Scaling Out Systems

COS 518: *Advanced Computer Systems*
Lecture 6

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[Credits: Selected content adapted from M. Freedman, B. Karp, R. Morris]

Today

1. **Scaling up: Reliable multicast**

2. Scaling out: Partitioning, DHTs and Chord

Recall the tradeoffs

- CAP: Distributed systems can have 2 of the following 3:
  - Consistency (Strong/Linearizability)
  - Availability
  - Partition Tolerance: Liveness despite arbitrary failures

- Bit of an oversimplification. Really: When you get P, do you choose A or C?

- Goal? **ALPS** (Coined by Lloyd and Freedman, 2011)
  - Available
  - Low-Latency
  - Partition-Tolerant
  - Scalable (to more than 1 “CPU” per site)

Reliable multicast motivation: Fast content purging in a CDN

- [Fastly CDN]
- CDN servers geographically distributed containing many replicas of data
- Want to give cusomters the ability to takedown content in a short period of time from across the CDN
- Your sales team advertises 150 ms takedown latency

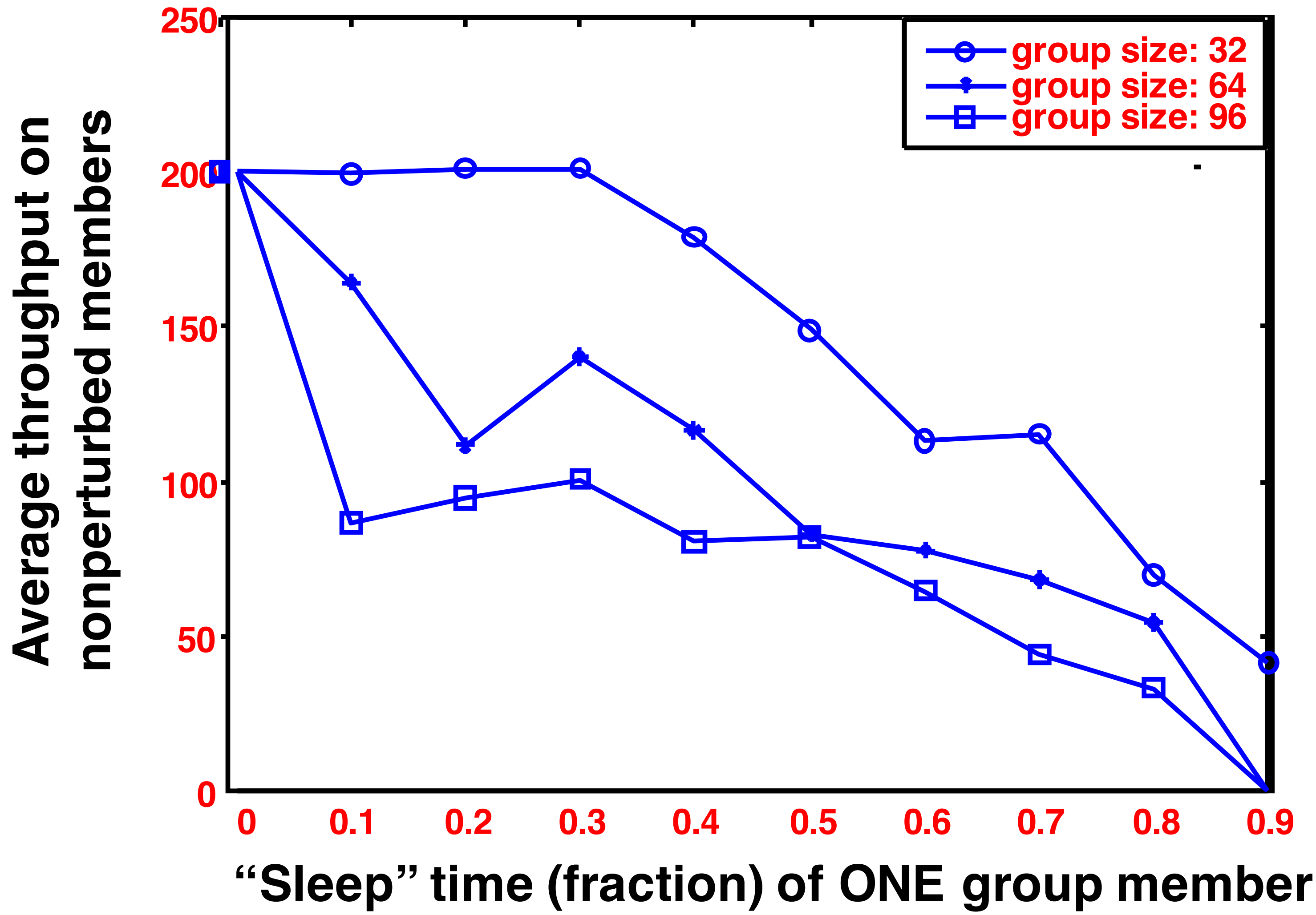
Reliable multicast protocols

- Reliable Multicast Transport Protocol (RMTP)
- Scalable Reliable Multicast (SRM)

- Sequenced, lossless bulk delivery of data from one sender to a group of receivers

- TCP-like cumulative sequence numbers on data
- Sequence numbers and bitmaps in acknowledgement packets back to sender
- Window-based flow control
- Retransmissions, failure monitoring among receivers

Reliable multicast performance



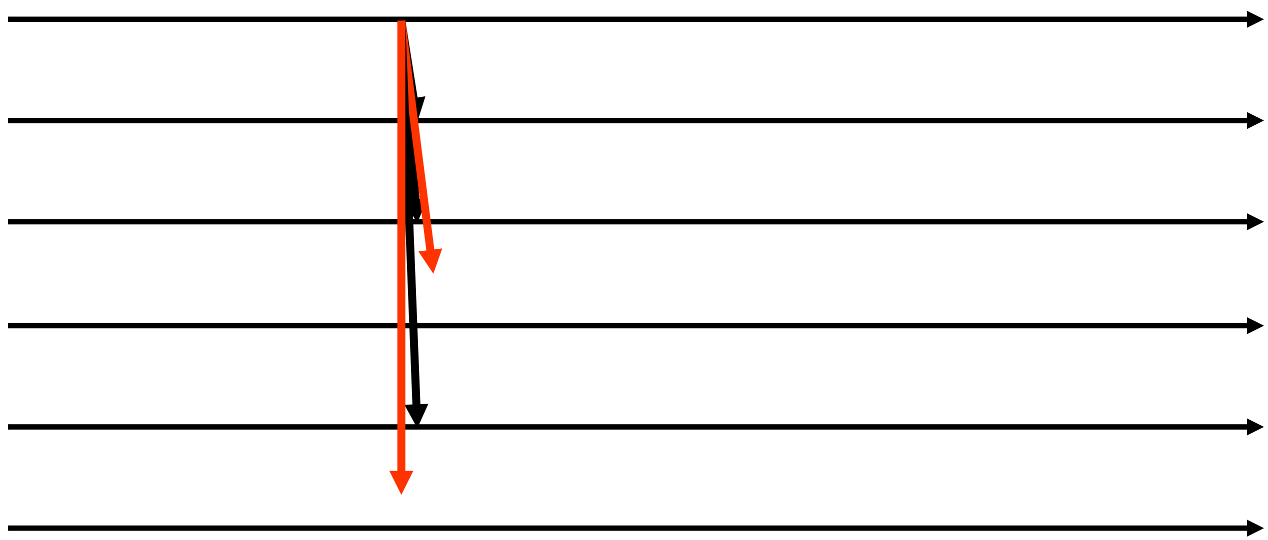
Bimodal multicast

- **pbcast:** Probabilistic broadcast
  - Birman *et al.*, ACM ToCS 17(2) 1999

- Atomicity property is the **bimodal delivery guarantee:**
  - High probability that each multicast will reach **almost all** processes
  - Low probability that a multicast will reach just a **very small set** of processes
  - Vanishingly small probability that it will reach some **intermediate number of processes**

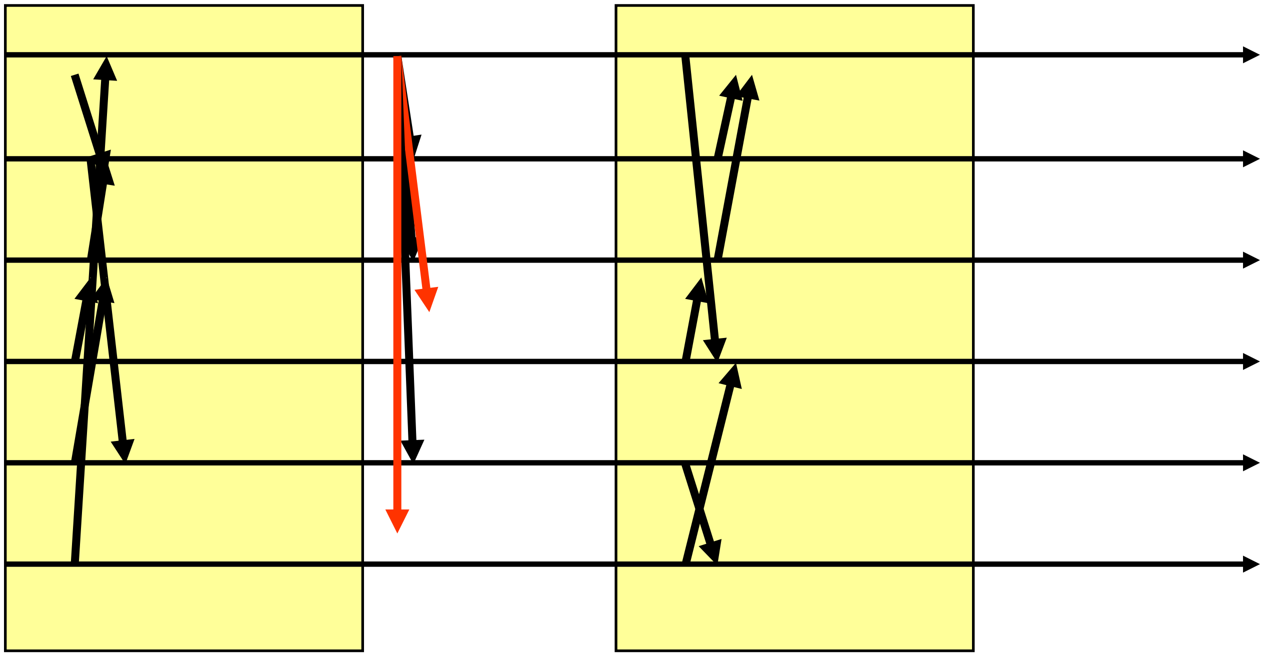
- The traditional “all or nothing” guarantee thus becomes “almost all or almost none.”

Bimodal multicast (1/4)



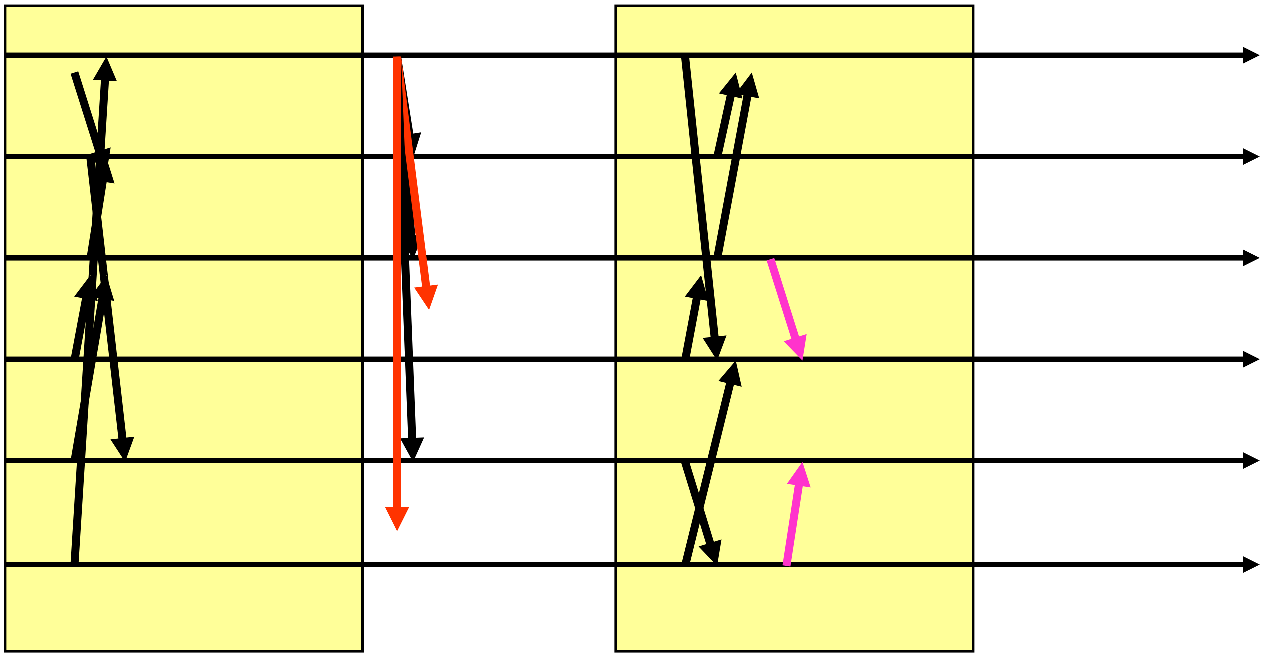
Initially use UDP/IP best effort multicast

Bimodal multicast (2/4)



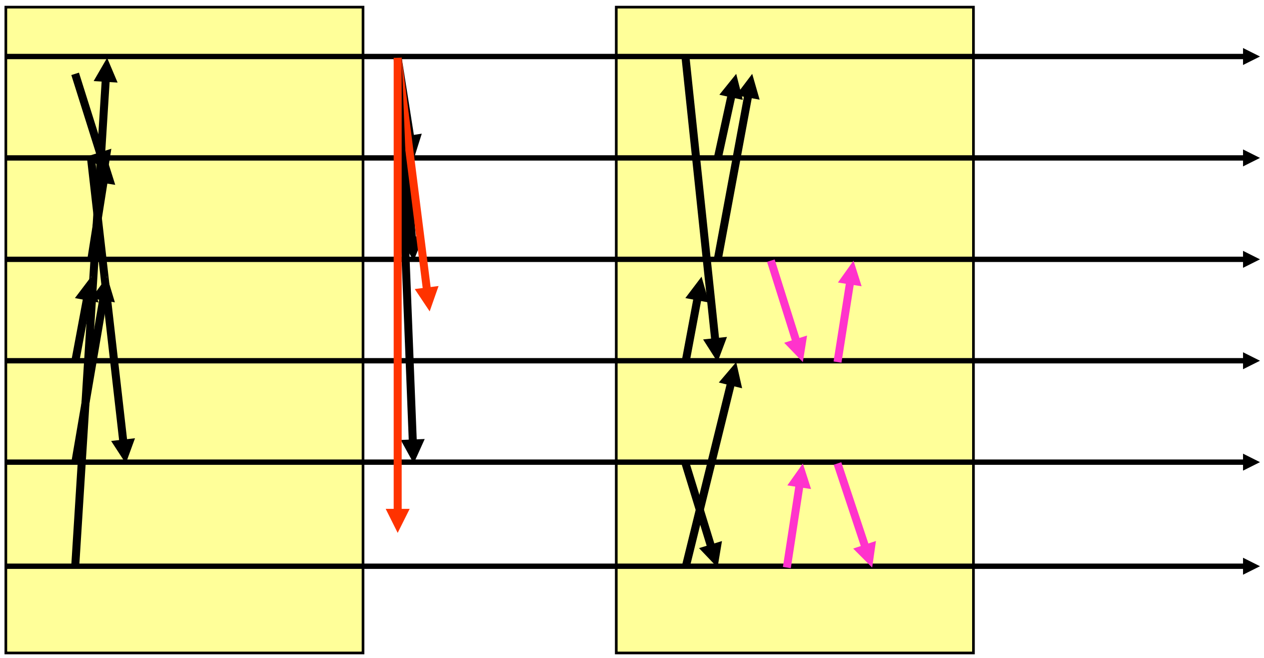
- Periodically (*e.g.* every 100ms):
  - Each node picks random group member, and send digest describing its state

Bimodal multicast (3/4)



- Recipient checks digest against own history
- For all missing message, *solicits* copy of msg

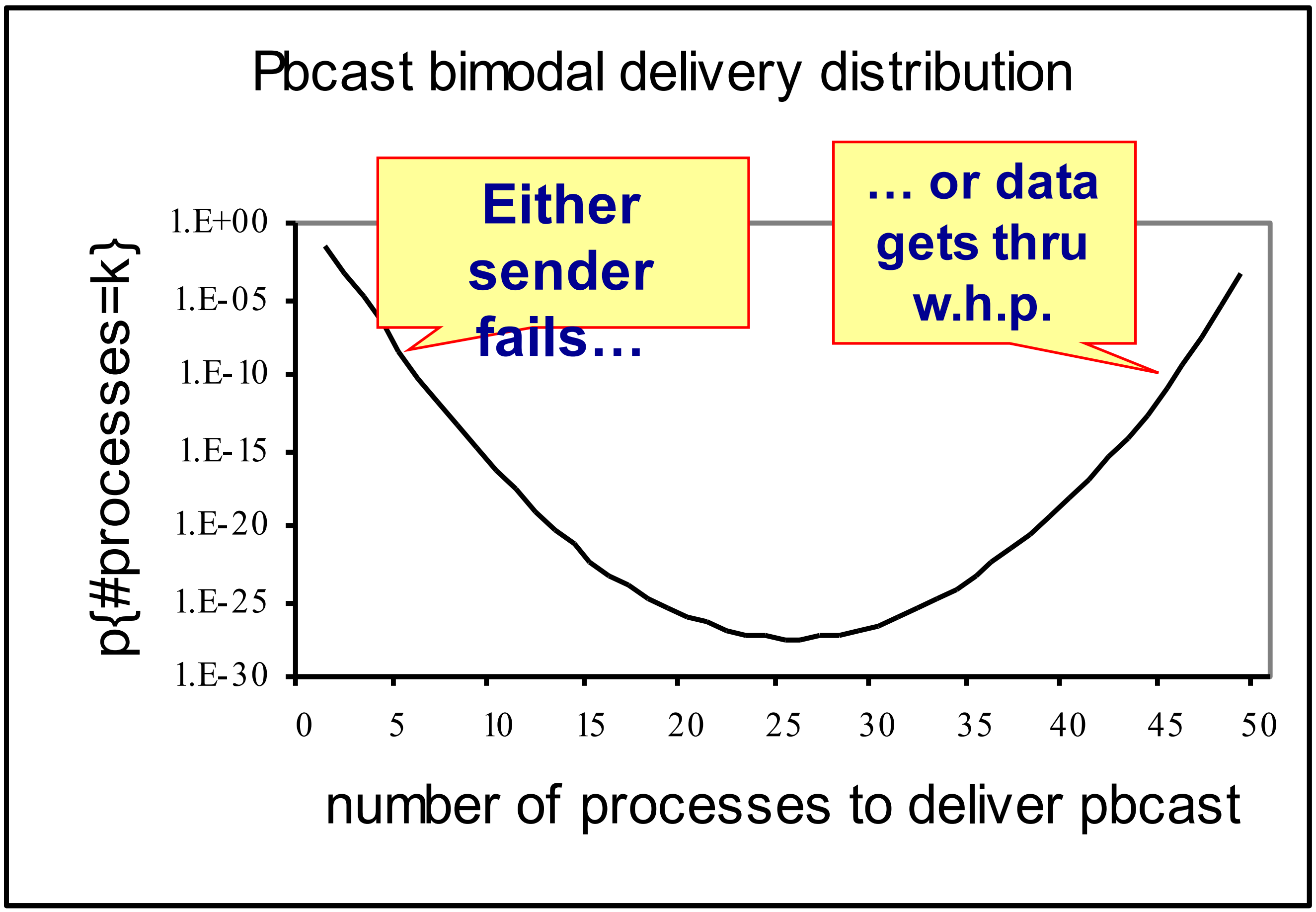
Bimodal multicast (4/4)



- Nodes respond to solicitations by retransmitting requested message(s)

Why "bimodal?"

- Two phases? Nope…
- Description of dual "modes" of result



Epidemic algorithms via gossiping

- Assume a fixed population of size ***n***
- For simplicity, assume “epidemic” (delivery) spreads homogenously through popularly
  - Simple randomized delivery: any one can deliver to any one with equal probability
- Assume that ***k*** members are already delivered
- Delivery occurs in rounds

Probability of delivery

- Probability $P_{deliver}(k,n)$ that a undelivered member is delivered to in a round, if *k* are already infected?

$$P_{deliver}(k,n) = 1 - P\,(\text{nobody delivers}) = 1 - (1 - 1/n)^k$$

$$E\,[\#\ \text{newly delivered}] = (n - k) \times P_{deliver}(k,n)$$

- Basically it's a Binomial distribution

- # rounds to deliver to the entire population is O(log n)

Two prevailing styles

- Gossip pull ("anti-entropy")
  - A asks B for something it is trying to "find"
  - Commonly used for management replicated data
    - Resolve differences between DBs by comparing digests

- Gossip push ("rumor mongering"):
  - A tells B something B doesn't know
  - Gossip for multicasting
    - Keep sending for bounded period of time: O (log n)
  - Also used to compute aggregates

- Push-pull gossip
  - Combines both mechanisms
  - O(n log log n) msgs to spread rumor in O(log n) time

Wednesday reading: *Bayou*

- Problem: Collaborative applications
  - E.g., Meeting room scheduling, bibliographic database

- Setting:
  - Mobile computing environment
  - Seek to support disconnected workgroups
  - Rely only on weak/opportunistic connectivity (occasional, pair-wise communication)

- Key technical problem: How to converge to (eventually) consistent state?
  - Use anti-entropy for pair-wise resolution
  - Observation: Need application-specific conflict detection and resolution at granularity of individual updates

Today

1. Scaling up: Reliable multicast

2. **Scaling out: Partitioning, DHTs and Chord**

Scaling out by partitioning data

- Every data object belongs to data “partition”
- Each partition resides on one or more nodes
  - Replication protocol between nodes hosting partition, e.g., could be strong or eventually consistent
- Every node hosts one or more partition

What is a DHT?

- Single-node hash table abstract:

```
key = Hash(name)
put(key, value)
get(key) → value
```

  – Service: O(1) storage

- How do I do this across millions of hosts on the Internet?
  – *Distributed* Hash Table

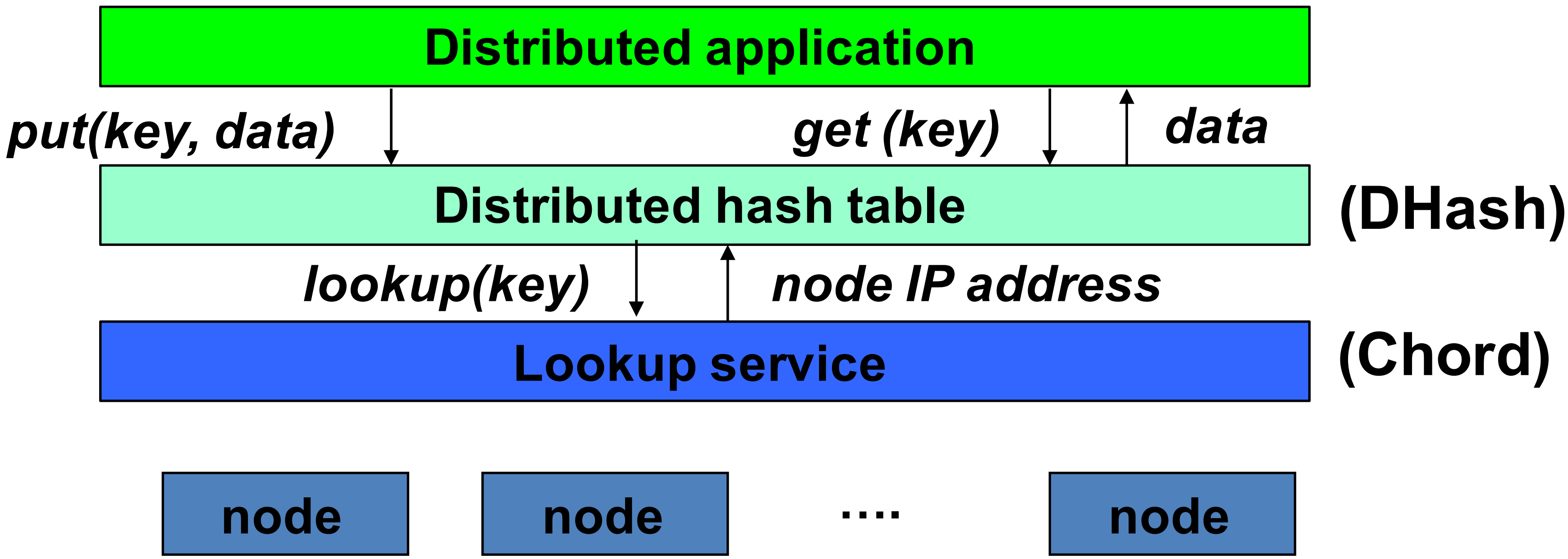
What Is a DHT? (and why?)

- Distributed Hash Table:

```
key = Hash(data)
lookup(key) → IP address   (Chord)
send-RPC(IP address, PUT, key, value)
send-RPC(IP address, GET, key) → value
```

- The first step towards truly **large-scale distributed systems**
  - a tuple in a global database engine
  - a data block in a global file system
  - rare.mp3 in a P2P file-sharing system

DHT Factoring



- Application may be distributed over many nodes
- DHT distributes data storage over many nodes

Why the put()/get() DHT interface?

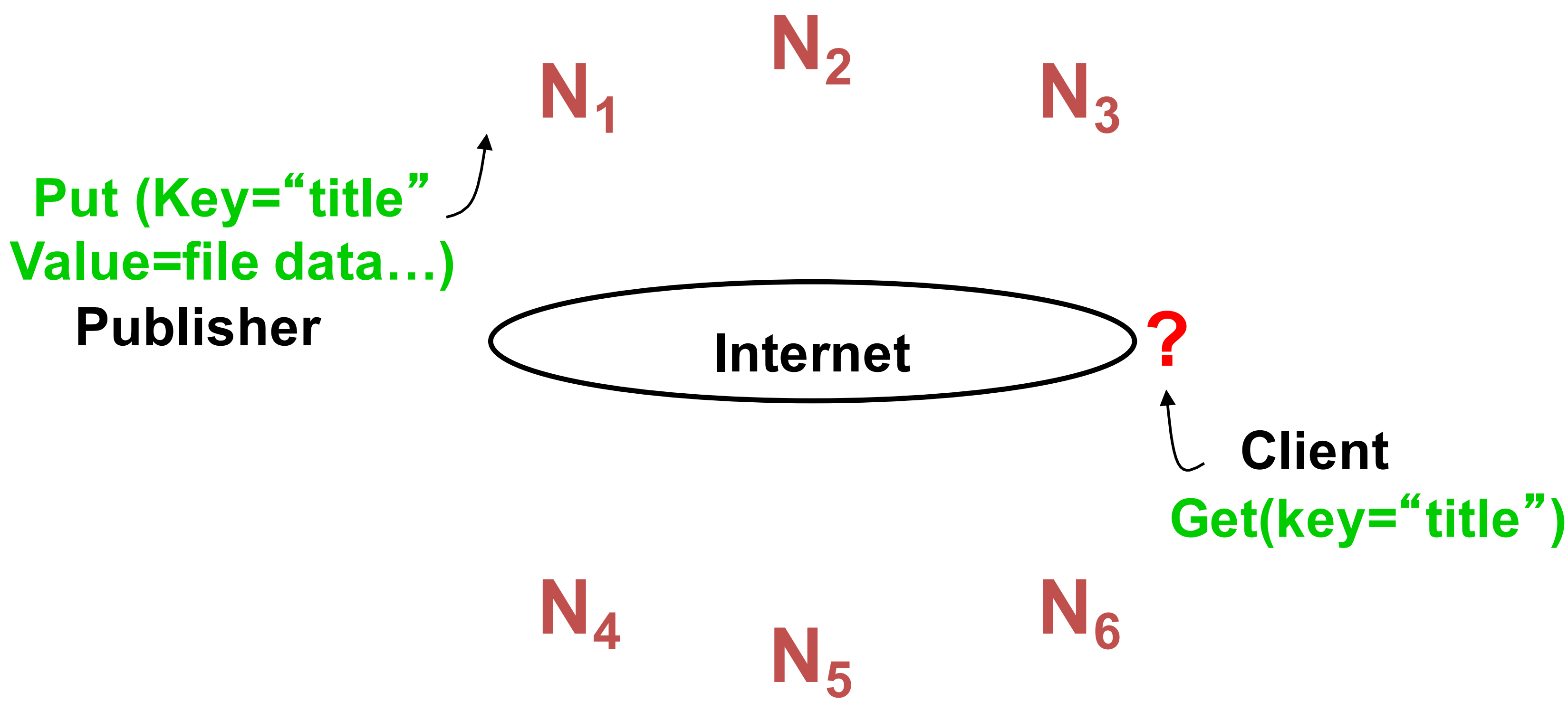
- API supports a wide range of applications
  - DHT imposes no structure/meaning on keys

- Key/value pairs are persistent and global
  - Can store keys in other DHT values
  - And thus build complex data structures

Why might DHT design be hard?

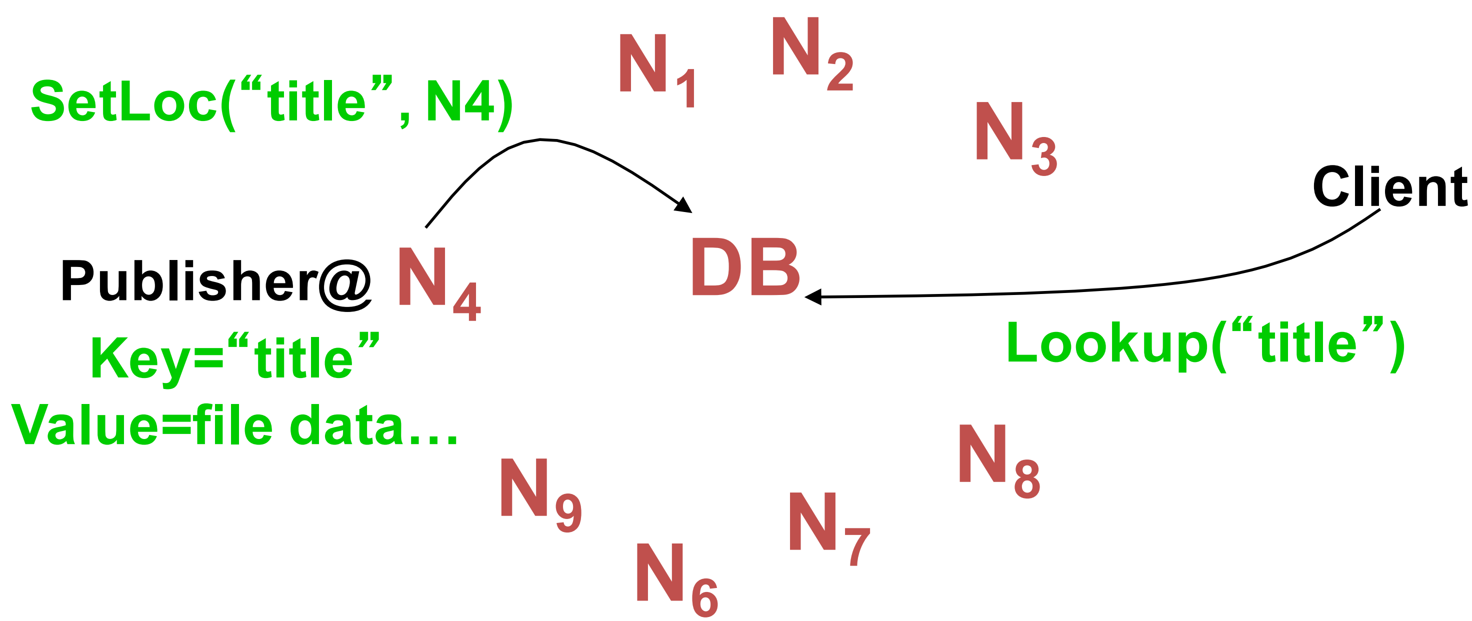
- Decentralized: no central authority
- Scalable: low network traffic overhead
- Efficient: find items quickly (latency)
- Dynamic: nodes fail, new nodes join
- General-purpose: flexible naming

The Lookup problem



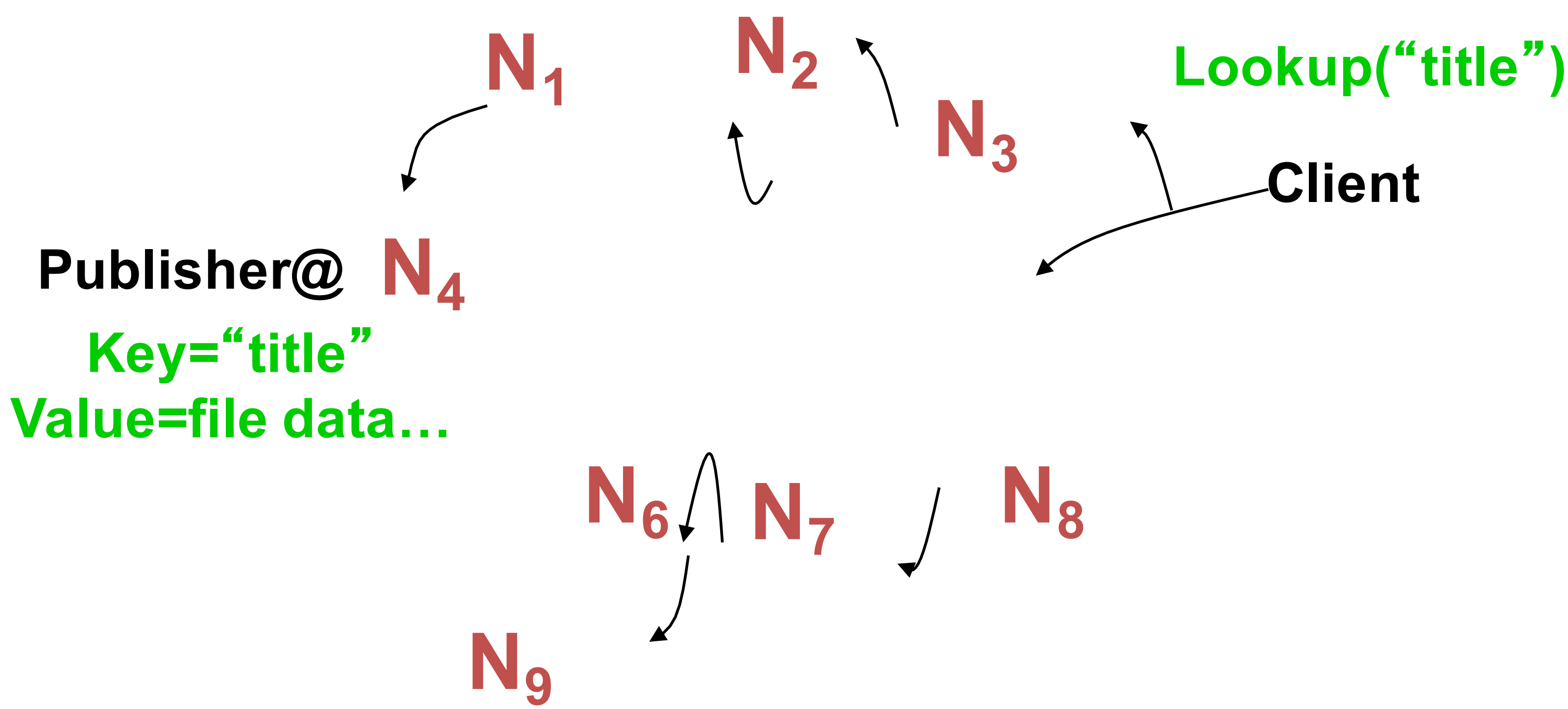
- At the heart of all DHTs

Motivation: Centralized lookup (Napster)



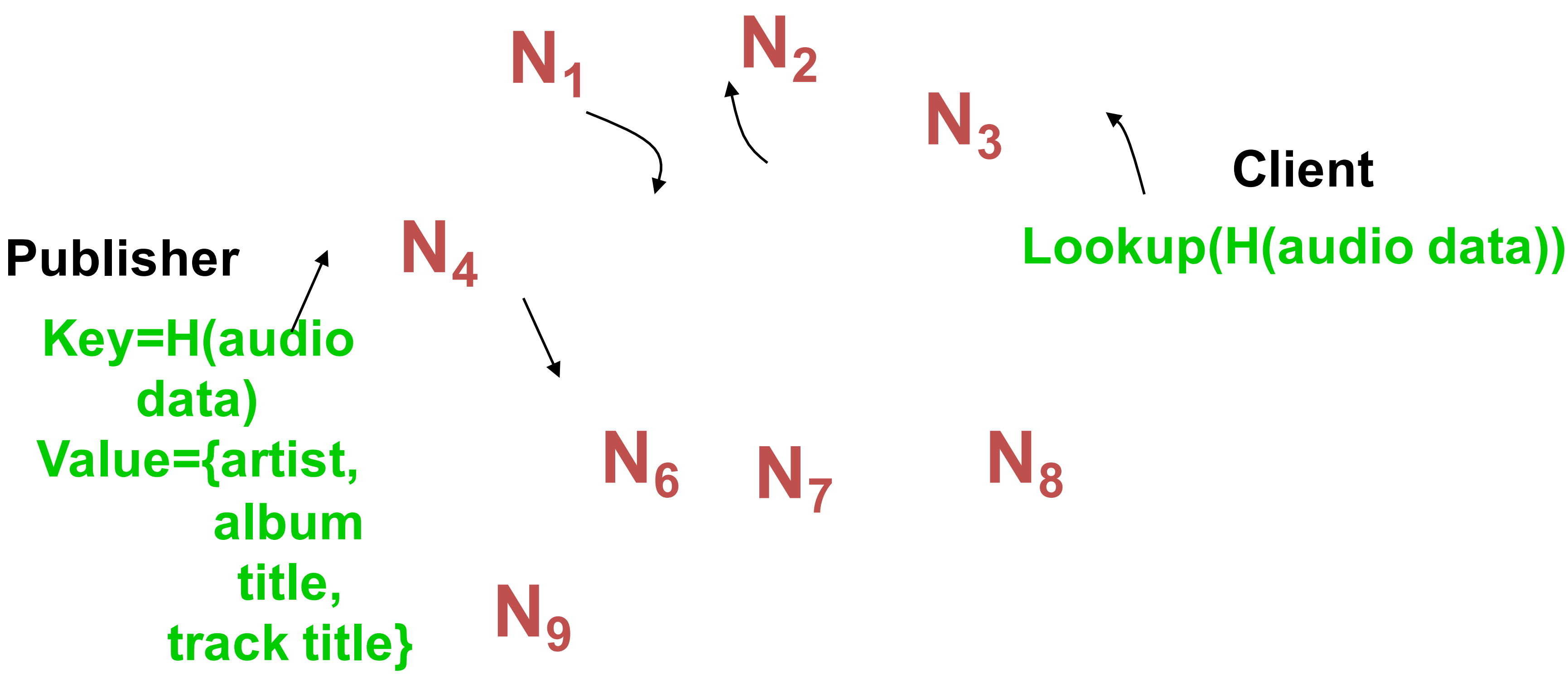
Simple, **but O(N) state and a single point of failure**

Motivation: Flooded Queries (Gnutella)



Robust, but worst case O(N) messages per lookup

Motivation: FreeDB, Routed DHT Queries (Chord, &c.)



DHT Applications

- They're not just for stealing music anymore…
  - global file systems [OceanStore, CFS, PAST, Pastiche, UsenetDHT]
  - naming services [Chord-DNS, Twine, SFR]
  - DB query processing [PIER, Wisc]
  - Internet-scale data structures [PHT, Cone, SkipGraphs]
  - communication services [i3, MCAN, Bayeux]
  - event notification [Scribe, Herald]
  - File sharing [OverNet]

Basic Approaches

- Require two features:
  - Partition management:
    - On which node(s) to place a partition
    - Including how to recover from a node failure, e.g., bringing another node into partition group
    - Changes in system size, e.g., nodes joining and leaving
  - Resolution:
    - Maintain mapping from data name to responsible node(s)

- Centralized: Cluster manager
- Decentralized: Deterministic hashing and algorithms

The partitioning problem

- Consider problem of data partition:
  - Given document X, choose one of k servers to use
- Suppose we use modulo hashing
  - Number servers 1..k
  - Place X on server i = (X mod k)
    - Problem? Data may not be uniformly distributed
  - Place X on server i = hash (X) mod k
    - Problem? What happens if a server fails or joins (k → k±1)?
    - Problem? What if different clients have different estimate of k?
    - Answer: All entries get remapped to new nodes!

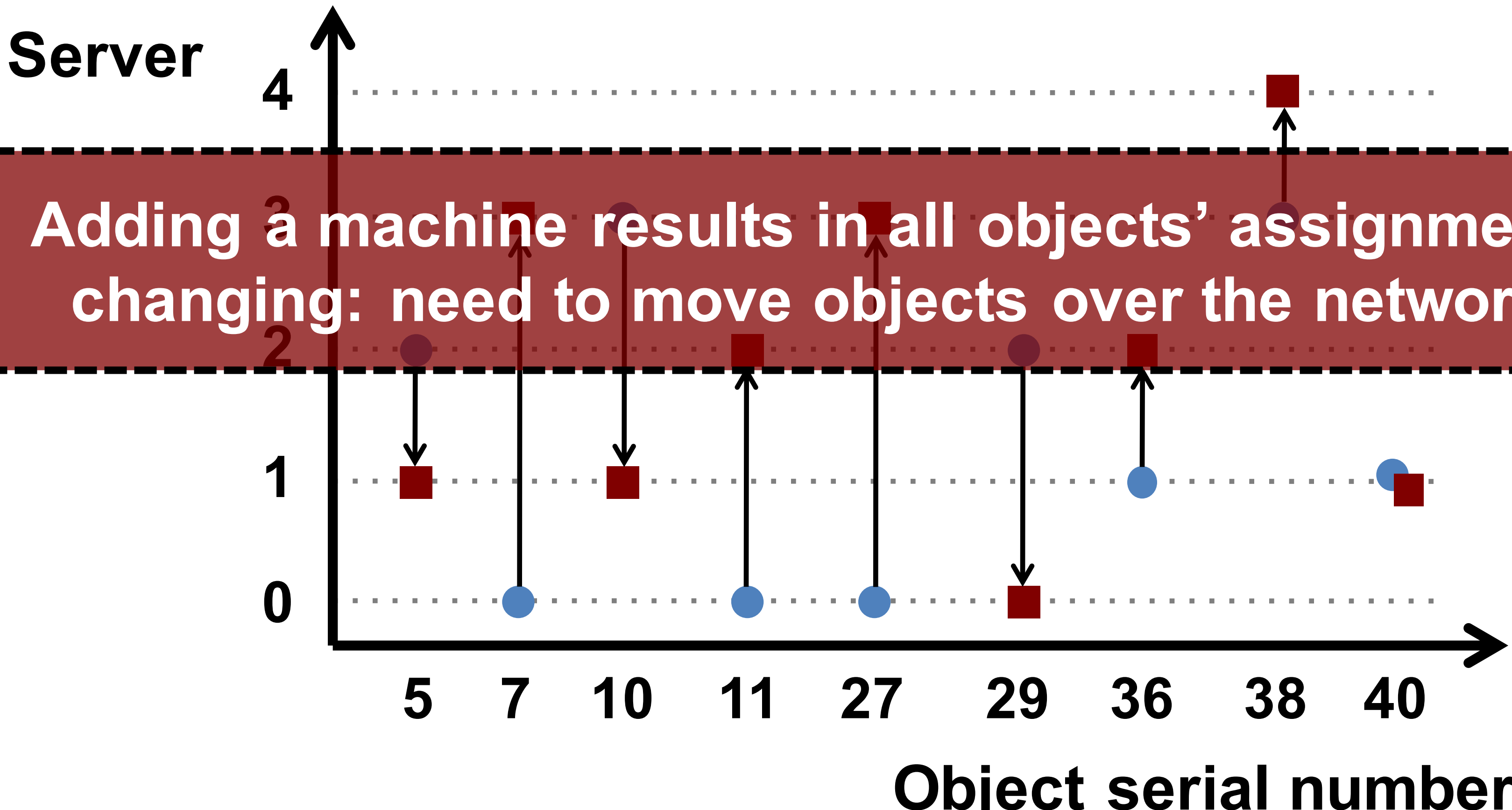
Placing objects on servers

- How to determine the server on which a certain object resides?
- Typical approach: Hash the object's identifier
- Hash function h maps object id x to a server id
  - E.g., $h(x) = [ax + b \pmod{p}]$, where
    - p is a prime integer
    - a, b are constant integers chosen uniformly at random from $[0, p-1]$
    - x is an object's serial number

Difficulty: Changing number of servers

$h(x) = x + 1 \pmod 4$

Add one machine: $h(x) = x + 1 \pmod 5$



Adding a machine results in all objects' assignments changing: need to move objects over the network.

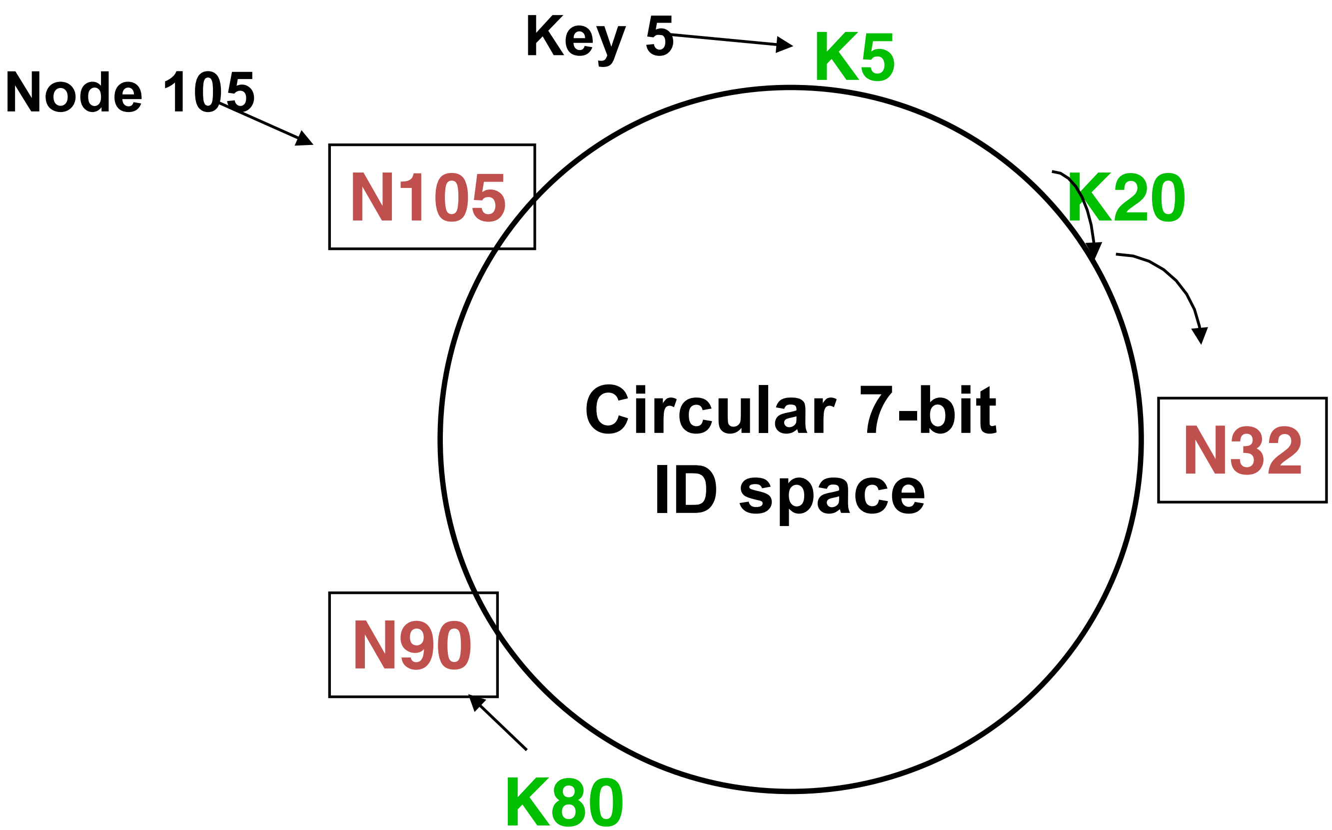
Chord Lookup Algorithm Properties

- Interface: lookup(key) → IP address
- Efficient: O(log N) messages per lookup
  - N is the total number of servers
- Scalable: O(log N) state per node
- Robust: survives massive failures
- Simple to analyze

Chord IDs

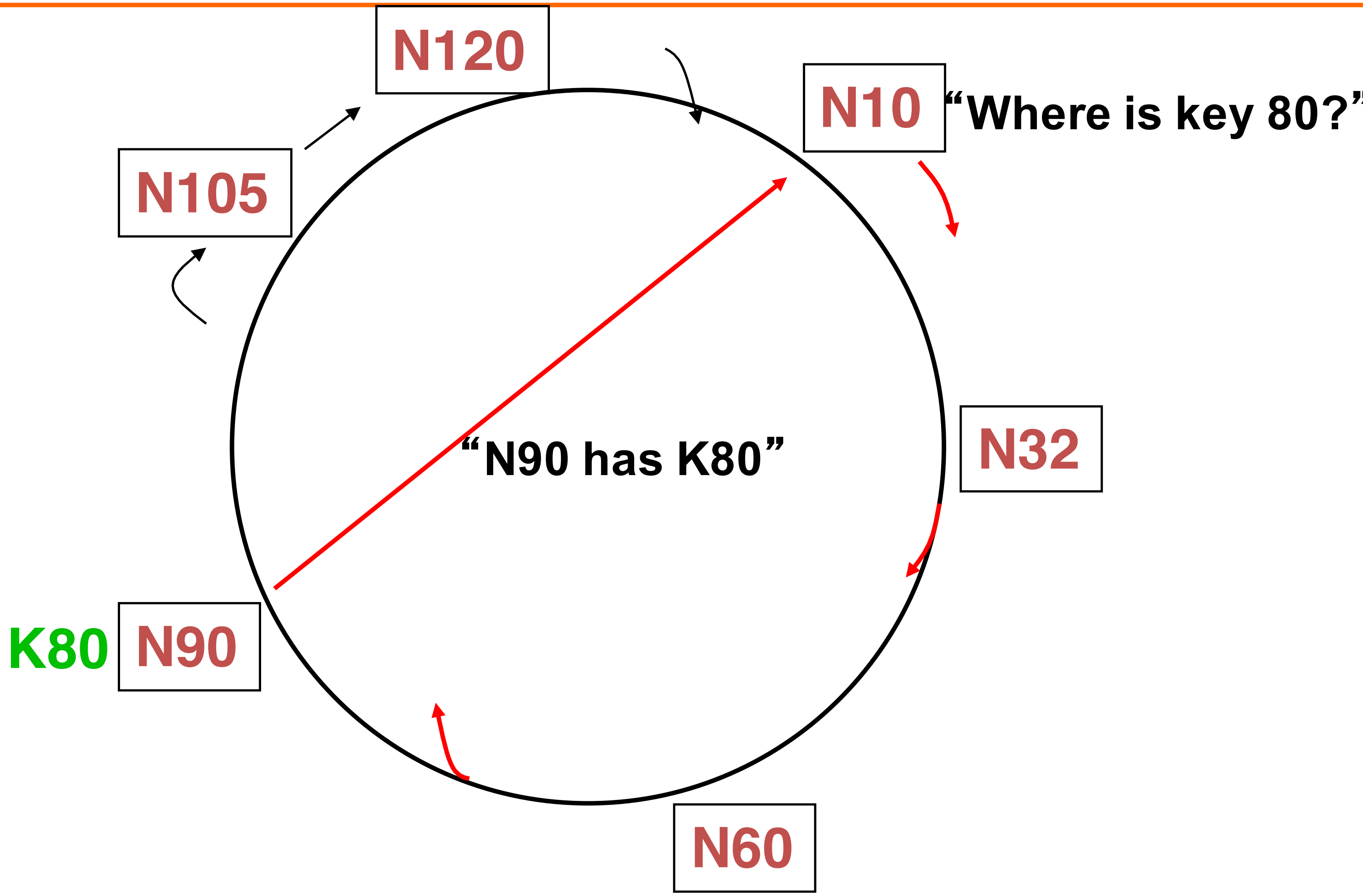
- Key identifier = SHA-1(key)
- Node identifier = SHA-1(IP address)
- SHA-1 distributes both uniformly
- ***How does Chord partition data?***
  – *i.e.*, map key IDs to node IDs

Consistent hashing [Karger '97]



A key is stored at its **successor:** node with next-higher ID

Basic Lookup

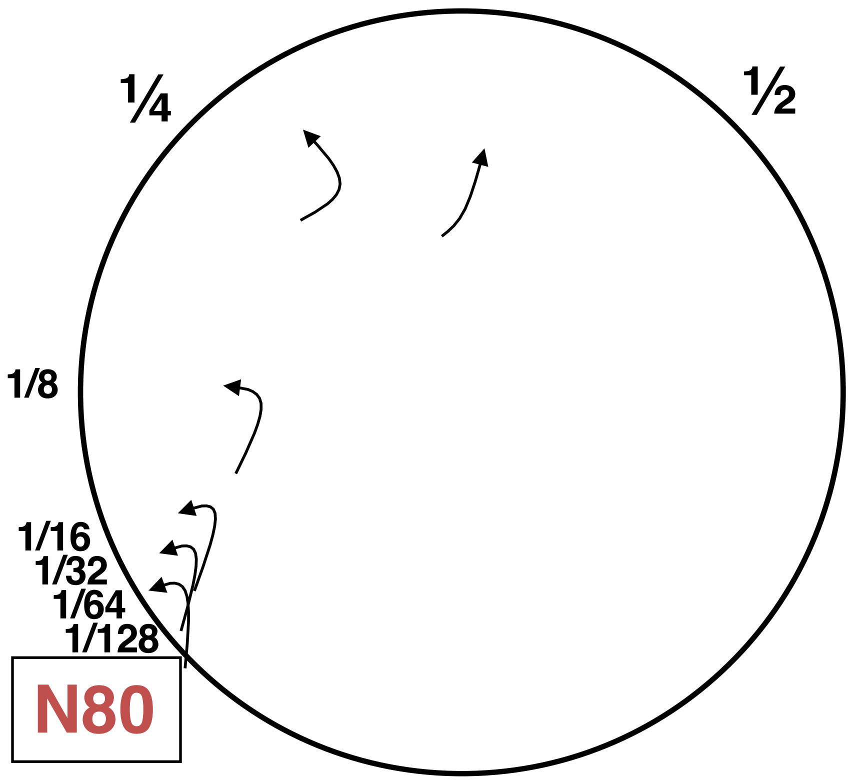


Simple lookup algorithm

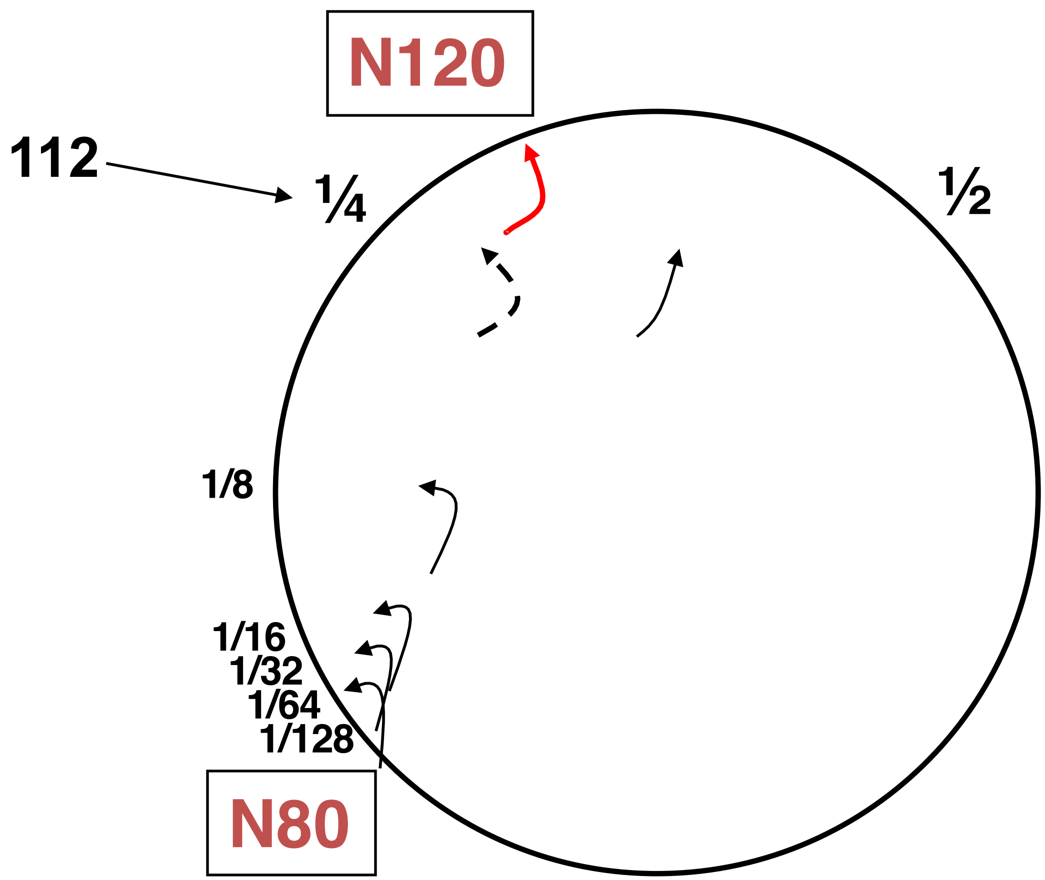
```
Lookup(my-id, key-id)
  n = my successor
  if my-id < n < key-id          // next hop
   call Lookup(key-id) on node n
  else                    // done
   return n
```

- Correctness depends only on successors

“Finger Table” Allows log(*N*)-time Lookups



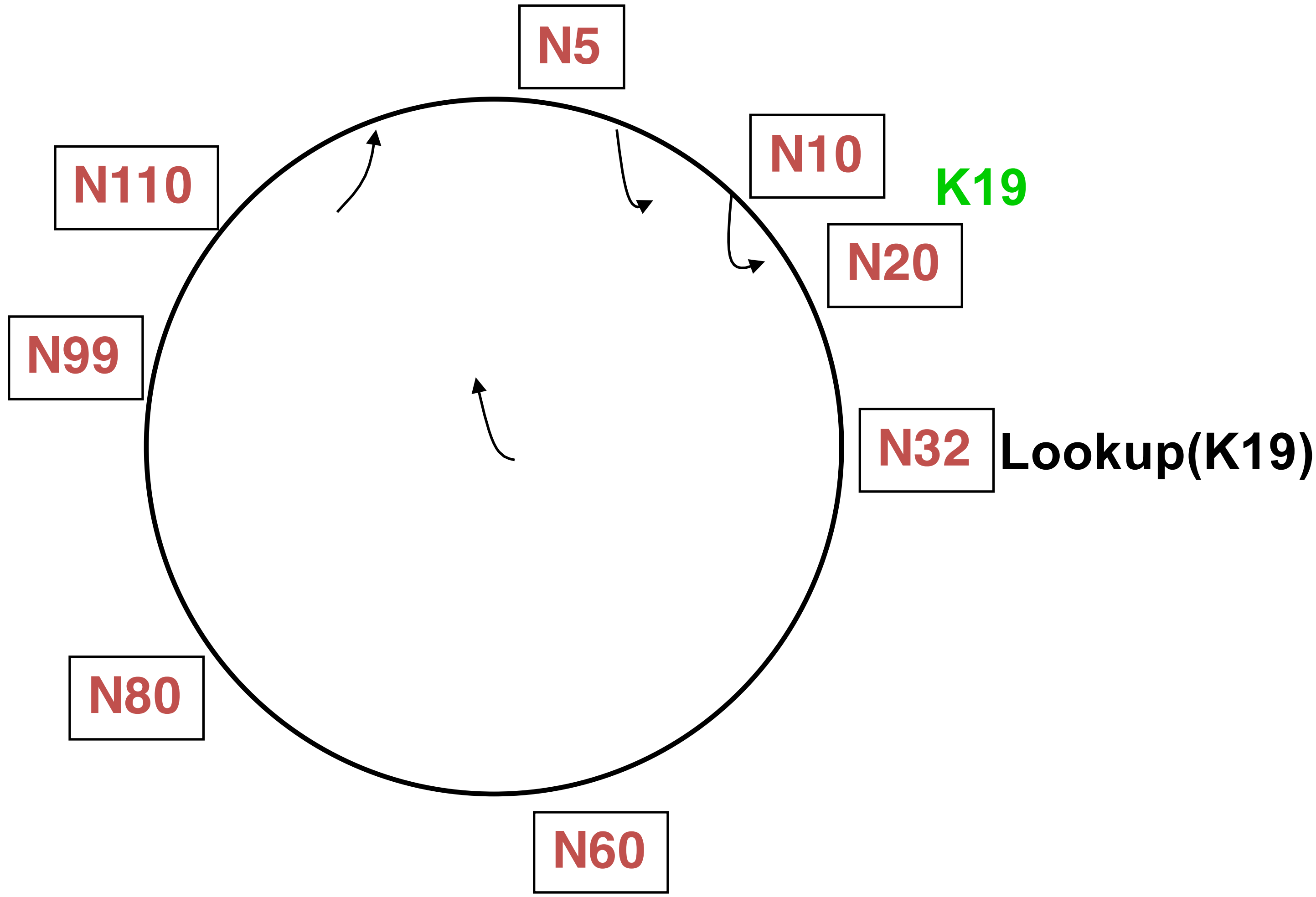
Finger i Points to Successor of $n+2^{i-1}$



Lookup with Fingers

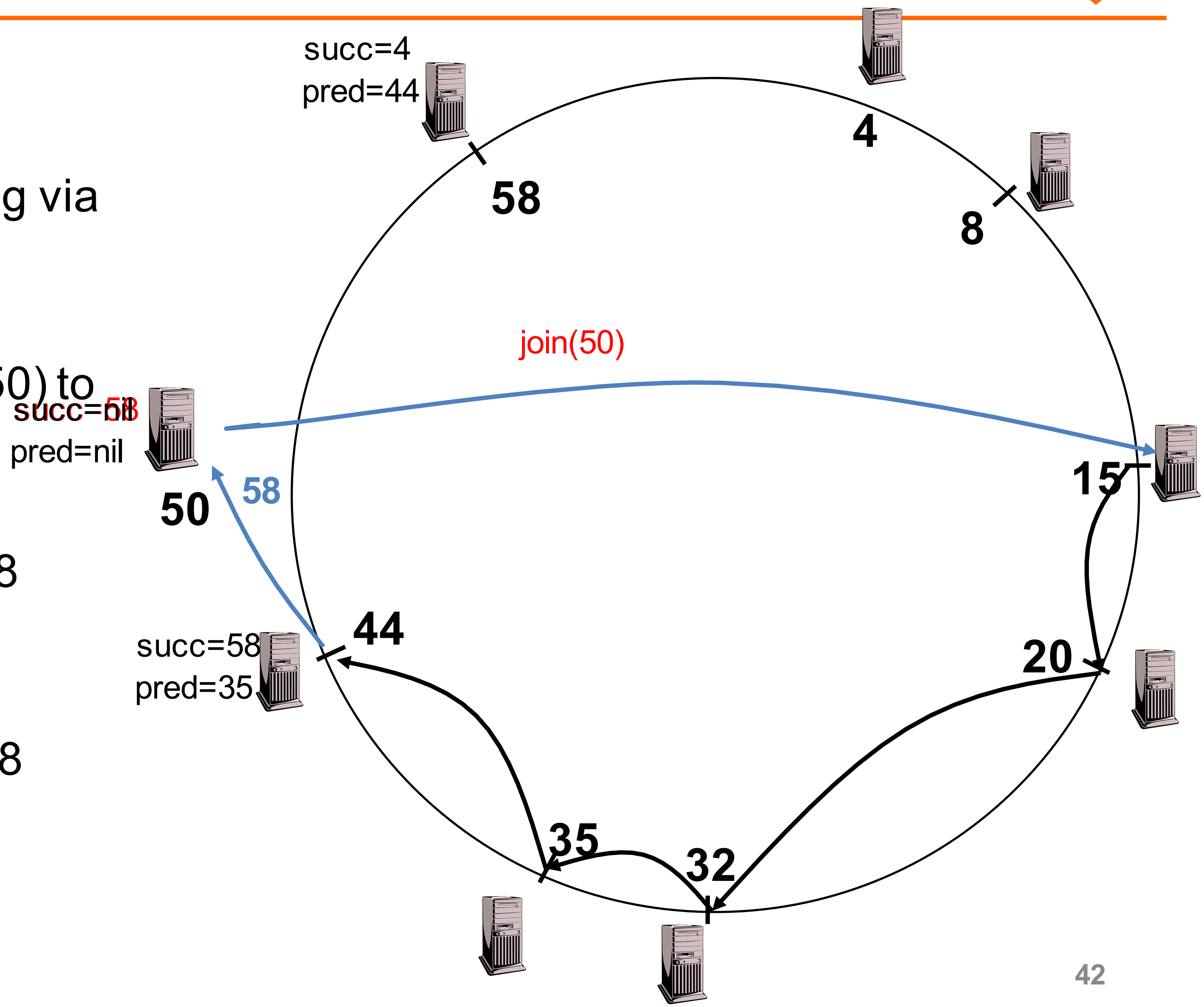
```
Lookup(my-id, key-id)
  look in local finger table for
   highest node n: my-id < n < key-id
  if n exists
   call Lookup(key-id) on node n   // next hop
  else
   return my successor   // done
```

Lookups Take O($\log N$) Hops



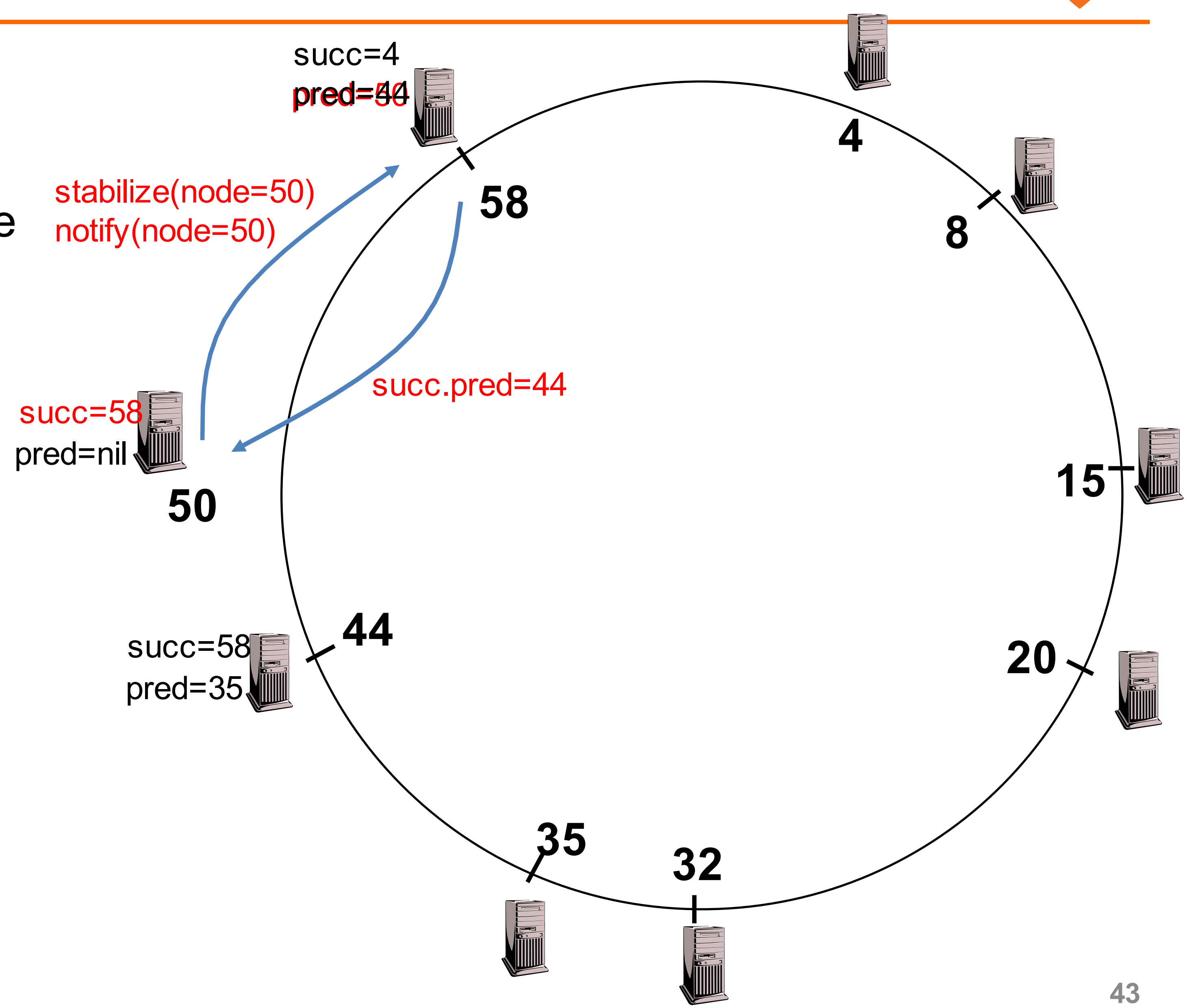
Join Operation

- N50 joins the ring via N15
- N50: send join(50) to N15
- N44: returns N58
- N50 updates its successor to N58



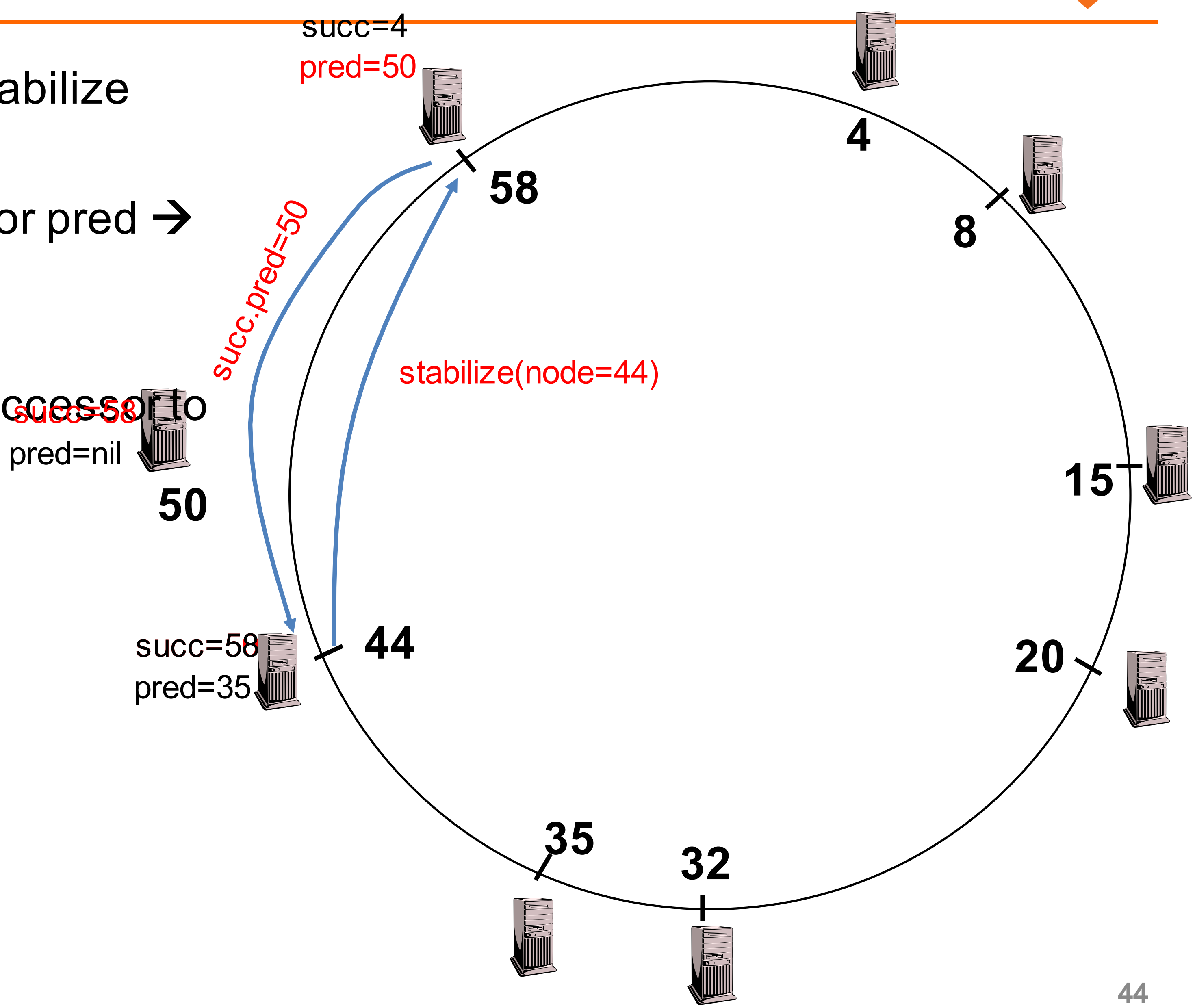
Periodic Stabilize

- N50: periodic stabilize
  - Sends stabilize message to N58
- N50: send notify message to N58
  - Update pred=44



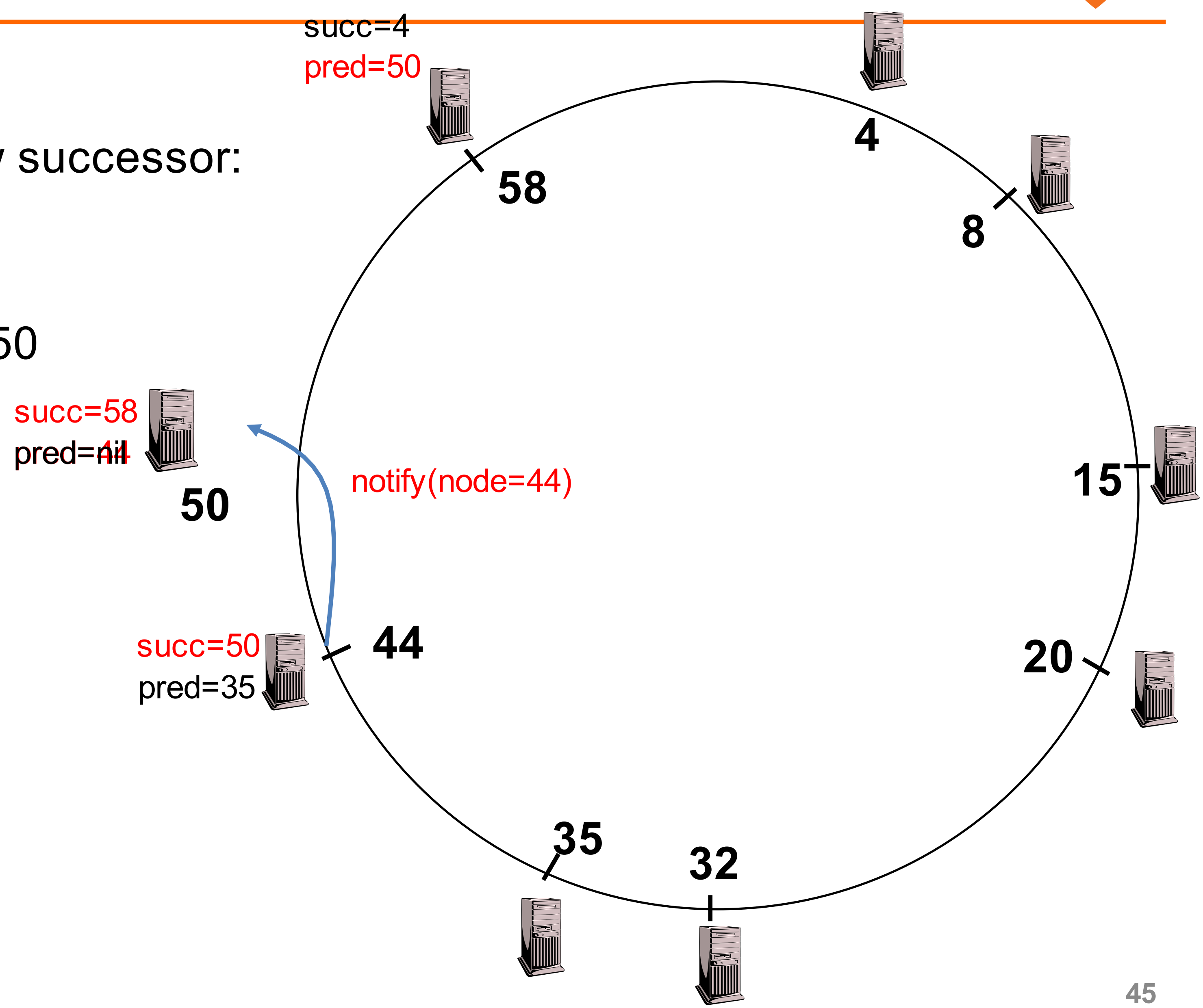
Periodic Stabilize

- N44: periodic stabilize
- N44 Asks N58 for pred → N50
- N44 updates successor to N50



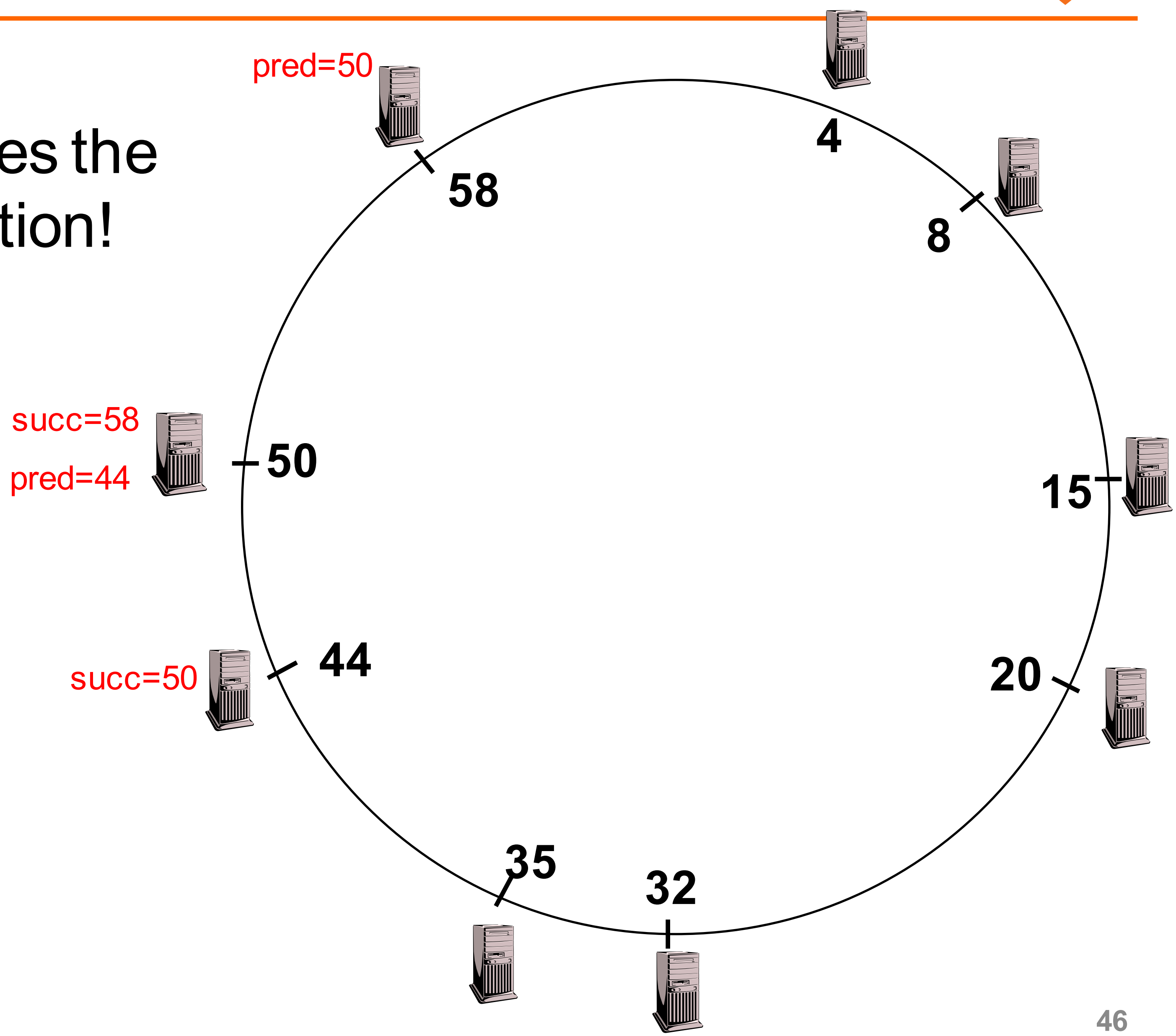
Periodic Stabilize

- N44 has a new successor: **N**50
- N44 notifies N50

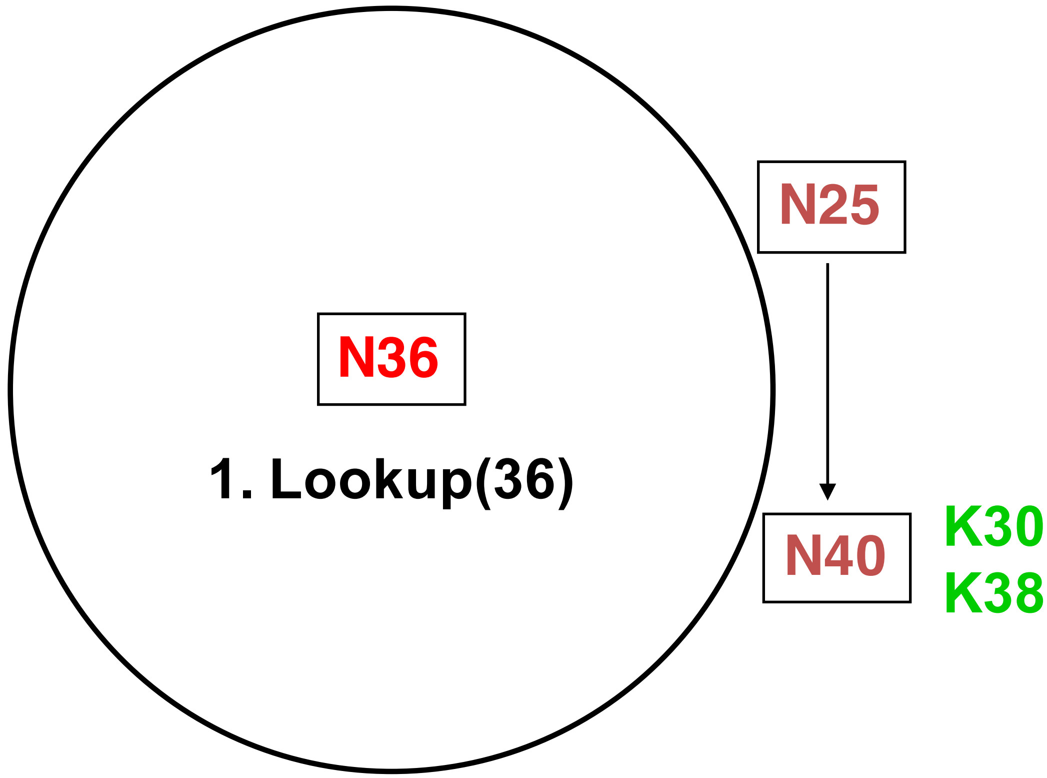


Periodic Stabilize Converges!

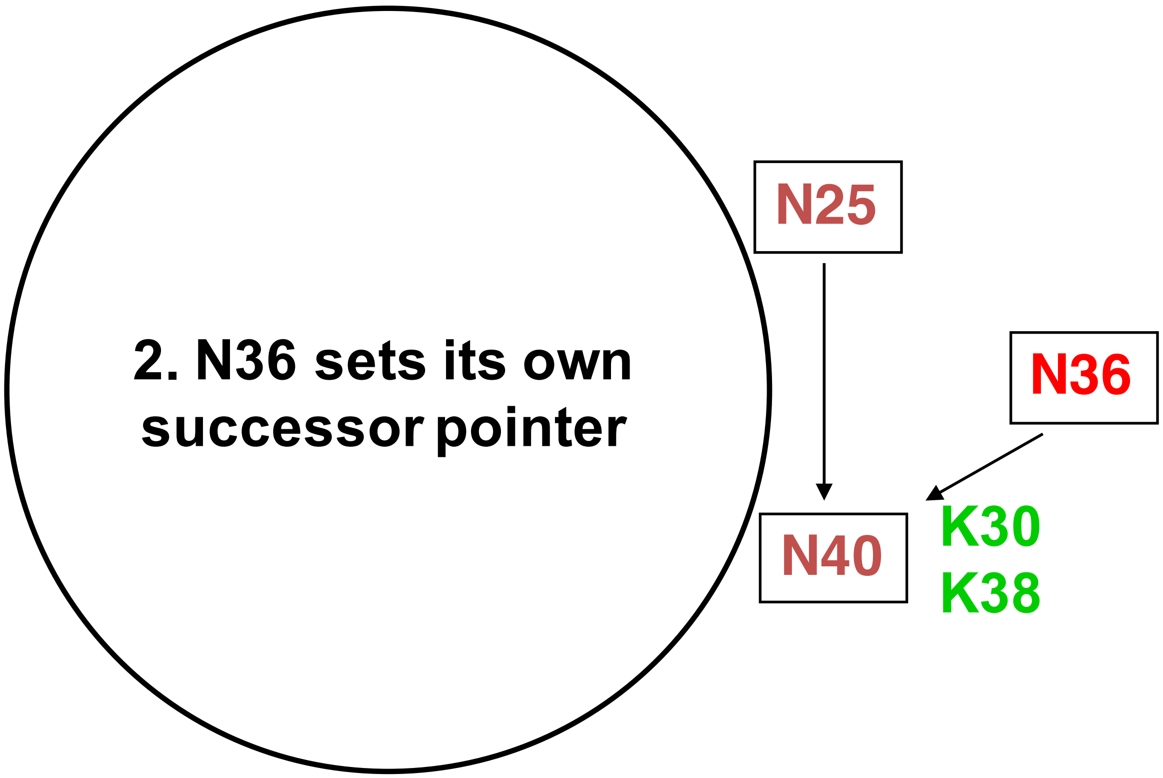
- This completes the joining operation!



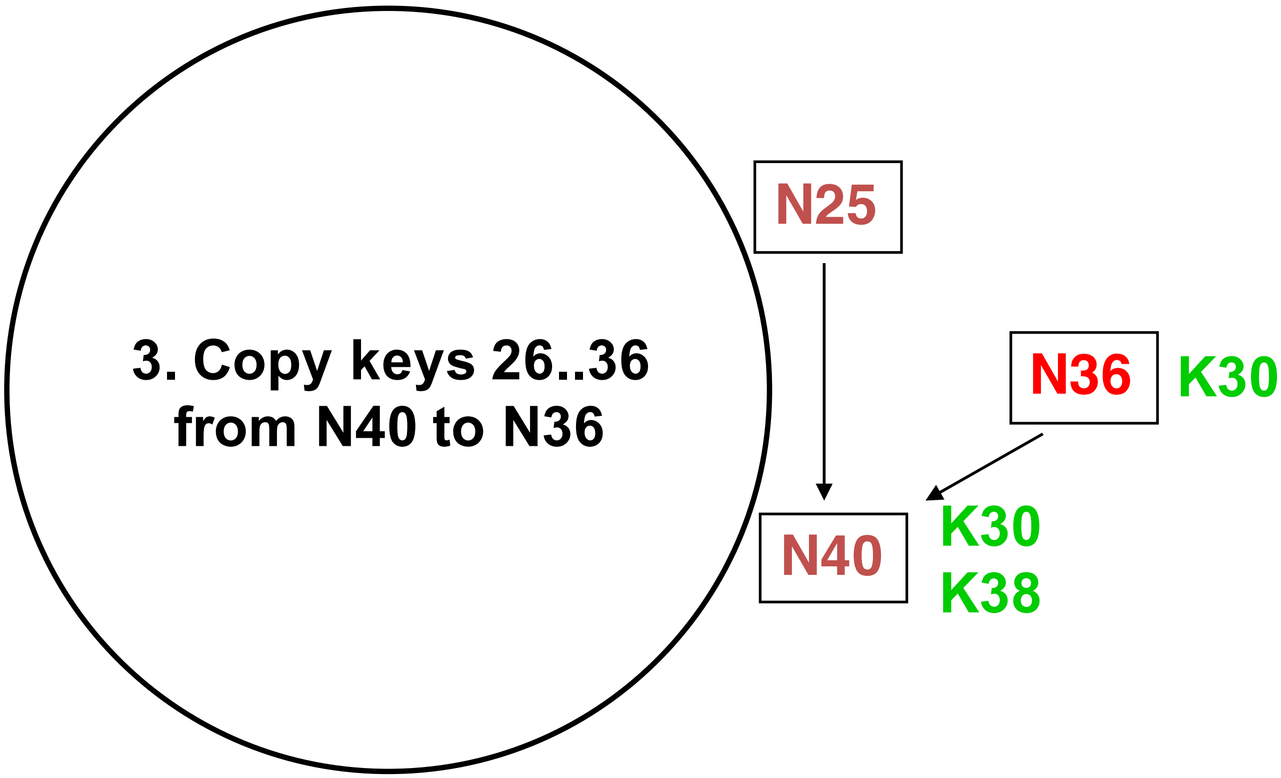
Joining: Linked List Insert



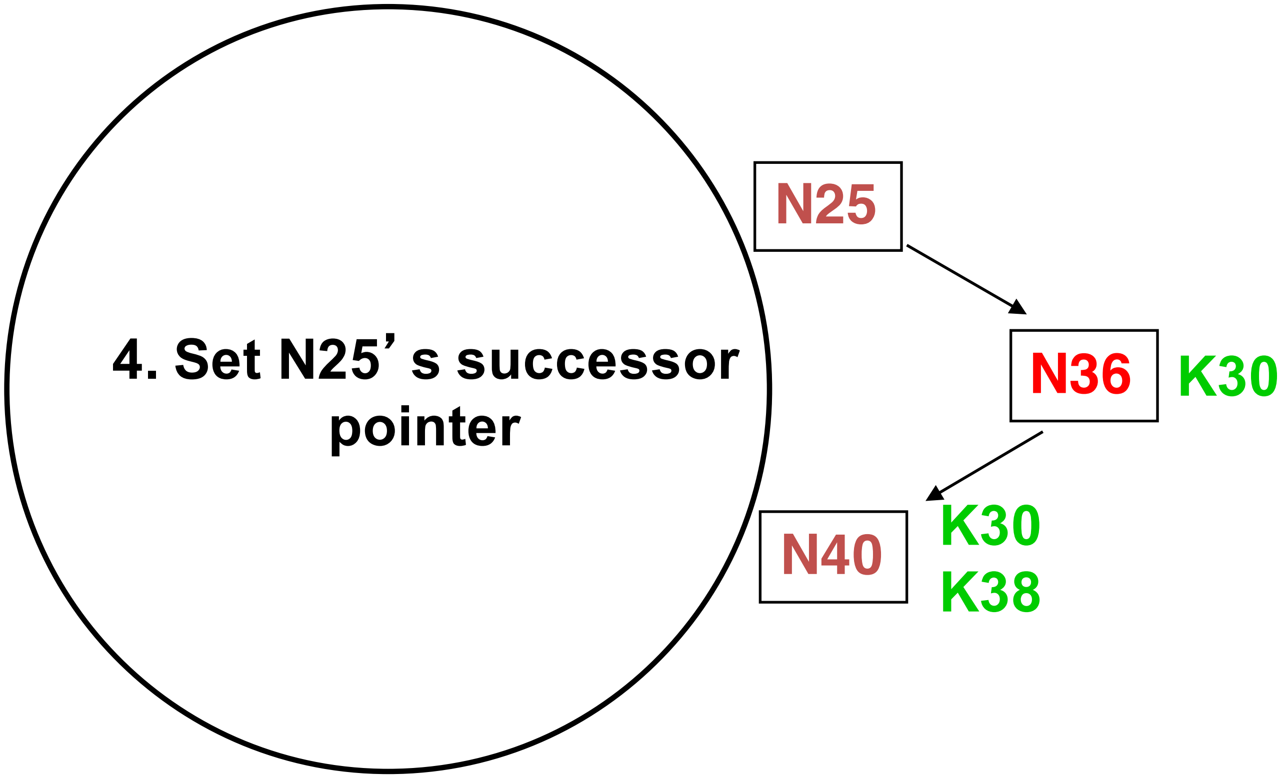
Join (2)



Join (3)

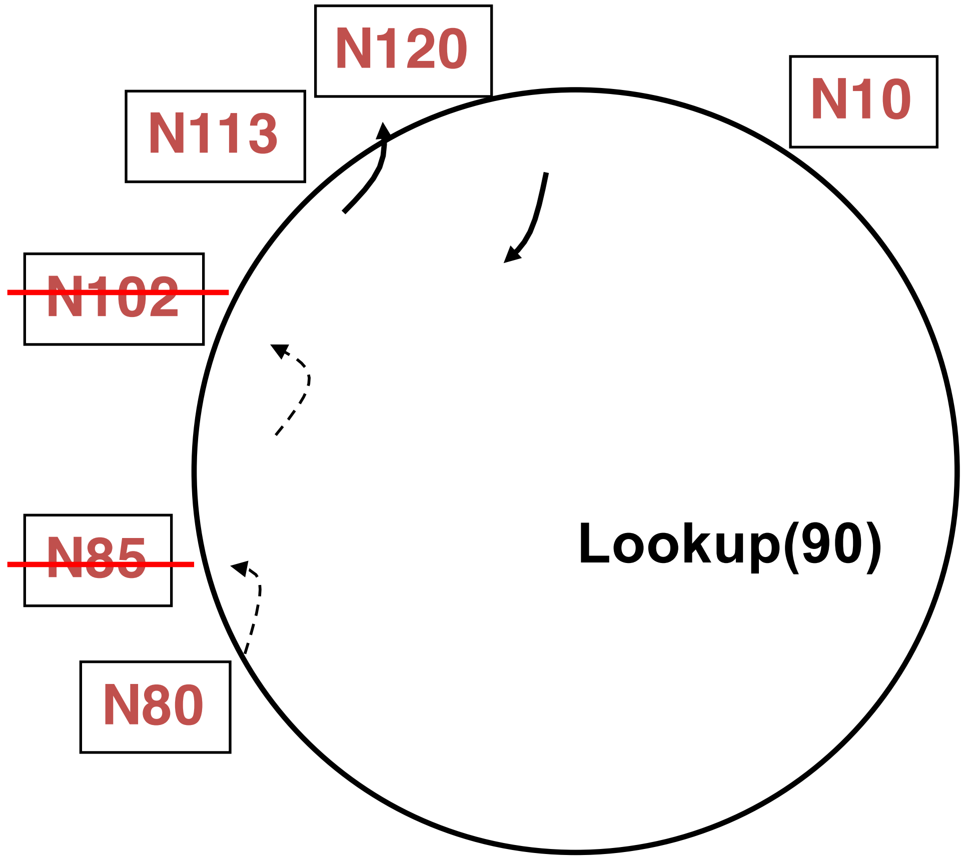


Join (4)



- Predecessor pointer allows link to new node
  - Update finger pointers in the background
- Correct successors produce correct lookups

Failures Might Cause Incorrect Lookup



N80 doesn't know correct successor, so incorrect lookup

Solution: Successor *Lists*

- Each node knows r immediate successors
- After failure, will know first live successor
- Correct successors guarantee correct lookups

- Guarantee is with some probability

Choosing Successor List Length

- Assume ½ the nodes fail

- P(successor list all dead) = $(1/2)^r$
  - *i.e.*, P(this node breaks the Chord ring)
  - Depends on independent failure

- Successor list of size r = O(log N) makes this probability 1/N: low for large N

Lookup with Fault Tolerance

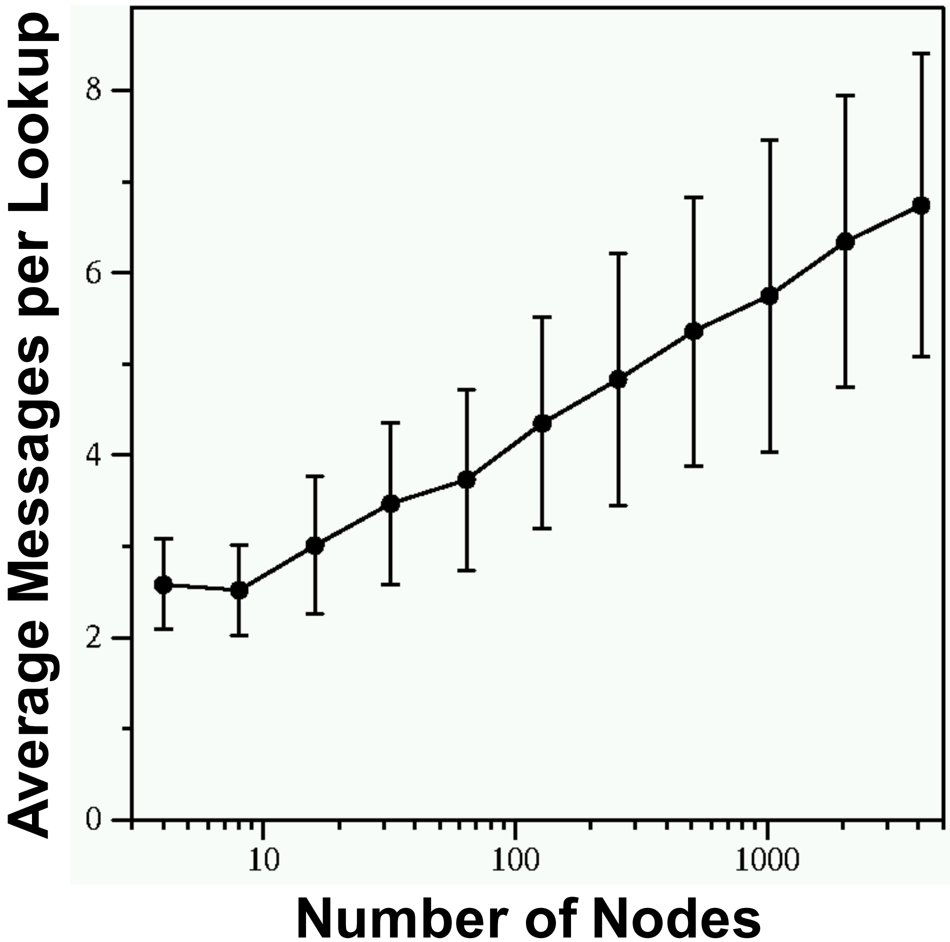
```
Lookup(my-id, key-id)
    look in local finger table and successor-list
     for highest node n s.t. my-id < n < key-id
    if n exists
     call Lookup(key-id) on node n    // next hop
     if call failed,
         remove n from finger table or successor-list
         return Lookup(my-id, key-id)
    else return my successor      // done
```

Experimental Overview

- Quick lookup in large systems
- Low variation in lookup costs
- Robust despite massive failure

Experiments confirm theoretical results

Chord Lookup Cost Is O(log N)

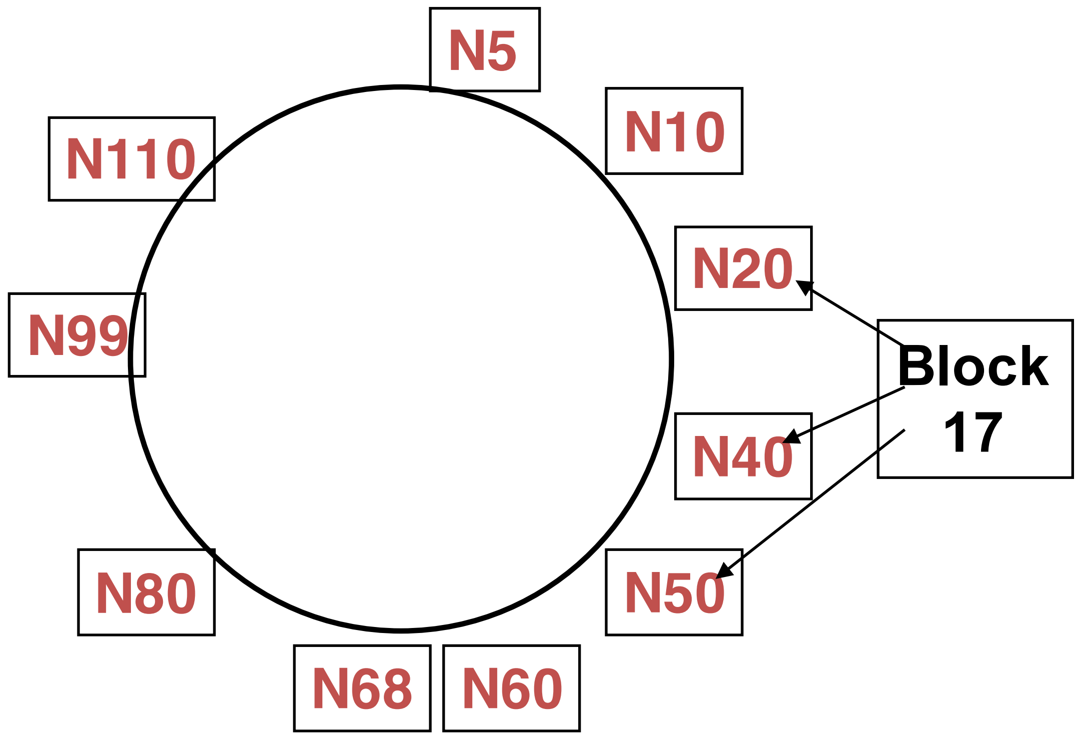


Constant is 1/2

Failure Experimental Setup

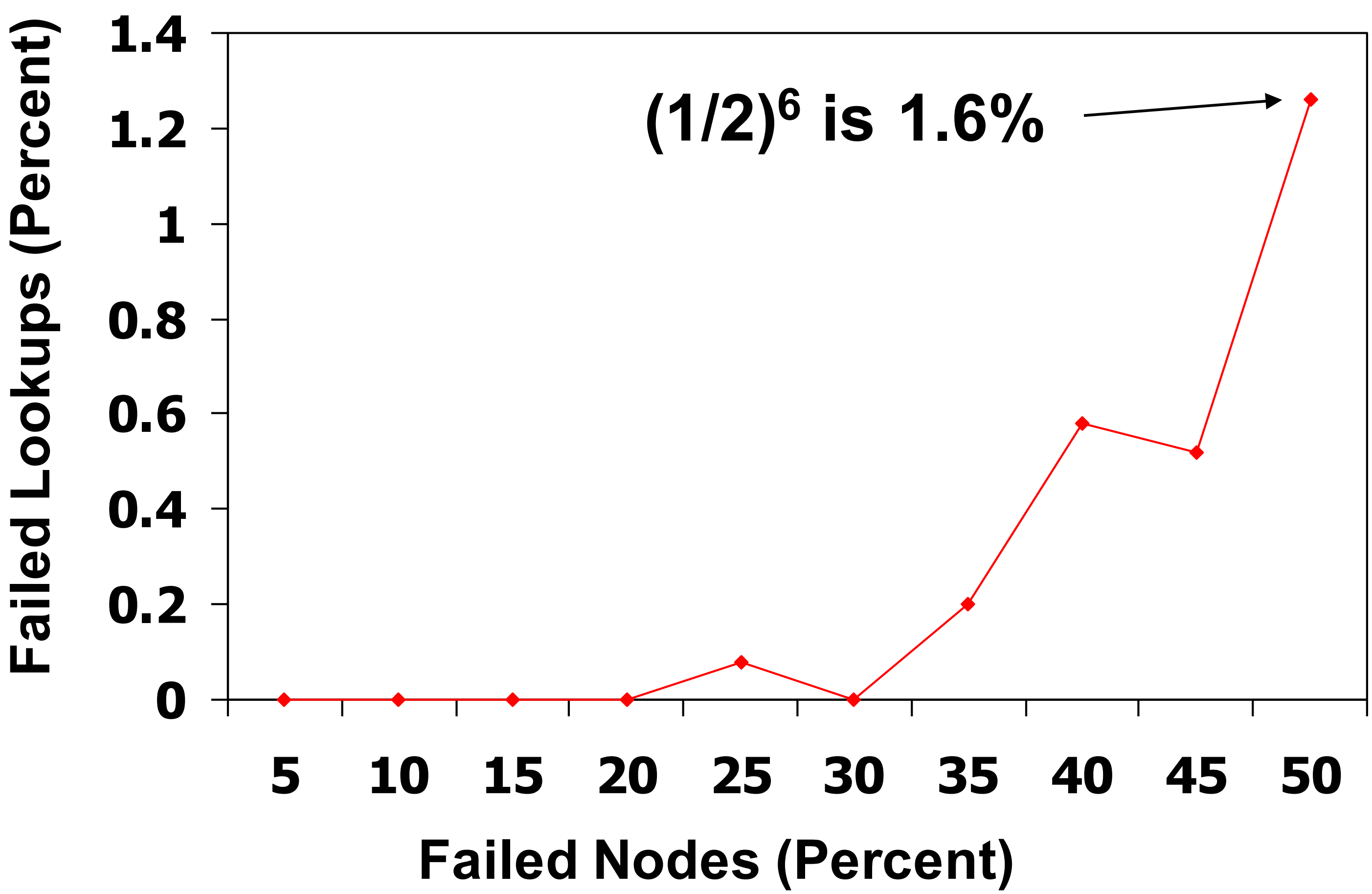
- Start 1,000 CFS/Chord servers
  - Successor list has 20 entries
- Wait until they stabilize
- Insert 1,000 key/value pairs
  - Five replicas of each
- Stop X% of the servers
- Immediately perform 1,000 lookups

DHash Replicates Blocks at *r* Successors



- Replicas are easy to find if successor fails
- Hashed node IDs ensure independent failure

Massive Failures Have Little Impact



DHash summary

- Builds key/value storage on Chord
- Replicates blocks for availability
  - Stores k replicas at the k successor servers after the block's successor on the Chord ring
- Caches blocks for load balance
  - Client sends copy of block to each of the servers it contacted along the lookup path
- Authenticates block contents

DHTs: A Retrospective

- Original DHTs (CAN, Chord, Kademlia, Pastry, Tapestry) proposed in 2001-02
- Following 5-6 years saw proliferation of DHT-based applications:
  - filesystems (e.g., CFS, Ivy, Pond, PAST)
  - naming systems (e.g., SFR, Beehive)
  - indirection/interposition systems (e.g., i3, DOA)
  - content distribution systems (e.g., Coral)
  - distributed databases (e.g., PIER)

What DHTs Got Right

- **Consistent hashing**
  - Elegant way to divide a workload across machines
  - Very useful in clusters: actively used today in Dynamo, FAWN-KV, ROAR, …
- **Replication** for high availability, efficient recovery after node failure
- **Incremental scalability:** "add nodes, capacity increases"
- **Self-management:** minimal configuration

- Unique trait: no single server to shut down, control, monitor
  - …well suited to "illegal" applications, be they sharing music or resisting censorship

DHTs' limitations

- High latency between peers
- Limited bandwidth between peers (as compared to within a cluster)
- Lack of trust in peers' correct behavior
  - securing DHT routing hard, unsolved in practice

Next time

- Wednesday 10/28 Paper Discussion: Weakening Consistency

- Bayou, Dynamo, Eiger