Key-Value Tables: Chord and DynamoDB

(Lecture 16, cs262a)

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UC Berkeley
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Today's Papers

Chord: A Scalable Peer-to-peer Lookup Service for Internet Applications,

Ion Stoica, Robert Morris, David Karger, M. Frans Kaashoek, Hari Balakrishnan, SIGCOMM'02

(https://pdos.csail.mit.edu/papers/chord:sigcomm01/chord_sigcomm.pdf)

Dynamo: Amazon's Highly Available Key-value Store,

Giuseppe DeCandia, Deniz Hastorun, Madan Jampani, Gunavardhan Kakulapati, Avinash Lakshman, Alex Pilchin, Swaminathan, Sivasubramanian, Peter Vosshall, and Werner Vogels, SOSP'07

(www.allthingsdistributed.com/files/amazon-dynamo-sosp2007.pdf)

Key Value Storage

Interface

- **put**(key, value); // insert/write “value” associated with “key”
- value = **get**(key); // get/read data associated with “key”

Abstraction used to implement

- File systems: value content → block
- Sometimes as a simpler but more scalable “database”

Can handle large volumes of data, e.g., PBs

- Need to distribute data over hundreds, even thousands of machines

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

Distributed file systems
- Key: Block ID
- Value: Block

System Examples

Google File System, Hadoop Dist. File Systems (HDFS)

Amazon

- Dynamo: internal key value store used to power Amazon.com (shopping cart)
- Simple Storage System (S3)

BigTable/Hbase: distributed, scalable data storage

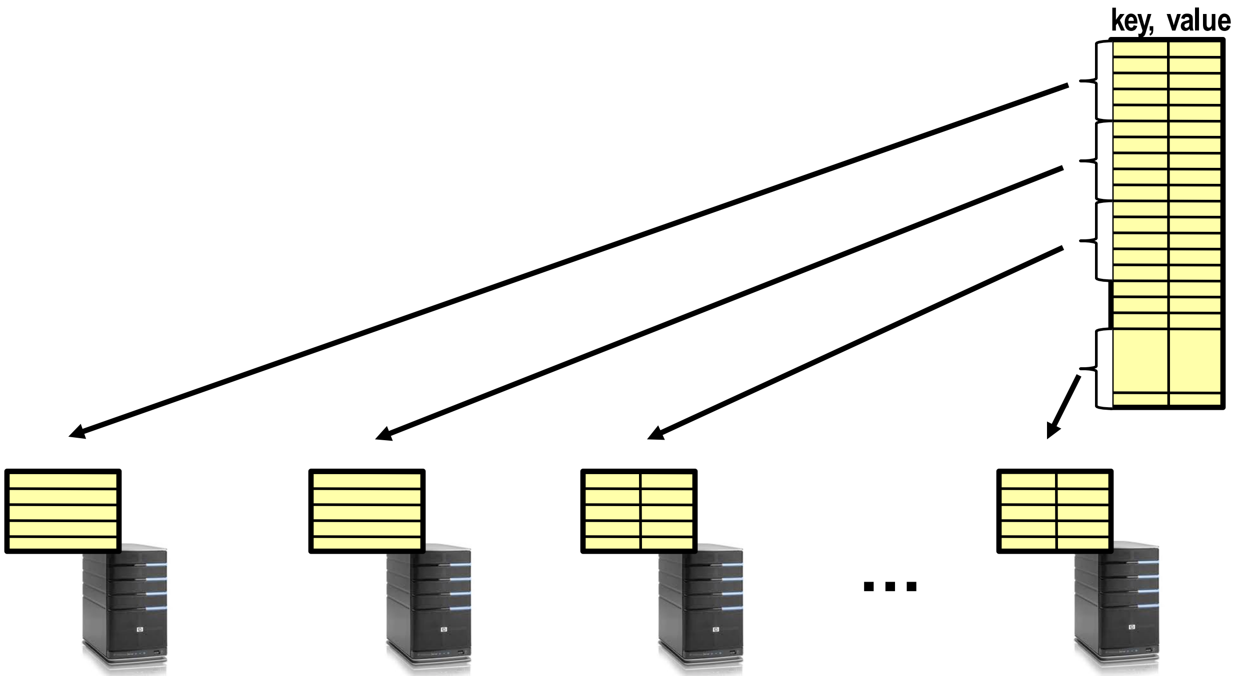
Cassandra: "distributed data management system" (Facebook)

Memcached: in-memory key-value store for small chunks of arbitrary data (strings, objects)

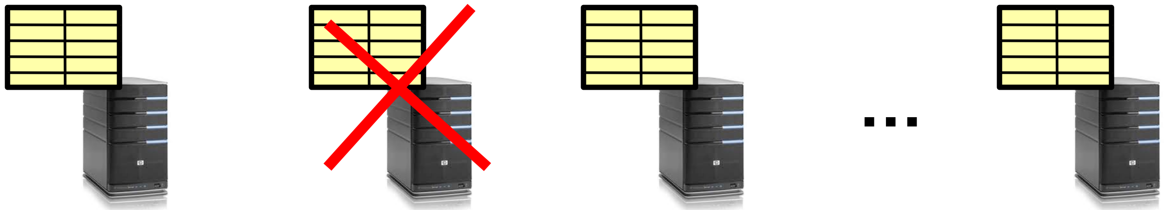
Key Value Store

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?

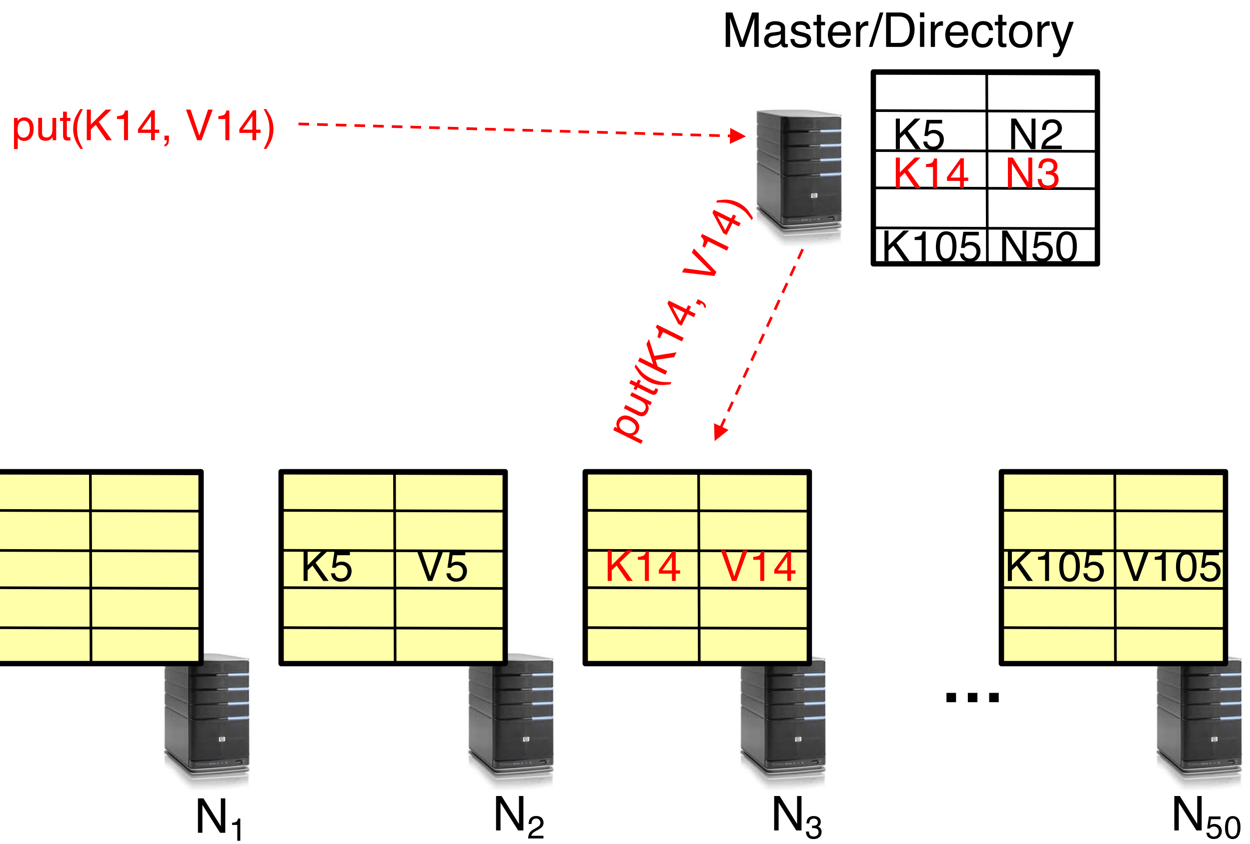
get(key): where is the value associated with a given “key” stored?

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**



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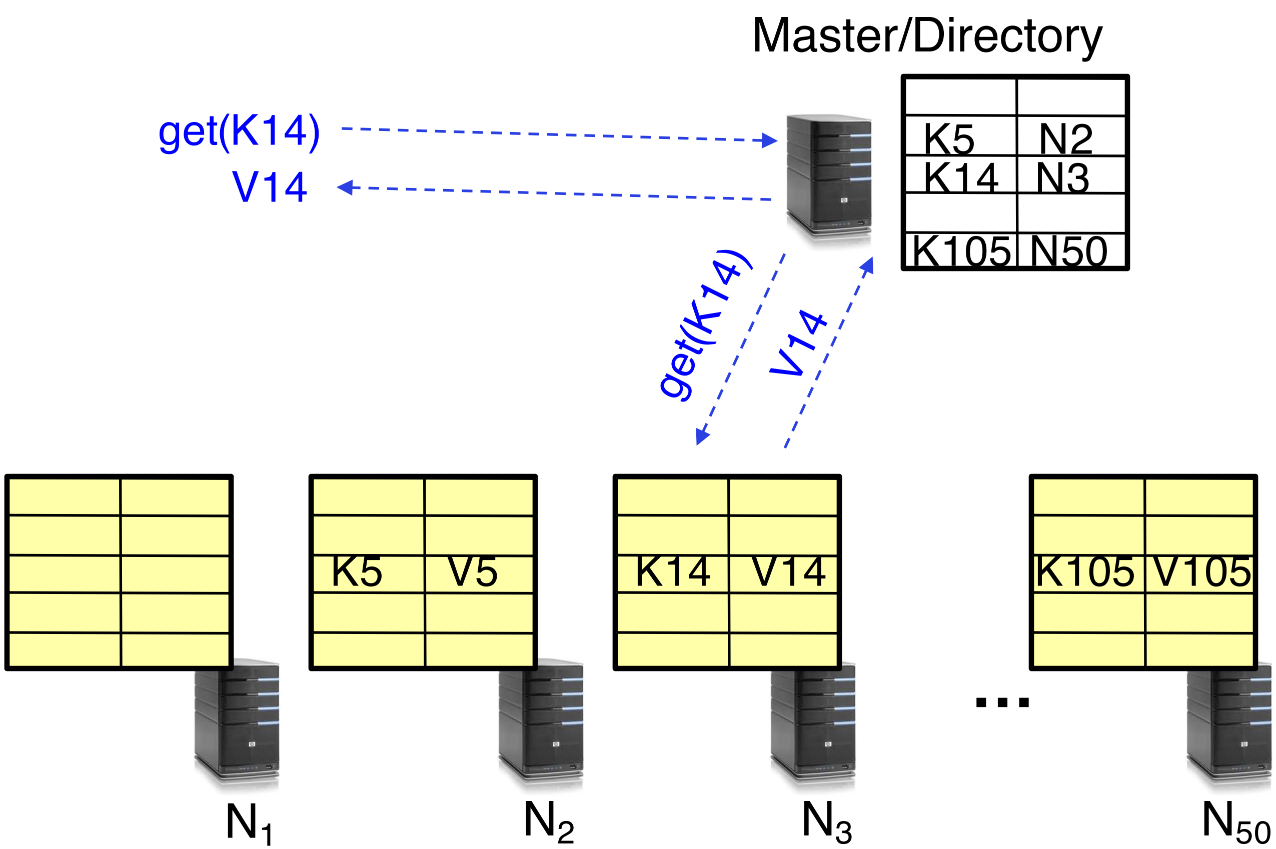
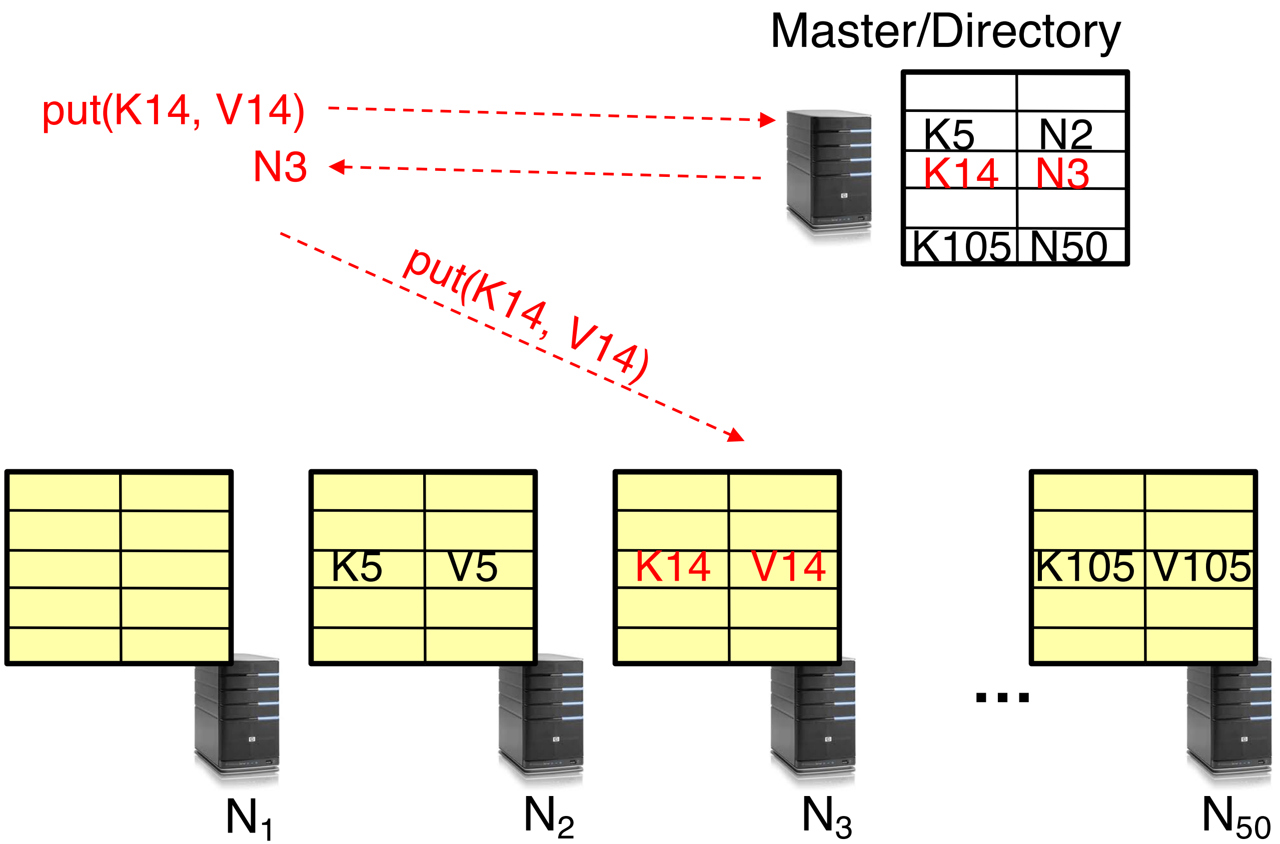


Directory-Based Architecture

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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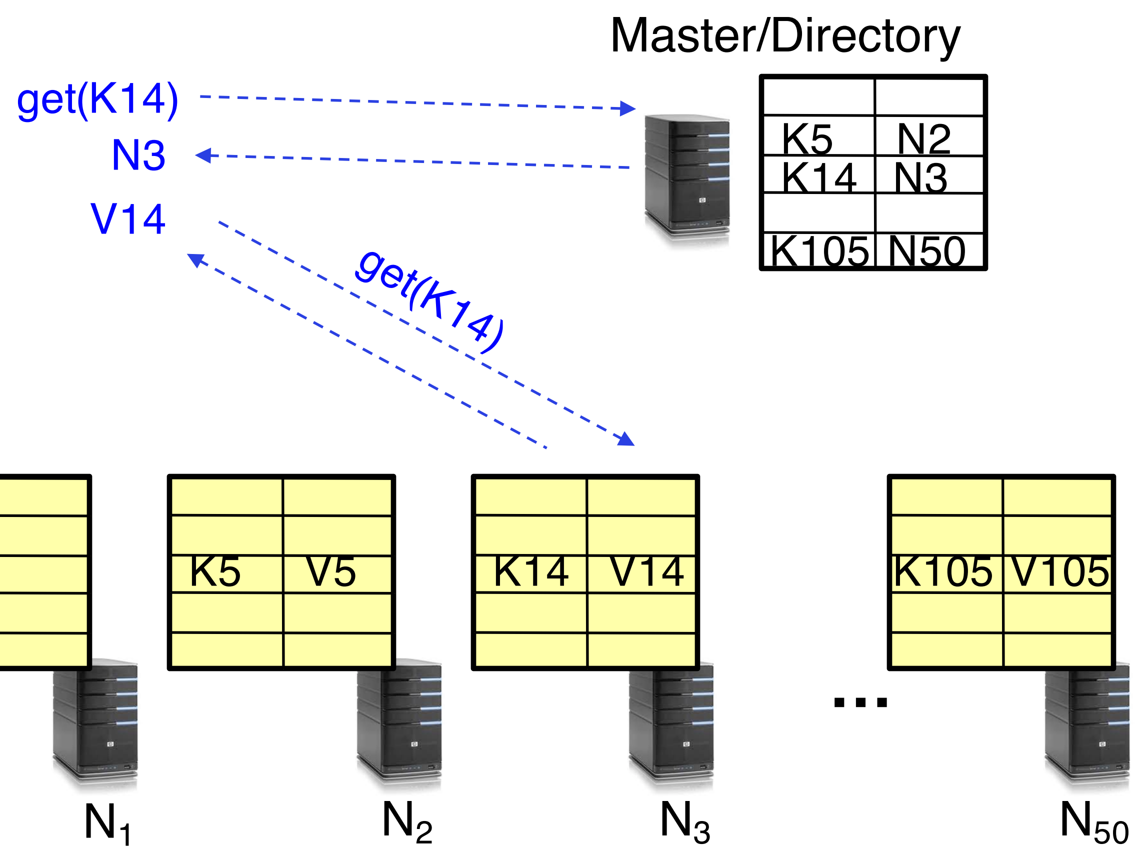
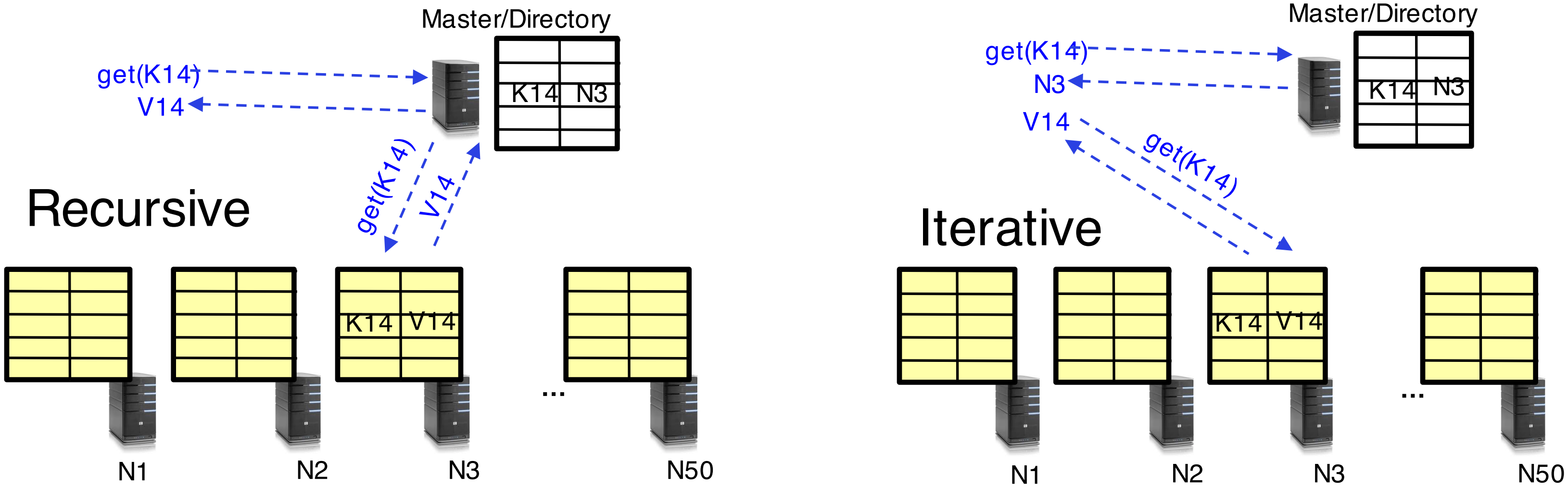


Discussion: Iterative vs. Recursive Query



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

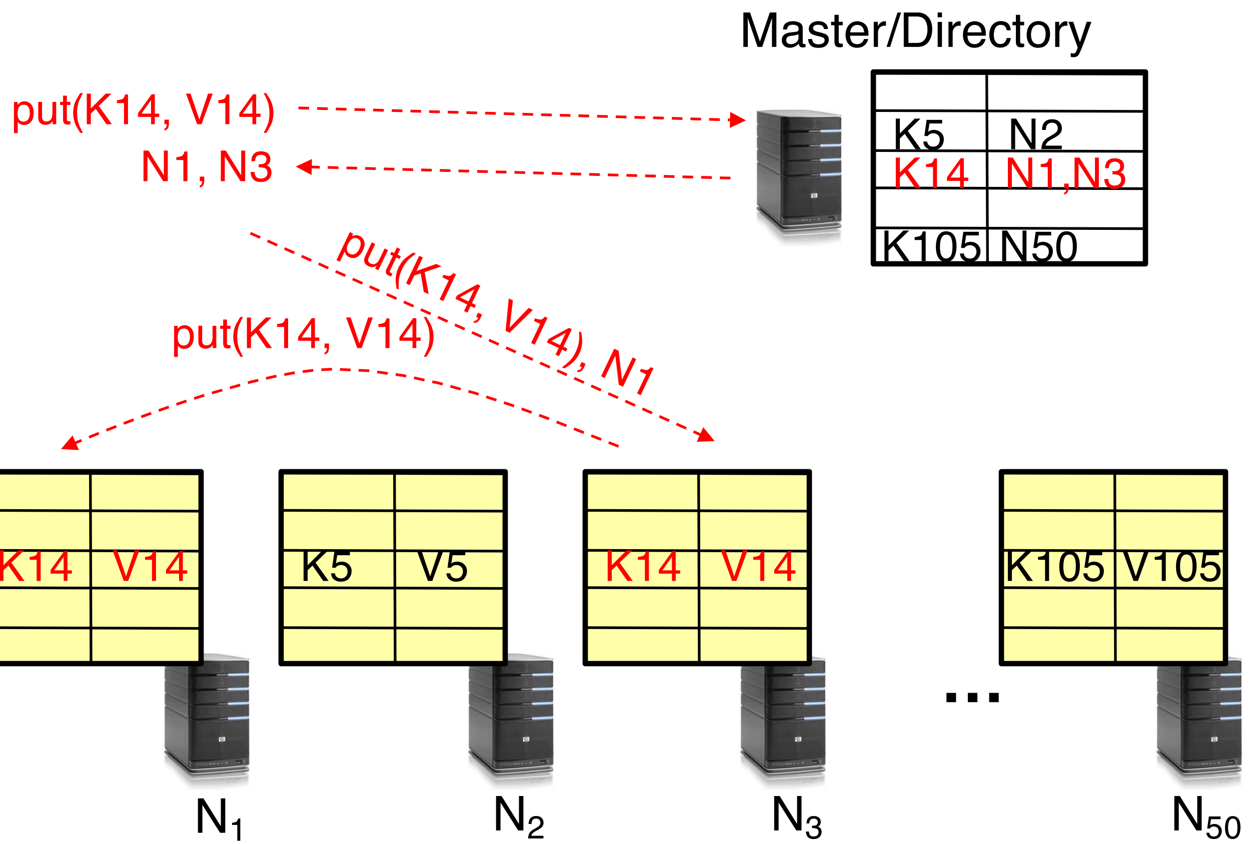
Iterative Query

- Advantages: more scalable
- Disadvantages: slower, harder to enforce data consistency

Fault Tolerance

Replicate value on several nodes

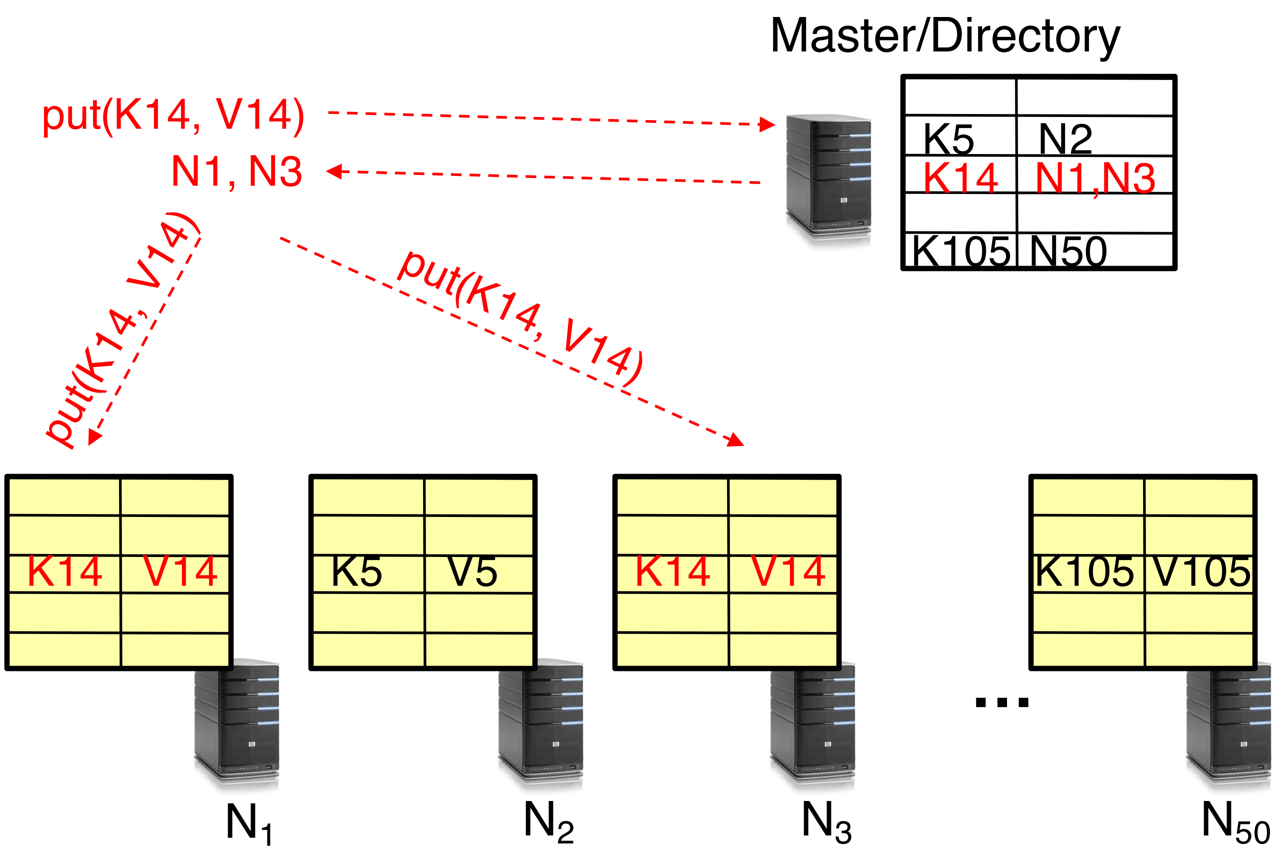
Usually, place replicas on different racks in a datacenter to guard against rack failures



Fault Tolerance

Again, we can have

- **Recursive** replication (previous slide)
- **Iterative** replication (this slide)



Scalability

Storage: use more nodes

Request throughput:

- 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 (see Chord)

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

Replication Challenges

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

How close does a distributed system emulate a single machine in terms of read and write semantics?

Q: Assume **put(K14, V14')** and **put(K14, V14'')** are concurrent, what value ends up being stored?

A: assuming **put()** is atomic, then either **V14'** or **V14''**, right?

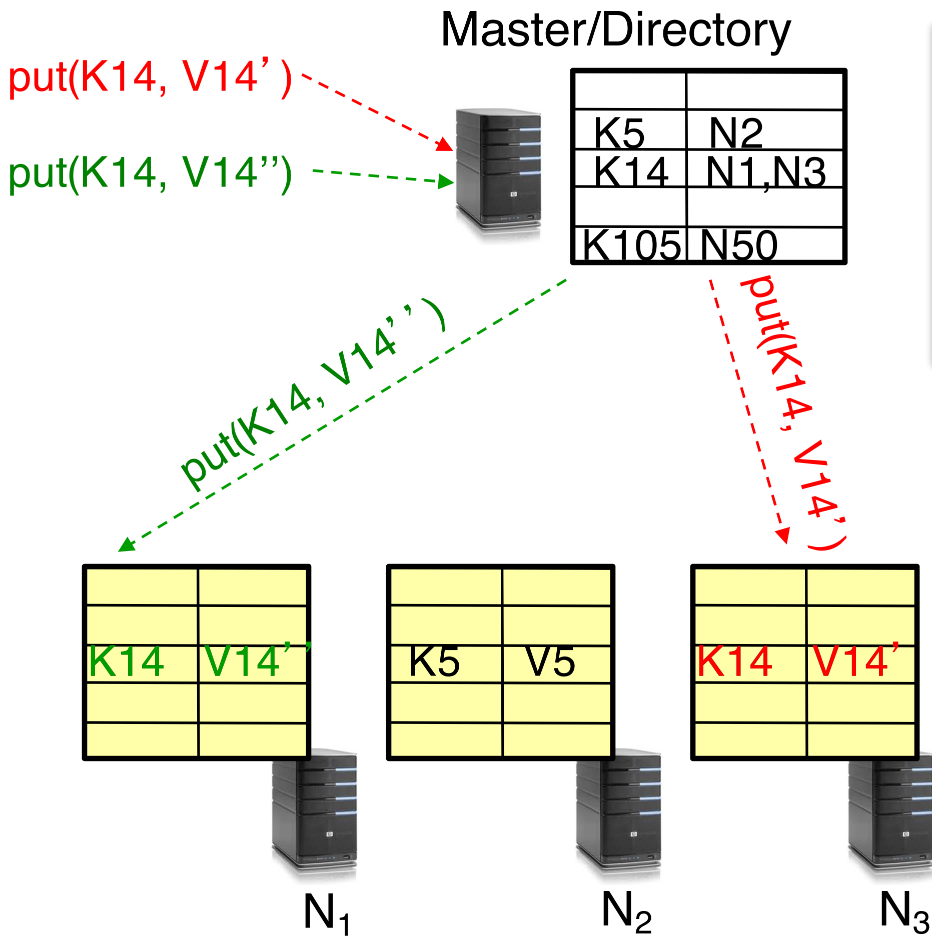
Q: Assume a client calls **put(K14, V14)** and then **get(K14)**, what is the result returned by **get()**?

A: It should be V14, right?

Above semantics, not trivial to achieve in distributed systems

Concurrent Writes (Updates)

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!

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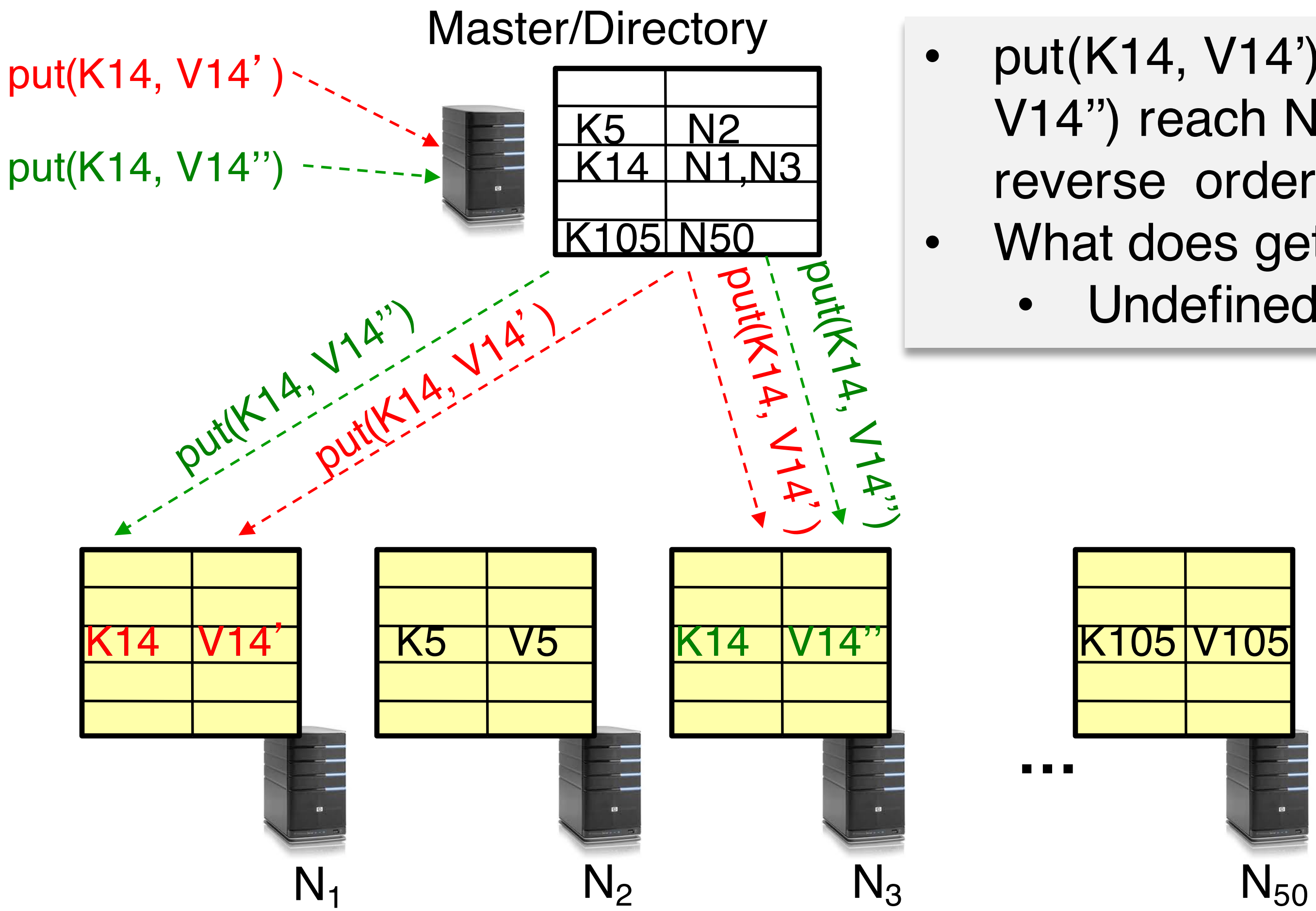
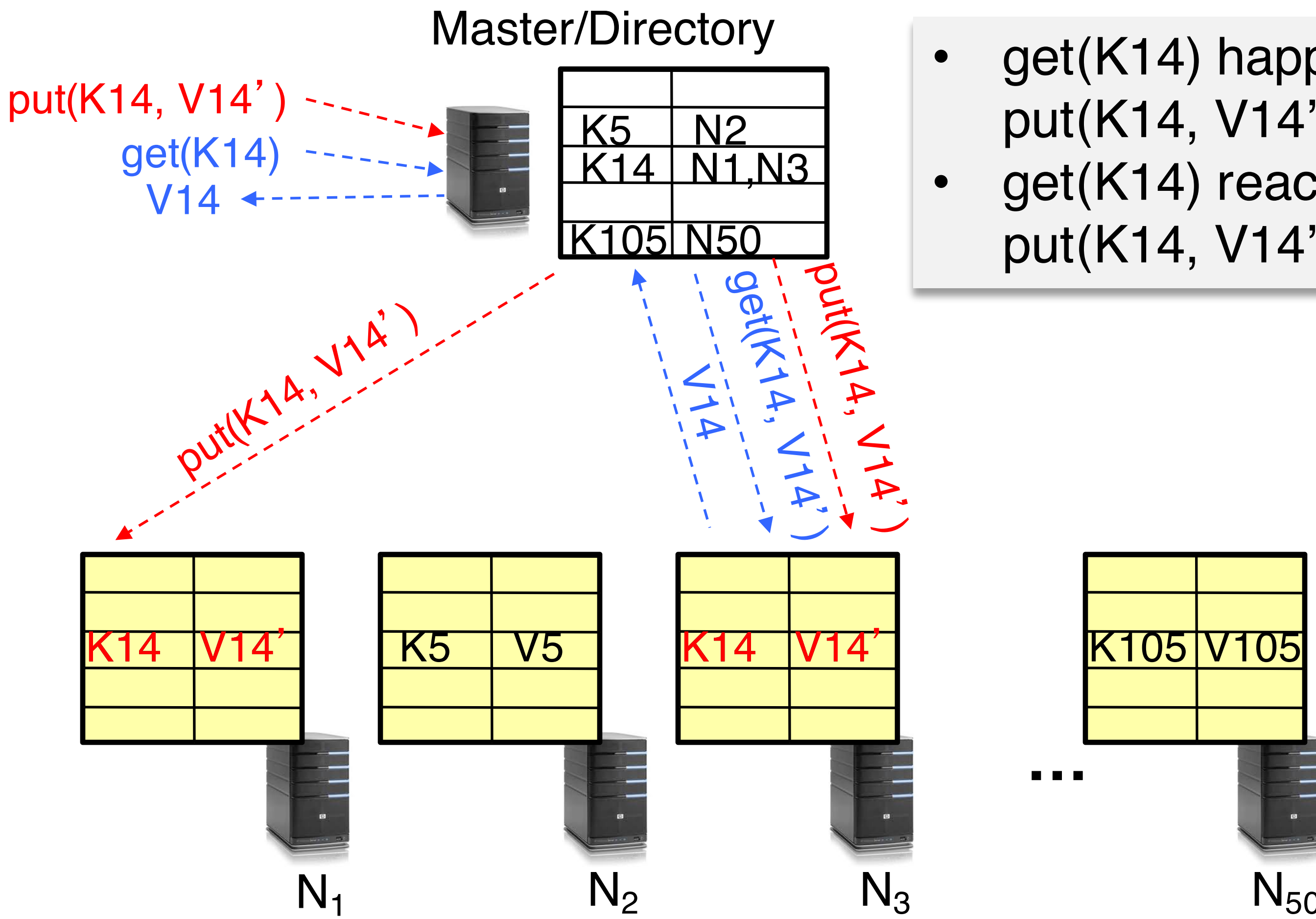


- put(K14, V14’) and put(K14, V14’’) reach N1 and N3 in reverse order
- What does get(K14) return?
  - Undefined!

Read after Write

Read not guaranteed to return value of latest write

– Can happen if Master processes requests in different threads



- get(K14) happens right after put(K14, V14')
- get(K14) reaches N3 before put(K14, V14')!

Consistency (cont’d)

Large variety of consistency models (we’ve already seen):

- 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
- 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, …

Strong Consistency

Assume Master serializes all operations

Challenge: master becomes a bottleneck

- Not addressed here

Still want to improve performance of reads/writes → quorum consensus

Quorum Consensus

Improve **put()** and **get()** operation performance

Define a replica set of size N

put() waits for acks 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

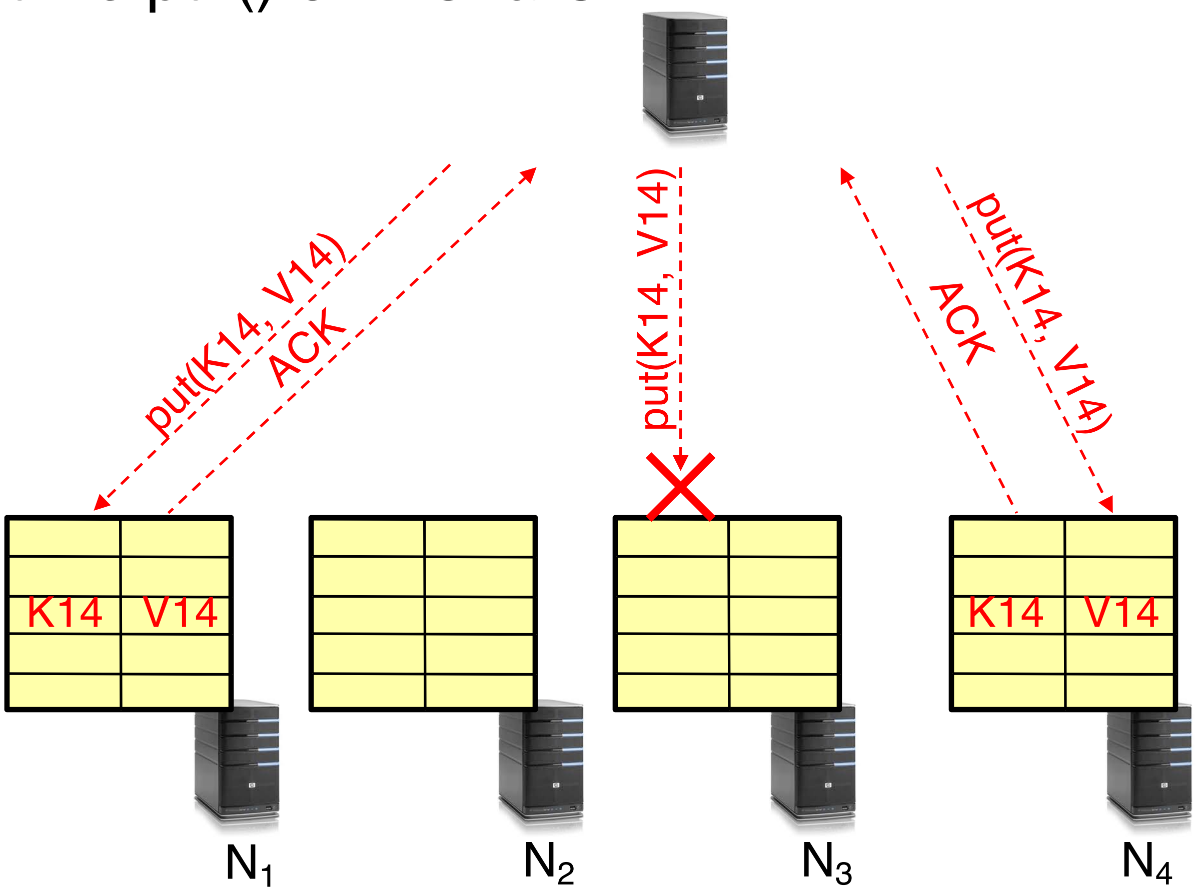
Why you may use W+R > N+1?

Quorum Consensus Example

N=3, W=2, R=2

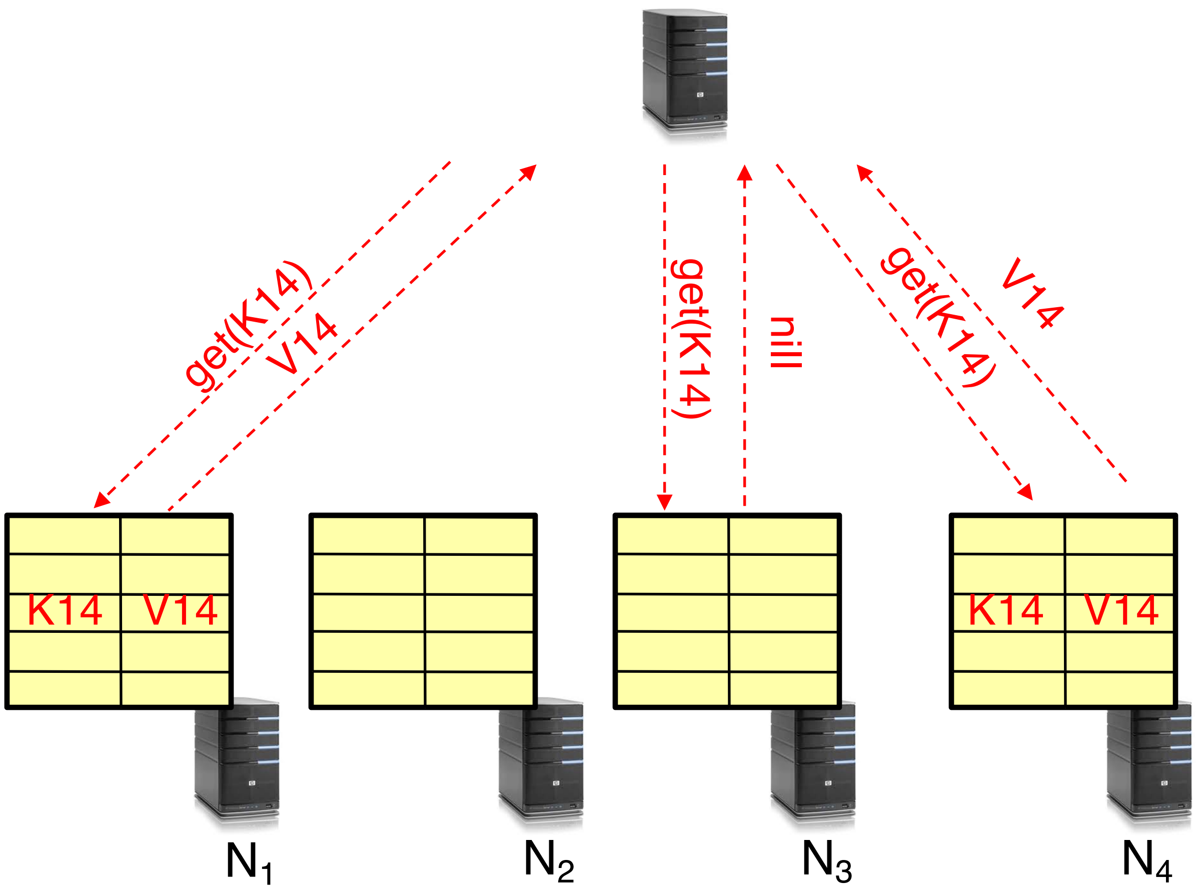
Replica set for K14: {N1, N2, N4}

Assume put() on N3 fails



Quorum Consensus Example

Now, for get() need to wait for any two nodes out of three to return the answer



Chord

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

Recap: Key to Node Mapping Example

m = 6 → ID space: 0..63

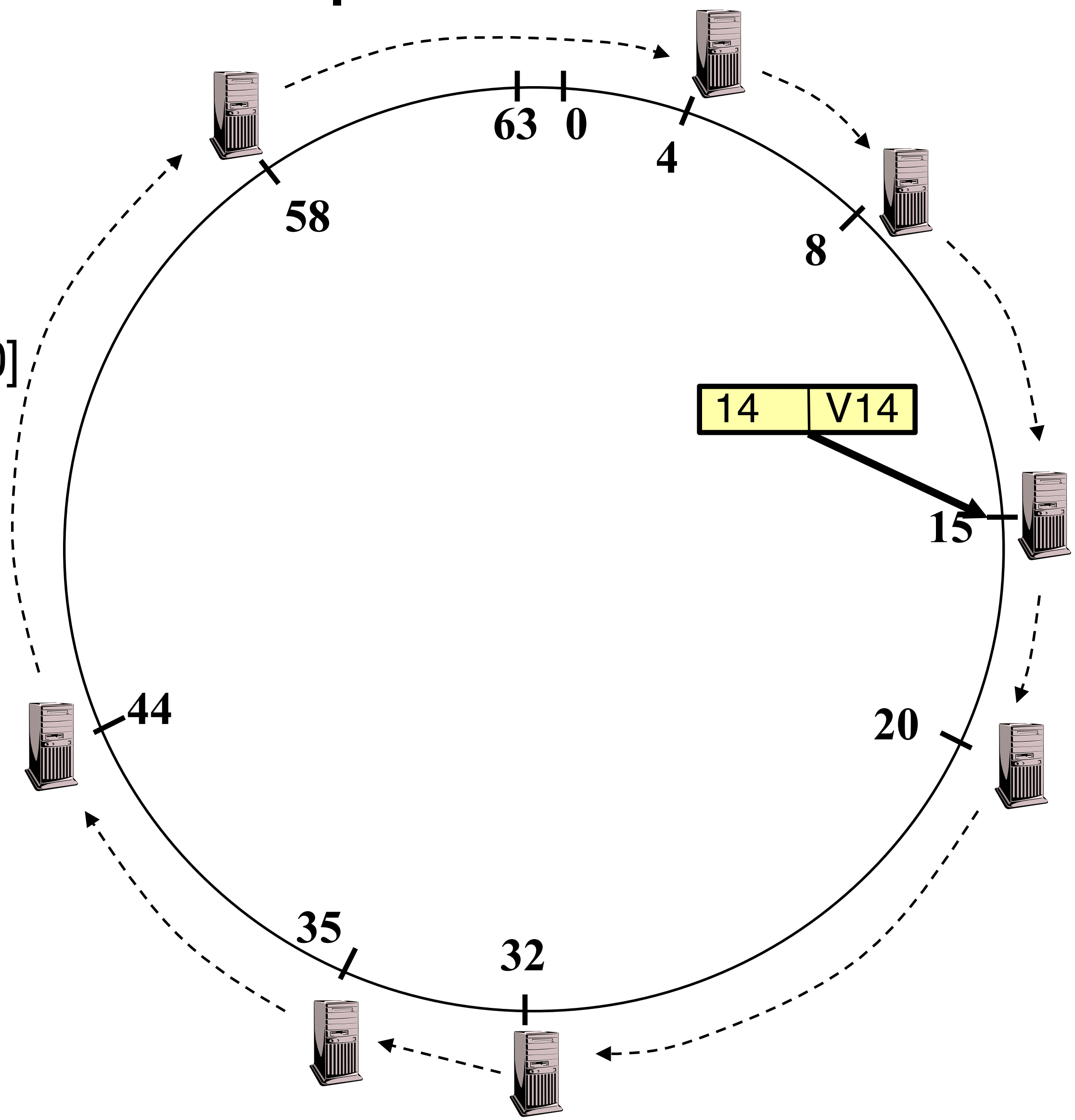
Node 8 maps keys [5,8]

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

Scaling Up Directory

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

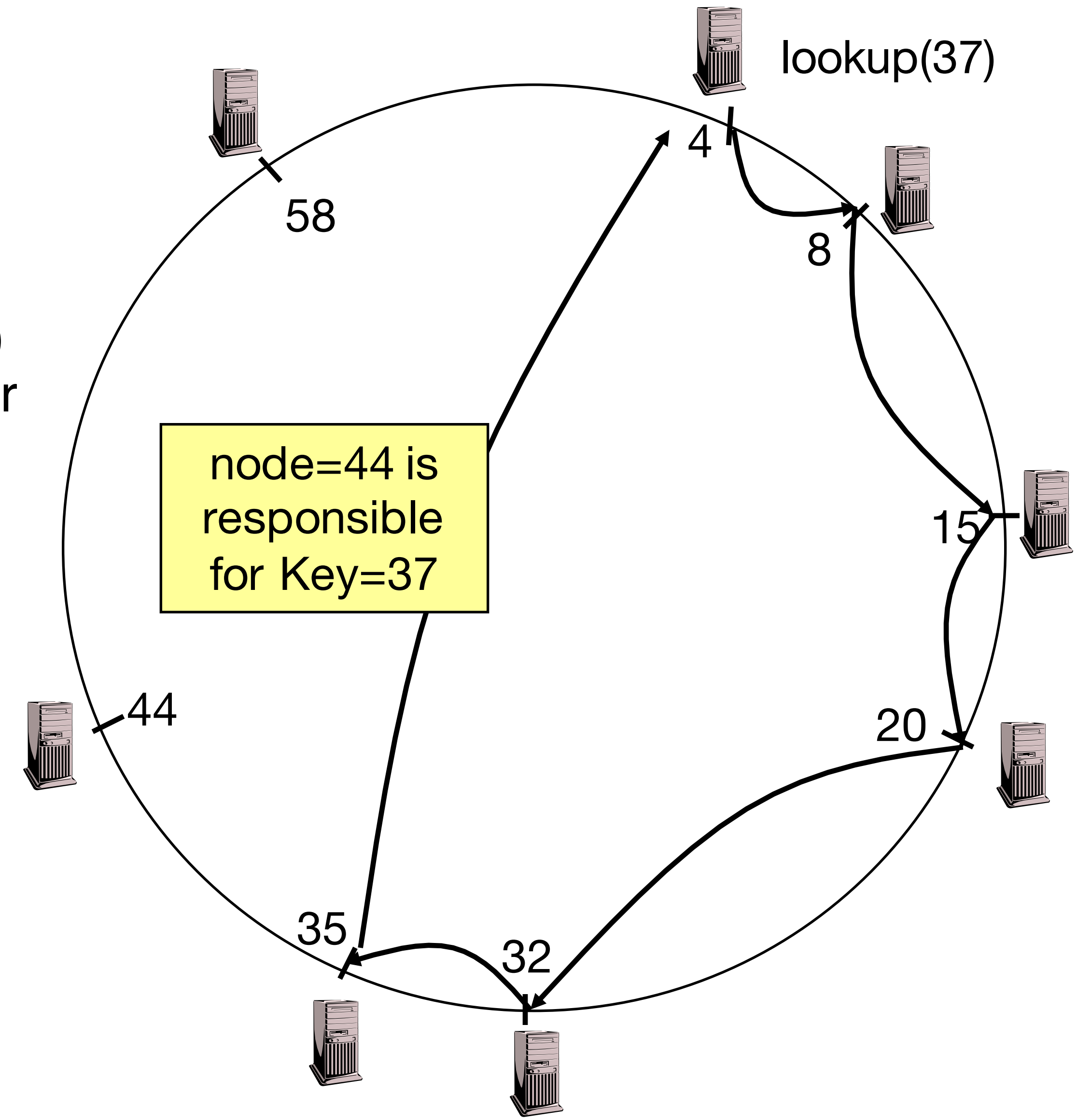
Many other lookup services: CAN, Tapestry, Pastry, Kademlia, …

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

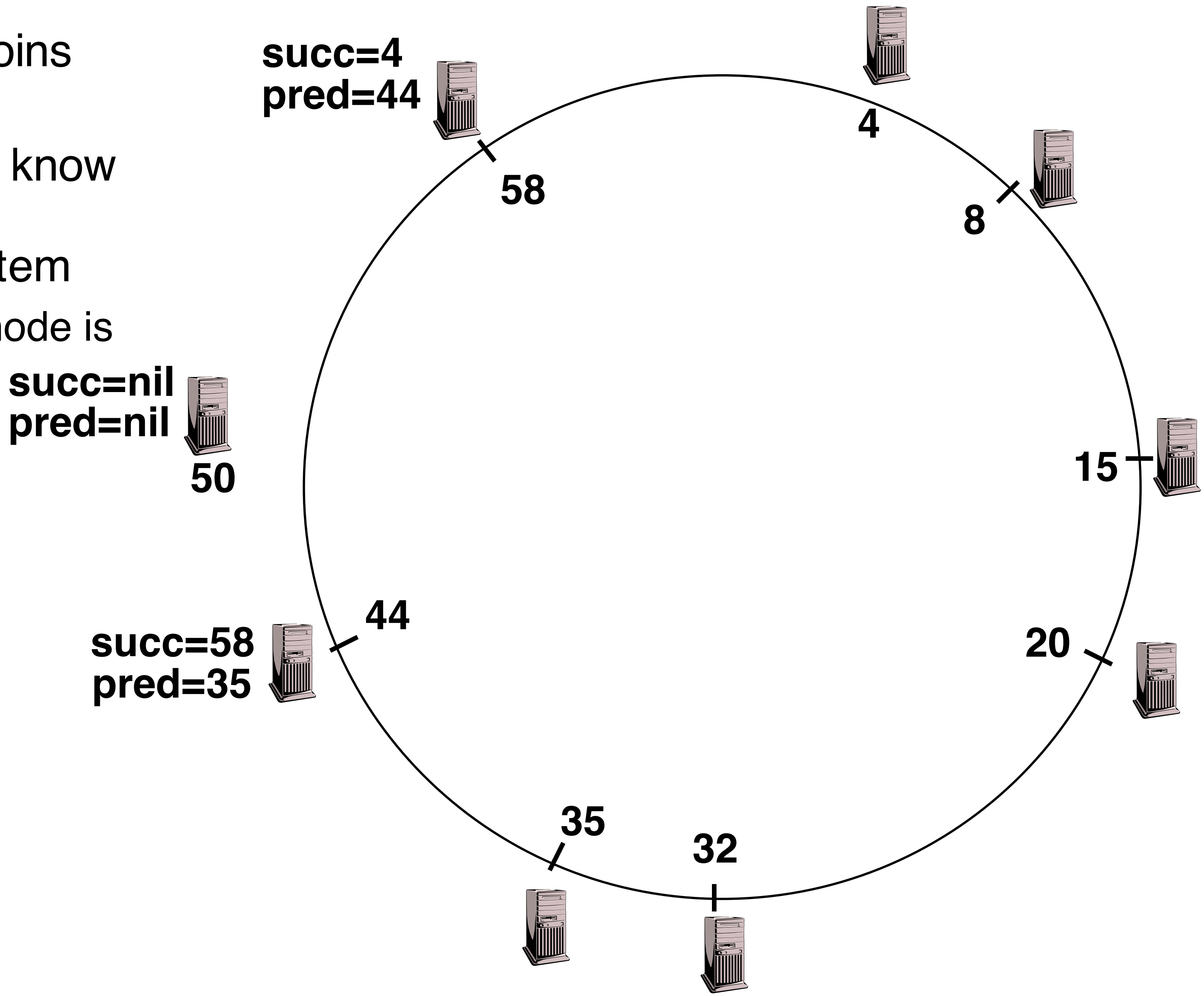
```
n.stabilize()
   x = succ.pred;
   if (x ∈ (n, succ))
      succ = x;        // if x better successor, update
   succ.notify(n); // n tells successor about itself

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

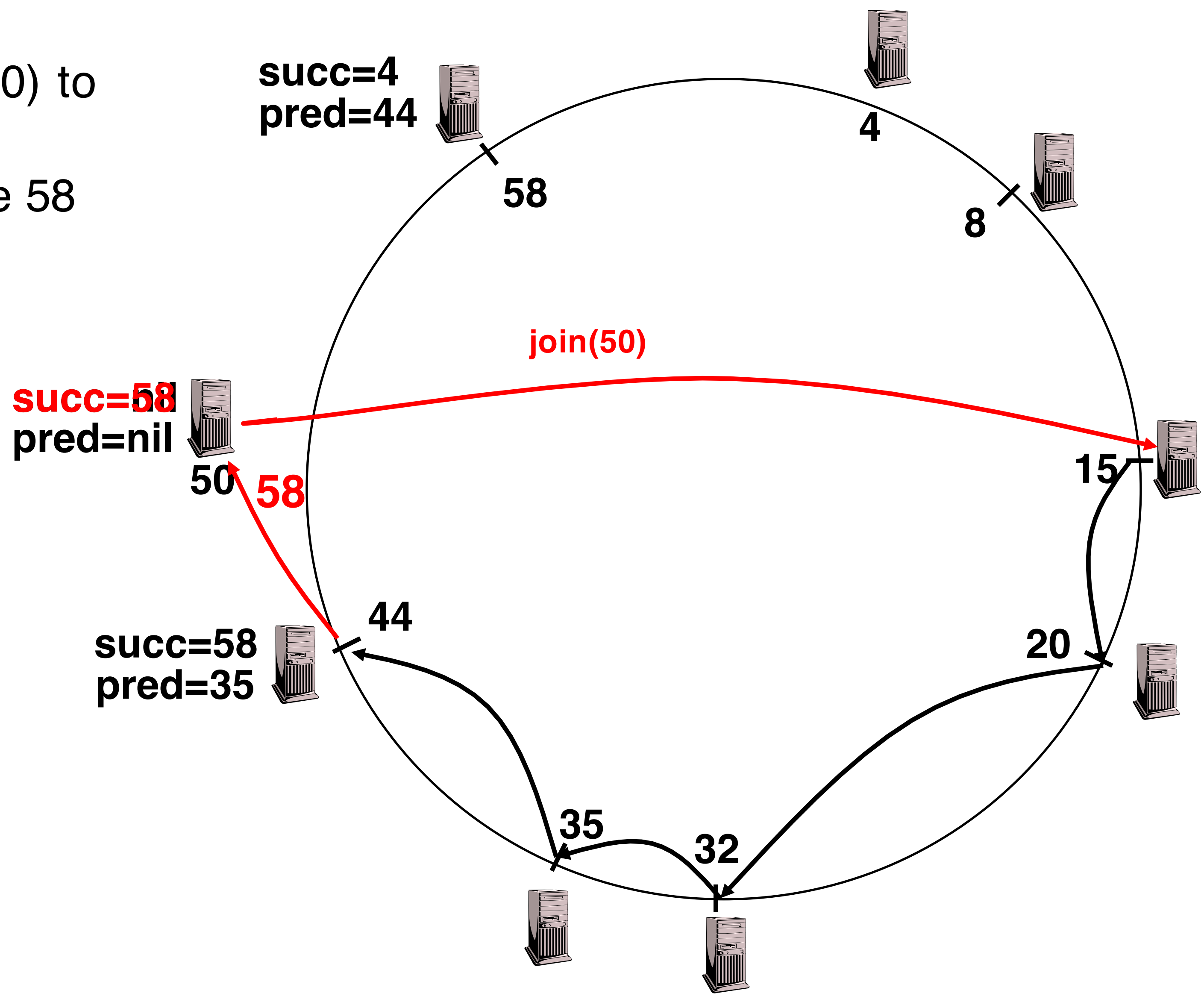
Node 50 needs to know at least one node already in the system

- Assume known node is 15



Joining Operation

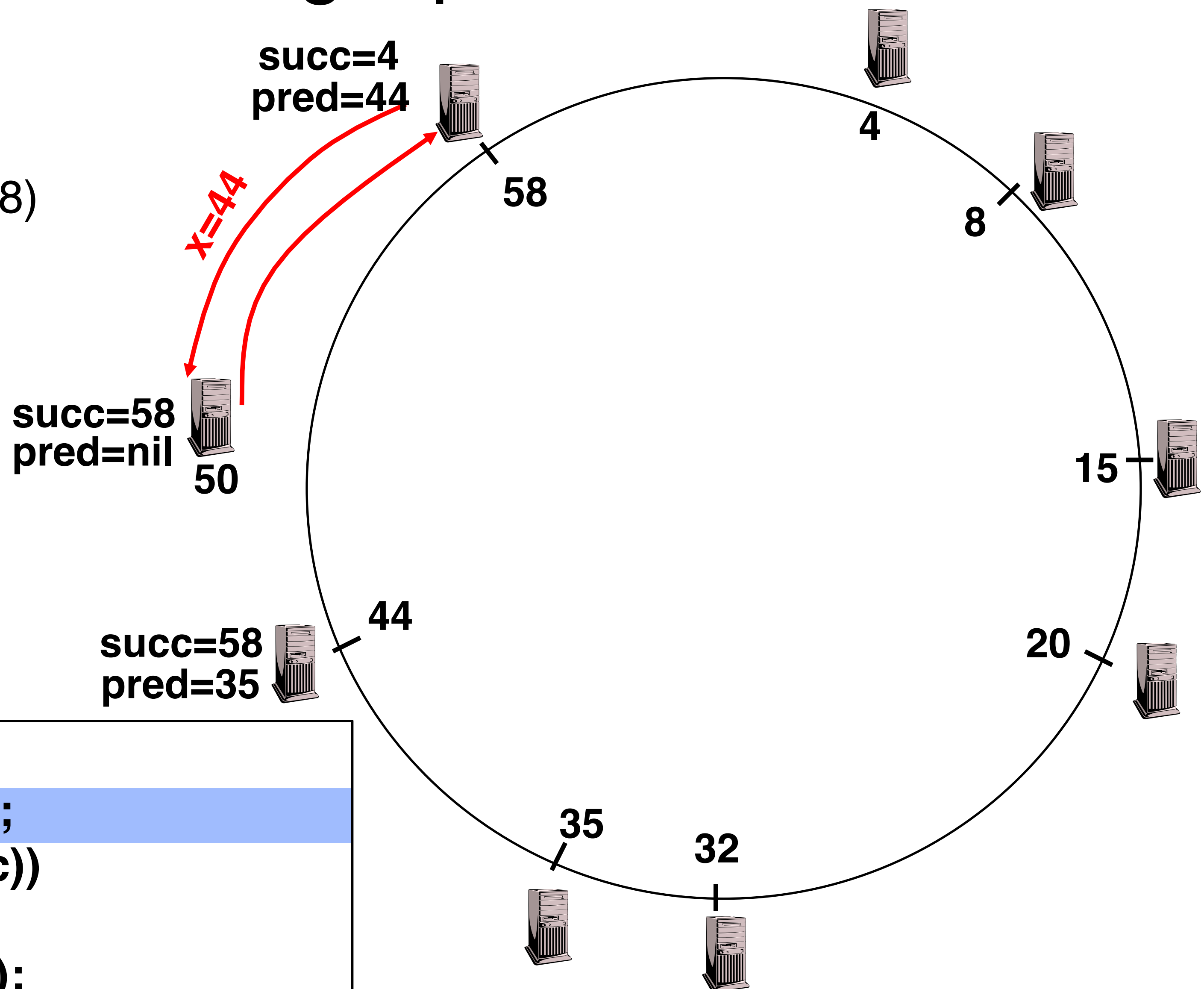
- n=50 sends join(50) to node 15
- n=44 returns node 58
- n=50 updates its successor to 58



Joining Operation

n=50 executes stabilize()

n's successor (58) returns x = 44

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    succ = x;
  succ.notify(n);
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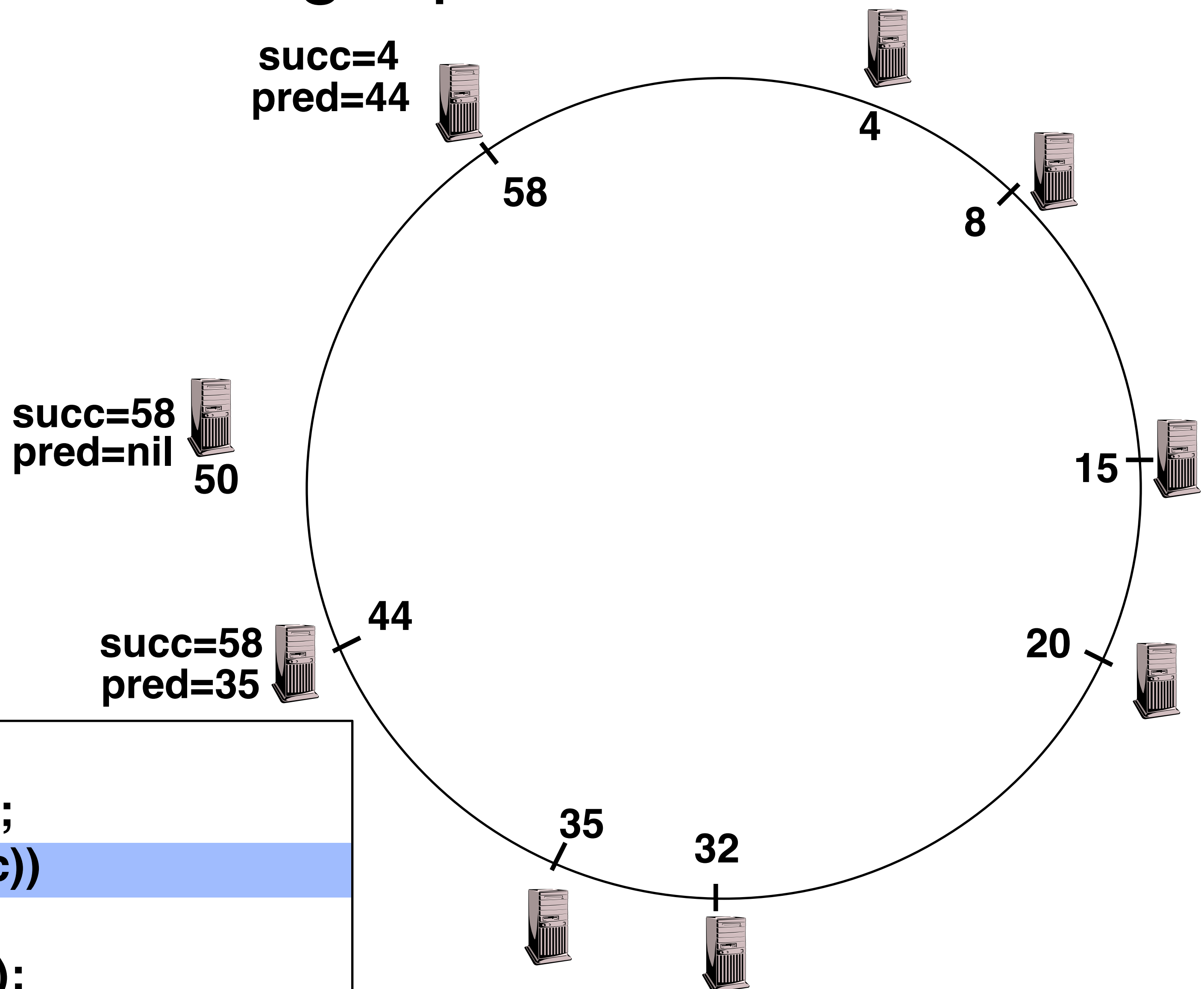
Joining Operation

n=50 executes stabilize()

x = 44

succ = 58

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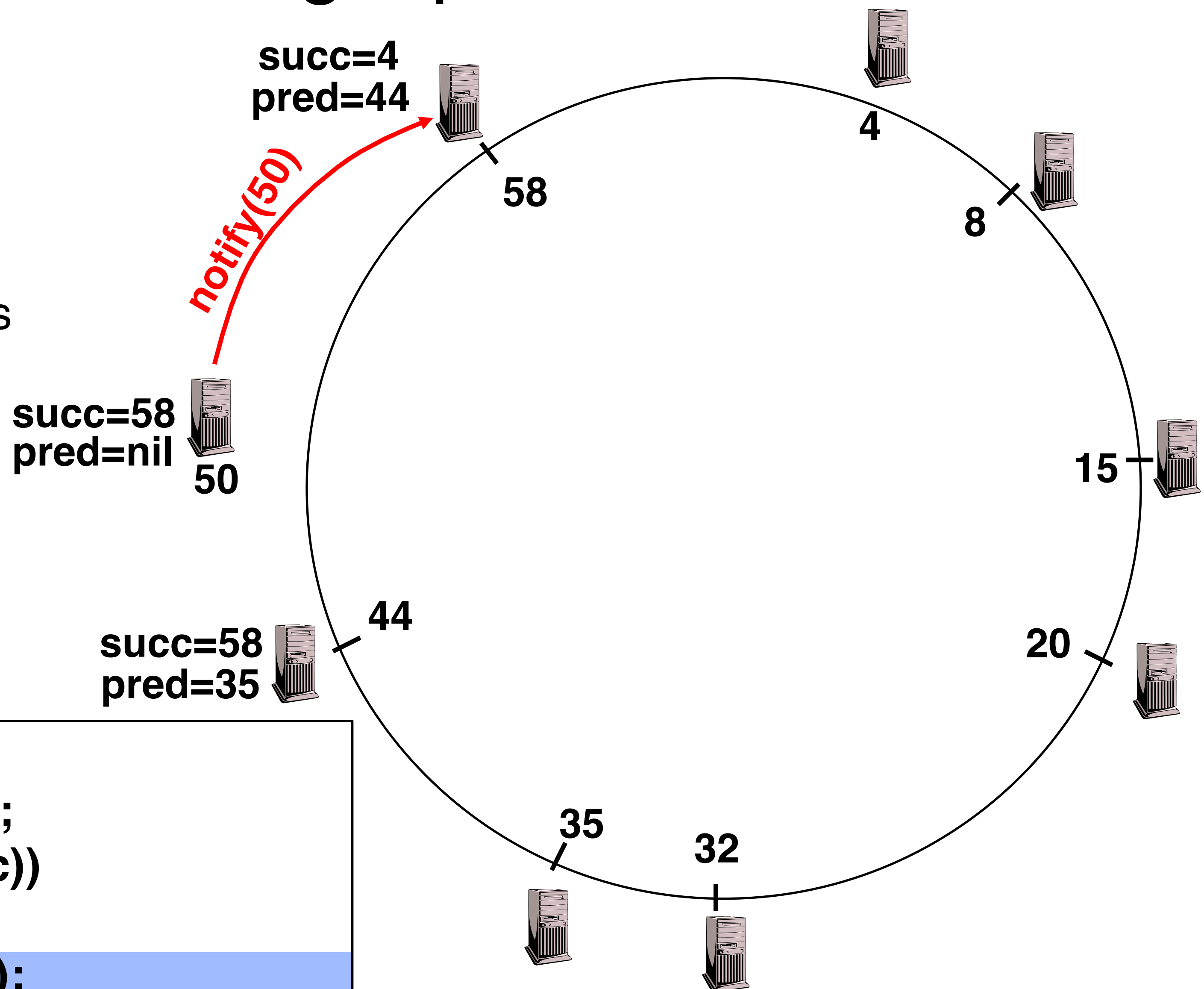
x = 44

succ = 58

n=50 sends to it's successor (58) notify(50)

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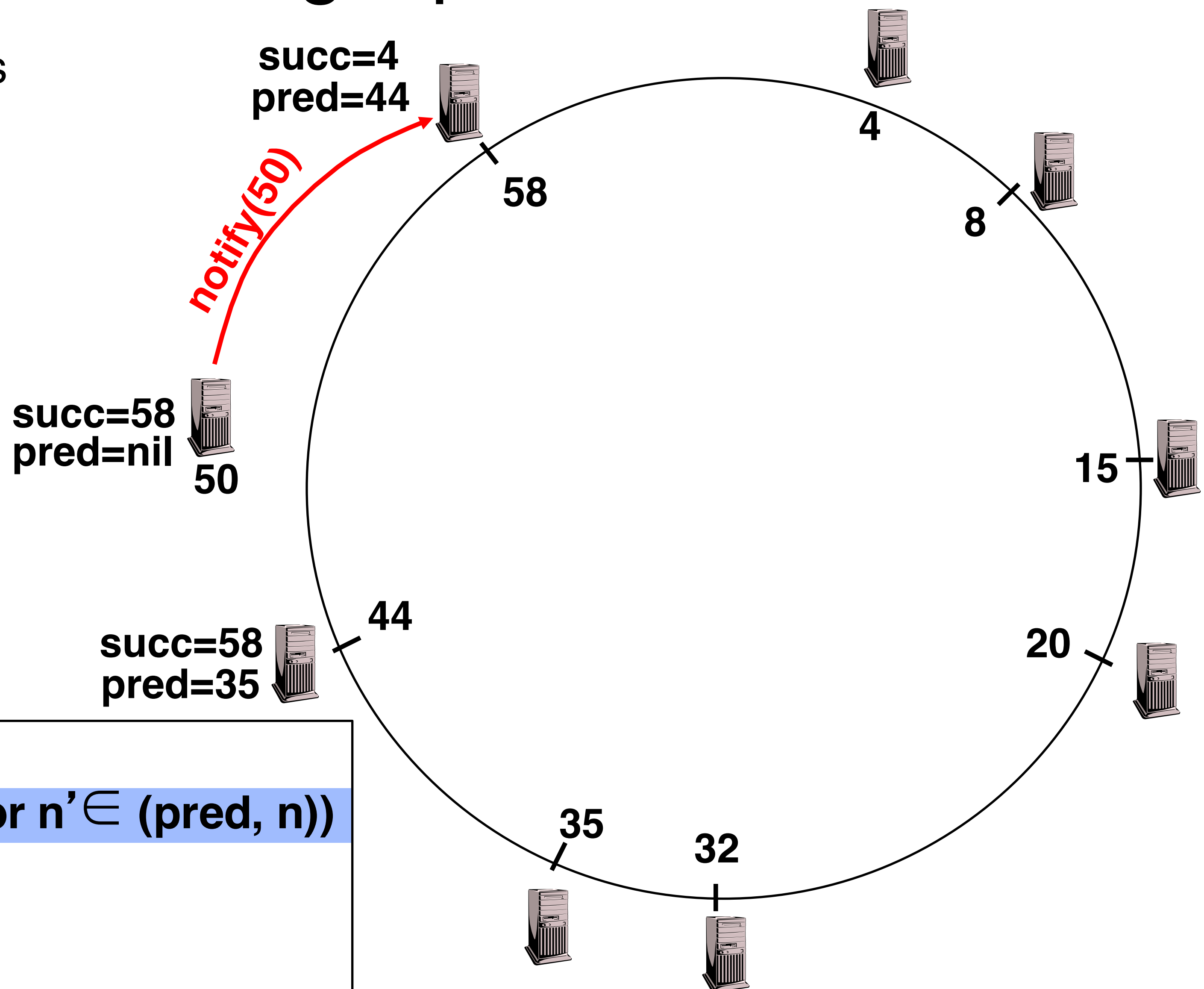
```

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

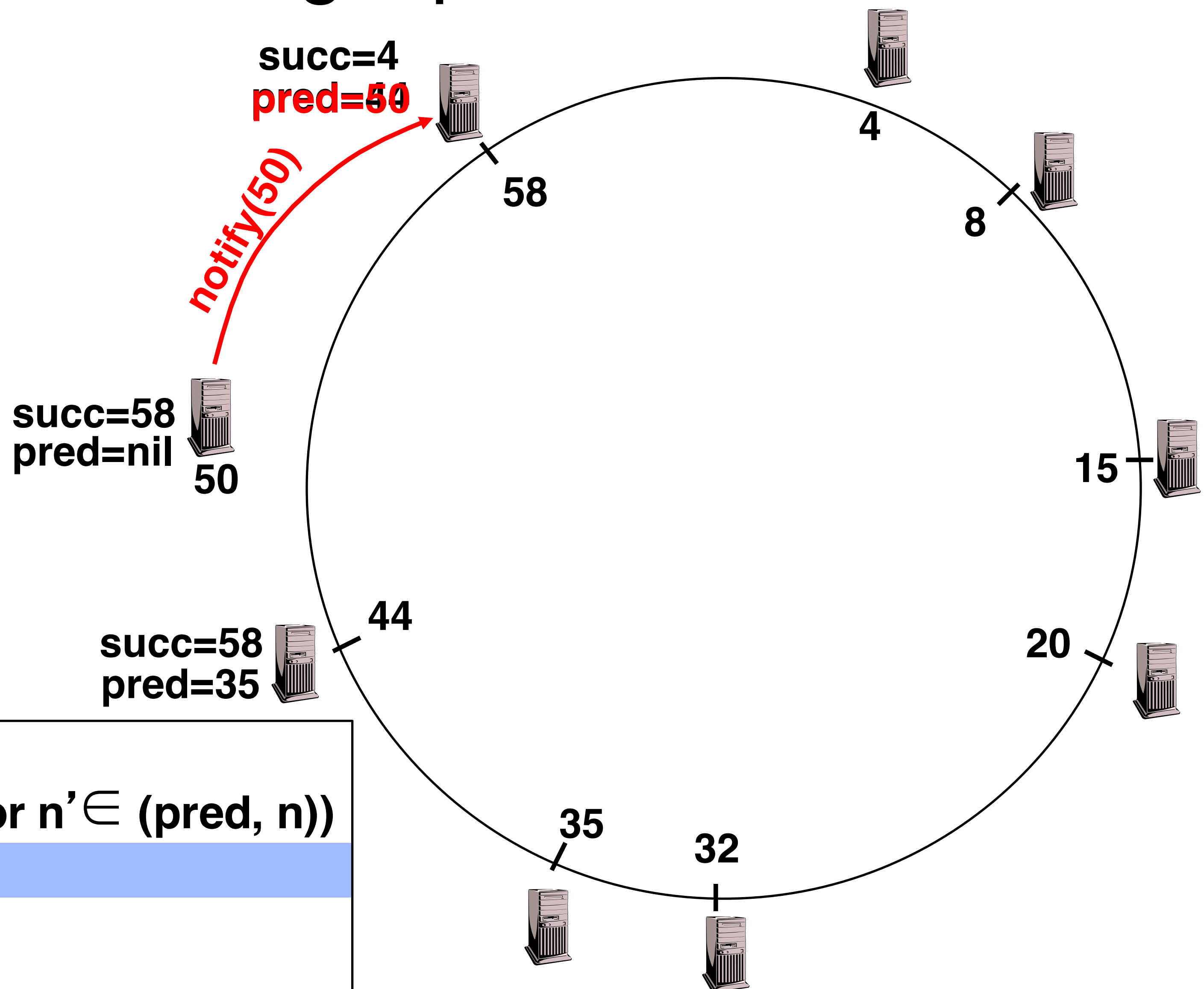
n=58 processes

notify(50)

pred = 44

n' = 50

set pred = 50

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n.notify(n')
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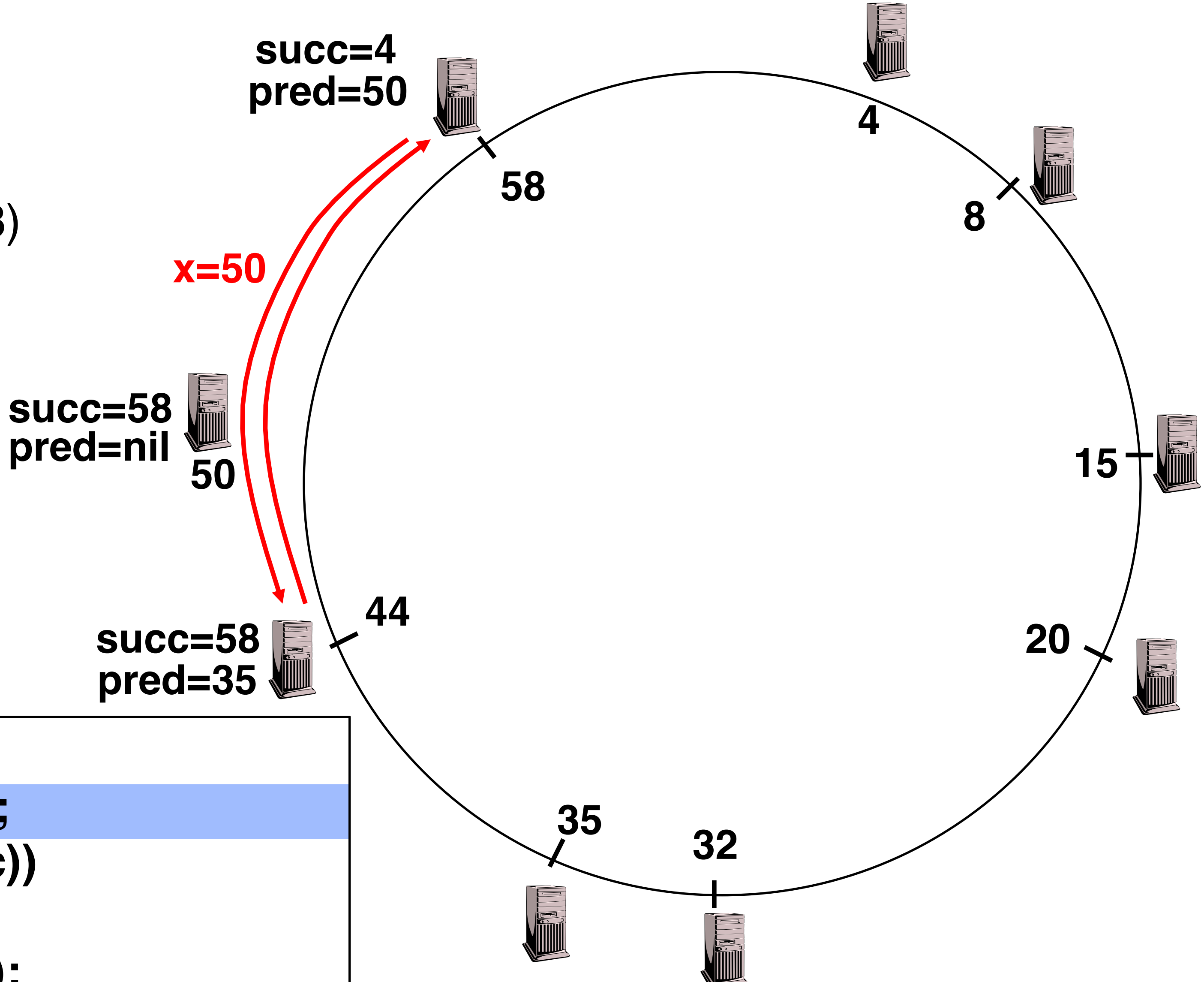
Joining Operation

n=44 runs stabilize()

n's successor (58) returns x = 50

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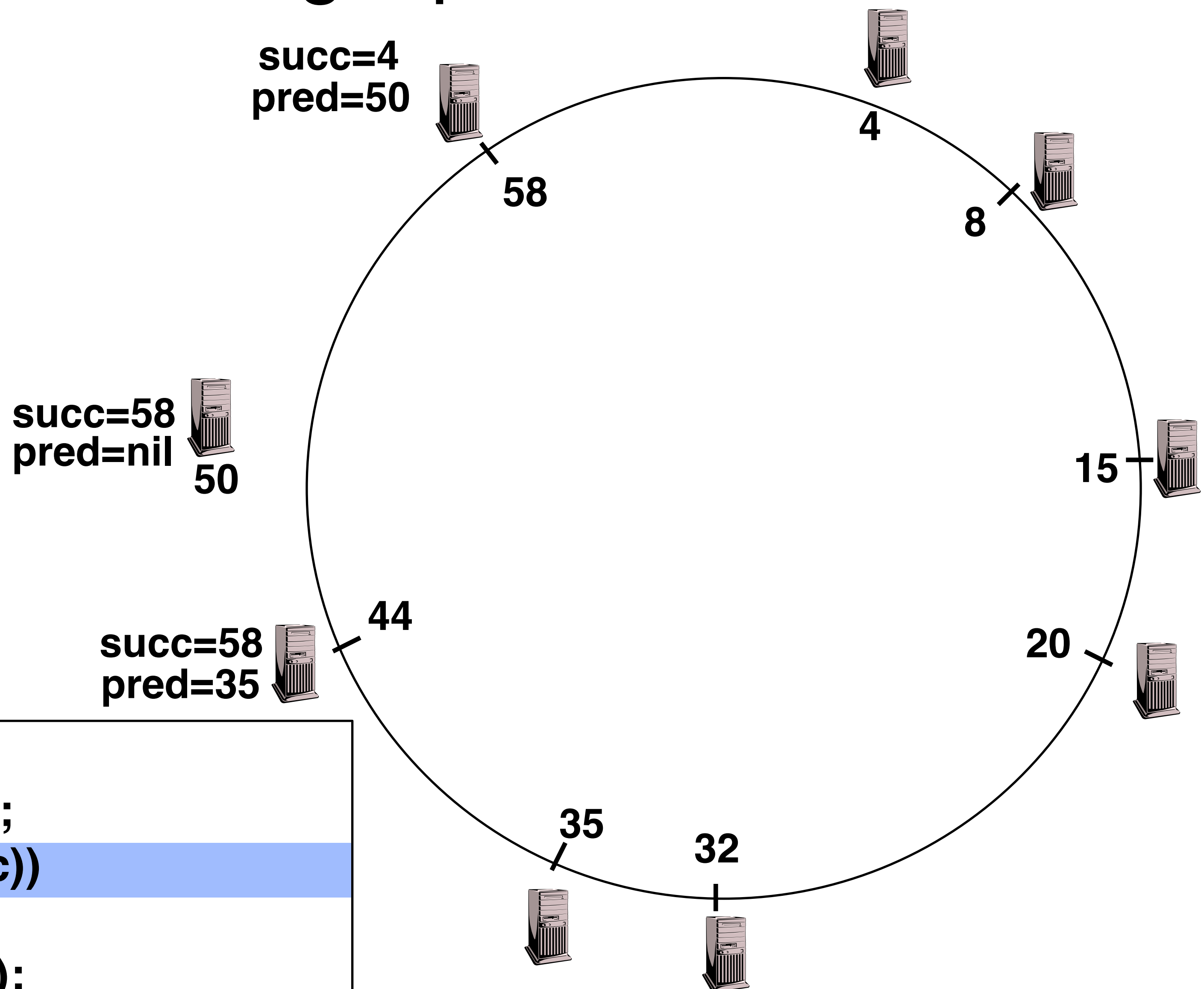


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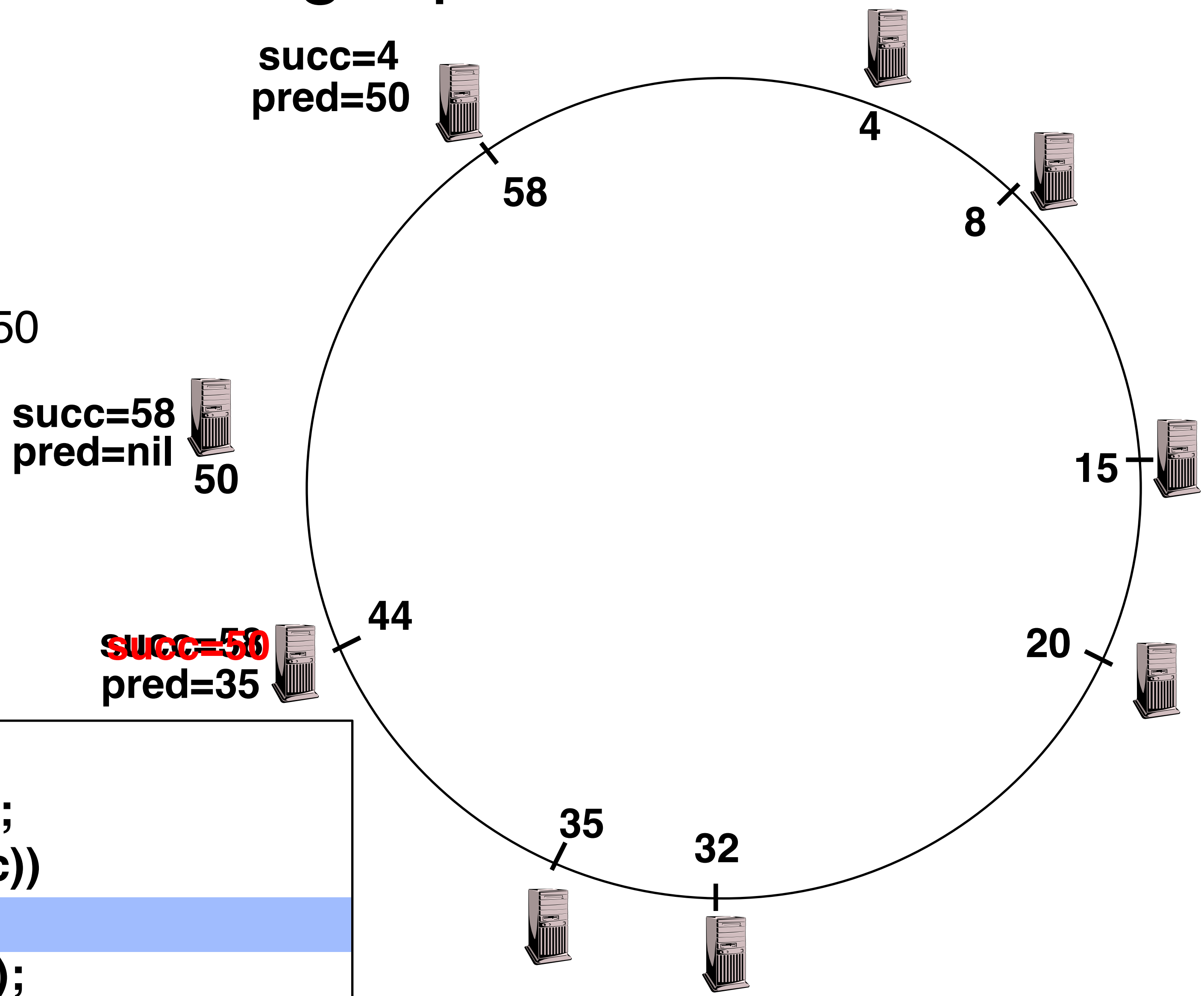


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    succ = x;
  succ.notify(n);
```
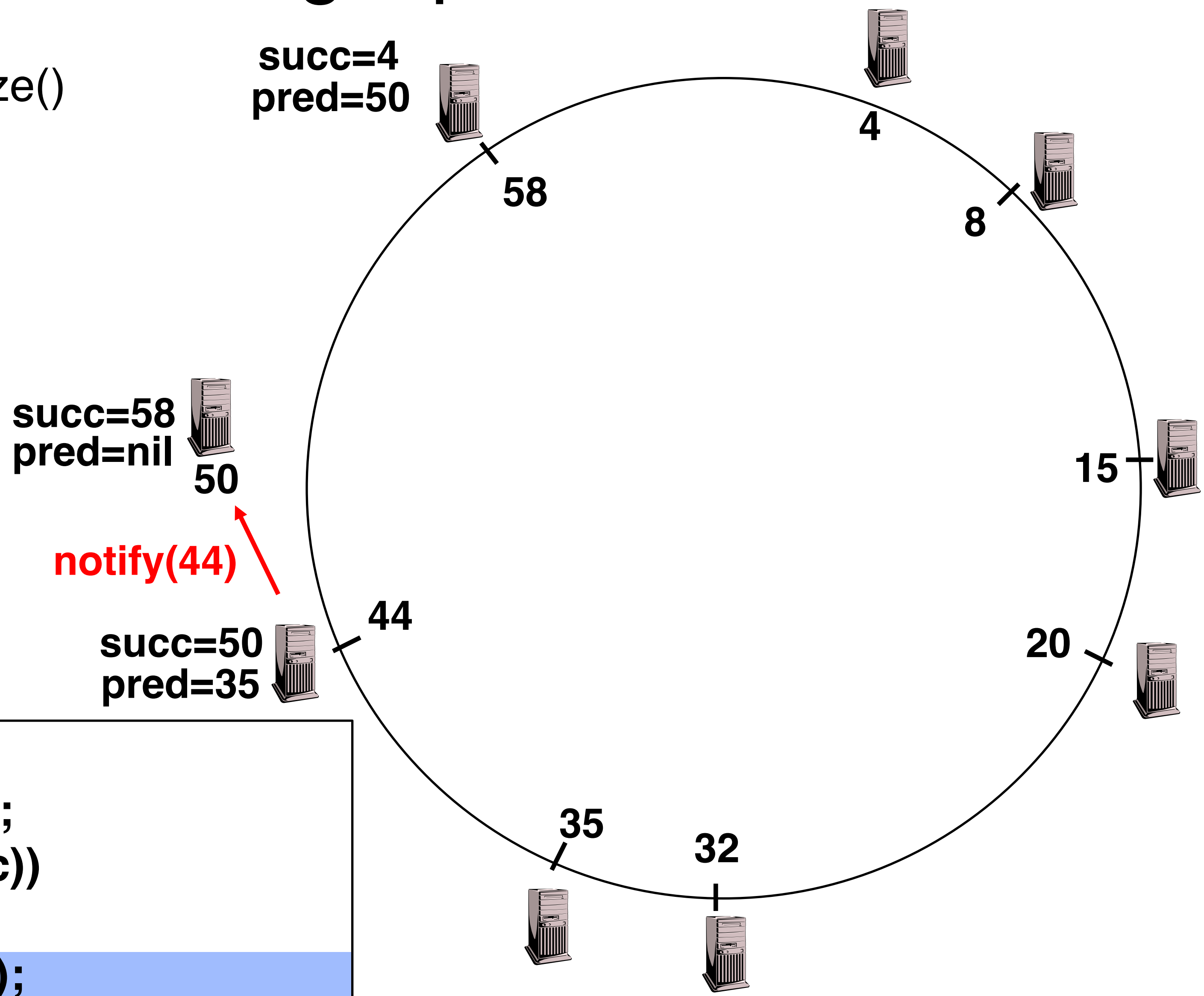

Joining Operation

n=44 runs stabilize()

n=44 sends notify(44) to its successor

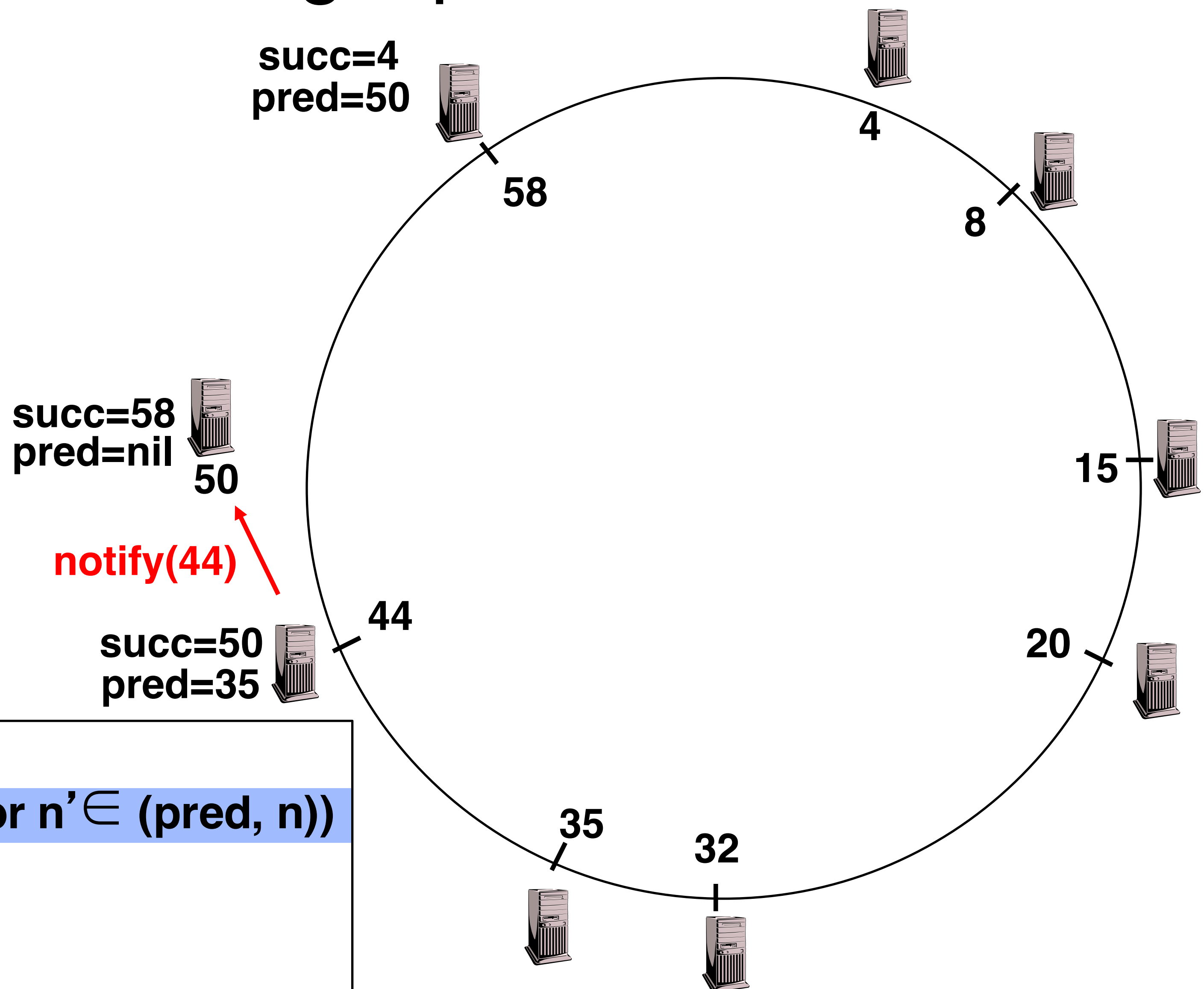



```
n.stabilize()
  x = succ.pred;
  if (x ∈ (n, succ))
    succ = x;
  succ.notify(n);
```

Joining Operation

n=50 processes
notify(44)

pred = nil



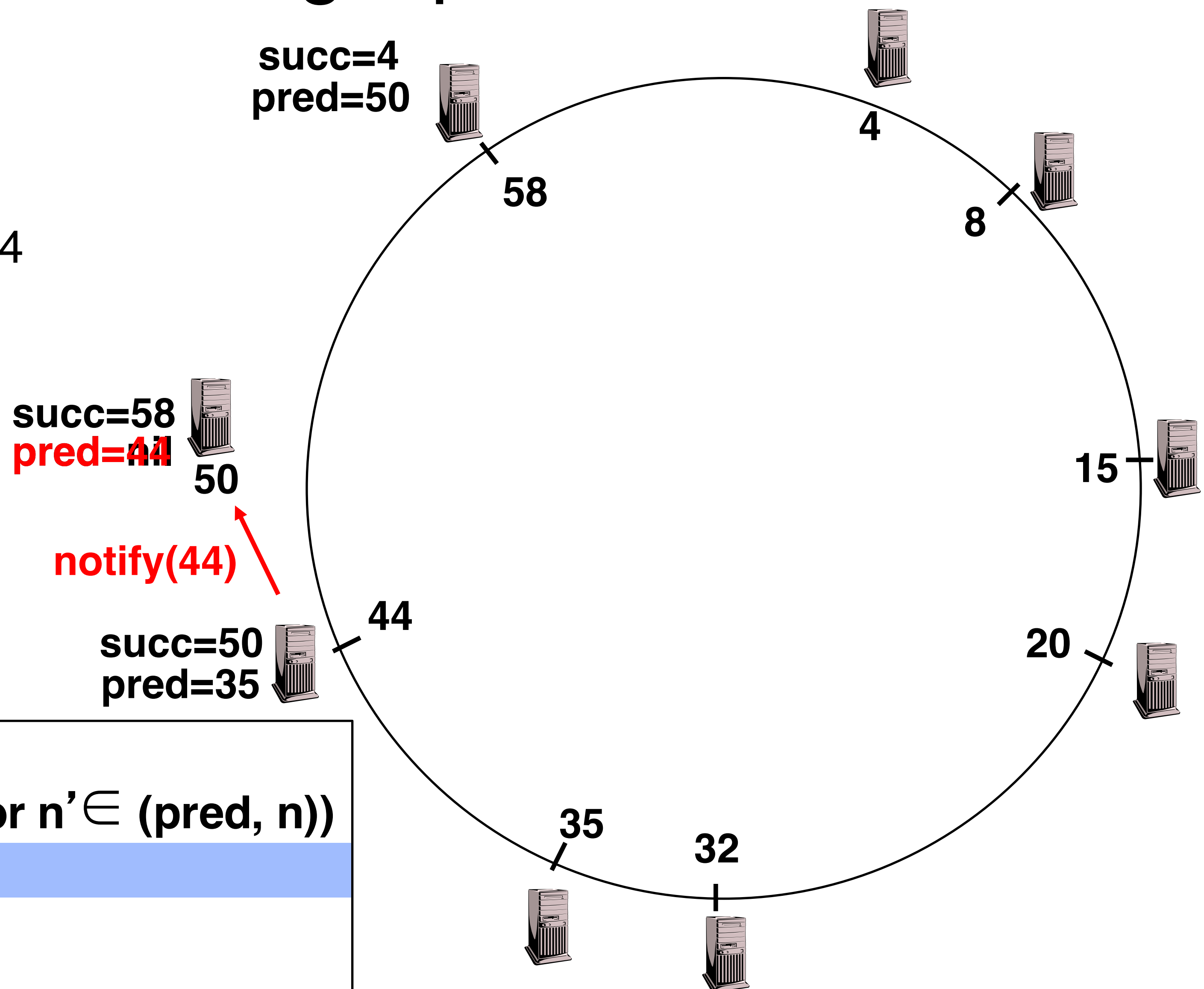

```
n.notify(n')
    if (pred = nil or n' ∈ (pred, n))
        pred = n'
```

Joining Operation

n=50 processes notify(44)

pred = nil

n=50 sets pred=44




```
n.notify(n')
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```
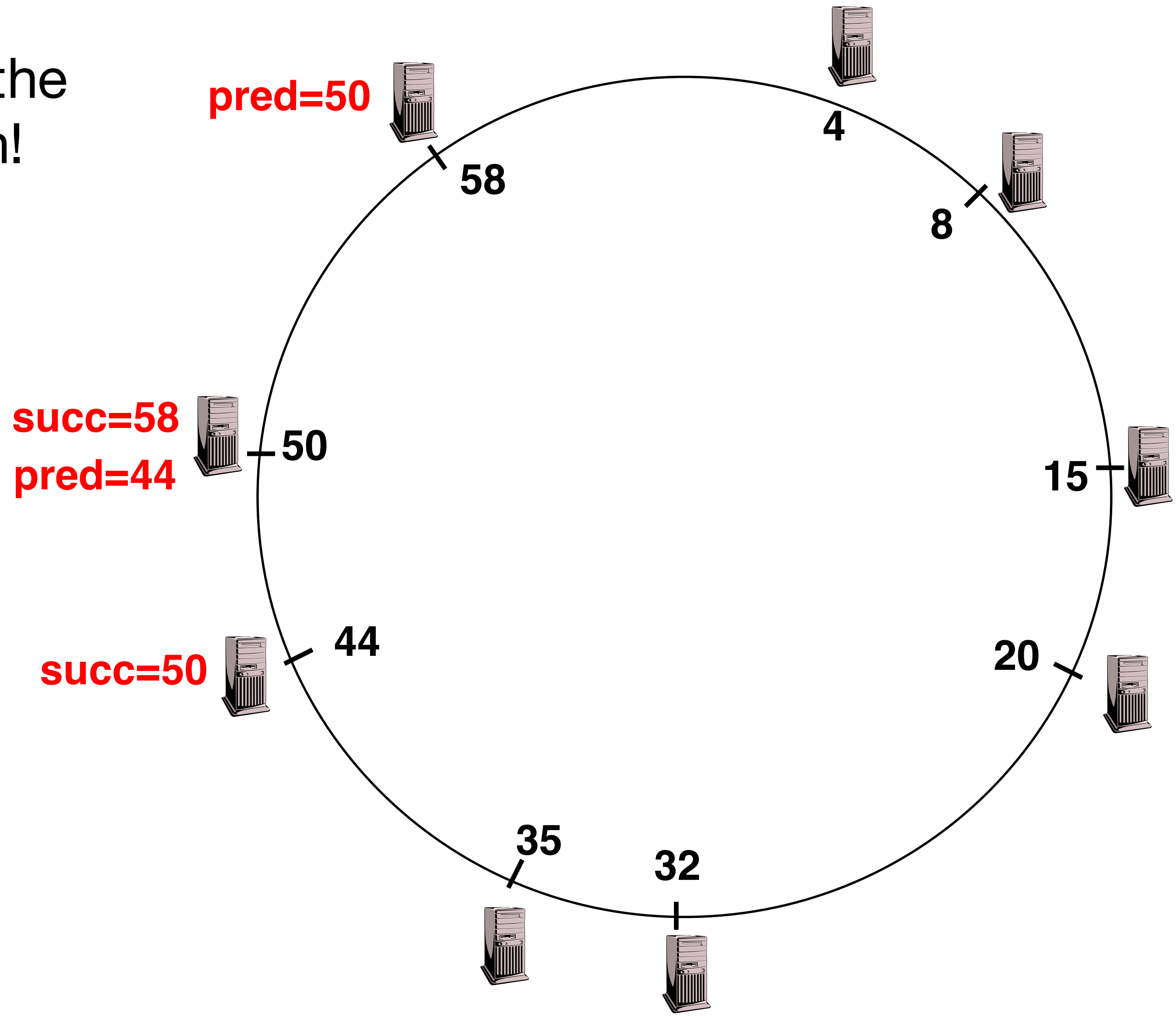

Joining Operation (cont’d)

This completes the joining operation!

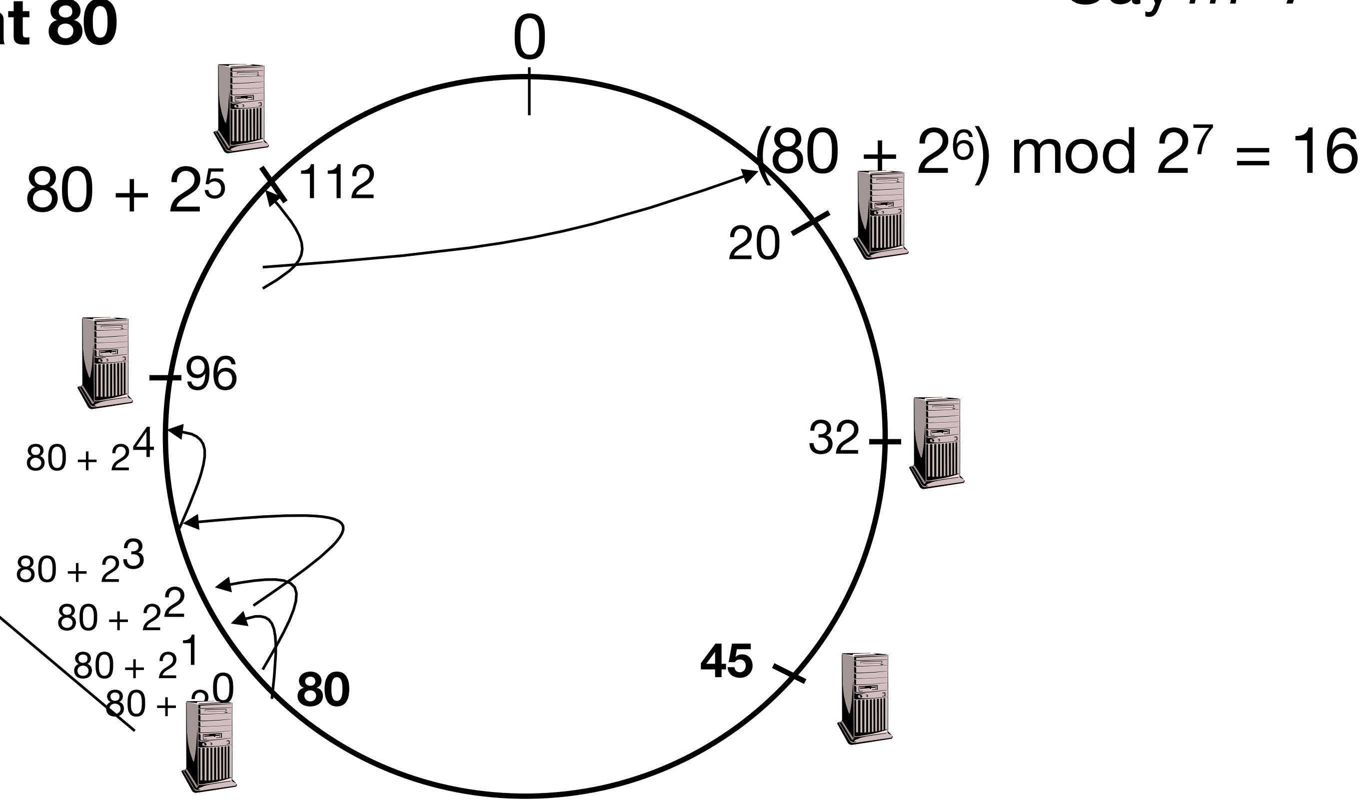


Achieving Efficiency: *finger tables*

Say *m*=7

Finger Table at 80

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



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

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

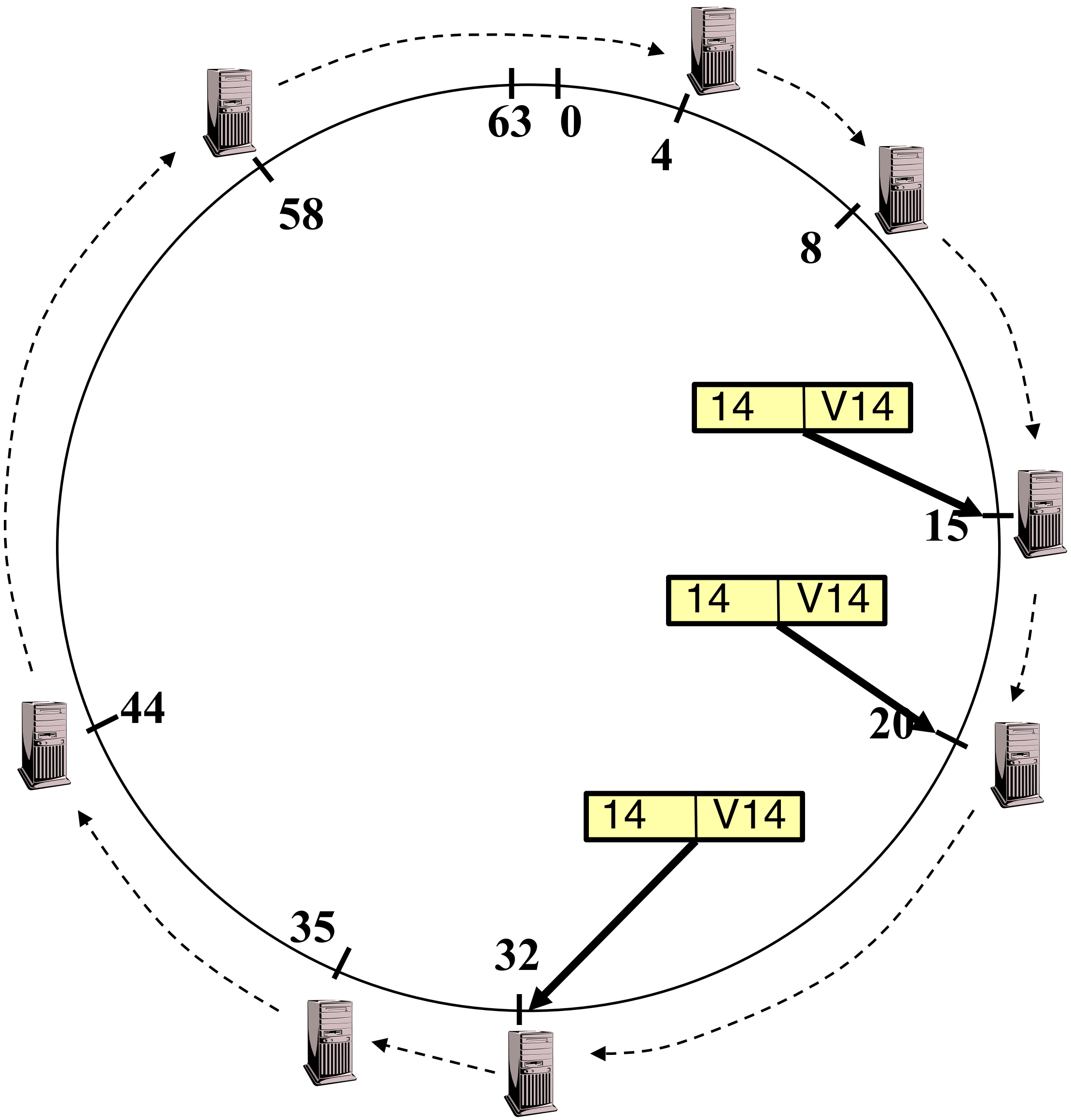
Upon receiving pred() message, B can update its successor list by concatenating the successor list received from A with its own list

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

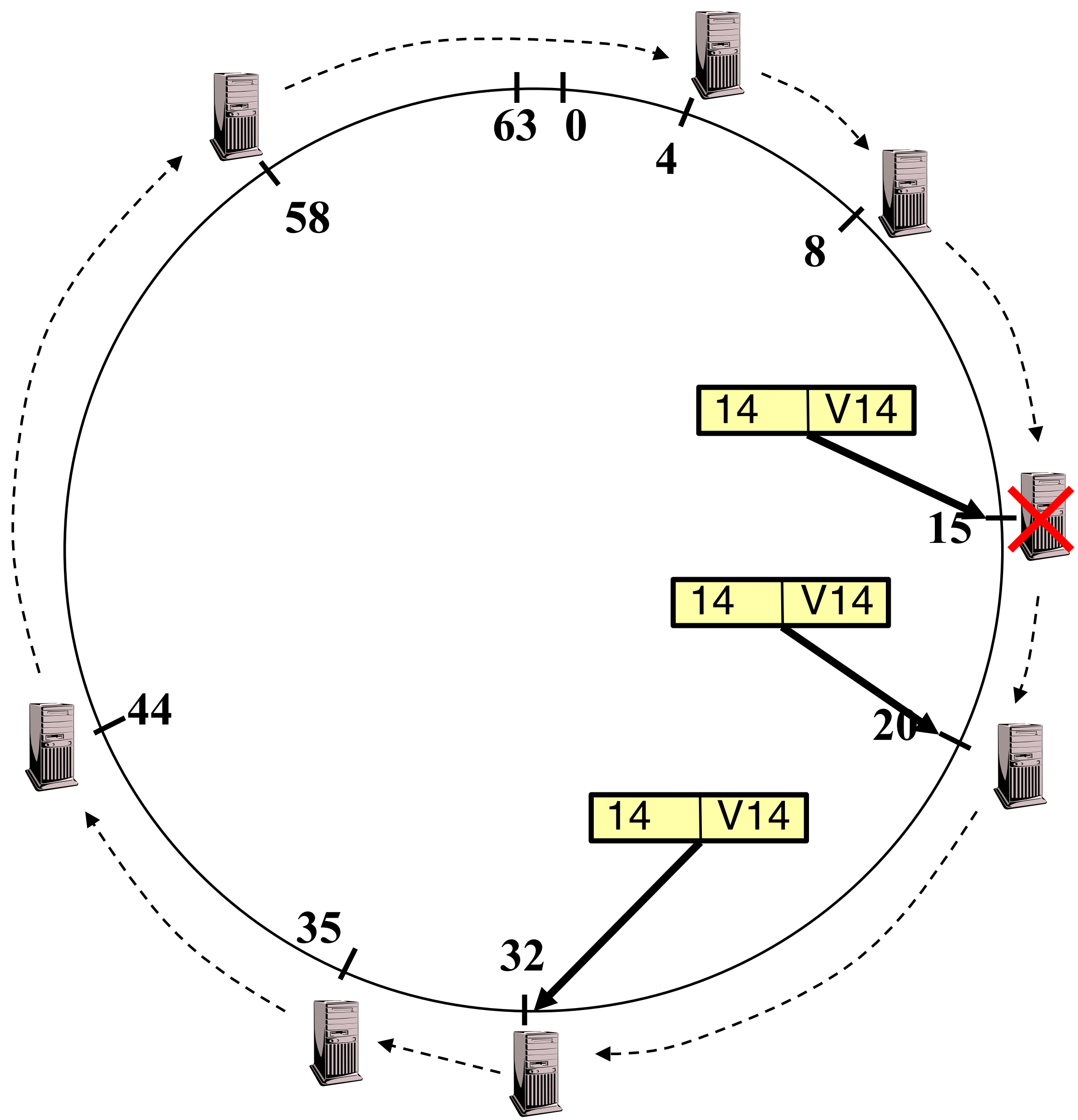


Storage Fault Tolerance

If node 15 fails, no reconfiguration needed

- Still have two replicas
- All lookups will be correctly routed

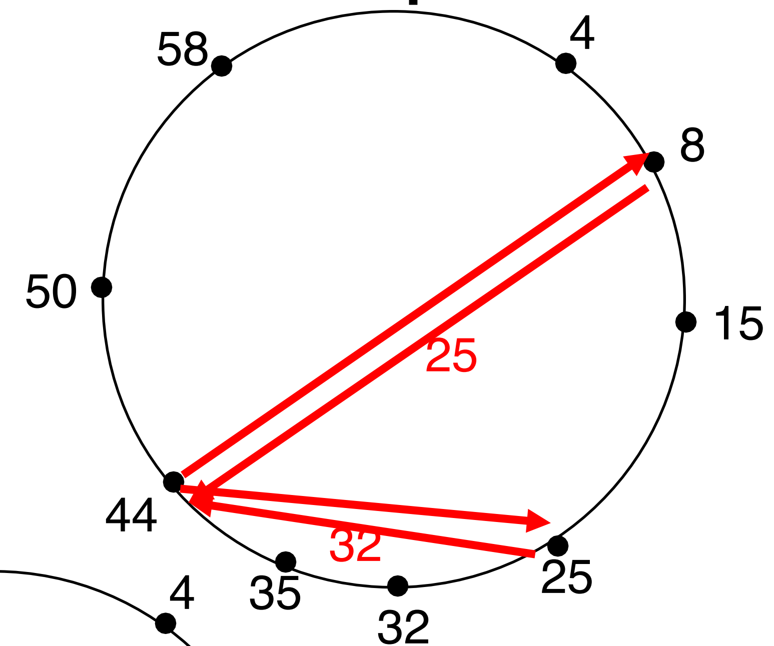
Will need to add a new replica on node 35



Iterative vs. Recursive Lookup

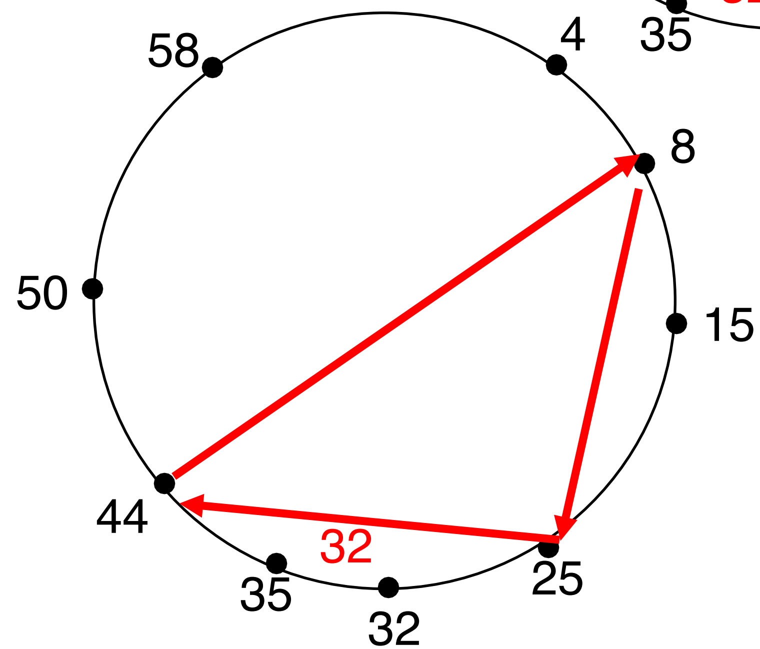
Iteratively:

- Example: node 44 issue query(31)



Recursively

- Example: node 44 issue query(31)



Dynamo

Motivation

Build a distributed storage system:

- Scale
- Symmetry: every node should have same functionality
- Simple: key-value
- **Highly available**
- **Heterogeneity: allow adding nodes with different capacities**
- **Guarantee Service Level Agreements (SLA)**

System Assumptions and Requirements

ACID Properties: Atomicity, Consistency, Isolation, Durability

- Weaker Consistency, i.e., eventual consistency
- High Availability
- No Isolation guarantees
- Only single key updates.

SLA (Service Level Agreement)*:* 99.9% performance guarantees

- E.g., 500ms latency for 99.9% of its requests for a peak client load of 500 requests per second
- average, median, variance not representative for user's experience

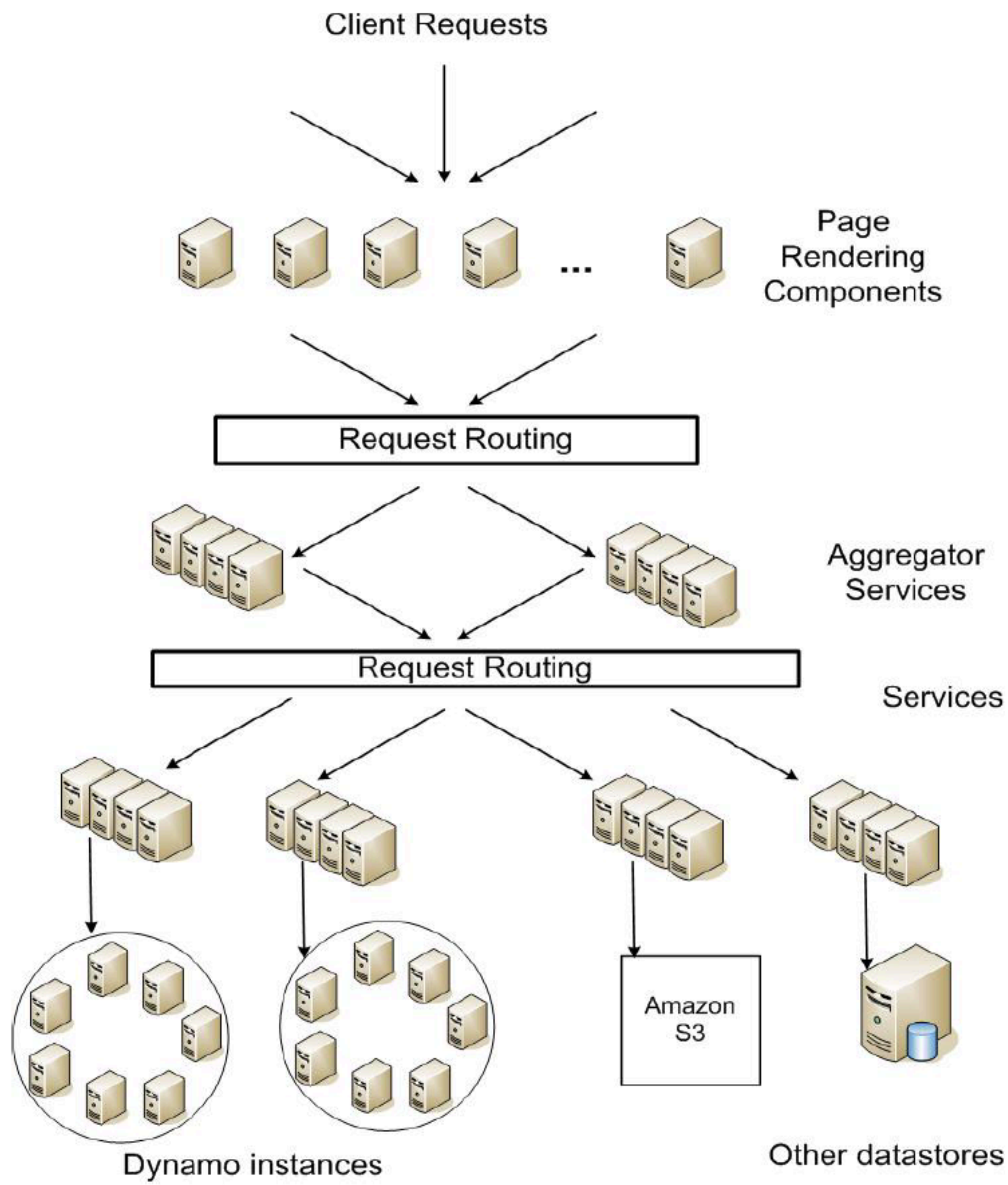
Other Assumptions: internal service, no security related requirements

Architecture

Service oriented architecture: modular, composable

Challenge: end-to-end SLAs

– Each service should provide even tighter latency bounds



Design Consideration

Sacrifice strong consistency for availability

Conflict resolution is executed during ***read*** instead of ***write***, i.e. "always writeable".

Other principles:

- Incremental scalability
- Symmetry
- Decentralization
- Heterogeneity

Summary of techniques used in *Dynamo* and their advantages

Problem	Technique	Advantage
Partitioning	Consistent Hashing	Incremental Scalability
High Availability for writes	Vector clocks with reconciliation during reads	Version size is decoupled from update rates.
Handling temporary failures	Sloppy Quorum and hinted handoff	Provides high availability and durability guarantee when some of the replicas are not available.
Recovering from permanent failures	Anti-entropy using Merkle trees	Synchronizes divergent replicas in the background.
Membership and failure detection	Gossip-based membership protocol and failure detection.	Preserves symmetry and avoids having a centralized registry for storing membership and node liveness information.

Data Versioning

A put() call may return to its caller before the update has been applied at all the replicas

A get() call may return many versions of the same object.

Challenge: an object having distinct version sub-histories, which the system will need to reconcile in the future.

Solution: uses vector clocks in order to capture causality between different versions of the same object.

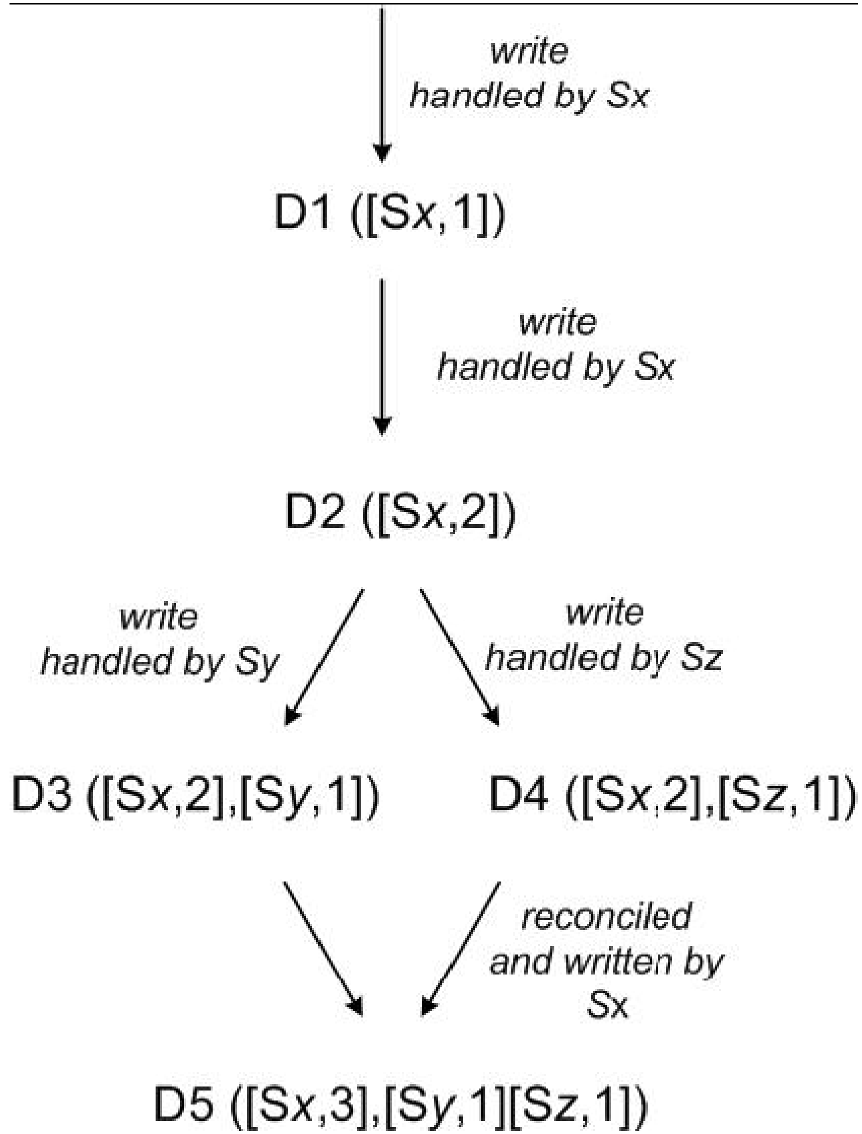
Vector clock

Vector clock: a list of (node, counter) pairs

Every object version is associated with one vector clock

v2 > v1, if the counter of every node in v2 is greater or equal to the counter of every node in v1

Vector clock example



Sloppy Quorum

Read and write operations are performed on the first N healthy nodes from the preference list

- May not always be the first N nodes encountered while walking the consistent hashing ring.

Recall: latency of a get (or put) operation is dictated by the slowest of the R (or W) replicas

Other techniques

Replica synchronization:

- **Merkle hash tree**
  - Hash tree where leaves are hashes of individual key values
  - Parent nodes hashes of their respective children
  - Each branch of the tree can be checked independently without requiring nodes to download the entire data set

Membership and Failure Detection:

- **Gossip**

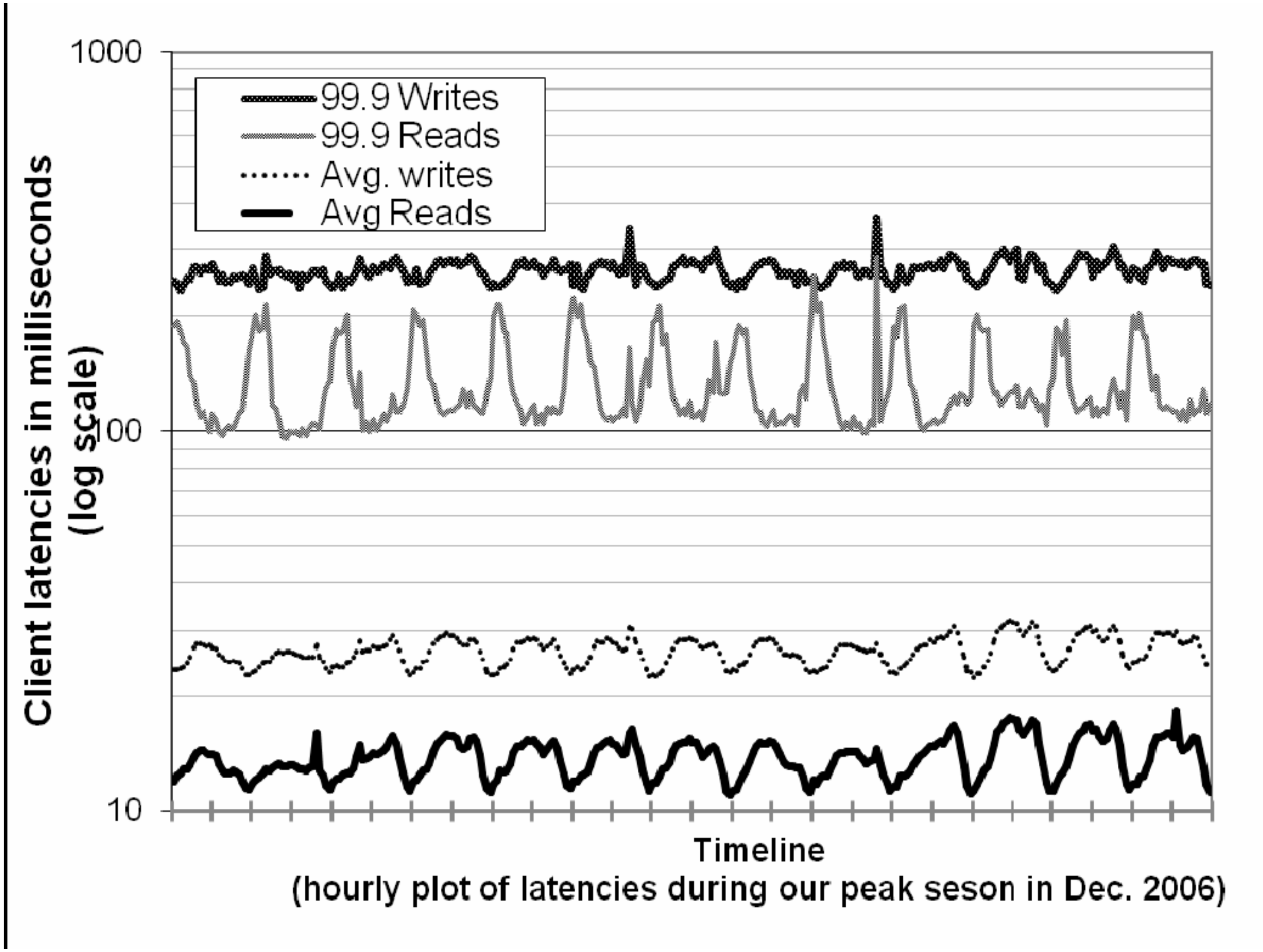
Implementation

Java

Local persistence:

- BerkeleyDB
- MySQL
- BDB Java Edition, etc.

Evaluation


1000
100
10
99.9 Writes
99.9 Reads
Avg. writes
Avg Reads
Client latencies in milliseconds
(log scale)
Timeline
(hourly plot of latencies during our peak seson in Dec. 2006)

Conclusions: Key Value Stores

- 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