CS162
Operating Systems and Systems Programming
Lecture 24

Distributed Storage, Key Value Stores, Chord

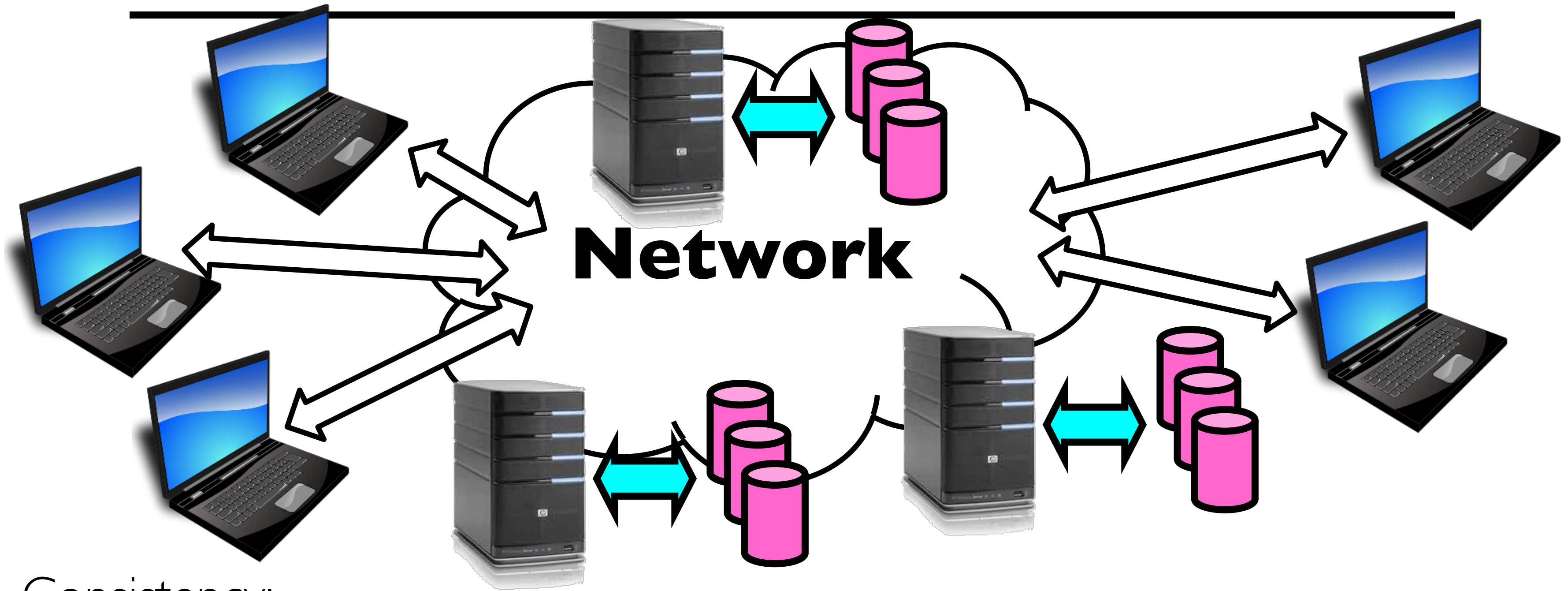
April 28th, 2020

Prof. John Kubiatowicz

http://cs162.eecs.Berkeley.edu

Acknowledgments: Lecture slides are from the Operating Systems course taught by John Kubiatowicz at Berkeley, with few minor updates/changes. *When slides are obtained from other sources, a a reference will be noted on the bottom of that slide, in which case a full list of references is provided on the last slide.*

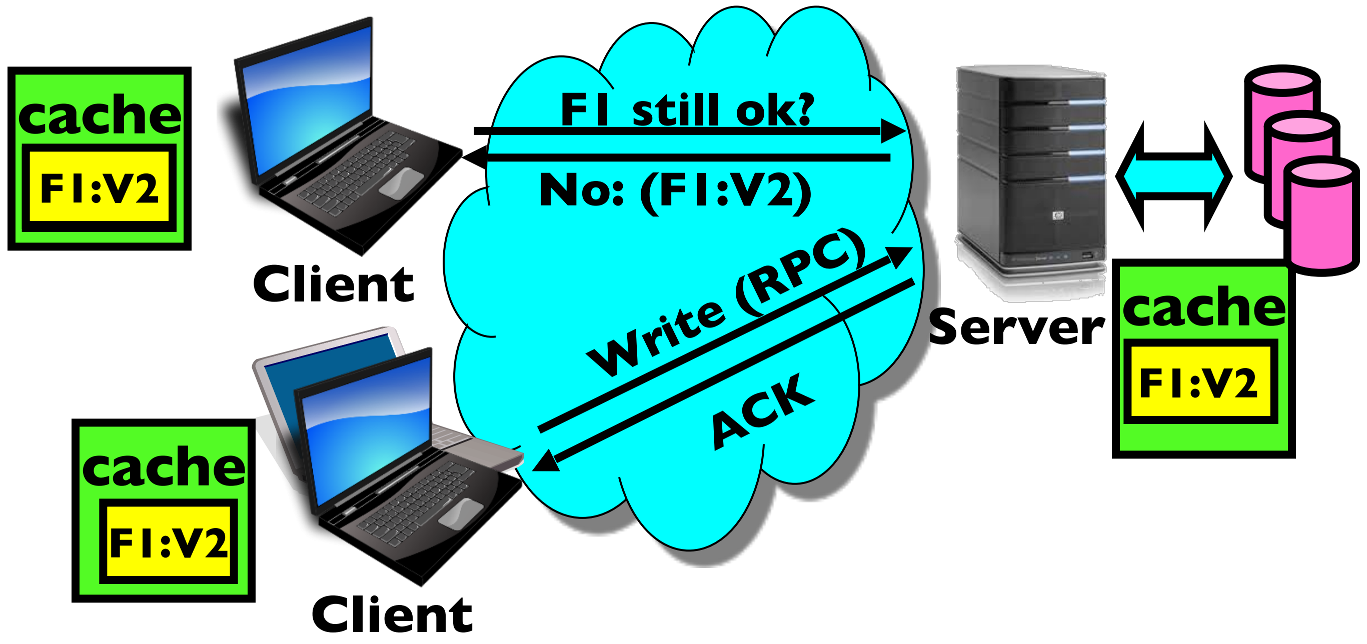
Recall: The CAP Theorem



- Consistency:
  - Changes appear to everyone in the same serial order
- Availability:
  - Can get a result at any time
- Partition-Tolerance
  - System continues to work even when network becomes partitioned
- Consistency, Availability, Partition-Tolerance (CAP) Theorem: Cannot have all three at same time
  - Otherwise known as "Brewer's Theorem"

Recall: NFS Cache consistency

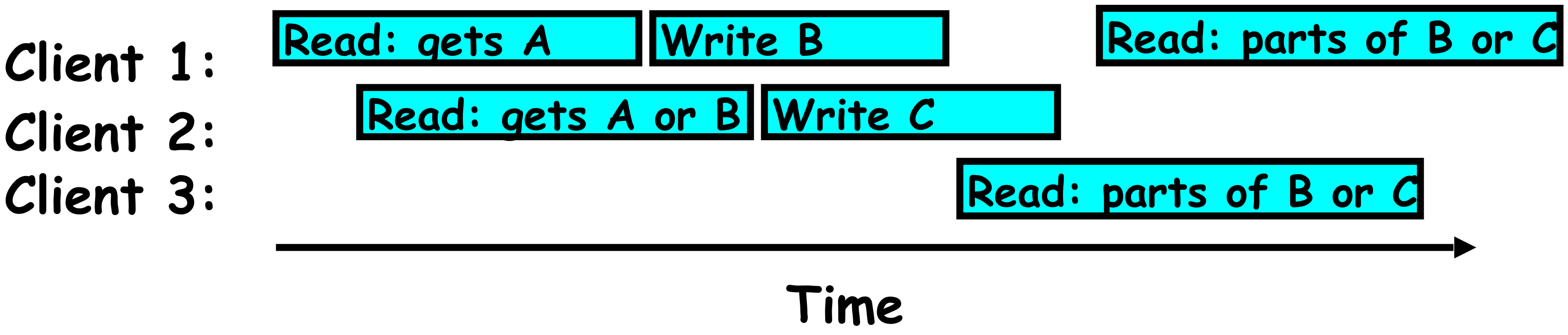
- NFS protocol: weak consistency
  - Client polls server periodically to check for changes
    - » Polls server if data hasn't been checked in last 3-30 seconds (exact timeout it tunable parameter).
    - » Thus, when file is changed on one client, server is notified, but other clients use old version of file until timeout.



  - What if multiple clients write to same file?
    - » In NFS, can get either version (or parts of both)
    - » Completely arbitrary!

NFS: Sequential Ordering Constraints

- What sort of cache coherence might we expect?
  - i.e. what if one CPU changes file, and before it's done, another CPU reads file?
- Example: Start with file contents = "A"



- What would we actually want?
  - Assume we want distributed system to behave exactly the same as if all processes are running on single system
    - » If read finishes before write starts, get old copy
    - » If read starts after write finishes, get new copy
    - » Otherwise, get either new or old copy
- For NFS:
    - » If read starts more than 30 seconds after write, get new copy; otherwise, could get partial update

Andrew File System

- Andrew File System (AFS, late 80's) → DCE DFS (commercial product)
- Callbacks: Server records who has copy of file
  - On changes, server immediately tells all with old copy
  - No polling bandwidth (continuous checking) needed
- Write through on close
  - Changes not propagated to server until close()
  - Session semantics: updates visible to other clients only after the file is closed
    - » As a result, do not get partial writes: all or nothing!
    - » Although, for processes on local machine, updates visible immediately to other programs who have file open
- In AFS, everyone who has file open sees old version
  - Don't get newer versions until reopen file

Andrew File System (con't)

- Data cached on local disk of client as well as memory
  - On open with a cache miss (file not on local disk):
    - » Get file from server, set up callback with server
  - On write followed by close:
    - » Send copy to server; tells all clients with copies to fetch new version from server on next open (using callbacks)
- What if server crashes? Lose all callback state!
  - Reconstruct callback information from client: go ask everyone "who has which files cached?"
- AFS Pro: Relative to NFS, less server load:
  - Disk as cache ⇒ more files can be cached locally
  - Callbacks ⇒ server not involved if file is read-only
- For both AFS and NFS: central server is bottleneck!
  - Performance: all writes→server, cache misses→server
  - Availability: Server is single point of failure
  - Cost: server machine's high cost relative to workstation

Sharing Data, rather than Files ?

- Key:Value stores are used everywhere
- Native in many programming languages
  - Associative Arrays in Perl
  - Dictionaries in Python
  - Maps in Go
  - …
- What about a collaborative key-value store rather than message passing or file sharing?
- Can we make it scalable and reliable?

Key Value Storage

Simple interface

- `put(key, value); // Insert/write "value" associated with key`

- `get(key); // Retrieve/read value associated with key`

Why Key Value Storage?

- Easy to Scale
  - Handle huge volumes of data (e.g., petabytes)
  - Uniform items: distribute easily and roughly equally across many machines
- Simple consistency properties
- Used as a simpler but more scalable "database"
  - Or as a building block for a more capable DB

Key Values: Examples

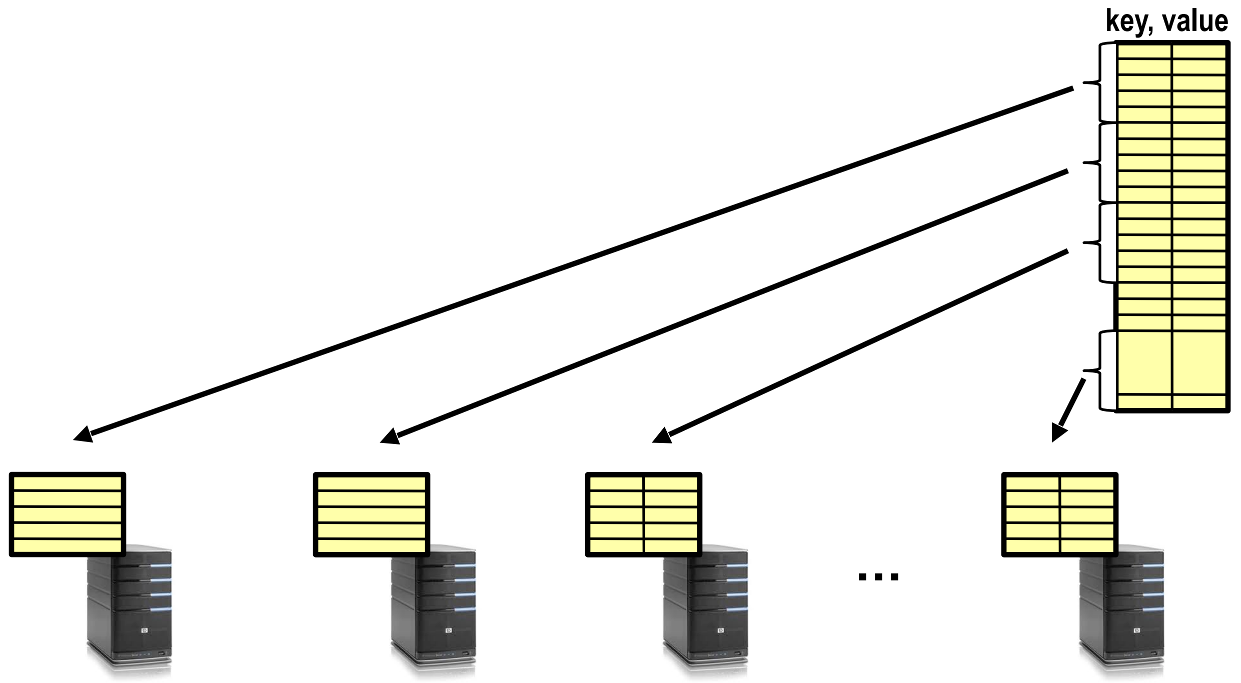
- Amazon:
  - Key: customerID
  - Value: customer profile (e.g., buying history, credit card, ..)
- Facebook, Twitter:
  - Key: UserID
  - Value: user profile (e.g., posting history, photos, friends, …)
- iCloud/iTunes:
  - Key: Movie/song name
  - Value: Movie, Song

Key-value storage systems in real life

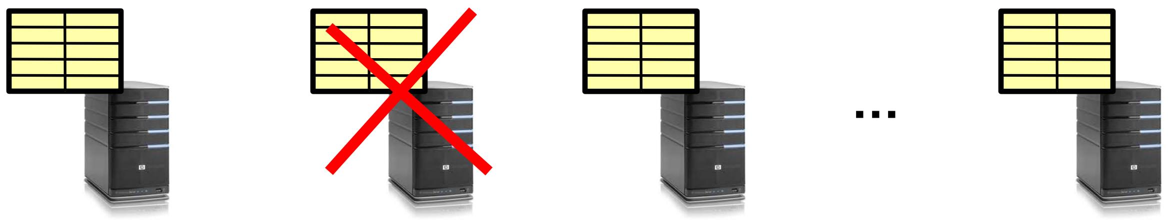
- Amazon
  - DynamoDB: internal key value store used to power Amazon.com (shopping cart)
  - Simple Storage System (S3)
- BigTable/HBase/Hypertable: distributed, scalable data storage
- Cassandra: "distributed data management system" (developed by Facebook)
- Memcached: in-memory key-value store for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

Key Value Store

- Also called Distributed Hash Tables (DHT)
- Main idea: simplify storage interface (i.e. put/get), then partition set of key-values across many machines



Challenges



- Scalability:
  - Need to scale to thousands of machines
  - Need to allow easy addition of new machines
- Fault Tolerance: handle machine failures without losing data and without degradation in performance
- 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

Important 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?

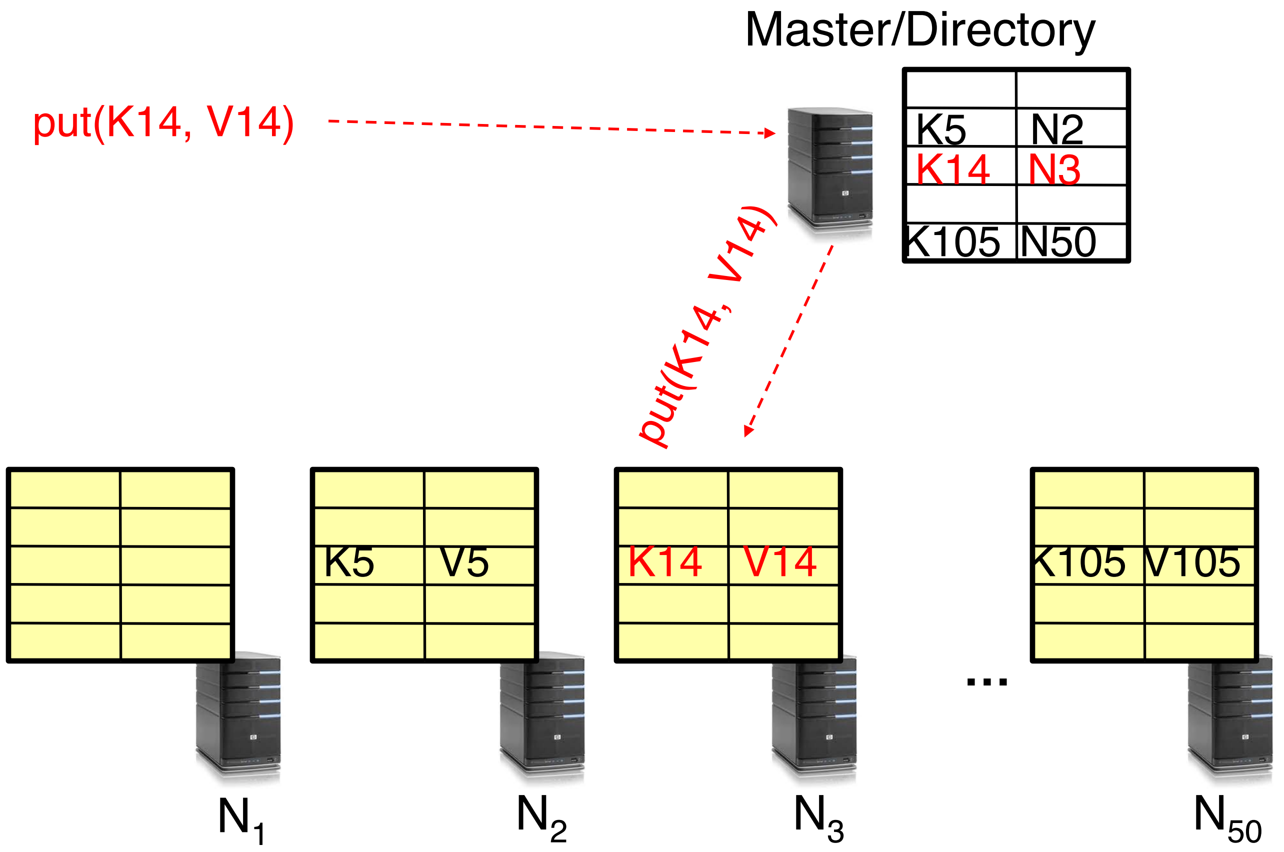
- And, do the above while providing
  – Scalability
  – Fault Tolerance
  – Consistency

How to solve the "where?"

- Hashing to map key space ⇒ location
  - But what if you don't know who are all the nodes that are participating?
  - Perhaps they come and go …
  - What if some keys are really popular?
- Lookup
  - Hmm, won't this be a bottleneck and single point of failure?

Recursive Directory Architecture (put)

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



Recursive Directory Architecture (get)

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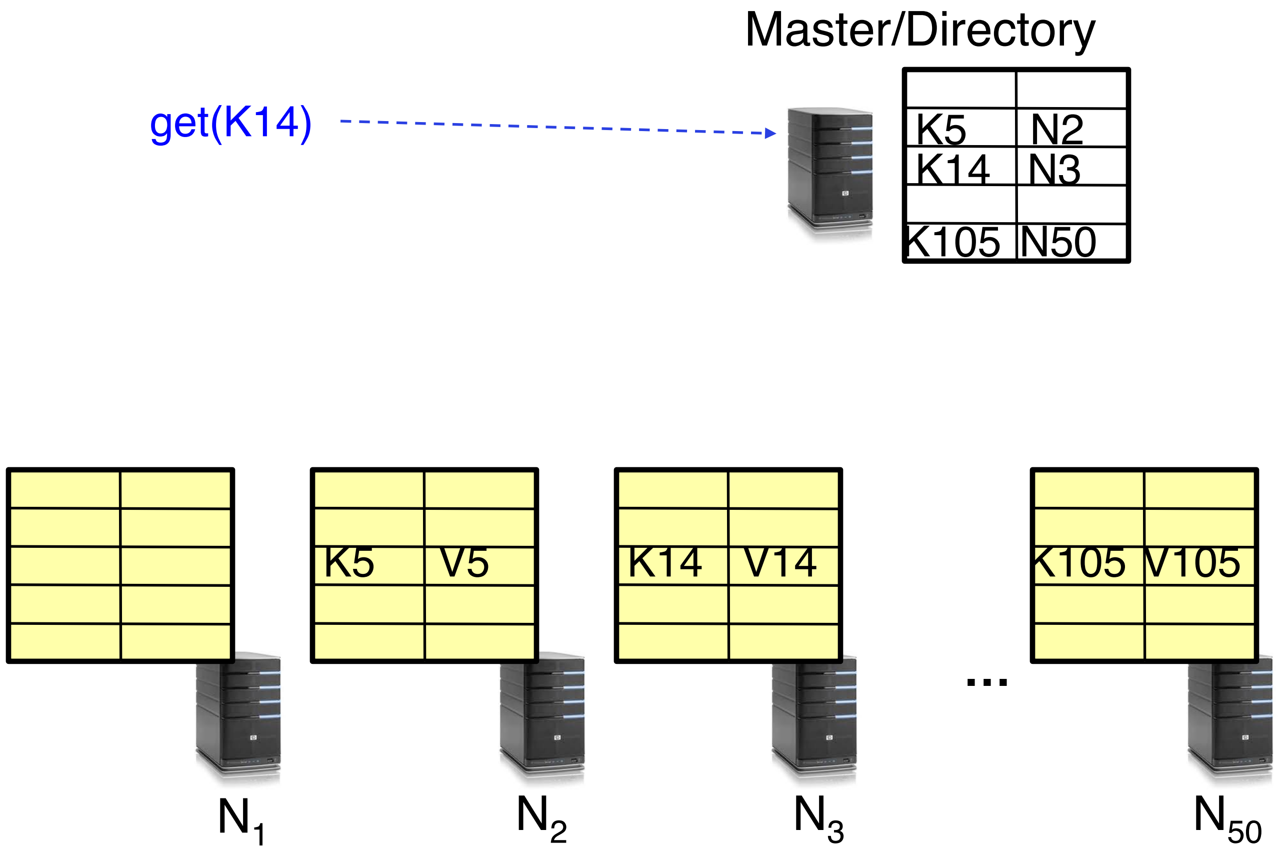

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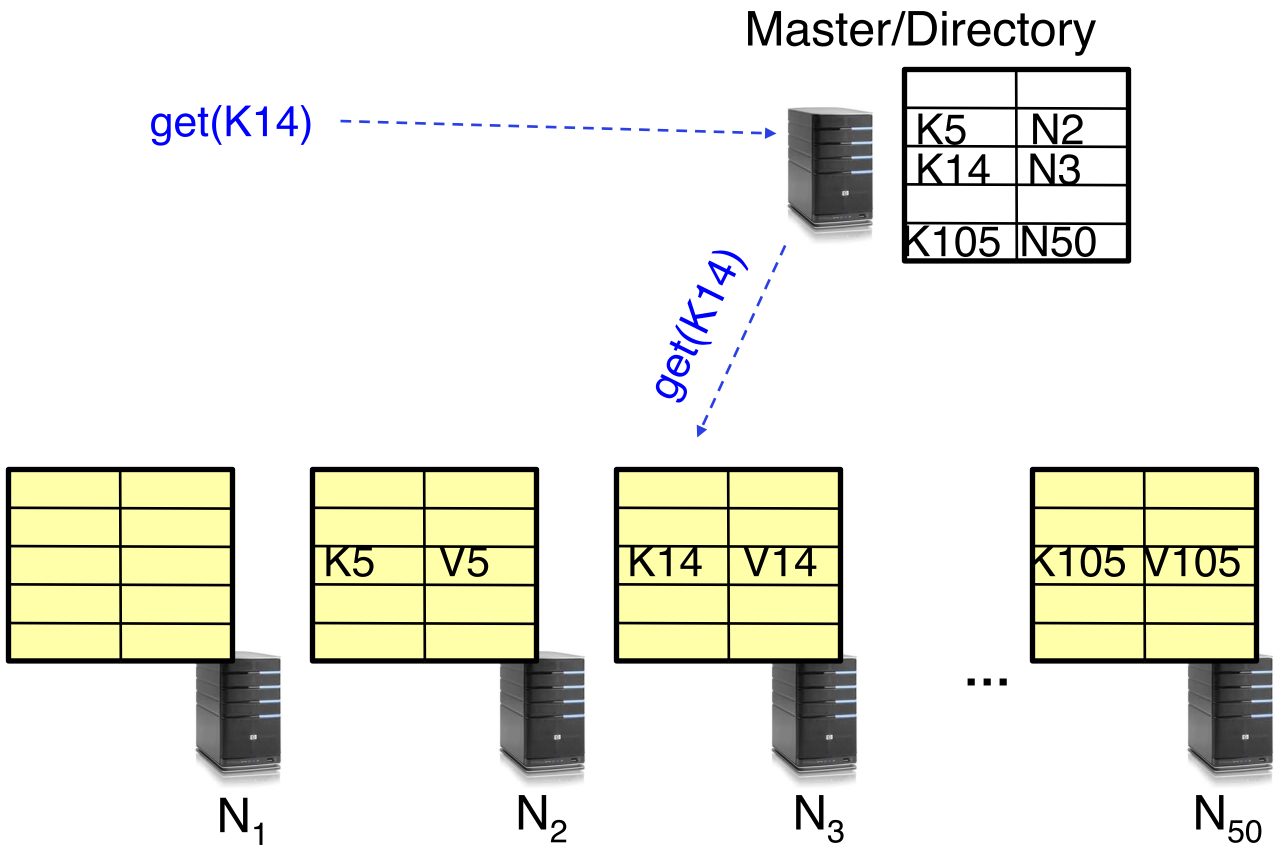

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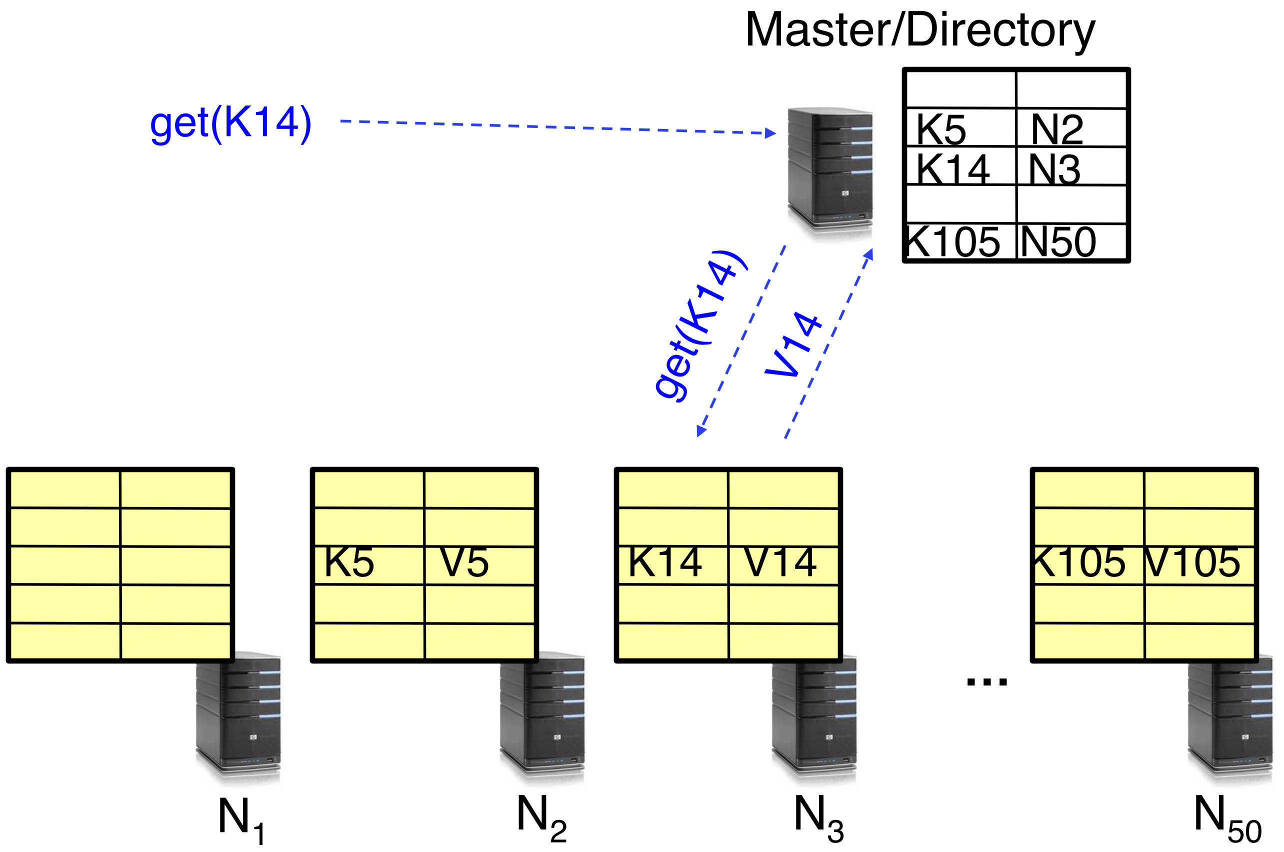

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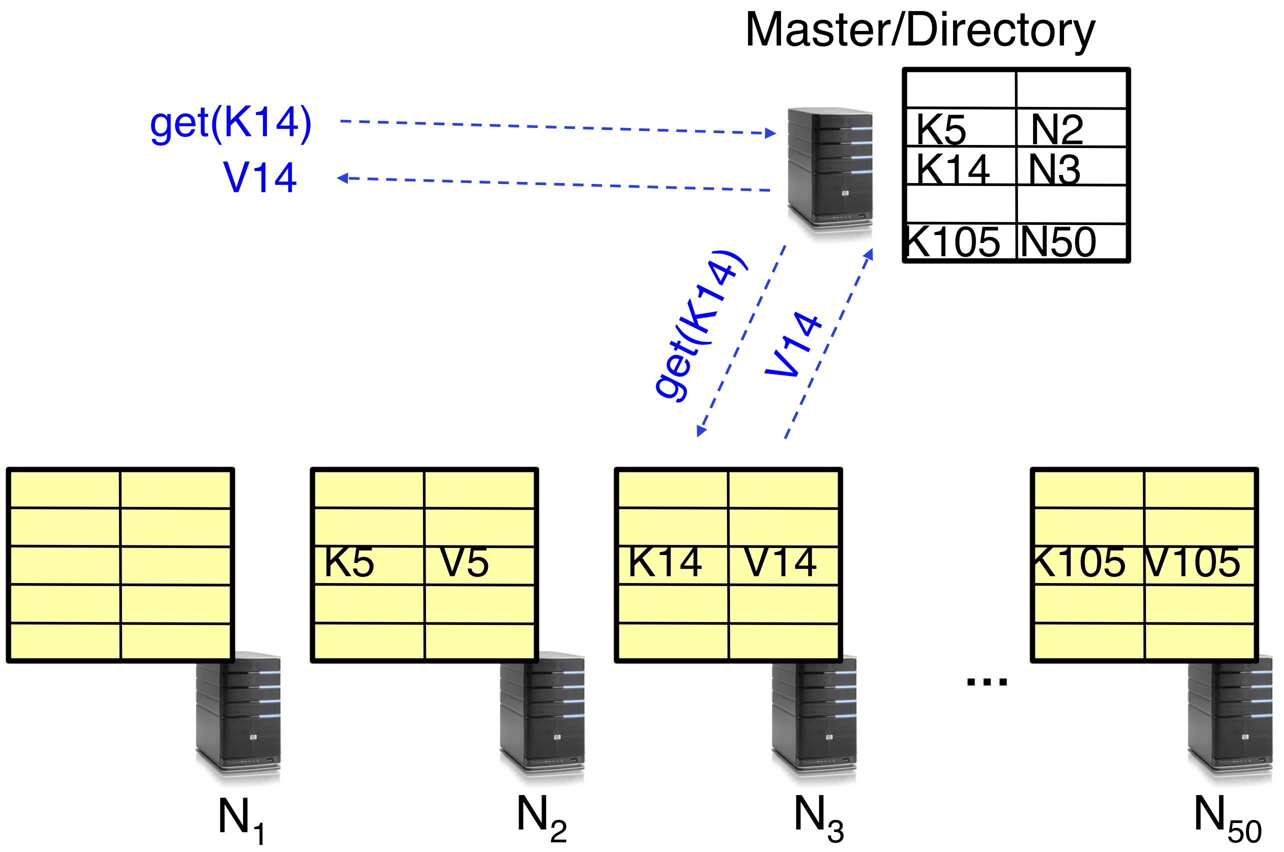
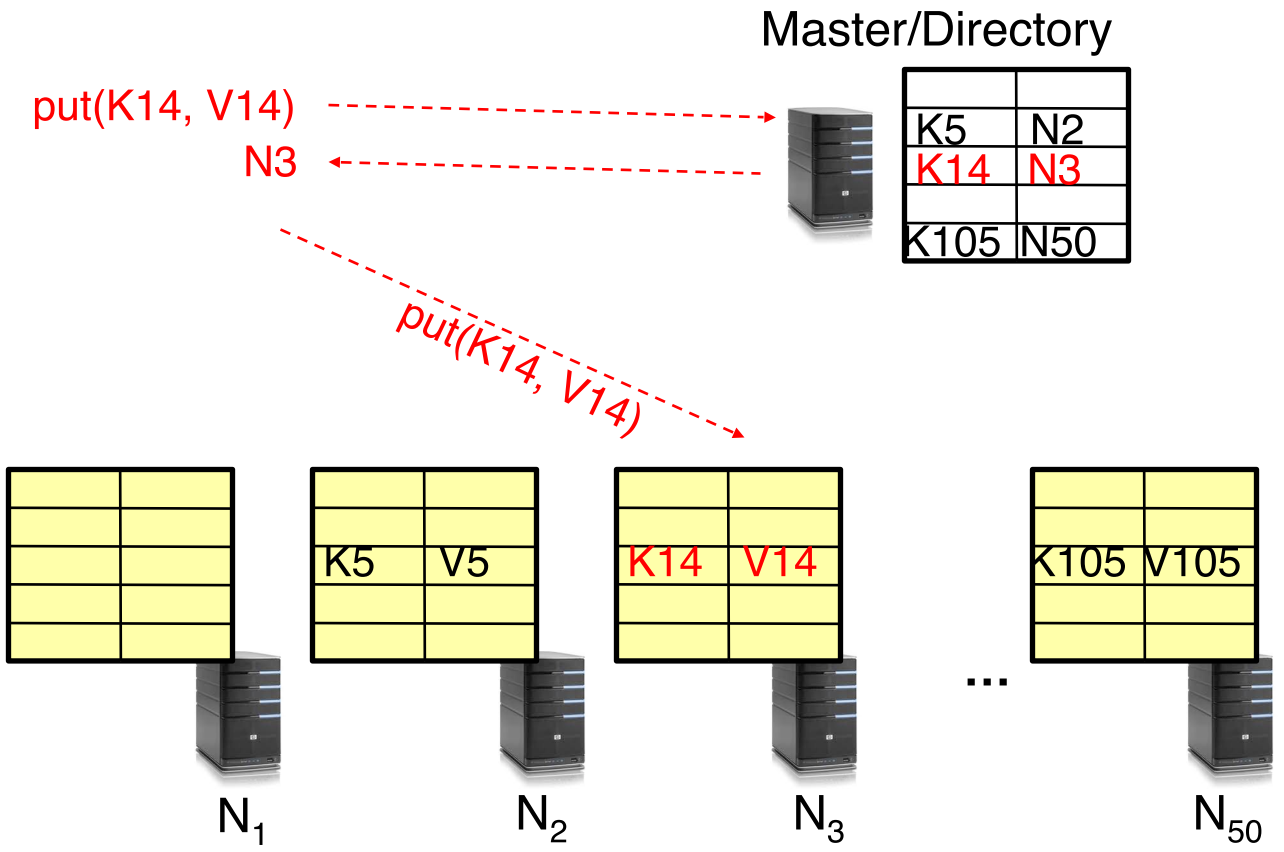


Iterative Directory Architecture (put)

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



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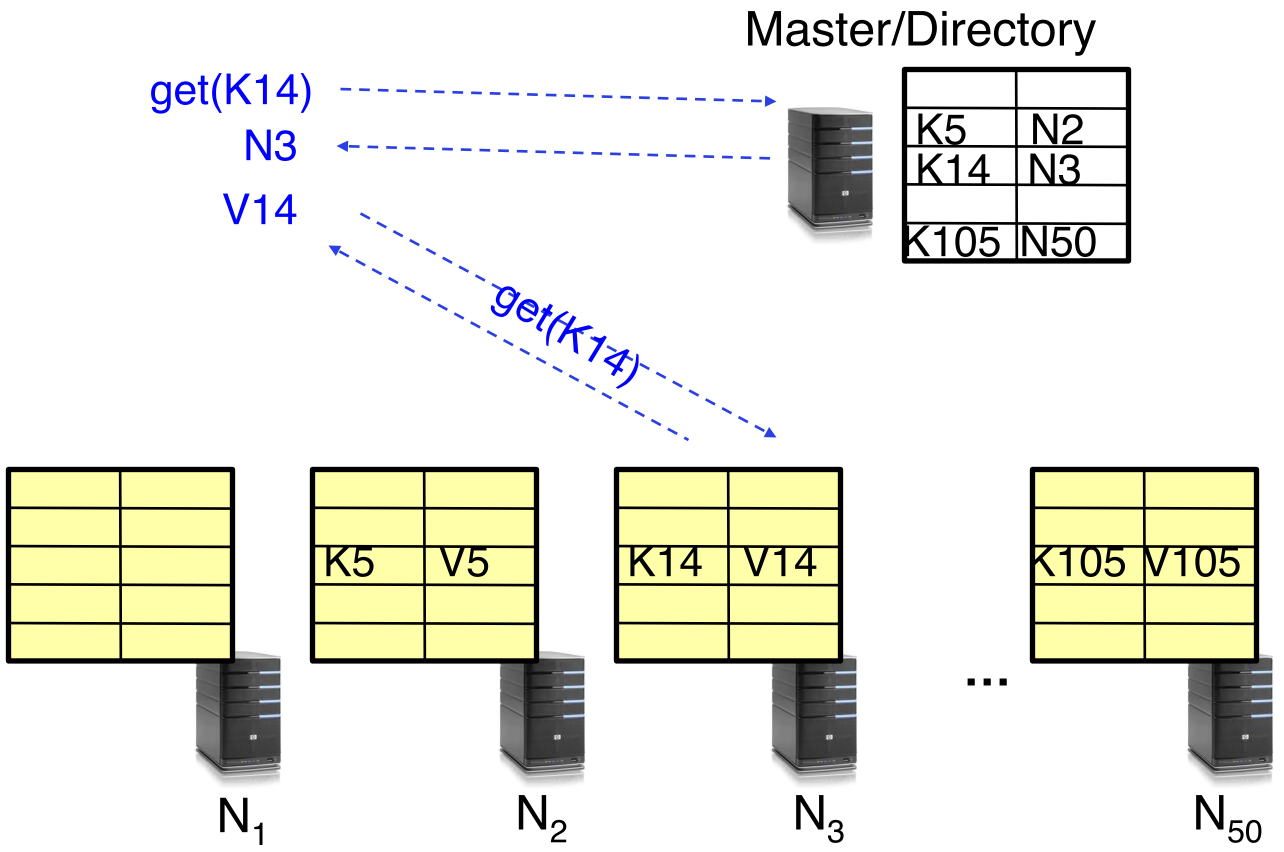
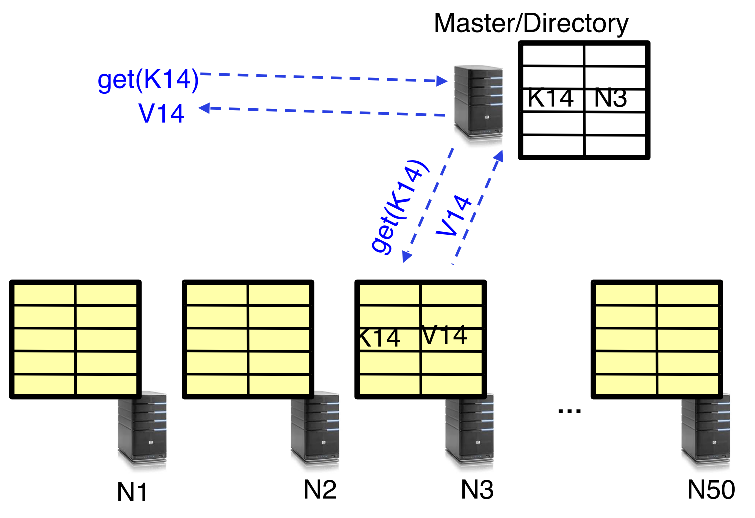
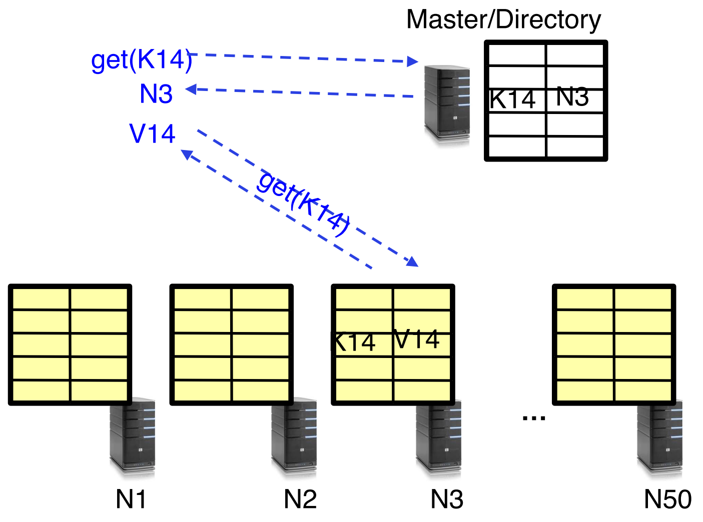


Iterative vs. Recursive Query





Recursive

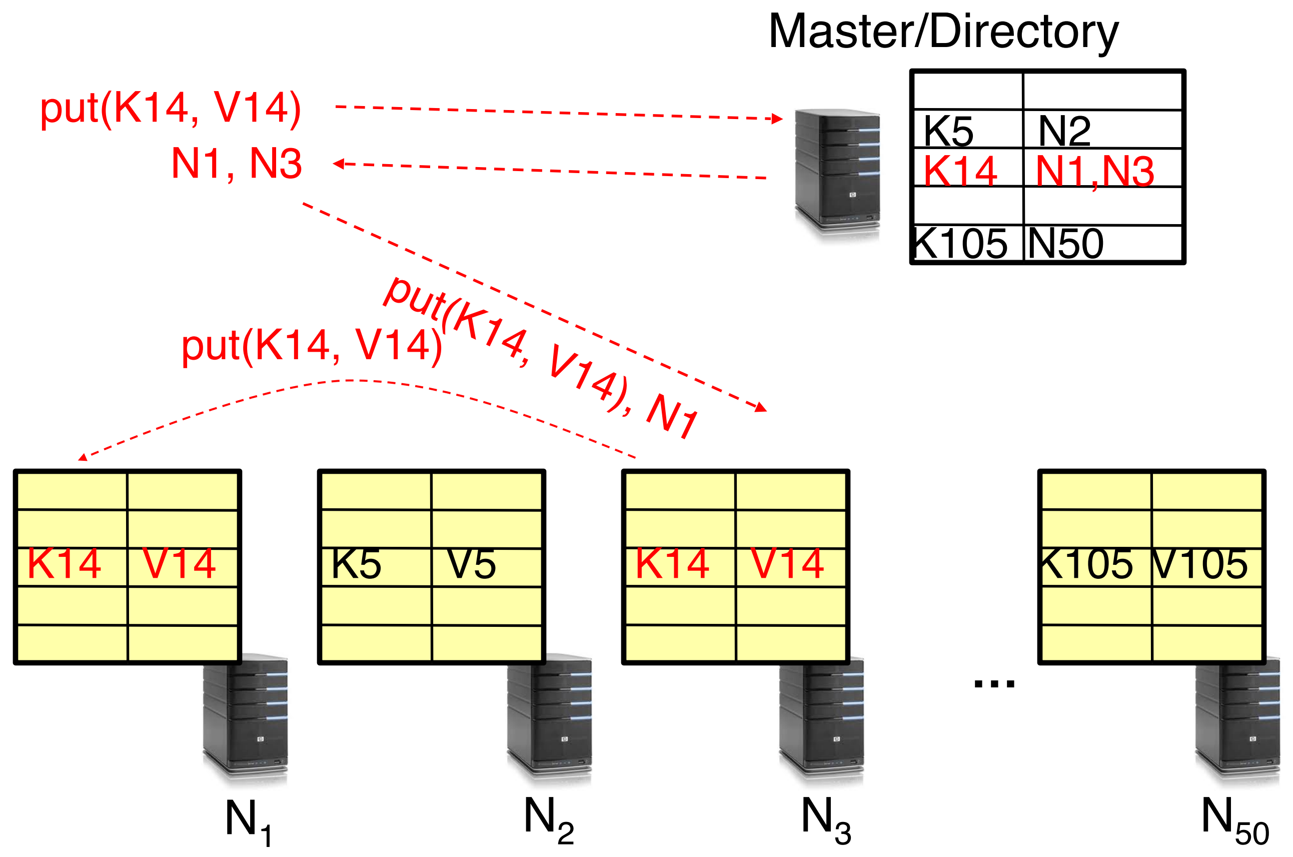
- + Faster, as directory server is typically close to storage nodes
- + Easier for consistency: directory can enforce an order for all puts and gets
- - Directory is a performance bottleneck

Iterative

- + More scalable, clients do more work
- - Harder to enforce consistency

Fault Tolerance

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

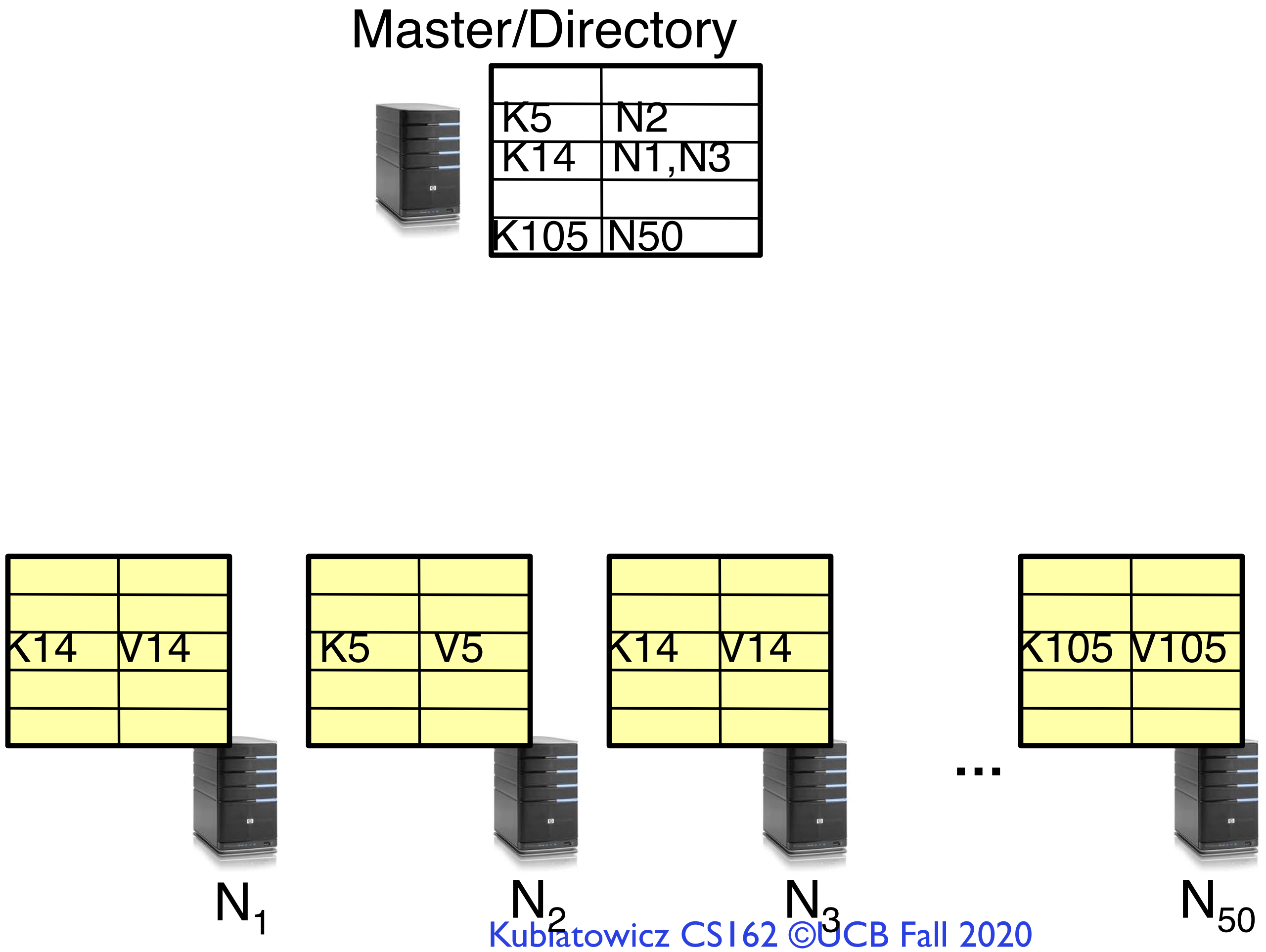


Consistency

- 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



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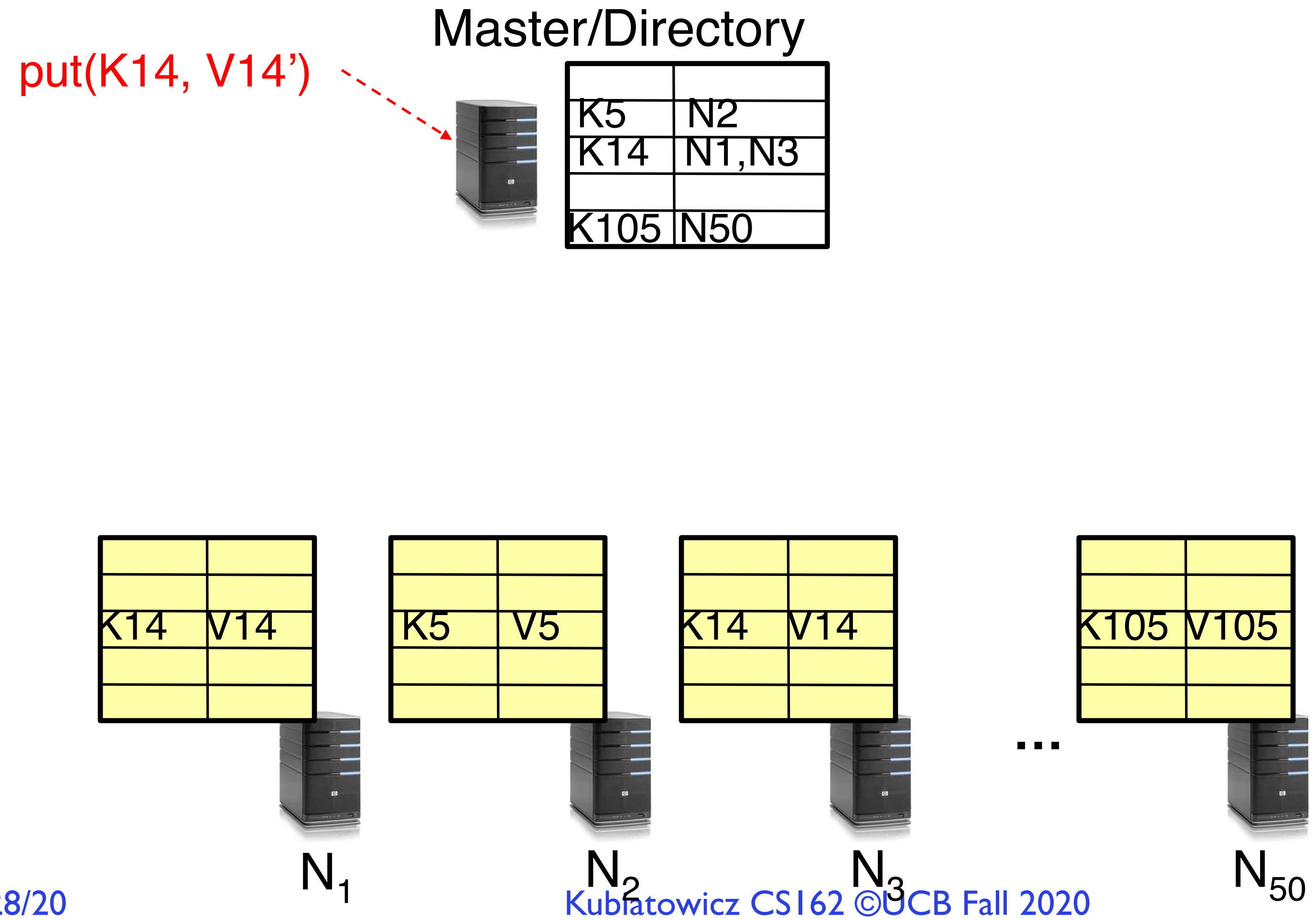

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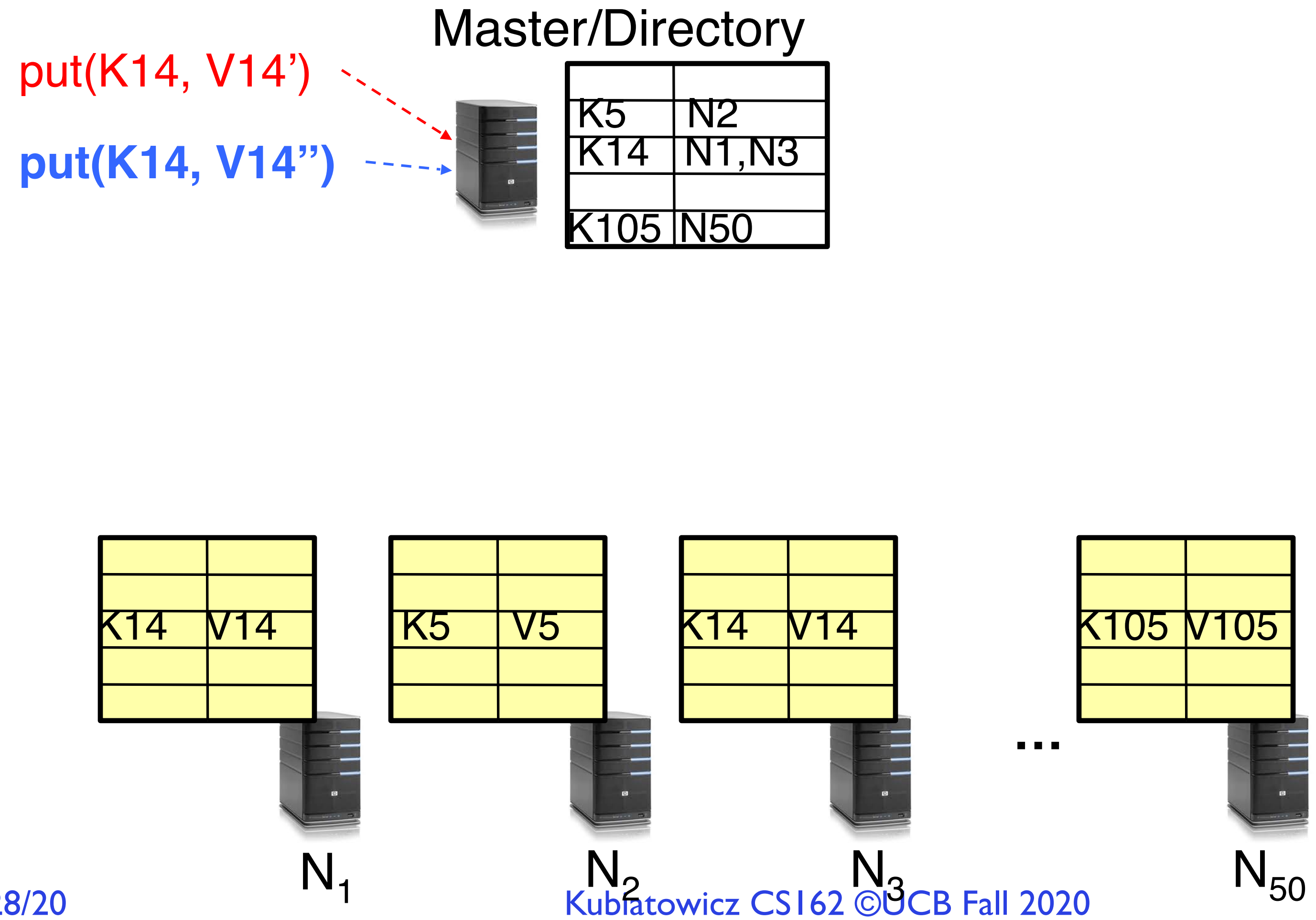

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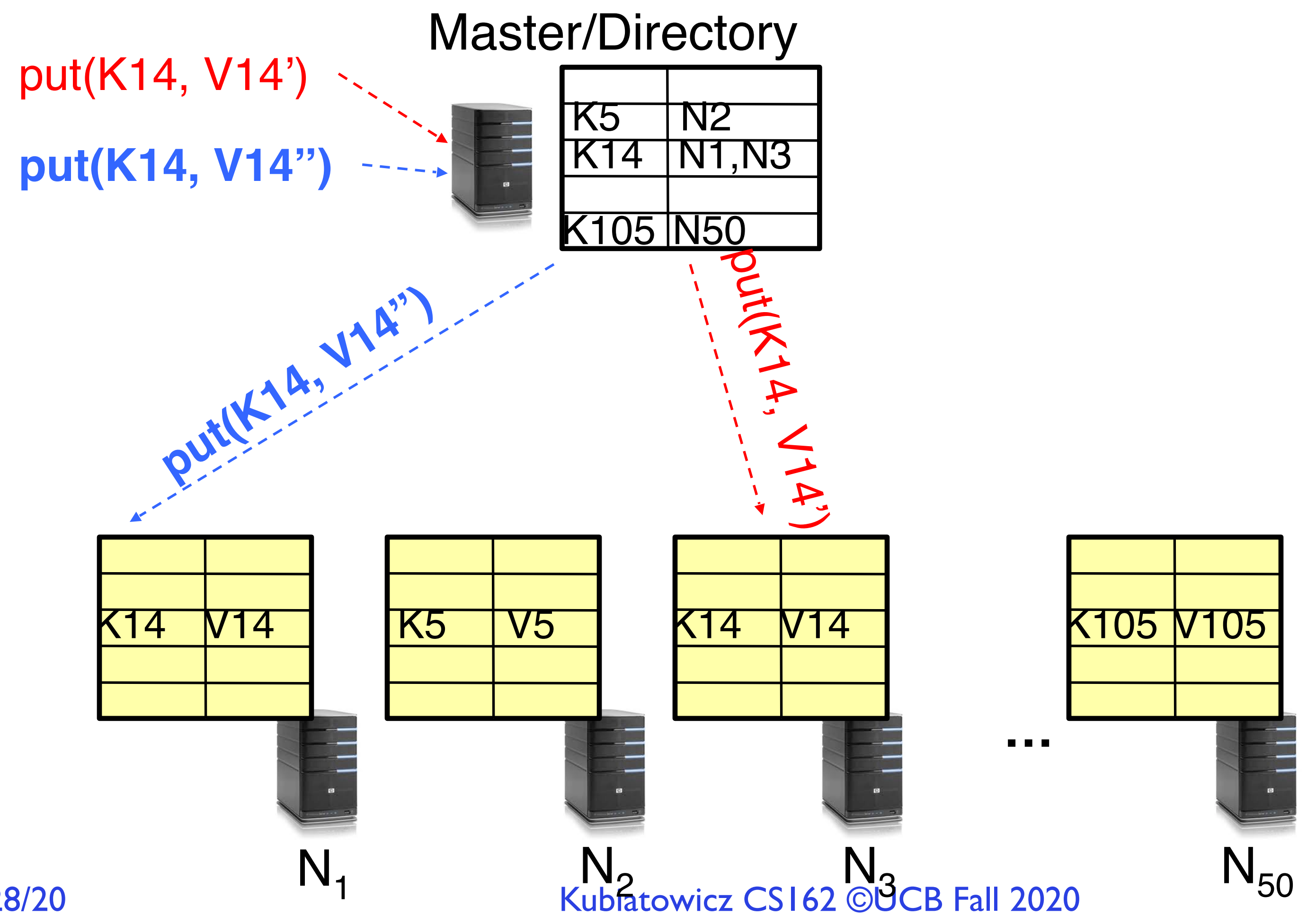

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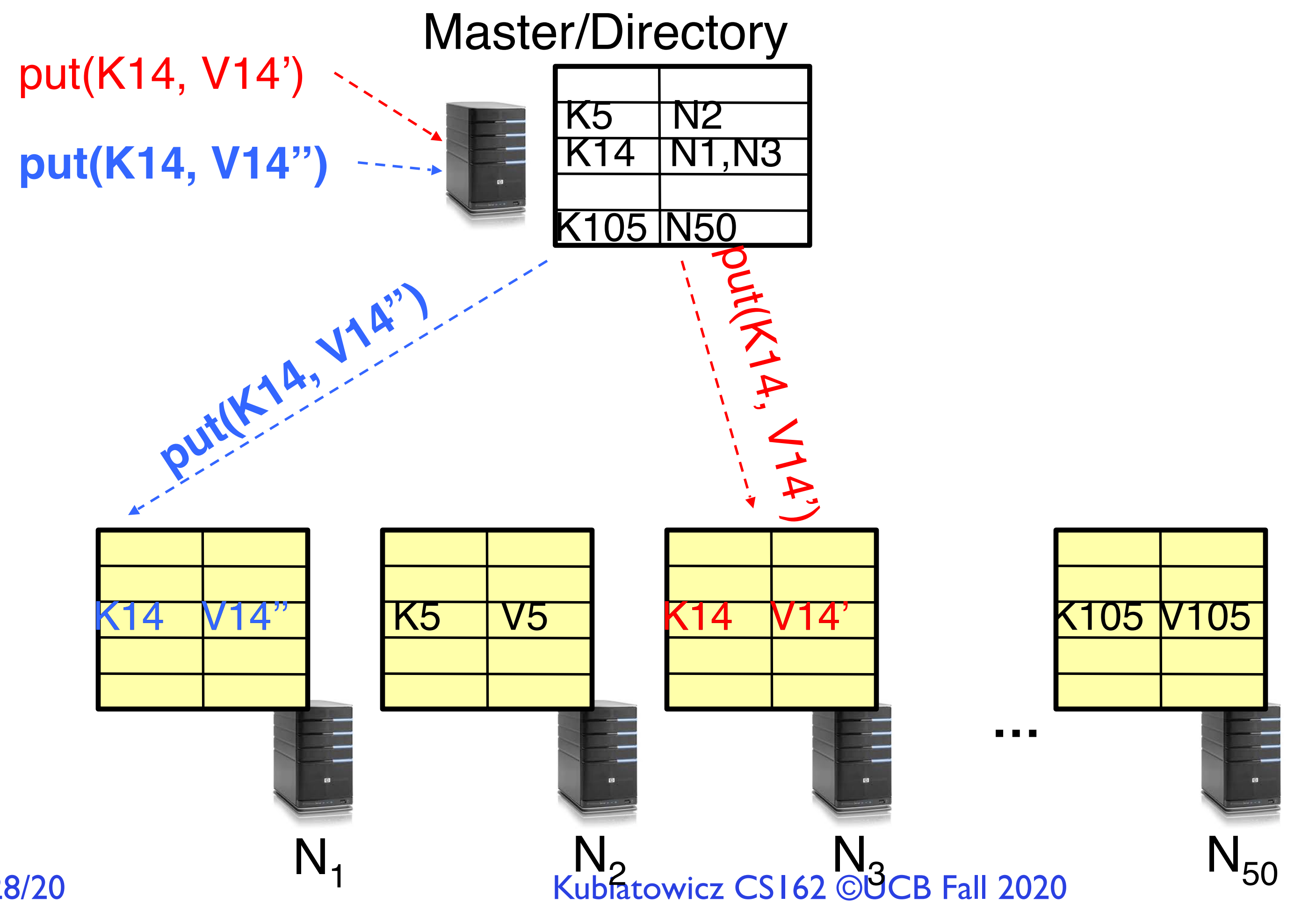

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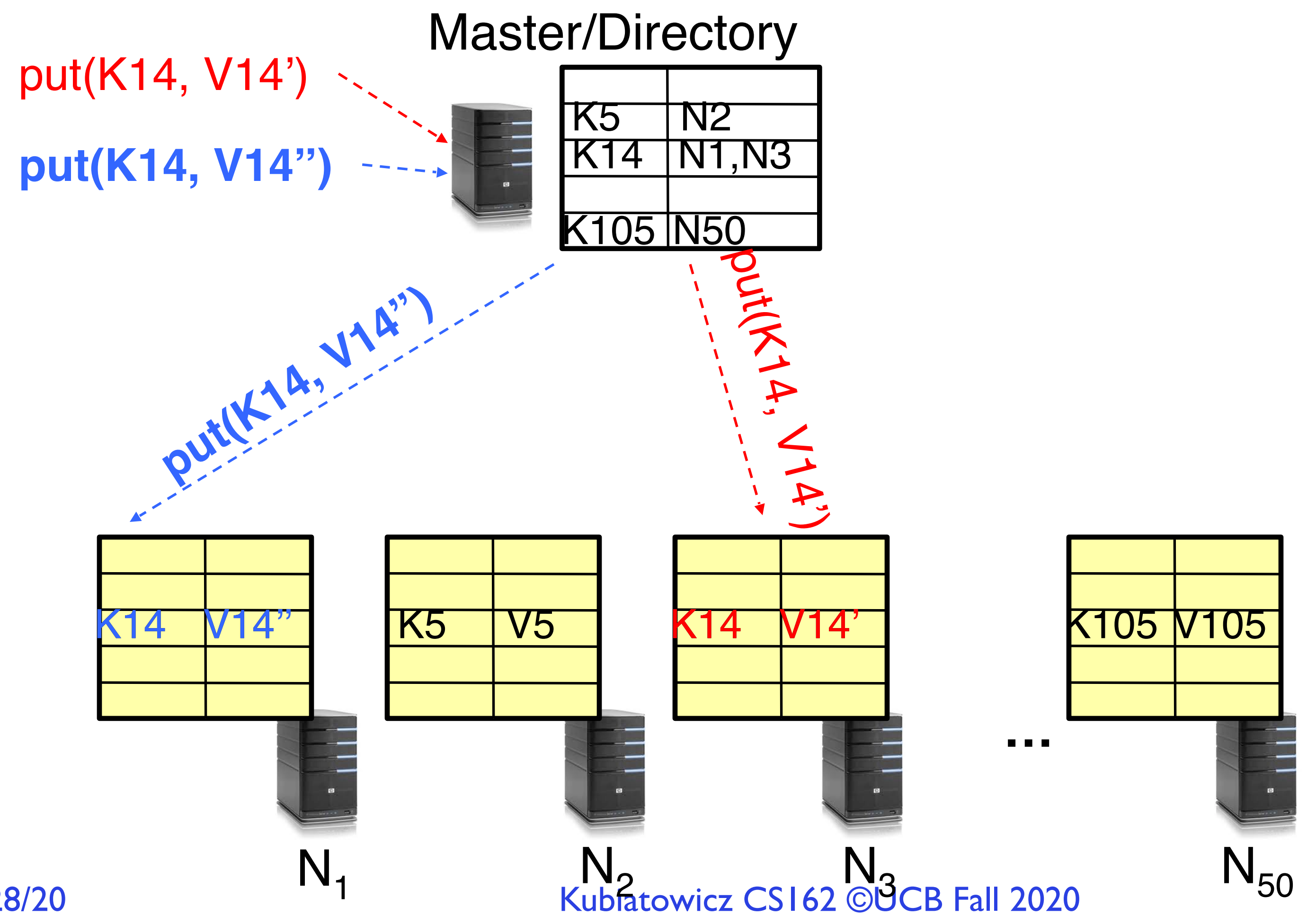
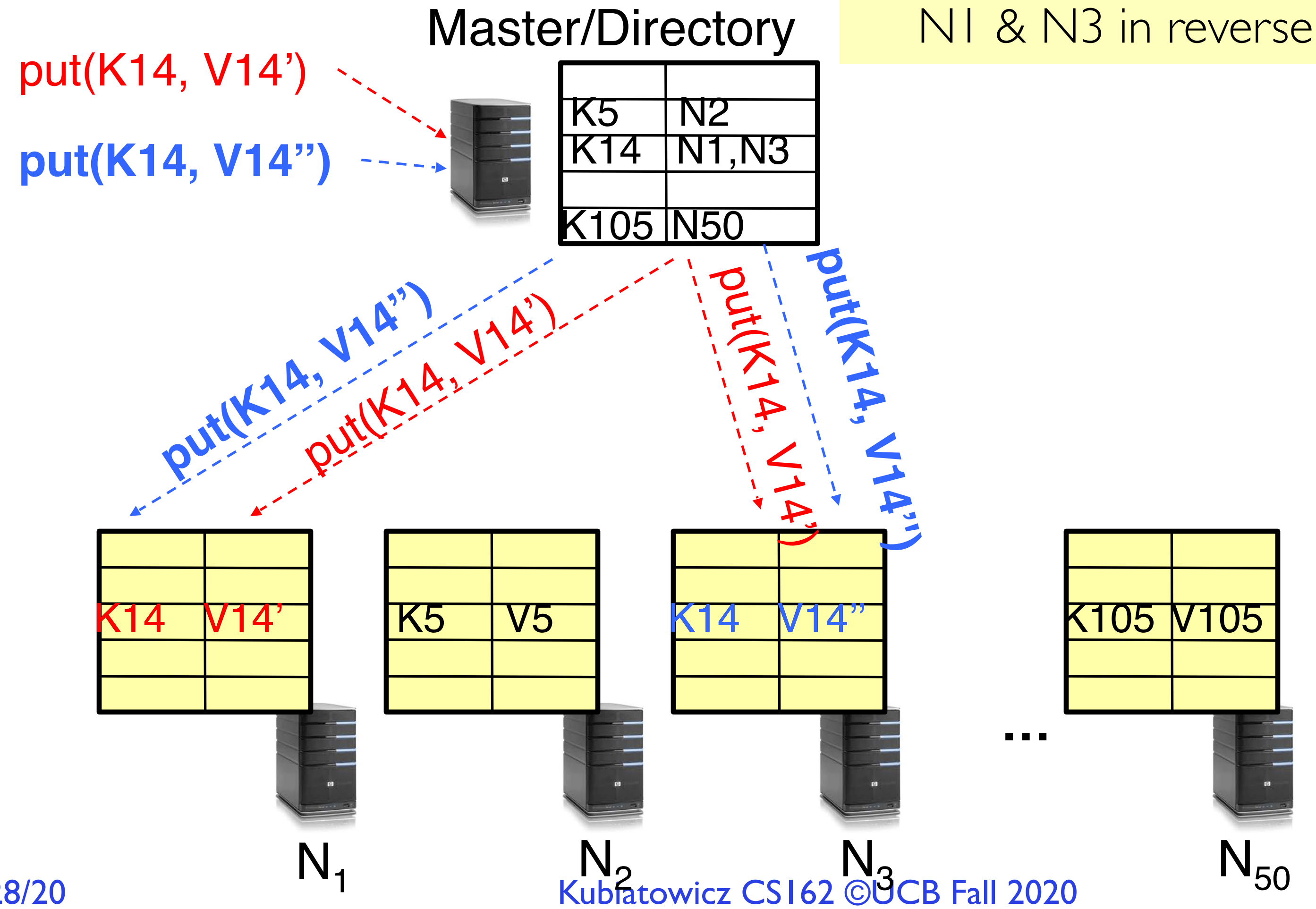


Consistency (cont'd)

- 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 & N3 in reverse order!



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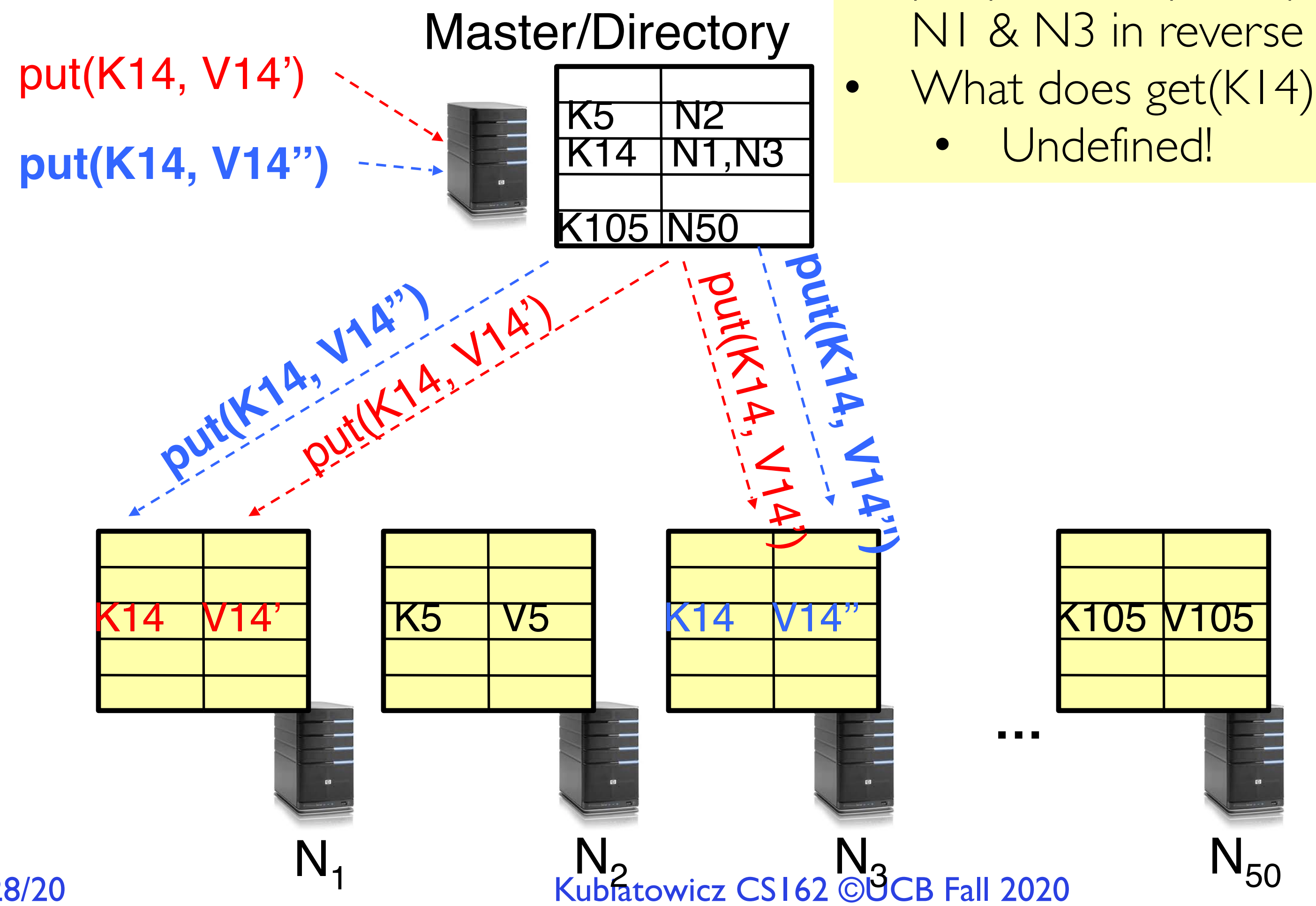


- put(K14,V14') and put(K14,V14'') reach N1 & N3 in reverse order!
- What does get(K14) return?
  - Undefined!

Large Variety of Consistency Models

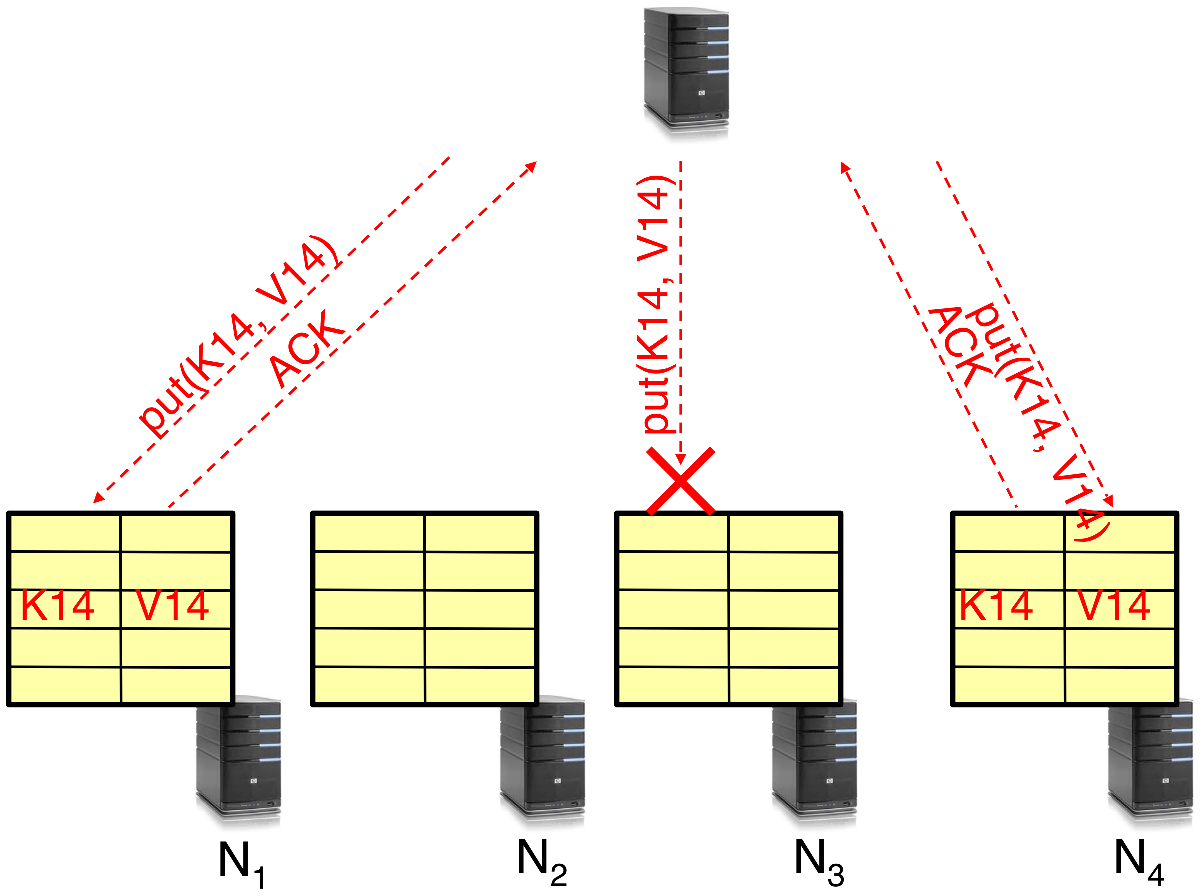
- Atomic consistency (linearizability): reads/writes (gets/puts) to replicas appear as if there was a single underlying replica (single system image)
  - Think "one updated at a time"
  - Transactions
- Eventual consistency: given enough time all updates will propagate through the system
  - One of the weakest form of consistency; used by many systems in practice
  - Must eventually converge on single value/key (coherence)
- *And many others: causal consistency, sequential consistency, strong consistency, …*

Quorum Consensus

- Improve put() and get() operation performance
  - In the presence of replication!
- Define a replica set of size N
  - put() waits for acknowledgements from at least W replicas
    - » Different updates need to be differentiated by something monotonically increasing like a timestamp
    - » Allows us to replace old values with updated ones
  - 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 might you use $W+R > N+1$?

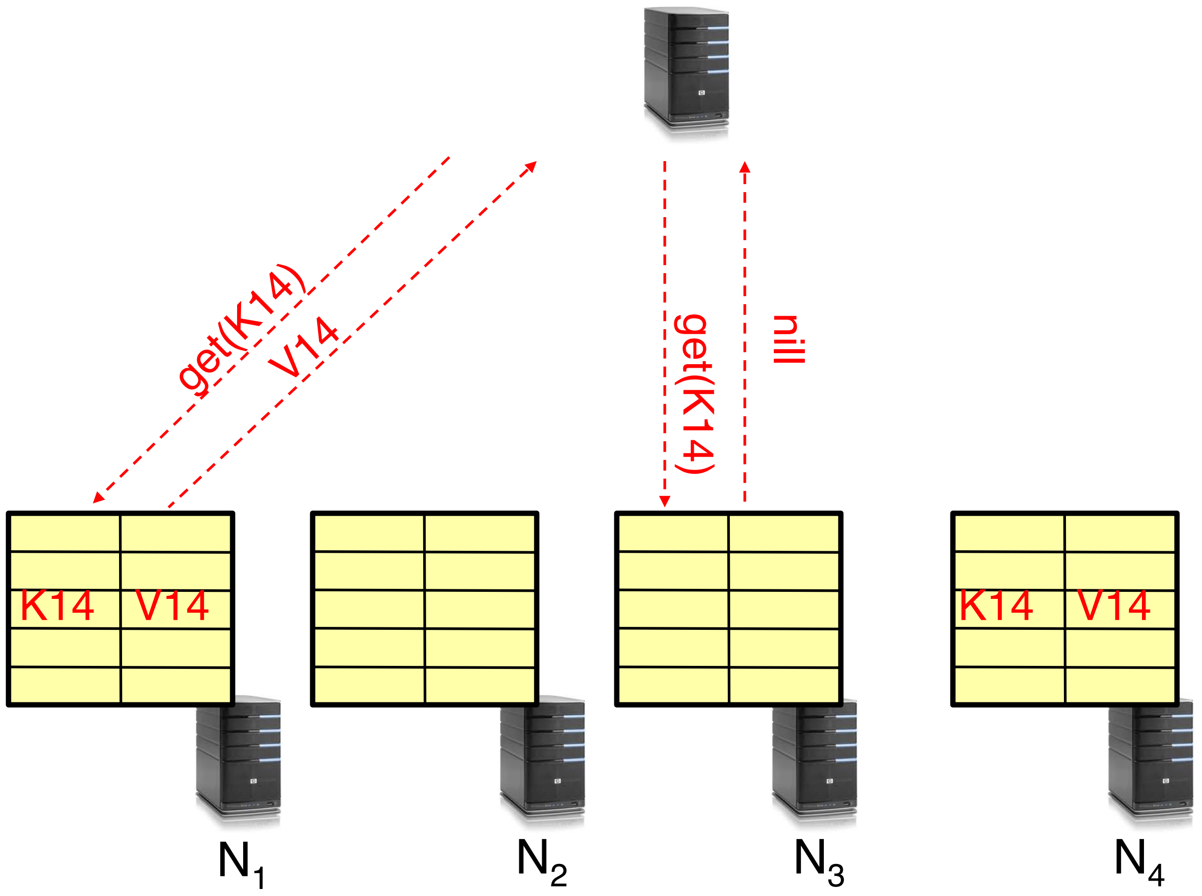
Quorum Consensus Example

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



Quorum Consensus Example

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



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 (multiple identical copies)
  - Partition it, so different keys are served by different masters/ directories
    - » How do you partition?

Scalability: Load Balancing

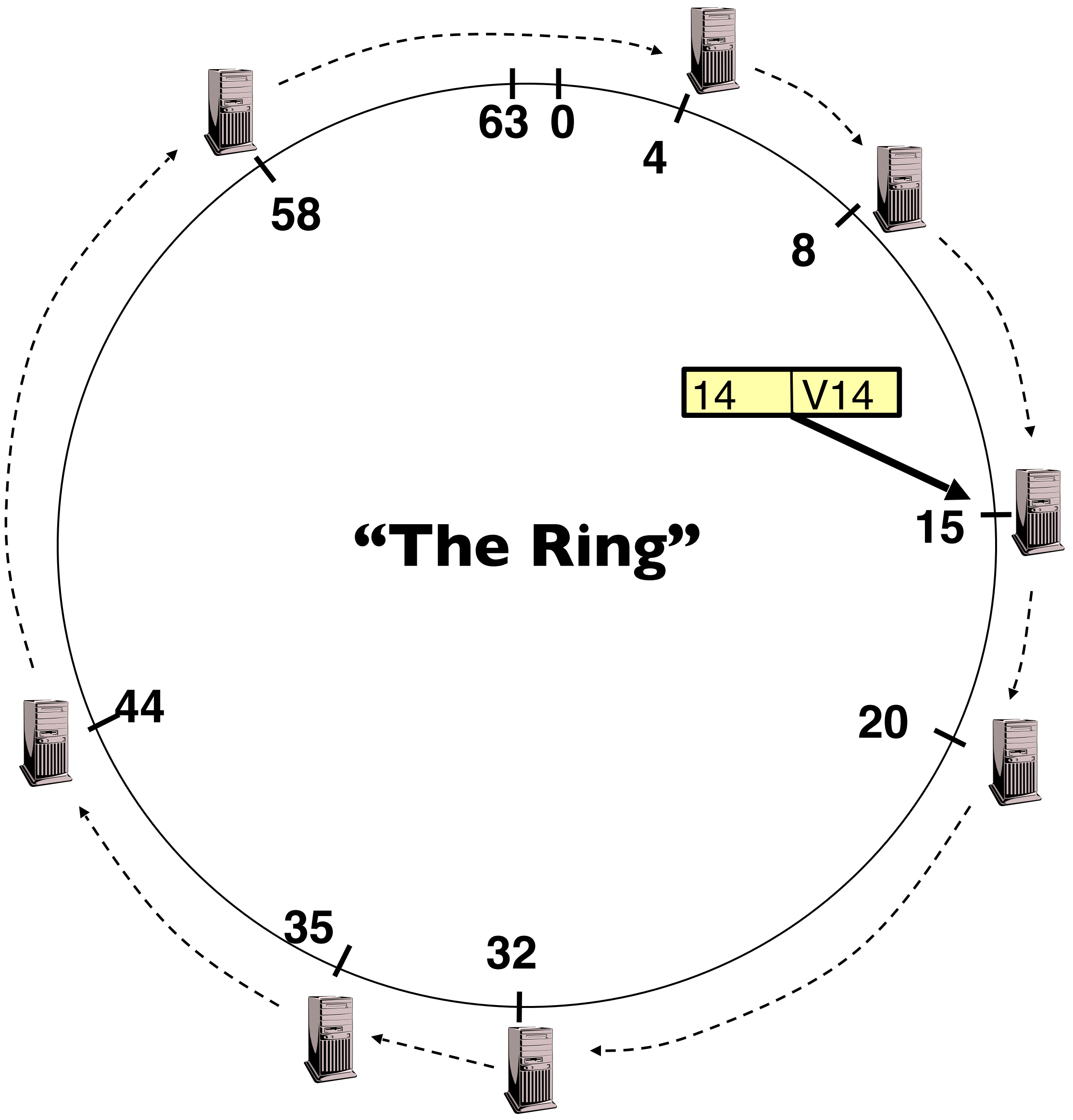
- Directory keeps track of the storage availability at each node
  - Preferentially insert new values on nodes with more storage available
- What happens when a new node is added?
  - Cannot insert only new values on new node. Why?
  - Move values from the heavy loaded nodes to the new node
- What happens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

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
  - Provides mechanism to divide [key,value] pairs amongst a (potentially large!) set of machines (nodes) on network
- Associate to each node a unique *id* in an *uni*-dimensional space $0..2^m-1 \Rightarrow$ Wraps around: Call this "the ring!"
  - Partition this space across *n* 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

- Paritioning example with 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]
- For this example, the mapping [14,V14] maps to node with ID=15
  - Node with smallest ID larger than 14 (the key)
- In practice, m=256 or more!
  - Uses cryptographically secure hash such as SHA-256 to generate the node IDs

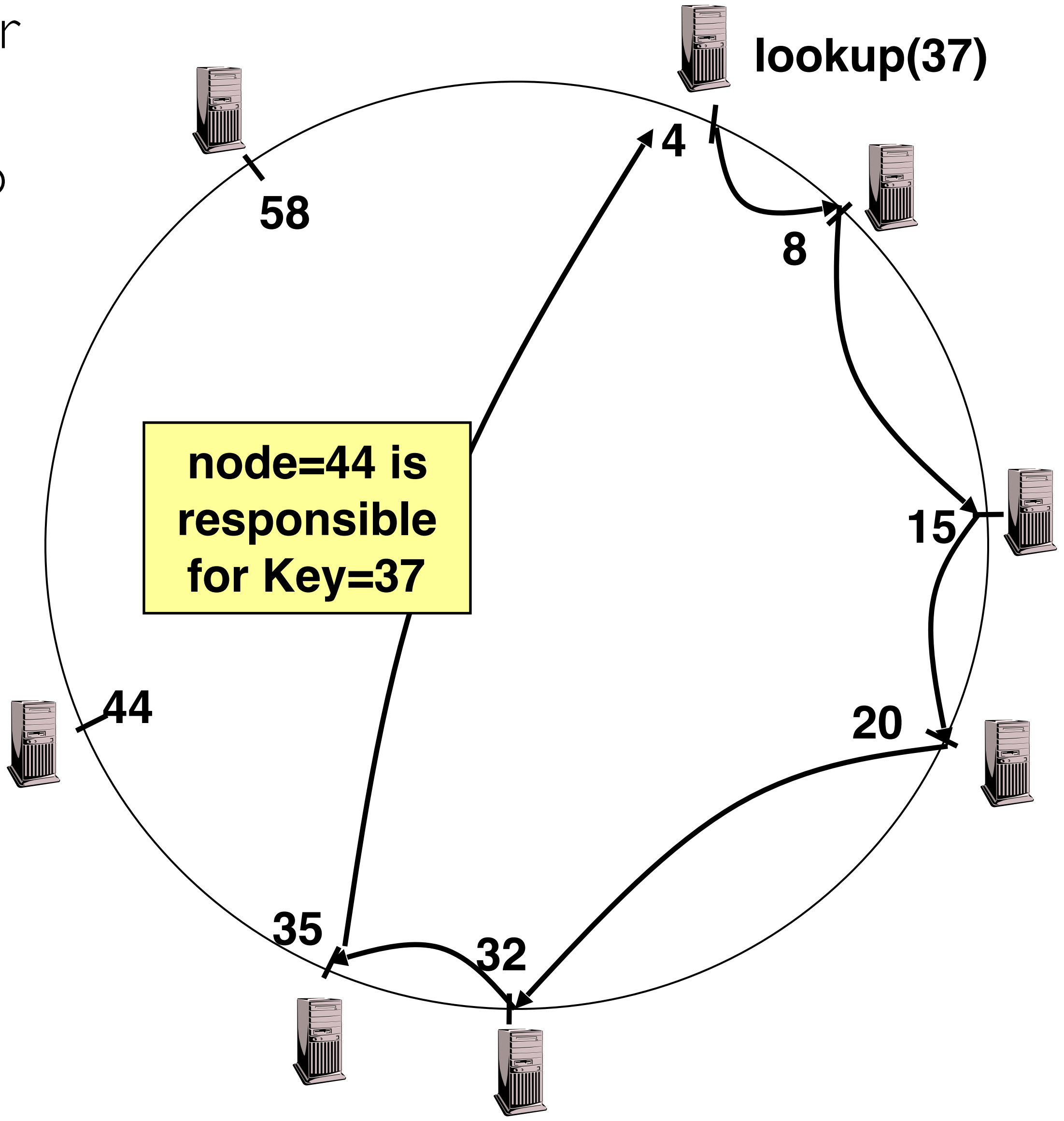


Chord: Distributed Lookup (Directory) Service

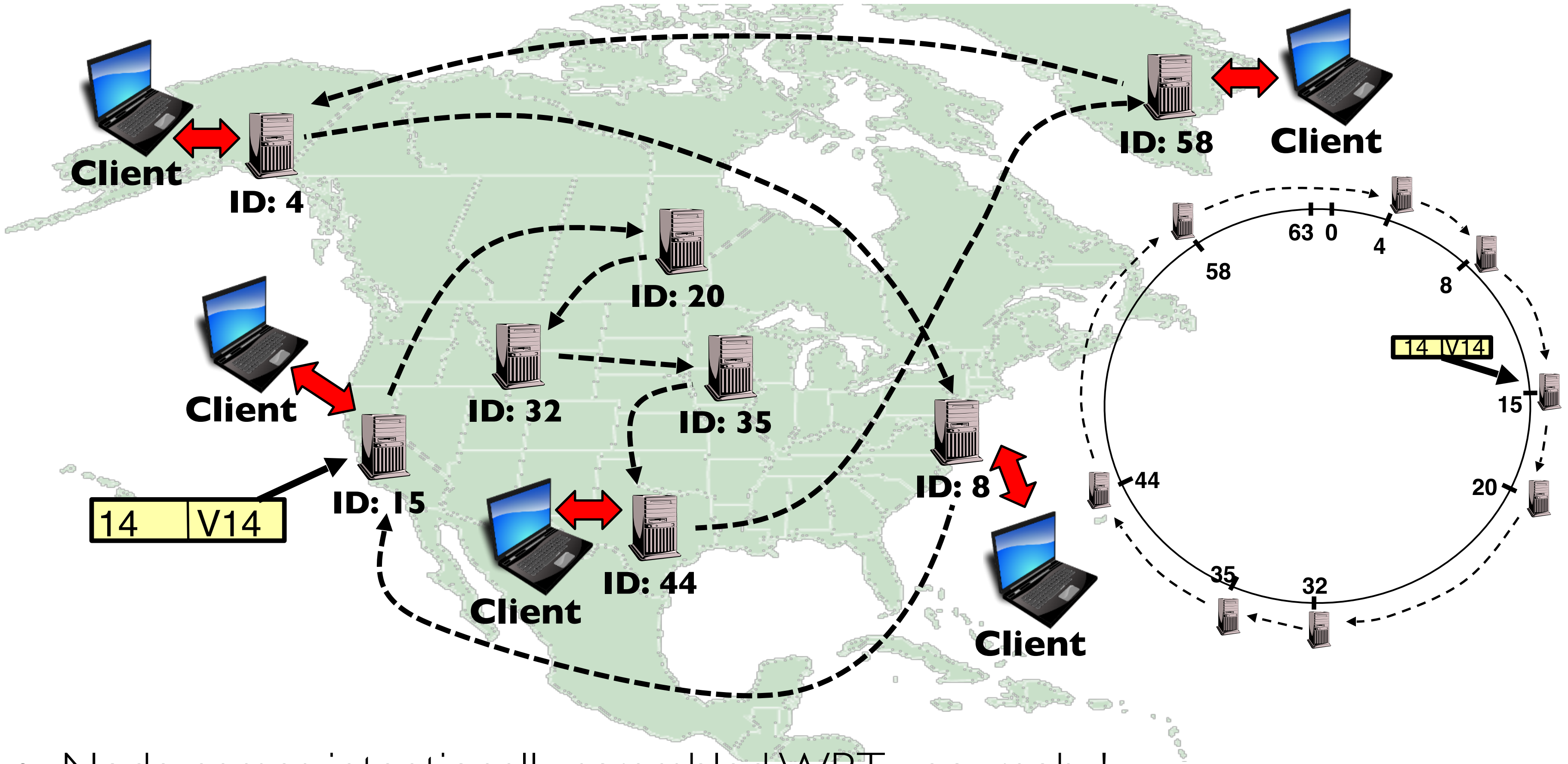
- "Chord" is a Distributed Lookup Service
  - Designed at MIT and here at Berkeley (Ion Stoica among others)
  - Simplest and cleanest algorithm for distributed storage
    - » Serves as comparison point for other options
- Import aspect of the design space:
  - Decouple correctness from efficiency
  - Combined *Directory* and *Storage*
- Properties
  - Correctness:
    - » Each node needs to know about neighbors on ring (one predecessor and one successor)
    - » Connected rings will perform their task correctly
  - Performance:
    - » 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 *Structured, Peer-to-Peer* lookup services:
  - CAN, Tapestry, Pastry, Bamboo, Kademlia, …
  - Several designed here at Berkeley!

Chord's Lookup Mechanism: Routing!

- 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
- Worst-case (correct) lookup is O(n)
  - But much better normal lookup time is O(log n)
  - Dynamic performance optimization (finger table mechanism)
    - » More later!!!



But what does this really mean??



- Node names intentionally scrambled WRT geography!
  - Node IDs generated by secure hashes over metadata
    - » Including things like the IP address
  - This geographic scrambling spreads load and avoids hotspots
- Clients access distributed storage by accessing system through any member of the network

Stabilization Procedure

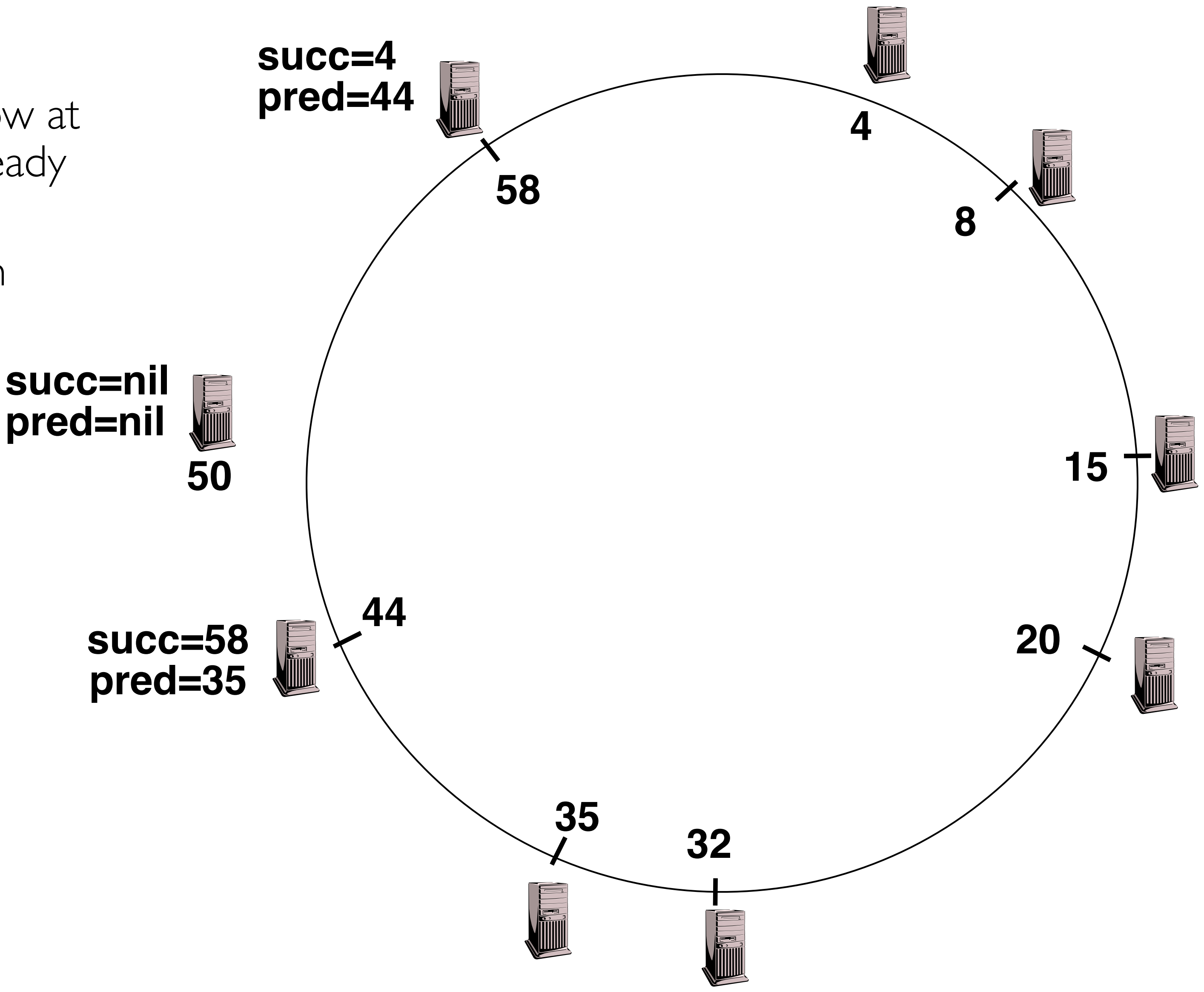
- Periodic operation performed by each node n to maintain its successor when new nodes join the system
  - The primary Correctness constraint

```
n.stabilize()
  x = succ.pred;
  if (x $\in$(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' $\in$(pred, n))
     pred = n';      // if n' is better predecessor, update
```

Joining Operation

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



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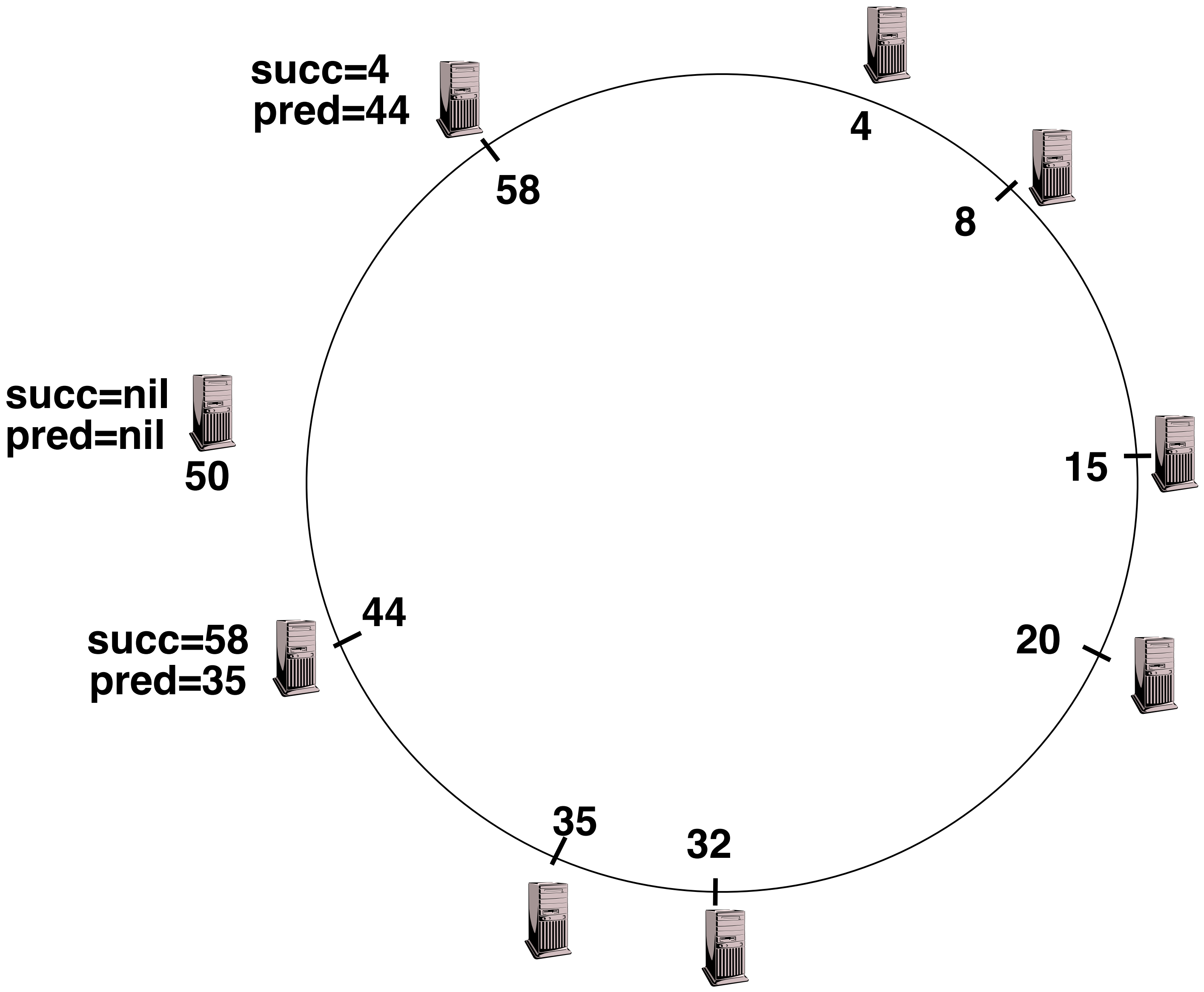
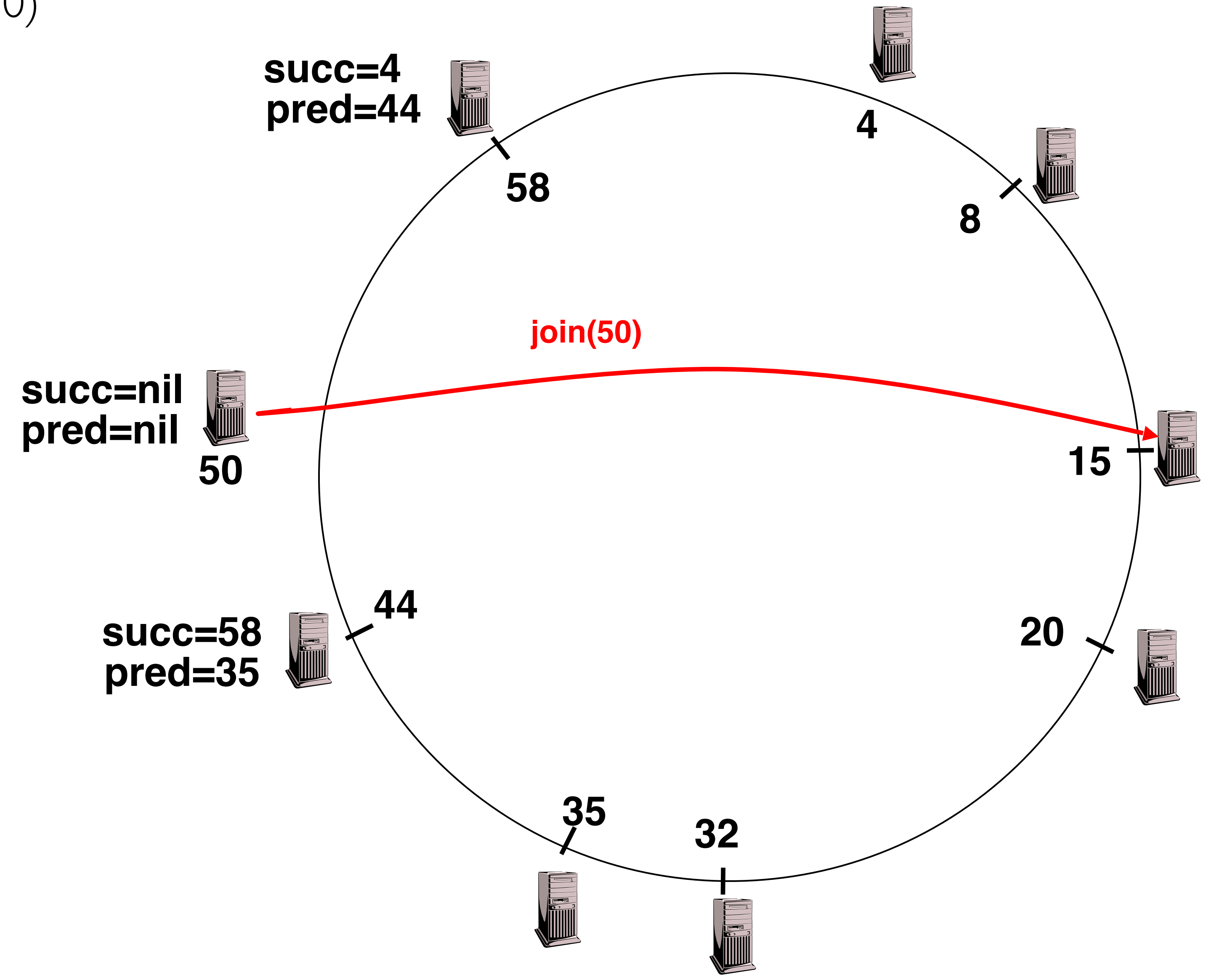


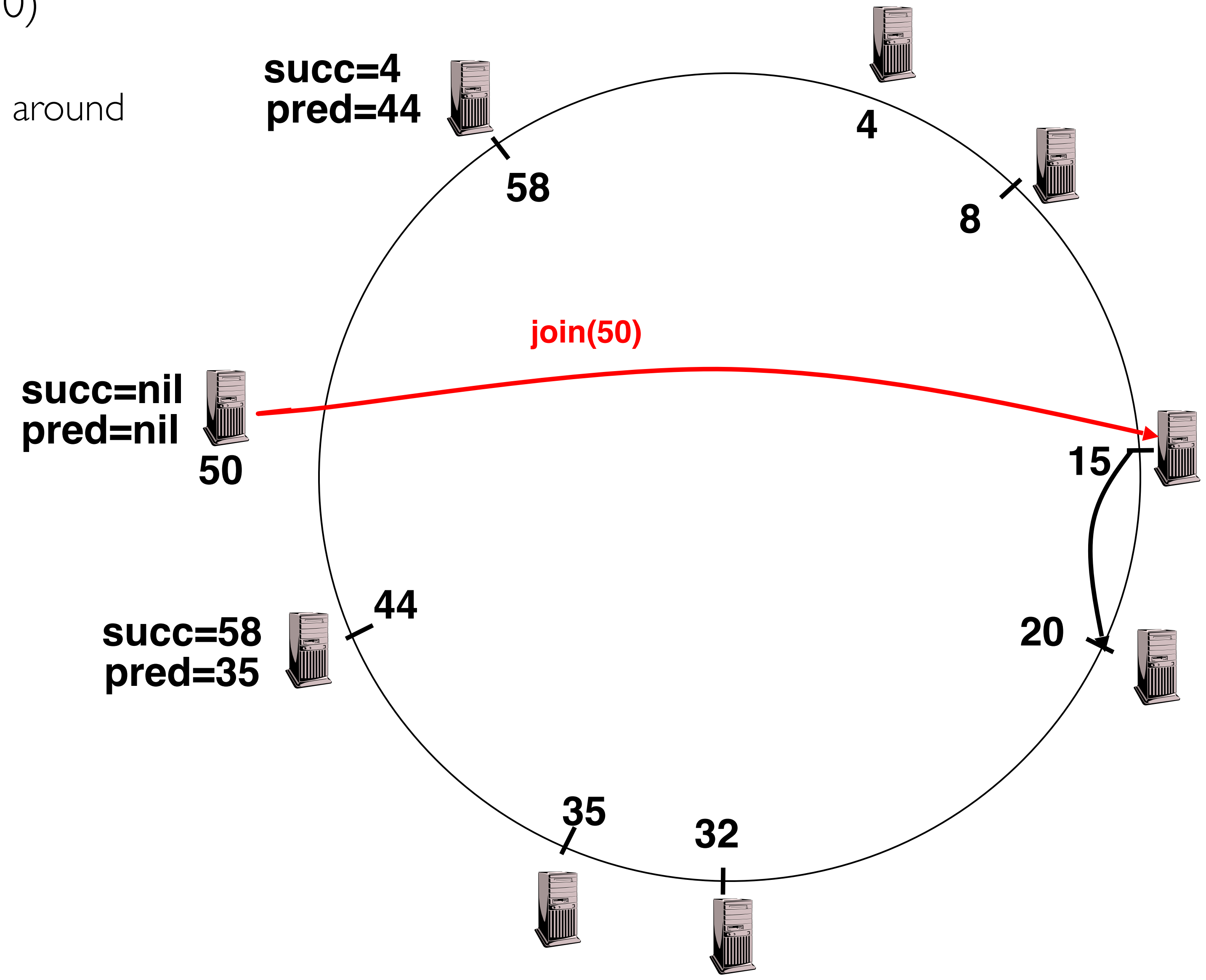
Joining Operation

- n=50 sends join(50) to node 15



Joining Operation

- n=50 sends join(50) to node 15
  - Join propagated around ring!



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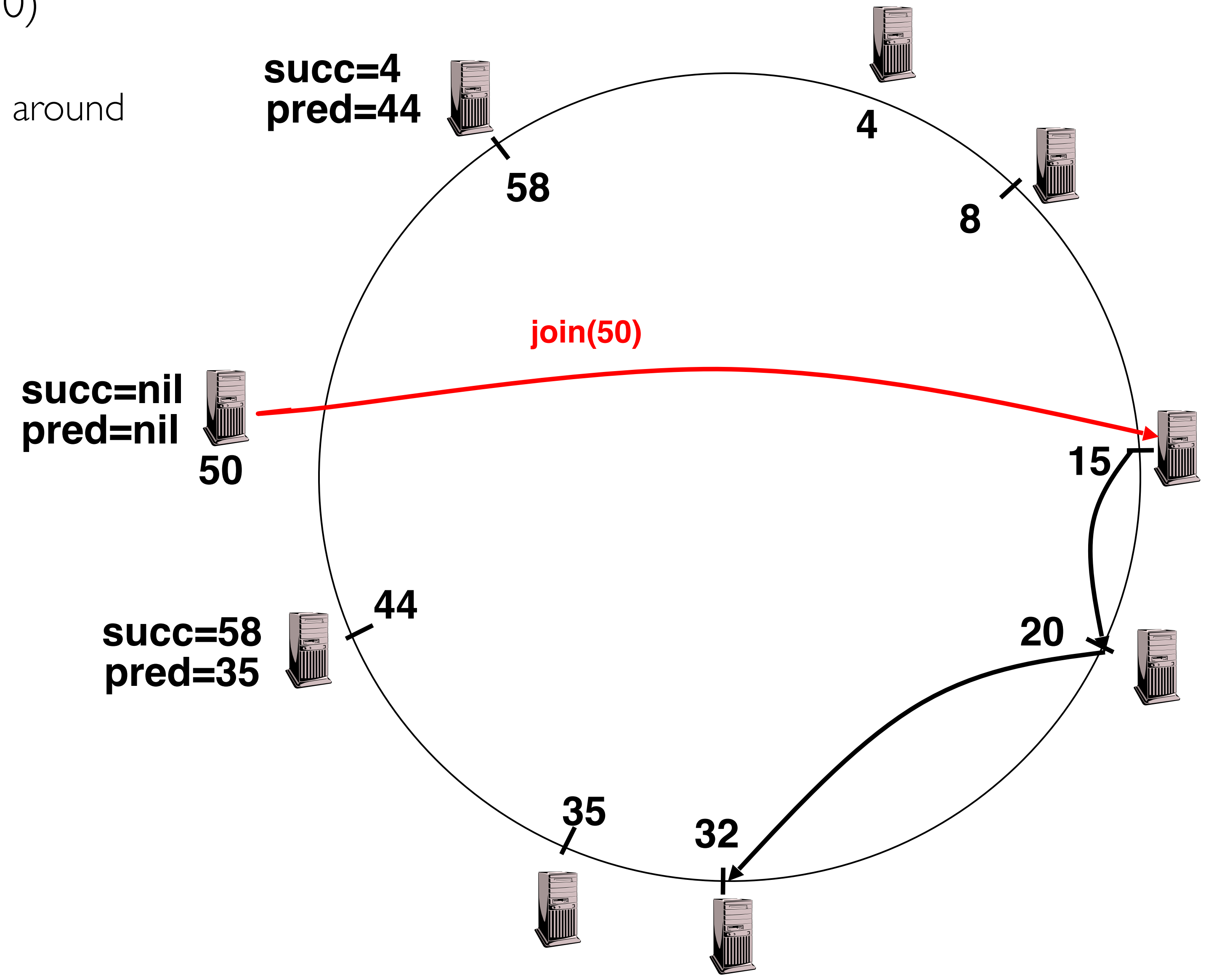

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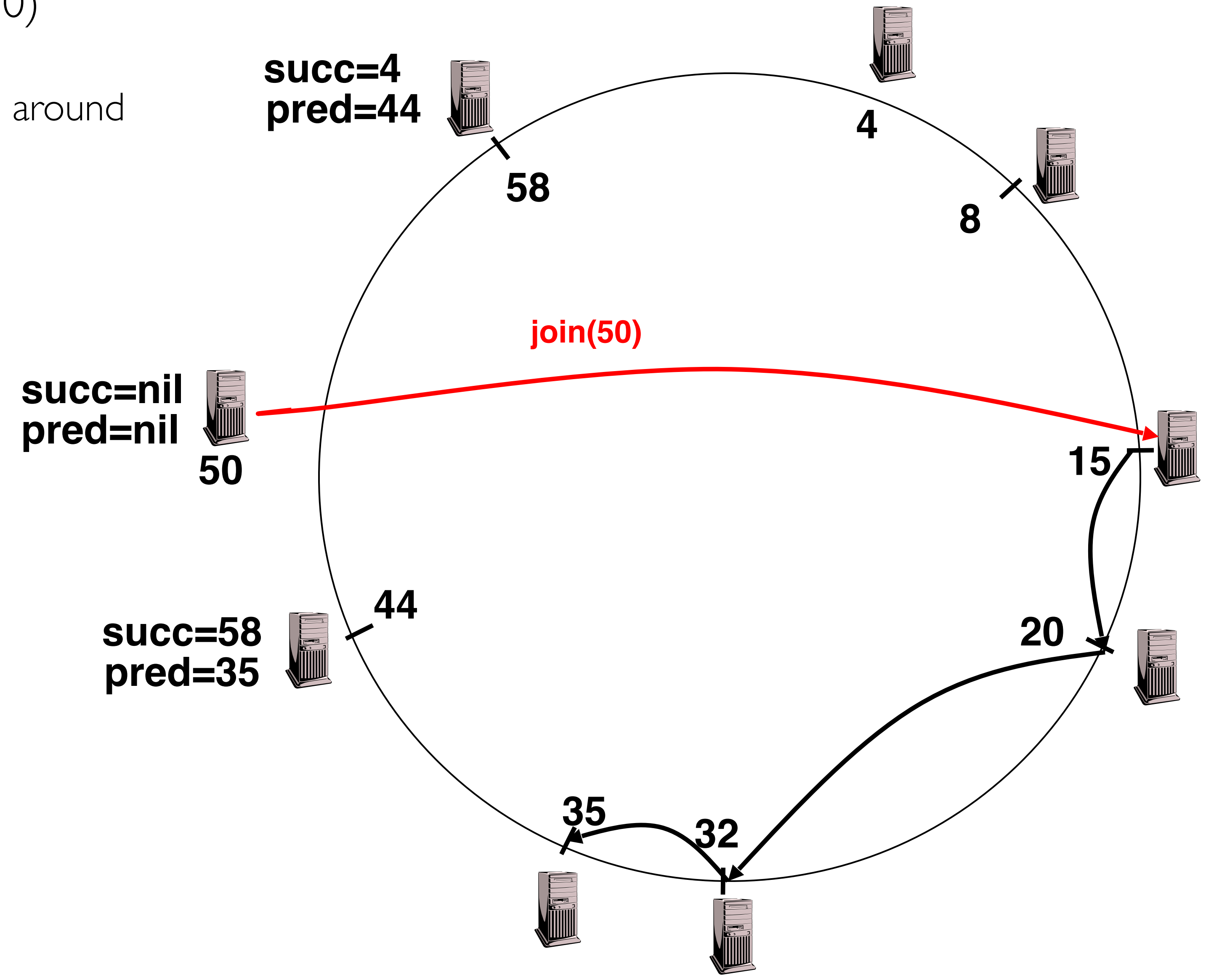

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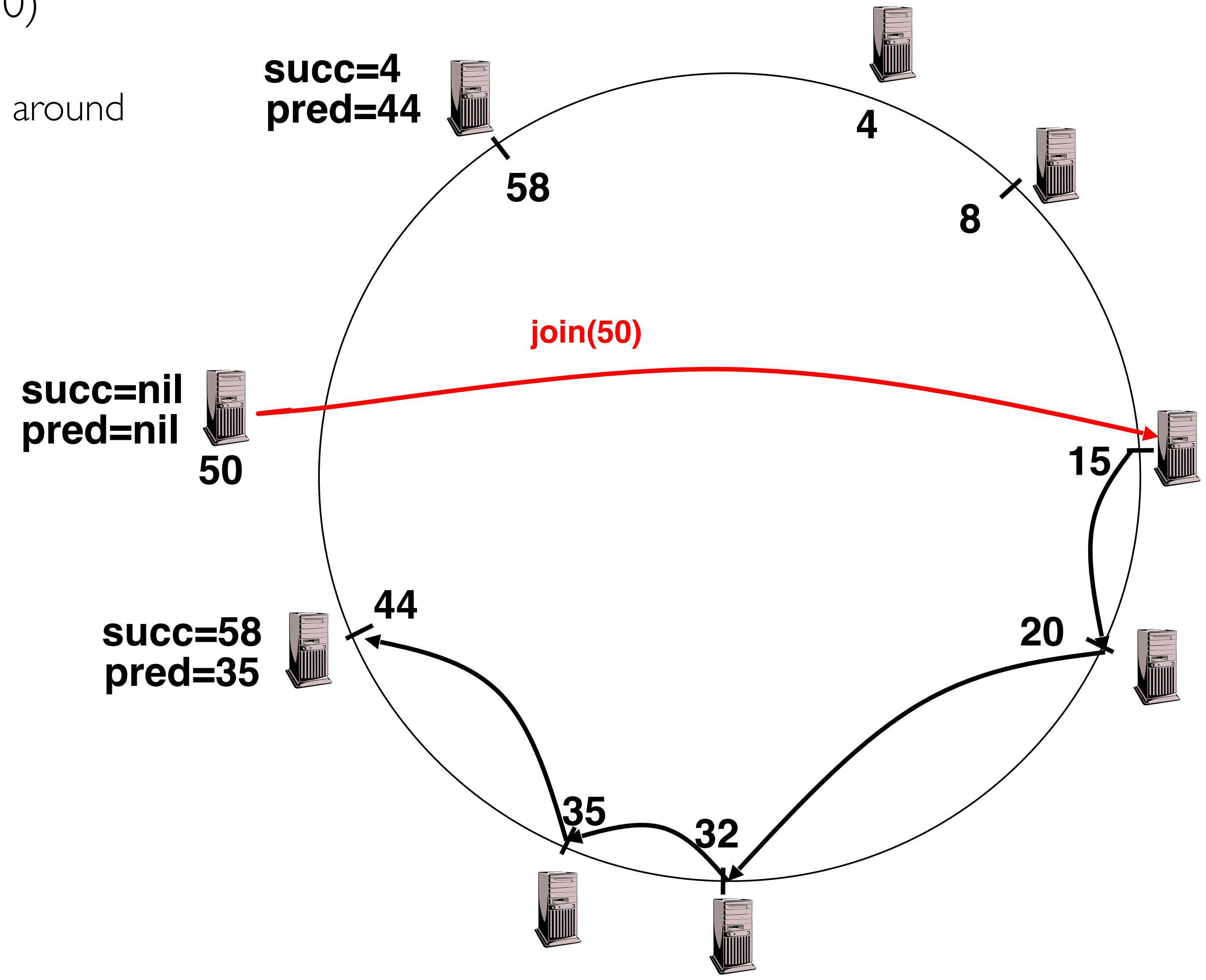
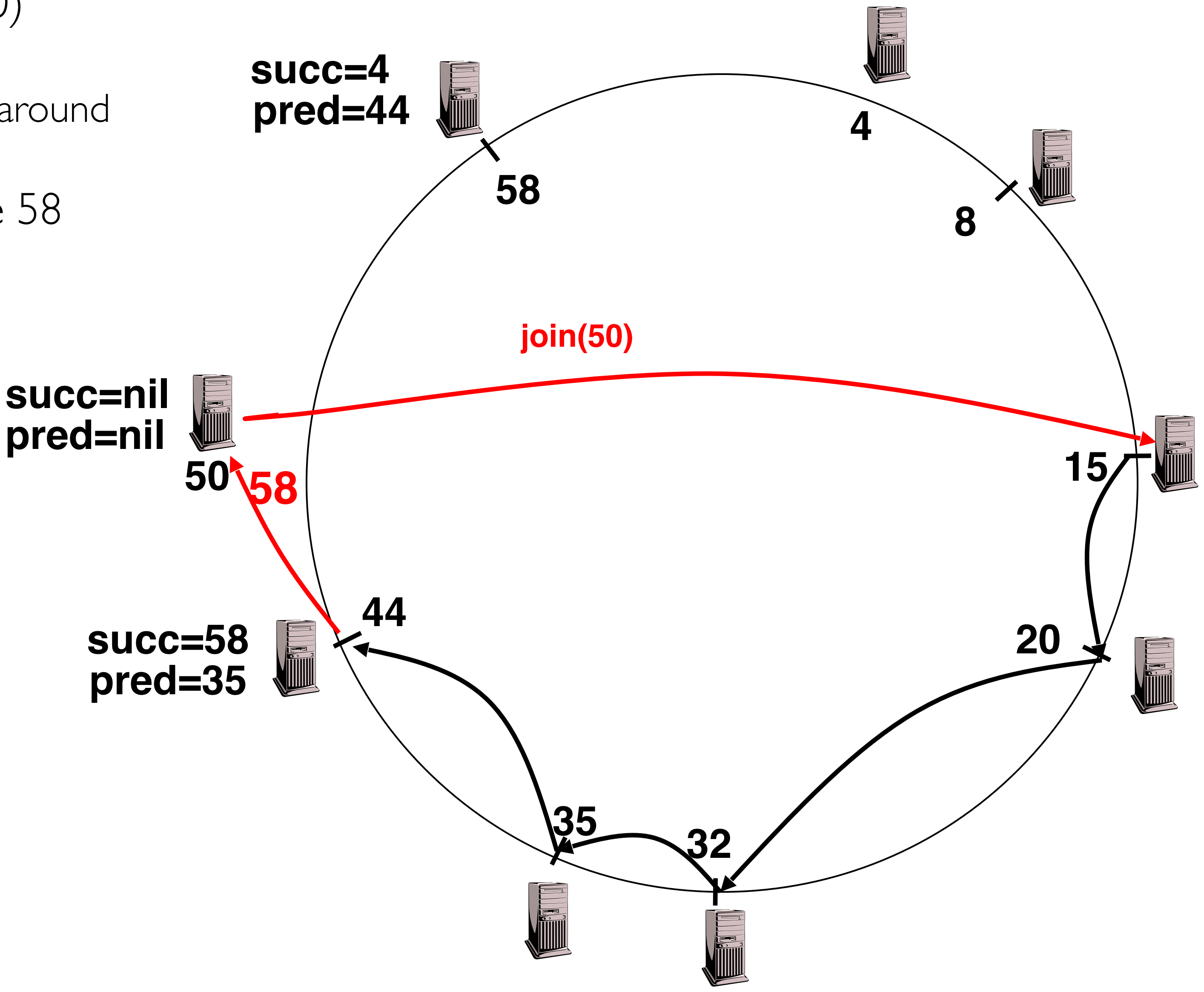


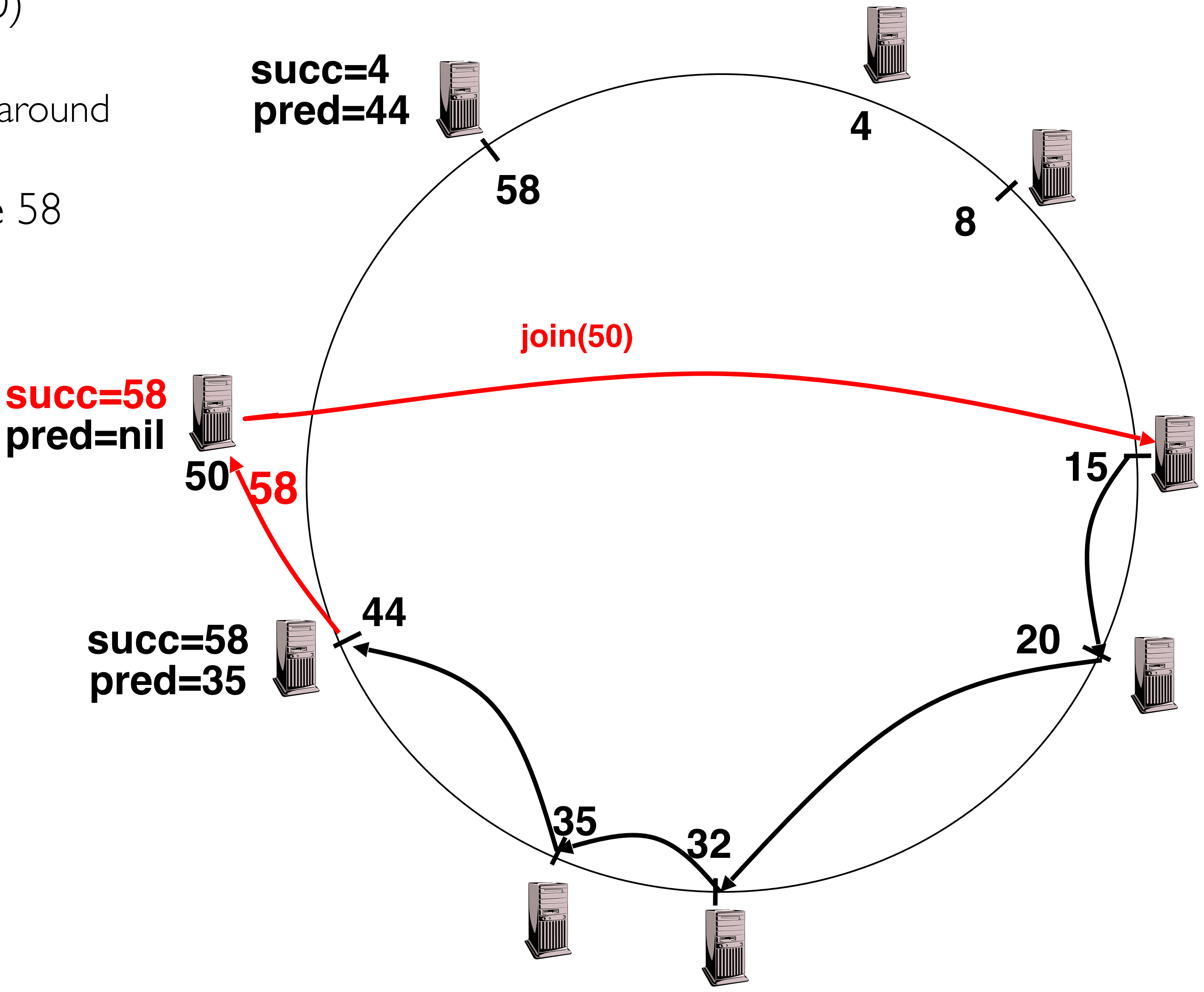
Joining Operation

- n=50 sends join(50) to node 15
  - Join propagated around ring!
- n=44 returns node 58

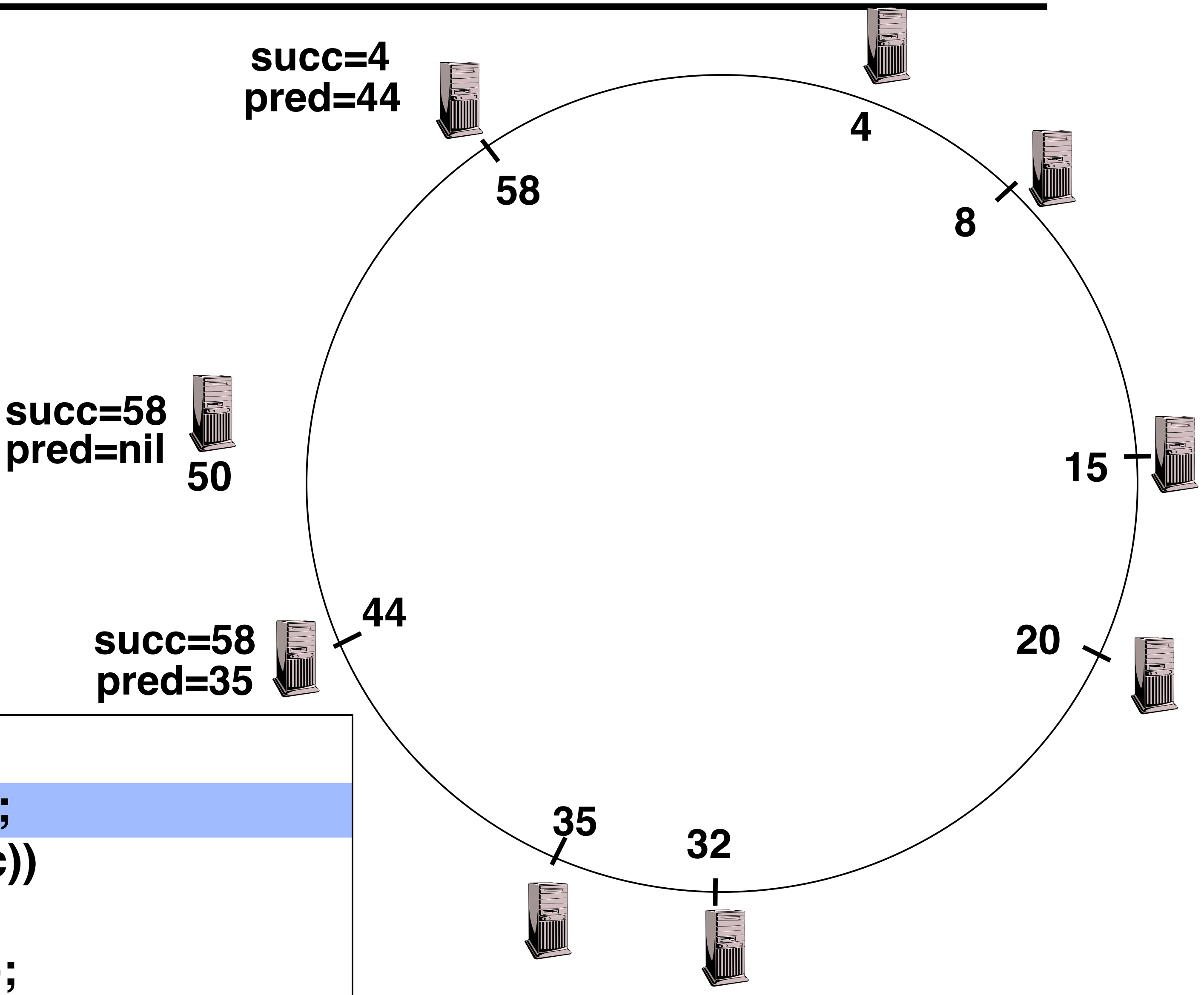


Joining Operation

- n=50 sends join(50) to node 15
  - Join propagated around ring!
- n=44 returns node 58
- n=50 updates its successor to 58



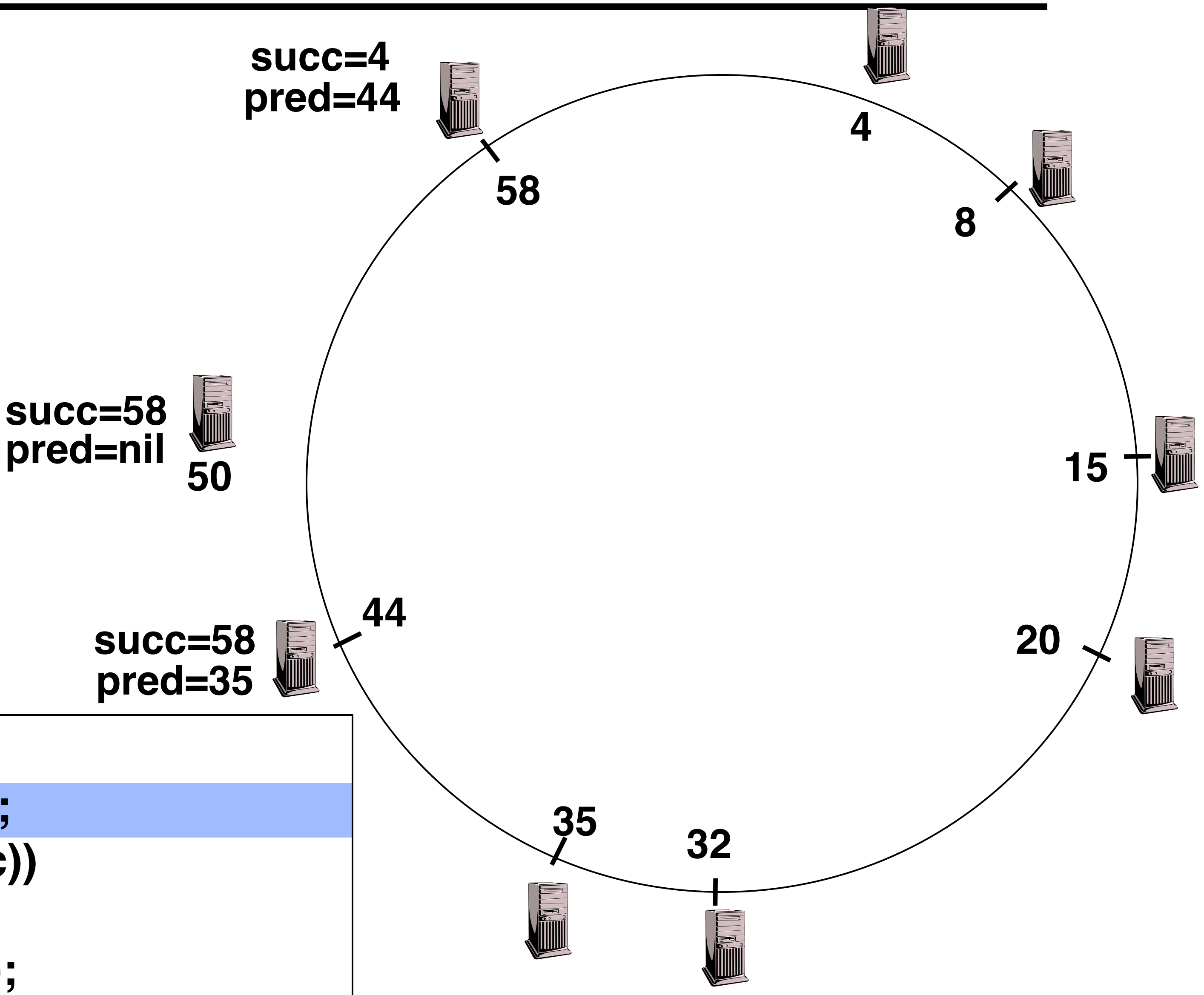
Joining Operation



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

Joining Operation

- n=50 executes stabilize()



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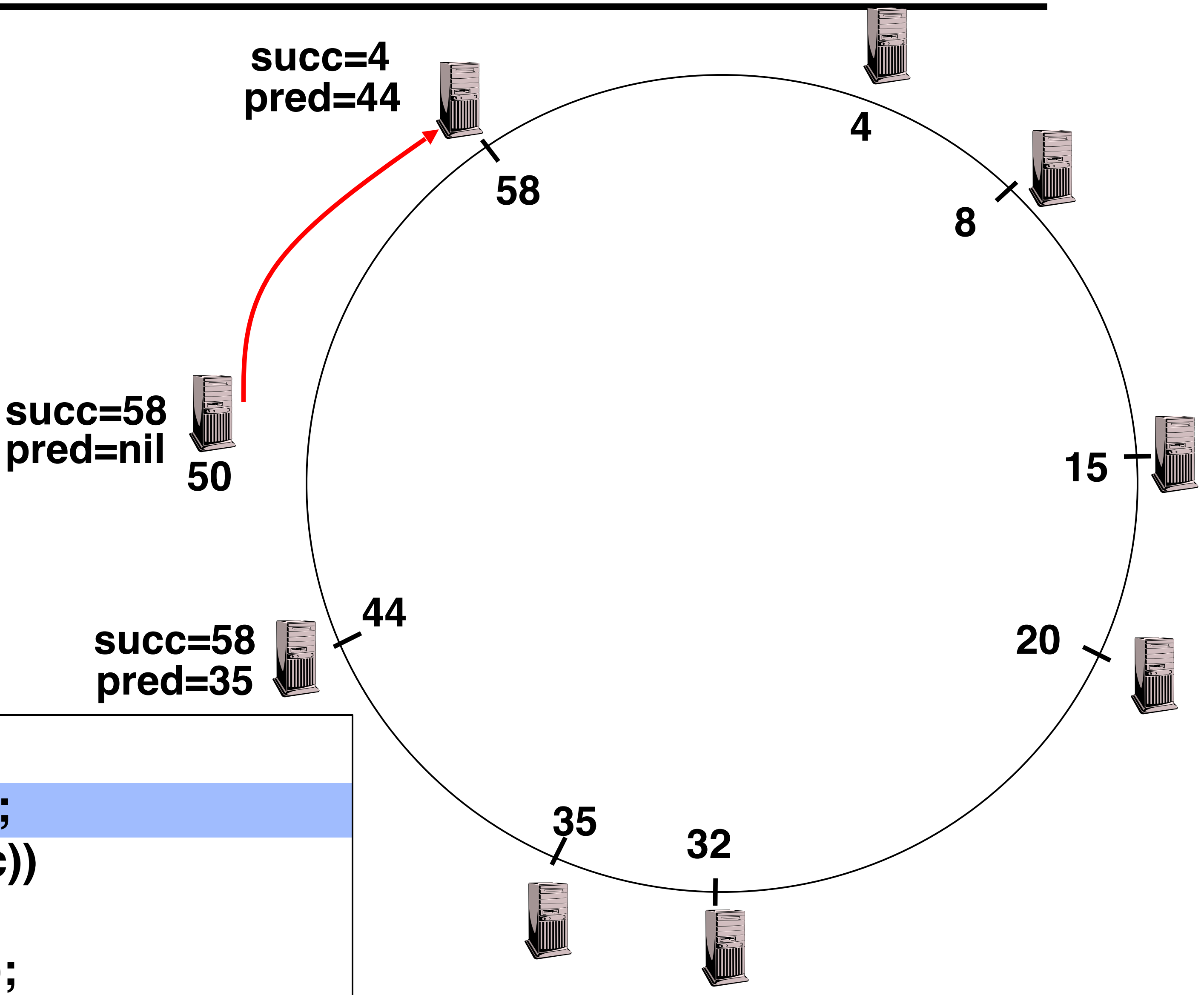
```

Joining Operation

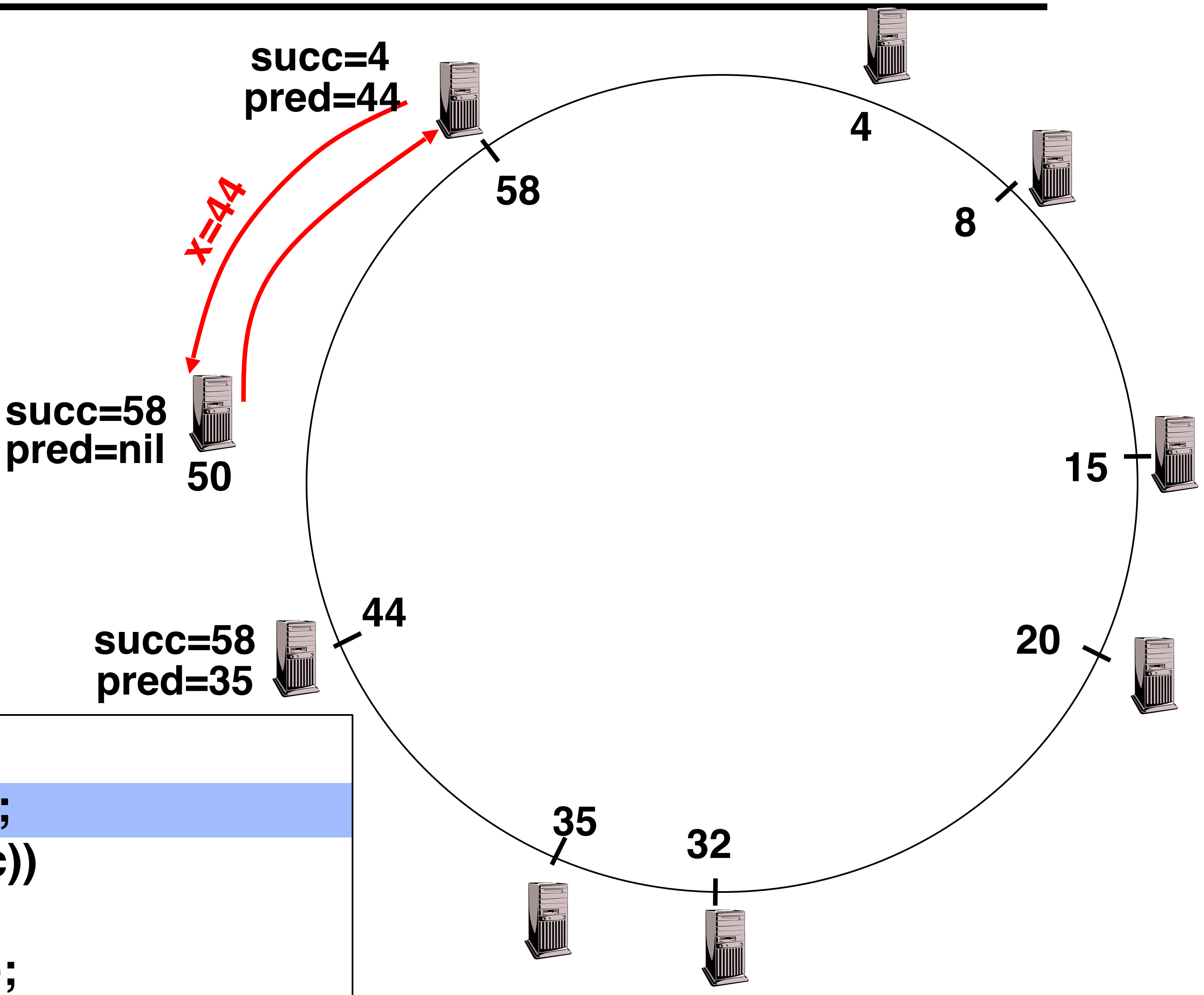
- n=50 executes stabilize()



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

Joining Operation

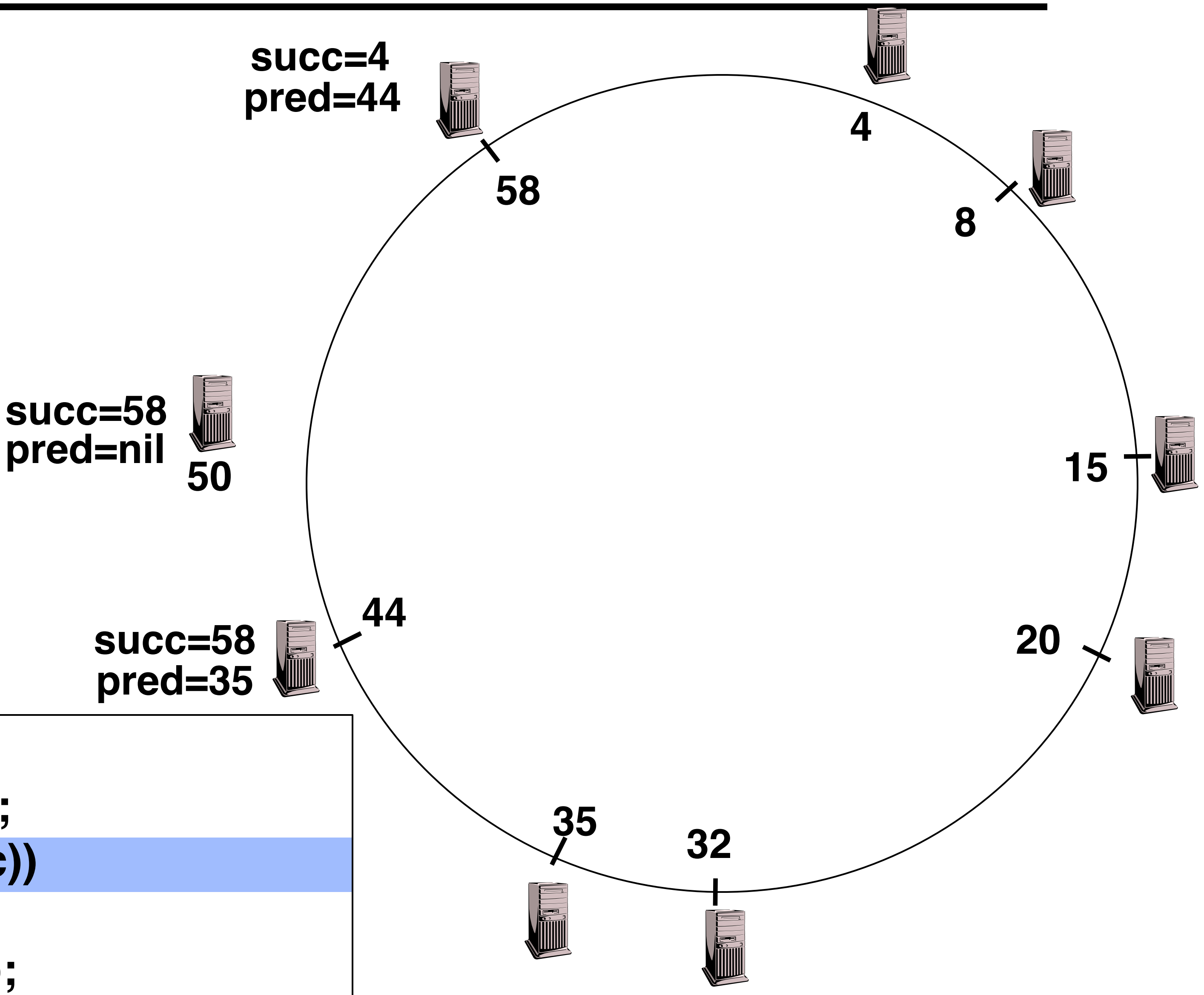
- n=50 executes stabilize()
- n's successor (58) returns x = 44



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

Joining Operation

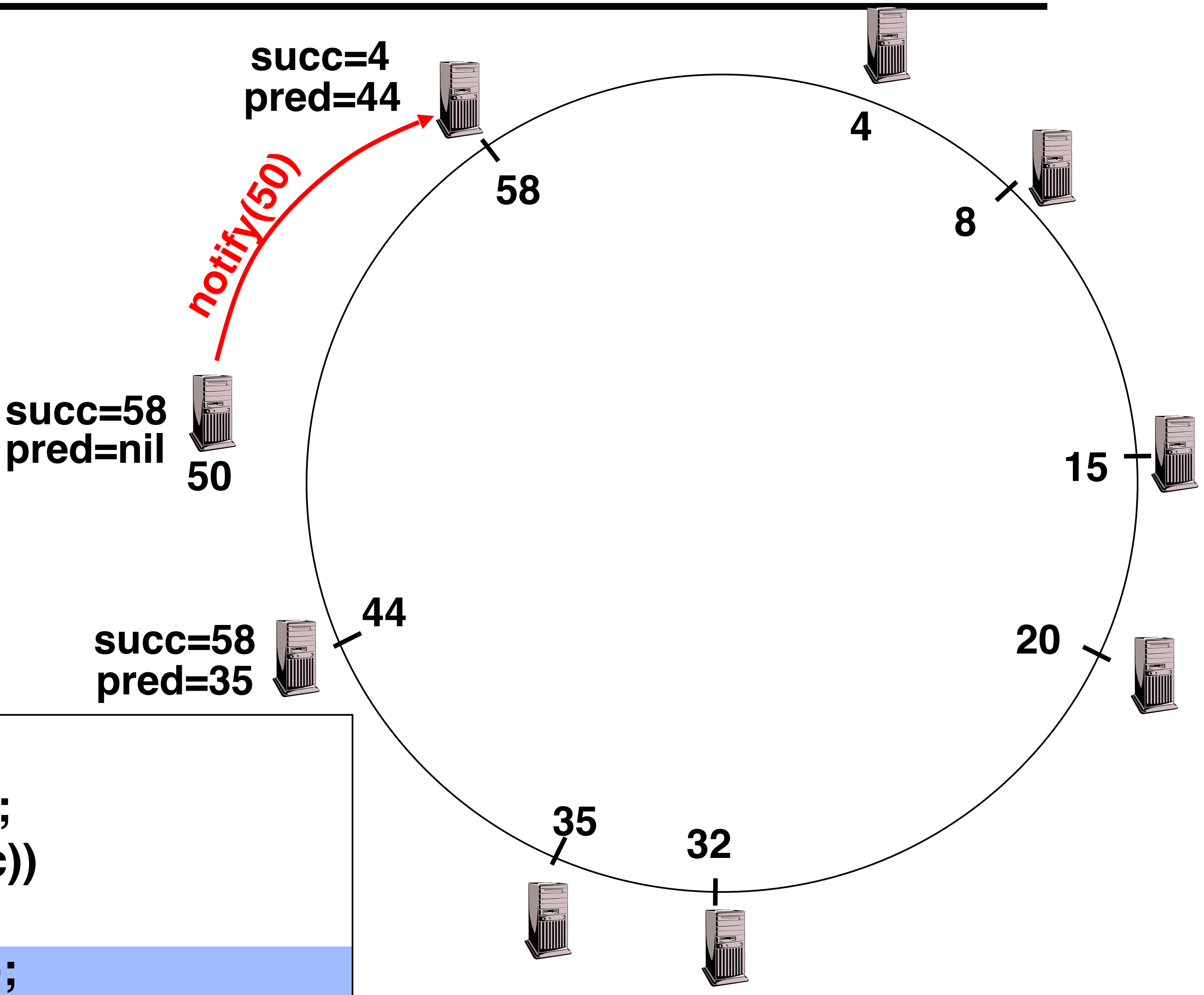
- n=50 executes stabilize()
  - x = 44
  - succ = 58



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

Joining Operation

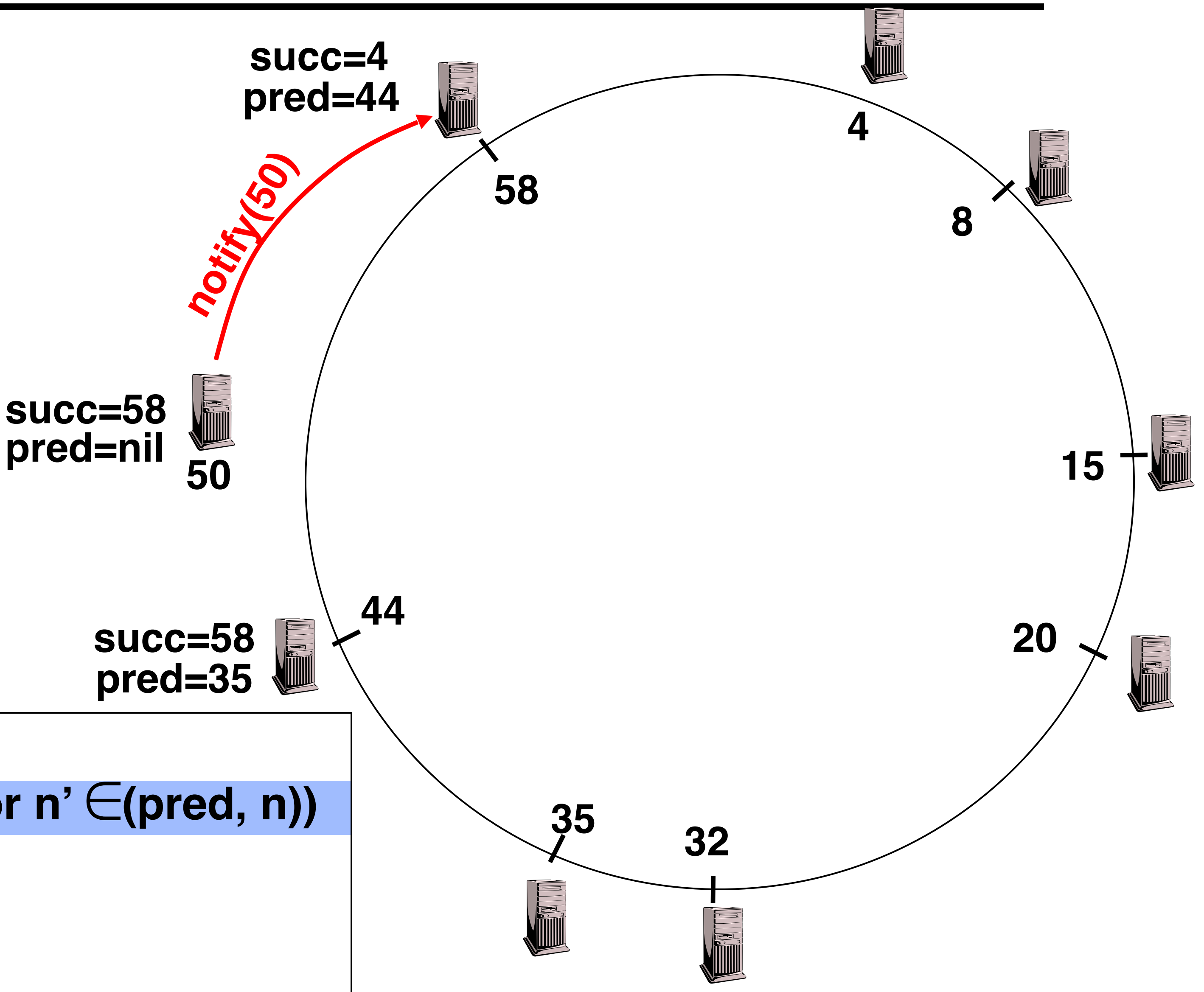
- n=50 executes stabilize()
  - x = 44
  - succ = 58
- n=50 sends to it's successor (58) notify(50)



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

Joining Operation

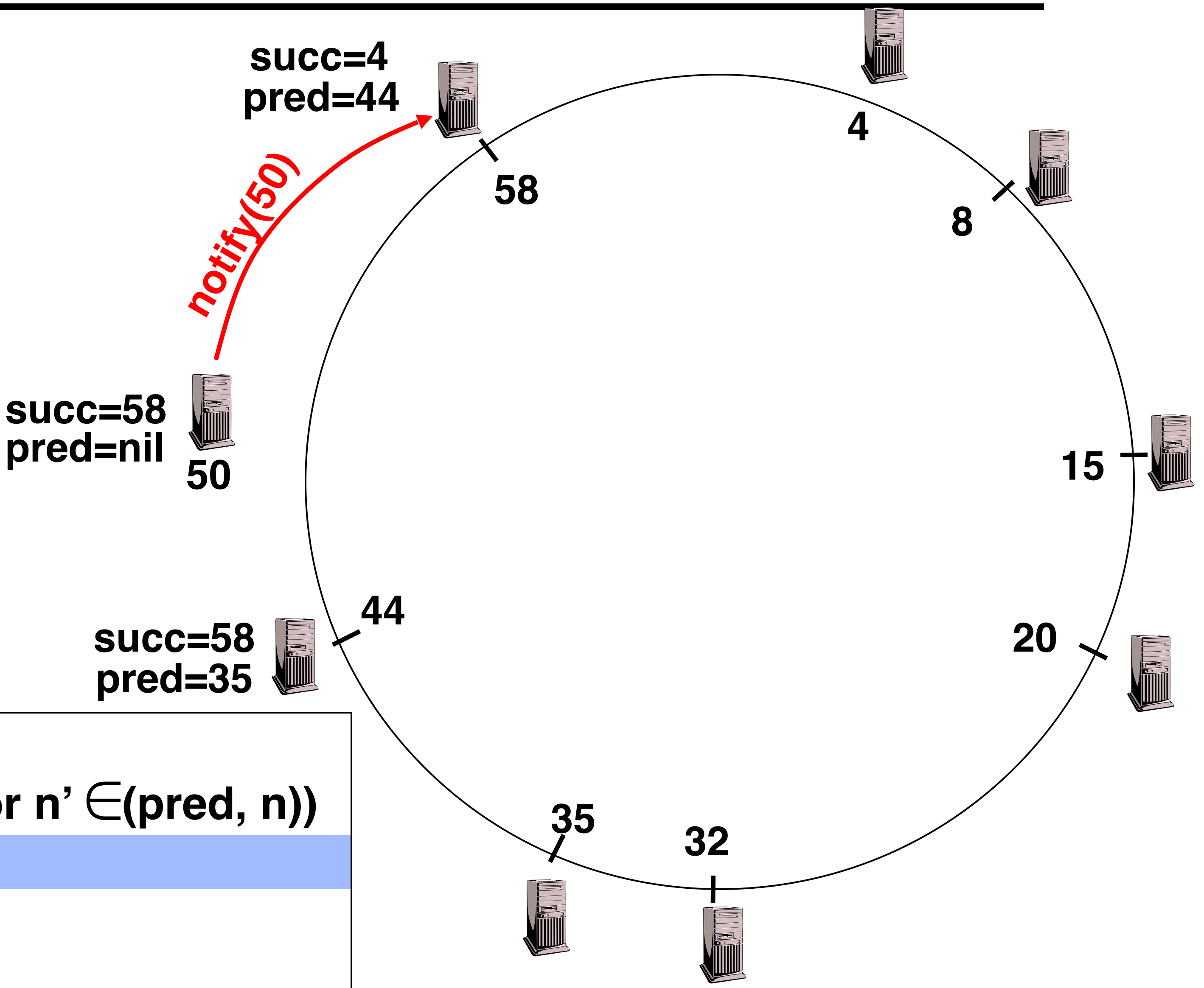
- n=58 executes notify(50)
  - pred = 44
  - n' = 50



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

Joining Operation

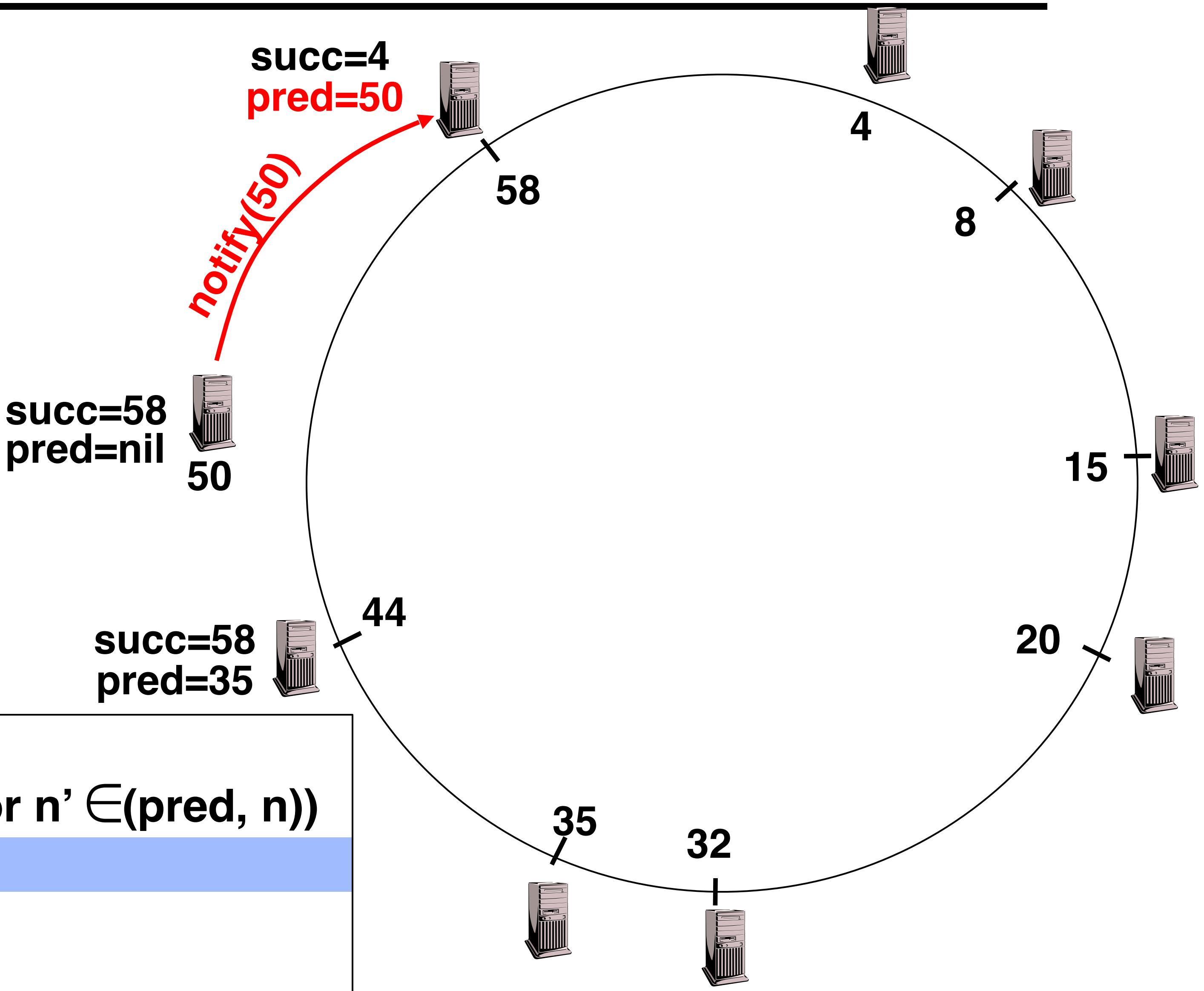
- n=58 executes notify(50)
  - pred = 44
  - n' = 50
- set pred = 50



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

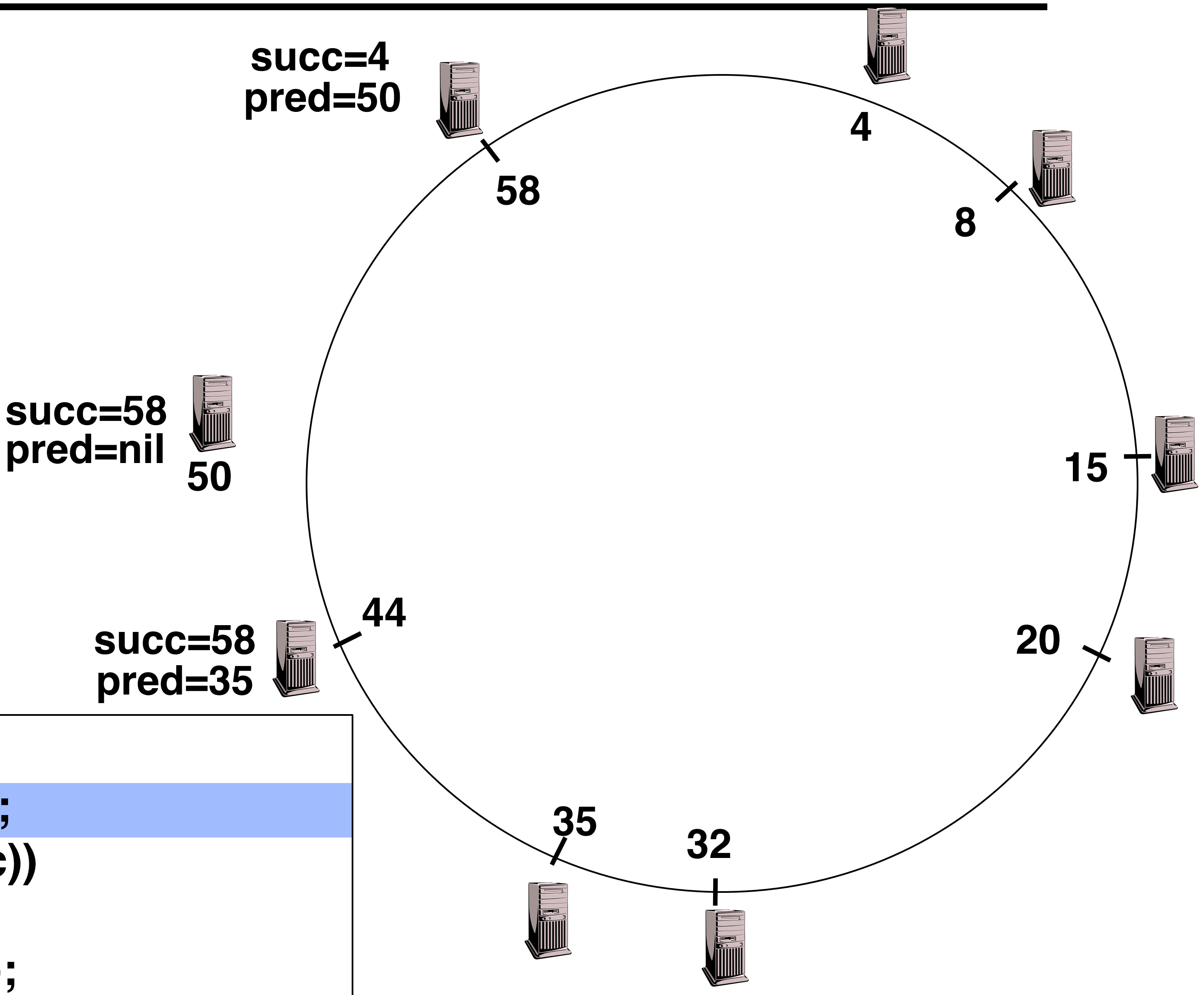
Joining Operation

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



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

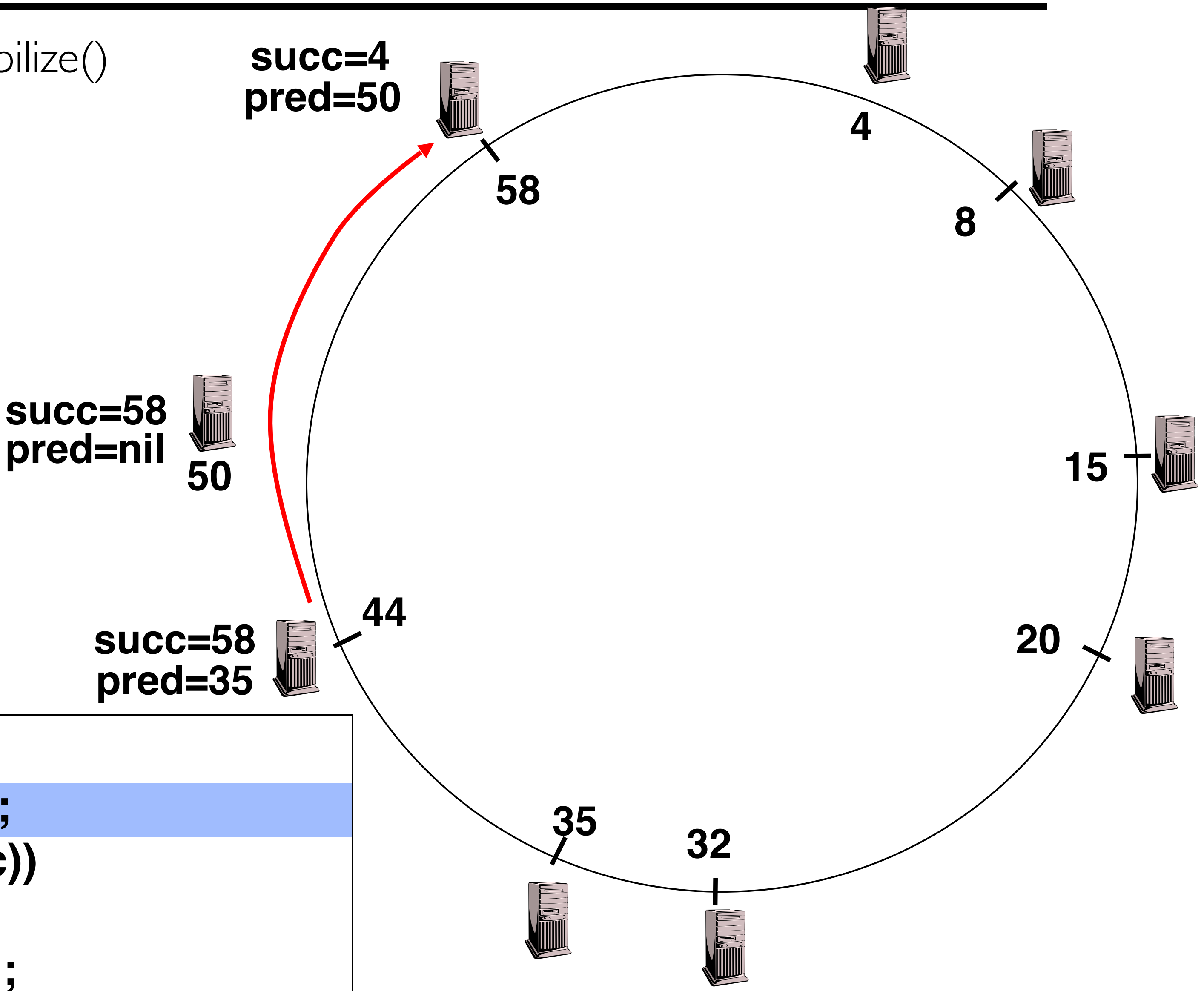
Joining Operation



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

Joining Operation

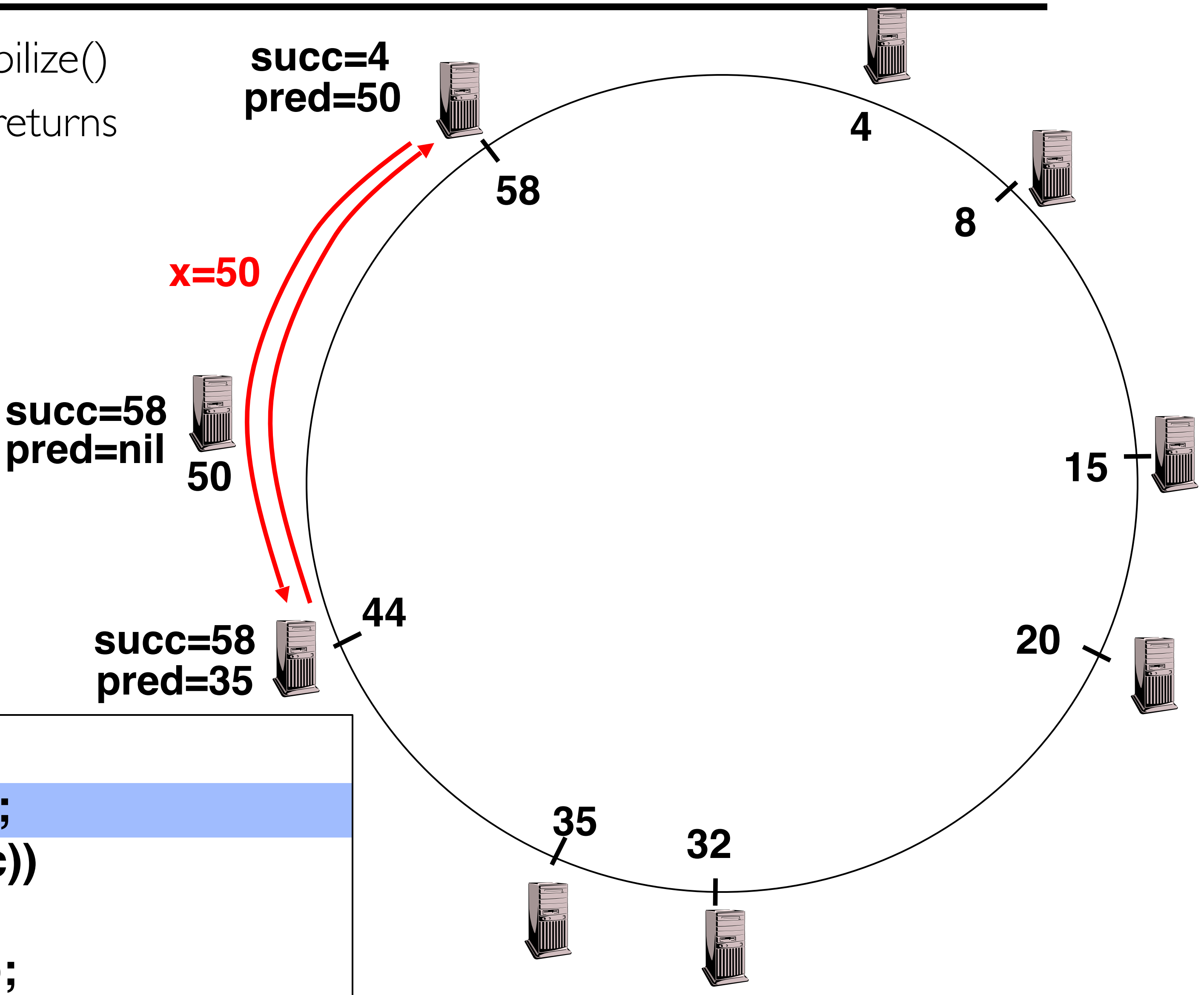
- n=44 executes stabilize()



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

Joining Operation

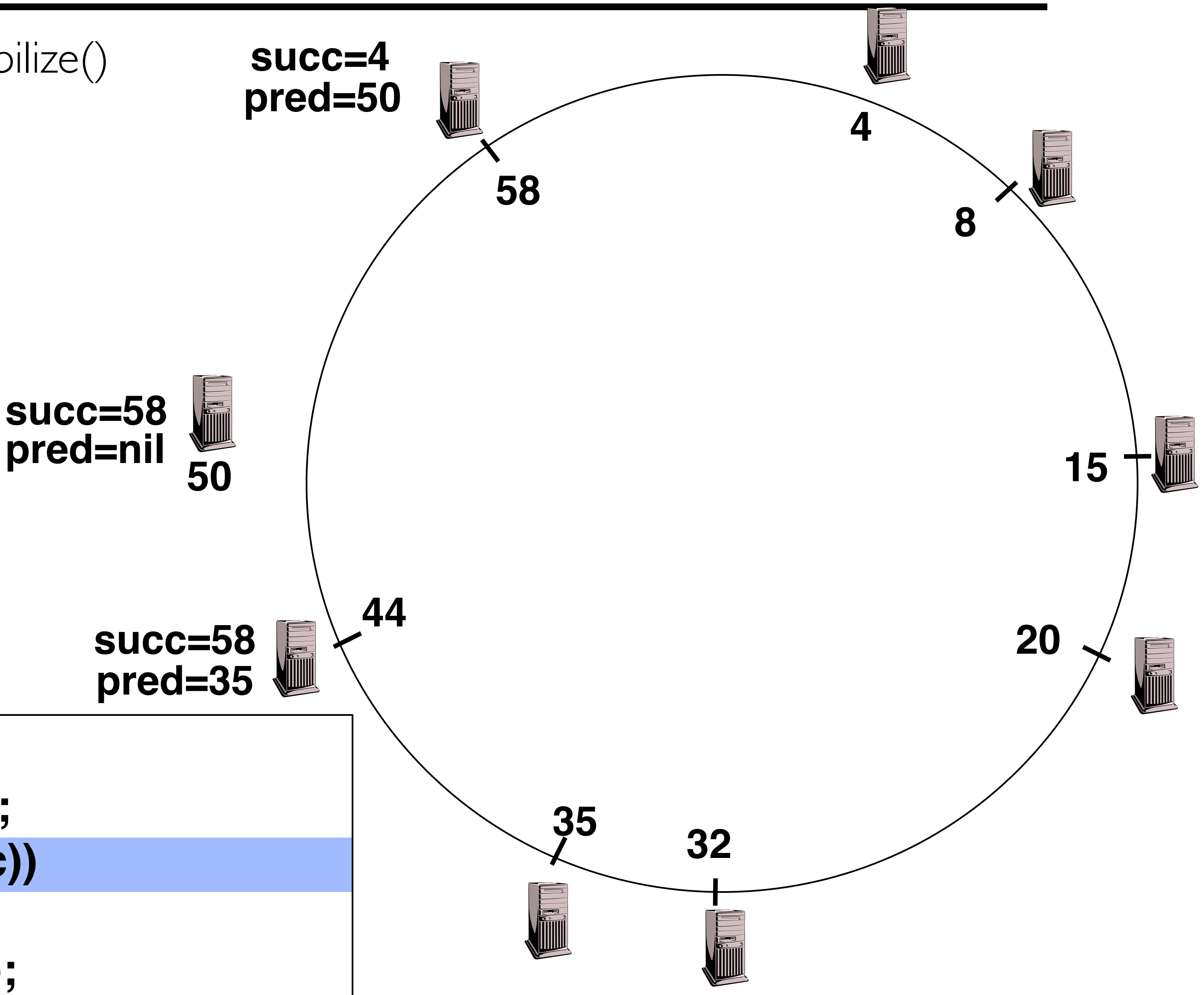
- n=44 executes stabilize()
- n's successor (58) returns x=50



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

Joining Operation

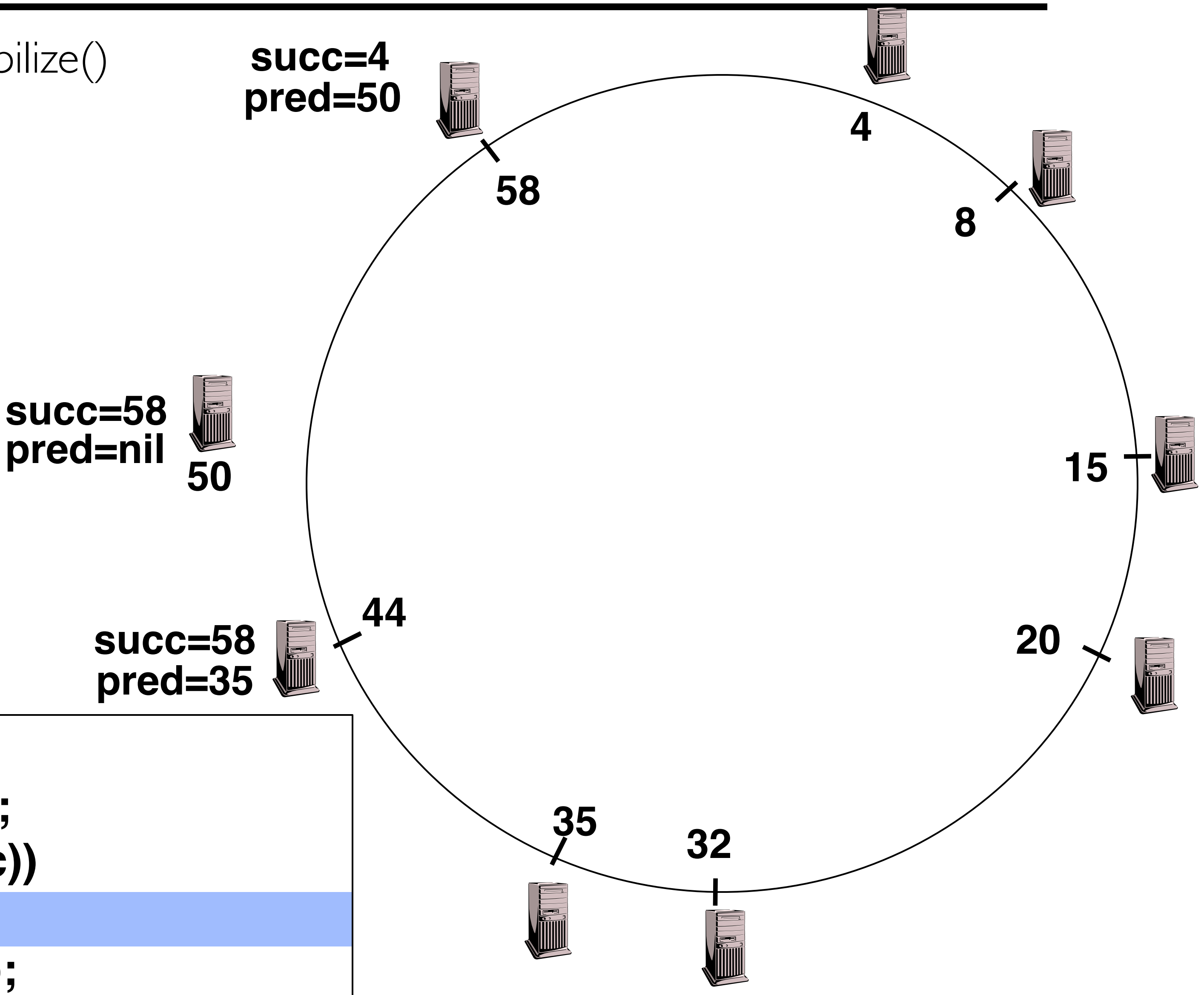
- n=44 executes stabilize()
  - x=50
  - succ=58



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

Joining Operation

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



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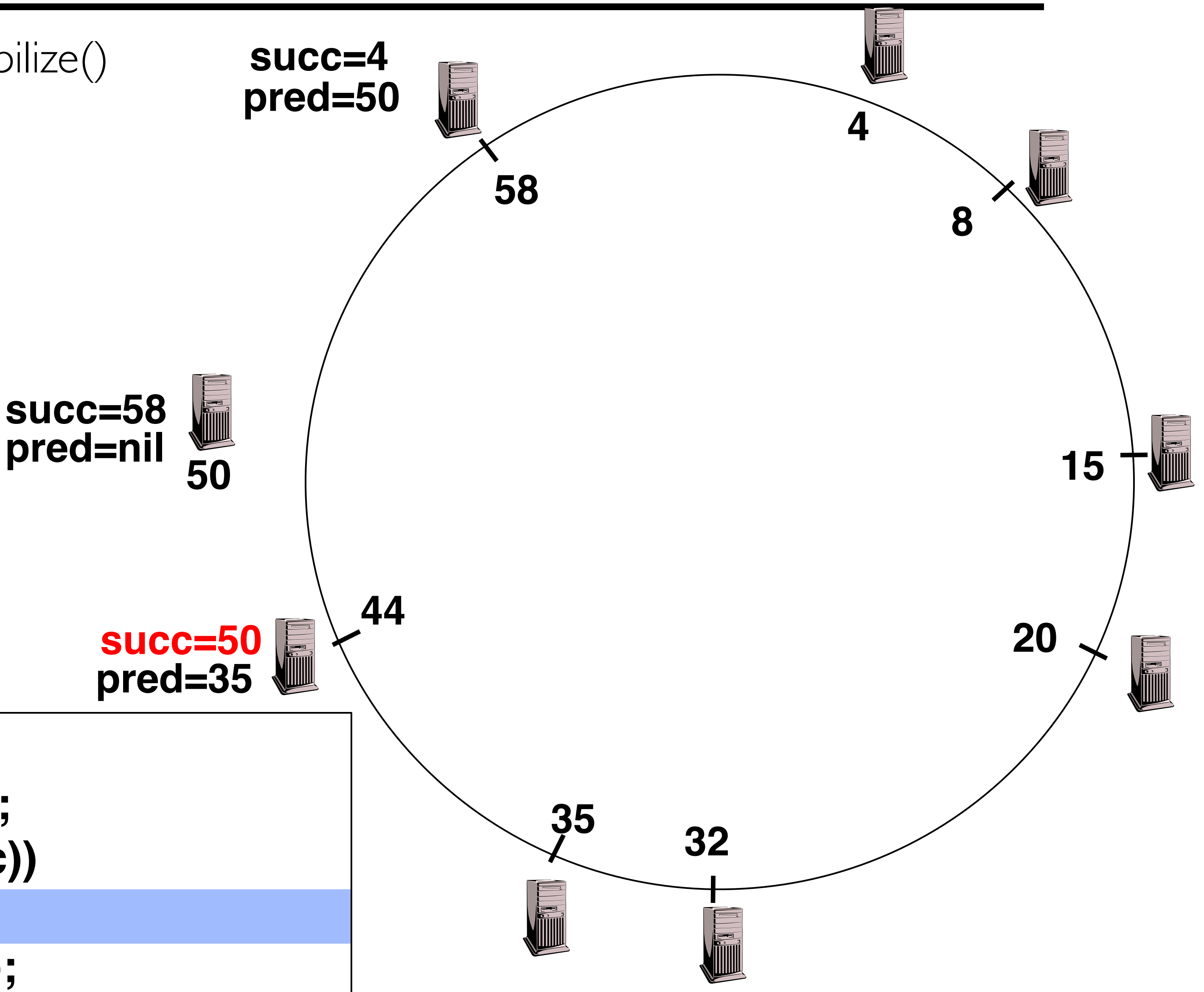

Joining Operation

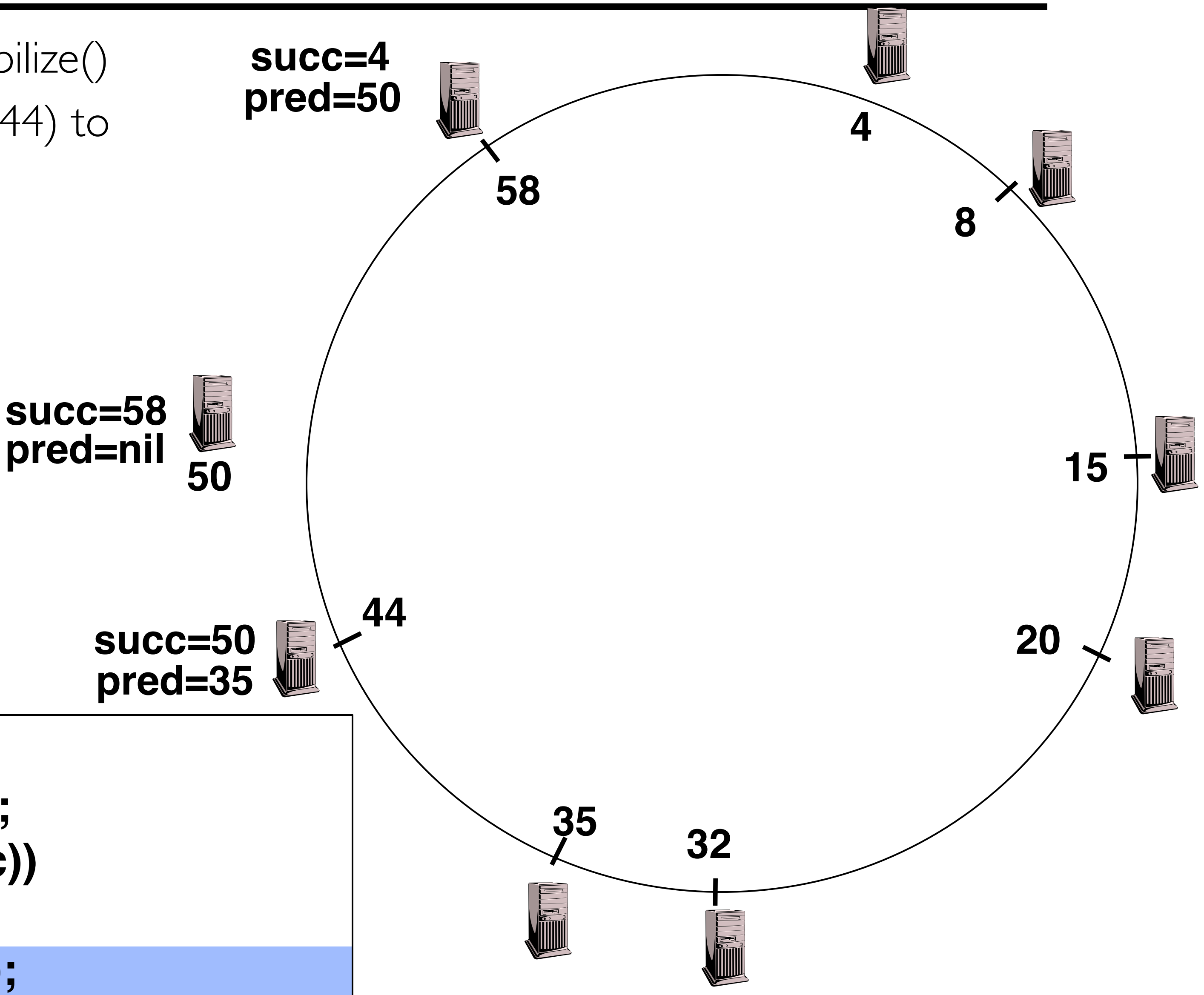
- n=44 executes stabilize()
  - x=50
  - succ=58
- n=44 sets succ=50



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

Joining Operation

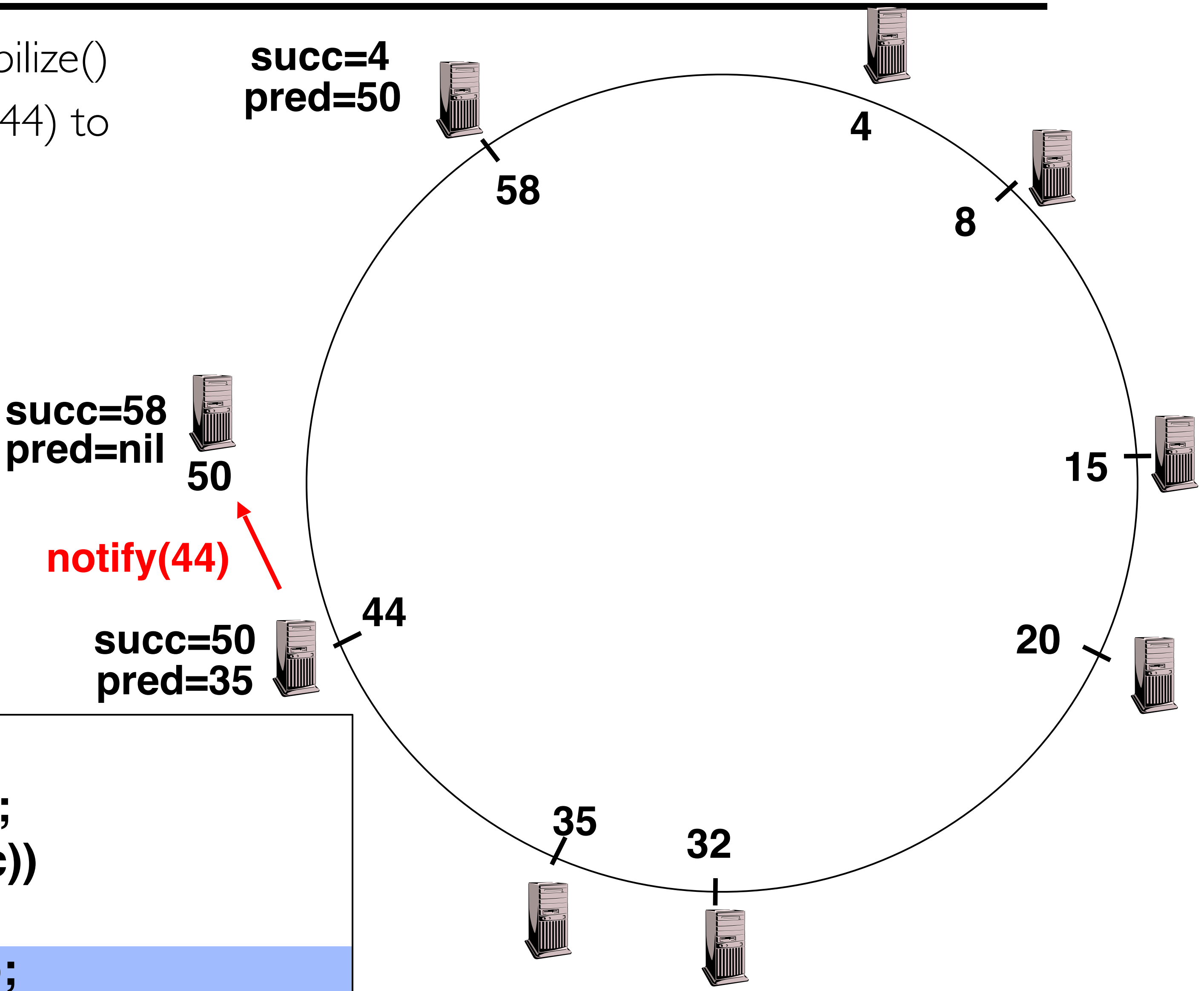
- n=44 executes stabilize()
- n=44 sends notify(44) to its successor



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

Joining Operation

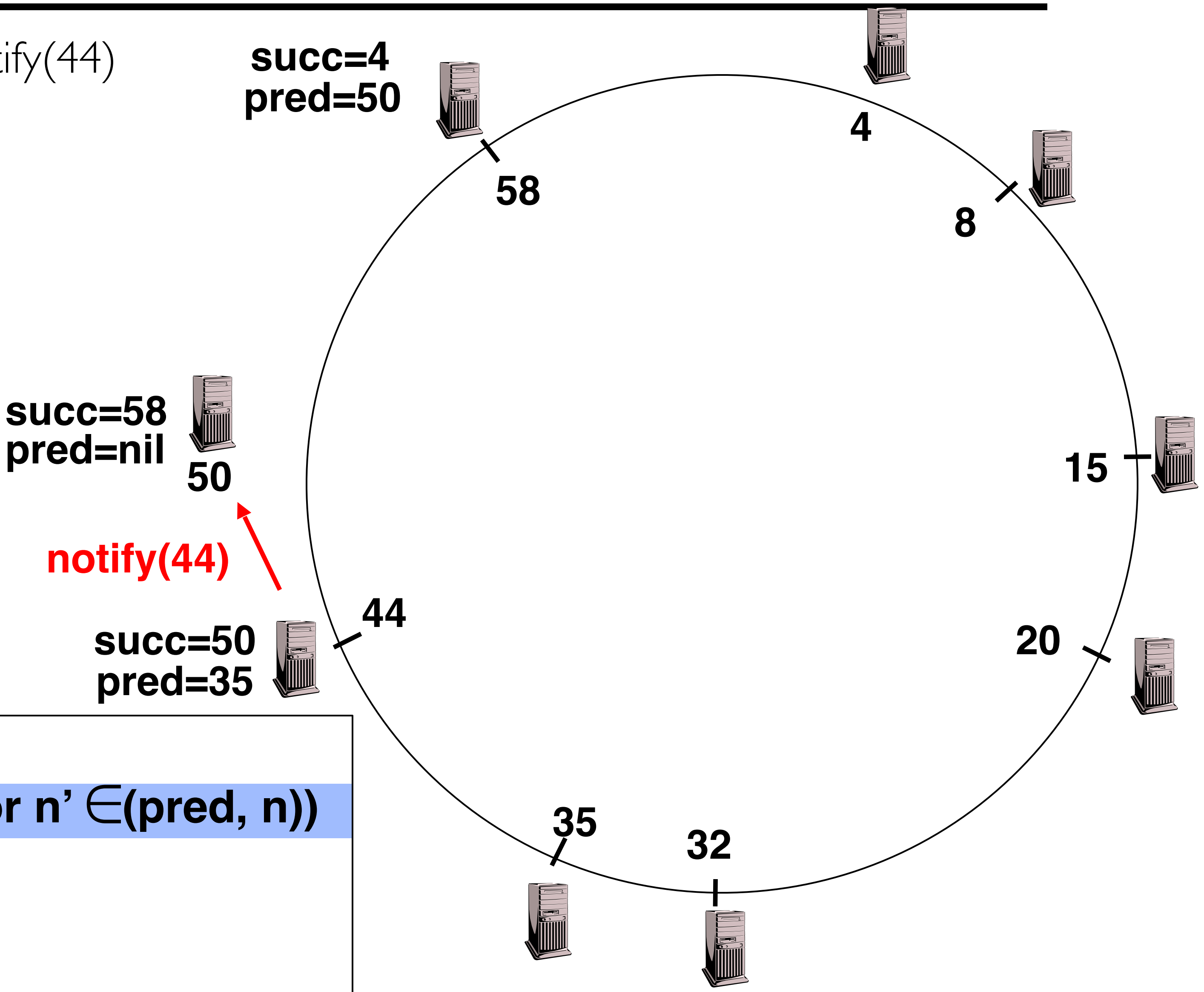
- n=44 executes stabilize()
- n=44 sends notify(44) to its successor



```
n.stabilize()
  x = succ.pred;
  if (x $\in$(n, succ))
    succ = x;
  succ.notify(n);
```

Joining Operation

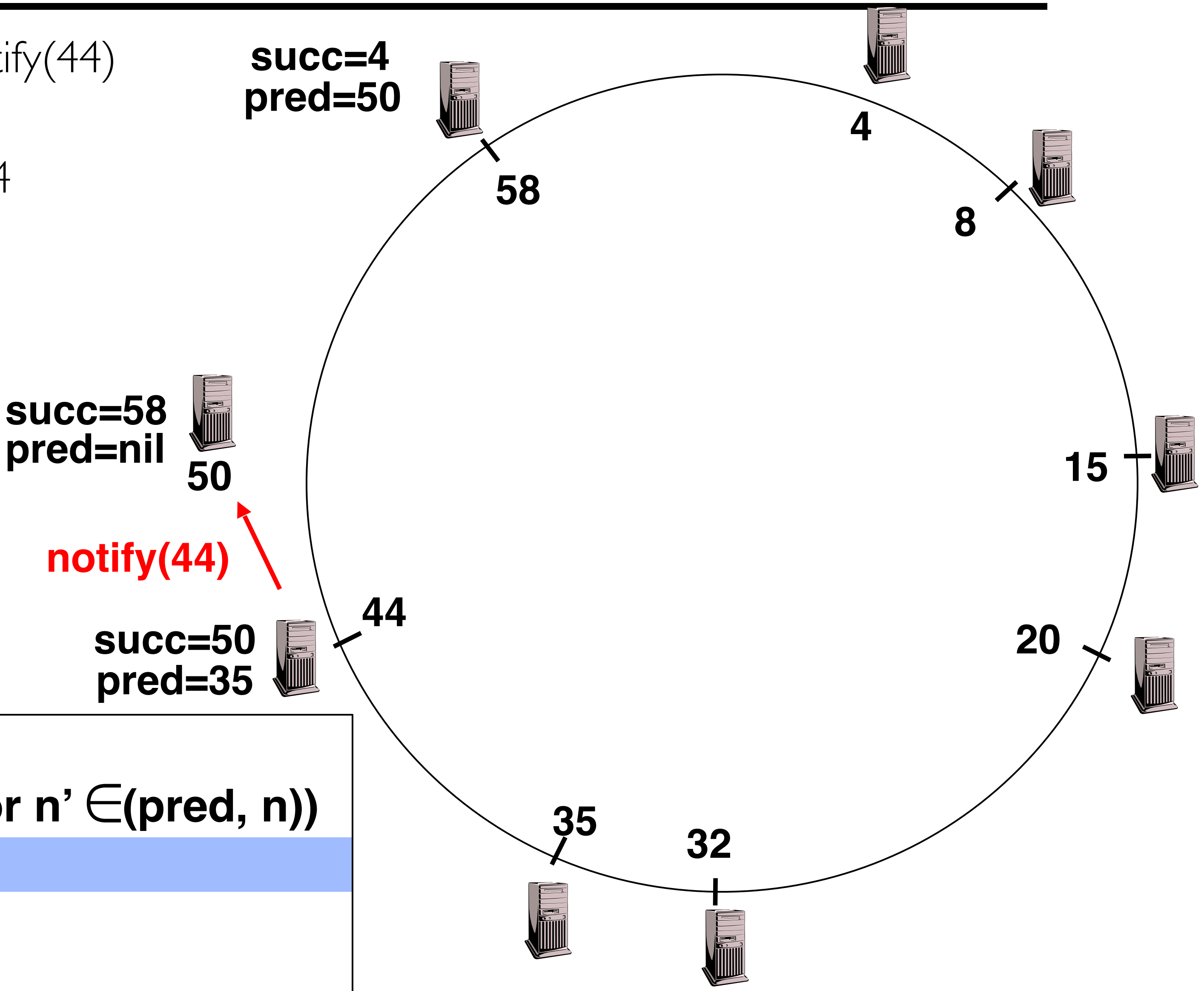
- n=50 executes notify(44)
  - pred=nil



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

Joining Operation

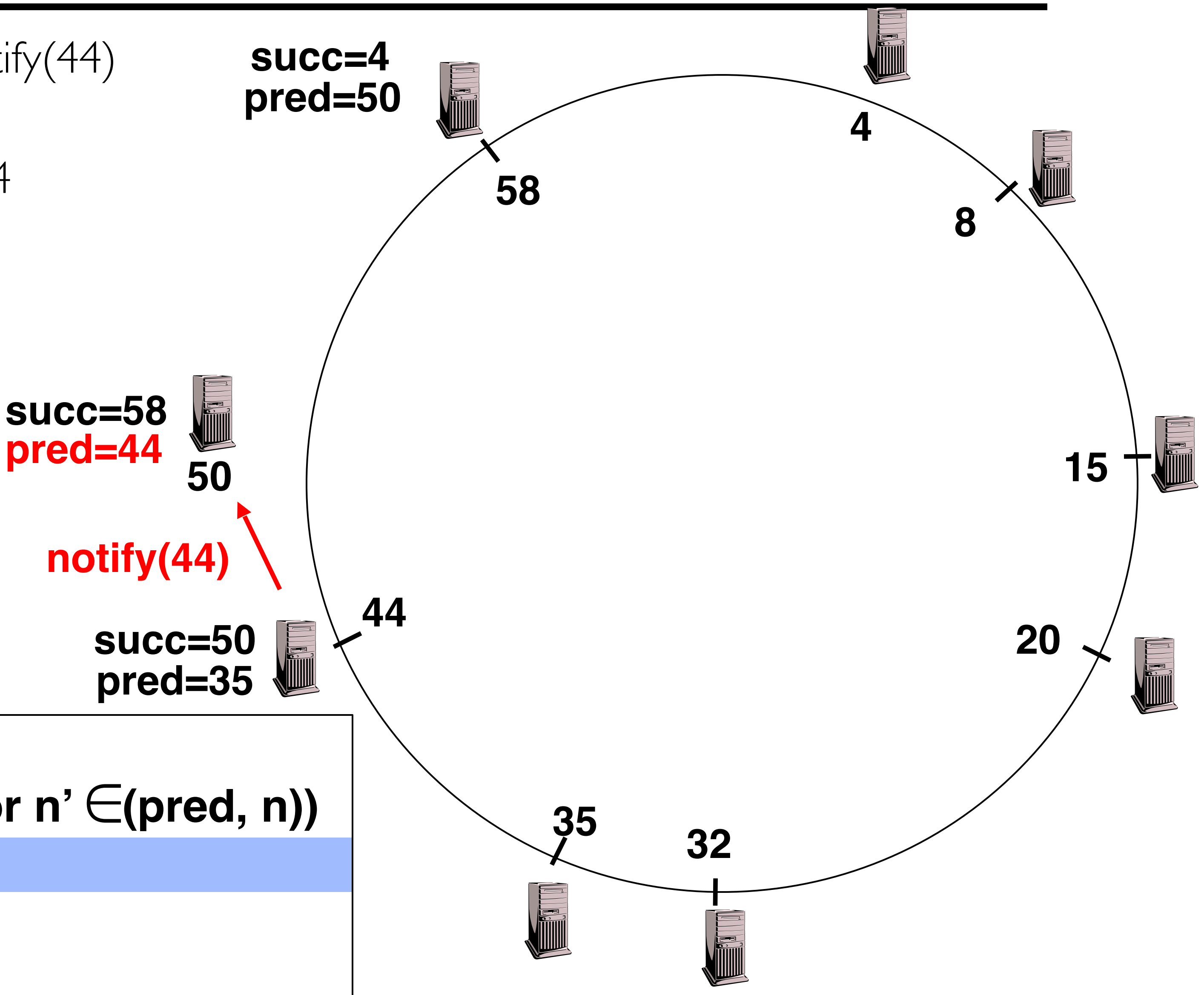
- n=50 executes notify(44)
  - pred=nil
- n=50 sets pred=44



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

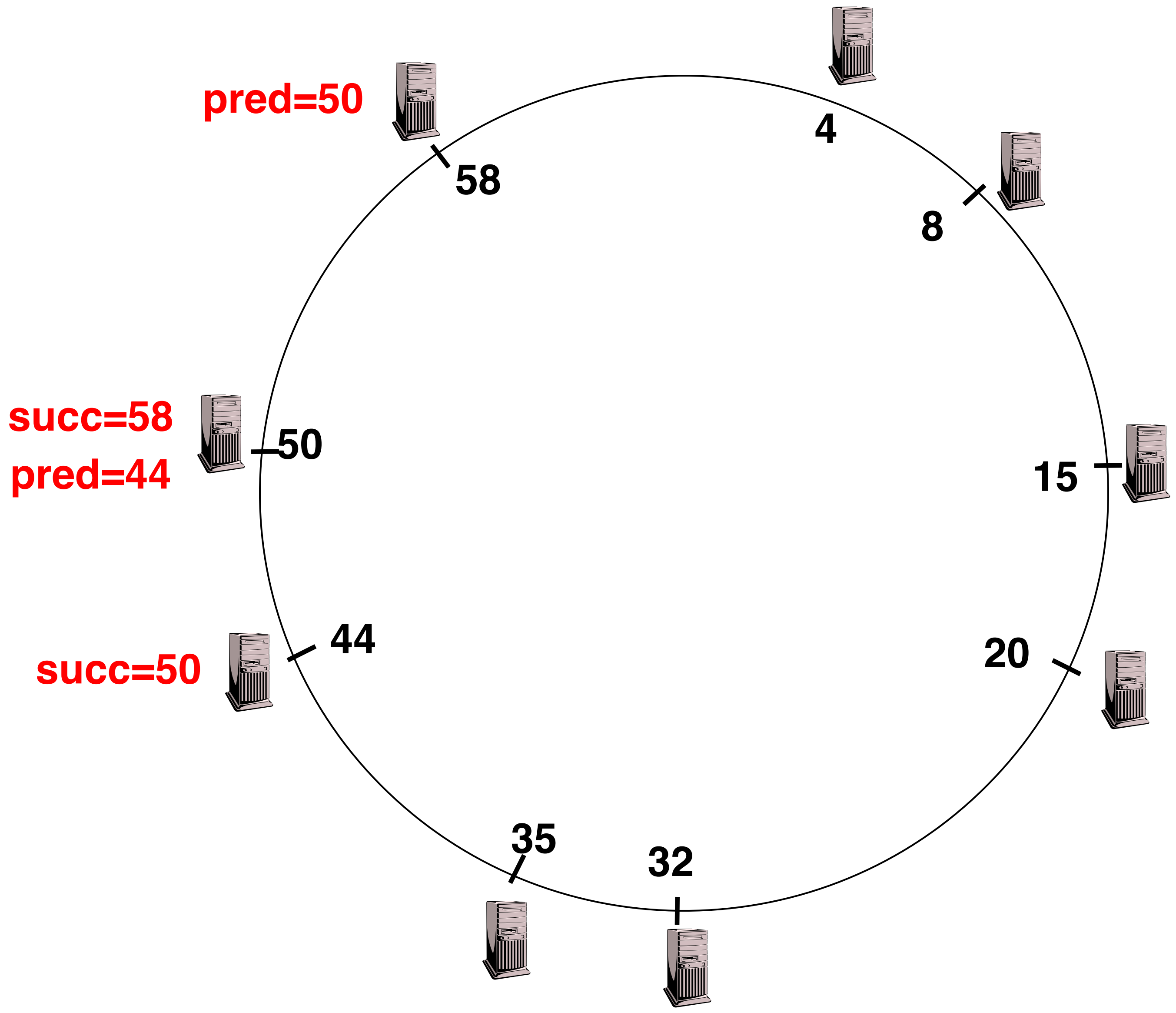
Joining Operation

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



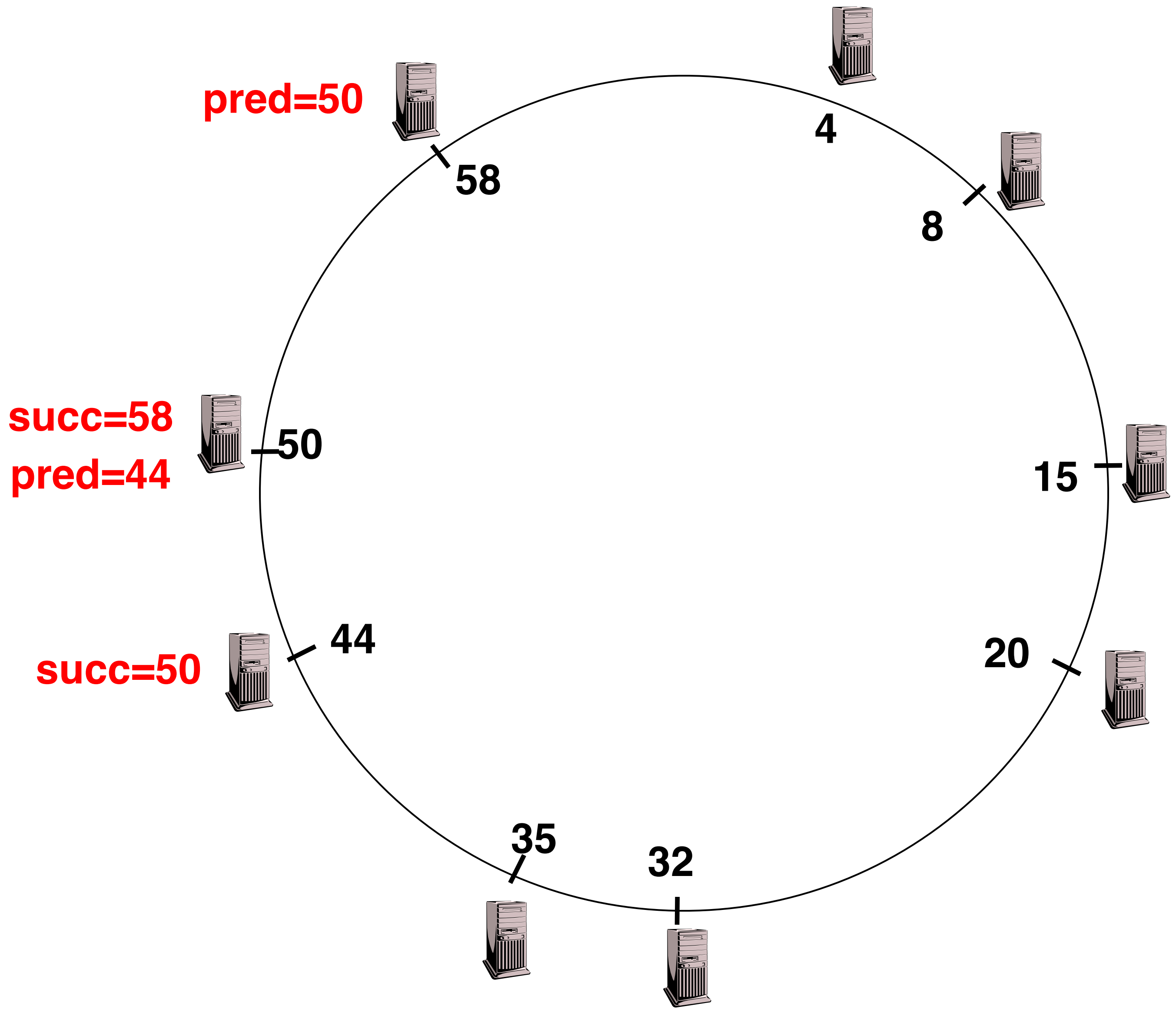
```
n.notify(n')
  if (pred = nil or n' ∈(pred, n))
      pred = n'
```

Joining Operation (cont'd)



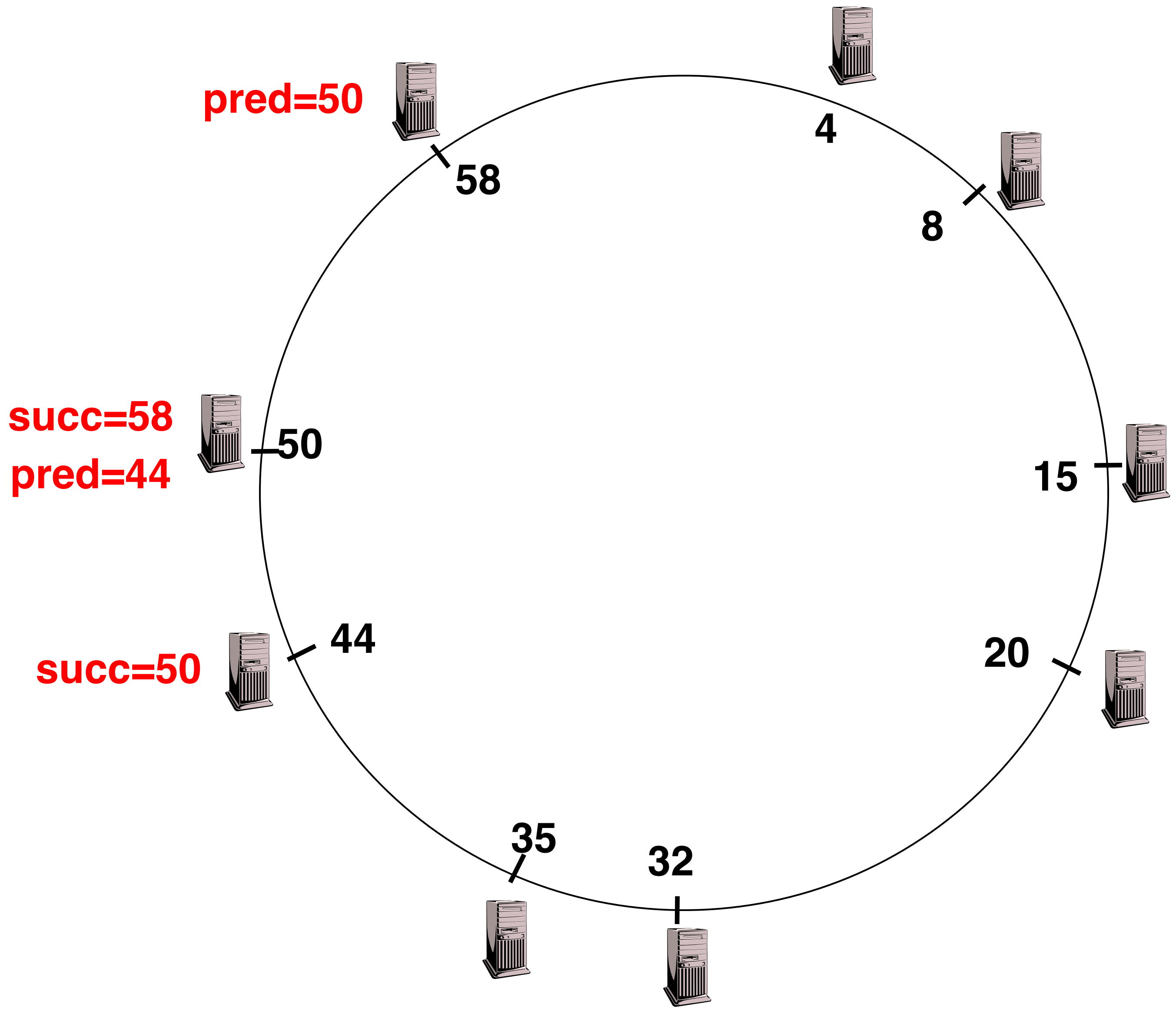
Joining Operation (cont'd)

- This completes the joining operation!



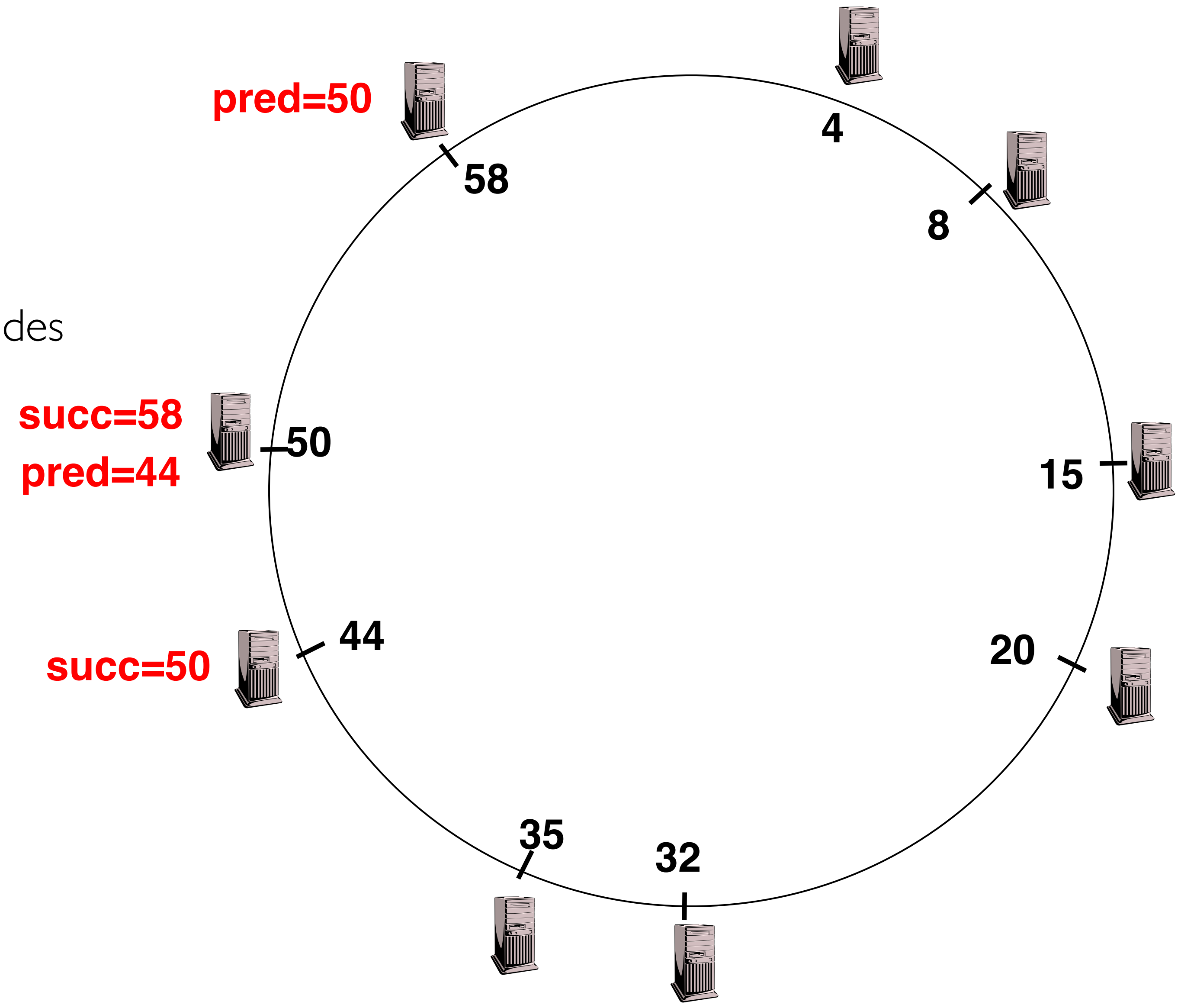
Joining Operation (cont'd)

- This completes the joining operation!
- The same stabilizing process will deal with failed nodes by reconnecting the ring



Joining Operation (cont'd)

- This completes the joining operation!
- The same stabilizing process will deal with failed nodes by reconnecting the ring
- What if 2 or more nodes in a row fail?
  - Keep track of more neighbors!
  - Called the "leaf set"

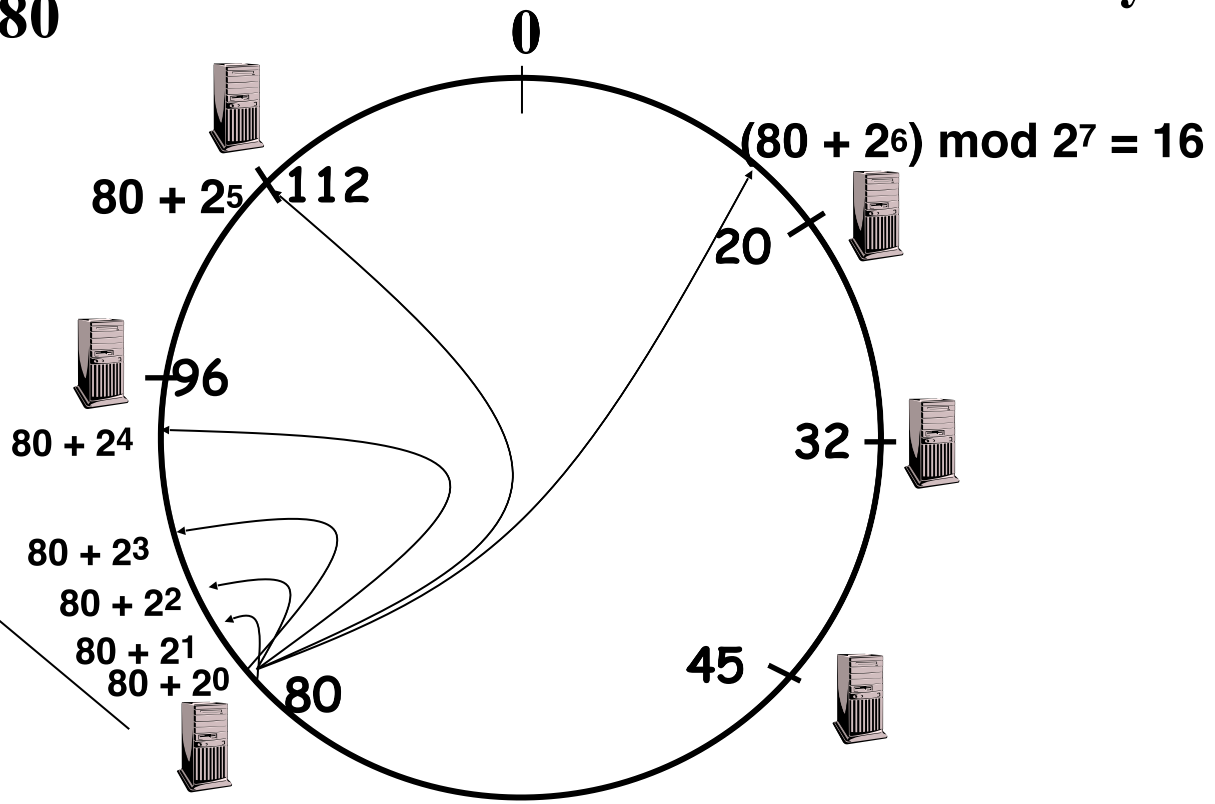


Achieving Efficiency: *finger tables*

Say *m*=7

Finger Table at 80

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



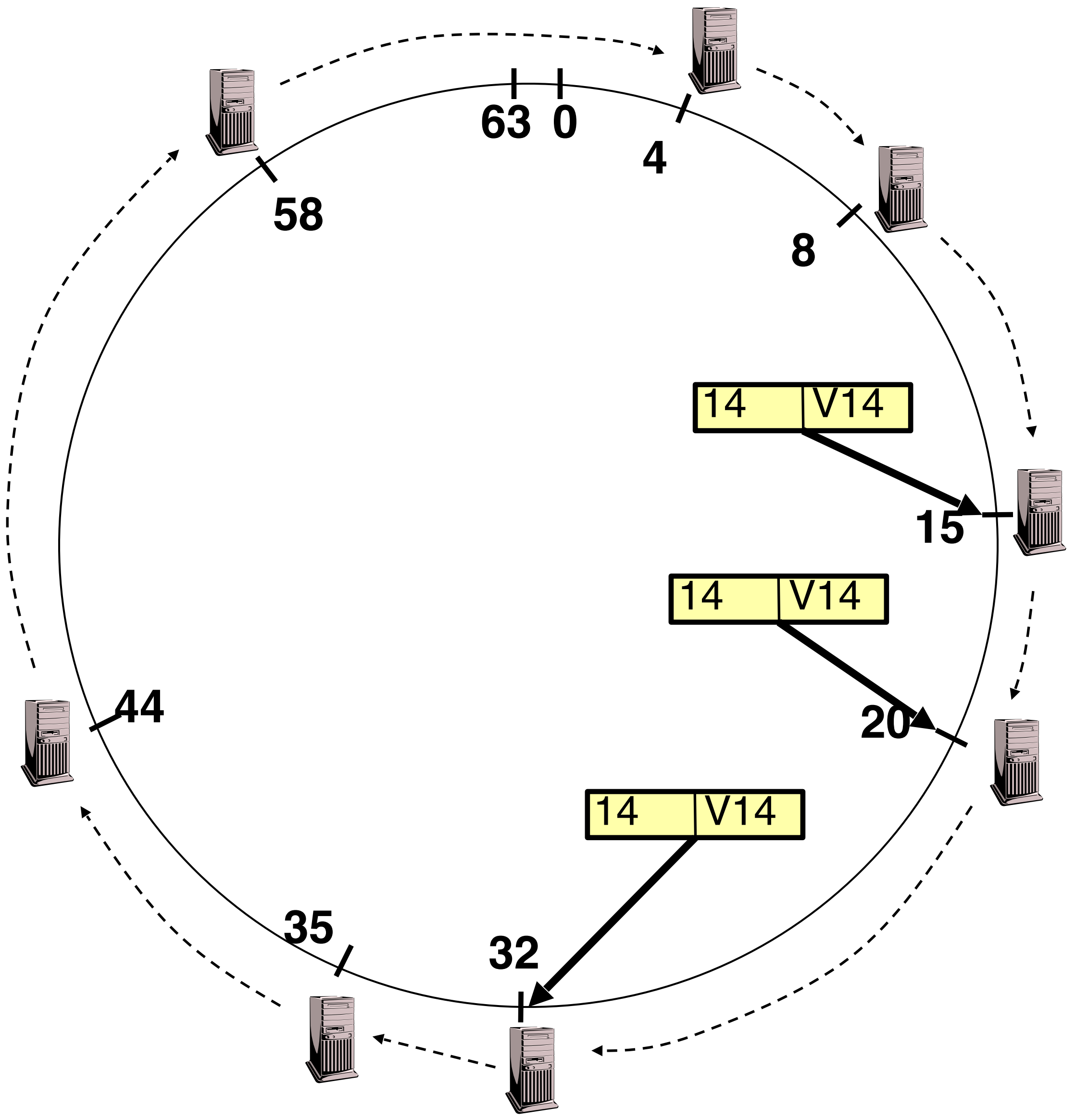
*i*th entry at peer with id *n* is first peer with id >= $n + 2^i \pmod{2^m}$

Achieving Fault Tolerance for Lookup Service

- To improve robustness each node maintains the k (> 1) immediate successors instead of only one successor
  - Again – called the "leaf set"
  - 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

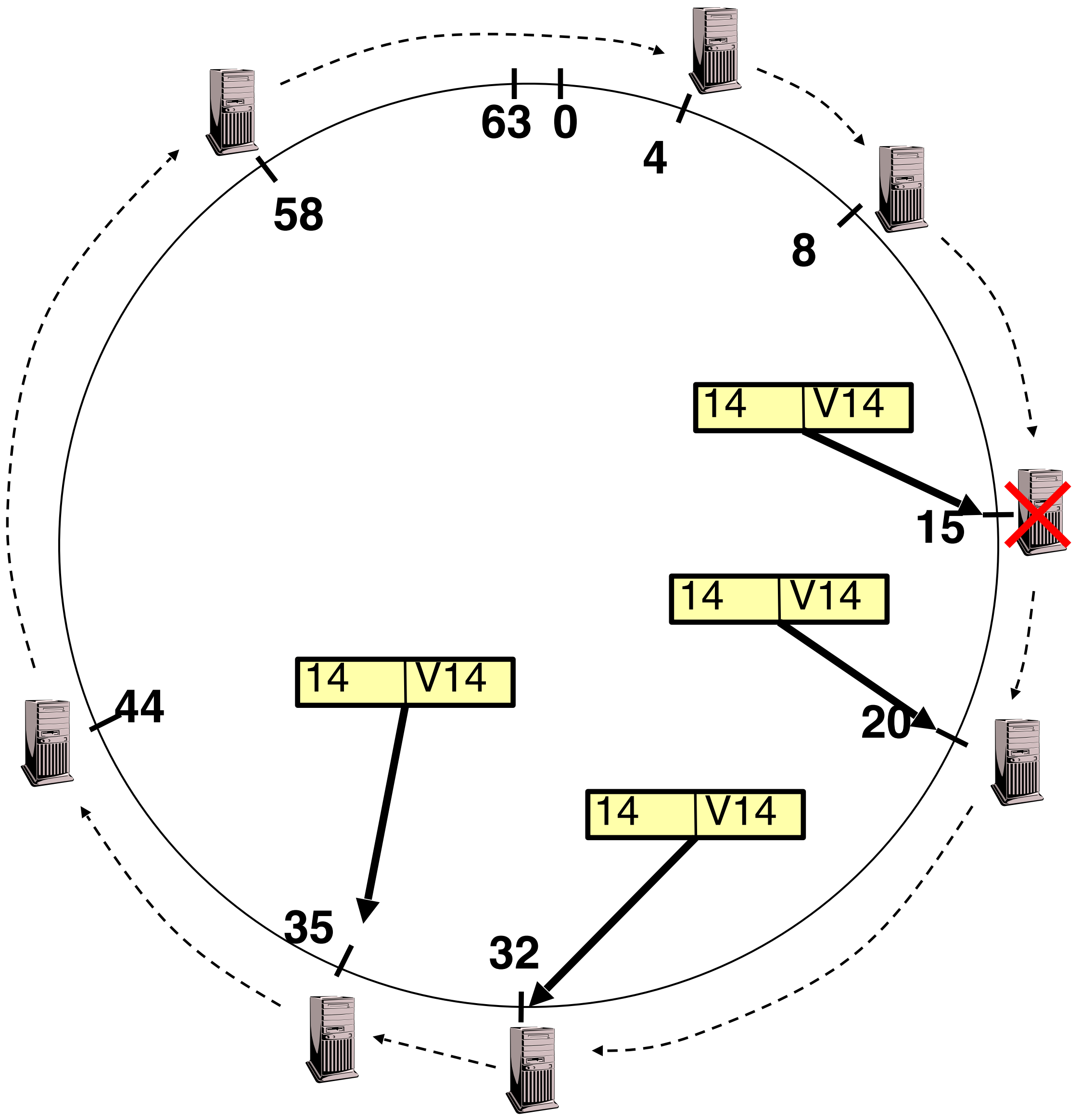
Storage Fault Tolerance

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

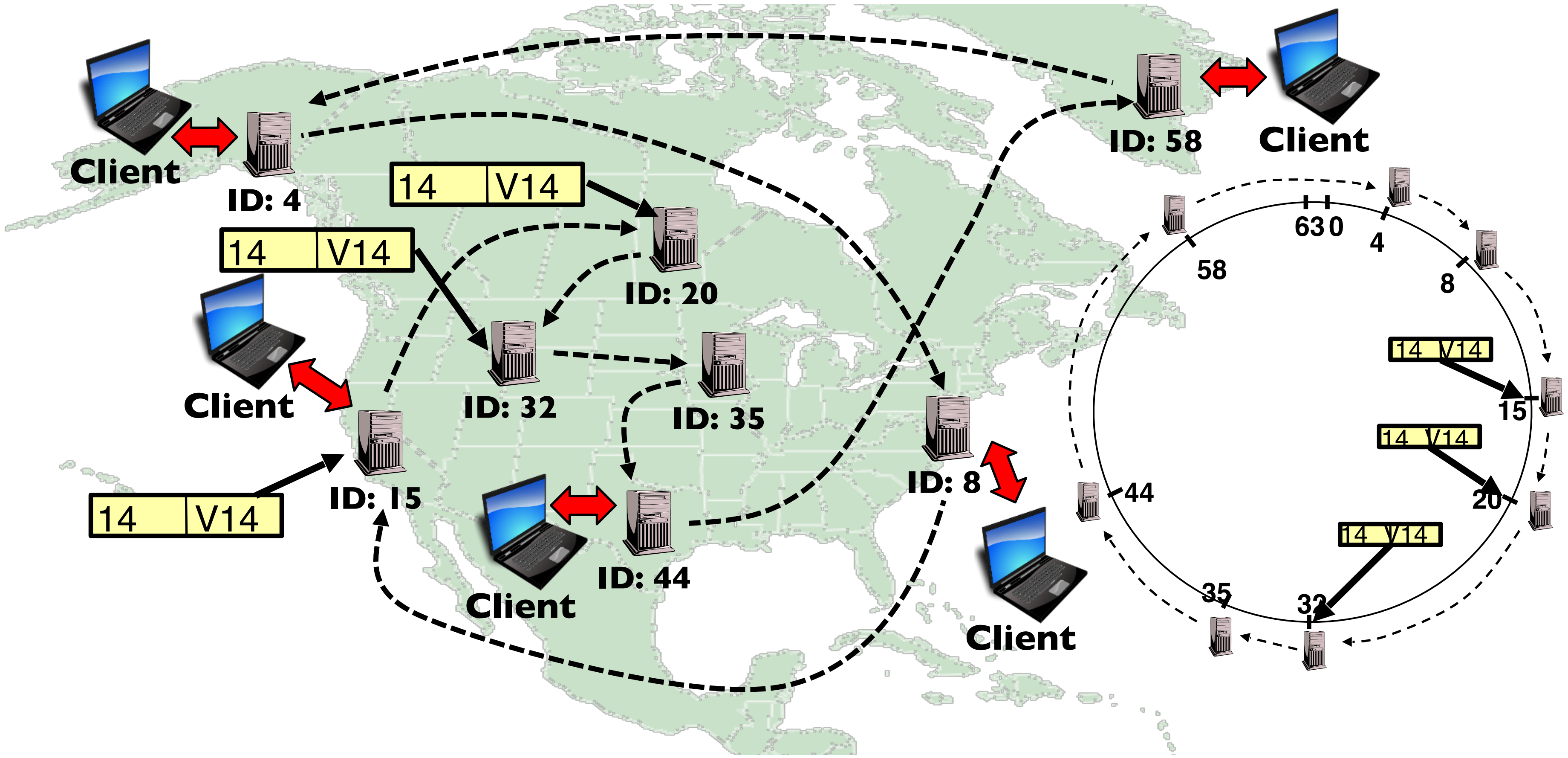


Storage Fault Tolerance

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



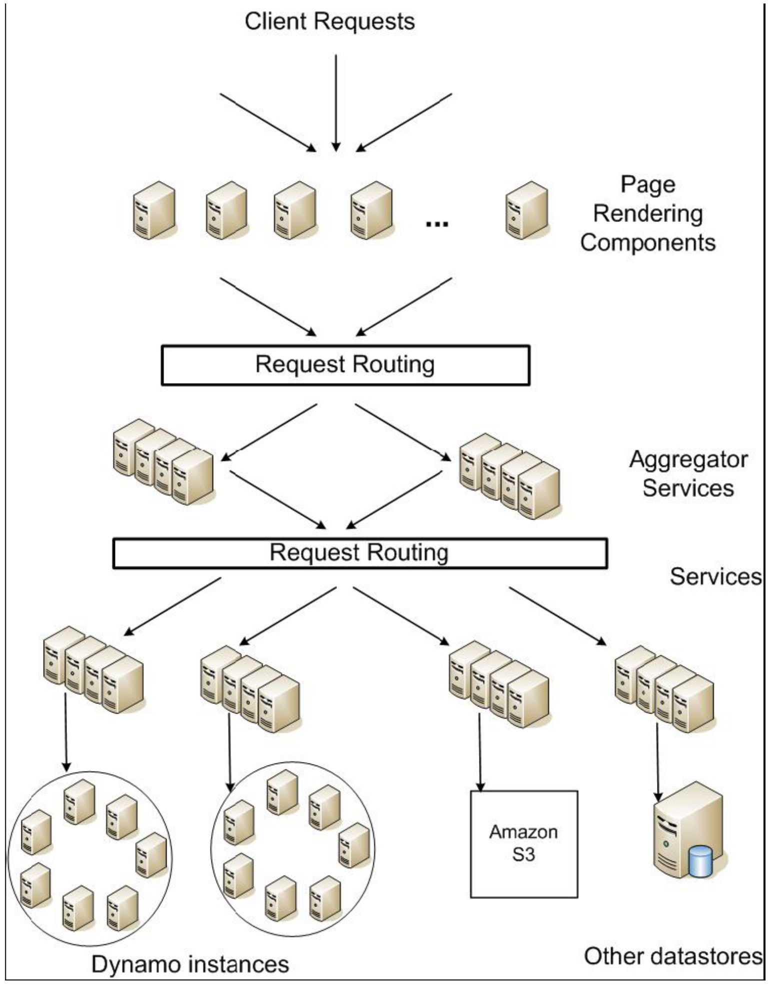
Replication in Physical Space



- Replicating in Adjacent nodes of virtual space ⇒ Geographic Separation in physical space
  – Avoids single-points of failure through randomness
  – More nodes, more replication, more geographic spread

DynamoDB Example: Service Level Agreements (SLA)

- Dynamo is Amazon's storage system using "Chord" ideas
- Application can deliver its functionality in a bounded time:
  - Every dependency in the platform needs to deliver its functionality with even tighter bounds.
- Example: service guaranteeing that it will provide a response within 300ms for 99.9% of its requests for a peak client load of 500 requests per second
- Contrast to services which focus on mean response time



Service-oriented architecture of Amazon's platform

What is Computer Security Today?

- Computing in the presence of an adversary!
  - Adversary is the security field's defining characteristic
- Reliability, robustness, and fault tolerance
  - Dealing with Mother Nature (random failures)
- Security
  - Dealing with actions of a knowledgeable attacker dedicated to causing harm
  - Surviving malice, and not just mischance
- Wherever there is an adversary, there is a computer security problem!

```
CuteMouse v1.9.1 alpha 1 [FreeDOS]
Installed at PS/2 port   CuteMouse v1.9.1 al
C:\>ver
            in drive C is FREEDOS_C95
FreeCom version 0.82 pl 3 XMS_Swap [Dec 10 2

C:\>dir                          v1.9.1 alph
 Vo    e    rive C is FREEDOS_C95
 V  um  Serial Num    is 0 4F-1 EB
 D rectory of  :\

FDOS                  IR>   8-26-04   6 23p
AU OEX C  B T          35   0 -26-04   6 24p
BO        B N          512  0  2        6 23p
COMMAND   COM       93,963  08-26-04   6:24p
CONFIG    SYS          801  08-26-04   6:24p
FDOSBOOT  BIN          512  08-26-04   6:24p
KERNEL    SYS       45,815  04-17-04   9:19p
6 file(s  6 file(s)          142,038 bytes
          1 dir(s)   1,064,517,632 bytes free

C:\>_ CuteMouse v1.9.1 alpha 1 [FreeDOS]
```

CIMPLICITY®
BlackEnergy
SCADA malware
(Supervisory Control and Data Acquisition)

Mirai IoT botnet

Protection vs. Security

- Protection: mechanisms for controlling access of programs, processes, or users to resources
  - Page table mechanism
  - Round-robin schedule
  - Data encryption
- Security: use of protection mechanisms to prevent misuse of resources
  - Misuse defined with respect to policy
    - » E.g.: prevent exposure of certain sensitive information
    - » E.g.: prevent unauthorized modification/deletion of data
  - Need to consider external operational environment
    - » Most well-constructed system cannot protect information if user accidentally reveals password – social engineering challenge

On The Importance of Data Integrity

- In July (2015), a team of researchers took total control of a Jeep SUV remotely
- They exploited a firmware update vulnerability and hijacked the vehicle over the Sprint cellular network
- They could make it speed up, slow down and even veer off the road

- Machine-to-Machine (M2M) communication has reached a dangerous tipping point
  - Cyber Physical Systems use models and behaviors that from elsewhere
  - Firmware, safety protocols, navigation systems, recommendations, …
  - IoT (whatever it is) is everywhere
- Do you know where your data came from? *PROVENANCE*
- Do you know that it is ordered properly? *INTEGRITY*
- *The rise of Fake Data!*
  - *Much worse than Fake News…*
  - *Corrupt the data, make the system behave very badly*

Security Requirements

- Authentication
  - Ensures that a user is who is claiming to be
- Data integrity
  - Ensure that data is not changed from source to destination or after being written on a storage device
- Confidentiality
  - Ensures that data is read only by authorized users
- Non-repudiation
  - Sender/client can't later claim didn't send/write data
  - Receiver/server can't claim didn't receive/write data

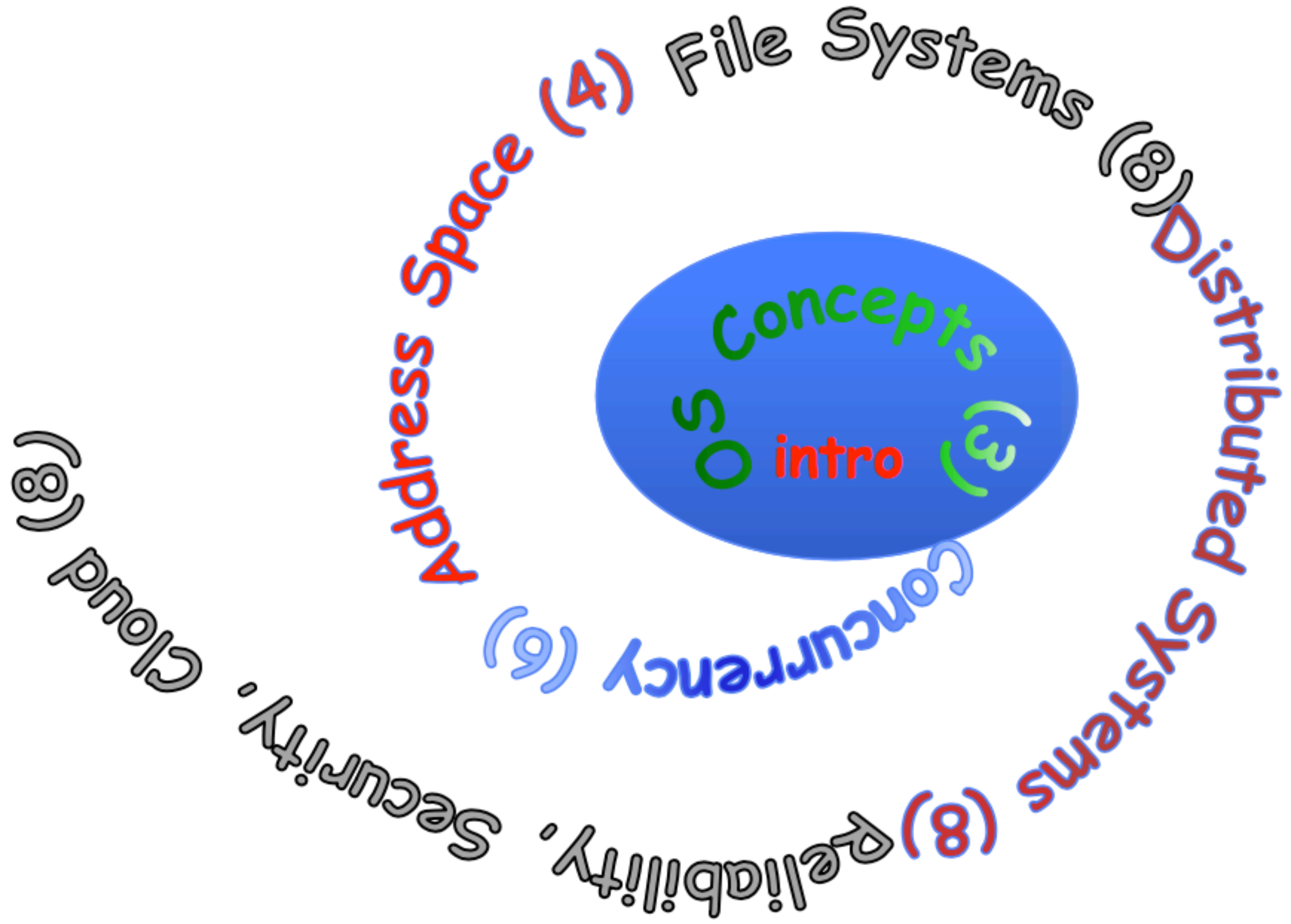
Summary (1/2)

- Distributed File System:
  - Transparent access to files stored on a remote disk
  - Caching for performance
- VFS: Virtual File System layer
  - Provides mechanism which gives same system call interface for different types of file systems
- Cache Consistency: Keeping client caches consistent with one another
  - If multiple clients, some reading and some writing, how do stale cached copies get updated?
  - NFS: check periodically for changes
  - AFS: clients register callbacks to be notified by server of changes

Summary (2/2)

- Key-Value Store:
  - 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
- 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

Thank you!


OS Concepts (3)
intro
Concurrency (6)
Address Space (4)
File Systems (8)
Distributed Systems (8)
Reliability, Security, Cloud (8)