VCSR: Mutable CSR Graph Format Using Vertex-Centric Packed Memory Array

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Wuhan University
Wuhan, China

Background: Graph

Graphs are everywhere!

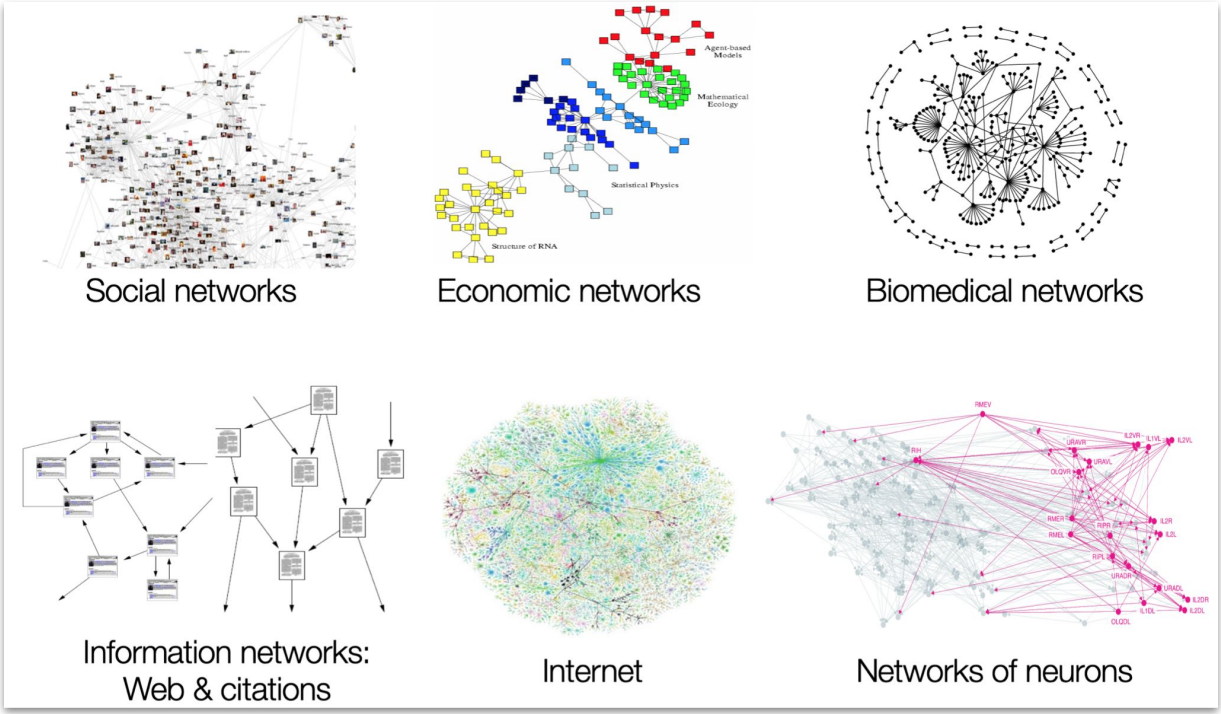


Image Source:
https://towardsdatascience.com/graph-theory-132122ac38f2

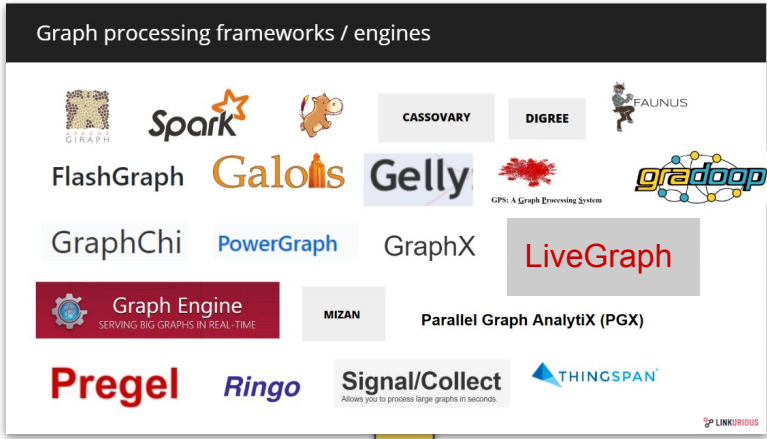
Background: Dynamic Graph

Graphs are dynamic!

Image Source: https://towardsdatascience.com/animate-dynamic-graphs-with-gephi-d6bd9faf5aec

Background: Graph Processing Systems

- Dynamic graph storage data structures



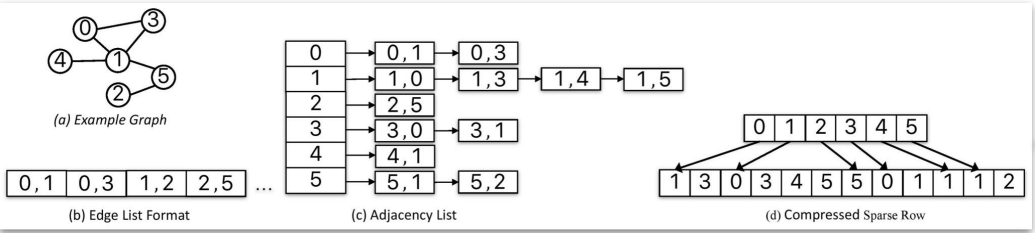


Image Source:

Background: Graph Processing Systems

- Dynamic graph storage data structures
- Expectations
  - Expectation-1: Efficient graph construction
  - Expectation-2: Efficient graph analysis

Dynamic In-Memory Graph Storage Data Structures

Common Graph Data-structures

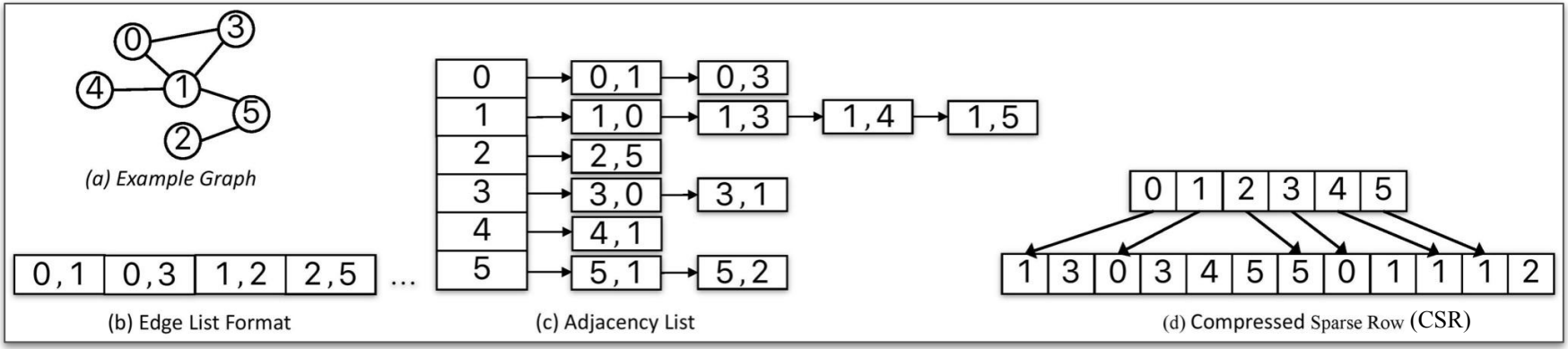


Figure: Three basic graph storage data structures.

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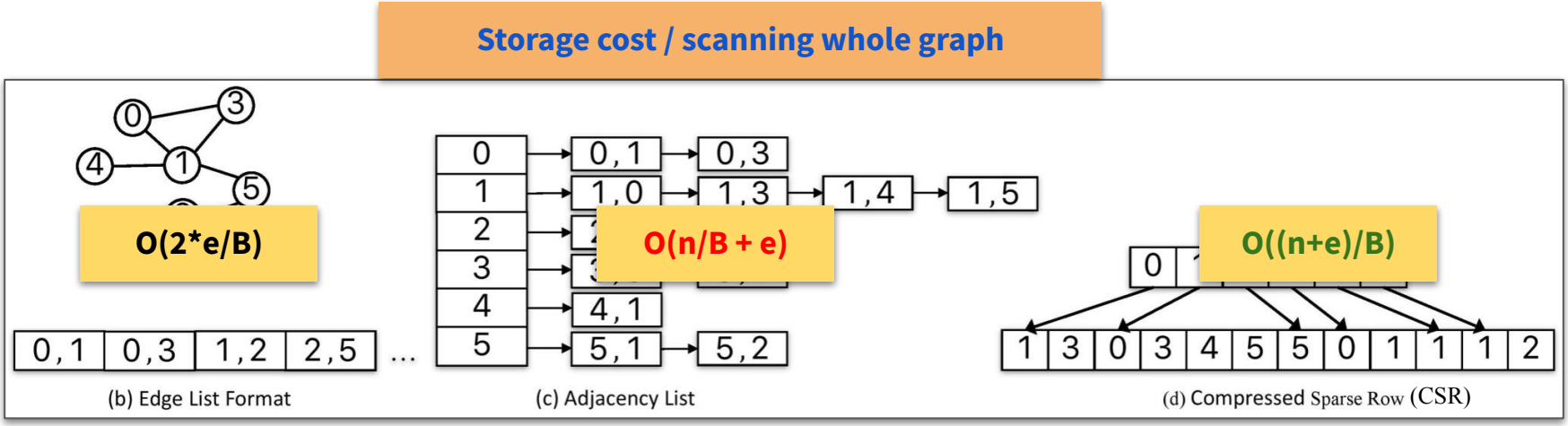

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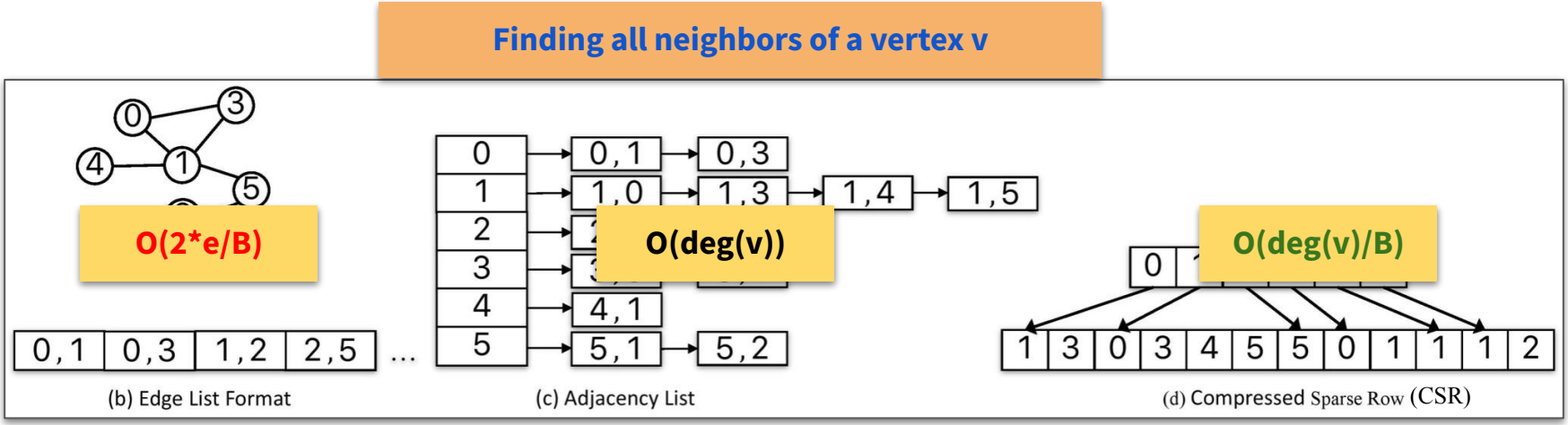

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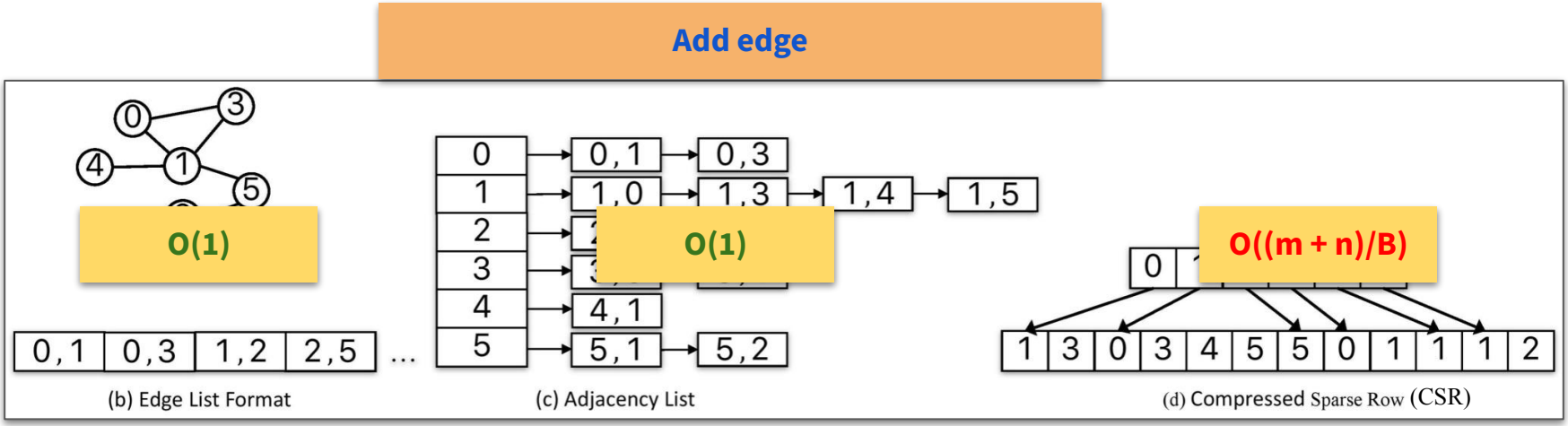

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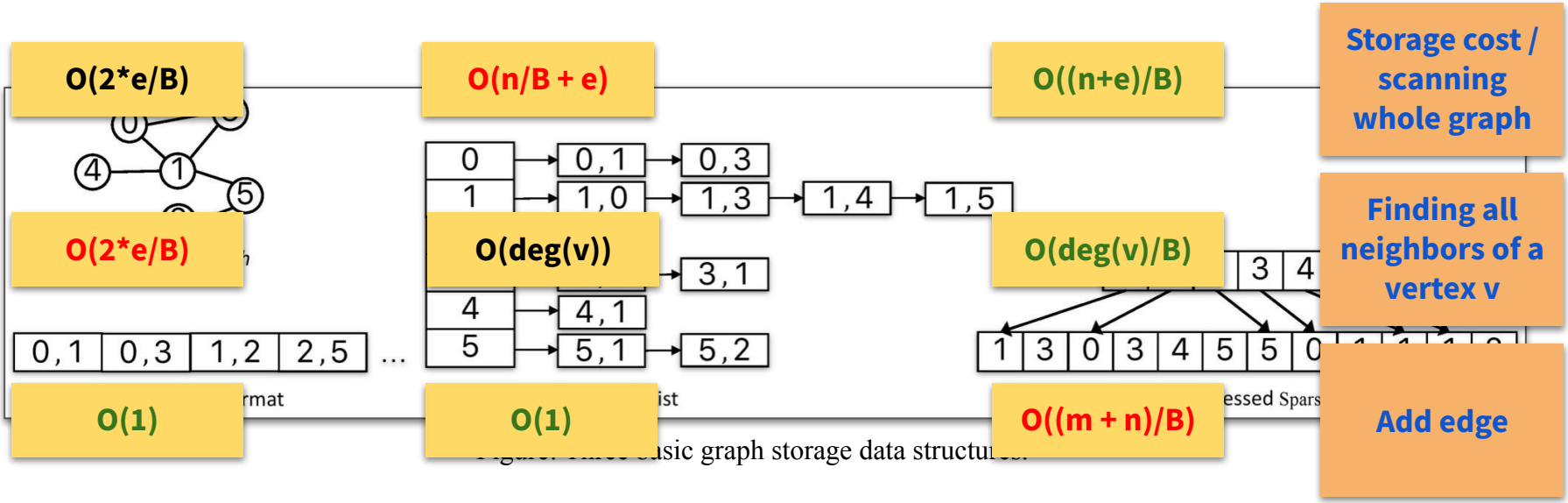

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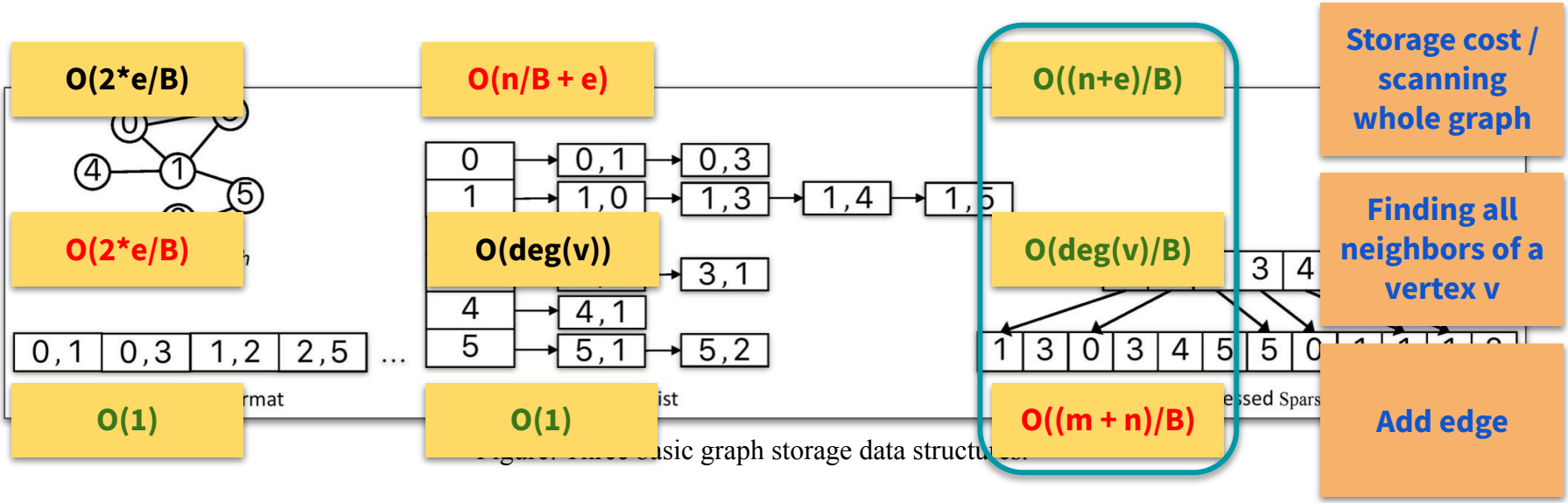

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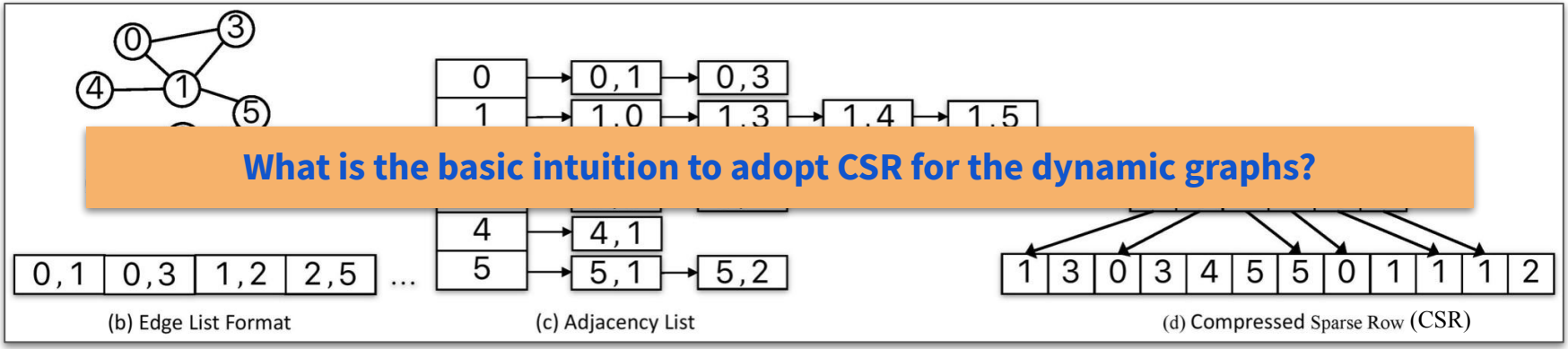

What is the basic intuition to adopt CSR for the dynamic graphs?

Figure: Three basic graph storage data structures.

CSR Variants for Dynamic Graphs

- Delta Map
  - LLAMA [Macko et. al., ICDE'15]
  - Graphchi [Kyrola et. al., OSDI'12]
- Log-Based
  - Grace [Vijayan et. al., ATC'12]
  - Connectivity Server [Bharat et. al., Elsevier'1998]
- Dynamic Block Linked Lists
  - PowerGraph [Gonzalez et. al., OSDI'12]
  - Graphlab [Low et. al., UAI'10]
- Packed Memory Array (PMA) Based Extensions
  - RMA [De Leo et. al., ICDE'19]
  - PCSR [Wheatman et. al., HPEC'18]
  - GPMA [Sha et. al., VLDB'17]
- Other Common Extensions
  - CSR++ [Firmli et. al., OPODIS'20]
  - Dynamic-CSR [King et. al., Springer'16]
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Figure: PMA data structure and one insertion example.

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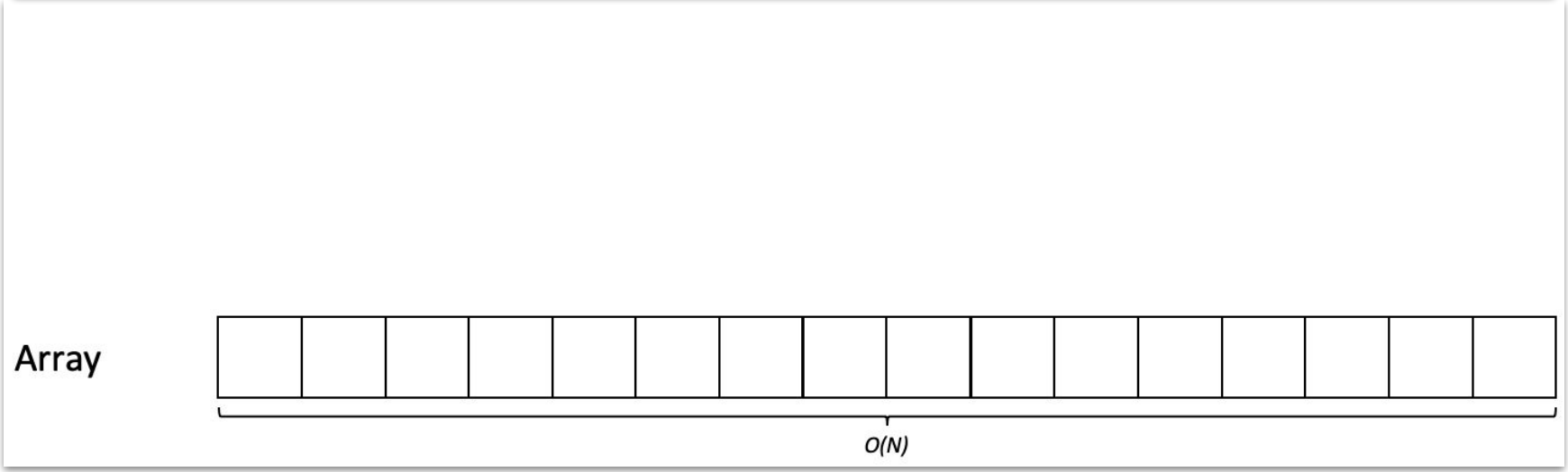

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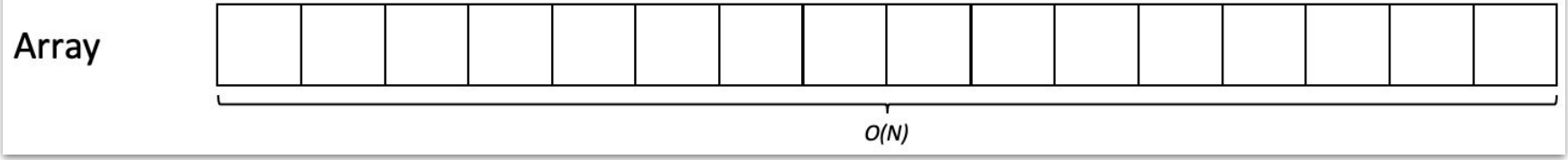

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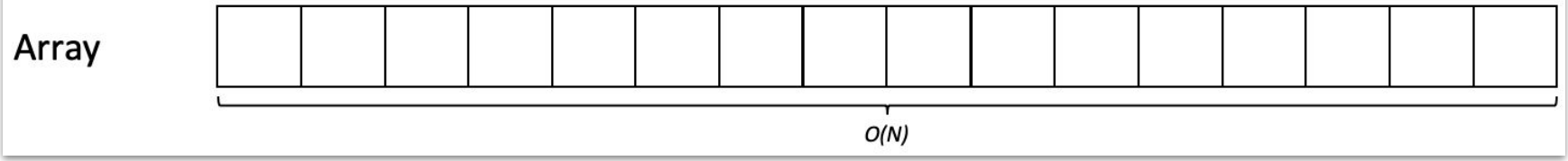

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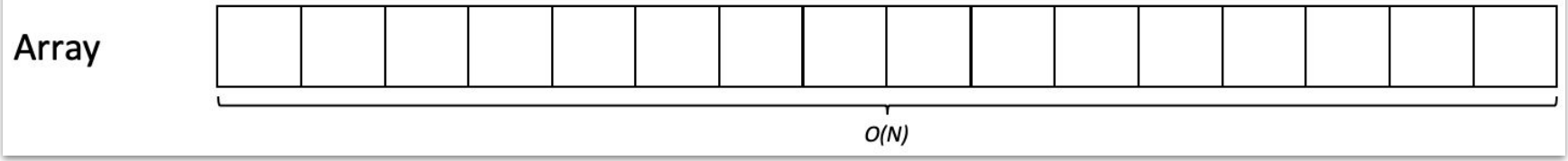
- Asymptotic computational complexity of each insertion: $O(\log^2 n)$



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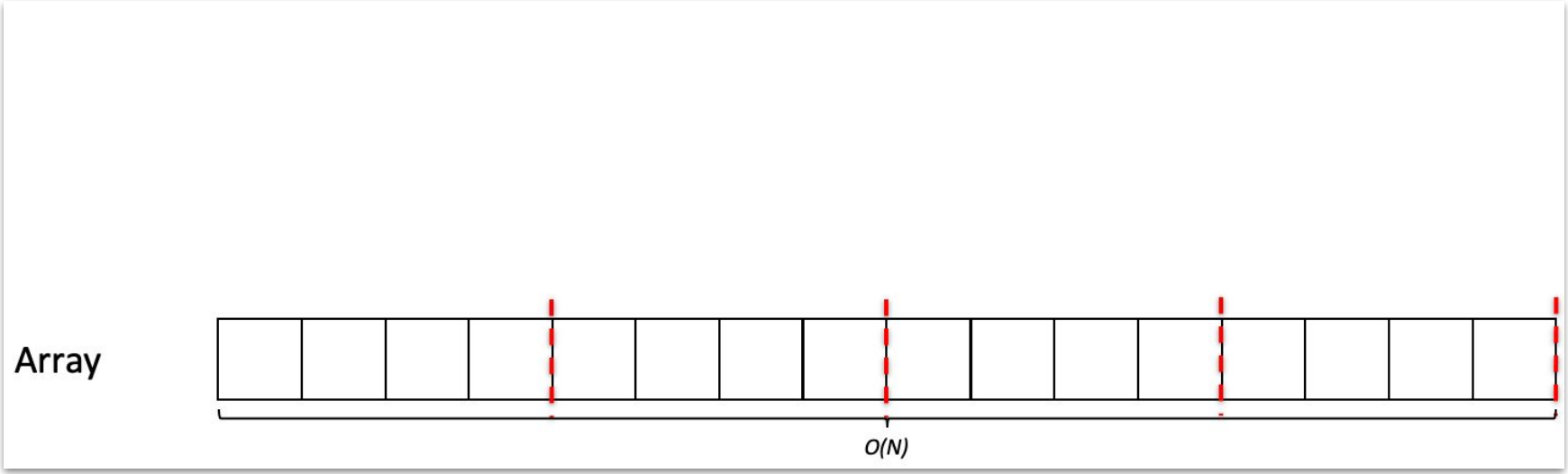

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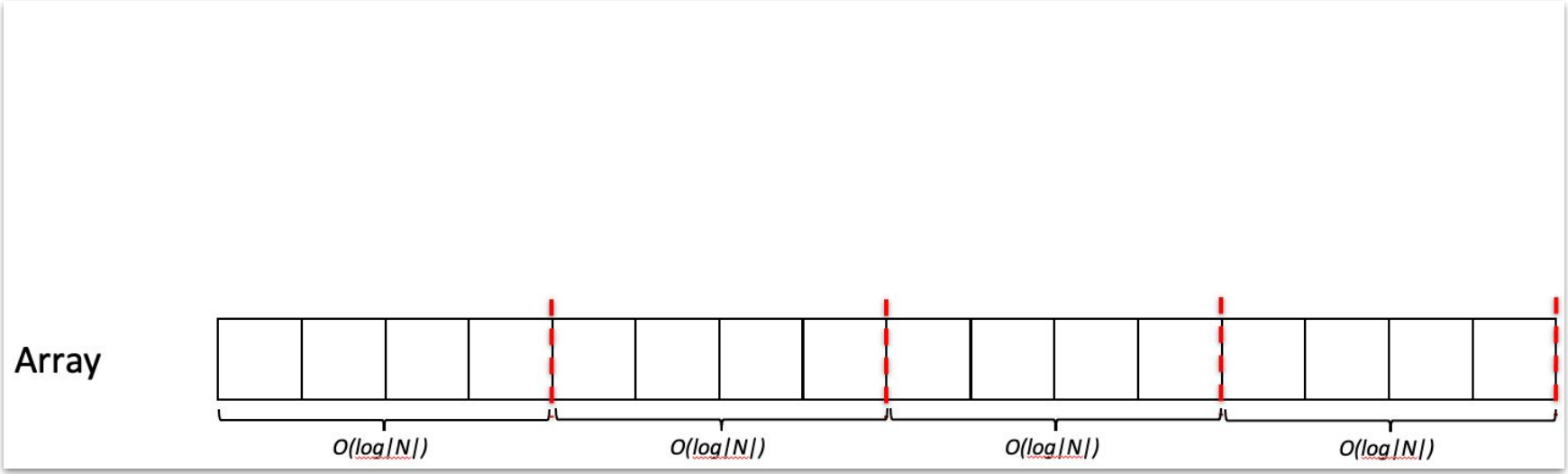

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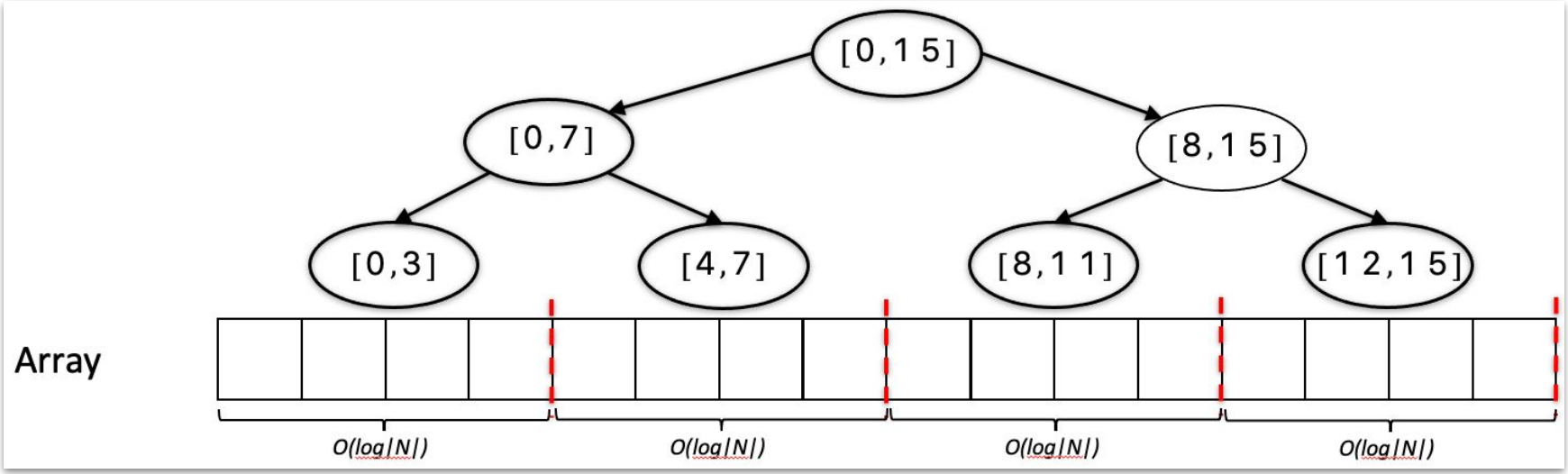

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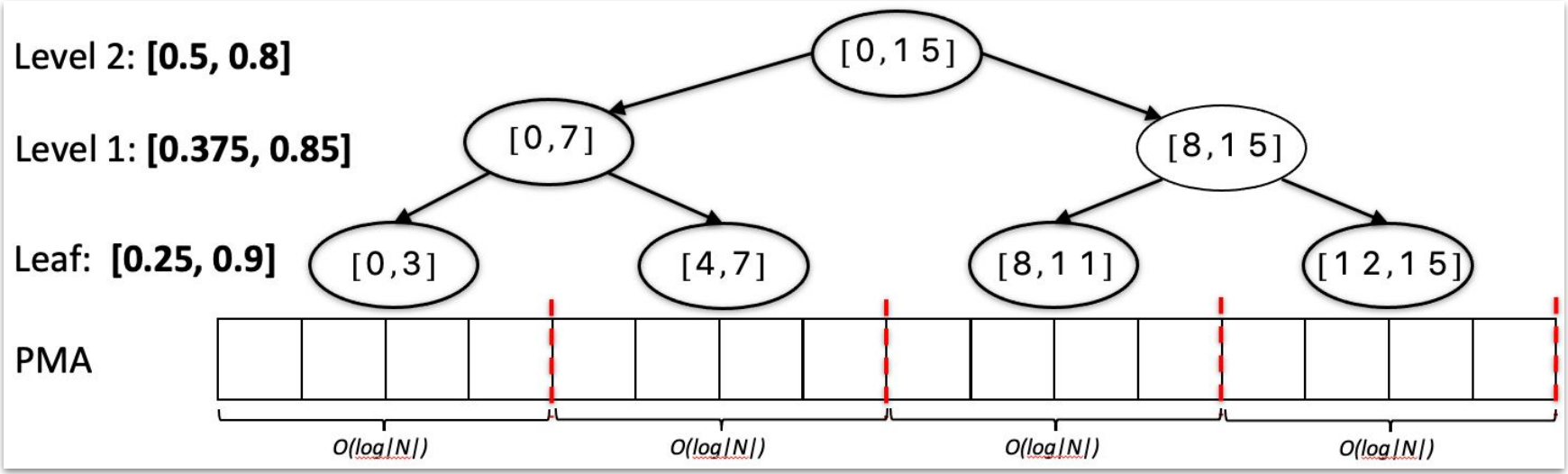

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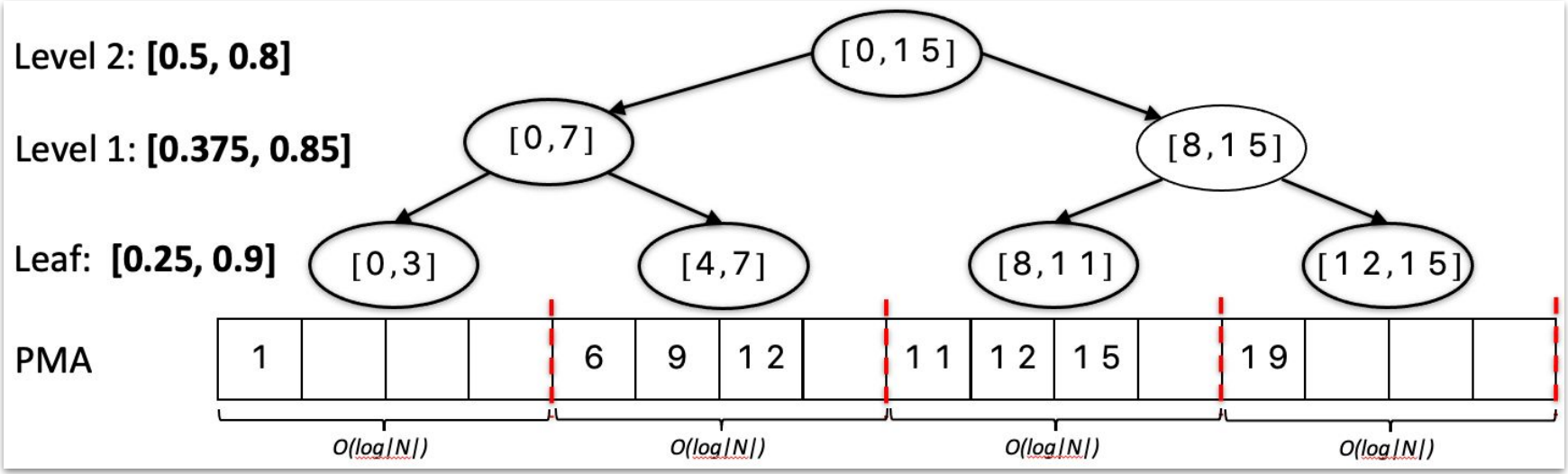

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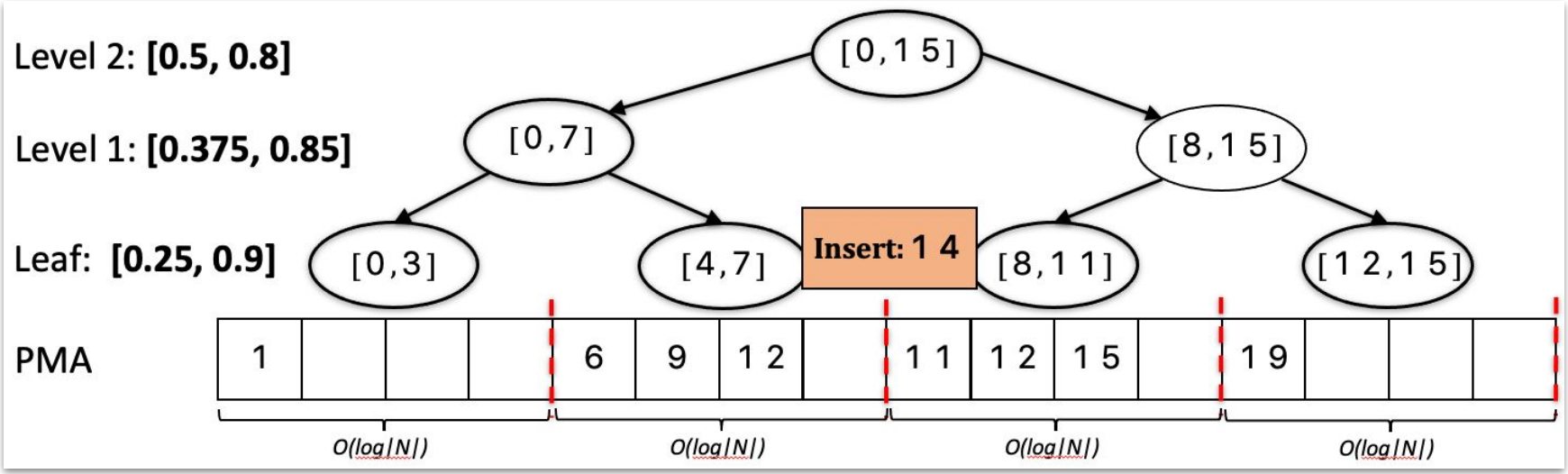

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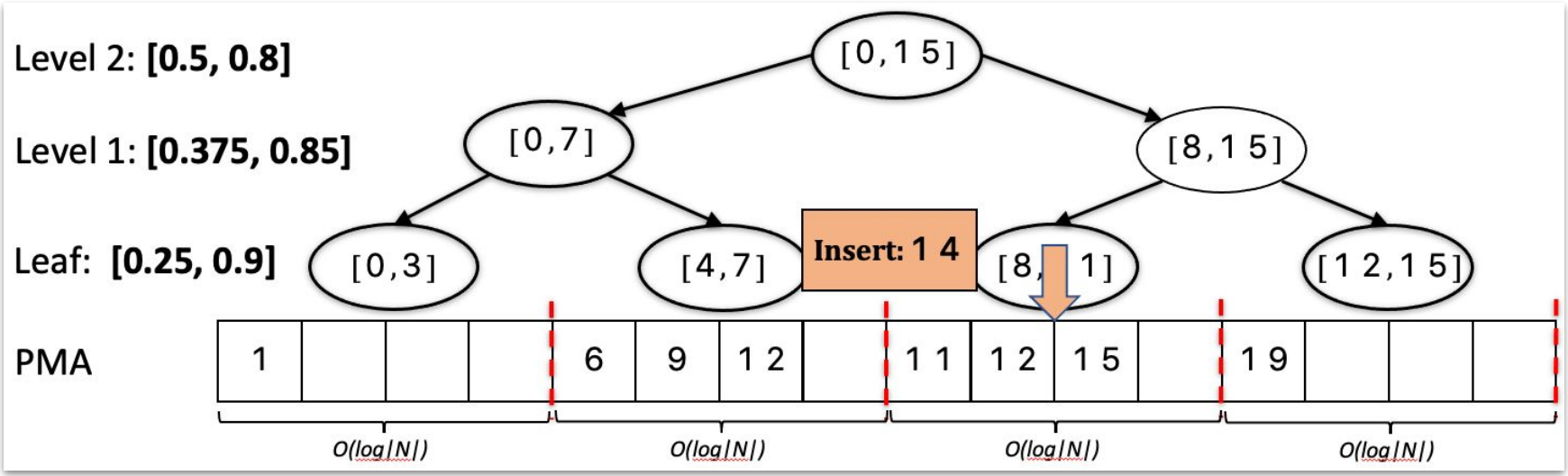

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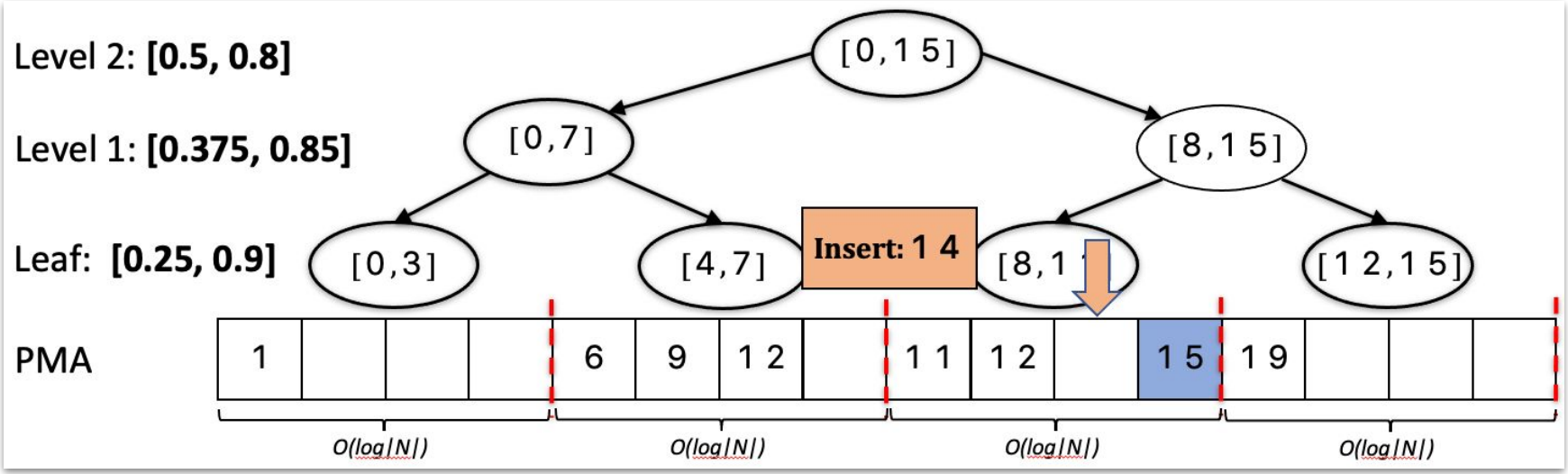

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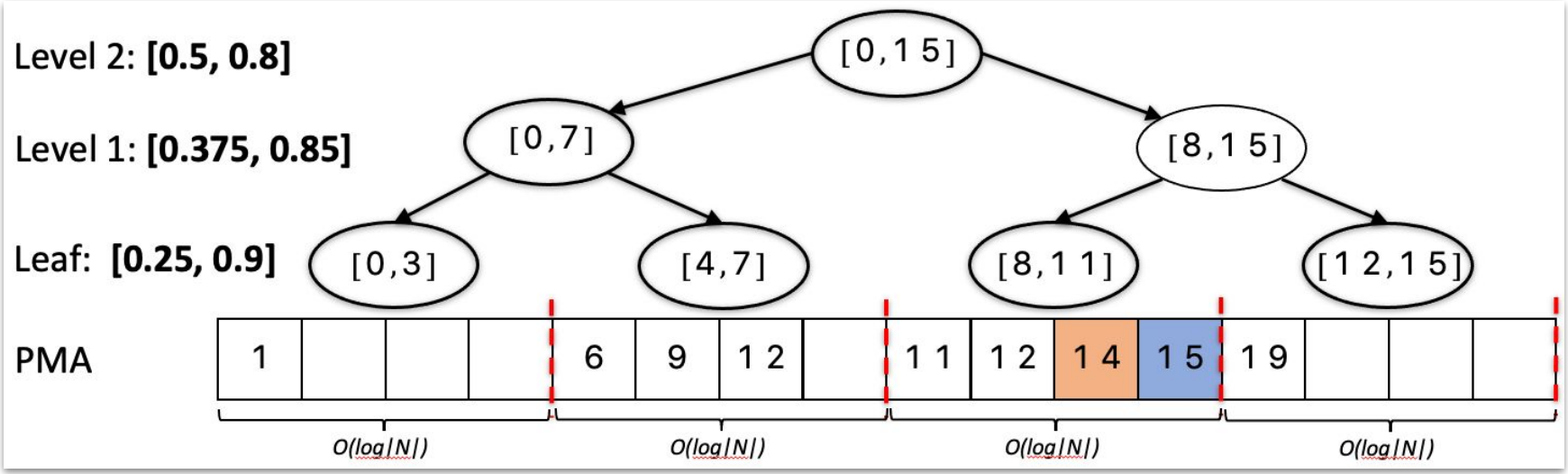

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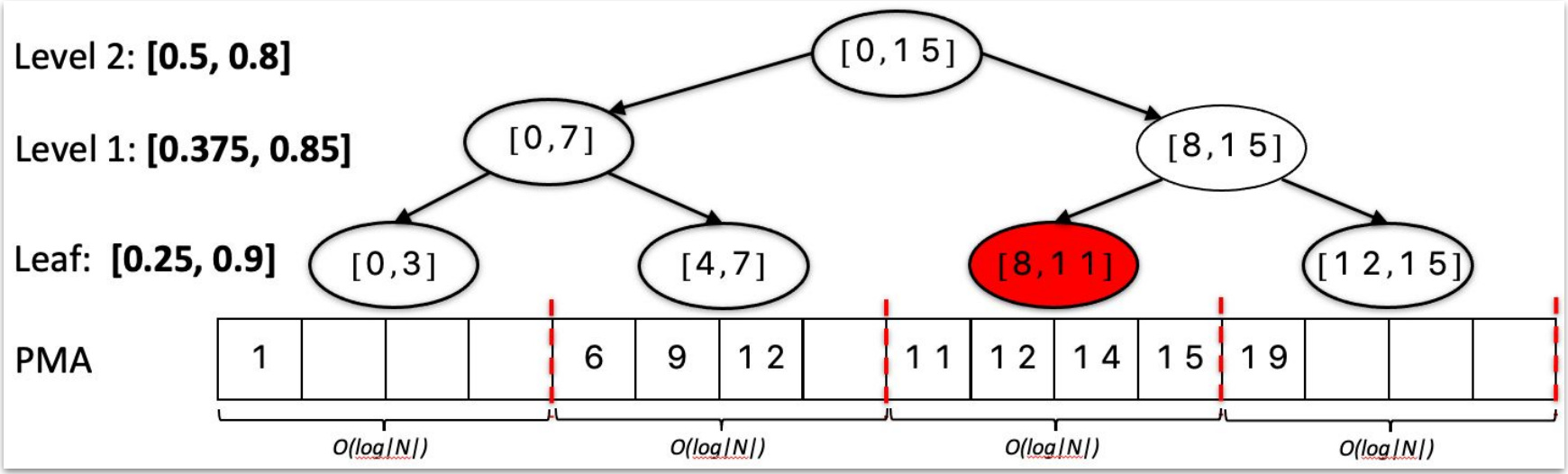

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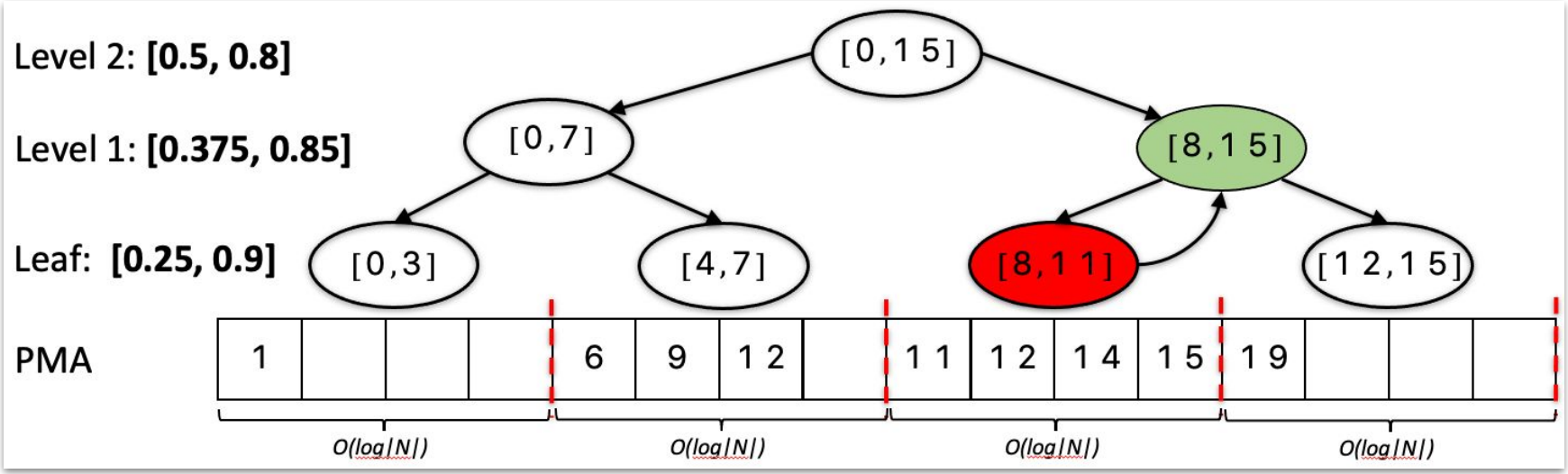

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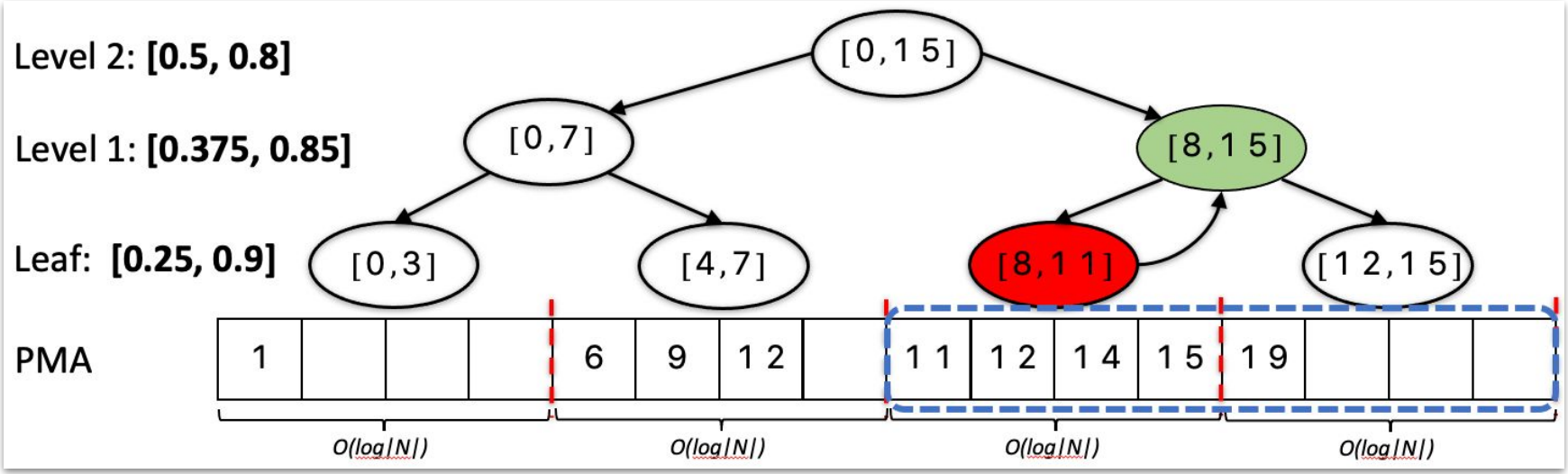

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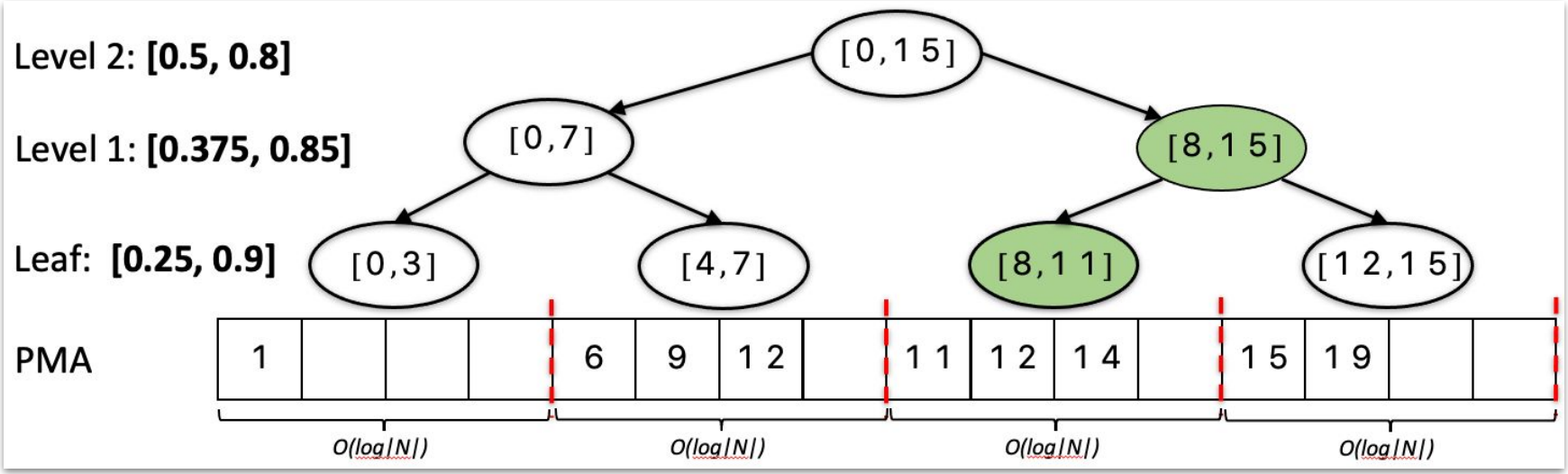

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PMA-Based CSR Extension: PCSR

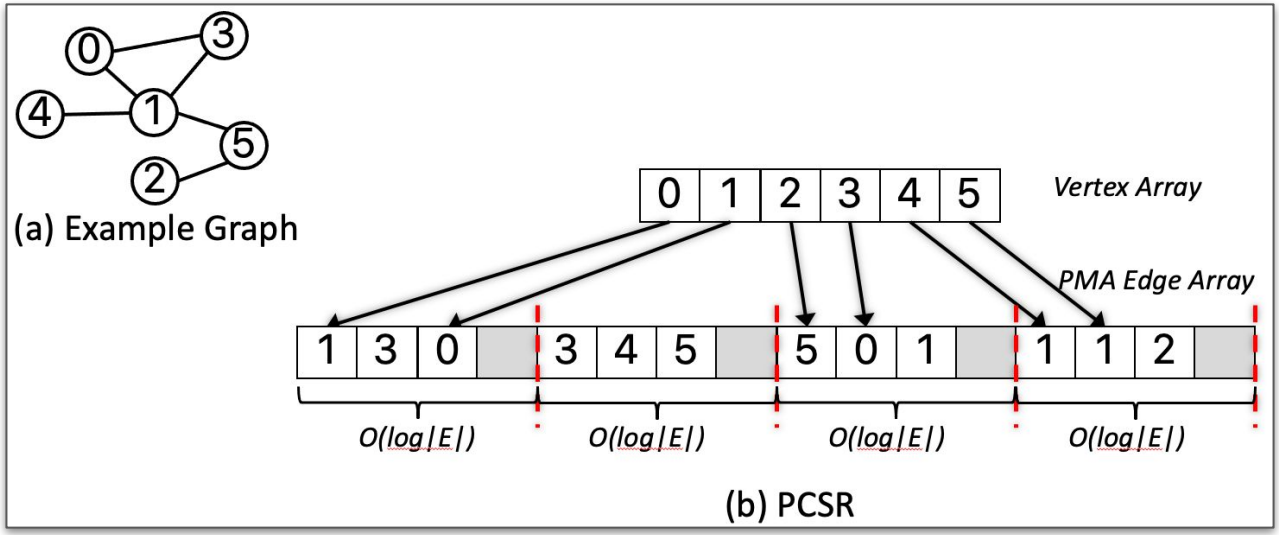


Figure: PMA-based CSR extension, PCSR.

Wheatman, B., & Xu, H. (2018). Packed Compressed Sparse Row: A Dynamic Graph Representation. 2018 IEEE High Performance Extreme Computing Conference, HPEC 2018.

Graph Skewness

Name: Orkut Graph
Category: Online social network
Number of nodes: 3,072,441
Number of edges: 117,184,899

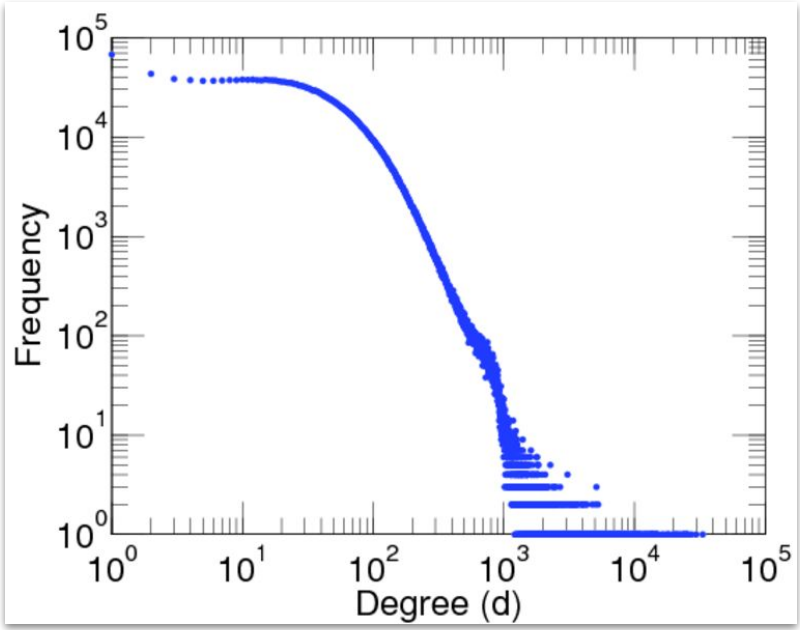


Image Source: http://konect.cc/networks/orkut-links/

Graph's Mutation Pattern

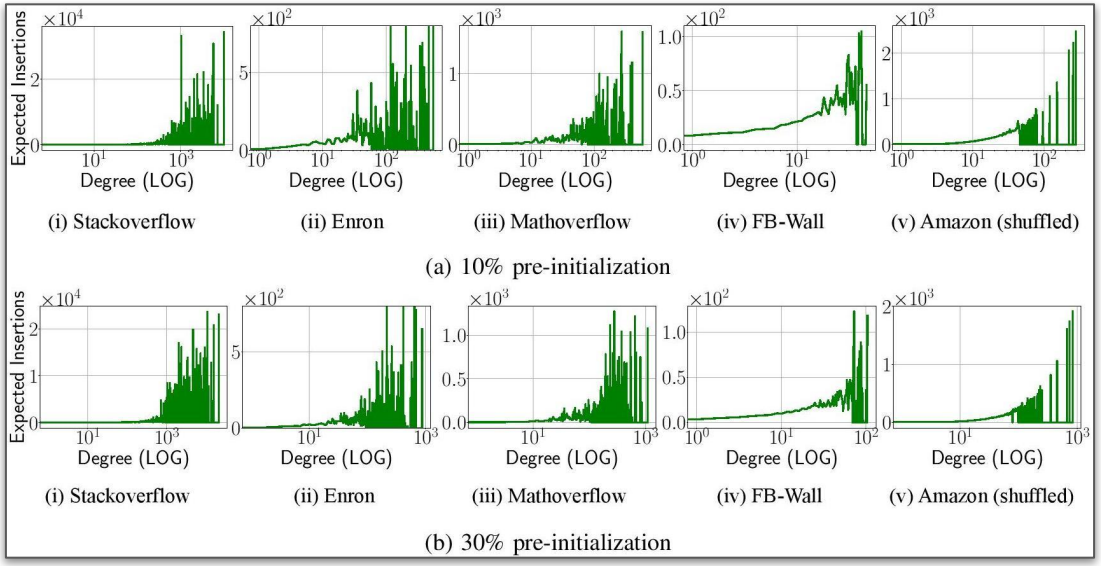
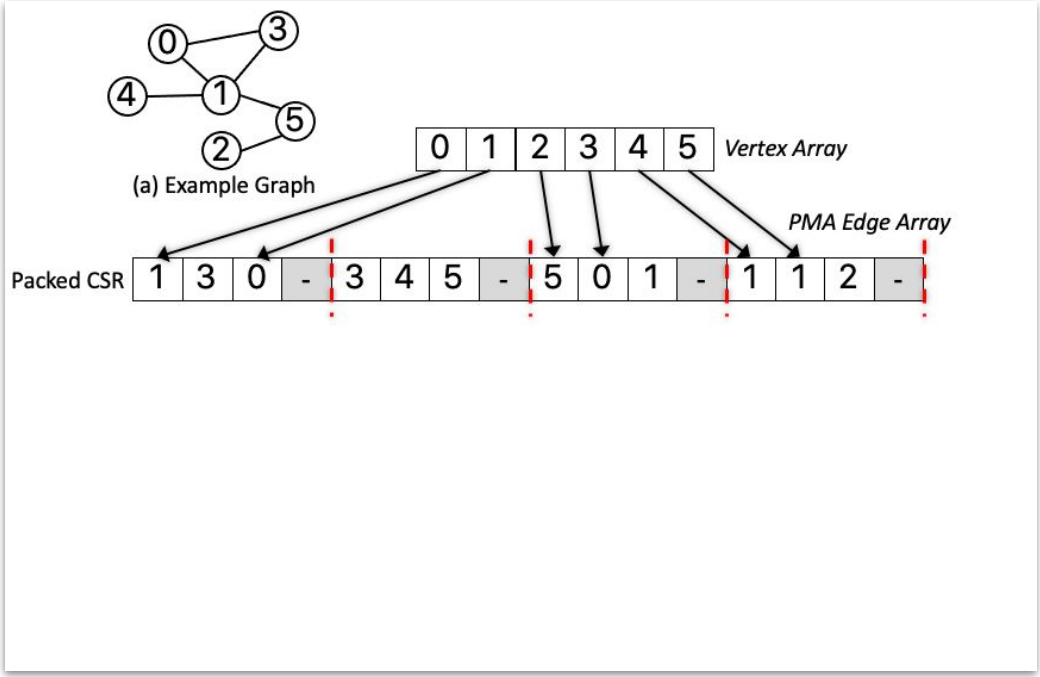


Figure: The relationship between vertex' base degree in both the 10% and 30% pre-initialization cases and their expected new edge insertions. x-axis is the degree; y-axis is the expected insertions; both are in log-scale.

PCSR: Edge Insertion



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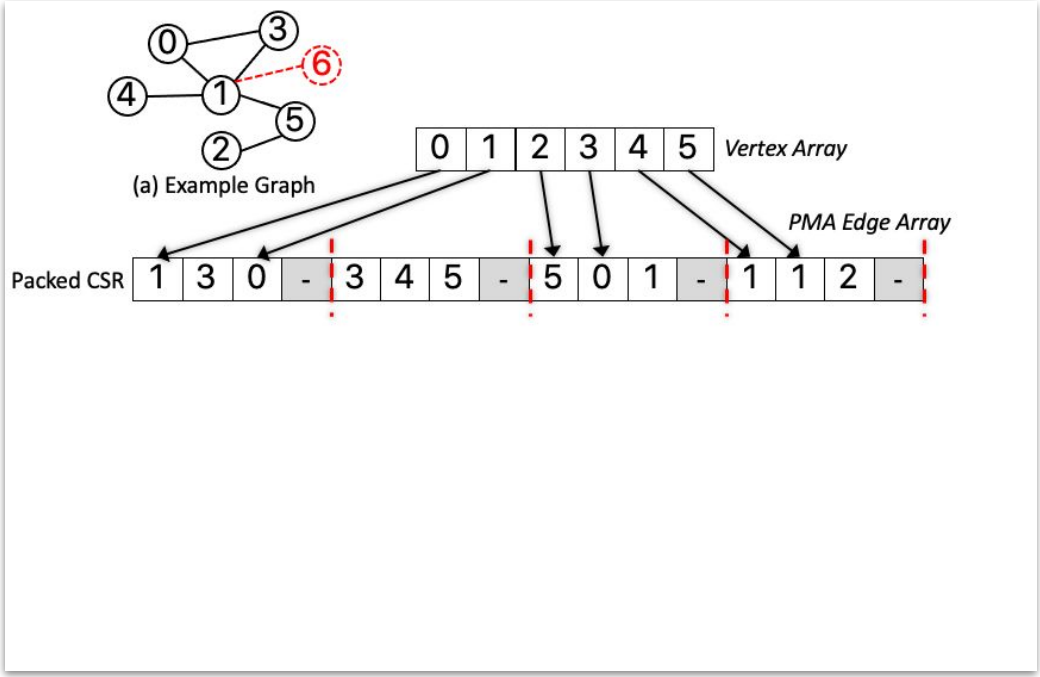

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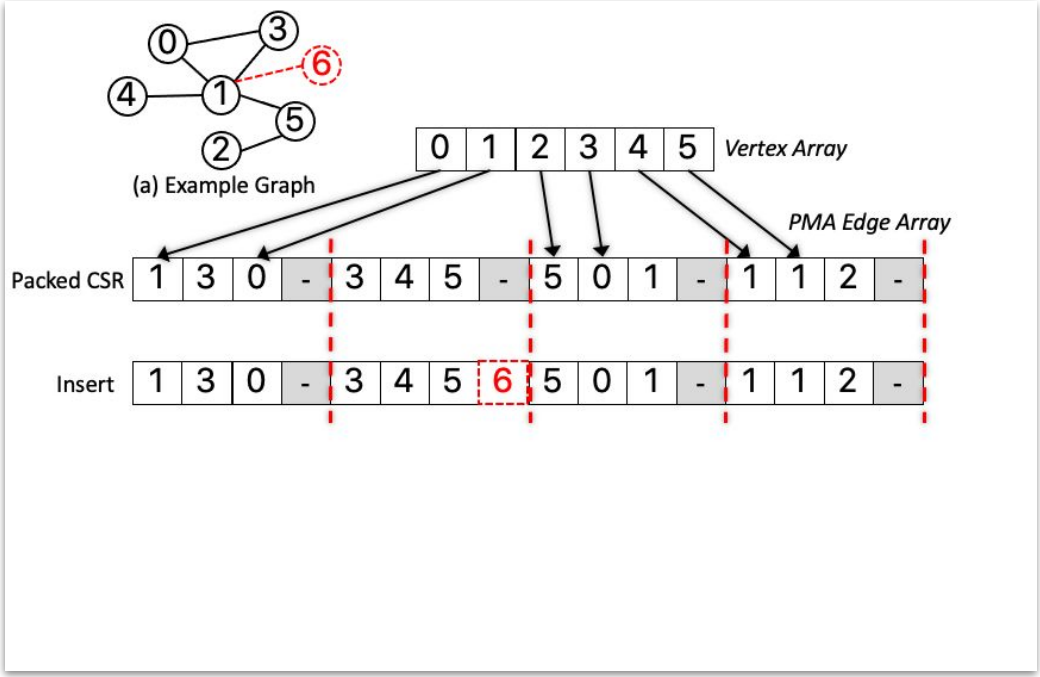

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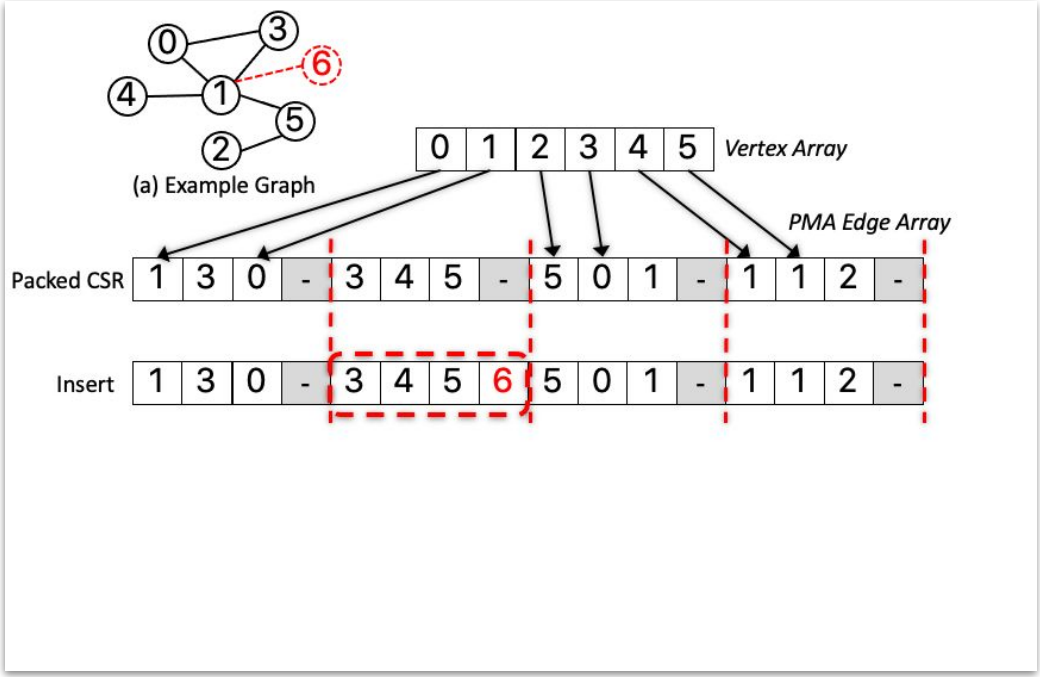

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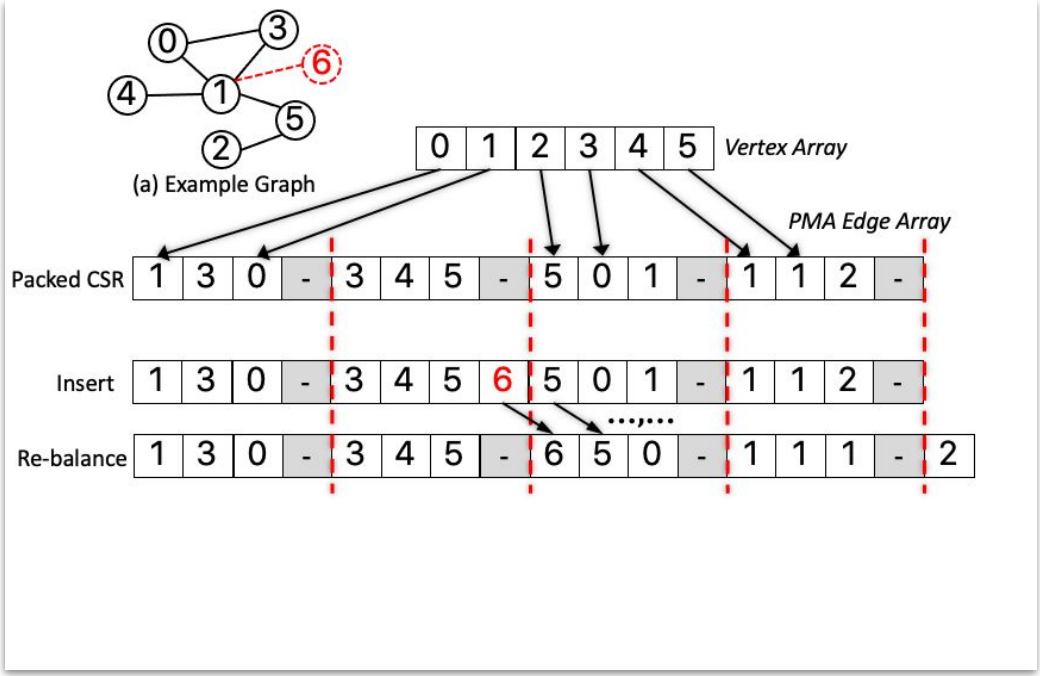

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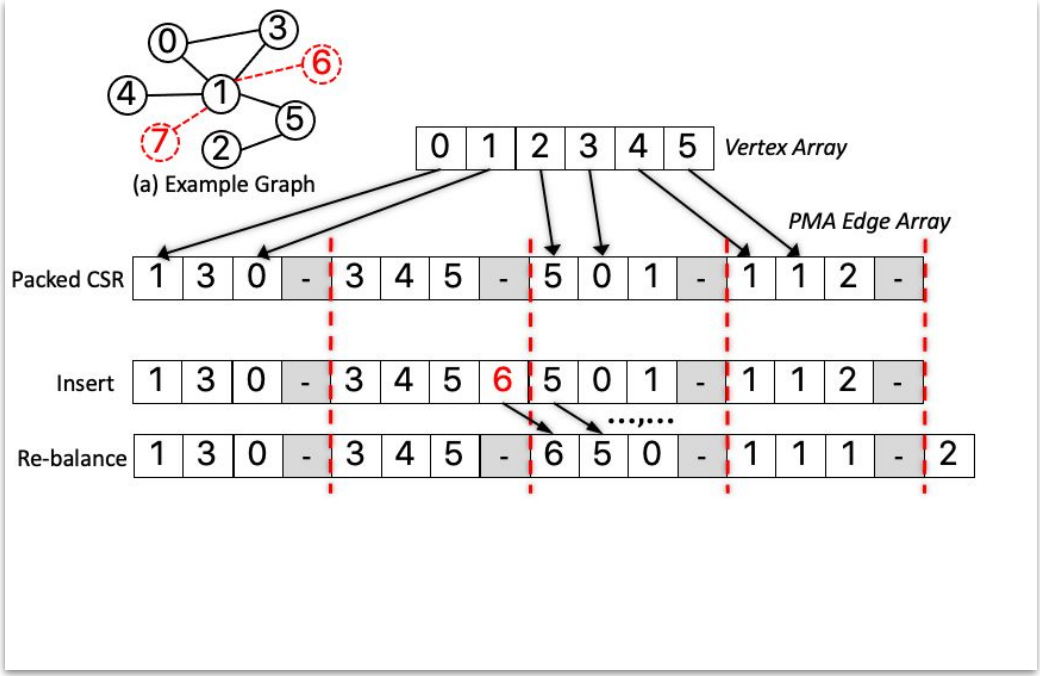

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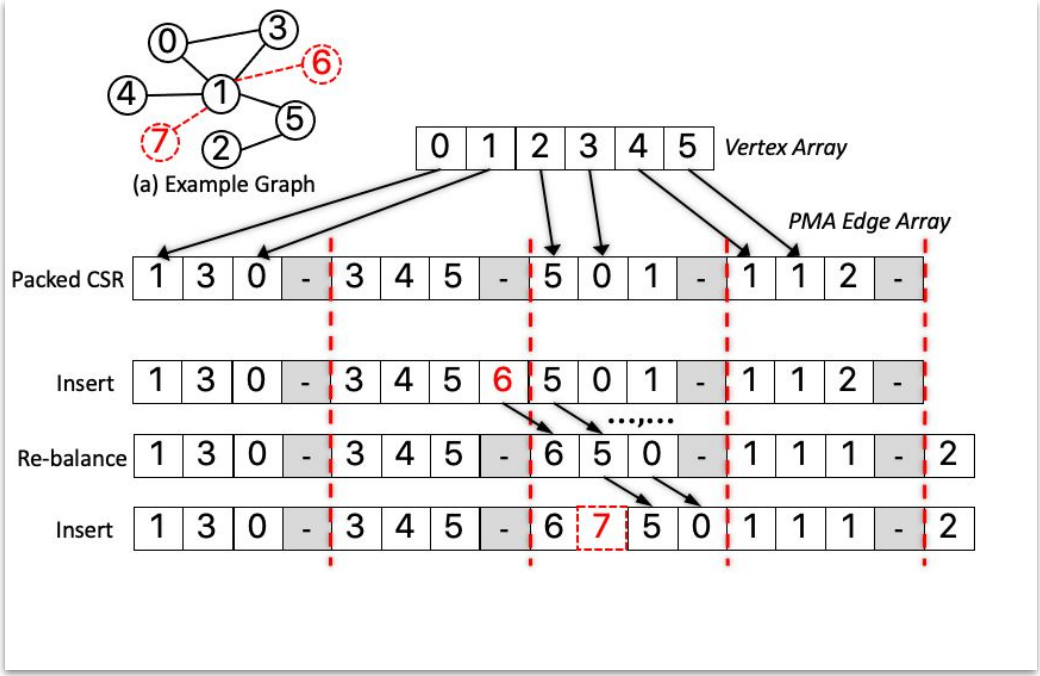

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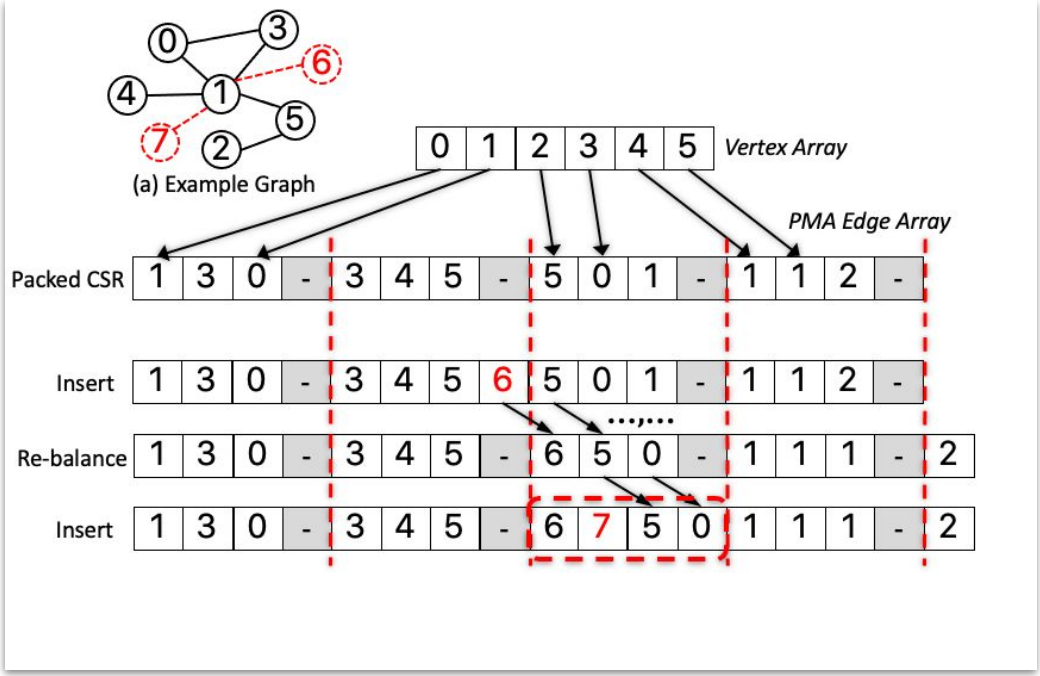

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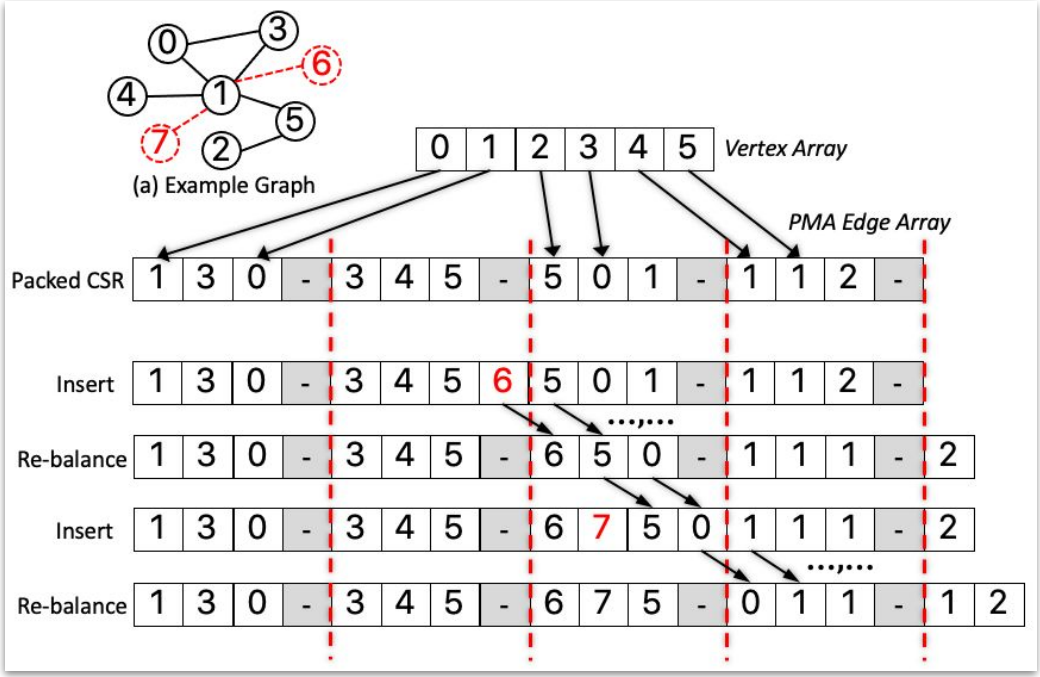

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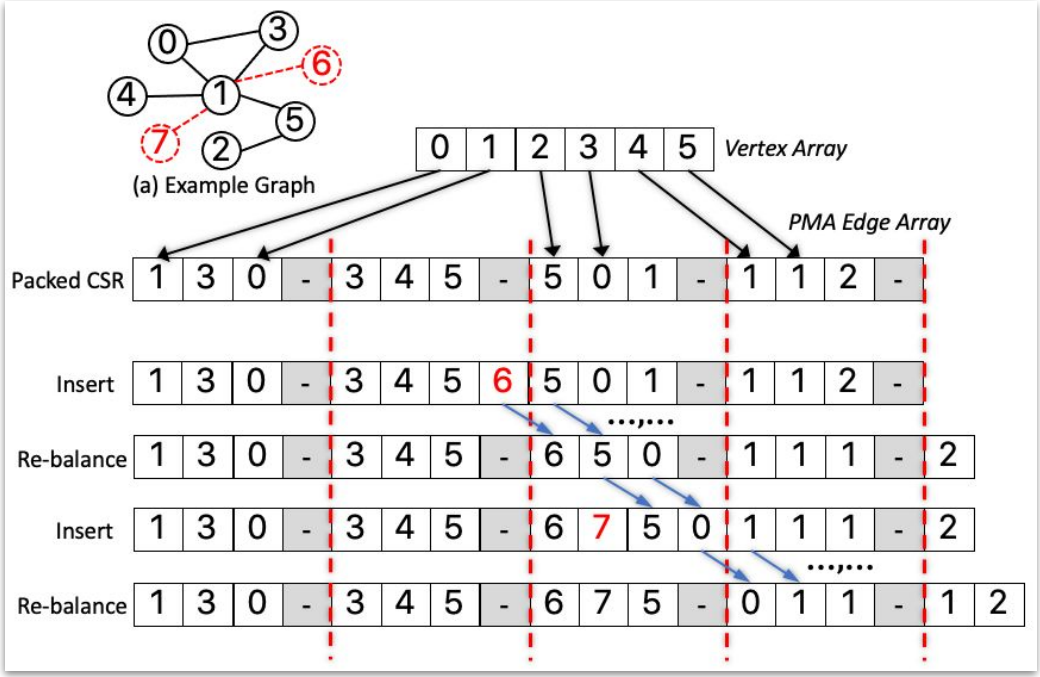

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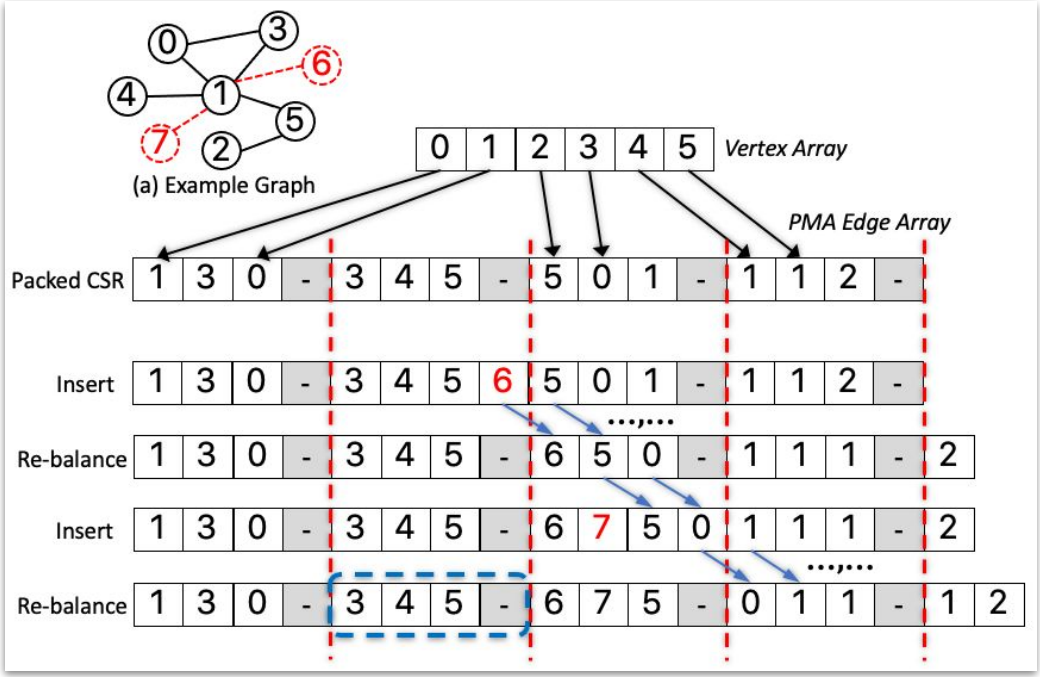

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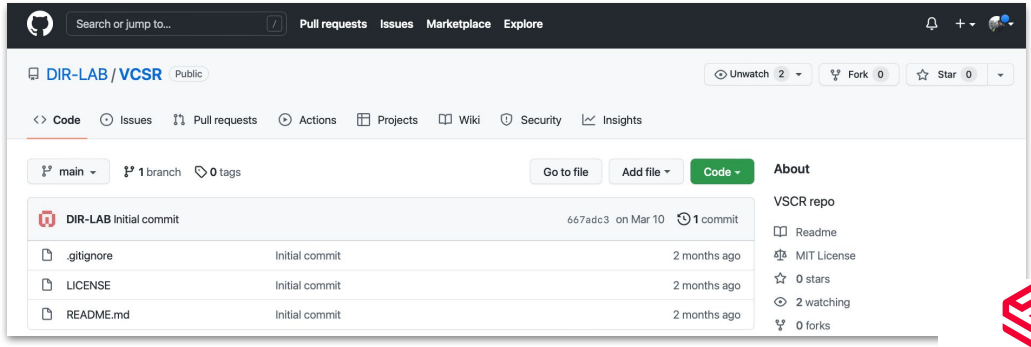
Our Contributions

- Design a novel vertex-centric CSR extension, VCSR, to solve the fundamental limitations in handling graph imbalances

- 1.41x-3.81x better performance in graph insertions
- 1.22x-2.05x better performance in running typical graph analytic algorithms

- We release our code at github



https://github.com/DIR-LAB/VCSR

Outlines

Novel Mutable CSR Design

Evaluation and Results

VCSR: Design

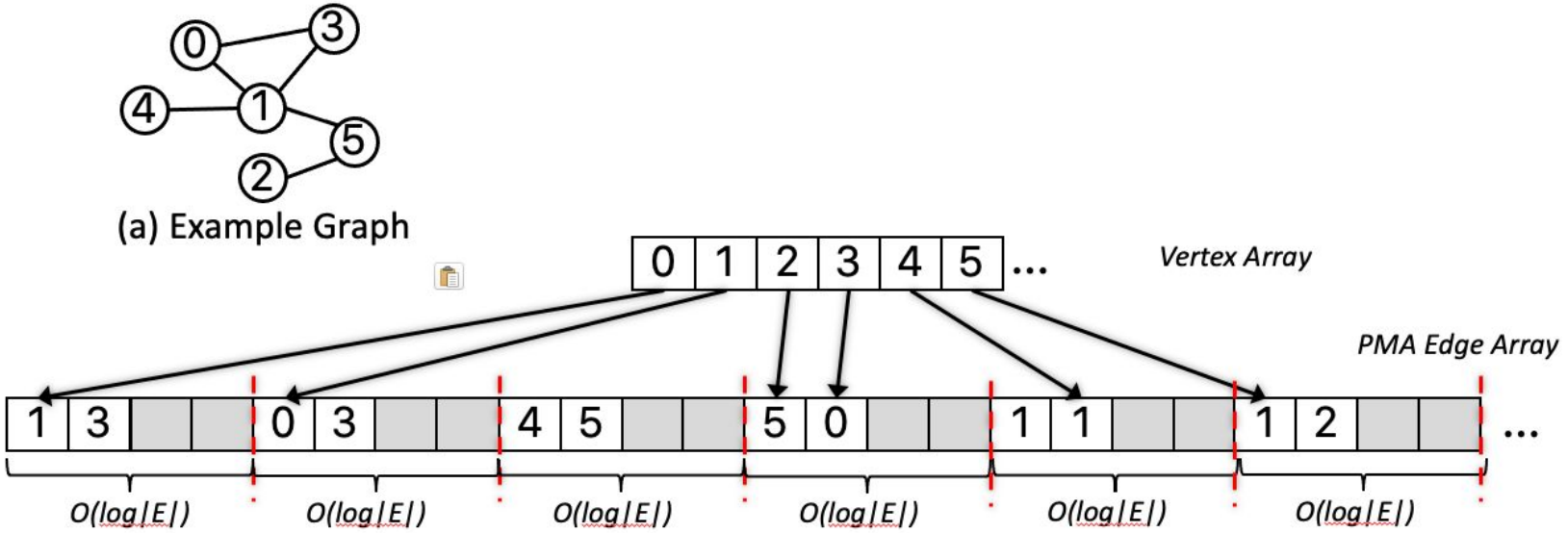


Figure: PMA-based Vertex-Centric Mutable CSR Extension, VCSR.

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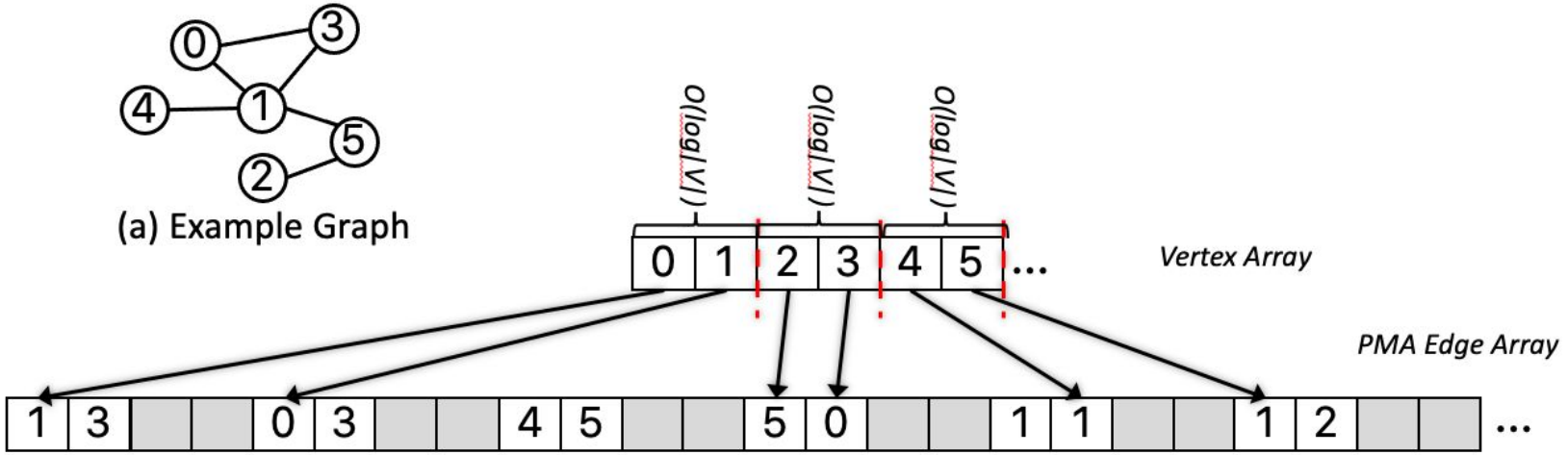

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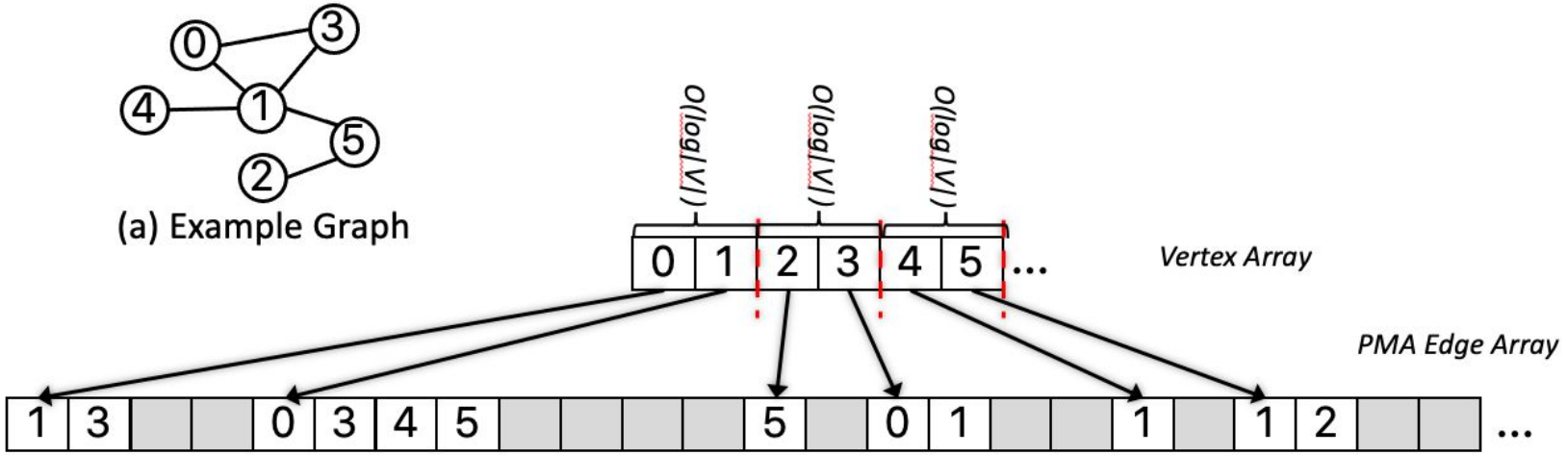

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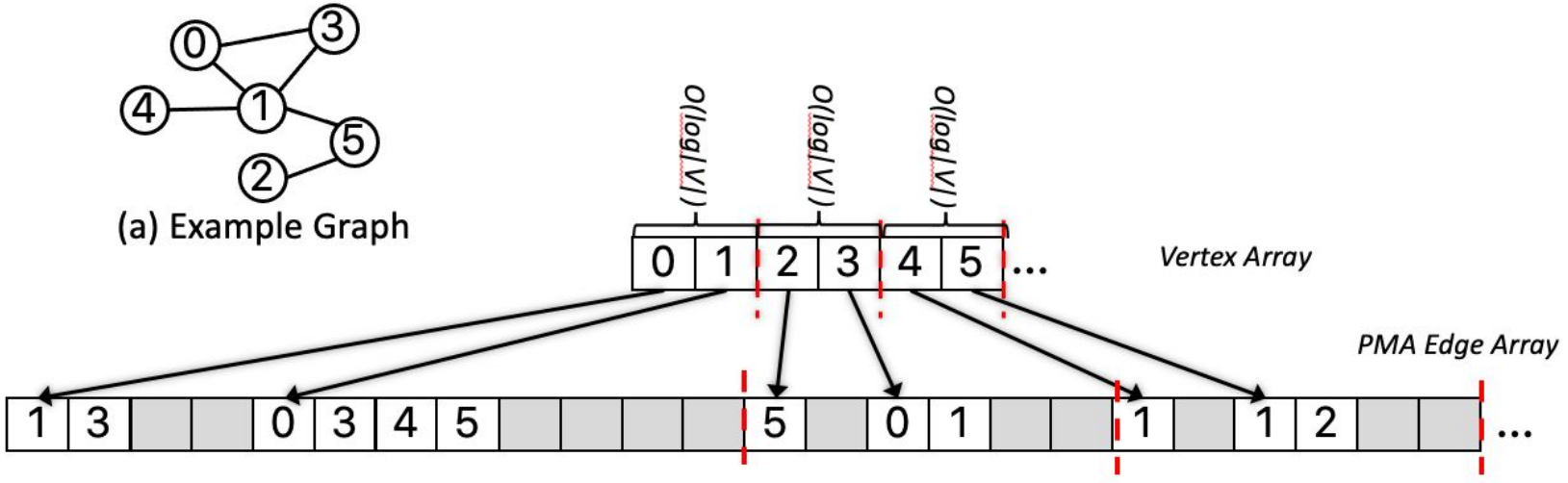

Figure: PMA-based Vertex-Centric Mutable CSR Extension, VCSR.

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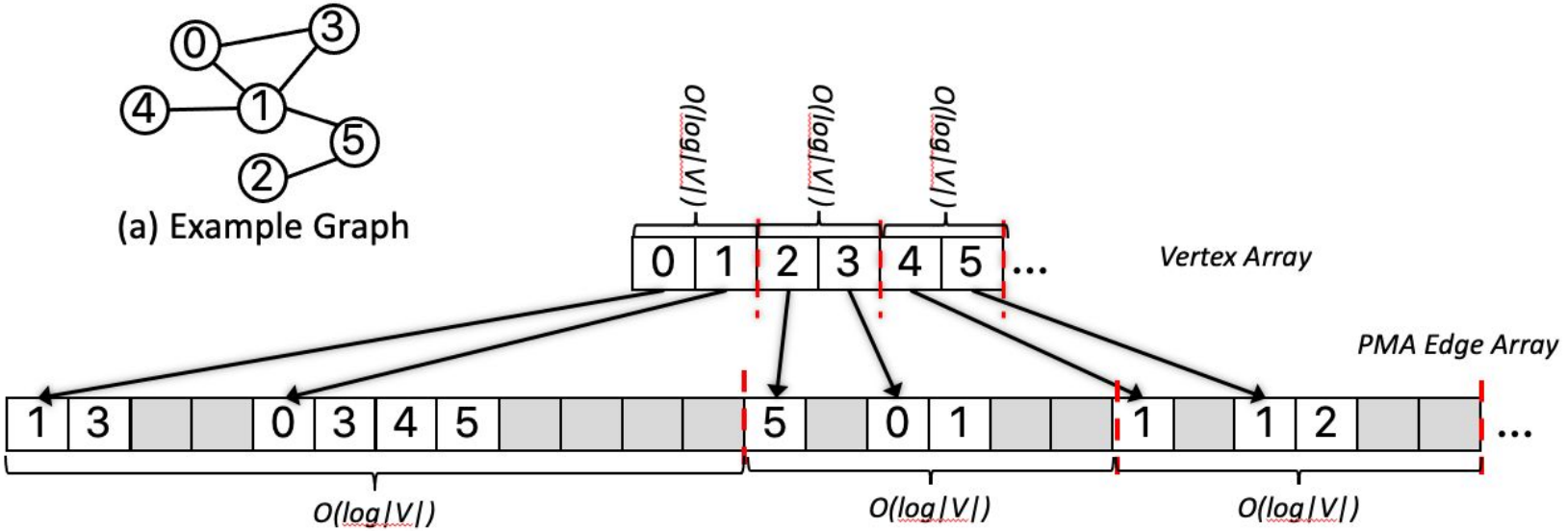

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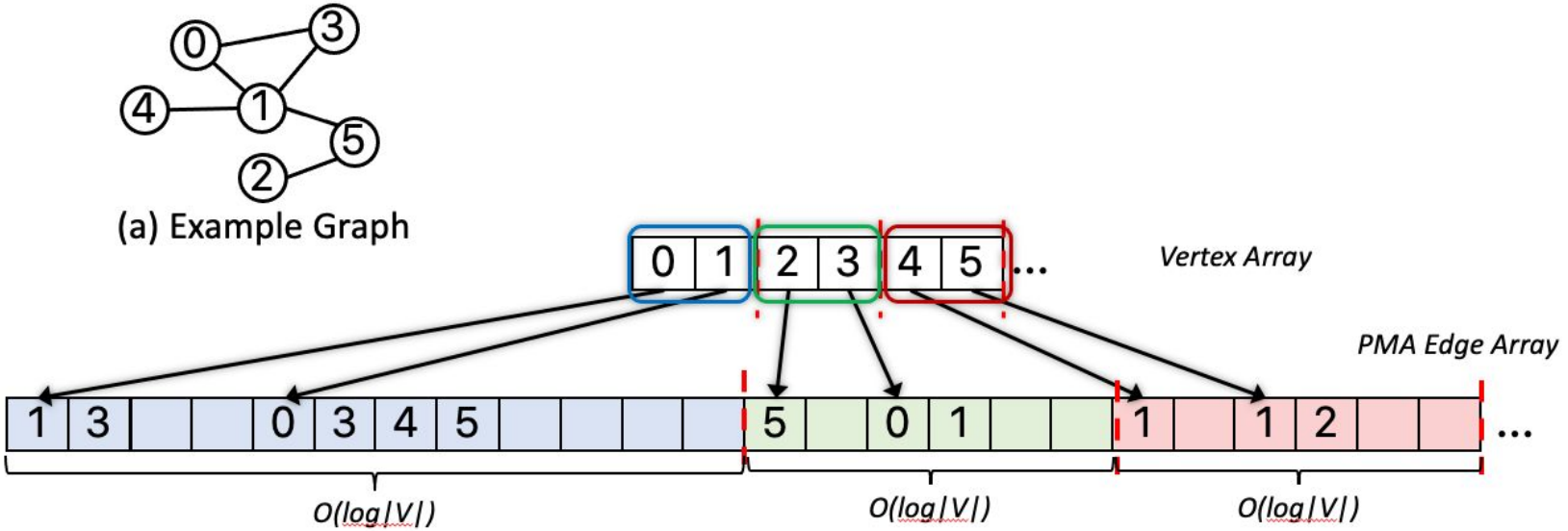

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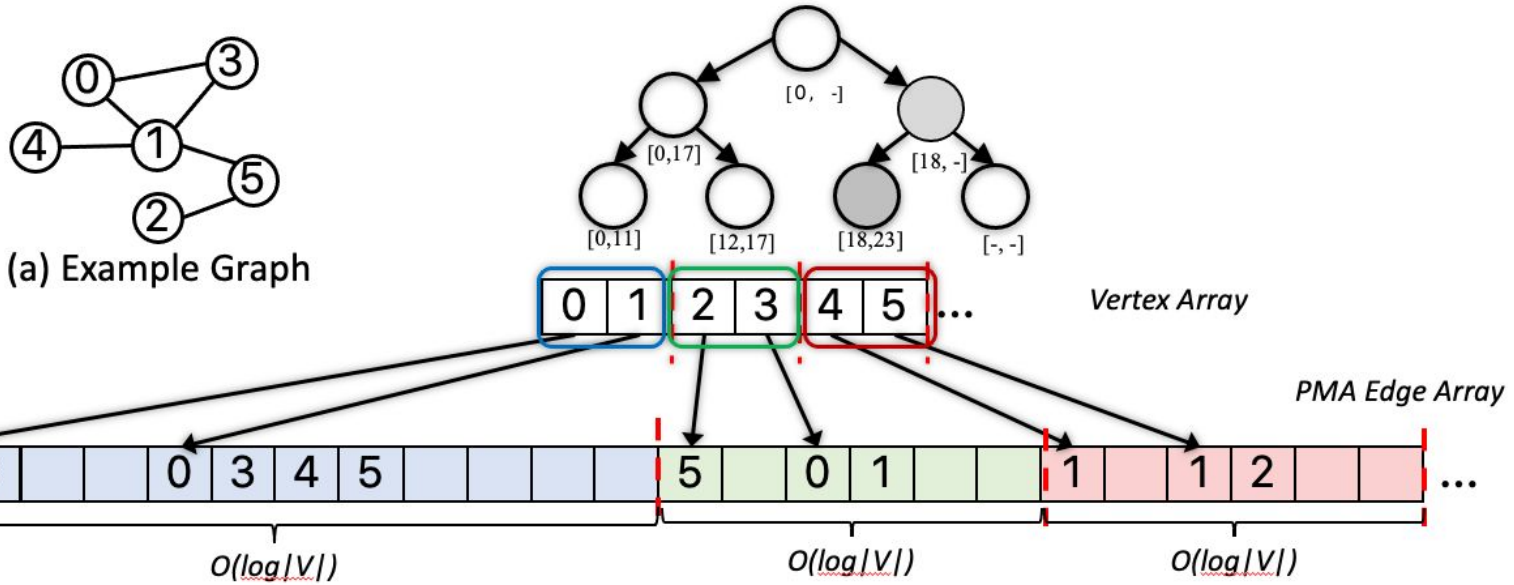

Figure: PMA-based Vertex-Centric Mutable CSR Extension, VCSR.

Outlines

Novel Mutable CSR Design

Evaluation and Results

Evaluation: Platform

- Dell R740 rack server with two sockets
- Each socket installs a 2nd generation Intel Xeon Scalable Processor (Gold 6254 @ 3.10G) with 18 physical (36 virtual) cores
- Ubuntu 18.04, Linux kernel version 4.15.0
- 6 DRAM DIMMS with 32GB each (192GB in total)

Evaluation: System Implementation

- Compressed Sparse Row (CSR)
- Blocked Adjacency-List (BAL)
- PMA-based CSR extension, PCSR
- Proposed vertex-centric PMA-based CSR extension, VCSR

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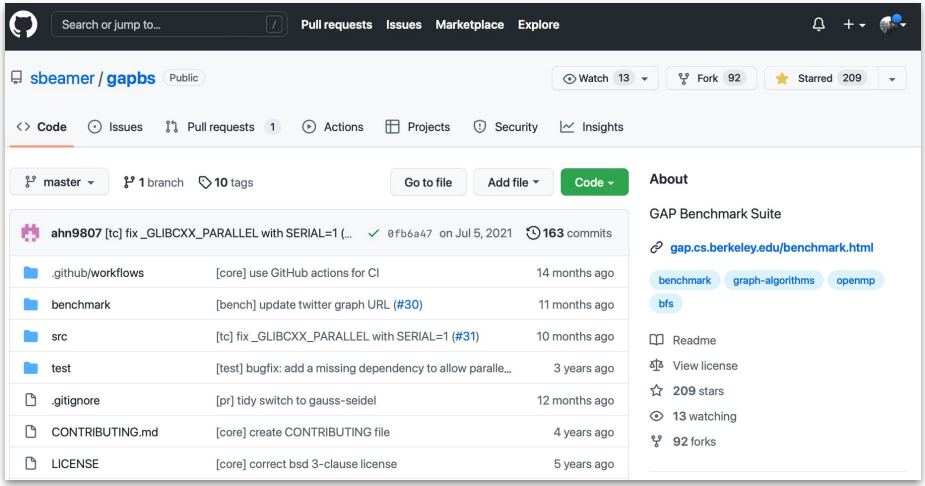
- We used GAPBS for benchmark



https://github.com/sbeamer/gapbs

Evaluation: Input Graphs

Datasets	Domain	$\|V\|$	$\|E\|$	$\|E\|/\|V\|$
Amazon	purchase	403393	4886816	12
Orkut	social	3072626	234370166	76
Live-journal	social	4847570	85702474	18
Cit-Patents	citation	6009554	33037894	6
Road	geo	1971280	5533214	3
as-Skitter	network	1696414	22190596	13
sx-stackoverflow	temporal	6024270	57724802	10
enron	temporal	87273	594912	7
sx-mathoverflow	temporal	88580	375972	4
fb-wall	temporal	63891	366824	6

Table: Graph inputs and their key properties.

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Hammer Workload

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Table: Graph inputs and their key properties.

Evaluation: Graph Algorithm Kernels

Graph kernel	Kernel Type	Input	Output	Notes
PageRank (PR)	Link Analysis	-	$\|V\|$-sized array of ranks	Fixed number (20) of iterations
Breadth-First Search (BFS)	Graph Traversal	Source vertex	$\|V\|$-sized array of parent IDs	Direction-Optimizing approach [27]
Single-Source Shortest Paths (SSSP)	Shortest Path	Source vertex	$\|V\|$-sized array of distances	δ-stepping [28]
Connected Components (CC)	Connectivity	-	$\|V\|$-sized array of component labels	Afforest subgraph sampling [29, 30]

Table: A list of graph kernels and inputs and outputs used to evaluate graph data-structures.

Evaluation: Graph Insertion Performance

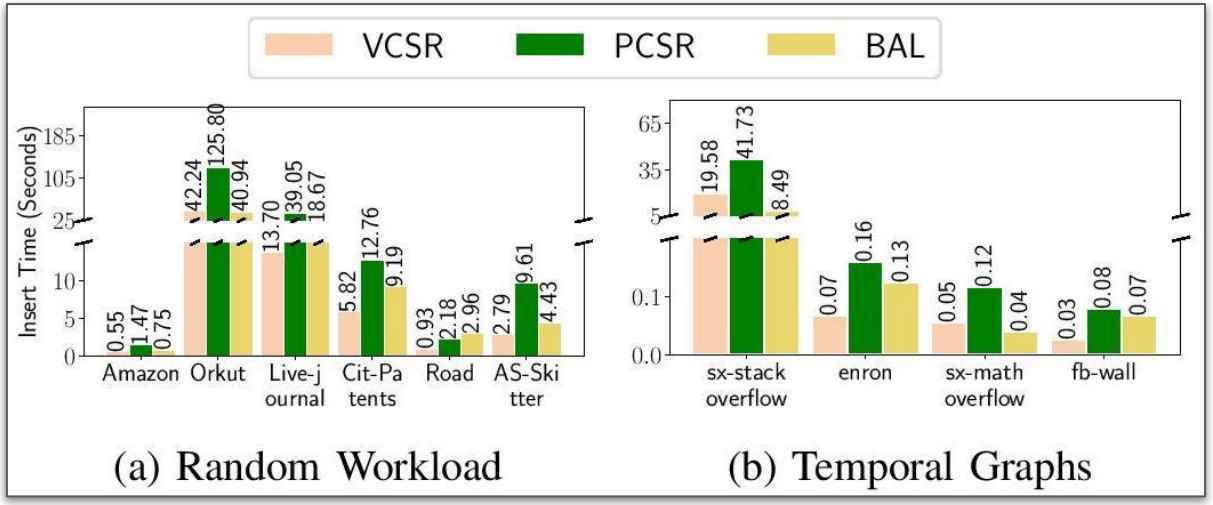
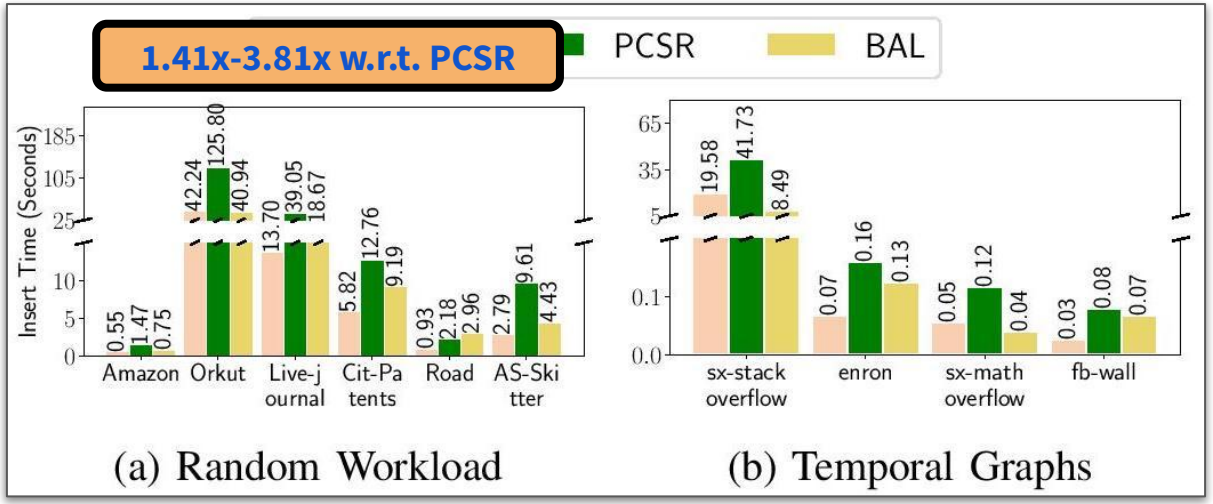


Figure: Comparing VCSR's dynamic graph insertion performance (in seconds) for 10% pre-initialization.

Evaluation: Graph Insertion Performance



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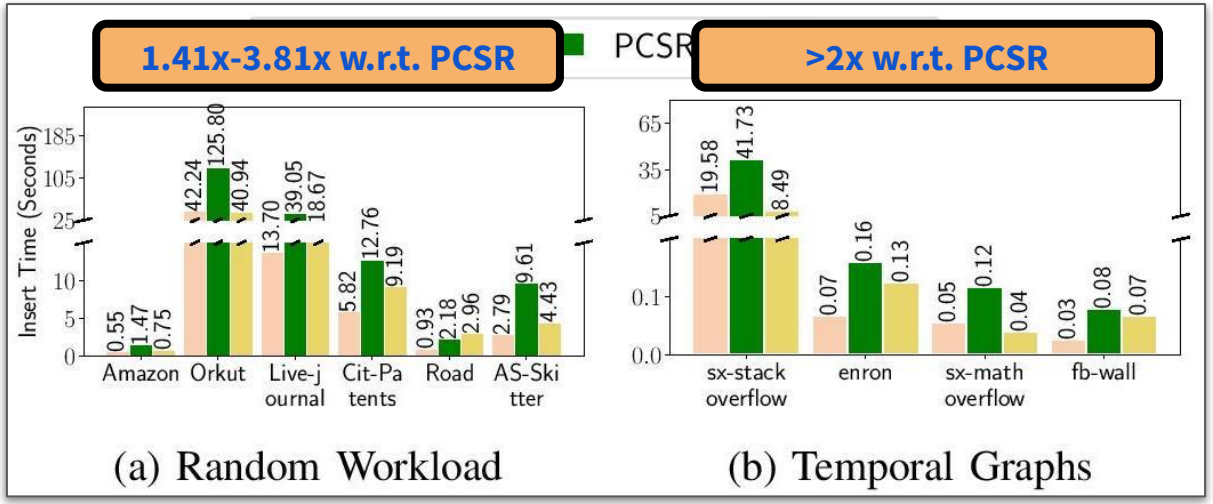

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Amazon (shuffled)	[1-3)	710 (0.84 M)	251077 (35.50 M)
	[3-7)	4 (0.02 M)	12964 (8.49 M)
	≥ 7	0 (0.00 M)	45 (0.41 M)
sx-Stack overflow	[1-3)	904363 (457.23 M)	13876752 (2262.72 M)
	[3-7)	357575 (1056.19 M)	3053307 (2720.56 M)
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Table: Number of re-balancing operations triggered by edge insertions in VCSR and PCSR on two graphs.

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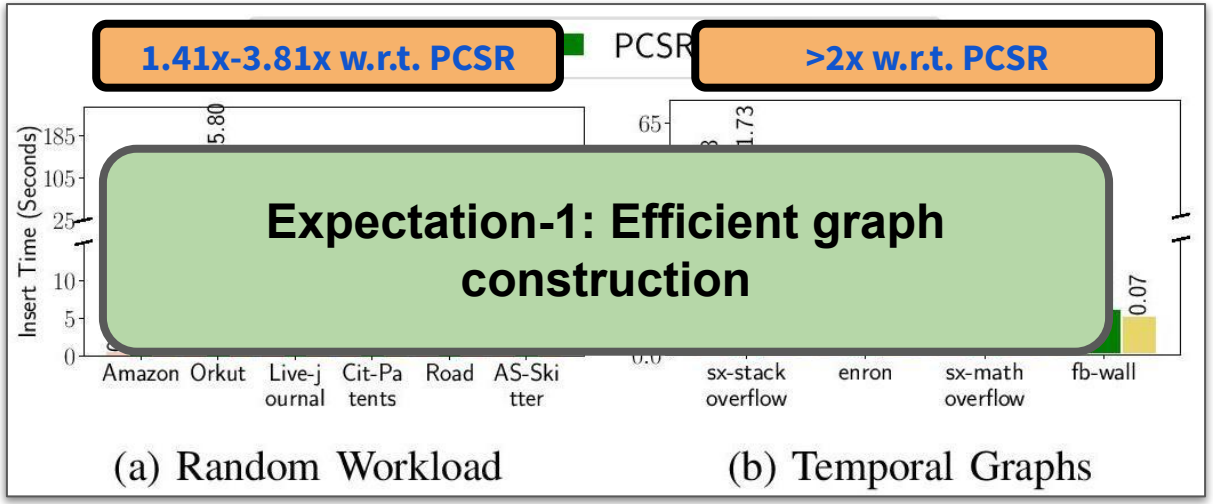

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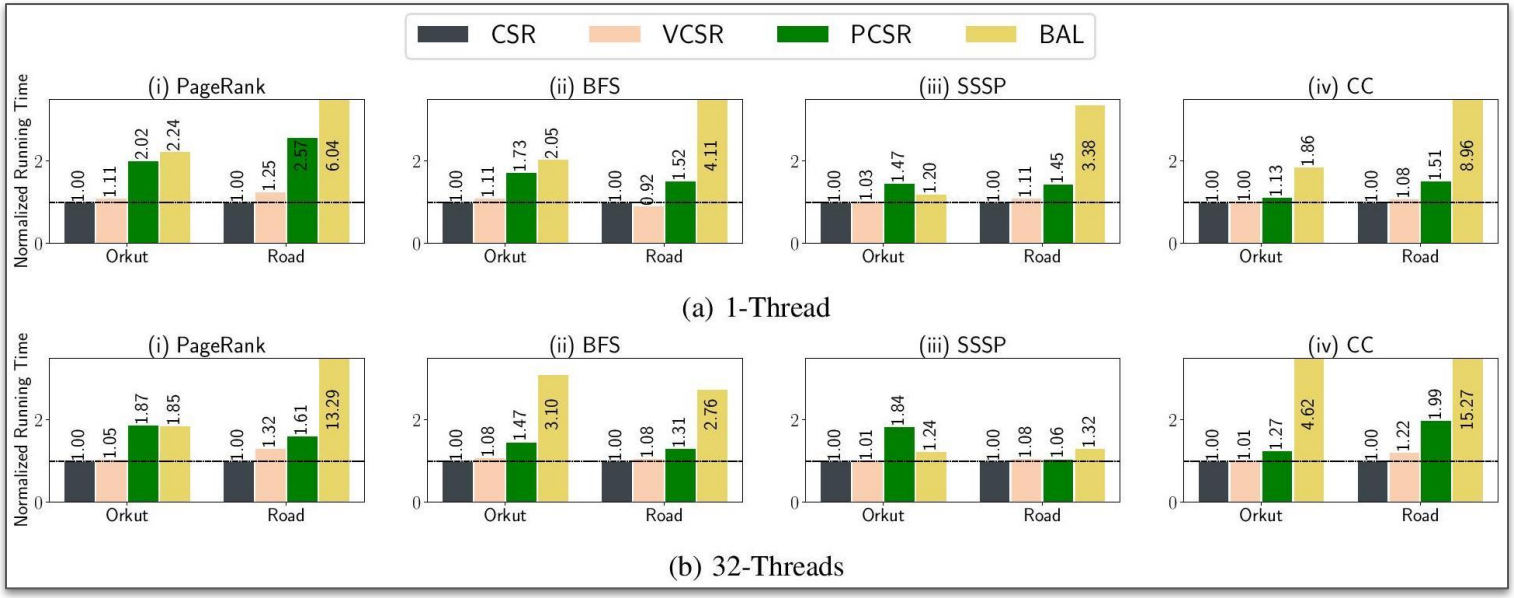
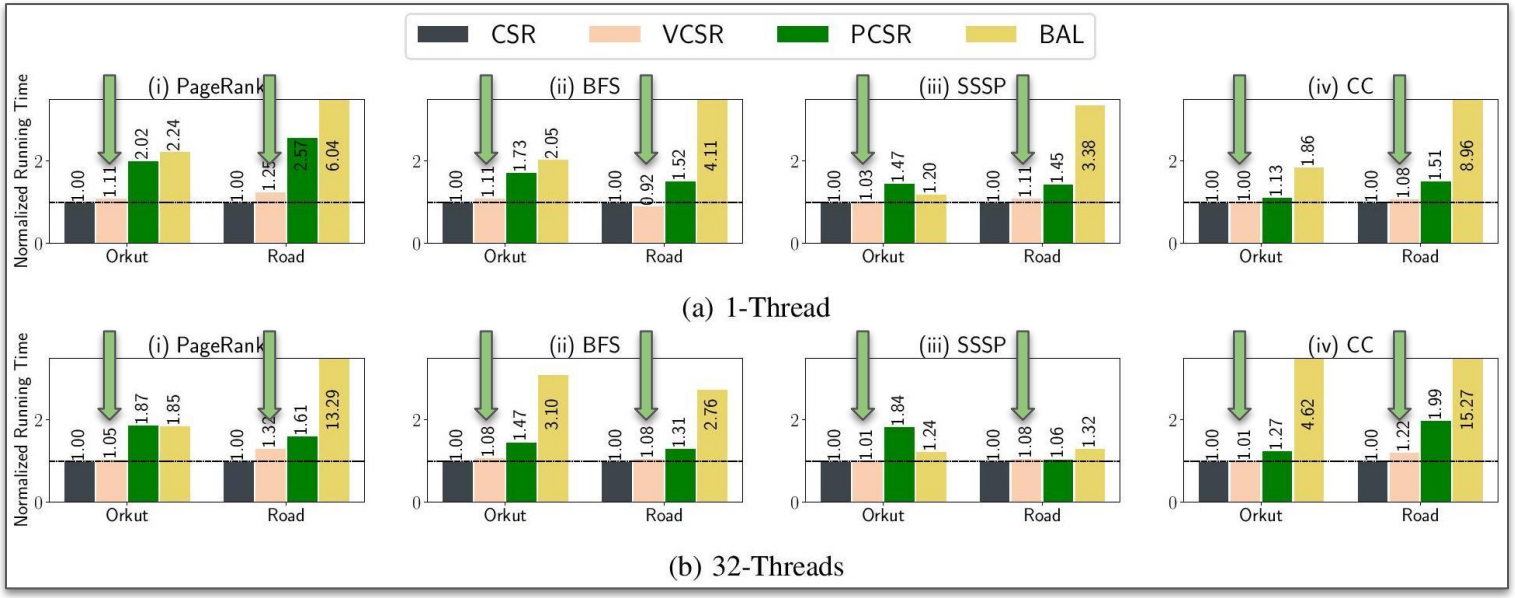


Figure: Comparing graph analysis runtime normalized to CSR.

Evaluation: Graph Analytic Algorithms Performance



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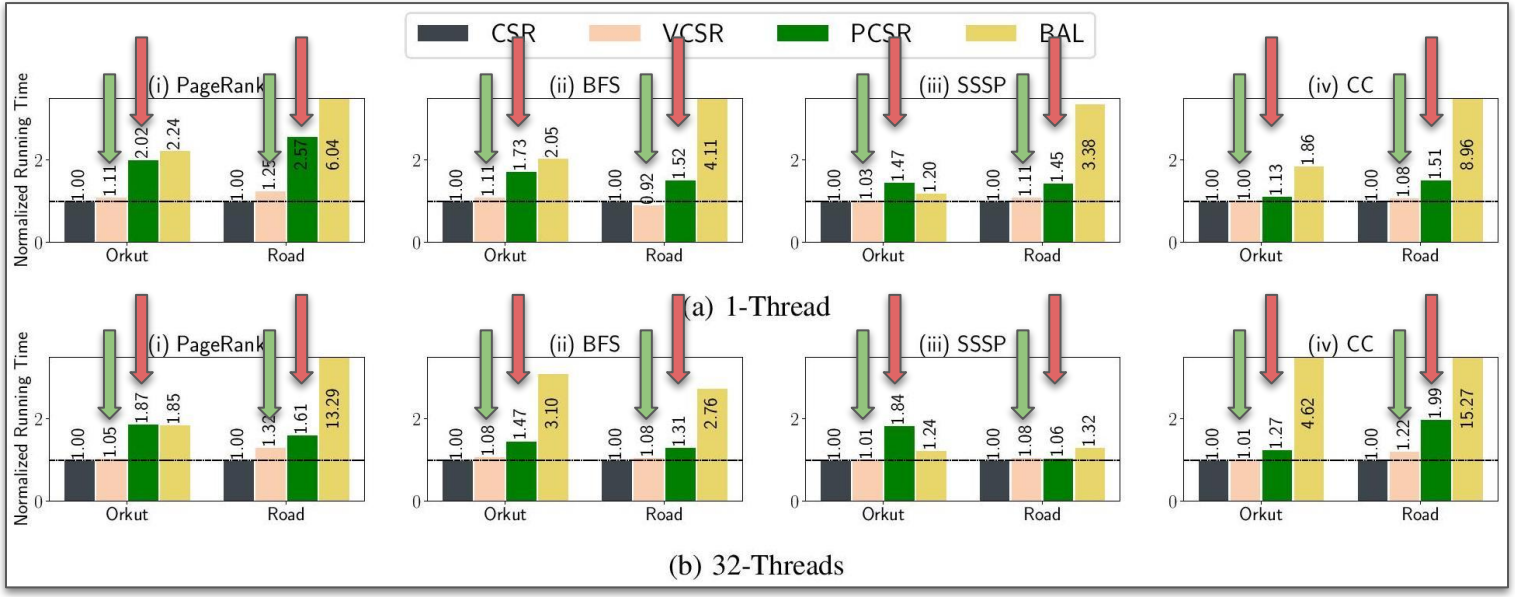

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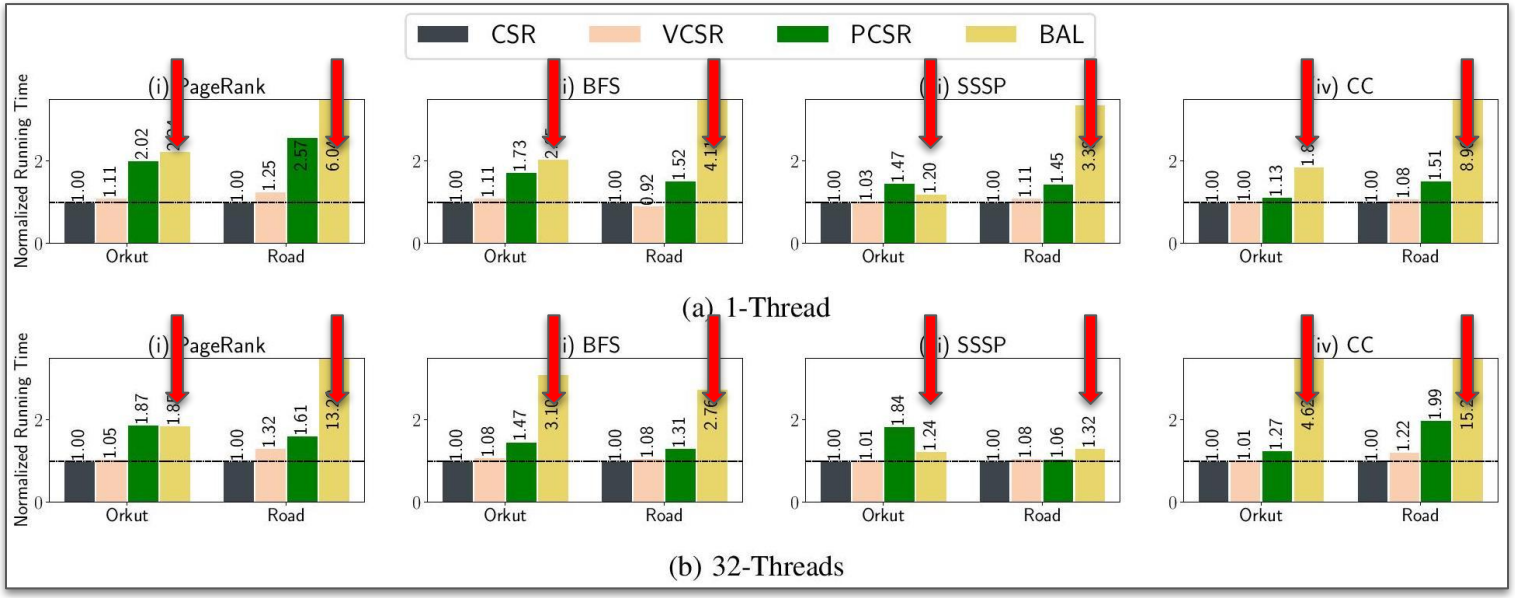

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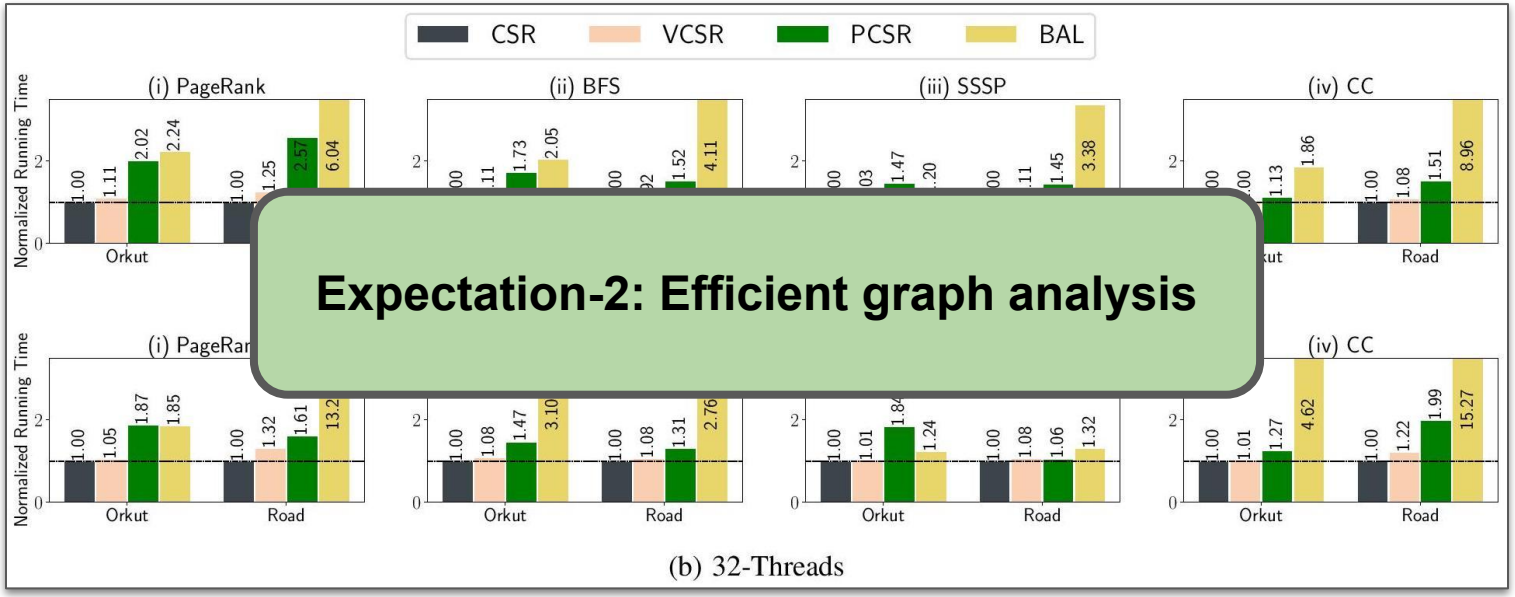

Expectation-2: Efficient graph analysis

Figure: Comparing graph analysis runtime normalized to CSR.

Summary

- Identify fundamental limitations in existing PMA based mutable CSR extension
- Demonstrate graph's power-law also exist while it evolves
- Design a novel vertex-centric CSR extension: VCSR
  - Solves the fundamental limitations in handling graph imbalances
- Evaluation results
  - 1.41x-3.81x better performance in graph insertions
  - 1.22x-2.05x better performance in running typical graph analytic algorithms

CHARLOTTE
COLLEGE OF COMPUTING AND INFORMATICS

Thank You

Question?

DIRLAB