Large Scale Graph Processing - Pregel and GraphLab

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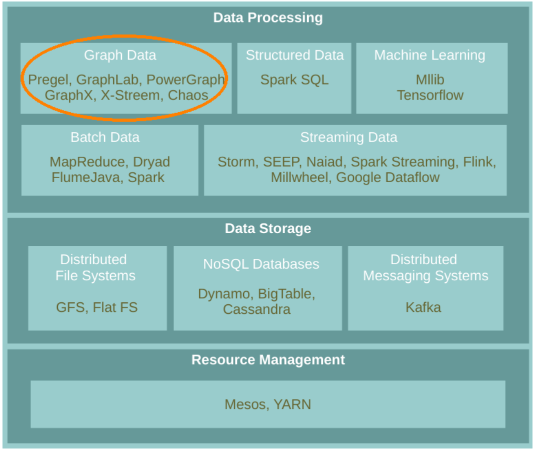
The Course Web Page

`https://id2221kth.github.io`

Where Are We?



Data Processing

Graph Data

Pregel, GraphLab, PowerGraph
GraphX, X-Streem, Chaos

Structured Data

Spark SQL

Machine Learning

Mllib
Tensorflow

Batch Data

MapReduce, Dryad
FlumeJava, Spark

Streaming Data

Storm, SEEP, Naiad, Spark Streaming, Flink,
Millwheel, Google Dataflow

Data Storage

Distributed
File Systems

GFS, Flat FS

NoSQL Databases

Dynamo, BigTable,
Cassandra

Distributed
Messaging Systems

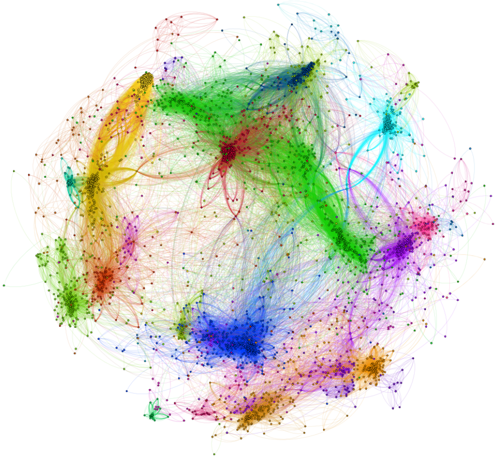
Kafka

Resource Management

Mesos, YARN

- A flexible abstraction for describing relationships between discrete objects.

Large Graph

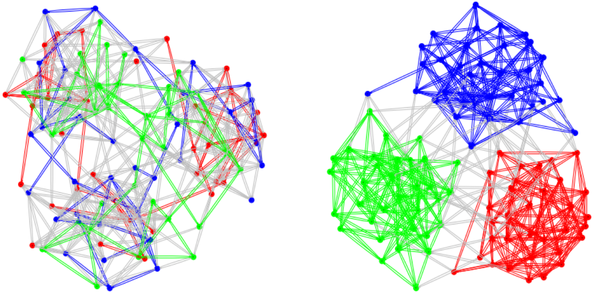


Graph Algorithms Challenges

- Difficult to extract parallelism based on partitioning of the data.
- Difficult to express parallelism based on partitioning of computation.
- Graph partition is a challenging problem.

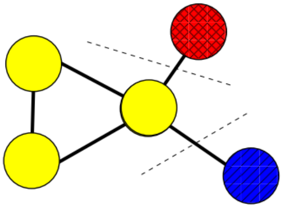
Graph Partitioning

- Partition large scale graphs and distribut to hosts.



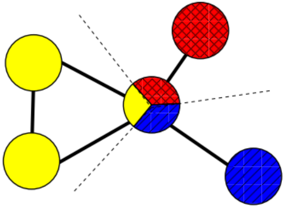
Edge-Cut Graph Partitioning

- Divide vertices of a graph into disjoint clusters.
- Nearly equal size (w.r.t. the number of vertices).
- With the minimum number of edges that span separated clusters.



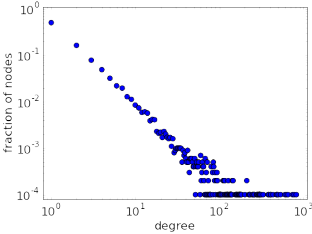
Vertex-Cut Graph Partitioning

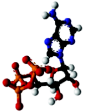
- Divide edges of a graph into disjoint clusters.
- Nearly equal size (w.r.t. the number of edges).
- With the minimum number of replicated vertices.



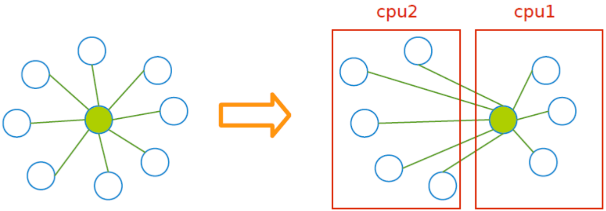
Edge-Cut vs. Vertex-Cut Graph Partitioning (1/2)

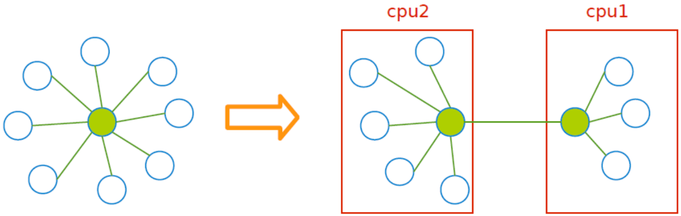
- Natural graphs: skewed Power-Law degree distribution.
- Edge-cut algorithms perform poorly on Power-Law Graphs.





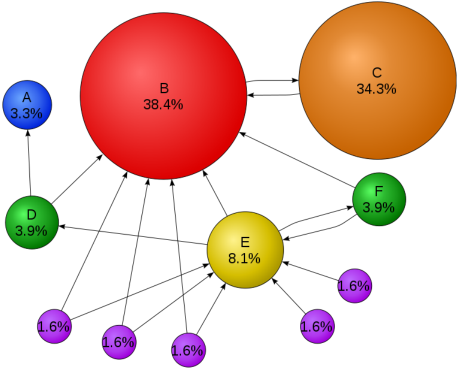
Edge-Cut vs. Vertex-Cut Graph Partitioning (2/2)





PageRank with MapReduce

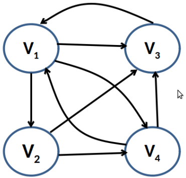
PageRank



$$\mathtt{R[i]} = \sum_{\mathtt{j \in Nbrs(i)}} \mathtt{w_{ji} R[j]}$$

PageRank Example (1/2)

- $\mathtt{R[i]} = \sum_{\mathtt{j} \in \mathtt{Nbrs(i)}} \mathtt{w_{ji}R[j]}$



- Input

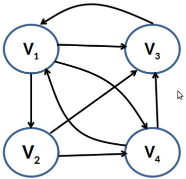
```
V1: [0.25, V2, V3, V4]
V2: [0.25, V3, V4]
V3: [0.25, V1]
V4: [0.25, V1, V3]
```

- Share the rank among all outgoing links

```
V1: (V2, 0.25/3), (V3, 0.25/3), (V4, 0.25/3)
V2: (V3, 0.25/2), (V4, 0.25/2)
V3: (V1, 0.25/1)
V4: (V1, 0.25/2), (V3, 0.25/2)
```

PageRank Example (2/2)

- $\mathtt{R[i]} = \sum_{\mathtt{j \in Nbrs(i)}} \mathtt{w_{ji} R[j]}$



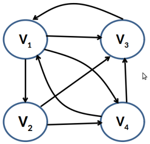
```
V1: (V2, 0.25/3), (V3, 0.25/3), (V4, 0.25/3)
V2: (V3, 0.25/2), (V4, 0.25/2)
V3: (V1, 0.25/1)
V4: (V1, 0.25/2), (V3, 0.25/2)
```

- Output after one iteration

```
V1: [0.37, V2, V3, V4]
V2: [0.08, V3, V4]
V3: [0.33, V1]
V4: [0.20, V1, V3]
```

PageRank in MapReduce - Map (1/2)

- Map function

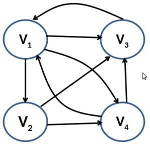


```
map(key: [url, pagerank], value: outlink_list)
  for each outlink in outlink_list:
        emit(key: outlink, value: pagerank / size(outlink_list))

  emit(key: url, value: outlink_list)
```

- Input (key, value)

```
((V1, 0.25), [V2, V3, V4])
((V2, 0.25), [V3, V4])
((V3, 0.25), [V1])
((V4, 0.25), [V1, V3])
```

PageRank in MapReduce - Map (2/2)



- Map function

```
map(key: [url, pagerank], value: outlink_list)
  for each outlink in outlink_list:
        emit(key: outlink, value: pagerank / size(outlink_list))

  emit(key: url, value: outlink_list)
```

- Intermediate (key, value)

```
(V2, 0.25/3), (V3, 0.25/3), (V4, 0.25/3), (V3, 0.25/2), (V4, 0.25/2), (V1, 0.25/1),
(V1, 0.25/2), (V3, 0.25/2)
(V1, [V2, V3, V4])
(V2, [V3, V4])
(V3, [V1])
(V4, [V1, V3])
```

PageRank in MapReduce - Shuffle

- Intermediate (key, value)

```
(V2, 0.25/3), (V3, 0.25/3), (V4, 0.25/3), (V3, 0.25/2), (V4, 0.25/2), (V1, 0.25/1),
(V1, 0.25/2), (V3, 0.25/2)
(V1, [V2, V3, V4])
(V2, [V3, V4])
(V3, [V1])
(V4, [V1, V3])
```

- After shuffling

```
(V1, 0.25/1), (V1, 0.25/2), (V1, [V2, V3, V4])
(V2, 0.25/3), (V2, [V3, V4])
(V3, 0.25/3), (V3, 0.25/2), (V3, 0.25/2), (V3, [V1])
(V4, 0.25/3), (V4, 0.25/2), (V4, [V1, V3])
```

PageRank in MapReduce - Reduce (1/2)

- Reduce function

```
reducer(key: url, value: list_pr_or_urls)
  outlink_list = []
  pagerank = 0

  for each pr_or_urls in list_pr_or_urls:
    if is_list(pr_or_urls):
      outlink_list = pr_or_urls
    else
      pagerank += pr_or_urls

  emit(key: [url, pagerank], value: outlink_list)
```

- Input of the Reduce function

```
(V1, 0.25/1), (V1, 0.25/2), (V1, [V2, V3, V4])
(V2, 0.25/3), (V2, [V3, V4])
(V3, 0.25/3), (V3, 0.25/2), (V3, 0.25/2), (V3, [V1])
(V4, 0.25/3), (V4, 0.25/2), (V4, [V1, V3])
```

PageRank in MapReduce - Reduce (2/2)

- Reduce function

```
reducer(key: url, value: list_pr_or_urls)
  outlink_list = []
  pagerank = 0

  for each pr_or_urls in list_pr_or_urls:
    if is_list(pr_or_urls):
      outlink_list = pr_or_urls
    else
      pagerank += pr_or_urls

  emit(key: [url, pagerank], value: outlink_list)
```

- Output

```
((V1, 0.37), [V2, V3, V4])
((V2, 0.08), [V3, V4])
((V3, 0.33), [V1])
((V4, 0.20), [V1, V3])
```

Problems with MapReduce for Graph Analytics

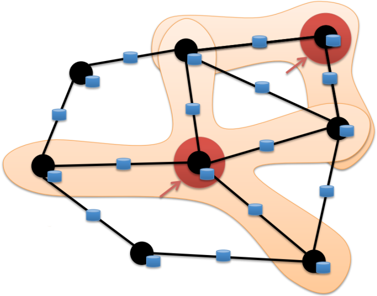
- MapReduce does not directly support iterative algorithms.
  - Invariant graph-topology-data re-loaded and re-processed at each iteration is wasting I/O, network bandwidth, and CPU

- Materializations of intermediate results at every MapReduce iteration harm performance.

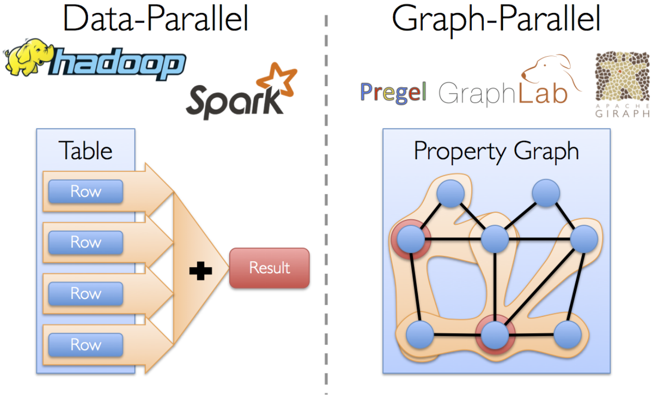
Think Like a Vertex

Think Like a Vertex

- Each vertex computes individually its value (in parallel).
- Computation typically depends on the neighbors.
- Also know as graph-parallel processing model.



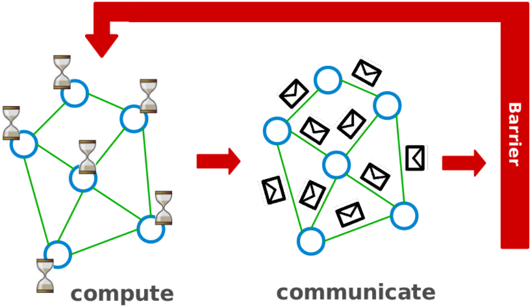
Data-Parallel vs. Graph-Parallel Computation



Pregel

Pregel

- Large-scale graph-parallel processing platform developed at Google.
- Inspired by bulk synchronous parallel (BSP) model.



Execution Model (1/2)

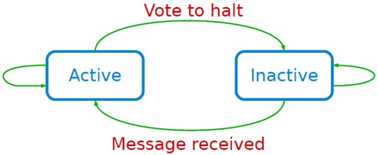
- Applications run in sequence of iterations, called supersteps.

- A vertex in superstep `S` can:
  - reads messages sent to it in superstep `S-1`.
  - sends messages to other vertices: receiving at superstep `S+1`.
  - modifies its state.

- Vertices communicate directly with one another by sending messages.

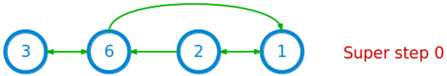
Execution Model (2/2)

- Superstep 0: all vertices are in the active state.
- A vertex deactivates itself by voting to halt: no further work to do.
- A halted vertex can be active if it receives a message.
- The whole algorithm terminates when:
  - All vertices are simultaneously inactive.
  - There are no messages in transit.



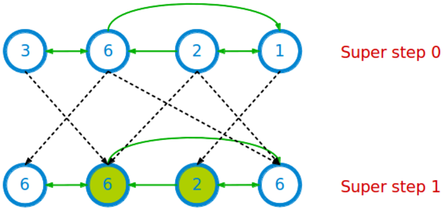
Example: Max Value (1/4)

```
i_val := val

for each message m
  if m > val then val := m

if i_val == val then
  vote_to_halt
else
  for each neighbor v
    send_message(v, val)
```



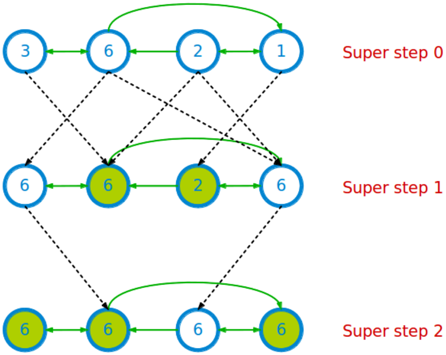
Example: Max Value (2/4)

```
i_val := val

for each message m
  if m > val then val := m

if i_val == val then
  vote_to_halt
else
  for each neighbor v
    send_message(v, val)
```



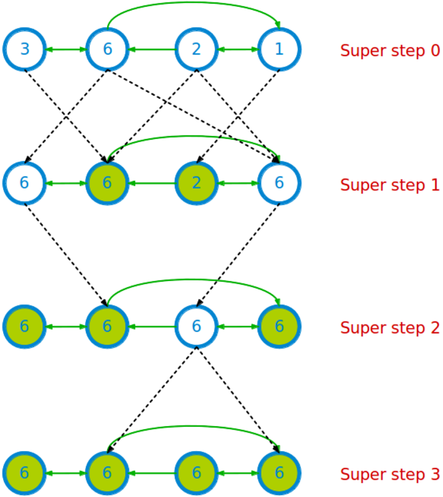
Example: Max Value (3/4)

```
i_val := val

for each message m
  if m > val then val := m

if i_val == val then
  vote_to_halt
else
  for each neighbor v
    send_message(v, val)
```

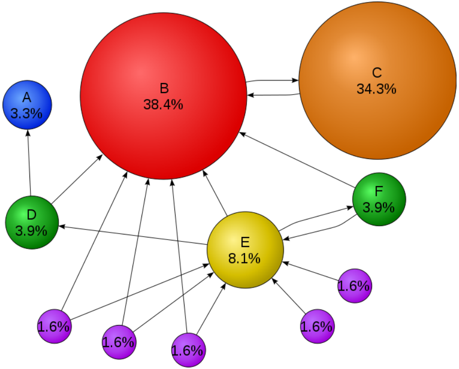


Example: Max Value (4/4)

```
i_val := val

for each message m
  if m > val then val := m

if i_val == val then
  vote_to_halt
else
  for each neighbor v
    send_message(v, val)
```



Example: PageRank



$$\mathtt{R[i]} = \sum_{\mathtt{j} \in \mathtt{Nbrs(i)}} \mathtt{w_{ji} R[j]}$$

Example: PageRank

```
Pregel_PageRank(i, messages):
  // receive all the messages
  total = 0
  foreach(msg in messages):
    total = total + msg

  // update the rank of this vertex
  R[i] = total

  // send new messages to neighbors
  foreach(j in out_neighbors[i]):
    sendmsg(R[i] * wij) to vertex j
```

$$\mathtt{R[i]} = \sum_{\mathtt{j} \in \mathtt{Nbrs(i)}} \mathtt{w_{ji}R[j]}$$

Graph Partitioning

- Edge-cut partitioning
- The pregel library divides a graph into a number of partitions.
- Each partition consists of vertices and all of those vertices' outgoing edges.
- Vertices are assigned to partitions based on their vertex-ID (e.g., hash(ID)).

System Model

- Master-worker model.

- The master
  - Coordinates workers.
  - Assigns one or more partitions to each worker.
  - Instructs each worker to perform a superstep.

- Each worker
  - Executes the local computation method on its vertices.
  - Maintains the state of its partitions.
  - Manages messages to and from other workers.

Fault Tolerance

- Fault tolerance is achieved through checkpointing.
  - Saved to persistent storage
- At start of each superstep, master tells workers to save their state:
  - Vertex values, edge values, incoming messages
- Master saves aggregator values (if any).
- When master detects one or more worker failures:
  - All workers revert to last checkpoint.

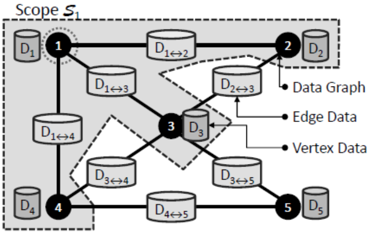
Pregel Limitations

- Inefficient if different regions of the graph converge at different speed.
- Runtime of each phase is determined by the slowest machine.

GraphLab/Turi

GraphLab

- GraphLab allows asynchronous iterative computation.
- Vertex scope of vertex v: the data stored in v, and in all adjacent vertices and edges.
- A vertex can read and modify any of the data in its scope (shared memory).



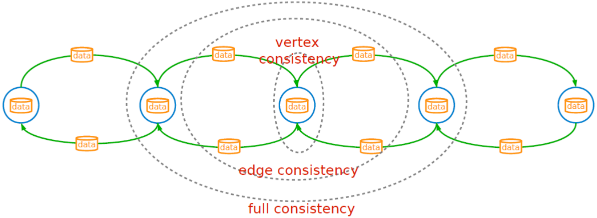
Example: PageRank (GraphLab)

```
GraphLab_PageRank(i)
  // compute sum over neighbors
  total = 0
  foreach(j in in_neighbors(i)):
    total = total + R[j] * wji

  // update the PageRank
  R[i] = total

  // trigger neighbors to run again
  foreach(j in out_neighbors(i)):
    signal vertex-program on j
```

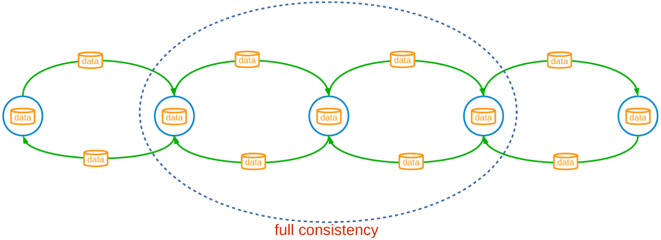
$$\mathtt{R[i]} = \sum_{\mathtt{j} \in \mathtt{Nbrs(i)}} \mathtt{w}_{\mathtt{ji}} \mathtt{R[j]}$$

Consistency (1/5)

- Overlapped scopes: race-condition in simultaneous execution of two update functions.

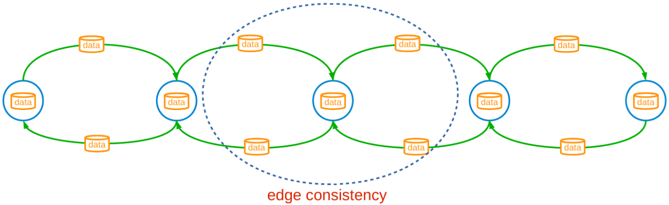


Consistency (2/5)



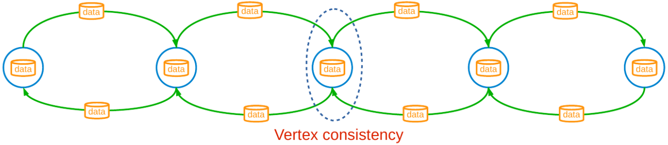
- Full consistency: during the execution `f(v)`, no other function reads or modifies data within the `v` scope.

Consistency (3/5)



- Edge consistency: during the execution `f(v)`, no other function reads or modifies any of the data on `v` or any of the edges adjacent to `v`.

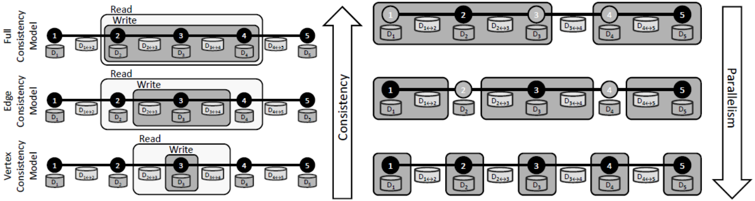
Consistency (4/5)



- Vertex consistency: during the execution `f(v)`, no other function will be applied to `v`.

Consistency (5/5)

Consistency vs. Parallelism



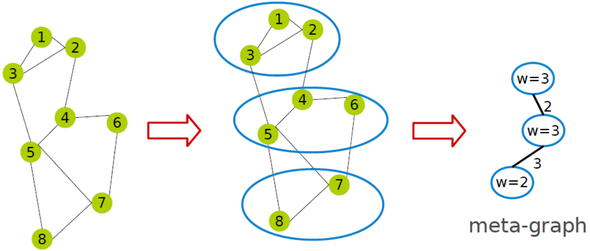
[Low, Y., GraphLab: A Distributed Abstraction for Large Scale Machine Learning (Doctoral dissertation, University of California), 2013.]

Consistency Implementation

- Distributed locking: associating a readers-writer lock with each vertex.
- Vertex consistency
  - Central vertex (write-lock)
- Edge consistency
  - Central vertex (write-lock), Adjacent vertices (read-locks)
- Full consistency
  - Central vertex (write-locks), Adjacent vertices (write-locks)
- Deadlocks are avoided by acquiring locks sequentially following a canonical order.

Graph Partitioning

- Edge-cut partitioning.
- Two-phase partitioning:
  1. Convert a large graph into a small meta-graph
  2. Partition the meta-graph

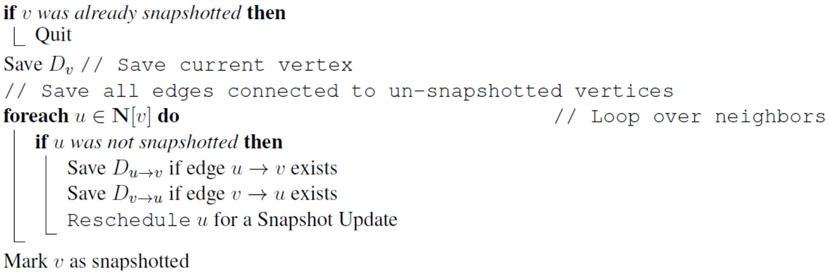


Fault Tolerance - Synchronous

- The systems periodically signals all computation activity to halt.
- Then synchronizes all caches, and saves to disk all data which has been modified since the last snapshot.
- Simple, but eliminates the systems advantage of asynchronous computation.

Fault Tolerance - Asynchronous

- Based on the Chandy-Lamport algorithm.
- The snapshot function is implemented as a function in vertices.
  - It takes priority over all other update functions.



```
if $v$ was already snapshotted then
    Quit
Save $D_v$ // Save current vertex
// Save all edges connected to un-snapshotted vertices
foreach $u \in \mathbf{N}[v]$ do                                // Loop over neighbors
    if $u$ was not snapshotted then
        Save $D_{u \to v}$ if edge $u \to v$ exists
        Save $D_{v \to u}$ if edge $v \to u$ exists
        Reschedule $u$ for a Snapshot Update
Mark $v$ as snapshotted
```

GraphLab2/Turi (PowerGraph)

PowerGraph

- Factorizes the local vertices functions into the Gather, Apply and Scatter phases.

Programming Model

- Gather-Apply-Scatter (GAS)
- Gather: accumulate information from neighborhood.
- Apply: apply the accumulated value to center vertex.
- Scatter: update adjacent edges and vertices.

Execution Model (1/2)

- Initially all vertices are active.
- It executes the vertex-program on the active vertices until none remain.
  - Once a vertex-program completes the scatter phase it becomes inactive until it is reactivated.
  - Vertices can activate themselves and neighboring vertices.
- PowerGraph can execute both synchronously and asynchronously.

Execution Model (2/2)

- Synchronous scheduling like Pregel.
  - Executing the gather, apply, and scatter in order.
  - Changes made to the vertex/edge data are committed at the end of each step.

- Asynchronous scheduling like GraphLab.
  - Changes made to the vertex/edge data during the apply and scatter functions are immediately committed to the graph.
  - Visible to subsequent computation on neighboring vertices.

Example: PageRank (PowerGraph)

```
PowerGraph_PageRank(i):
  Gather(j -> i):
    return wji * R[j]

  sum(a, b):
    return a + b

  // total: Gather and sum
  Apply(i, total):
    R[i] = total

  Scatter(i -> j):
    if R[i] changed then activate(j)
```

$$\mathtt{R[i]} = \sum_{\mathtt{j} \in \mathtt{Nbrs(i)}} \mathtt{w_{ji}R[j]}$$

Graph Partitioning (1/2)

- Vertx-cut partitioning.
- Random vertex-cuts: randomly assign edges to machines.
- Completely parallel and easy to distribute.
- High replication factor.

Graph Partitioning (2/2)

- Greedy vertex-cuts
- $\mathtt{A(v)}$: set of machines that vertex $\mathtt{v}$ spans.
- Case 1: If $\mathtt{A(u)} \cap \mathtt{A(v)} \neq \emptyset$, then the edge $(\mathtt{u}, \mathtt{v})$ should be assigned to a machine in the intersection.
- Case 2: If $\mathtt{A(u)} \cap \mathtt{A(v)} = \emptyset$, then the edge $(\mathtt{u}, \mathtt{v})$ should be assigned to one of the machines from the vertex with the most unassigned edges.
- Case 3: If only one of the two vertices has been assigned, then choose a machine from the assigned vertex.
- Case 4: If $\mathtt{A(u)} = \mathtt{A(v)} = \emptyset$, then assign the edge $(\mathtt{u}, \mathtt{v})$ to the least loaded machine.

Summary

Summary

- Think like a vertex
  - Pregel: BSP, synchronous parallel model, message passing, edge-cut
  - GraphLab: asynchronous model, shared memory, edge-cut
  - PowerGraph: synchronous/asynchronous model, GAS, vertex-cut

References

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- J. Gonzalez et al., “Powergraph: distributed graph-parallel computation on natural graphs”, OSDI 2012

Questions?