Everything you always wanted to know about multicore graph processing but were afraid to ask

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Graphs are everywhere

Social networks

Item recommendation

Search and website ranking

The maze of graph analytics platforms

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	In-memory	Out-of-core
Single machine	Ligra Polymer Galois	GraphChi X-Stream GridGraph Mosaic
Distributed	Pregel Powergraph PowerLyra Gemini	Chaos

The maze of graph analytics platforms

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	In-memory	Out-of-core
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Everything you always wanted to know…

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What techniques work and why?

Why is our work different?

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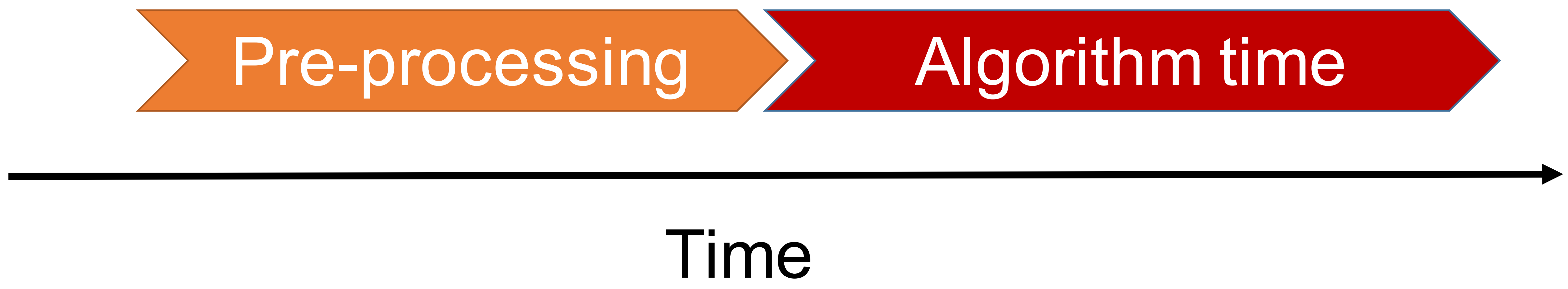
- End-to-end evaluation

- Comparison of techniques, rather than systems

End-to-end evaluation

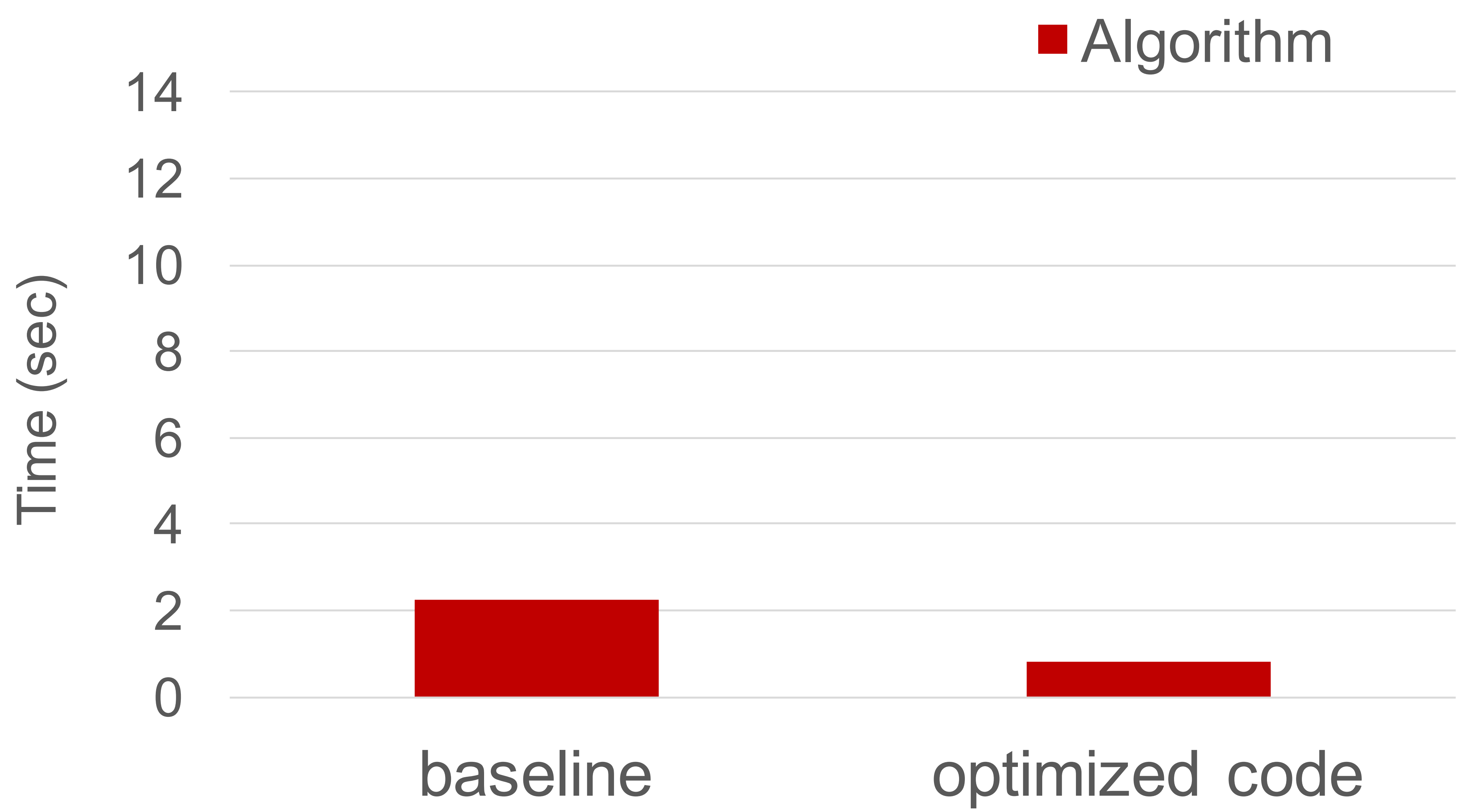
- Executing the algorithm is only one piece of the puzzle



End-to-end time = Pre-processing + Algorithm time

Motivation: Why end-to-end time?

- BFS on Twitter [Ligra]



Motivation: Why end-to-end time?

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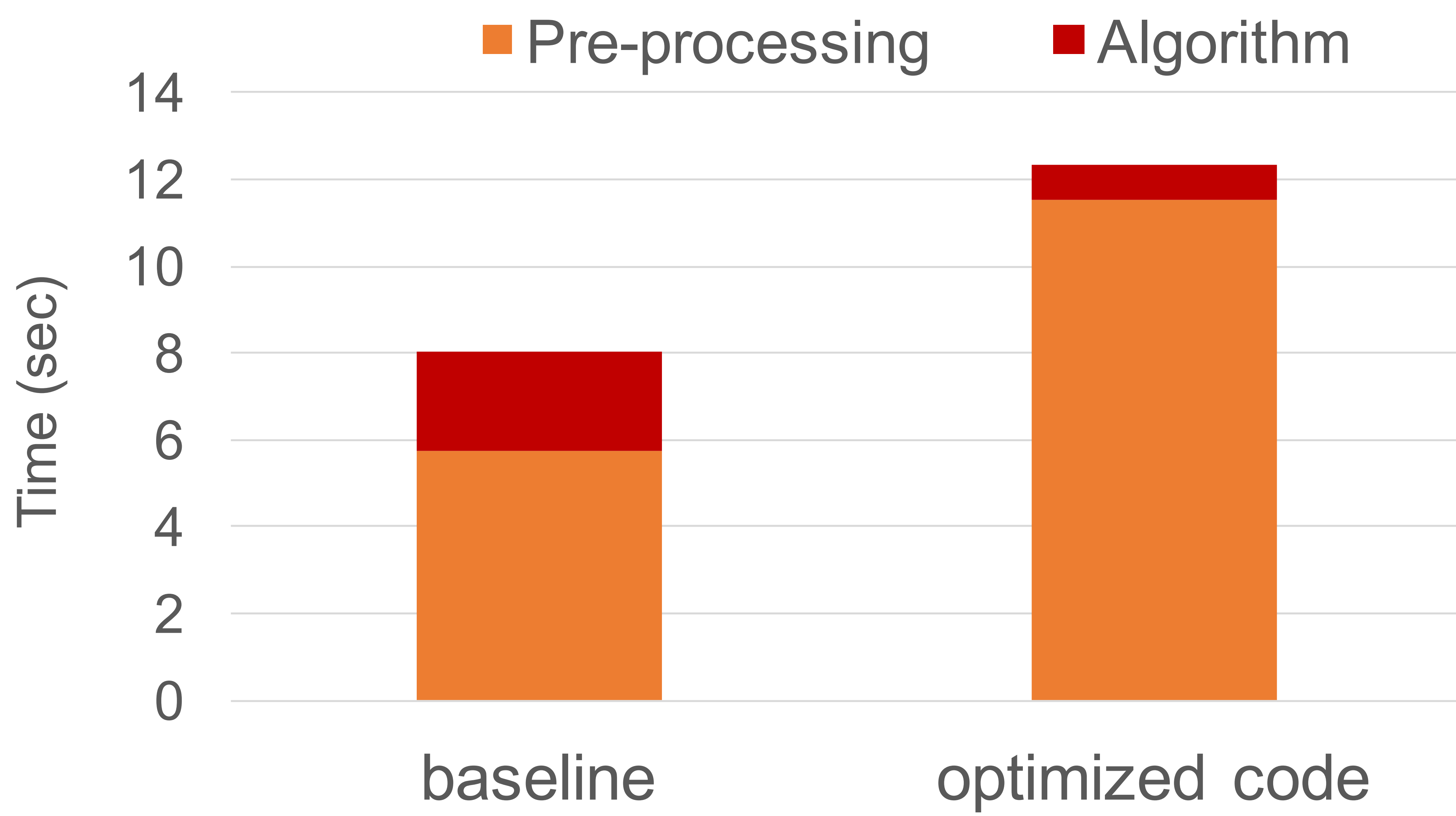

Need to understand the trade-off in end-to-end time!

Comparison of techniques not systems

- Implement techniques from different systems within **one system**

- Evaluation of techniques in isolation
  - Not constrained by system defined API

- Implementation is comparable/better than the original system

Questions we want to answer:

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Pre-processing

- How to represent the graph?
- Cost of creating the representation?
- What data layout is best?

Algorithm

- Can we improve cache locality?
- Should we optimize for NUMA?
- Information flow: **push**, **pull** or a **both**?

The answers depend on:

- Algorithm – differ in # of active vertices per iteration
  - Only a subset active: **BFS**
  - Entire graph active: **Pagerank**, **SpMV**…
- Graph shape
  - Social networks (power law) graphs
  - **Synthetic graph; 1B edges 64M vertices**
  - Stored as edge array

Questions we want to answer:

Pre-processing

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Algorithm

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Graph representation

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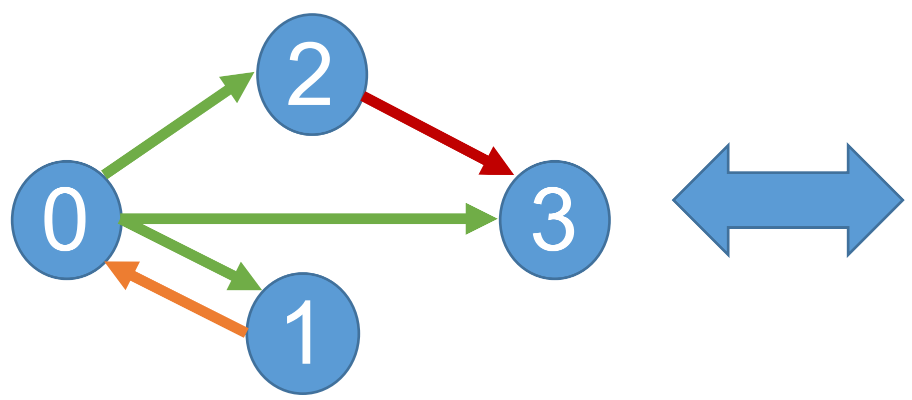

Edge array

0 - 2	2 -3	0 - 3	1 - 0	0 - 1

✓ Layout is the same as input – no pre-processing

x To locate edges of a vertex, need to read all edges

Adjacency list: outgoing edges

0 →	2	3	1
1 →	0		
2 →	3		
3			

x Pre-processing to group edges by vertex

✓ Easy to locate edges of a particular vertex

Questions we want to answer:

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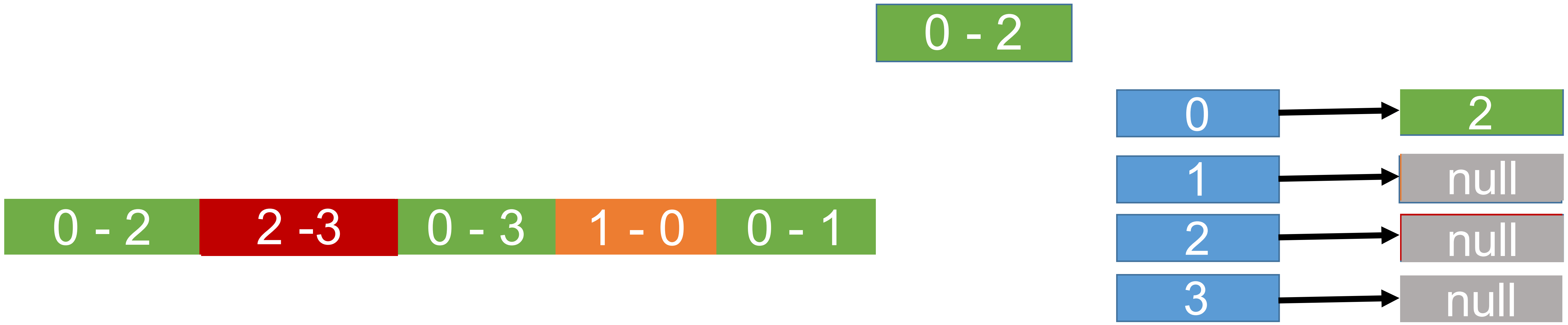
Pre-processing

- ✓ How to represent the graph?
  - Adjacency lists
  - Edge arrays
- **Cost of creating the representation?**
- What data layout is best?

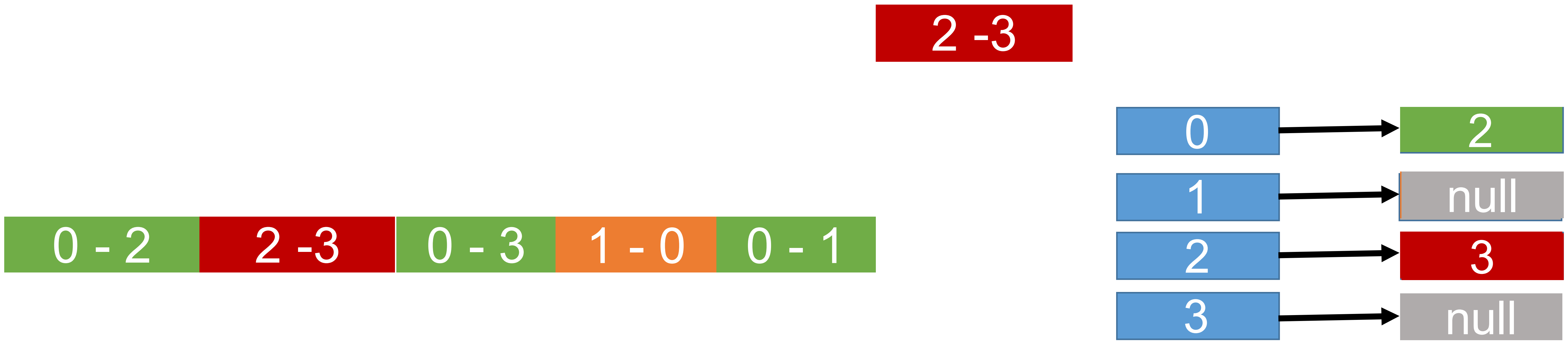
Algorithm

- Can we improve cache locality?
- Should we optimize for hardware?(NUMA)
- Information flow: **push**, **pull** or a **both**?

Creating adjacency lists using dynamic allocation



Creating adjacency lists using dynamic allocation



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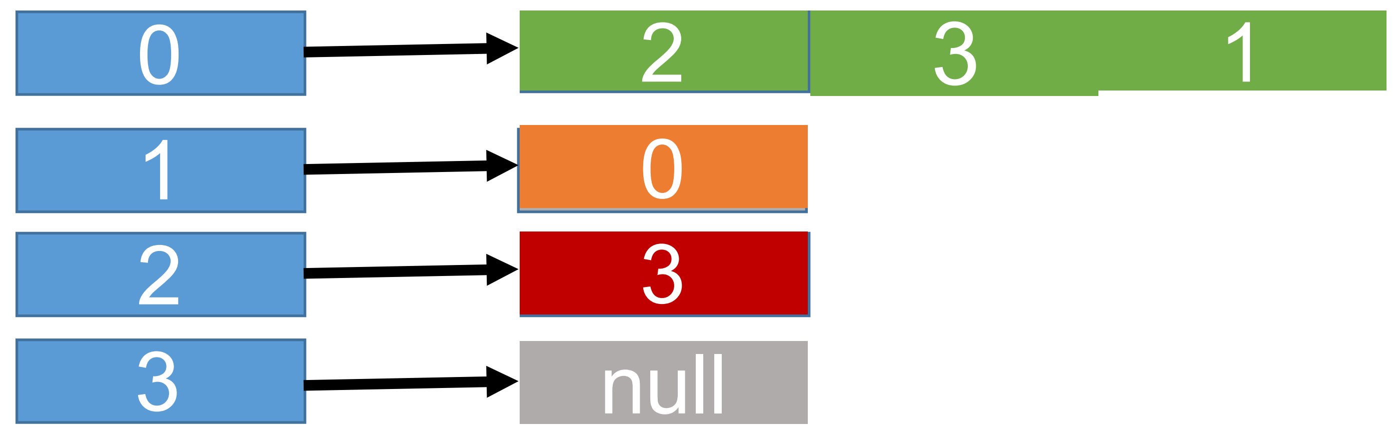
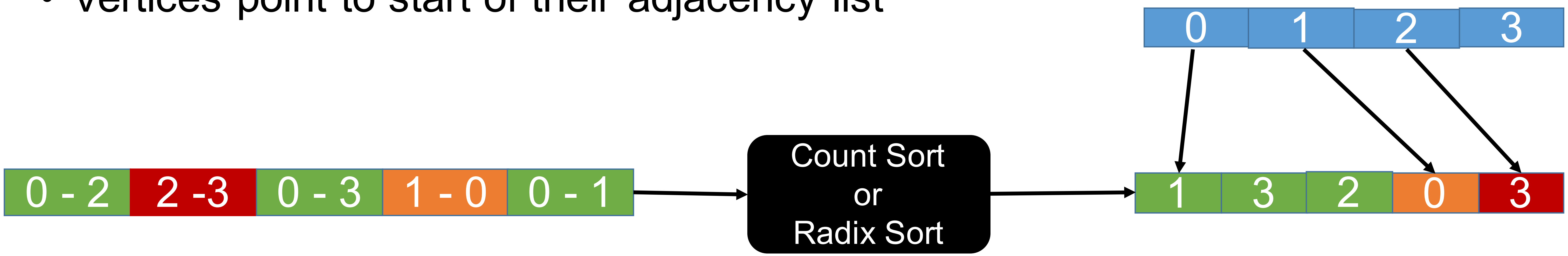


- Frequent reallocations
- Adjacency lists spread out in memory

Creating adjacency lists using sorting

- Load edge array into memory
- Sort by source or destination
- Vertices point to start of their adjacency list



✓ Avoid reallocations

✓ Adjacency lists contiguous in memory

Creating adjacency lists using sorting

- Load edge array into memory
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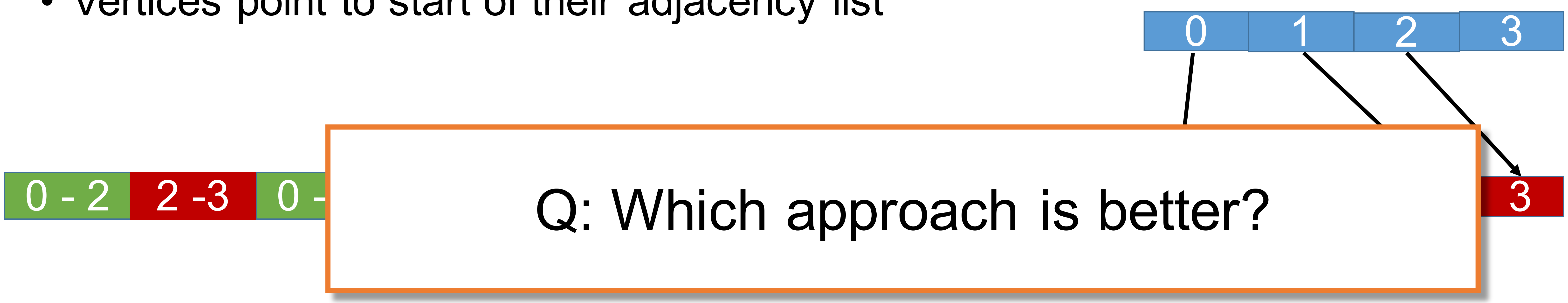

Q: Which approach is better?

✓ Avoid reallocations

✓ Adjacency lists contiguous in memory

Which pre-processing method is better?

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Pre-processing technique	Time (sec)	LLC misses
Dynamic	15.0	69%
Count sort	13.5	71%
Radix sort	**4.0**	**26%**

Radix sort low LLC miss rate => 3.5X better

Questions we want to answer:

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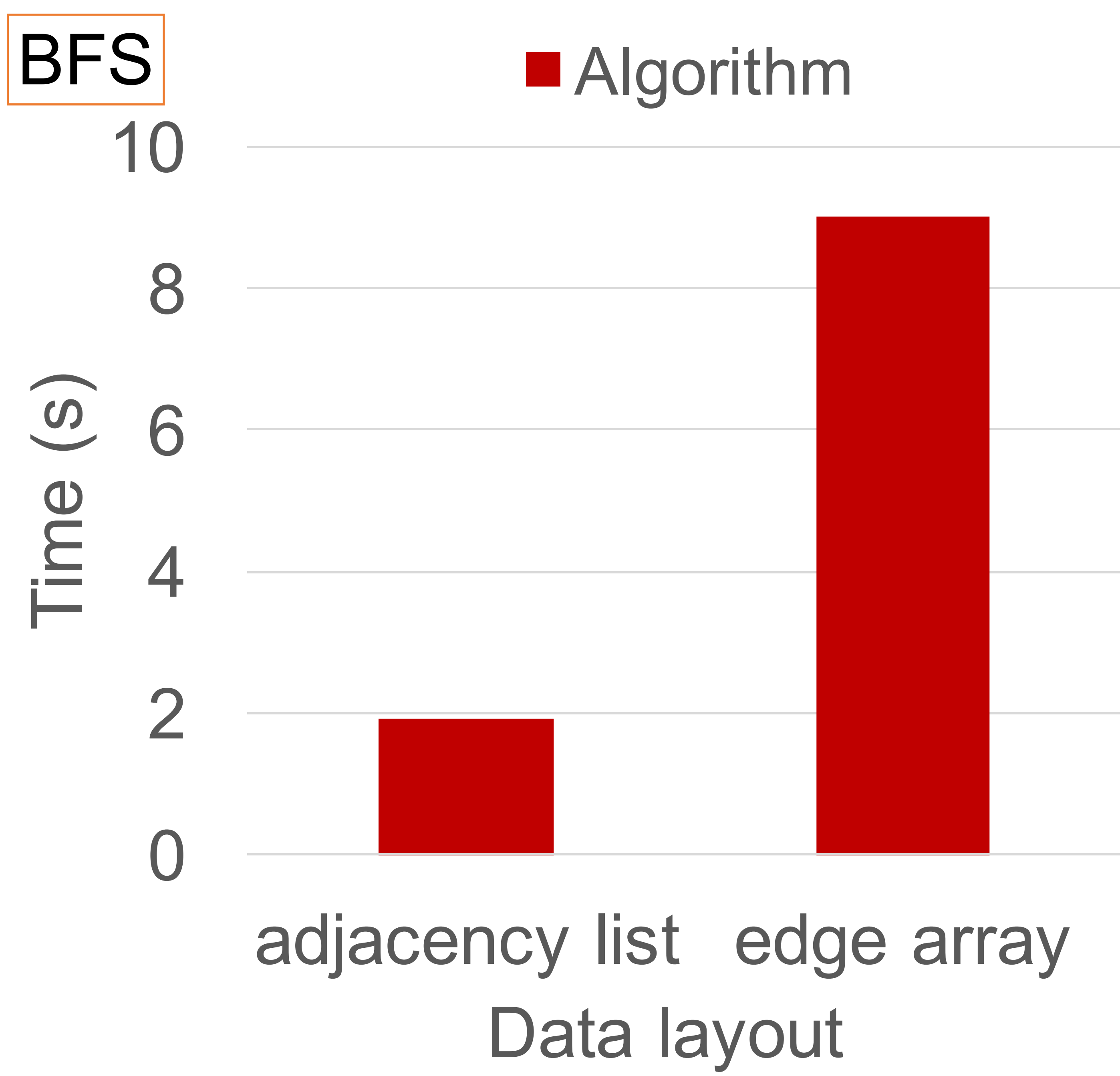
Pre-processing

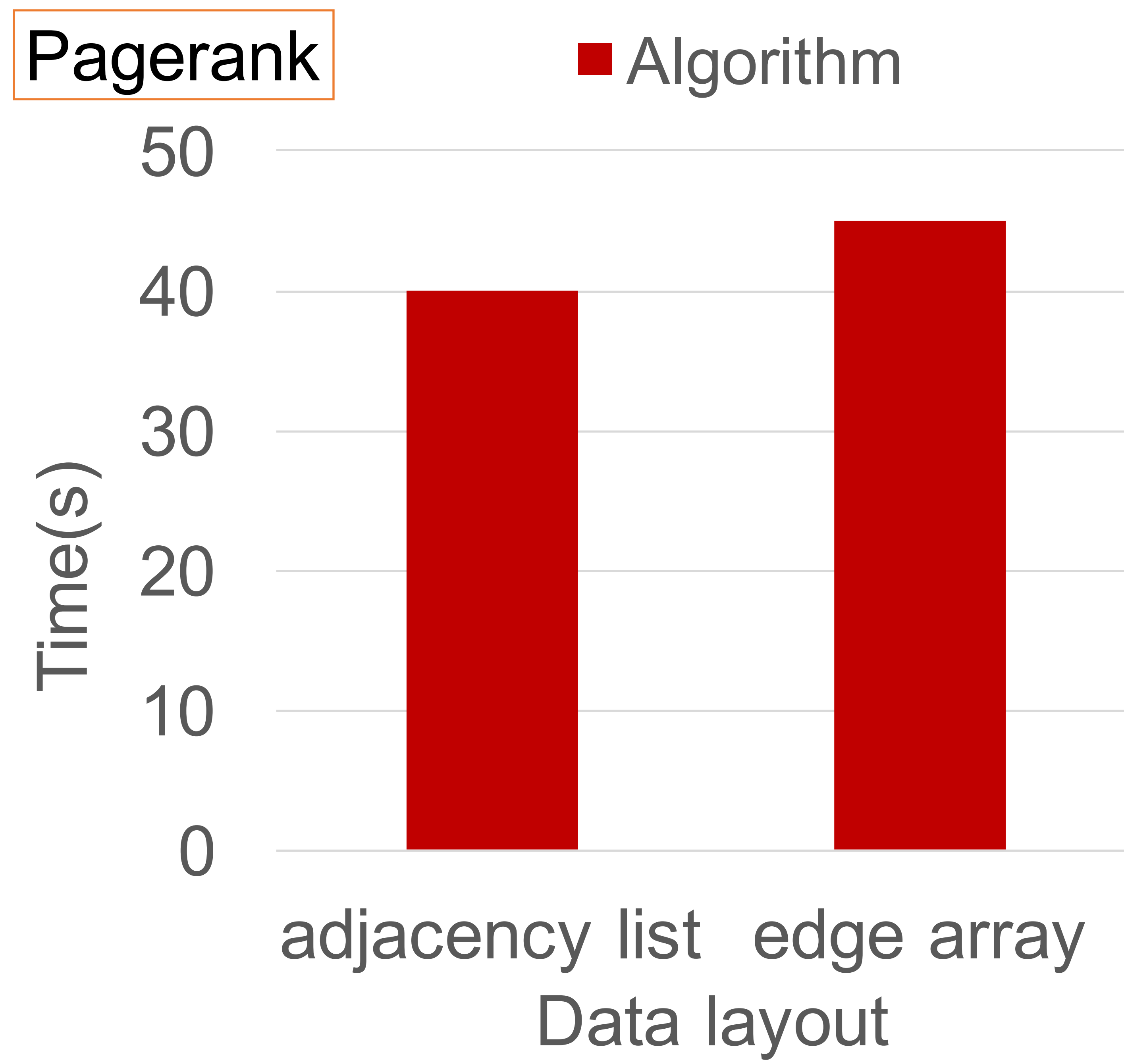
- ✓ How to represent the graph?
  - ○ Adjacency lists ○ Edge arrays
- ✓ Cost of creating the representation?
  - ○ Radix sort wins for adjacency lists
- **What data layout is best?**

Algorithm

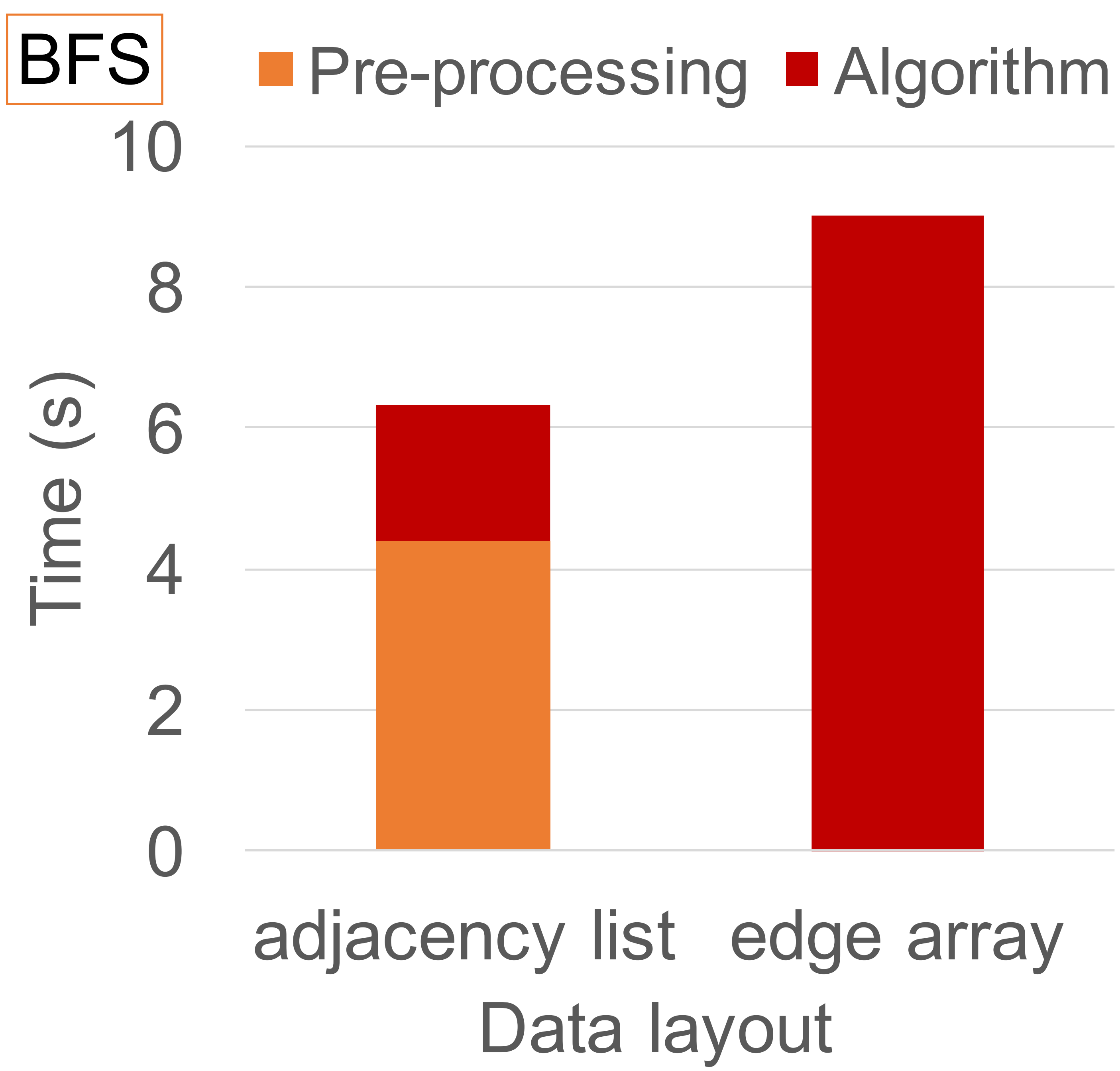
- Can we improve cache locality?
- Should we optimize for NUMA?
- Information flow: **push**, **pull** or a **both**?

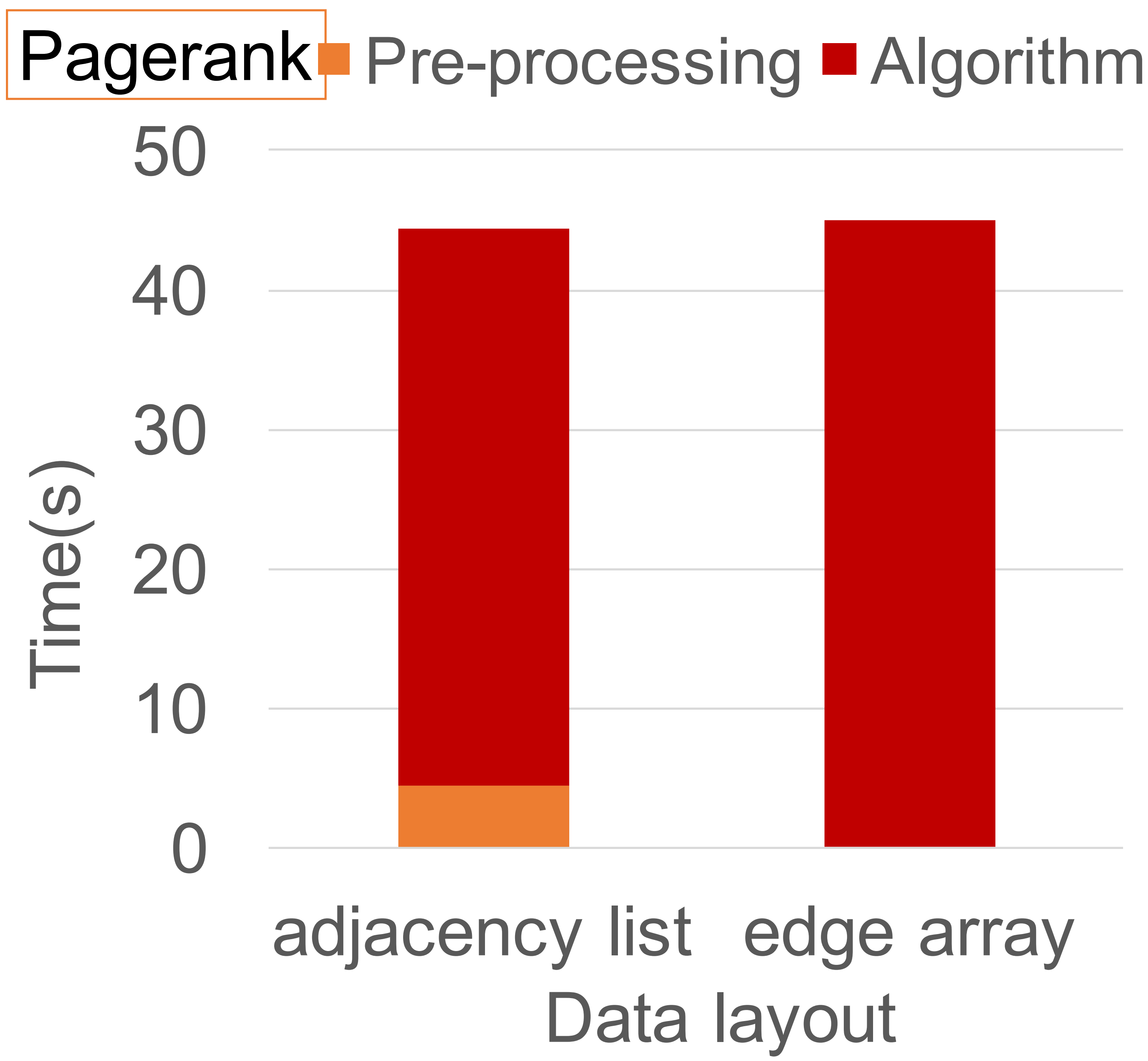
Which is data layout is better?





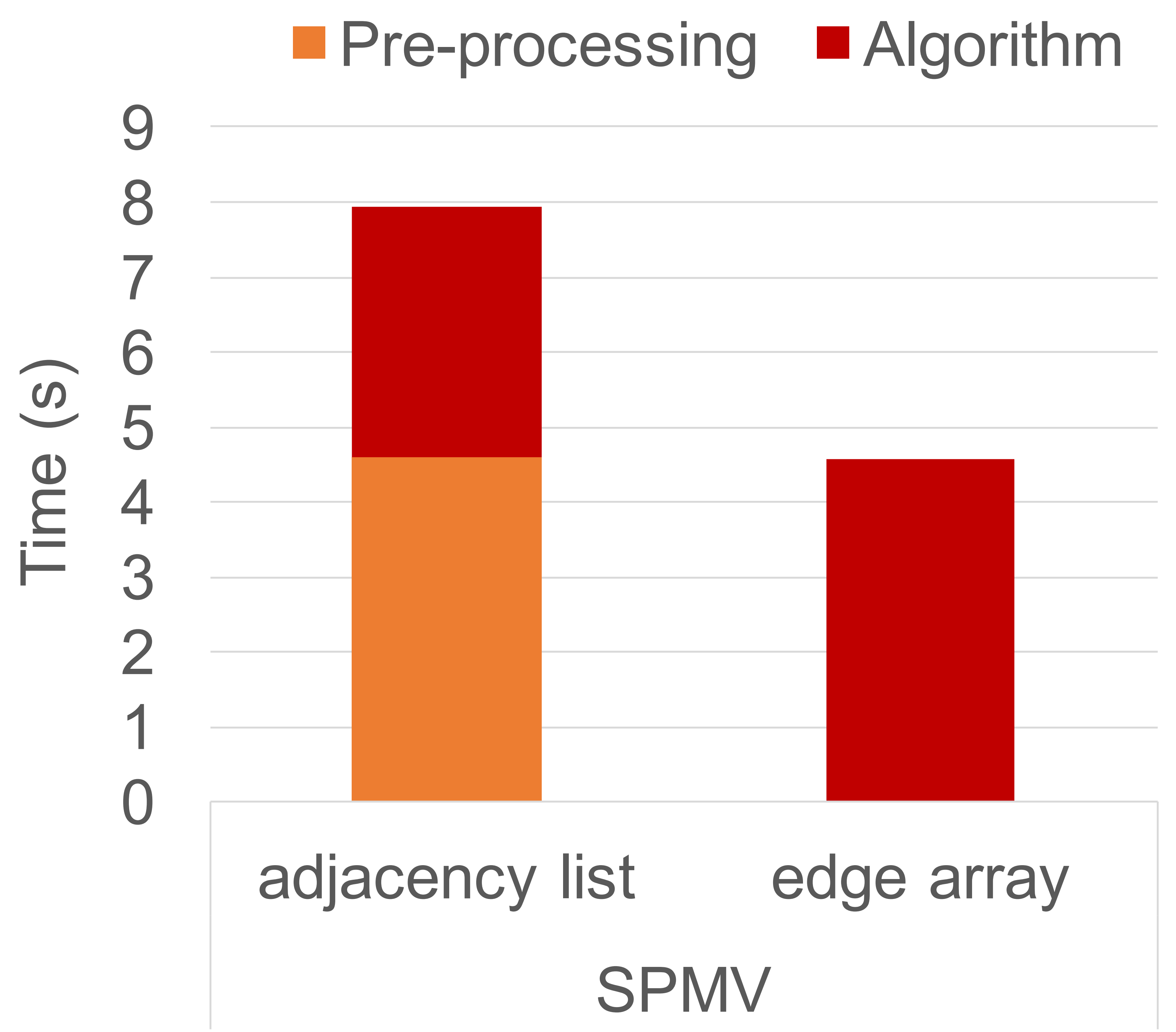
Which is better?





Adjacency lists always wins?

- SpMV – one pass over the edge array
- Pre-processing not amortized
  - Cost is = pass over edge array



Questions we want to answer:

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Pre-processing

- ✓ How to represent the graph? → ○ Adjacency lists ○ Edge arrays
- ✓ Cost of creating the representation? → ○ Radix sort wins for adjacency lists
- ✓ What data layout is best? → ○ BFS: Adj. list ○ PR: Adj.list ○ SpMV: Edge array

Algorithm

- **Can we improve cache locality?**
- Should we optimize for NUMA?
- Information flow: **push**, **pull** or a **both**?

Memory accesses – edge arrays

Edge array:

0 - 3	2 -3	0 - 1	1 - 0	0 - 2

Vertex state array:

S(0)
S(1)
S(2)
S(3)

Fetch edge:

Fetch state of source:

Fetch state of destination:

Memory accesses – edge arrays

Edge array:	0 - 3	2 -3	0 - 1	1 - 0	0 - 2

Vertex state array:

S(0)
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Fetch edge: 0 - 3

Fetch state of source:

Fetch state of destination:

✓Cache-friendly edge read

Memory accesses – edge arrays

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Fetch edge: 0 - 3

Fetch state of source: S(0)

Fetch state of destination:

✓ Cache-friendly edge read

x Potentially random access to source state

Memory accesses – edge arrays

Edge array: 0 - 3 | 2 -3 | 0 - 1 | 1 - 0 | 0 - 2

Vertex state array:

S(0)
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Fetch edge: 0 - 3

Fetch state of source: S(0)

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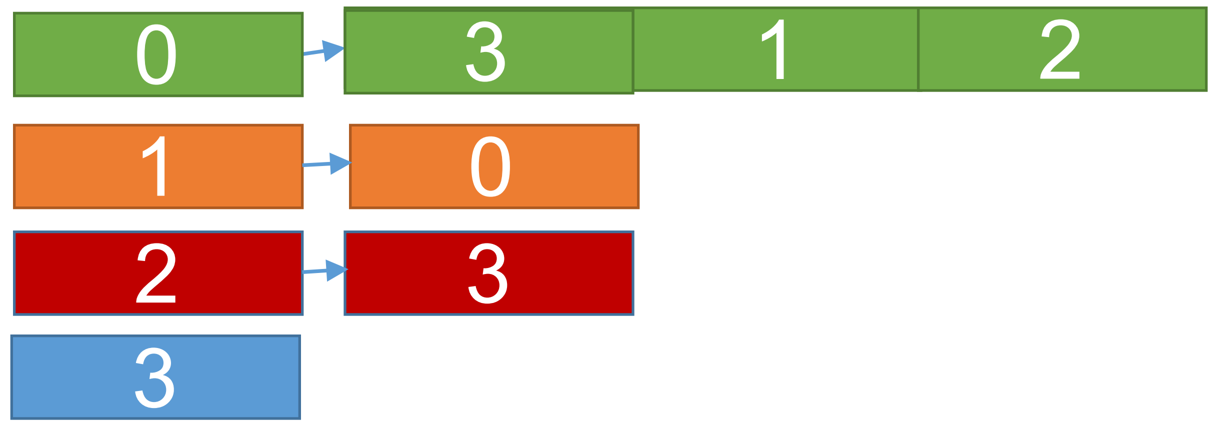
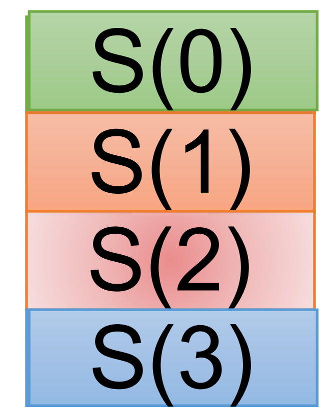
✓ Cache-friendly edge read
x Potentially random access to source state
x Random access to destination state

Memory accesses – adjacency lists

Adjacency list



Vertex state array:



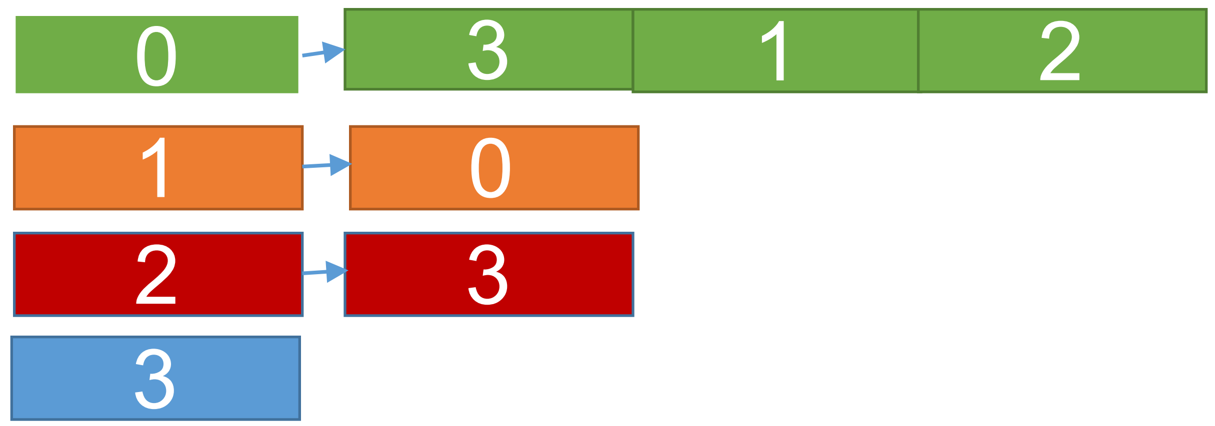
Fetch edge:

Fetch state of source:

Fetch state of destination:

Memory accesses – adjacency lists

Adjacency list



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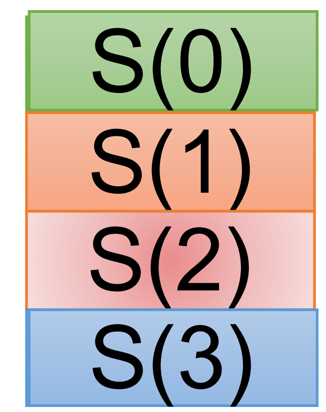

Fetch edge:

Fetch state of source:

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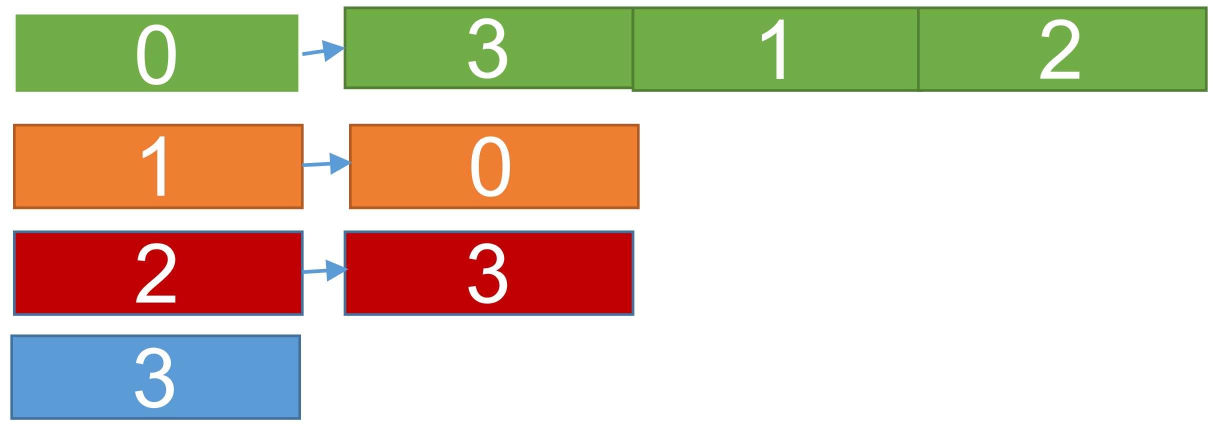
Memory accesses – adjacency lists

Adjacency list



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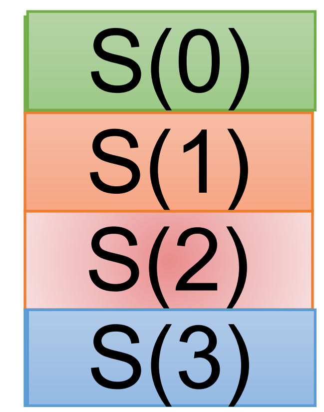

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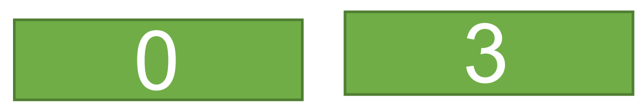


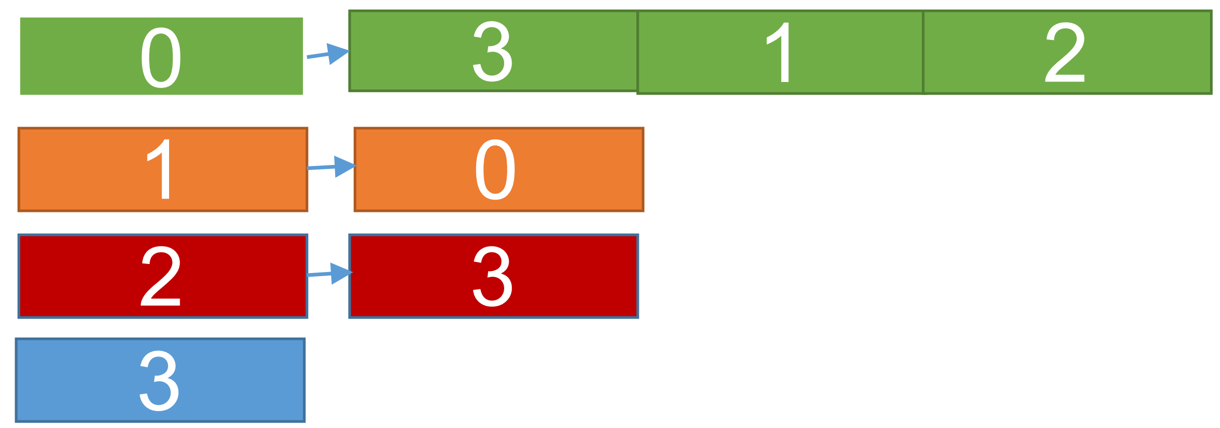
Fetch state of source:

Fetch state of destination:

✓Cache-friendly edge read

Memory accesses – adjacency lists

Adjacency list



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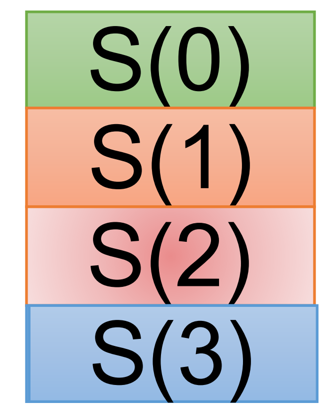
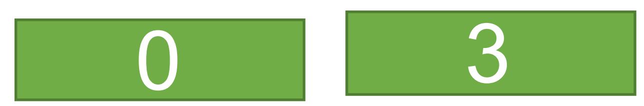
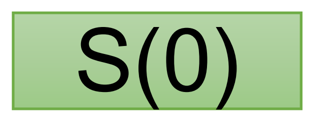


Fetch edge:



Fetch state of source:



Fetch state of destination:

✓Cache-friendly edge read
✓Cache-friendly source state read

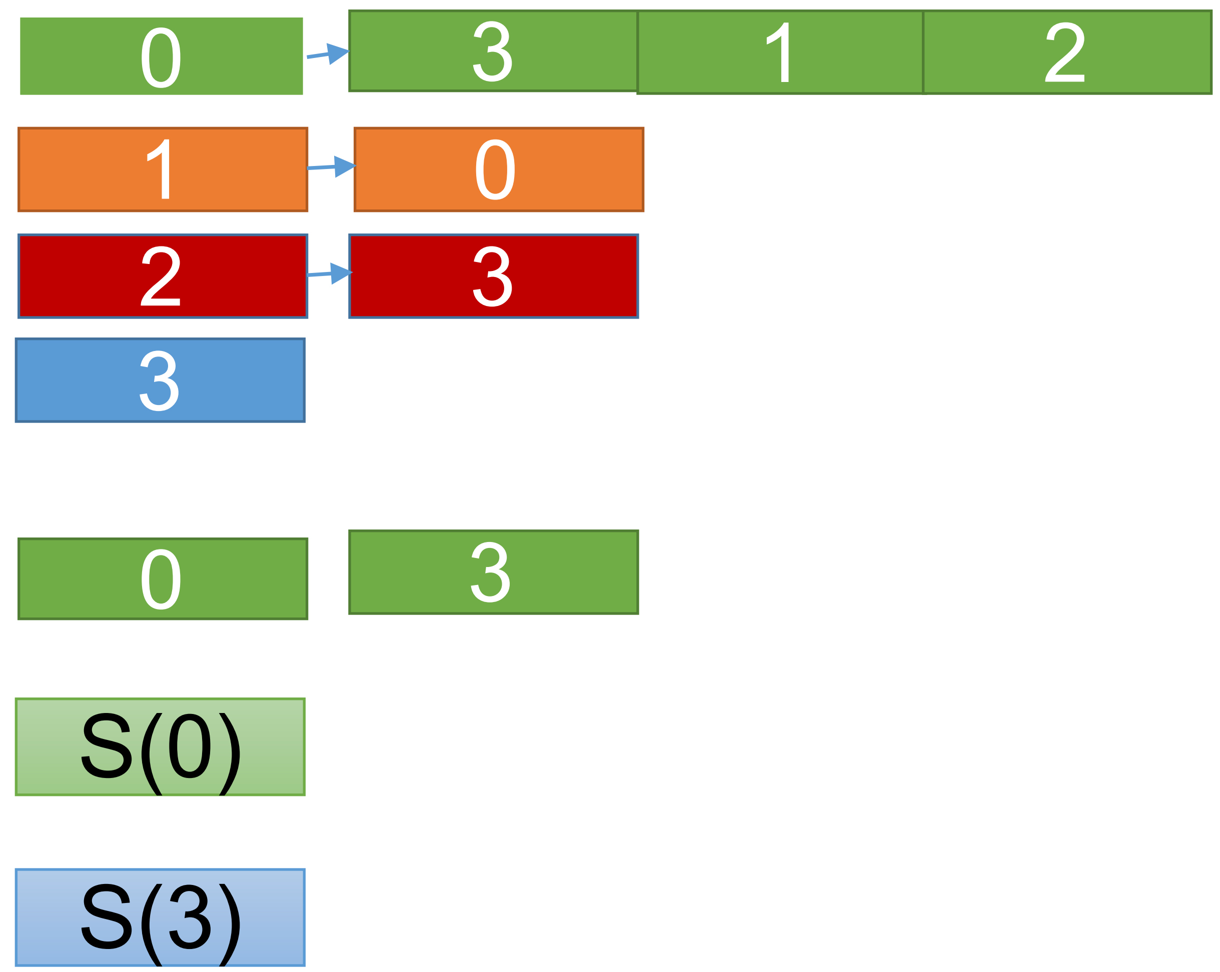
Memory accesses – adjacency lists

Adjacency list

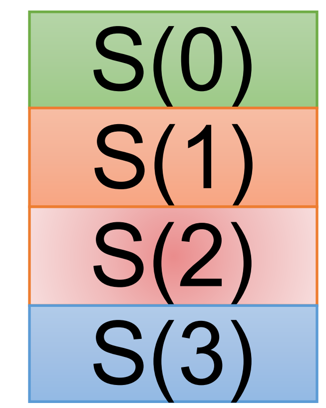
Fetch edge:

Fetch state of source:

Fetch state of destination:



Vertex state array:



✓ Cache-friendly edge read
✓ Cache-friendly source state read
x Random access to destination state

LLC miss rate

Data layout	BFS	PageRank
Edge array	57%	83%
Adjacency list	63%	78%

LLC miss rate

Data layout	BFS	PageRank
Edge array	57%	83%
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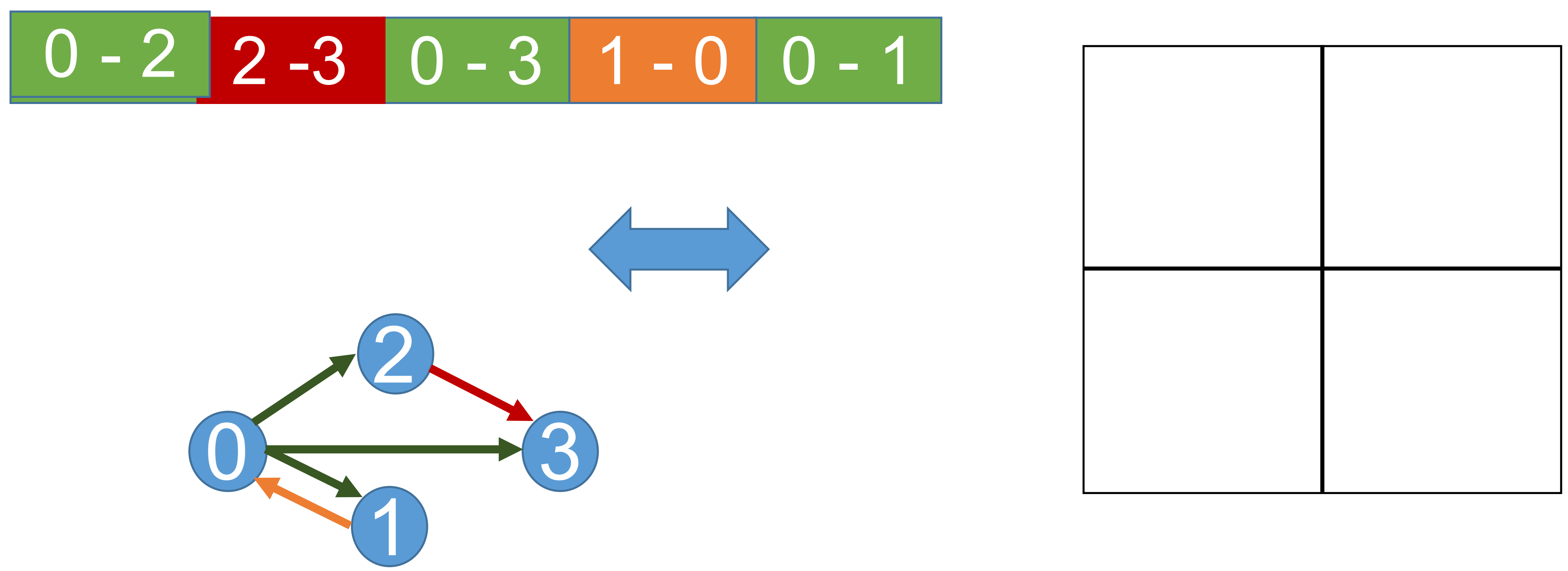
Q: Can the miss rate be improved ? At what cost?

Improving cache locality

Idea: Constrain the number of vertices accessed

Solution: Use out-of core technique – 2D Grid [from GridGraph]



Improving cache locality

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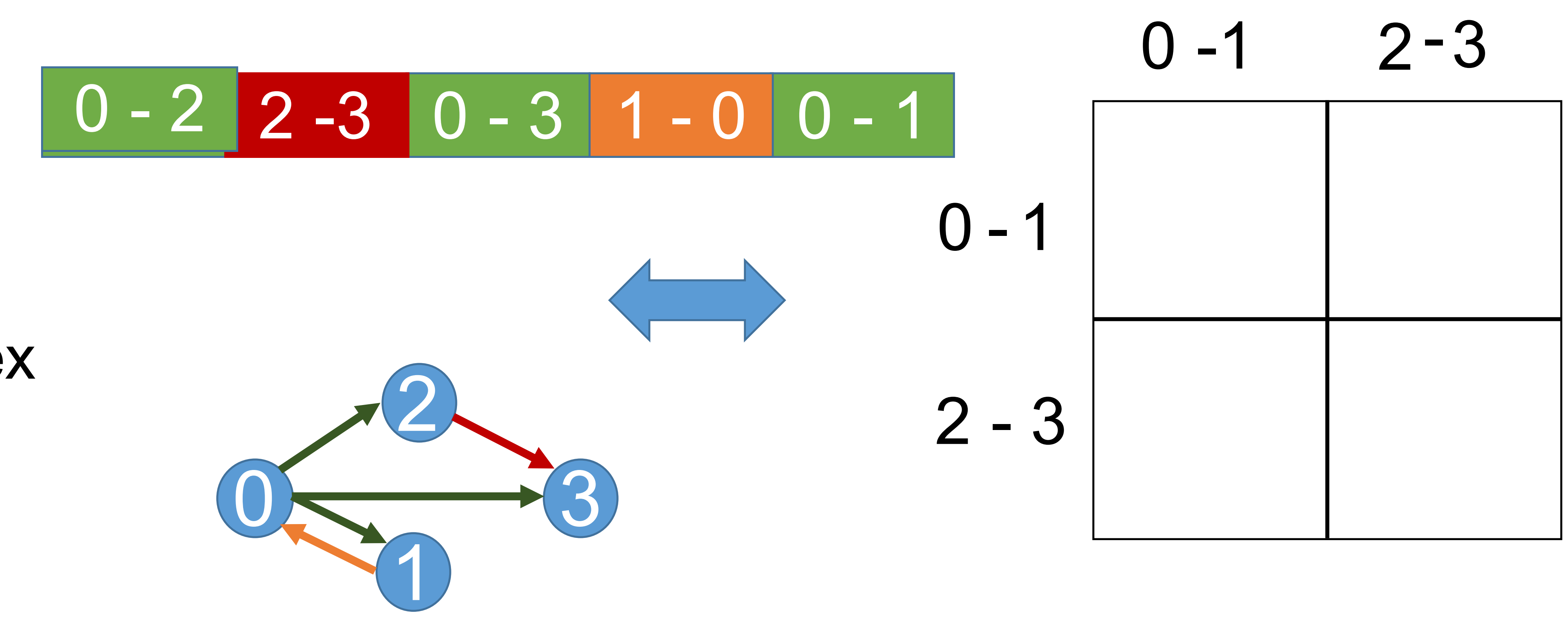
Solution: Use out-of core technique – 2D Grid [from GridGraph]

- Vertices divided into ranges
- Edges placed in a cell:
  - Row of source vertex
  - Column of destination vertex



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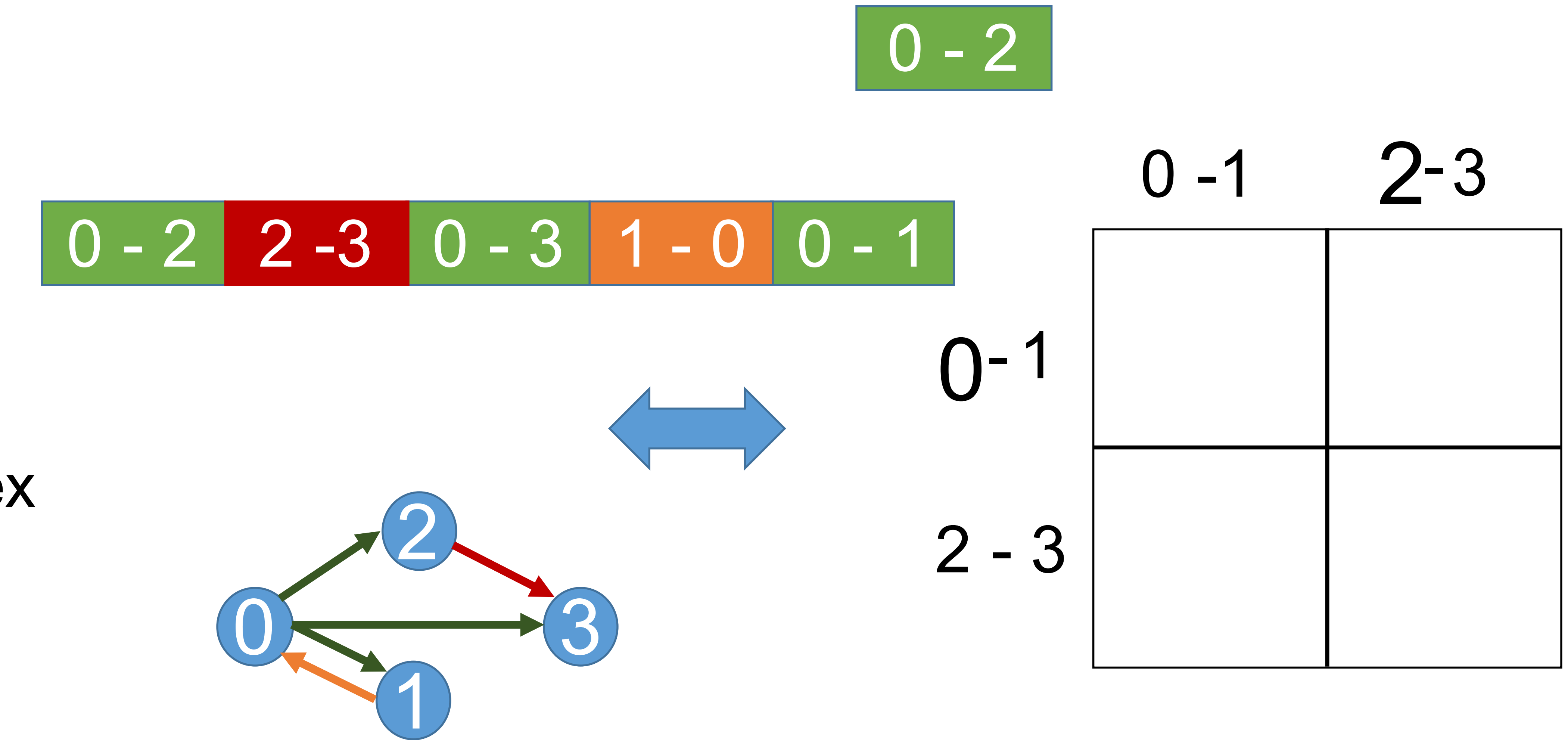

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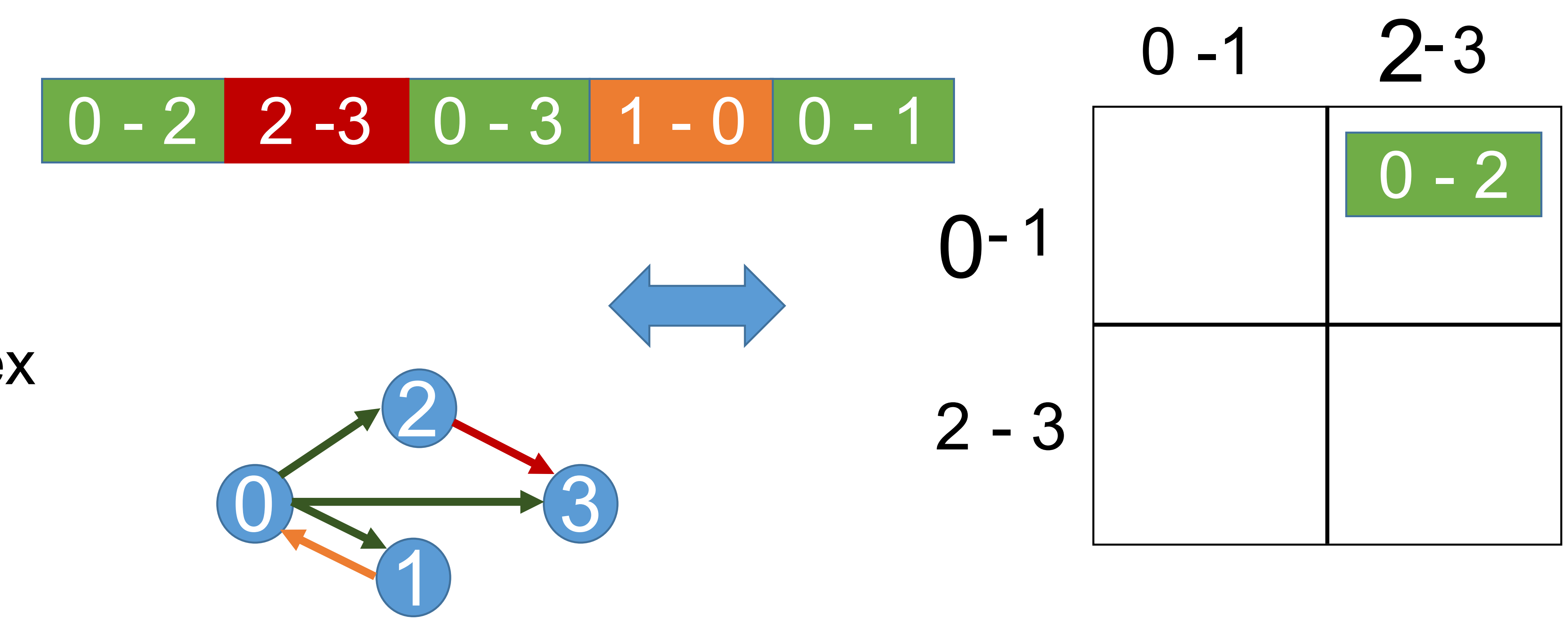

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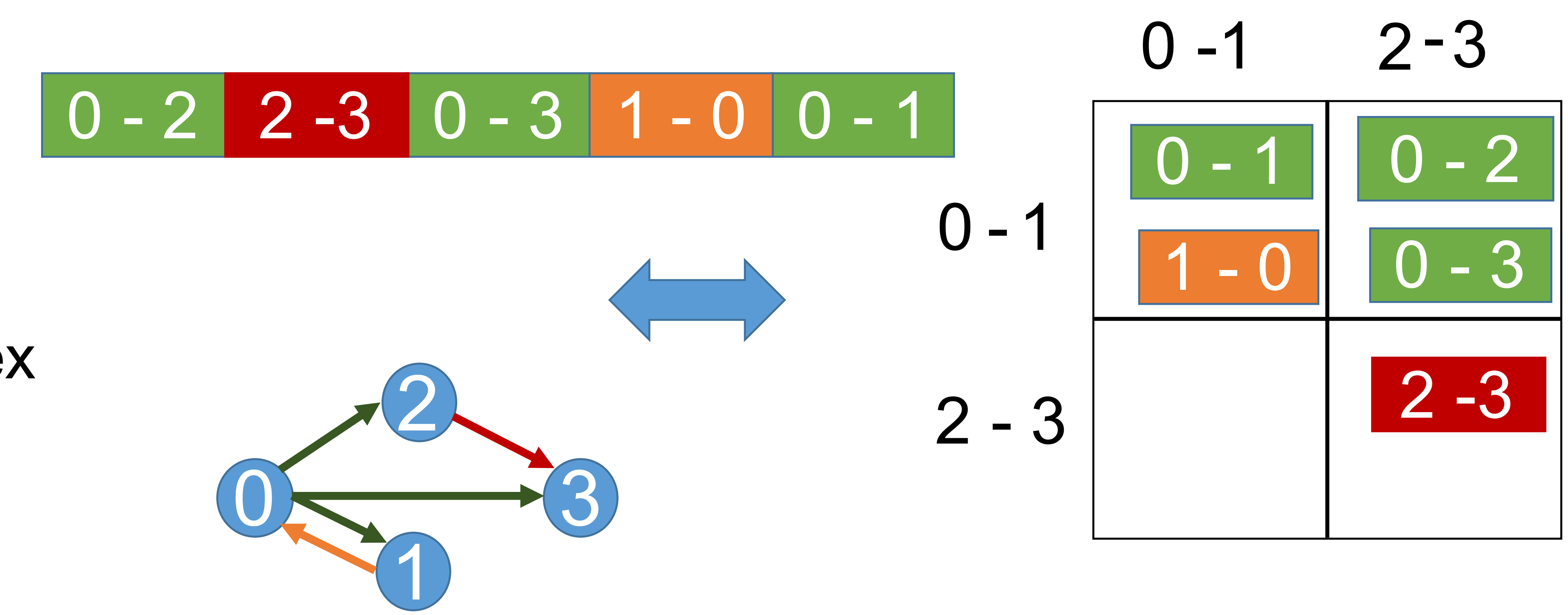

Improving cache locality

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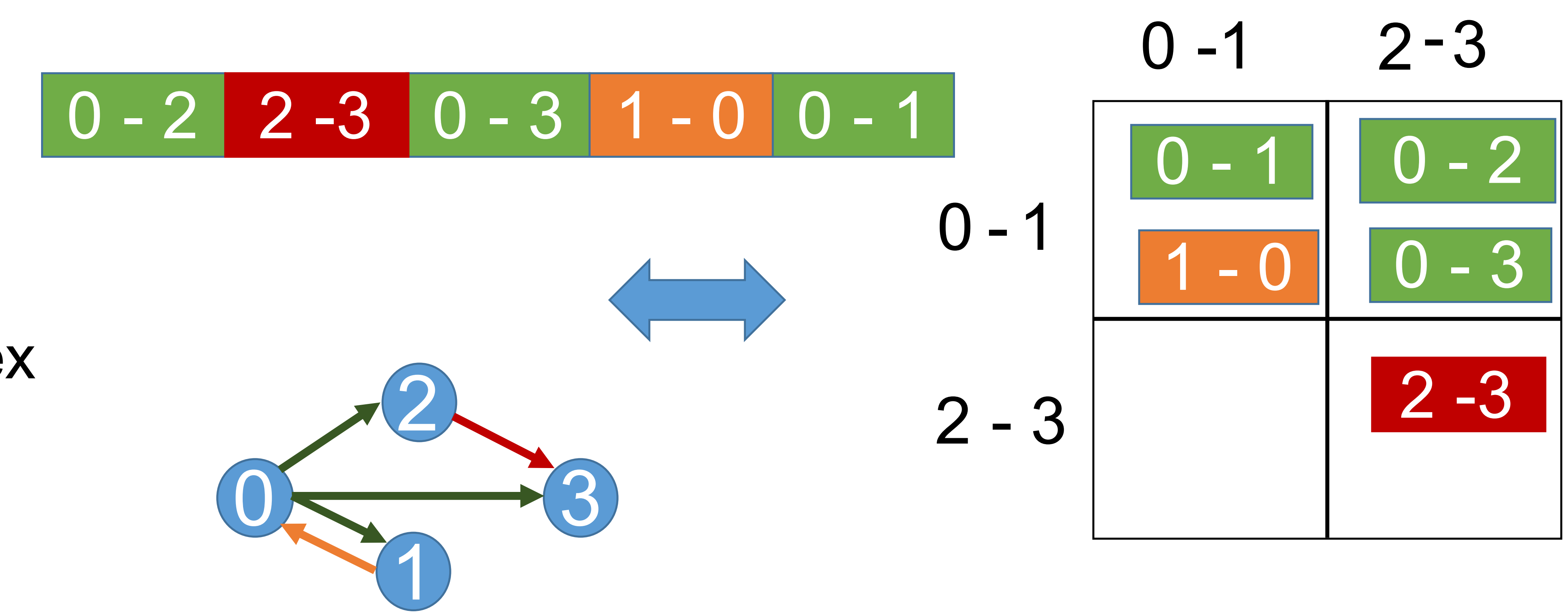

- Compute over cells of row or column

Cache-miss rate: Grid

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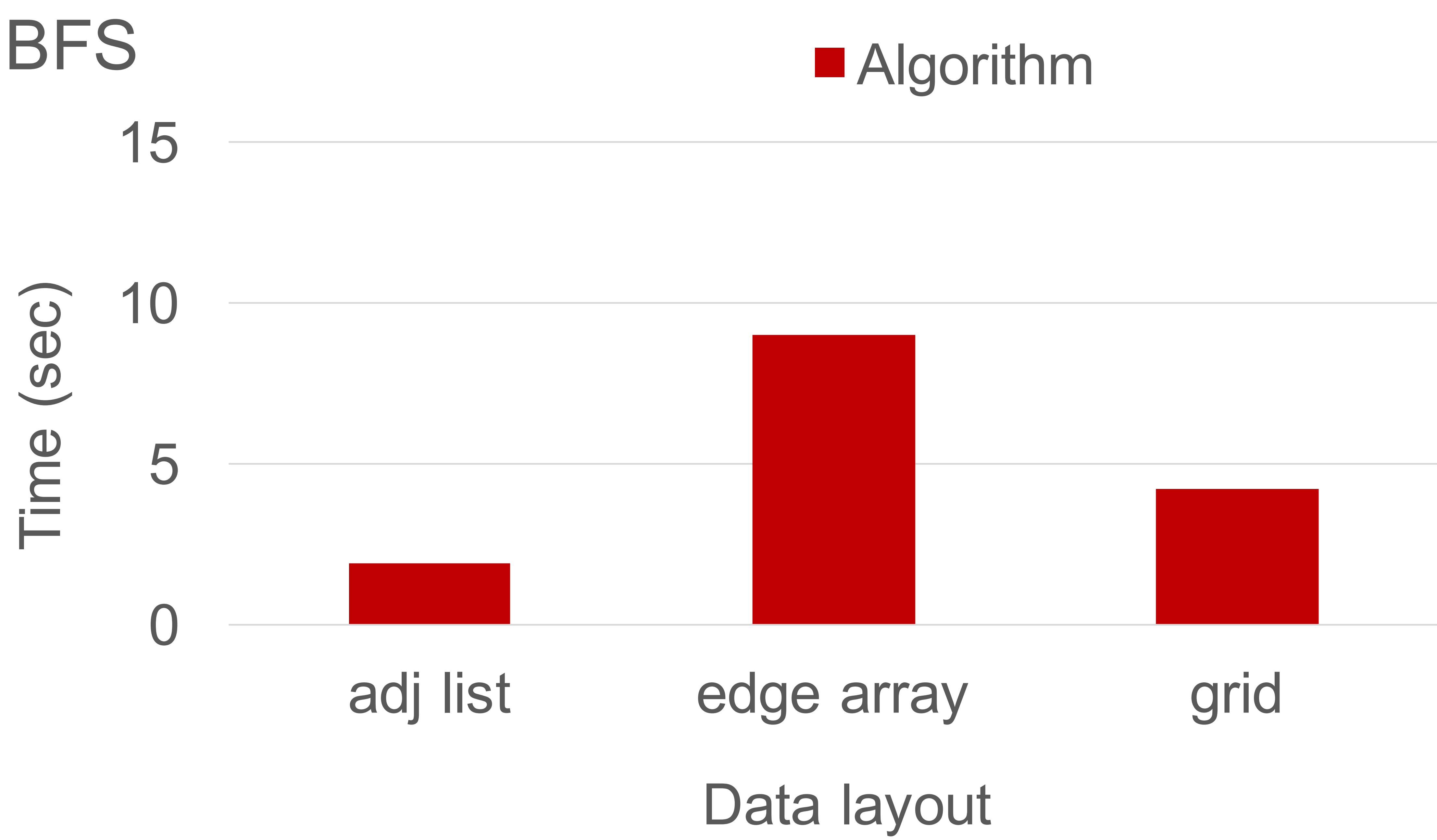
Data layout	BFS	PageRank
Edge array	57%	83%
Adjacency list	63%	78%
2D Grid	**23%**	**35%**

Evaluation: cache-optimization (BFS)



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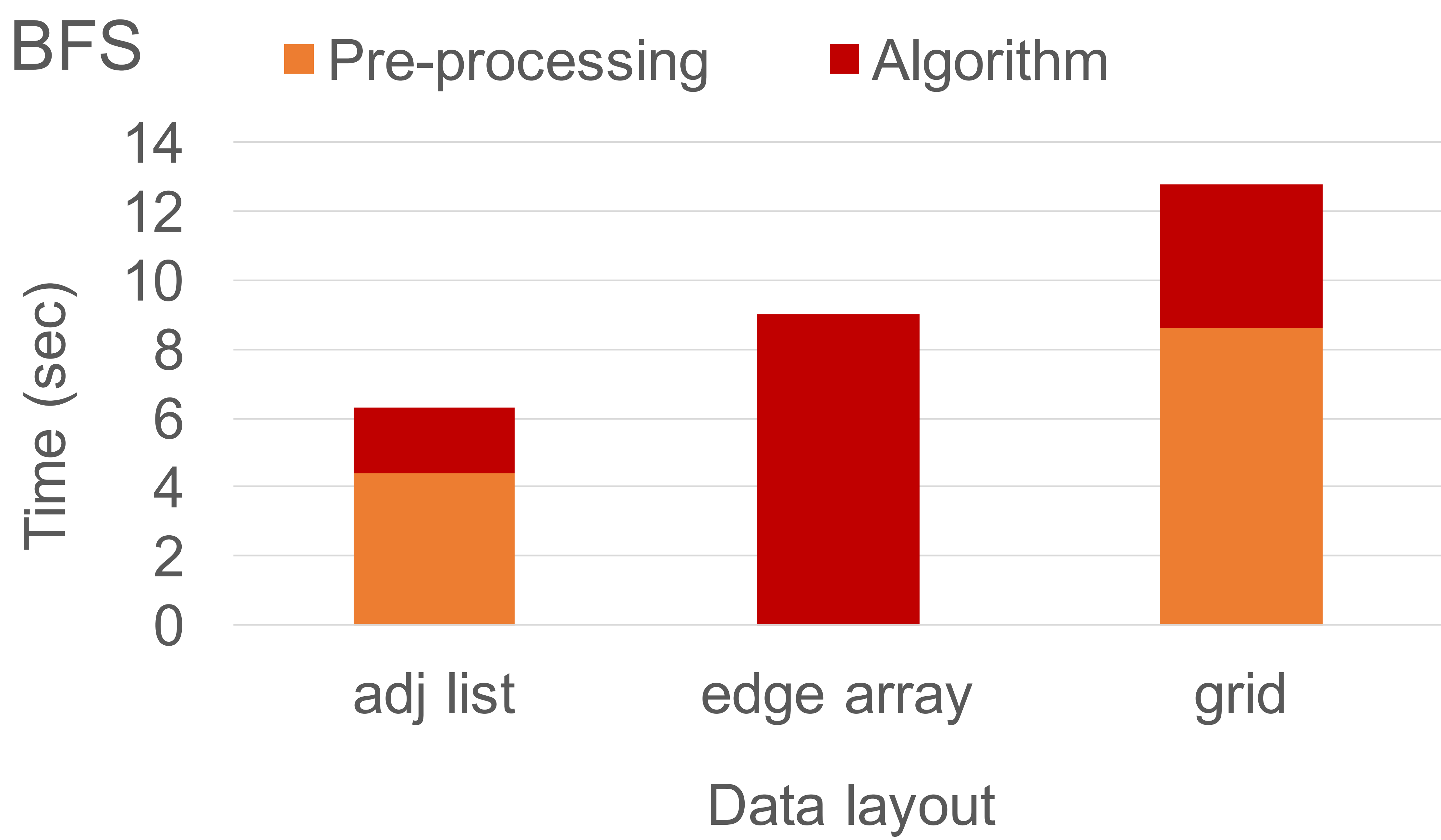

Evaluation: cache-optimization (BFS)

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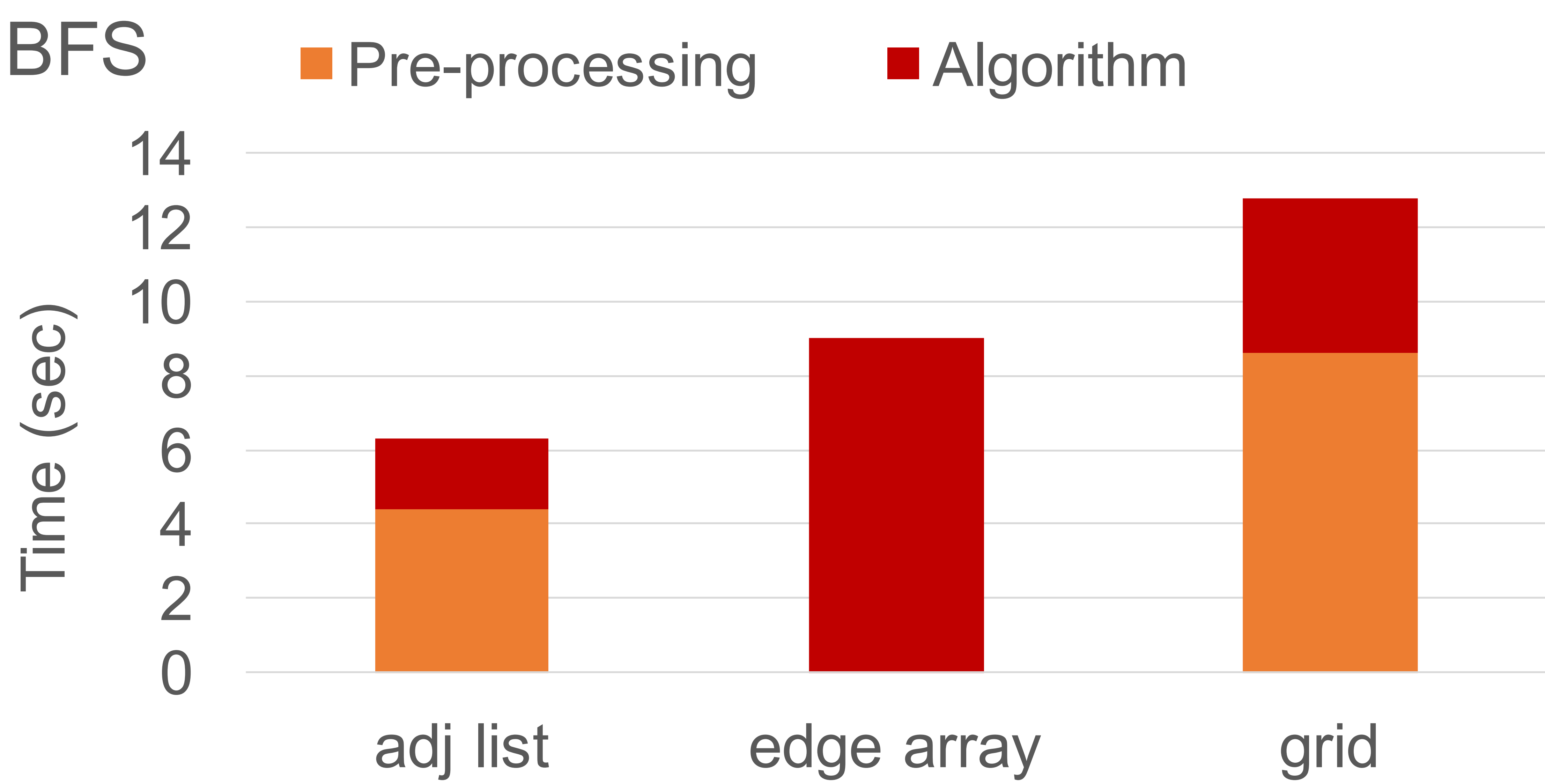
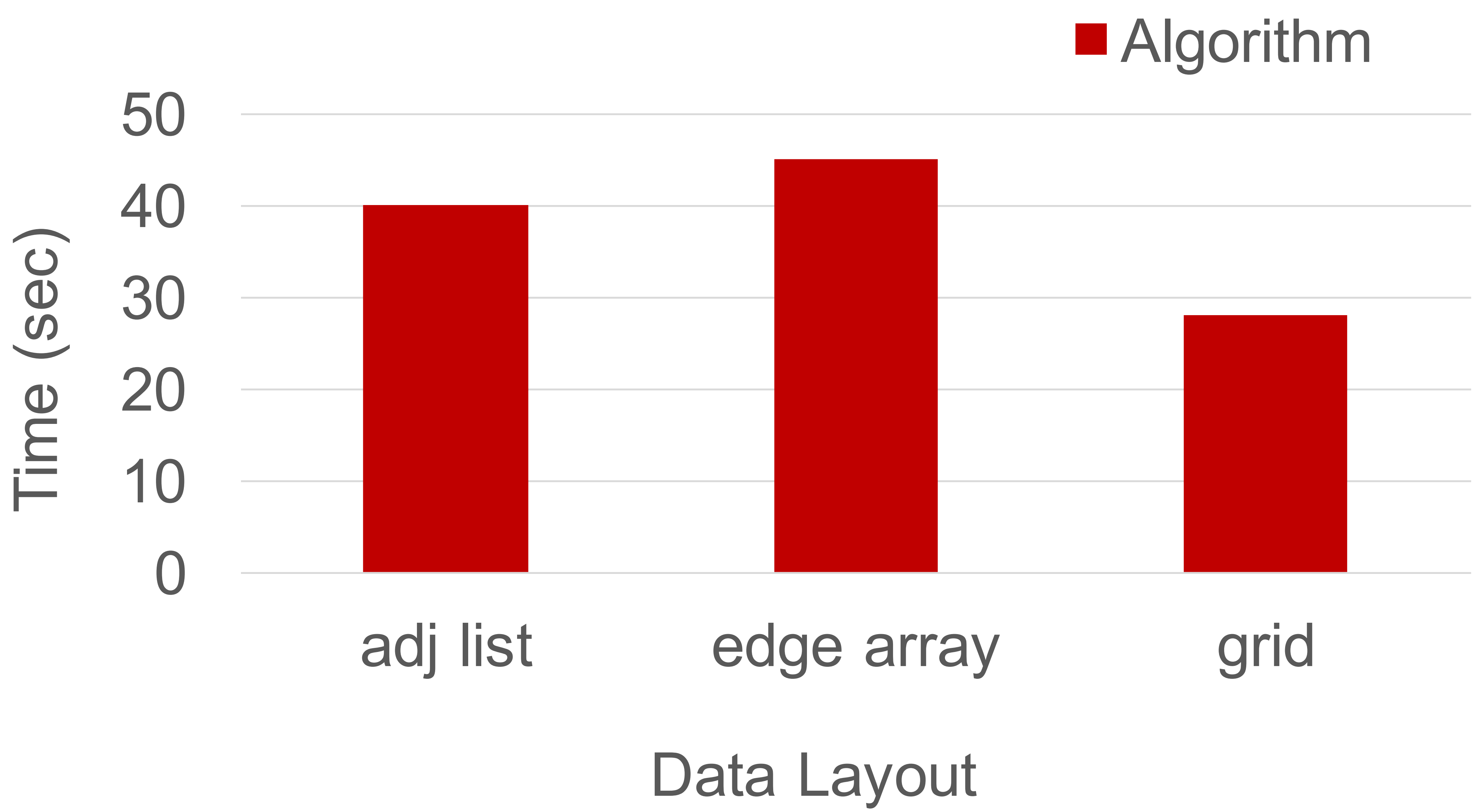


Adjacency lists have the best performance on BFS.

Evaluation: cache-optimization (PageRank)



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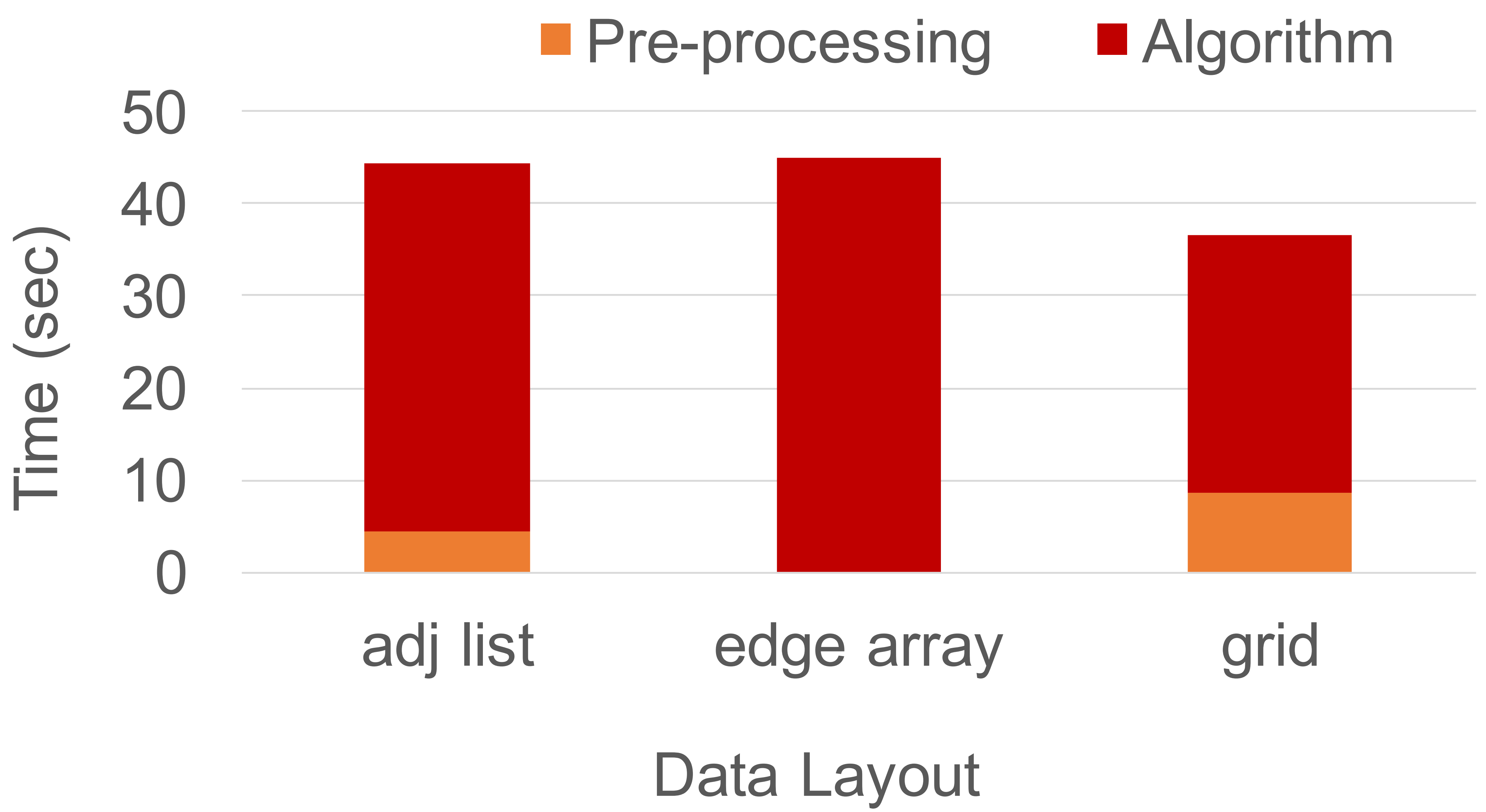

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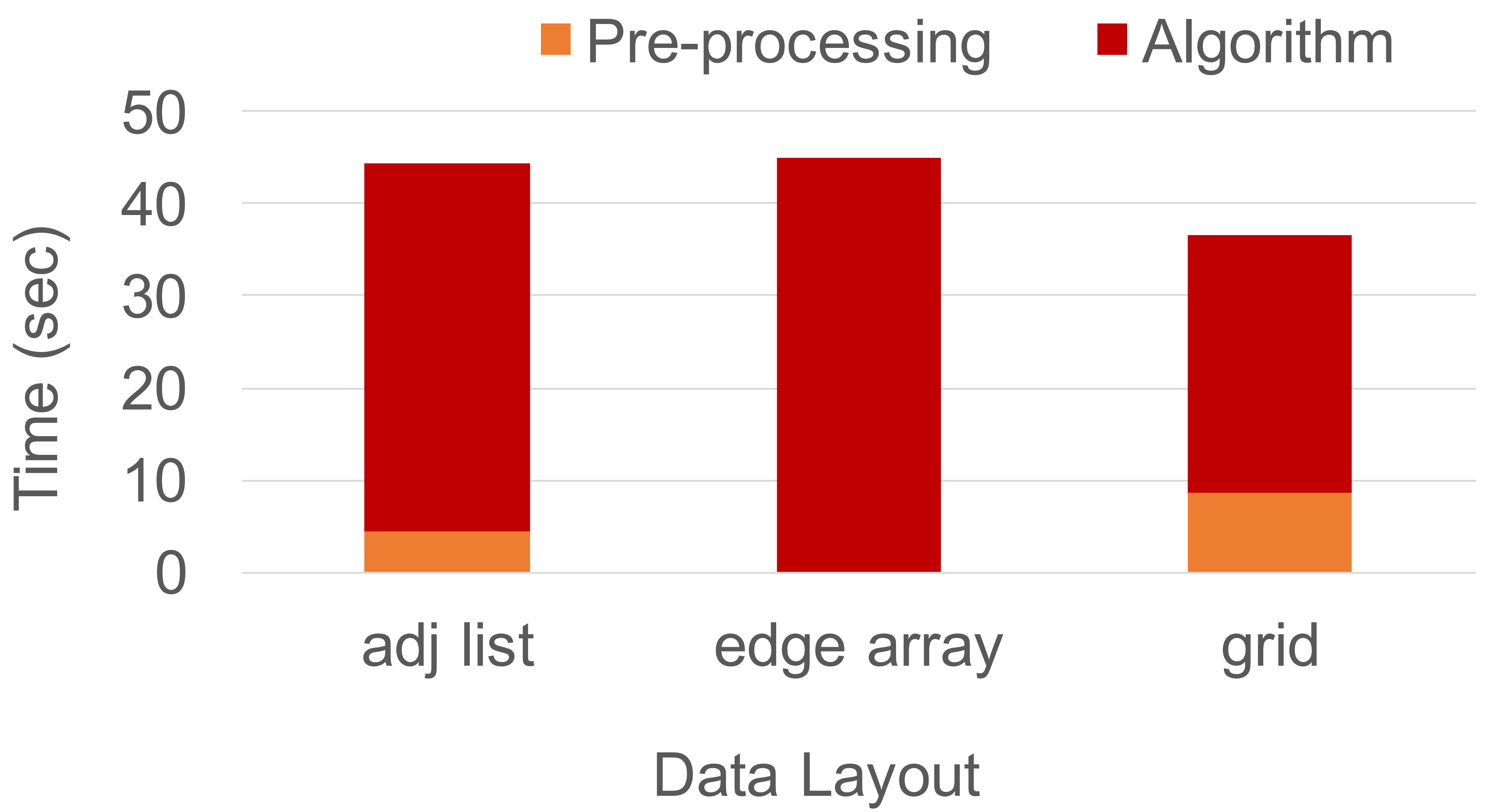

For Pagerank, the grid is the winning approach.

Questions we want to answer:

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Pre-processing

- ✓ How to represent the graph?
  - Adjacency lists
  - Edge arrays
- ✓ Cost of creating the representation?
  - Radix sort wins for adjacency lists
- ✓ What data layout is best?
  - BFS: Adj. list
  - PR: Grid
  - SpMV: Edge array

Algorithm

- ✓ Can we improve cache locality?
  - Yes. By laying out the edges in a grid format
  - BFS: Adj. list
  - PR: Grid
  - SpMV: Edge array
- **Should we optimize for NUMA?**
- Information flow: **push**, **pull** or a **both**?

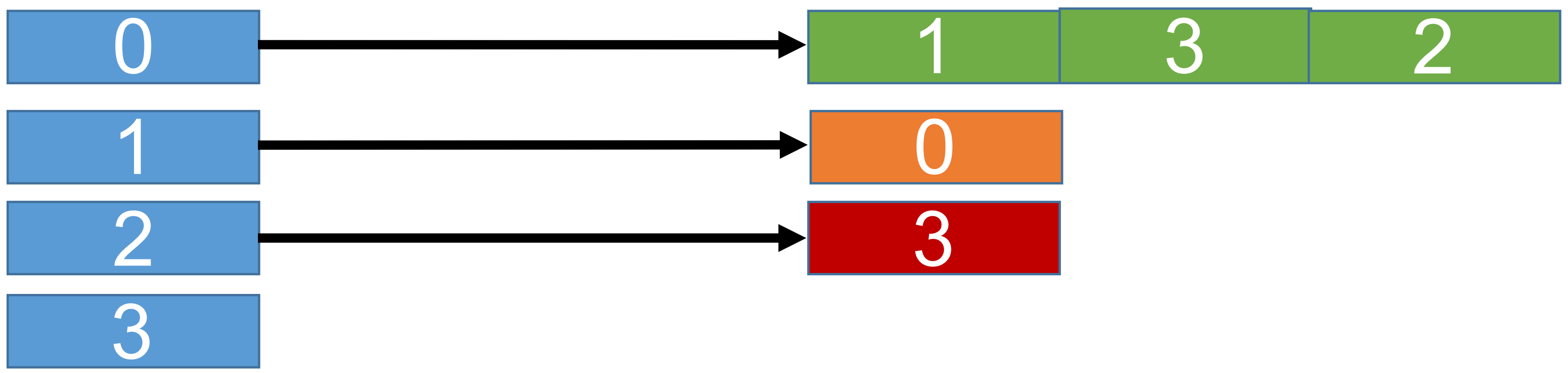
NUMA-Aware optimizations

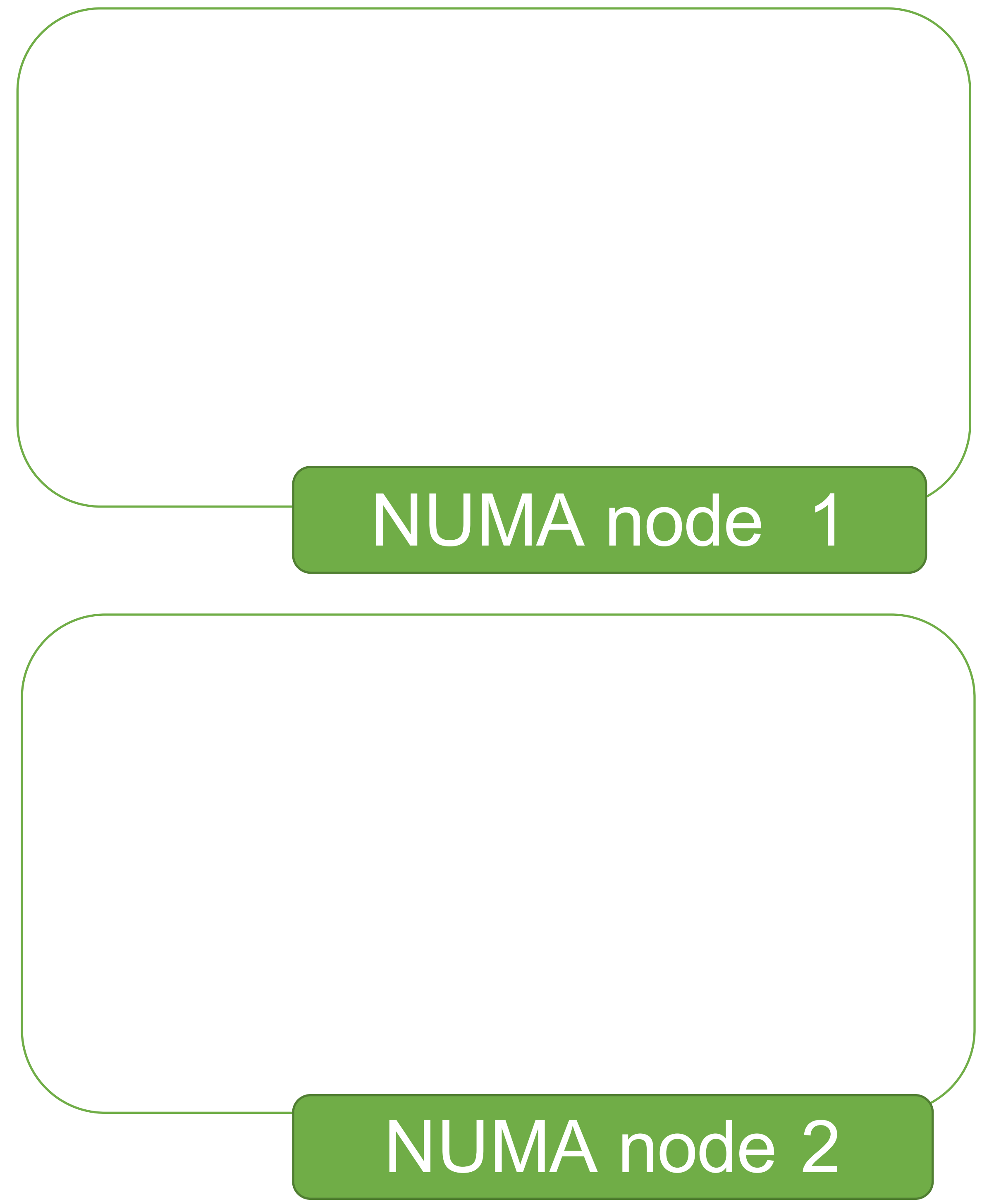
- NUMA-Aware data placement
  - Additional partitioning step in the pre-processing phase

- NUMA-Aware computation
  - Threads compute on local data

- Evaluation environment
  - Machine A: 2 NUMA nodes, 128GB DRAM, 16 Cores
  - Machine B: 4 NUMA nodes, 256GB DRAM, 32 Cores

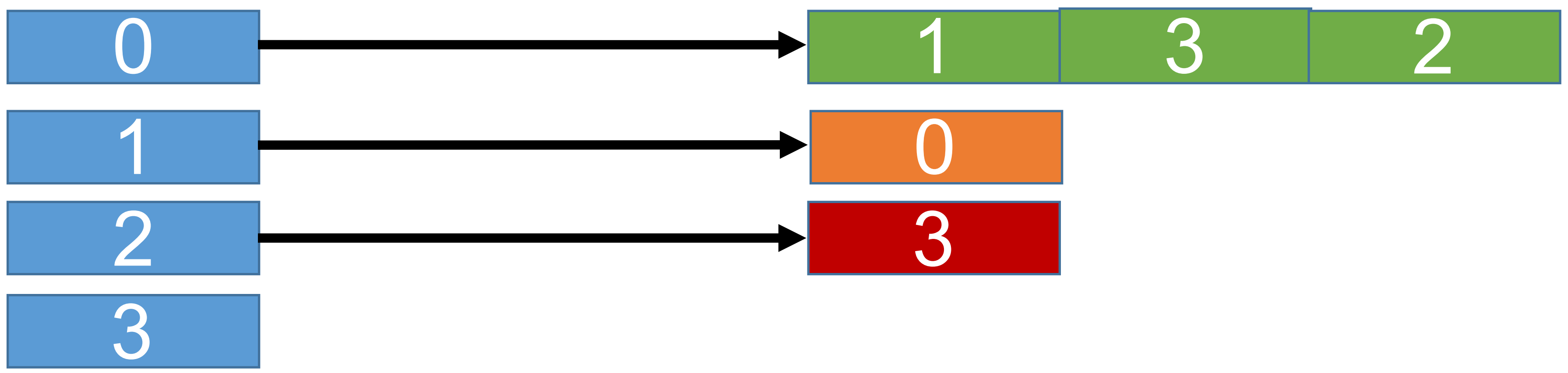
NUMA-Aware data placement

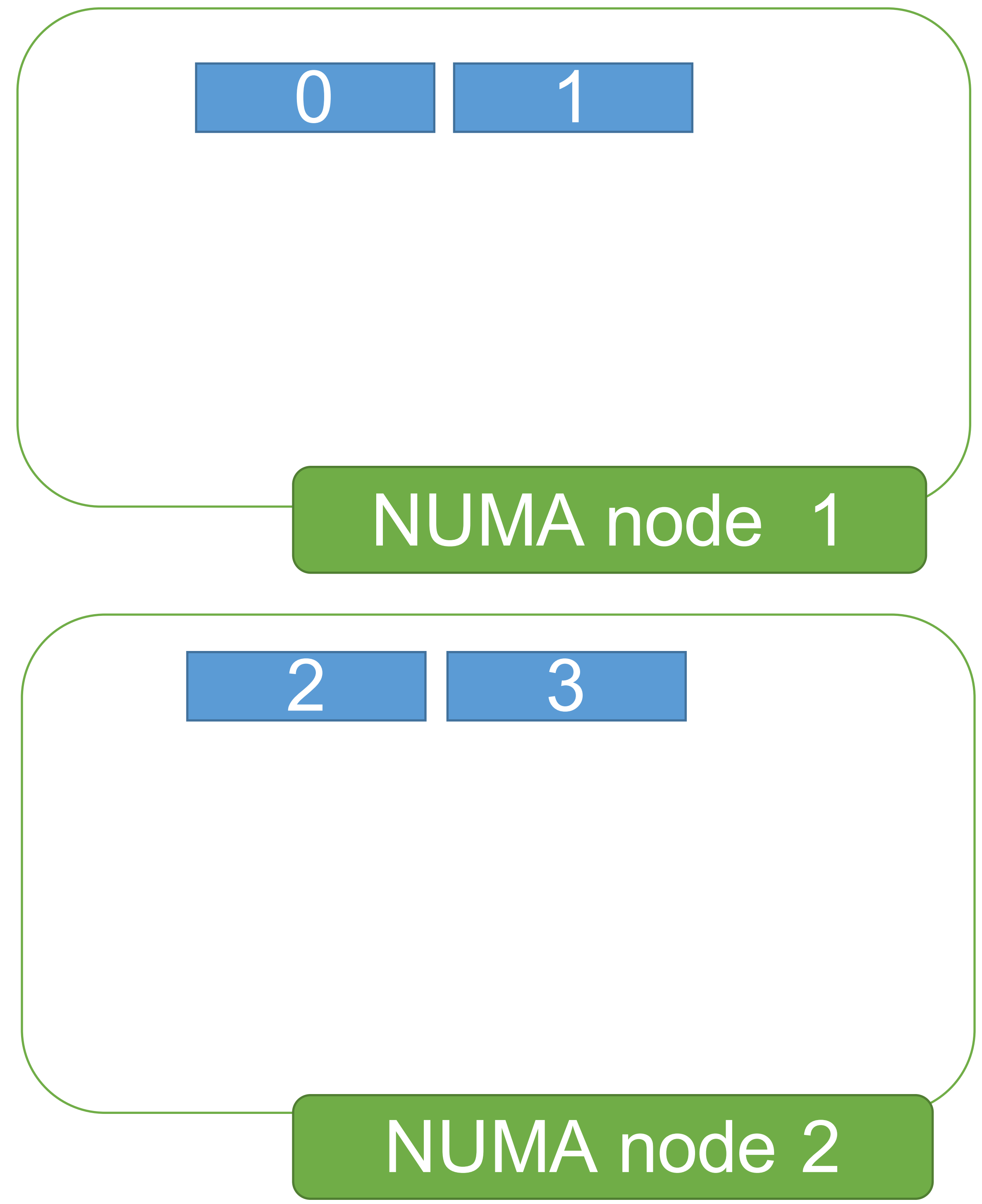




- Vertices spread across NUMA nodes
- Edges collocated with their destination vertex

NUMA-Aware data placement





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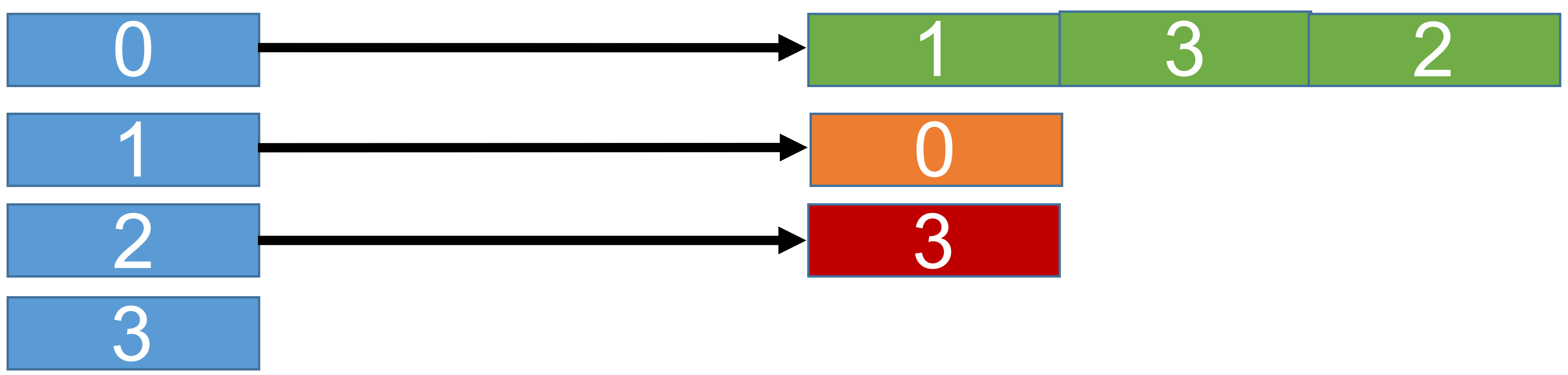
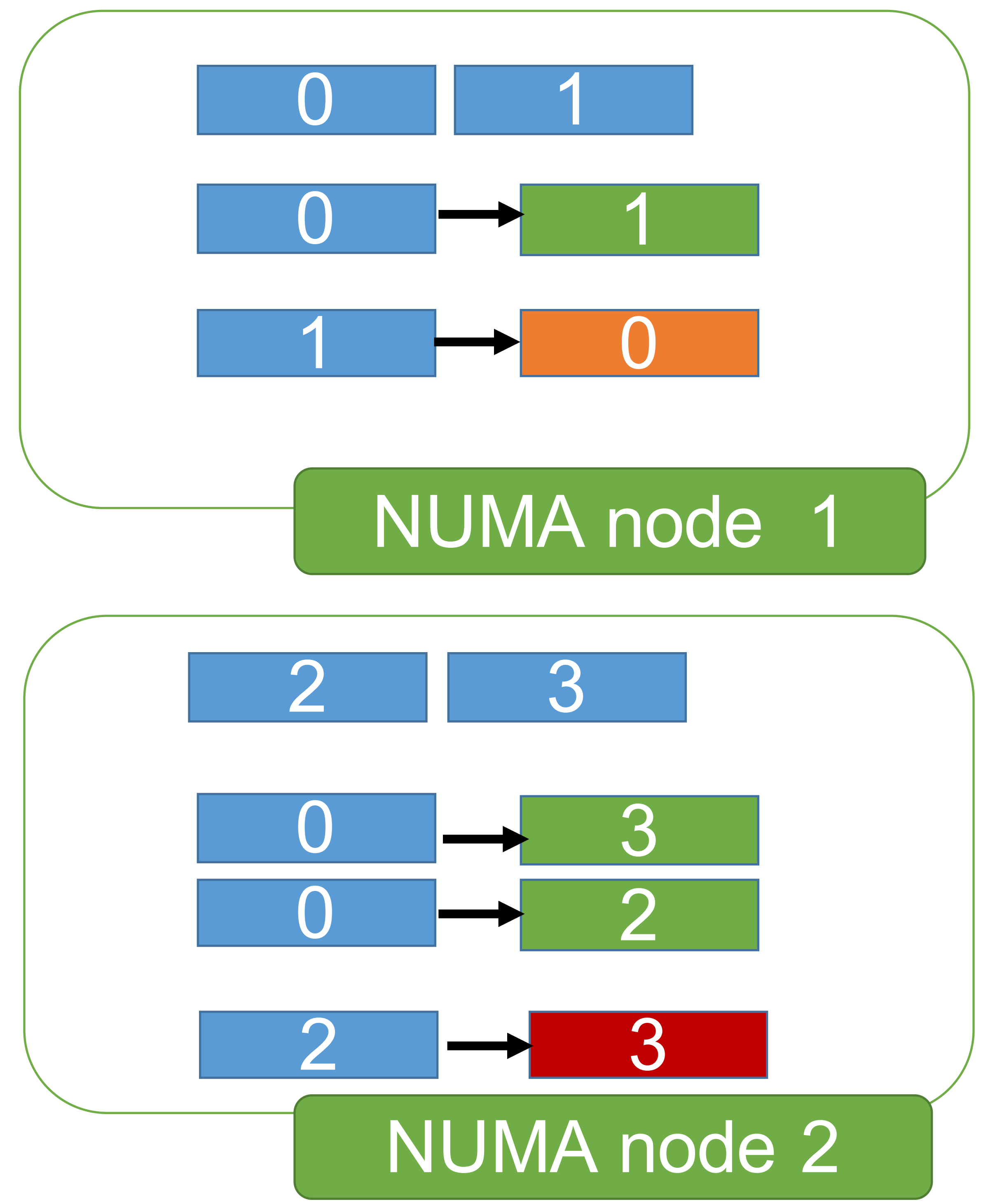
NUMA-Aware data placement





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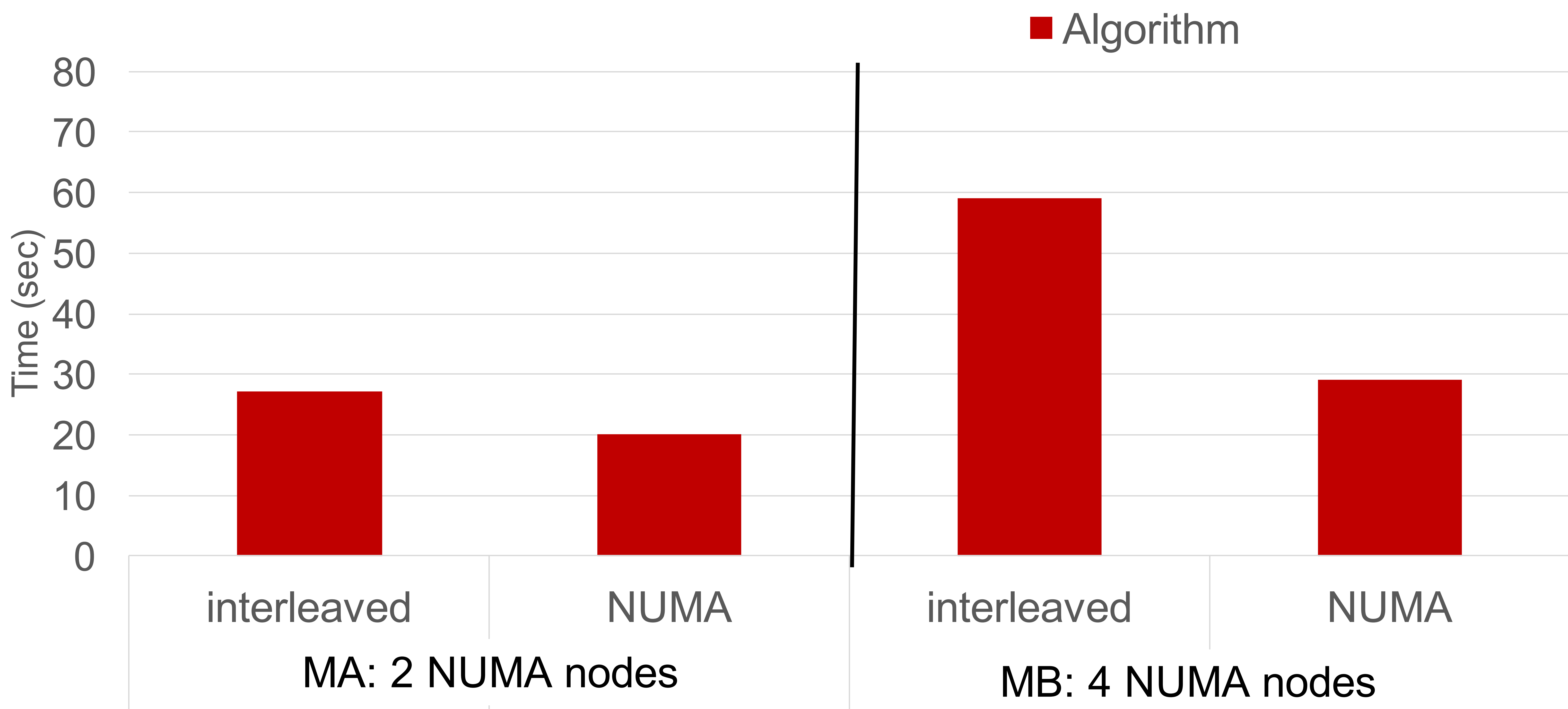
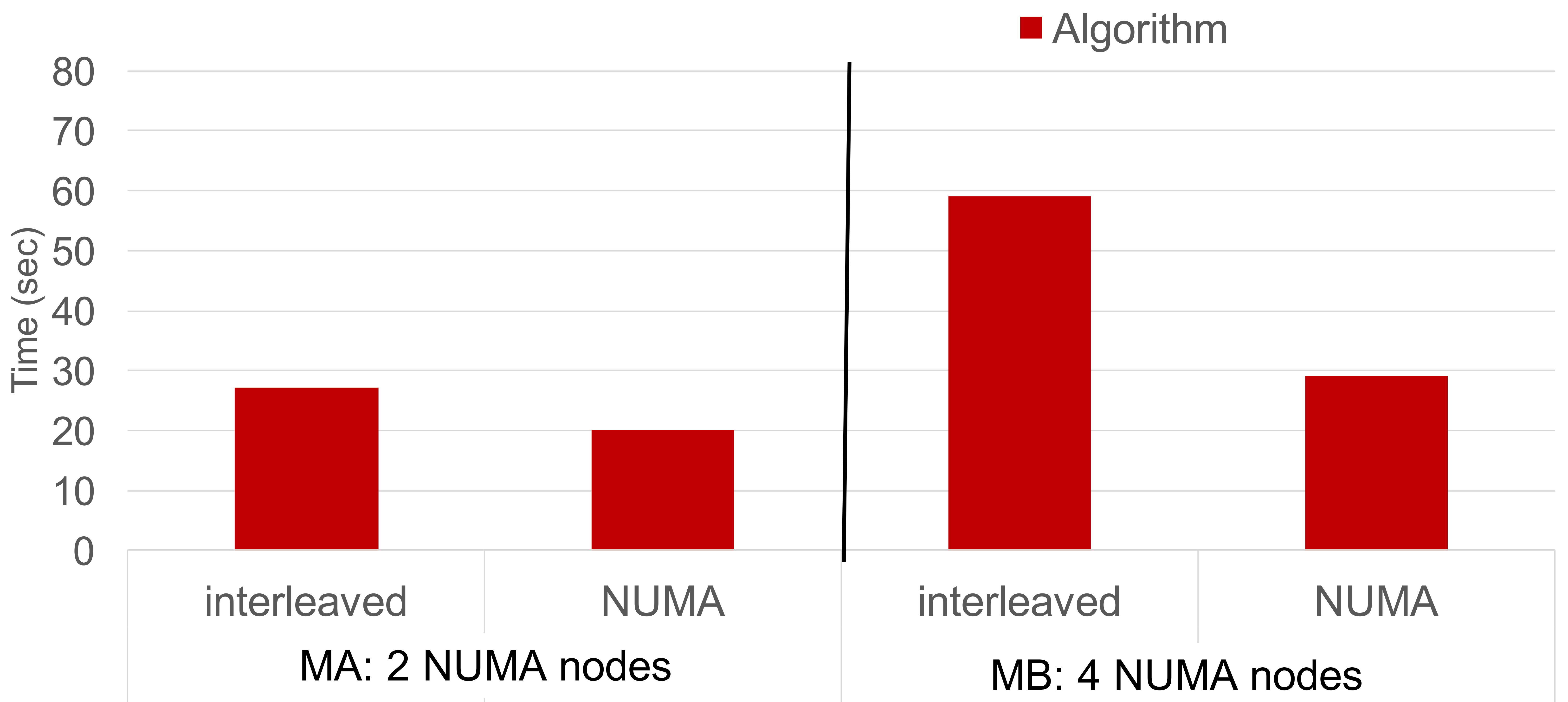
- Edges collocated with their destination vertex

PageRank

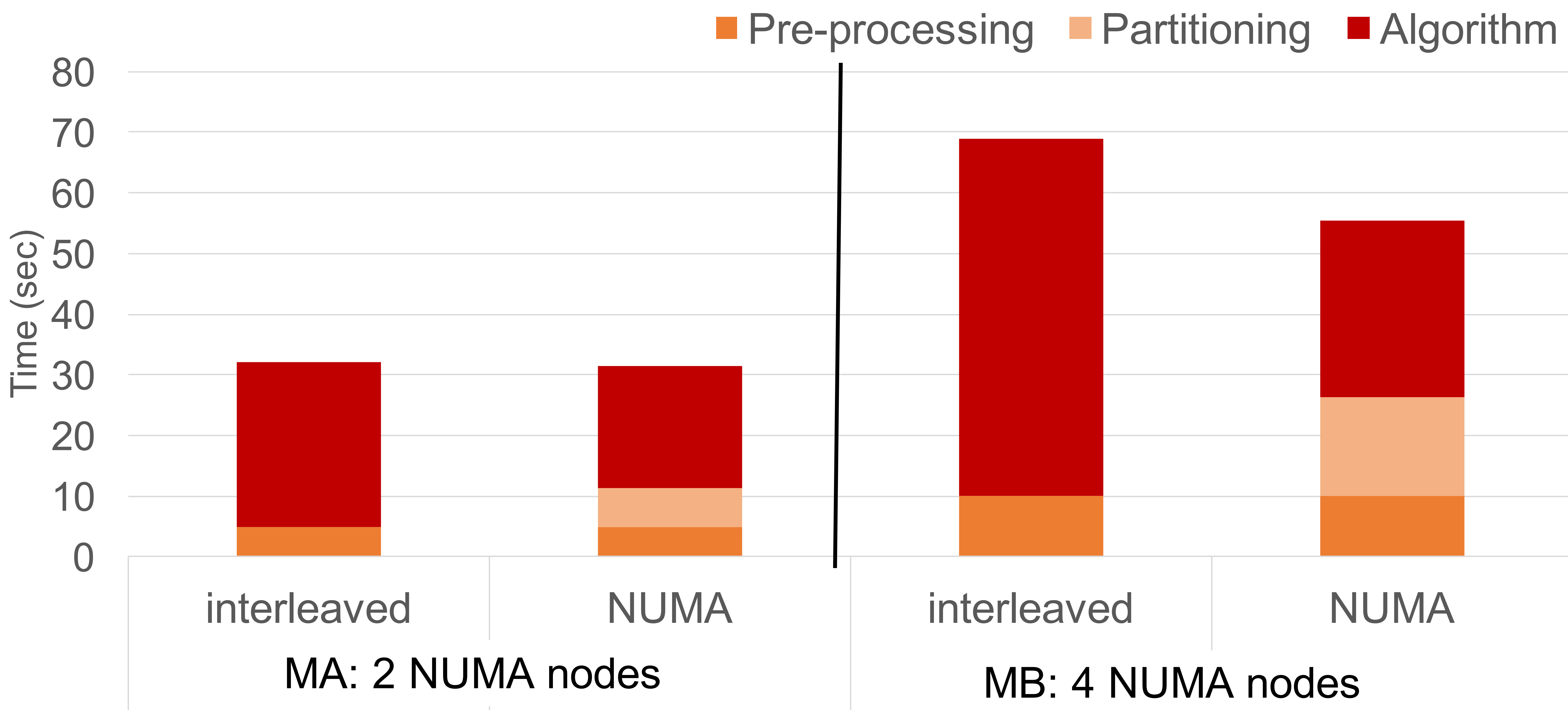

Algorithm
Time (sec)
80
70
60
50
40
30
20
10
0
interleaved
NUMA
interleaved
NUMA
MA: 2 NUMA nodes
MB: 4 NUMA nodes

PageRank



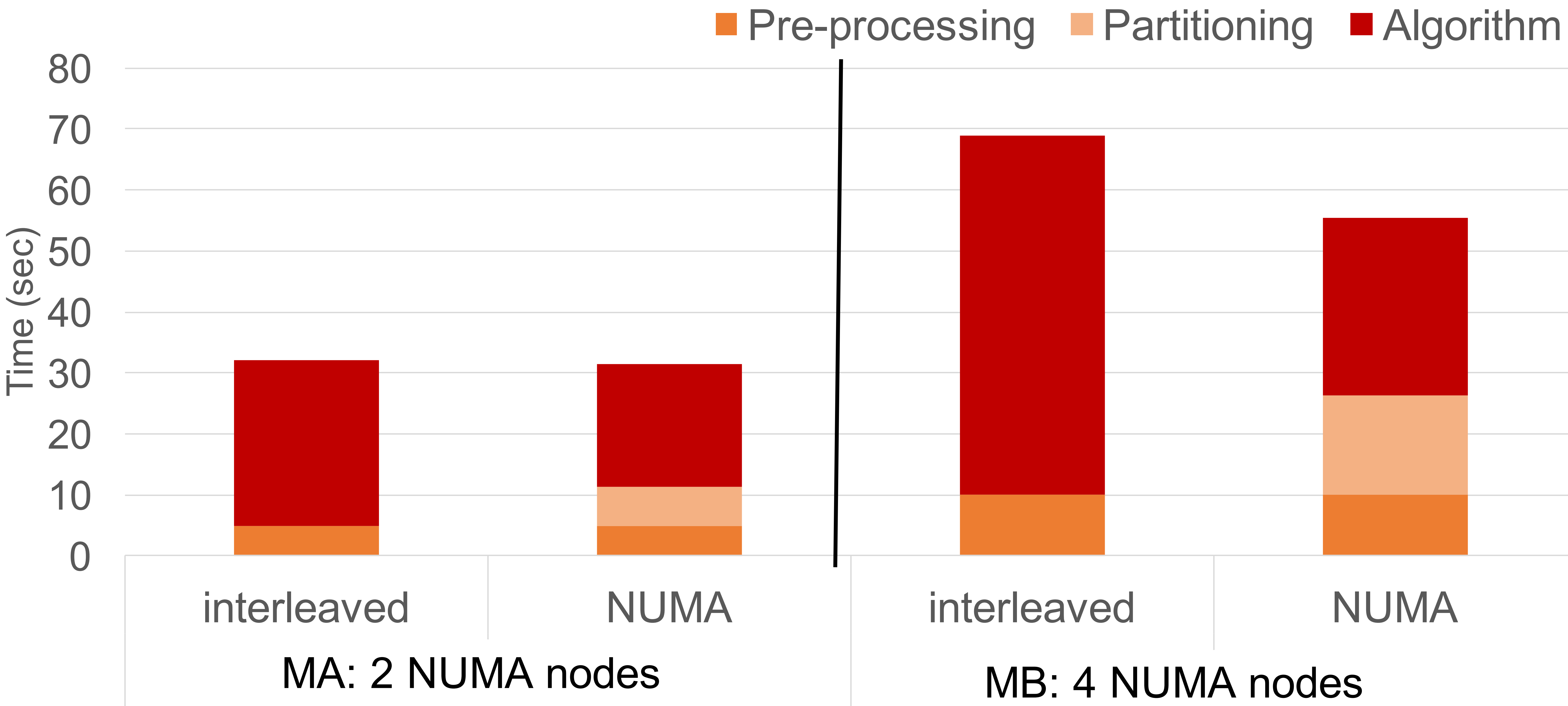
27% - 50% Improved compute time

PageRank



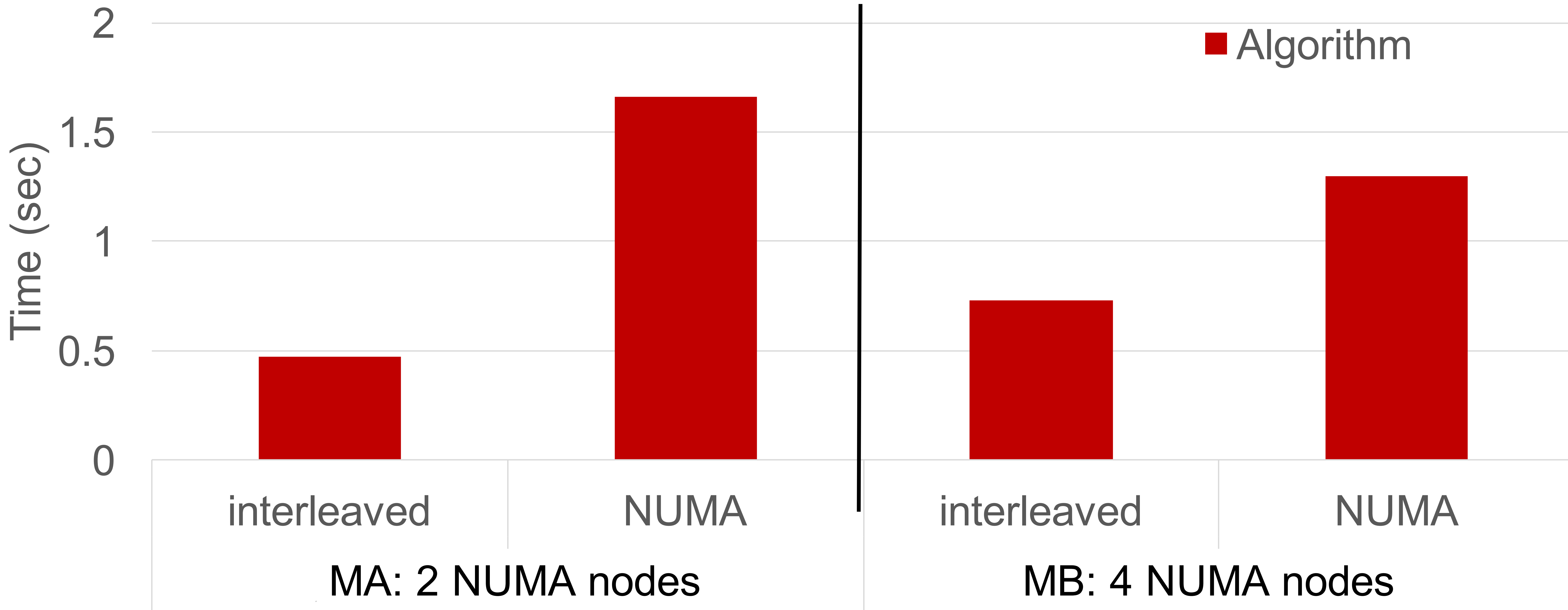
Pre-processing
Partitioning
Algorithm
Time (sec)
0
10
20
30
40
50
60
70
80
interleaved
NUMA
interleaved
NUMA
MA: 2 NUMA nodes
MB: 4 NUMA nodes

PageRank



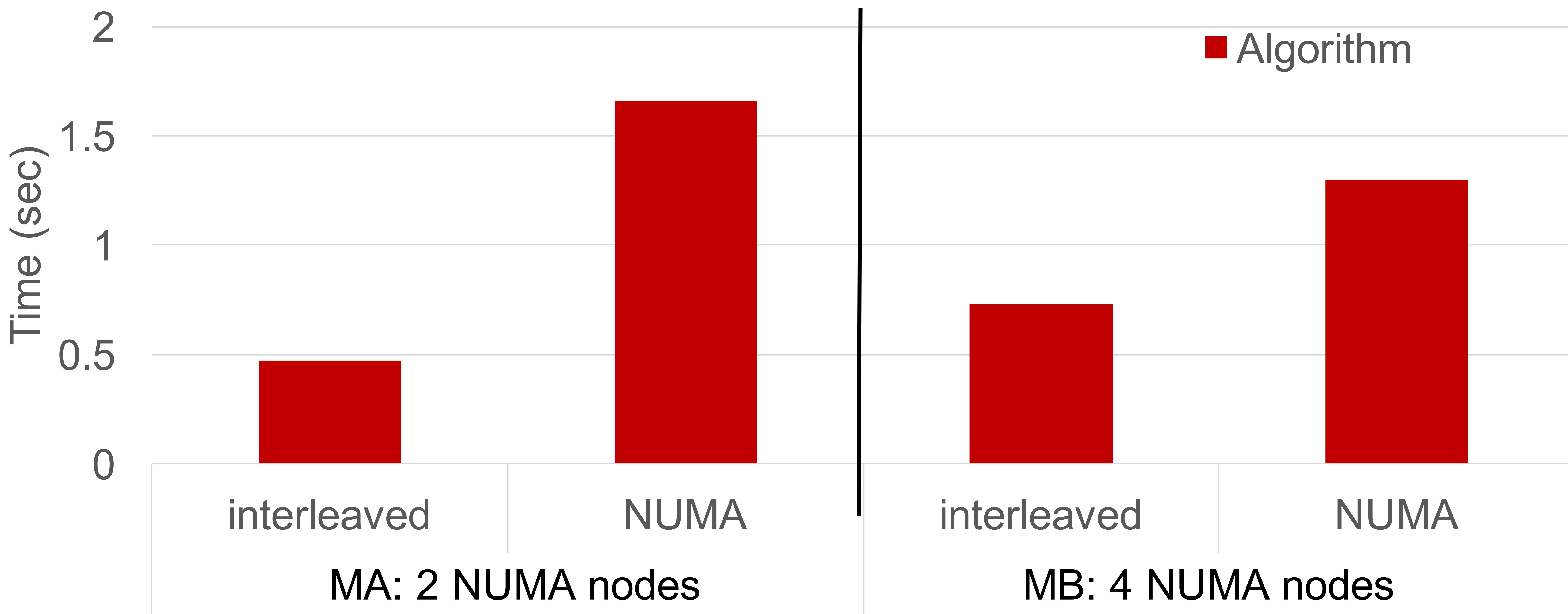
Pre-processing amortized only on Machine B

BFS



Algorithm
Time (sec)
2
1.5
1
0.5
0
interleaved
NUMA
interleaved
NUMA
MA: 2 NUMA nodes
MB: 4 NUMA nodes

BFS



No gain in algorithm time, contention on memory bus

Questions we want to answer:

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Pre-processing

- ✓ How to represent the graph?
  - ○ Adjacency lists ○ Edge arrays
- ✓ Cost of creating the representation?
  - ○ Radix sort wins for adjacency lists
- ✓ What data layout is best?
  - ○ BFS: Adj. list ○ PR: Grid ○ SpMV: Edge array

Algorithm

- ✓ Can we improve cache locality?
  - ○ Yes. By laying out the edges in a grid format
  - ○ BFS: Adj. list ○ PR: Grid ○ SpMV: Edge array
- ✓ Should we optimize for NUMA?
  - ○ Can pay off only on big machines
  - ○ BFS & SpMV: No gain ○ PR: NUMA-optimize
- **Information flow: push, pull or a both?**

Information flow

- Push
  - You **push** information to your neighbors
  - You need **outgoing edges**

- Pull
  - You **pull** information from your neighbors
  - You need **incoming** edges

Which one is better?

- Push
  - You **push** information to your neighbors - write to state of others
- Pull
  - You **pull** information from your neighbors – write to own state

Which one is better?

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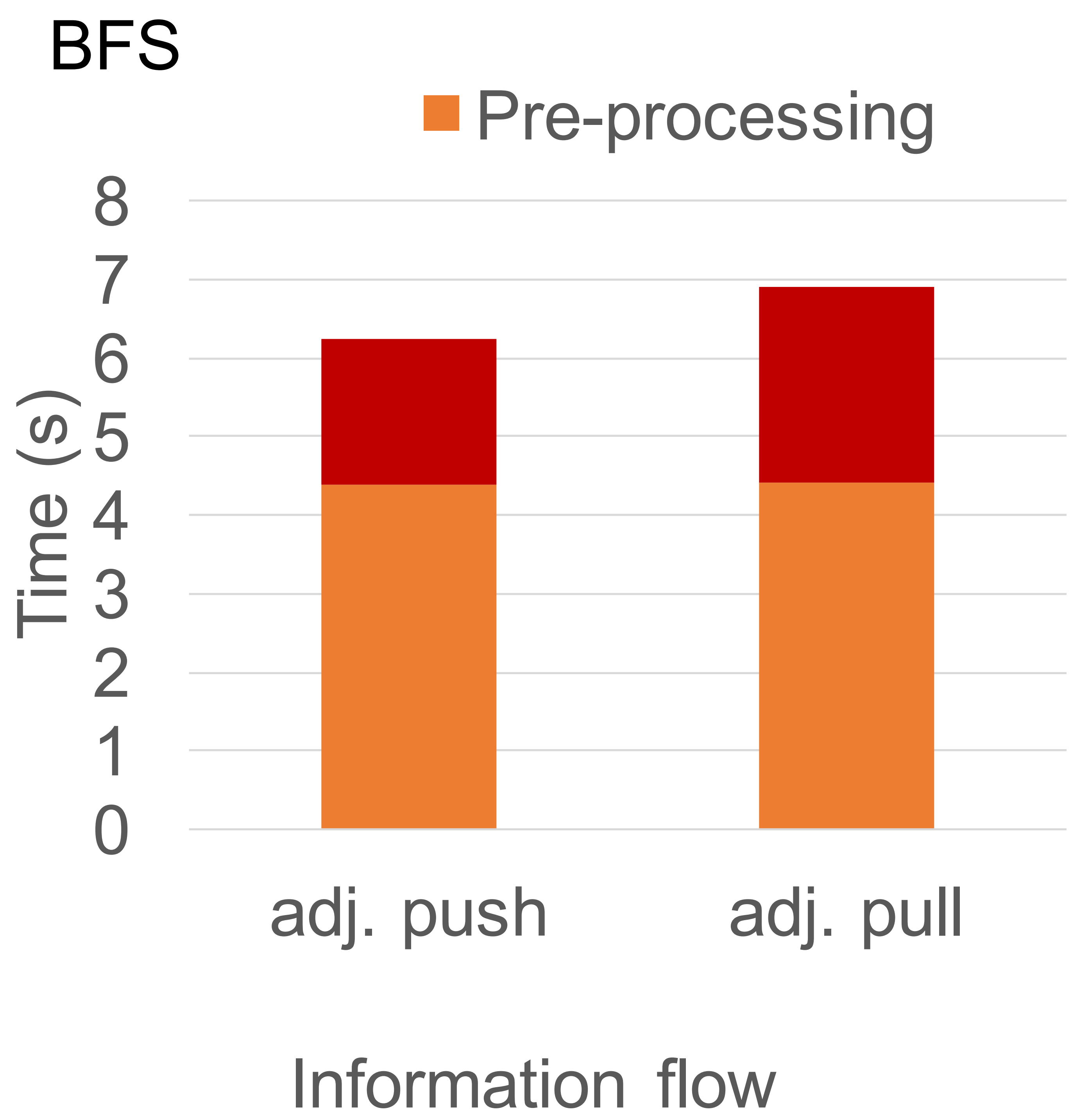
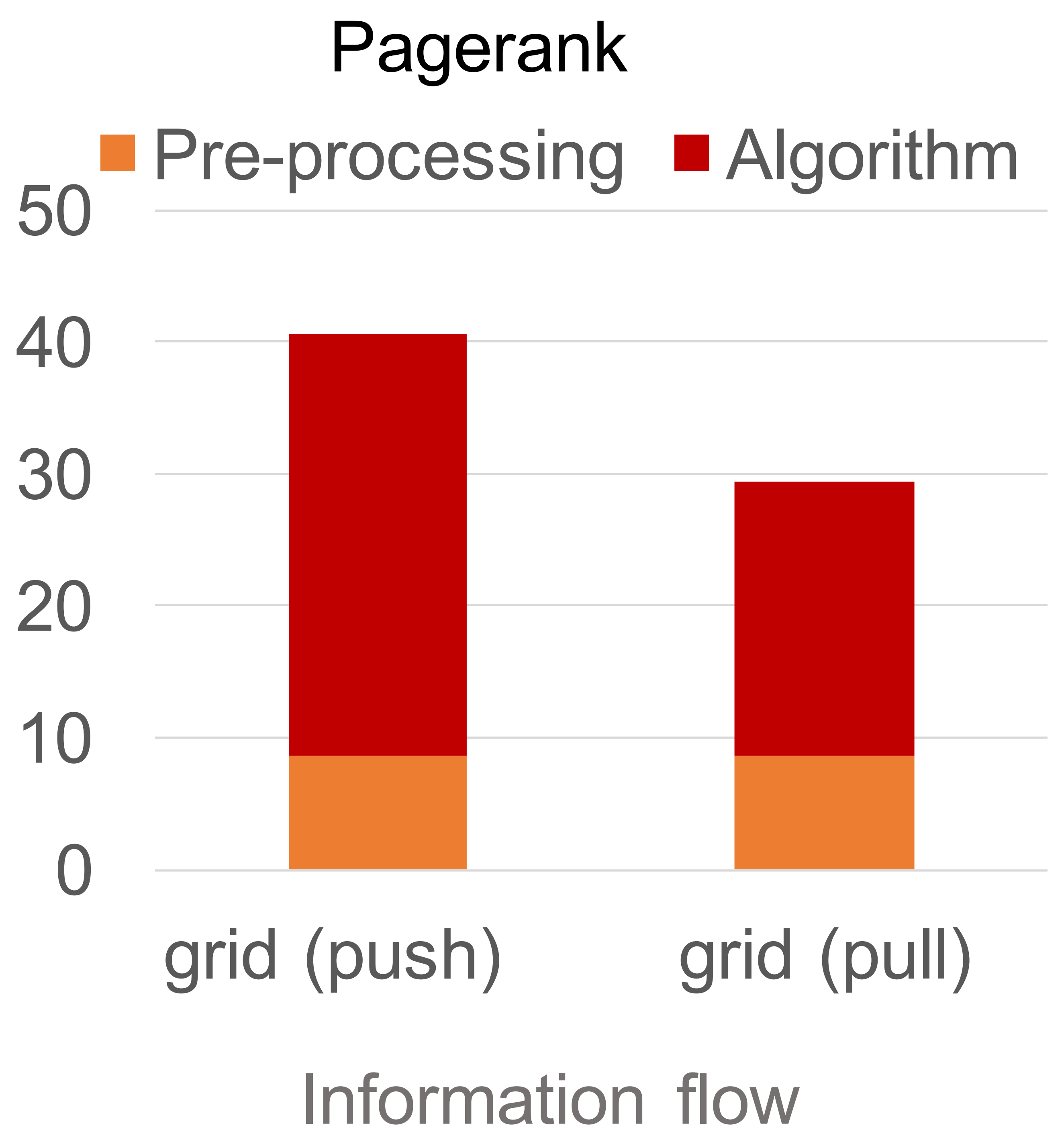
- Push
  - You **push** information to your neighbors - write to state of others
  - ✓Good when few vertices are active
  - x Needs locks

- Pull
  - You **pull** information from your neighbors – write to own state
  - ✓Good when many vertices are active
  - ✓Locks can be avoided

PUSH vs. PULL – BFS & PR





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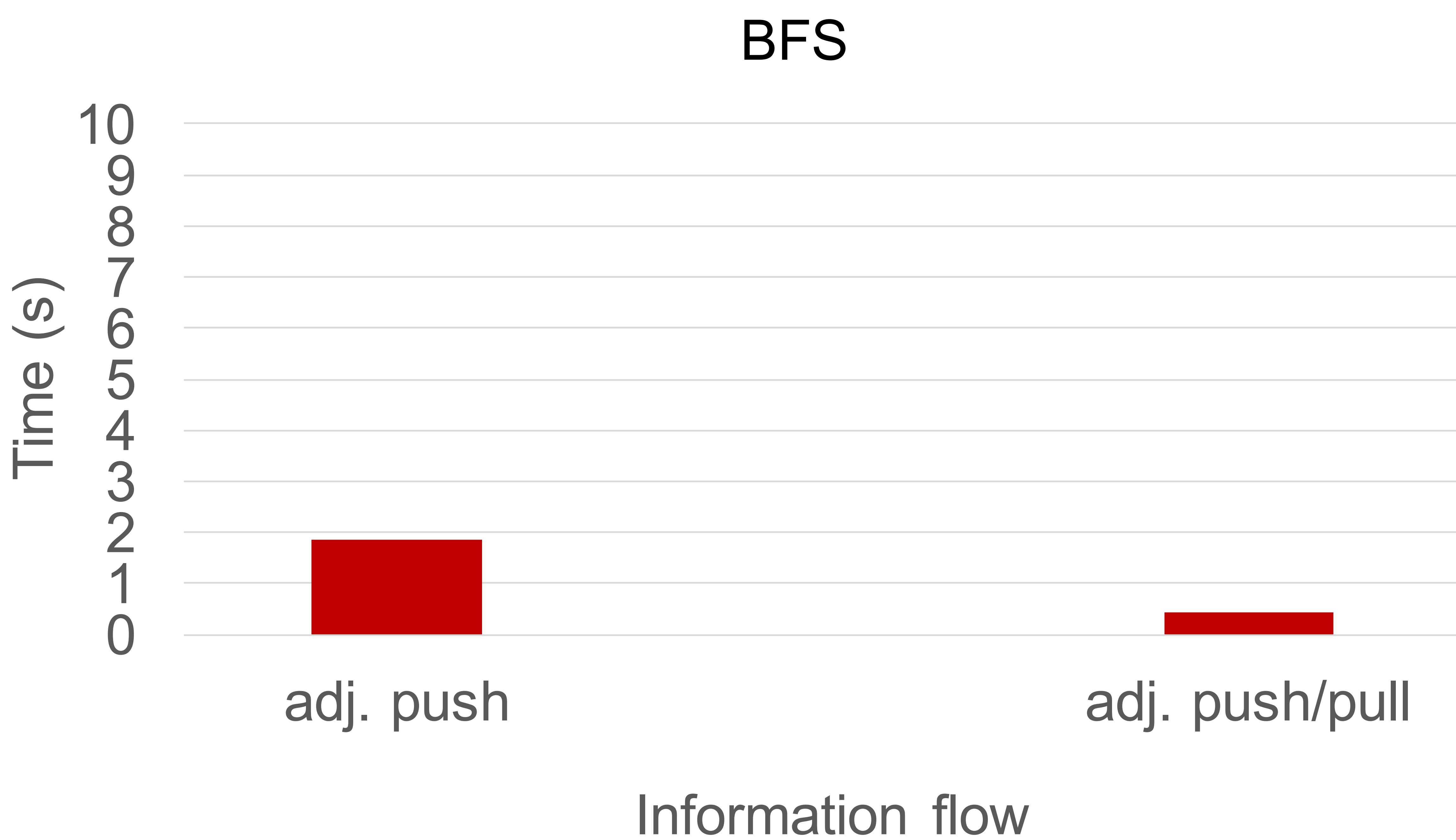
  - BFS & SpMV: No gain
  - PR: NUMA-optimize
- Information flow: **push**, **pull** or a **both**?
  - Less synchronization not always a win
  - BFS: Push (locks)
  - PR: Pull (no locks)

Push & Pull both win in different situations

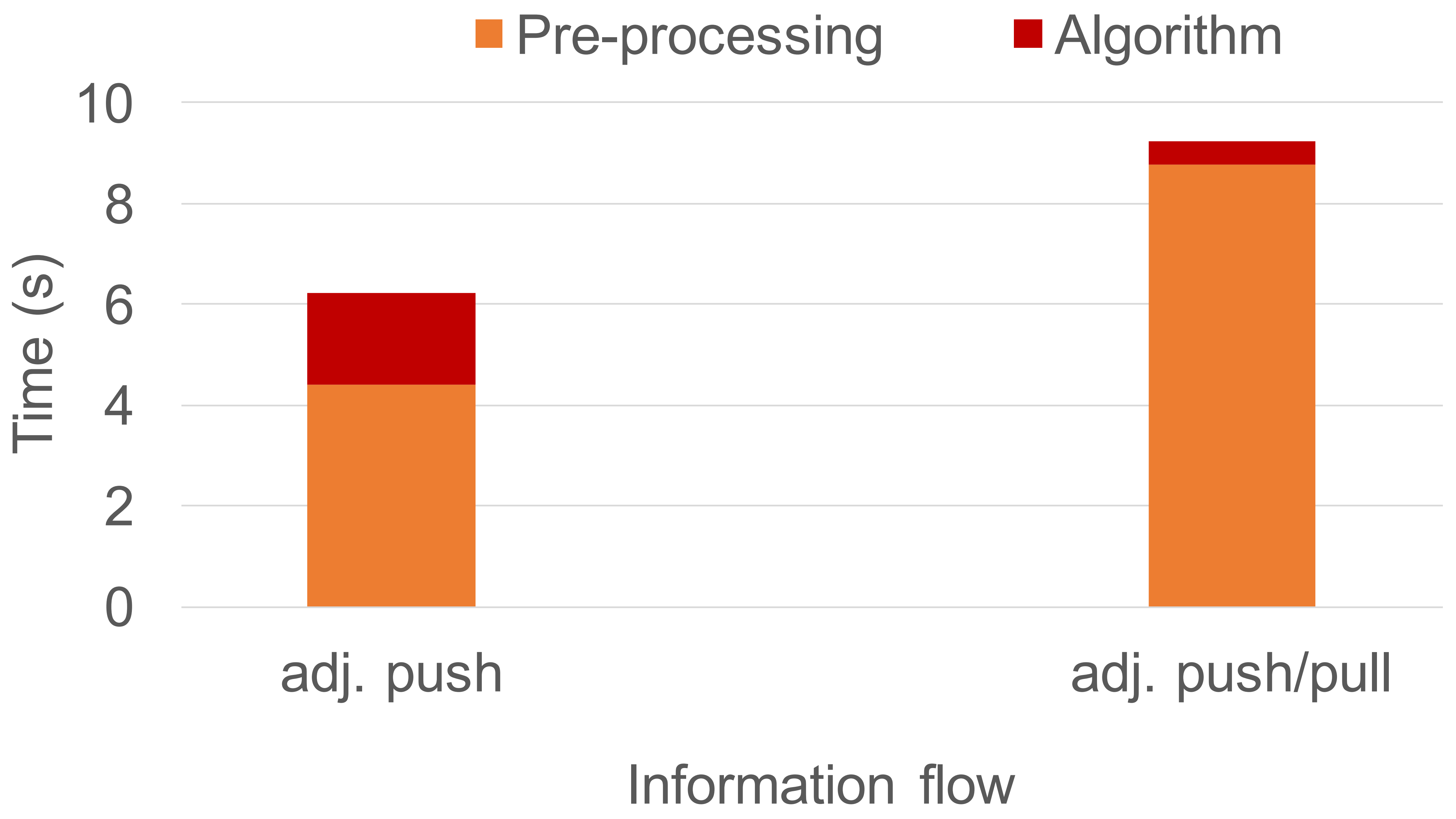
- Combine them
  - Use push when it is efficient
  - Use pull when it is efficient
  - Cost: You need **both**, incoming **and** outgoing edges

Benefit of Push/Pull



Benefit of Push/Pull

BFS



Questions we want to answer:

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Pre-processing

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  - PR: NUMA-optimize
- ✓ Information flow: **push**, **pull** or a **both**?
  - Less synchronization not always a win
  - BFS: Push (locks)
  - PR: Pull (no locks)
  - Push/Pull no win in end-to-end (directed graphs)

Additional results in the paper

- Scalability of pre-processing approaches
- Relation between pre-processing and loading from HDD and SSD
- Results on other algorithms
- Results for different graph types

Systems that motivated the paper

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System	Data Layout	Iteration Model	Push or Pull	NUMA-Aware
Ligra [PPoPP '13]	Adj. List	Vertex-centric	Push & Pull	-
Polymer [PPoPP '15]	Adj. List	Vertex-centric	Push & Pull	✔
Gemini [OSDI'16]	Adj. List	Vertex-centric	Push & Pull	✔
X-Stream [SOSP'13]	Edge Array	Edge-centric	Push	-
GridGraph [ATC '15]	Grid	Grid-cell	Push	-

Summary

Pre-processing

- Edge arrays
- Adjacency lists
- Sorting techniques

Algorithm time

- Cache-optimizations
- Push vs. Pull
- Synchronization
- NUMA-aware computation

Conclusion

- **Improvement in computation is not free**
- **Trade-off between added pre-processing time and algorithm time**

Whether optimization cost in pre-processing is amortized, depends on algorithm:

- SpMV: Short algorithm and does not benefit from additional optimizations
- BFS: Building adjacency lists
- Pagerank: Optimizing for cache locality (grid) & NUMA-Awareness

Fork us on GitHub: https://github.com/epfl-labos/EverythingGraph.git