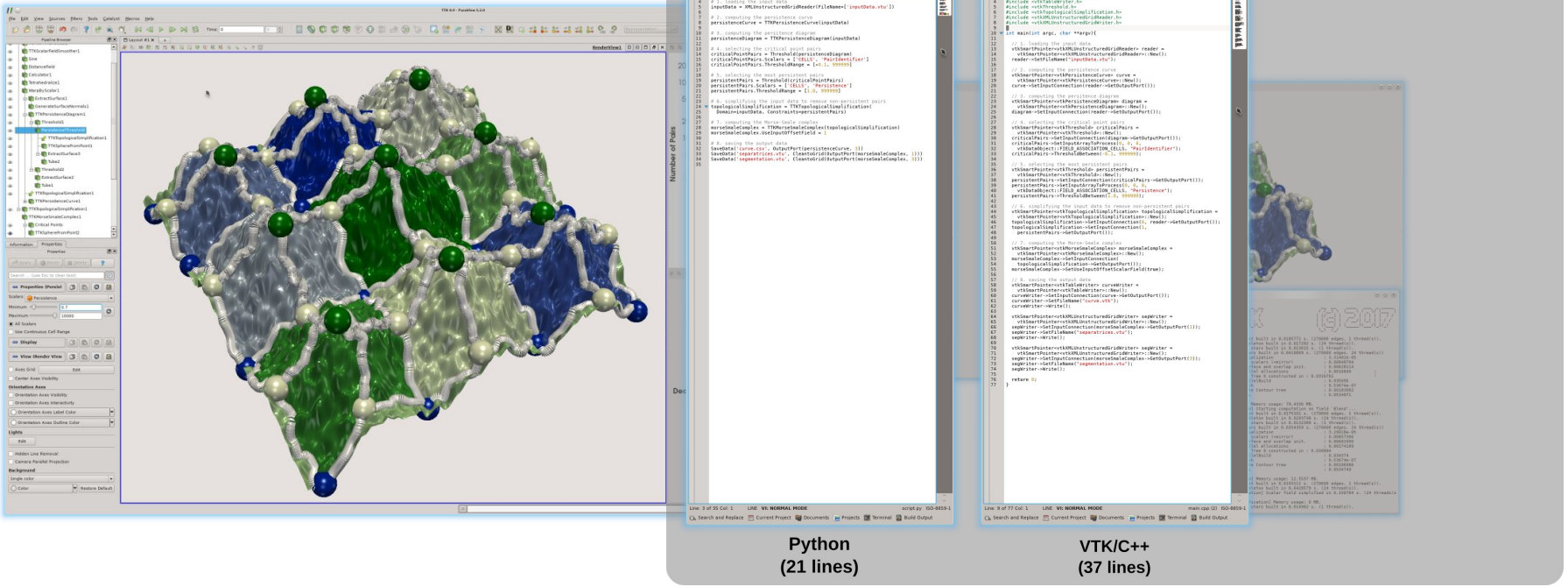




```
# Trigger Pipeline Execution
from paraview.simple import *

# 1: loading the input data
inputData = XMLUnstructuredGridReader(FileName=['inputData.vtu'])

# 2: computing the persistence curve
persistenceCurve = TTKPersistenceCurve(inputData)

# 3: computing the persistence diagram
persistenceDiagram = TTKPersistenceDiagram(inputData)

# 4: selecting the critical point pairs
criticalPointPairs = Threshold(persistenceDiagram)
criticalPointPairs.Scalars = ['CELLS', 'PairIdentifier']
criticalPointPairs.ThresholdRange = [-1, 999999]

# 5: selecting the most persistent pairs
persistentPairs = Threshold(criticalPointPairs)
persistentPairs.Scalars = ['CELLS', 'Persistence']
persistentPairs.ThresholdRange = [1.0, 999999]

# 6: simplifying the input data to remove non-persistent pairs
topologicalSimplification = TTKTopologicalSimplification(
  Domain=inputData, Constraints=persistentPairs)

# 7: computing the Morse Smale complex
morseSmaleComplex = TTKMorseSmaleComplex(topologicalSimplification)
morseSmaleComplex.UseInputOffsetField = 1

# 8: saving the output data
SaveData('curve.csv', OutputPort(persistenceCurve, 1))
SaveData('separatrices.vtu', CleanToGrid(OutputPort(morseSmaleComplex, 1)))
SaveData('segmentation.vtu', CleanToGrid(OutputPort(morseSmaleComplex, 3)))
```

Python
(21 lines)

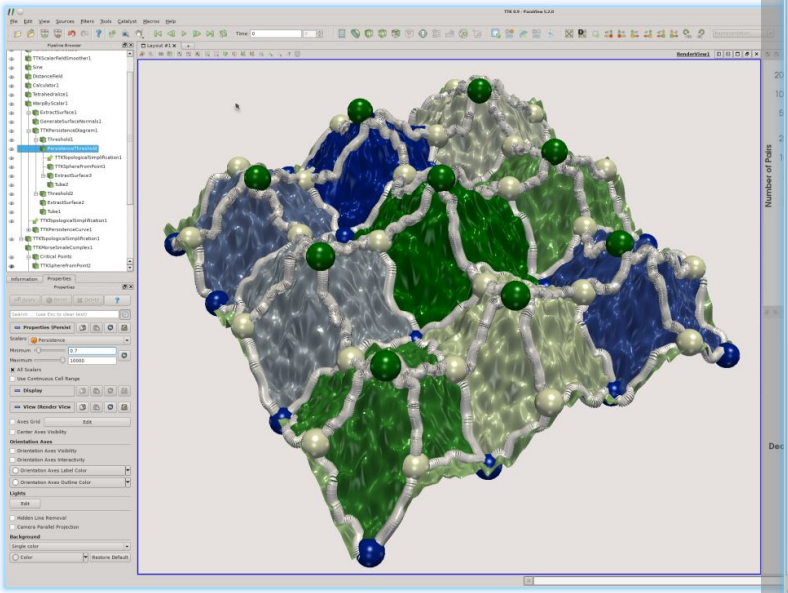
User experience

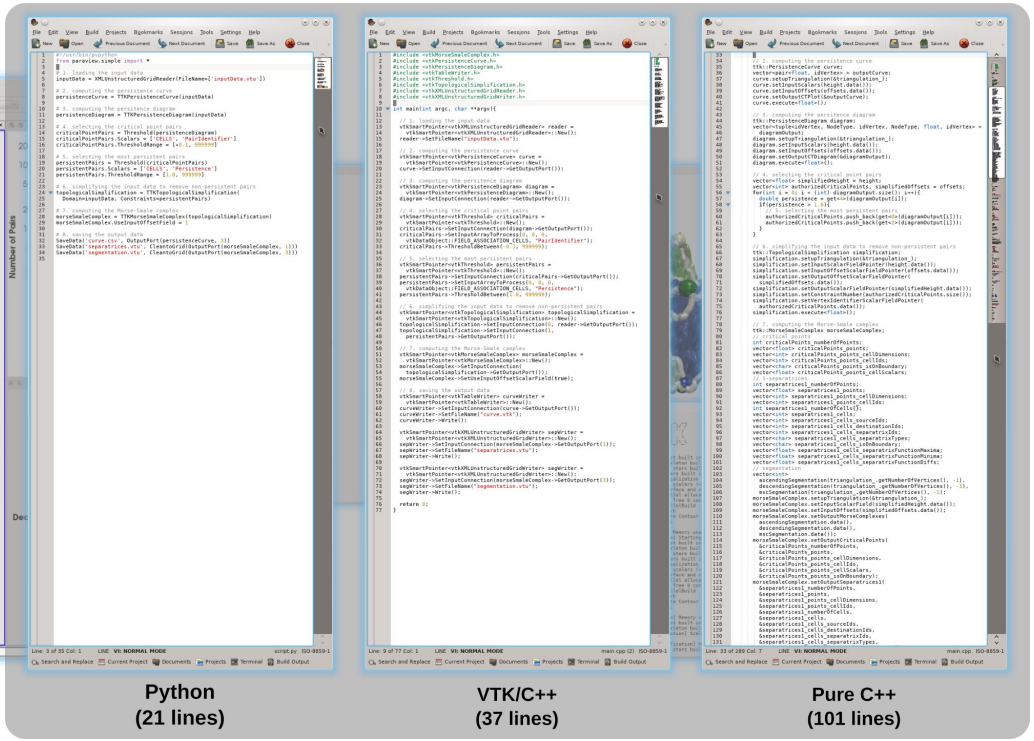


Python
(21 lines)

VTK/C++
(37 lines)

User experience



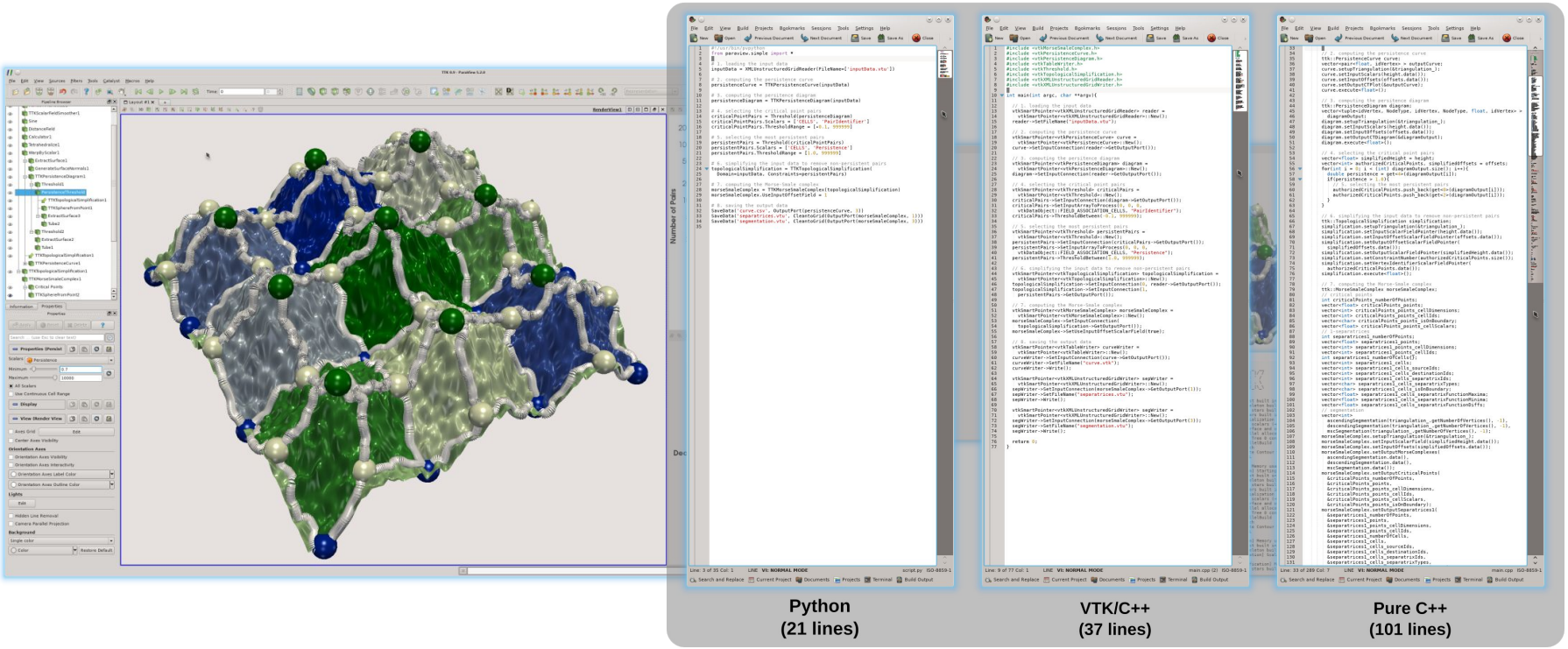


Python
(21 lines)

VTK/C++
(37 lines)

Pure C++
(101 lines)

User experience



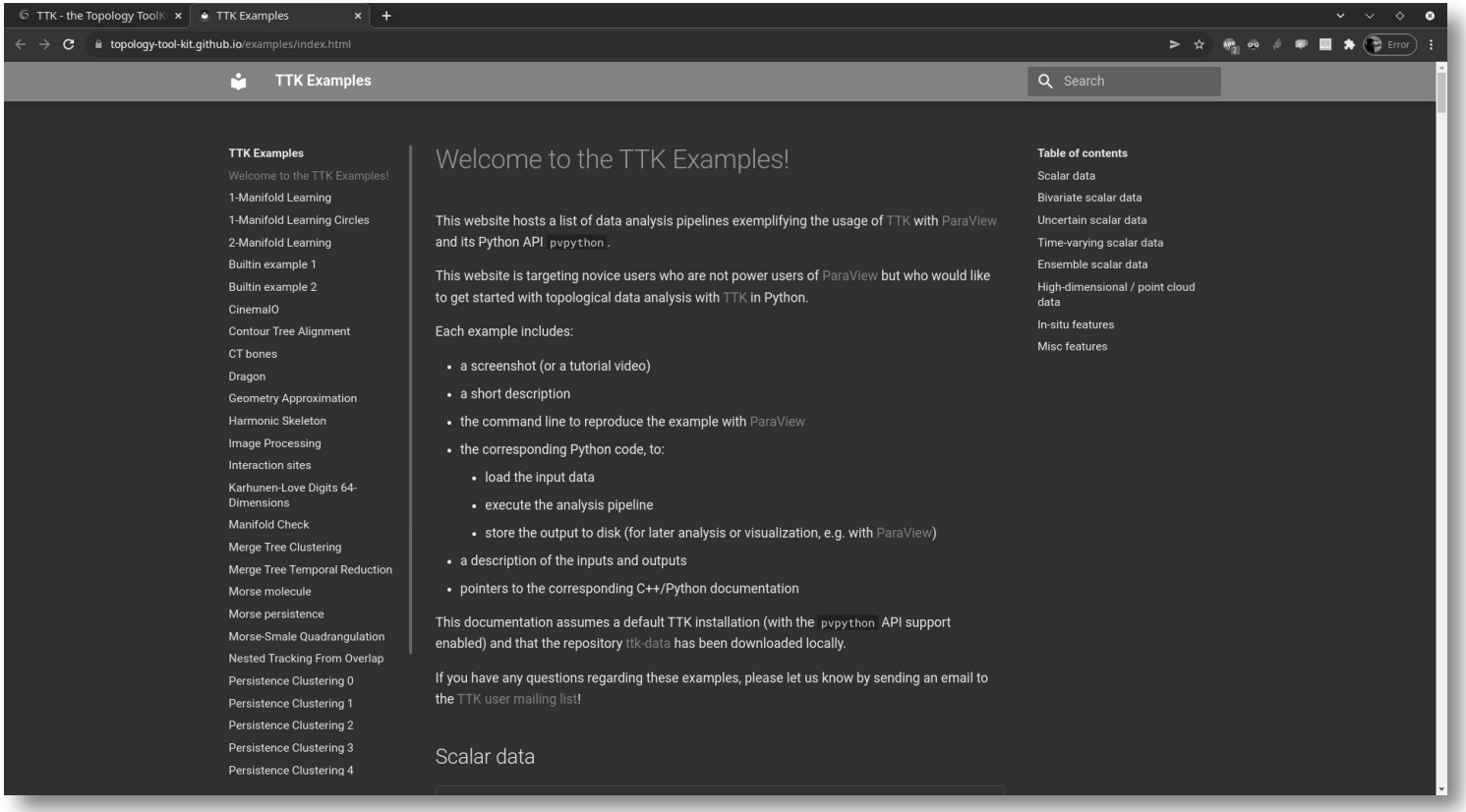
Python
(21 lines)

VTK/C++
(37 lines)

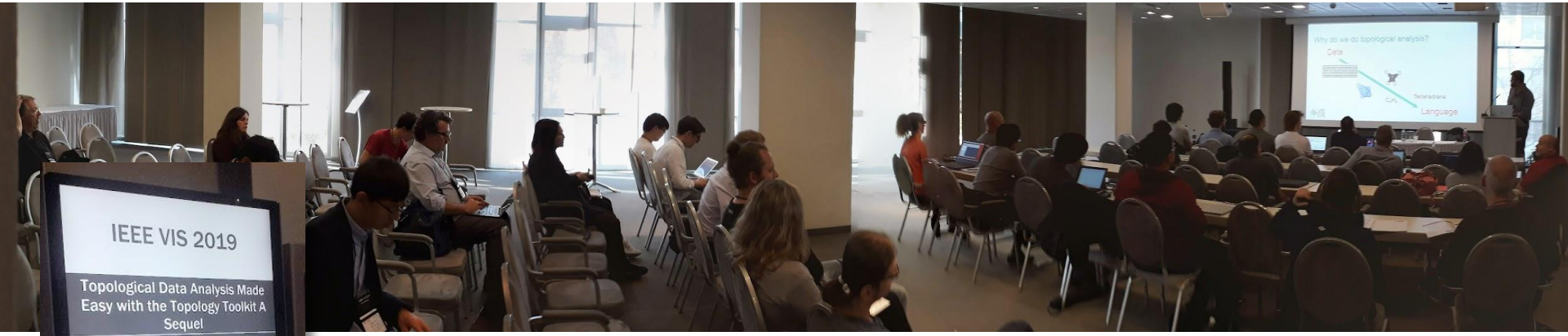
Pure C++
(101 lines)

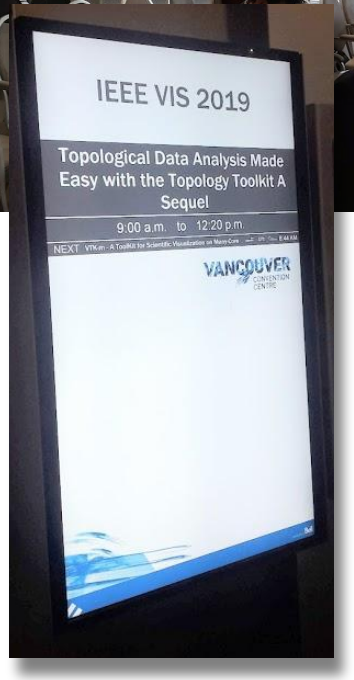
- https://github.com/topology-tool-kit/ttk/tree/dev/examples

TTK data & examples



IEEE VIS Tutorials 2018-2021





- **Overview**
  - Presentations + hands-on
  - ~10 speakers, attendance: ~50
  - **https://topology-tool-kit.github.io/ieeeVisTutorial.html**
  - Slides, data, examples, pre-installed virtual machines, more

erc TORI

- **Large-scale data reduction**
  - Until 2025
  - High-Performance TDA
  - Statistical framework for ensembles

- **We're hiring!**
  - ~~4~~ 1 Ph.D. offer~~s~~
  - ~~2~~ 1 Post-doc~~s~~
  - ~~2~~ 1 engineer~~s~~

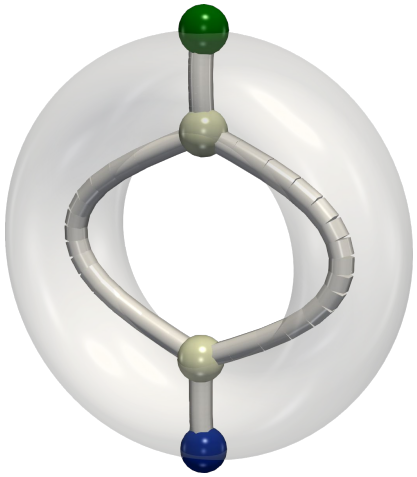
- **Website**
  - **http://erc-tori.github.io/**

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

- We are hiring!
  - 1 Ph.D. student, 1 post-doc, 1 engineer
  - http://erc-tori.github.io/

- 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

- **J. Tierny**, "Topological Data Analysis for Scientific Visualization", Springer 2018.
- 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.**
- M. Soler, M. Petitfrere, G. Darche, M. Plainchault, B. Conche, **J. Tierny**, "Ranking Viscous Finger Simulations to an Acquired Ground Truth with Topology-Aware Matchings", IEEE LDAV 2019, **Best paper award.**
- T. Bridel-Bertomeu, B. Fovet, **J. Tierny**, F. Vivodtzev, "Topological Analysis of High Velocity Turbulent Flow", Proc. of IEEE LDAV 2019 (shorts).
- 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)
- M. Soler, M. Plainchault, B. Conche, **J. Tierny**, "Lifted Wasserstein Matcher for Fast and Robust Topology Tracking", Proc. of IEEE LDAV 2018. **Best paper honorable mention**.
- M. Soler, M. Plainchault, B. Conche, **J. Tierny**, "Topologically Controlled Lossy Compression", Proc. of IEEE PacificViz 2018.
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