Pregel: A System For Large Scale Graph Processing

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Real World Graph Processing

- Web graph:
  - PageRank (influential vertices)
- Social graph:
  - Popularity rank, personalized rank, shortest paths, shared connections, clustering (communities), propagation
- Advertisement:
  - Target ads
- Communication network:
  - Maximum flow, transportation routes
- Biology network
  - protein interactions
- Pathology network
  - find anomalies

Graph Processing is Different

- Poor locality of memory access.
- Very little work done per vertex.
- Changes degree of parallelism over the course of execution.

Why not MapReduce (MR)

- Graph algorithms can be expressed as series of MR jobs.
- Data must be reloaded and reprocessed at each iteration, wasting I/O, network. bandwidth, and processor resources.
- Needs an extra MR job for each iteration just to detect termination condition.
- MR isn't very good at dynamic dependency graph.

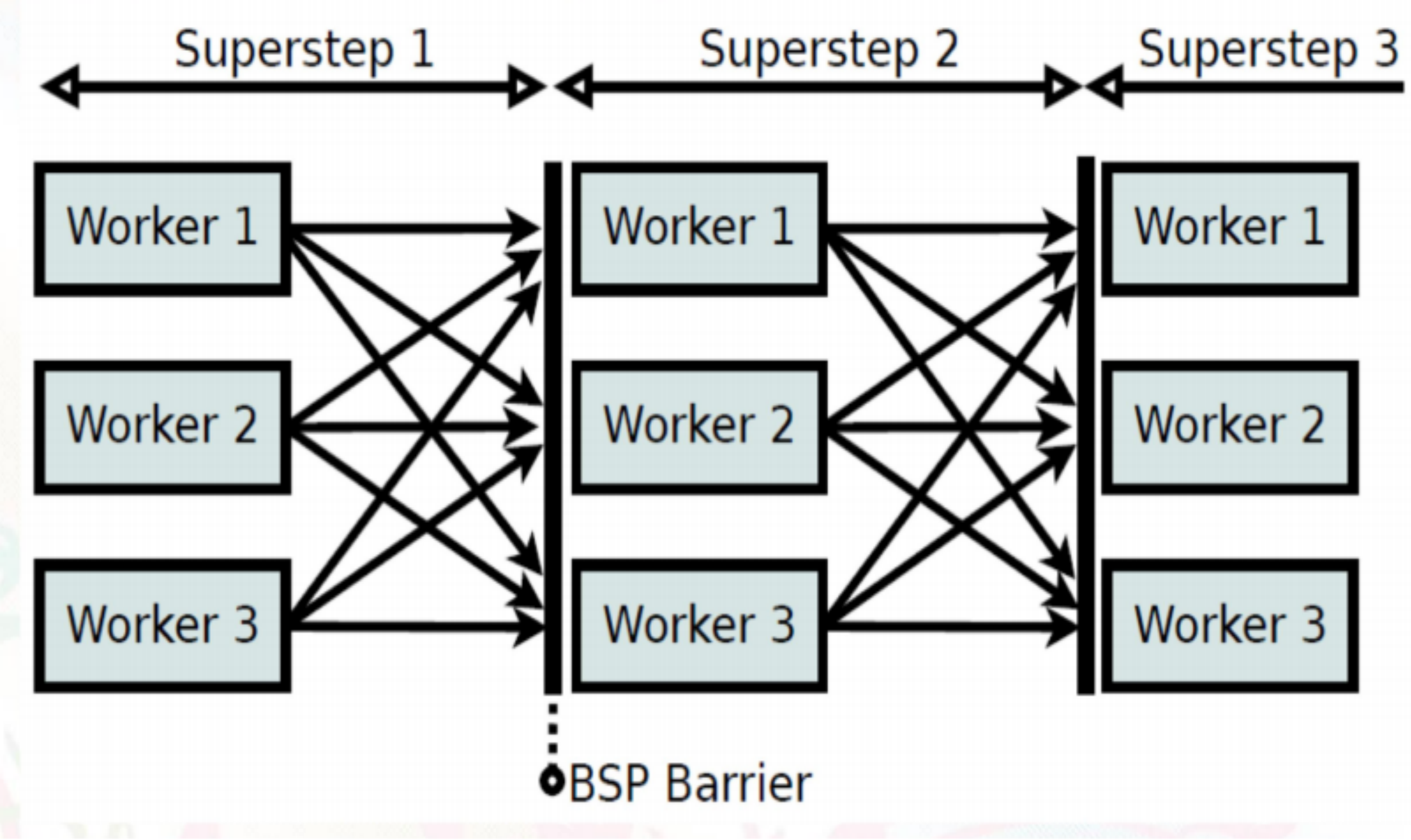
Pregel

- Developed at Google
- Modeled after Bulk Synchronous Parallel (BSP) computing model
- Distributed message passing system
- Computes in vertex-centric fashion
  - "*Think like a vertex*"
- Scalable and fault tolerant
- Influenced systems like Apache Giraph and other BSP distributed systems

Bulk Synchronous Parallel

- Leslie Valiant introduced in 1990.
- Computations are consist of a sequence of iterations, called *superstep*.
- During superstep, framework calls user-defined *computation* function on every vertex.
- Computation function specifies behaviour at a single vertex *V* and a single superstep *S*.
- Supersteps end with barrier synchronization.
- All communications are from superstep *S* to superstep *S+1*.
- Performance of the model is predictable.

Bulk Synchronous Parallel



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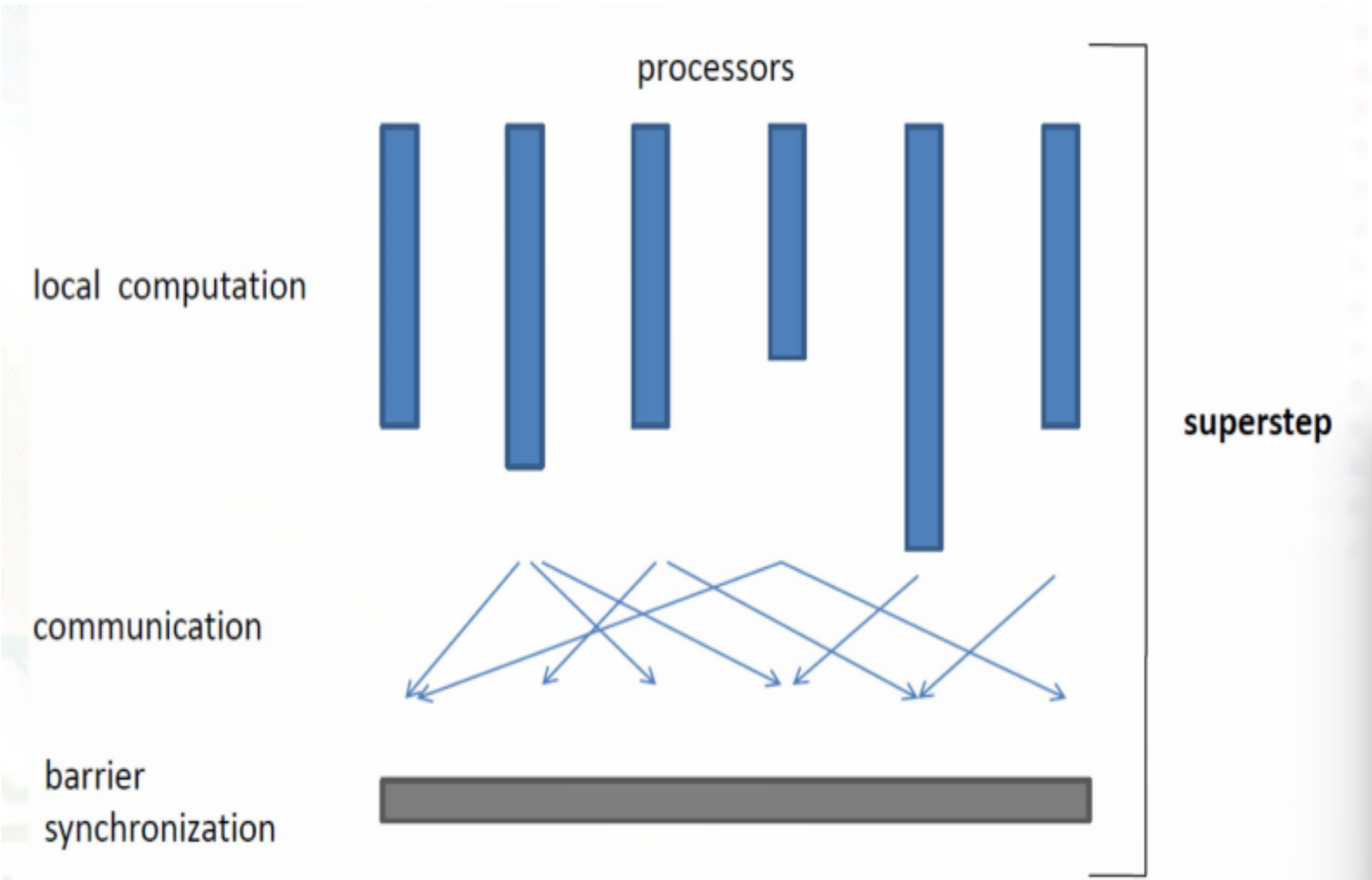
Bulk Synchronous Parallel



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Pregel Computation Model

- Computation on locally stored data.
- Computations are in-memory.
- Terminates when all vertices are inactive or no messages to be delivered.
- Vertices are distributed among workers using *hash(ID) mod N*, where N is the number of partitions (default partitioning)
- Barrier synchronization
  - Wait and synchronize before the end of superstep
  - Fast processors can be delayed by slow ones
- Persistent data is stored on a distributed storage system (GFS/BigTable)
- Temporary data is stored in disk.

C++ 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();
};
```

Figure 3: The Vertex API foundations.

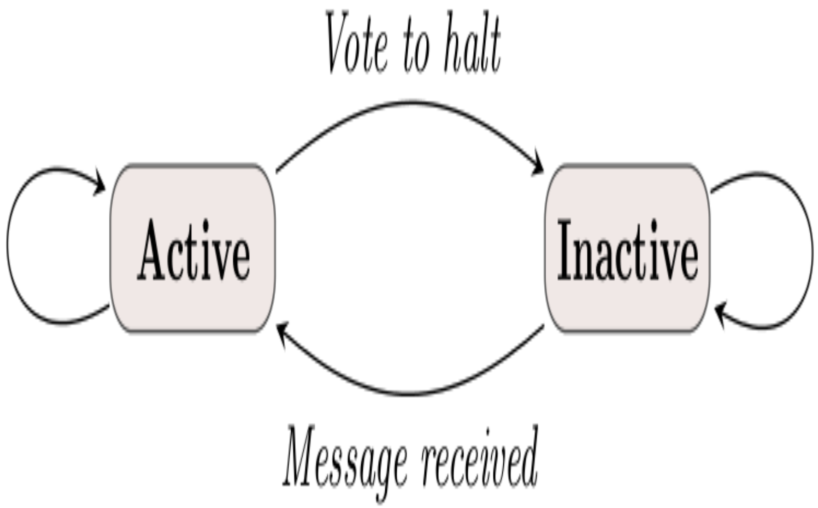
Source: http://kowshik.github.io/JPregel/pregel_paper.pdf

Vertex

- Can mutate local value and value on outgoing edges.
- Can send arbitrary number of messages to any other vertices.
- Receive messages from previous superstep.
- Can mutate local graph topology.
- All active vertices participate in the computation in a superstep.

Vertex State Machine

- Initially, every vertices are active.
- A vertice can deactivate itself by *vote to halt*.
- Deactivated vertices don't participate in computation.
- Vertices are reactivated upon receiving message.



Example

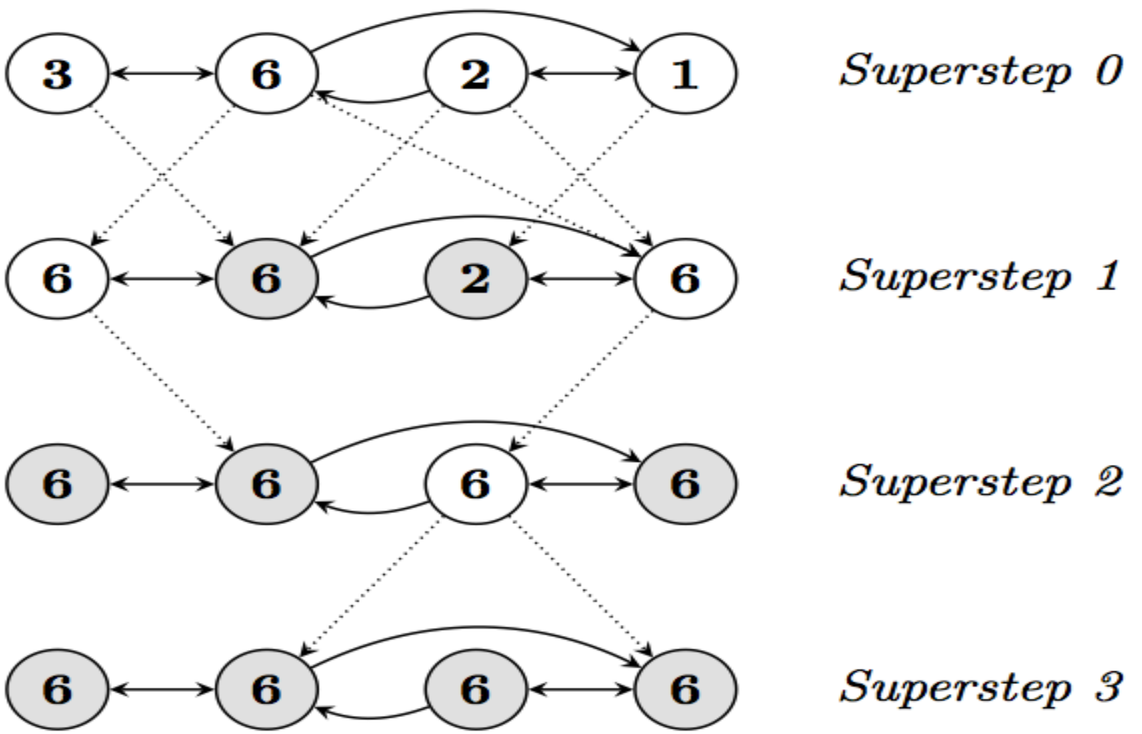


Figure 2: Maximum Value Example. Dotted lines are messages. Shaded vertices have voted to halt.

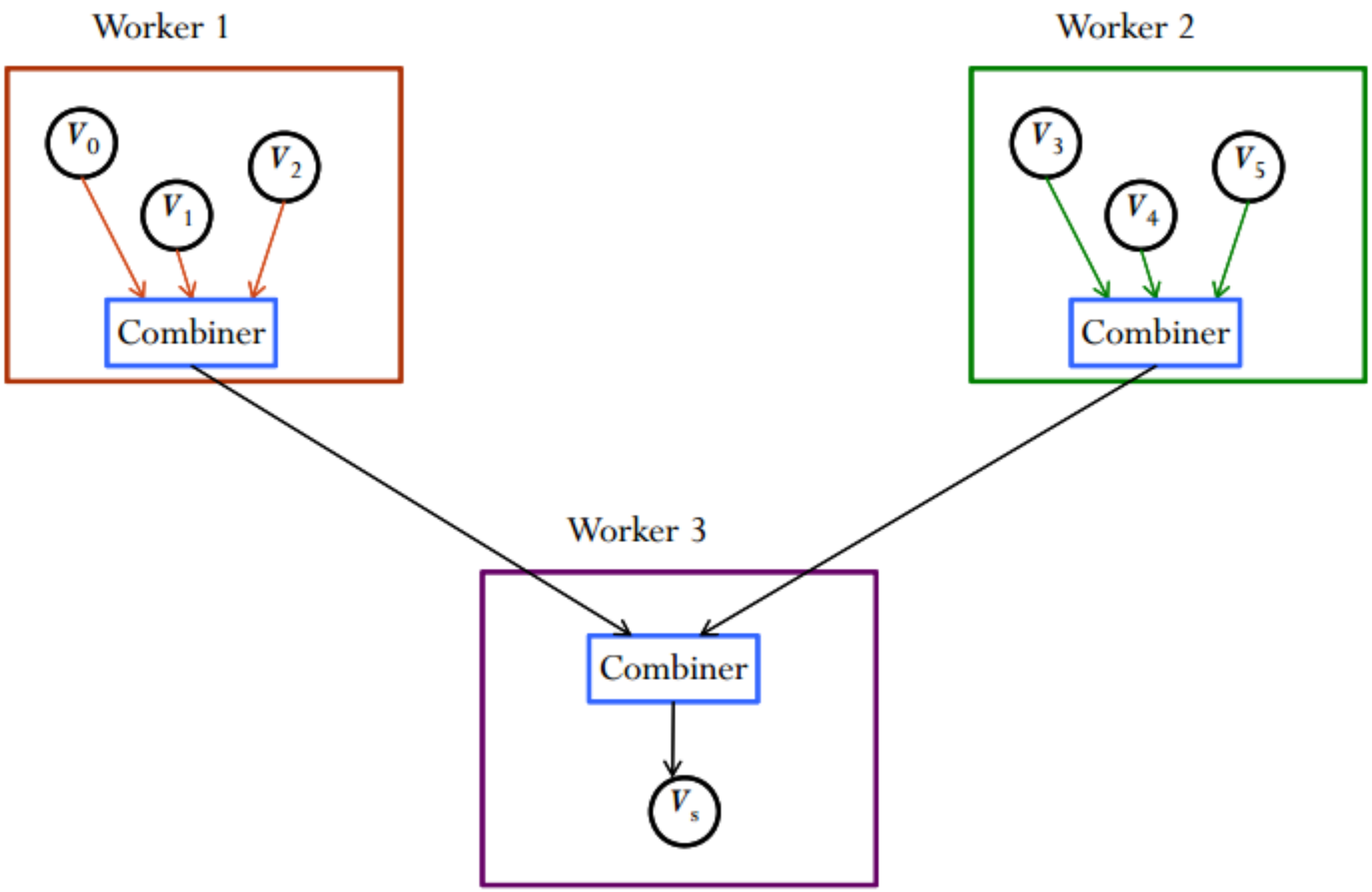
Messages

- Consists of a message value and destination vertex.
- Typically sent along outgoing edges.
- Can be sent to any vertex whose identifier is known.
- Are only available to receiver at the beginning of superstep.
- Guaranteed to be delivered.
- Guaranteed not to be duplicated.
- Can be out of order.

Combiner

- Sending messages incurs overhead.
- System calls *Combine()* for several messages intended for a vertex *V* into a single message containing the combined message.
- No guarantees which messages will be combined or the order of combination.
- Should be enabled for commutative and associative messages.
- Not enabled by default.

Combiner

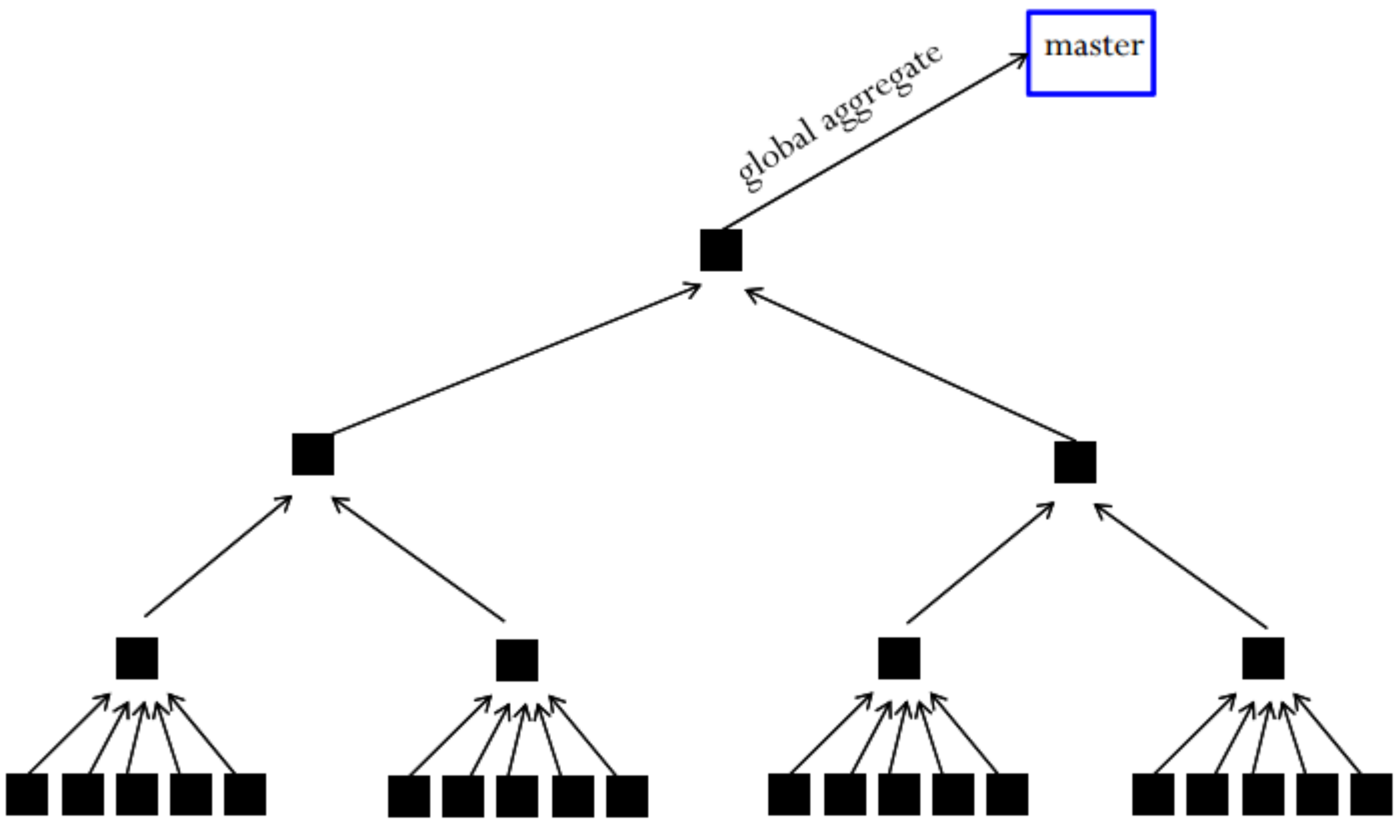


Source: https://wiki.engr.illinois.edu/download/attachments/188588798/pregel.pdf?version=1

Aggregator

- Mechanism for global communication, monitoring and global state.
  - Vertices provide value to aggregator in superstep *S*.
  - Values are combined using a reduction operator.
  - Resulting value is available to all vertices at superstep *S+1*.
- New aggregator is defined by subclassing "*Aggregator*" class.
- Reduction operator should be associative and commutative.

Reduction (Aggregator)



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Topology Mutation

- Vertices can dynamically create/destroy vertices, edges.
- Mutations and conflict resolution take place at barrier.
- Except local mutation (self-edge) immediately takes place.
- Order of mutations
  - Edge deletion
  - Vertex deletion
  - Vertex addition
  - Edge addition

Master

- Partitions the input and assigns one or more partitions to each worker.
- Keeps list of
    - All alive workers
    - Worker's unique identifiers
    - Addressing informations
    - Partition of the graph is assigned to the worker.
- Coordinates barrier synchronization i.e., superstep.
- Fault tolerance by checkpoint, failure detection and reassignment.
- Maintains statistics of the progress of computation and the state of the graph.
- Doesn’t participate in computation.
- Not responsible for load-balancing.

Worker

- Responsible for computation of assigned vertices.
- Keeps two copies of active vertices and incoming messages
  - Current superstep
  - Next superstep
- Place *local messages* immediately in message queue.
- Buffer *remote messages*.
  - Flush asynchronously in single message if threshold reached.

Fault Tolerance

- Checkpoint at the beginning of superstep.
  - Master saves aggregators.
  - Workers save vertices, edges and incoming messages.
- Worker failure detected by ping messages.
- Recovery
  - Master reassigns failed worker partition to other available workers.
  - All workers restart from superstep *S* by loading state from the most recently available checkpoint.
- *Confined recovery*: recovery is only confined to lost partitions
  - Workers also save outgoing messages.
  - Recomputes using logged messages from healthy partitions and recalculated ones from recovering partitions.

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();
    }
  }
};
```

Figure 4: PageRank implemented in Pregel.

Source: http://kowshik.github.io/JPregel/pregel_paper.pdf

Performance

Experimental Setup:

- Hardware: A cluster of 300 multi-core commodity PCs.
- Algorithm: SSSP with unit weight edges.
    - All-pairs shortest paths impractical b/c O(|V|2) storage.
- Measures scalability w.r.t. both the number of workers and the number of vertices.
- Data collected for:
    - Binary trees (to test scalability).
    - log-normal random graphs (to study performance in a realistic setting).
- No checkpointing.

Performance

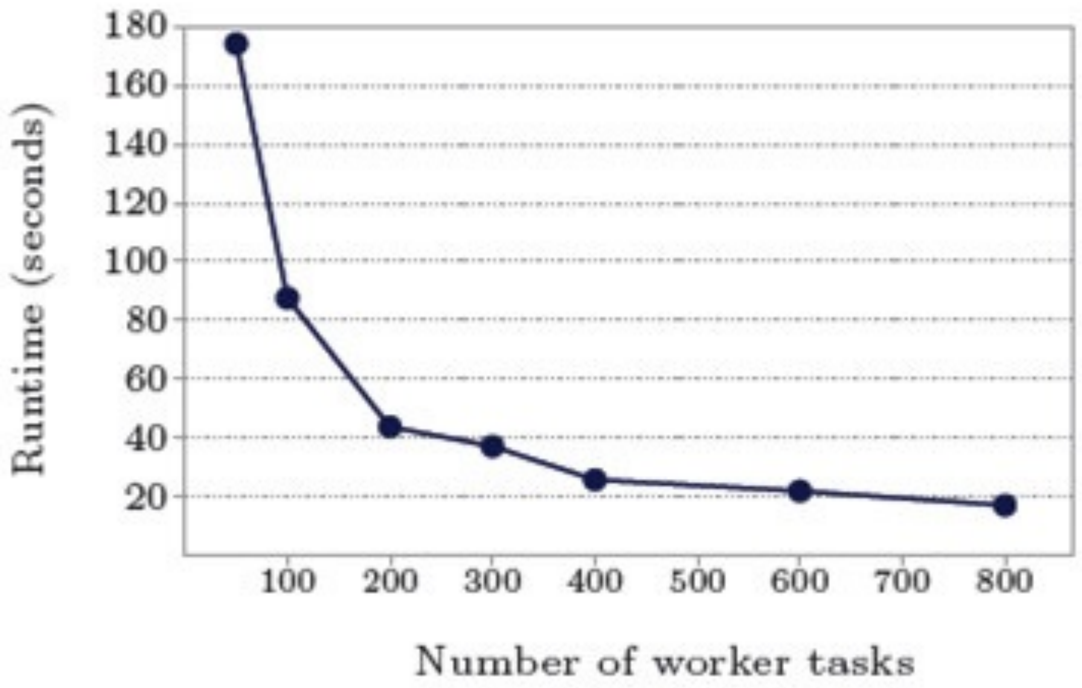

Figure 7: SSSP—1 billion vertex binary tree: varying number of worker tasks scheduled on 300 multicore machines

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Performance

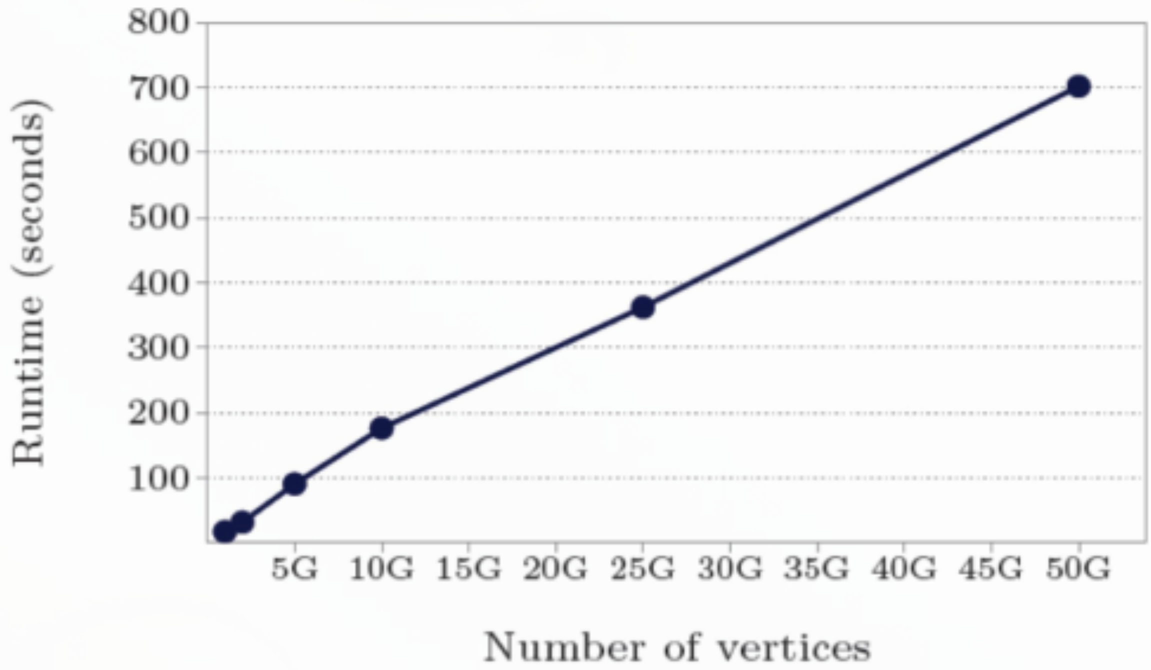

Figure 8: SSSP—binary trees: varying graph sizes on 800 worker tasks scheduled on 300 multicore machines

Source: http://kowshik.github.io/JPregel/pregel_paper.pdf

Performance

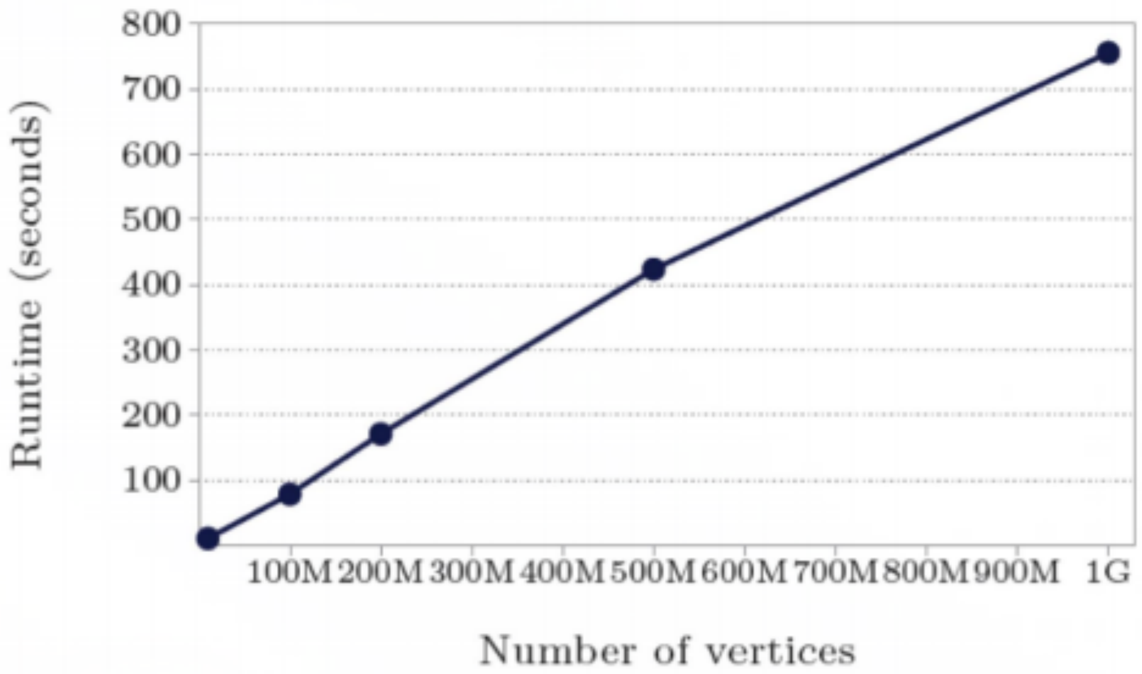

Figure 9: SSSP—log-normal random graphs, mean out-degree 127.1 (thus over 127 billion edges in the largest case): varying graph sizes on 800 worker tasks scheduled on 300 multicore machines

Source: http://kowshik.github.io/JPregel/pregel_paper.pdf

Summary

- Distributed system for large scale graph processing.
- Vertex-centric BSP model
  - Message passing API
  - A sequence of supersteps
  - Barrier synchronization
- Coarse grained parallelism
- Fault tolerance by checkpointing
- Runtime performance scales near linearly to the size of the graph (CPU bound)

Discussion

- No fault tolerance for master is mentioned in the paper (Probably Paxos or replication).
- Static partitioning! What happens if a worker is too slow?
- Dynamic partitioning, network overhead for reassigning vertices and state.
- Good for sparse graph. But communication overhead for dense graph can bring the system down to knees.