CS162
Operating Systems and Systems Programming
Lecture 14

Key Value Storage Systems

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Key Value Storage

- Handle huge volumes of data, e.g., PBs
  - Store (key, value) tuples
- Simple interface
  - **put**(key, value); // insert/write “value” associated with “key”
  - value = **get**(key); // get/read data associated with “key”
- Used sometimes as a simpler but more scalable “database”

Key Values: Examples

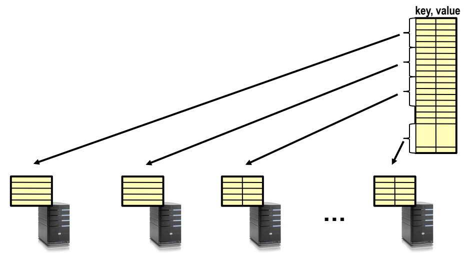
- Amazon:
  - Key: customerID
  - Value: customer profile (e.g., buying history, credit card, ..)
- Facebook, Twitter:
  - Key: UserID
  - Value: user profile (e.g., posting history, photos, friends, …)
- iCloud/iTunes:
  - Key: Movie/song name
  - Value: Movie, Song

System Examples

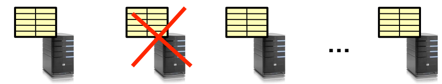
- **Amazon**
  - Dynamo: internal key value store used to power Amazon.com (shopping cart)
  - Simple Storage System (S3)
- **BigTable/HBase/Hypertable:** distributed, scalable data storage
- **Cassandra**: “distributed data management system” (developed by Facebook)
- **Memcached:** in-memory key-value store for small chunks of arbitrary data (strings, objects)
- **eDonkey/eMule:** peer-to-peer sharing system
- …

Key Value Store

- Also called a Distributed Hash Table (DHT)
- Main idea: partition set of key-values across many machines



Challenges



- **Fault Tolerance:** handle machine failures without losing data and without degradation in performance
- **Scalability:**
  - Need to scale to thousands of machines
  - Need to allow easy addition of new machines
- **Consistency:** maintain data consistency in face of node failures and message losses
- **Heterogeneity** (if deployed as peer-to-peer systems):
  - Latency: 1ms to 1000ms
  - Bandwidth: 32Kb/s to 100Mb/s

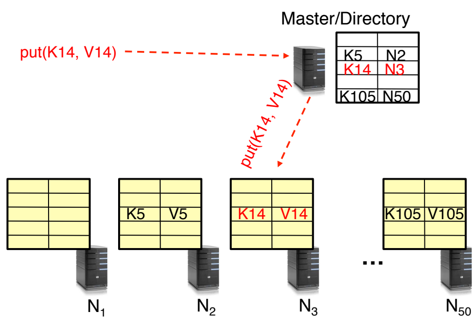
Key Questions

- put(key, value): where do you store a new (key, value) tuple?
- get(key): where is the value associated with a given "key" stored?

- And, do the above while providing
  - Fault Tolerance
  - Scalability
  - Consistency

Directory-Based Architecture

- Have a node maintain the mapping between **keys** and the **machines (nodes)** that store the **values** associated with the **keys**



Directory-Based Architecture

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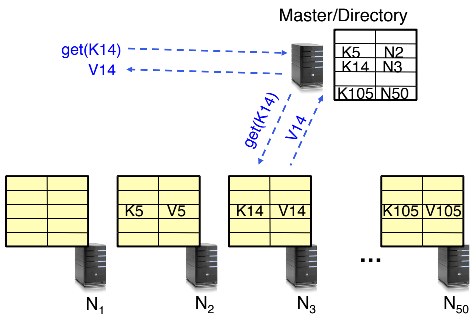
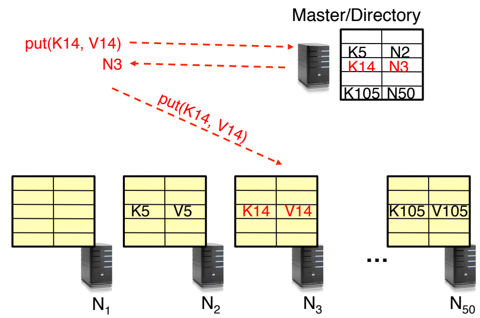


Directory-Based Architecture

- Having the master relay the requests → **recursive query**
- Another method: **iterative query** (this slide)
  - Return node to requester and let requester contact node



Directory-Based Architecture

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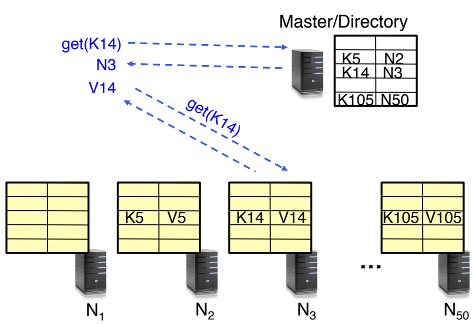
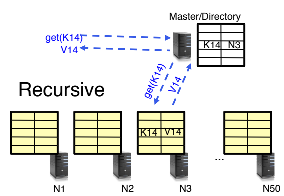
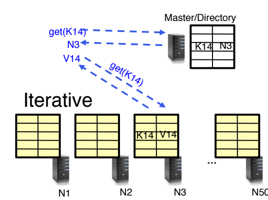


Discussion: Iterative vs. Recursive Query

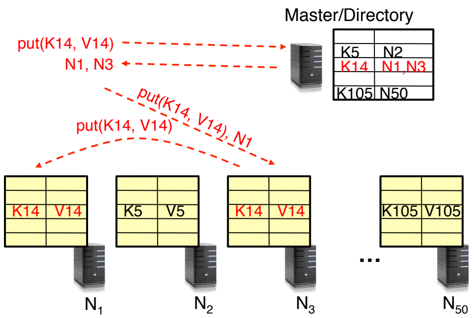




- Recursive Query:
  - Advantages:
    - » Faster, as typically master/directory closer to nodes
    - » Easier to maintain consistency, as master/directory can serialize puts()/gets()
  - Disadvantages: scalability bottleneck, as all "Values" go through master/directory
- Iterative Query
  - Advantages: more scalable
  - Disadvantages: slower, harder to enforce data consistency

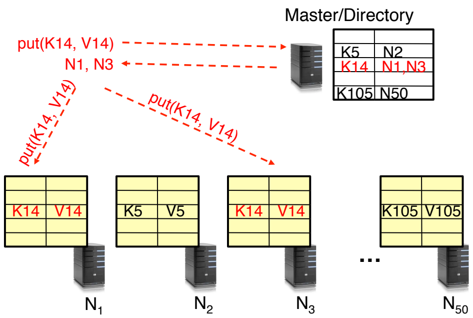
Fault Tolerance

- Replicate value on several nodes
- Usually, place replicas on different racks in a datacenter to guard against rack failures



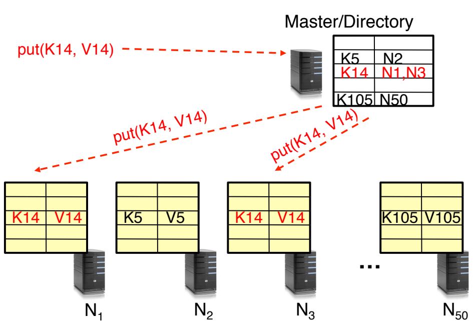
Fault Tolerance

- Again, we can have
  - **Recursive** replication (previous slide)
  - **Iterative** replication (this slide)



Fault Tolerance

- Or we can use **recursive** query and **iterative** replication…



Scalability

- Storage: use more nodes
- Number of requests:
  - Can serve requests from all nodes on which a value is stored in parallel
  - Master can replicate a popular value on more nodes
- Master/directory scalability:
  - Replicate it
  - Partition it, so different keys are served by different masters/directories
    - » How do you partition?

Scalability: Load Balancing

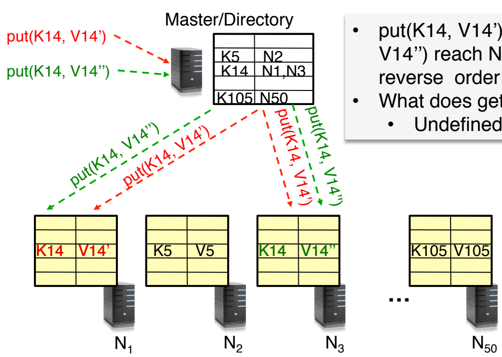
- Directory keeps track of the storage availability at each node
  – Preferentially insert new values on nodes with more storage available
- What happens when a new node is added?
  – Cannot insert only new values on new node. Why?
  – Move values from the heavy loaded nodes to the new node
- What happens when a node fails?
  – Need to replicate values from fail node to other nodes

Consistency

- Need to make sure that a value is replicated correctly
- How do you know a value has been replicated on every node?
  – Wait for acknowledgements from every node
- What happens if a node fails during replication?
  – Pick another node and try again
- What happens if a node is slow?
  – Slow down the entire put()? Pick another node?
- In general, with multiple replicas
  – Slow puts and fast gets

Consistency (cont'd)

- If concurrent updates (i.e., puts to same key) may need to make sure that updates happen in the same order



- put(K14, V14') and put(K14, V14'') reach N1 and N3 in reverse order
- What does get(K14) return?
  - Undefined!

Consistency (cont'd)

- Large variety of consistency models:
  – Atomic consistency (linearizability): reads/writes (gets/puts) to replicas appear as if there was a single underlying replica (single system image)
    » Think "one updated at a time"
    » Transactions (later in the class)
  – Eventual consistency: given enough time all updates will propagate through the system
    » One of the weakest form of consistency; used by many systems in practice
  – And many others: causal consistency, sequential consistency, strong consistency, …

Quorum Consensus

- Improve put() and get() operation performance

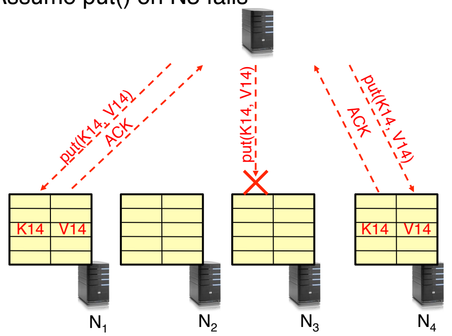
- Define a replica set of size N
- put() waits for acknowledgements from at least W replicas
- get() waits for responses from at least R replicas
- W+R > N

- Why does it work?
  – There is at least one node that contains the update

- Why you may use W+R > N+1?

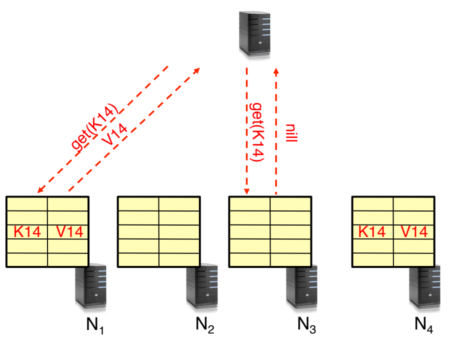
Quorum Consensus Example

- N=3, W=2, R=2
- Replica set for K14: {N1, N2, N4}
- Assume put() on N3 fails



Quorum Consensus Example

- Now, issuing get() to any two nodes out of three will return the answer



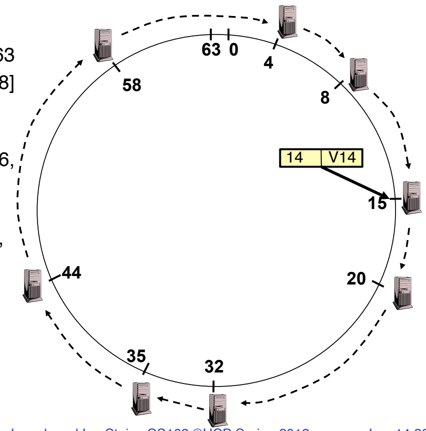
5min Break

Scaling Up Directory

- Challenge:
  - Directory contains a number of entries equal to number of (key, value) tuples in the system
  - Can be tens or hundreds of billions of entries in the system!
- Solution: **consistent hashing**
- Associate to each node a unique *id* in an *uni*-dimensional space $0..2^m-1$
  - Partition this space across *m* machines
  - Assume keys are in same uni-dimensional space
  - Each (Key, Value) is stored at the node with the smallest ID larger than Key

Key to Node Mapping Example

- m = 8 → ID space: 0..63
- Node 8 maps keys [5,8]
- Node 15 maps keys [9,15]
- Node 20 maps keys [16, 20]
- …
- Node 4 maps keys [59, 4]



Scaling Up Directory

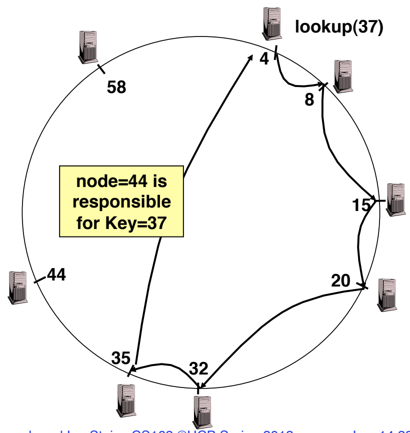
- With consistent hashing, directory contains only a number of entries equal to number of nodes
  - Much smaller than number of tuples
- Next challenge: every query still needs to contact the directory
- Solution: distributed directory (a.k.a. lookup) service:
  - Given a **key**, find the **node** storing that key
- Key idea: route request from node to node until reaching the node storing the request's key
- Key advantage: totally distributed
  - No point of failure; no hot spot

Chord: Distributed Lookup (Directory) Service

- Key design decision
  - Decouple correctness from efficiency
- Properties
  - Each node needs to know about O(log(*M*)), where *M* is the total number of nodes
  - Guarantees that a tuple is found in O(log(*M*)) steps
- Many other lookup services: CAN, Tapestry, Pastry, Kademlia, …

Lookup

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



Stabilization Procedure

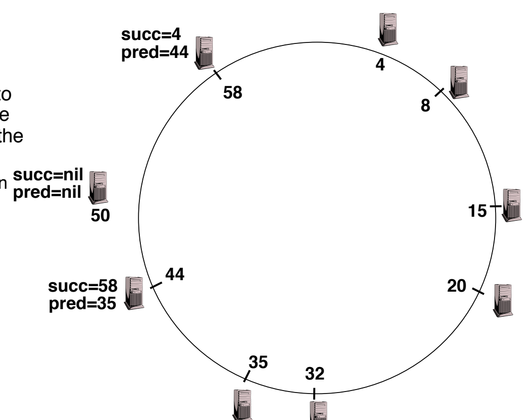
- Periodic operation performed by each node n to maintain its successor when new nodes join the system

```
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
```

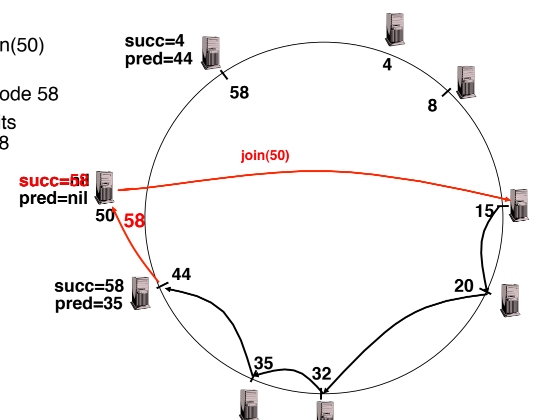

Joining Operation

- 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



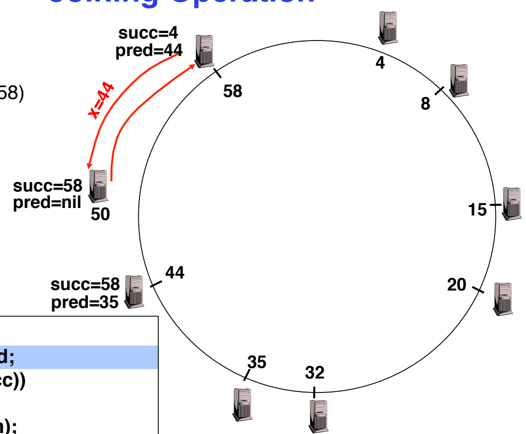
Joining Operation

- 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

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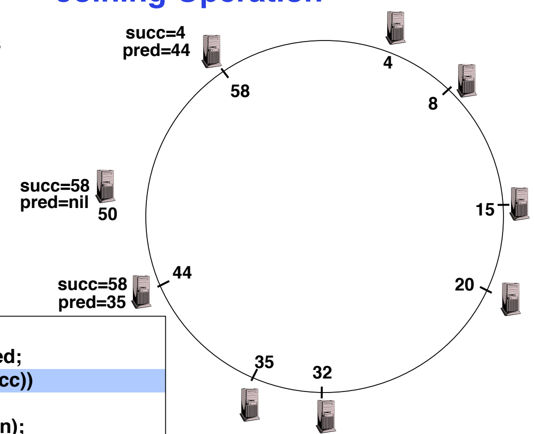
     succ = x;
  succ.notify(n);
```


Joining Operation

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

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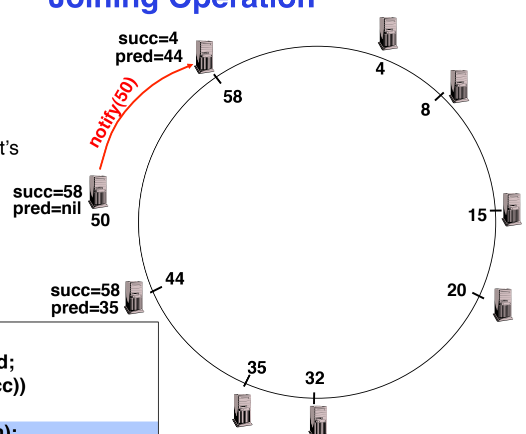
Joining Operation

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

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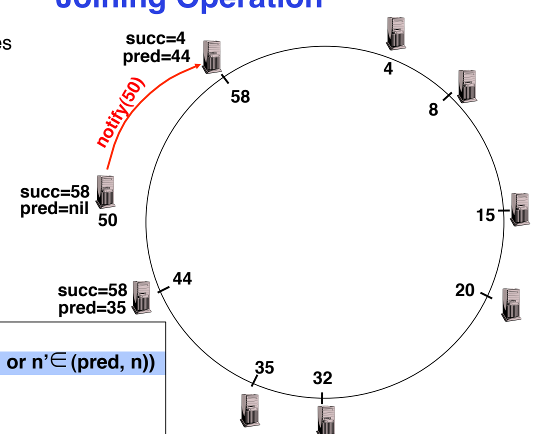


Joining Operation

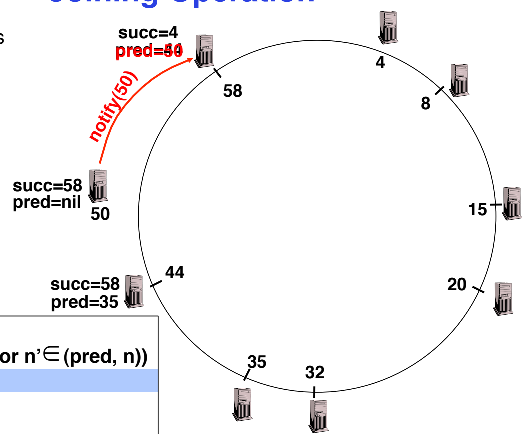
- n=58 processes notify(50)
  - pred = 44
  - n' = 50




```
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

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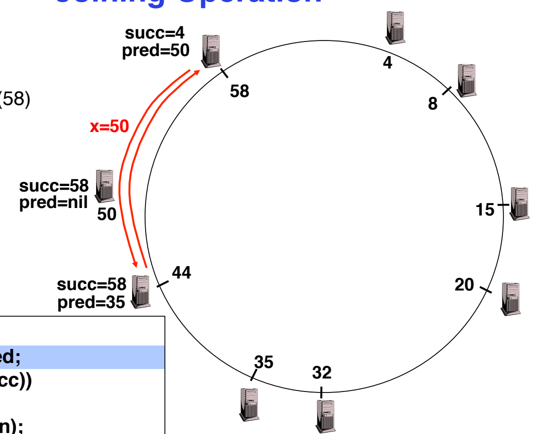
Joining Operation

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

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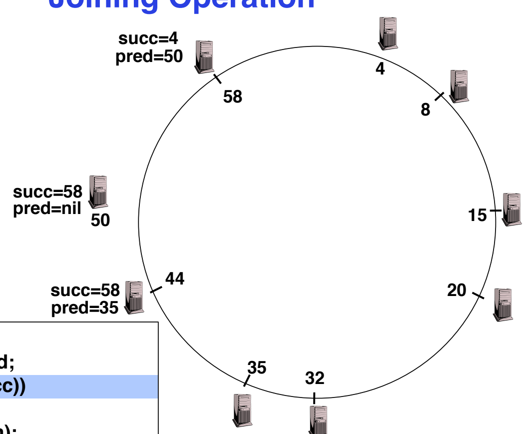


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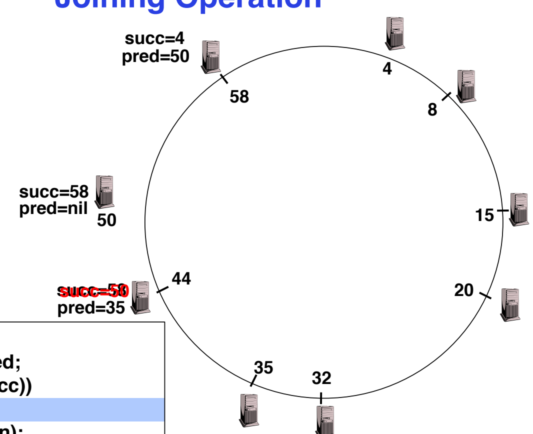
Joining Operation

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




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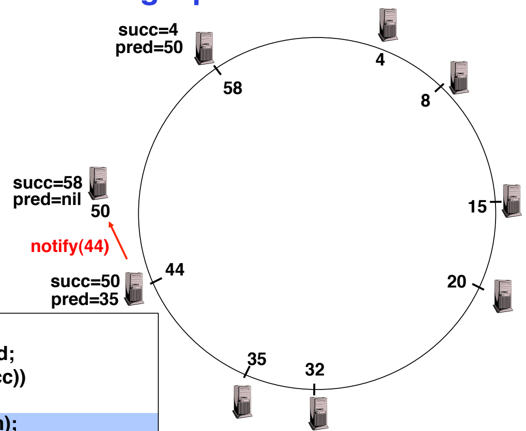

Joining Operation

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




```
n.stabilize()
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   succ.notify(n);
```
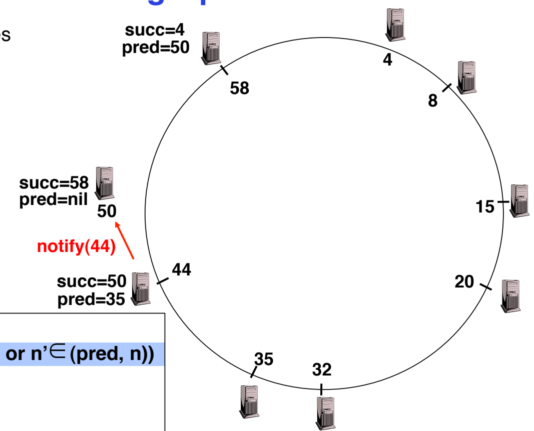


Joining Operation

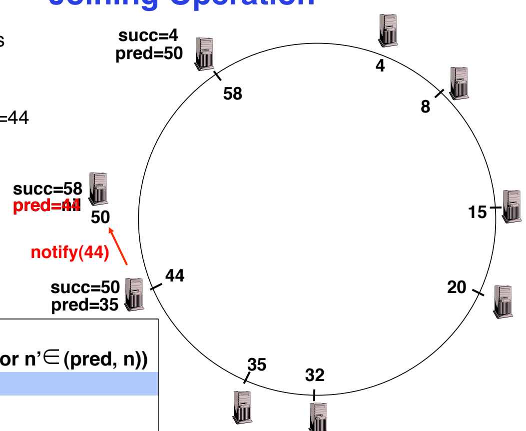
- n=50 processes notify(44)
  - pred = nil




```
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')
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```
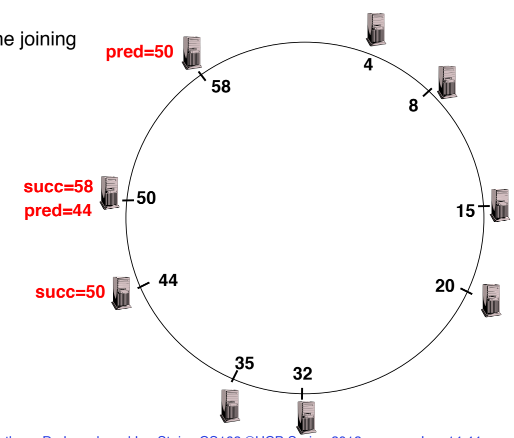


Joining Operation (cont'd)

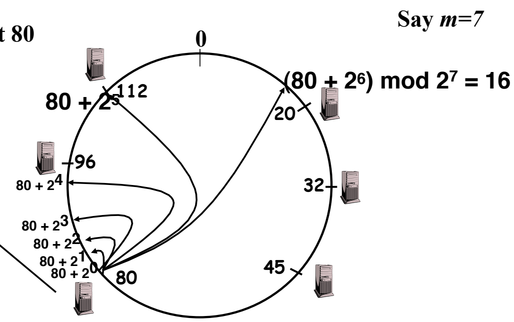
- This completes the joining operation!



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



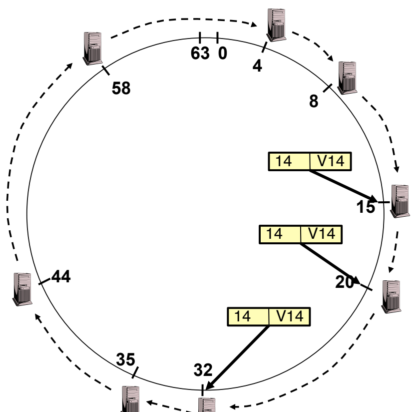
ith entry at peer with id n is first peer with id >= $n + 2^i (\bmod 2^m)$

Achieving Fault Tolerance for Lookup Service

- To improve robustness each node maintains the k (> 1) immediate successors instead of only one successor
- In the pred() reply message, node A can send its k-1 successors to its predecessor B
- Upon receiving pred() message, B can update its successor list by concatenating the successor list received from A with its own list
- If k = log(M), lookup operation works with high probability even if half of nodes fail, where M is number of nodes in the system

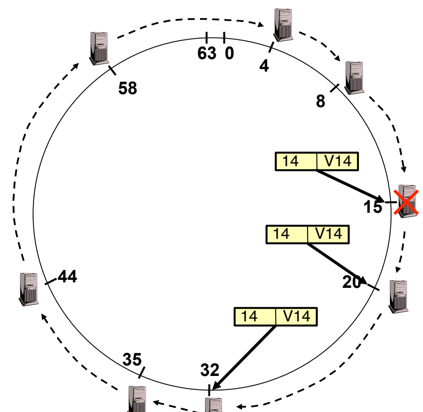
Storage Fault Tolerance

- Replicate tuples on successor nodes
- Example: replicate (K14, V14) on nodes 20 and 32



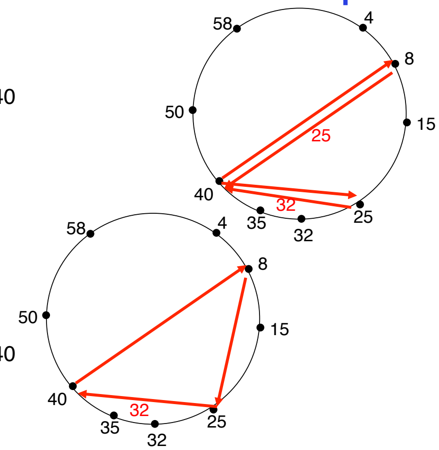
Storage Fault Tolerance

- If node 15 fails, no reconfiguration needed
  - Still have two replicas
  - All lookups will be correctly routed
- Will need to add a new replica on node 35



Iterative vs. Recursive Lookup

- Iteratively:
  - Example: node 40 issue query(31)
- Recursively
  - Example: node 40 issue query(31)



Conclusions: Key Value Store

- Very large scale storage systems
- Two operations
  - put(key, value)
  - value = get(key)
- Challenges
  - Fault Tolerance → replication
  - Scalability → serve get()'s in parallel; replicate/cache hot tuples
  - Consistency → quorum consensus to improve put() performance

Conclusions: Chord

- Highly scalable distributed lookup protocol
- Each node needs to know about O(log(*M*)), where *m* is the total number of nodes
- Guarantees that a tuple is found in O(log(*M*)) steps
- Highly resilient: works with high probability even if half of nodes fail