Principles of Software Construction

MapReduce

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Administrivia

- Homework 5c due tonight
- Homework 6 coming soon

Key concepts from Thursday

TCP, networking in Java

- The java.net.InetAddress:

```
static InetAddress getByName(String host);
static InetAddress getByAddress(byte[] b);
static InetAddress getLocalHost();
```

- The java.net.Socket:

```
Socket(InetAddress addr, int port);
boolean      isConnected();
boolean      isClosed();
void         close();
InputStream  getInputStream();
OutputStream getOutputStream();
```

- The java.net.ServerSocket:

```
ServerSocket(int port);
Socket       accept();
void         close();
…
```

Our destination: Distributed systems

- Multiple system components (computers) communicating via some medium (the network)
- Challenges:
  - Scale
  - Concurrency
  - Heterogeneity
  - Geography
  - Failures
  - Security

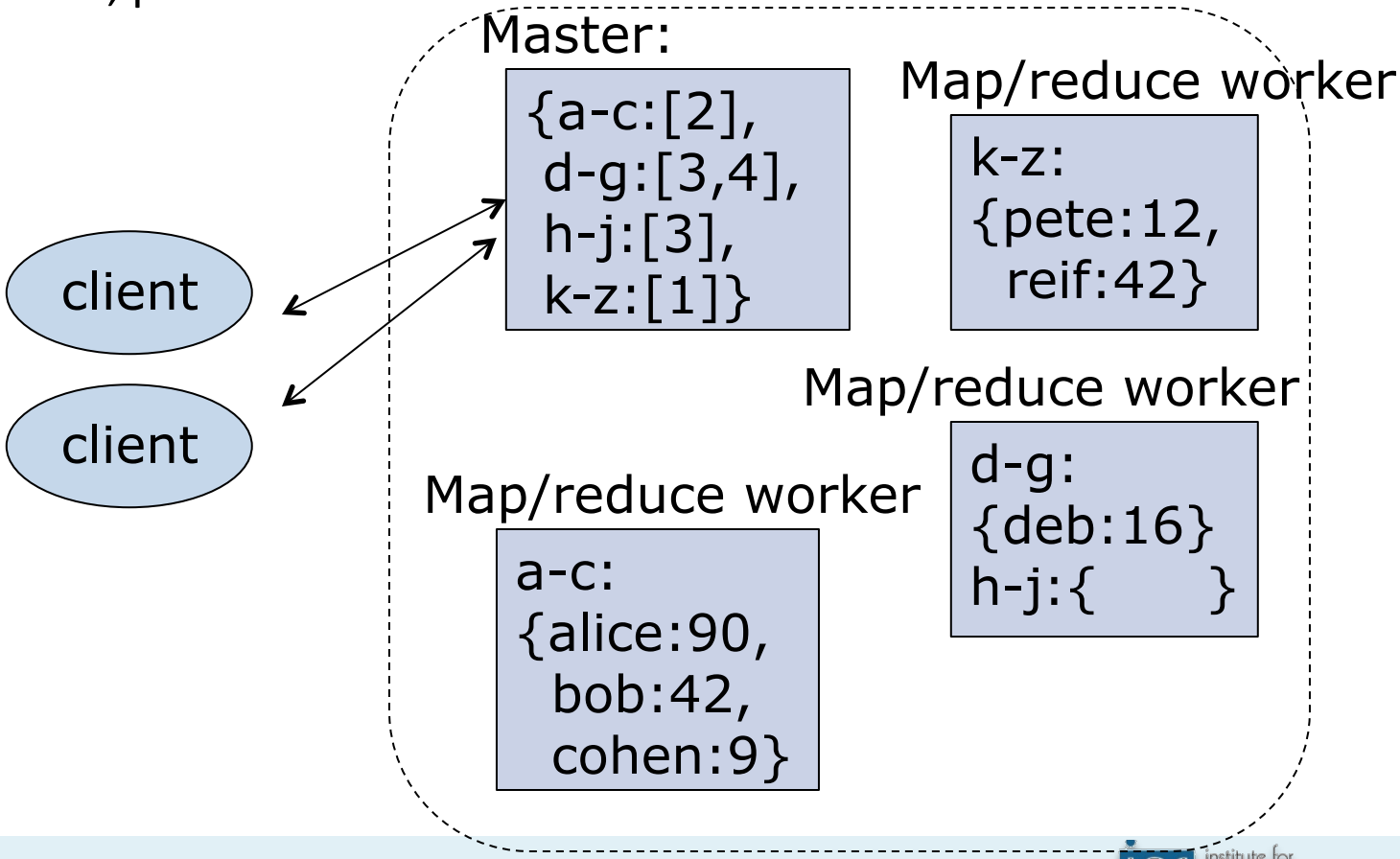
(courtesy of http://www.cs.cmu.edu/~dga/15-440/F12/lectures/02-internet1.pdf

Metrics of success

- Reliability
  - Often in terms of availability: fraction of time system is working
    - 99.999% available is "5 nines of availability"
- Scalability
  - Ability to handle workload growth

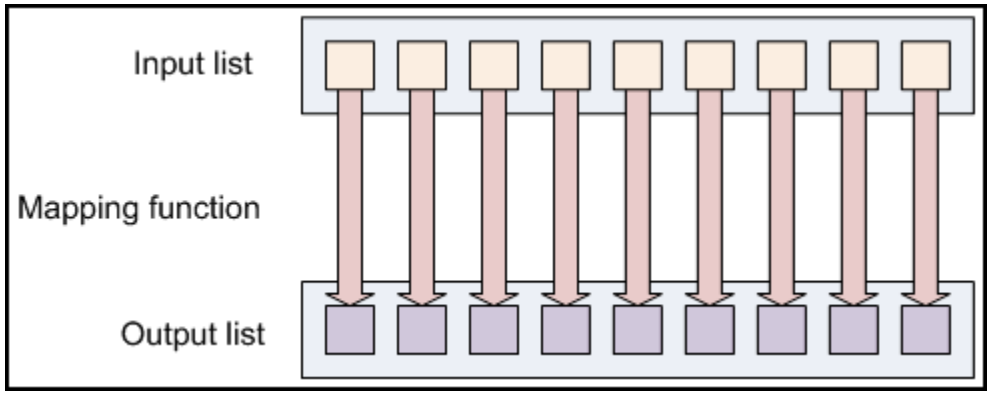
Today: Distributed system design

- 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:

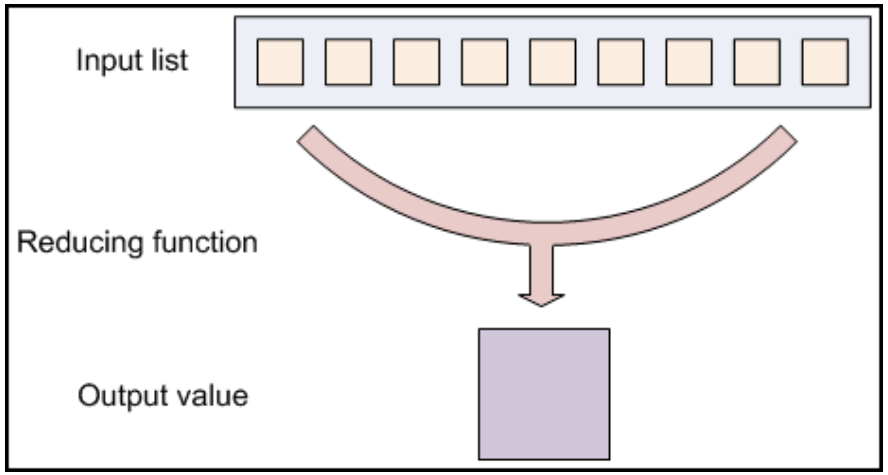
```
def reduce(f, x):
    if len(x) == 1: return x[0]
    return reduce(f, [f(x[0],x[1])] + x[2:])
```

  - e.g., in Python:

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

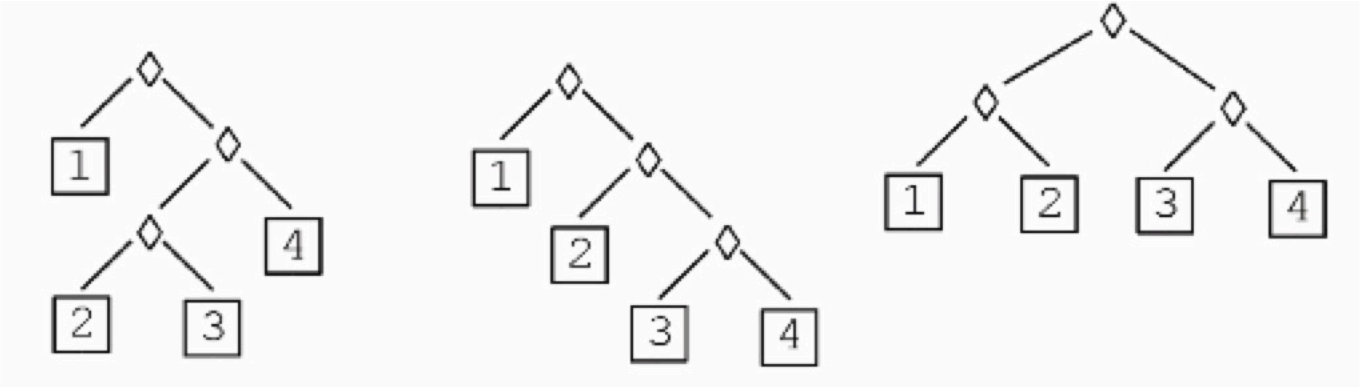
would return 10 as

```
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)

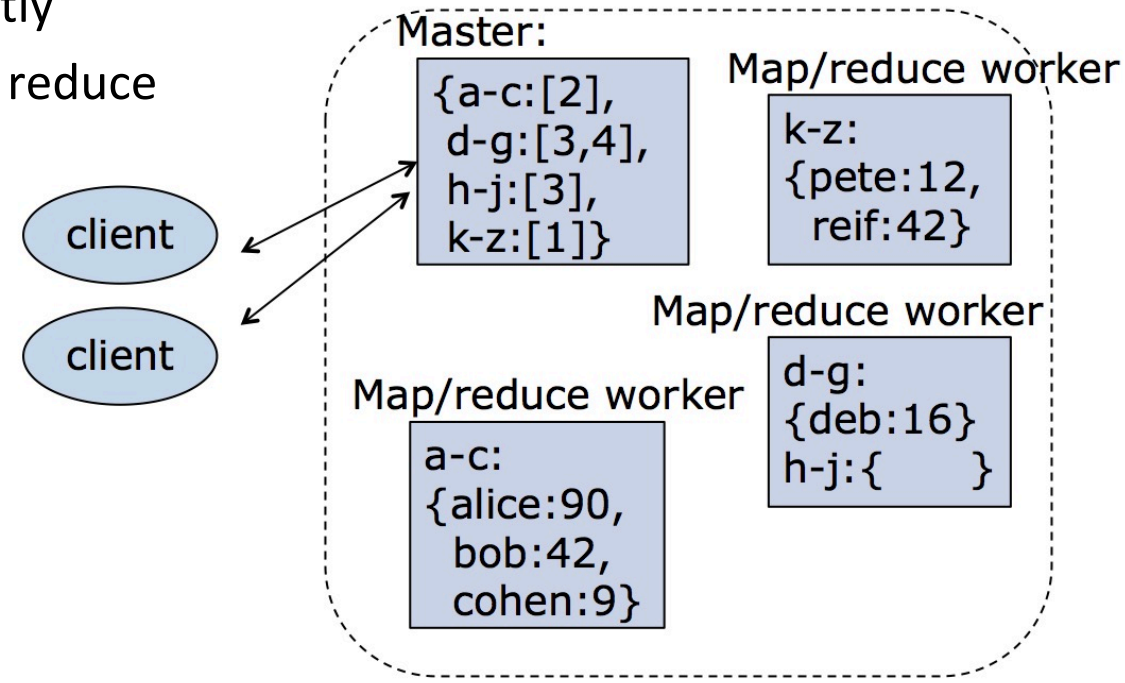
- Parallel reduce implementation is also easy
  - What is the work? What is the depth?

Distributed MapReduce

- Distributed MapReduce is similar to (but not the same as!):

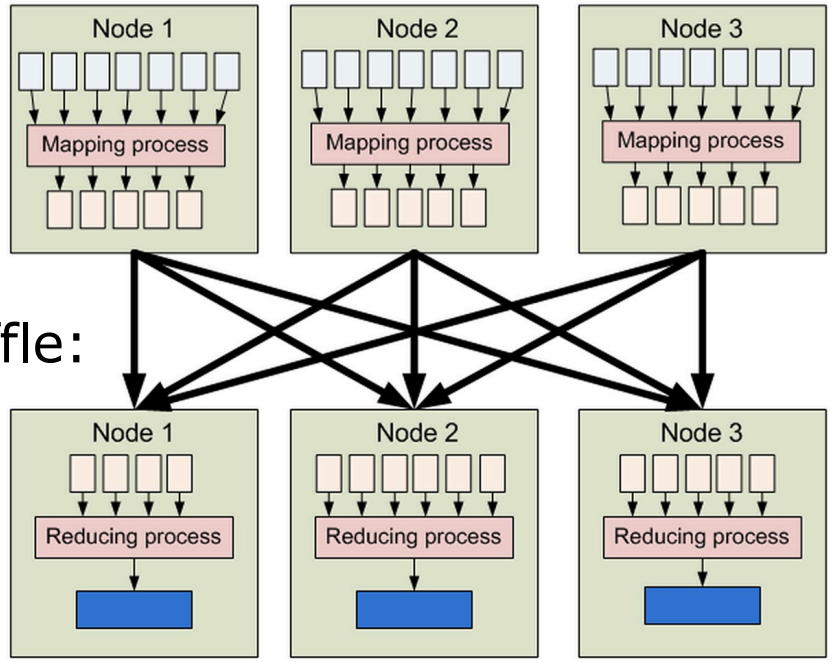
```
reduce(f2, map(f1, x))
```

- Key idea: "data-centric" architecture
  - Send function `f1` directly to the data
    - Execute it concurrently
  - Then merge results with reduce
    - Also concurrently



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
- 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);
```

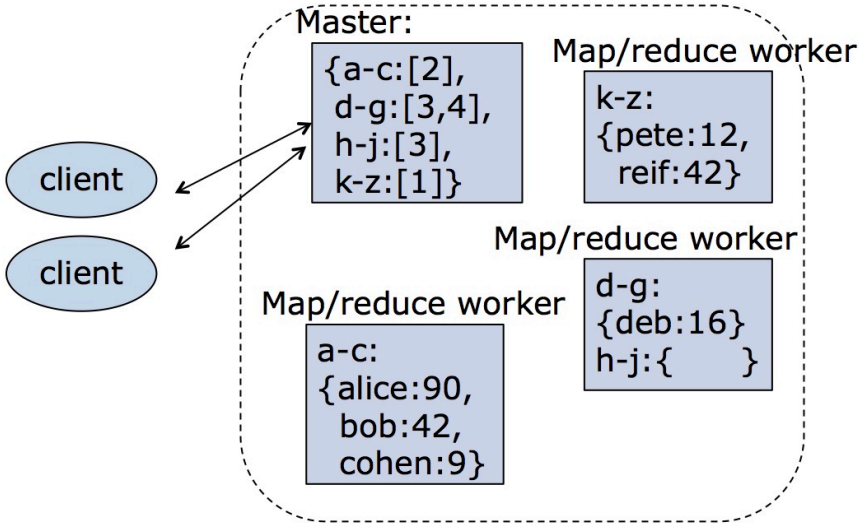
Map: (key1, v1) → (key2, v2)* Reduce: (key2, v2*) → (key3, v3)*

MapReduce: (key1, v1)* → (key3, v3)*

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

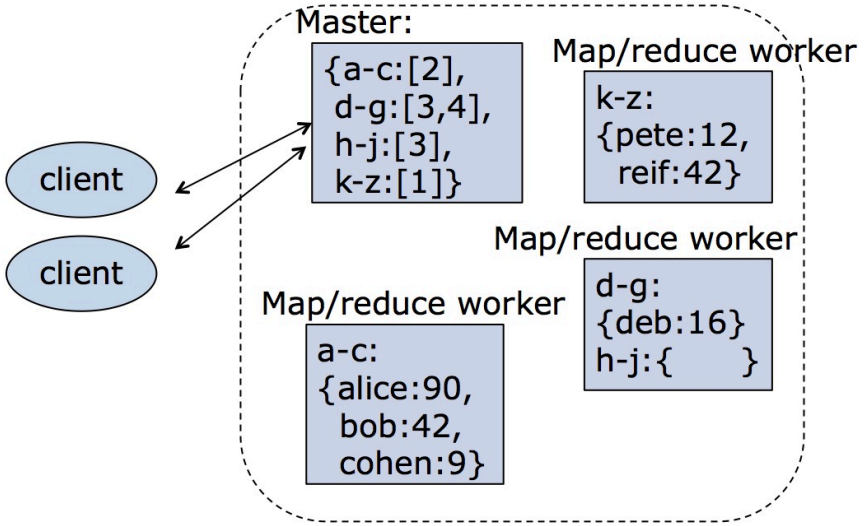
MapReduce architectural details

- 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) can be 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 link, `values` is a list of 1s

```
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 a pair of people, `values` is a list of their mutual friends

```
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):
```

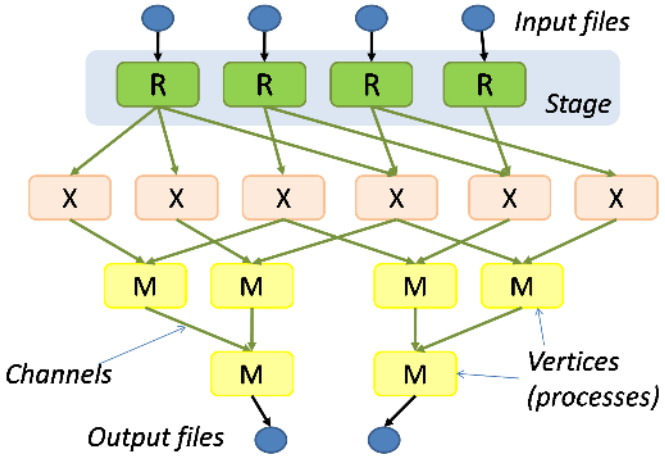
MapReduce: (person, friends)* → (person, count of f + fof + fofof)*

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…



MapReduce summary

- "Data-centric" architecture allows efficient computation on large data sets
- Framework allows programmer to focus on the computation
  - Internally allocates work
  - Internally handles failures

Next time…