Large Scale Graph Processing - X-Stream and GraphX

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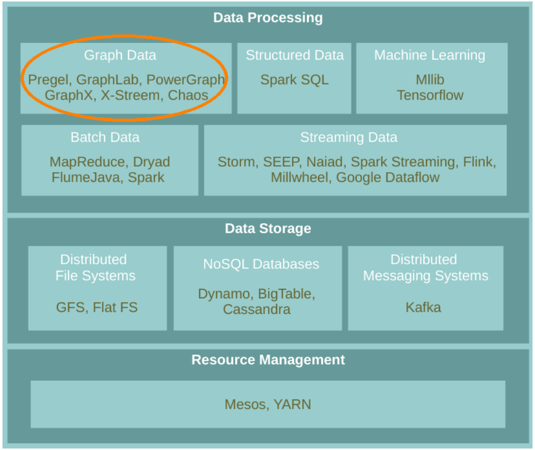
The Course Web Page

https://id2221kth.github.io

https://tinyurl.com/y4qph82u

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

Graph Algorithms Challenges

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

Think Like an Edge

Motivation

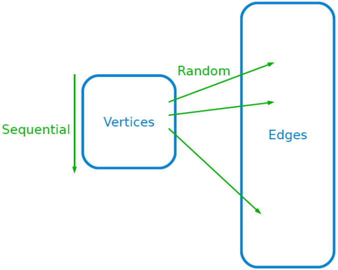
Could we compute big graphs on a single machine?

Vertex-Centric

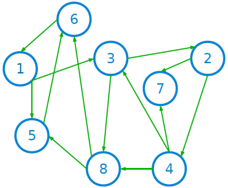
- Vertex-centric gather-scatter: iterates over vertices

```
Until convergence {
  // the scatter phase
  for all vertices v that need to scatter updates
    send updates over outgoing edges of v

  // the gather phase
  for all vertices v that have updates
    apply updates from inbound edges of v
}
```



Vertex-Centric Breadth First Search (1/5)



vertices

v
1
2
3
4
5
6
7
8

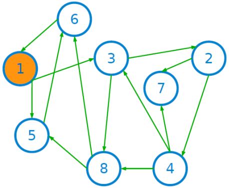
edges

src	dest
1	3
1	5
2	7
2	4
3	2
3	8
4	3
4	7
4	8
5	6
6	1
8	5
8	6

```
Until convergence {
  // the scatter phase
  for all vertices v that need to scatter updates
    send updates over outgoing edges of v

  // the gather phase
  for all vertices v that have updates
    apply updates from inbound edges of v
}
```

Vertex-Centric Breadth First Search (2/5)



vertices

v
1
2
3
4
5
6
7
8

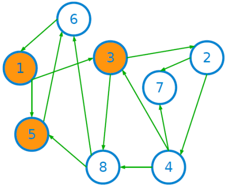
edges

src	dest
1	3
1	5
2	7
2	4
3	2
3	8
4	3
4	7
4	8
5	6
6	1
8	5
8	6

```
Until convergence {
  // the scatter phase
  for all vertices v that need to scatter updates
    send updates over outgoing edges of v

  // the gather phase
  for all vertices v that have updates
    apply updates from inbound edges of v
}
```

Vertex-Centric Breadth First Search (3/5)



vertices

v
1
2
3
4
5
6
7
8

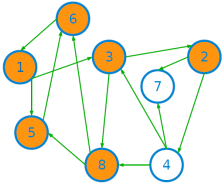
edges

src	dest
1	3
1	5
2	7
2	4
3	2
3	8
4	3
4	7
4	8
5	6
6	1
8	5
8	6

```
Until convergence {
  // the scatter phase
  for all vertices v that need to scatter updates
    send updates over outgoing edges of v

  // the gather phase
  for all vertices v that have updates
    apply updates from inbound edges of v
}
```

Vertex-Centric Breadth First Search (4/5)



vertices

v
1
2
3
4
5
6
7
8

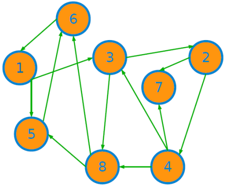
edges

src	dest
1	3
1	5
2	7
2	4
3	2
3	8
4	3
4	7
4	8
5	6
6	1
8	5
8	6

```
Until convergence {
  // the scatter phase
  for all vertices v that need to scatter updates
    send updates over outgoing edges of v

  // the gather phase
  for all vertices v that have updates
    apply updates from inbound edges of v
}
```

Vertex-Centric Breadth First Search (5/5)



vertices

v
1
2
3
4
5
6
7
8

edges

src	dest
1	3
1	5
2	7
2	4
3	2
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4	7
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```
Until convergence {
  // the scatter phase
  for all vertices v that need to scatter updates
    send updates over outgoing edges of v

  // the gather phase
  for all vertices v that have updates
    apply updates from inbound edges of v
}
```

X-Stream

X-Stream

- Could we process massive graphs on a single machine?
- X-Stream makes graph edges accesses sequential.
- Edge-centric scatter-gather model.

- Disk-based processing
  - Graph traversal = random access
  - Random access is inefficient for storage

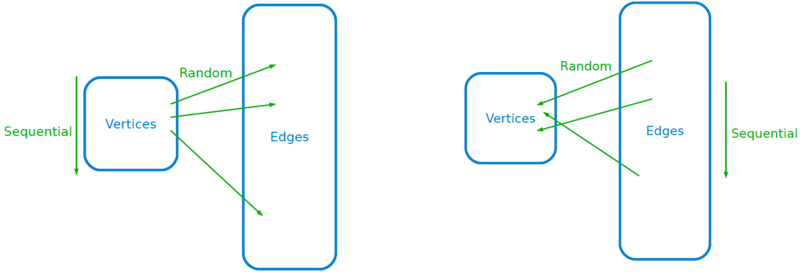
Medium	Read (MB/s)		Write (MB/s)	
	Random	Sequential	Random	Sequential
RAM	567	2605	1057	2248
SSD	22.64	355	49.16	298
Disk	0.61	174	1.27	170

Note: 64 byte cachelines, 4K blocks (disk random), 16M chunks (disk sequential)

Eiko Y., and Roy A., "Scale-up Graph Processing: A Storage-centric View", 2013.

Vertex-Centric vs. Edge-Centric Programming Model (1/2)

- Vertex-centric gather-scatter: iterates over vertices
- Edge-centric gather-scatter: iterates over edges



Vertex-Centric vs. Edge-Centric Programming Model (2/2)

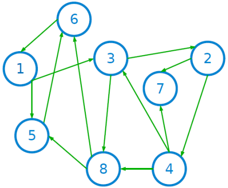
```
Until convergence {
  // the scatter phase
  for all vertices v that need to scatter updates
    send updates over outgoing edges of v

  // the gather phase
  for all vertices v that have updates
    apply updates from inbound edges of v
}
```

```
Until convergence {
  // the scatter phase
  for all edges e
    send update over e

  // the gather phase
  for all edgaes e that have updates
    apply update to e.destination
}
```

Vertex-Centric Breadth First Search (1/5)



vertices

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edges

src	dest
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1	5
2	7
2	4
3	2
3	8
4	3
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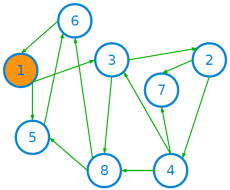
4	8
5	6
6	1
8	5
8	6

```
Until convergence {
  // the scatter phase
  for all vertices v that need to scatter updates
    send updates over outgoing edges of v

  // the gather phase
  for all vertices v that have updates
    apply updates from inbound edges of v
}
```

Vertex-Centric Breadth First Search (2/5)



vertices

v
1
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4
5
6
7
8

edges

src	dest
1	3
1	5
2	7
2	4
3	2
3	8
4	3
4	7
4	8
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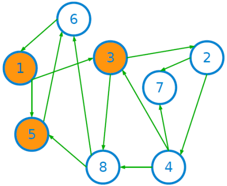
6	1
8	5
8	6

```
Until convergence {
  // the scatter phase
  for all vertices v that need to scatter updates
    send updates over outgoing edges of v

  // the gather phase
  for all vertices v that have updates
    apply updates from inbound edges of v
}
```

Vertex-Centric Breadth First Search (3/5)



vertices

v
1
2
3
4
5
6
7
8

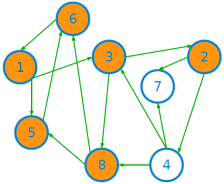
edges

src	dest
1	3
1	5
2	7
2	4
3	2
3	8
4	3
4	7
4	8
5	6
6	1
8	5
8	6

```
Until convergence {
  // the scatter phase
  for all vertices v that need to scatter updates
    send updates over outgoing edges of v

  // the gather phase
  for all vertices v that have updates
    apply updates from inbound edges of v
}
```

Vertex-Centric Breadth First Search (4/5)



vertices

v
1
2
3
4
5
6
7
8

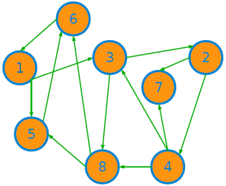
edges

src	dest
1	3
1	5
2	7
2	4
3	2
3	8
4	3
4	7
4	8
5	6
6	1
8	5
8	6

```
Until convergence {
  // the scatter phase
  for all vertices v that need to scatter updates
    send updates over outgoing edges of v

  // the gather phase
  for all vertices v that have updates
    apply updates from inbound edges of v
}
```

Vertex-Centric Breadth First Search (5/5)



vertices

v
1
2
3
4
5
6
7
8

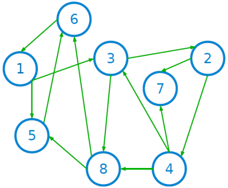
edges

src	dest
1	3
1	5
2	7
2	4
3	2
3	8
4	3
4	7
4	8
5	6
6	1
8	5
8	6

```
Until convergence {
  // the scatter phase
  for all vertices v that need to scatter updates
    send updates over outgoing edges of v

  // the gather phase
  for all vertices v that have updates
    apply updates from inbound edges of v
}
```

Edge-Centric Breadth First Search (1/5)



vertices

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edges

src	dest
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4	7
4	8
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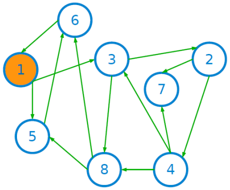
```
Until convergence {
  // the scatter phase
  for all edges e
    send update over e

  // the gather phase
  for all edgaes e that have updates
    apply update to e.destination
}
```

Edge-Centric Breadth First Search (2/5)



vertices

v
1
2
3
4
5
6
7
8

edges

src	dest
1	3
1	5
2	7
2	4
3	2
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```
Until convergence {
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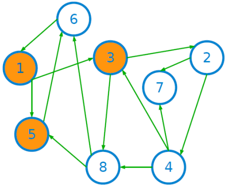
}
```

Edge-Centric Breadth First Search (3/5)



vertices

v
1
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edges

src	dest
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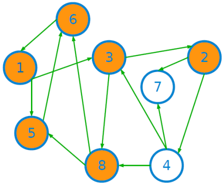
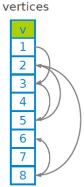
}
```

Edge-Centric Breadth First Search (4/5)





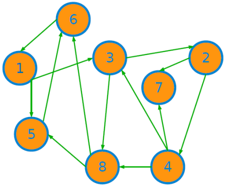
edges

src	dest
1	3
1	5
2	7
2	4
3	2
3	8
4	3
4	7
4	8
5	6
6	1
8	5
8	6

```
Until convergence {
  // the scatter phase
  for all edges e
    send update over e

  // the gather phase
  for all edgaes e that have updates
    apply update to e.destination
}
```

Edge-Centric Breadth First Search (5/5)



vertices

v
1
2
3
4
5
6
7
8

edges

src	dest
1	3
1	5
2	7
2	4
3	2
3	8
4	3
4	7
4	8
5	6
6	1
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```
Until convergence {
  // the scatter phase
  for all edges e
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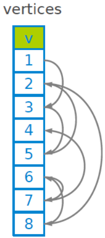
  for all edgaes e that have updates
    apply update to e.destination
}
```

Vertex-Centric vs. Edge-Centric Tradeoff

- Vertex-centric scatter-gather: $\frac{\texttt{EdgeData}}{\texttt{RandomAccessBandwidth}}$
- Edge-centric scatter-gather: $\frac{\texttt{Scatters} \times \texttt{EdgeData}}{\texttt{SequentialAccessBandwidth}}$
- Sequential Access Bandwidth $\gg$ Random Access Bandwidth.
- Few scatter gather iterations for real world graphs.

Streaming Partitions (1/4)

- Problem: still have random access to vertex set.



Solution

Partition the graph into streaming partitions.

Streaming Partitions (2/4)

vertices

v1
1
2
3
4

edges

src	dest
1	3
4	7
2	7
4	8
3	2
3	8
4	3
1	5
2	4

v2
5
6
7
8

src	dest
5	6
8	6
8	5
6	1

Subset of vertices

v1
1
2
3
4

Fast storage

edges

src	dest
1	3
4	7
2	7
4	8
3	2
3	8
4	3
1	5
2	4

Slow storage

Streaming Partitions (3/4)

- A streaming partition consists of: a vertex set, an edge list, and an update list.
- The vertex set: a subset of the vertex set of the graph that fits into the memory.
  - Vertex sets are mutually disjoint.
  - Their union equals the vertex set of the entire graph.
- The edge list: all edges whose source vertex is in the partition's vertex set.
- The update list: all updates whose destination vertex is in the partition's vertex set.

Streaming Partitions (4/4)

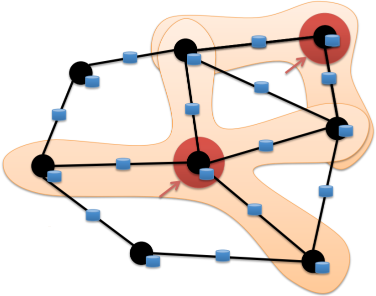
```
// Scatter phase:
for each streaming_partition p
    read in vertex set of p
    for each edge e in edge list of p
        append update to Uout
```

```
// shuffle phase:
for each update u in Uout
    p = partition containing target of u
    append u to Uin(p)
destroy Uout
```

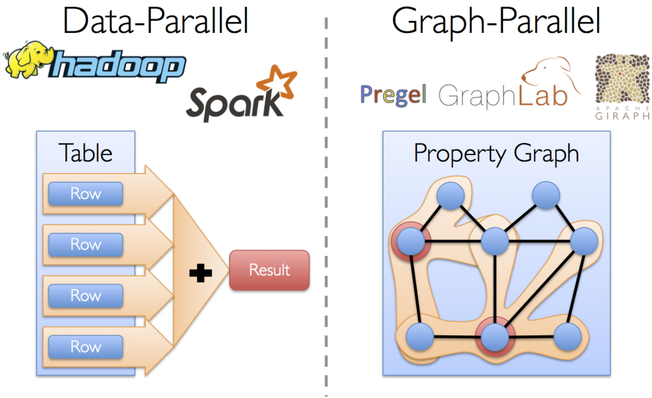
```
//gather phase:
for each streaming_partition p
    read in vertex set of p
    for each update u in Uin(p)
        edge_gather(u)
    destroy Uin(p)
```

Think Like a Table

Graph-Parallel Processing Model

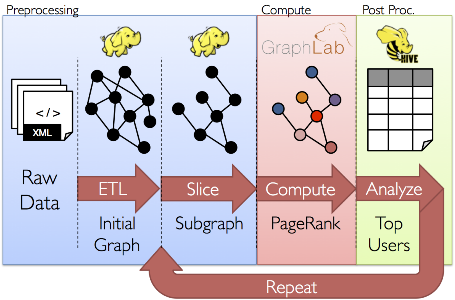


Data-Parallel vs. Graph-Parallel Computation

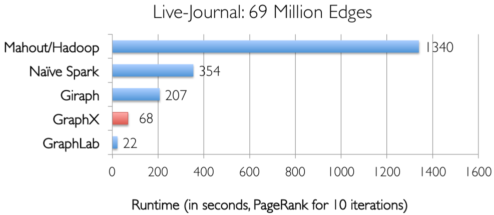


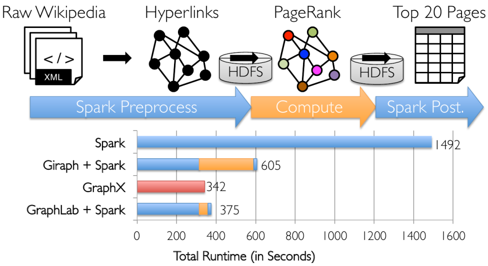
Motivation (2/3)

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



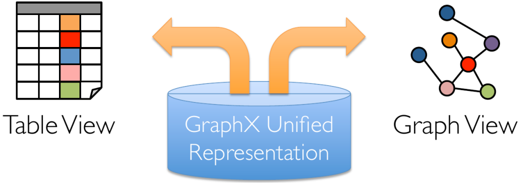
Motivation (3/3)





Think Like a Table

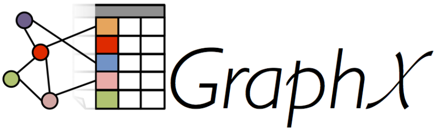
- Unifies data-parallel and graph-parallel systems.
- Tables and Graphs are composable views of the same physical data.



GraphX

GraphX

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

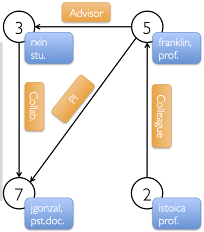


The Property Graph Data Model

- 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`

```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

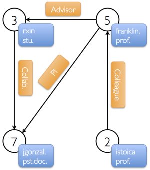
The Vertex Collection

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

```
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



Vertex Table

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2	(istoica, professor)

Edge Table

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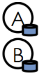
5	3	Advisor
2	5	Colleague
5	7	PI

Vertices:



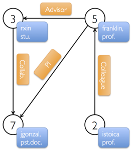
The Edge Collection

- 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]]
```

Property Graph



Vertex Table

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

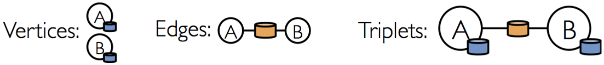
Edge Table

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

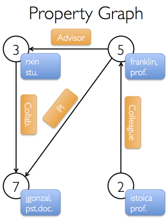
Edges: 

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



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

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

```
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, "-")))
```

```
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

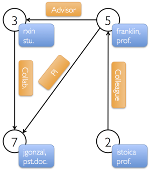
```
val numEdges: Long
val numVertices: Long
val inDegrees: VertexRDD[Int]
val outDegrees: VertexRDD[Int]
val degrees: VertexRDD[Int]
```

- 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)

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

```
// 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]
```

```
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]
```

```
// 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.
  - 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.

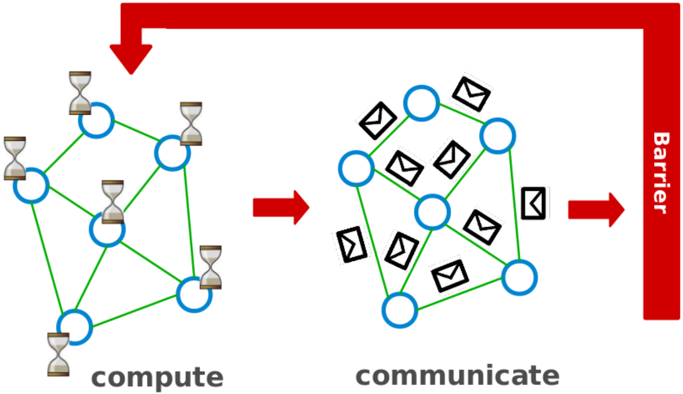
```
def aggregateMessages[Msg: ClassTag](
  sendMsg: EdgeContext[VD, ED, Msg] => Unit, // map
  mergeMsg: (Msg, Msg) => Msg, // reduce
  tripletFields: TripletFields = TripletFields.All):
  VertexRDD[Msg]
```

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)

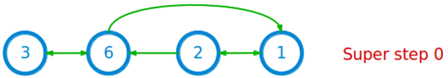


Iterative Computation (2/9)

```
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)
```

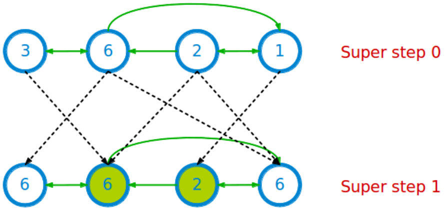


Iterative Computation (3/9)

```
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)
```

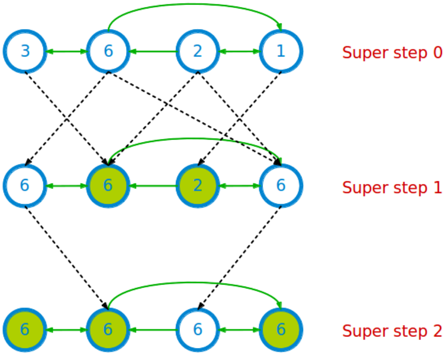


Iterative Computation (4/9)

```
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)
```

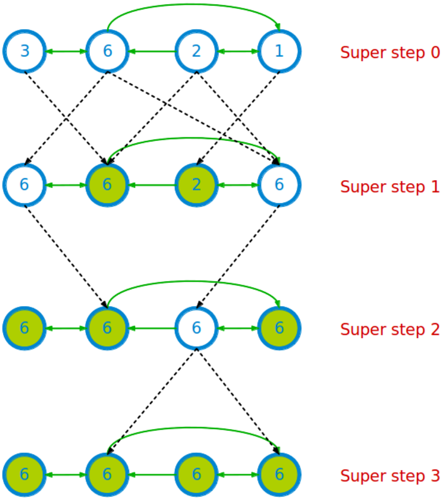


Iterative Computation (5/9)

```
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)
```

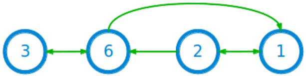


Iterative Computation (6/9)

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



Super step 0

```
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)
```

```
// 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
    // propogate new (updated) value to the destination vertex
    Iterator((triplet.dstId, sourceVertex._1))
}
```

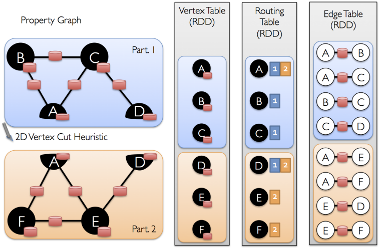
Iterative Computation (9/9)

```
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 an edge
    - XStream: edge-centric GAS, streaming partition

- Think like a table
    - Graphx: unifies data-parallel and graph-parallel systems.

References

- A. Roy et al., "X-stream: Edge-centric graph processing using streaming partitions", ACM SOSP 2013.
- J. Gonzalez et al., "GraphX: Graph Processing in a Distributed Dataflow Framework", OSDI 2014

Questions?