# High-Performance Frameworks for Static and Streaming Graph Processing

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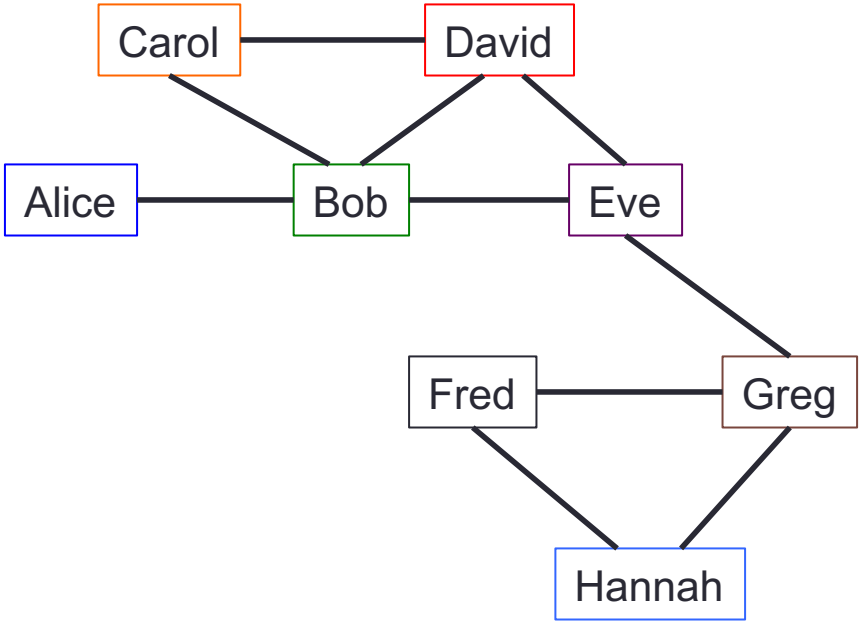
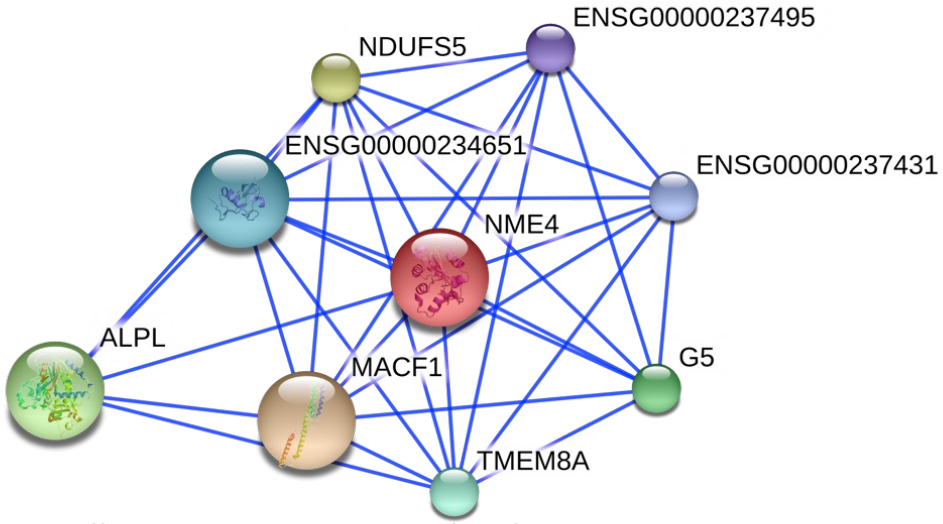
# What is a graph?

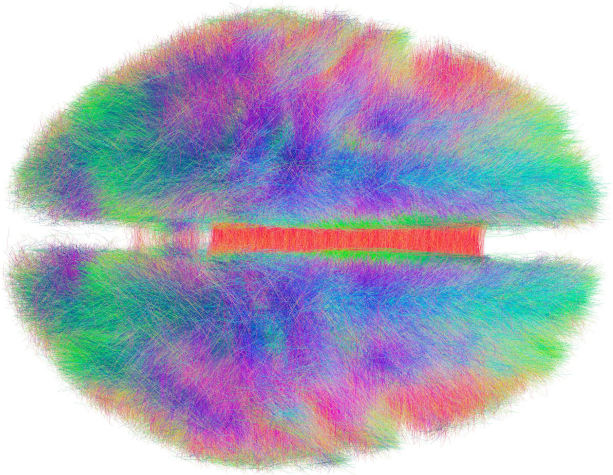

- **Vertices** model objects
- **Edges** model relationships between objects



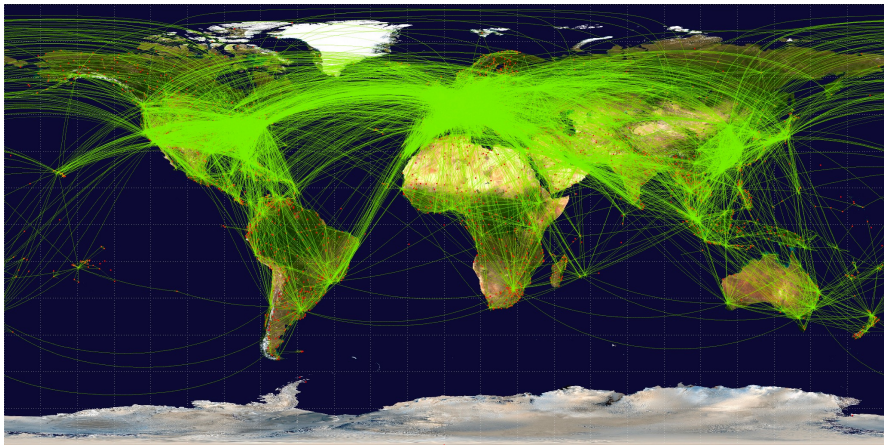




https://commons.wikimedia.org/wiki/File:Protein_Interaction_Network_for_TMEM8A.png

# Graph Applications



Connectomics



Transportation

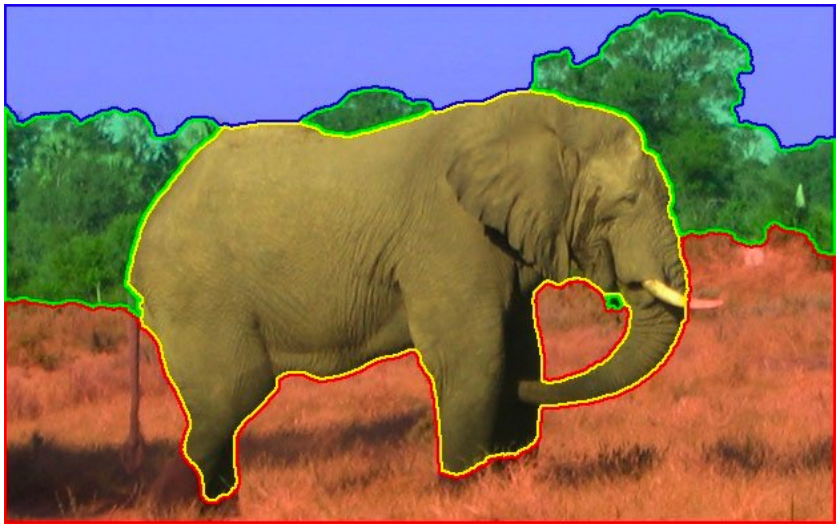
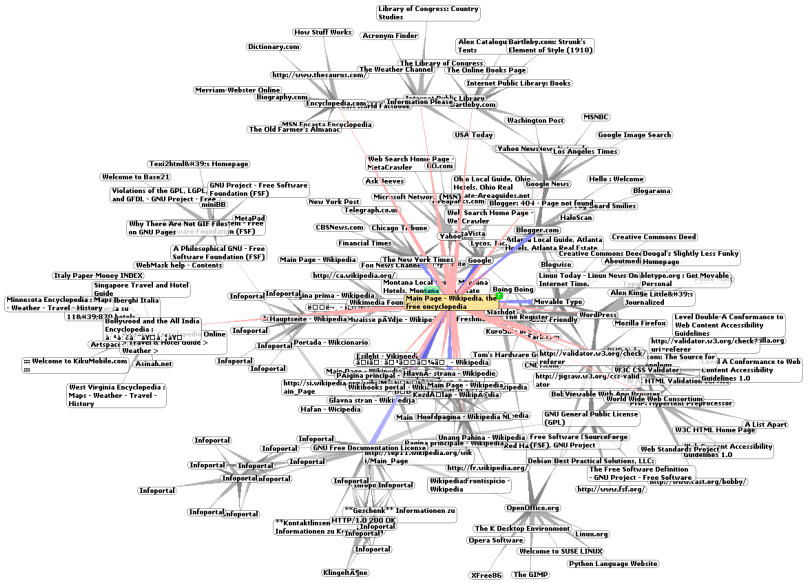


Image Segmentation



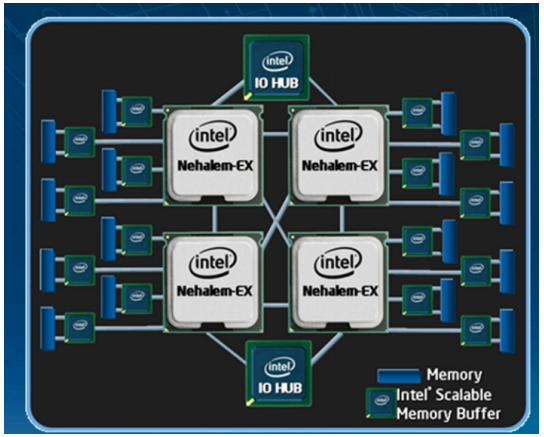
Internet

# Graphs are becoming very large

| | Size | |
|---|---|---|
| Common Crawl | 3.5 billion vertices<br>128 billion edges | *Largest publicly available graph* |
| YAHOO! | 272 billion vertices<br>5.9 trillion edges | *Proprietary graph* |
| Google | > 100 billion vertices<br>6 trillion edges | *Proprietary graph* |

*Need high-performance solutions to analyze graphs in a timely fashion*

# High Performance via Parallelism



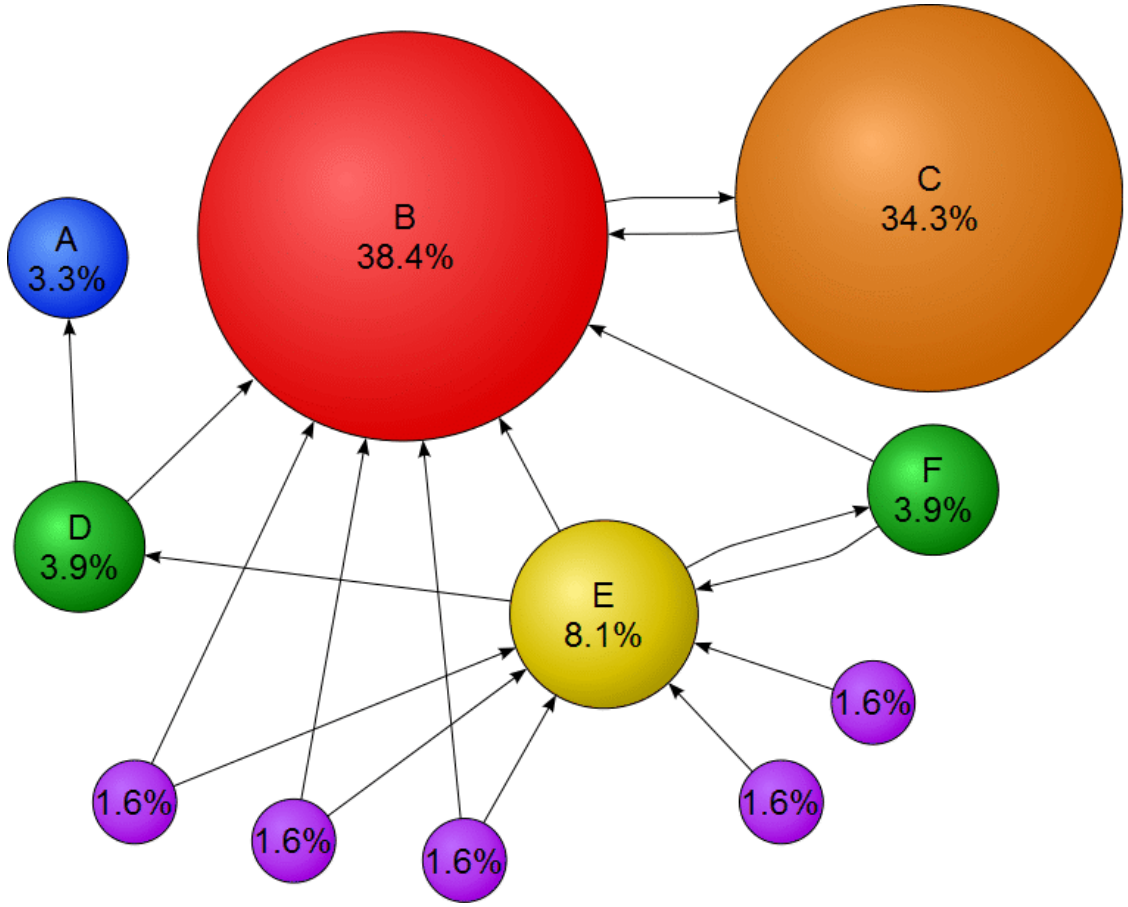

- Need parallel graph algorithms and codes
- Need high-level programming frameworks to enable non-experts to easily write their own parallel graph programs

# Outline

- GraphIt: graph DSL that enables easy exploration of large graph optimization space

- Aspen: streaming graph framework that enables concurrent queries and updates with low latency

# PageRank




$$\mathrm{PR}[v] = \frac{1-\gamma}{|V|} + \gamma \sum_{u \in N^-(v)} \frac{\mathrm{PR}[u]}{deg^+(u)}$$

# Simple PageRank Code in C++

```
void pagerank(Graph &graph, double * new_rank, double * old_rank, int * out_degree, int max_iter){
    for (i = 0; i < max_iter; i++) {
        for (src : graph.vertices()) {
            for (dst : graph.getOutgoingNeighbors(node)) {
                new_rank[dst] += old_rank[src]/out_degree[src]; } }
        for (node : graph.vertices()) {
            new_rank[node] = base_score + damping*new_rank[node]; }
        swap (old_rank, new_rank);
    }
}
```

# High-Performance PageRank Code

```
template<typename APPLY_FUNC>
void edgeset_apply_pull_parallel(Graph &g, APPLY_FUNC apply_func) {
    int64_t numVertices = g.num_nodes(), numEdges = g.num_edges();
    parallel_for(int n = 0; n < numVertices; n++) {
        for (int socketId = 0; socketId < omp_get_num_places(); socketId++) {
            local_new_rank[socketId][n] = new_rank[n]; } }
    int numPlaces = omp_get_num_places();
    int numSegments = g.getNumSegments("s1");
    int segmentsPerSocket = (numSegments + numPlaces - 1) / numPlaces;
        #pragma omp parallel num_threads(numPlaces) proc_bind(spread){
        int socketId = omp_get_place_num();
        for (int i = 0; i < segmentsPerSocket; i++) {
            int segmentId = socketId + i * numPlaces;
            if (segmentId >= numSegments) break;
            auto sg = g.getSegmentedGraph(std::string("s1"), segmentId);
            #pragma omp parallel num_threads(omp_get_place_num_procs(socketId)) proc_bind(close){
                #pragma omp for schedule(dynamic, 1024)
                for (NodeID localId = 0; localId < sg->numVertices; localId++) {
                    NodeID d = sg->graphId[localId];
                    for (int64_t ngh = sg->vertexArray[localId]; ngh < sg->vertexArray[localId + 1]; ngh++) {
                        NodeID s = sg->edgeArray[ngh];
                        local_new_rank[socketId][d] += contrib[s]; }}}}}
    parallel_for(int n = 0; n < numVertices; n++) {
        for (int socketId = 0; socketId < omp_get_num_places(); socketId++) {
            new_rank[n] += local_new_rank[socketId][n]; }}}
struct updateVertex {
    void operator() (NodeID v) {
        double old_score = old_rank[v];
        new_rank[v] = (beta_score + (damp * new_rank[v]));
        error[v] = fabs((new_rank[v] - old_rank[v])) ;
        old_rank[v] = new_rank[v];
        new_rank[v] = ((float) 0) ; }; };
void pagerank(Graph &g, double *new_rank, double *old_rank, int *out_degree, int max_iter) {
    for (int i = (0); i < (max_iter); i++) {
        parallel_for(int v_iter = 0; v_iter < builtin_getVertices(edges); v_iter ++) {
            contrib[v] = (old_rank[v] / out_degree[v]);};
        edgeset_apply_pull_parallel(edges, updateEdge());
        parallel_for(int v_iter = 0; v_iter < builtin_getVertices(edges); v_iter ++) {
            updateVertex()(v_iter); }; }
```

## More than 23x faster

Intel Xeon E5-2695 v3 CPUs with 12 cores each for a total of 24 cores.

**Multi-Threaded**

**Load Balanced**

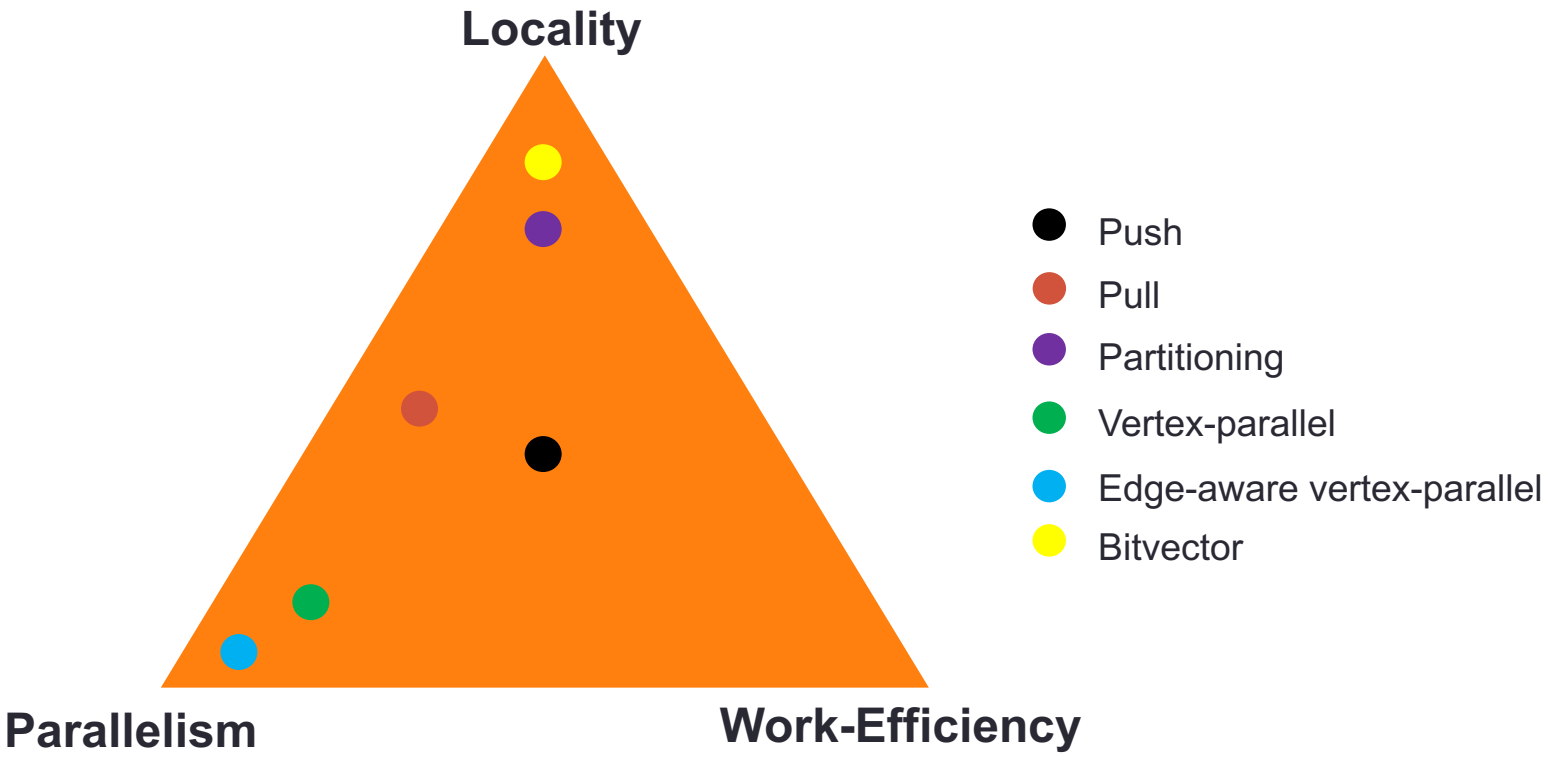
**Cache Optimized**

**NUMA Optimized**

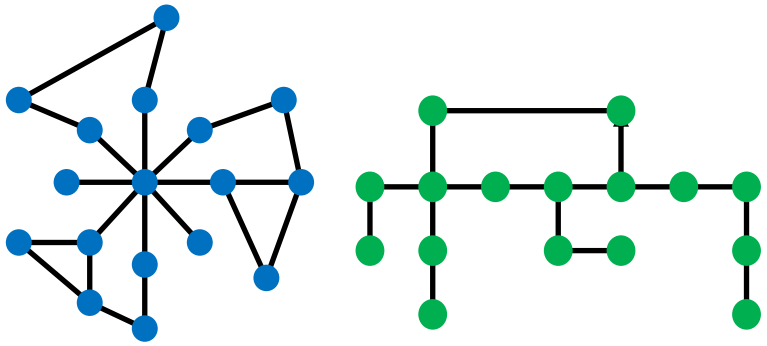
(1) Hard to write correctly

(2) Extremely difficult to experiment with different combinations of optimizations

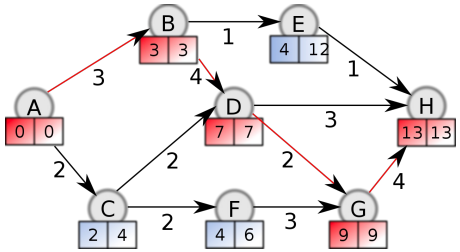
# Graph Optimization Tradeoff Space

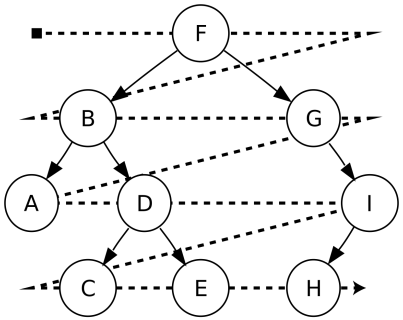


# Graph Optimization Tradeoff Space

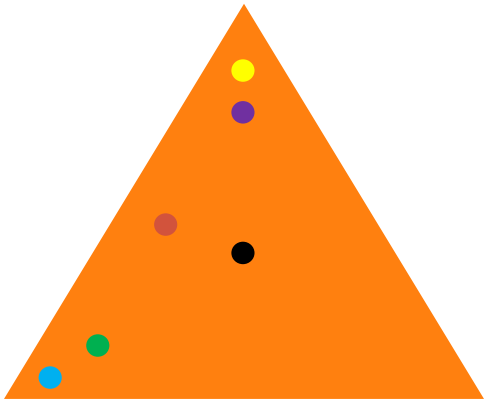


Graphs




Algorithms



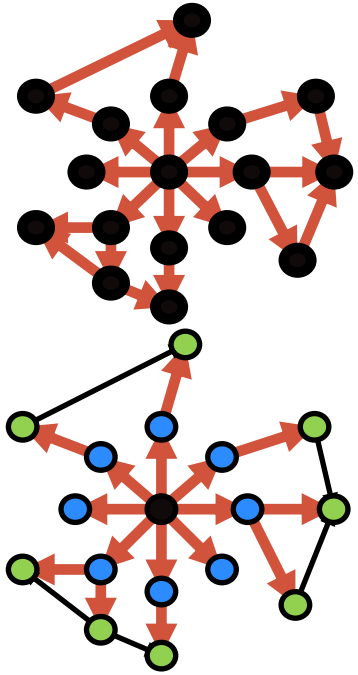
Optimizations

Hardware

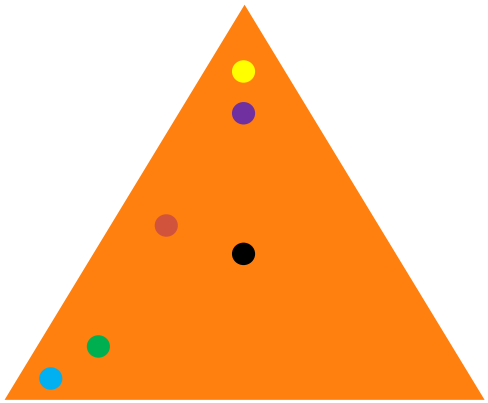
# GraphIt – A Domain-Specific Language for Graph Analytics

- Decouple Algorithm from Optimization
  - Algorithm language: What to compute
  - Optimization (scheduling) language: How to compute
- Compiler will generate optimized code for desired platform
  - Easy to use for programmers to try different combinations of optimizations

# GraphIt – A Domain-Specific Language for Graph Analytics



**Algorithm Language**



**Optimization Representation**

- Scheduling Language
- Schedule Representation (i.e., Graph Iteration Space)
- Compiler

**Autotuner**

# GraphIt Algorithm Language

- Data structures for representing sets of vertices and sets of edges
- Operators
  - Function for mapping computation over a set of vertices
  - Function for mapping computation over edges associated with a set of vertices
- No low-level implementation details (atomics, deduplication) needed
- Exposes plenty of opportunities for optimization

# PageRank in GraphIt

**Algorithm Specification**

```
func updateEdge (src: Vertex, dst: Vertex)
    new_rank[dst] += old_rank[src] / out_degree[src]
end
func updateVertex (v: Vertex)
    new_rank[v] = beta_score + 0.85*new_rank[v];
    old_rank[v] = new_rank[v];
    new_rank[v] = 0;
end
func main()
    for i in 1:max_iter
        #s1# edges.apply(updateEdge);
        vertices.apply(updateVertex);
    end
end
```

# GraphIt Scheduling Language – Schedule 1

**Algorithm Specification**

```
func updateEdge (src: Vertex, dst: Vertex)
    new_rank[dst] += old_rank[src] / out_degree[src]
end
func updateVertex (v: Vertex)
    new_rank[v] = beta_score + 0.85*new_rank[v];
    old_rank[v] = new_rank[v];
    new_rank[v] = 0;
end
func main()
    for i in 1:max_iter
        #s1# edges.apply(updateEdge);
        vertices.apply(updateVertex);
    end
end
```

**Pseudo Generated Code**

```
double * new_rank = new double[num_verts];
double * old_rank = new double[num_verts];
int * out_degree = new int[num_verts];

…

for (NodeID src : vertices) {
  for(NodeID dst : G.getOutNgh(src)){
     new_rank[dst]  +=  old_rank[src] / out_degree[src];
   }
}

….
```

**Scheduling Functions**

```
schedule:
  program->configApplyDirection("s1", "SparsePush");
```

# GraphIt Scheduling Language – Schedule 2

**Algorithm Specification**

```
func updateEdge (src: Vertex, dst: Vertex)
    new_rank[dst] += old_rank[src] / out_degree[src]
end
func updateVertex (v: Vertex)
    new_rank[v] = beta_score + 0.85*new_rank[v];
    old_rank[v] = new_rank[v];
    new_rank[v] = 0;
end
func main()
    for i in 1:max_iter
        #s1# edges.apply(updateEdge);
        vertices.apply(updateVertex);
    end
end
```

**Pseudo Generated Code**

```
double * new_rank = new double[num_verts];
double * old_rank = new double[num_verts];
int * out_degree = new int[num_verts];

…

parallel_for (NodeID src : vertices) {
  for(NodeID dst : G.getOutNgh(src)){
      atomic_add (new_rank[dst],
          old_rank[src] / out_degree[src] );
   }
}

….
```

**Scheduling Functions**

```
schedule:
  program->configApplyDirection("s1", "SparsePush");
  program->configApplyParallelization("s1", "dynamic-vertex-parallel");
```

# GraphIt Scheduling Language – Schedule 3

**Algorithm Specification**

```
func updateEdge (src: Vertex, dst: Vertex)
    new_rank[dst] += old_rank[src] / out_degree[src]
end
func updateVertex (v: Vertex)
    new_rank[v] = beta_score + 0.85*new_rank[v];
    old_rank[v] = new_rank[v];
    new_rank[v] = 0;
end
func main()
    for i in 1:max_iter
        #s1# edges.apply(updateEdge);
        vertices.apply(updateVertex);
    end
end
```

**Pseudo Generated Code**

```
double * new_rank = new double[num_verts];
double * old_rank = new double[num_verts];
int * out_degree = new int[num_verts];

…

parallel_for (NodeID dst : vertices) {
  for(NodeID src : G.getInNgh(dst)){
     new_rank[dst]  += old_rank[src] / out_degree[src];
   }
}

….
```

**Scheduling Functions**

```
schedule:
  program->configApplyDirection("s1", "DensePull");
  program->configApplyParallelization("s1", "dynamic-vertex-parallel");
```

# GraphIt Scheduling Language – Schedule 4

**Algorithm Specification**

```
func updateEdge (src: Vertex, dst: Vertex)
    new_rank[dst] += old_rank[src] / out_degree[src]
end
func updateVertex (v: Vertex)
    new_rank[v] = beta_score + 0.85*new_rank[v];
    old_rank[v] = new_rank[v];
    new_rank[v] = 0;
end
func main()
    for i in 1:max_iter
        #s1# edges.apply(updateEdge);
        vertices.apply(updateVertex);
    end
end
```

**Pseudo Generated Code**

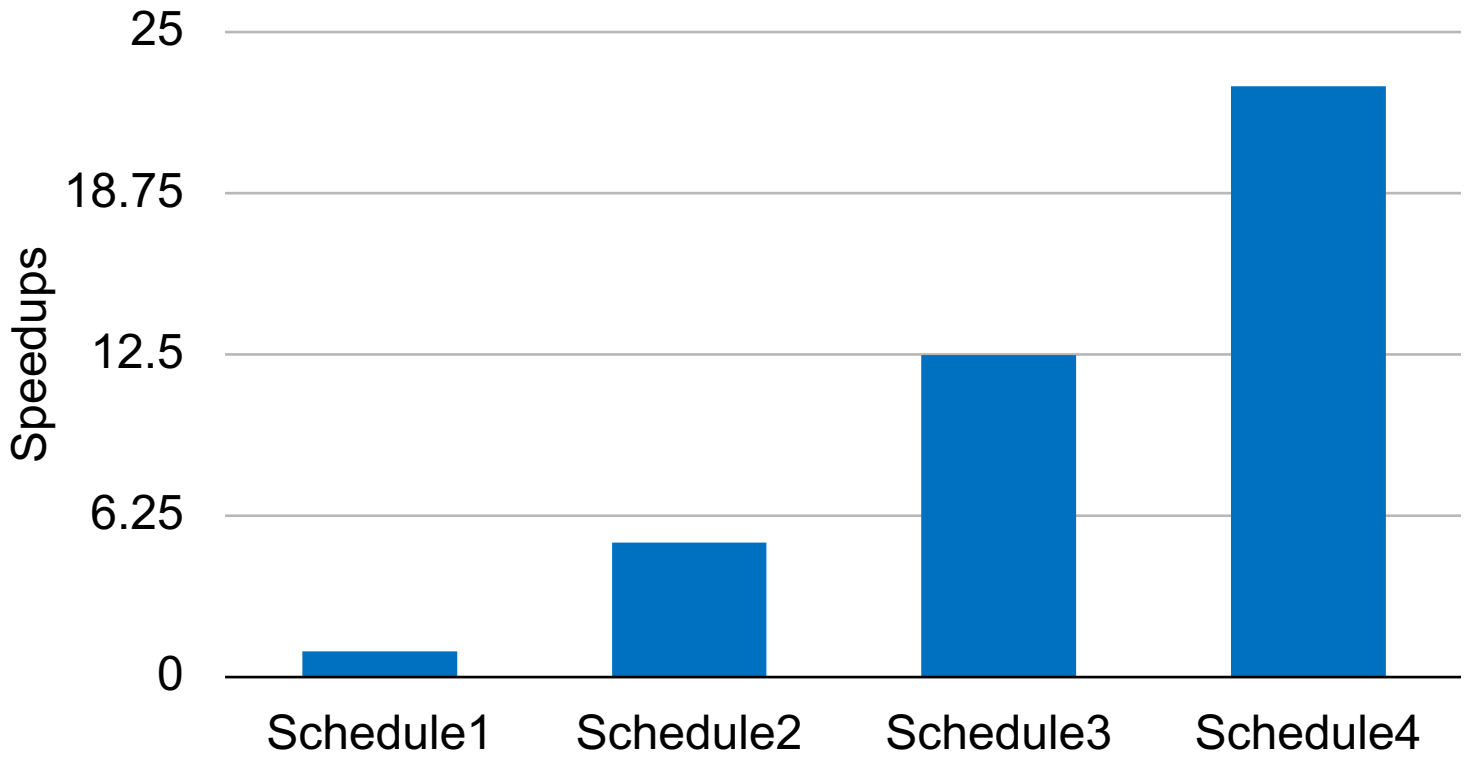
```
double * new_rank = new double[num_verts];
double * old_rank = new double[num_verts];
int * out_degree = new int[num_verts];

…
for (Subgraph sg : G.subgraphs) {
  parallel_for (NodeID dst : vertices) {
    for(NodeID src : G.getInNgh(dst)){
     new_rank[dst]  += old_rank[src] / out_degree[src];
    }
  }
}
….
```

**Scheduling Functions**

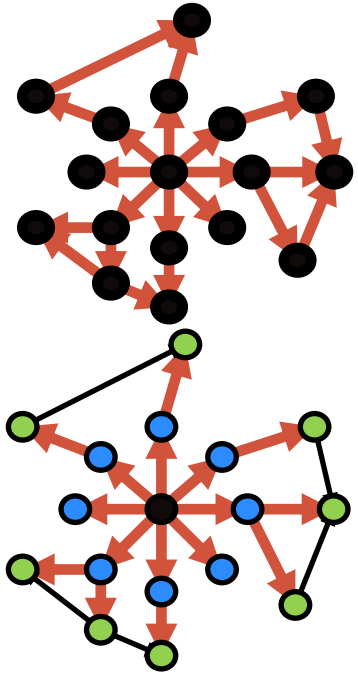
```
schedule:
  program->configApplyDirection("s1", "DensePull");
  program->configApplyParallelization("s1", "dynamic-vertex-parallel");
  program->configApplyNumSSG("s1", "fixed-vertex-count", 10);
```

# Speedups of Schedules

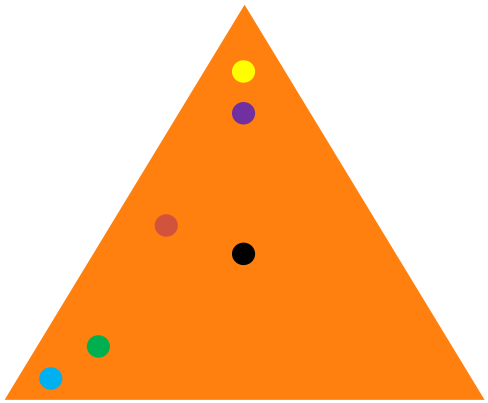



Twitter graph with 41M vertices and 1.5B edges
Intel Xeon E5-2695 v3 CPUs with 12 cores each for a total of 24 cores

# GraphIt – A Domain-Specific Language for Graph Analytics



**Algorithm Language**



**Optimization Representation**

- Scheduling Language
- Schedule Representation (i.e., Graph Iteration Space)
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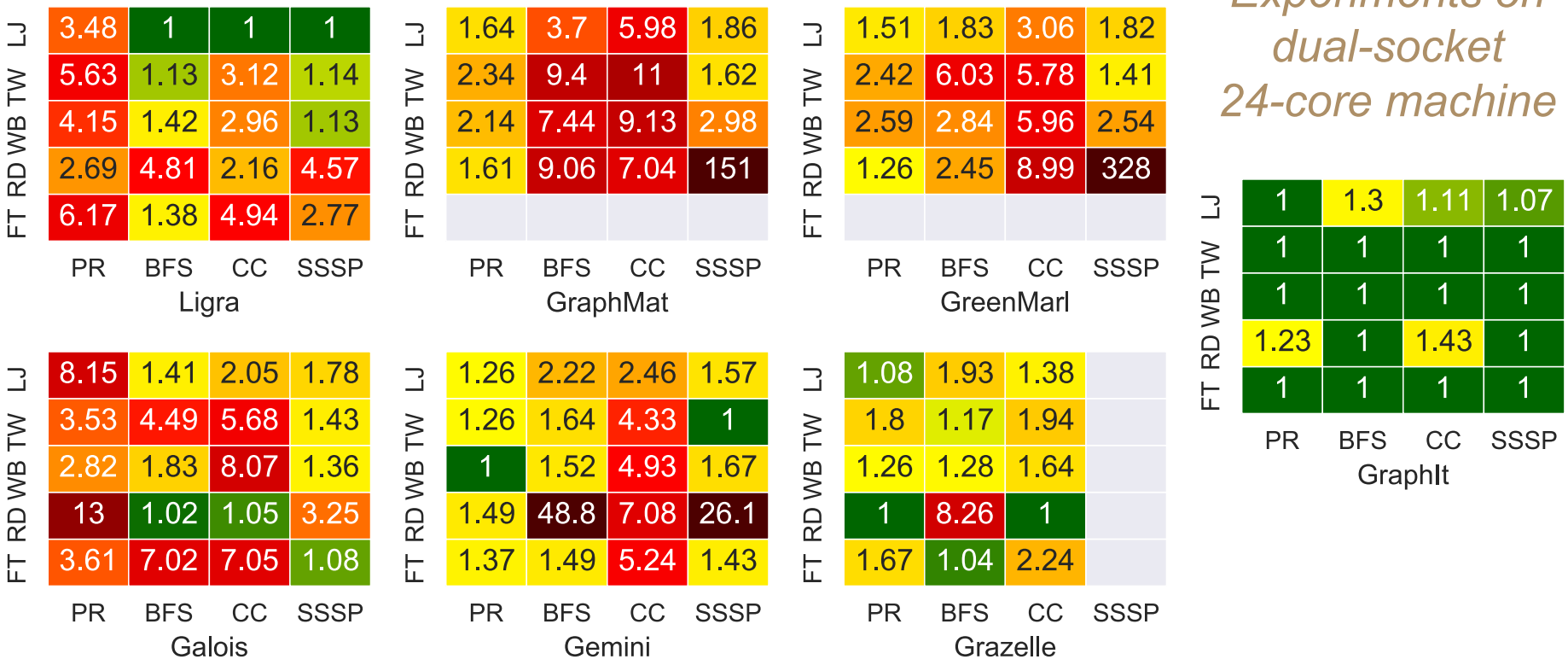
**Autotuner**

# Multicore GraphIt Performance Results

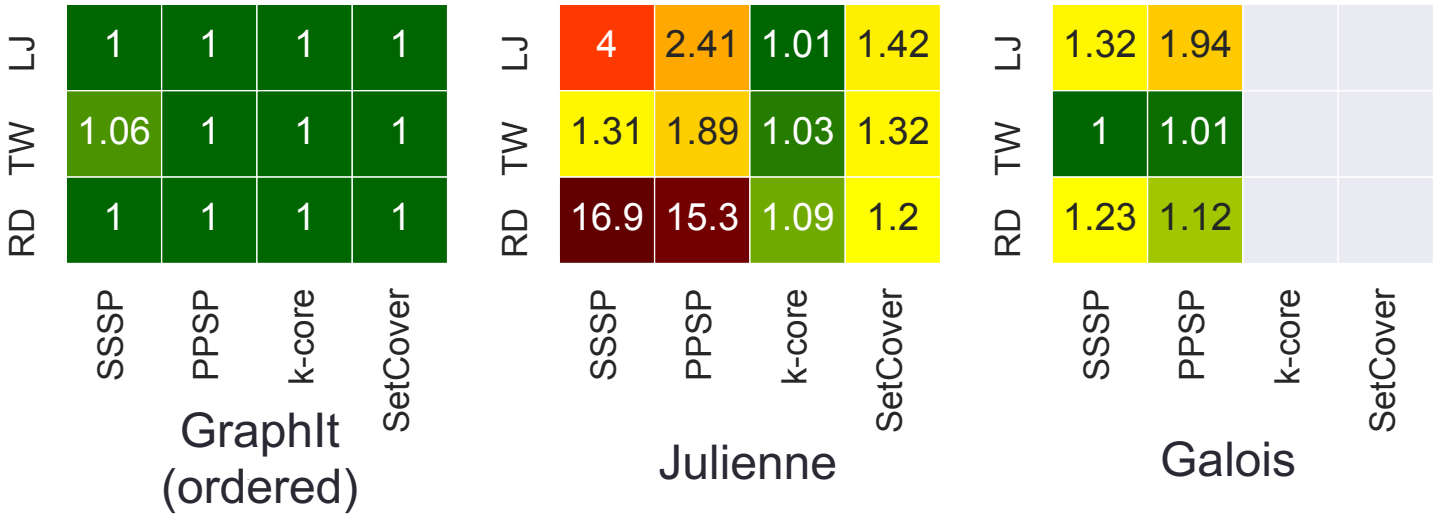
*Experiments on dual-socket 24-core machine*




- Slowdowns compared to fastest implementation (lower is better)
- By exploring orders of magnitude more schedules, GraphIt is able to achieve the best performance in most cases (up to 4.8x faster)
- By using a compiler approach, global optimizations (e.g., data structure transformation and kernel fusion) can easily be applied

# Ordered Graph Algorithms

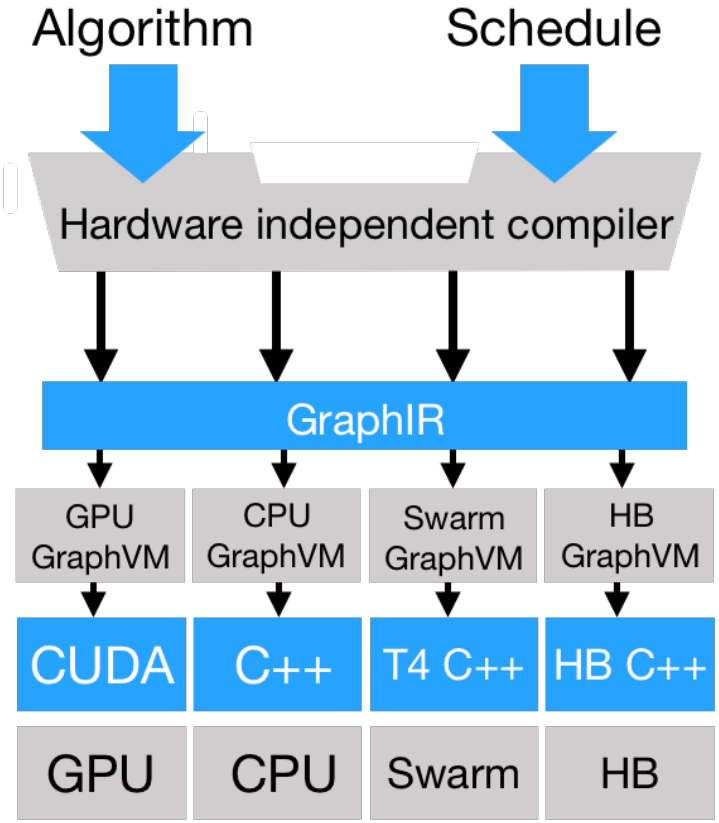
- Original GraphIt was designed for **unordered** graph algorithms, where vertices can be executed in any order per iteration
- **Ordered** graph algorithms, where priorities of vertices change dynamically, can achieve better work-efficiency
- We have extended GraphIt's algorithm and scheduling language to support ordered graph algorithms




*Experiments on dual-socket 24-core machine*

- Up to 2x faster than Galois and 17x faster than Julienne

# Achieving Portability with GraphIR




- **GraphIR** consists of hardware-independent compiler passes
- Extensible to new hardware backends (**GraphVMs**)
- GraphVMs have their own scheduling languages inherited from a base scheduling language

# Outline

- GraphIt: graph DSL that enables easy exploration of large graph optimization space

- **Aspen: streaming graph framework that enables concurrent queries and updates with low latency**

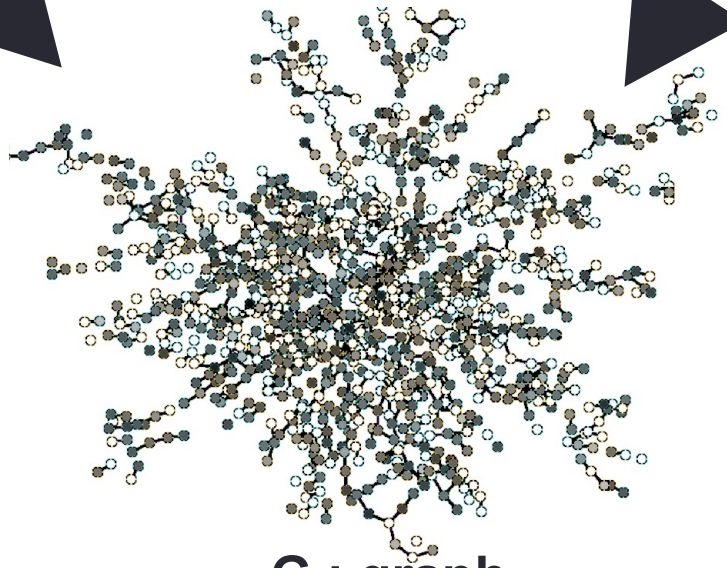
# Streaming Graph Processing

...

...
insert($e_4$)

delete($e_3$)
insert($e_2$)
insert($e_1$)

**Update Stream**



**G : graph**

...

ClusteringCoefficient(v)

Connectivity(G)

Reachable(u—>v)?

**Query Stream**

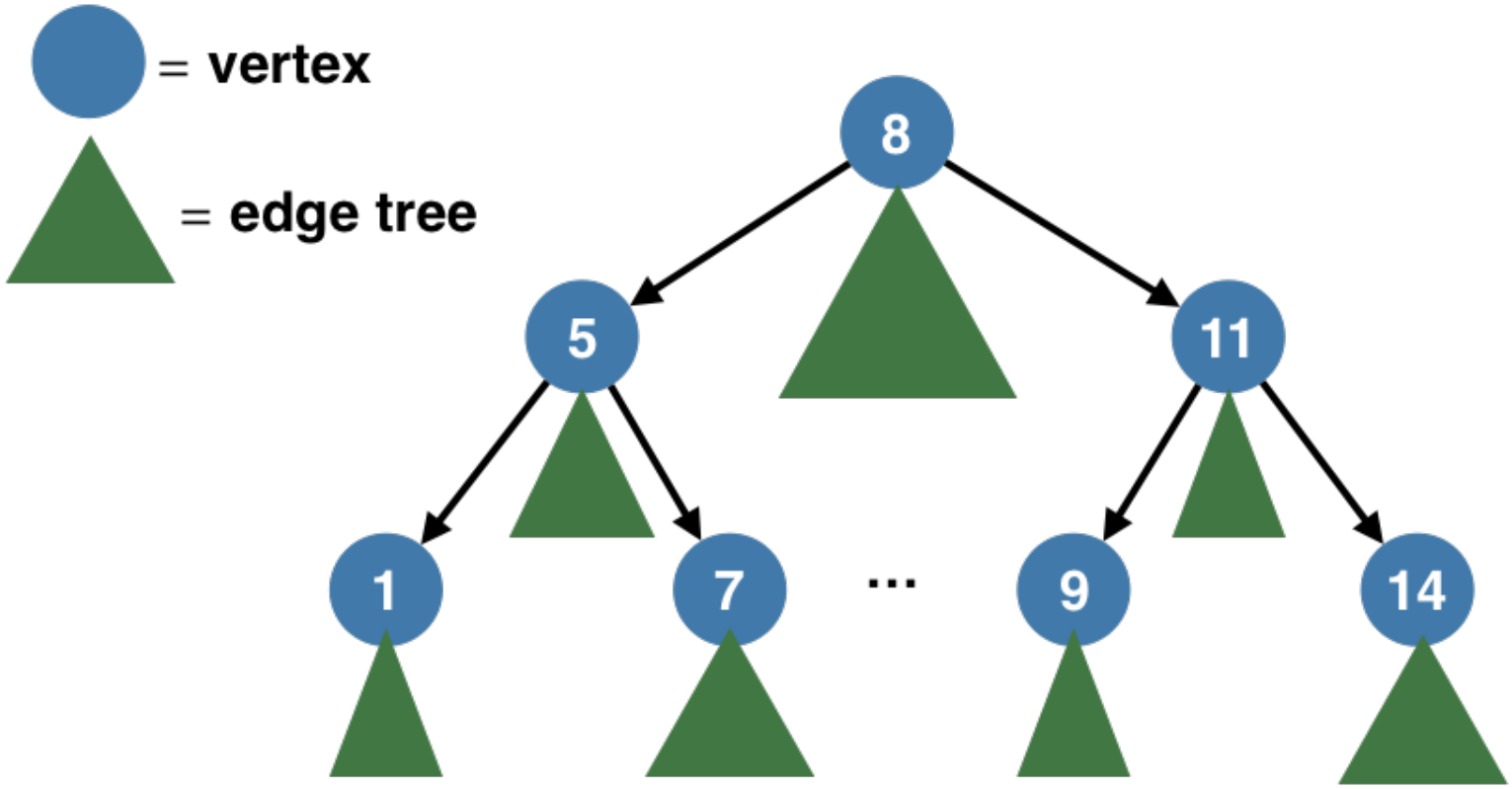
**Goals: Serializability for updates/queries, achieve low latency and high throughput**

# Existing Work

- Single Version Systems
  - Maintain a **single** version of the graph
  - Common approach in graph streaming (e.g., STINGER, cuSTINGER, and KickStarter)
  - Need to separate queries from updates for serializability
- Multi-Version Systems
  - Support multiple graph snapshots (e.g., LLAMA, Kineograph, and some graph databases)
  - Snapshots are not space-efficient and lead to high latency
- **Aspen** uses lightweight snapshots to enable low-latency concurrent queries and updates

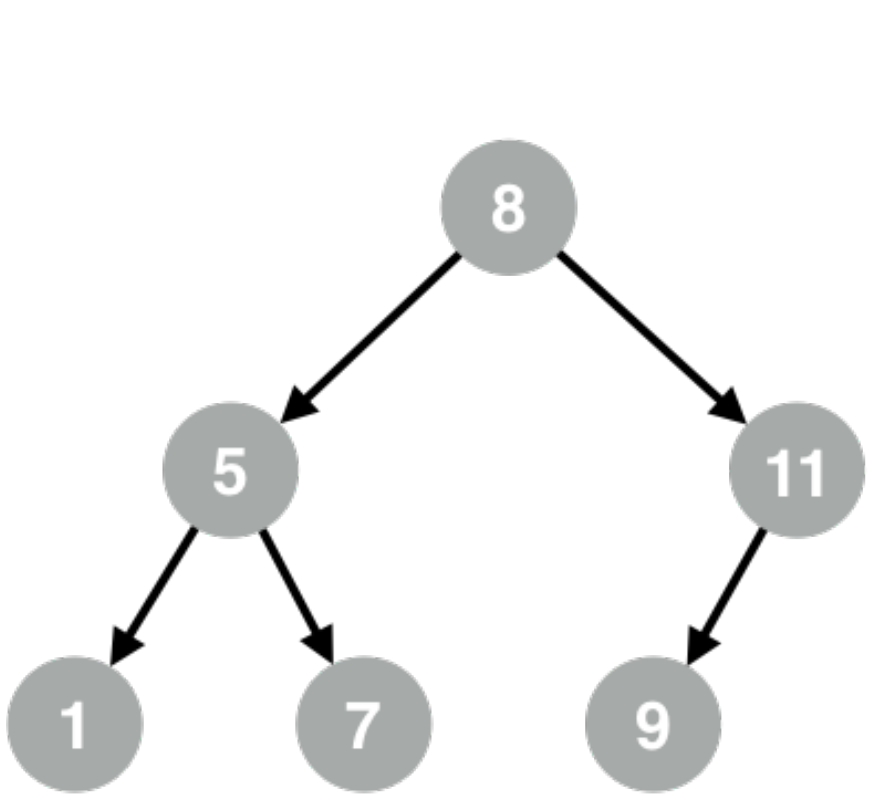
# Graphs Using Purely Functional Trees

- Purely functional trees can be updated efficiently (in logarithmic time/space) while retaining old copy of tree
- Aspen uses tree of **vertices**, where each vertex stores a tree of its incident **edges**



# Updates via Path Copying

- Easy to generate new versions via path copying



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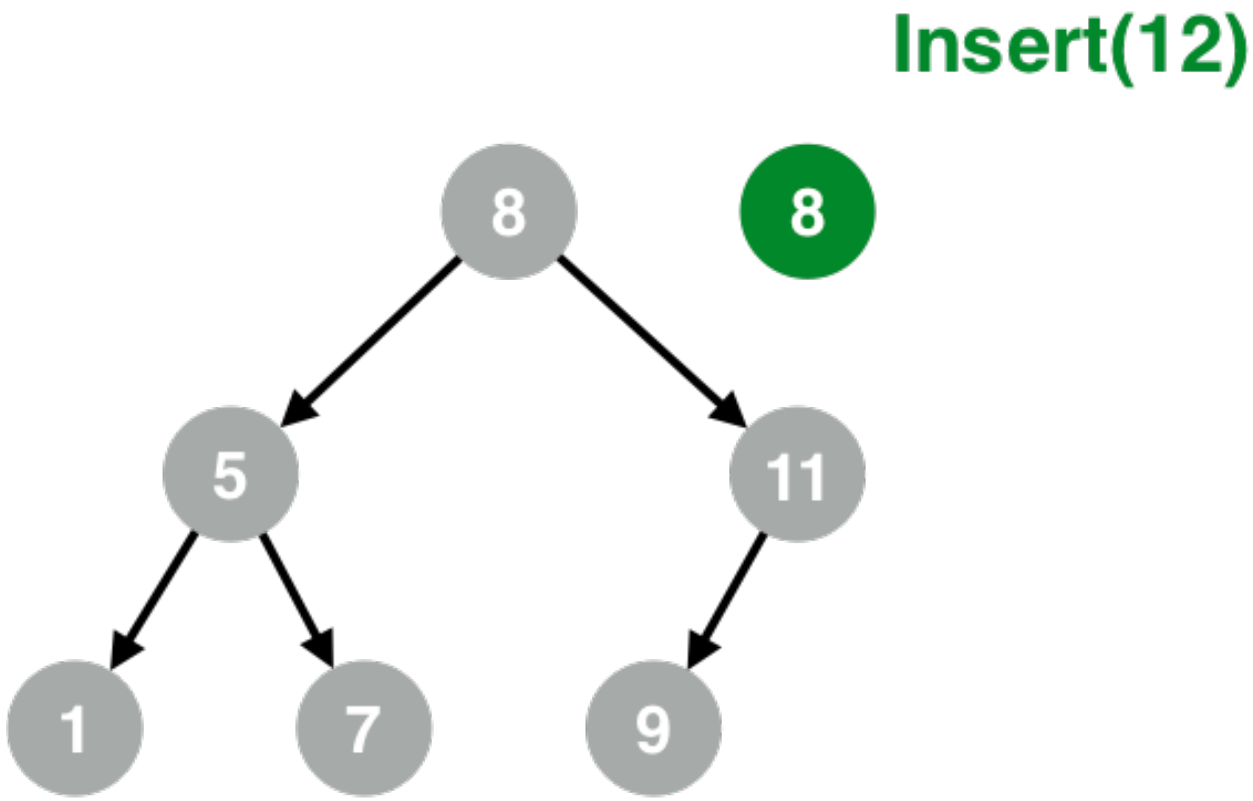

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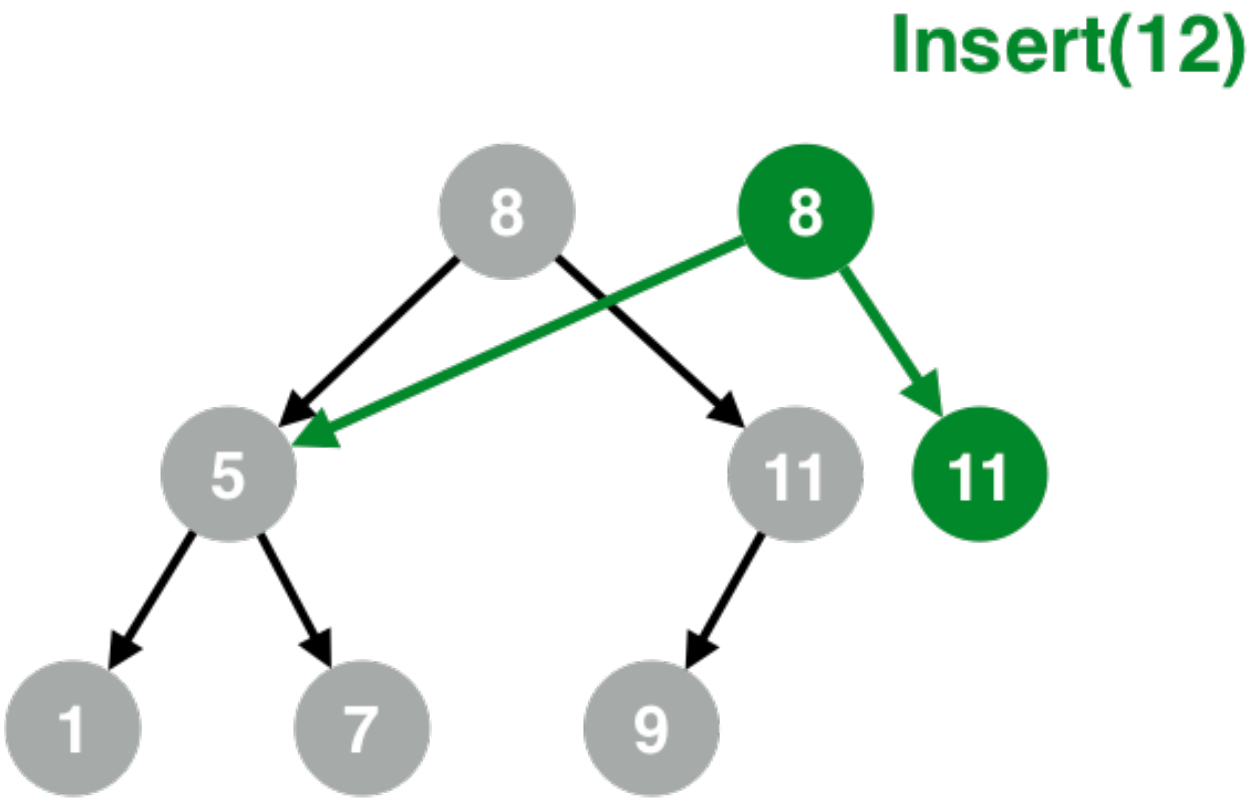

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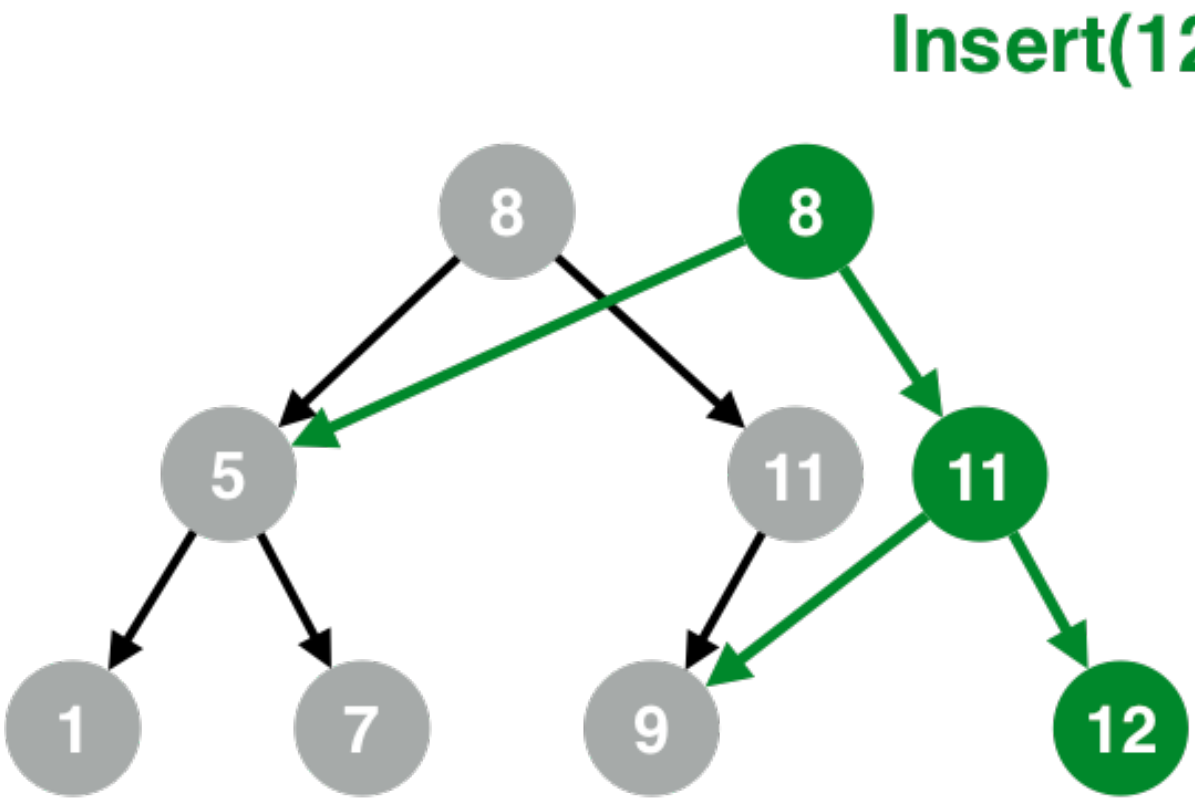
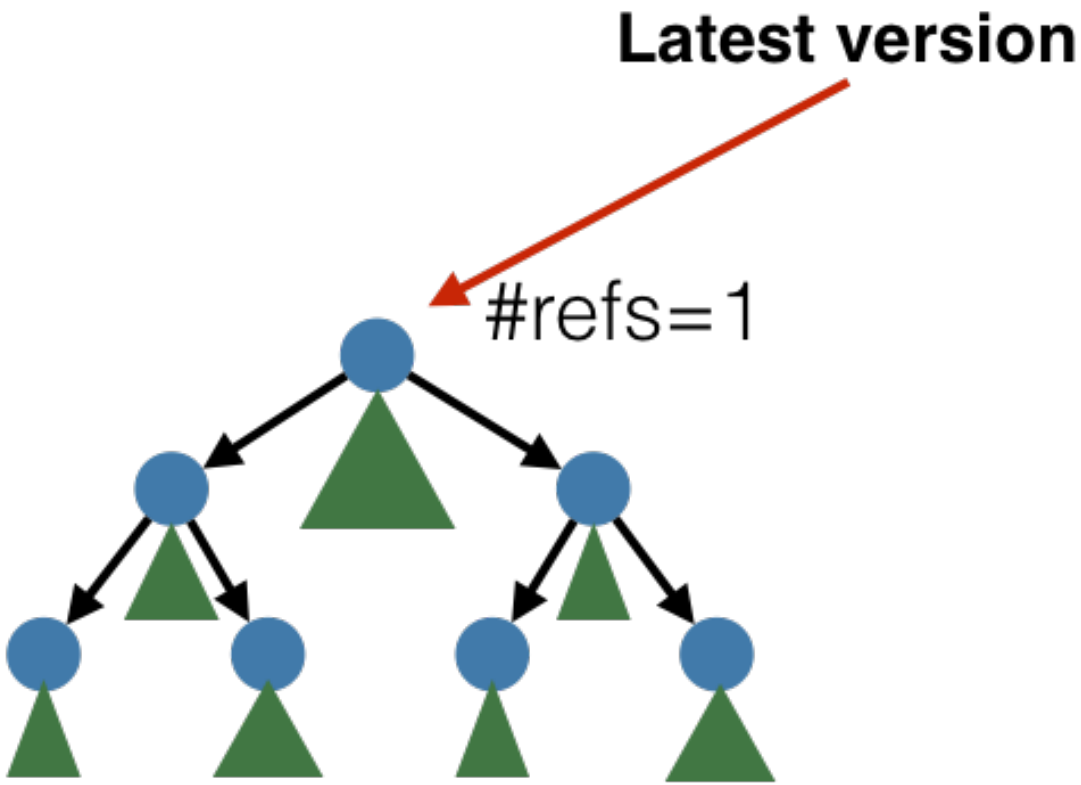


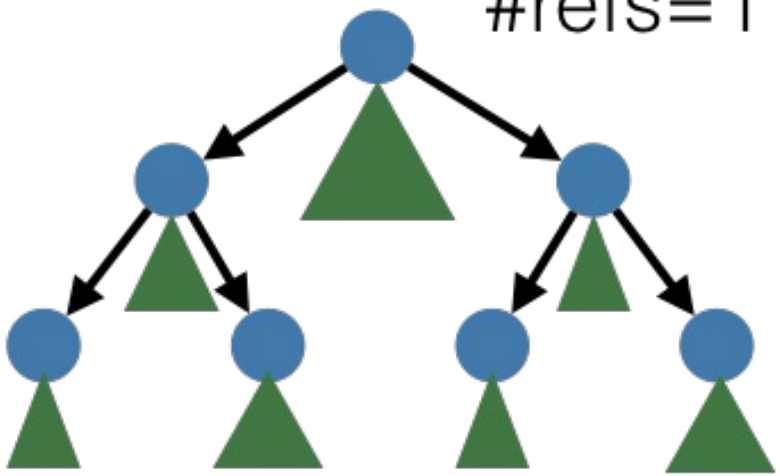
# Immutability Enables Concurrency



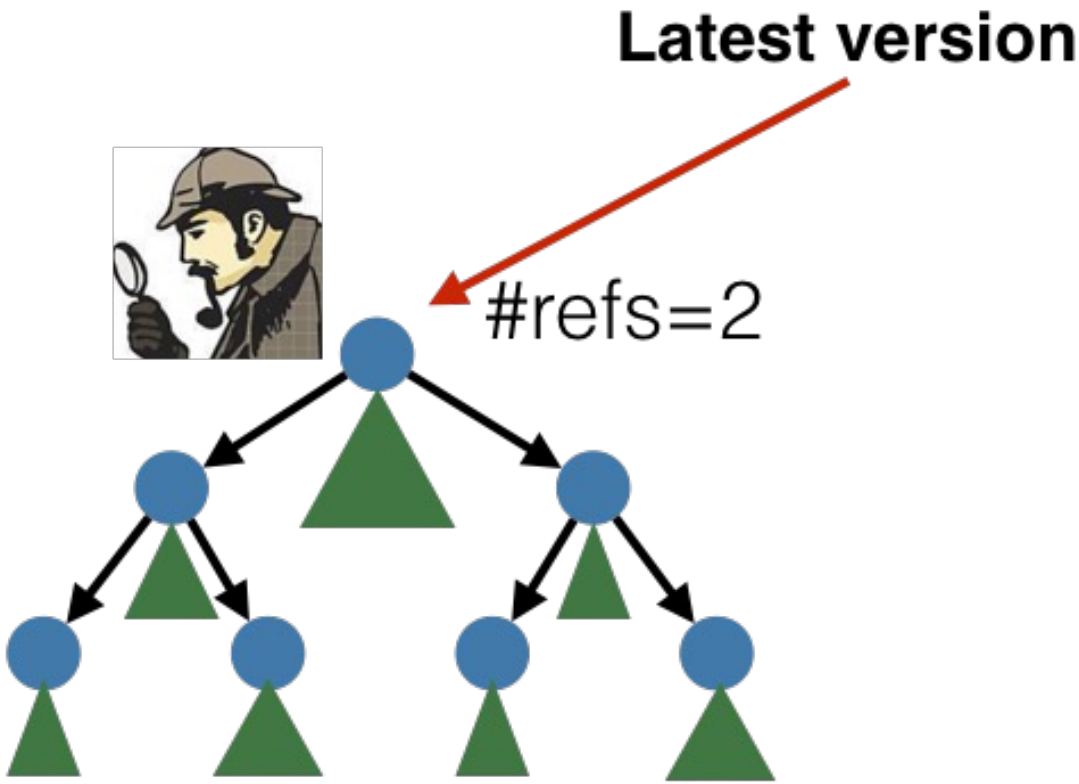
# Immutability Enables Concurrency

**Latest version**

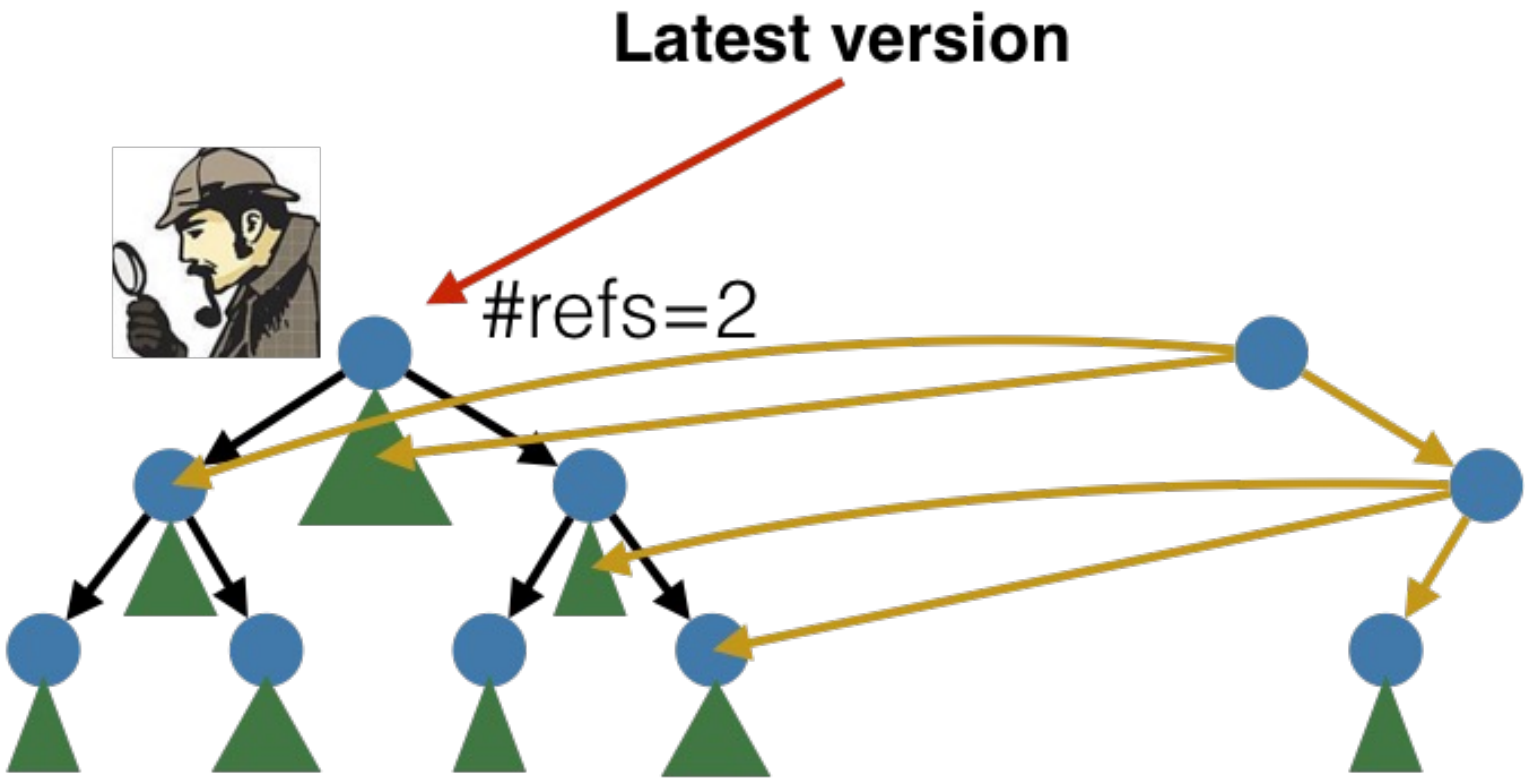
#refs=1



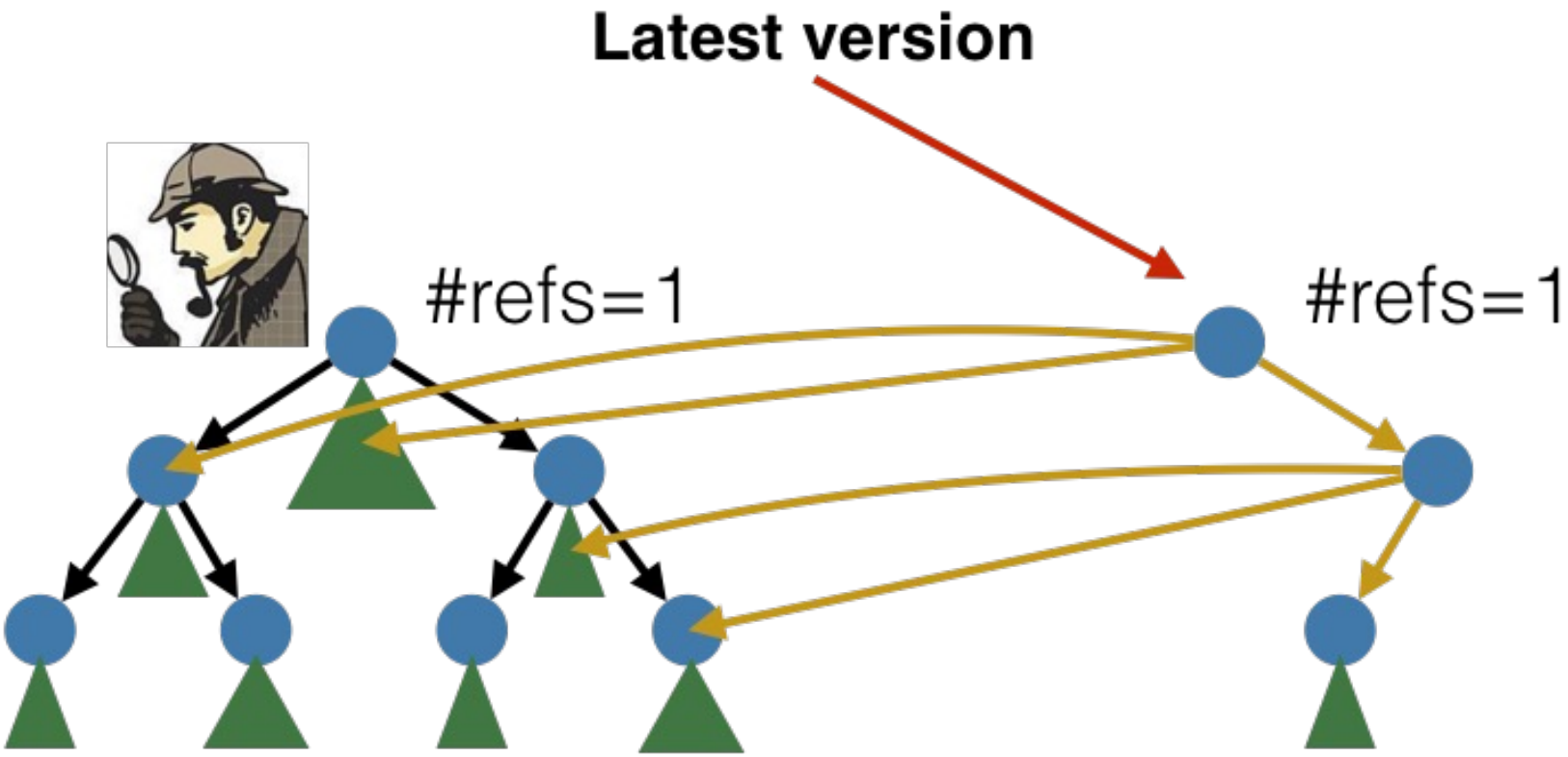
# Immutability Enables Concurrency



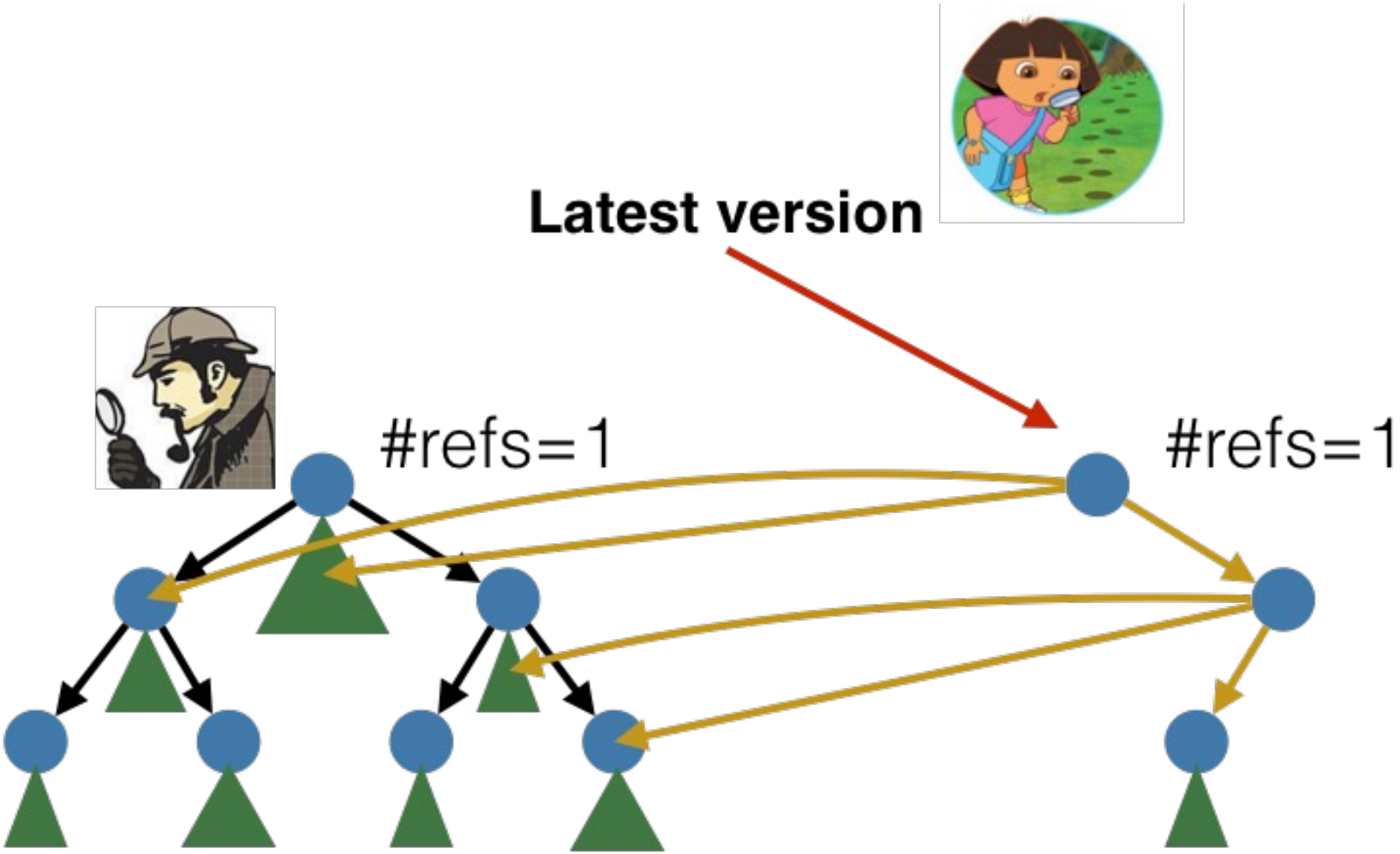
# Immutability Enables Concurrency



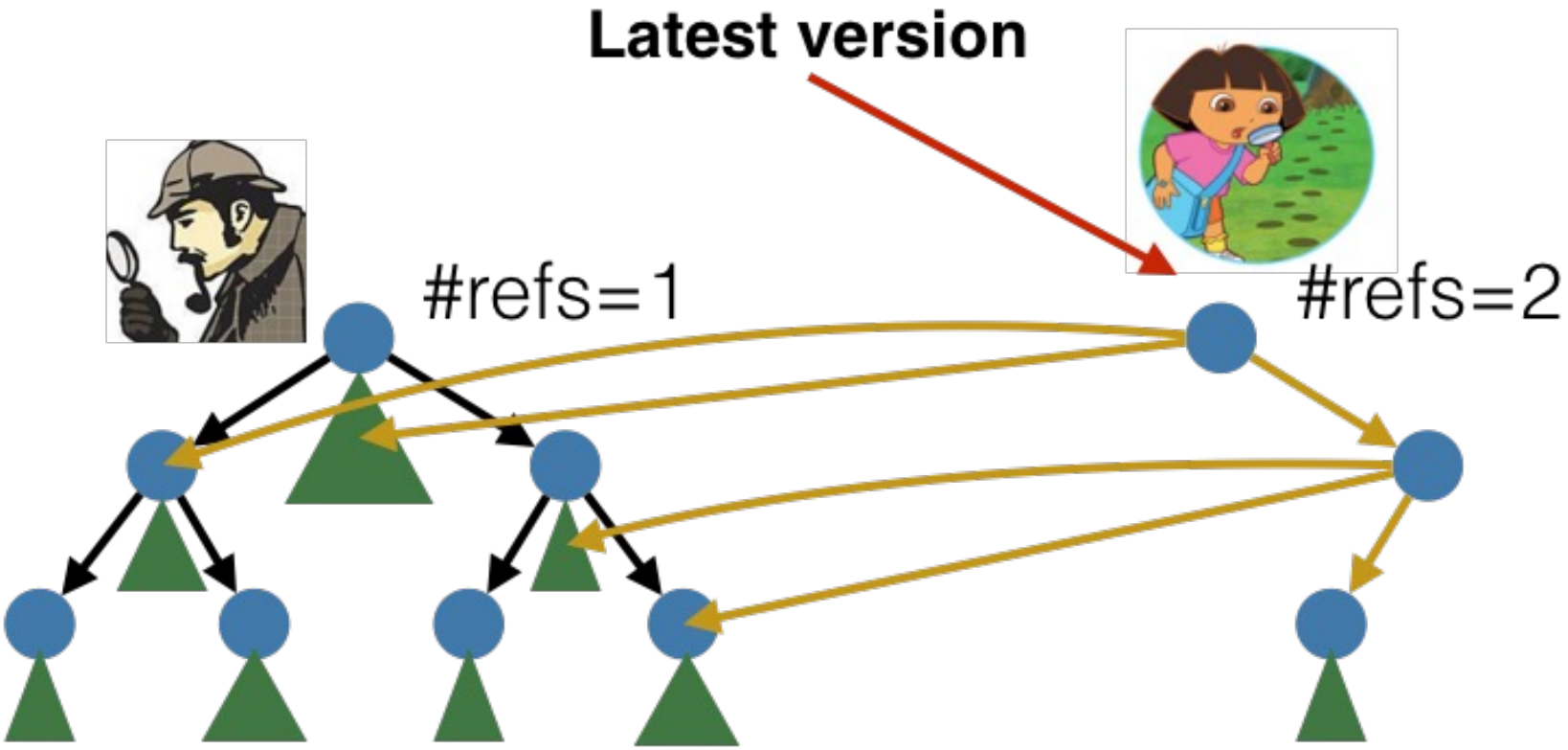
# Immutability Enables Concurrency



# Immutability Enables Concurrency

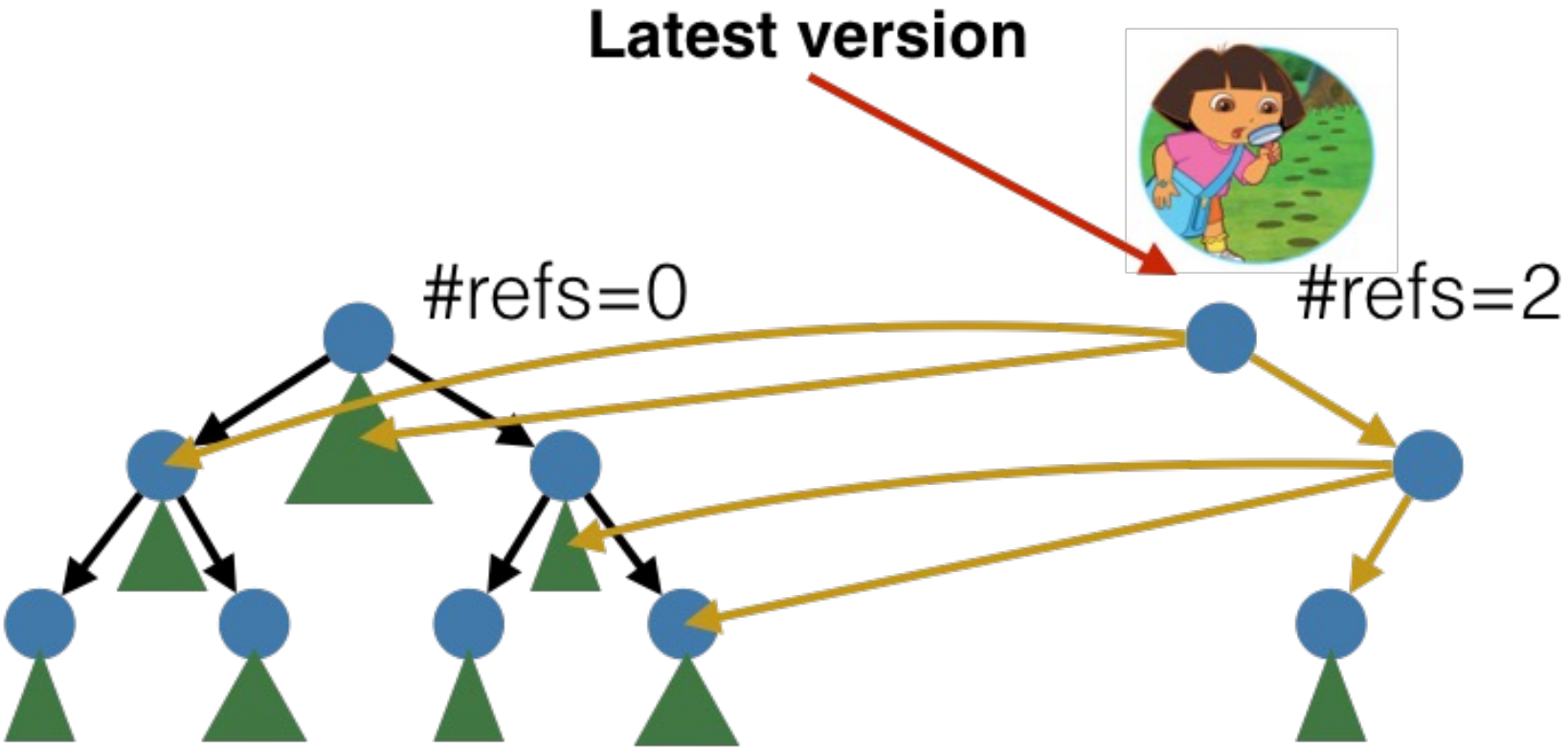


# Immutability Enables Concurrency



# Immutability Enables Concurrency

*Garbage collect all tree nodes whose reference count is decremented to 0*

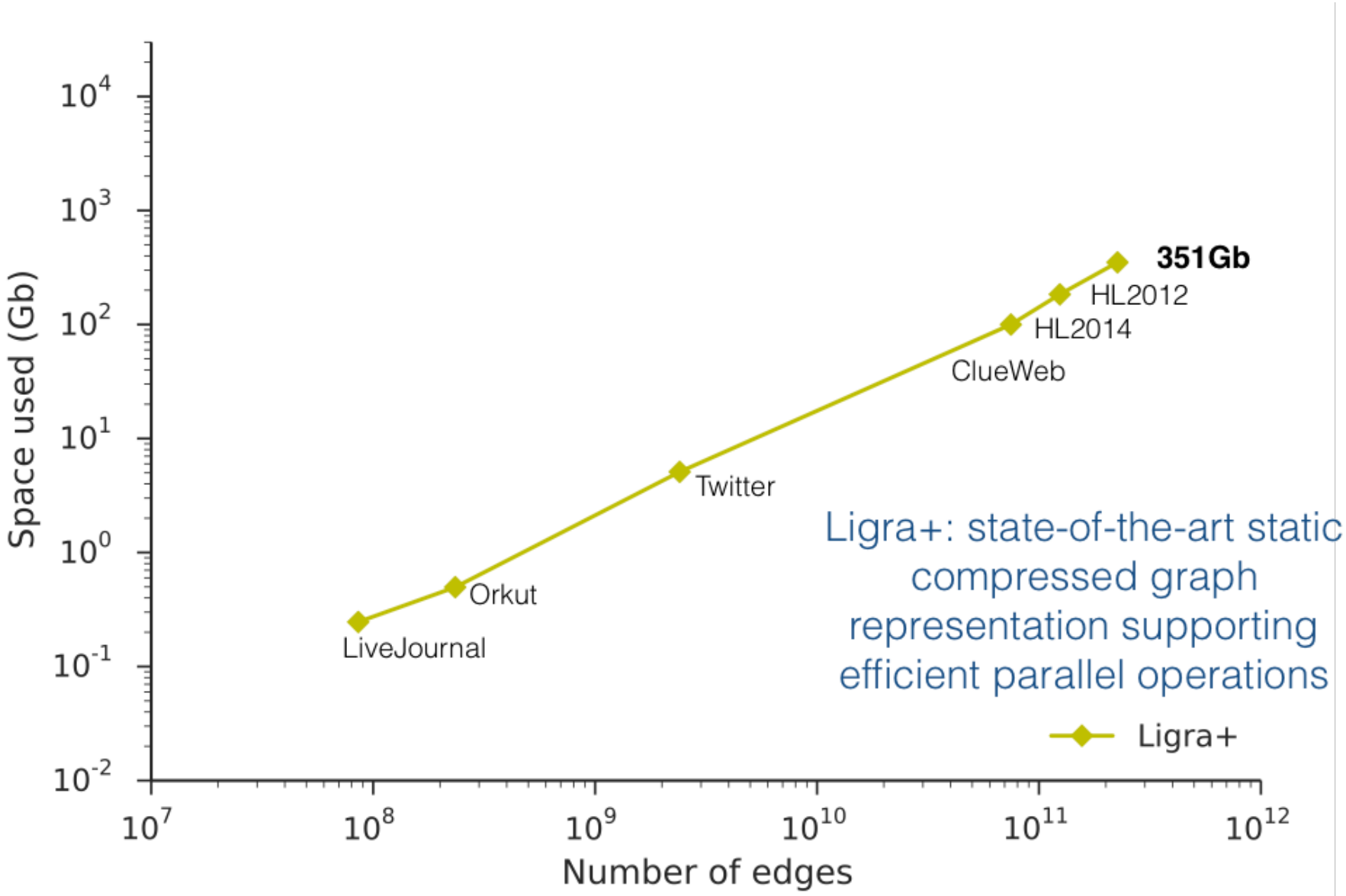


# Disadvantages of representing graphs using trees

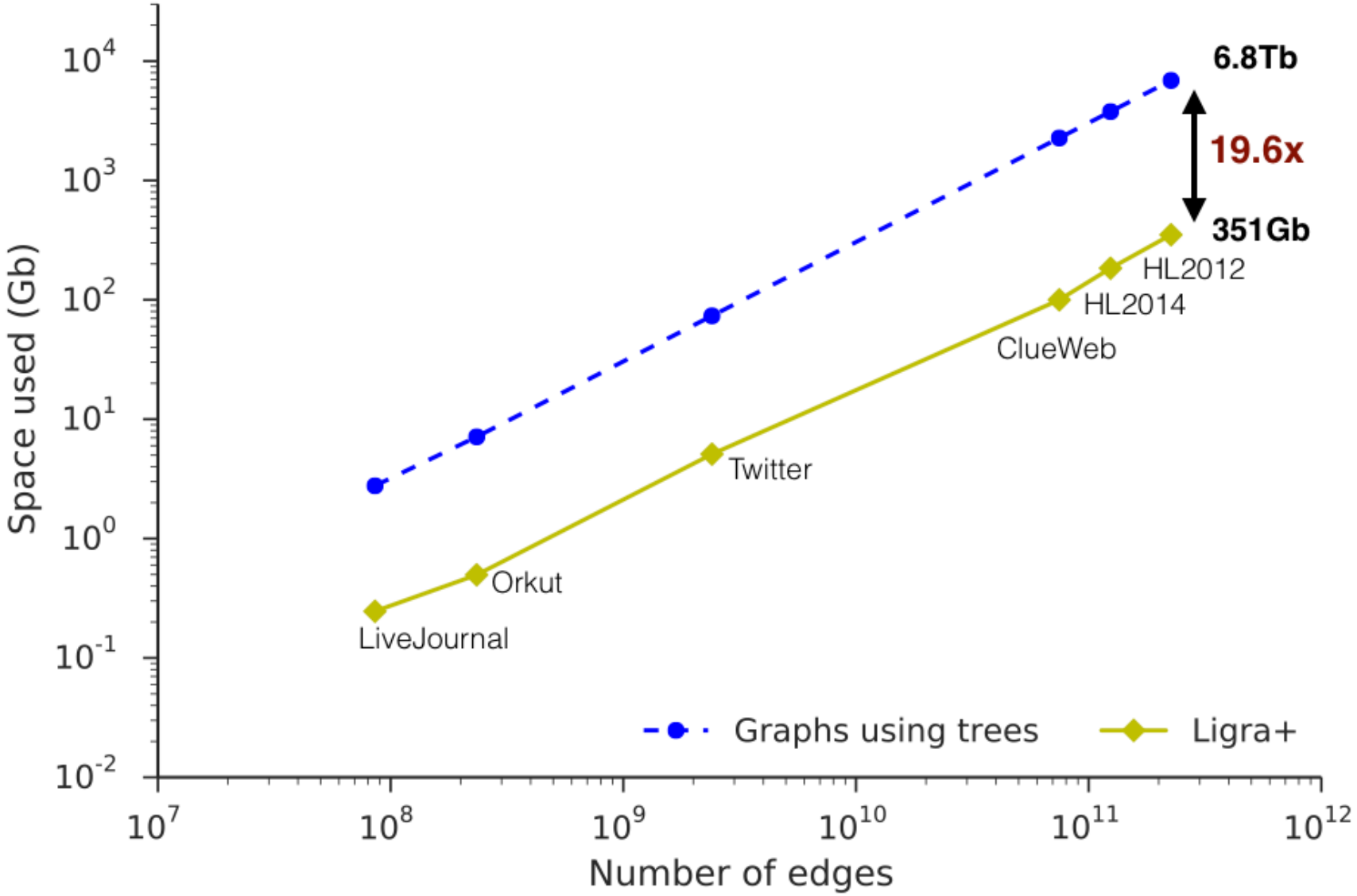
- Poor Cache Usage
  - One tree node per vertex and edge
  - One cache miss per edge access in the worst case
- Space Inefficiency
  - Need to store children pointers and metadata on tree nodes
  - Lose ability to perform integer compression

Requires close to 7TB of memory to store the symmetrized Common Crawl graph (225B edges)!

# Space Overhead of Graphs using Trees

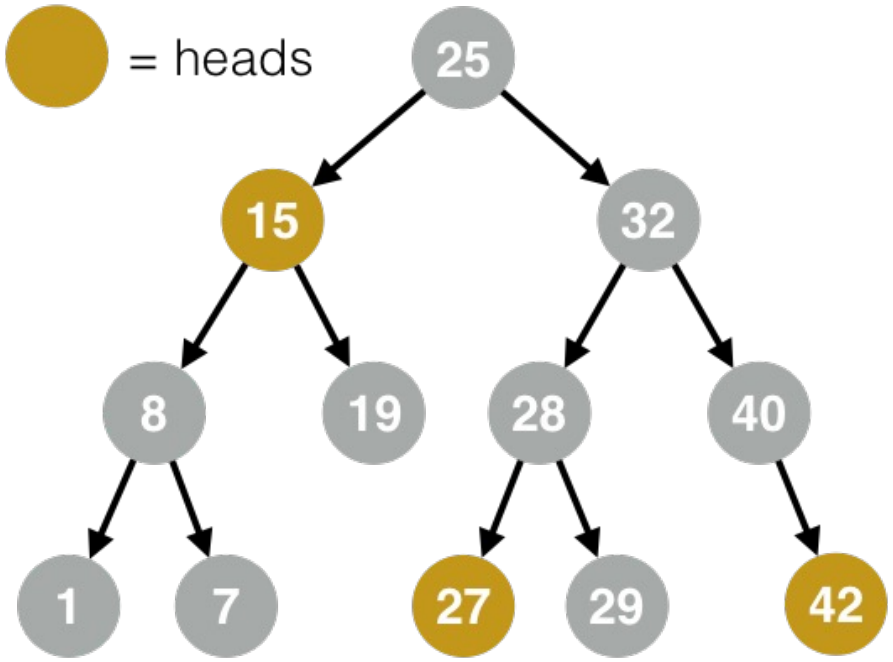


# Space Overhead of Graphs using Trees



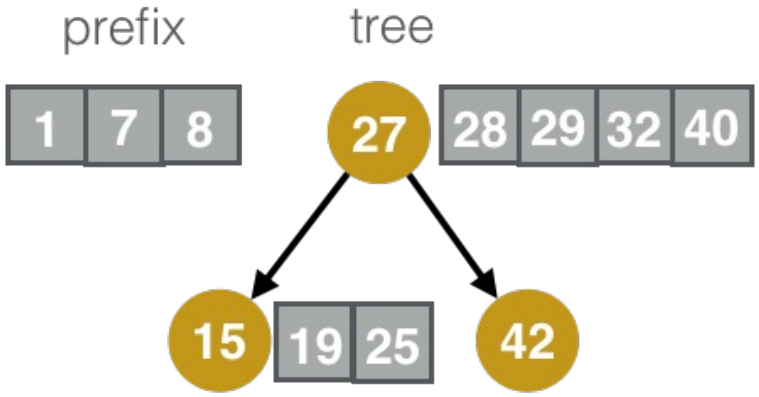
# C-tree

- Purely functional **compressed** tree data structure
- Chunking parameter = B. Fix a hash function *h*.
- Select elements as **heads** with probability **1/B** using *h*.




Tree

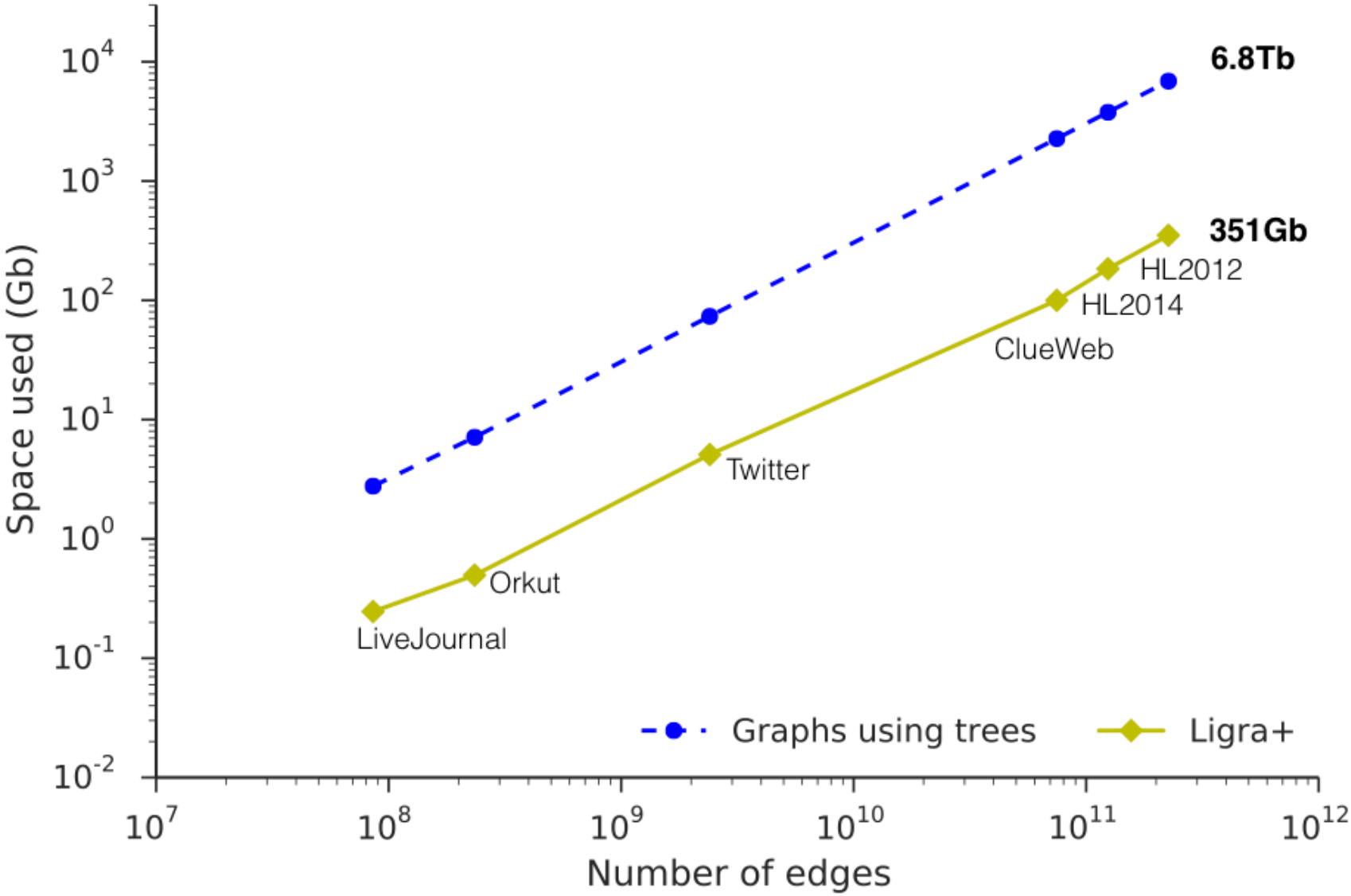
*More cache-efficient traversals*
*Further improve space usage for integer C-trees by difference encoding chunks*



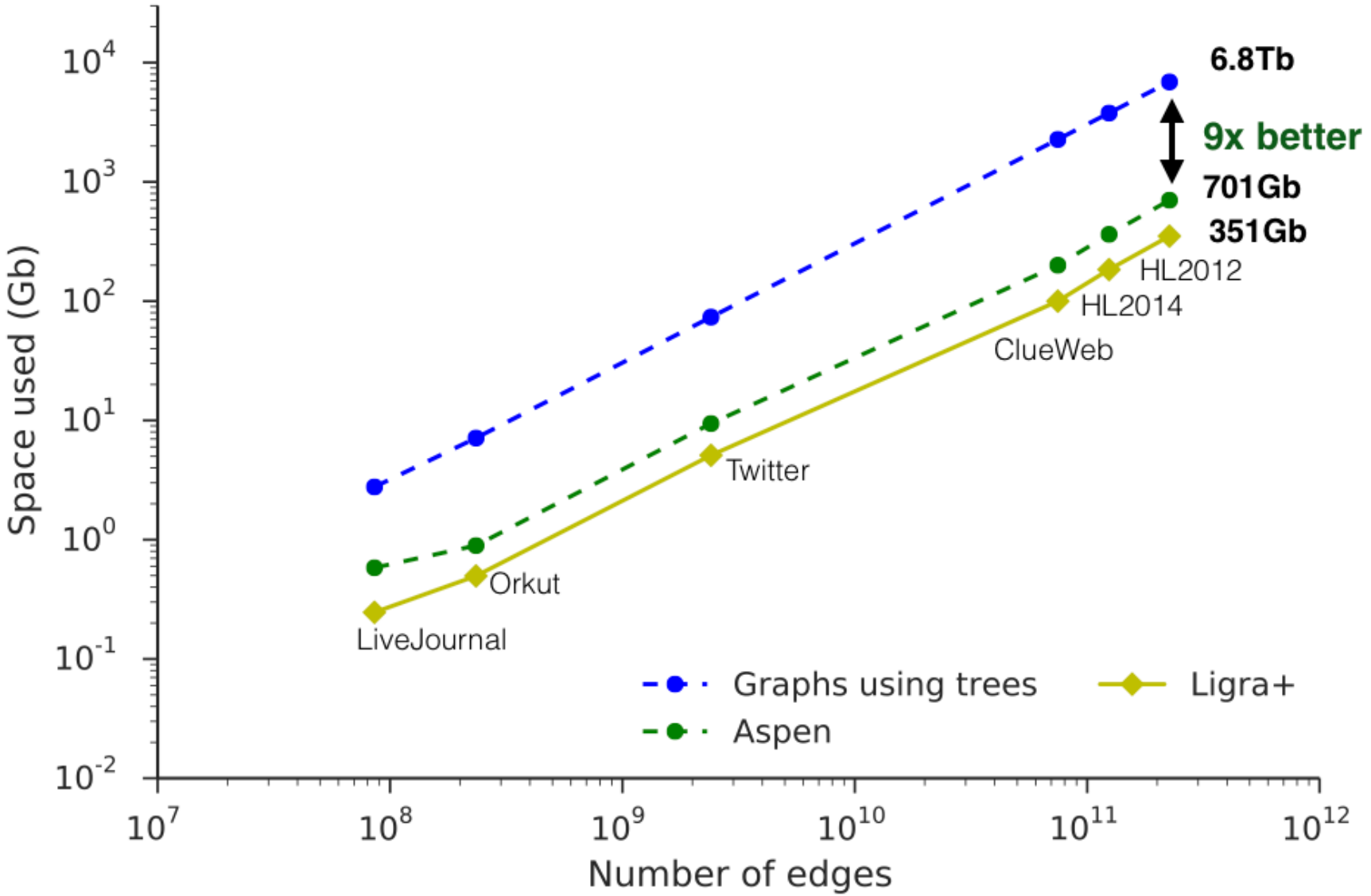

C-tree

- Supports parallel bulk insertions and deletions efficiently

# Space Usage of Graphs using C-trees

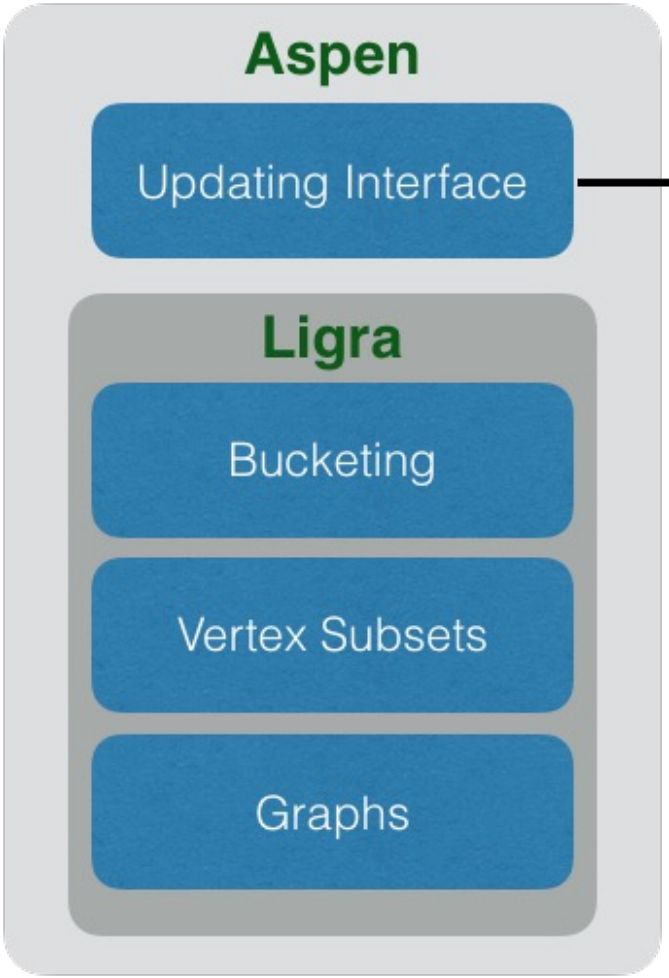


# Space Usage of Graphs using C-trees



# Aspen Framework

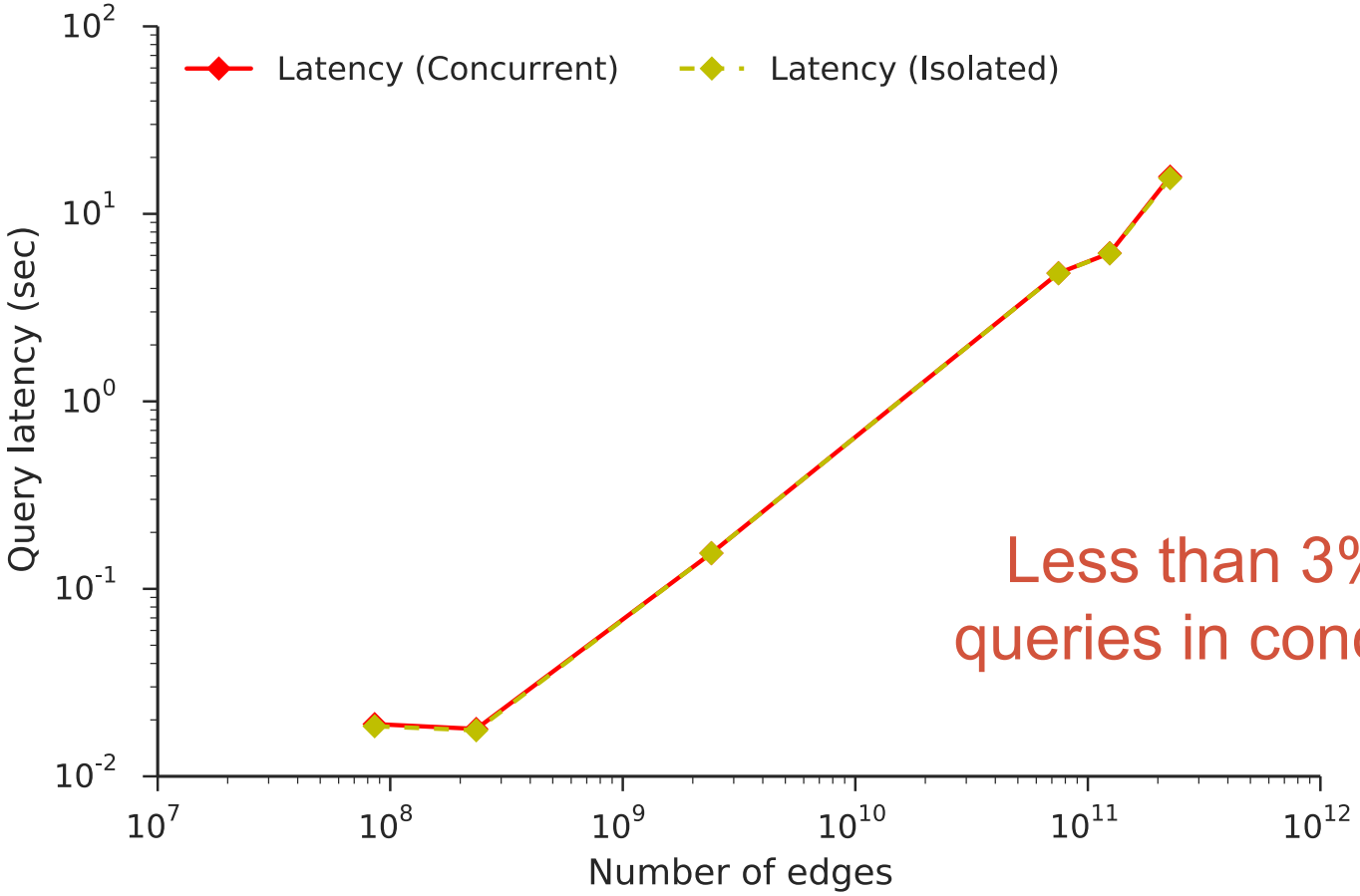
- Extension of Ligra with primitives for **updating graphs**
- Supports single-writer multi-reader concurrency




versioned graph
acquire()
release($G_s$)
multi_insert($E_B$), multi_delete($E_B$)
...

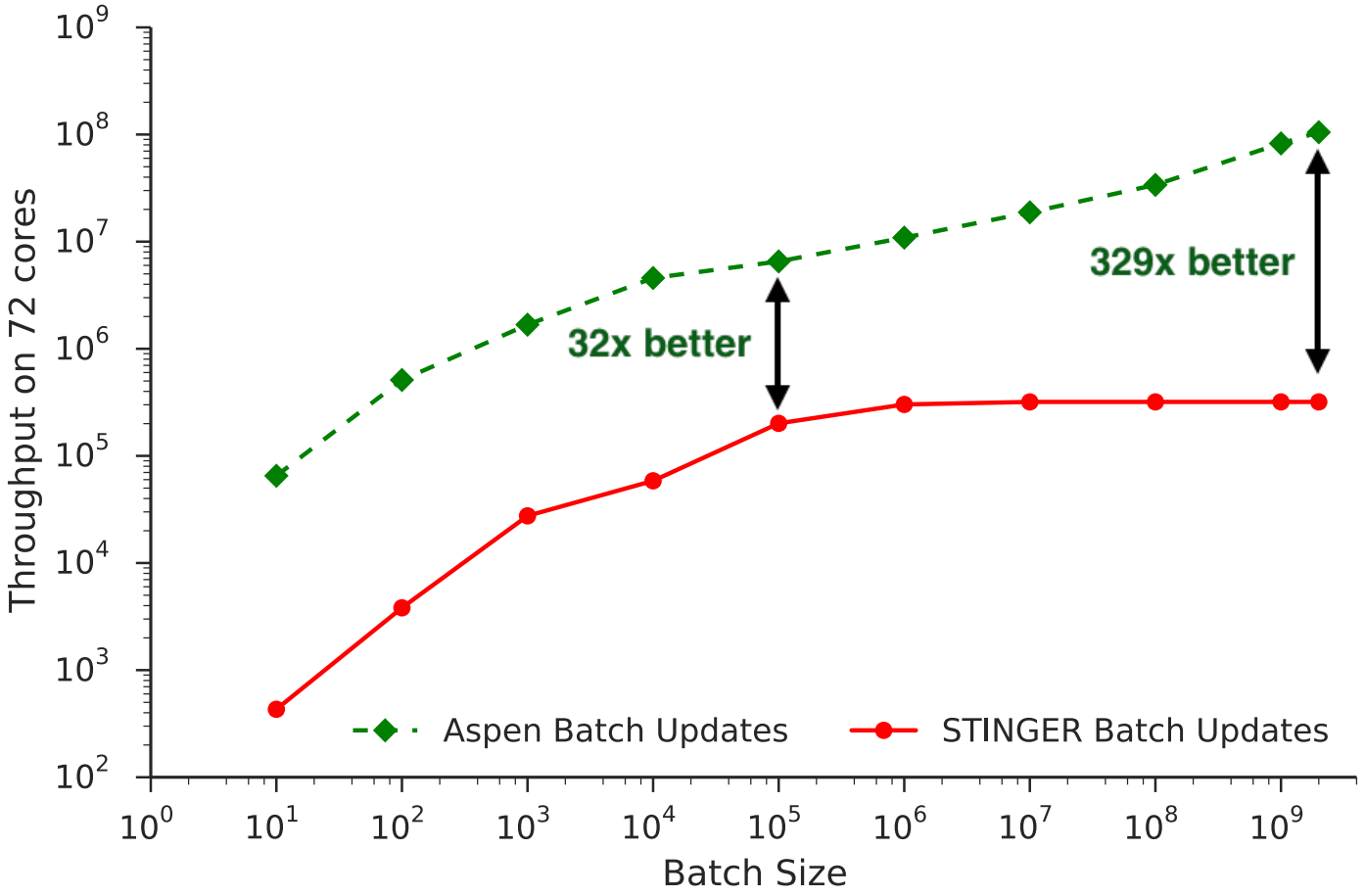
# Concurrent Queries and Update Task

- 72-core hyper-threaded machine with 1TB RAM
- 1 hyper-thread updating graph while remaining hyper-threads running parallel BFS




Less than 3% impact on queries in concurrent setting

# Parallel Batch Updates




- Aspen processes the Common Crawl graph at over 100M edge updates per second

# Conclusion

- GraphIt: graph DSL that enables easy exploration of large graph optimization space
  - https://graphit-lang.org/

- Aspen: streaming graph framework that enables concurrent queries and updates with low latency
  - https://github.com/ldhulipala/aspen/