MapReduce isn't always the answer

- MapReduce works well for certain problems
  - Provides automatic parallelization
  - Automatic job distribution

- For others
  - May require many iterations
  - Data locality usually not preserved between Map and Reduce
    - Lots of communication between map and reduce workers

Bulk Synchronous Parallel (BSP)

- Computing model for parallel computation
- Series of supersteps
  1. Concurrent computation
  2. Communication
  3. Barrier synchronization

- Messaging is restricted to the end of a computation superstep
- Each worker sends a message to 0 or more workers
- These messages are inputs for the next superstep

Series of supersteps
1. Concurrent computation
2. Communication
3. Barrier synchronization

Processes (workers) are randomly assigned to processors
Each process uses only local data
Each computation is asynchronous of other concurrent computation
Computation time may vary
Bulk Synchronous Parallel (BSP)

- Series of supersteps
  1. Concurrent computation
  2. Communication
  3. Barrier synchronization

  - The next superstep does not begin until all messages have been received
  - Barriers ensure no deadlock: no circular dependency can be created
  - Provide an opportunity to checkpoint results for fault tolerance
    - If failure, restart computation from last superstep

BSP Implementation: Apache Hama

- Hama: BSP framework on top of HDFS
  - Provides automatic parallelization & distribution
  - Uses Hadoop RPC
    - Data is serialized with Google Protocol Buffers
    - Zookeeper for coordination (Apache version of Google’s Chubby)
    - Handles notifications for Barrier Sync

  - Good for applications with data locality
    - Matrices and graphs
    - Algorithms that require a lot of iterations

Hama programming (high-level)

- Pre-processing
  - Define the number of peers for the job
  - Split initial inputs for each of the peers to run their supersteps
  - Framework assigns a unique ID to each worker (peer)

- Superstep: the worker function is a superstep
  - getCurrentMessage() – input messages from previous superstep
  - Compute – your code
  - send(peer, msg) – send messages to a peer
  - sync() – synchronize with other peers (barrier)

- File I/O
  - Key/value model used by Hadoop MapReduce & HBase
    - readNext(key, value)
    - write(key, value)

For more information

- Architecture, examples, API
  - Take a look at:
    - Apache Hama project page
    - http://hama.apache.org
    - Hama BSP tutorial
      - Apache Hama Programming document

Graphs are common in computing

- Social links
  - Friends
  - Academic citations
  - Music
  - Movies

- Web pages
- Network connectivity
- Roads
- Disease outbreaks

Processing graphs on a large scale is hard

- Computation with graphs
  - Poor locality of memory access
  - Little work per vertex

- Distribution across machines
  - Communication complexity
  - Failure concerns

- Solutions
  - Application-specific, custom solutions
  - MapReduce or databases
    - but require many iterations (and a lot of data movement)
  - Single-computer libraries: limits scale
  - Parallel libraries: do not address fault tolerance
    - BSP: close but too general
Pregel: a vertex-centric BSP

- Input: directed graph
  - A vertex is an object
  - Each vertex uniquely identified with a name
  - Each vertex has a modifiable value
- Directed edges: links to other objects
  - Associated with source vertex
  - Each edge has a modifiable value
  - Each edge has a target vertex identifier

Pregel: computation

- Computation: series of supersteps
  - Same user-defined function runs on each vertex
  - Receives messages sent from the previous superstep
  - May modify the state of the vertex or of its outgoing edges
  - Sends messages that will be received in the next superstep
    - Typically to outgoing edges
    - But can be sent to any known vertex
  - May modify the graph topology
- Each superstep ends with a barrier (synchronization point)

Pregel: termination

Pregel terminates when every vertex votes to halt

- Initially, every vertex is in an active state
  - Active vertices compute during a superstep
- Each vertex may choose to deactivate itself by voting to halt
  - The vertex has no more work to do
  - Will not be executed by Pregel
- UNLESS the vertex receives a message
  - Then it is reactivated
  - Will stay active until it votes to halt again
- Algorithm terminates when all vertices are inactive and there are no messages in transit

Pregel: output

- Output is the set of values output by the vertices
- Often a directed graph
  - May be non-isomorphic to original since edges & vertices can be added or deleted
  - ... Or summary data

Examples of graph computations

- Shortest path to a node
  - Each iteration, a node sends the shortest distance received to all neighbors
- Cluster identification
  - Each iteration: get info about clusters from neighbors.
    - Add myself
    - Pass useful clusters to neighbors (e.g., within a certain depth or size)
    - May combine related vertices
  - Output is a smaller set of disconnected vertices representing clusters of interest
- Graph mining
  - Traverse a graph and accumulate global statistics
- Page rank
  - Each iteration: update web page ranks based on messages from incoming links

Simple example: find the maximum value

- Each vertex contains a value
- In the first superstep:
  - A vertex sends its value to its neighbors
- In each successive superstep:
  - If a vertex learned of a larger value from its incoming messages, it sends it to its neighbors
  - Otherwise, it votes to halt
- Eventually, all vertices get the largest value
- When no vertices change in a superstep, the algorithm terminates
Simple example: find the maximum value

Semi-pseudocode:

```cpp
class MaxValueVertex : public Vertex<int, void, int> {
    void Compute(MessageIterator *msgs) {
        int maxv = GetValue();
        for (; !msgs->Done(); msgs->Next())
            maxv = max(msgs.Value(), maxv);
        if (maxv > GetValue() || (step == 0)) {
            *MutableValue() = maxv;
            OutEdgeIterator out = GetOutEdgeIterator();
            for (; !out.Done(); out.Next())
                sendMessageTo(out.Target(), maxv);
        } else
            VoteToHalt();
    }
};
```

Locality

- Vertices and edges remain on the machine that does the computation
- To run the same algorithm in MapReduce
  - Requires chaining multiple MapReduce operations
  - Entire graph state must be passed from Map to Reduce
  - ... and again as input to the next Map

Pregel API: Basic operations

- A user subclasses a Vertex class
- Methods
  - `Compute(MessageIterator*)`: Executed per active vertex in each superstep
  - `GetValue()`: Get the current value of the vertex
  - `MutableValue()`: Set the value of the vertex
  - `GetOutEdgeIterator()`: Get a list of outgoing edges
  - `sendMessageTo()`: Send a message to a vertex
    - Any number of messages can be sent
    - Ordering among messages is not guaranteed
    - A message can be sent to any vertex (but our vertex needs to have its ID)
**Pregel API: Advanced operations**

**Combiners**
- Each message has an overhead — let’s reduce # of messages
  - Many vertices are processed per worker (multi-threaded)
  - Pregel can combine messages targeted to one vertex into one message
- Combiners are application specific
  - Programmer subclasses a `Combiner` class and overrides `Combine()` method
- No guarantee on which messages may be combined

![Combiner Diagram]

**Aggregators**
- Handle global data
  - A vertex can provide a value to an aggregator during a superstep
    - Aggregator combines received values to one value
    - Value is available to all vertices in the next superstep
- User subclasses an `Aggregator` class
  - Examples
    - Keep track of total edges in a graph
    - Generate histograms of graph statistics
    - Global flags: execute until some global condition is satisfied
    - Election: find the minimum or maximum vertex

![Aggregator Diagram]

**Topology modification**
- Examples
  - If we’re computing a spanning tree: remove unneeded edges
  - If we’re clustering: combine vertices into one vertex
- Add/remove edges/vertices
- Modifications visible in the next superstep

![Topology Modification Diagram]

**Execution environment**
- Many copies of the program are started on a cluster of machines
- One copy becomes the `master`
  - Will not be assigned a portion of the graph
  - Responsible for coordination
- Cluster’s name server = `chubby`
  - Master registers itself with the name service
  - Workers contact the name service to find the master

![Execution Environment Diagram]

**Partition assignment**
- Master determines # partitions in graph
- One or more partitions assigned to each worker
  - Partition = set of vertices
  - Default: for `N` partitions
    \[
    \text{hash(vertex ID) mod } N = \text{worker}
    \]
  - May deviate: e.g., place vertices representing the same web site in one partition
    - More than 1 partition per worker: improves load balancing
  - Worker
    - Responsible for its section of the graph
    - Each worker knows the vertex assignments of other workers

![Partition Assignment Diagram]
Input assignment

• Master assigns parts of the input to each worker
  – Data usually sits in GFS or HBase

• Input = set of records
  – Record = vertex data and edges
  – Assignment based on file boundaries

• Worker reads input
  – If it belongs to any of the vertices it manages, messages sent locally
  – Else worker sends messages to remote workers

• After data is loaded, all vertices are active

Computation

• Master tells each worker to perform a superstep
  – Iterates through vertices (one thread per partition)
  – Calls Compute() method for each active vertex
  – Delivers messages from the previous superstep
  – Outgoing messages
    • Sent asynchronously
    • Delivered before the end of the superstep

• When done
  – Worker tells master how many vertices will be active in the next superstep
  – Computation done when no more active vertices in the cluster
  – Master may instruct workers to save their portion of the graph

Handling failure

• Checkpointing
  – Controlled by master ... every N supersteps
  – Master asks a worker to checkpoint at the start of a superstep
    • Save state of partitions to persistent storage
      – Vertex values
      – Edge values
      – Incoming messages
    – Master is responsible for saving aggregator values

• Master sends “ping” messages to workers
  – If worker does not receive a ping within a time period
    ⇒ Worker terminates
  – If the master does not hear from a worker
    ⇒ Master marks worker as failed

• When failure is detected
  – Master reassigns partitions to the current set of workers
  – All workers reload partition state from most recent checkpoint

Pregel outside of Google

• Apache Giraph
  – Initially created at Yahoo
  – Used at Facebook to analyze the social graph of users
  – Runs under Hadoop MapReduce framework
  – Runs as a Map-only job
  – Adds fault-tolerance to the master by using ZooKeeper for coordination
  – Uses Java instead of C++

• Mizan
  – Pregel clone – compatible with Pregel API and written in C++
  – Created at King Abdullah University of Science and Technology
  – http://thegraphsblog.wordpress.com/the-graph-blog/mizan/

Conclusion

• Vertex-centric approach to BSP

• Computation = set of supersteps
  – Compute() called on each vertex per superstep
  – Communication between supersteps: barrier synchronization

• Hides distribution from the programmer
  – Framework creates lots of workers
  – Distributes partitions among workers
  – Distributes input
  – Handles message sending, receipt, and synchronization
    – A programmer just has to think from the viewpoint of a vertex

• Checkpoint-based fault tolerance

The End