A Framework for Processing Large Graphs in Shared Memory

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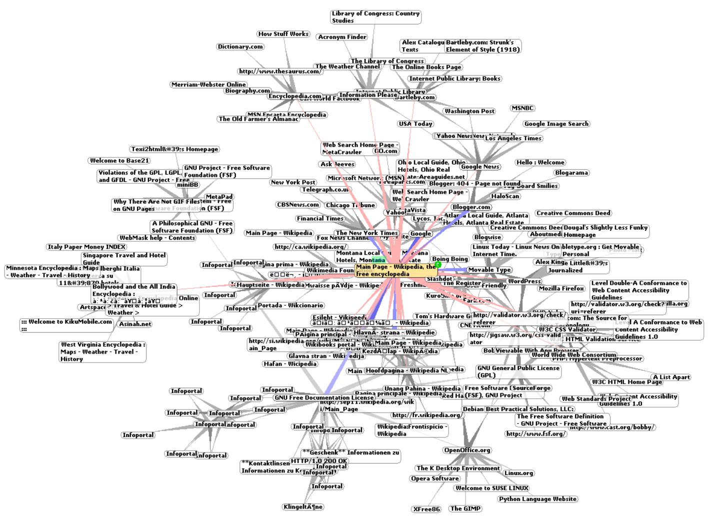
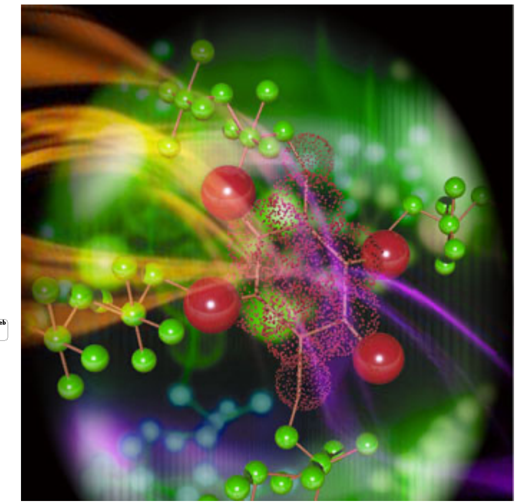
Based on joint work with Guy Blelloch and Laxman Dhulipala

What are graphs?



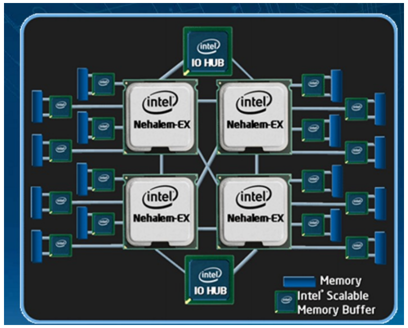


Graph Data is Everywhere!

- Can contain up to billions of vertices and edges
- Need simple, efficient, and scalable ways to analyze them

Efficient Graph Processing

- Use parallelism



- Design efficient algorithms

Breadth-first search	Single-source shortest paths
Betweenness centrality	Eccentricity estimation
Connected components	(Personalized) PageRank
…	…

  - Write/optimize code for each application
  - Build a general framework

Ligra Graph Processing Framework

EdgeMap | **VertexMap**

- Breadth-first search
- Betweenness centrality
- Connected components
- Triangle counting
- K-core decomposition
- Maximal independent set
- Set cover
- Single-source shortest paths
- Eccentricity estimation
- (Personalized) PageRank
- Local graph clustering
- Biconnected components
- Collaborative filtering
- …

Simplicity, Performance, Scalability

Graph Processing Systems

- Existing: Pregel/Giraph/GPS, GraphLab, Pegasus, Knowledge Discovery Toolbox, GraphChi, etc.

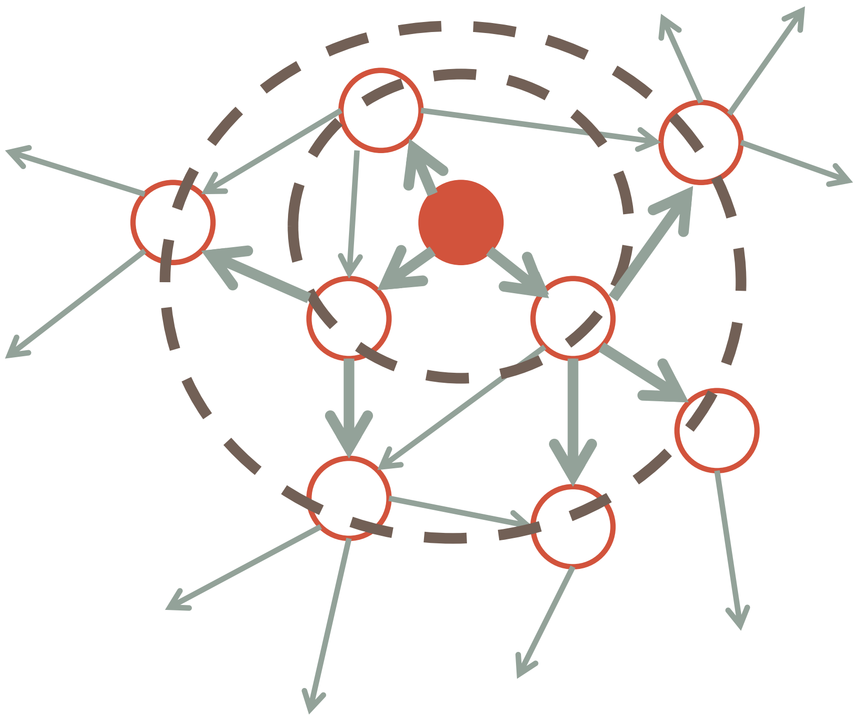
- Our system: Ligra - Lightweight graph processing system for shared memory

Takes advantage of "frontier-based" nature of many algorithms (active set is dynamic and often small)

Breadth-first Search (BFS)

- Compute a BFS tree rooted at source *r* containing all vertices reachable from *r*

Applications
Betweenness centrality
Eccentricity estimation
Maximum flow
Web crawlers
Network broadcasting
Cycle detection
…



- Can process each frontier in parallel
- Race conditions, load balancing

Steps for Graph Traversal

Many graph traversal algorithms do this!

Graph

- Operate on a subset of vertices — VertexSubset
- Map computation over subset of edges in parallel
- Return new subset of vertices

} EdgeMap

- Map computation over subset of vertices in parallel — VertexMap

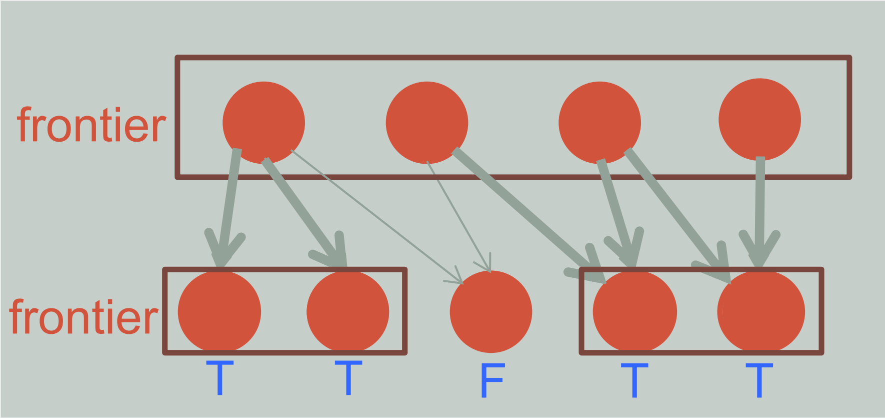
*We built the **Ligra** abstraction for these kinds of computations*

Think with flat data-parallel operators

Abstraction enables optimizations
(hybrid traversal and graph compression)

Breadth-first Search in Ligra

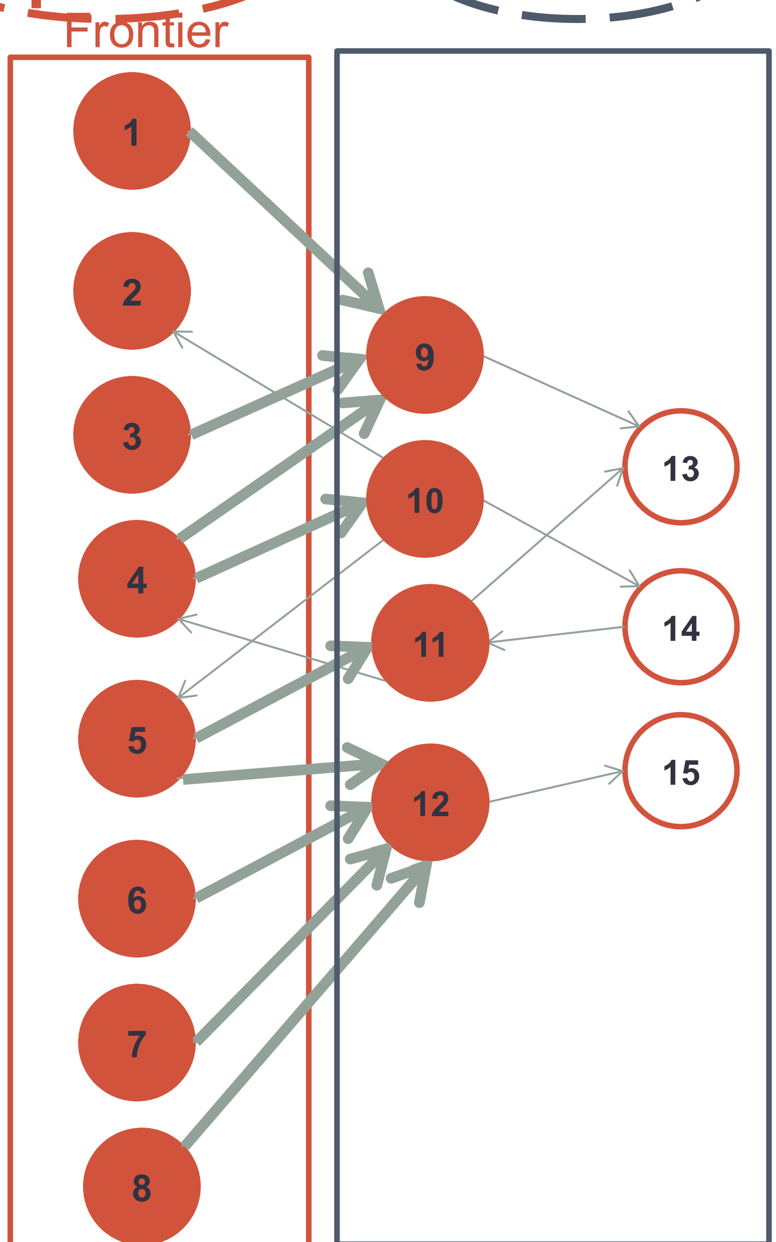
```
parents = {-1, …, -1};   //-1 indicates "unexplored"

procedure UPDATE(s, d):
    return compare_and_swap(parents[d], -1, s);

procedure COND(v):
    return parents[v] == -1;   //checks if "unexplored"

procedure BFS(G, r):
    parents[r] = r;
    frontier = {r}; //VertexSubset
    while (size(frontier) > 0):
        frontier = EDGEMAP(G, frontier, UPDATE, COND);
```



Actual BFS code in Ligra

```
#include "ligra.h"

struct BFS_F {
  intT* Parents;
  BFS_F(intT* _Parents) : Parents(_Parents) {}
  inline bool update (intT s, intT d) { //Update
    if(Parents[d] == -1) { Parents[d] = s; return 1; }
    else return 0;
  }
  inline bool updateAtomic (intT s, intT d){ //atomic version of Update
    return (CAS(&Parents[d],(intT)-1,s));
  }
  //cond function checks if vertex has been visited yet
  inline bool cond (intT d) { return (Parents[d] == -1); }
};

template <class vertex>
void Compute(graph<vertex> GA, intT start) {
  intT n = GA.n;
  //creates Parents array, initialized to all -1, except for start
  intT* Parents = newA(intT,GA.n);
  parallel_for(intT i=0;i<GA.n;i++) Parents[i] = -1;
  Parents[start] = start;

  vertexSubset Frontier(n,start); //creates initial frontier

  while(!Frontier.isEmpty()){ //loop until frontier is empty
    vertexSubset output = edgeMap(GA, Frontier, BFS_F(Parents));
    Frontier.del();
    Frontier = output; //set new frontier
  }
  Frontier.del();
  free(Parents);
}
```

Sparse or Dense EdgeMap?



- Dense method better when frontier is large and many vertices have been visited
- Sparse (traditional) method better for small frontiers
- Switch between the two methods based on frontier size [Beamer et al. SC '12]

Limited to BFS?

EdgeMap

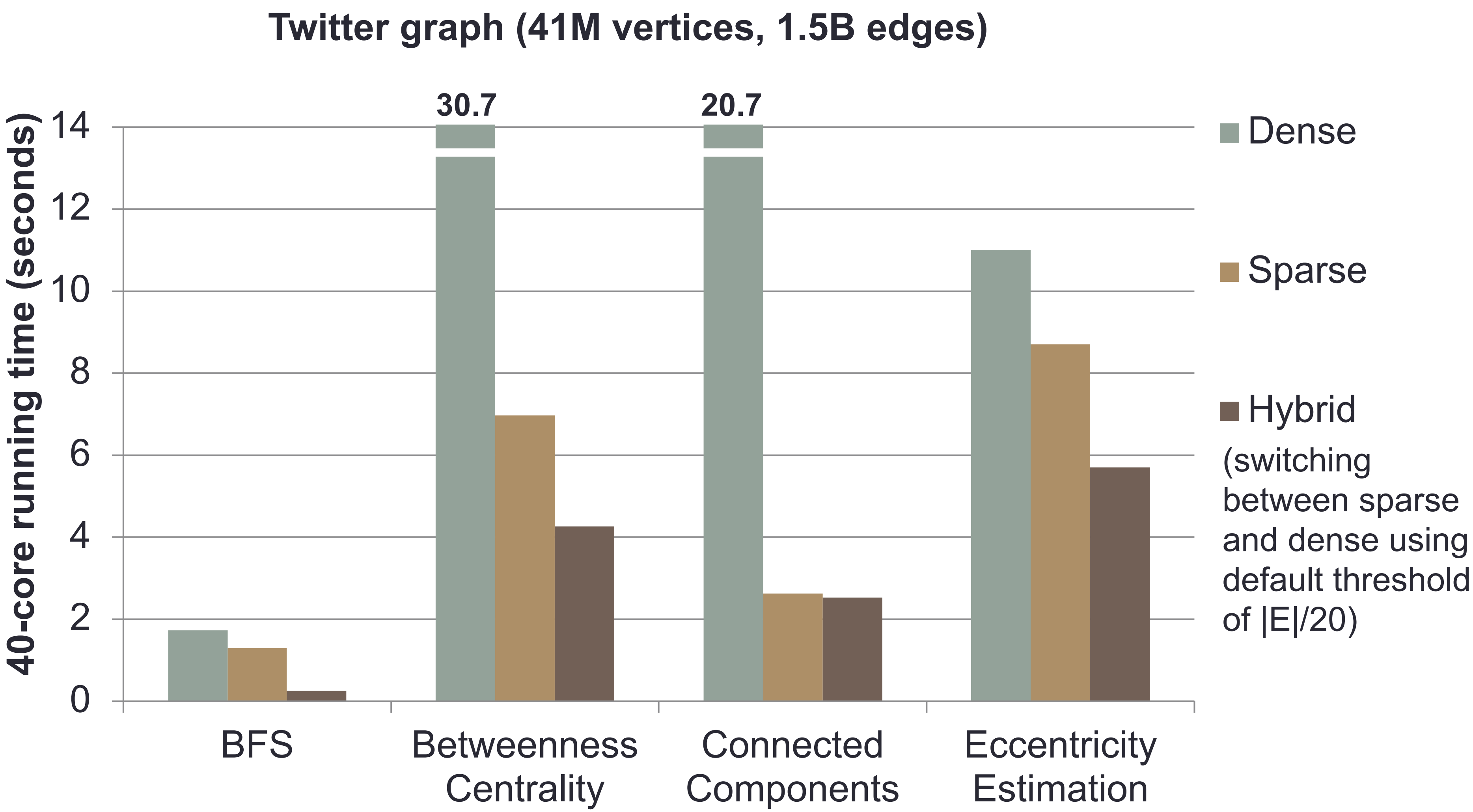
```
procedure EDGEMAP(G, frontier, Update, Cond):
    if (size(frontier) + sum of out-degrees > threshold) then:
        return EDGEMAP_DENSE(G, frontier, Update, Cond);
    else:
        return EDGEMAP_SPARSE(G, frontier, Update, Cond);
```

Loop through outgoing edges of frontier vertices in parallel

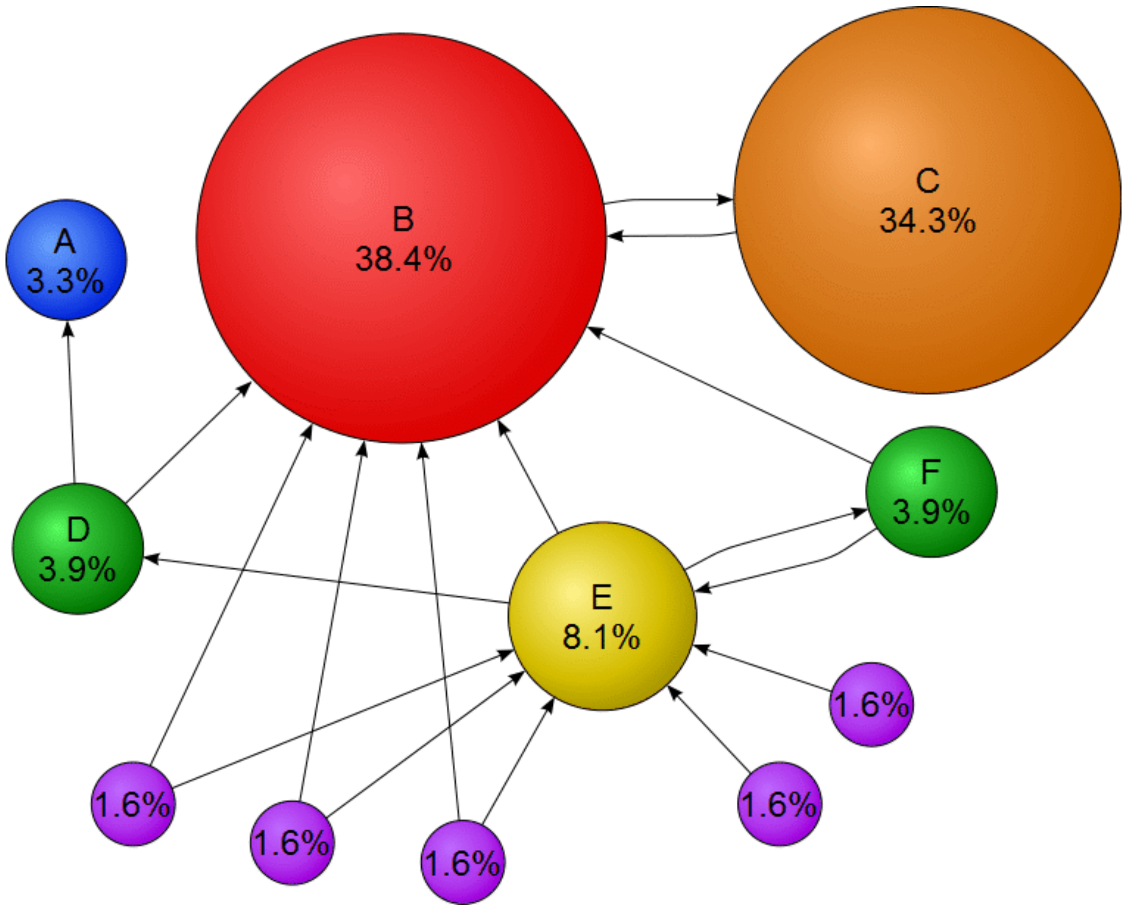
Loop through incoming edges of “unexplored” vertices (in parallel), breaking early if possible

- More general than just BFS!
- Generalized to many other problems
  - For example, betweenness centrality, connected components, sparse PageRank, shortest paths, eccentricity estimation, graph clustering, k-core decomposition, set cover, etc.
- Users need not worry about this

Frontier-based approach enables hybrid traversal

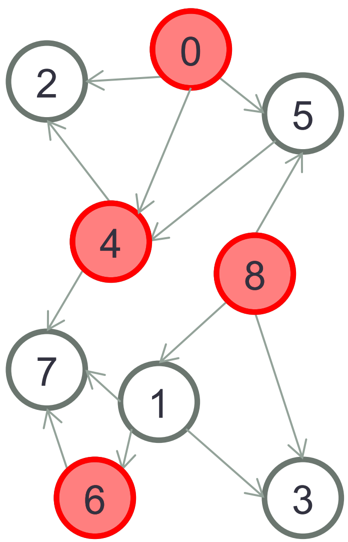


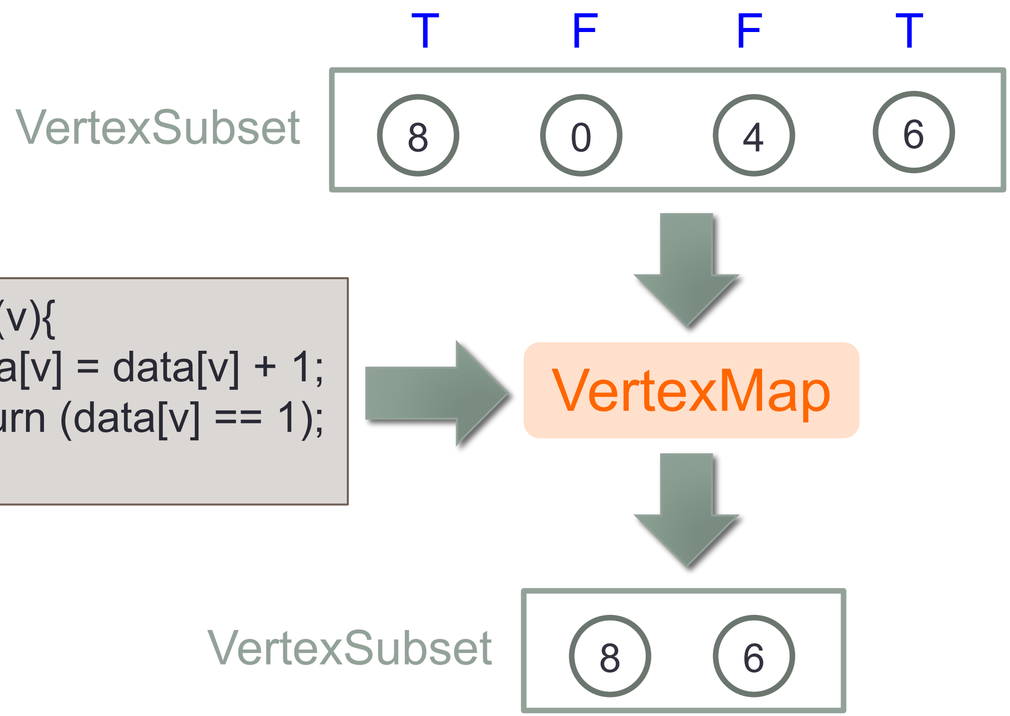
PageRank



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

VertexMap






```
bool f(v){
    data[v] = data[v] + 1;
    return (data[v] == 1);
}
```

PageRank in Ligra

```
p_curr = {1/|V|, …, 1/|V|};     p_next = {0, …, 0};     diff = {};     error =∞;

procedure UPDATE(s, d):
    atomic_increment(p_next[d], p_curr[s] / degree(s));
    return 1;

procedure COMPUTE(i):
    p_next[i] = α · p_next[i] + (1- α) · (1/|V|);
    diff[i] = abs(p_next[i] – p_curr[i]);
    p_curr[i] = 0;
    return 1;

procedure PageRank(G, α, ε):
    frontier = {0, …, |V|-1};
    while (error > ε):
        frontier = EDGEMAP(G, frontier, UPDATE, COND_true);
        frontier = VERTEXMAP(frontier, COMPUTE);
        error = sum of diff entries;
        swap(p_curr, p_next)
    return p_curr;
```

PageRank

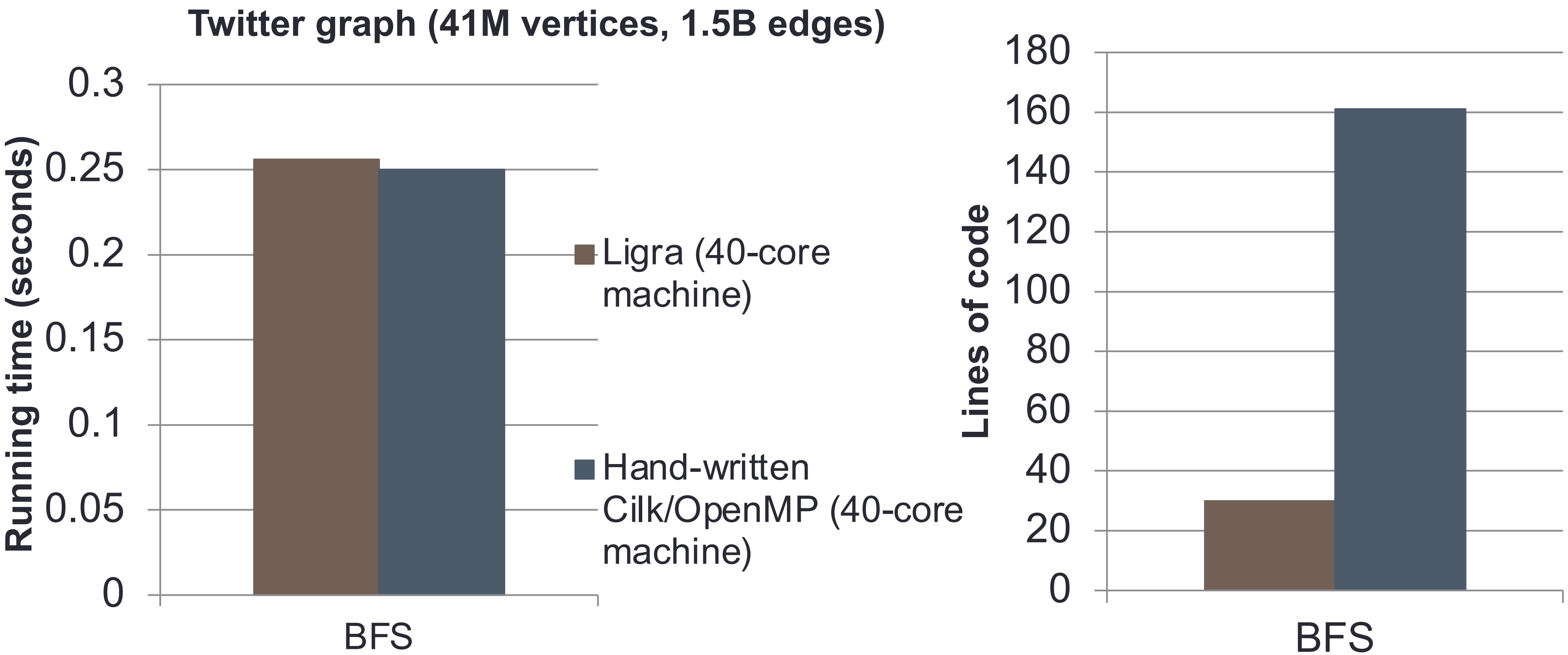
- *Sparse version?*
  - PageRank-Delta: Only update vertices whose PageRank value has changed by more than some Δ-fraction (discussed in PowerGraph and McSherry WWW ‘05)

PageRank-Delta in Ligra

```
PR[i] = {1/|V|, …, 1/|V|};
nghSum = {0, …, 0};
Change = {};                    //store changes in PageRank values

procedure UPDATE(s, d):                 //passed to EdgeMap
        atomic_increment(nghSum[d], Change[s] / degree(s));
        return 1;

procedure COMPUTE(i):                   //passed to VertexMap
        Change[i] = α · nghSum[i];
        PR[i] = PR[i] + Change[i];
        return (abs(Change[i]) > Δ);    //check if absolute value of change is big enough
```

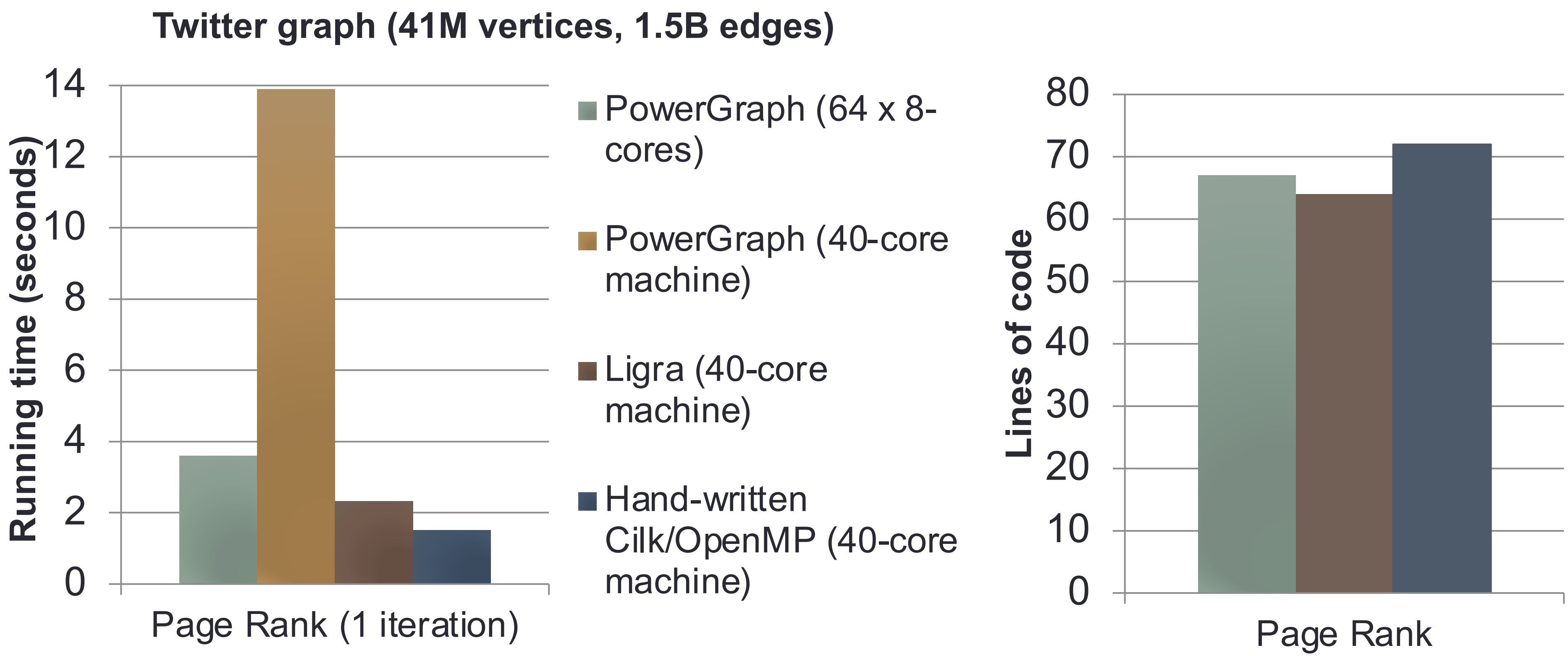
Performance of Ligra

Ligra BFS Performance



- Comparing against hybrid traversal BFS code by Beamer et al.

Ligra PageRank Performance

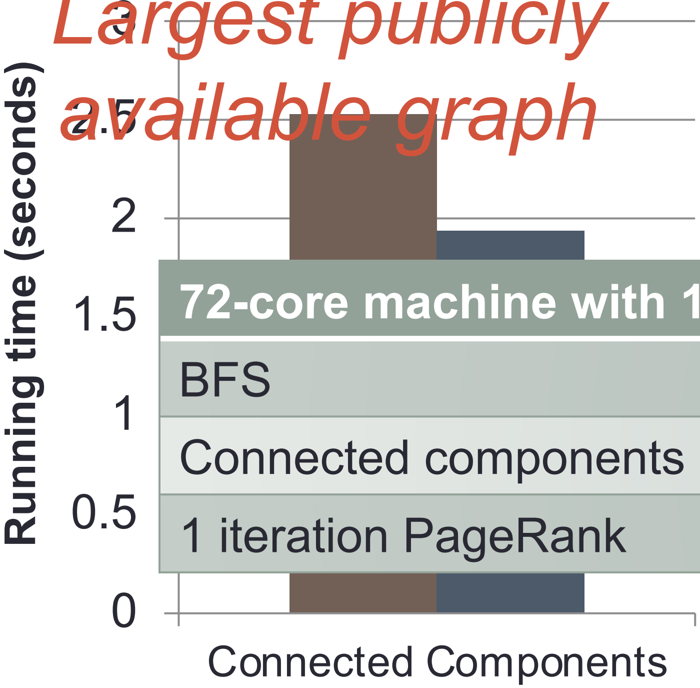


- Easy to implement “sparse” version of PageRank in Ligra

Connected Components Performance

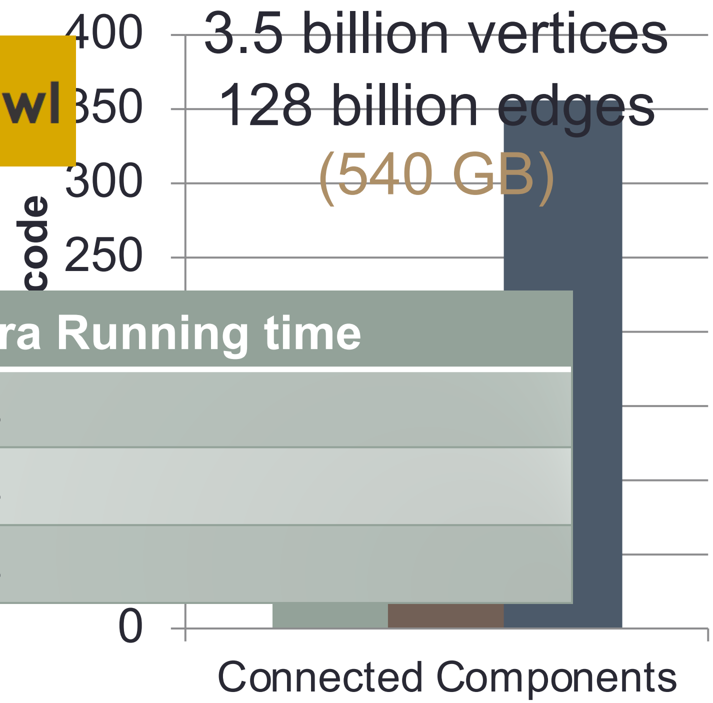
Twitter graph (41M vertices, 1.5B edges)

Largest publicly available graph



Common Crawl

3.5 billion vertices
128 billion edges
(540 GB)



72-core machine with 1TB RAM	Ligra Running time
BFS	12s
Connected components	42s
1 iteration PageRank	28s

- Ligra's performance is close to hand-written code
- Faster than best existing system
- Subsequent systems have used Ligra's abstraction and hybrid traversal idea, e.g., Galois [SOSP '13], Polymer [PPoPP '15], Gunrock [PPoPP '16], Gemini [OSDI '16], GraphGrind [ICS '17], Grazelle [PPoPP '18]

Large Graphs

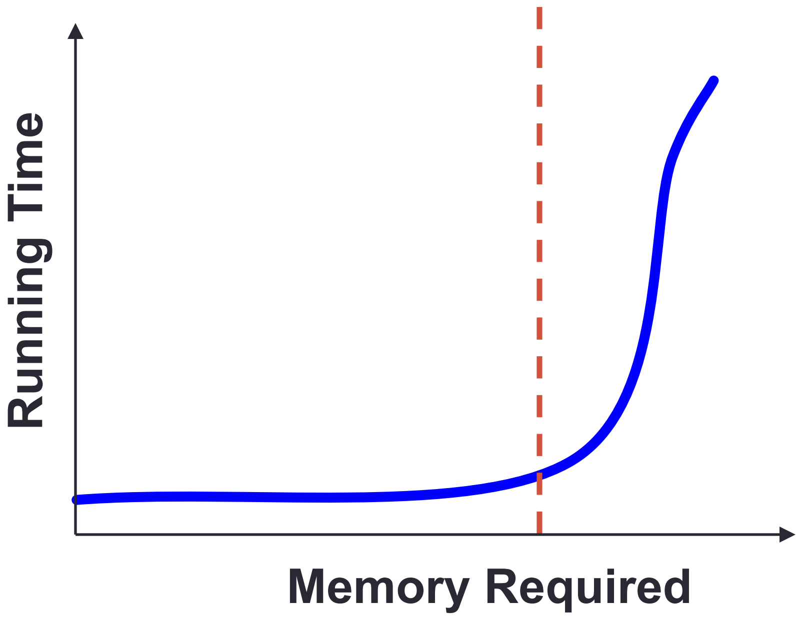
Amazon EC2

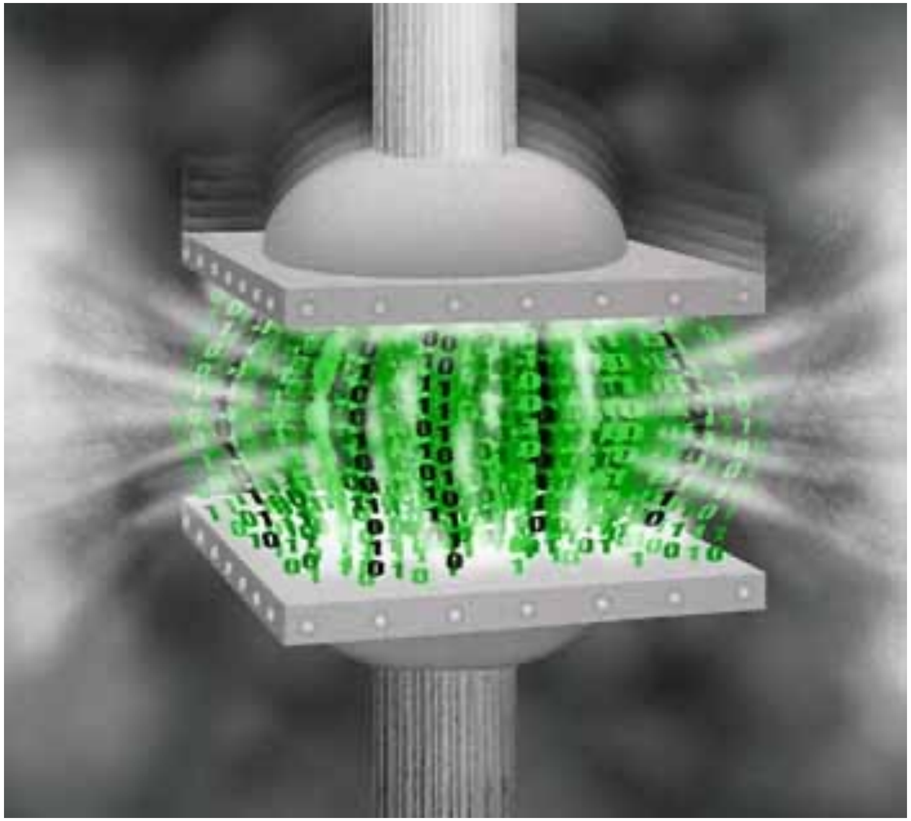
	vCPU	ECU	Memory (GiB)	Instance Storage (GB)	Linux/UNIX Usage
x1e.xlarge	4	12	122	1 x 120 SSD	$0.834 per Hour
x1e.2xlarge	8	23	244	1 x 240 SSD	$1.668 per Hour
x1e.4xlarge	16	47	488	1 x 480 SSD	$3.336 per Hour
x1e.8xlarge	32	91	976	1 x 960	$6.672 per Hour
x1e.16xlarge	64	179	1952	1 x 1920 SSD	$13.344 per Hour
x1e.32xlarge	128	340	3904	2 x 1920 SSD	$26.688 per Hour

- Most can fit on commodity shared memory machine

Example
Dell PowerEdge R930:
Up to 96 cores and 6 TB of RAM

What if you don't have or can't afford that much memory?





Graph Compression

Ligra+: Adding Graph Compression to Ligra

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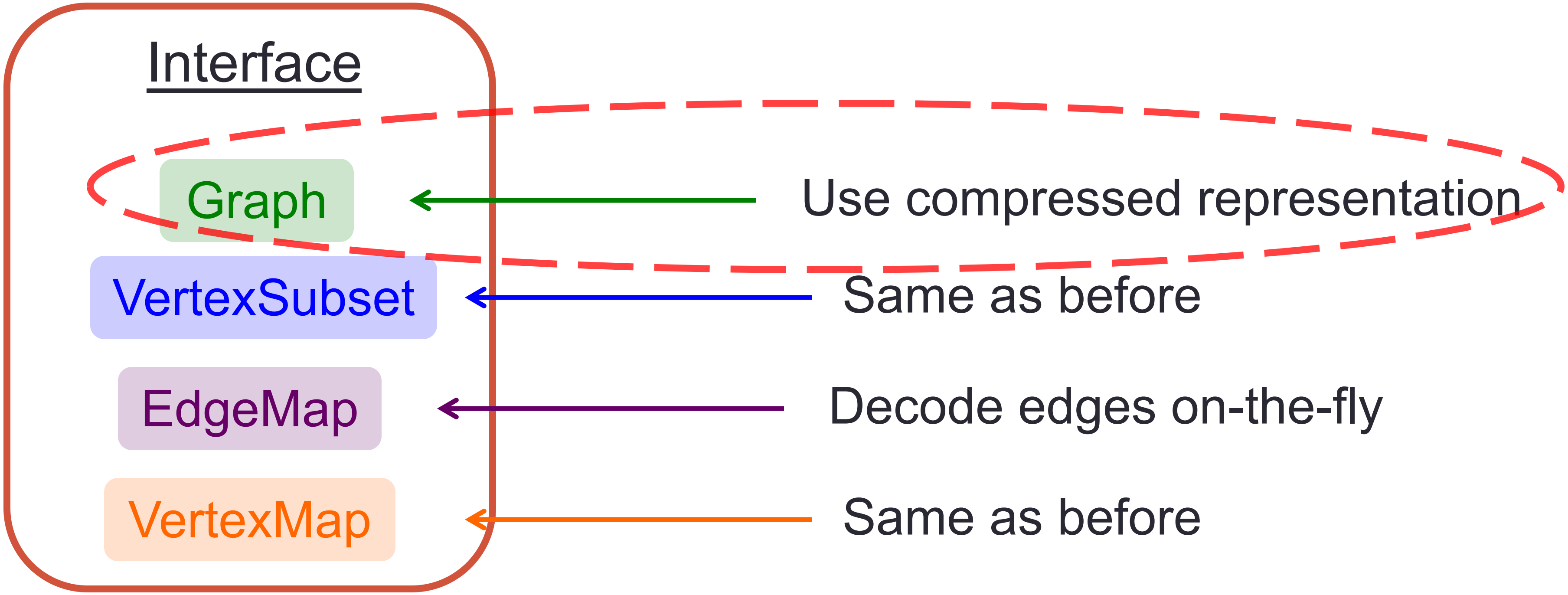
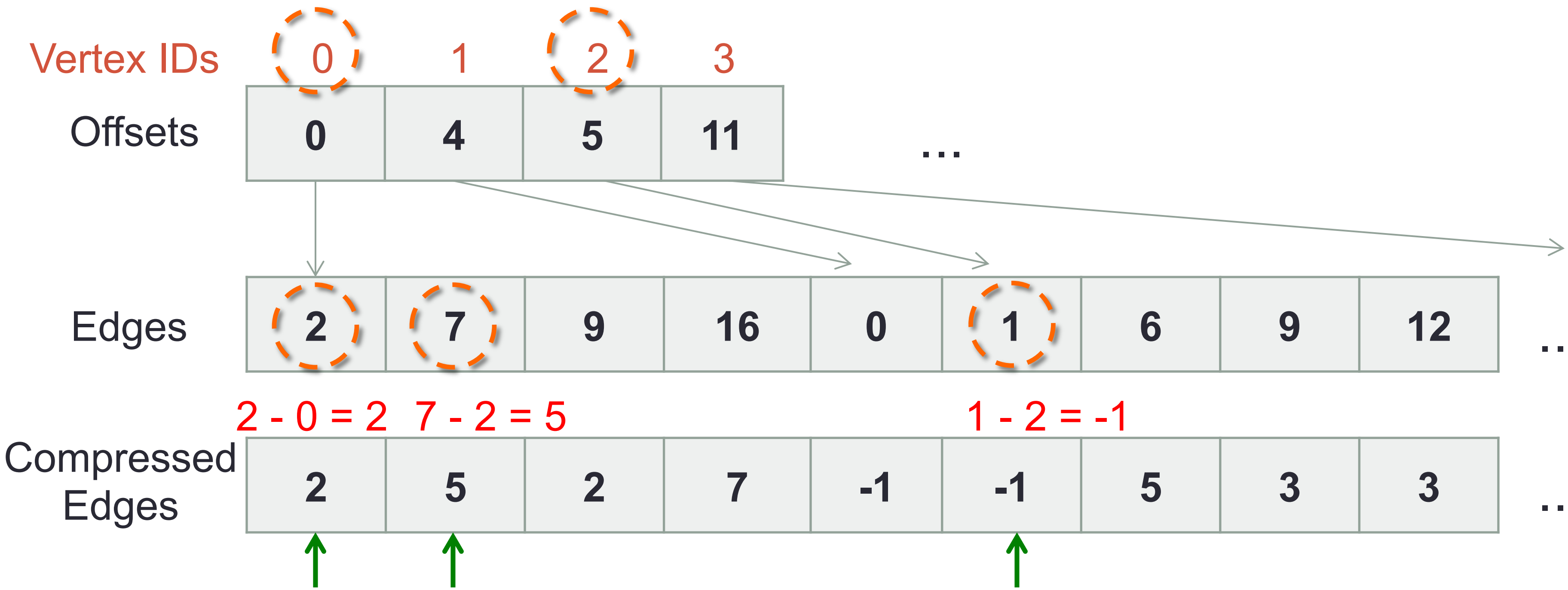


- Same interface as Ligra
- All changes hidden from the user!

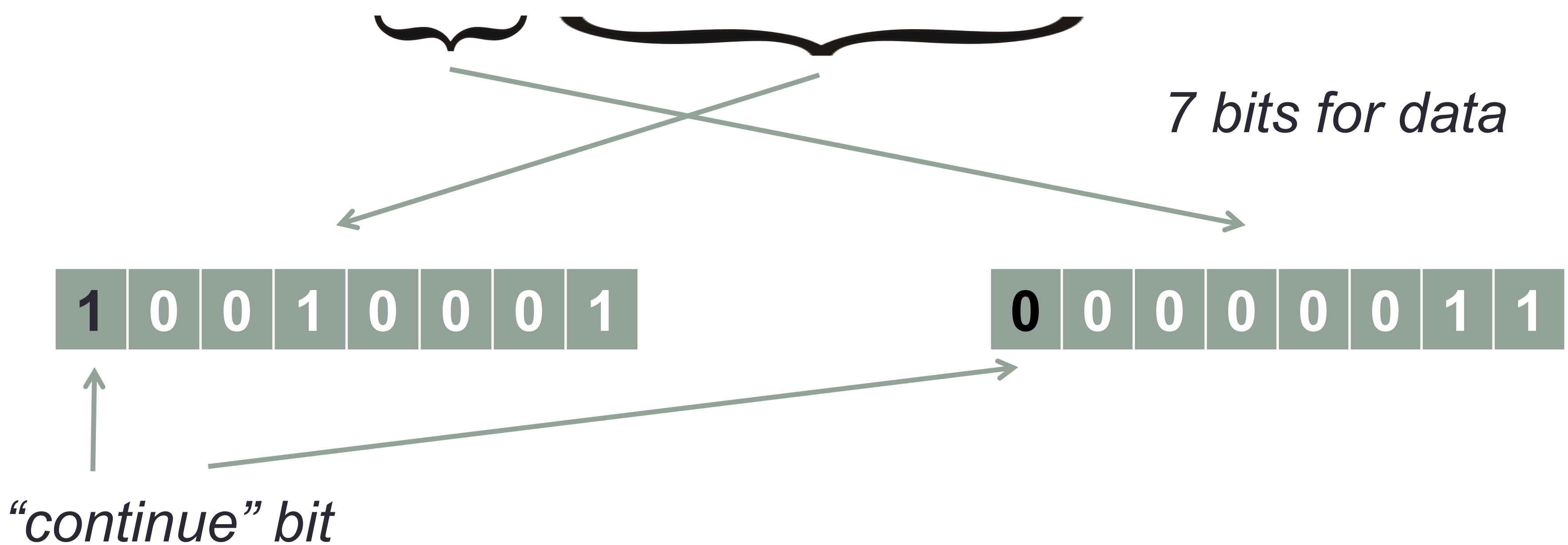
Graph representation



Sort edges and encode differences

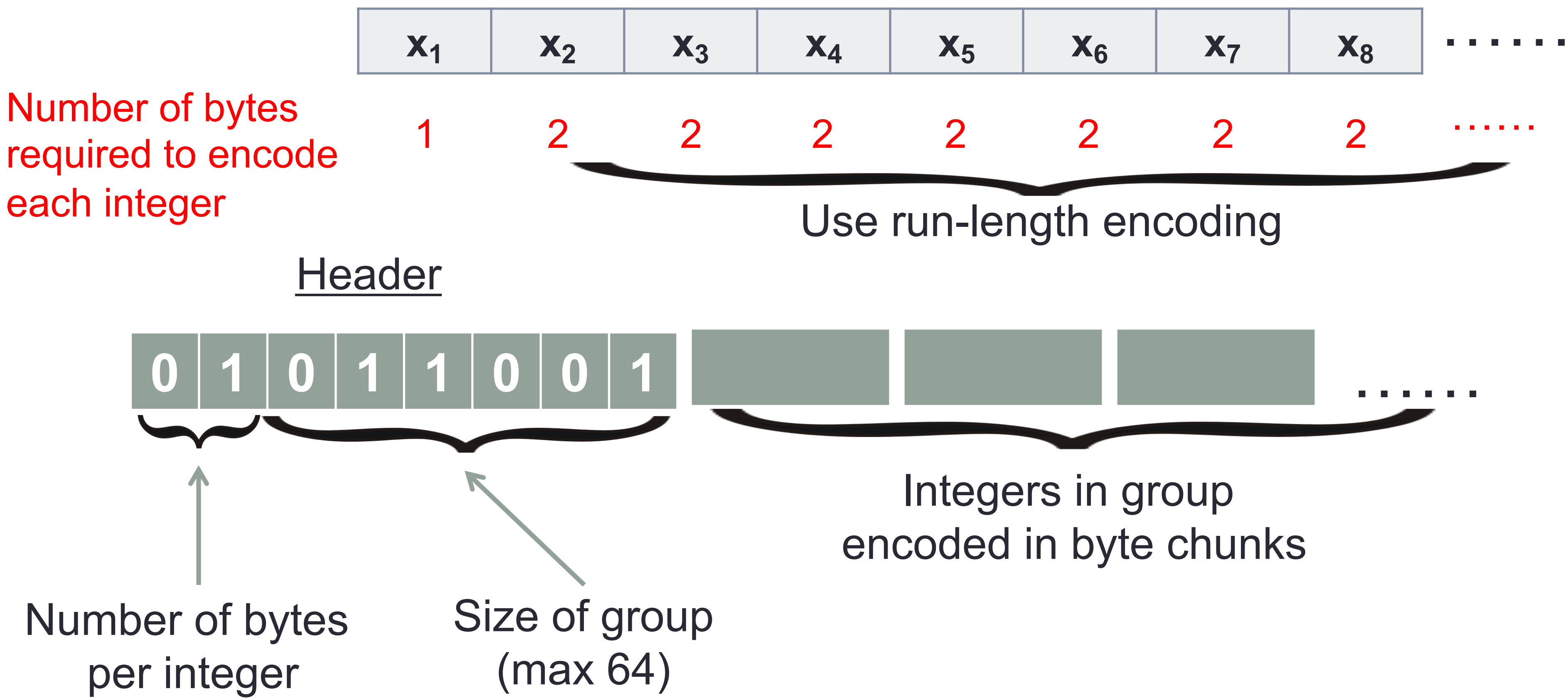
Variable-length codes

- k-bit codes
  - Encode value in chunks of k bits
  - Use k-1 bits for data, and 1 bit as the "continue" bit
- Example: encode "401" using 8-bit (byte) code
- In binary: 1 1 0 0 1 0 0 0 1



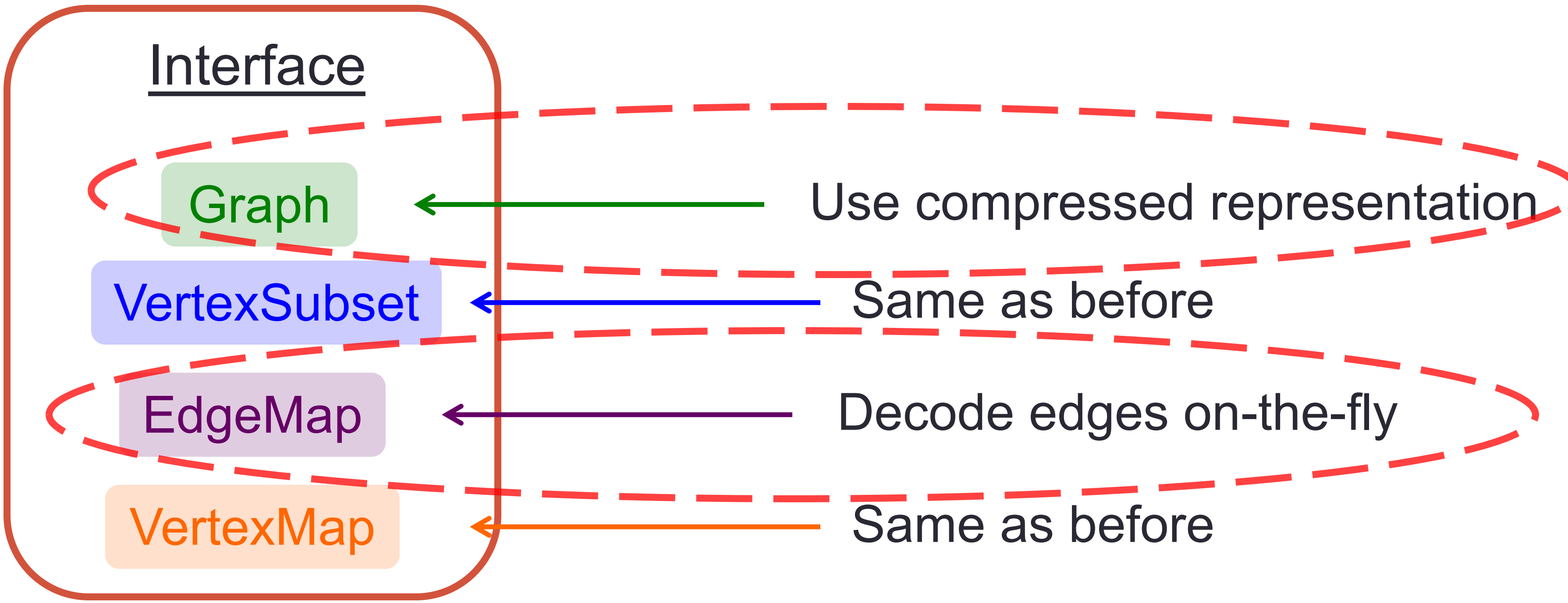
Encoding optimization

- Another idea: get rid of "continue" bits



- Increases space, but makes decoding cheaper (no branch misprediction from checking "continue" bit)

Ligra+: Adding Graph Compression to Ligra



- Same interface as Ligra
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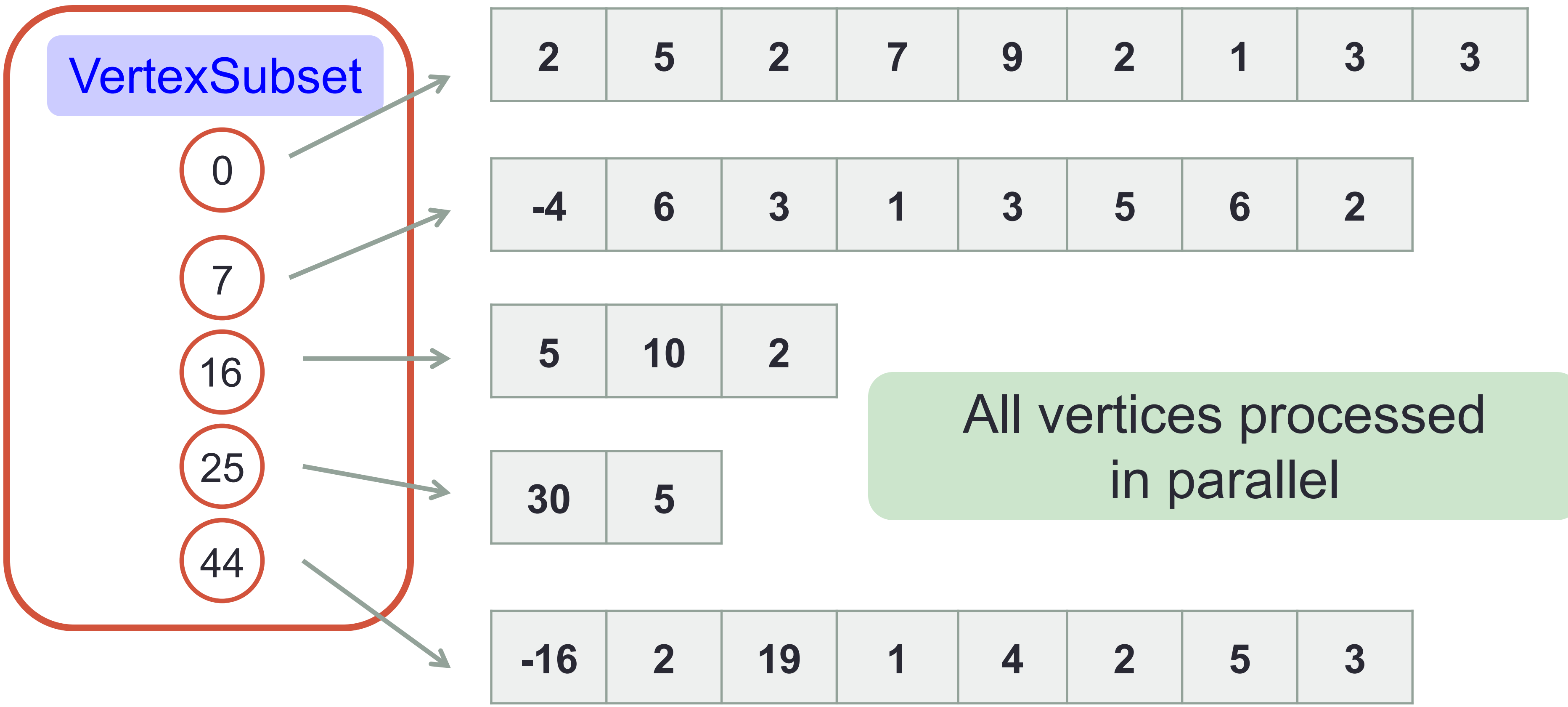
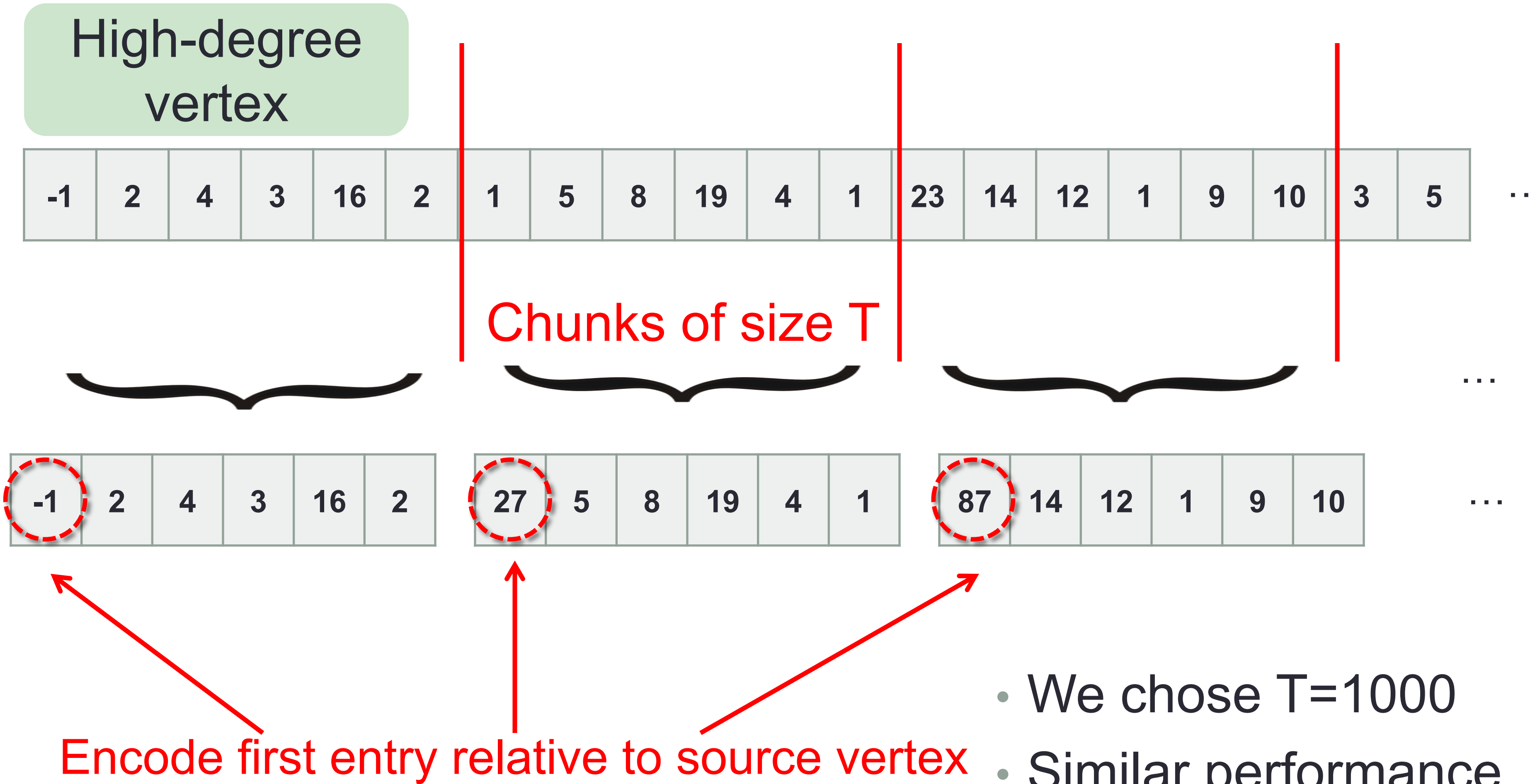
Modifying EdgeMap

- Processes outgoing edges of a subset of vertices



What about high-degree vertices?

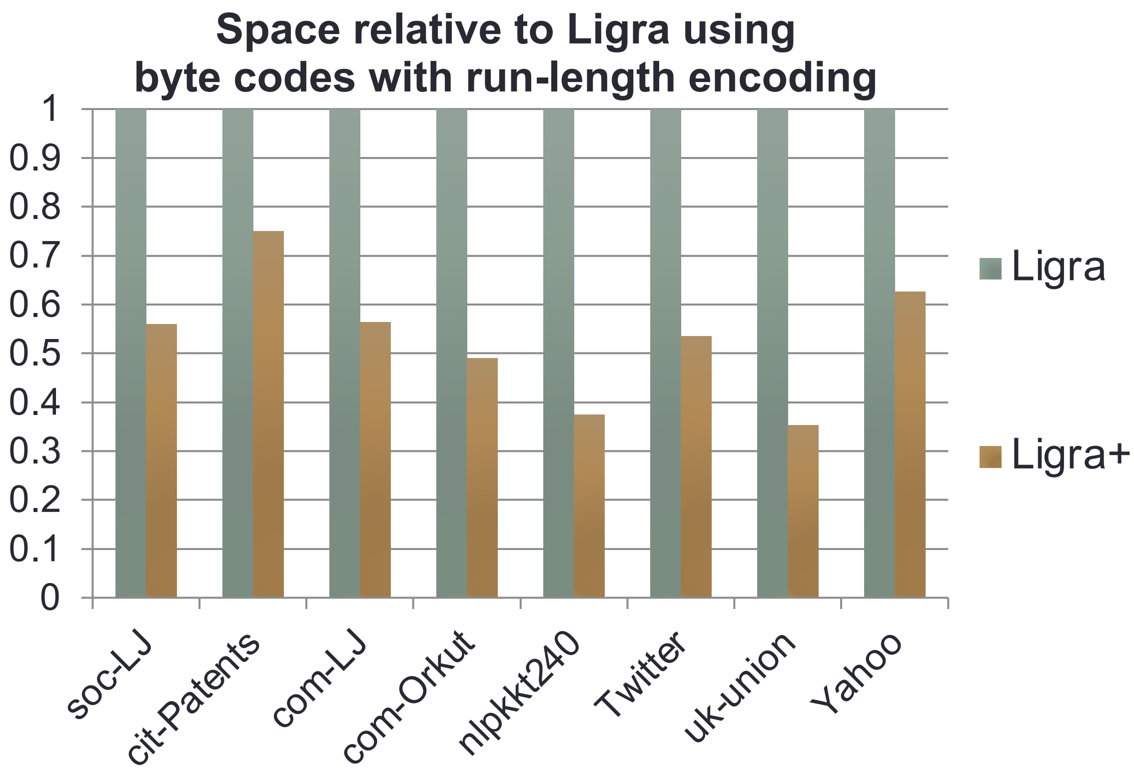
Handling high-degree vertices



All chunks can be decoded in parallel!

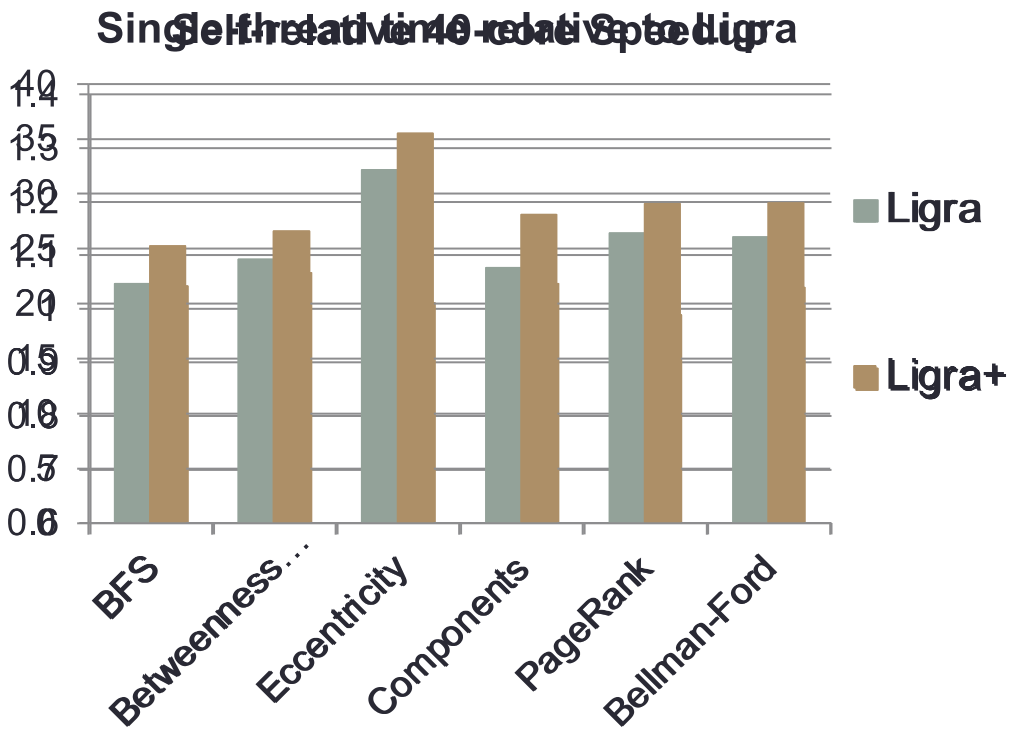
- We chose T=1000
- Similar performance and space usage for a wide range of T

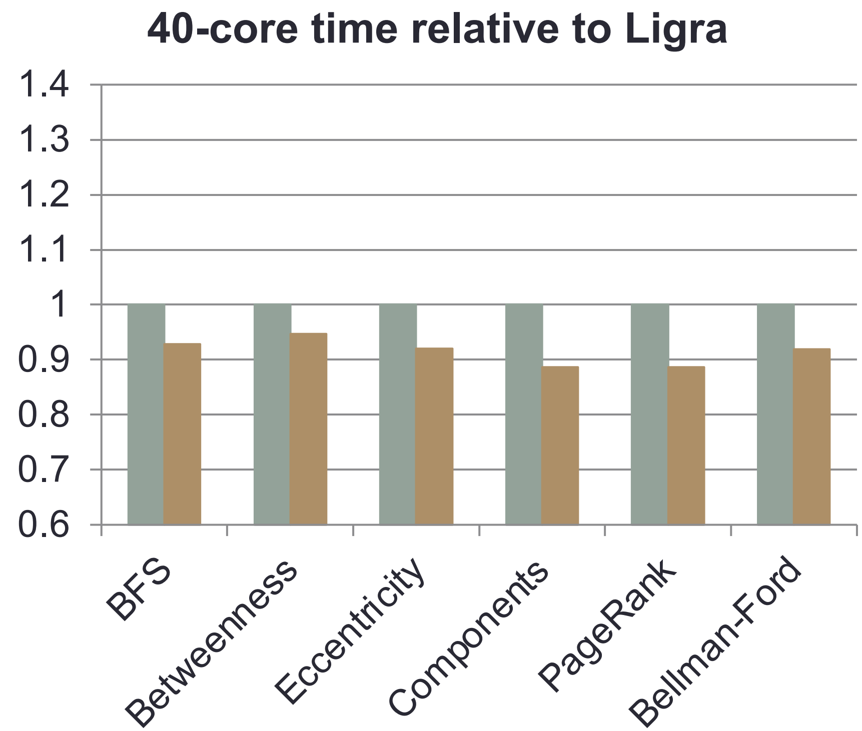
Ligra+ Space Savings



- Space savings of about 1.3—3x
- Could use more sophisticated schemes to further reduce space, but more expensive to decode
- Cost of decoding on-the-fly?

Ligra+ Performance





- Cost of decoding on-the-fly?
- Memory subsystem is a scalability bottleneck in parallel as these graph algorithms are memory-bound
- Ligra+ decoding gets better parallel speed up

Ligra Summary

VertexSubset | VertexMap | EdgeMap

Optimizations: Hybrid traversal and graph compression

Breadth-first search	Single-source shortest paths
Betweenness centrality	Eccentricity estimation
Connected components	(Personalized) PageRank
Triangle counting	Local graph clustering
K-core decomposition	Biconnected components
Maximal independent set	Collaborative filtering
…	…

Simplicity, Performance, Scalability

Thank you!

J. Shun and G. E. Blelloch. Ligra: *A Lightweight Graph Processing Framework for Shared Memory*, Principles and Practice of Parallel Programming, 2013.

J. Shun, L. Dhulipala and G. E. Blelloch. Smaller and Faster: *Parallel Processing of Compressed Graphs with Ligra+*, Data Compression Conference, 2015.

Code: https://github.com/jshun/ligra/