Pregel: A System for Large-Scale Graph Processing

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Outline

- Motivation
- Model of Computation
- The C++ API
- Implementation
- Applications
- Experiments
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- Discussion

Motivation

- Google needs applications that perform Internet-related graph algorithms
- Processing a large graph is challenging
  - Poor locality of memory access
  - Very little work per vertex
  - A changing degree of parallelism over the course of execution

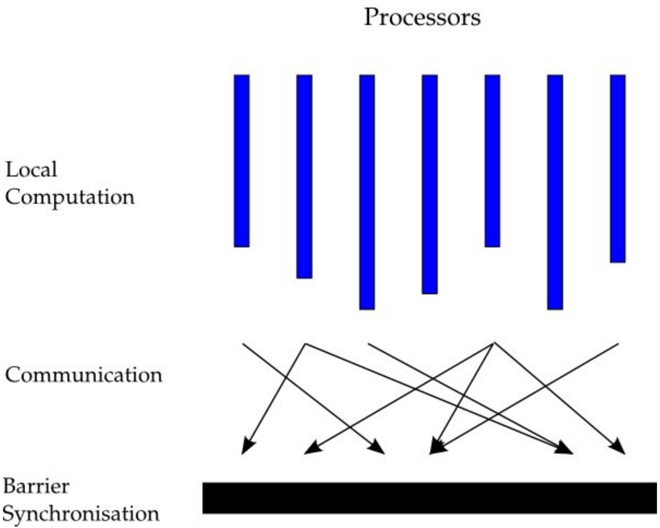
Motivation

- Four options (at 2010)
  - Writing a custom infrastructure
  - Using a distributed computing platform like MapReduce
  - Using a single-computer graph algorithm library
  - Using an existing parallel graph system

Model of Computation

- Bulk Synchronous Parallel model
  - A computation proceeds in a series of global supersteps
  - Three components: local computation, communication, barrier synchronization

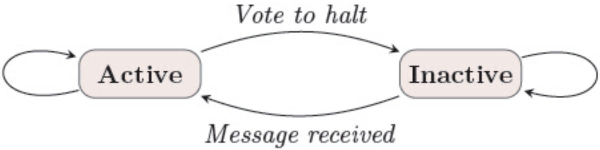
Model of Computation



from http://en.wikipedia.org/wiki/Bulk_synchronous_parallel

Model of Computation

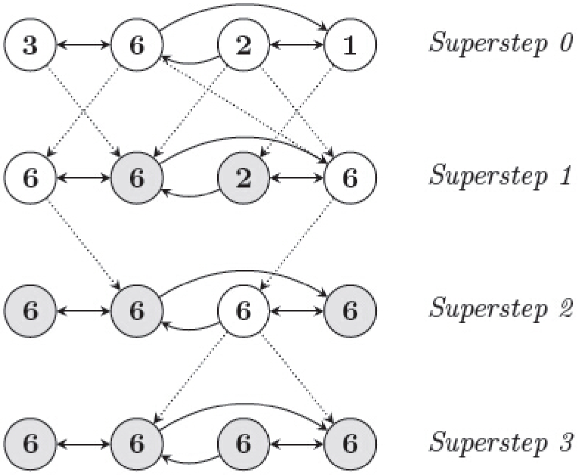
- Take a graph as input
- Run at each vertex in parallel (Think as vertex)
- Run until vertices vote to halt
- Finish with output



Model of Computation

- Within each superstep, a vertex can
  - Modify its state or that of its outgoing edges
  - Read messages sent to it in the previous superstep
  - Send messages to other (to be received in the next superstep)
  - Mutate the topology of the graph

Model of Computation



The C++ API

- 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();
};
```

The C++ API

- Message Passing
  - No guaranteed order of messages in the iterator
  - Guarante that messages will be delivered once
  - Can send messages to any vertex
  - User handlers are executed for the missing vertex
- Combiners
  - Not enabled by default
  - Combine multiple messages to the same vertex into a single one
  - Only for commutative and associative operations

The C++ API

- Aggregators
  - A mechanism for global communication, monitoring, and data
  - Each vertex sends a value to an aggregator in superstep S
  - All vertices receive the resulting value in superstep $S + 1$.
  - Can be used for statistics and global coordination

The C++ API

- Topology Mutations
  - Vertices can issue requests to add or remove vertices or edges
  - Resolving conflicting requests in the same superstep:
    - Partial ordering - edge removal before vertex removal; vertex addition before edge addition
    - User-defined handlers
  - Local mutations have no conflicts
- Input and output
  - Support various file formats, even custom Reader and Writer

Implementation

- Basic architecture
  - Copies of user program are sent to the cluster - master/workers
  - Master assigns graph partitions to workers - vertex partition
  - Master assigns a portion of user input to each worker
  - Supersteps begin
  - Save the output graphs

Implementation

- Fault tolerance
  - Achieved through checkpointing
  - At the beginning of a superstep:
    - Workers persists the state of their partitions
    - Master saves the aggregator values
  - If one or more workers fail, everyone starts over from the most recent checkpoint
  - Confined recovery with message logs is under development

Implementation

- The Worker
  - A worker keeps its portion of the graph in memory
  - Two copies of of the active vertex flags and the incoming message queue for the current and next superstep
  - Messages to a remote worker are buffered
  - Combiner may be used

Implementation

- The Master
  - Keeps track of which portion of the graph a worker is assigned
  - Coordinates the activities of workers using barriers
  - Maintains the statistics of the progress and the graph for user monitoring

Implementation

- Aggregators
  - An aggregator computes a global value with values from workers
  - Workers form a tree to reduce partially reduced aggregators
  - A tree structure is better than chain pipelining

Applications - PageRank

- Ranks web pages according to their popularity
- Named after Larry Page instead of Web Page
- Computes the page rank of every vertex in a directed graph iteratively
- At every iteration, each vertex computes its rank according to its neighbors' rank values at last iteration

Applications - PageRank (cont.)

```
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();
    }
  }
};
```

Applications - Single Source Shortest Paths

- Parallel breadth first search

```
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();
  }
};
```

Applications - Bipartite Matching

- Input: a bipartite graph with two distinct sets of vertices
- Output: a subset of edges with no common endpoints
- Vertices maintain two values: a set flag (left or right) and its matched vertex
- The program proceeds in cycles of four phases:
  - Each unmatched left vertex sends a message to its neighbors and then votes to halt
  - Each unmatched right vertex grants one request and denies others and then votes to halt
  - Each unmatched left vertex accepts one grants it receives
  - An unmatched right vertex receives at most one acceptance message

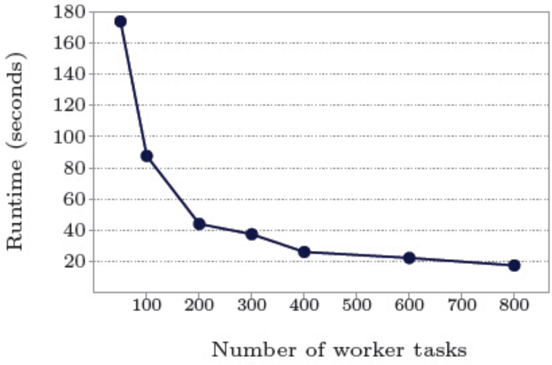
Applications - Semi-Clustering

- A semi-cluster in a social graph is a group of people interacting frequently with each other and less frequently with others
- Input: a weighted, undirected graph
- Output: at most C_{max} semi-clusters
- Each vertex V maintains a list containing at most C_{max} semi-clusters, sorted by score
- In superstep 0, V enters itself in that list as a semi-cluster of size 1 and score 1, and publishes itself to all of its neighbors
- In subsequent supersteps, V adds itself to received semi-clusters, sorts them by score and propagates best ones to neighbors, and at last updates its list
- The algorithm terminates either when the semi-clusters stop changing or when the number of supersteps reaches a user-specified limit

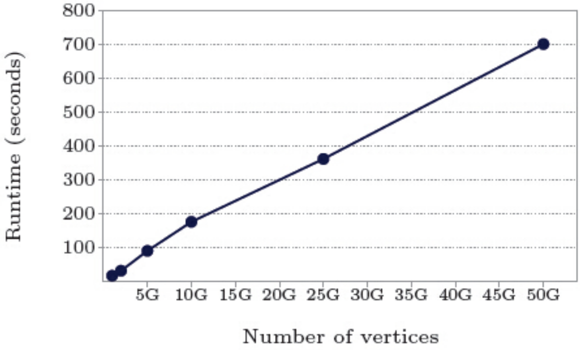
Experiments

- Use the single-source shortest paths implementation
- Conduct experiments on a cluster of 300 multicore machines
- Measure running time with checkpointing disabled
- Measure how Pregel scales with increasing worker tasks
- Measure how Pregel scales with increasing number of vertices
- Use both binary trees and log-normal graphs

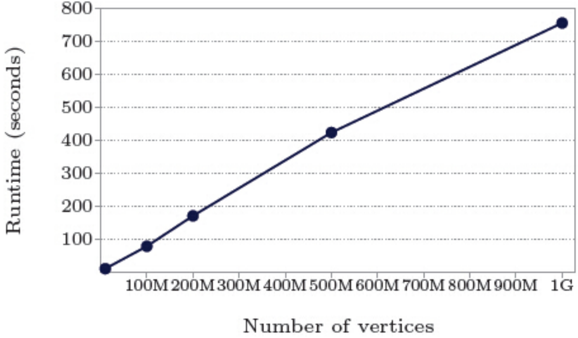
Experiments



Experiments



Experiments



Conclusion

- Pregel is a scalable, general-purpose system for implementing graph algorithms in a distributed environment
- Run a program in supersteps in which vertices do computation and send messages to others for the next superstep
- The API is intuitive, flexible, and easy to use
- Future work
  - Spill data to local disk
  - Topology-aware partitioning and dynamic re-partitioning

Questions

Discussion

- BSP - straggler problem
  - A small number of threads (the stragglers) take longer than the others to execute a given iteration
  - Asynchronous Parallel Model?
- Load Balancing
  - Graphs have power-law degree distribution
  - Does topology-aware graph partitioning suffice?
  - What do we need to consider to implement dynamic re-partitioning?
- How does Pregel deal with Master failure?