Pregel: A System for Large-Scale Graph Processing

Ashvin Goel

Electrical and Computer Engineering
University of Toronto

ECE1724

Authors: Grzegorz Malewicz, Matthew Austern, Aart Bik, James Dehnert, Ilan Horn, Naty Leiser, Grzegorz Czajkowski (Google, Inc.)

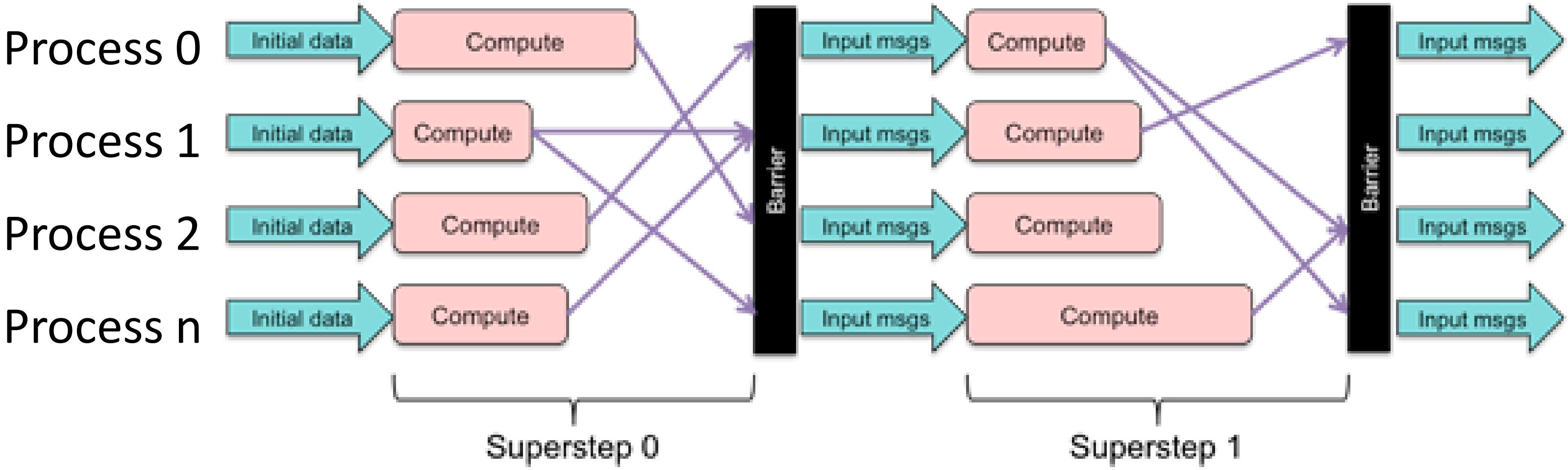
Some slides adapted from Aishwarya G, Subhasish Saha

What is Pregel?

- Scalable and fault-tolerant graph processing framework
- Provides flexible API for expressing arbitrary graph algorithms
  - Vertex-centric computation model (think like a vertex)
  - Bulk Synchronous Parallel (BSP) message-passing model for communication and synchronization

BSP Model

- In BSP, computation is a sequence of supersteps
- In each superstep:
  - Each process reads input messages, executes code independently, and sends messages to other processes
  - When a process completes, it waits for others to complete
  - All messages are delivered at the start of the next superstep



Pregel Computation Model

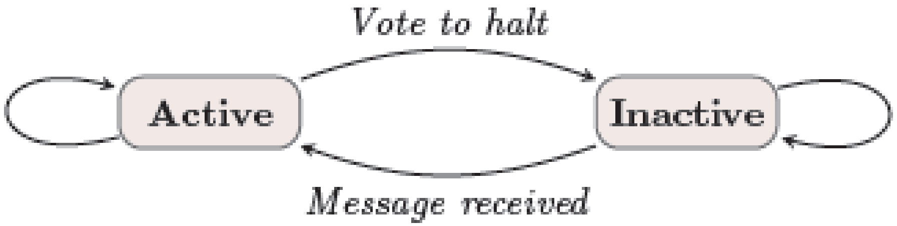
- Programmer writes a user-defined function that operates on a vertex (think like a vertex)
  - Similar to map-reduce, or stream processing, which operate on a single key

- Vertex state:

  Vertex ID
  Current value
  List of outgoing edges and their values
  A queue containing incoming message
  A flag to determine if vertex is active

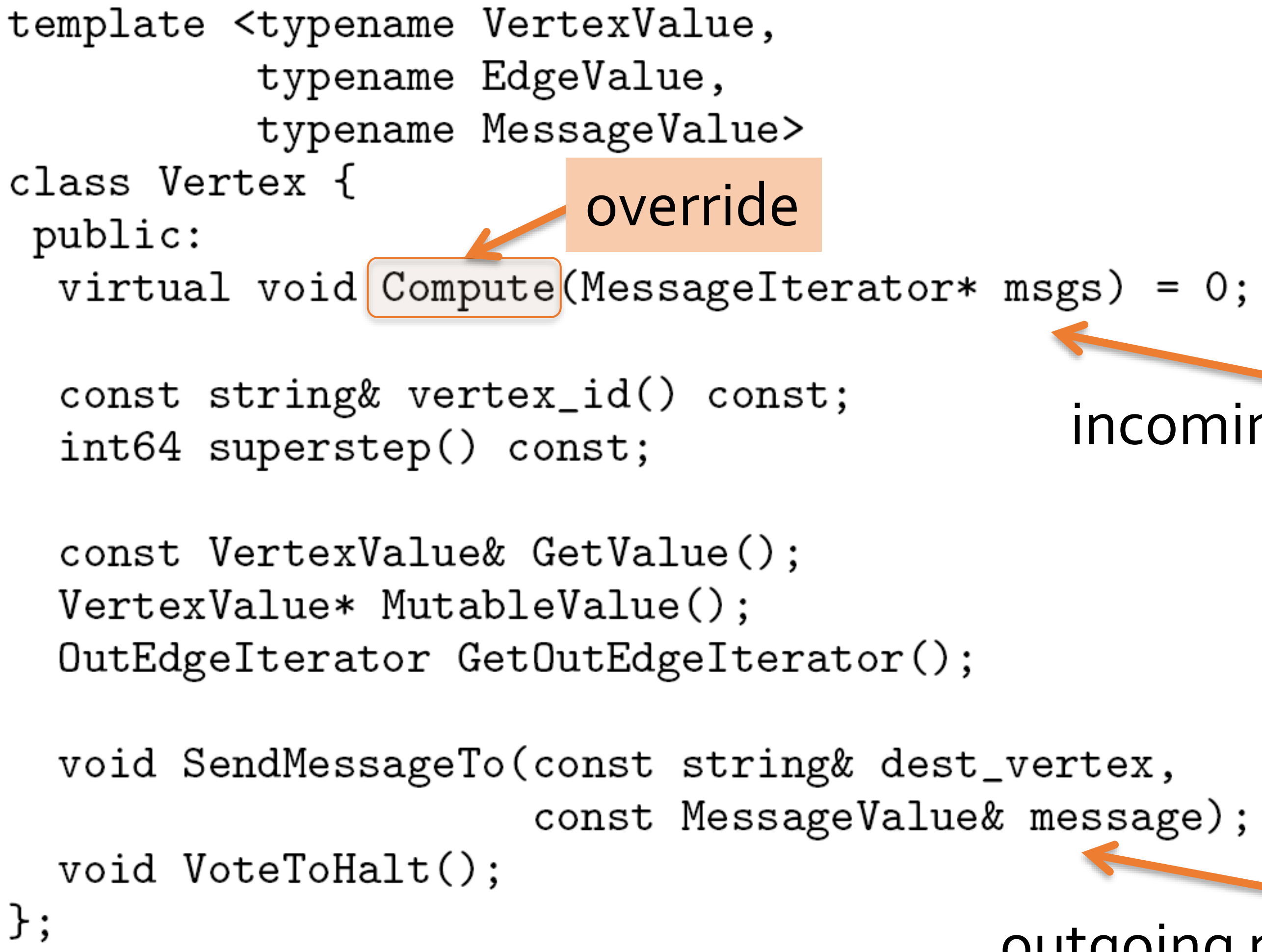
Pregel Computation Model

- Each vertex:
  - Receives messages sent in the previous superstep
  - Executes the user-defined function
  - May modify its state or state of outgoing edges
  - May send messages to outgoing edge vertices
    - These messages are received at the start of the next superstep
  - May mutate the topology of the graph (e.g., add edge)
  - Votes to halt if it has no further work to do
- Program termination:
  - When all vertices are inactive, and no messages in transit



Pregel API

- Programmer subclasses Vertex class



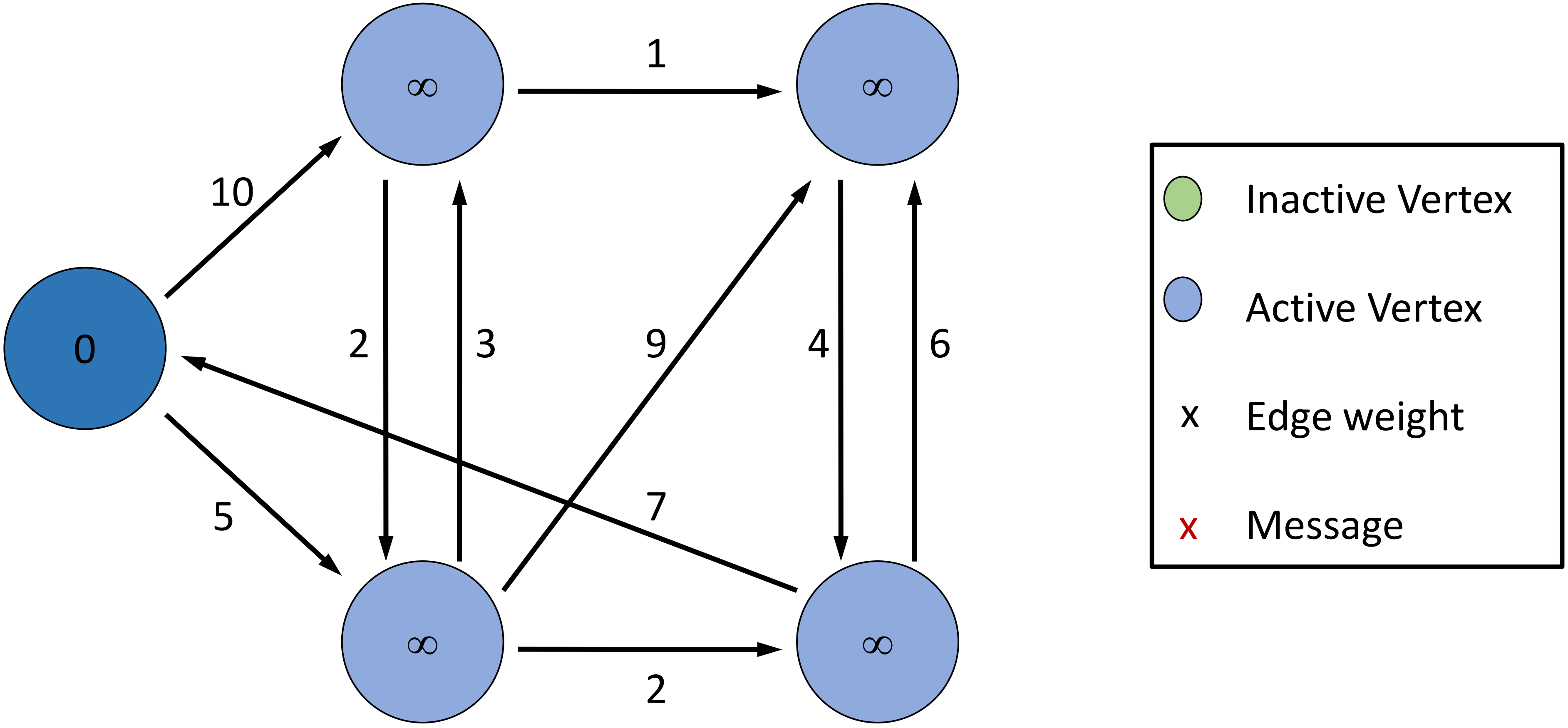
```
template <typename VertexValue,
          typename EdgeValue,
          typename MessageValue>
class Vertex {
 public:
  virtual void Compute(MessageIterator* msgs) = 0;

  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();
};
```

override

incoming msgs

outgoing message

Example: Parallel SSSP in Pregel



🟢 Inactive Vertex

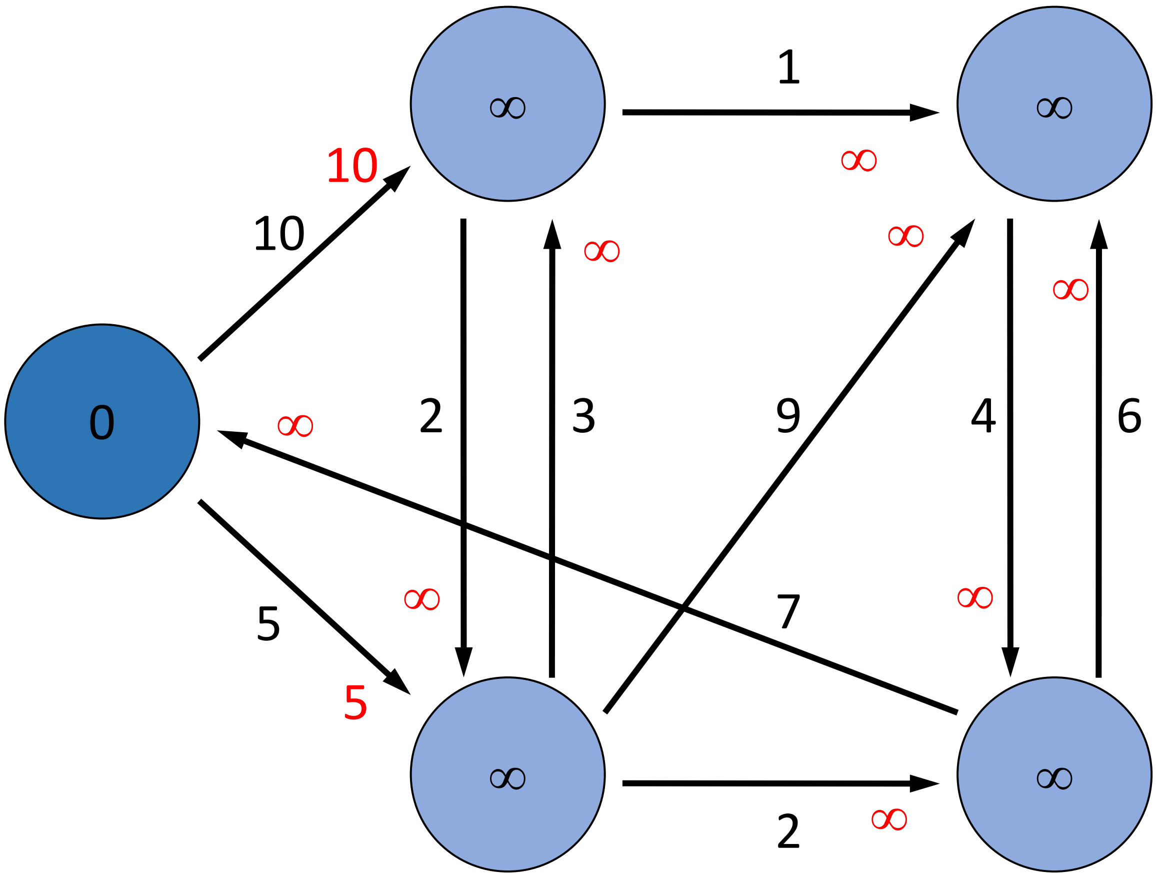
🔵 Active Vertex

x Edge weight

x Message

Example taken from talk by Taewhi Lee, 2010

Example: Parallel SSSP in Pregel



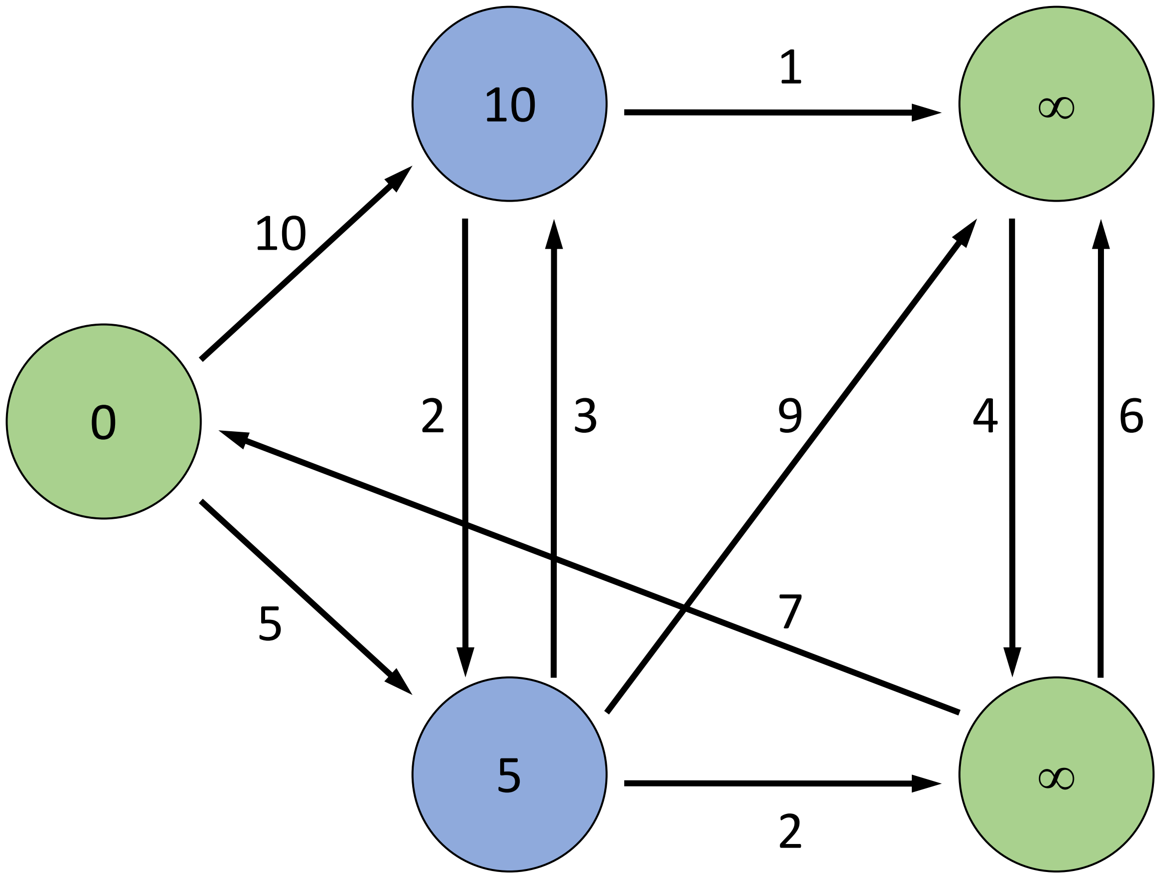
🟢 Inactive Vertex

🔵 Active Vertex

x Edge weight

x Message

Example: Parallel SSSP in Pregel



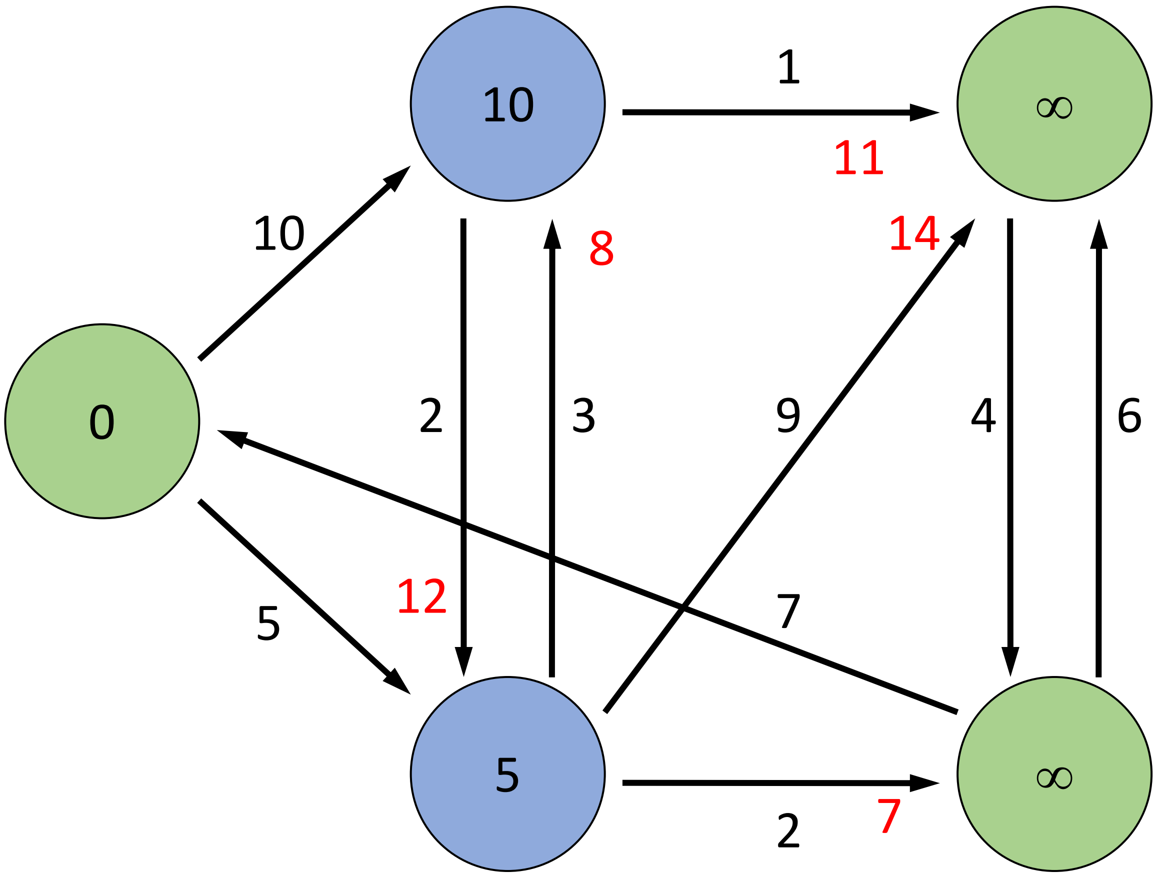
🟢 Inactive Vertex

🔵 Active Vertex

x Edge weight

x Message

Example: Parallel SSSP in Pregel



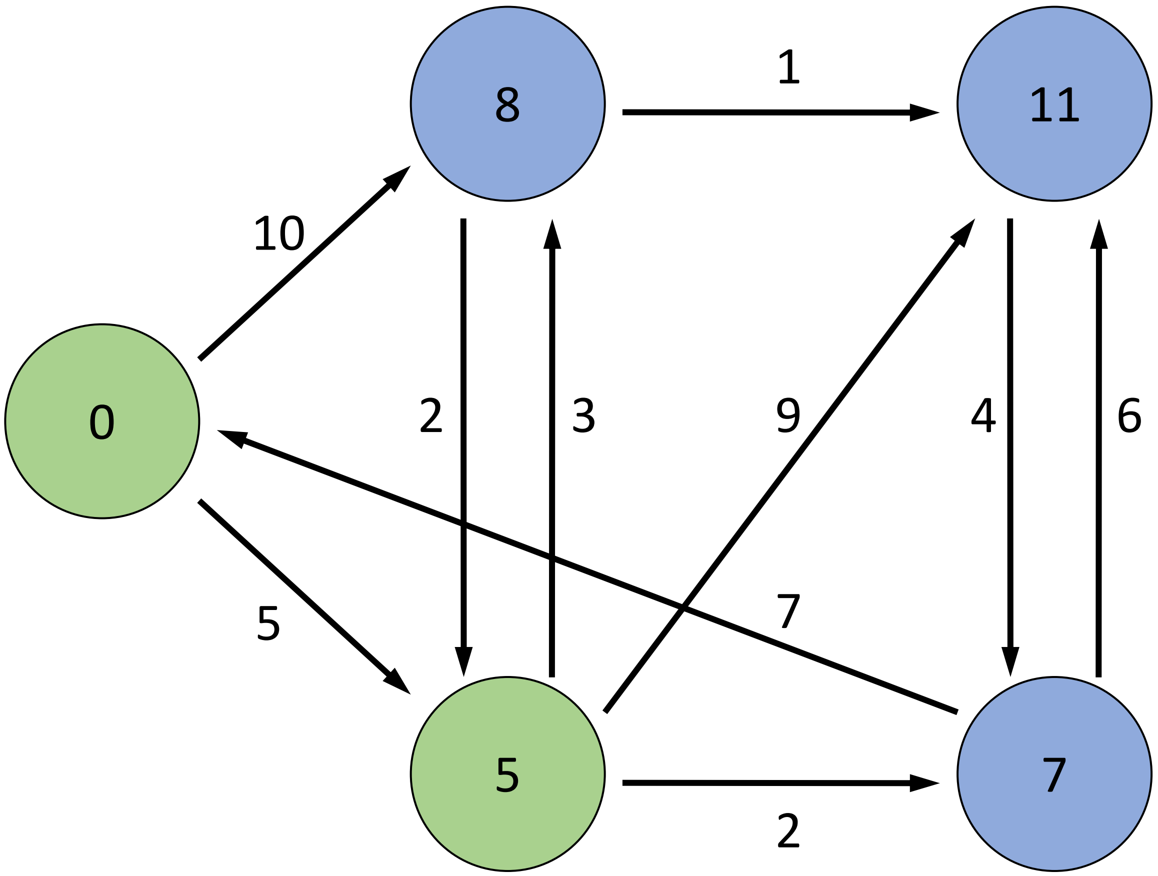
🟢 Inactive Vertex

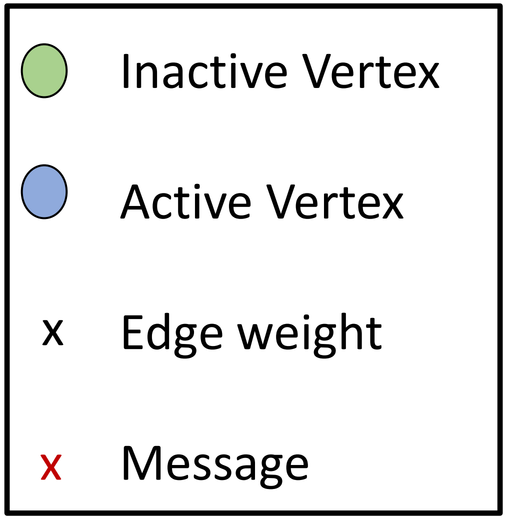
🔵 Active Vertex

x Edge weight

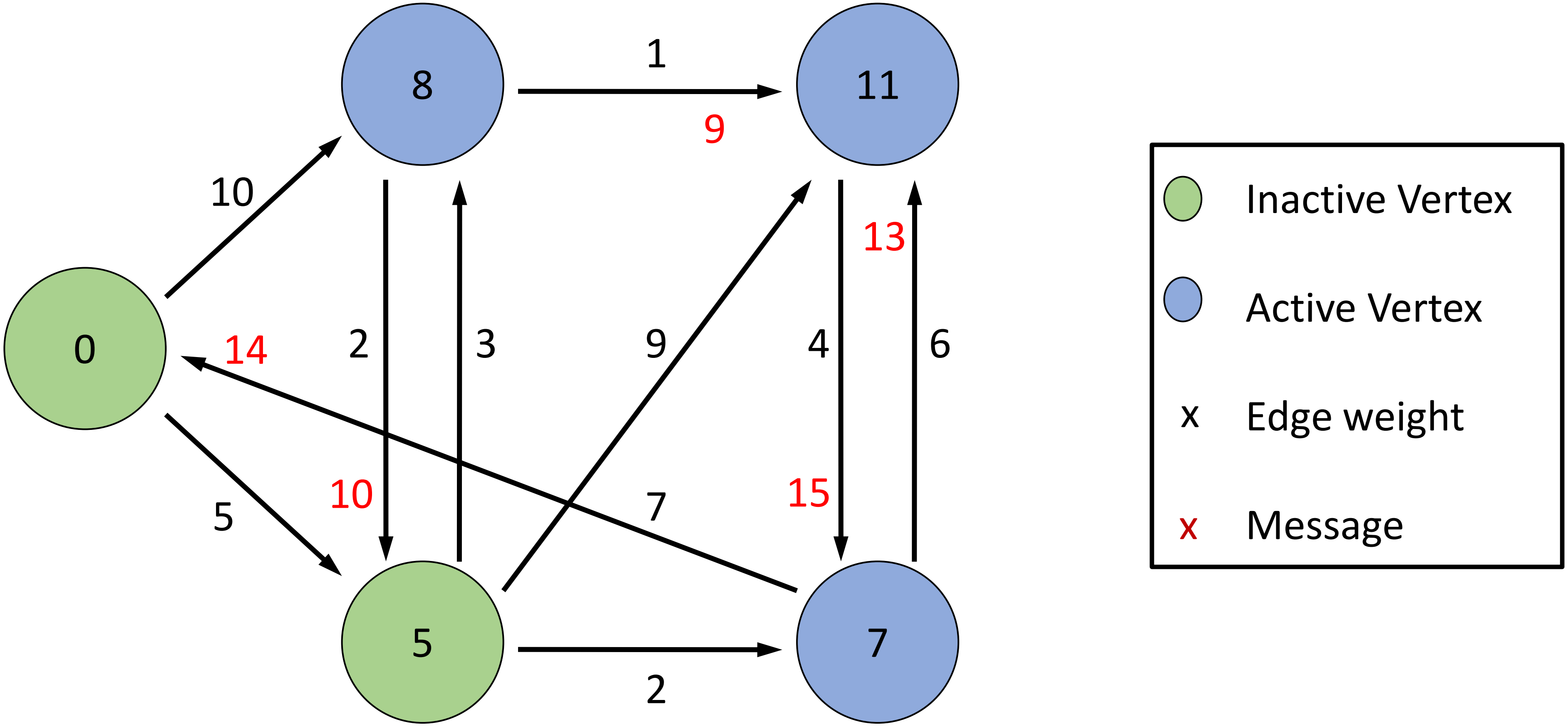
x Message

Example: Parallel SSSP in Pregel

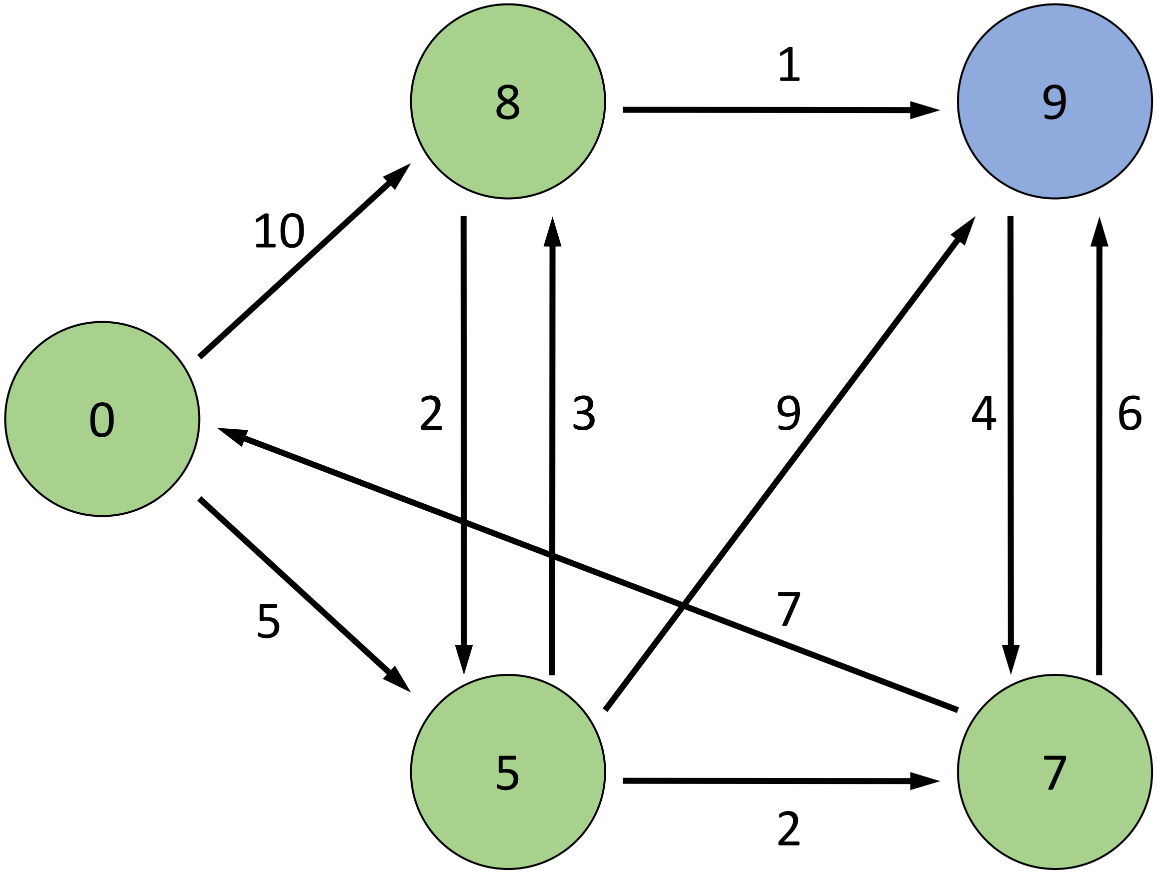




Example: Parallel SSSP in Pregel

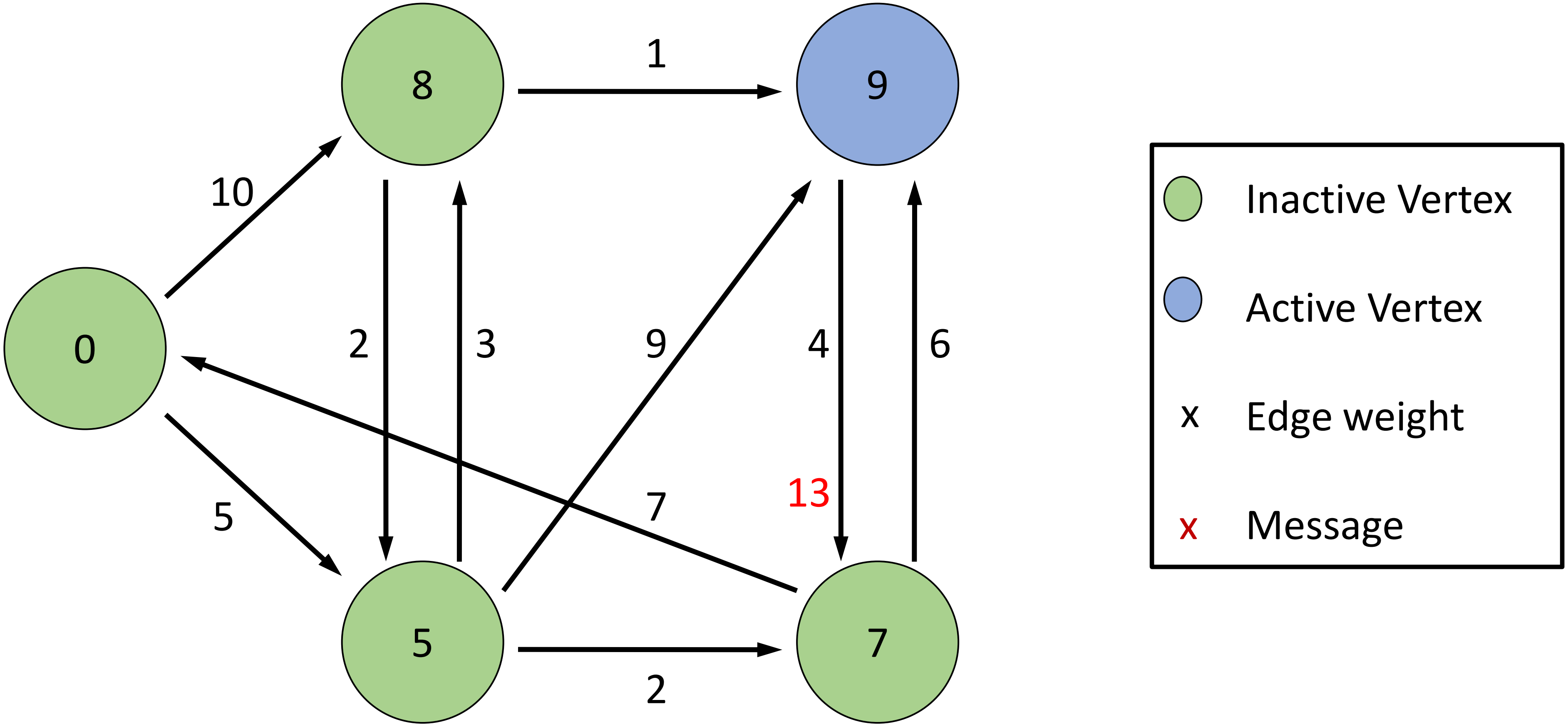


Example: Parallel SSSP in Pregel



- 🟢 Inactive Vertex
- 🔵 Active Vertex
- x Edge weight
- x Message

Example: Parallel SSSP in Pregel



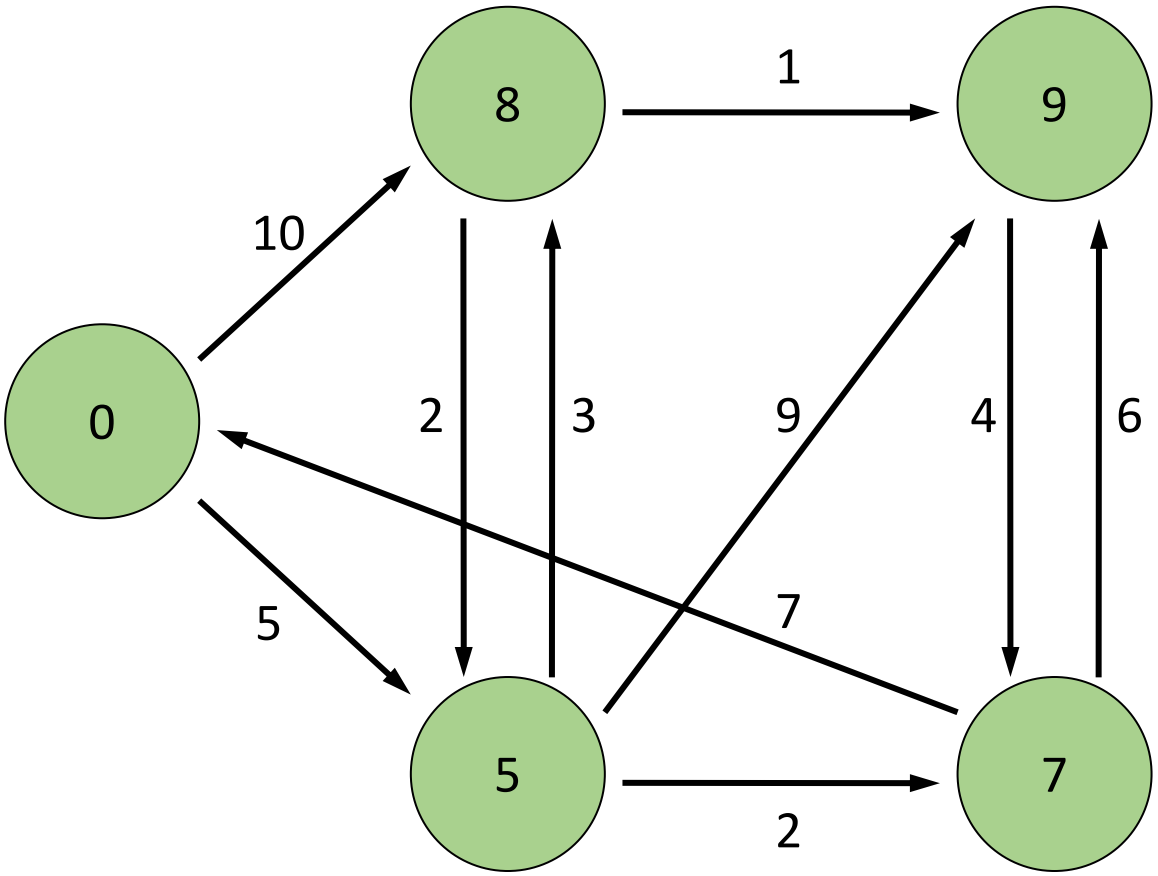
🟩 Inactive Vertex

🟦 Active Vertex

x Edge weight

x Message

Example: Parallel SSSP in Pregel



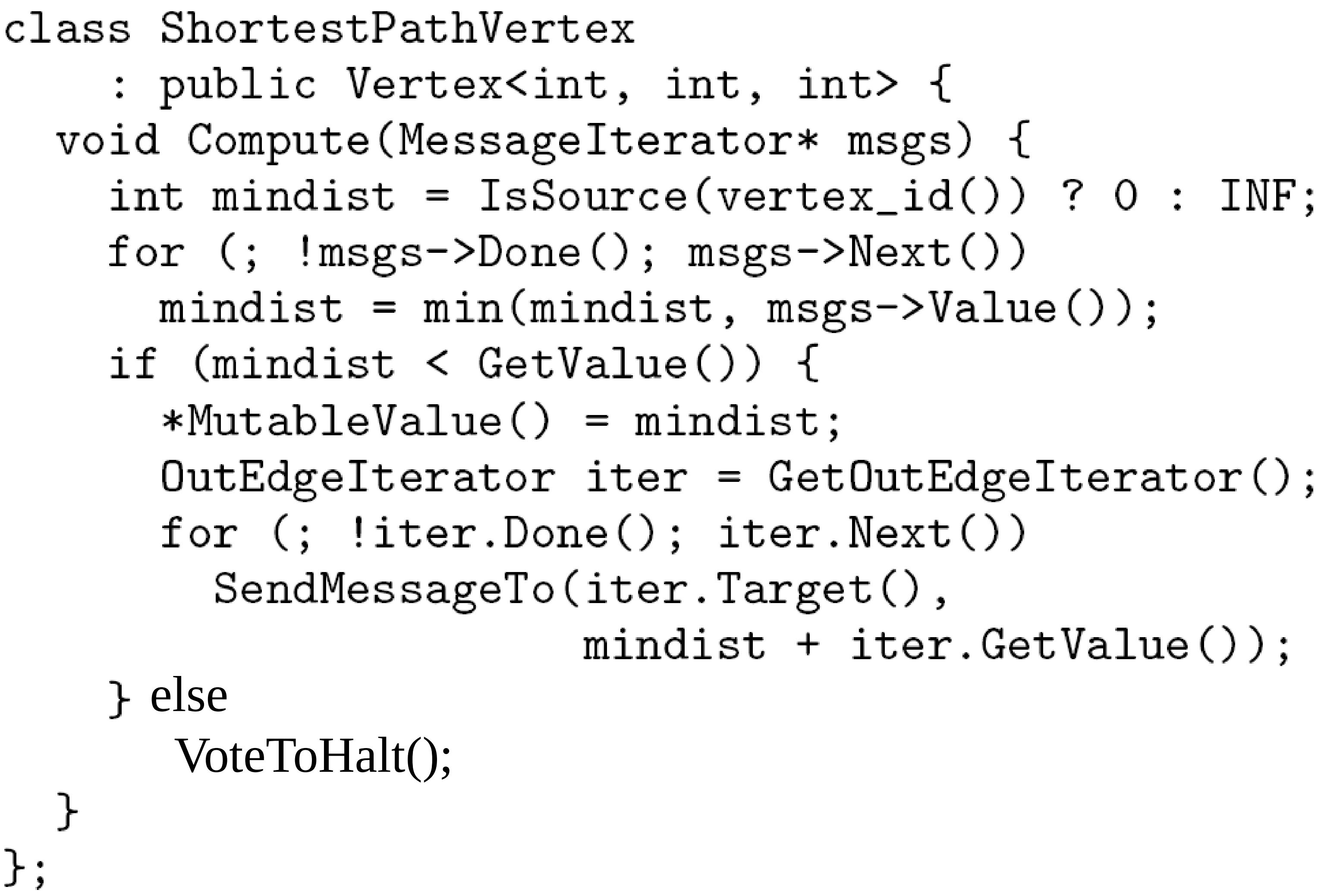
🟢 Inactive Vertex

🔵 Active Vertex

x Edge weight

x Message

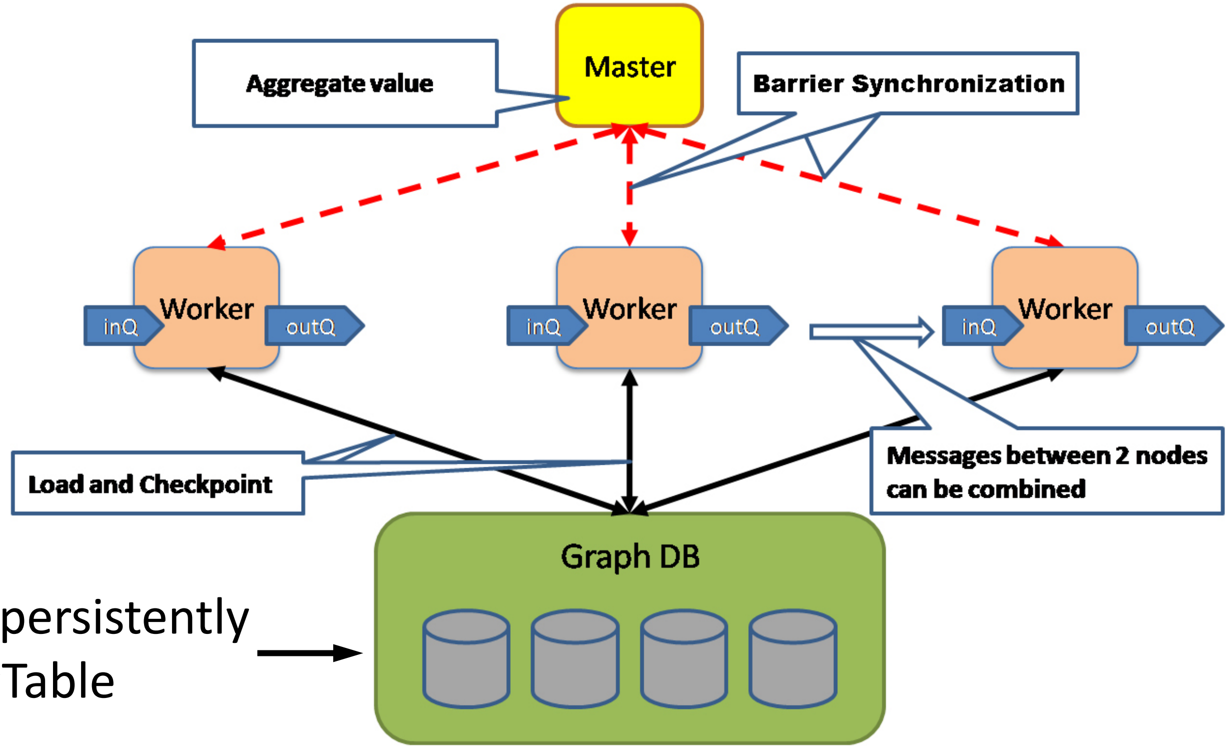
SSSP Vertex Class



```
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());
    } else
          VoteToHalt();
  }
};
```

Pregel Architecture

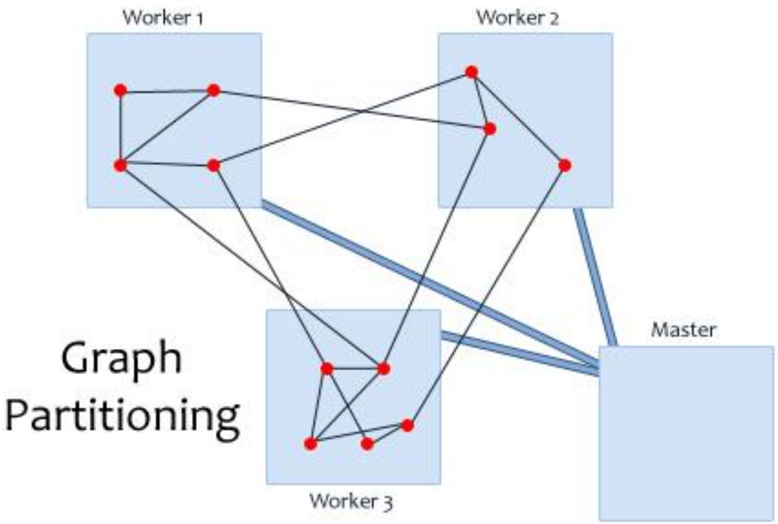
- Pregel uses a master/worker model
  - Master coordinates workers, handles worker failures
  - Workers process their tasks, communicate with other workers asynchronously (computation and communication overlap)



Graph data stored persistently in GFS or BigTable

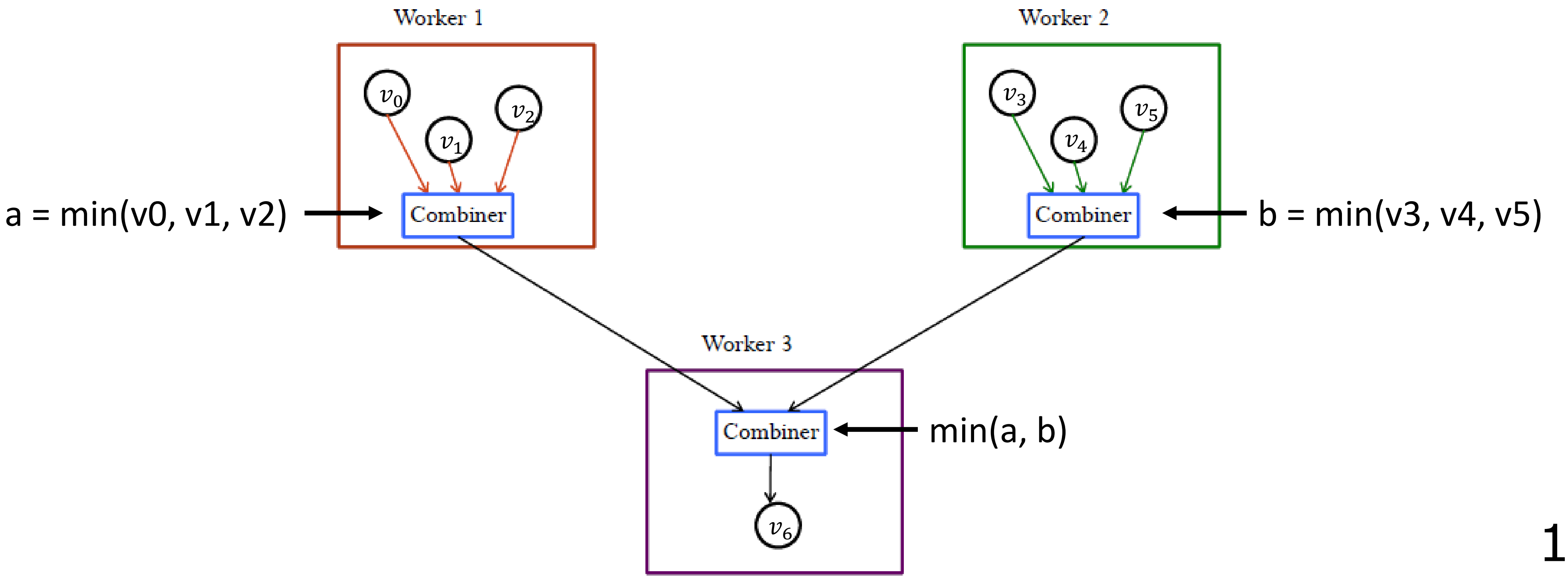
Pregel Execution

- Master decides the number of graph partitions and assigns one or more partitions to each worker
    - A vertex is deterministically mapped to a partition based on ID
    - So, all workers know the partition to which any vertex belongs
- Workers load input graph data in parallel
- Each worker initializes its vertices marks them active
- Each worker executes compute() on all active vertices in a loop, using a separate thread per partition



Combiners

- A worker can combine messages sent to a given vertex
    - Requires combiner() to be commutative and associative
    - Reduces message traffic and disk space on the receiver side
- E.g., for SSSP, say v0-v5 send a message to v6



a = min(v0, v1, v2)

b = min(v3, v4, v5)

min(a, b)

Aggregator

- Used for global communication, and synchronization
    - E.g., compute aggregate statistics from vertex-reported values
- During a superstep:
    - Each worker aggregates values from its vertices to form a partially aggregated value
    - At the end of superstep, partially aggregated values from each worker are aggregated into a global aggregate
    - Global aggregate is sent to the master
- Master sends global aggregate values to all workers at the beginning of next superstep

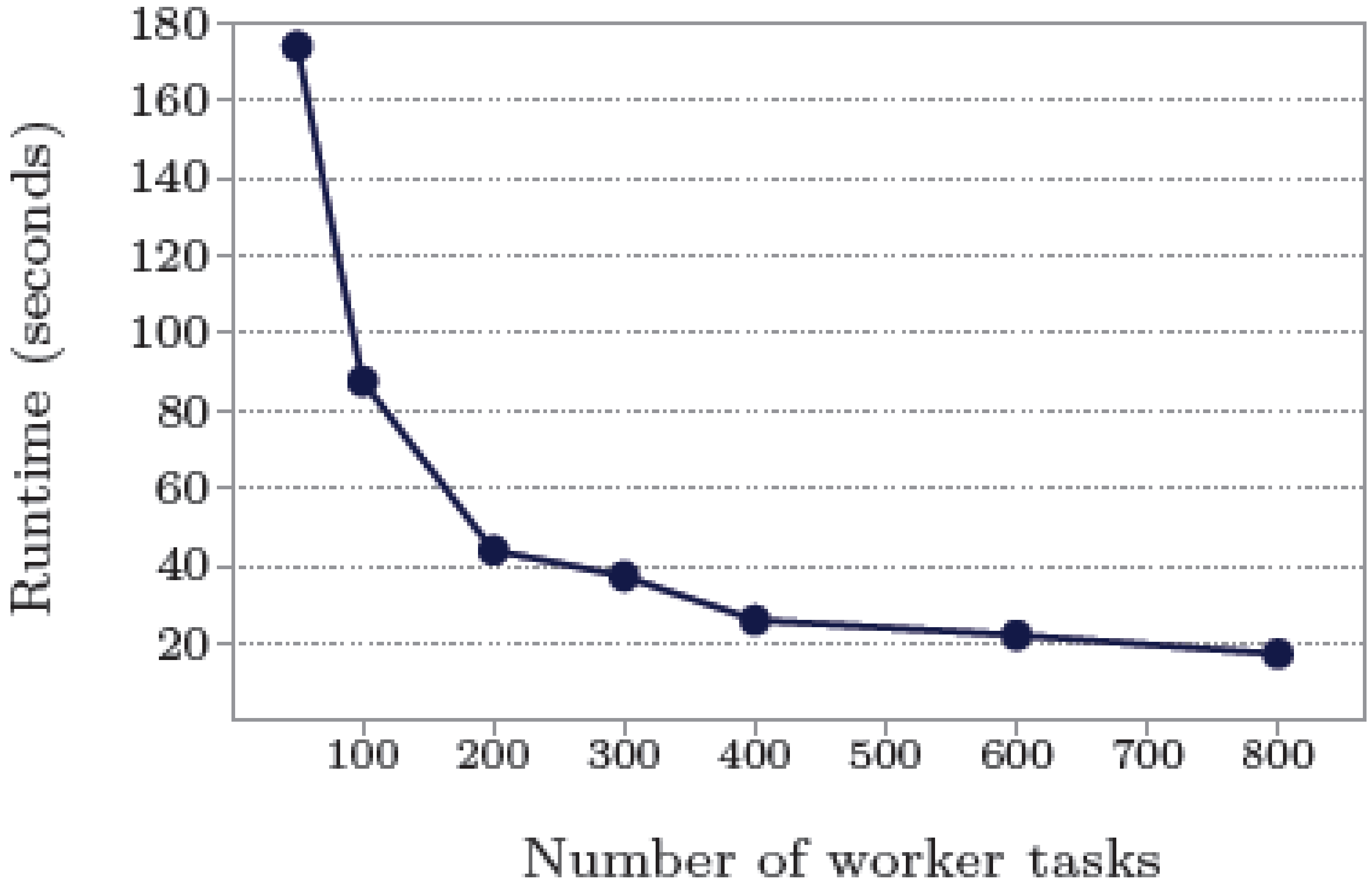
Topology Mutations

- Needed for clustering applications
  - Output is a smaller graph
- Problem is that mutations may race and conflict
  - Two requests to add vertex V with different values
- Solution: apply the mutations at start of next superstep, in order:
  - Remove edges, then vertices
  - Add vertices, then edges
- Resolve rest of the conflicts with user-defined handlers

Pregel Fault Tolerance

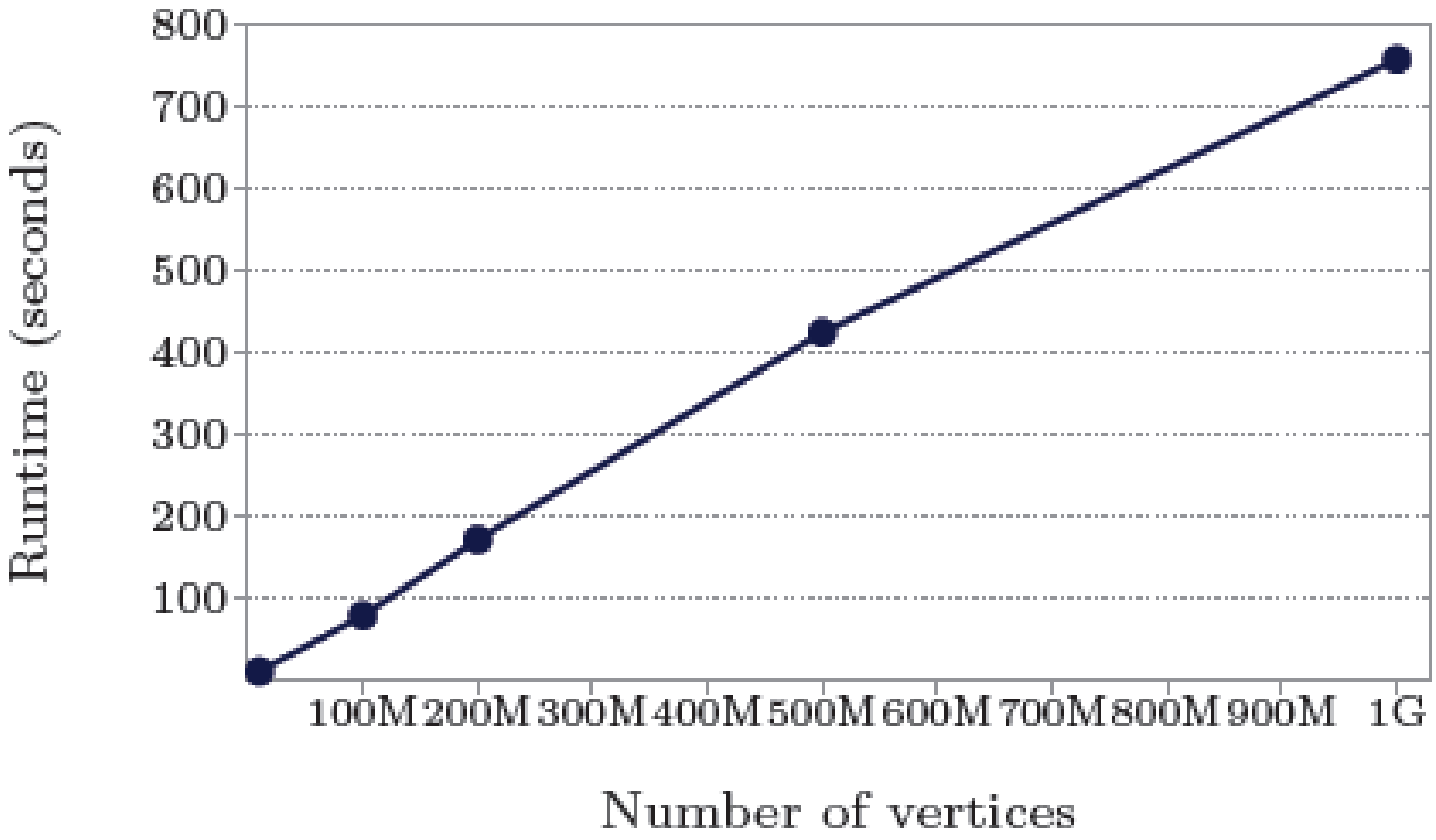
- Uses checkpointing for failure recovery
  - The master periodically instructs workers to save the state of their partitions to persistent storage
    - Partition state includes vertex values, edge values, incoming messages
- Failure detection
  - Master uses regular ping messages
- Failure recovery
  - The master reassigns graph partitions to the currently available workers
  - All workers reload their partition state from most recent available checkpoint

Evaluation



SSSP on a 1 billion vertex binary tree

Evaluation



SSSP on log-normal graph (mean out-degree is 127.1)
with 800 workers

Conclusions

- “Think like a vertex” computation model
- Combiners, aggregator, topology mutations enable many graph algorithms to be run on Pregel
- Highly influential
    - Apache Giraph builds on Pregel design
    - Facebook made improvements, used it on its trillion-edge social graph (look for: scaling apache giraph to a trillion edges)

Discussion

Q1

- We have discussed it briefly but let’s reconsider why Map-Reduce is not a good fit for graph processing?

Q2

- Why must the combiner() function be commutative and associative?

Q3

- Worker processing in each superstep is shown below:
  1. Receive incoming messages
  2. Persist incoming messages, graph state (vertex, edge values)
  3. Compute, modify vertex and outgoing edge state
  4. Buffer outgoing messages
  5. Barrier
- What guarantees are provided by Pregel's processing model (and how)? Why are these guarantees useful?