



Large Scale Graph Processing

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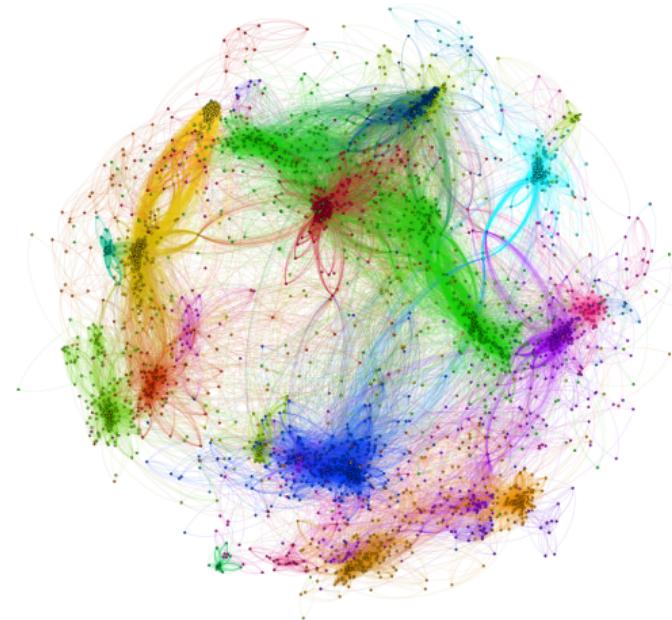




- ▶ A **flexible abstraction** for describing relationships between **discrete objects**.



Large Graph





Graph Algorithms Challenges

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

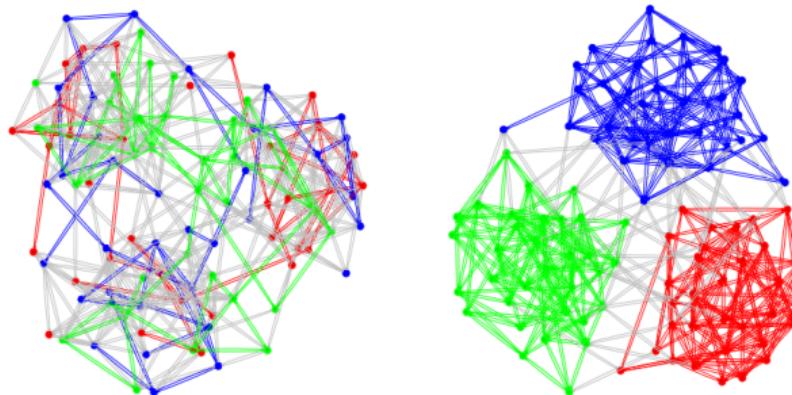


Graph Algorithms Challenges

- ▶ 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.

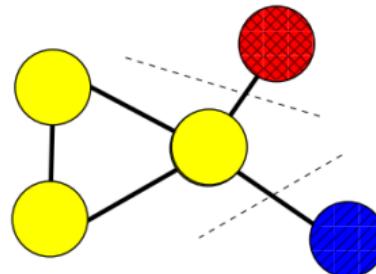
Graph Partitioning

- ▶ Partition large scale graphs and **distribut to hosts.**



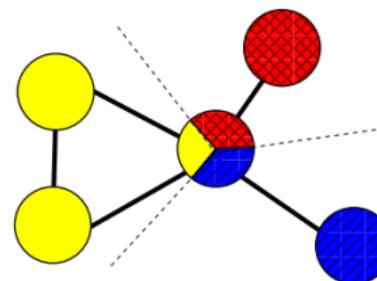
Edge-Cut Graph Partitioning

- ▶ 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.



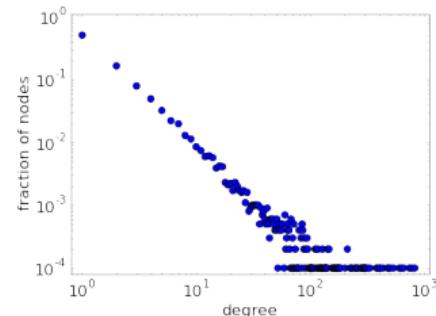
Vertex-Cut Graph Partitioning

- ▶ 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**.

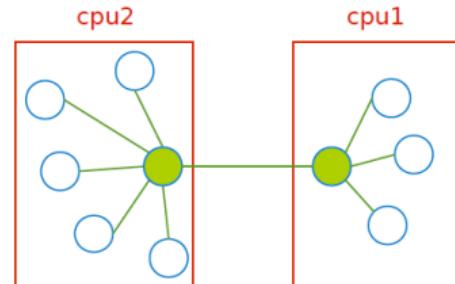
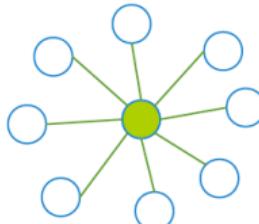
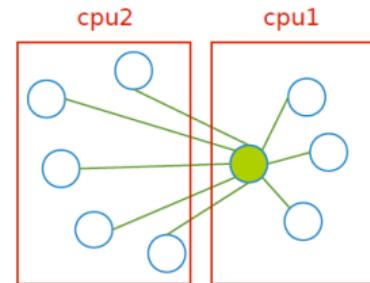
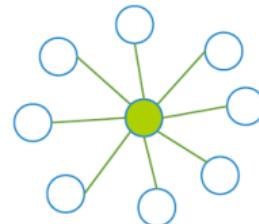


Edge-Cut vs. Vertex-Cut Graph Partitioning (1/2)

- ▶ 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)

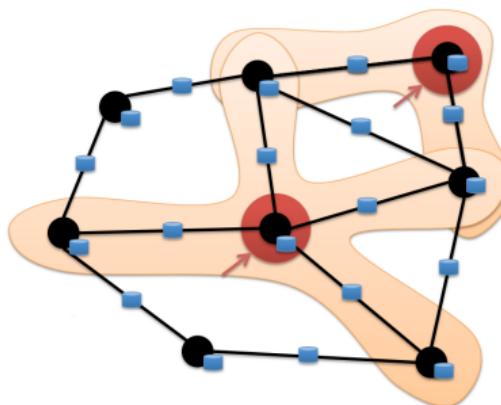




Think Like a Vertex

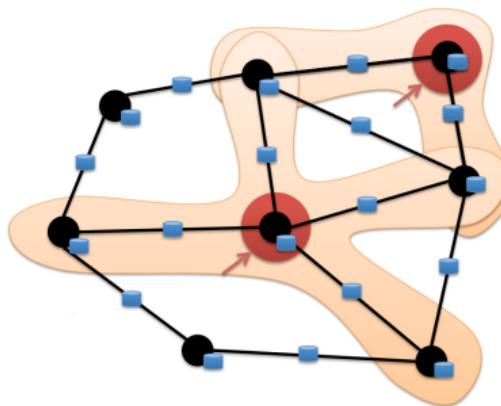
Think Like a Vertex

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

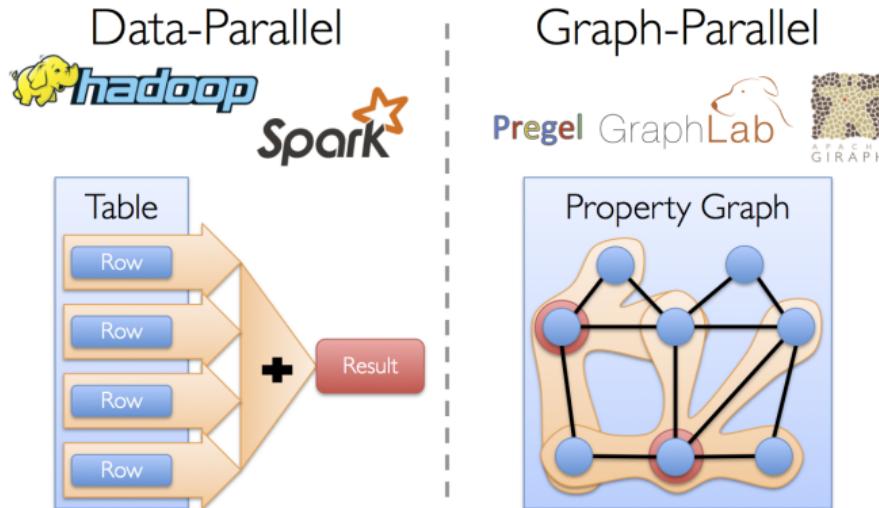


Think Like a Vertex

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



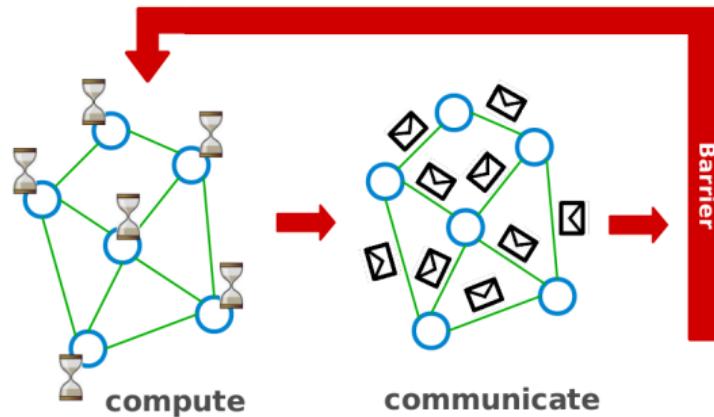
Data-Parallel vs. Graph-Parallel Computation





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**.



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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.

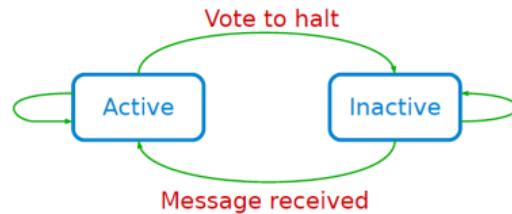


Execution Model (1/2)

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 - **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**.

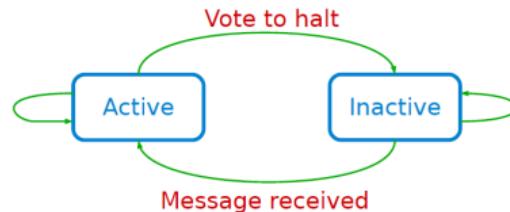
Execution Model (2/2)

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



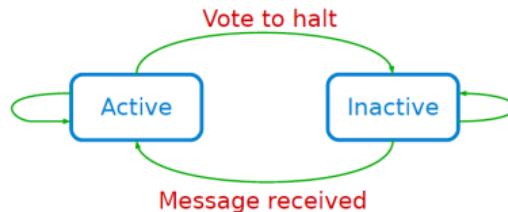
Execution Model (2/2)

- ▶ Superstep 0: all vertices are in the **active** state.
- ▶ A vertex **deactivates** itself by voting to **halt**: no further work to do.



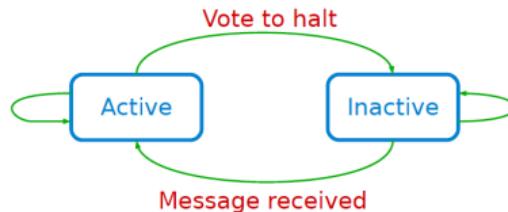
Execution Model (2/2)

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- ▶ A halted vertex can be active if it **receives a message**.



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

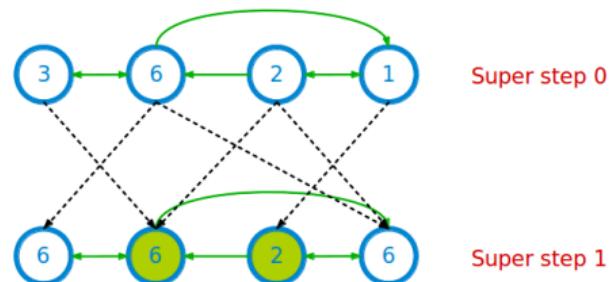
if i_val == val then
    vote_to_halt
else
    for each neighbor v
        send_message(v, val)
```



Super step 0

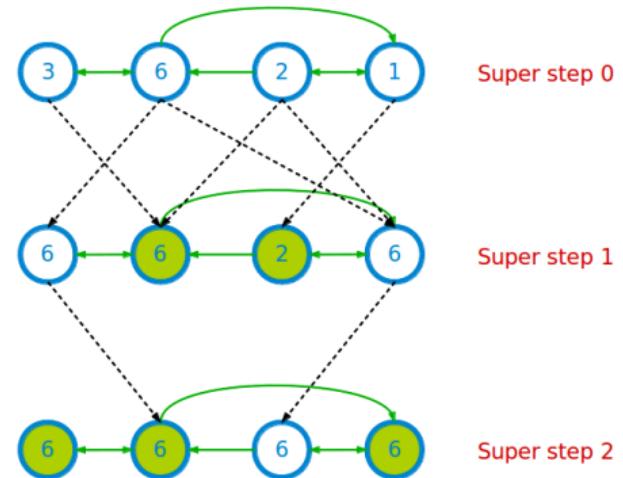
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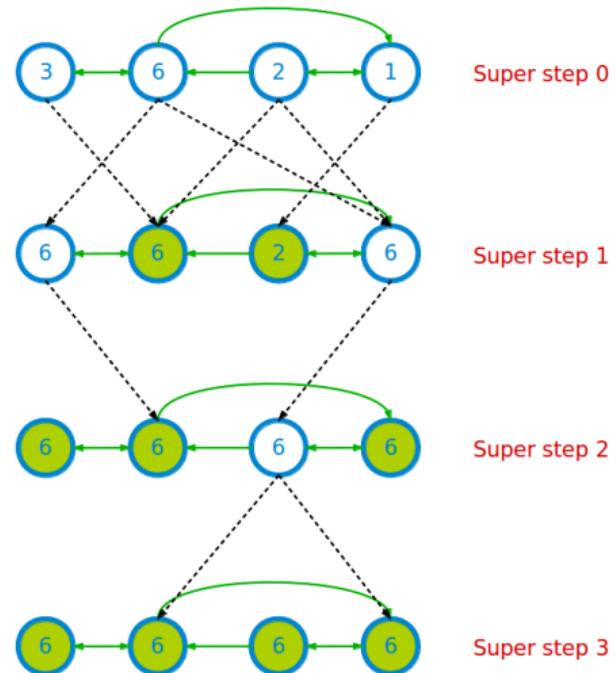
Example: Max Value (3/4)

```
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else  
  for each neighbor v  
    send_message(v, val)
```

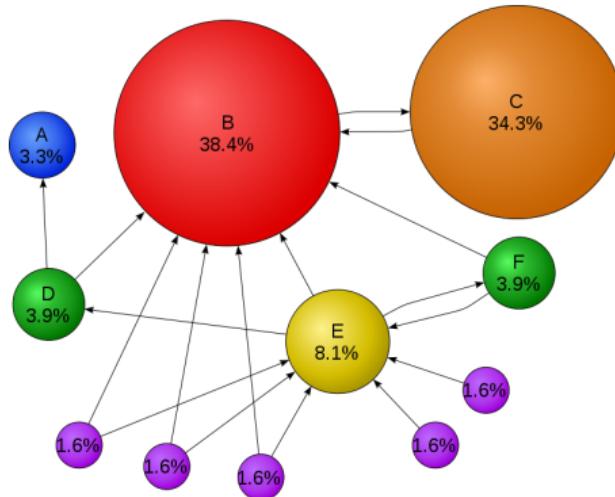


Example: Max Value (4/4)

```
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



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



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
```

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



Graph Partitioning

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- ▶ Each partition consists of vertices and all of those vertices' outgoing edges.



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., $\text{hash}(\text{ID})$).



System Model

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



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



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- ▶ At **start of each superstep**, master tells workers to **save** their state:
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Fault Tolerance

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- ▶ Master saves **aggregator values** (if any).



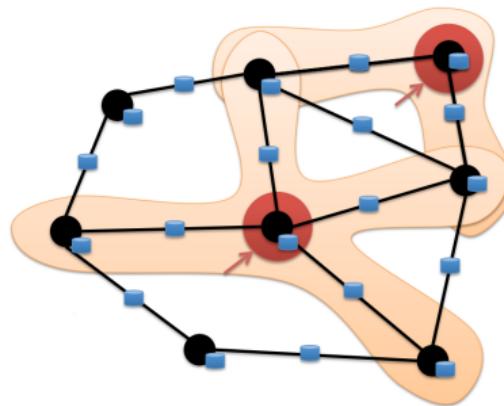
Fault Tolerance

- ▶ 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**.

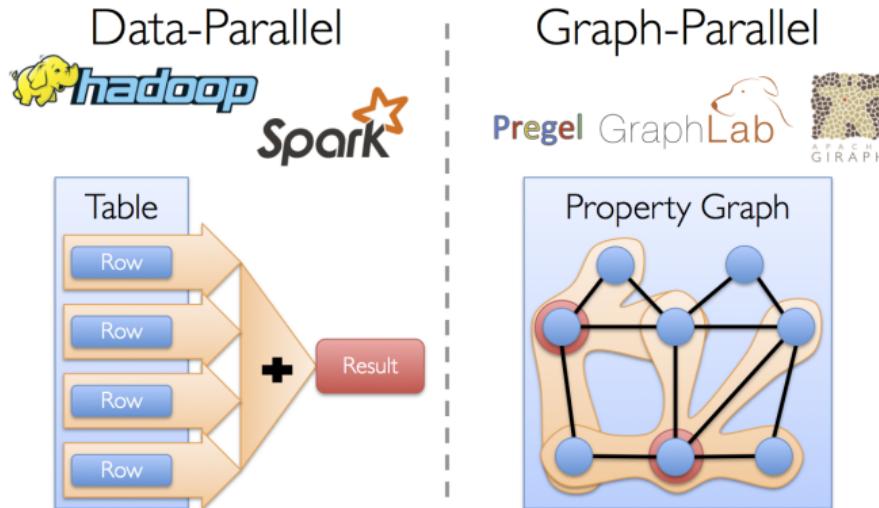


Think Like a Table

Graph-Parallel Processing Model



Data-Parallel vs. Graph-Parallel Computation



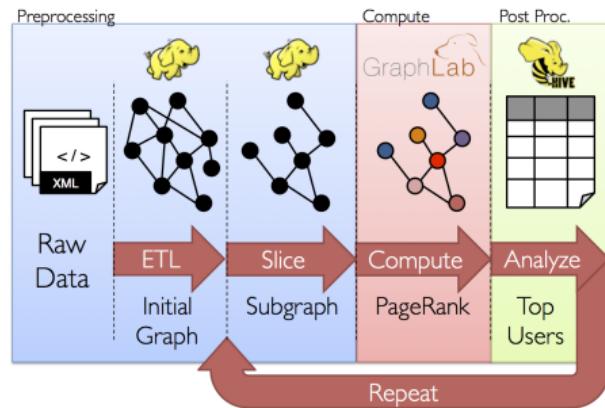


Motivation (2/3)

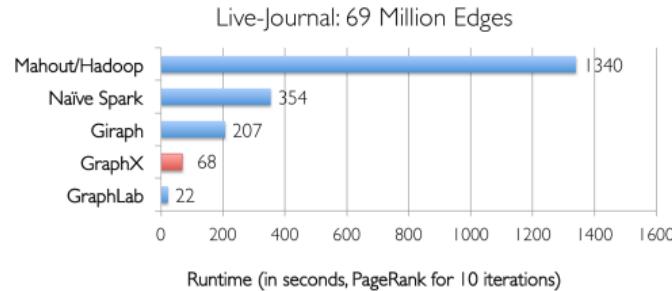
- ▶ Graph-parallel computation: **restricting** the types of computation to achieve **performance**.

Motivation (2/3)

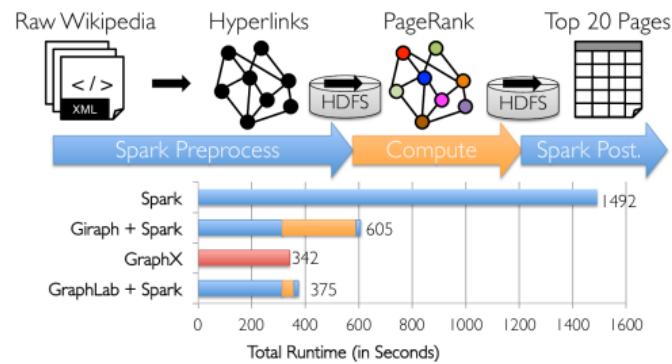
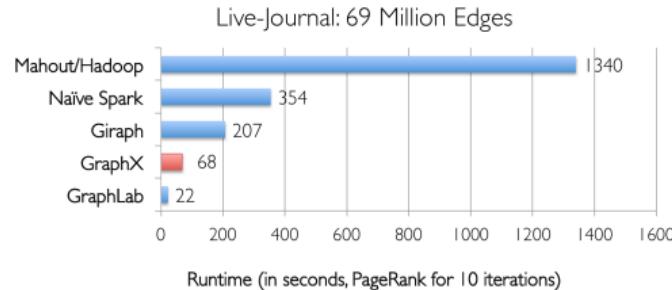
- ▶ Graph-parallel computation: **restricting** the types of computation to achieve **performance**.
- ▶ The same restrictions make it **difficult** and **inefficient** to express many stages in a typical graph-analytics **pipeline**.



Motivation (3/3)

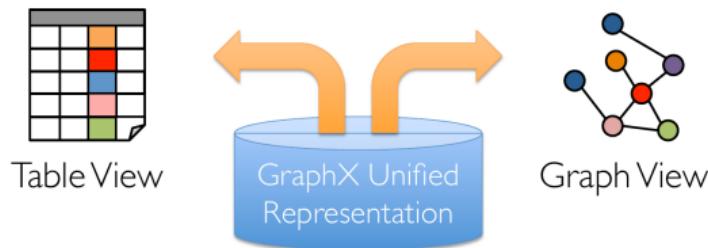


Motivation (3/3)



Think Like a Table

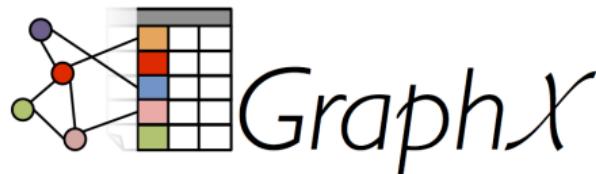
- ▶ Unifies **data-parallel** and **graph-parallel** systems.
- ▶ **Tables** and **Graphs** are **composable views** of the **same physical data**.





GraphX

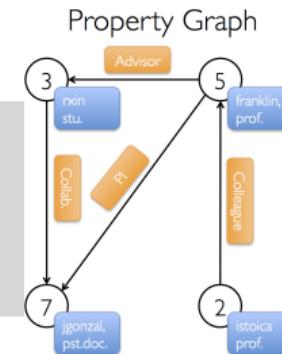
- ▶ GraphX is the library to perform graph-parallel processing in Spark.
- ▶ In-memory caching.
- ▶ Lineage-based fault tolerance.



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**

```
// 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]
}
```



Vertex Table

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

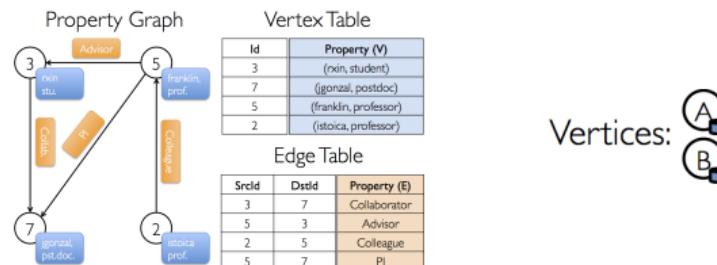
Edge Table

SrcId	DstdId	Property (E)
3	7	Collaborator
5	3	Adviser
2	5	Colleague
5	7	Pi

The Vertex Collection

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

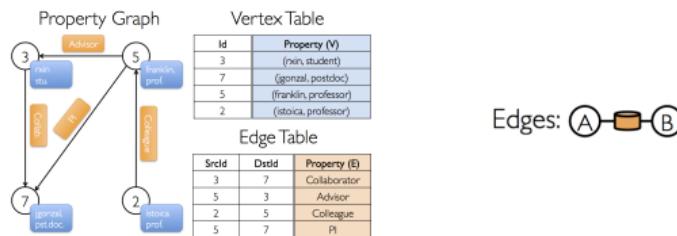
```
class Graph[VD, ED] {  
    val vertices: VertexRDD[VD]  
    val edges: EdgeRDD[ED]  
}  
  
// VD: the type of the vertex attribute  
abstract class VertexRDD[VD] extends RDD[(VertexId, VD)]
```



The Edge Collection

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

```
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]]
```



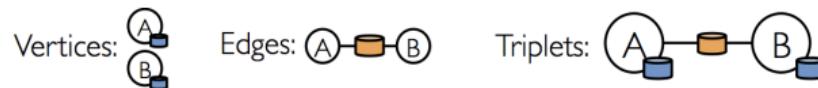
The Triplet Collection

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



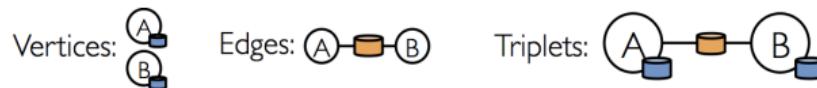
The Triplet Collection

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- ▶ It logically joins the **vertex and edge properties**: `RDD[EdgeTriplet[VD, ED]]`.

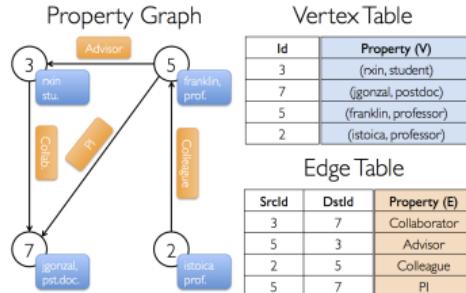


The Triplet Collection

- ▶ 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.

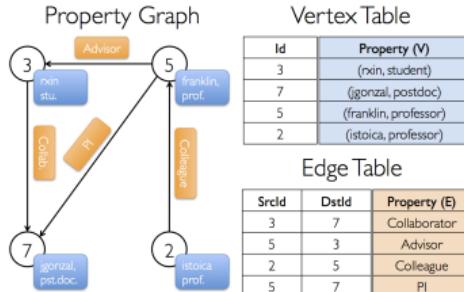


Building a Property Graph



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

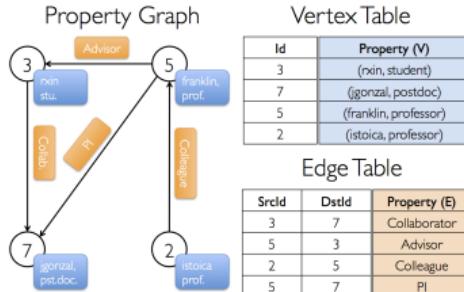
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```
val relationships: RDD[Edge[String]] = sc.parallelize(Array(Edge(3L, 7L, "collab"),  
    Edge(5L, 3L, "advisor"), Edge(2L, 5L, "colleague"), Edge(5L, 7L, "pi"), Edge(5L, 1L, "-")))
```

Building a Property Graph

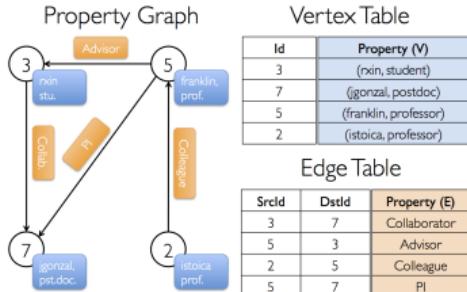


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```
val defaultUser = ("John Doe", "Missing")
```

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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
- ▶ ...



Information About The Graph (1/2)

- ▶ Information about the graph

```
val numEdges: Long
val numVertices: Long
val inDegrees: VertexRDD[Int]
val outDegrees: VertexRDD[Int]
val degrees: VertexRDD[Int]
```



Information About The Graph (1/2)

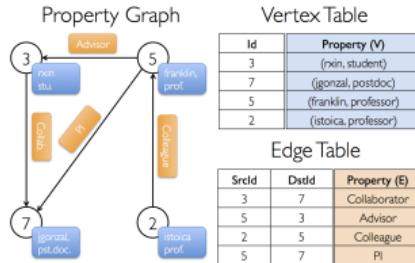
- ▶ Information about the graph

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val numEdges: Long
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val inDegrees: VertexRDD[Int]
val outDegrees: VertexRDD[Int]
val degrees: VertexRDD[Int]
```

- ▶ Views of the graph as collections

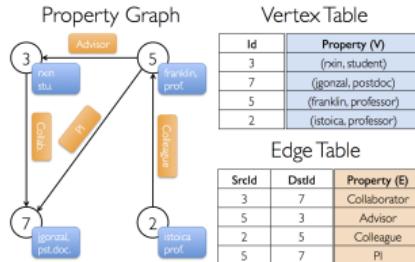
```
val vertices: VertexRDD[VD]
val edges: EdgeRDD[ED]
val triplets: RDD[EdgeTriplet[VD, ED]]
```

Information About The Graph (2/2)



```
// Constructed from above
val graph: Graph[(String, String), String]
```

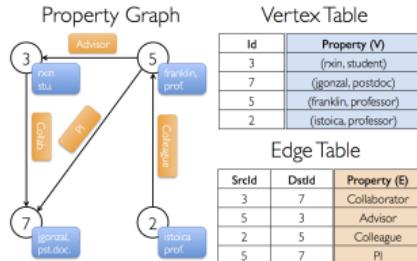
Information About The Graph (2/2)



```
// Constructed from above
val graph: Graph[(String, String), String]
```

```
// Count all users which are postdocs
graph.vertices.filter { case (id, (name, pos)) => pos == "postdoc" }.count
```

Information About The Graph (2/2)



```
// Constructed from above
val graph: Graph[(String, String), String]
```

```
// Count all users which are postdocs
graph.vertices.filter { case (id, (name, pos)) => pos == "postdoc" }.count
```

```
// Count all the edges where src > dst
graph.edges.filter(e => e.srcId > e.dstId).count
```



Property Operators

- ▶ Transform vertex and edge attributes
- ▶ Each of these operators yields a new graph with the vertex or edge properties modified by the user defined map function.

```
def mapVertices[VD2](map: (VertexId, VD) => VD2): Graph[VD2, ED]
def mapEdges[ED2](map: Edge[ED] => ED2): Graph[VD, ED2]
def mapTriplets[ED2](map: EdgeTriplet[VD, ED] => ED2): Graph[VD, ED2]
```



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def mapEdges[ED2](map: Edge[ED] => ED2): Graph[VD, ED2]
def mapTriplets[ED2](map: EdgeTriplet[VD, ED] => ED2): Graph[VD, ED2]
```

```
val relations: RDD[String] = graph.triplets.map(triplet =>
    triplet.srcAttr._1 + " is the " + triplet.attr + " of " + triplet.dstAttr._1)
relations.collect.foreach(println)
```



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- ▶ Each of these operators yields a new graph with the vertex or edge properties modified by the user defined map function.

```
def mapVertices[VD2](map: (VertexId, VD) => VD2): Graph[VD2, ED]
def mapEdges[ED2](map: Edge[ED] => ED2): Graph[VD, ED2]
def mapTriplets[ED2](map: EdgeTriplet[VD, ED] => ED2): Graph[VD, ED2]
```

```
val relations: RDD[String] = graph.triplets.map(triplet =>
    triplet.srcAttr._1 + " is the " + triplet.attr + " of " + triplet.dstAttr._1)
relations.collect.foreach(println)
```

```
val newGraph = graph.mapTriplets(triplet =>
    triplet.srcAttr._1 + " is the " + triplet.attr + " of " + triplet.dstAttr._1)
newGraph.edges.collect.foreach(println)
```



Structural Operators

- ▶ `reverse` returns a new graph with all the edge directions reversed.
- ▶ `subgraph` takes vertex/edge predicates and returns the graph containing only the vertices/edges that satisfy the given predicate.

```
def reverse: Graph[VD, ED]

def subgraph(epred: EdgeTriplet[VD, ED] => Boolean, vpred: (VertexId, VD) => Boolean):
    Graph[VD, ED]
```



Structural Operators

- ▶ `reverse` returns a new graph with all the edge directions reversed.
- ▶ `subgraph` takes vertex/edge predicates and returns the graph containing only the vertices/edges that satisfy the given predicate.

```
def reverse: Graph[VD, ED]

def subgraph(epred: EdgeTriplet[VD, ED] => Boolean, vpred: (VertexId, VD) => Boolean):
    Graph[VD, ED]
```

```
// Remove missing vertices as well as the edges to connected to them
val validGraph = graph.subgraph(vpred = (id, attr) => attr._2 != "Missing")

validGraph.vertices.collect.foreach(println)
```



Join Operators

- ▶ `joinVertices` joins the `vertices` with the `input RDD`.

```
def joinVertices[U](table: RDD[(VertexId, U)])(map: (VertexId, VD, U) => VD): Graph[VD, ED]
```



Join Operators

- ▶ `joinVertices` joins the `vertices` with the `input RDD`.
 - Returns a new graph with the vertex properties obtained by applying the user defined `map` function to the `result of the joined vertices`.
 - Vertices without a matching value in the RDD retain their `original value`.

```
def joinVertices[U](table: RDD[(VertexId, U)])(map: (VertexId, VD, U) => VD): Graph[VD, ED]
```

```
val rdd: RDD[(VertexId, String)] = sc.parallelize(Array((3L, "phd")))

val joinedGraph = graph.joinVertices(rdd)((id, user, role) => (user._1, role + " " + user._2))

joinedGraph.vertices.collect.foreach(println)
```



Aggregation (1/2)

- ▶ `aggregateMessages` applies a user defined `sendMsg` function to each `edge` triplet in the graph and then uses the `mergeMsg` function to aggregate those messages at their destination vertex.

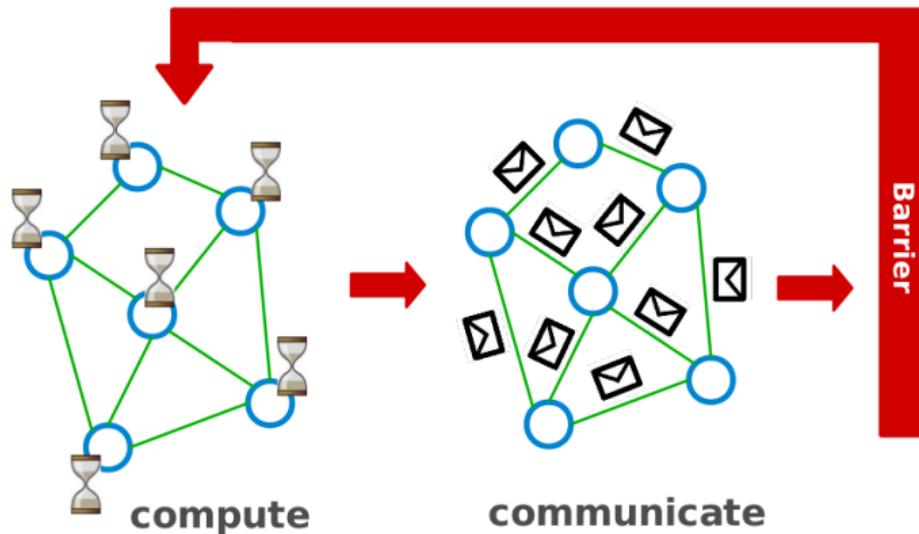
```
def aggregateMessages[Msg: ClassTag] (
  sendMsg: EdgeContext[VD, ED, Msg] => Unit, // map
  mergeMsg: (Msg, Msg) => Msg, // reduce
  tripletFields: TripletFields = TripletFields.All): VertexRDD[Msg]
```



Aggregation (2/2)

```
// count and list the name of friends of each user
val profs: VertexRDD[(Int, String)] = validUserGraph.aggregateMessages[(Int, String)](
    // map
    triplet => {
        triplet.sendToDst((1, triplet.srcAttr._1))
    },
    // reduce
    (a, b) => (a._1 + b._1, a._2 + " " + b._2)
)
profs.collect.foreach(println)
```

Iterative Computation (1/9)



Iterative Computation (2/9)

```
i_val := val

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

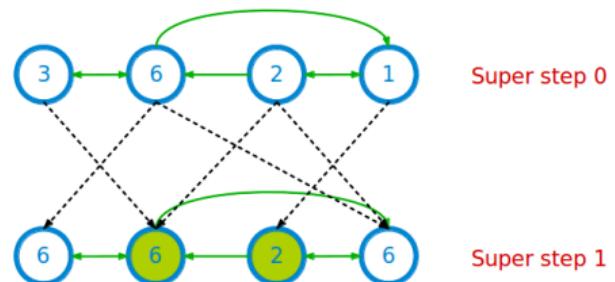
if i_val == val then
    vote_to_halt
else
    for each neighbor v
        send_message(v, val)
```



Super step 0

Iterative Computation (3/9)

```
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)
```

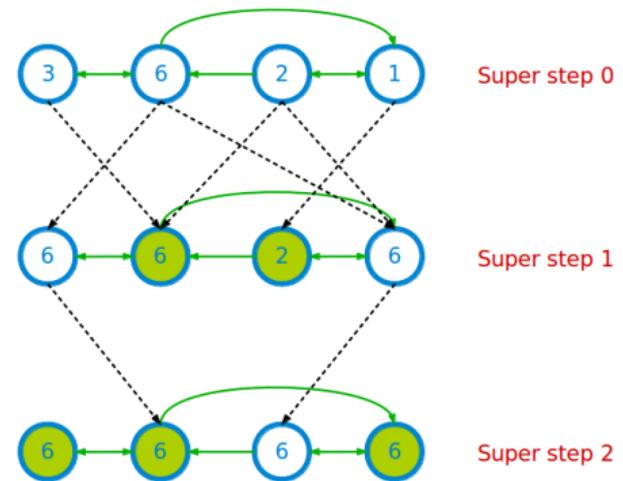


Super step 0

Super step 1

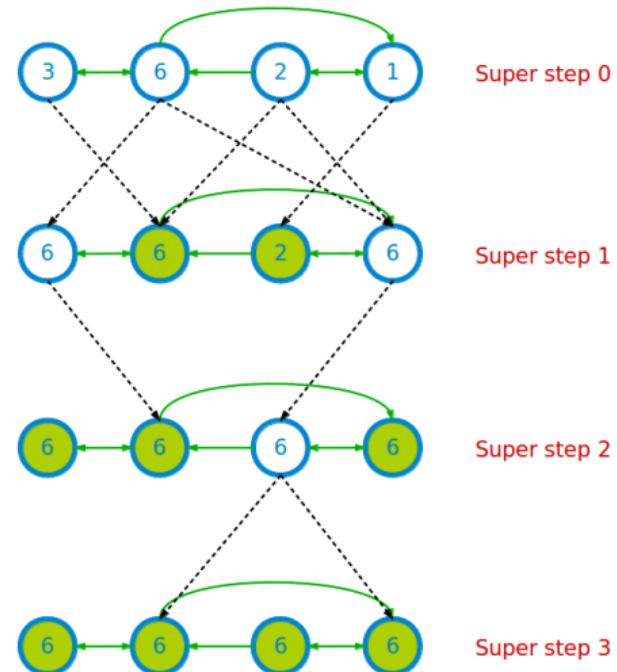
Iterative Computation (4/9)

```
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)
```



Iterative Computation (5/9)

```
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)
```





Iterative Computation (6/9)

- ▶ `pregel` takes two argument lists: `graph.pregel(list1)(list2)`.

```
def pregel[A]
  (initialMsg: A, maxIter: Int = Int.MaxValue, activeDir: EdgeDirection = EdgeDirection.Out)
  (vprog: (VertexId, VD, A) => VD, sendMsg: EdgeTriplet[VD, ED] => Iterator[(VertexId, A)],
   mergeMsg: (A, A) => A):
  Graph[VD, ED]
```



Iterative Computation (6/9)

- ▶ `pregel` takes two argument lists: `graph.pregel(list1)(list2)`.
- ▶ The first list contains configuration parameters
 - The initial message, the maximum number of iterations, and the edge direction in which to send messages.

```
def pregel[A]
  (initialMsg: A, maxIter: Int = Int.MaxValue, activeDir: EdgeDirection = EdgeDirection.Out)
  (vprog: (VertexId, VD, A) => VD, sendMsg: EdgeTriplet[VD, ED] => Iterator[(VertexId, A)],
   mergeMsg: (A, A) => A):
  Graph[VD, ED]
```

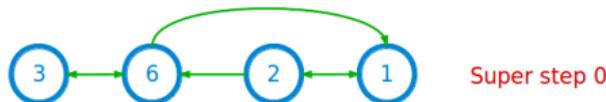


Iterative Computation (6/9)

- ▶ `pregel` takes two argument lists: `graph.pregel(list1)(list2)`.
- ▶ The **first list** contains **configuration parameters**
 - The initial message, the maximum number of iterations, and the edge direction in which to send messages.
- ▶ The **second list** contains the **user defined functions**.
 - Gather: `mergeMsg`, Apply: `vprog`, Scatter: `sendMsg`

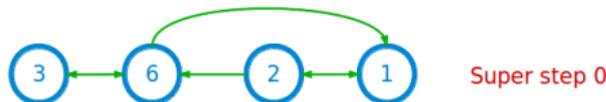
```
def pregel[A]
  (initialMsg: A, maxIter: Int = Int.MaxValue, activeDir: EdgeDirection = EdgeDirection.Out)
  (vprog: (VertexId, VD, A) => VD, sendMsg: EdgeTriplet[VD, ED] => Iterator[(VertexId, A)],
   mergeMsg: (A, A) => A):
  Graph[VD, ED]
```

Iterative Computation (7/9)



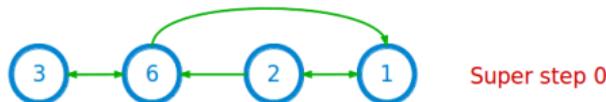
```
import org.apache.spark._  
import org.apache.spark.graphx._  
import org.apache.spark.rdd.RDD  
  
val initialMsg = -9999
```

Iterative Computation (7/9)



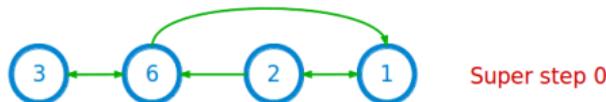
```
import org.apache.spark._  
import org.apache.spark.graphx._  
import org.apache.spark.rdd.RDD  
  
val initialMsg = -9999  
  
// (vertexID, (new vertex value, old vertex value))  
val vertices: RDD[(VertexId, (Int, Int))] = sc.parallelize(Array((1L, (1, -1)),  
(2L, (2, -1)), (3L, (3, -1)), (6L, (6, -1))))
```

Iterative Computation (7/9)



```
import org.apache.spark._  
import org.apache.spark.graphx._  
import org.apache.spark.rdd.RDD  
  
val initialMsg = -9999  
  
// (vertexID, (new vertex value, old vertex value))  
val vertices: RDD[(VertexId, (Int, Int))] = sc.parallelize(Array((1L, (1, -1)),  
  (2L, (2, -1)), (3L, (3, -1)), (6L, (6, -1))))  
  
val relationships: RDD[Edge[Boolean]] = sc.parallelize(Array(Edge(1L, 2L, true),  
  Edge(2L, 1L, true), Edge(2L, 6L, true), Edge(3L, 6L, true), Edge(6L, 1L, true),  
  Edge(6L, 3L, true)))
```

Iterative Computation (7/9)



```
import org.apache.spark._  
import org.apache.spark.graphx._  
import org.apache.spark.rdd.RDD  
  
val initialMsg = -9999  
  
// (vertexID, (new vertex value, old vertex value))  
val vertices: RDD[(VertexId, (Int, Int))] = sc.parallelize(Array((1L, (1, -1)),  
    (2L, (2, -1)), (3L, (3, -1)), (6L, (6, -1))))  
  
val relationships: RDD[Edge[Boolean]] = sc.parallelize(Array(Edge(1L, 2L, true),  
    Edge(2L, 1L, true), Edge(2L, 6L, true), Edge(3L, 6L, true), Edge(6L, 1L, true),  
    Edge(6L, 3L, true)))  
  
val graph = Graph(vertices, relationships)
```



Iterative Computation (8/9)

```
// Gather: the function for combining messages
def mergeMsg(msg1: Int, msg2: Int): Int = math.max(msg1, msg2)
```



Iterative Computation (8/9)

```
// Gather: the function for combining messages
def mergeMsg(msg1: Int, msg2: Int): Int = math.max(msg1, msg2)

// Apply: the function for receiving messages
def vprog(vertexId: VertexId, value: (Int, Int), message: Int): (Int, Int) = {
    if (message == initialMsg) // superstep 0
        value
    else // superstep > 0
        (math.max(message, value._1), value._1) // return (newValue, oldValue)
}
```



Iterative Computation (8/9)

```
// Gather: the function for combining messages
def mergeMsg(msg1: Int, msg2: Int): Int = math.max(msg1, msg2)

// Apply: the function for receiving messages
def vprog(vertexId: VertexId, value: (Int, Int), message: Int): (Int, Int) = {
    if (message == initialMsg) // superstep 0
        value
    else // superstep > 0
        (math.max(message, value._1), value._1) // return (newValue, oldValue)
}

// Scatter: the function for computing messages
def sendMsg(triplet: EdgeTriplet[(Int, Int), Boolean]): Iterator[(VertexId, Int)] = {
    val sourceVertex = triplet.srcAttr
    if (sourceVertex._1 == sourceVertex._2) // newValue == oldValue for source vertex?
        Iterator.empty // do nothing
    else
        // propagate new (updated) value to the destination vertex
        Iterator((triplet.dstId, sourceVertex._1))
}
```



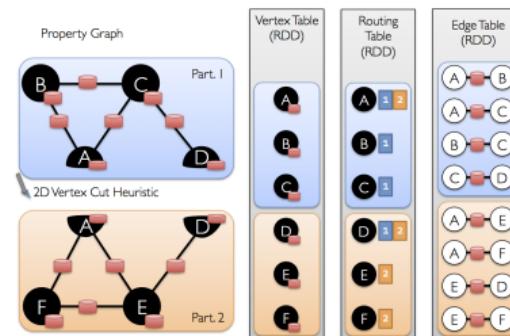
Iterative Computation (9/9)

```
val minGraph = graph.pregel(initialMsg,
    Int.MaxValue,
    EdgeDirection.Out)(
    vprog, // apply
    sendMsg, // scatter
    mergeMsg) // gather

minGraph.vertices.collect.foreach{
  case (vertexId, (value, original_value)) => println(value)
}
```

Graph Representation

- ▶ **Vertex-cut** partitioning
- ▶ Representing graphs using **two RDDs**: **edge-collection** and **vertex-collection**
- ▶ **Routing table**: a **logical map** from a vertex id to the set of edge partitions that contains adjacent edges.





Summary



Summary

- ▶ Think like a vertex
 - Pregel: BSP, synchronous parallel model, message passing, edge-cut
- ▶ Think like a table
 - Graphx: unifies data-parallel and graph-parallel systems



References

- ▶ G. Malewicz et al., “Pregel: a system for large-scale graph processing”, ACM SIGMOD 2010
- ▶ J. Gonzalez et al., “GraphX: Graph Processing in a Distributed Dataflow Framework”, OSDI 2014



Questions?