Graphite: Optimizing Graph Neural Networks on CPUs Through Cooperative Software-Hardware Techniques

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Graph Neural Network (GNN)

- Traditional DNNs (e.g. CNNs) can hardly process graphs
- GNN specializes in processing graphs
- Application domains:
  - Recommender systems
  - Social networks
  - Knowledge graphs
  - Physics
  - Life science
  - And many more

GNN Characteristic: Alternating Phases

- Two alternating phases: **Aggregation** and **Update**

- **Aggregation**: each vertex gathers and reduces features from neighbors/edges

$$\mathbf{a}_v^k = \text{AGGREGATE}(\mathbf{h}_u^{(k-1)} \mid \forall u \in \mathcal{N}(v) \cup \{v\})$$

  - **Sparse** connections
  - **Irregular** memory access patterns
  - **Poor** locality
  - **Memory intensive**
  - **Variable** execution time for each vertex, correlated with the vertex's degree

- **Update**: each vertex computes its output features from the aggregation outputs with a DL op (e.g. MLP)

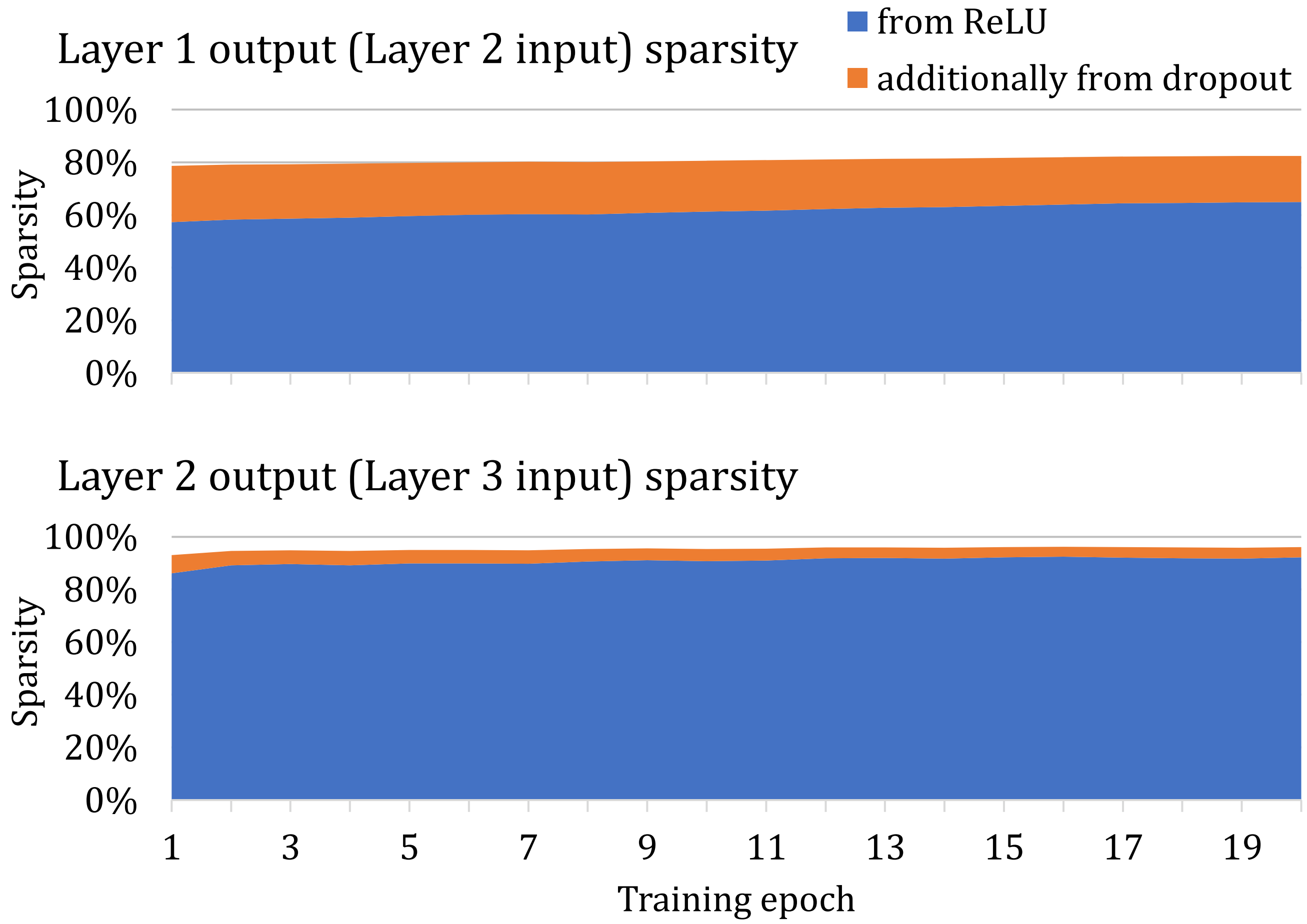
$$\mathbf{h}_v^k = \text{UPDATE}(\mathbf{a}_v^k)$$

  - **Dense** computation
  - **Regular** memory access patterns
  - **Good** locality
  - **Compute intensive**
  - **Similar** execution time for each vertex

GNN Characteristic: Activation (Feature) Sparsity

- Sparsity: zeros in the working sets
- ReLU: 20-80% sparse
- Dropout in training: often 50% dropped
- Combined: often >80% sparse
- Dynamic and unstructured
- Operating on zeros: ineffectual

Example: feature sparsity during 3-layer *GraphSAGE* training



Other GNN Characteristics

- Long feature length
  - Traditional graph analytics: often scalar feature
  - GNN: often hundreds to thousands

Dataset	Vertex feature length
Cora	1,433
Citeseer	3,703
Reddit	602
Ogbn-products	100

- Reuses input graphs in training

Motivation: GNNs on CPUs

- Real-world graphs are often huge
  - Millions to billions of vertices and edges
- CPUs: viable platforms for GNNs
  - Terabyte-level memory capacity
  - Have high availability
- GNNs on CPUs are memory bandwidth bound
  - 3-layer GraphSAGE training on CPUs:
  - 10% of pipeline slots do useful work
  - 62% of pipeline slots are stalled waiting for memory

Graph	$\|V\|$	$\|E\|$
Ogbn-products	2.5M	124M
Ogbn-papers100M	111M	1.6B
wikipedia	3.6M	45M
twitter	62M	1.5B

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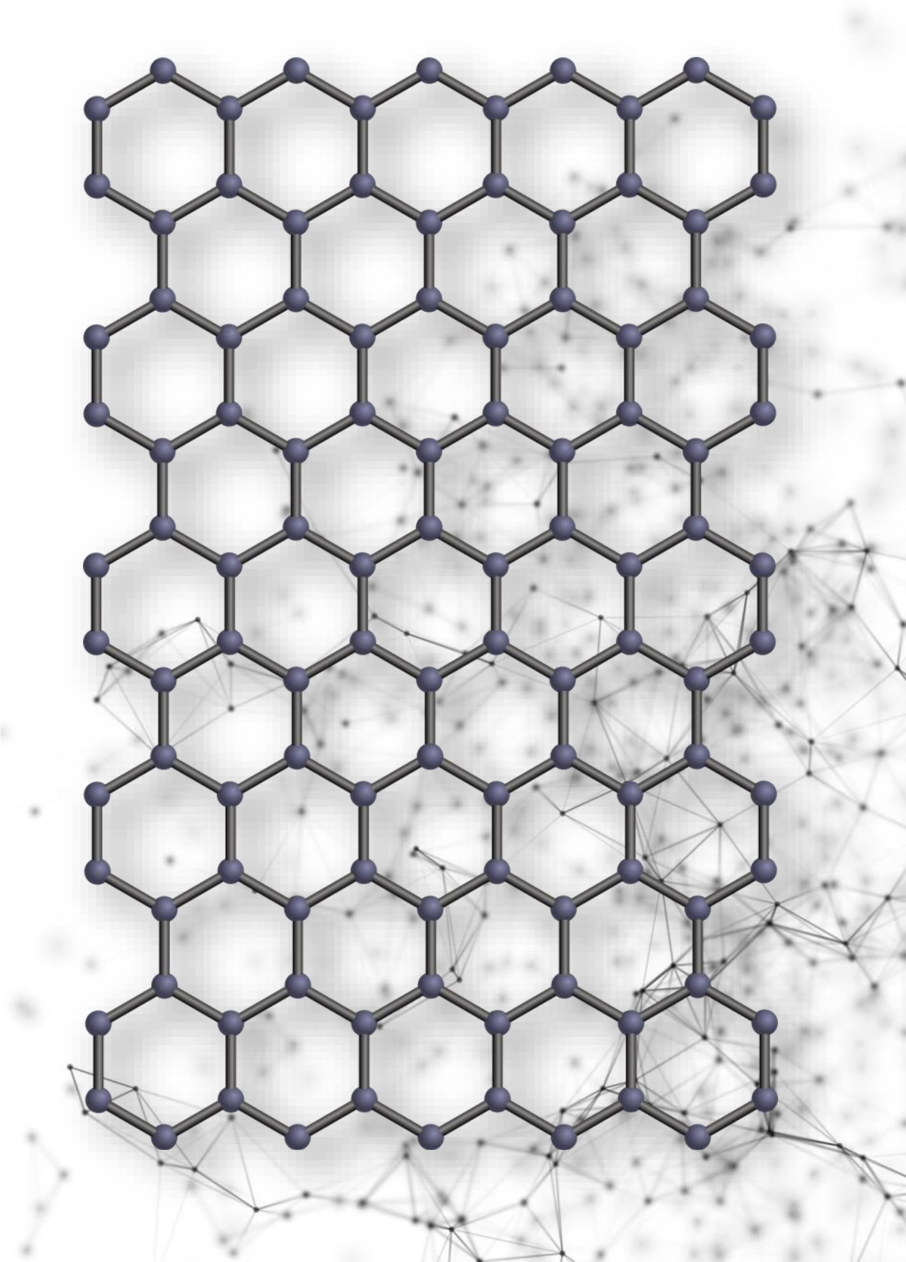
Contribution: Graphite

- Graphite: cooperative SW-HW techniques that optimize GNNs on CPUs
- Software techniques:
  - Layer fusion: overlap compute and memory
  - Feature compression: reduce memory traffic
  - Input preprocessing: increase locality
  - Inference 1.8x, training 1.9x speedup
- HW-SW co-design techniques:
  - Enhanced DMA engine: offload aggregation
  - Inference 1.8x, training 2.4x speedup



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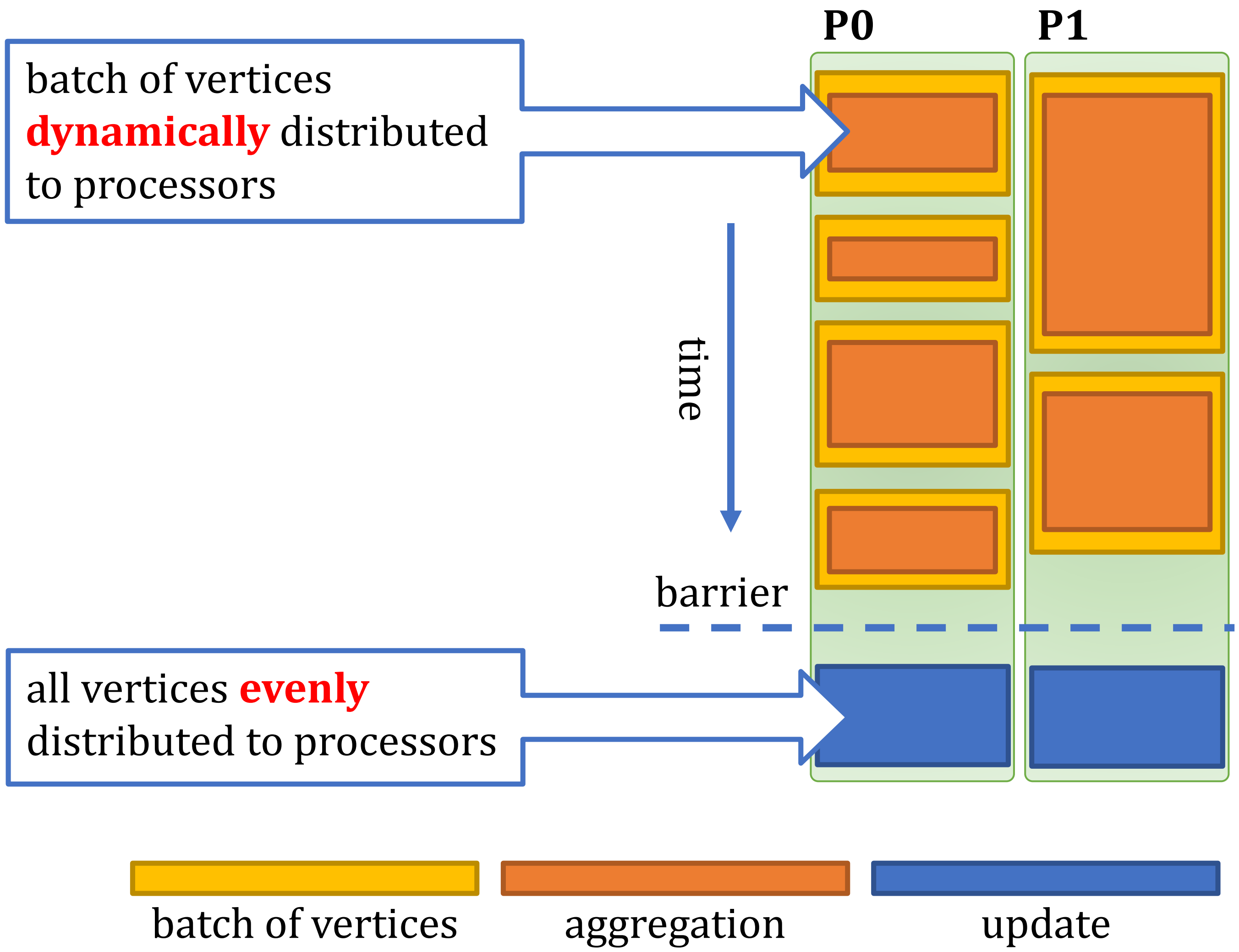
Graphite Software Techniques

Basic Optimized Implementation

- **Aggregates** all vertices then **updates** them
- **Aggregation**
  - JIT-assembled kernel
  - Output parallelized
  - Hand vectorized
  - Software prefetch
  - OpenMP dynamic scheduling
- **Update**
  - Stock library GEMM



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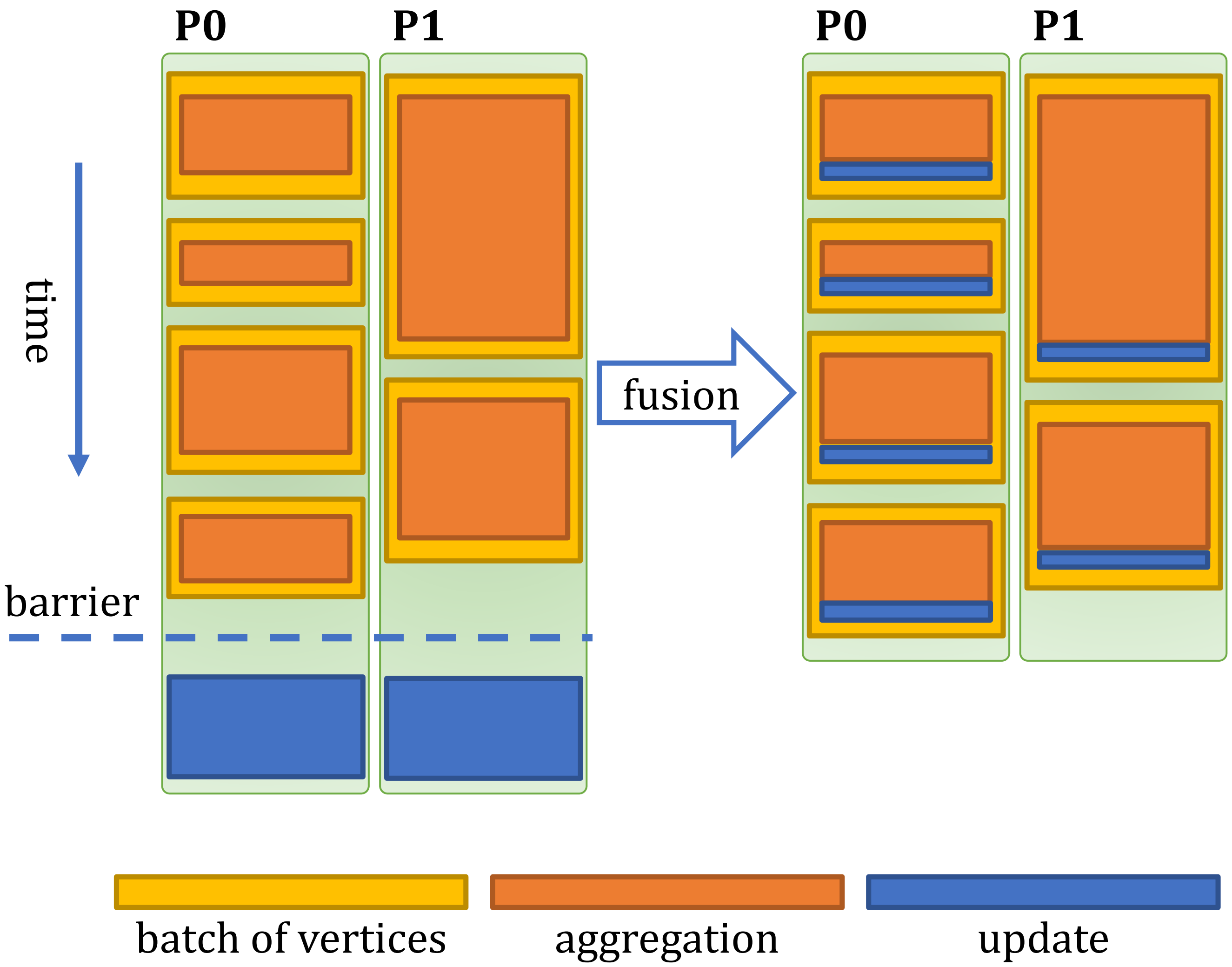
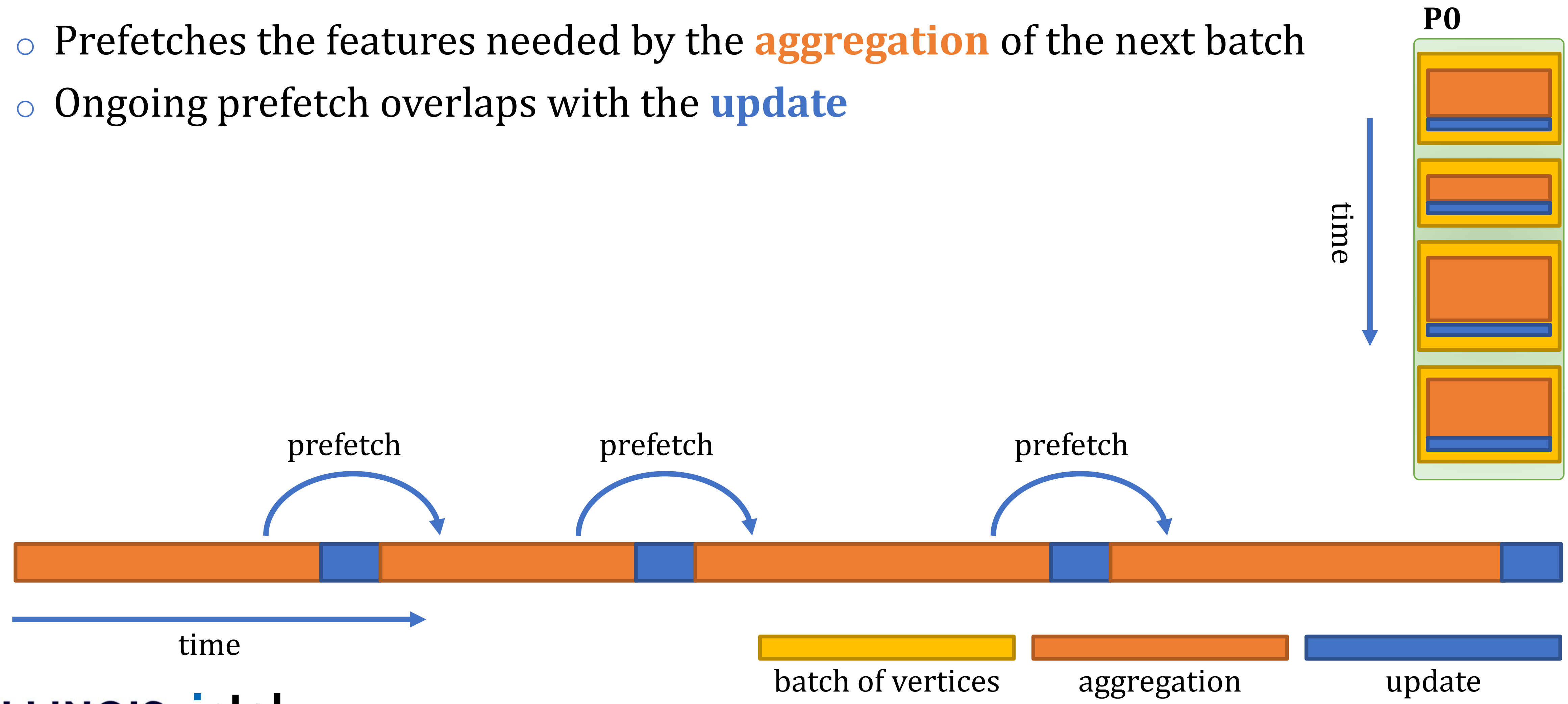
Layer Fusion

- Goal: overlap memory-bound and compute-bound operations
- Fusion: interleave **aggregation** and **update** of vertex batches



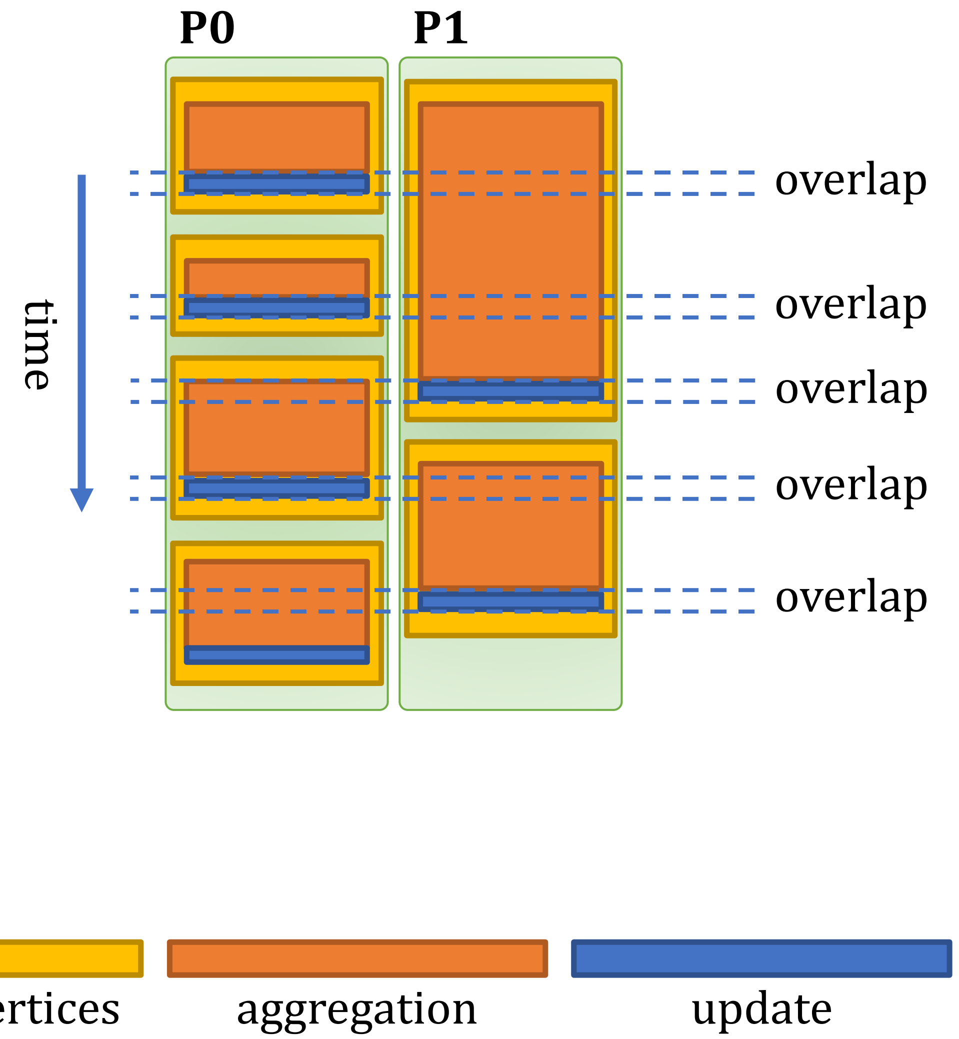
Overlapping Compute-Memory: Within a Processor

- Prefetches the features needed by the the **aggregation** of the next batch
- Ongoing prefetch overlaps with the **update**



Overlapping Compute-Memory: Among Processors

- **Aggregation**: variable time
- **Update**: fixed time
- Executions on different processors naturally go out-of-phase
- Memory bandwidth: a shared resource



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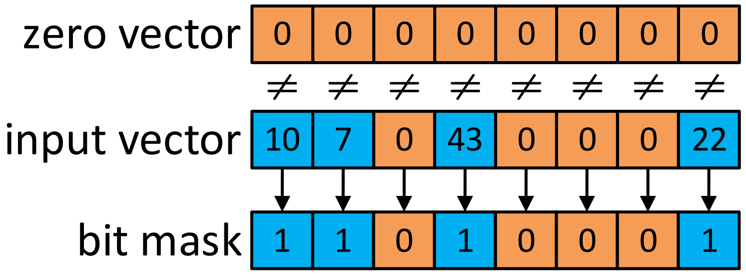
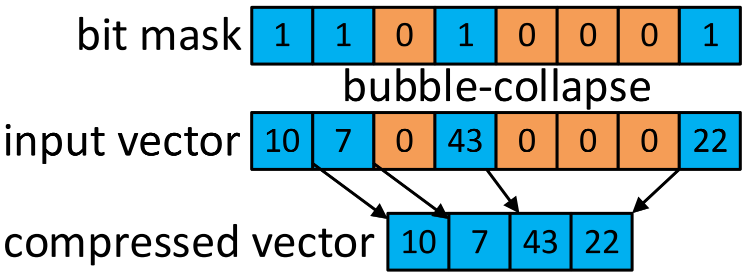
Feature Compression

Compression



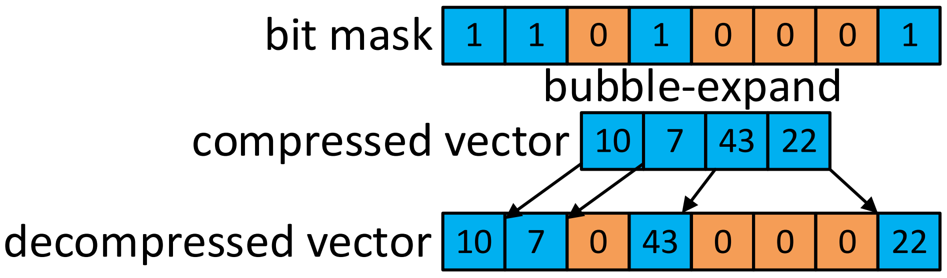
Step 1: generate bit-mask



Step 2: bubble collapse

- Goal: reduce memory traffic
- Avoid loading/storing zeros
- Fast vector comparison and (de)compression instructions

Decompression



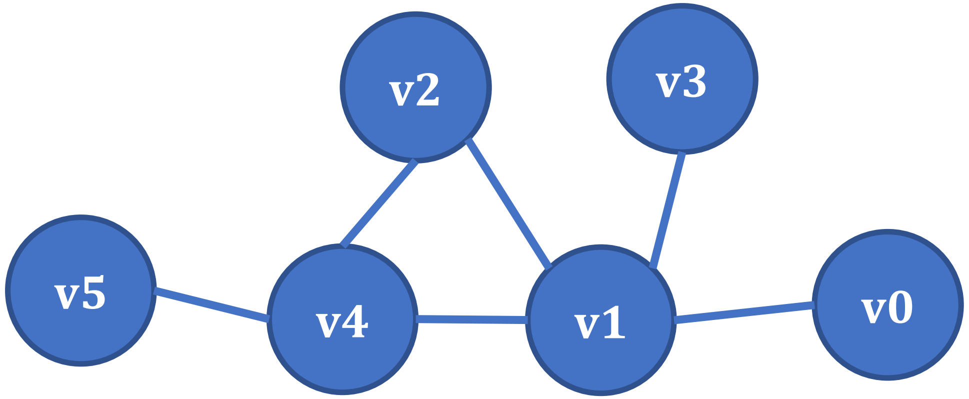
bubble expand

Increasing Locality in Aggregation

- Aggregation: each vertex gathers neighbors' features
  - Features span multiple cache lines
  - Temporal locality of features is important
- Goal: increase temporal reuse of vertex features

Increasing Locality in Aggregation: Algorithm

- Computes a new processing order of vertices
- Grouping: assigns each **vertex** to the group of its **highest-degree neighbor**
- Vertices in a group are processed temporally closely and reuse at least one feature vector



Group of v1:
v0, v2, v3, v4

Group of v4:
v1, v5

Original processing order: v0, v1, v2, v3, v4, v5
New processing order: v0, v2, v3, v4, v1, v5

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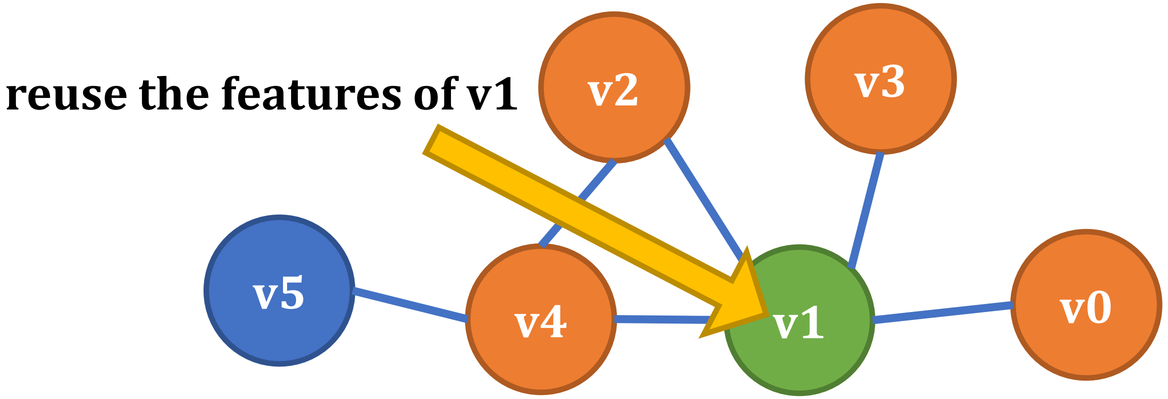

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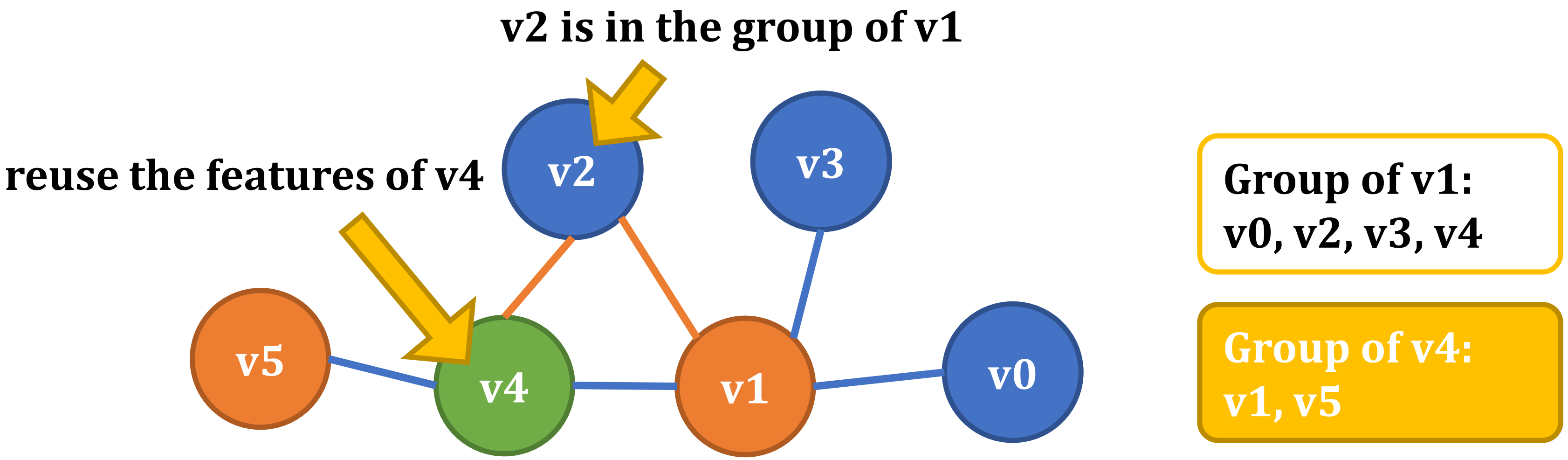

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New processing order: v0, v2, v3, v4, v1, v5

Increasing Locality in Aggregation: Overhead

- Linear complexity O(V+E), good scalability
- We only apply the optimization in GNN training
  - Training contains many epochs
  - The cost of preprocessing the inputs is amortized

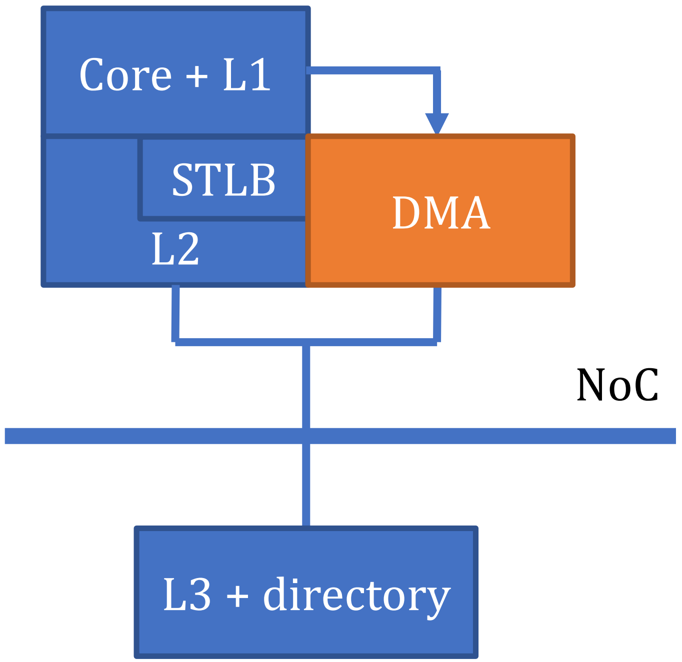
Graphite HW-SW Co-design Techniques

GNN Aggregation and DMA

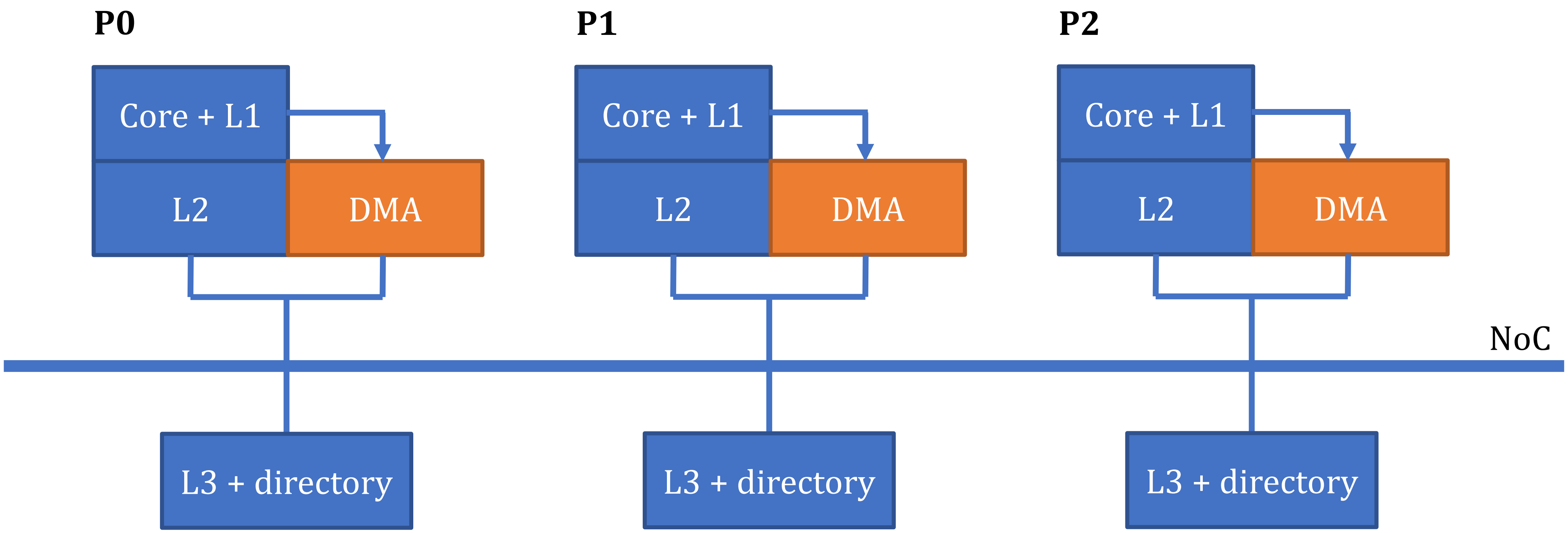
- Aggregation: gather and reduce
- Gathered features have low reuse
- Scatter-gather is a common DMA operation
- Graphite enhances DMA to perform aggregation

Graphite DMA Structure

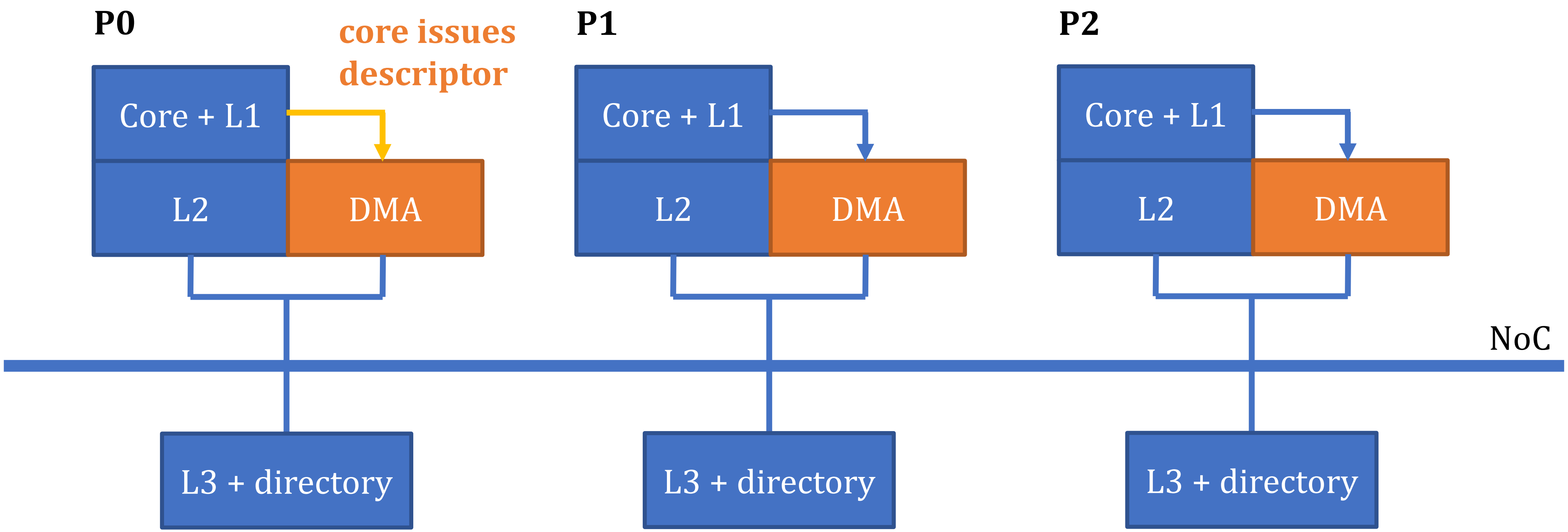
- One DMA engine per processor
  - Connected to NoC
  - Virtual address: L2 STLB for address translation
  - Works in user-space
  - Reuses function units in existing DMA
  - Adds a narrow vector unit to perform reductions
- Descriptor-based programming model
  - 64B descriptor encodes an aggregation
  - Easily built from CSR encoded adjacency matrices
- Incompatible with feature compression for cost reason



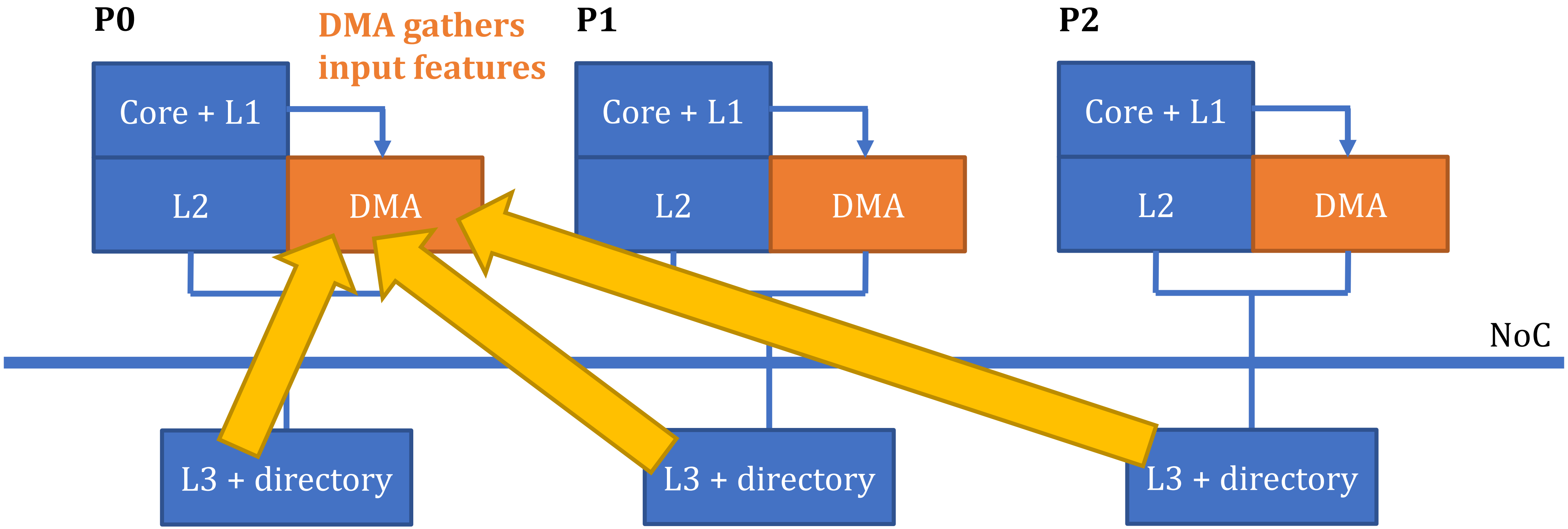
DMA Aggregation



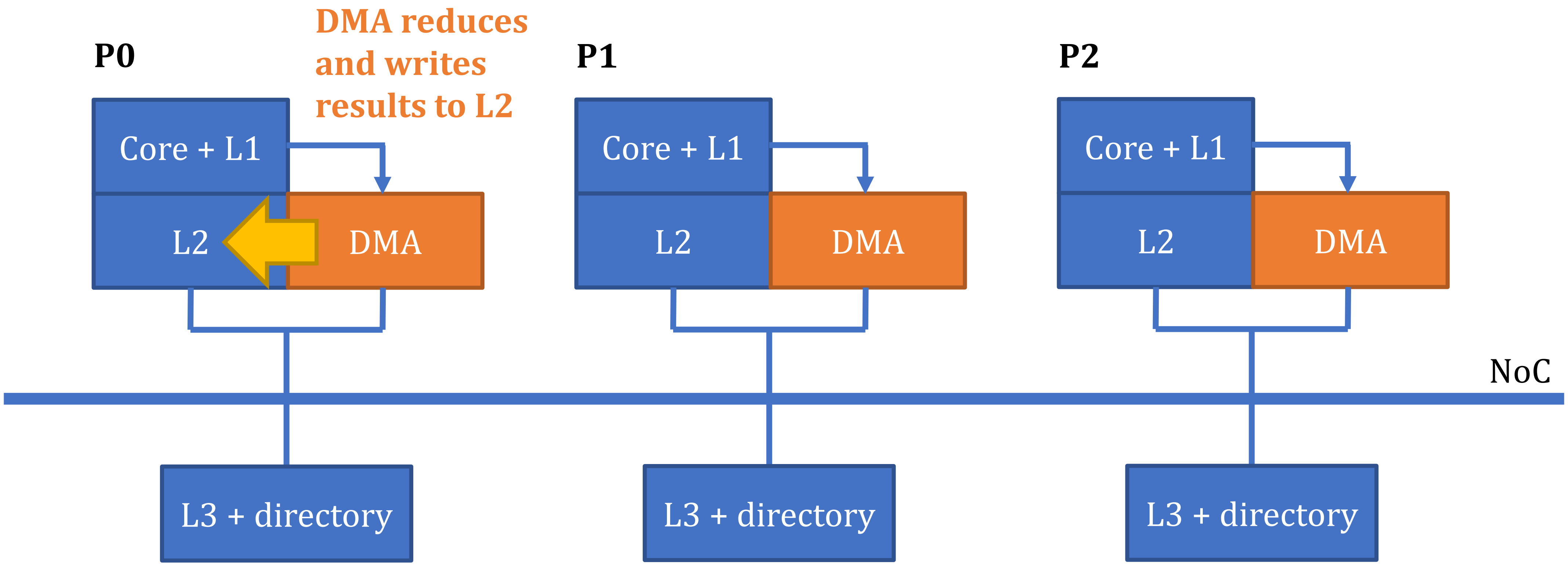
DMA Aggregation



DMA Aggregation

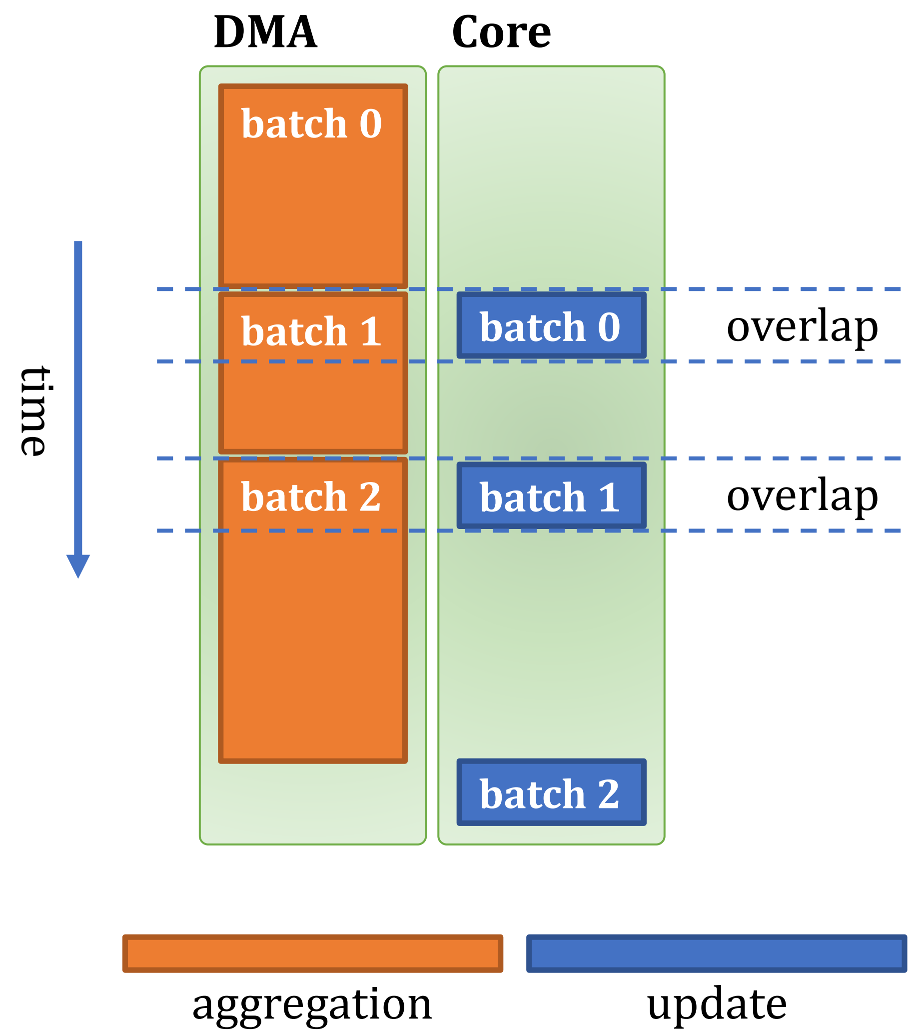


DMA Aggregation



DMA Assisted Layer Fusion

- On each processor:
  - DMA: aggregation
  - Core: update
- The update of a vertex batch overlaps with the aggregation of the next vertex batch

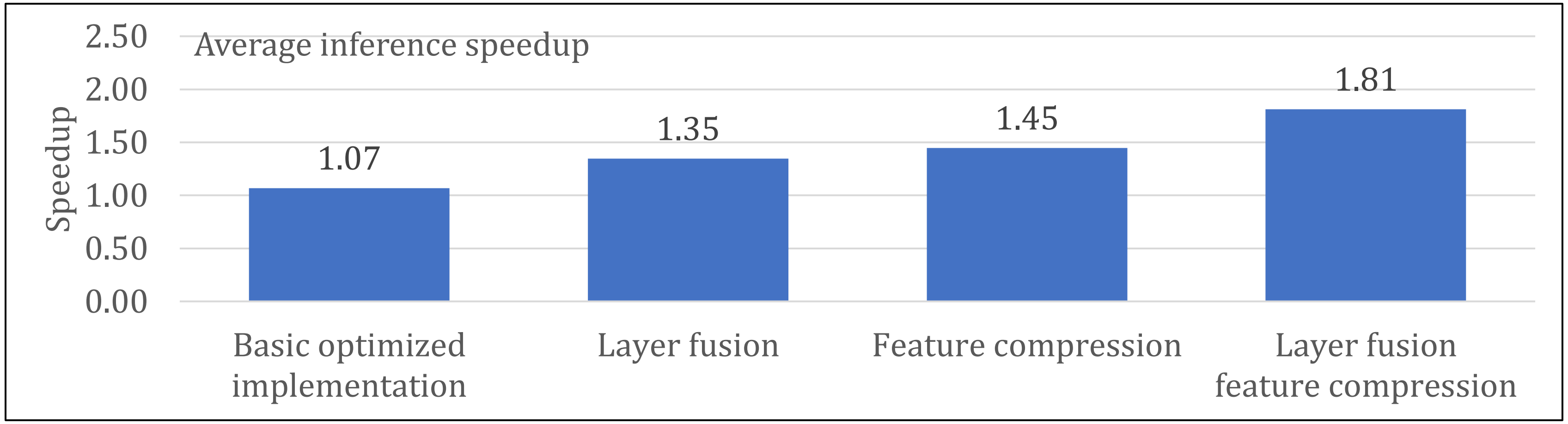


Evaluation Setup

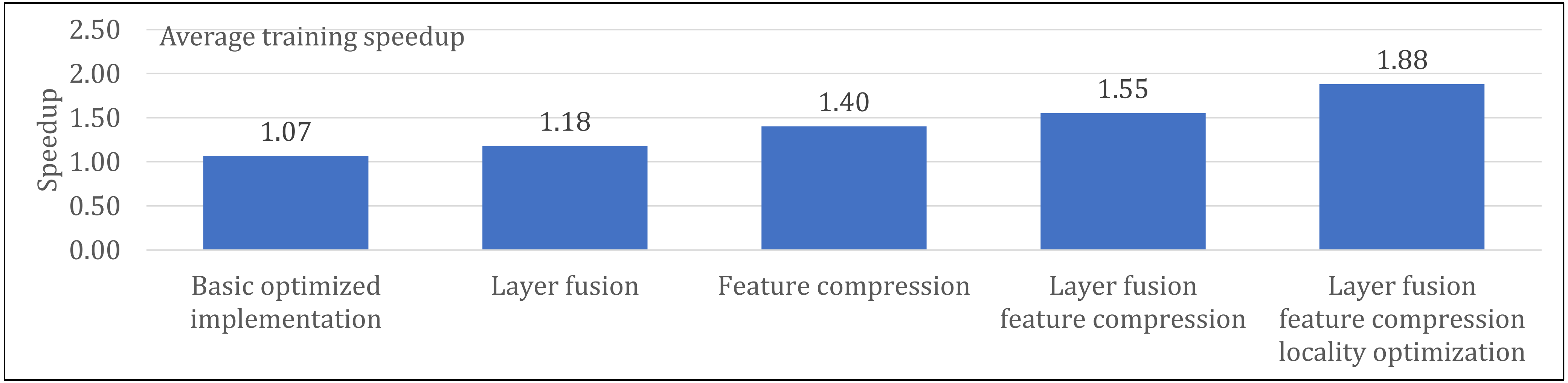
- GNN Models:
  - 3-layer *GCN* and *GraphSAGE*
- Datasets:
  - 4 graphs with 2.5M-111M vertices and 45M-1.6B edges
- Baseline:
  - SOTA SpMM from *DistGNN*[1] + MKL GEMM
- Evaluation:
  - SW-only techniques: 28-core Cascade Lake server running 28 threads
  - HW+SW techniques: *Sniper*[2] multi-core simulator simulating the 28-core server

[1] Vasimuddin Md, et al. 2021. DistGNN: scalable distributed training for large-scale graph neural networks. SC '21
[2] Trevor E. Carlson, et al. 2011. Sniper: Exploring the Level of Abstraction for Scalable and Accurate Parallel Multi-Core Simulations. SC'11

Performance: SW-Only Techniques



- Feature compression @ 50% sparsity
- Locality optimization only on training
- Techniques are synergetic



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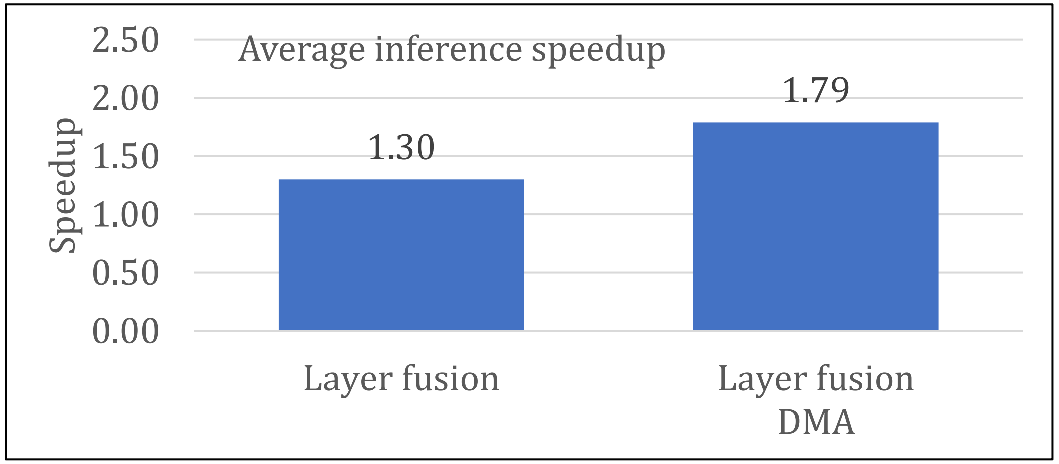
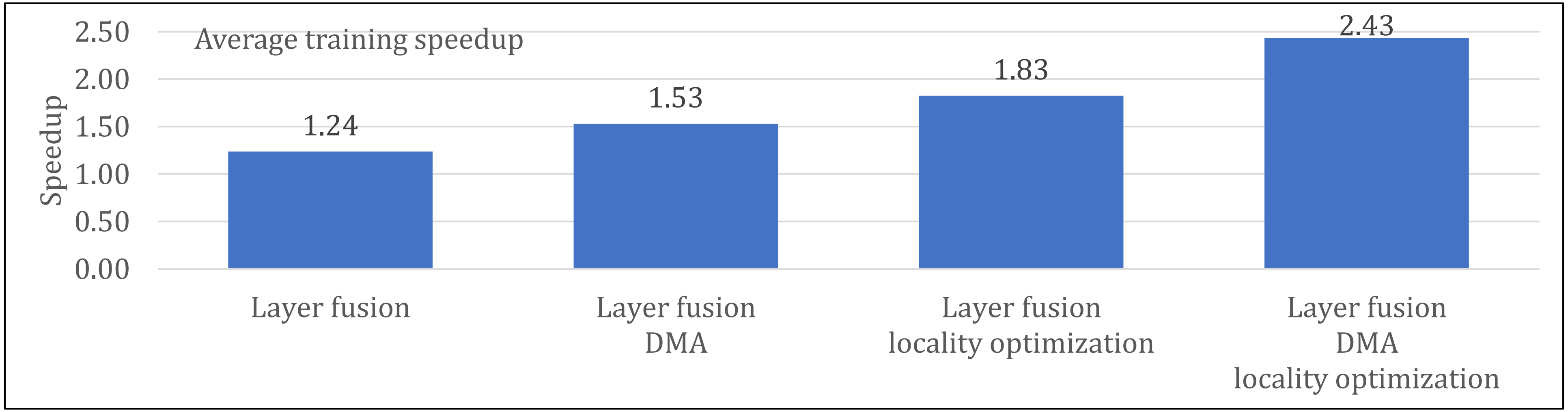
Performance: HW+SW Techniques



- DMA aggregation is incompatible with feature compression
- DMA fusion is more effective than SW-only fusion



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Conclusion

- GNNs on CPUs: memory bandwidth bound
- Graphite alleviates memory pressure by:
  - Fusing layers to overlap compute and memory
  - Compressing features to reduce memory traffic
  - Optimizing the vertex processing order to improve locality
  - Augmenting the DMA engine to offload aggregation
- Evaluated with 28 cores
  - SW-only techniques: inference 1.8x, training 1.9x speedup (native)
  - HW+SW techniques: inference 1.8x, training 2.4x speedup (simulated)

More in the paper:
- Algorithms of the techniques
- DMA descriptor design
- In-depth evaluation of individual techniques
- And more…

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Thanks