Scaling Spatial Overlay Operations and Flock Pattern Discovery

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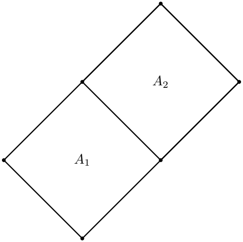
Plan

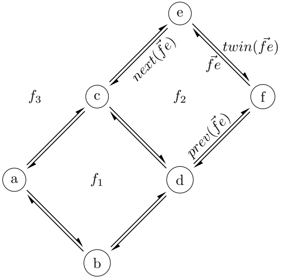
1. Scalable overlay operations over DCEL polygons layers
2. Scaling DCEL Overlay Operations to Support Dangle and Cut Edges
3. Scalable Processing of Moving Flock Patterns

WHAT IS A DCEL?

- **Doubly Connected Edge List** - DCEL.
- A spatial data structure to **represent planar subdivisions** of surfaces.
- Represent topological and geometric information as vertices, edges, and faces.
- **Applications**: polygon overlays, polygon triangulation and their applications in surveillance, robot motion planing, circuit board printing, etc.

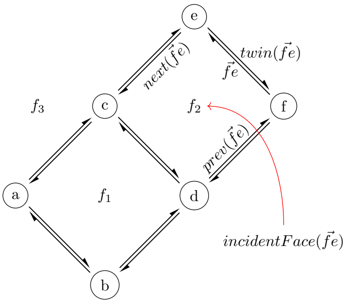


Planar subdivision



DCEL representation

- DCEL uses three tables: Vertices, Faces and Half-edges.



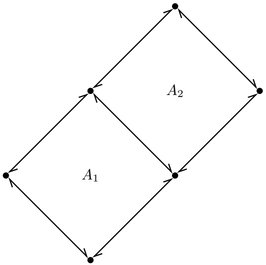
vertex	coordinates	incident edge
a	(0,2)	$\vec{ba}$
b	(2,0)	$\vec{db}$
c	(2,4)	$\vec{dc}$
⋮	⋮	⋮

face	boundary edge	hole list
f_1	$\vec{ab}$	nil
f_2	$\vec{fe}$	nil
f_3	nil	nil

half-edge	origin	face	twin	next	prev
$\vec{fe}$	f	f_2	$\vec{ef}$	$\vec{ec}$	$\vec{df}$
$\vec{ca}$	c	f_1	$\vec{ac}$	$\vec{ab}$	$\vec{dc}$
$\vec{db}$	d	f_3	$\vec{bd}$	$\vec{ba}$	$\vec{fd}$
⋮	⋮	⋮	⋮	⋮	⋮

DCEL Advantages

- **Efficiency**: very efficient for computation of *overlay operators*.
- **Re-usability**: allows multiple operations over the same DCEL.
- **Pipelining**: the output of a DCEL operator can be input to another DCEL operator.



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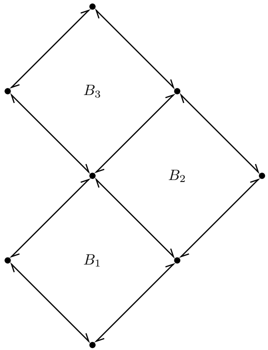

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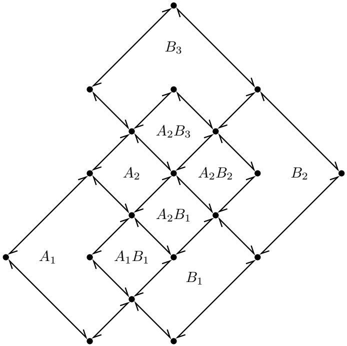

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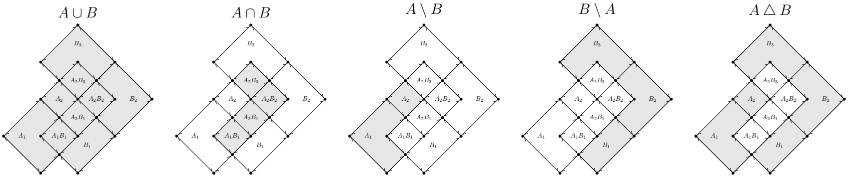
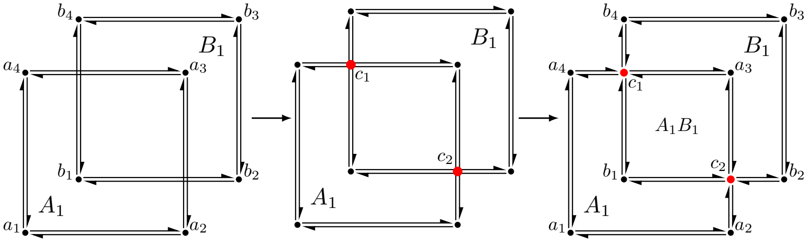


Challenges and Contributions

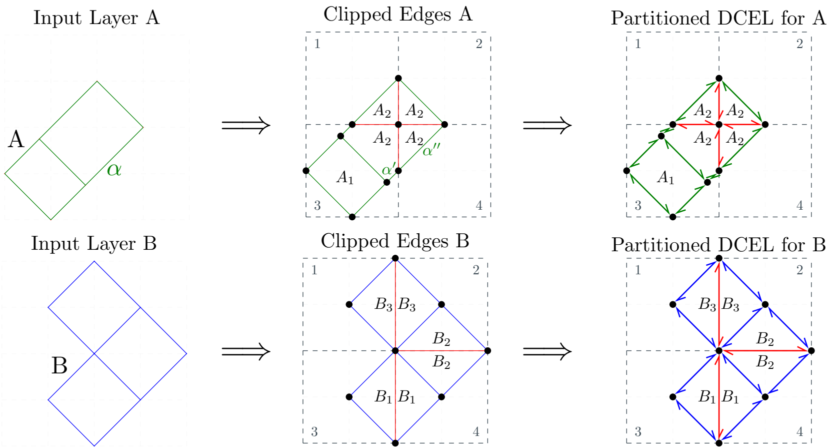
- Currently only sequential DCEL implementations exist.
- Unable to deal with large datasets (i.e. US Census tracks at national level).
- We propose a *scalable distributed* approach to compute the overlay of two polygon layers using DCELs.
- Distribution enables scalability, but introduces challenges: the ***orphan-cell*** problem and the ***orphan-hole*** problem.
- Optimization for reducing and merging results and unbalanced layer sizes.

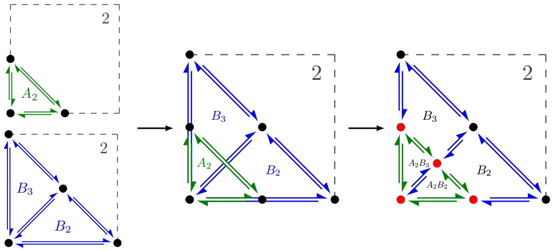
- Consider two (simple) input DCELs A_1 and B_1. The sequential algorithm first finds the intersections of half-edges.
- Then, new vertices (e.g. c_1, c_2) are created, half-edges are updated, new faces are added and labeled (e.g. A_1B_1).



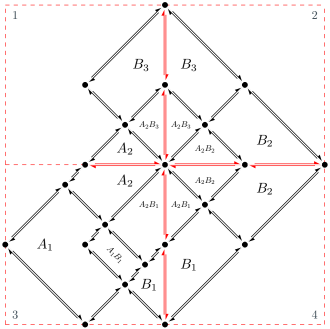
- Two phases: (1) Distributed DCEL construction, and (2) Distributed overlay evaluation.
- Distribution is based on a spatial index (e.g. quadtree)
- Each input DCEL layer (e.g. A, B) is partitioned using the same index
- Each index cell should contain all information needed so that it can compute the overlay DCEL locally
- For each cell to be independent, we need to create "artificial" edges and vertices

Scalable Implementation





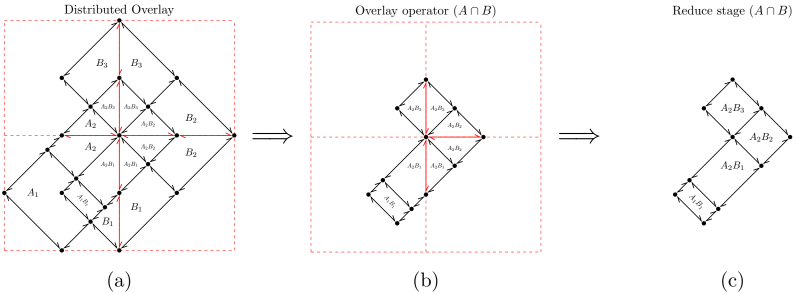
2
A_2
2
B_3
B_2
2
B_3
A_2
B_2
2
B_3
A_2B_3
A_2B_2
B_2



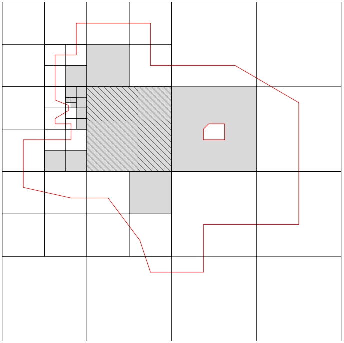
1
2
3
4
B_3
B_3
A_2B_3
A_2B_3
A_2
A_2B_2
B_2
A_2
A_2B_2
B_2
A_2B_1
A_2B_1
A_1
A_1B_1
B_1
B_1

Overlay evaluation

- Answering global overlay queries...
  - To compute a particular overlay operator, we query local DCELs.
  - This work is done independently at each cell (node).
  - SDCEL then collects back all local DCEL answers and computes the final answer (by removing artificial edges and concatenating the resulting faces).

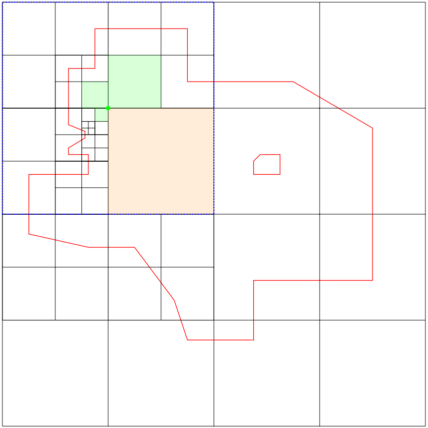


- We next discuss the **orphan cell** problem (orphan holes are handled similarly).
- A large face (e.g. the red polygon in the figure) can contain cells that do not intersect with any of the face's boundary edges (called *regular edges*).
- Such cells do not contain any label and thus we do not know which face they belong to.



Labeling orphan cells and orphan holes

- We provide an algorithm to efficiently solve the orphan cell problem.



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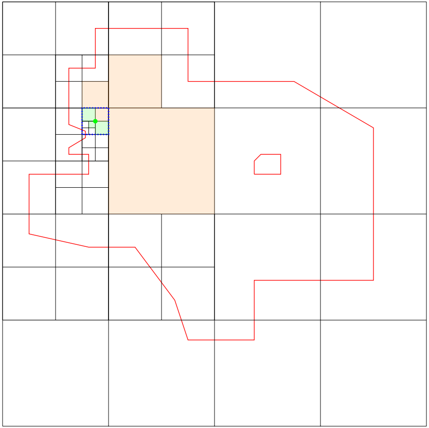

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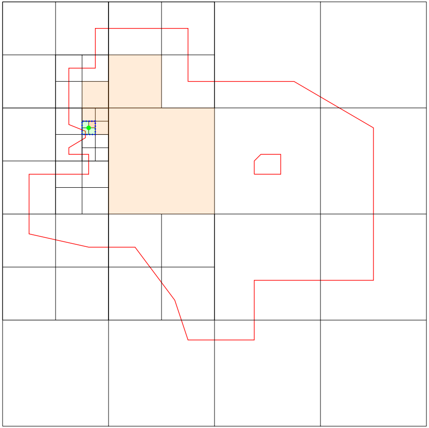


Overlay optimizations

- Optimizing for faces overlapping many cells...
  - Naive approach sends all faces that overlap a cell to a master node (that will combine them).
  - We propose an intermediate reduce processing step.
    - The user provides a level in the quadtree structure and faces are evaluated at those intermediate reducers.
  - We also consider another approach that re-partitions such faces using their labels as the key.
    - It avoids the reduce phase but implies an additional shuffle.
    - However, as we show in the experiments this overhead is minimal.

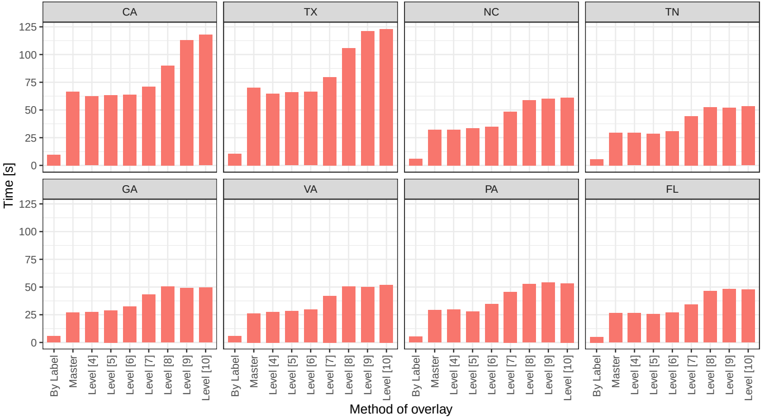
Overlay optimizations

- Optimizing for unbalanced layers...
  - Finding intersections is the most critical part of the overlay computation.
  - However, in many cases one of the layers has much more half-edges than the other.
  - Sweep-line algorithms to detect intersections run over all the edges.
  - Instead we scan the larger dataset only for the x-intervals where there are half-edges from the smaller dataset.

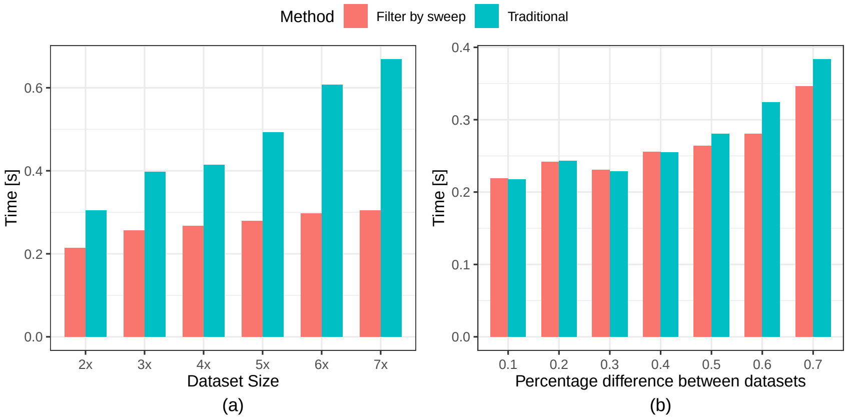
- Datasets.

Dataset	Layer	Number of polygons	Number of edges
MainUS	Polygons for 2000	64983	35417146
	Polygons for 2010	72521	36764043
GADM	Polygons for Level 2	160241	64598411
	Polygons for Level 3	223490	68779746
CCT	Polygons for 2000	7028	2711639
	Polygons for 2010	8047	2917450

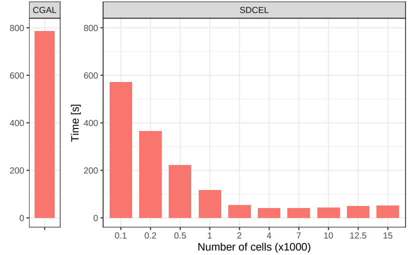
- Evaluation of the overlapping faces optimization.

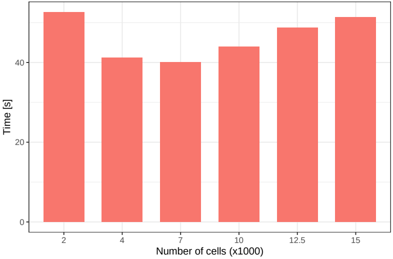


- Evaluation of the unbalanced layers optimization.

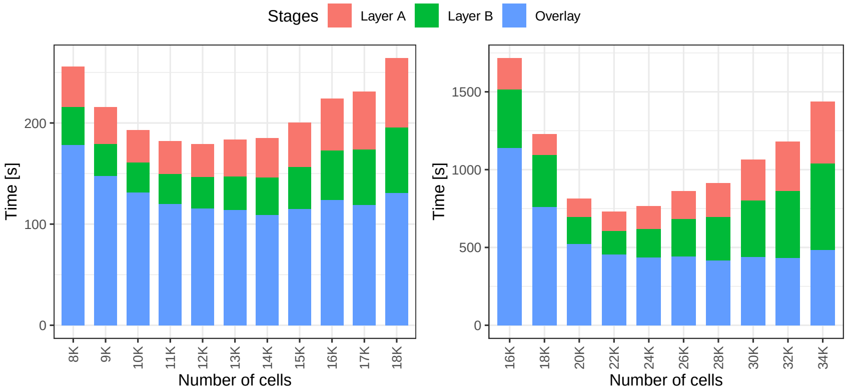


- Performance varying number of partition cells (CCT dataset).





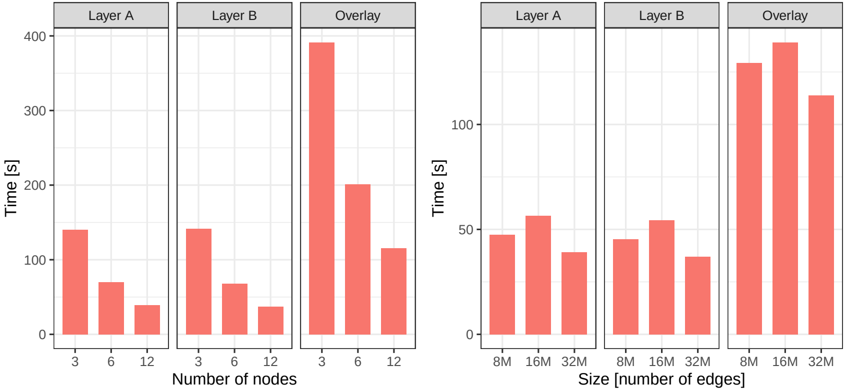
- Performance with MainUS and GADM datasets.



(a) (b)

Experimental evaluation

- Scale-up and Speed-up.



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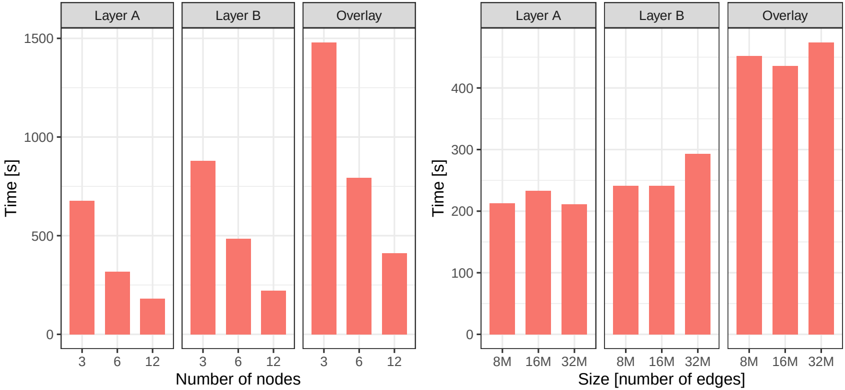
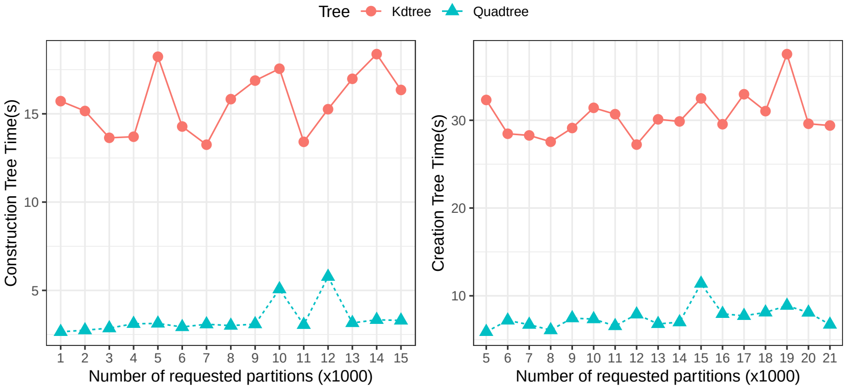


(a) (b)

- Space-oriented vs Data-oriented partitioners.



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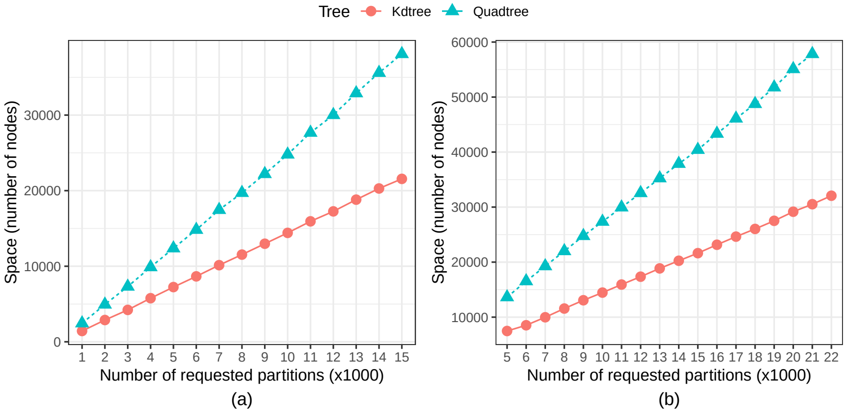

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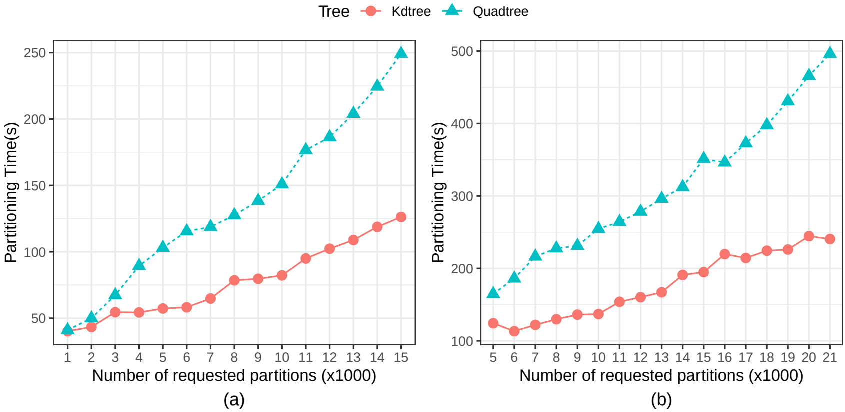

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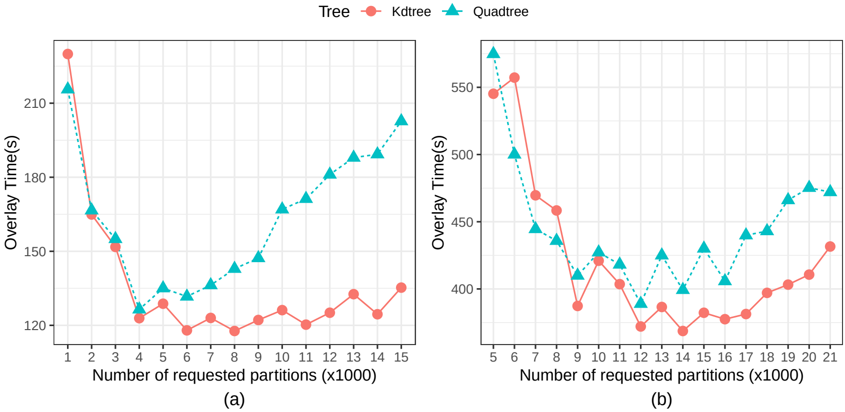

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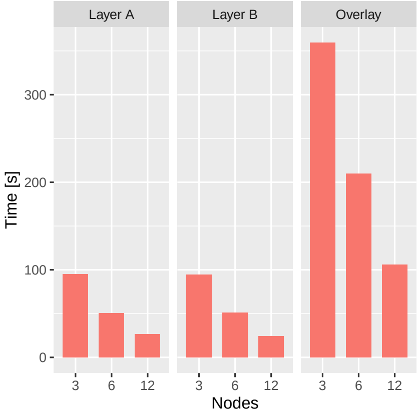
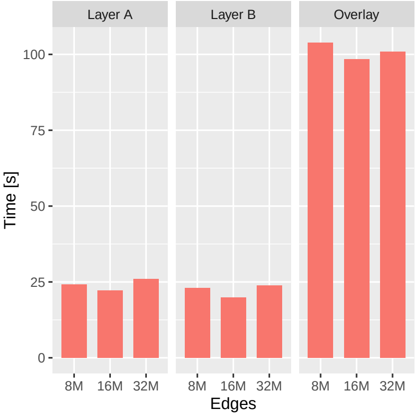




Plan

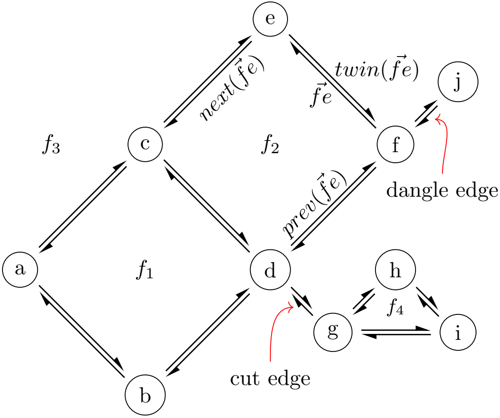
1. Scalable overlay operations over DCEL polygons layers

2. Scaling DCEL Overlay Operations to Support Dangle and Cut Edges

3. Scalable Processing of Moving Flock Patterns

- We extend the overlay DCEL approach to accept scattered and noisy line segments (including dangles and cut edges) as input, rather than being restricted to clean polygon data.
- This chapter extends the previous work in [Calderon et al, 2023][1] by building on the scalable polygonization methods presented in [Abdelhafeez et al, 2023][2].

[1] Scalable Overlay Operations over DCEL Polygon Layers.(SSTD'23).
[2] DDCEL: Efficient Distributed Doubly Connected Edge List for Large Spatial Networks. (MDM'23).


e
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f_1
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f_3
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$next(\vec{fe})$
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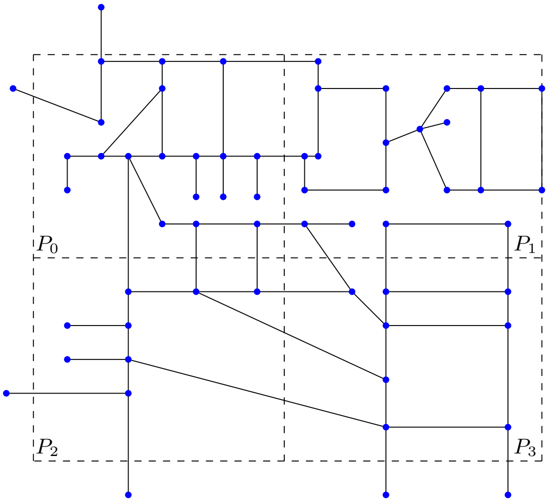
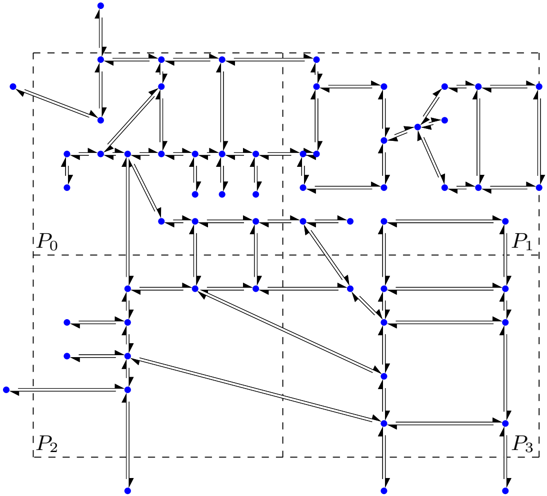
$\vec{fe}$
$prev(\vec{fe})$
dangle edge
cut edge

Dangle and cut edges



Dangle and cut edges



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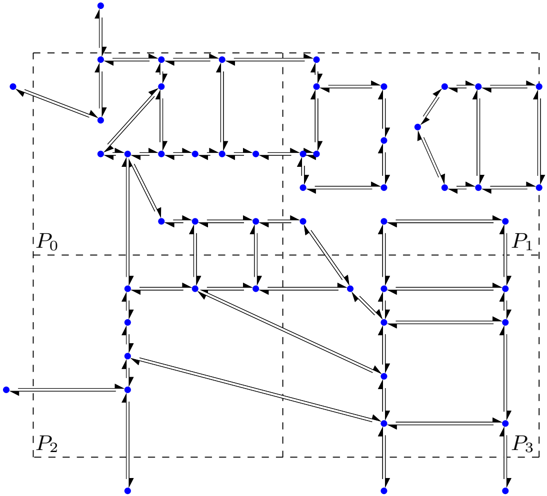
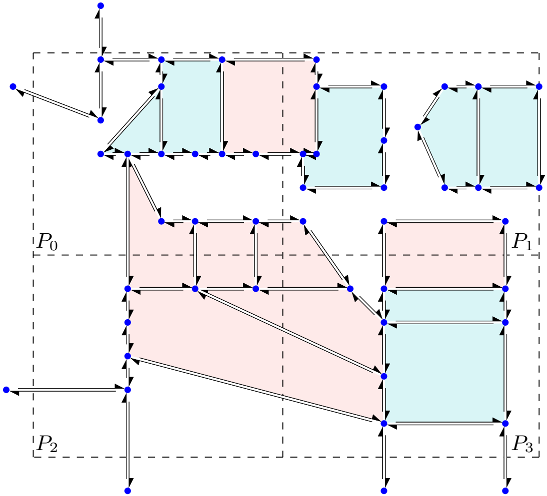
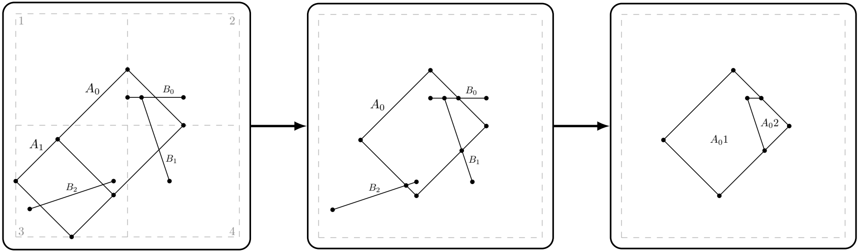


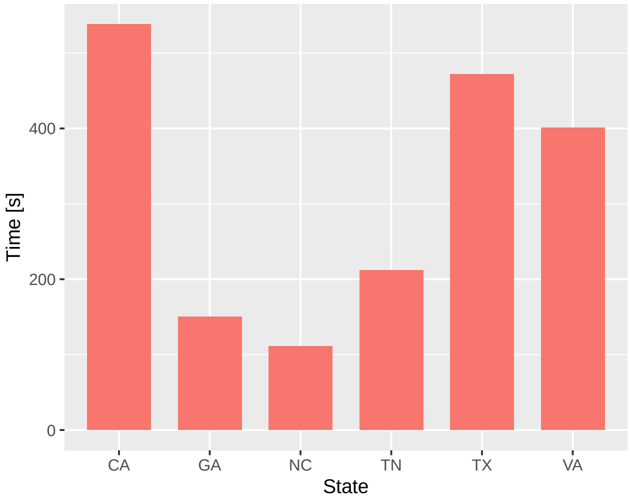

P_0
P_1
P_2
P_3



(a) (b) (c)

Dataset	Number of Polygons Layer A	Number of Edges Layer B	Result Polygons
TN	1,272	3,380,780	41,761
GA	1,633	4,647,171	49,125
NC	1,272	7,212,604	22,413
TX	4,399	8,682,950	98,635
VA	1,554	8,977,361	38,941
CA	7,038	9,103,610	96,916

Dangle and cut edges



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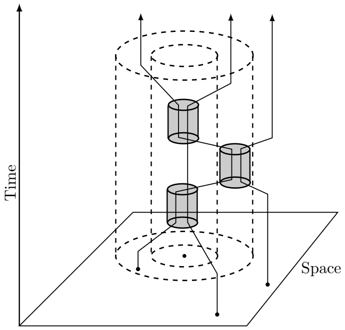
2. Scaling DCEL Overlay Operations to Support Dangle and Cut Edges

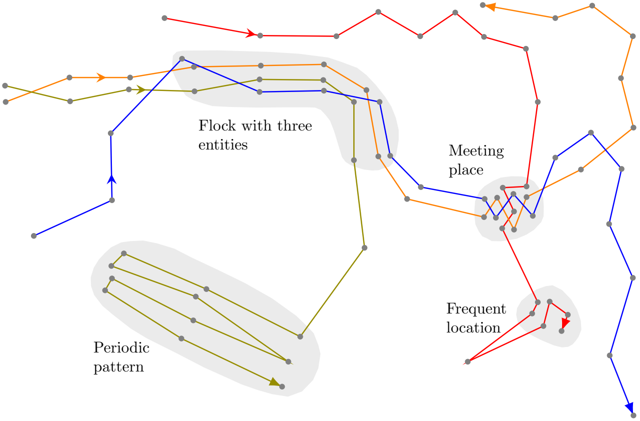
3. Scalable Processing of Moving Flock Patterns

- A spatial trajectory is a trace in time generated by a moving entity in a geographical space.
- i.e. $p_1 \rightarrow p_2 \rightarrow \cdots \rightarrow p_n$
- A trajectory is stored as a time-ordered sequence of points, $p_i = (x, y, t)$ (spatial coordinate + time instant).



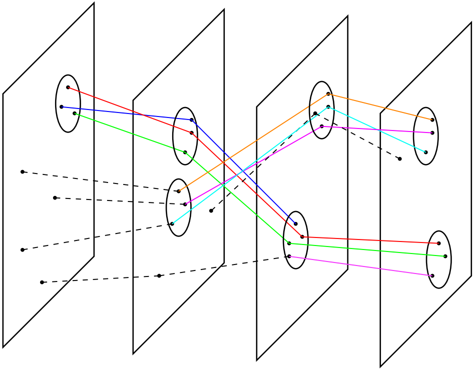
(Shoval, 2017)

Movement patterns



(Gudmundsson, et al. 2008)

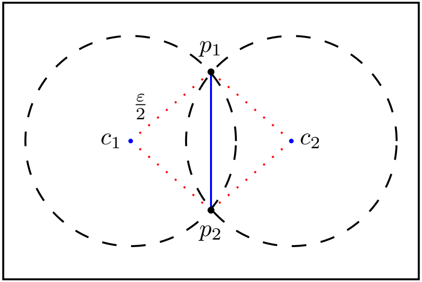
- i.e. convoys, moving clusters, swarms, gatherings, **flocks**, ...



- ε: Diameter of the circle which contains all the objects.
- μ: Minimum number of objects.
- δ: Minimum time interval the objects travel ‘together’.

Basic Flock Evaluation algorithm

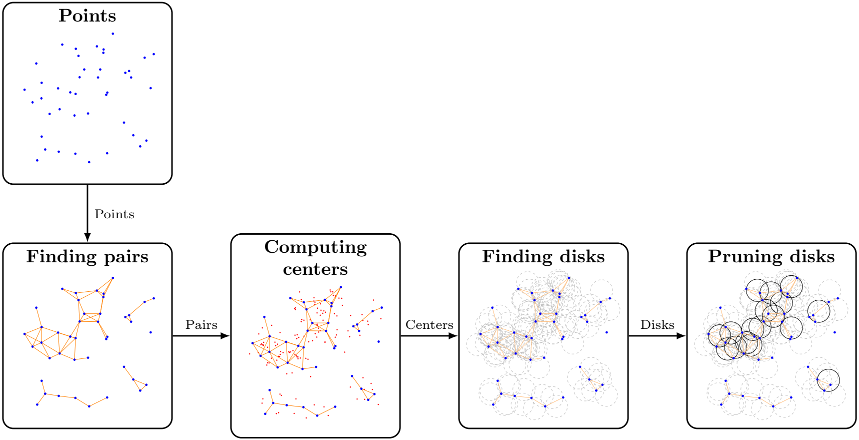
- The first polynomial-time solution for determining disk locations (Vieira, et al. 2009).
- The algorithm generates a finite set of disk locations based on a given pair of points.
- Under fixed time duration it has polynomial time complexity $O(\delta|\tau|^{(2\delta)+1})$.



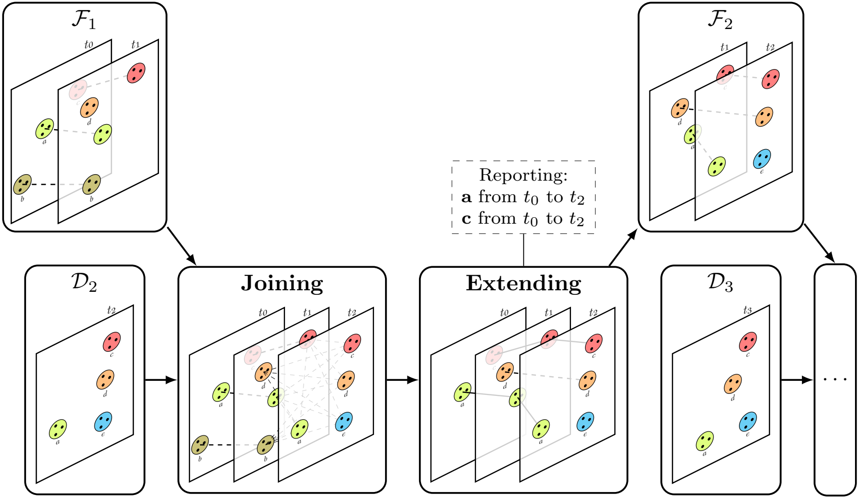
Basic Flock Evaluation algorithm

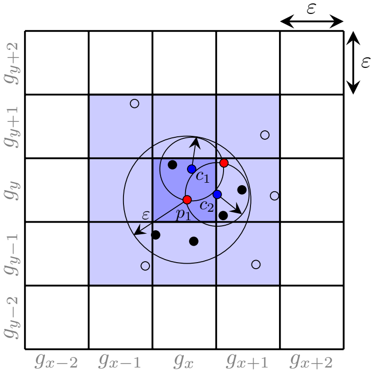
- Two main parts:
  - In the spatial domain it finds maximal disks at each time instant.
  - In the temporal domain it joins consecutive times to match set of maximal disks.

- BFE overview...

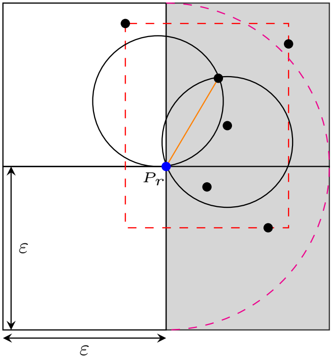


- BFE overview...





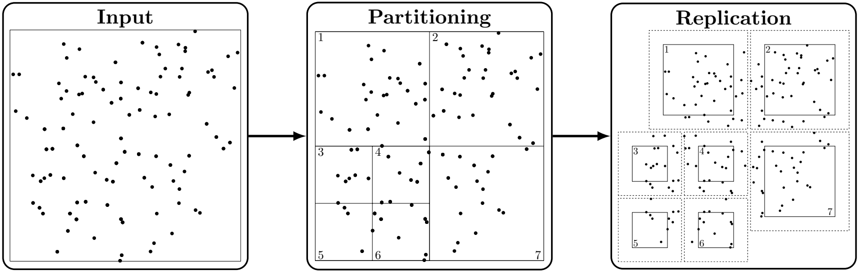
(Vieira, et al. 2009)



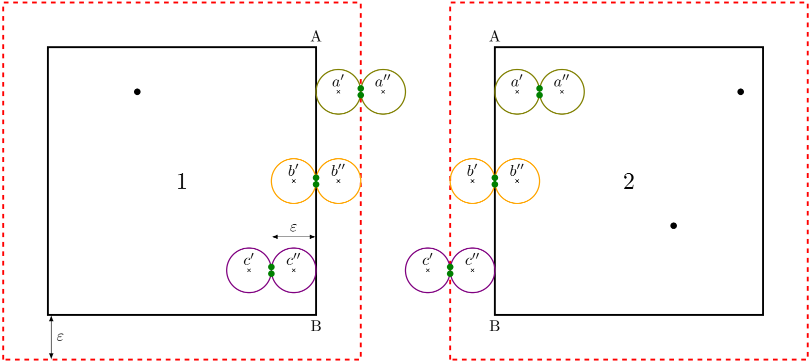
(Tanaka, et al. 2016)

- High complexity limits scalability.
- Large datasets with dense clusters of moving entities per time instant significantly impact performance.
- Specifically,
    - identifying maximal disks is hindered by the extensive number of candidates requiring pruning.
    - when parallelizing, we must address moving flocks that traverse contiguous partitions.
- We propose a parallel and scalable solution for both spatial and temporal domains.

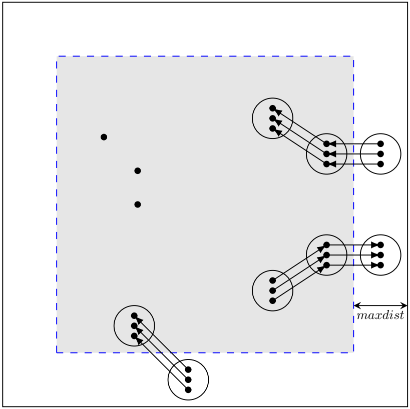
- Partitioning strategy...



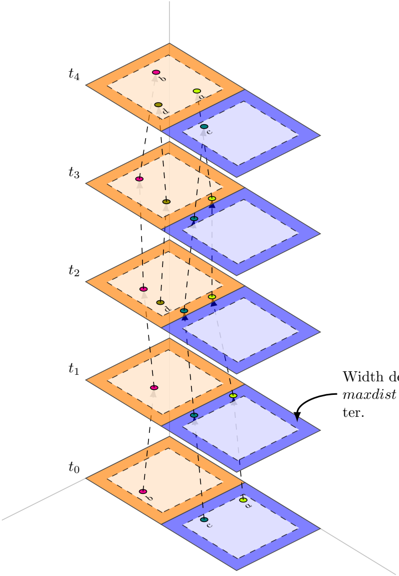
- Handling duplication...



- We introduce the *maxdist* parameter to define an area were we have to track **crossing partial flocks** (CPFs)...



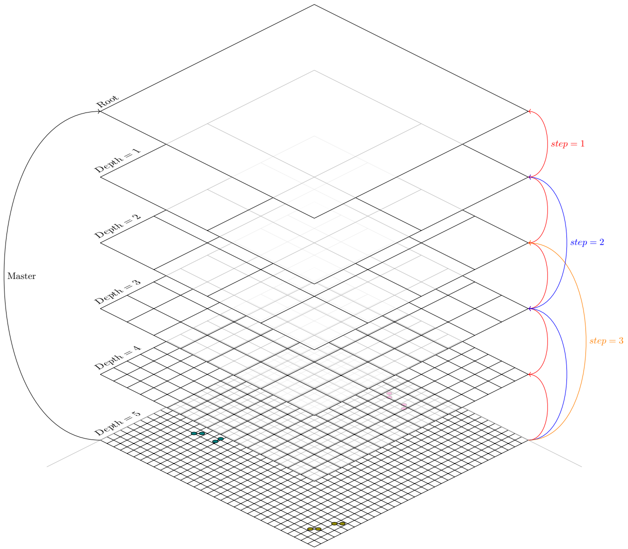
On the temporal domain



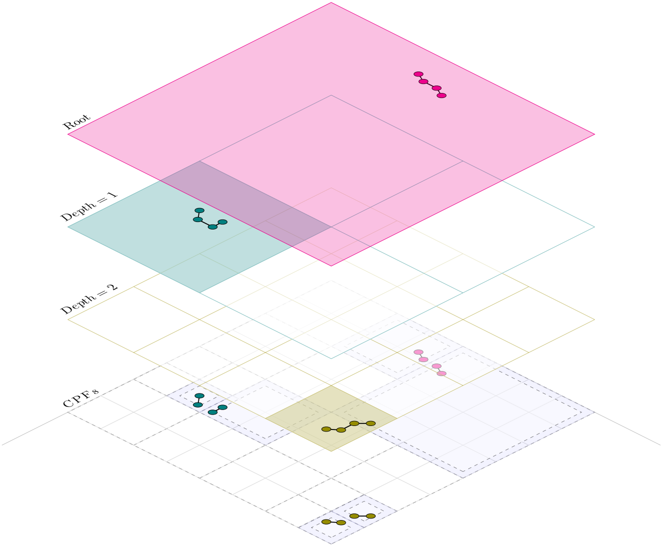
Width depends on *maxdist* parameter.

*a,b,c and d are flocks moving along time.

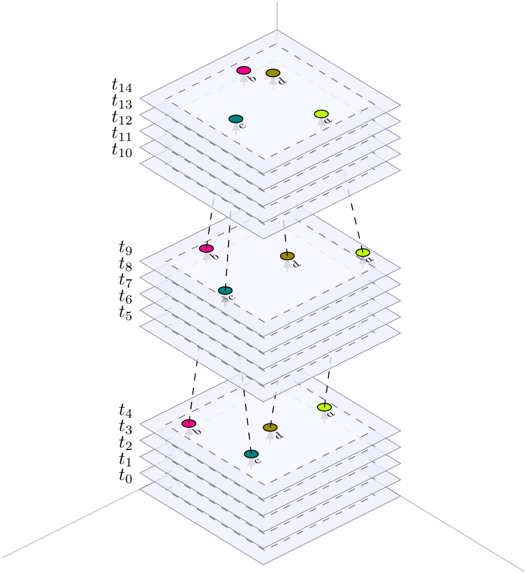
- Discovered flocks inside the safe area are ready to be reported.
- CPFs require post-processing. We propose four alternatives:
    - Master
    - By-Level
    - Least Common Ancestor (LCA)
    - Cube-based


Root
Depth = 1
Depth = 2
Depth = 3
Depth = 4
Depth = 5
Master
$step = 1$
$step = 2$
$step = 3$

On the temporal domain



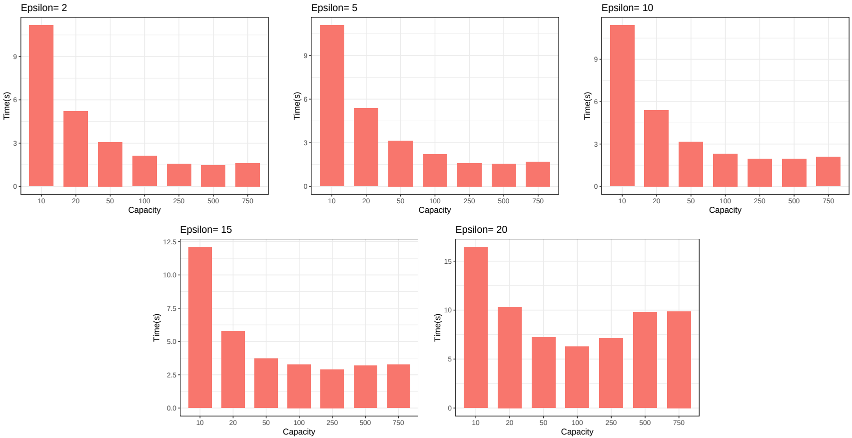
On the temporal domain



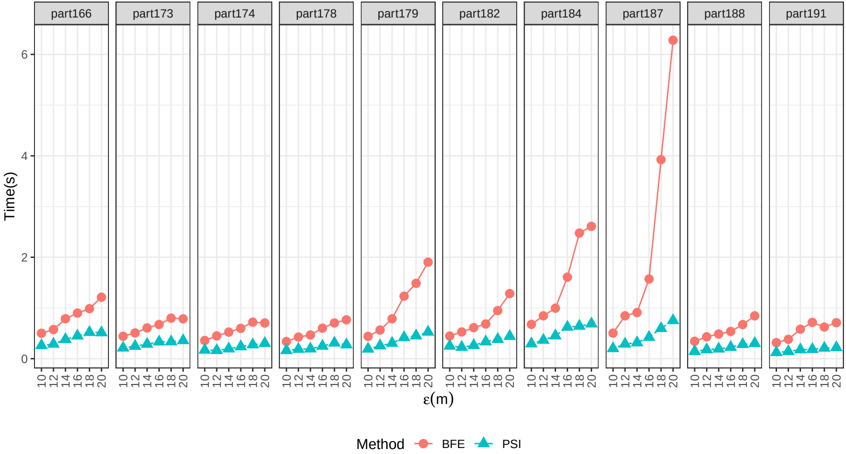
*a,b,c and d are flocks moving along time.

Dataset	Number of Trajectories	Total number of points	Maximum Duration (min)
Berlin10K	10000	97526	10
LA25K	25000	1495637	30
LA50K	50000	2993517	60

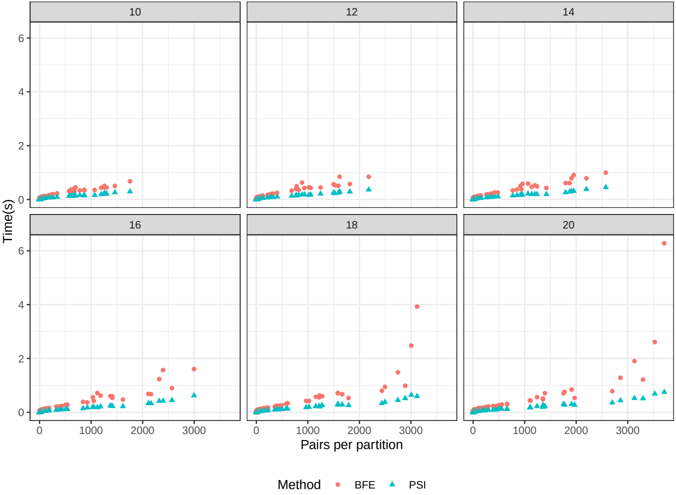
- Optimizing the number of partitions for Phase 1.



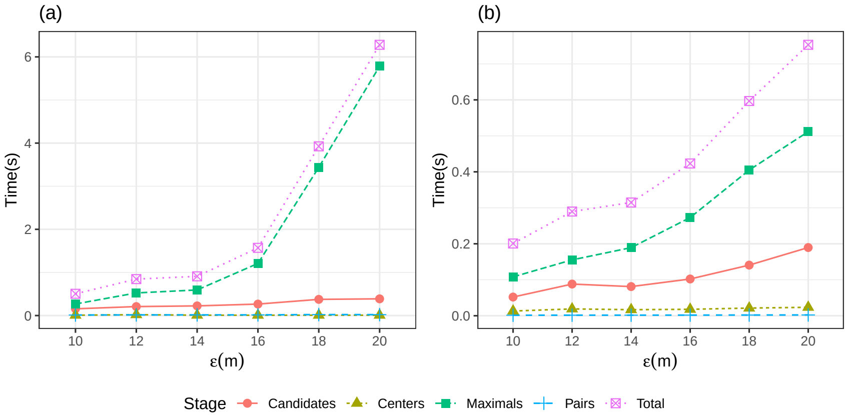
- Analyzing most costly partitions.
  - Top 10 most costly partitions.



- Analyzing most costly partitions.
  - By Pairs density..

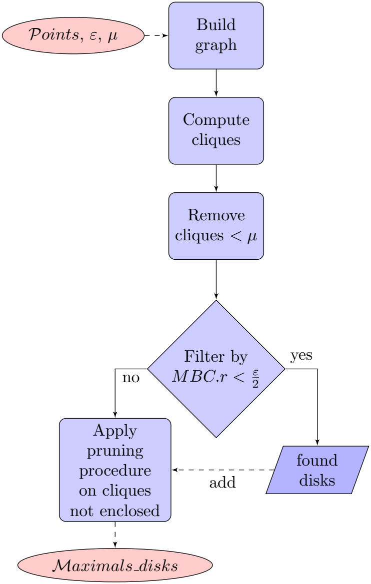


- Analyzing most costly partitions.
  - By Stages in the most costly partition [(a) BFE (b) PSI].

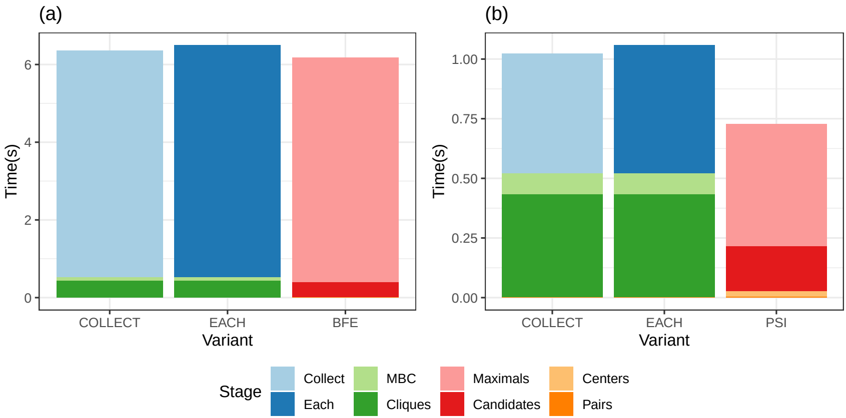


Can we reduce pruning time?

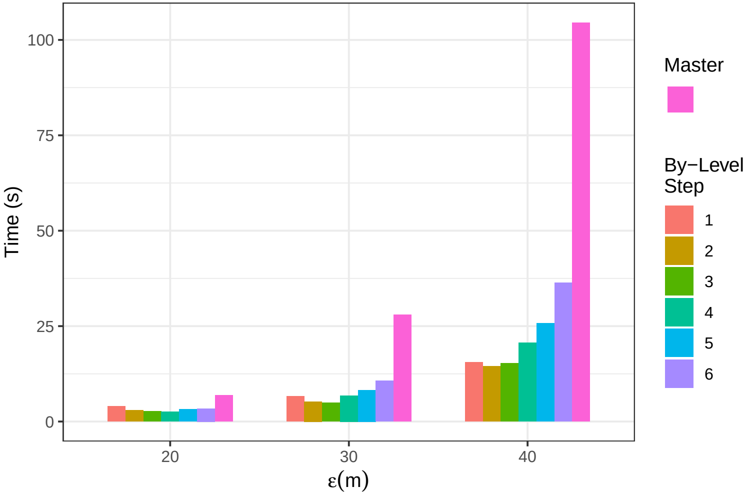
- **Maximal clique (MC)**: Given an undirected graph, a MC is a subset of vertices, each directly connected to every other in the subset, that cannot be expanded by adding additional vertices.
- **Minimum Bounding Circle (MBC)**: Given a set of points in Euclidean space, the MBC is the smallest circle that can enclose all the points.


$\mathcal{P}oints$, ε, μ
Build graph
Compute cliques
Remove cliques $< \mu$
Filter by $MBC.r < \frac{\varepsilon}{2}$
yes
no
Apply pruning procedure on cliques not enclosed
found disks
add
$\mathcal{M}aximals\_disks$

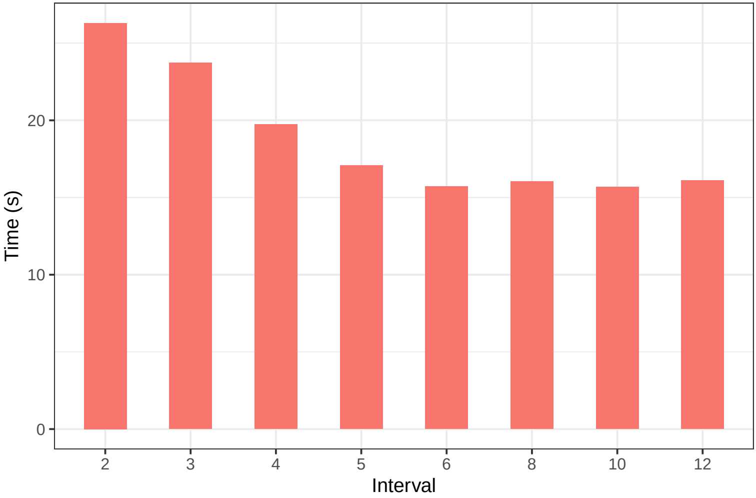
- Phase 1 variants performance [(a) vs BFE (b) vs PSI].



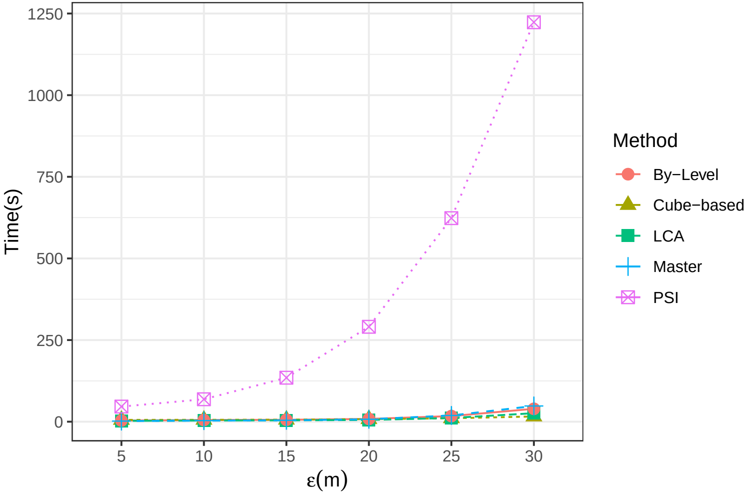
- Finding best *step* value for By-Level alternative.



- Finding best *interval* value for Cube-based alternative.

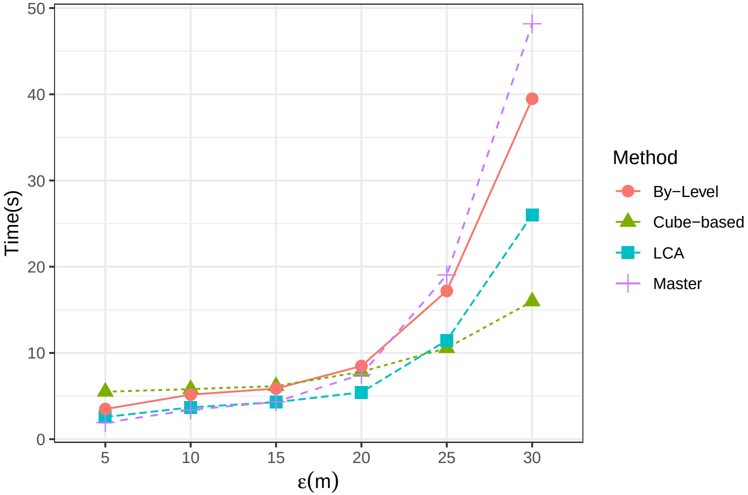


- Scalable alternatives vs standard PSI.

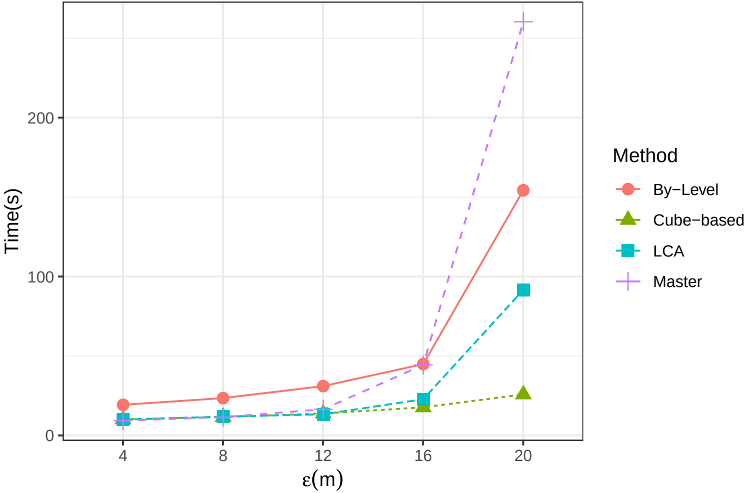


Experiments

- Scalable alternatives in LA25K dataset.



- Scalable alternatives in LA50K dataset.



Thank you!