CSE 486/586 Distributed Systems
Graph Processing

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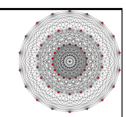
Recap

- Byzantine generals problem
  - They must decide on a common plan of action.
  - But, some of the generals can be traitors.
- Requirements
  - All loyal generals decide upon the same plan of action (e.g., attack or retreat).
  - A small number of traitors cannot cause the loyal generals to adopt a bad plan.
- Impossibility result
  - In general, with less than $3f + 1$ nodes, we cannot tolerate f faulty nodes.

Today

- Distributed Graph Processing
- Google's Pregel system
  - Inspiration for many newer graph processing systems: Piccolo, Giraph, GraphLab, PowerGraph, LFGraph, X-Stream, etc.

What Graphs?



- Large graphs are all around us
- Internet Graph: vertices are routers/switches and edges are links
- World Wide Web: vertices are webpages, and edges are URL links on a webpage pointing to another webpage
  - Called "Directed" graph as edges are uni-directional
- Social graphs: Facebook, Twitter, LinkedIn
- Biological graphs: DNA interaction graphs, ecosystem graphs, etc.

What Graph Analysis?

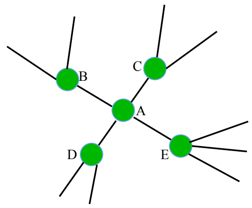
- Need to derive properties from these graphs
- Need to summarize these graphs into statistics
- E.g., find shortest paths between pairs of vertices
  - Internet (for routing)
  - LinkedIn (degrees of separation)
- E.g., do matching
  - Dating graphs in match.com (for better dates)
- PageRank
  - Web Graphs
  - Google search, Bing search, Yahoo search: all rely on this
- And many (many) other examples!

What Are the Difficulties?

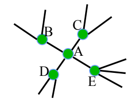
- Large!
  - Human social network has 100s Millions of vertices and Billions of edges
  - WWW has Millions of vertices and edges
- Hard to store the entire graph on one server and process it
  - Slow on one server (even if beefy!)
- Need a distributed solution

Example

- Are C and D connected?
- Can we get all connected pairs?



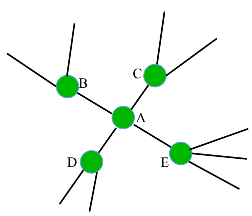
Typical Graph Processing



- Works in *iterations*
- Each vertex assigned a *value*
- In each iteration, each vertex:
  - Gathers values from its immediate neighbors (vertices who join it directly with an edge). E.g., @A: B→A, C→A, D→A,…
  - Does some computation using its own value and its neighbors values.
  - Updates its new value and sends it out to its neighboring vertices. E.g., A→B, C, D, E
- Graph processing terminates after: i) fixed iterations, or ii) vertices stop changing values

Example

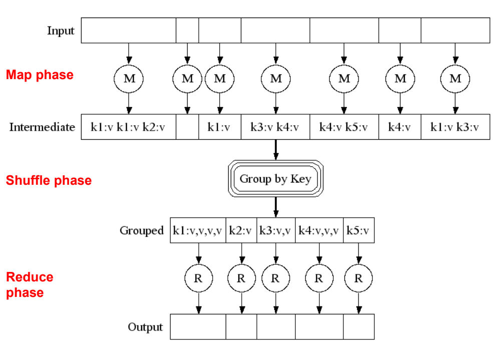
- Are C and D connected?



One Possible Way

- Each vertex has two Boolean variables.
  - Cflag: true/false
  - Dflag: true/false
- Goal
  - Cflag: Am I connected to C?
  - Dflag: Am I connected to D?
  - If both are true at any of the vertices, C and D are connected.
  - Initially all false, except at C and D.
- Every iteration:
  - Propagates its values to neighboring vertices.
  - Collects the values from other vertices.
  - Updates the variables with OR, i.e., if any one of the values is true, it's true.
- Iterate N times, where N is the length of the longest path in the entire graph.

Recall MapReduce?



Can We Use MapReduce?

- Run MapReduce N times, where N is the length of the longest path. Goal for each iteration:
  - Propagate each vertex's Cflag & Dflag values to their neighboring vertices.
  - Collect Cflag & Dflag values from other vertices.
  - Update each of the Cflag & Dflag variables with OR, i.e., if any one of the values is true, it's true.
- Map
  - Input (key, value)? Computation? Output list of (intermediate key, intermediate value)?
- Shuffle: Grouping based on intermediate keys.
  - Each intermediate key will get a list of intermediate values.
- Reduce
  - Input (intermediate key, list of intermediate values)? Computation? Output (final key, final value)?

MapReduce

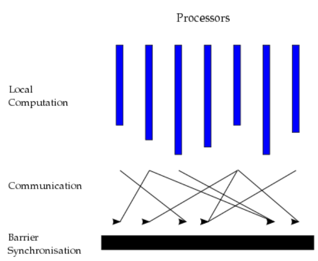
- Run MapReduce N times
- Map
  - Input (key, value): (vertex id, (current Cflag & Dflag values))
  - Computation: nothing.
  - Output list of (intermediate key, intermediate value): list of (neighboring vertex id, current Cflag & Dflag values)
    - » For each neighboring vertex, propagate Cflag & Dflag values
- Shuffle
  - Grouping based on vertex ids.
- Reduce
  - Input (intermediate key, intermediate value): (vertex id, list of neighbors' current Cflag & Dflag values)
  - Computation: OR
  - Output (key, value): (vertex id, updated Cflag & Dflag values)

Pros and Cons

- Pros
  - Well-known
  - The system is there.
  - It works.
- Cons
  - Not quite a good fit
  - Need to re-think in terms of keys, values, maps, and reduces.
- Question
  - Can we provide a system that is a better fit for graph processing?

Bulk Synchronous Parallel Model

- Originally by Valiant (1990)



Better Programming Model

- Vertex-centric programming
- In each iteration, each vertex performs **Gather-Apply-Scatter** for all its assigned vertices
  - Gather: get all neighboring vertices' values
  - Apply: compute own new value from own old value and gathered neighbors' values
  - Scatter: send own new value to neighboring vertices

Google Pregel

- Gives simple APIs for easier graph processing
- Vertex-centric programming
- Developer's code subclasses Vertex class
- Implements Compute() method.
- Vertex class allows a developer to:
  - Get/set vertex values
  - Get/set outgoing edge values (e.g., for weighted graphs)
  - Send/receive messages to any vertex
- Gather-apply-scatter
  - Gather is done automatically (with scatter from the previous iteration)
  - Apply is done by Compute()
  - Scatter is done by explicit message passing

Page Rank Example

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

Shortest Path Example

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


Google Pregel

- Pregel uses the master/worker model
  - Master (one server)
    - » Maintains list of worker servers
    - » Monitors workers; restarts them on failure
    - » Provides Web-UI monitoring tool of job progress
  - Worker (rest of the servers)
    - » Processes its vertices
    - » Communicates with the other workers
- Naturally captures a graph structure (vertex per worker)
- Persistent data is stored as files on a distributed storage system (such as GFS or BigTable)
- Temporary data is stored on local disk

Pregel Execution

1. Many copies of the program begin executing on a cluster
2. The master assigns a partition of input (vertices) to each worker
   1. Each worker loads the vertices and marks them as *active*
3. The master instructs each worker to perform a iteration
   1. Each worker loops through its active vertices & computes for each vertex
   2. Messages can be sent whenever, but need to be delivered before the end of the iteration (i.e., the barrier)
   3. When all workers reach iteration barrier, master starts next iteration
4. Computation halts when, in some iteration: no vertices are active and when no messages are in transit
5. Master instructs each worker to save its portion of the graph

Summary

- Lots of (large) graphs around us
- Need to process these
- MapReduce not a good match
- Distributed Graph Processing systems: Pregel by Google

Acknowledgements

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