Graph databases, algorithms and indexing

Poseidon: A OneGraph Engine

19th Scheduling for large-scale systems workshop
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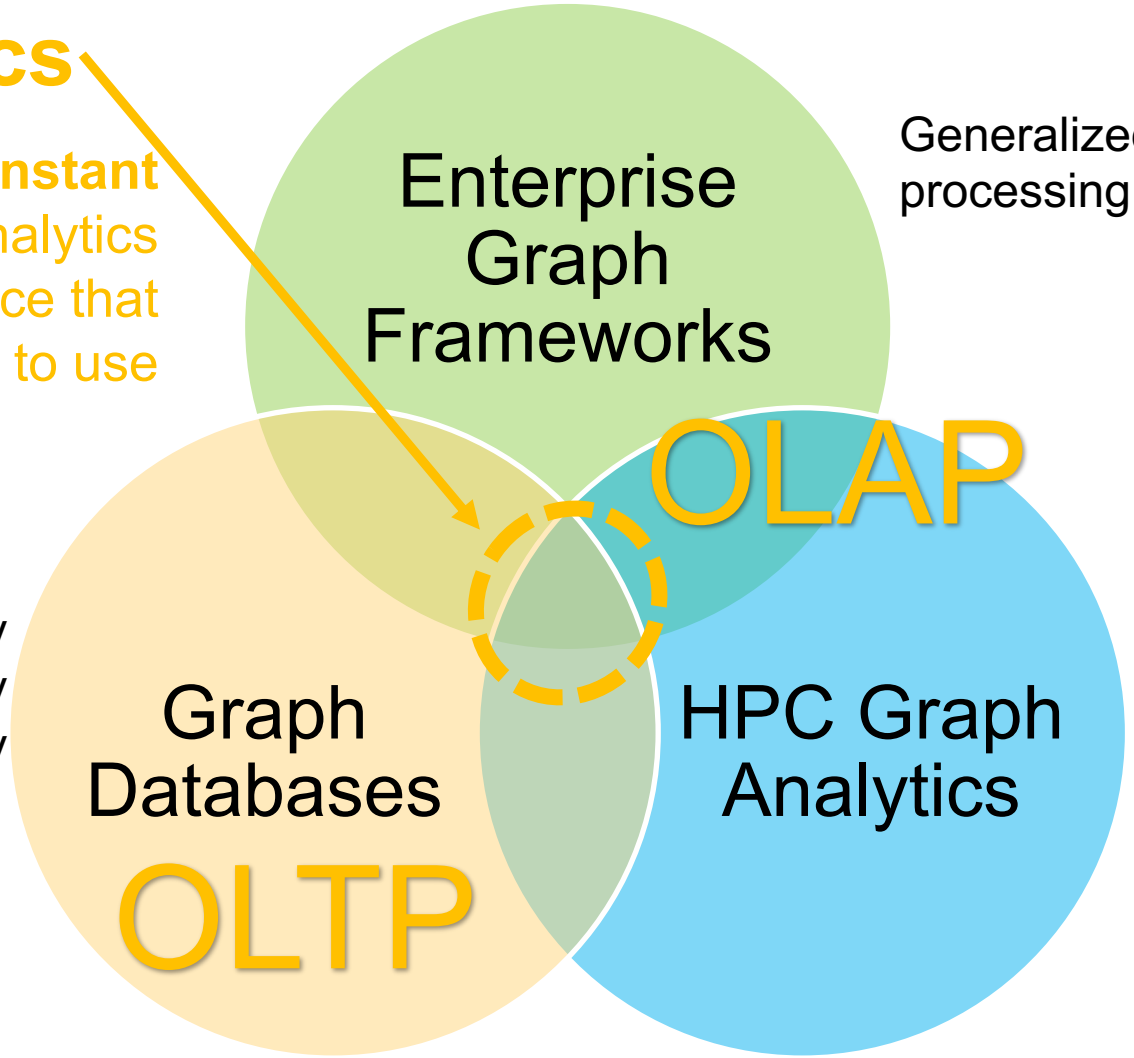
to appear in SIGMOD'26 available in arXiv

Landscape of current “Graph World”

Neptune Analytics

Performance is within a **constant factor** of HPC Graph Analytics delivered as a managed service that is easy to use



Generalized APIs for graph processing

Generalized graph query languages with consistency and durability

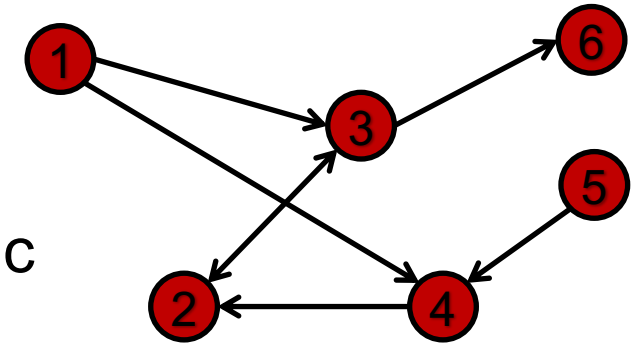
High performance for specific graph problems

Outline

- Graph? What is it?
- Interoperability – Logical Data Model
- DB challenges: In-memory DB – compact storage
- DB challenges: Access Patterns
- DB challenges: (Partitioned) Indices
- Graph Analytics challenges: Kernel Access Patterns

Graph is a sparse matrix

- Adjacency matrix
- For n vertices and m edges
  - Directed -> binary, not symmetric



1	3, 4
2	3
3	2, 6
4	2
5	4
6	

Adjacency List

Space: $O(n+m)$

	1	2	3	4	5	6
1			1	1		
2			1			
3		1				1
4		1				
5				1		
6						

Adjacency ***Sparse*** Matrix

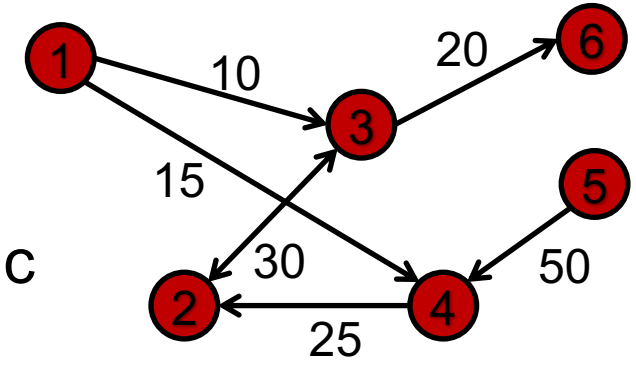
	1	2	3	4	5	6
1	0	0	1	1	0	0
2	0	0	1	0	0	0
3	0	1	0	0	0	1
4	0	1	0	0	0	0
5	0	0	0	1	0	0
6	0	0	0	0	0	0

Adjacency Matrix

Space: $O(n^2)$

Graph is a sparse matrix

- Adjacency matrix
- For n vertices and m edges
  - Directed -> binary, not symmetric
  - Weighted



1	3	4
2	3	
3	2	6
4	2	
5	4	
6		

Adjacency List

Space: $O(n+m)$

w	10	15	30	30	20	25	50
adj	3	4	3	2	6	2	4
xadj	1	3	4	6	7	8	8
	1	2	3	4	5	6	7

Compressed Adjacency List / Compressed Sparse Row (CSR)

Space: $O(n+m)$

Space = $2m+n+1$

s	t	w
1	3	10
1	4	15
2	3	30
3	2	30
3	6	20
4	2	25
5	4	50

Edge List / Coordinate (COO)

Space: $O(m)$

Space = $3m$

Fixed schema

Graph Data Models

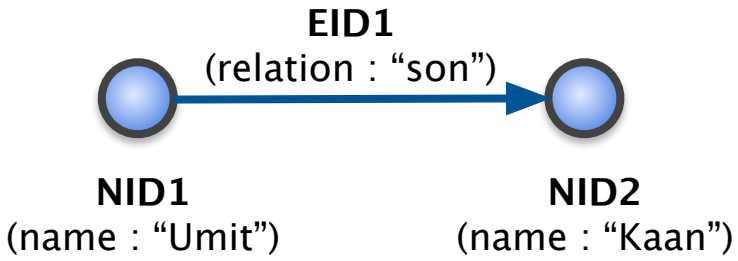
LPG: Labeled Property Graphs

Vertices

Nodes: Label/ID + *Properties* (set of key-value pairs)

Edges

Relationships: Label/ID + Type + Properties



RDF: Resources Description Framework

Vertices

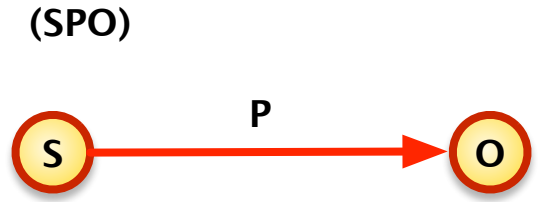
Resources: URIs

Attribute Values: Literals

Edges

Relationships: URIs

RDF Triple: **S**ubject-**P**redicate-**O**bject



There is no internal structure for nodes and edges

Real World Graph Samples

CSV files: Gremlin, OpenCypher (w/ minor differences)

nodes.csv

```
~id, name:String, val:Int, ~label
v1,"Bryan",1,person;human
v2,"Michael",2,person;human
v3,"Umit",3,person;human
v4,"Olaf",4,person;human
v5,"Brad",5,person;human
```

edges.csv

```
~id, ~from, ~to, ~label, since:Int
e1,v1,v2,knows,2010
e2,v1,v3,knows,2020
e3,v2,v4,knows,2014
e4,v3,v4,knows,2022
e5,v3,v5,knows,2020
e6,v4,v5,knows,2015
```

Real World Graph Samples

in an N-Triples compliant 1G syntax

```
<http://www.mapgraph.com/1> <http://xmlns.com/foaf/0.1/knows> <http://www.mapgraph.com/2> _:sid1 .
<http://www.mapgraph.com/1> <http://xmlns.com/foaf/0.1/knows> <http://www.mapgraph.com/3> _:sid2 .
<http://www.mapgraph.com/2> <http://xmlns.com/foaf/0.1/knows> <http://www.mapgraph.com/4> _:sid3 .
<http://www.mapgraph.com/3> <http://xmlns.com/foaf/0.1/knows> <http://www.mapgraph.com/4> _:sid4 .
<http://www.mapgraph.com/3> <http://xmlns.com/foaf/0.1/knows> <http://www.mapgraph.com/5> _:sid5 .
<http://www.mapgraph.com/4> <http://xmlns.com/foaf/0.1/knows> <http://www.mapgraph.com/5> _:sid6 .
<http://www.mapgraph.com/1> <http://www.w3.org/1999/02/22-rdf-syntax-ns:label> "Bryan" _:sid7 .
<http://www.mapgraph.com/2> <http://www.w3.org/1999/02/22-rdf-syntax-ns:label> "Michael" _:sid8 .
<http://www.mapgraph.com/3> <http://www.w3.org/1999/02/22-rdf-syntax-ns:label> "Umit" _:sid9 .
<http://www.mapgraph.com/4> <http://www.w3.org/1999/02/22-rdf-syntax-ns:label> "Olaf" _:sid10 .
<http://www.mapgraph.com/5> <http://www.w3.org/1999/02/22-rdf-syntax-ns:label> "Brad" _:sid11 .
_:sid1 <http://www.mapgraph.com/since> "2010"^^<http://www.w3.org/2001/XMLSchema#int> _:sid17 .
_:sid2 <http://www.mapgraph.com/since> "2020"^^<http://www.w3.org/2001/XMLSchema#int> _:sid18 .
_:sid3 <http://www.mapgraph.com/since> "2014"^^<http://www.w3.org/2001/XMLSchema#int> _:sid19 .
_:sid4 <http://www.mapgraph.com/since> "2022"^^<http://www.w3.org/2001/XMLSchema#int> _:sid20 .
_:sid5 <http://www.mapgraph.com/since> "2020"^^<http://www.w3.org/2001/XMLSchema#int> _:sid21 .
_:sid6 <http://www.mapgraph.com/since> "2015"^^<http://www.w3.org/2001/XMLSchema#int> _:sid22 .
```

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Graph interoperability

- What if we did not have to choose between RDF and LPG?
- What if we could use OpenCyper or Gremlin over RDF, or SPARQL over LPG?
- Interoperability: single graph (meta)model, free use of any query language

- 1G model (“one graph to rule them all”)
  - "Graph? Yes! Which one? Help!", O. Lassila, M. Schmidt, B. Bebee, D. Bechberger, W. Broekema, A. Khandelwal, K. Lawrence, R. Sharda, B. Thompson, arXiv:2110.13348v1, 2021.

Storage Challenges: Interoperable Physical Data Model

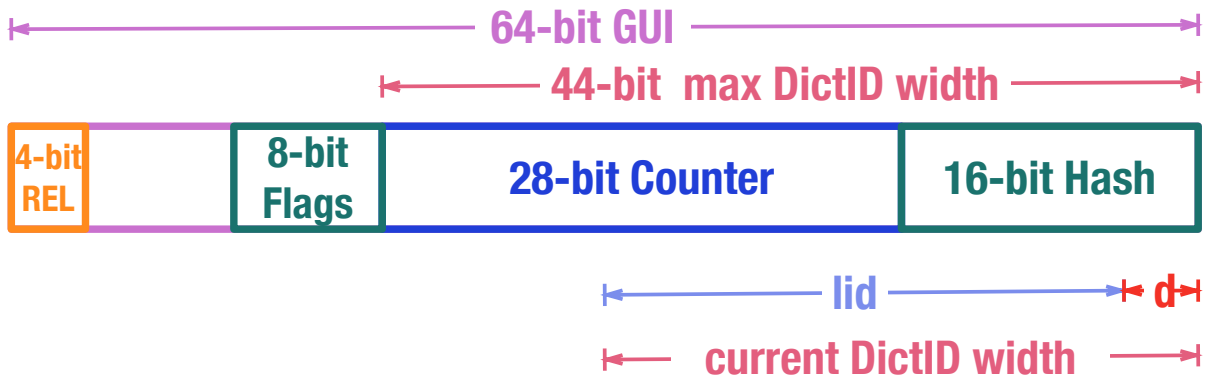
- 1G Graph Storage
  - Three kinds of relations
    - Dictionaries: URIs/Literals → IDs
    - Graph Structure: Topologies – relations between (S)ubject and (O)bject, in other words between "vertices"
    - Graph Data: Values – properties of vertices and edges
  - In 1G, Edges/Properties (of vertices and edges) can become "vertices"
- How to dynamically distribute data?
  - Blocked partition (coarse-grain 2D) as a sweet spot between performance and architecture agnostic algorithm development [1]
- System generated IDs are uniform random
  - Remember graph vertices comes as URIs (strings)
  - Load-balanced partitioning (declustering) is favored against locality for initial load
    - Graph-aware re-partitioning can be done after graph is loaded

[1] PGAbB: A Block-Based Graph Processing Framework for Heterogeneous Platforms
Abdurrahman Yasar, Sivasankaran Rajamanickam, Jonathan W. Berry, Umit V. Catalyurek
https://arxiv.org/abs/2209.04541

Dictionary Encoding

- Convert “Strings” (URIs/Literals) into dictionary encoded 64-bit values

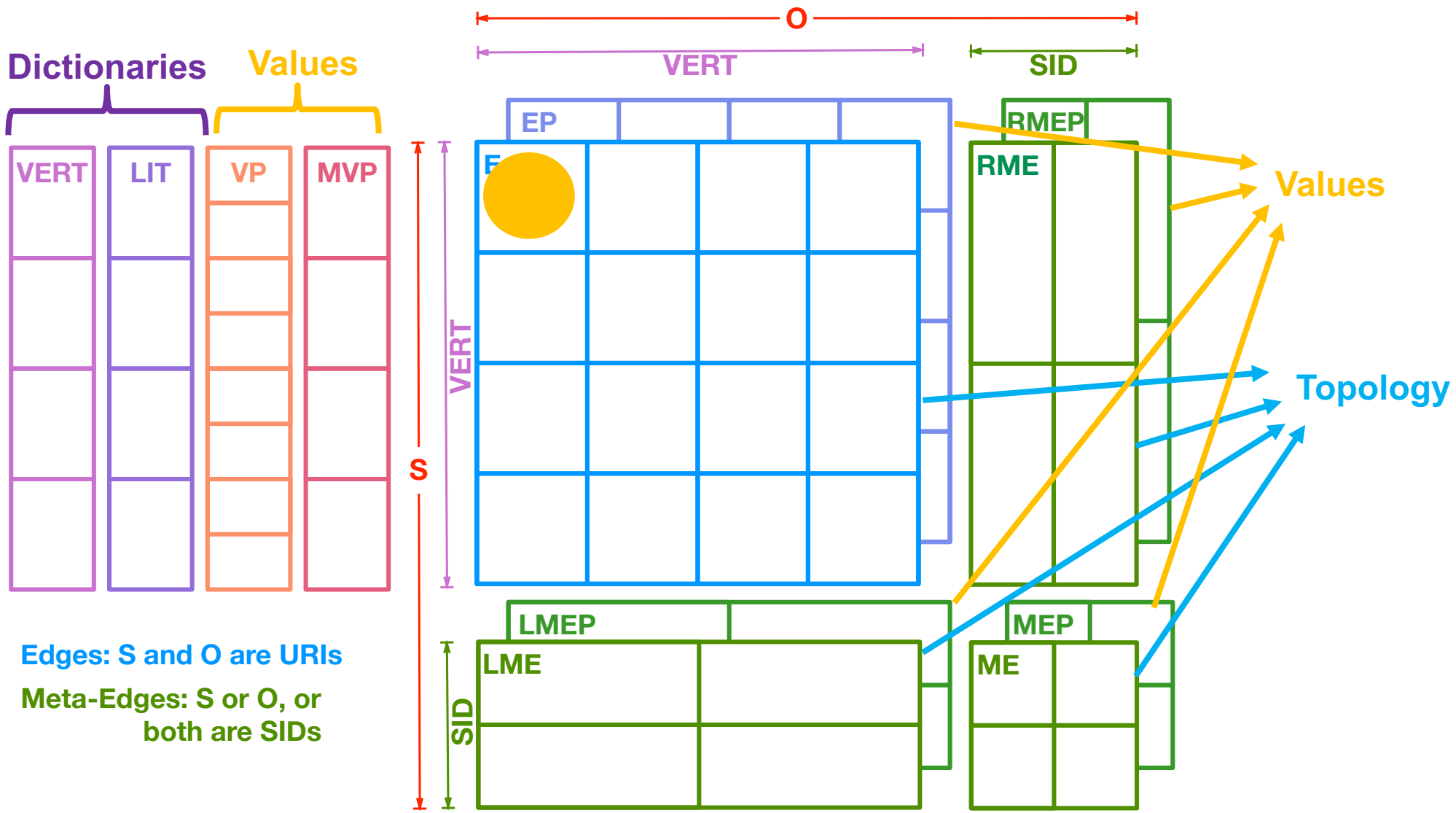
- Partitioned hash
  - Use a hash function to partition (16-bit)
- Use a second hash function to hash/map in each part
- Generate 64-bit Global Unique Identifier (GUI)



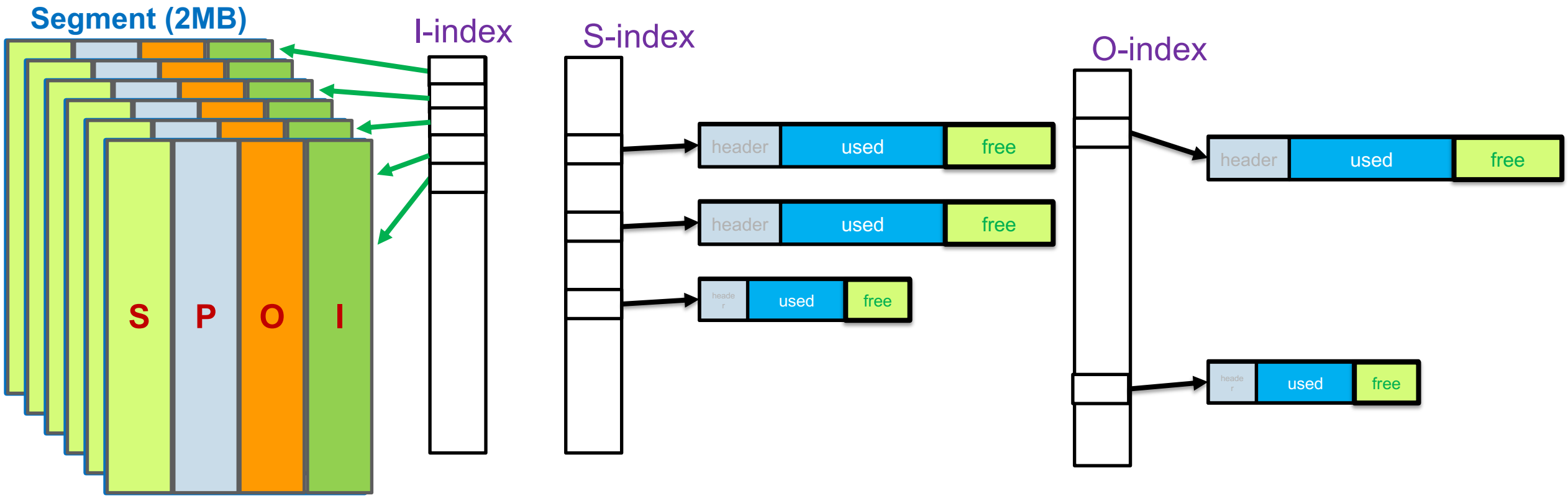
d : partition number, up to 16 bits

lid : 28-bit local id, part of it is coming from Hash, and the rest from the Counter

1D and 2D partitioning of Poseidon Relations



Single Partition of a Relation



TOP: 4x4-byte = 16 bytes

VAL: 3 (S/P/I) x 4-bytes + 8 bytes (O) + 1 byte (Flags) = 21 bytes

WID: 2 (P/I) x 4-bytes + 2 (S/O) x 8-bytes = 24 bytes

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DB Challenges: Access Pattern Language

- Language agnostic to physical data model
- Declarative, abstract (relation separation & internal partitioning)
- Concise and efficient

#	Expression	Meaning	Additional Arguments
1	`SP_^_`	retrieve the O value of every SPOI tuple that has a given S value and a given P value	i) value for S, ii) value for P, iii) pointer to data structure to which the O values of the selected tuples are written
2	`_[]P_^_^`	retrieve the O and the I value of all SPOI tuples that have both a specific P value and an S value that is one of the elements in a list of such values	i) value for P, ii) pointer to data structure with frontier for S; iii–iv) pointers to two data structures to which the O and the I values of the selected tuples, respectively are written
3	`s_^_l__`	retrieve all SIDs that are S values of SPOI tuples with a literal in the O position	i) pointer to data structure to which the S values of the selected tuples are written
4	`SP_^x__^_^_`	join every SPOI tuple (s, p, o, i) with every SPOI tuple (s', p', o', i') such that $i = s'$, and retrieve o, p', and o' of every result tuple	i–iii) pointers to three data structures to which the three values of every result tuple are written, respectively

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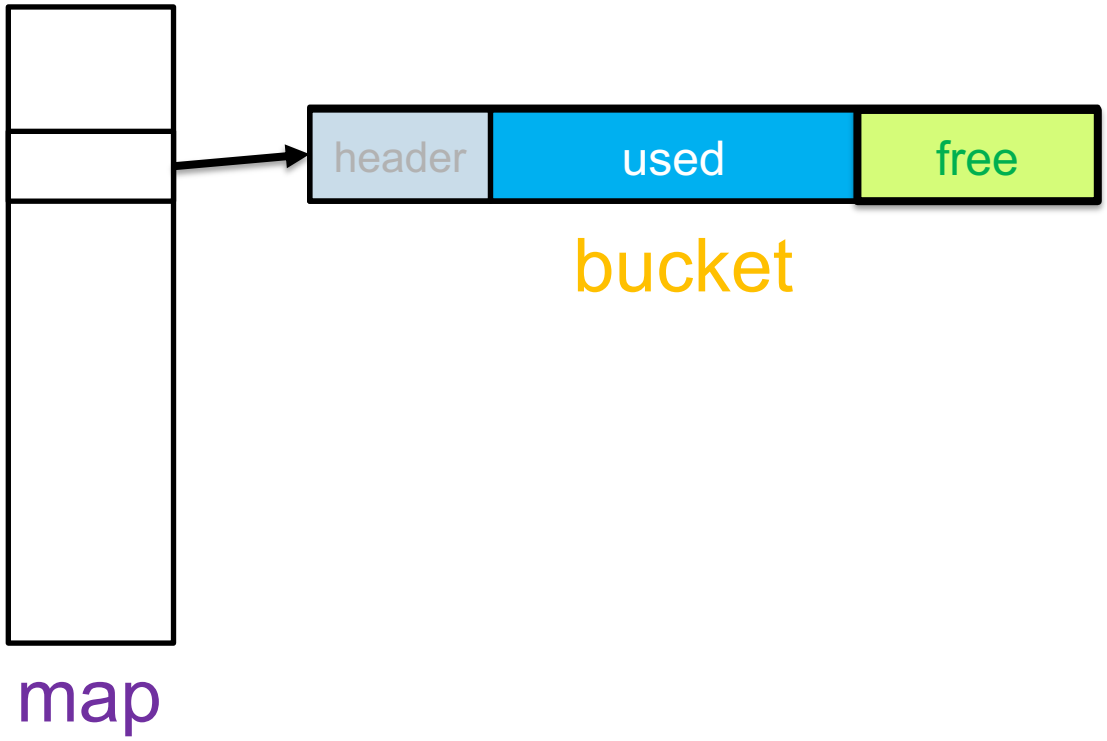
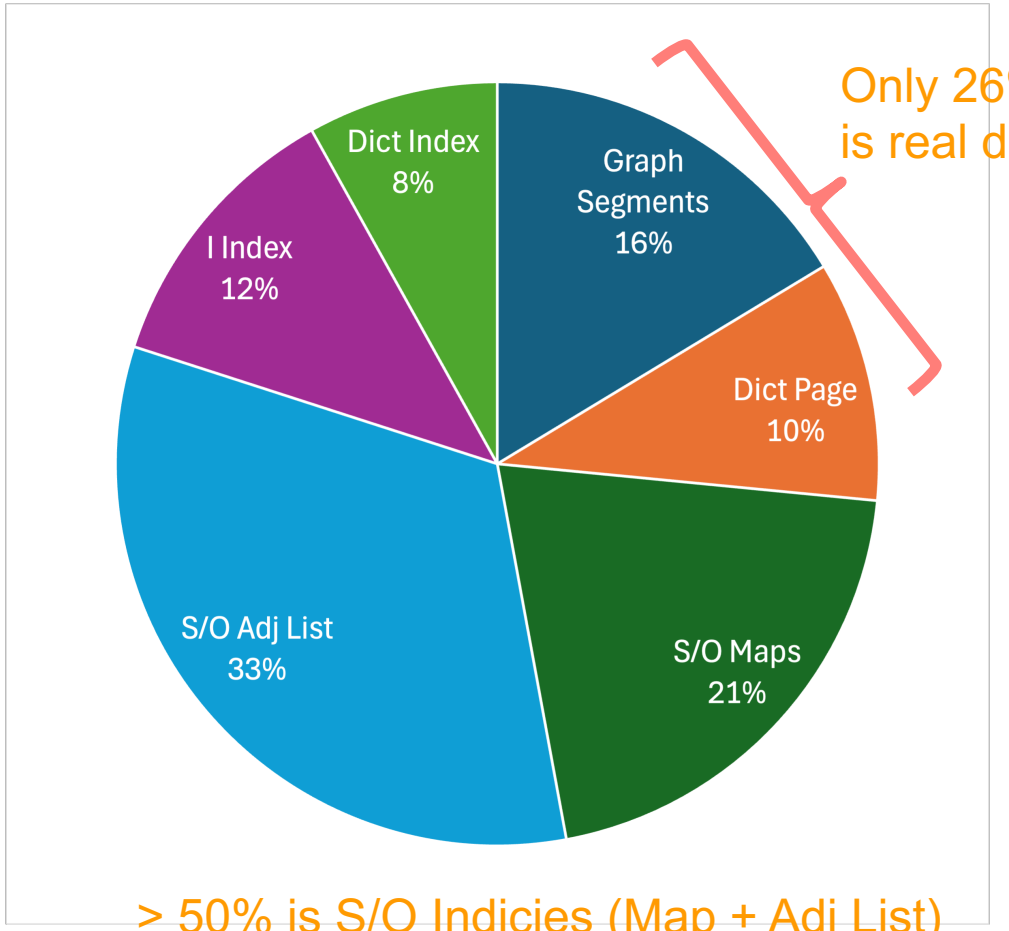
Poseidon Indices

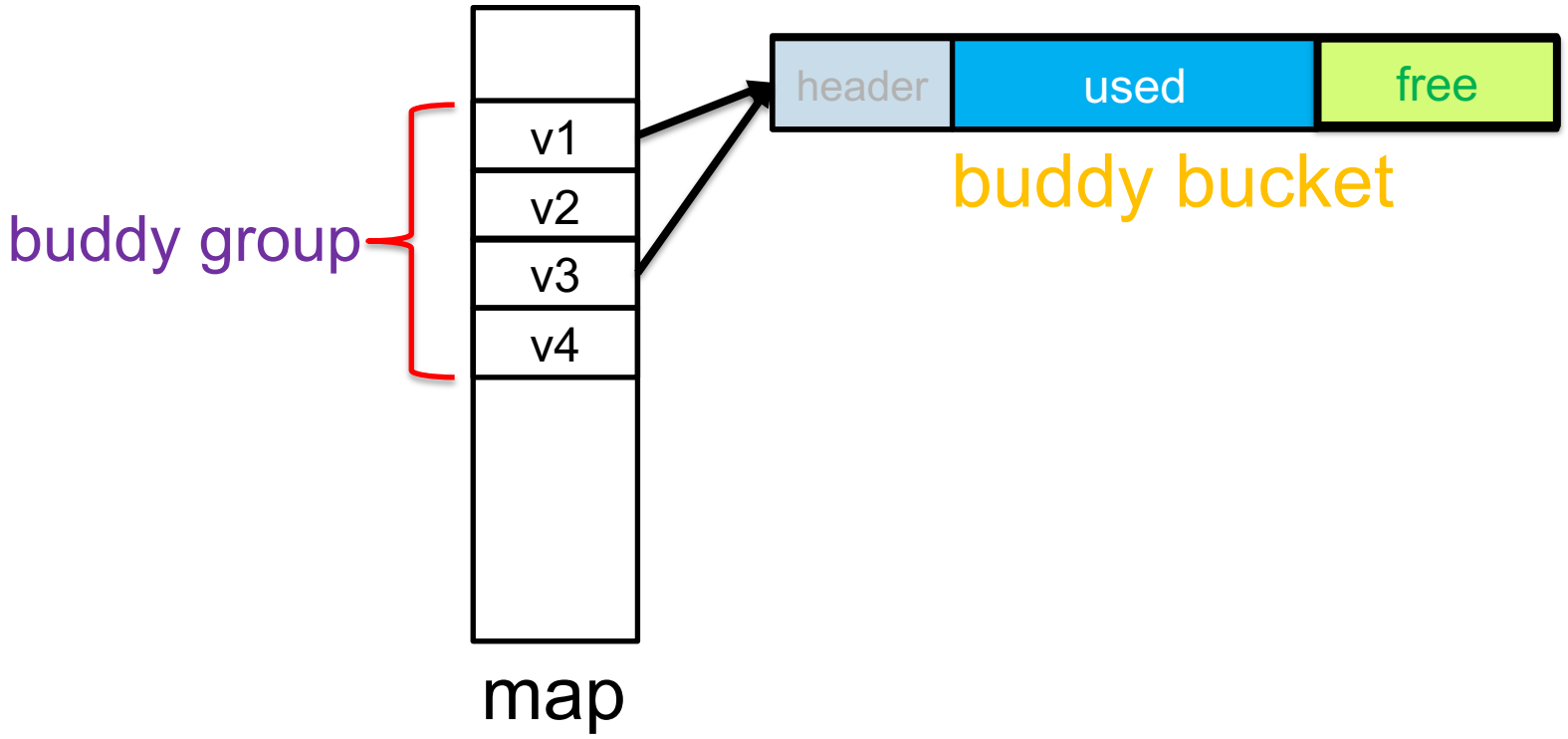
- Each non-dictionary part has three indices : S, O, I
- Each S/O index is a map to a fixed-size bucket that has room for new entries.
- Inserts/deletes are lock-free





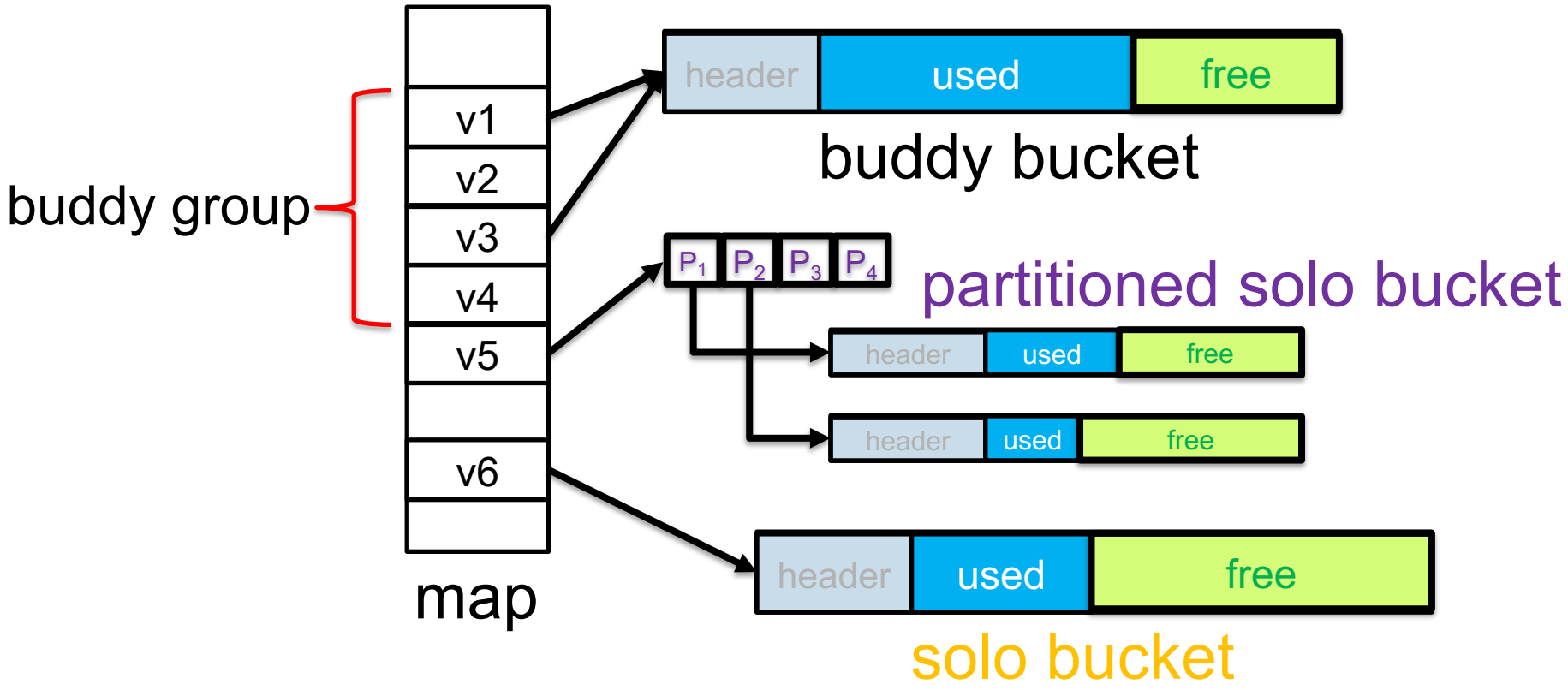
Index improvements: Buddy Buckets

- Share buckets for multiple vertices: buddy group

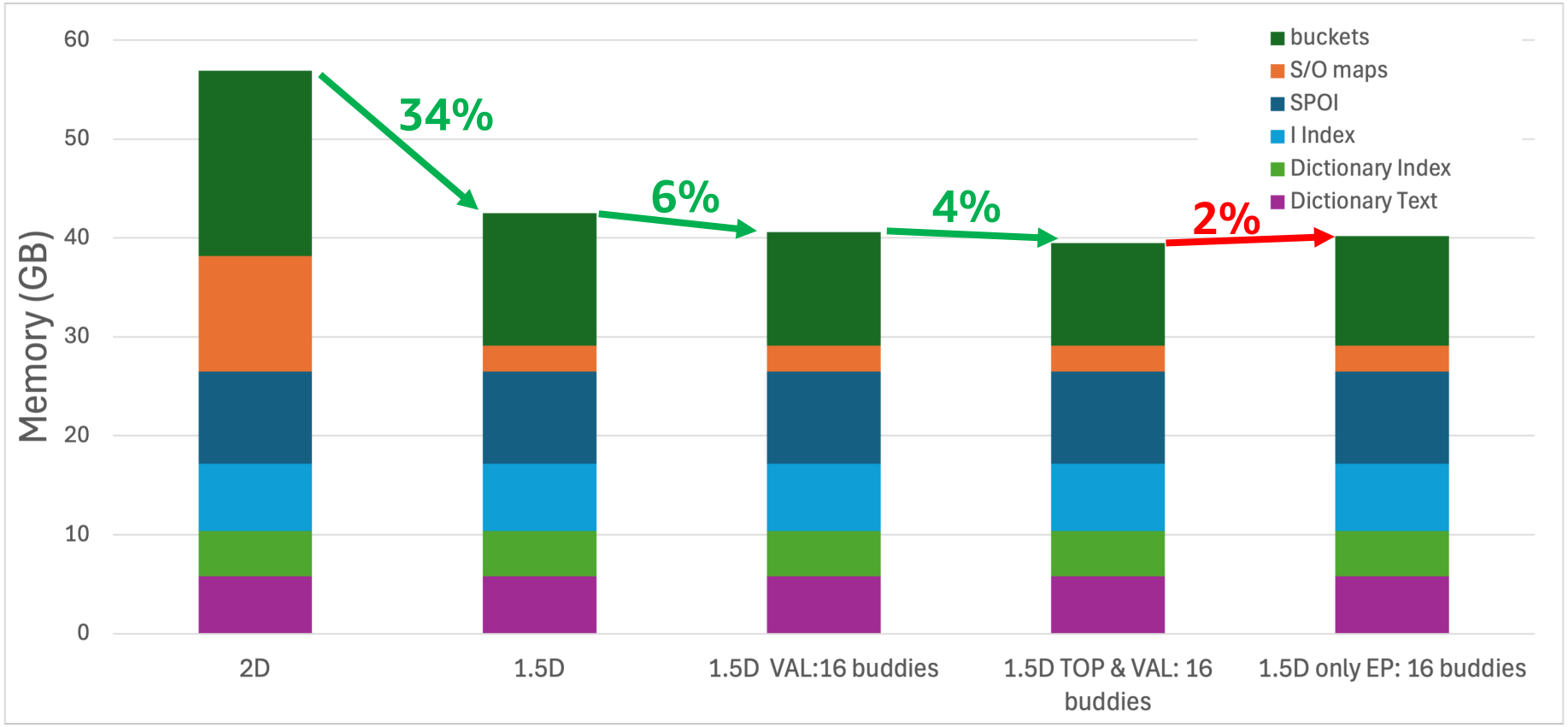


Topology Index improvements: 1.5D

- *Low degree vertices*: Share bucket (called solo bucket) for rows / columns of 2D topology partitioned
- *High degree vertices*: have partitioned solo bucket



Memory: 2D vs 1.5D + buddy buckets



1.5D only EP: 16 buddies:
Sweet spot for runtime performance and 42% space savings

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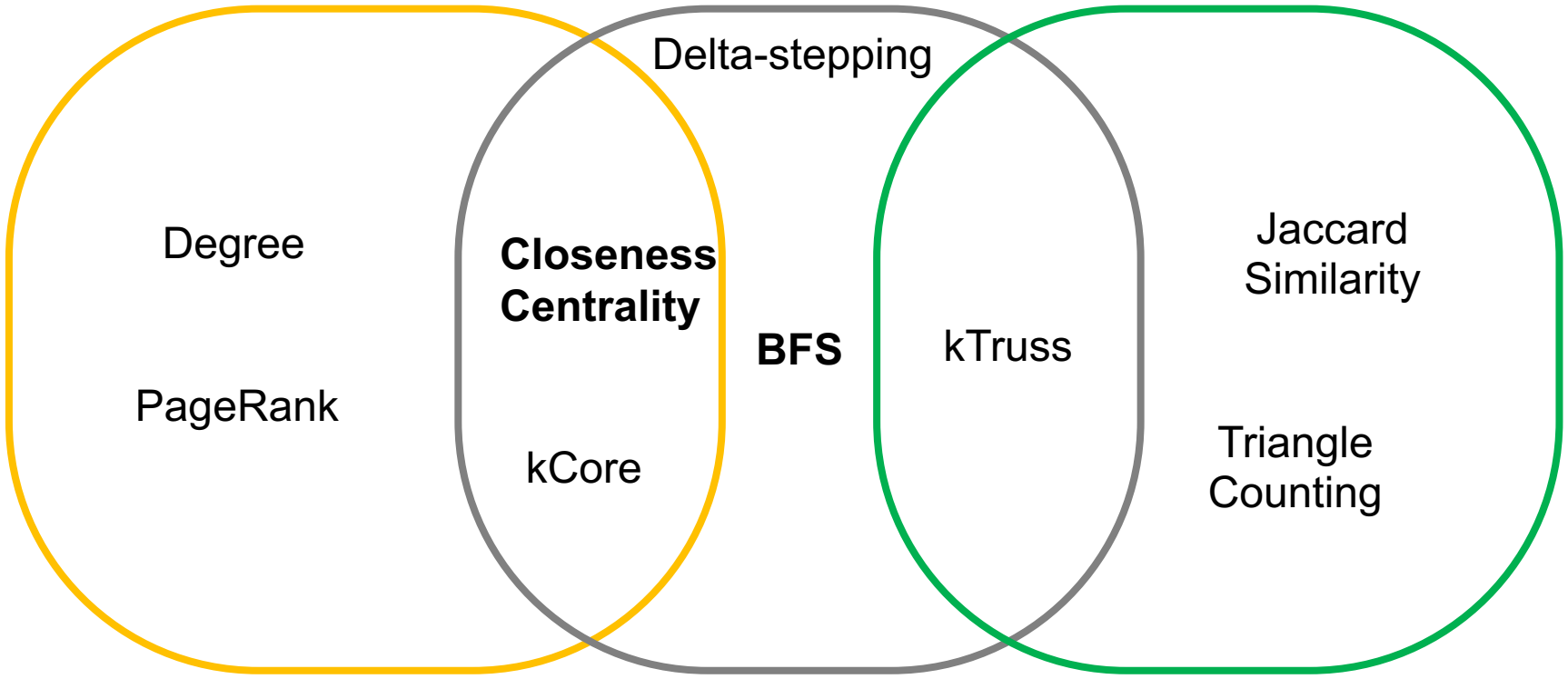
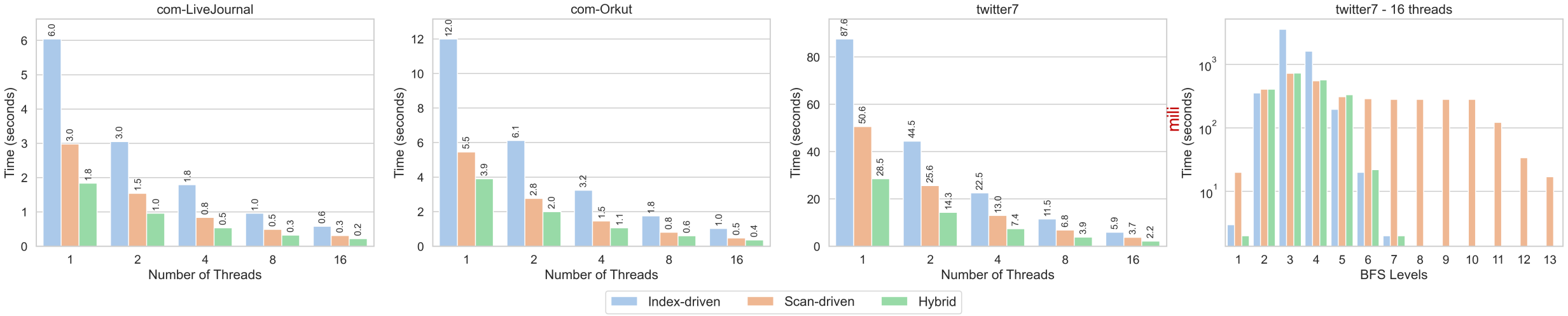
Categorizing graph algorithms



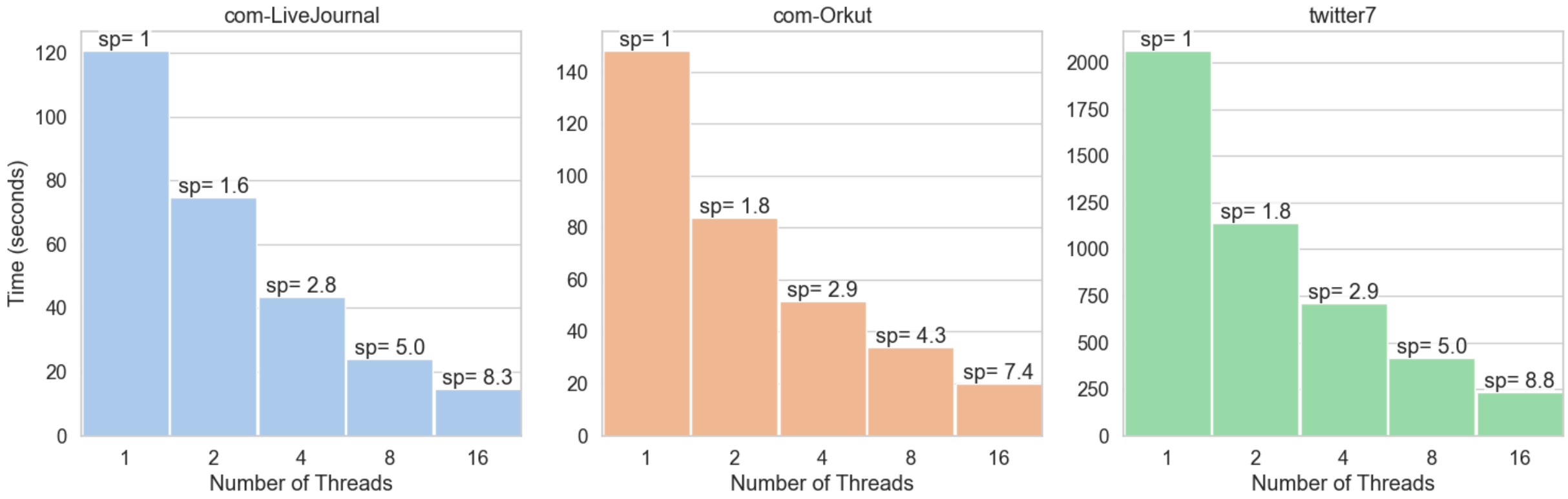
Properties of test graphs

Dataset	Number of vertices	Number of edges
com-LiveJournal	3,997,963	69,362,378
com-Orkut	3,072,441	234,370,166
twitter7	41,652,230	1,468,364,884

BFS: indexed vs scan vs hybrid



Approximate Closeness Centrality



Take away messages

- Identify and optimize common Access Patterns
  - Point lookups requires efficient indices
  - Full pass transaction/algorithms requires efficient scans
- Higher level applications may alternate between different access patterns
- Abstraction at the Access Pattern level
  - Simplifies application development
  - Enables targeted optimizations can be more easily leveraged by multiple applications
- One size never fits all, BUT we can get very close!

What about Scheduling?

- Online scheduling
- We know nothing about Customer workloads and data
  - Characteristic sets capture structural patterns in the data
- Coarse-grain Dataflow engine
- Mixed workload
  - Low-latency queries
  - Analytical queries
- Data-locality matters
  - Even in vertically-scaled (single node, multi NUMA)
  - especially when we move to horizontally-scaled (distributed)

Thank you!

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