High-Performance Graph Processing: Locality, Vectorization and Reduced Precision

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GRAPH ALGORITHMS

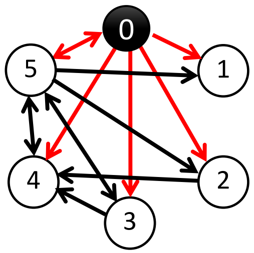
Iteratively calculate a property of each vertex in a graph

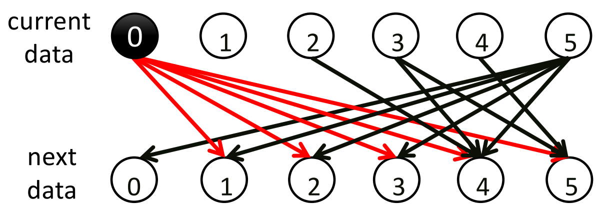
E.g.: PageRank values, label of connected components, embeddings in graph convolutional neural networks, etc.

Vertex model

Driven by frontier: set of active vertices

Many updates in parallel, with conflicts





Programming Interface

size(U : frontier) : N

returns |U|

EdgeMap(G : graph,

U : frontier,

F : (vertex × vertex) → bool,

C : vertex → bool) : frontier

VertexMap(U : frontier,

F : vertex → bool) : frontier

Ligra [Shun PPoPP'13]

Assume graph G=(V,E)

EdgeMap applies an operation F to each edge (u,v) ∈ E where u ∈ U and C(v) = true. It returns a frontier that contains all v where any call to F(u,v) returned true

VertexMap applies an operation F to each vertex v ∈ U and returns a frontier that contains v iff v ∈ U and F(v) = true

In both cases, F may have side effects, e.g., updating properties for the vertices

EXAMPLE: CONNECTED COMPONENTS

```
Graph G = ...;                                    // Graph object
VID label[G.getNumVertices()];                    // Vertex property
G.vertexmap( [&](VID v) { label[v] = v; } );      // Initialise unique IDs
Frontier F = Frontier::all_true();                // Set of active vertices
while( ! F.empty() ) {
        Frontier newF = G.edgemap( F,             // Selectively apply
            [&](VID src, VID dst) { return label[dst] min= label[src]; } );   // Reduction operation
                                                  // returns true if modified

        F = newF;
}
```

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Question: How to implement vertexmap and edgemap efficiently?

Part I: Non-Uniform Memory Architectures

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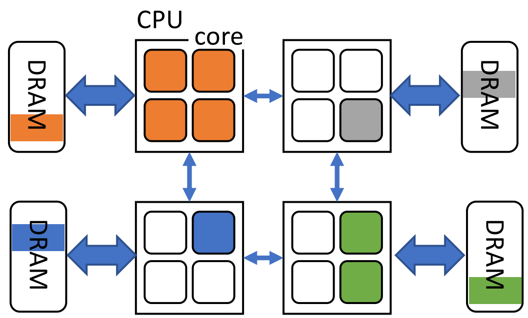
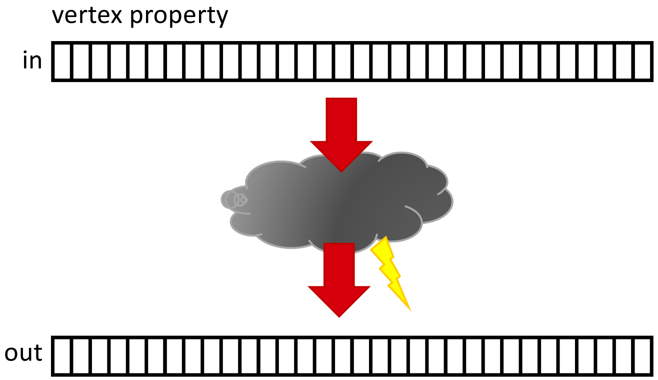
GOAL

How to map graph analytics over immutable graphs onto a NUMA architecture while minimising execution time?

Remote access has higher latency, lower bandwidth than local access

Stores are more affected than loads





EDGEMAP, VERTEXMAP AND NUMA-AWARENESS

Goal: map code and data to NUMA nodes

One type of arrays

- Properties (per vertex)

Two types of loops

- Loops over edges
- Loops over vertices

Two types of iteration

- Sparse frontier
- Dense frontier

RECAP: DATA RACES

A pair of load and store instructions, at least one of which is a store, that access the same memory location

In a concurrent program with data races, the outcome of the program may differ depending on the relative execution speed of threads

Typical solutions:

- mutual exclusion
- atomic memory operations
- owner-computes

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OWNER-COMPUTES

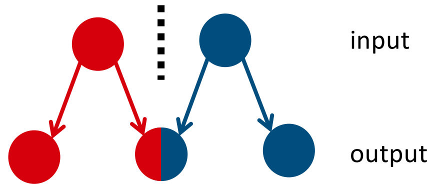
Decomposition based on partitioning input/output data is referred to as the owner computes rule

Each partition performs all the computations involving data that it owns

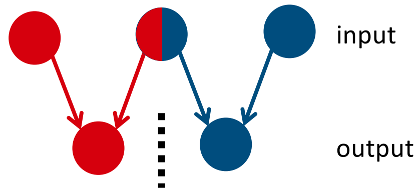
- **Input data decomposition:** A task performs all the computations that can be done using these input data
- **Output data decomposition:** A task computes all the results in the partition assigned to it

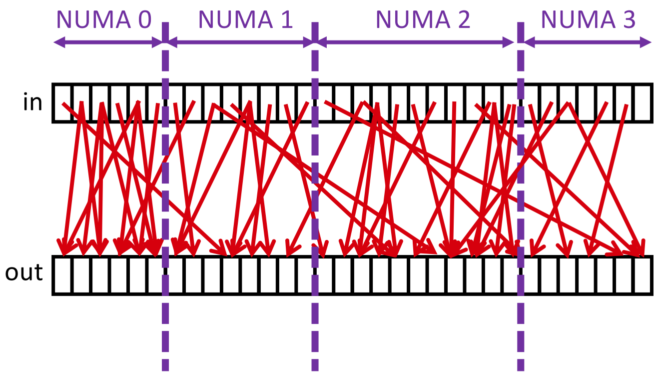
Input partitioning

Red and blue processors



Output partitioning





NUMA-AWARE LAYOUT FOR EDGEMAP

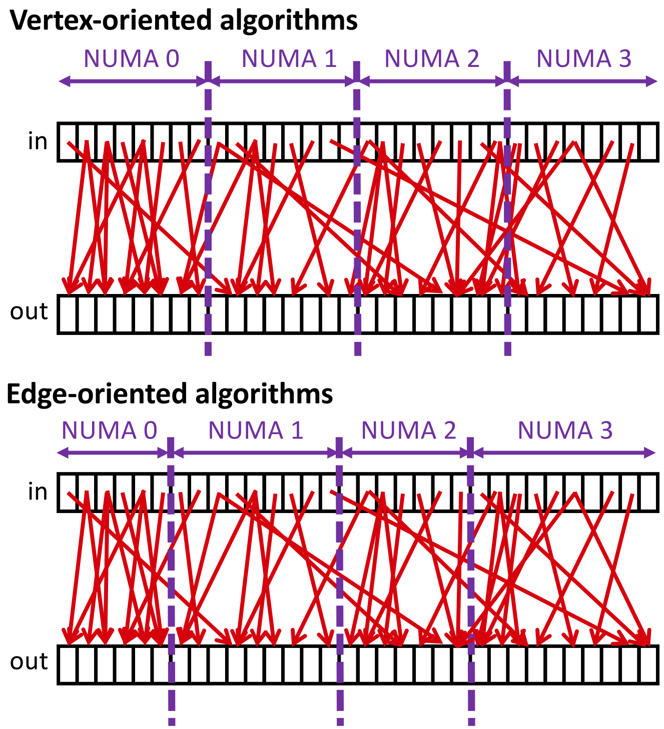
Goal

Determine cuts of { code, data } such that performance is maximised

How?

Partition graph such that each partition (NUMA node) has an equal:

1. #edges, #cuts [PowerGraph OSDI'12]
   … breaks locality
2. #sources [X-stream SOSP'13]
   … remote updates
3. #edges [Polymer PPoPP '15]
4. (α #destinations + #edges) [Gemini OSDI'16]



NUMA-AWARE LAYOUT FOR EDGEMAP

It depends! [GraphGrind ICS'17]

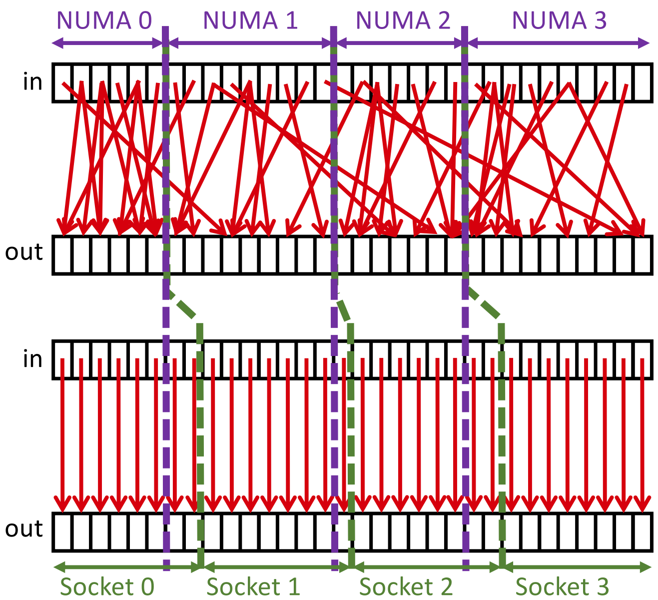
"Vertex-oriented" algorithms

- Best performance with equal #destinations
- Frontier density mostly below 50%
- BFS, Betweenness Centrality, Bellman-Ford

"Edge-oriented" algorithms

- Best performance with equal #edges
- Frontier density mostly close to 100%
- PageRank, SpMV, Belief Prop., PageRankDelta

Edge-oriented algorithms



NUMA-AWARE LAYOUT FOR VERTEXMAP

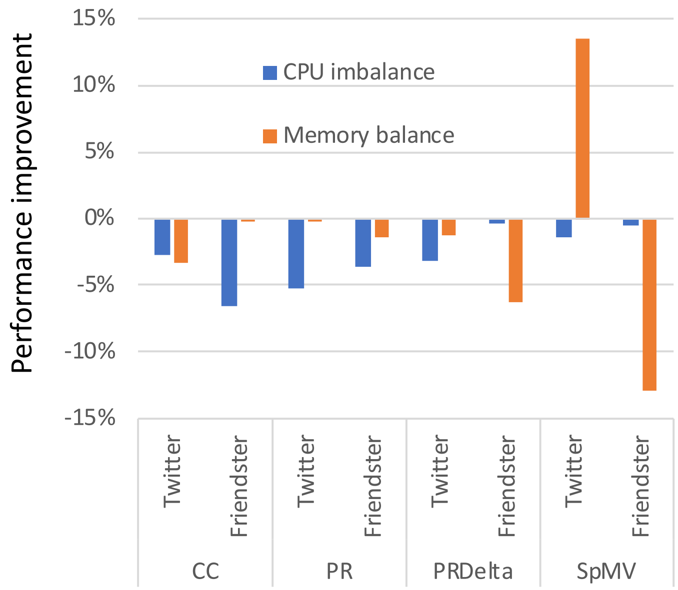
"Vertex-oriented" algorithms

- Trivial

"Edge-oriented" algorithms

- Need to choose between balancing compute and minimising traffic across NUMA nodes
- Better to balance compute and incur additional inter-node traffic [GraphGrind ICS'17]
- Consequently, data is partitioned the same way as compute in edgemap, but differently in vertexmap

4-socket 2.6GHz Intel Xeon E7-4860 v2, 48 threads, 256 GiB

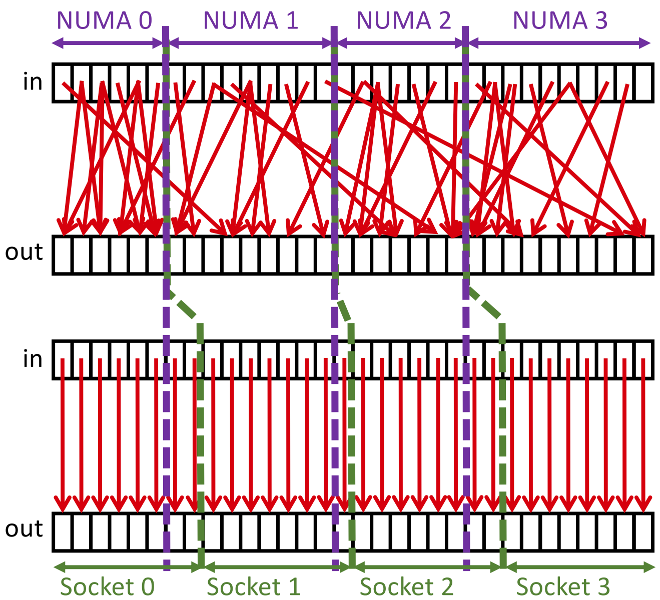


J. Sun, H. Vandierendonck and D. S. Nikolopoulos,
”GraphGrind: addressing load imbalance of graph partitioning”, ICS’17

NUMA-AWARENESS CHOICES

- Baseline is CPU balance and memory imbalance
  - Implies remote accesses during vertex map
- CPU imbalance
  - No remote accesses during vertex map
- Memory balance
  - No remote accesses during vertex map
  - Many remote accesses during edge map

Edge-oriented algorithms

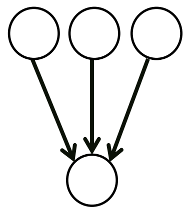


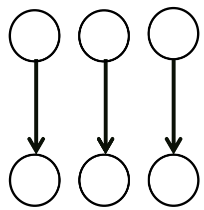
CAN WE MEET BOTH REQUIREMENTS?

Have our cake and eat it too!

LOAD BALANCE

Revisiting edge balance:
Two partitions with 3 edges
Which partition is processed faster?



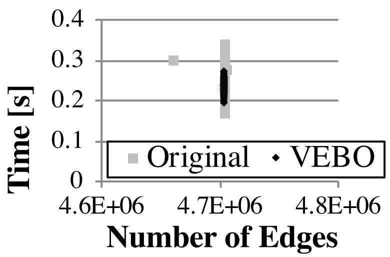


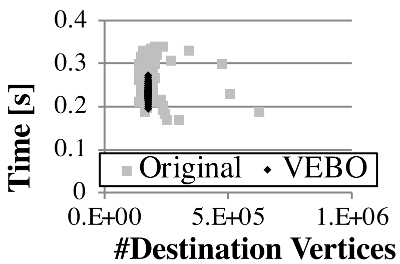
Execution time/partition highly dependent on the degree of vertices

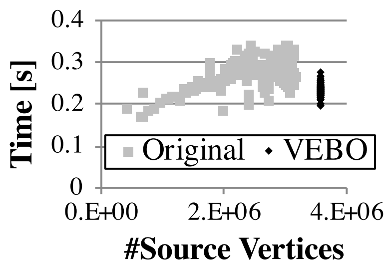
Reorder vertices

- in order of decreasing in-degree
- using list scheduling

VEBO: Vertex and Edge Balanced Partitioning

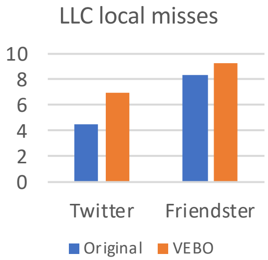


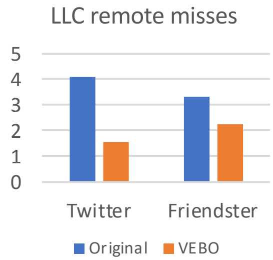


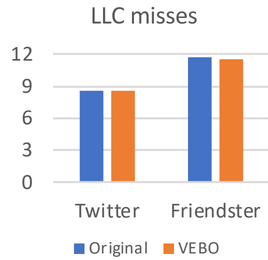


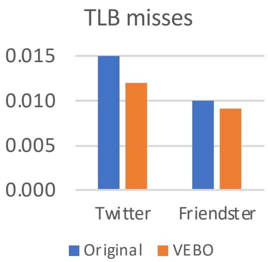
Friendster
PageRank

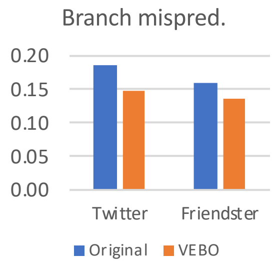
VEBO BENEFITS











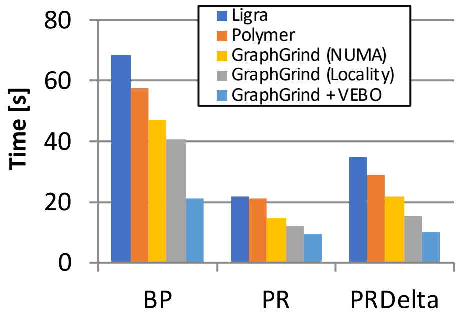
All metrics per thousand instructions

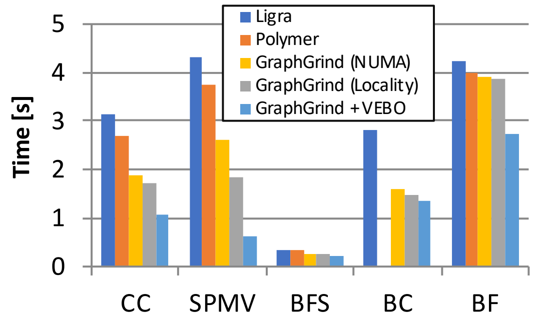
Partitions are processed faster as a side-effect of reordering

Remote cache misses are traded for local misses

PageRank

PERFORMANCE





Comparing Ligra, Polymer (NUMA-aware), and 3 versions of GraphGrind

Twitter graph

4-socket 2.6GHz Intel Xeon E7-4860 v2, 48 threads, 256 GiB

Similar results hold for other graphs

VEBO relabels vertex IDs to achieve load balance

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