Contour Forests: Fast Multi-threaded Augmented Contour Trees

Journée Visu 2017

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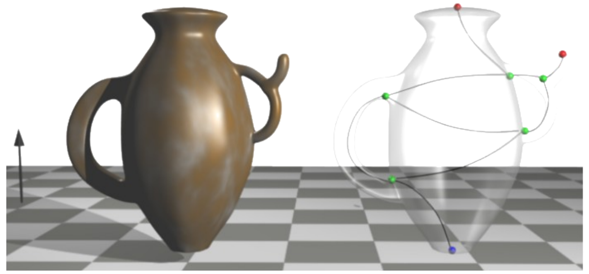
Pierre Fortin, UPMC
Julien Jomier, Kitware
Julien Tierny, UPMC

VIS 2016

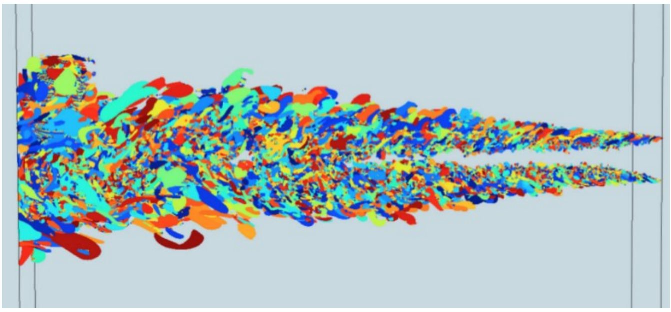
Introduction

- Context
- Related Works
- Challenges
- Contributions

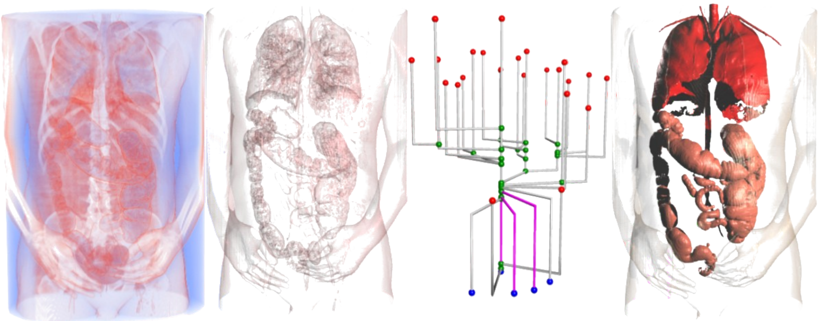
- Topological analysis: classical approach in Sci Viz
  - **Contour Trees**, Reeb Graphs, Morse-Smale Complexes...



[DoraiswamyTVCG13]



[LandgeSC14]



[MaadasamyHiPC12]

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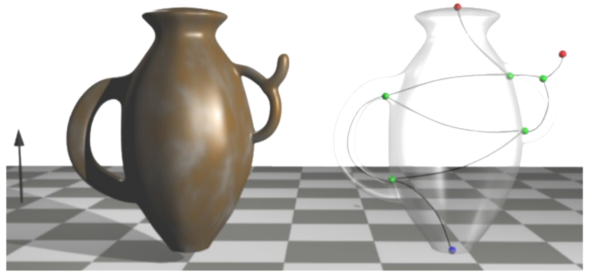
- Topological analysis: classical approach in Sci Viz
  - **Contour Trees**, Reeb Graphs, Morse-Smale Complexes...
- Increasing data size and complexity
  - Challenge for interactive exploration
  - Multi-core architectures are common

$\}$ Motivation for multi-threaded parallelism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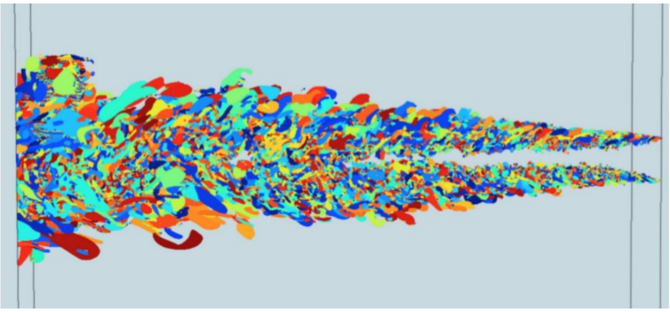
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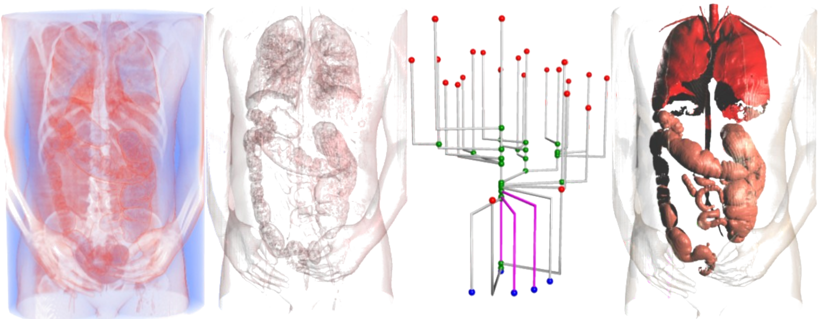
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Sequential:

- [CarrSODA00,ChiangCG05]

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Ref	CT	Tet. mesh	Augmented	Combination
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Parallel:

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Distributed:

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  - Intrinsically sequential approaches
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- Contour Tree:
  - No complete parallelization (only subroutines)
  - No efficient parallel algorithm for augmented trees

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- Efficient multi-threaded algorithm for contour tree computation
  - Simple approach
  - Good parallel efficiency on workstations

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- Efficient multi-threaded algorithm for contour tree computation
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  - Good parallel efficiency on workstations

- Ready-to-use VTK-based C++ implementation: in TTK
  - Generic input (VTU/VTI, 2D/3D)
  - Generic output (augmented trees)

Summary

1) Introduction

2) Preliminaries
- Background
- Overview

3) Algorithm
- Domain partitioning
- Local computation
- Contour forest stitching

4) Experimental results
- Scalability
- Efficiency
- Limitations

5) Application

6) Conclusion
- Recall
- Perspective

Preliminaries

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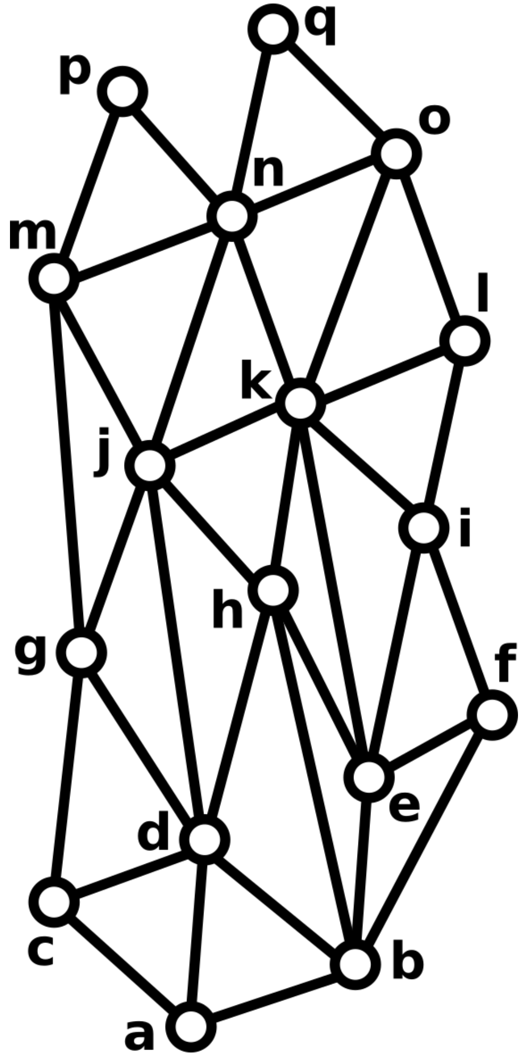
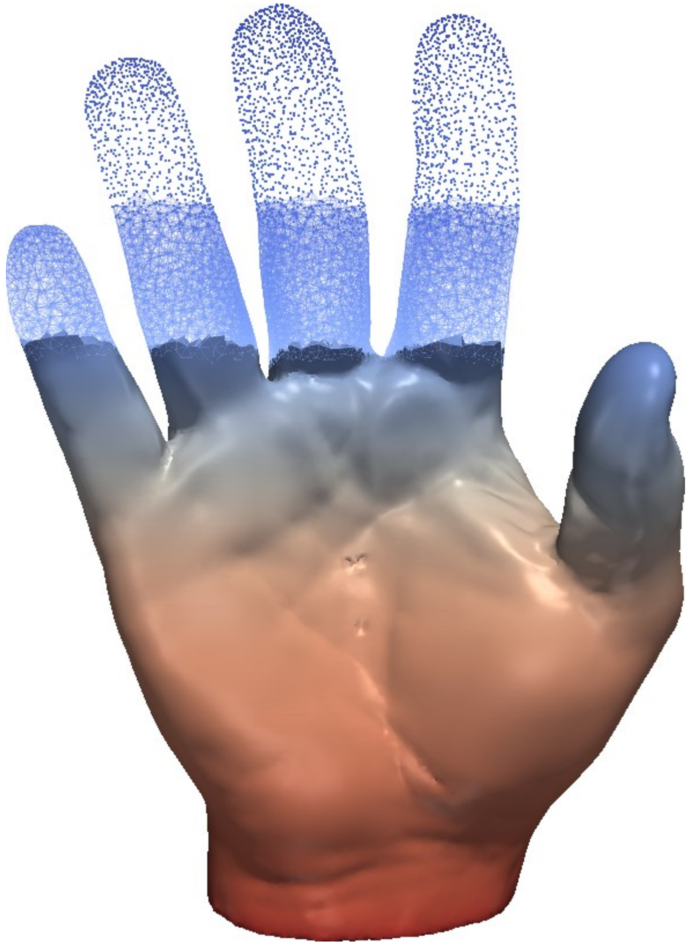
Input data:

- Piecewise linear scalar field

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



2D Example



3D Example

Preliminaries

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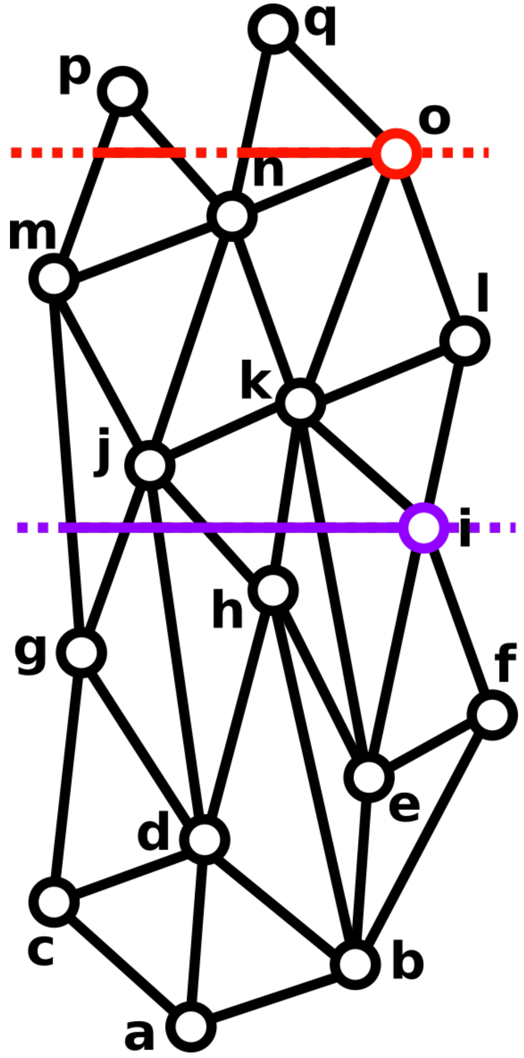
Level set:

- Preimage of a scalar value
- Isovalue: $i \in \mathbb{R}$ onto $\mathcal{M}$

$$f^{-1}(i) = \{p \in \mathcal{M} | f(p) = i\}$$



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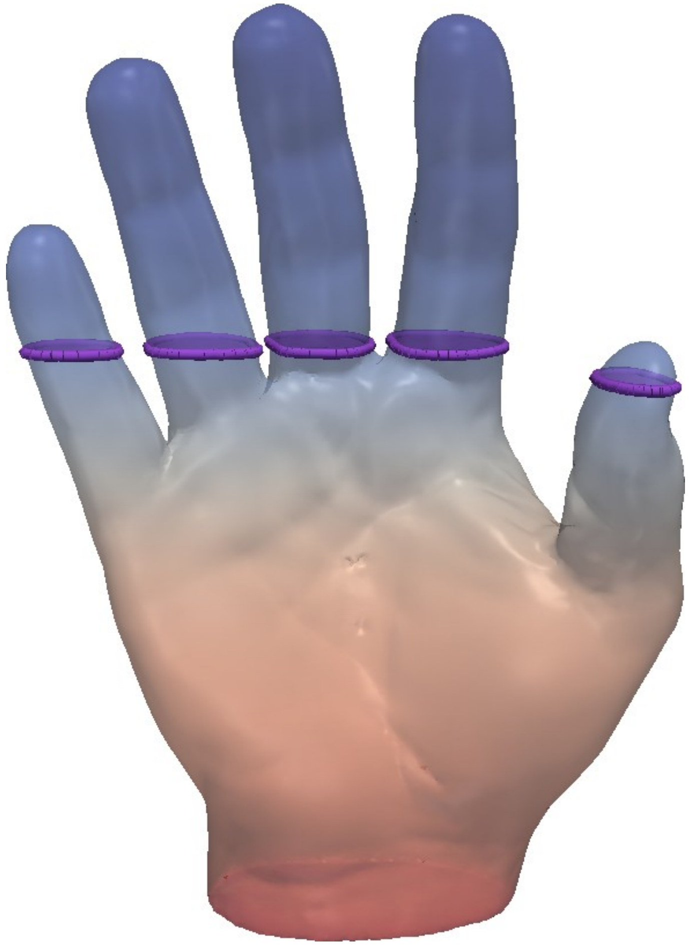

3D Example

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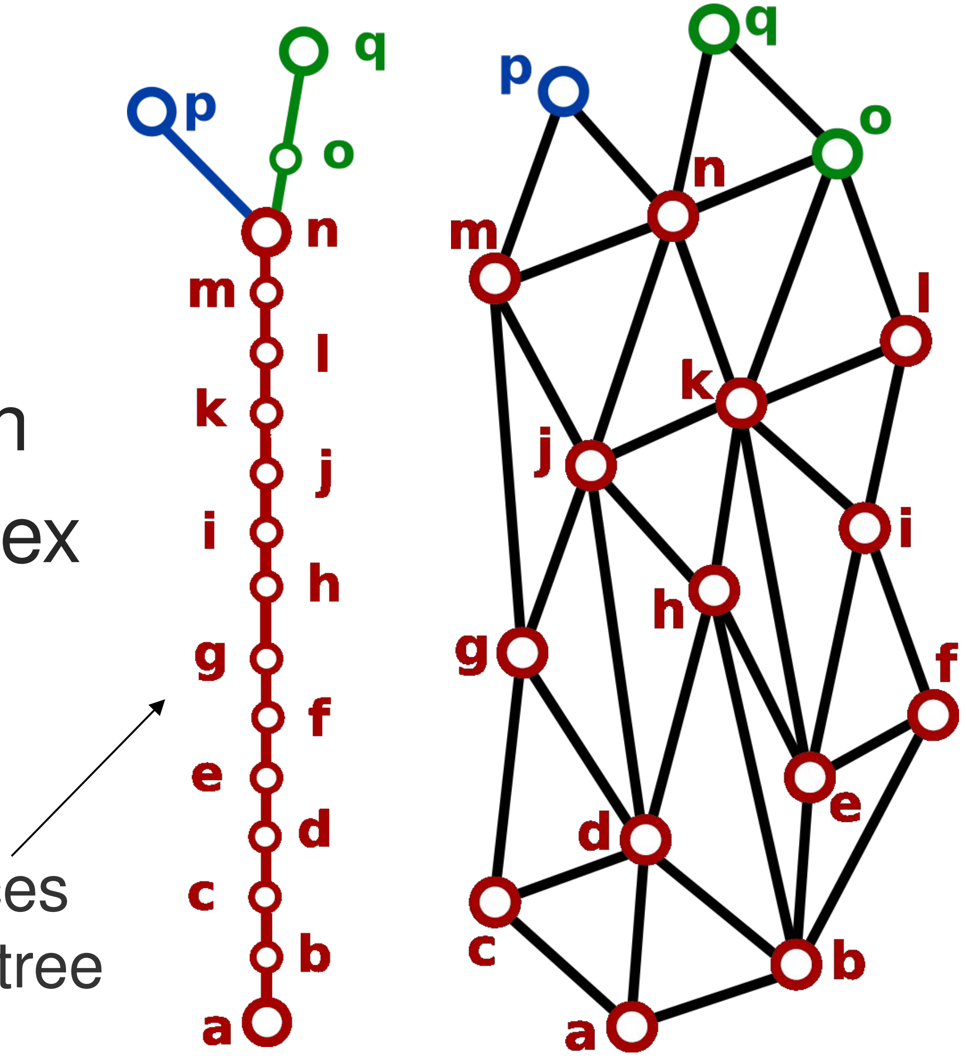
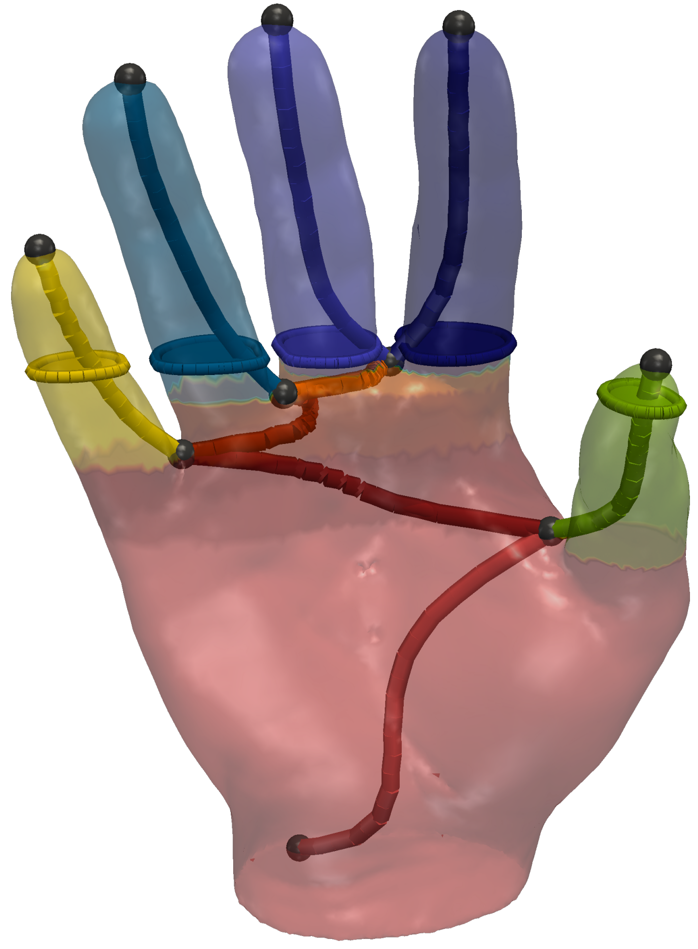
Contour tree:

- Simply connected input domain
- 1-dimensional simplicial complex



Regular vertices in augmented tree

2D Example



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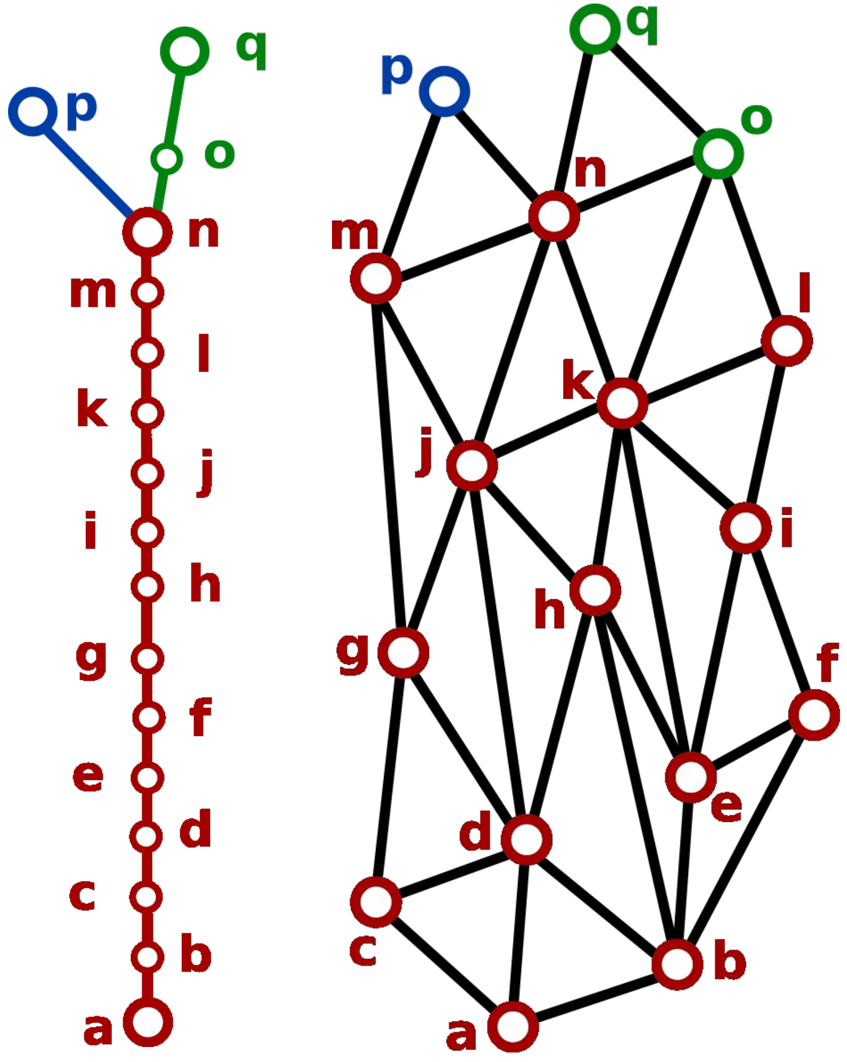
Contour tree:

- Quotient space: $\mathcal{C}(f) = \mathcal{M}/\sim$
- Equivalence relation: $p_1 \sim p_2$

$$\begin{cases} f(p_1) = f(p_2) \\ p_2 \in f^{-1}(f(p_1))_{p_1} \end{cases}$$



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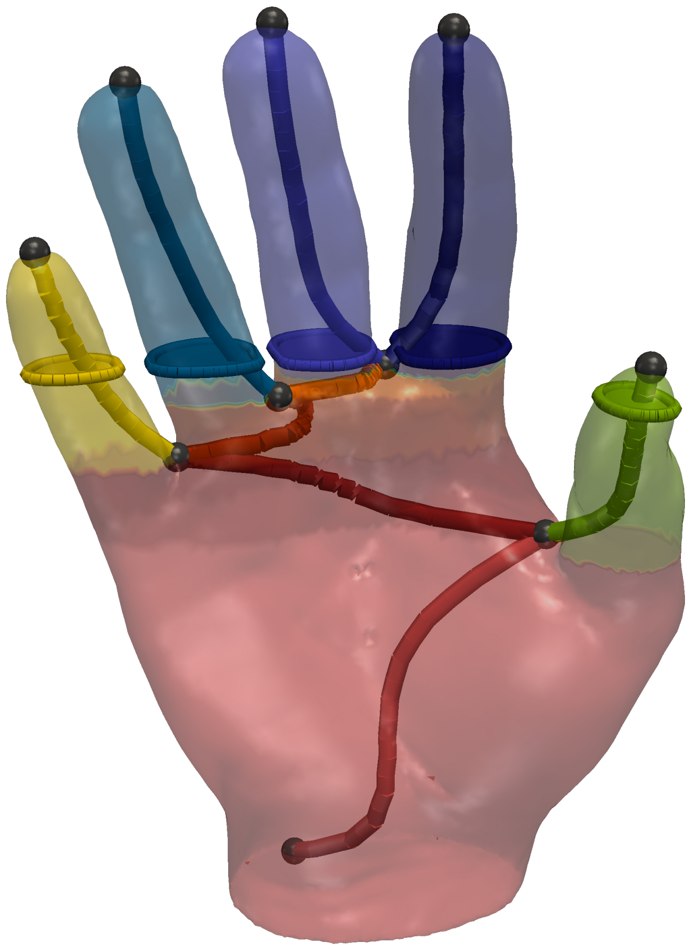

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<u>Main steps of our approach</u>:

1) Sort vertices
2) Create partitions using level sets
3) Compute local trees
4) Stitch local trees

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Pros:

- Simple approach
- Local computation of CT
- Augmented trees
- Simple stitching of the forests

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Cons:

- Depends on interface level sets

Algorithm

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- Domain partitioning
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- Range driven partitions
- Sorted scalars ⇒ balanced partitions
- Use $n_t/2$ partitions

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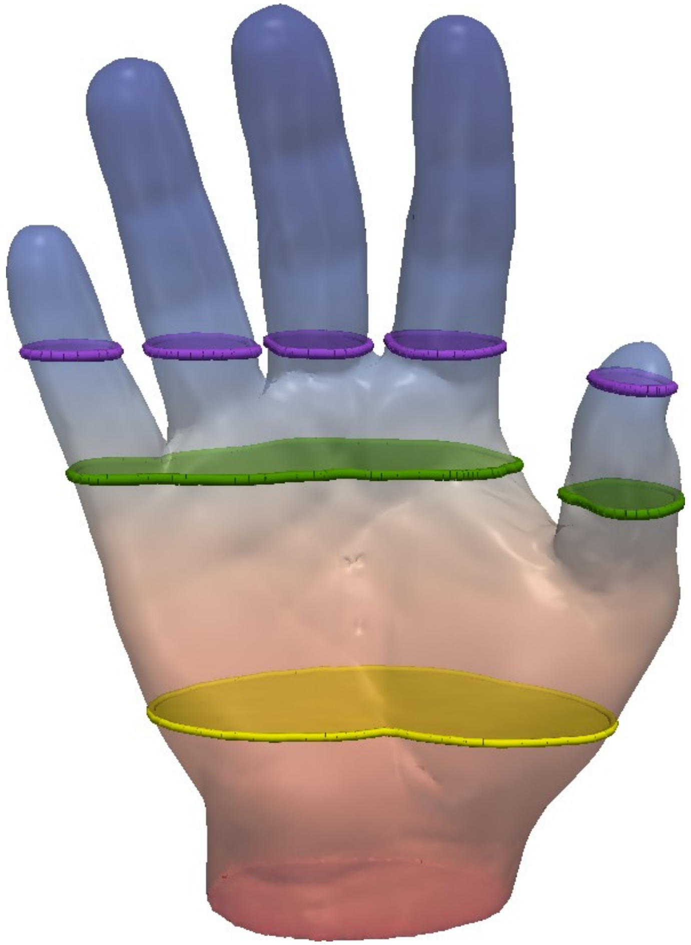

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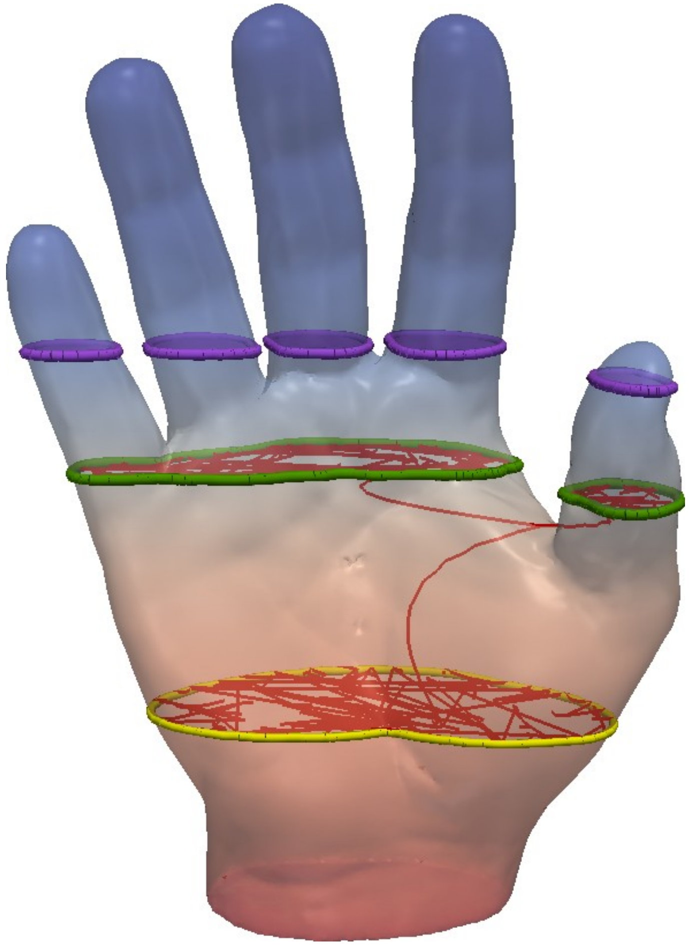

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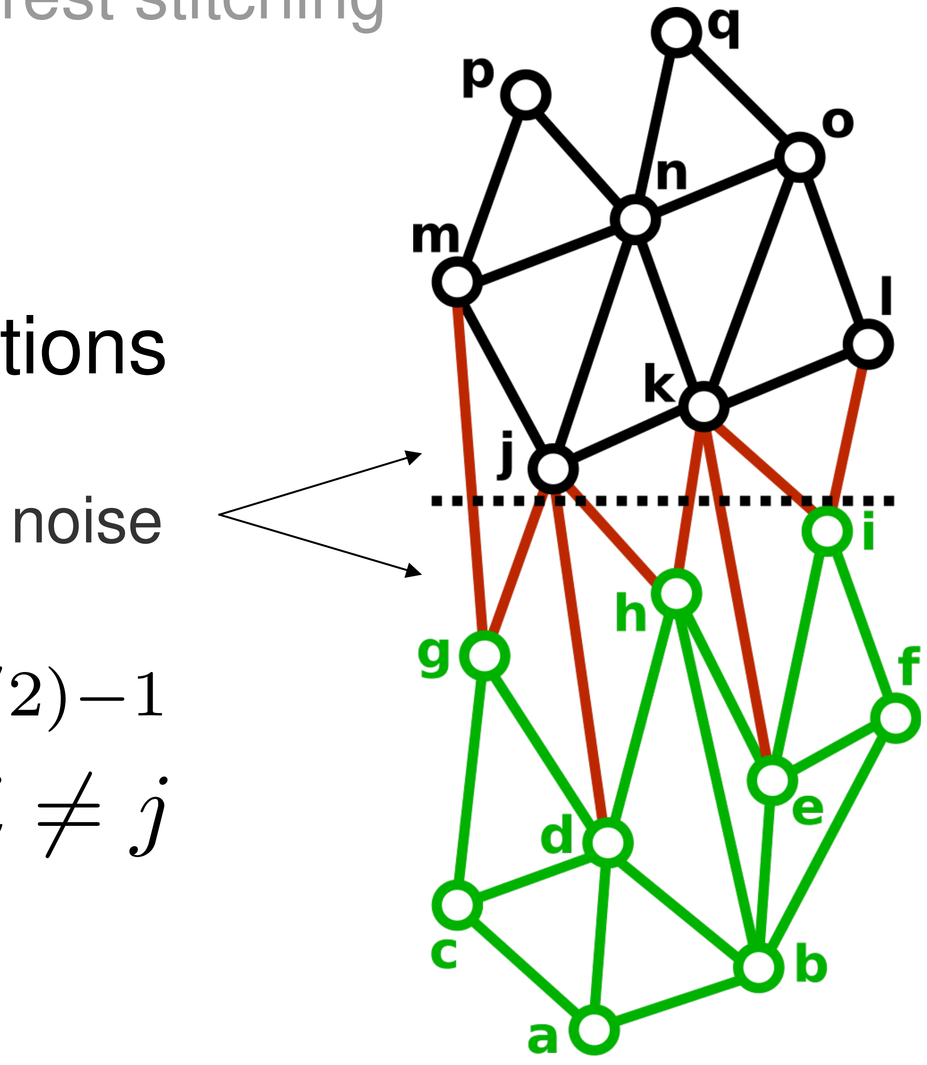

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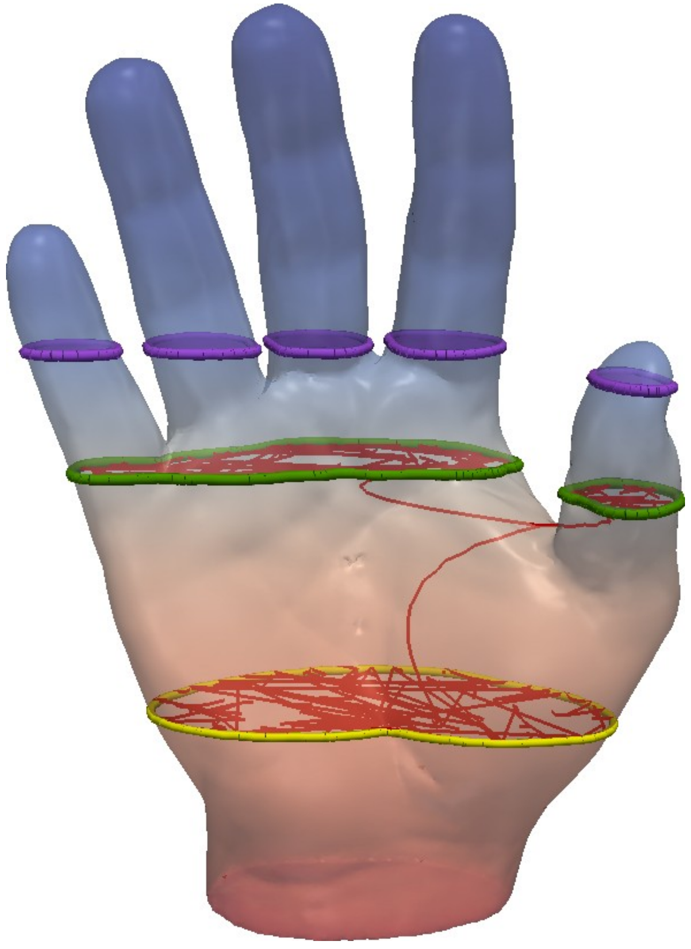

3D Example

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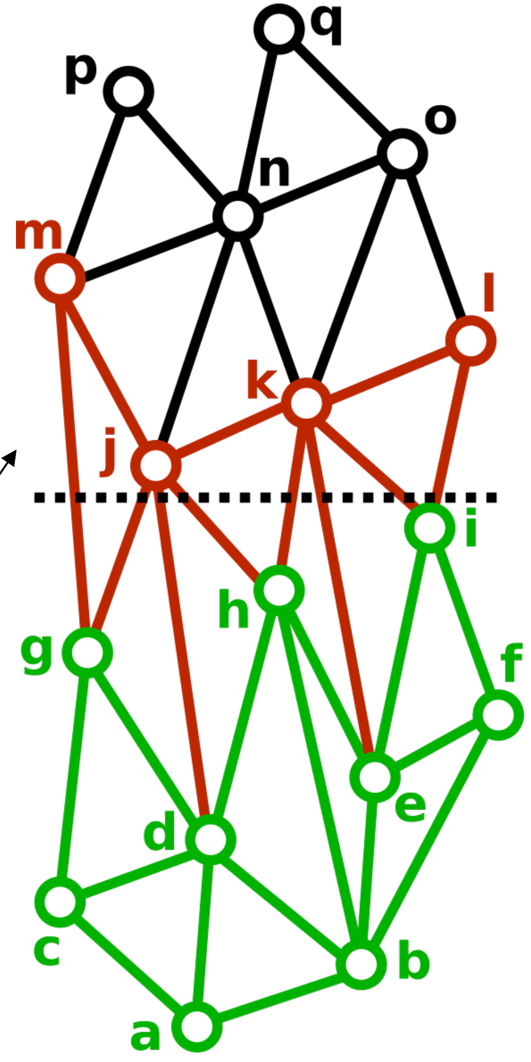
Redundant computations:

- Extended partition:
  initial partition + boundary vertices
- Correct tree in initial partition
- Visit all edges in parallel

extended
green + red



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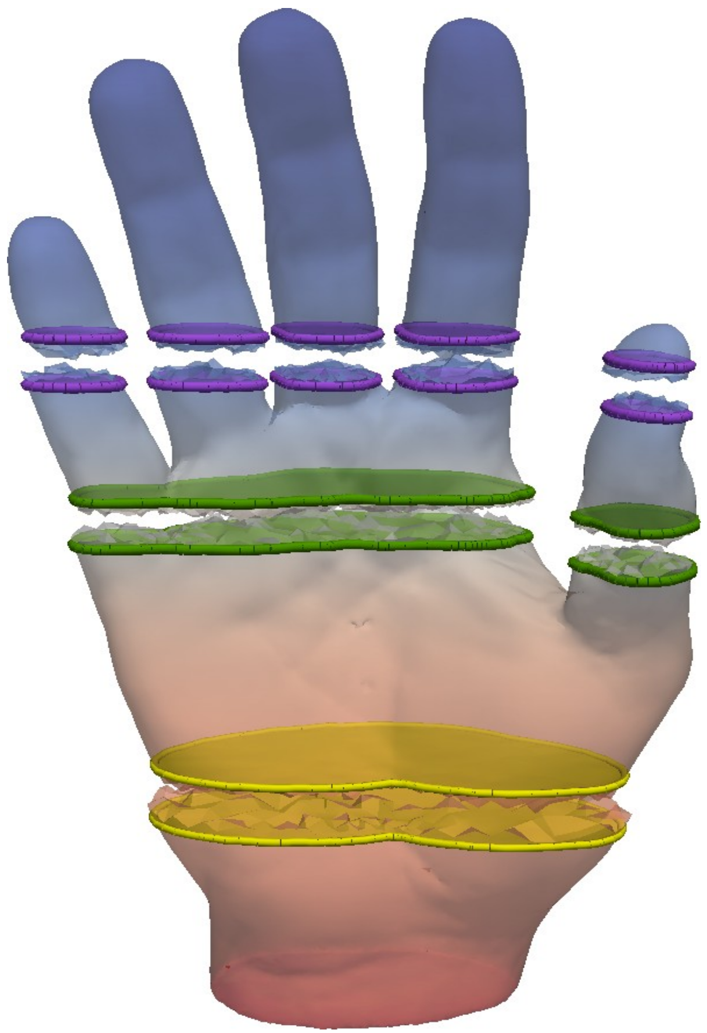

3D Example

Algorithm

- Domain partitioning
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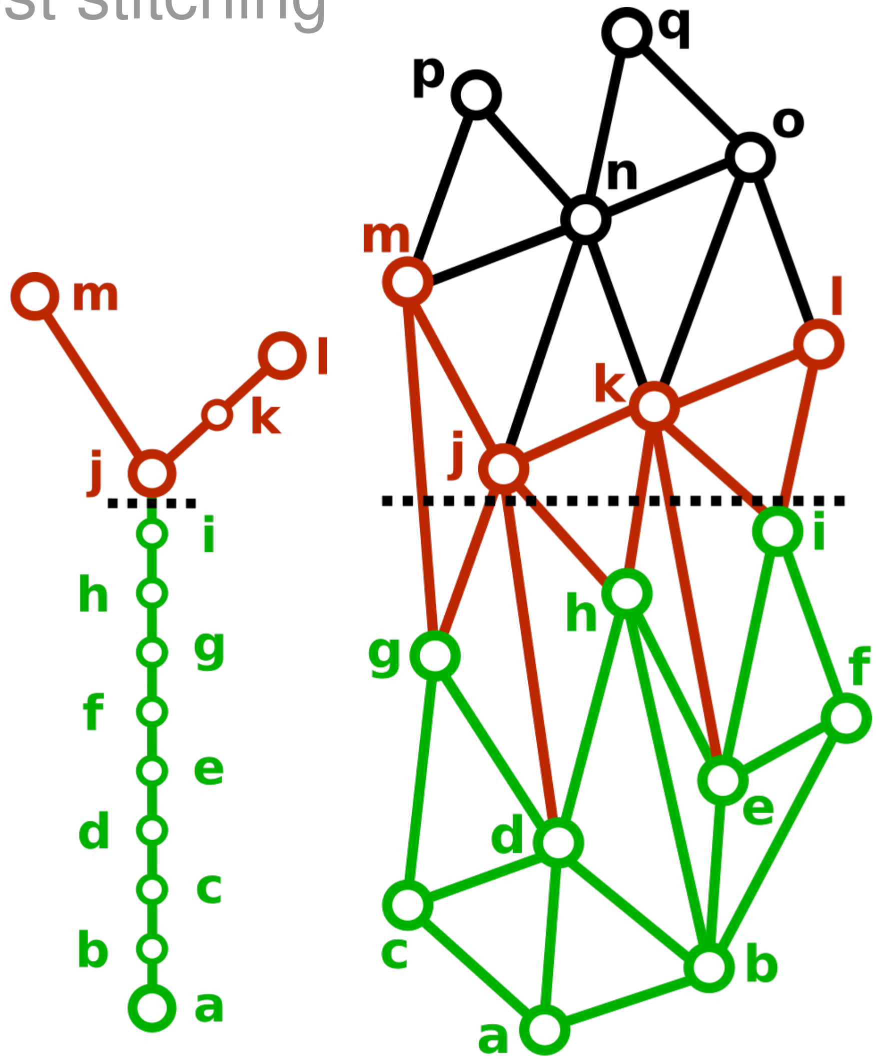
- In extended partitions
- Using Carr *et al.* Algorithm:
  - Join Tree
  - Split Tree
  - Combination
- Union-Find [CormenItA01]

Independent



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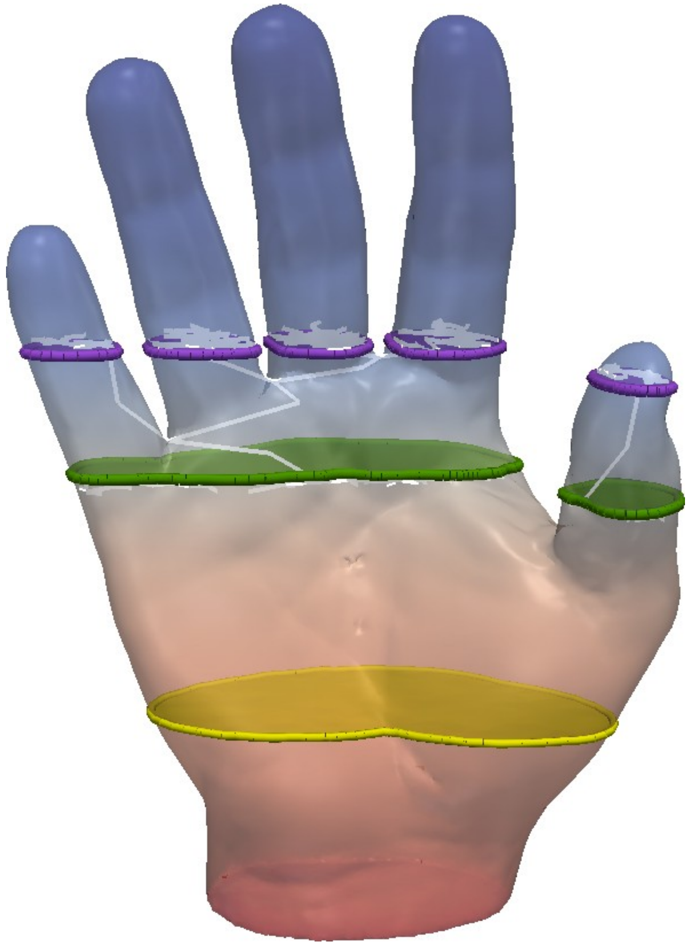

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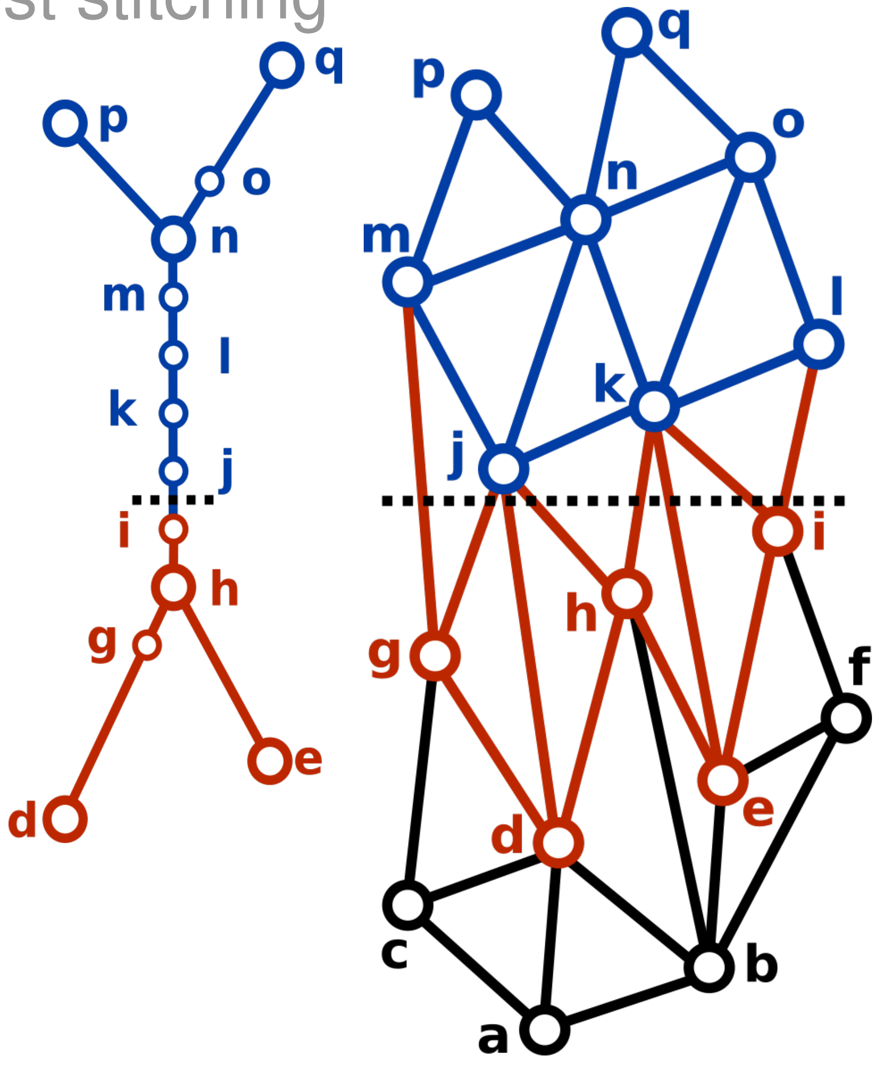
Each partition:

- Join and Split trees: 2 threads
- Combine: 1 thread
- $O(|\sigma^i| \times \alpha(|\sigma^i|)) + O(|\mathcal{C}(f)|)$
- Keep arcs on the boundary (n-h)



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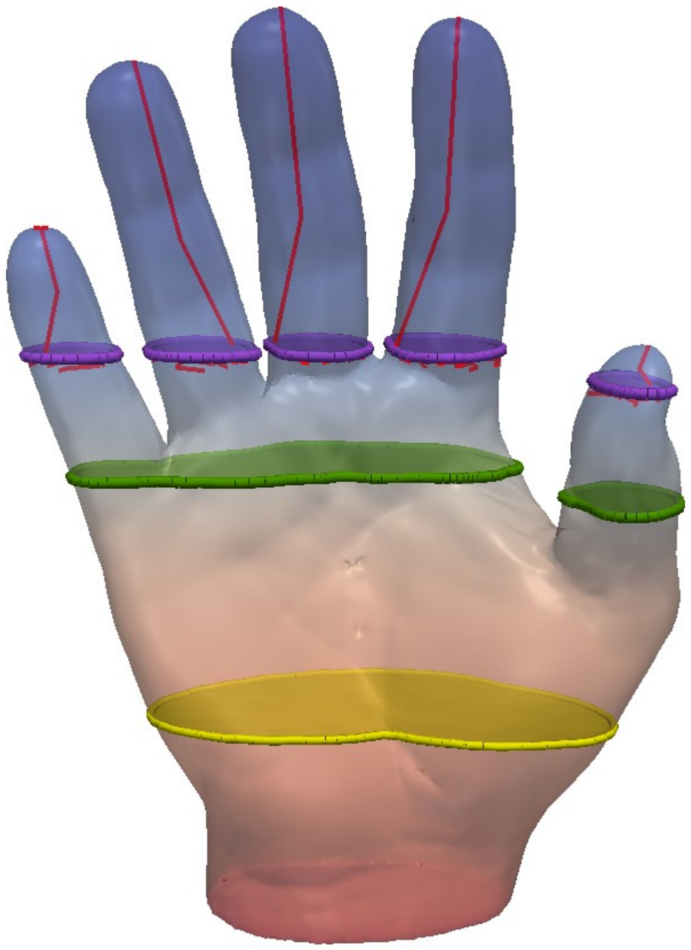

3D Example

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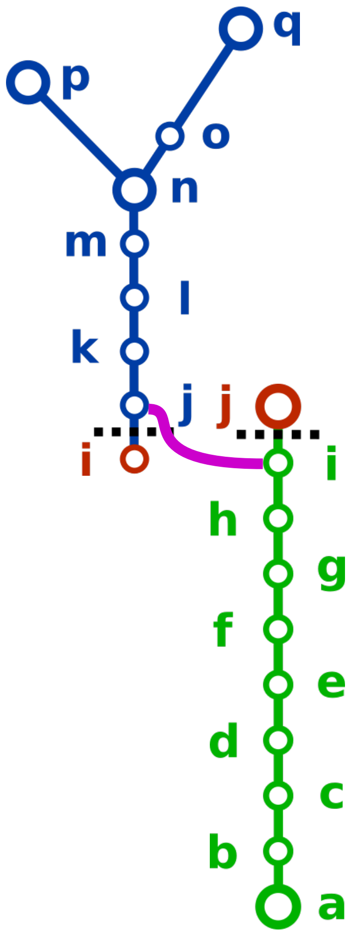
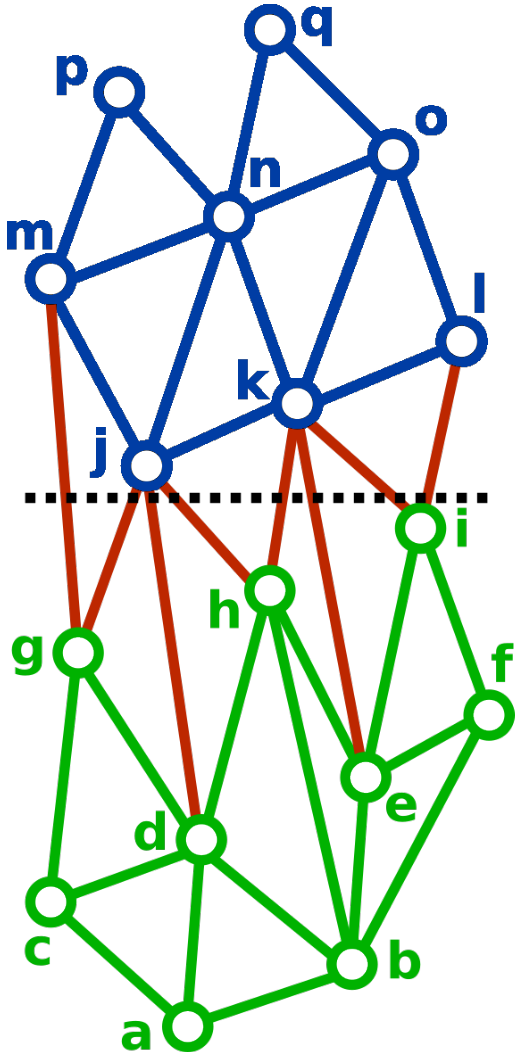
- Simple step
- Visit crossing arcs
- Cut *interface* arcs
  - Segmentation: fast lookup





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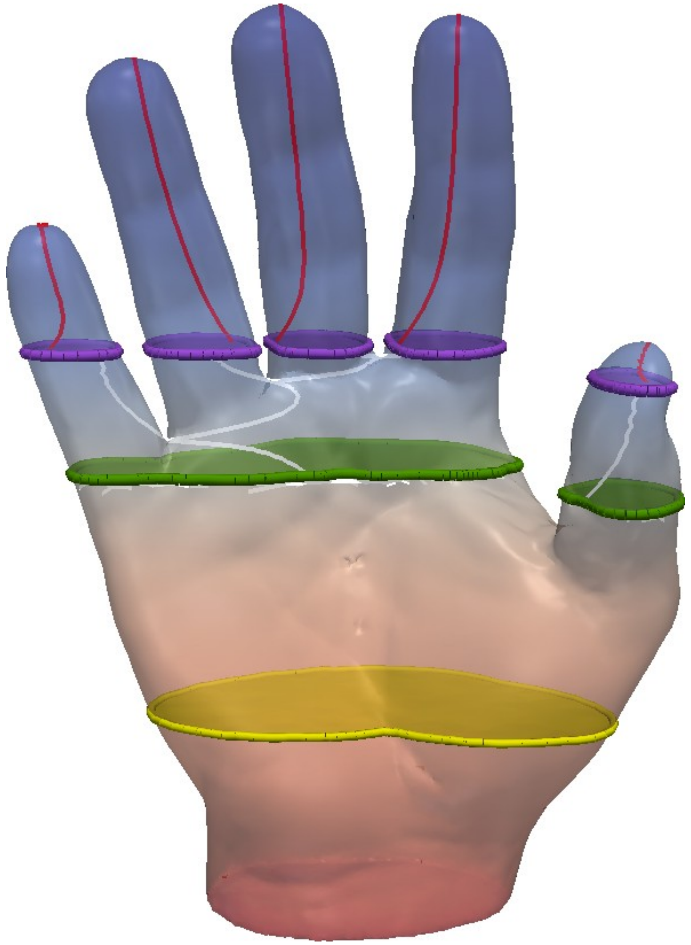

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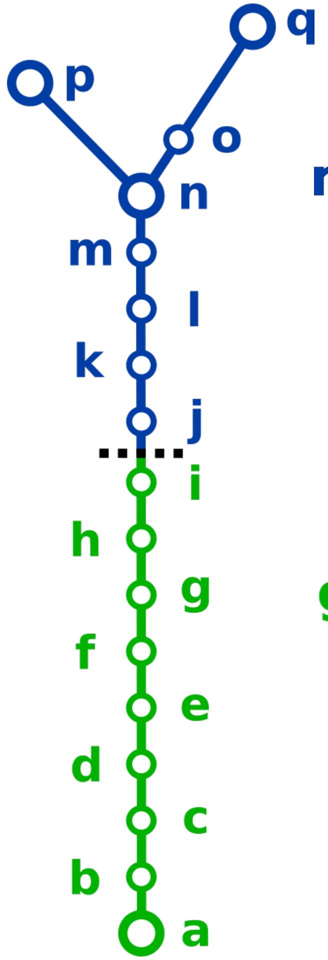
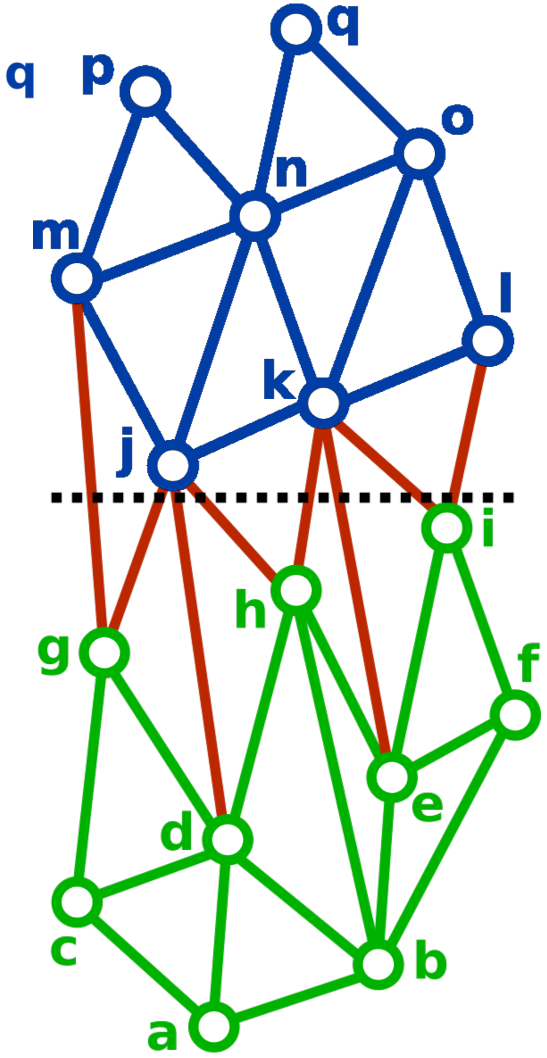
- New super-arc:
  - Union of the two facing halves
- Once per connected component of level set (~ crossing arc)





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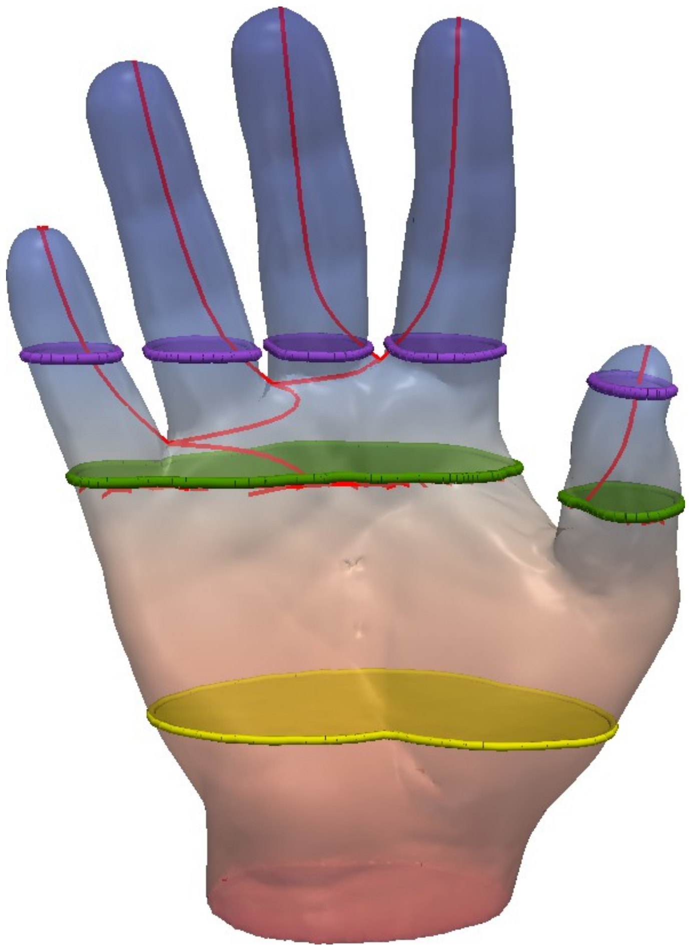

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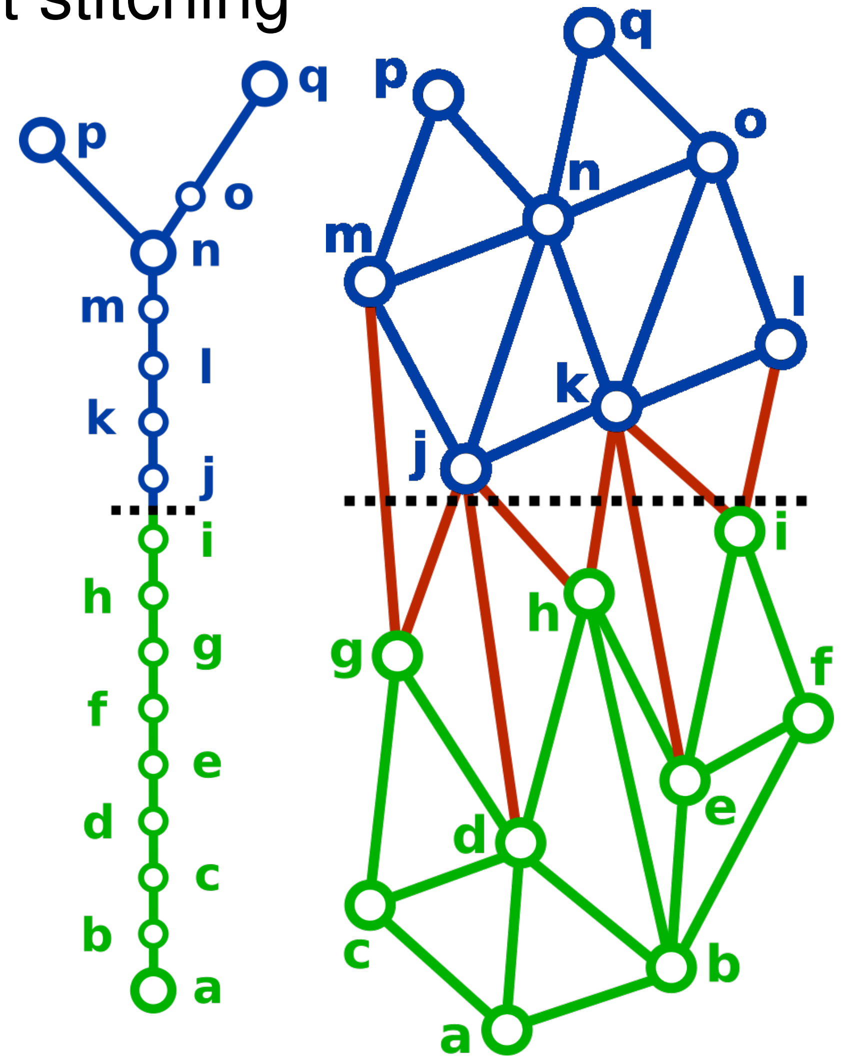
- Repeat for each interface
- Fast in practice



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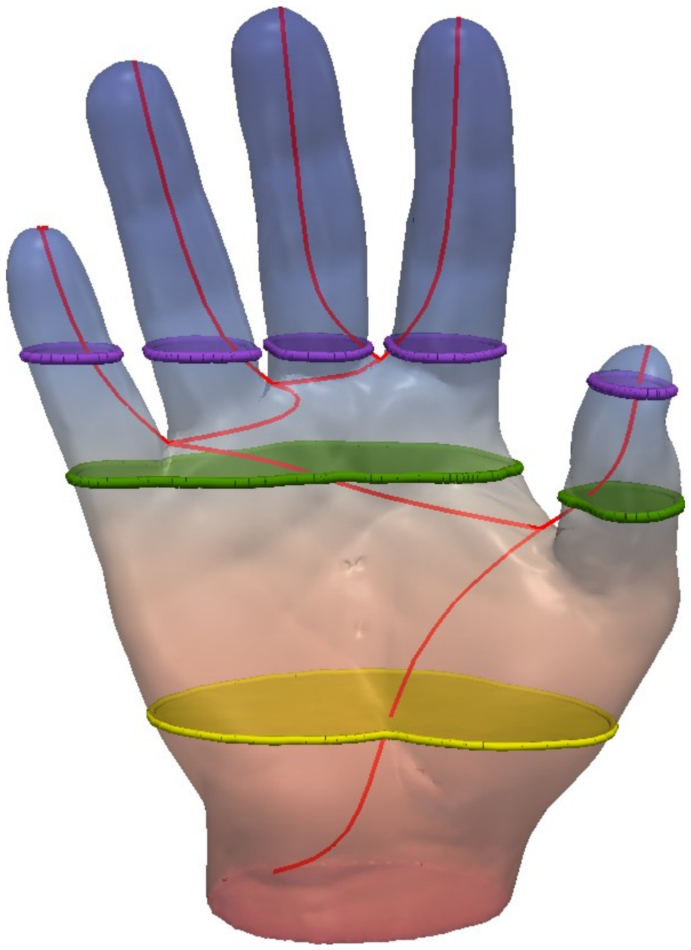


3D Example

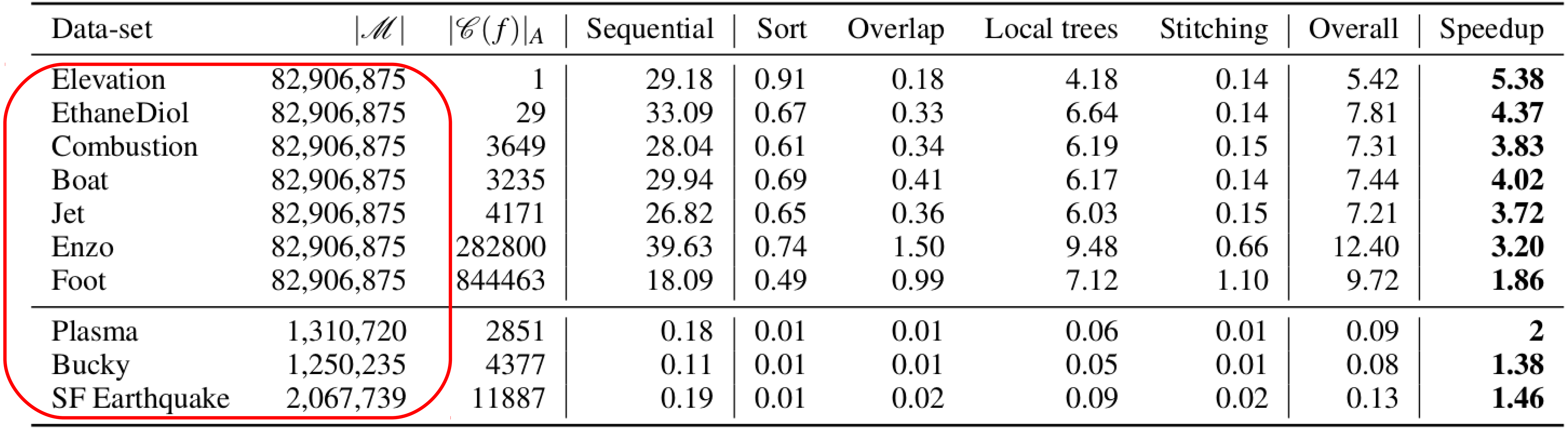
Experimental results

Intel Xeon CPU E5-2630 v3 (2.4 Ghz, 8 cores)
64GB of RAM
C++ (GCC-4.9), VTK, OpenMP (additional material)

Exp. Results

- Efficiency
- Comparison
- Speed
- Pros & cons

8 threads, 4 partitions



Data-set	$\lvert\mathscr{M}\rvert$	$\lvert\mathscr{C}(f)\rvert_A$	Sequential	Sort	Overlap	Local trees	Stitching	Overall	Speedup
Elevation	82,906,875	1	29.18	0.91	0.18	4.18	0.14	5.42	**5.38**
EthaneDiol	82,906,875	29	33.09	0.67	0.33	6.64	0.14	7.81	**4.37**
Combustion	82,906,875	3649	28.04	0.61	0.34	6.19	0.15	7.31	**3.83**
Boat	82,906,875	3235	29.94	0.69	0.41	6.17	0.14	7.44	**4.02**
Jet	82,906,875	4171	26.82	0.65	0.36	6.03	0.15	7.21	**3.72**
Enzo	82,906,875	282800	39.63	0.74	1.50	9.48	0.66	12.40	**3.20**
Foot	82,906,875	844463	18.09	0.49	0.99	7.12	1.10	9.72	**1.86**
Plasma	1,310,720	2851	0.18	0.01	0.01	0.06	0.01	0.09	**2**
Bucky	1,250,235	4377	0.11	0.01	0.01	0.05	0.01	0.08	**1.38**
SF Earthquake	2,067,739	11887	0.19	0.01	0.02	0.09	0.02	0.13	**1.46**

- Uniform sampling

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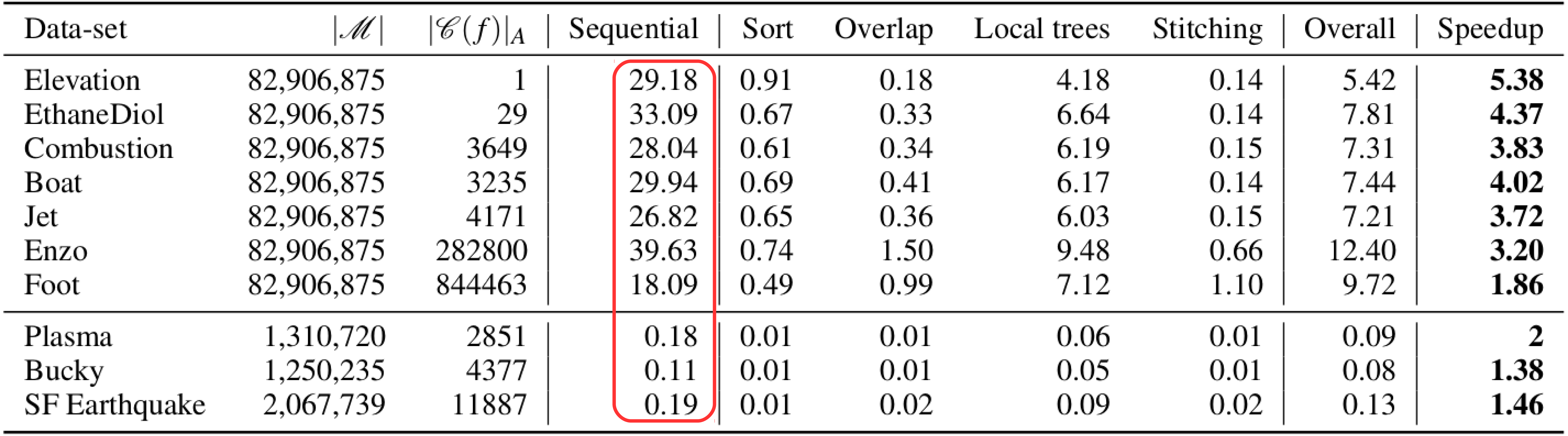

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- Foot: fast computation

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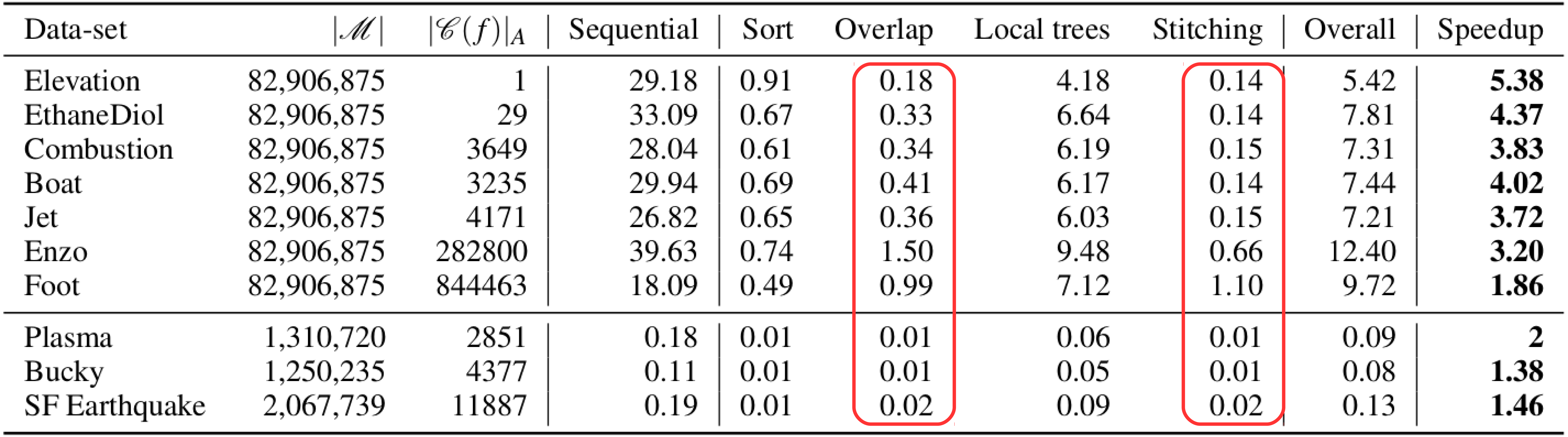

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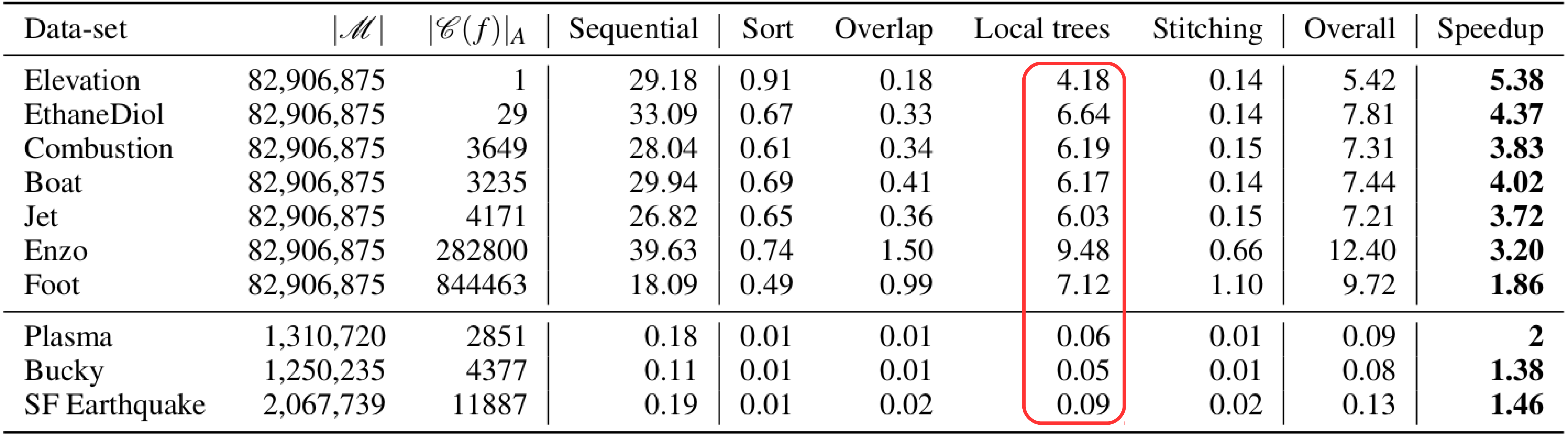
Boat	82,906,875	3235	29.94	0.69	0.41	6.17	0.14	7.44	**4.02**
Jet	82,906,875	4171	26.82	0.65	0.36	6.03	0.15	7.21	**3.72**
Enzo	82,906,875	282800	39.63	0.74	1.50	9.48	0.66	12.40	**3.20**
Foot	82,906,875	844463	18.09	0.49	0.99	7.12	1.10	9.72	**1.86**
Plasma	1,310,720	2851	0.18	0.01	0.01	0.06	0.01	0.09	**2**
Bucky	1,250,235	4377	0.11	0.01	0.01	0.05	0.01	0.08	**1.38**
SF Earthquake	2,067,739	11887	0.19	0.01	0.02	0.09	0.02	0.13	**1.46**

- Overlap and Stitching: efficient

Exp. Results

- Efficiency
- Comparison
- Speed
- Pros & cons

8 threads, 4 partitions



Data-set	$\lvert\mathscr{M}\rvert$	$\lvert\mathscr{C}(f)\rvert_A$	Sequential	Sort	Overlap	Local trees	Stitching	Overall	Speedup
Elevation	82,906,875	1	29.18	0.91	0.18	4.18	0.14	5.42	**5.38**
EthaneDiol	82,906,875	29	33.09	0.67	0.33	6.64	0.14	7.81	**4.37**
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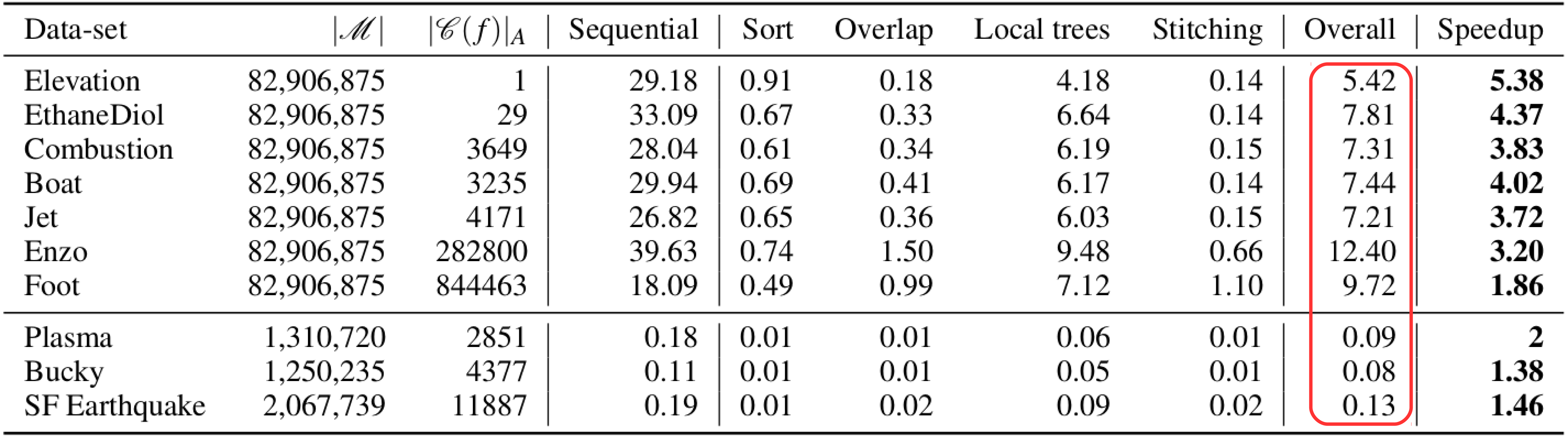
- High range of value

Exp. Results

- Efficiency
- Comparison
- Speed
- Pros & cons

8 threads, 4 partitions



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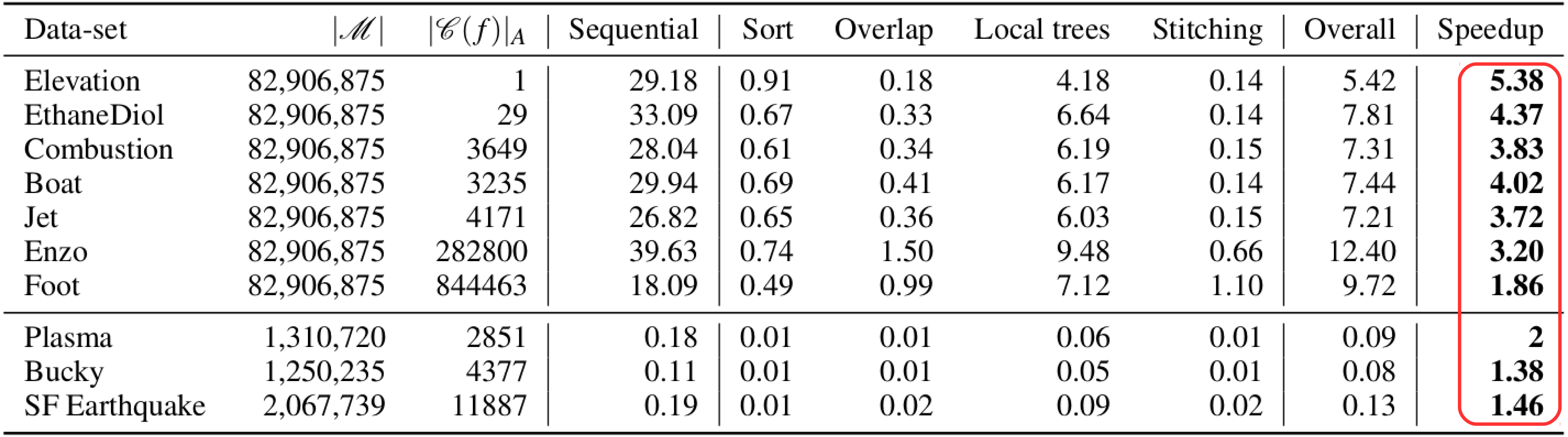
SF Earthquake	2,067,739	11887	0.19	0.01	0.02	0.09	0.02	0.13	**1.46**

- About ten seconds

Exp. Results

- Efficiency
- Comparison
- Speed
- Pros & cons

8 threads, 4 partitions



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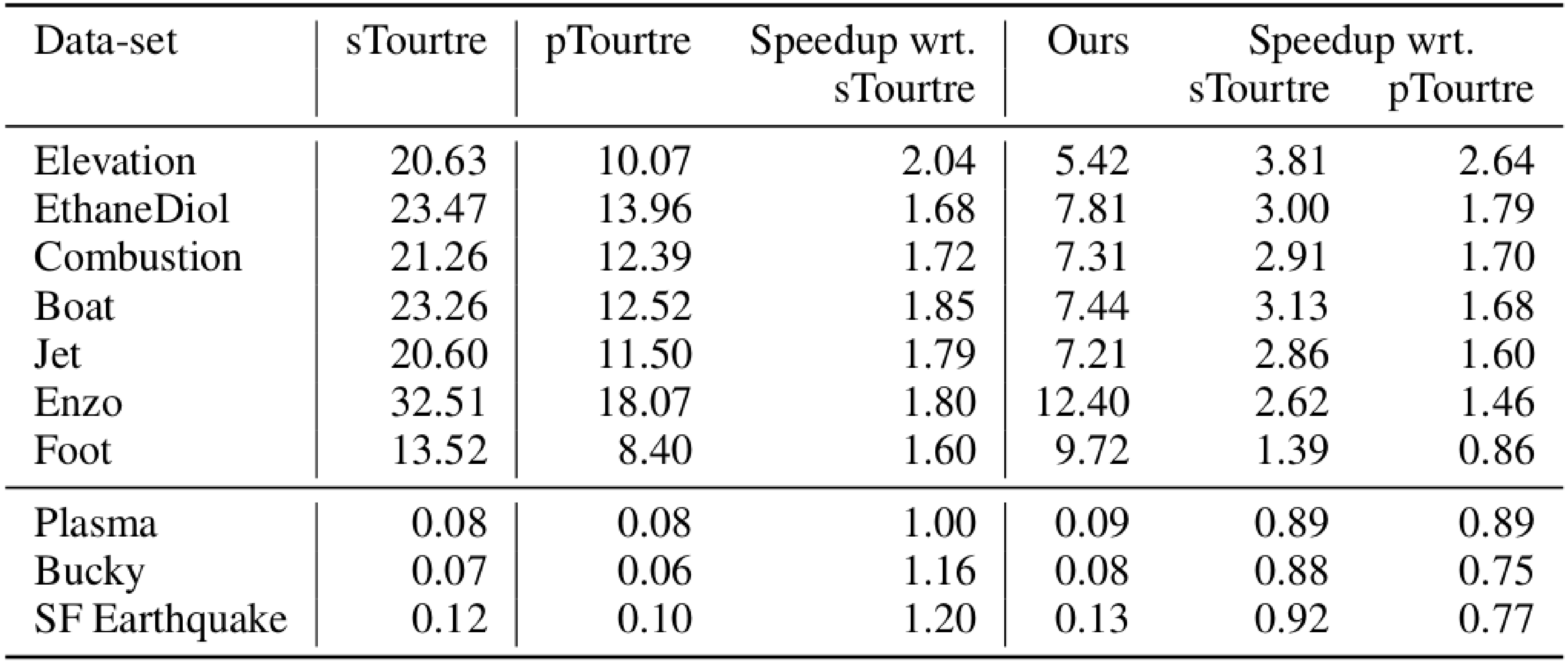
SF Earthquake	2,067,739	11887	0.19	0.01	0.02	0.09	0.02	0.13	**1.46**

- Parallel efficiency max: 67% (speedup / n_t)
- Parallel efficiency: 40 ~ 55 % (except extrema)

Exp. Results

- Efficiency
- Comparison
- Speed
- Pros & cons



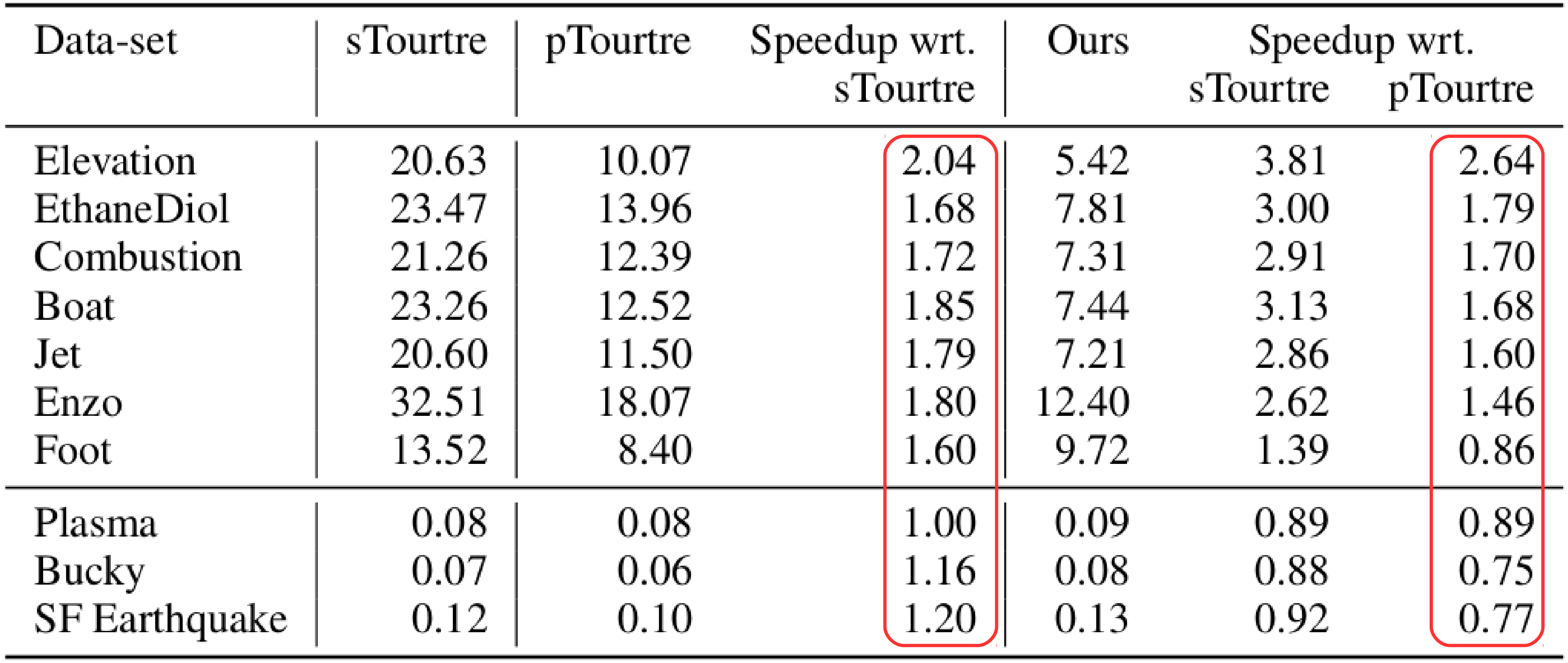
Data-set	sTourtre	pTourtre	Speedup wrt.	Ours	Speedup wrt.	
			sTourtre		sTourtre	pTourtre
Elevation	20.63	10.07	2.04	5.42	3.81	2.64
EthaneDiol	23.47	13.96	1.68	7.81	3.00	1.79
Combustion	21.26	12.39	1.72	7.31	2.91	1.70
Boat	23.26	12.52	1.85	7.44	3.13	1.68
Jet	20.60	11.50	1.79	7.21	2.86	1.60
Enzo	32.51	18.07	1.80	12.40	2.62	1.46
Foot	13.52	8.40	1.60	9.72	1.39	0.86
Plasma	0.08	0.08	1.00	0.09	0.89	0.89
Bucky	0.07	0.06	1.16	0.08	0.88	0.75
SF Earthquake	0.12	0.10	1.20	0.13	0.92	0.77

Libtourtre:

- Open-source reference implementation
- pTourtre: naive parallel version

Exp. Results

- Efficiency
- Comparison
- Speed
- Pros & cons



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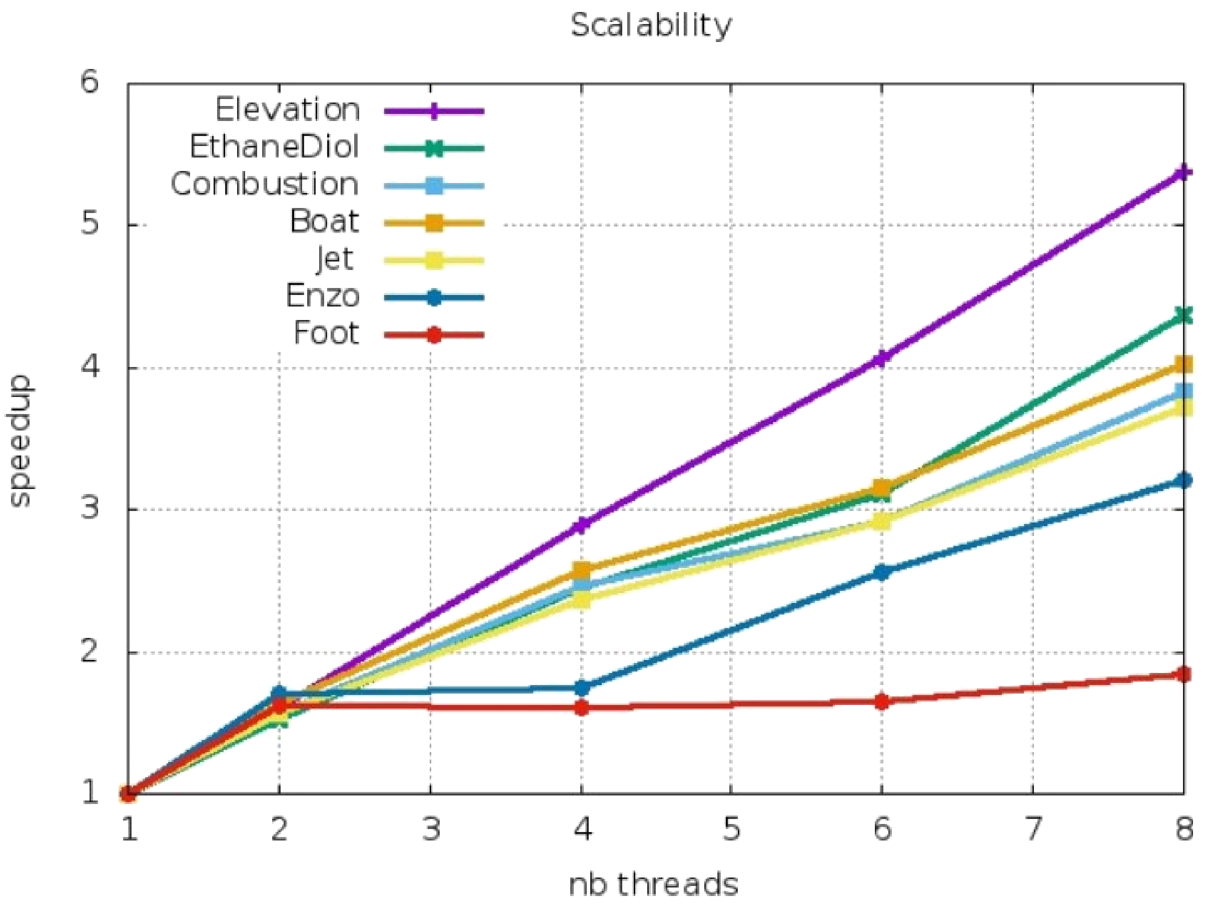
Foot	13.52	8.40	1.60	9.72	1.39	0.86
Plasma	0.08	0.08	1.00	0.09	0.89	0.89
Bucky	0.07	0.06	1.16	0.08	0.88	0.75
SF Earthquake	0.12	0.10	1.20	0.13	0.92	0.77

Libtourtre:

- Open-source reference implementation
- pTourtre: naive parallel version
- Always better than sequential libtourtre for big data sets
- Better than parallel except for the foot data set

Exp. Results

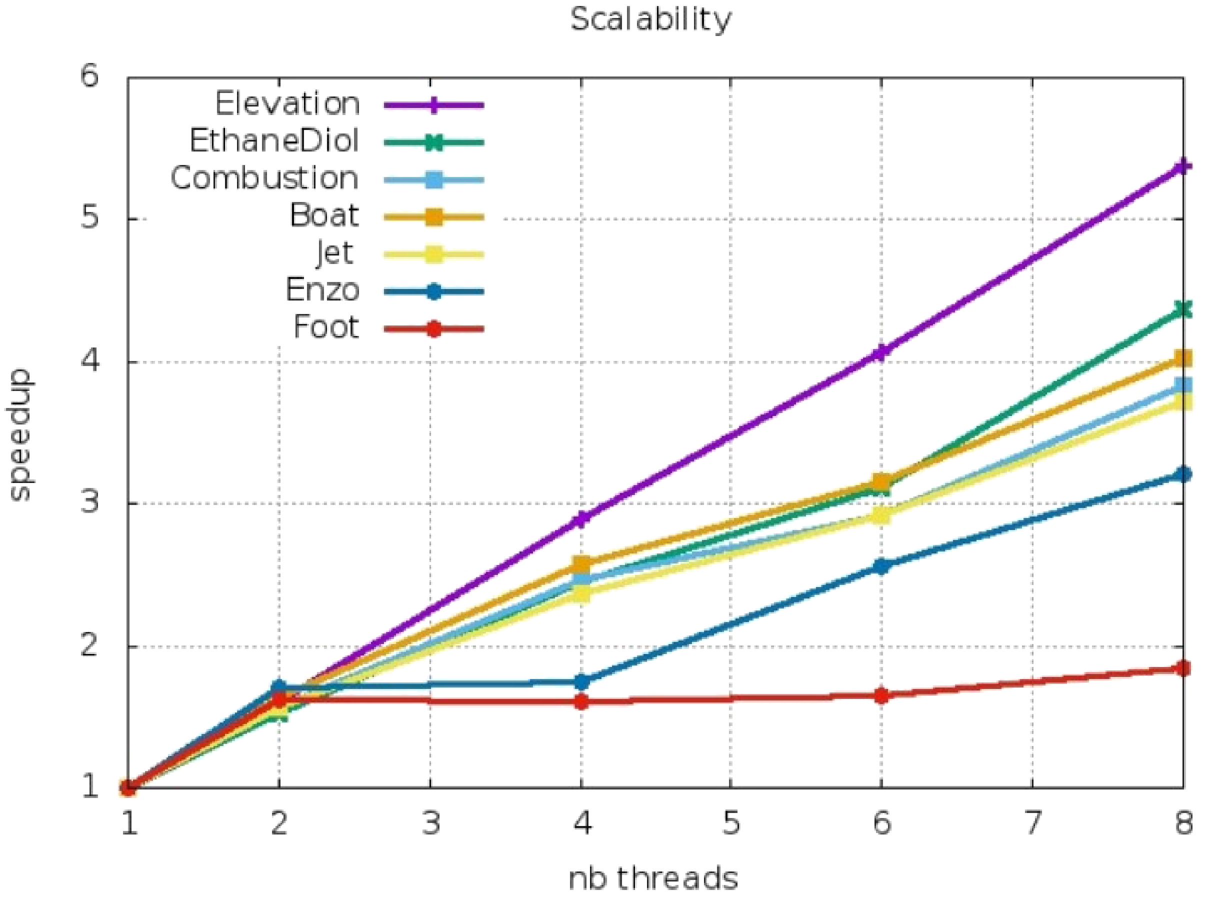
- Efficiency
- Comparison
- Speed
- Pros & cons



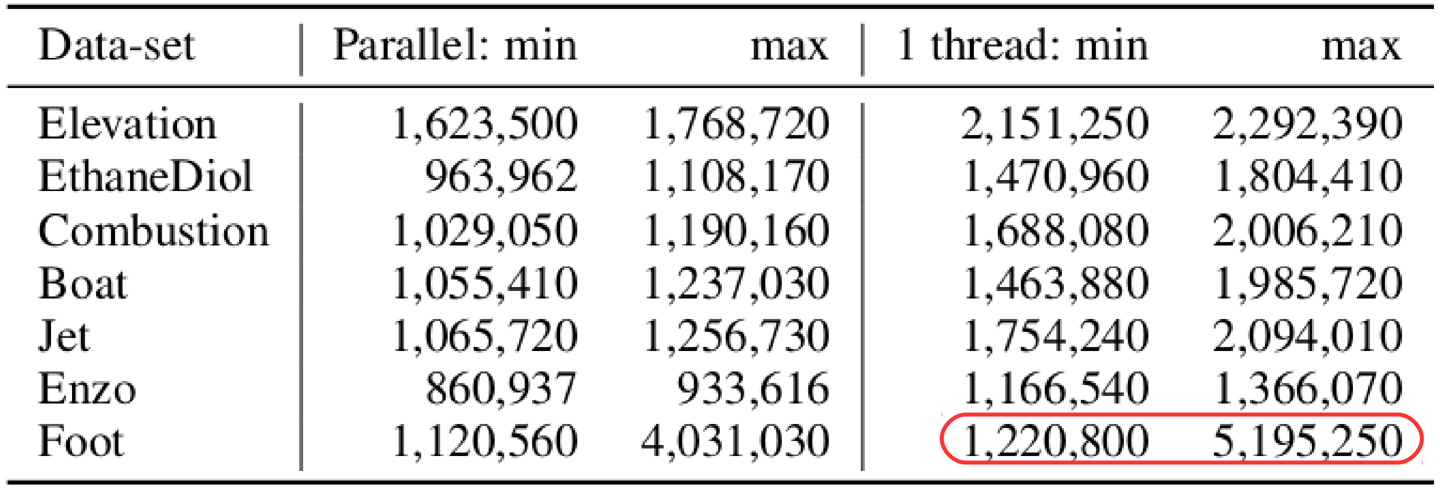
- Different slopes
- Few arithmetic operations per memory access

Exp. Results

- Efficiency
- Comparison
- Speed
- Pros & cons



- Different slopes
- Few arithmetic operations per memory access
- Load imbalance

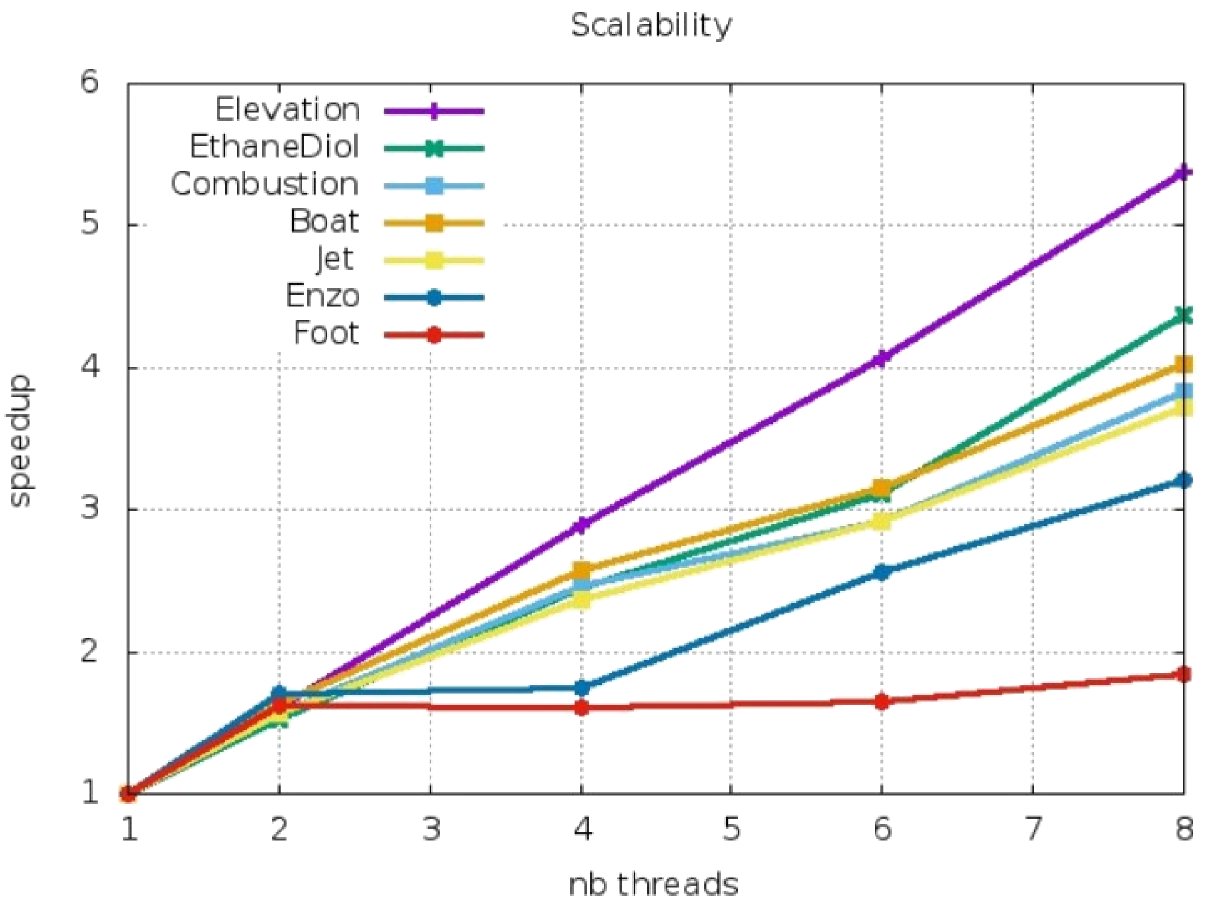


Data-set	Parallel: min	max	1 thread: min	max
Elevation	1,623,500	1,768,720	2,151,250	2,292,390
EthaneDiol	963,962	1,108,170	1,470,960	1,804,410
Combustion	1,029,050	1,190,160	1,688,080	2,006,210
Boat	1,055,410	1,237,030	1,463,880	1,985,720
Jet	1,065,720	1,256,730	1,754,240	2,094,010
Enzo	860,937	933,616	1,166,540	1,366,070
Foot	1,120,560	4,031,030	1,220,800	5,195,250

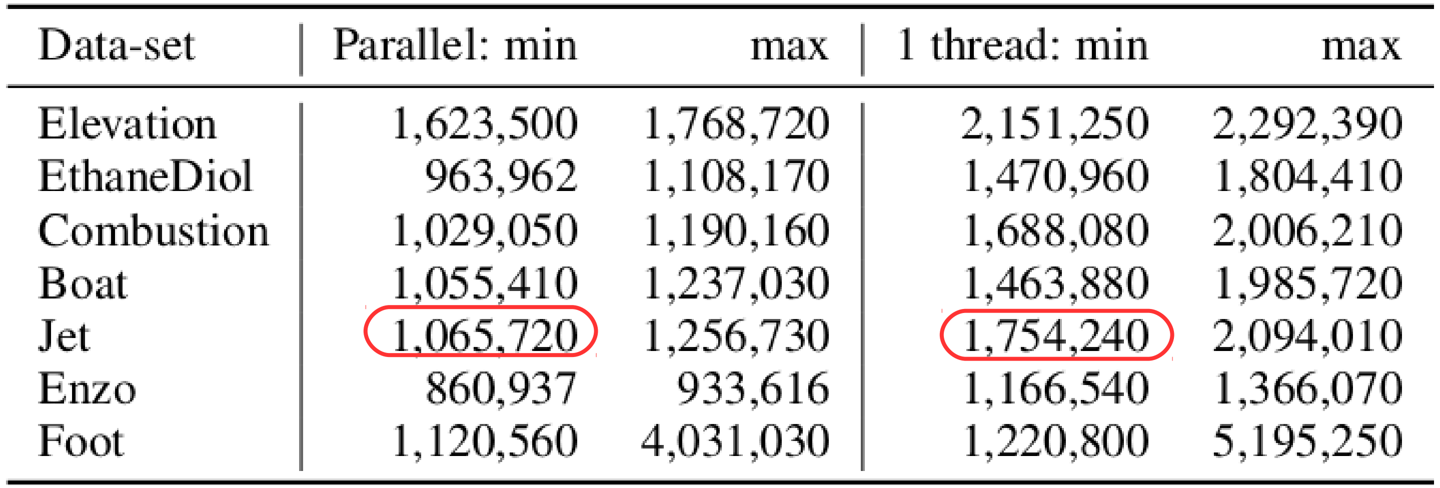
Computational speed: vertices/second

Exp. Results

- Efficiency
- Comparison
- Speed
- Pros & cons



- Different slopes
- Few arithmetic operations per memory access
- Load imbalance
- Memory congestion



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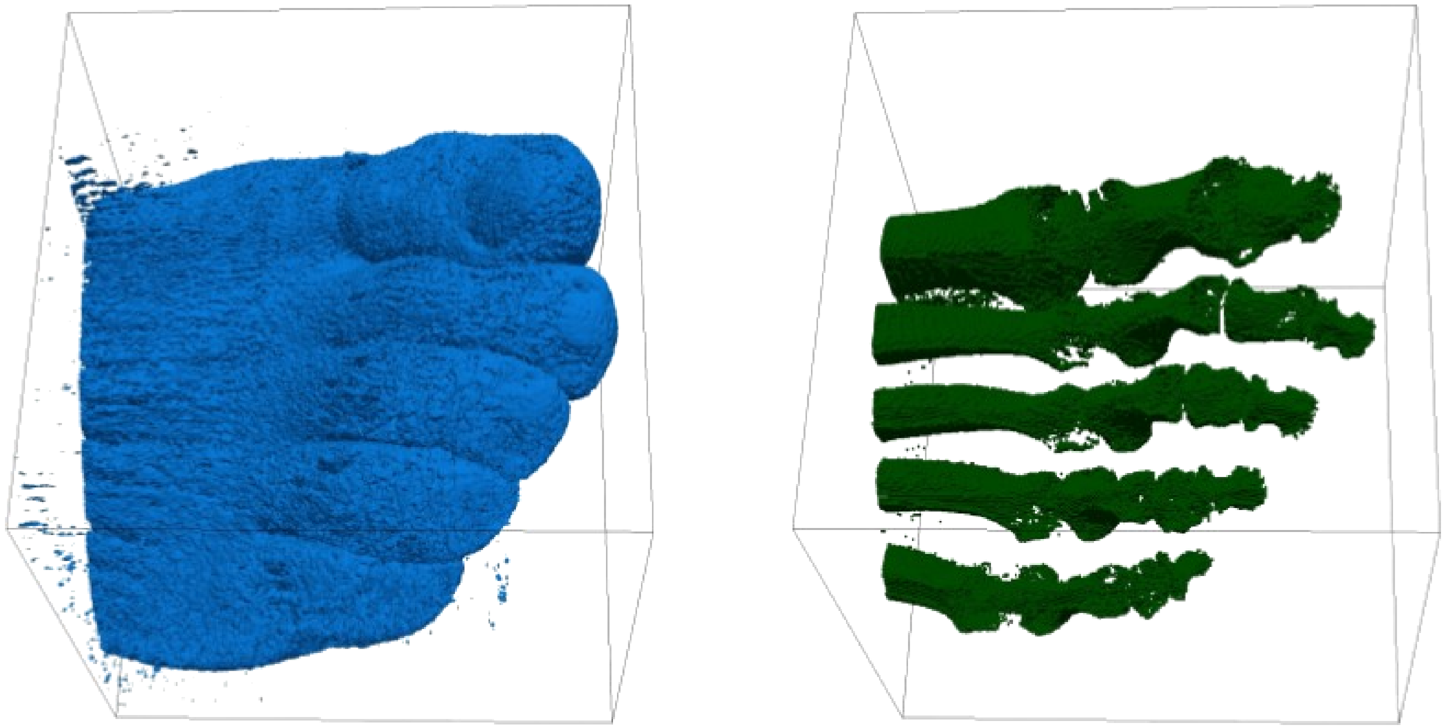
Foot	1,120,560	4,031,030	1,220,800	5,195,250

Computational speed: vertices/second

Exp. Results

- Efficiency
- Comparison
- Speed
- Pros & cons


(a)

(b)

- Different slopes
- Few arithmetic operations per memory access
- Load imbalance
- Memory congestion
- Redundant computations

Data-set	ideal	min	max
Elevation	4,194,304	4,259,840	4,325,376
EthaneDiol	4,194,304	4,362,086	4,616,938
Combustion	4,194,304	4,353,986	4,635,078
Boat	4,194,304	4,418,409	4,791,092
Jet	4,194,304	4,358,176	4,701,586
Enzo	4,194,304	5,234,144	6,474,322
Foot	4,194,304	4,499,572	6,044,708

Partitions sizes in vertices

Exp. Results

- Efficiency
- Comparison
- Speed
- Pros & cons

Pros:

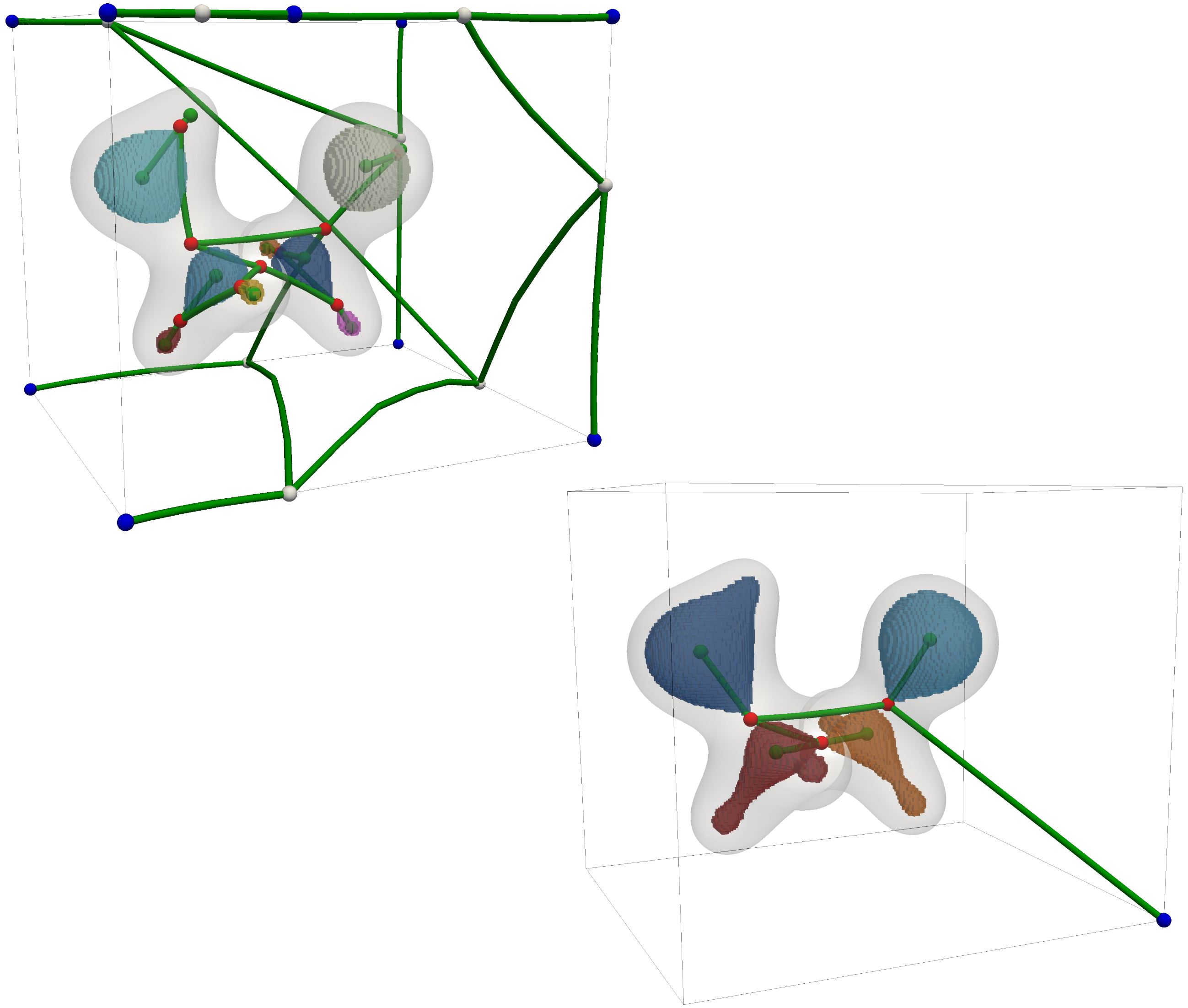
- Good parallel efficiency
- Faster than reference implementation
- Large spectrum of data

Cons:

- Redundant computation
- Load imbalance
- Memory congestion (augmented tree)

Application

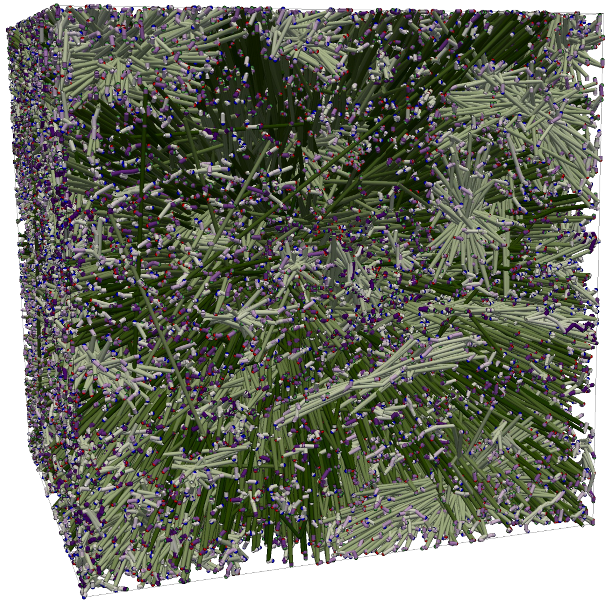
Application

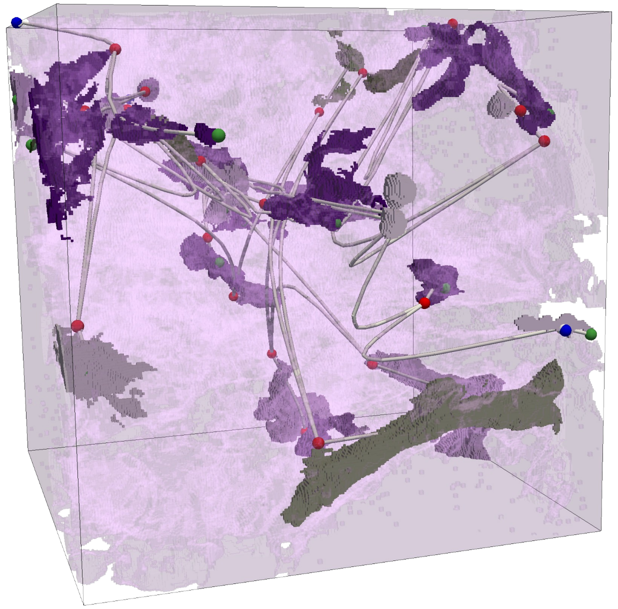


Exploration:

- Highlight features
- Allows features grouping

Application





Occlusion reduction:

- Remove noise
- Keep the most important features

Conclusion

Conclusion

- Recall
- Perspective

Take home message:

- Efficient algorithm:
    - Multi-threaded
    - Augmented
    - Simple approach, subtle details

Conclusion

- Recall
- Perspective

Take home message:

- Efficient algorithm:
  - Multi-threaded
  - Augmented
  - Simple approach, subtle details

- VTK-based implementation:
  - Generic input
    - VTU,VTI
    - 2D/3D
  - Generic output (augmented trees)
  - Ready-to-use
  - Integrated in TTK

Conclusion

- Recall
- Perspective

Take home message:

- Efficient algorithm:
  - Multi-threaded
  - Augmented
  - Simple approach, subtle details

- VTK-based implementation:
  - Generic input
    - VTU,VTI
    - 2D/3D
  - Generic output (augmented trees)
  - Ready-to-use
  - Integrated in TTK
- Lesson learned
  - Memory bound
  - Memory congestion: price to pay for augmented trees
  - Efficient implementation: hard

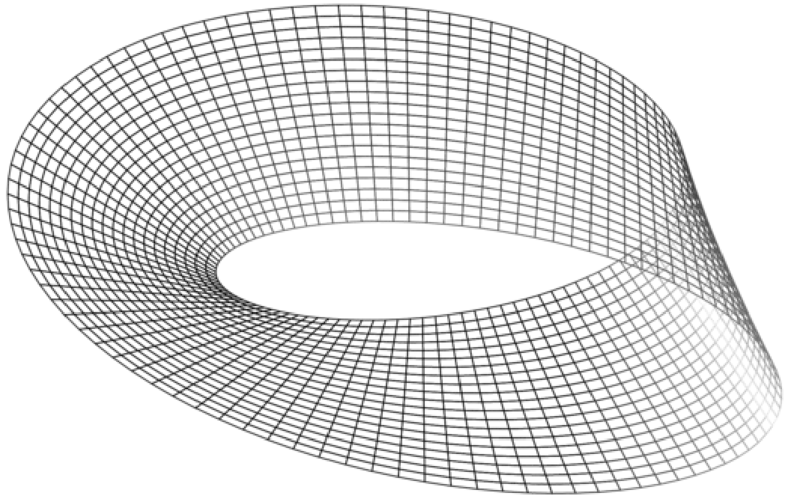
Conclusion

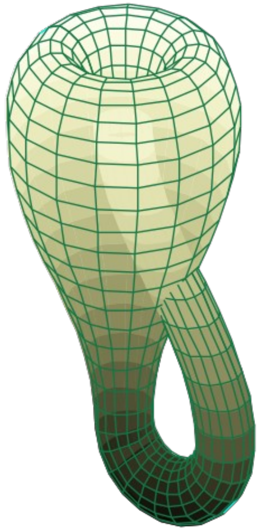
- Recall
- Perspective

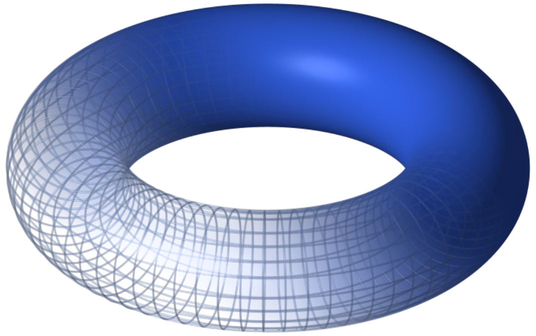
- Improve partitioning:
  - Better cutting isovalue selection
  - Contour Spectrum

- Distributed systems

The end







Thank you for your attention,

Do you have any question ?

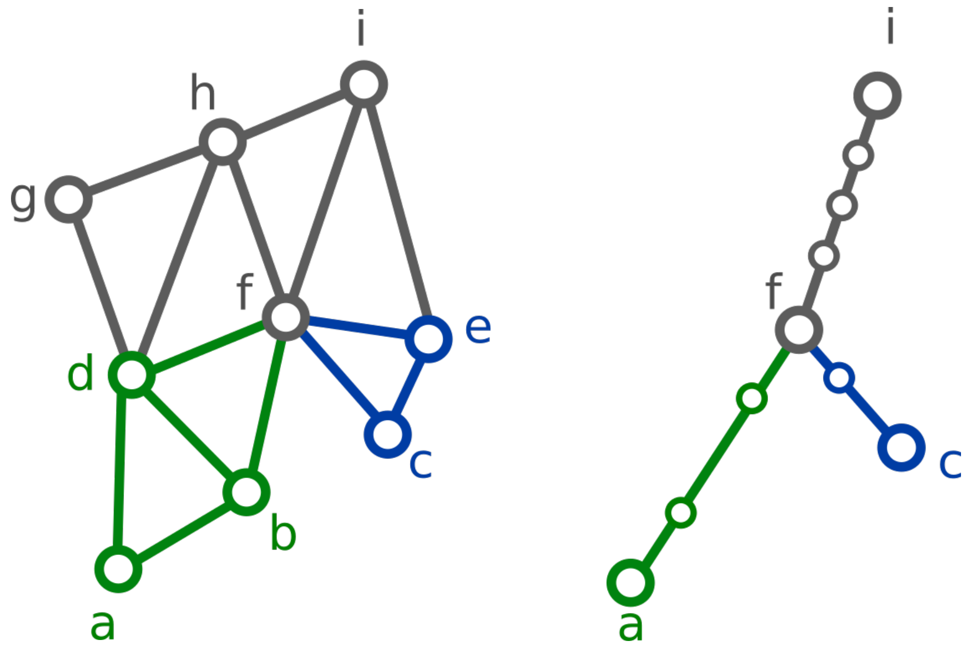
Paper at: http://www-pequan.lip6.fr/~tierny/
Code at: https://github.com/topology-tool-kit/ttk

This work is partially supported by the Bpifrance grant “AVIDO” (Programme d’Investissements d’Avenir, reference P112017-2661376/DOS0021427) and by the French National Association for Research and Technology (ANRT), in the framework of the LIP6 - Kitware SAS CIFRE partnership reference 2015/1039.

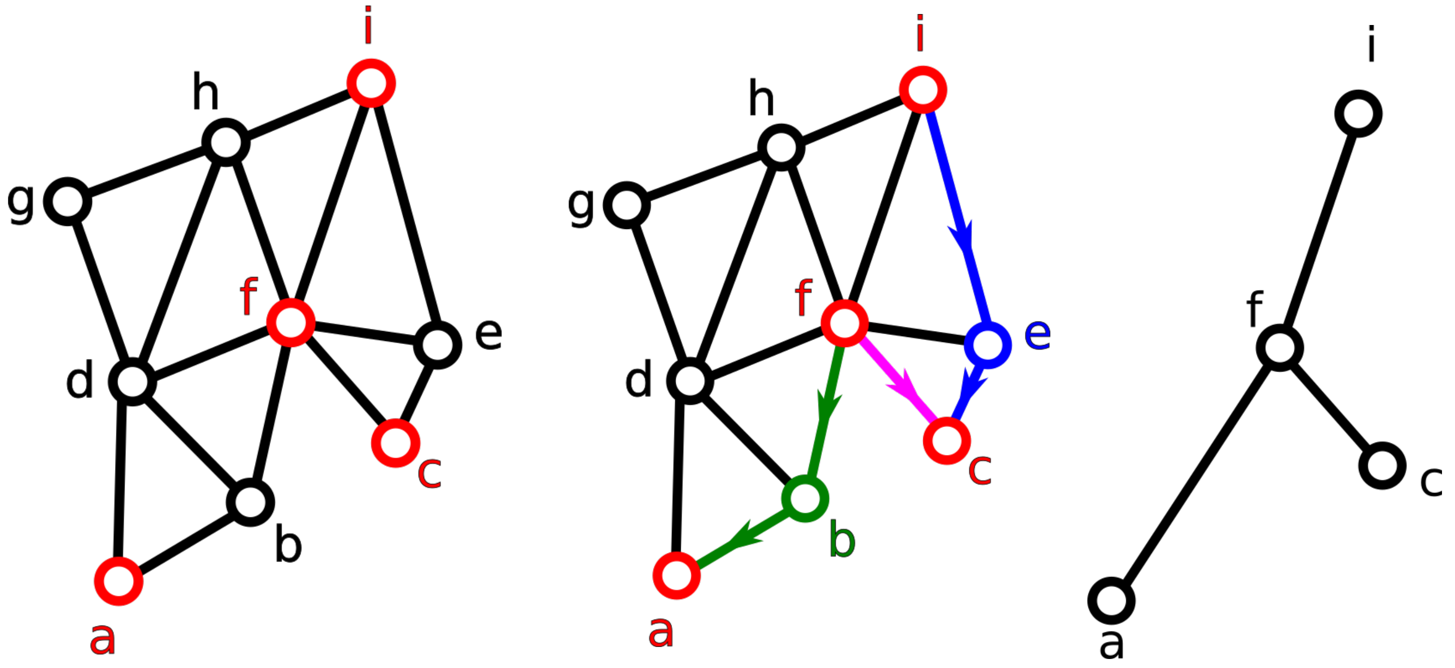
Appendice

Seq. Approaches

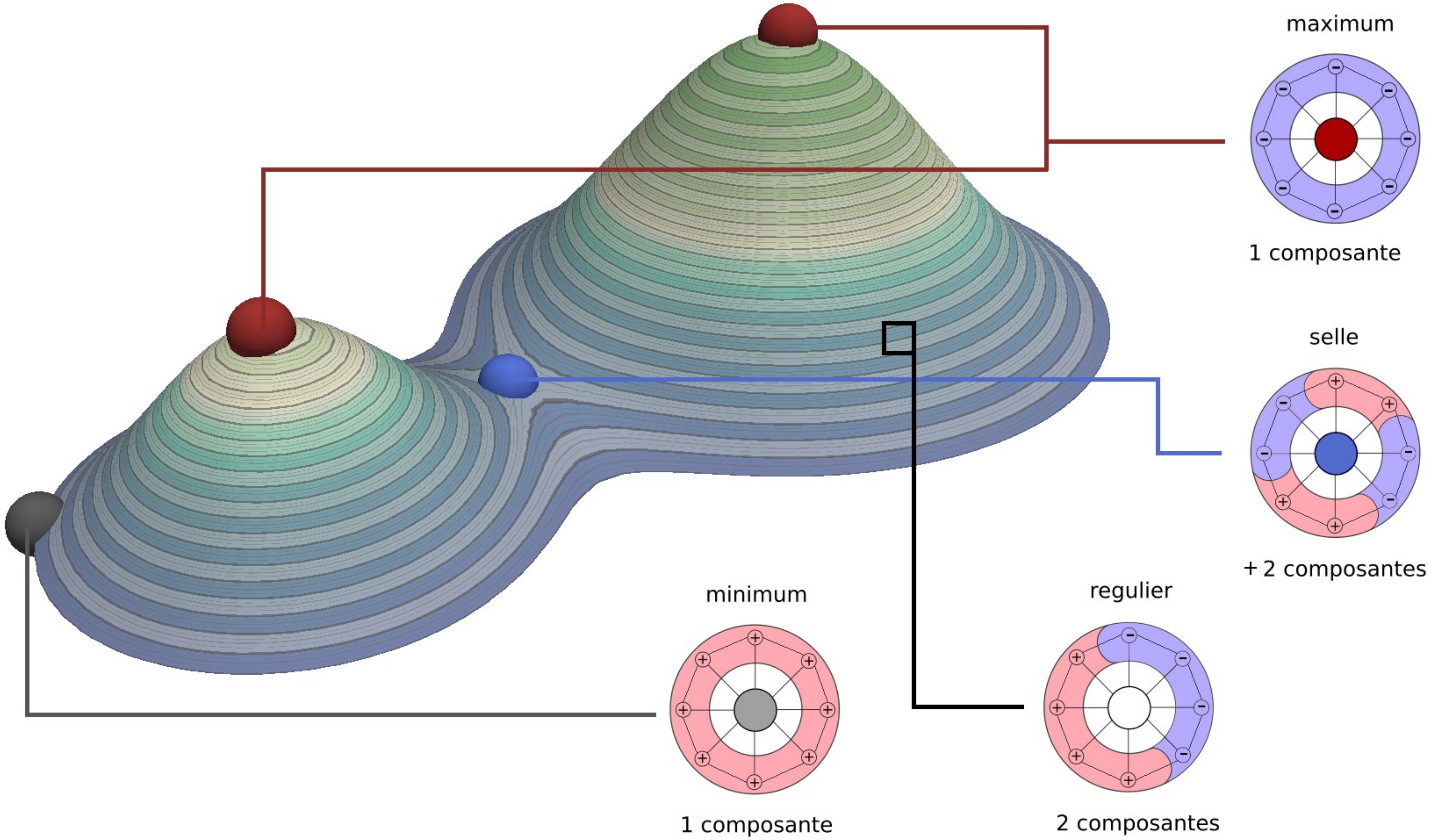
Union find:



Monotone paths:



Critical points


maximum
1 composante
selle
+ 2 composantes
minimum
1 composante
regulier
2 composantes