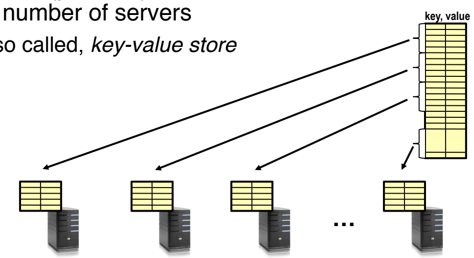
CS162
Operating Systems and Systems Programming
Lecture 24

DHTs and Cloud Computing

April 25, 2011
Ion Stoica
http://inst.eecs.berkeley.edu/~cs162

Distributed Hash Tables (DHTs)

- Distribute (partition) a hash table data structure across a large number of servers
  - Also called, *key-value store*



- Two operations
  - **put**(key, data); // insert "data" identified by "key"
  - data = **get**(key); // get data associated to "key"

Distributed Hash Tables (DHTs) (cont'd)

- Just need a lookup service, i.e., given a key (ID), map it to machine n
  n = **lookup**(key);

- Invoking put() and get() at node m

```
m.put(key, data) {
    n = lookup(key); // get node "n" mapping "key"
    n.store(key, data); // store data at node "n"
}

data = m.get(key) {
    n = lookup(key); // get node "n" storing data associated to "key"
    return n.retrieve(key); // get data stored at "n" associated to "key"
}
```

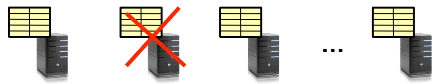

Distributed Hash Tables (DHTs) (cont'd)

- Many lookup proposals: CAN, Chord, Pastry, Tapestry, Kademlia, …

- Used in practice:
  - p2p: eDonkey (based on Kademlia)
  - Dynamo (Amazon)
  - Cassandra (Facebook)
  - …

Challenges

- System churn: machines can fail or exit the system any time



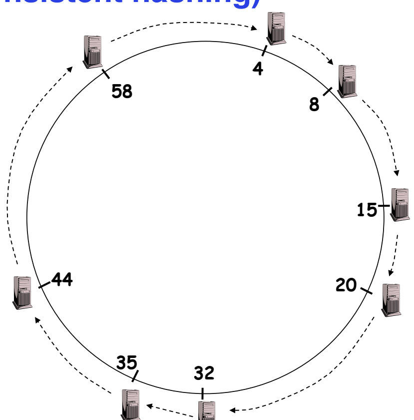
- Scalability: need to scale to 10s or 100s of thousands machines
- Heterogeneity:
  – Latency: 1ms to 1000ms
  – Bandwidth: 32Kb/s to 100Mb/s
  – Nodes stay in system from 10s to a year

Chord Lookup Service

- Associate to each node and item a unique *id/key* in an *uni*-dimensional space $0..2^m-1$
  – Partition this space across N machines
  – Each id is mapped to the node with the smallest largest ID (consistent hashing)
- Key design decision
  – Decouple correctness from efficiency
- Properties
  – Routing table size O(log(*N*)) , where *N* is the total number of nodes
  – Guarantees that a file is found in O(log(*N*)) steps

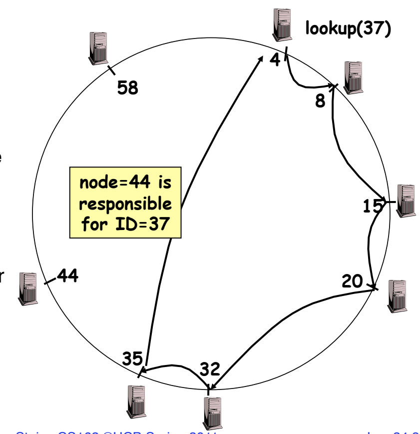
Identifier to Node Mapping Example (Consistent hashing)

- Node 8 maps [5,8]
- Node 15 maps [9,15]
- Node 20 maps [16, 20]
- …
- Node 4 maps [59, 4]
- Each node maintains a pointer to its successor



Lookup

- Each node maintains pointer to its successor
- Route packet (ID, data) to the node responsible for ID using successor pointers
- E.g., node=4 lookups for node responsible for ID=37



Stabilization Procedure

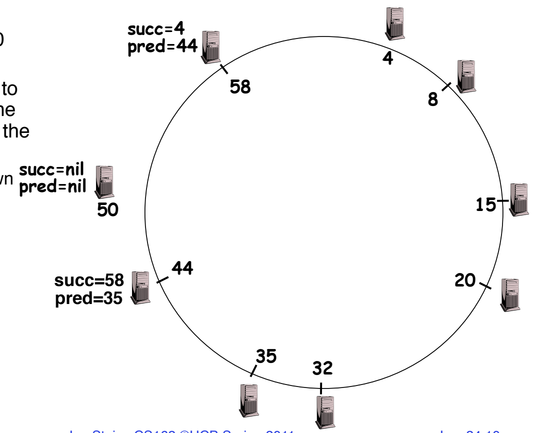
- Periodic operation performed by each node n to maintain its successor when new nodes join the system

```
n.stabilize()
  x = succ.pred;
  if (x∈(n, succ))
     succ = x;      // if x better successor, update
  succ.notify(n); // n tells successor about itself

n.notify(n')
  if (pred = nil or n'∈ (pred, n))
     pred = n';      // if n' is better predecessor, update
```

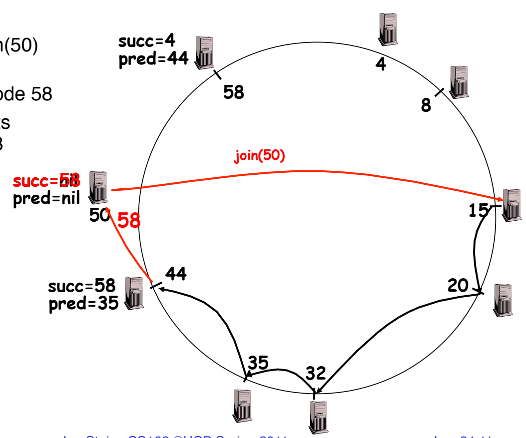

Joining Operation

- Node with id=50 joins the ring
- Node 50 needs to know at least one node already in the system
  - Assume known node is 15



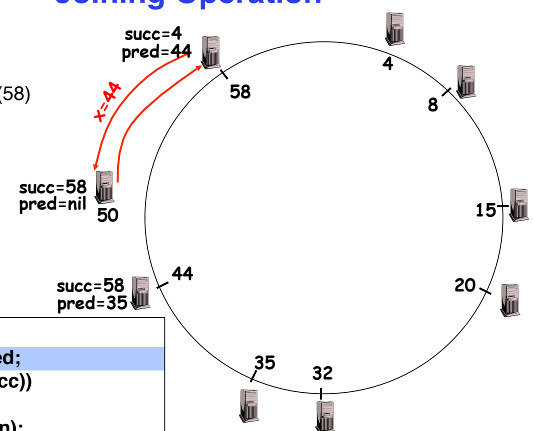
Joining Operation

- n=50 sends join(50) to node 15
- n=44 returns node 58
- n=50 updates its successor to 58



Joining Operation

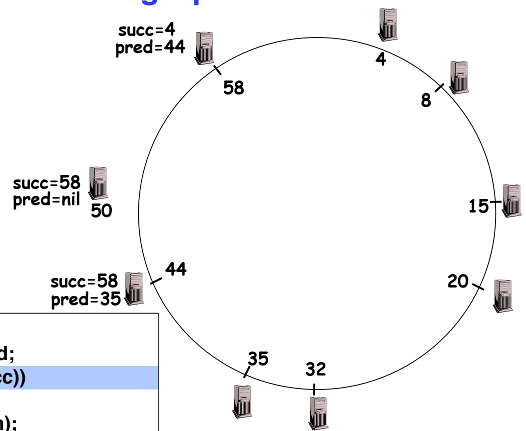
- n=50 executes stabilize()
- n's successor (58) returns x = 44




```
n.stabilize()
  x = succ.pred;
  if (x∈(n, succ))
     succ = x;
  succ.notify(n);
```

Joining Operation

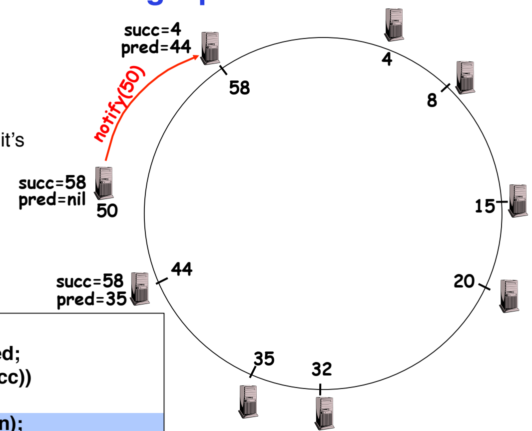
- n=50 executes stabilize()
  - x = 44
  - succ = 58




```
n.stabilize()
  x = succ.pred;
  if (x∈(n, succ))
    succ = x;
  succ.notify(n);
```


Joining Operation

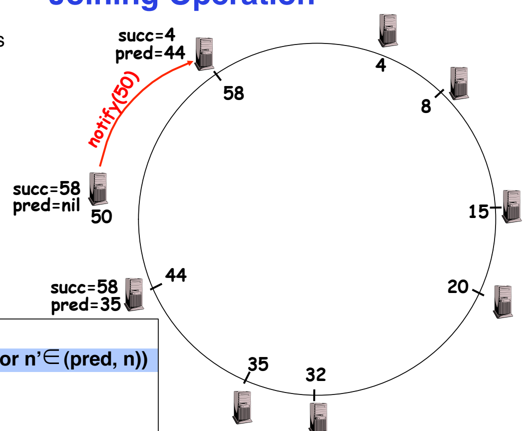
- n=50 executes stabilize()
  - x = 44
  - succ = 58
- n=50 sends to it's successor (58) notify(50)




```
n.stabilize()
  x = succ.pred;
  if (x∈(n, succ))
    succ = x;
  succ.notify(n);
```


Joining Operation

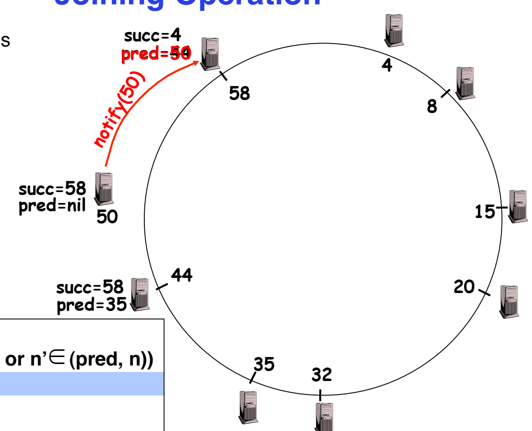
- n=58 processes notify(50)
  - pred = 44
  - n' = 50




```
n.notify(n')
  if (pred = nil or n'∈(pred, n))
    pred = n'
```


Joining Operation

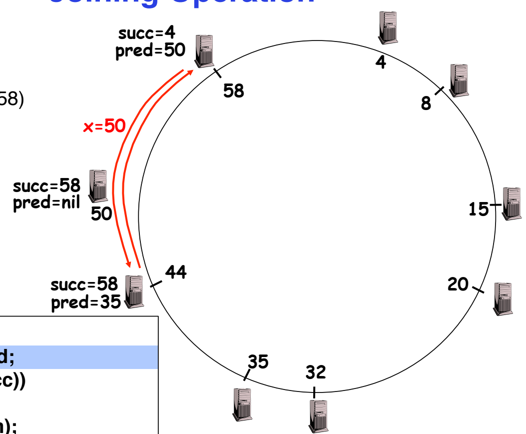
- n=58 processes notify(50)
  - pred = 44
  - n' = 50
- set pred = 50




```
n.notify(n')
  if (pred = nil or n'∈(pred, n))
    pred = n'
```

Joining Operation

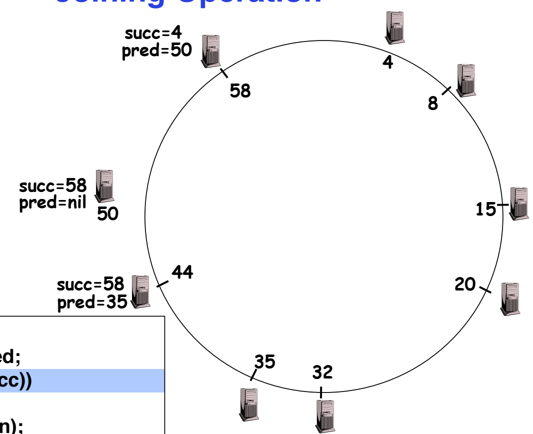
- n=44 runs stabilize()
- n's successor (58) returns x = 50




```
n.stabilize()
  x = succ.pred;
  if (x∈(n, succ))
    succ = x;
  succ.notify(n);
```


Joining Operation

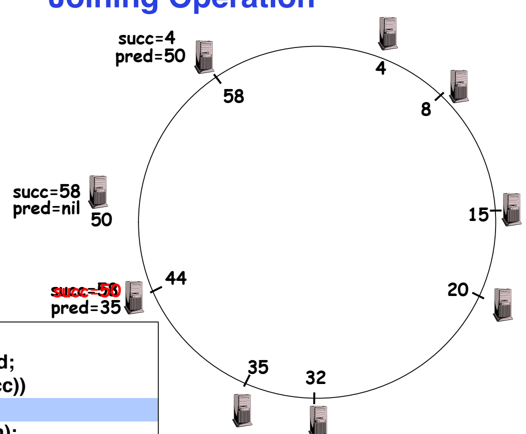
- n=44 runs stabilize()
  - x = 50
  - succ = 58




```
n.stabilize()
  x = succ.pred;
  if (x∈(n, succ))
    succ = x;
  succ.notify(n);
```


Joining Operation

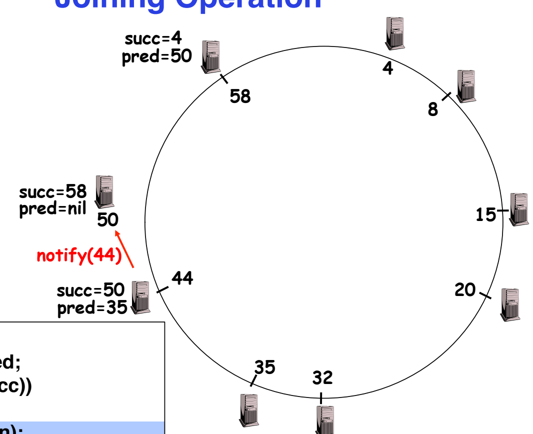
- n=44 runs stabilize()
  - x = 50
  - succ = 58
- n=44 sets succ=50




```
n.stabilize()
  x = succ.pred;
  if (x∈(n, succ))
    succ = x;
  succ.notify(n);
```


Joining Operation

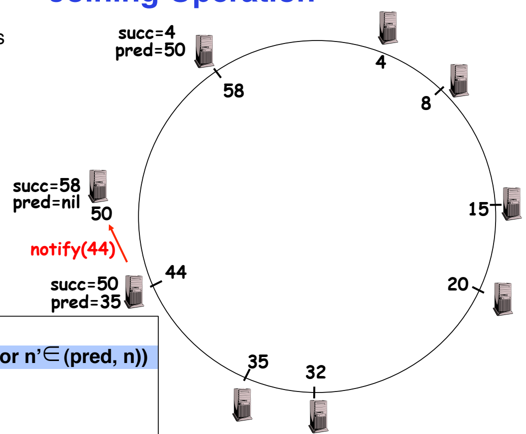
- n=44 runs stabilize()
- n=44 sends notify(44) to its successor




```
n.stabilize()
  x = succ.pred;
  if (x∈(n, succ))
    succ = x;
  succ.notify(n);
```

Joining Operation

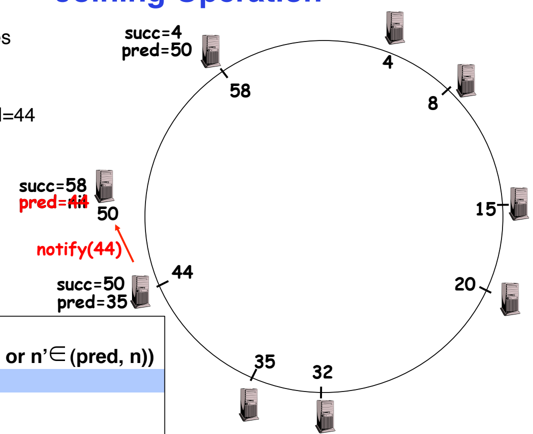
- n=50 processes notify(44)
  - pred = nil




```
n.notify(n')
  if (pred = nil or n'∈(pred, n))
     pred = n'
```


Joining Operation

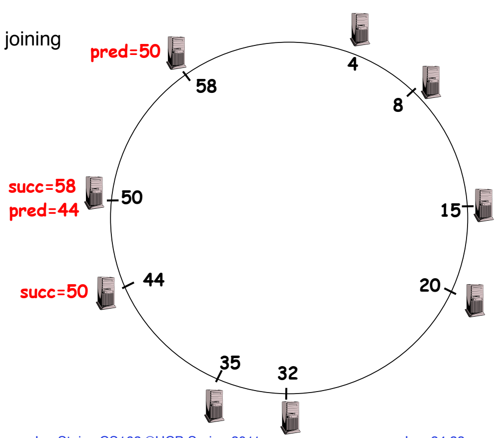
- n=50 processes notify(44)
  - pred = nil
- n=50 sets pred=44




```
n.notify(n')
  if (pred = nil or n'∈(pred, n))
     pred = n'
```


Joining Operation (cont'd)

- This completes the joining operation!

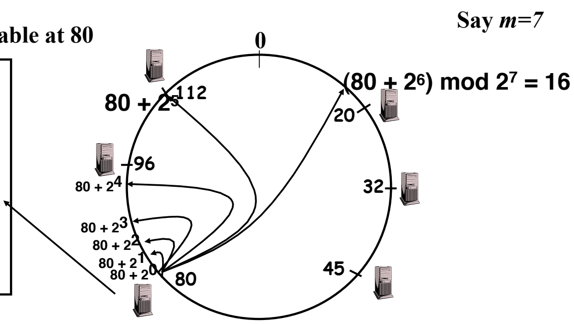


Achieving Efficiency: *finger tables*

Finger Table at 80

i	*ft[i]*
0	96
1	96
2	96
3	96
4	96
5	112
6	20

Say *m=7*



*i*th entry at peer with id *n* is first peer with id >= $n + 2^i \pmod{2^m}$

Achieving Robustness

- To improve robustness each node maintains the k (> 1) immediate successors instead of only one successor
- Successor S of a node N can send its K-1 successors to N during N's stabilize() procedure

Administrivia

- Project 4 design due tomorrow: Tuesday, April 26
- Project 3 code available
- Final exam: Friday, May 13, 8-11am (2060 VLSB)
  - Provide some exam question examples next lecture

What is Cloud Computing?

- "Cloud" refers to large Internet services running on 10,000s of machines (Google, Facebook, etc)
- "Cloud computing" refers to services by these companies that let <u>external customers</u> rent cycles
  - Amazon EC2: virtual machines at 8.5¢/hour, billed hourly
  - Amazon S3: storage at 10-15¢/GB/month
  - Windows Azure: applications using Azure API
- Attractive features:
  - Scale: 100s of nodes available in minutes
  - Fine-grained billing: pay only for what you use
  - Ease of use: sign up with credit card, get root access

What Can You Run in Cloud Computing?

- Almost everything!
- Virtual Machine instances
- Storage services
  - Simple Storage Service (S3)
  - Elastic Block Storage (RBS)
- Databases:
  - Database instances (e.g., mySQL, SQL Server, …)
  - SimpleDB
- Content Distribution Network: CloudFront
- **MapReduce**: Amazon Elastic MapReduce
- …

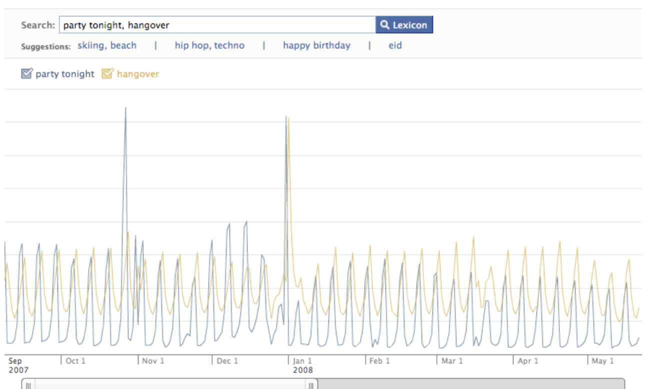
What is MapReduce?

- Data-parallel programming model for clusters of commodity machines
- Pioneered by Google
  - Processes 20 PB of data per day
- Popularized by Apache Hadoop project
  - Used by Yahoo!, Facebook, Amazon, …

What is MapReduce Used For?

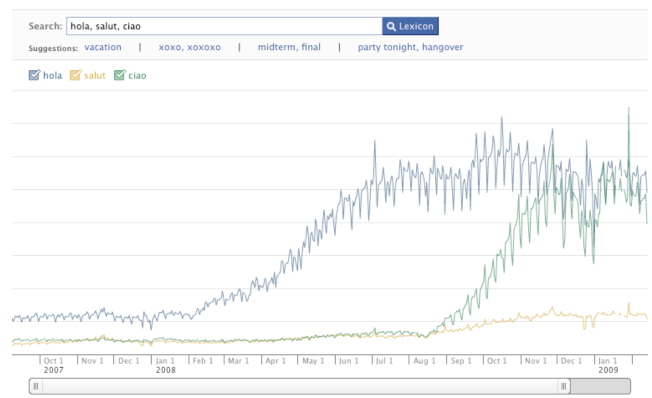
- At Google:
  - Index building for Google Search
  - Article clustering for Google News
  - Statistical machine translation
- At Yahoo!:
  - Index building for Yahoo! Search
  - Spam detection for Yahoo! Mail
- At Facebook:
  - Data mining
  - Ad optimization
  - Spam detection

Example: Facebook Lexicon (discontinued, February 2010)



www.facebook.com/lexicon

Example: Facebook Lexicon (discontinued, February 2010)

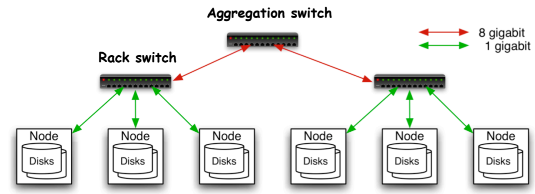


www.facebook.com/lexicon

MapReduce Goals

- **Scalability** to large data volumes:
  - Scan 100 TB on 1 node @ 50 MB/s = 24 days
  - Scan on 1000-node cluster = 35 minutes
- **Cost-efficiency:**
  - Commodity nodes (cheap, but unreliable)
  - Commodity network (low bandwidth)
  - Automatic fault-tolerance (fewer admins)
  - Easy to use (fewer programmers)

Typical Hadoop Cluster



- 40 nodes/rack, 1000-4000 nodes in cluster
- 1 Gbps bandwidth in rack, 8 Gbps out of rack
- Node specs (Facebook):
  8-16 cores, 32-48 GB RAM, 10×2TB disks

Hadoop Cluster

Challenges of Cloud Environment

- Cheap nodes fail, especially when you have many
  - Mean time between failures for 1 node = 3 years
  - MTBF for 1000 nodes = 1 day
  - **Solution:** Build fault-tolerance into system
- Commodity network = low bandwidth
  - **Solution:** Push computation to the data
- Programming distributed systems is hard
  - **Solution:** Restricted programming model: users write data-parallel "map" and "reduce" functions, system handles work distribution and failures

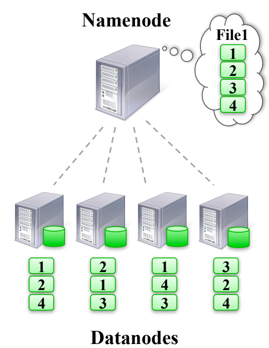
Hadoop Components

- Distributed file system (HDFS)
  - Single namespace for entire cluster
  - Replicates data 3x for fault-tolerance
- MapReduce framework
  - Runs jobs submitted by users
  - Manages work distribution & fault-tolerance
  - Colocated with file system

hadoop

Hadoop Distributed File System (HDFS)

- Files split into 128MB blocks
- Blocks replicated across several datanodes (often 3)
- Namenode stores metadata (file names, locations, etc)
- Optimized for large files, sequential reads
- Files are append-only



MapReduce Programming Model

- Data type: key-value *records*
- Map function:

$$(K_{in}, V_{in}) \rightarrow \text{list}(K_{inter}, V_{inter})$$

- Reduce function:

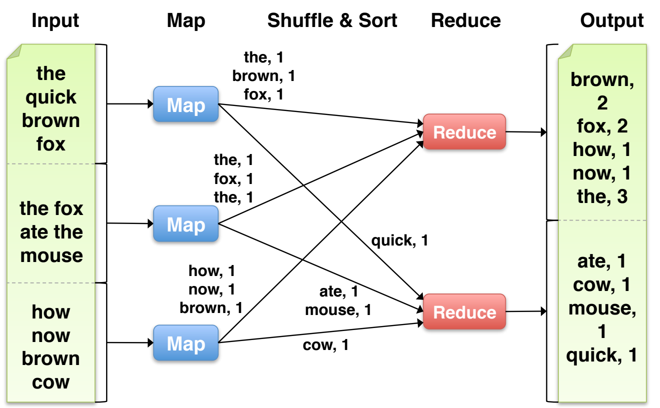
$$(K_{inter}, \text{list}(V_{inter})) \rightarrow \text{list}(K_{out}, V_{out})$$

Example: Word Count

```
def mapper(line):
    foreach word in line.split():
        output(word, 1)


def reducer(key, values):
    output(key, sum(values))
```

Word Count Execution



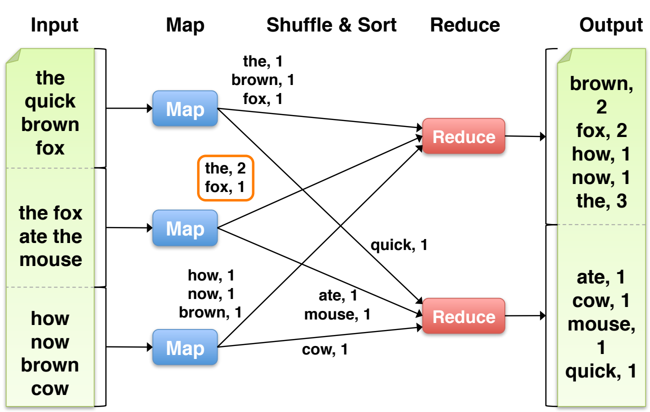
An Optimization: The Combiner

- Local reduce function for repeated keys produced by same map
- For associative ops. like sum, count, max
- Decreases amount of intermediate data

- Example: local counting for Word Count:

```
def combiner(key, values):
    output(key, sum(values))
```


Word Count with Combiner



MapReduce Execution Details

- Mappers preferentially scheduled on same node or same rack as their input block
  - Minimize network use to improve performance
- Mappers save outputs to local disk before serving to reducers
  - Allows recovery if a reducer crashes
  - Allows running more reducers than # of nodes

Fault Tolerance in MapReduce

1. If a task crashes:
   - Retry on another node
     - » OK for a map because it had no dependencies
     - » OK for reduce because map outputs are on disk
   - If the same task repeatedly fails, fail the job or ignore that input block

➢ **Note: For the fault tolerance to work, *user tasks must be deterministic and side-effect-free***

Fault Tolerance in MapReduce

2. If a node crashes:
   - Relaunch its current tasks on other nodes
   - Relaunch any maps the node previously ran
     - » Necessary because their output files were lost along with the crashed node

Fault Tolerance in MapReduce

3. If a task is going slowly (straggler):
   - Launch second copy of task on another node
   - Take the output of whichever copy finishes first, and kill the other one

•Critical for performance in large clusters (many possible causes of stragglers)

Takeaways

- By providing a restricted data-parallel programming model, MapReduce can control job execution in useful ways:
  - Automatic division of job into tasks
  - Placement of computation near data
  - Load balancing
  - Recovery from failures & stragglers

Conclusions

- The key challenge of building wide area P2P systems is a scalable and robust directory/lookup service
  – Naptser: centralized location service
  – Gnutella: broadcast-based decentralized location service
  – CAN, Chord, Tapestry, Pastry: efficient-routing decentralized solution
- Cloud computing
  – Pay-as-you go services
  – Rapidly scale up the service
  – Commodity hardware, large scale: failures become the norm
  – MapReduce: Data-parallel programming model for clusters of commodity machines