Objects Analysis Threads Design

15-214

Principles of Software Construction: Objects, Design, and Concurrency

Distributed System Design, Part 3
MapReduce

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Administrivia

- Homework 5c due Thursday night
- Homework 6 available Friday morning
  - Checkpoint due Tuesday, December 2nd
  - Due Thursday, December 4th
  - Late days to Saturday, December 6th
- Final exam Monday, December 8th
  - Review session Sunday, Dec. 7th, noon – 3 p.m. DH 1212

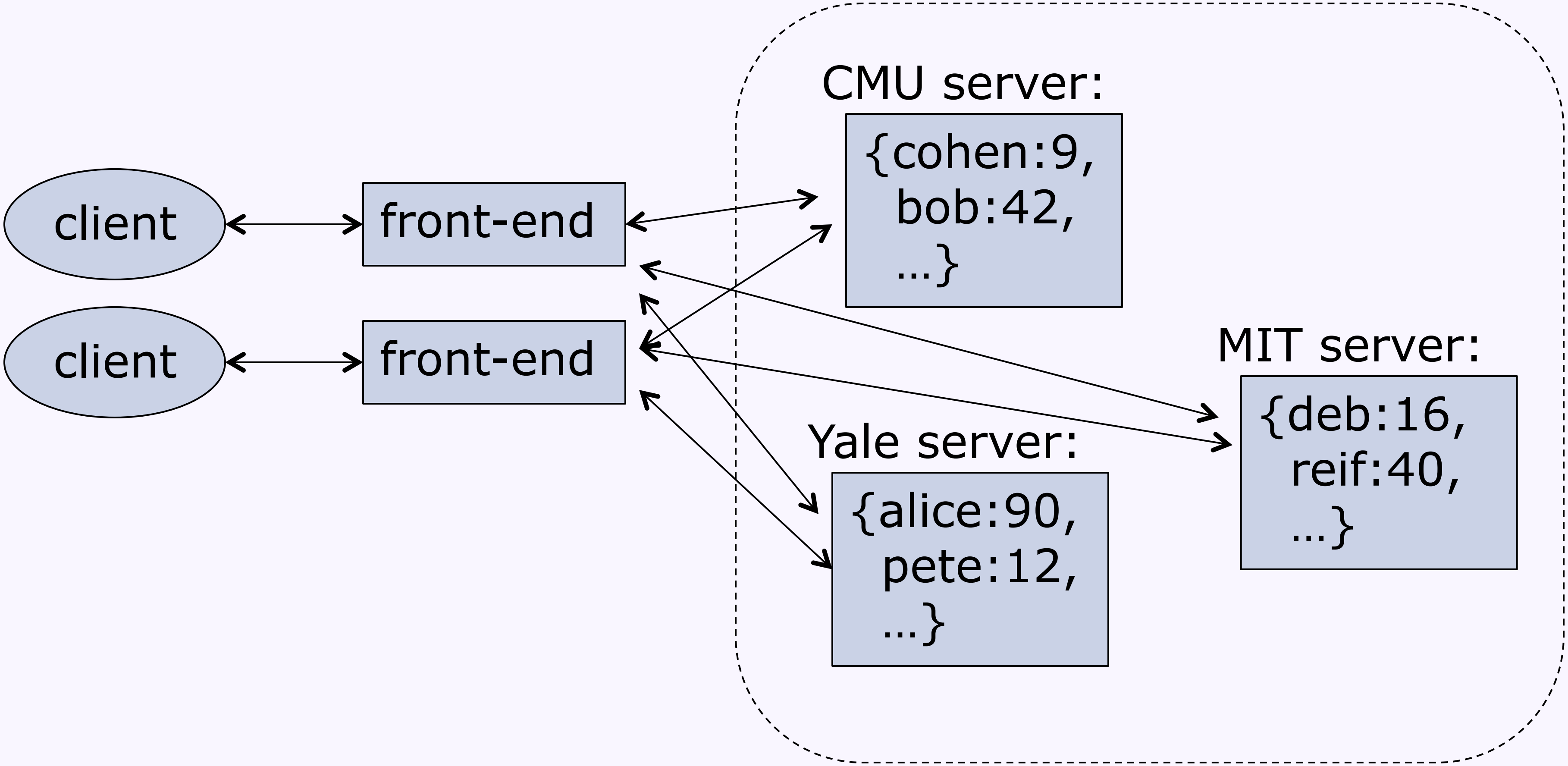
Key concepts from last Thursday

Some distributed system design goals

- The end-to-end principle
  - When possible, implement functionality at the ends (rather than the middle) of a distributed system
- The robustness principle
  - Be strict in what you send, but be liberal in what you accept from others
    - Protocols
    - Failure behaviors
- Benefit from incremental changes
- Be redundant
  - Data replication
  - Checks for correctness

Partitioning for scalability

- Partition data based on some property, put each partition on a different server

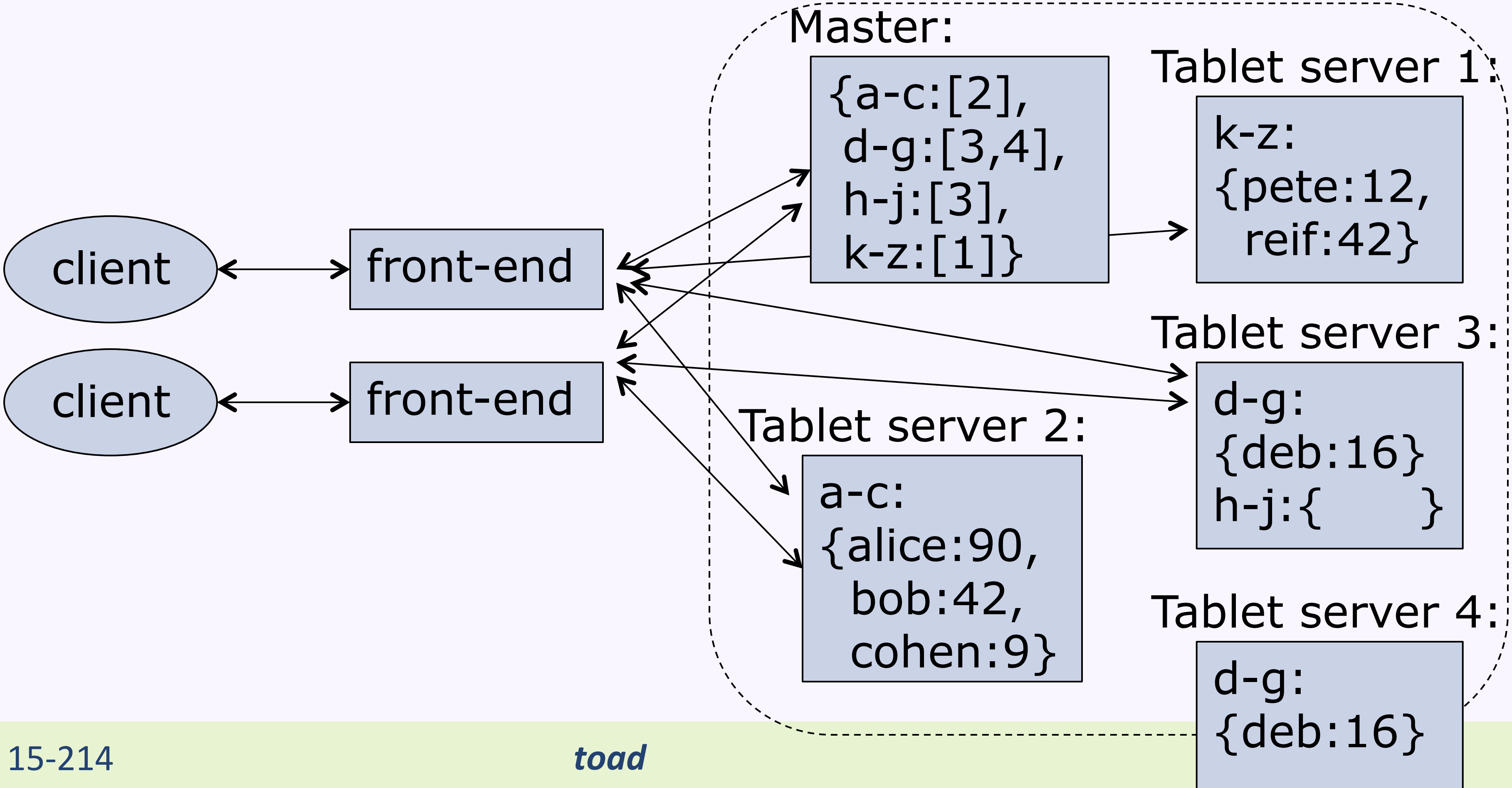


Consistent hashing

- Goal: Benefit from incremental changes
  - Resizing the hash table (i.e., adding or removing a server) should not require moving many objects
- E.g., Interpret the range of hash codes as a ring
  - Each bucket stores data for a range of the ring
    - Assign each bucket an ID in the range of hash codes
    - To store item `x` don't compute `x.hashCode() % n`. Instead, place `x` in bucket with the same ID as or next higher ID than `x.hashCode()`

Master/tablet-based systems

- Dynamically allocate range-based partitions
  - Master server maintains tablet-to-server assignments
  - Tablet servers store actual data
  - Front-ends cache tablet-to-server assignments

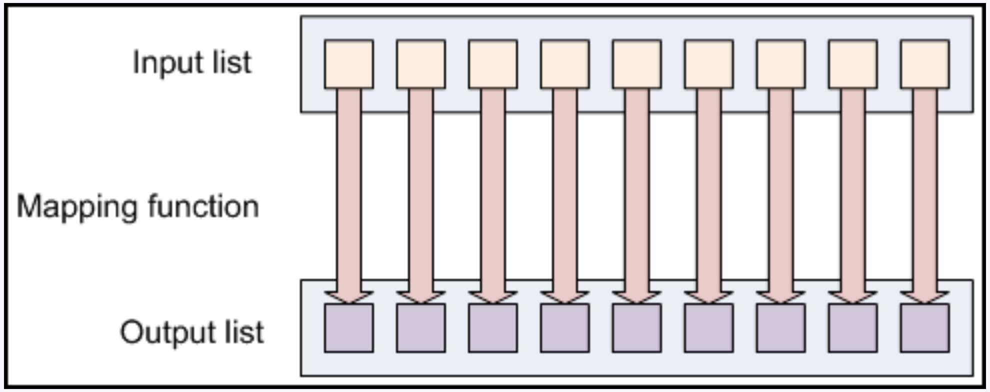


Today: Distributed system design

- MapReduce: A robust, scalable framework for distributed computation…
    - …on replicated, partitioned data

Map from a functional perspective

- `map(f, x[0…n-1])`
  - Apply the function `f` to each element of list `x`



map/reduce images src: Apache Hadoop tutorials

- E.g., in Python:

```
def square(x): return x*x
```

`map(square, [1, 2, 3, 4])` would return `[1, 4, 9, 16]`

- Parallel map implementation is trivial
  - What is the work? What is the depth?

Reduce from a functional perspective

- `reduce(f, x[0…n-1])`
  - Repeatedly apply binary function `f` to pairs of items in `x`, replacing the pair of items with the result until only one item remains
  - One sequential Python implementation:

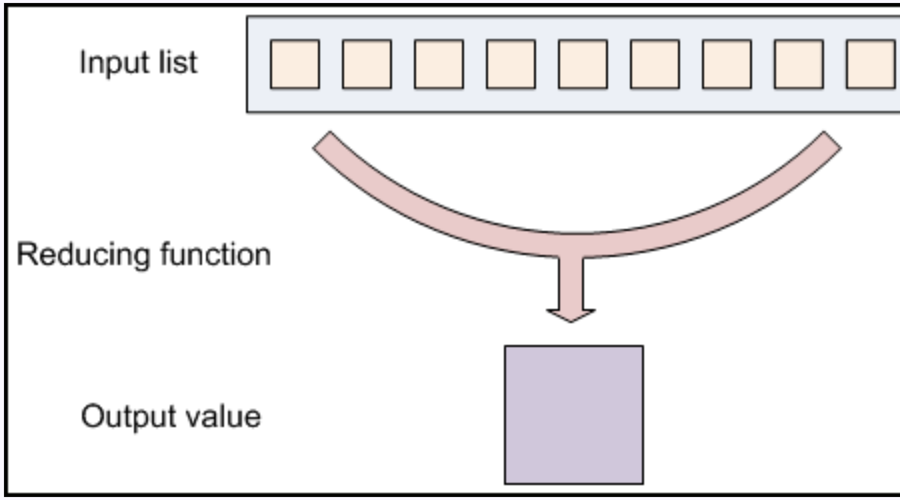
```
def reduce(f, x):
  if len(x) == 1: return x[0]
  return reduce(f, [f(x[0],x[1])] + x[2:])
```

  - e.g., in Python:

```
def add(x,y): return x+y
reduce(add, [1,2,3,4])
```

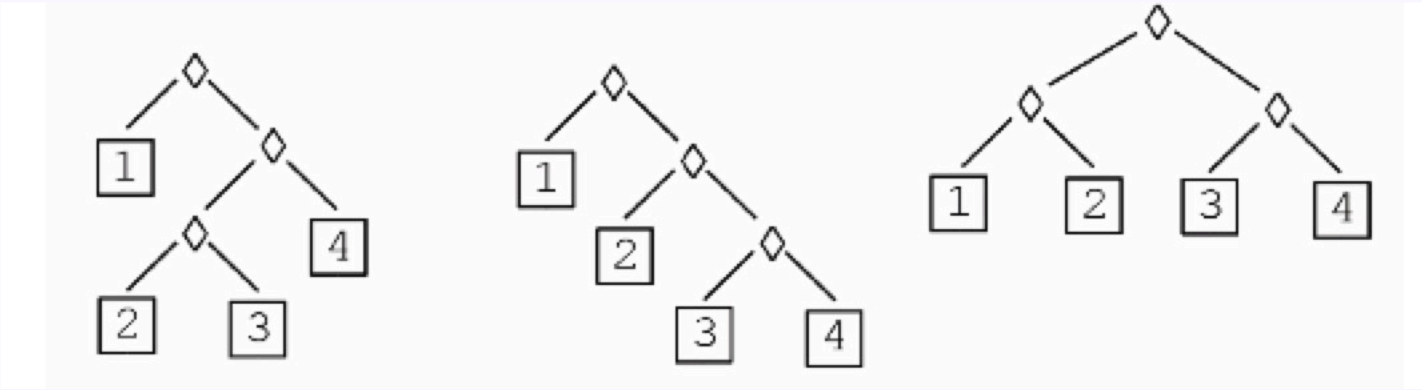
would return 10 as

```
reduce(add, [1,2,3,4])
reduce(add, [3,3,4])
reduce(add, [6,4])
reduce(add, [10]) -> 10
```



Reduce with an associative binary function

- If the function `f` is associative, the order `f` is applied does not affect the result



1 + ((2+3) + 4)   1 + (2 + (3+4))   (1+2) + (3+4)

- Parallel reduce implementation is also easy
  - What is the work? What is the depth?

Distributed MapReduce

- The distributed MapReduce idea is similar to (but not the same as!):

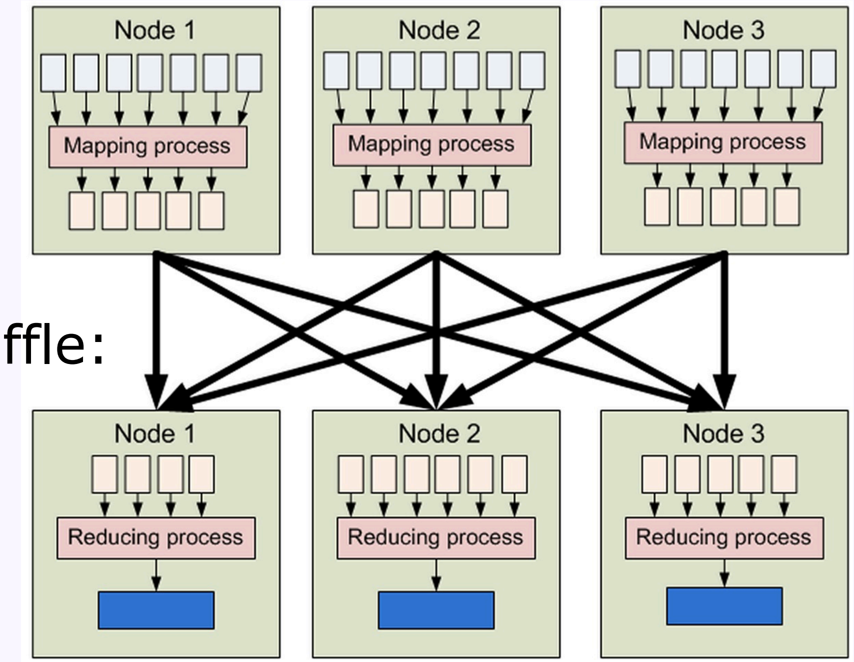
```
reduce(f2, map(f1, x))
```

- Key idea: a "data-centric" architecture
  - Send function `f1` directly to the data
    - Execute it concurrently
  - Then merge results with reduce
    - Also concurrently
- Programmer can focus on the data processing rather than the challenges of distributed systems

MapReduce with key/value pairs (Google style)

- Master
  - Assign tasks to workers
  - Ping workers to test for failures
- Map workers
  - Map for each key/value pair
  - Emit intermediate key/value pairs

the shuffle:



- Reduce workers
  - Sort data by intermediate key and aggregate by key
  - Reduce for each key

MapReduce with key/value pairs (Google style)

- E.g., for each word on the Web, count the number of times that word occurs
  - For Map: `key1` is a document name, `value` is the contents of that document
  - For Reduce: `key2` is a word, `values` is a list of the number of counts of that word

```
f1(String key1, String value):
  for each word w in value:
    EmitIntermediate(w, 1);
```

```
f2(String key2, Iterator values):
  int result = 0;
  for each v in values:
    result += v;
  Emit(key2, result);
```

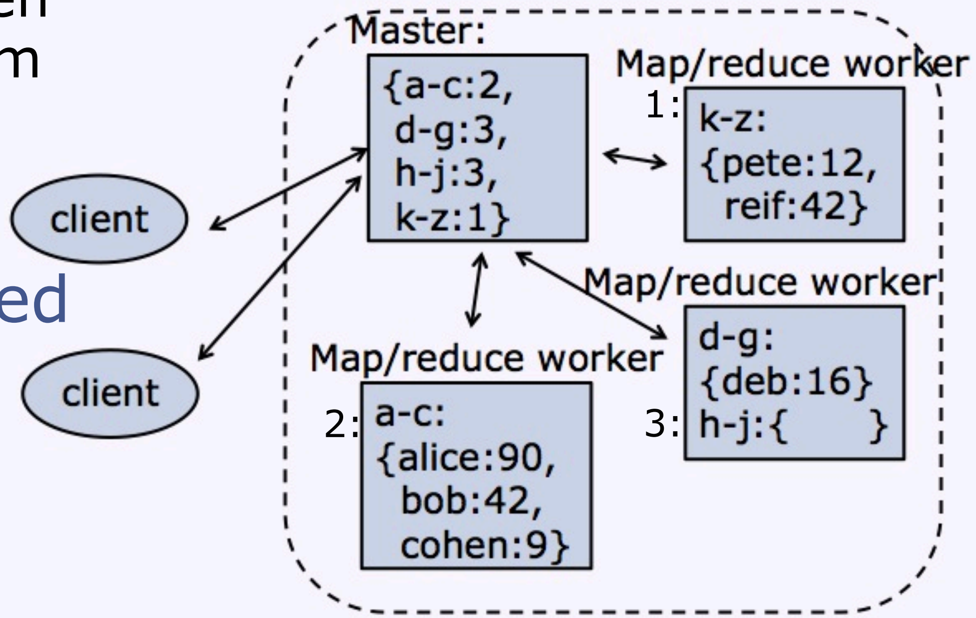
Map: (key1, v1) → (key2, v2)*   Reduce: (key2, v2*) → (key3, v3)*

MapReduce: (key1, v1)* → (key3, v3)*

MapReduce: (docName, docText)* → (word, wordCount)*

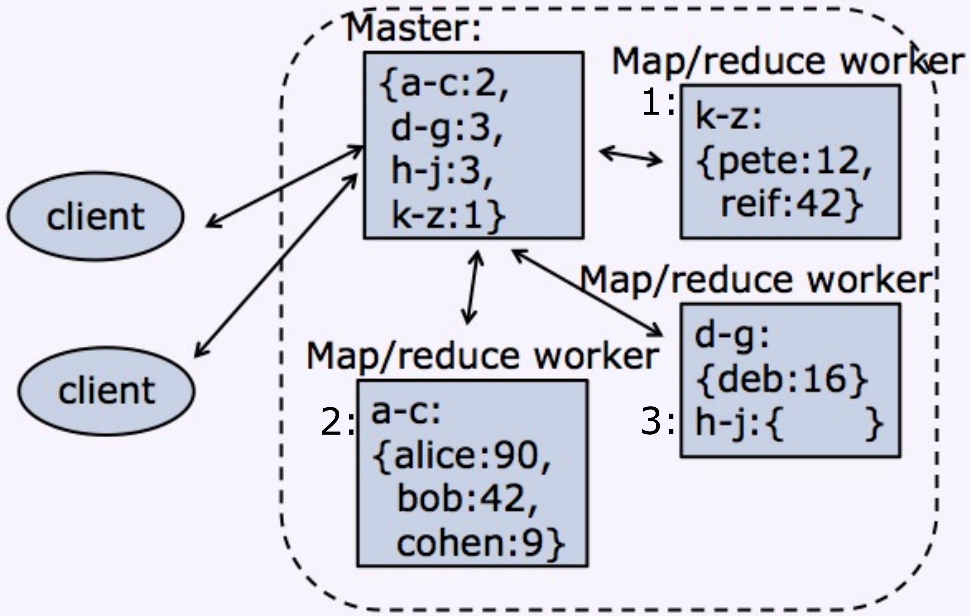
MapReduce architectural details

- Usually integrated with a distributed storage system
  - Map worker executes function on its share of the data
- Map output usually written to worker's local disk
  - Shuffle: reduce worker often pulls intermediate data from map worker's local disk
- Reduce output usually written back to distributed storage system



Handling server failures with MapReduce

- Map worker failure:
  - Re-map using replica of the storage system data
- Reduce worker failure:
  - New reduce worker can pull intermediate data from map worker's local disk, re-reduce
- Master failure:
  - Options:
    - Restart system using new master
    - Replicate master
    - …



The beauty of MapReduce

- Low communication costs (usually)
  - The shuffle (between map and reduce) is expensive
- MapReduce can be iterated
  - Input to MapReduce: key/value pairs in the distributed storage system
  - Output from MapReduce: key/value pairs in the distributed storage system

MapReduce to count mutual friends

- E.g., for person in a social network graph, output the number of mutual friends they have
  - For Map: `key1` is a person, `value` is the list of her friends
  - For Reduce: `key2` is ???, `values` is a list of ???

```
f1(String key1, String value):
```

```
f2(String key2, Iterator values):
```

MapReduce: (person, friends)* → (pair of people, count of mutual friends)*

MapReduce to count mutual friends

- E.g., for person in a social network graph, output the number of mutual friends they have
  - For Map: `key1` is a person, `value` is the list of her friends
  - For Reduce: `key2` is a pair of people, `values` is a list of 1s, for each mutual friend that pair has

```
f1(String key1, String value):

  for each pair of friends
        in value:

    EmitIntermediate(pair, 1);
```

```
f2(String key2, Iterator values):

  int result = 0;

  for each v in values:

    result += v;

  Emit(key2, result);
```

MapReduce: (person, friends)* → (pair of people, count of mutual friends)*

MapReduce to count incoming links

- E.g., for each page on the Web, count the number of pages that link to it
  - For Map: `key1` is a document name, `value` is the contents of that document
  - For Reduce: `key2` is ???, `values` is a list of ???

```
f1(String key1, String value):
```

```
f2(String key2, Iterator values):
```

MapReduce: (docName, docText)* → (docName, number of incoming links)*

MapReduce to count incoming links

- E.g., for each page on the Web, count the number of pages that link to it
  - For Map: `key1` is a document name, `value` is the contents of that document
  - For Reduce: `key2` is ???, `values` is a list of ???

```
f1(String key1, String value):
  for each link in value:
    EmitIntermediate(link, 1)
```

```
f2(String key2, Iterator values):
  int result = 0;
  for each v in values:
    result += v;
  Emit(key2, result);
```

MapReduce: (docName, docText)* → (docName, number of incoming links)*

MapReduce to create an inverted index

- E.g., for each page on the Web, create a list of the pages that link to it
  - For Map: `key1` is a document name, `value` is the contents of that document
  - For Reduce: `key2` is ???, `values` is a list of ???

```
f1(String key1, String value):
  for each link in value:
    EmitIntermediate(link, key1)
```

```
f2(String key2, Iterator values):
  Emit(key2, values)
```

MapReduce: (docName, docText)* → (docName, list of incoming links)*

List the mutual friends

- E.g., for each pair in a social network graph, list the mutual friends they have
  - For Map: `key1` is a person, `value` is the list of her friends
  - For Reduce: `key2` is ???, `values` is a list of ???

```
f1(String key1, String value):
```

```
f2(String key2, Iterator values):
```

MapReduce: (person, friends)* → (pair of people, list of mutual friends)*

List the mutual friends

- E.g., for each pair in a social network graph, list the mutual friends they have
  - For Map: `key1` is a person, `value` is the list of her friends
  - For Reduce: `key2` is ???, `values` is a list of ???

```
f1(String key1, String value):

  for each pair of friends
         in value:

    EmitIntermediate(pair, key1);
```

```
f2(String key2, Iterator values):

  Emit(key2, values)
```

MapReduce: (person, friends)* → (pair of people, list of mutual friends)*

Count friends + friends of friends

- E.g., for each person in a social network graph, count their friends and friends of friends
  - For Map: `key1` is a person, `value` is the list of her friends
  - For Reduce: `key2` is ???, `values` is a list of ???

```
f1(String key1, String value):
```

```
f2(String key2, Iterator values):
```

MapReduce: (person, friends)* → (person, count of f + fof)*

Count friends + friends of friends

- E.g., for each person in a social network graph, count their friends and friends of friends
  - For Map: `key1` is a person, `value` is the list of her friends
  - For Reduce: `key2` is ???, `values` is a list of ???

```
f1(String key1, String value):
  for each friend1 in value:
    EmitIntermediate(friend1, key1)
    for each friend2 in value:
      EmitIntermediate(friend1,
                        friend2);
```

```
f2(String key2, Iterator values):
  distinct_values = {}
  for each v in values:
    if not v in distinct_values:
      distinct_values.insert(v)
  Emit(key2, len(distinct_values))
```

MapReduce: (person, friends)* → (person, count of f + fof)*

Friends + friends of friends + friends of friends of friends

- E.g., for each person in a social network graph, count their friends and friends of friends and friends of friends of friends
  - For Map: `key1` is a person, `value` is the list of her friends
  - For Reduce: `key2` is ???, `values` is a list of ???

```
f1(String key1, String value):
```

```
f2(String key2, Iterator values):
```

MapReduce: (person, friends)* → (person, count of f + fof + fofof)*

Problem: How to reach distance 3 nodes?

- Solution: Iterative MapReduce
  - Use MapReduce to get distance 1 and distance 2 nodes
  - Feed results as input to a second MapReduce process
- Also consider:
  - Breadth-first search
  - PageRank
  - …

Dataflow processing

- High-level languages and systems for complex MapReduce-like processing
  - Yahoo Pig, Hive
  - Microsoft Dryad, Naiad
- MapReduce generalizations…