Large Scale Graph Processing

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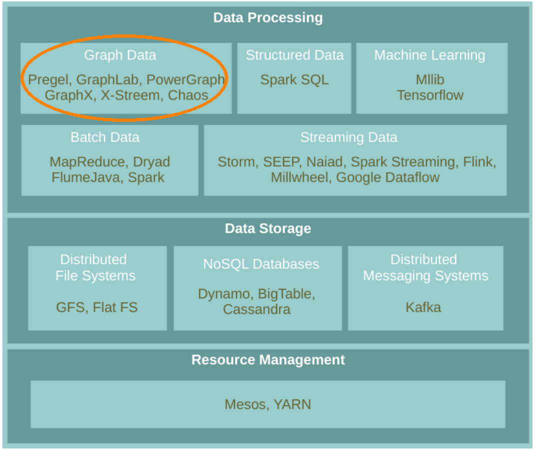
The Course Web Page

https://id2221kth.github.io

The Questions-Answers Page

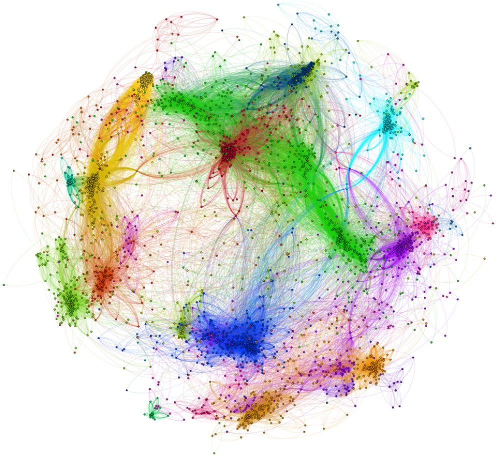
https://tinyurl.com/hk7hzpw5

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

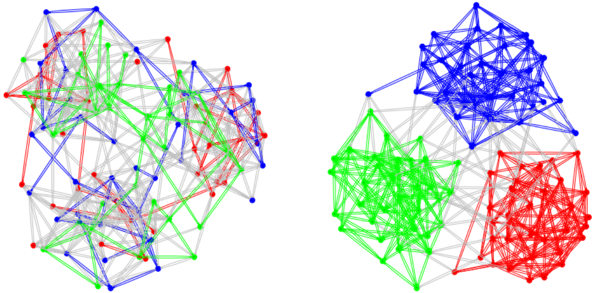
- Difficult to extract parallelism based on partitioning of the data.
- Difficult to express parallelism based on partitioning of computation.

Graph 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.

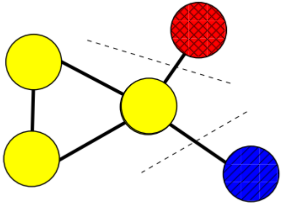
Graph Partitioning

- Partition large scale graphs and distribut to hosts.



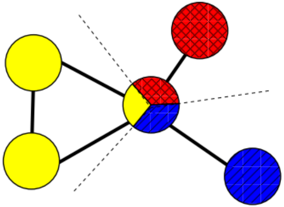
Edge-Cut Graph Partitioning

- 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.



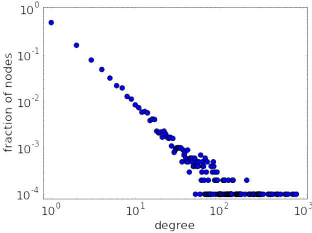
Vertex-Cut Graph Partitioning

- 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.

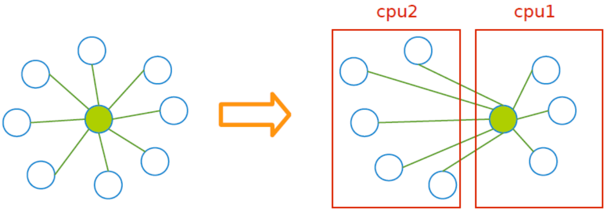


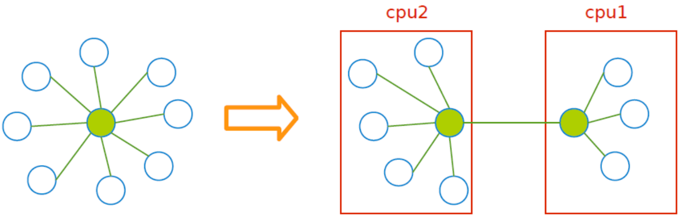
Edge-Cut vs. Vertex-Cut Graph Partitioning (1/2)

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



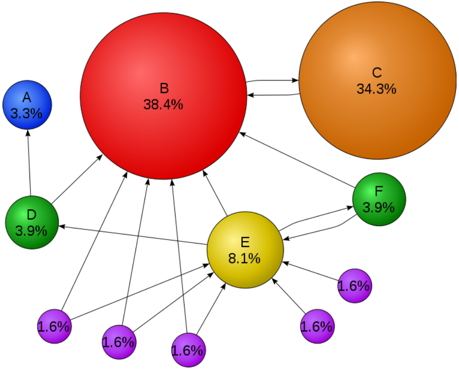
Edge-Cut vs. Vertex-Cut Graph Partitioning (2/2)





PageRank with MapReduce

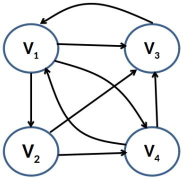
PageRank



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

PageRank Example (1/2)

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



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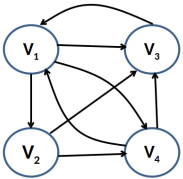
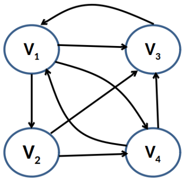


- Input

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

PageRank Example (1/2)

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



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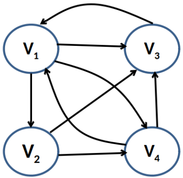
```
V1: [0.25, V2, V3, V4]
V2: [0.25, V3, V4]
V3: [0.25, V1]
V4: [0.25, V1, V3]
```

- 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)

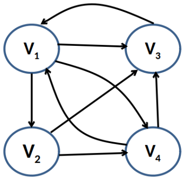
- $\mathtt{R[i]} = \sum_{\mathtt{j} \in \mathtt{Nbrs(i)}} \mathtt{w_{ji}R[j]}$




```
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)
```

PageRank Example (2/2)

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

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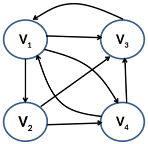
V1: (V2, 0.25/3), (V3, 0.25/3), (V4, 0.25/3)
V2: (V3, 0.25/2), (V4, 0.25/2)
V3: (V1, 0.25/1)
V4: (V1, 0.25/2), (V3, 0.25/2)
```

- 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

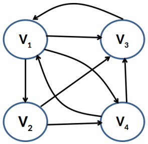



```
map(key: [url, pagerank], value: outlink_list)
  for each outlink in outlink_list:
        emit(key: outlink, value: pagerank / size(outlink_list))

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

PageRank in MapReduce - Map (1/2)

- Map function

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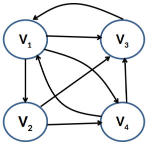
  emit(key: url, value: outlink_list)
```

- 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

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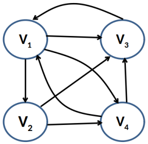


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  emit(key: url, value: outlink_list)
```

- 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)

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

PageRank in MapReduce - Shuffle

- Intermediate (key, value)

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(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)
```

PageRank in MapReduce - Reduce (1/2)

- Reduce function

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```

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

PageRank in MapReduce - Reduce (2/2)

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- Output

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

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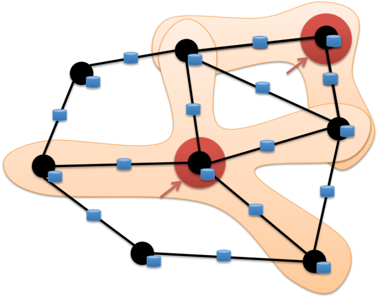
- MapReduce does not directly support iterative algorithms.
  - Invariant graph-topology-data re-loaded and re-processed at each iteration is wasting I/O, network bandwidth, and CPU

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

Think Like a Vertex

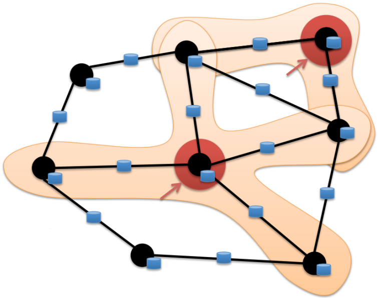
Think Like a Vertex

- Each vertex computes individually its value (in parallel).
- Computation typically depends on the neighbors.

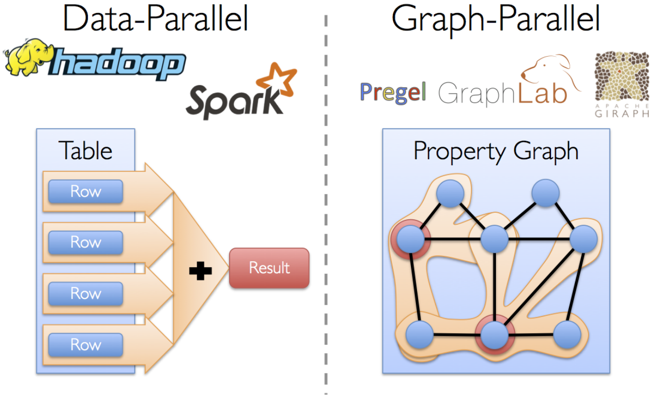


Think Like a Vertex

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



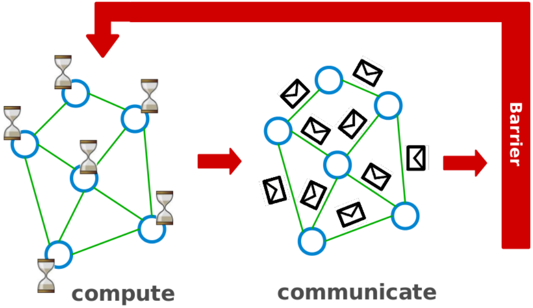
Data-Parallel vs. Graph-Parallel Computation



Pregel

Pregel

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



Execution Model (1/2)

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  - modifies its state.

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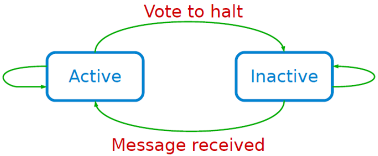
- A vertex in superstep S can:
  - reads messages sent to it in superstep S−1.
  - sends messages to other vertices: receiving at superstep S+1.
  - modifies its state.
- Vertices communicate directly with one another by sending messages.

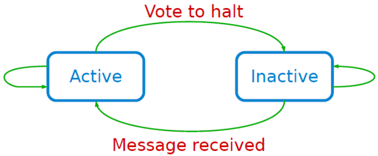
Execution Model (2/2)

- Superstep 0: all vertices are in the active state.



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.



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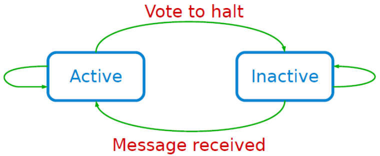
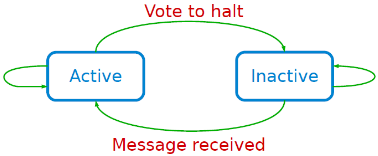


Execution Model (2/2)

- 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.

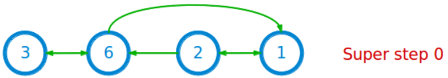


Example: Max Value (1/4)

```
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)
```



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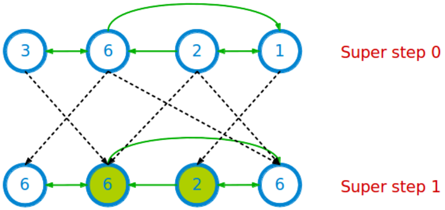
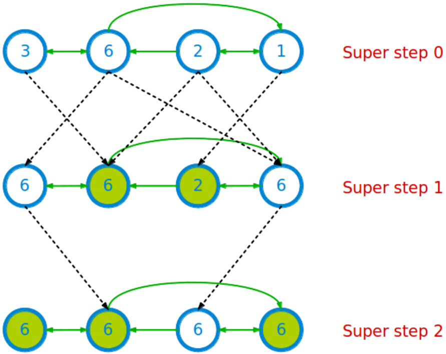


Example: Max Value (3/4)

```
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)
```

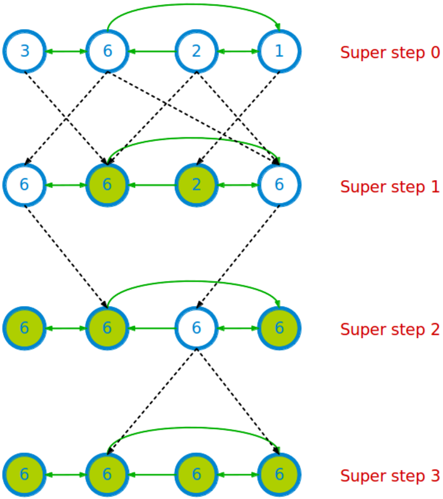


Example: Max Value (4/4)

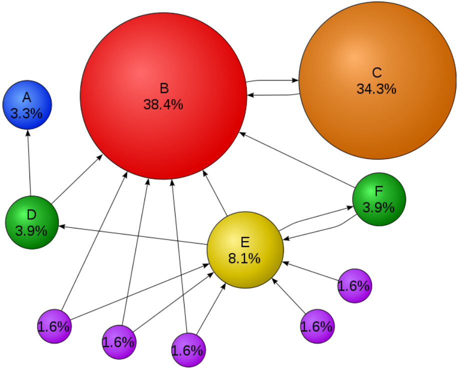
```
i_val := val

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
```

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

GraphLab/Turi

GraphLab

- GraphLab allows asynchronous iterative computation.

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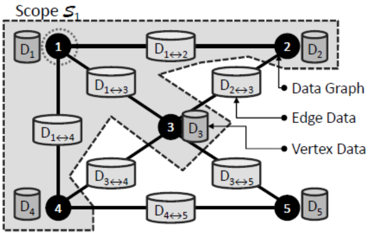
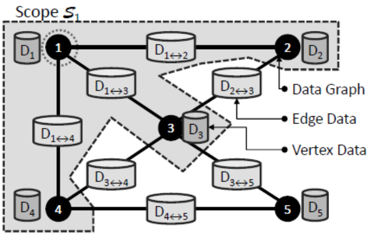
- Vertex scope of vertex v: the data stored in v, and in all adjacent vertices and edges.



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
```

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

Gather-Apply-Scatter (GAS)

- Factorizes the local vertices functions into the Gather, Apply and Scatter phases.
- Gather: accumulate information from neighborhood.
- Apply: apply the accumulated value to center vertex.
- Scatter: update adjacent edges and vertices.

Example: PageRank (GraphLab - GAS)

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

  sum(a, b):
    return a + b

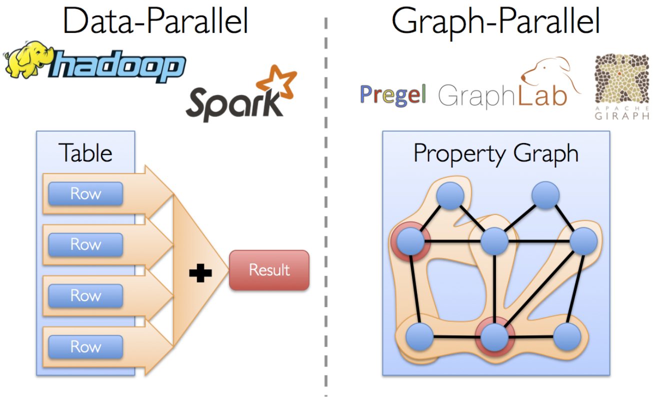
  // total: Gather and sum
  Apply(i, total):
    R[i] = total

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

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

Think Like a Table

Data-Parallel vs. Graph-Parallel Computation

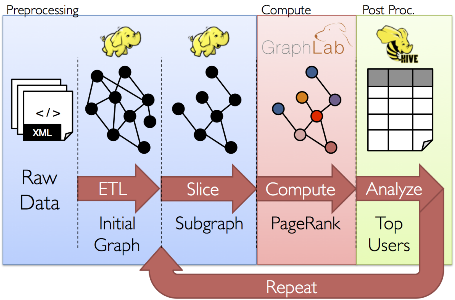


Motivation (2/3)

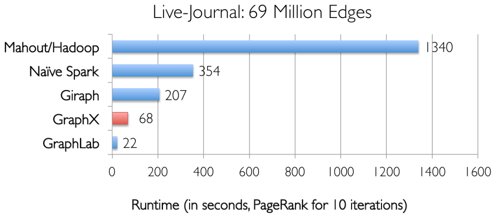
- Graph-parallel computation: restricting the types of computation to achieve performance.

Motivation (2/3)

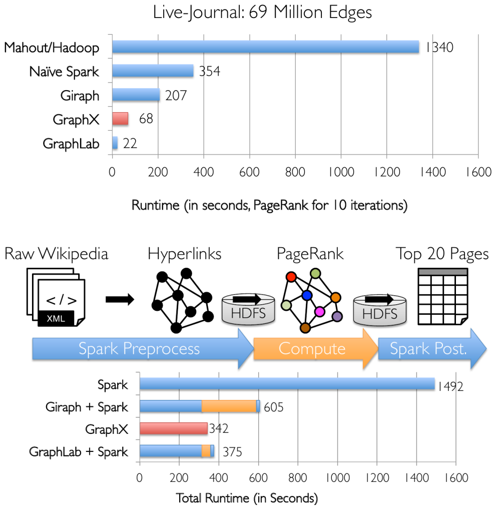
- Graph-parallel computation: restricting the types of computation to achieve performance.
- The same restrictions make it difficult and inefficient to express many stages in a typical graph-analytics pipeline.



Motivation (3/3)

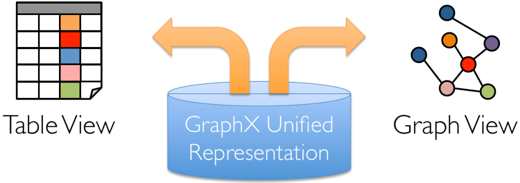


Motivation (3/3)



Think Like a Table

- Unifies data-parallel and graph-parallel systems.
- Tables and Graphs are composable views of the same physical data.



GraphX

GraphX

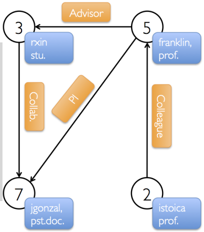
- GraphX is the library to perform graph-parallel processing in Spark.

The Property Graph Data Model

- Spark represent graph structured data as a property graph.
- It is logically represented as a pair of vertex and edge property collections.
  - `VertexRDD` and `EdgeRDD`

```scala
// VD: the type of the vertex attribute
// ED: the type of the edge attribute
class Graph[VD, ED] {
  val vertices: VertexRDD[VD]
  val edges: EdgeRDD[ED]
}
```

Property Graph



Vertex Table

Id	Property (V)
3	(rxin, student)
7	(jgonzal, postdoc)
5	(franklin, professor)
2	(istoica, professor)

Edge Table

SrcId	DstId	Property (E)
3	7	Collaborator
5	3	Advisor
2	5	Colleague
5	7	PI

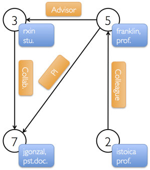
The Vertex Collection

- VertexRDD: contains the vertex properties keyed by the vertex ID.

```scala
class Graph[VD, ED] {
  val vertices: VertexRDD[VD]
  val edges: EdgeRDD[ED]
}

// VD: the type of the vertex attribute
abstract class VertexRDD[VD] extends RDD[(VertexId, VD)]
```

Property Graph



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Vertices: 

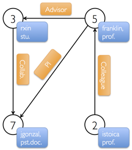
The Edge Collection

- EdgeRDD: contains the edge properties keyed by the source and destination vertex IDs.

```scala
class Graph[VD, ED] {
  val vertices: VertexRDD[VD]
  val edges: EdgeRDD[ED]
}

// ED: the type of the edge attribute
case class Edge[ED](srcId: VertexId, dstId: VertexId, attr: ED)
abstract class EdgeRDD[ED] extends RDD[Edge[ED]]
```

Property Graph



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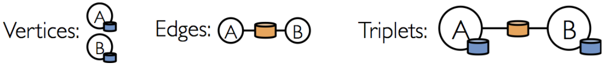
Edges: 

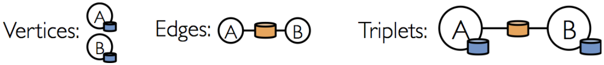
The Triplet Collection

- The triplets collection consists of each edge and its corresponding source and destination vertex properties.



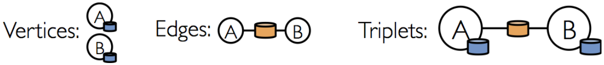
The Triplet Collection

- The triplets collection consists of each edge and its corresponding source and destination vertex properties.
- It logically joins the vertex and edge properties: `RDD[EdgeTriplet[VD, ED]]`.



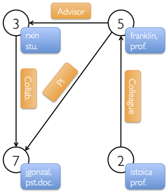
The Triplet Collection

- The triplets collection consists of each edge and its corresponding source and destination vertex properties.
- It logically joins the vertex and edge properties: `RDD[EdgeTriplet[VD, ED]]`.
- The `EdgeTriplet` class extends the `Edge` class by adding the `srcAttr` and `dstAttr` members, which contain the source and destination properties respectively.



Building a Property Graph

Property Graph



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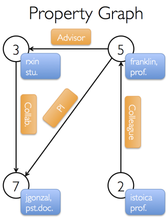
```scala
val users: RDD[(VertexId, (String, String))] = sc.parallelize(Array((3L, ("rxin", "student")),
  (7L, ("jgonzal", "postdoc")), (5L, ("franklin", "prof")), (2L, ("istoica", "prof"))))
```

Building a Property Graph



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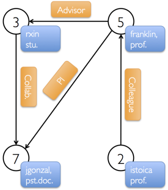
```scala
val relationships: RDD[Edge[String]] = sc.parallelize(Array(Edge(3L, 7L, "collab"),
  Edge(5L, 3L, "advisor"), Edge(2L, 5L, "colleague"), Edge(5L, 7L, "pi"), Edge(5L, 1L, "-")))
```

Building a Property Graph

Property Graph



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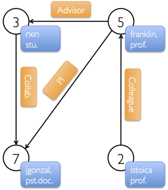
```

```
val defaultUser = ("John Doe", "Missing")
```

Building a Property Graph

Property Graph



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```

```
val defaultUser = ("John Doe", "Missing")
```

```
val graph: Graph[(String, String), String] = Graph(users, relationships, defaultUser)
```

Graph Operators

- Information about the graph
- Property operators
- Structural operators
- Joins
- Aggregation
- Iterative computation
- ...

Summary

Summary

- Think like a vertex
  - Pregel: BSP, synchronous parallel model, message passing
  - GraphLab: asynchronous model, shared memory, GAS
- Think like a table
  - Graphx: unifies data-parallel and graph-parallel systems.

References

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- Y. Low et al., “Distributed GraphLab: a framework for machine learning and data mining in the cloud”, VLDB 2012
- J. Gonzalez et al., “Powergraph: distributed graph-parallel computation on natural graphs”, OSDI 2012
- J. Gonzalez et al., “GraphX: Graph Processing in a Distributed Dataflow Framework”, OSDI 2014

Questions?