# Efficient Skyline Maintenance
for Streaming Data
with Partially-Ordered Domains

Yuan Fang
Institute for Infocomm Research

Chee-Yong Chan
National University of Singapore

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Outline

- Introduction
- STARS
- STARS$^+$
- SkyGrid
- Experiments
- Conclusion

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- Introduction
  - Concept
  - Problem settings
- STARS
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Definitions

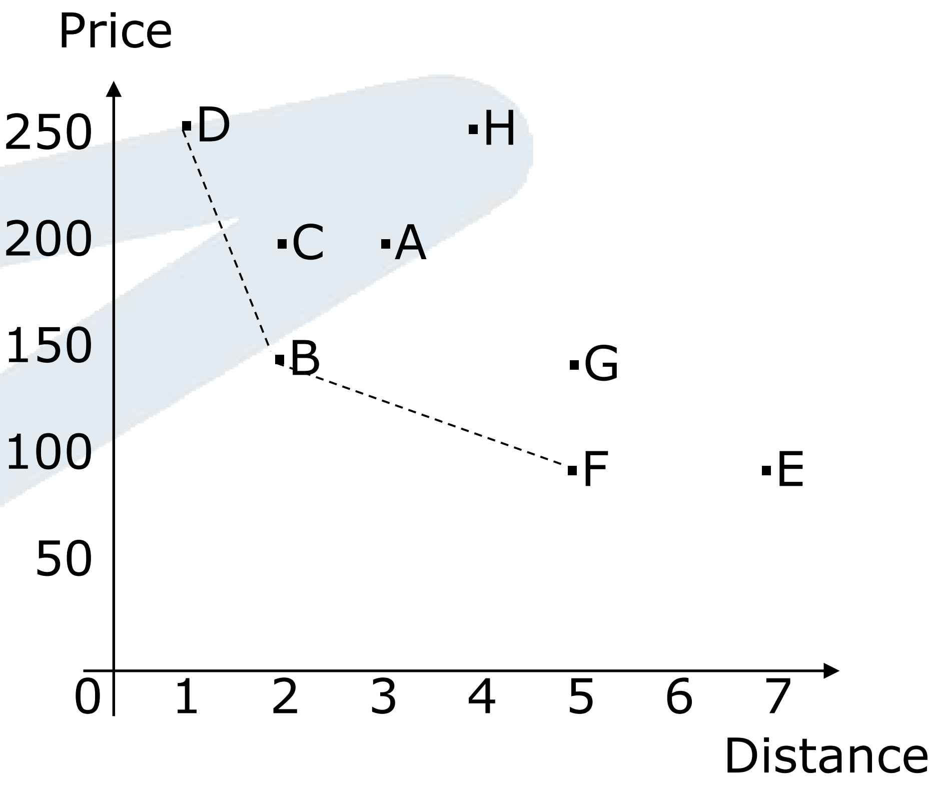
- A tuple X **dominates** Y iff for a set of relevant attributes A:
  - (1) X is better than or equal to Y in every attribute in A; and
  - (2) X is better than Y in at least one attribute in A.
- The **skyline** consists of:
  - all tuples not dominated by any other tuple.

Hotel example

- Tourist looking for a hotel
  - Cheap
  - Close to the city
- Relevant attributes
  - Price
  - Distance
- A hotel X dominates Y iff:
  - (1) X.price ≤ Y.price; and
  - (2) X.distance ≤ Y.distance; and
  - (3) at least one of (1) and (2) is strict.

Hotel example

Hotel	Price ($)	Distance to city (km)
A	200	3
B	150	2
C	200	2
D	250	1
E	100	7
F	100	5
G	150	5
H	250	4



Data domain

- Total-order
  - A linear ordering of every value
  - E.g., price, grade
- Partial-order
  - Lack a total linear ordering
  - Values can be comparable and incomparable
  - Good for hierarchies, preferences, intervals
  - E.g., user prefers yellow to red and blue to red, but there is no preference between yellow and blue.

Query context

- Offline
  - For disk-resident data (relatively static)
  - Answer query on demand
- Online
  - For streaming data (fast-changing)
  - Infeasible to answer the query from scratch
  - Maintain a skyline continuously

Problem settings

- Data domain: partially-ordered
- Query context: streaming
  - Count-based sliding window model
  - Maintain a buffer of size N
  - New tuple inserted into buffer
  - Oldest tuple deleted from buffer
- Baseline: Streaming Arrangment Skyline (STARS)
- Contributions
  - STARS$^+$
  - SkyGrid

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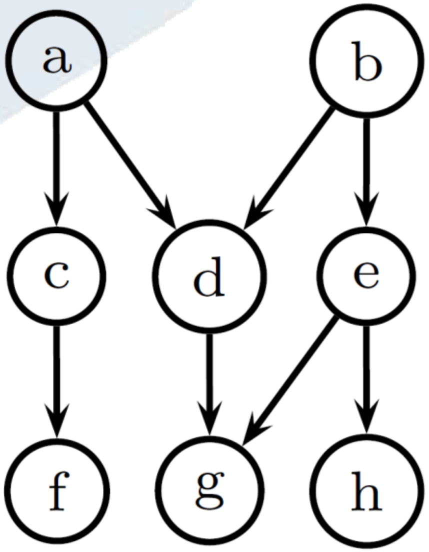
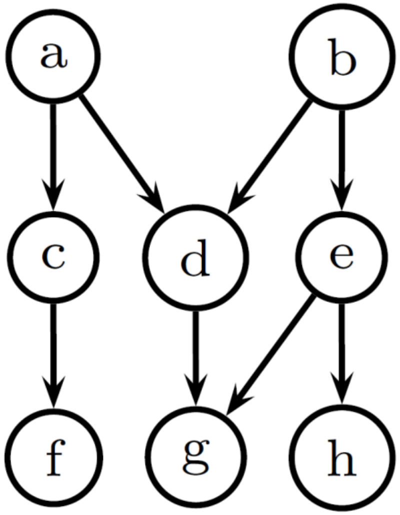
Domain representation

- Directed acyclic graph (DAG)
- Vertex – values
- Edge – relationship
  - a dominates d
  - d dominates g
  - d, e incomparable



Domain transformation

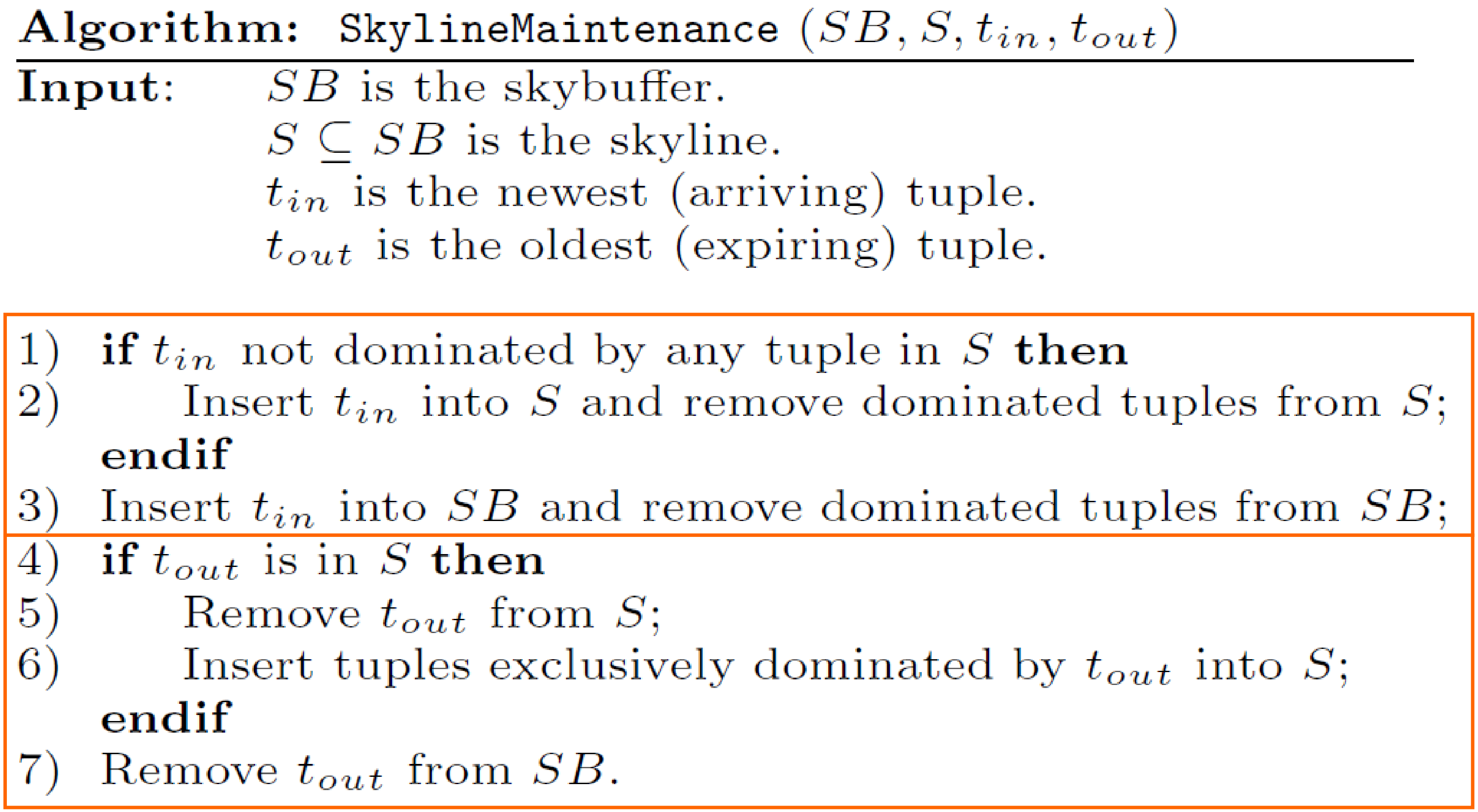
- Values → *topological sorting* orders
- A topological sort of a DAG is:
  - A linear ordering of all the vertices
  - For any directed edge, source vertex is always listed before the destination vertex
  - Denote vertex v's position by r(v)
- If r(v) ≥ r(v'), v cannot dominate v'
  - Inverse is not true
- Example: a, b, c, …, h
  - r(c) > r(a)
  - c does not dominate a



SkyBuffer

- Discard irrelevant tuples from buffer
- Given t’ and t, if:
  - (1) t’ is younger than t, and
  - (2) t’ dominates t.
- t can never get promoted to the skyline
- t is irrelevant
- SkyBuffer: the relevant part of the buffer

Skyline maintenance



Algorithm: `SkylineMaintenance` (SB, S, t_{in}, t_{out})

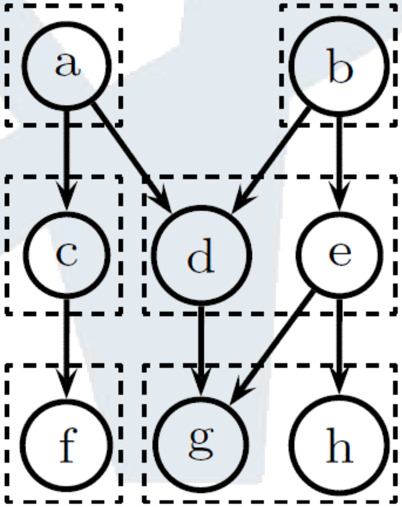
Input: SB is the skybuffer.
$S \subseteq SB$ is the skyline.
t_{in} is the newest (arriving) tuple.
t_{out} is the oldest (expiring) tuple.

```
if $t_{in}$ not dominated by any tuple in $S$ then
    Insert $t_{in}$ into $S$ and remove dominated tuples from $S$;
endif
Insert $t_{in}$ into $SB$ and remove dominated tuples from $SB$;
if $t_{out}$ is in $S$ then
    Remove $t_{out}$ from $S$;
    Insert tuples exclusively dominated by $t_{out}$ into $S$;
endif
Remove $t_{out}$ from $SB$.
```

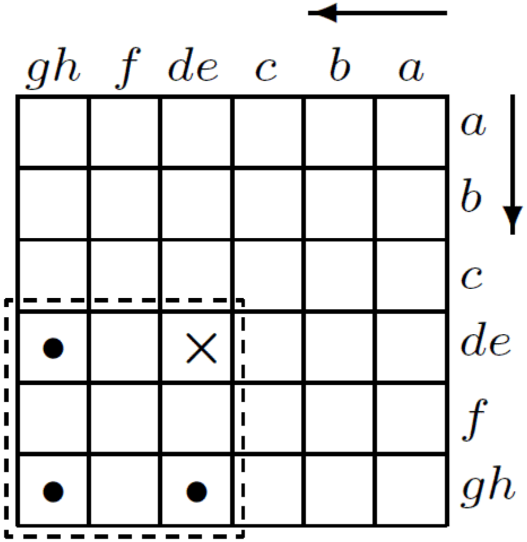
Buffer organization

- Main query: to find tuples dominated by a query tuple
- Multi-dimensional grid
- Value grouping for scalability
- Focused search

(a) DAG for $\mathcal{D}$



(b) Skybuffer grid



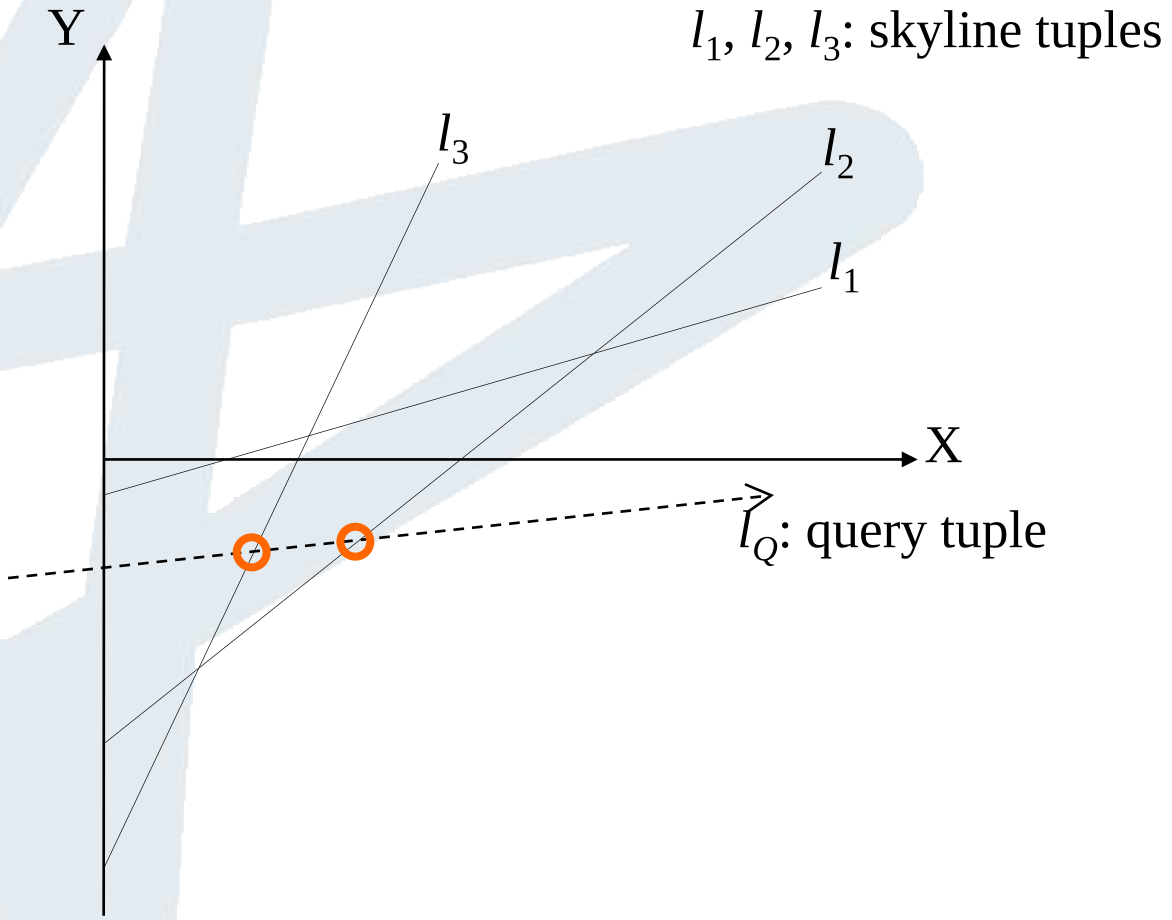
Skyline organization

- Main query: to check whether any tuple dominates a query tuple
- Each tuple mapped to a line

  $$y = r(a) \cdot x - r(b),$$

  where a, b are two arbitrarily attributes
- Skyline: a geometric arrangement
  - Only need to check lines intersecting with the query line on the positive half of the x-axis
  - Doubly-Connected-Edge-List (DCEL)

Progressive query of skyline tuples



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- STARS
- STARS$^+$
  - Dominating Tuple
  - Empty Cell
  - Minmax
- SkyGrid
- Experiments
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STARS$^+$

- An improved STARS
- Drawbacks of STARS
  - Expensive exclusive dominance checking
  - Sparse buffer grid
  - Inefficient geometric arrangement
    - Arbitrary tuple-line mapping
    - Unknown pruning power
    - Quadratic space complexity

Exclusive dominance checking

- Required for every tuple in the buffer dominated by an expiring skyline tuple
- Each checking requires a query to skyline
- Many such queries in a single update when a skyline tuple expires

Dominating Tuple optimization

- Eager approach
  - When a tuple comes in, find all dominating skyline tuples
- Lazy approach
  - Defer computation until needed
- **Semi-eager approach**
  - Only remember one dominating tuple
  - Virtually no extra computation
  - "Dominating Tuple" optimization

Complexity analysis

- Time complexity for a given buffer tuple
- s: size of the skyline.
- Assume independent attribute values.
- Assume exclusive dominance checking is required for every expiring skyline.

	Lazy	Eager	Semi-eager
Exclusive dominance checking	O(s)	O(1)	O(ln(s))
Pre-computation overhead	O(1)	O(s)	O(1)

Sparse buffer grid

- Most of the tuples in the buffer are irrelevant
- Only SkyBuffer affects skyline
- The buffer grid is very sparse
  - Assume independent attribute values
  - SkyBuffer size: $O(\ln^d N)$
  - Density: $\rho = O(\ln^d N/g^d)$
  - E.g., $\rho = 0.022$ when $N = 10^5$, $d = 4$, $g = 30$
  - Most of the cells are empty

d: # of dimensions
g: # of buckets/dim
N: buffer size

A*STAR I²R

Empty Cell optimization

- Maintain d – 1 additional structures (index grids)
  - Keep track of # of tuples in the grid regions.
  - Each index grid C_i ($1 \le i \le d-1$) is i-dimensional
  - C_i maintains # of tuples in the regions identified by first i dimentions
- During Focused search
  - Candidate cells are examined by enumerating the cell coordinates
  - Early termination of the enumeration if an empty region is detected

Problems in geometric arrangement

- d > 2 is common in real life
- Arbitrary attribute selection in line mapping
  - Performance gap can exceed 20%
  - No heuristic to optimize this selection
- Only utilize two attributes for mapping
  - Intuitively, using more attributes is likely to provide better pruning power

Minmax optimization

- Consider a d-tuple $t = (a_1, \dots, a_d)$
- Minmax maps t to the line

  $y = C \cdot x - D$, where

  $C = \max(r(t.a_1), \dots, r(t.a_d))$,

  $D = \min(r(t.a_1), \dots, r(t.a_d))$
- Proven correctness for pruning lines
- An intuitively better heuristic
  - Utilize all attributes
  - Two extreme values may help prune more

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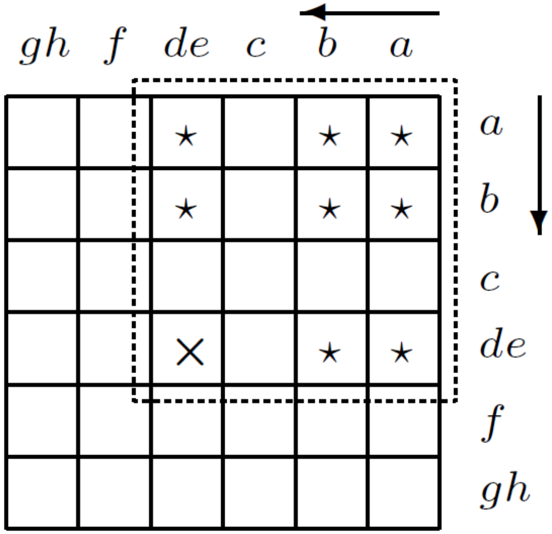
Why geometric arrangement

- Pruning ratio
  - Assume independent attribute values
  - Suppose no “progressiveness”
  - Proven to be less than ½
- Space complexity
  - Quadratic space $O(s^2)$

SkyGrid

- Eliminate geometric arrangement
- SkyGrid: everything in one place
  - Both SkyBuffer and skyline in the same grid
  - Distinguish skyline with a status bit
  - Utilize two sets of index grids for Empty Cell optimization
- Allows focused search
  - On the other direction



Benefits of SkyGrid

- Potentially higher pruning ratio
- No extra space required for skyline
  - Except for the linear requirement of status bit
- Simplified skyline maintenance
  - No manipulation of geometric arrangment (O(s))
  - Only update a status bit (O(1))

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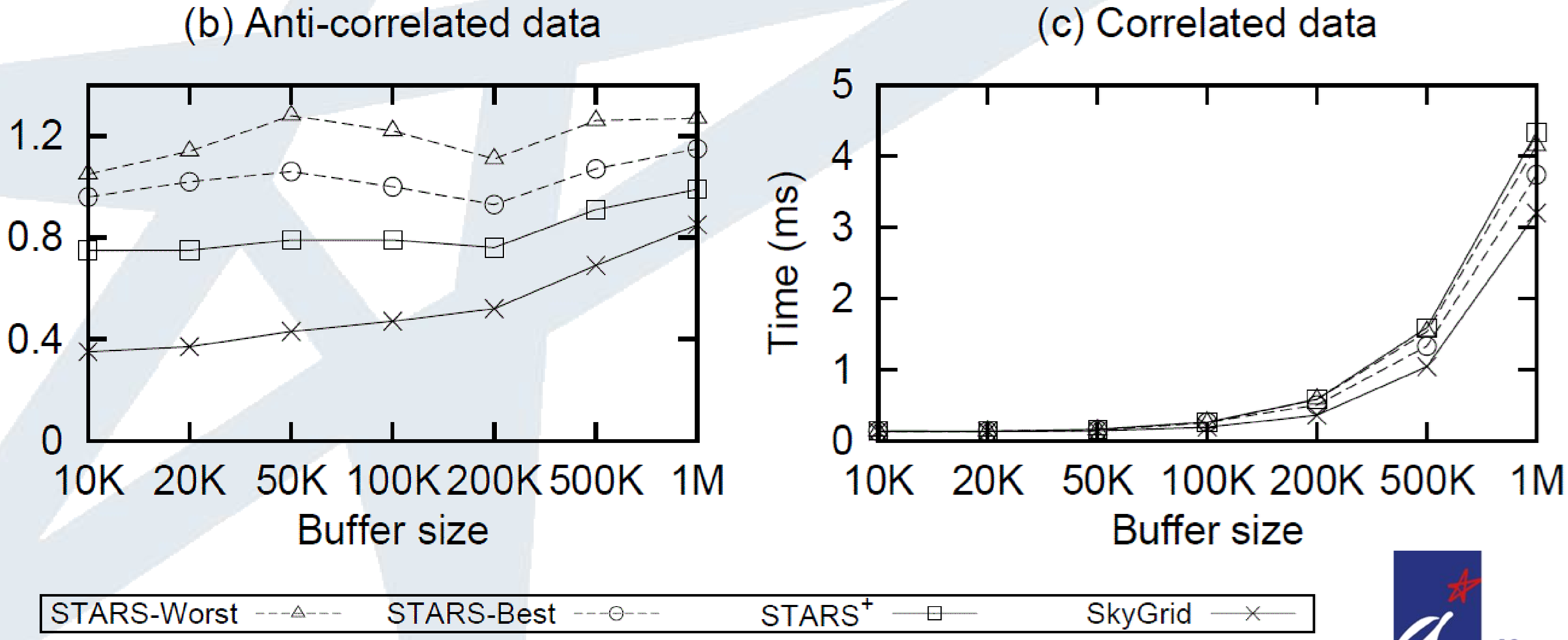
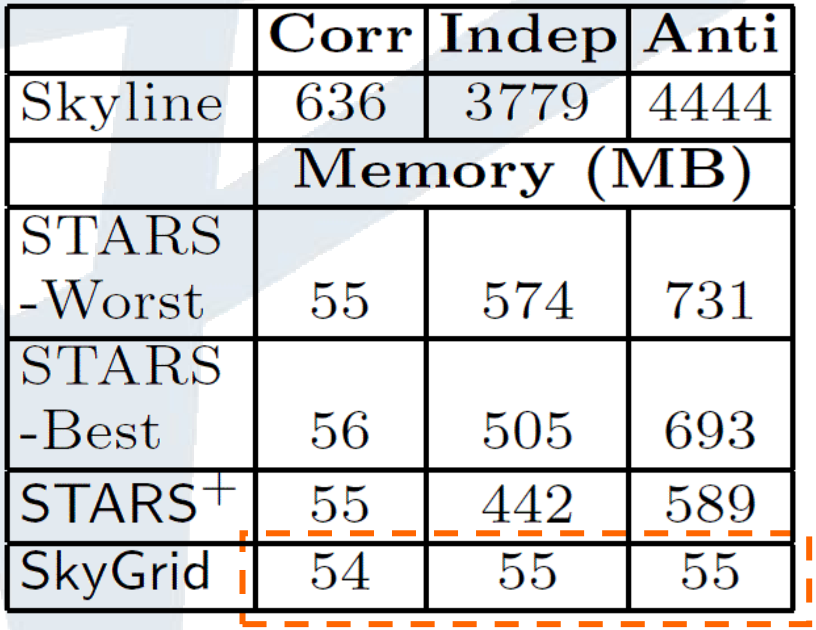
Amortized update time

- STARS-Best, STARS-worst, STARS$^+$, SkyGrid
- With two orthogonal optimizations in all (DT/EC)



Space requirement

- Buffer size = 100K
- SkyGrid uses the least memory



	Corr	Indep	Anti
Skyline	636	3779	4444
	Memory (MB)		
STARS -Worst	55	574	731
STARS -Best	56	505	693
STARS$^+$	55	442	589
SkyGrid	54	55	55

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Conclusion

- Two new approaches for streaming data on partially-ordered domains
  - STARS$^+$
  - SkyGrid
- Both outperforms STARS
- The surprising result: SkyGrid, being the simplest, is the best approach.

Questions?

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