Dynamic Graphs on the GPU

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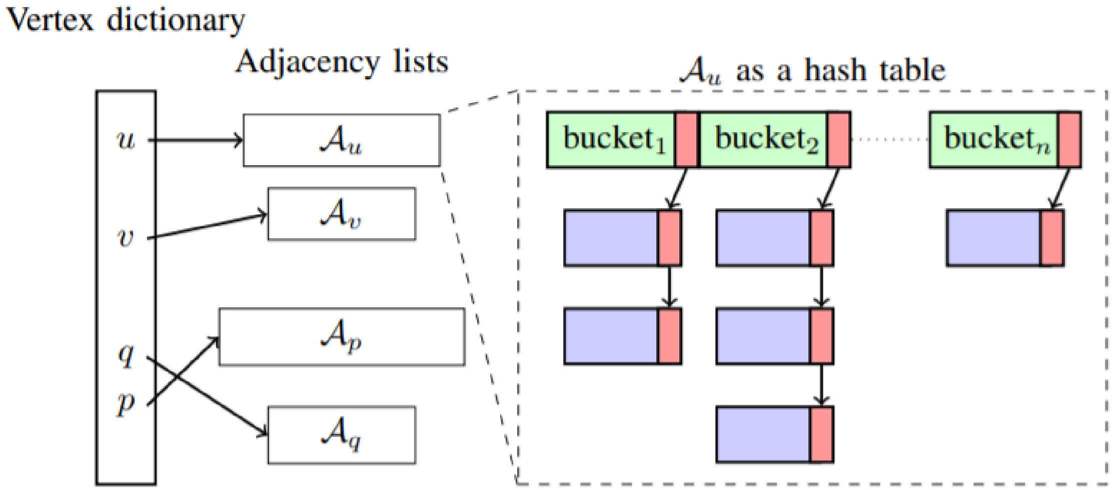
Dynamic Graphs on the GPU

- **Goal:** High-performance dynamic graph data structure optimized for updates and queries.
- **Approach:** Hash-table-based graph data structure.
- **Argument:** List-based data structures add the complexity of maintaining sorted adjacency lists to optimize queries and updates.



High level schematic of our graph data structure

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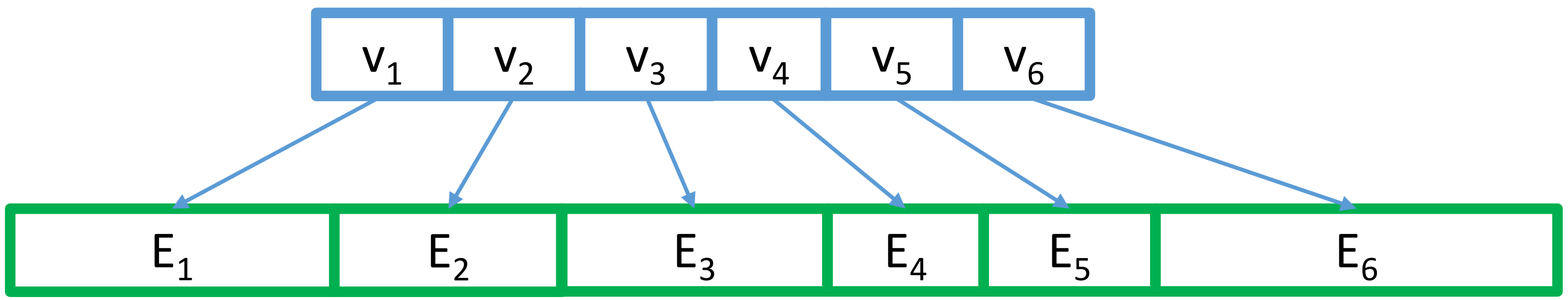
Graph Data Structures

Vertex Dictionary

Edge List (CSR)
Fixed-size array

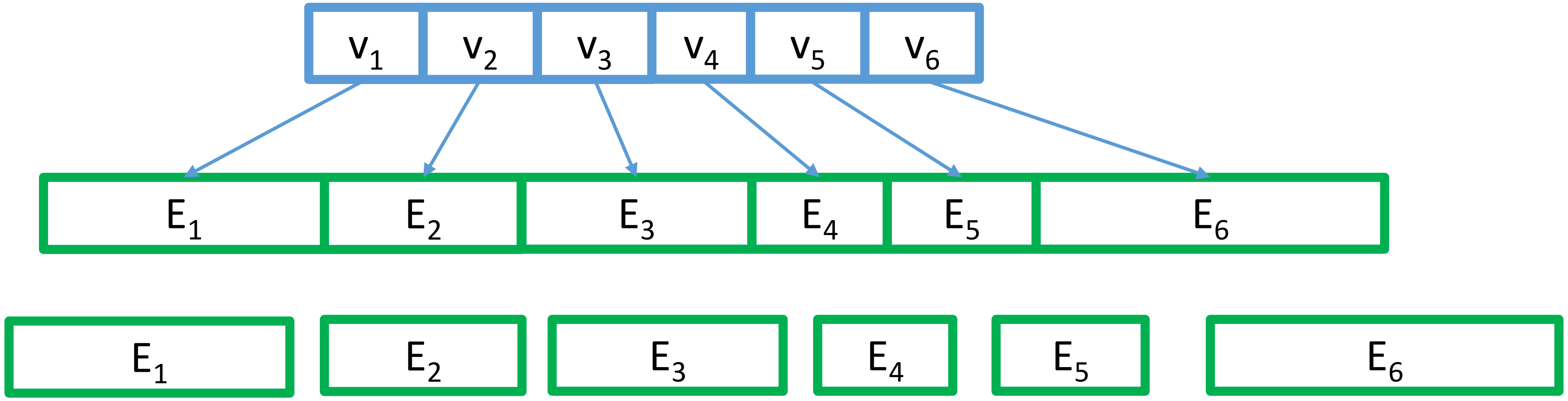


Graph Data Structures

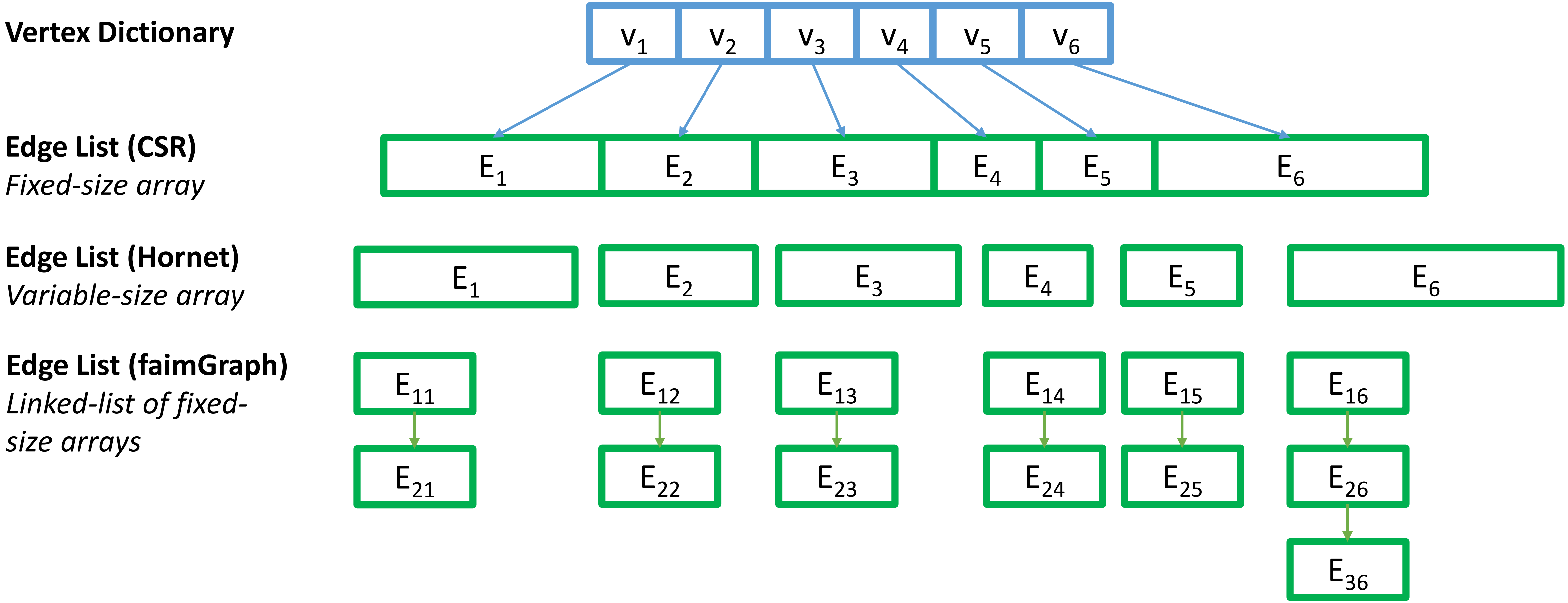
Vertex Dictionary

Edge List (CSR)
Fixed-size array

Edge List (Hornet)
Variable-size array



Graph Data Structures



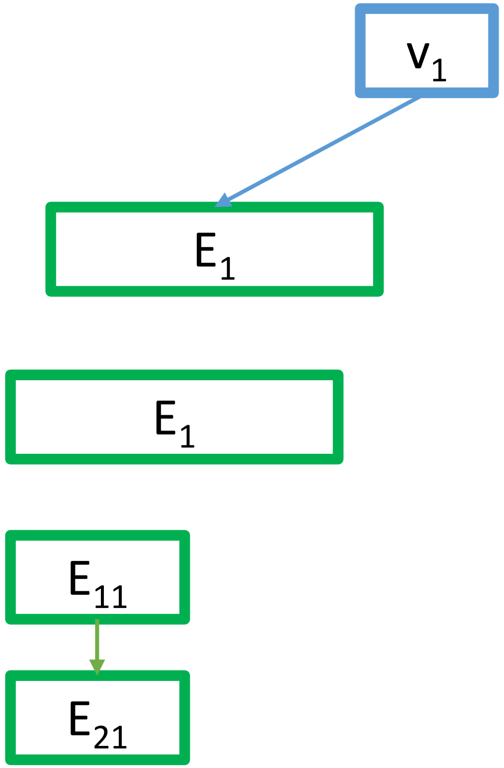
Graph Data Structures

Vertex Dictionary

Edge List (CSR)
Fixed-size array

Edge List (Hornet)
Variable-size array

Edge List (faimGraph)
Linked-list of fixed-size arrays



Edge exist query is an essential query.
Example: insertion while maintaining unique edges per-vertex.

Query cost if the adjacency list is not sorted:

- $O(|E|)$

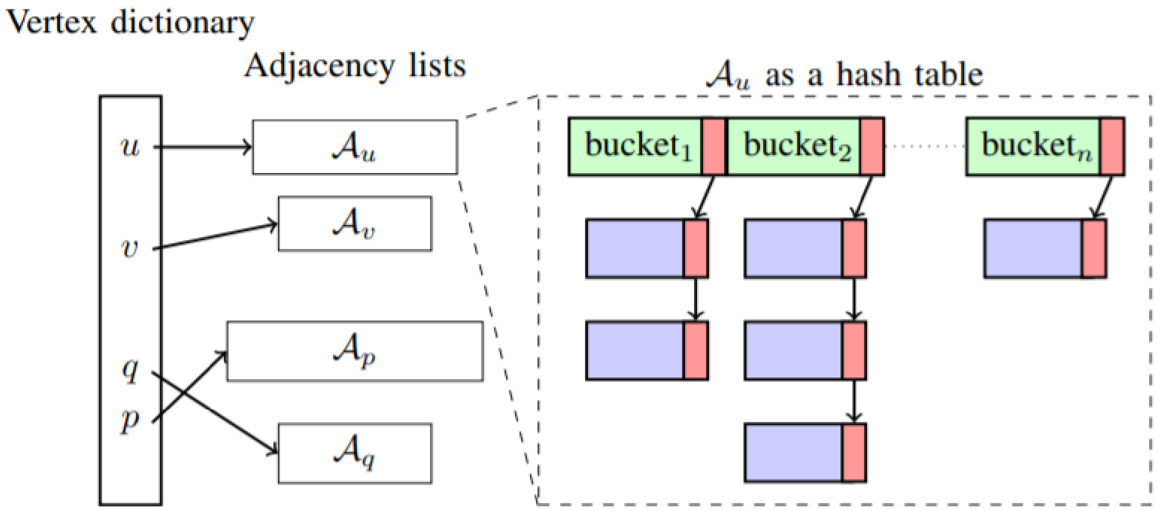
And if sorted:

- $O(\log(|E|))$

… But we must maintain the sorting order during updates.

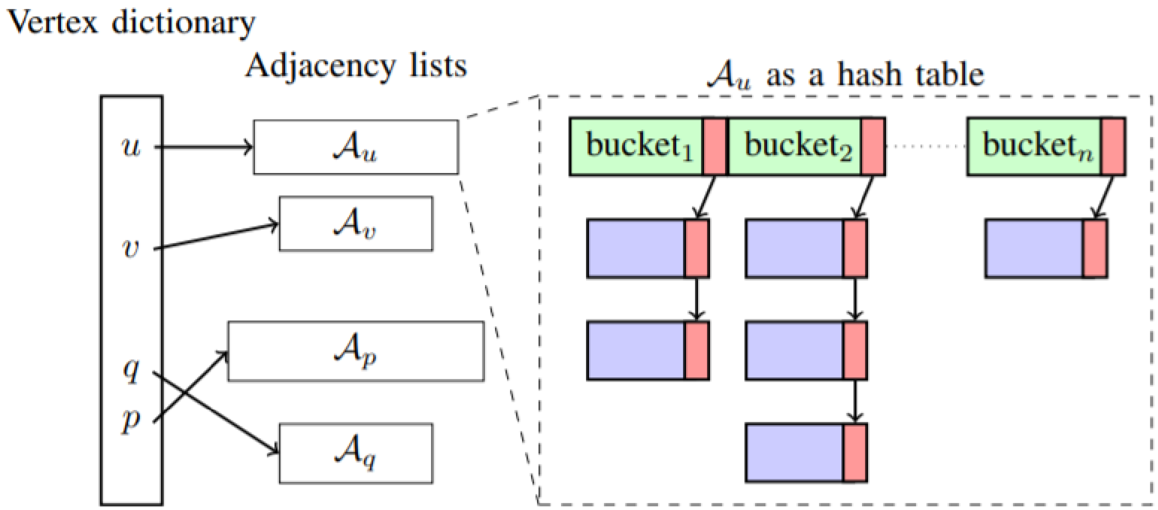
Our Dynamic Graph Data Structure

- Hash-table-based graph data structure.



Our Dynamic Graph Data Structure

- Hash-table-based graph data structure.
- Each vertex has:
  - Pointer to its own hash table (we use Slab Hash*).
  - Additional counters for number of edges and other metrics.



Query Performance:

- O(1)

* Saman Ashkiani, Martin Farach-Colton, and John D. Owens. **A Dynamic Hash Table for the GPU**. In *Proceedings of the 32nd IEEE International Parallel and Distributed Processing Symposium*, IPDPS 2018, pages 419–429, May 2018. [bib | DOI | code | http]

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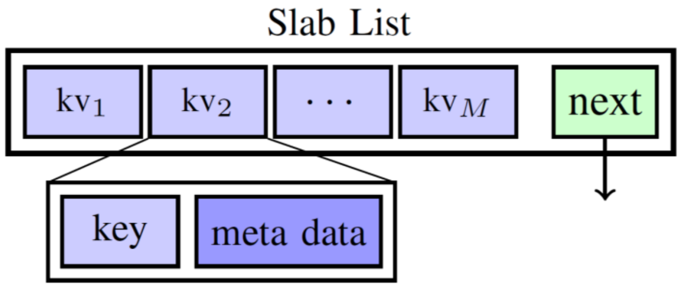
Slab Hash*

- Load factor defines the initial number of buckets.
- Each bucket is a *128 bytes* slab.
- Collision is resolved using a linked-list of dynamically allocated slabs.
- Offers *concurrent multimap* ***(duplicate keys)*** and our additions:
    - *Concurrent map* **(unique keys)** -> used in weighted graphs
    - *Concurrent set* ***(unique keys and no values)*** -> used in unweighted graphs



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Our Dynamic Graph Data Structure

We support the following operations:

- **Low-level Operations**
  - Edge insertion and deletion
  - Vertex insertion and deletion
- **Bulk build**
- **Queries**
  - Edge exist query
  - Iterator over a vertex's adjacency list

Example Operation: Edge Insertion

- Using warp cooperative work sharing strategy (WCWS).
  - Per-thread assignment.
  - Per-warp processing.

Algorithm 1 Graph edge insertion algorithm.

```
procedure INSERTEDGES(GpuGraph graph, Edges edges)
    thread_edge ← edges[threadIdx]
    to_insert ← thread_edge.src != thread_edge.dst
    while work_queue ← ballot(to_insert) do
        current_lane ← find_first_set_bit(work_queue)
        current_src ← shuffle(thread_edge.src, current_lane)
        same_src ← thread_edge.src == current_src
        success ← graph[current_src].replace(thread_edge, same_src & to_insert)
        added_count ← popc(ballot(success))
        graph[current_src].incrementEdgesCount(added_count)
        if same_src & to_insert then
            to_insert ← false
        end if
    end while
end procedure
```

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Build a queue of new edges →

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Build a queue of new edges →

Warp-wide single edge insertion →

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Build a queue of new edges → while work_queue ← ballot(to_insert) do

Warp-wide single edge insertion → success ← graph[current_src].replace(thread_edge, same_src & to_insert)

Maintain per-vertex edge count → graph[current_src].incrementEdgesCount(added_count)

Example Operation: Edge Insertion

- Using warp cooperative work sharing strategy (WCWS).
  - Per-thread assignment.
  - Per-warp processing.
- WCWS benefits:
  - Eliminates branch divergence.
  - Coalesced memory access.

Evaluating a Dynamic Graph Data Structure

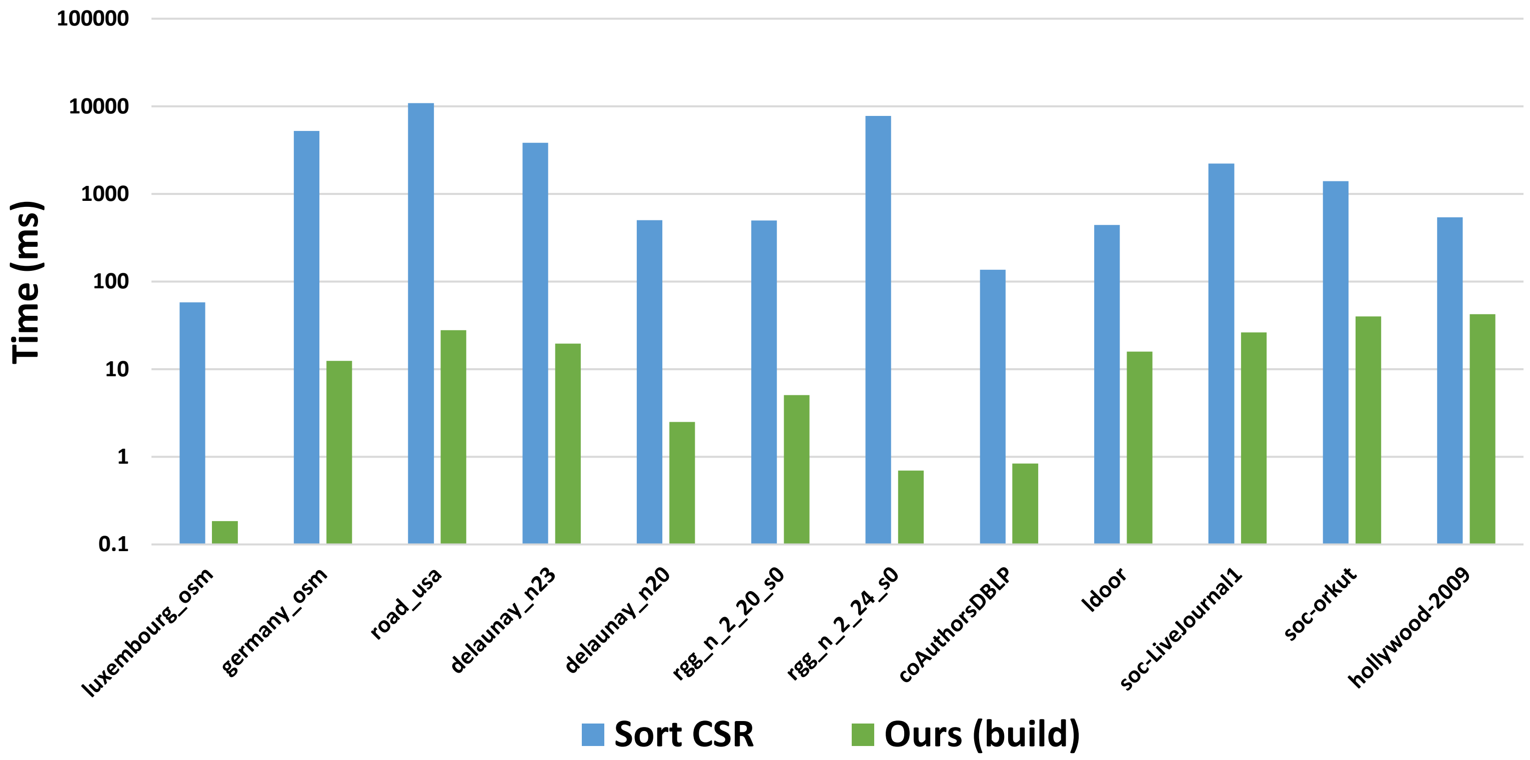
We define a set of benchmarks to evaluate a dynamic graph data structure:

- **Low-level Operations:**
    - Edge insertion and deletion
    - Vertex insertion and deletion
- **Workloads:**
    - Bulk build
    - Incremental build
- **Applications:**
    - Static and dynamic graph application (we use triangle counting)

We evaluate our graph data structure and compare it to Hornet and faimGraph.

Results*

- Sorting CSR† compared to building our data structure (log scale).



* Using an NVIDIA TITAN V (Volta) GPU.

† Using CUB's Segmented Sort

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Results*

- High throughput low-level operations.

Operation	Rate (MOp/s)	Speedup vs. Hornet	Speedup vs. faimGraph
Edge insertion	646	**5.8-14.8x**	**3.4-5.4x**
Edge deletion	1024.87	**1.0-7.0x**	**3.6-5.7x**
Vertex deletion	26.49	**--**	**8.9-12.2x**

- High throughput in graph building workloads.
  - Incremental build: 993.82 MEdge/s (5x faster than Hornet).
  - Bulk build: 2–30x faster than Hornet.
    - In hollywood-2009 dataset 45% of Hornet’s time is spent in deduplication (same time required to build or data structure).

*** Using an NVIDIA TITAN V (Volta) GPU.**

*** Averaged over different datasets**

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Results*

- Dynamic triangle counting.
  - Intersection: given two adjacency lists, count the number of common vertices.
  - Two phases: 1) compute the intersections, 2) update the graph.

- Although performing intersection using hash tables is slower than using sorted lists, the update phase makes up for the slowdown.
  - 5 rounds of updates (1M Edge insertion).
  - Hollywood-2009: 56,774 ms (0.91x Hornet).
  - Road_usa: 325.8 ms (1.83x Hornet).

*** Using an NVIDIA TITAN V (Volta) GPU.**

Conclusions and Future Work

- **Hash-table-based dynamic graph data structure offers superior performance compared to alternative list-based graph data structures.**

- **Vertices have different workloads (updates and queries).**
    - Load factor controls this tradeoff and we can have different load factors per-vertex.

Conclusions and Future Work

- **Hash tables are not suited for all graph problems.**
  - A sorted adjacency list is useful for some application, we can replace a hash table with a B-Tree*.
- **Concurrent updates and queries.**
- **Dynamic graph problems and workloads.**

* Muhammad A. Awad, Saman Ashkiani, Rob Johnson, Martín Farach-Colton, and John D. Owens. **Engineering a High-Performance GPU B-Tree**. In *Proceedings of the 24th ACM SIGPLAN Symposium on Principles and Practice of Parallel Programming*, PPoPP 2019, pages 145–157, February 2019. [bib | DOI | http]

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- Send us your questions:
  - Muhammad A. Awad: mawad@ucdavis.edu
  - Saman Ashkiani: sashkiani@ucdavis.edu
  - Serban D. Porumbescu: sdporumbescu@ucdavis.edu
  - John D. Owens: jowens@ece.ucdavis.edu
- Our code:
  - In Gunrock: https://github.com/gunrock/gunrock/tree/dynamic-graph
  - Open issues if you have questions about the code or how to use it.