Graph Processing & Bulk Synchronous Parallel Model

CompSci 590.03
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Recap: Graph Algorithms

- Many graph algorithms need iterative computation

- No native support for iteration in Map-Reduce
  - Each iteration writes/reads data from disk leading to overheads
  - Need to design algorithms that can minimize number of iterations

This Class

- Iteration Aware Map-Reduce

- Pregel (Bulk Synchronous Parallel Model) for Graph Processing

ITERATION AWARE MAP-REDUCE

Iterative Computations

PageRank:

do

$p^{next} = (cM + (1\text{-}c)\ U)p^{cur}$

while(p^{next} != p^{cur})

- Loops are not supported in Map-Reduce
  - Need to encode iteration in the launching script
- M is a loop invariant. But needs to written to disk and read from disk in every step.
- M may not be co-located with mappers and reducers running the iterative computation.

HaLoop

- Iterative Programs

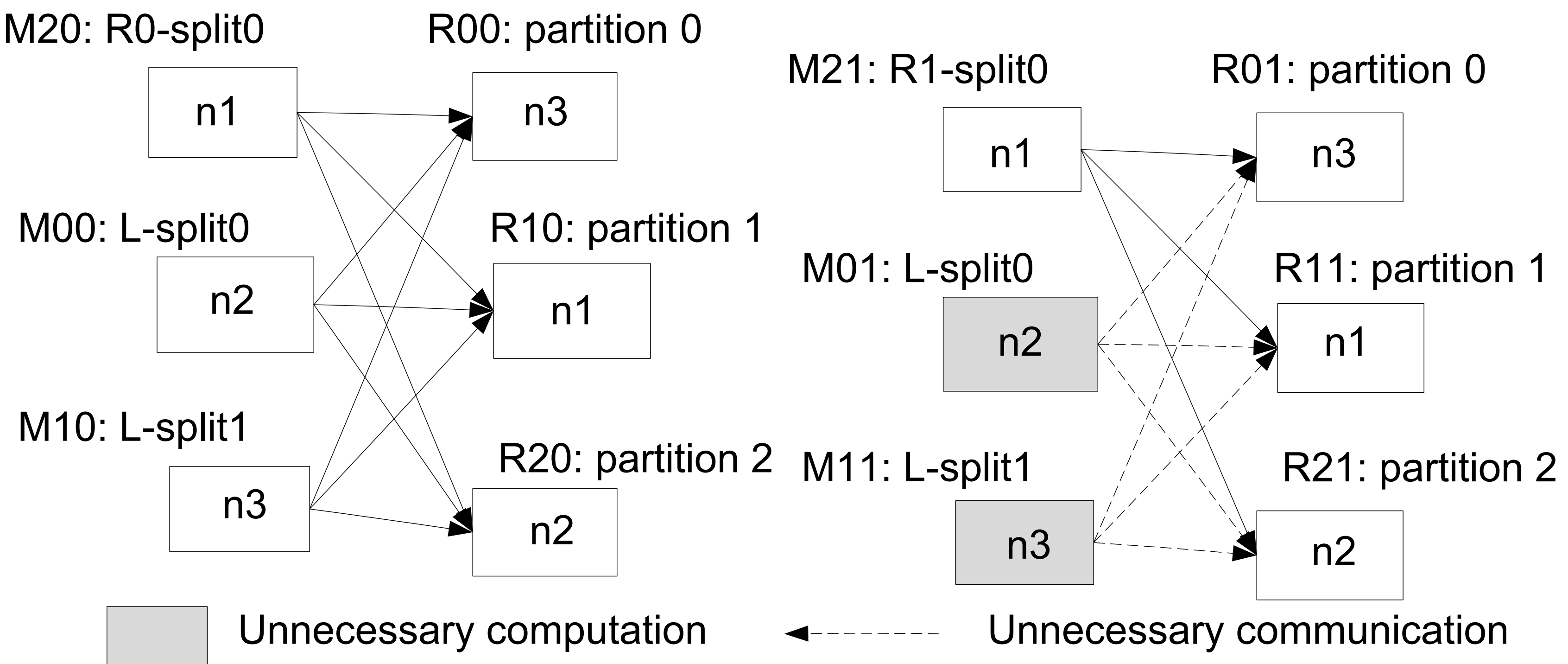
$$R_{i+1} = R_0 \cup (R_i \bowtie L)$$

Initial Relation

Invariant Relation

Loop aware task scheduling

- Inter-Iteration Locality
- Caching and Indexing of invariant tables



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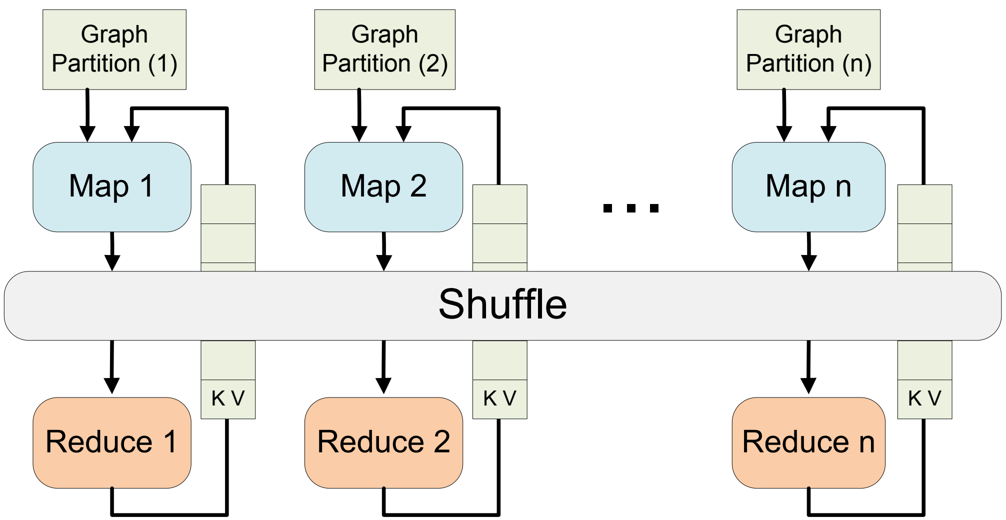
iMapReduce

- Reduce output is directly sent to mappers, instead of writing to distributed file system.
- Loop invariant is loaded onto the maps only once.



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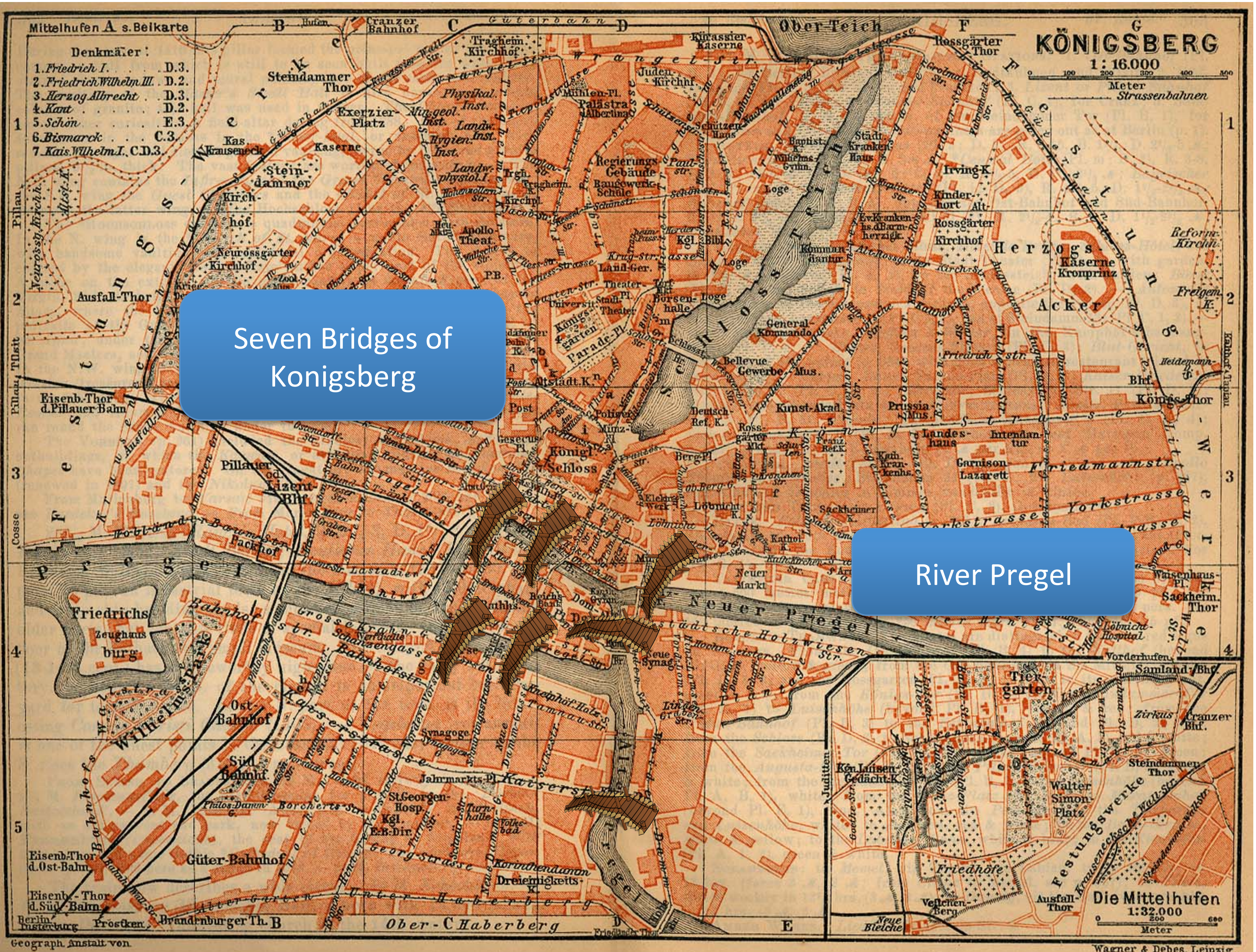
PREGEL


Seven Bridges of Konigsberg
River Pregel
KÖNIGSBERG
1 : 16.000
Die Mittelhufen
1:32.000
Wagner & Debes, Leipzig.

Pregel Overview

- Processing occurs in a series of supersteps
- In superstep S:
  Vertex may read messages sent to V in superstep S-1
  Vertex may perform some computation
  Vertex may send messages to other vertices
- Vertex computation within a superstep can be arbitrarily parallelized.
- All communication happens between two supersteps

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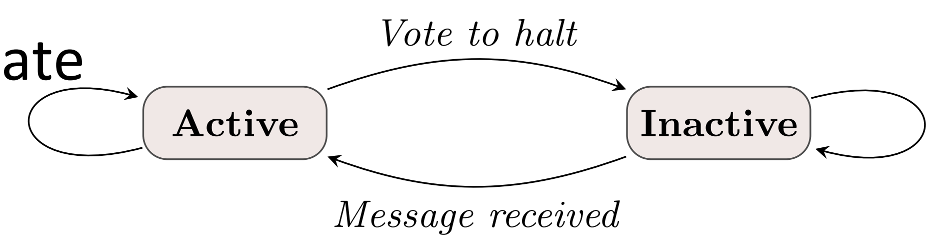
Pregel

- Input: A directed graph G.
  Each vertex is associated with an id and a value.
  Edges may also contain values.

- Edges are not a first class citizen – they have no associated computation
  - Vertices can modify its state/edge state/edge set

- Computation finishes when
  all vertices enter the inactive state



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Example

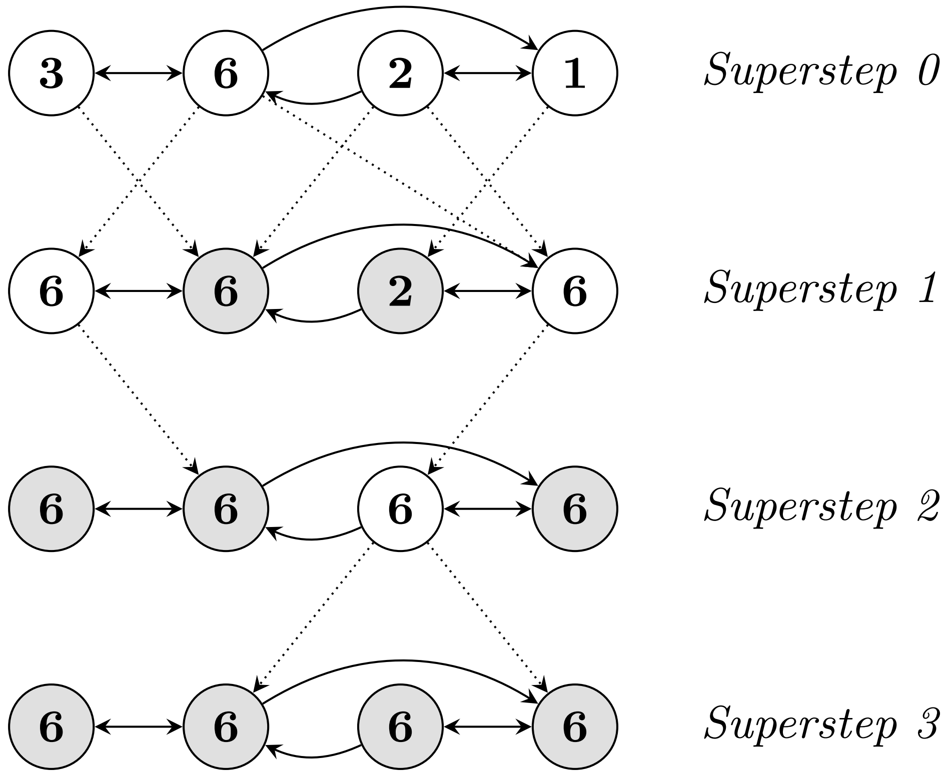

Figure 2: Maximum Value Example. Dotted lines are messages. Shaded vertices have voted to halt.

Vertex API

```
template <typename VertexValue,
          typename EdgeValue,
          typename MessageValue>
class Vertex {
 public:
  virtual void Compute(MessageIterator* msgs) = 0;

  const string& vertex_id() const;
  int64 superstep() const;

  const VertexValue& GetValue();
  VertexValue* MutableValue();
  OutEdgeIterator GetOutEdgeIterator();

  void SendMessageTo(const string& dest_vertex,
                     const MessageValue& message);
  void VoteToHalt();
};
```

User overrides this compute function

Vertex value can be modified

Messages can be sent to any dest_vertex (whose id is known)

Vertex API

- MessageIterator contains all the messages received.
- Message ordering is not guaranteed, but all messages are guaranteed to be delivered without duplication.
- Vertices can also send messages to other vertices (whose id it knows from prior messages)
- No need to explicitly maintain an edgeset.

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PageRank

```
class PageRankVertex
    : public Vertex<double, void, double> {
 public:
  virtual void Compute(MessageIterator* msgs) {
    if (superstep() >= 1) {
      double sum = 0;
      for (; !msgs->Done(); msgs->Next())
        sum += msgs->Value();
      *MutableValue() =
          0.15 / NumVertices() + 0.85 * sum;
    }

    if (superstep() < 30) {
      const int64 n = GetOutEdgeIterator().size();
      SendMessageToAllNeighbors(GetValue() / n);
    } else {
      VoteToHalt();
    }
  }
};
```

Combiners

- If messages are aggregated ("reduced") using an associative and commutative function, then the system can combine several messages intended for a vertex into 1.

- Reduces the number of messages communicated/buffered.

Single Source Shortest Paths

```
class ShortestPathVertex
    : public Vertex<int, int, int> {
  void Compute(MessageIterator* msgs) {
    int mindist = IsSource(vertex_id()) ? 0 : INF;
    for (; !msgs->Done(); msgs->Next())
      mindist = min(mindist, msgs->Value());
    if (mindist < GetValue()) {
      *MutableValue() = mindist;
      OutEdgeIterator iter = GetOutEdgeIterator();
      for (; !iter.Done(); iter.Next())
        SendMessageTo(iter.Target(),
                      mindist + iter.GetValue());
    }
    VoteToHalt();
  }
};
```

All Vertices initialized to INF

Distance to source

Edge Weight

```
class MinIntCombiner : public Combiner<int> {
  virtual void Combine(MessageIterator* msgs) {
    int mindist = INF;
    for (; !msgs->Done(); msgs->Next())
      mindist = min(mindist, msgs->Value());
    Output("combined_source", mindist);
  }
};
```

Aggregation

- Global communication
- Each vertex can provide a value to an aggregator in a superstep S. Resulting value is made available to all vertices in superstep S+1.
- System aggregates these values using a reduce step.

Topology Mutations

- Compute function can add or remove vertices
- But this can cause race conditions
  - Vertex 1 creates an edge to vertex 100
    Vertex 2 deletes vertex 100
  - Vertex 1 creates vertex 100 with value 10
    Vertex 2 also creates vertex 100 with value 12
- Partial Order on operations
  - Edge removal < vertex removal < vertex add < edge add (< means earlier)
- Handlers for conflicts
  - Default: Pick a random action
  - Can specify more complex handlers

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PREGEL ARCHITECTURE

Graph Partitioning

- Vertices are assigned to machines based on
  hash(vertex.id) mod N

- Can define other partitions: co-locate all web pages from the same site

- Sparsest Cut Problem: minimize the edges across partitions

Processing

- Master coordinates a set of workers.
  - Determines the number of partitions
  - Determines assignment of partitions to workers

- Worker processes one or more partitions
  - Workers know the entire set of partition to worker assignments and the partition function
  - All vertices in Worker's partition are initialized to active
  - Worker loops through vertex list and sends any messages asynchronously
  - Worker notifies master of # active vertices at the end of a superstep

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Fault Tolerance

- Checkpoint: master instructs workers to save state to persistent storage (e.g. HDFS)
  - Vertex values
  - Edge values
  - Incoming messages
- Master saves to disk aggregator values

- Worker failure is detected using a heartbeat.

- New worker is created using state from previous checkpoint (which could be several supersteps before current superstep)

Summary

- Map-reduce has no native support for iterations
  - No Loop construct
  - Write to disk and read from disk in each step, even if a the data is an invariant in the loop.

- Systems like HaLoop introduce inter-iteration locality and caching to help iterations on map-reduce.

- Pregel is a vertex oriented programming model and system for graph processing with built in features for iterative processing on graphs.