Distributed Hash Tables

CS425 /ECE428 – DISTRIBUTED SYSTEMS – FALL 2021

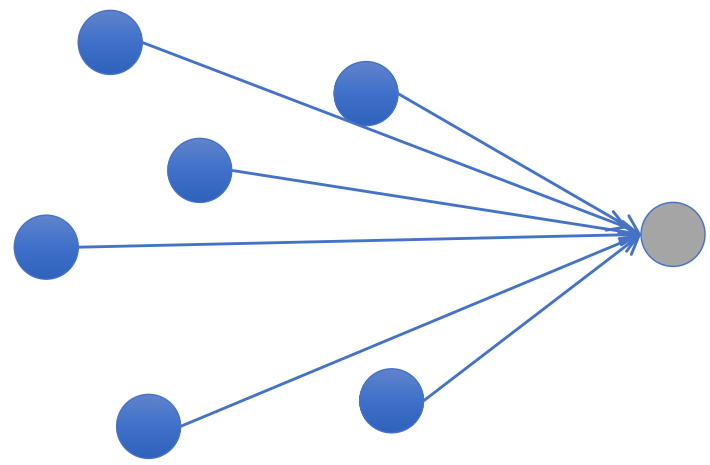
Material derived from slides by I. Gupta, M. Harandi,
J. Hou, S. Mitra, K. Nahrstedt, N. Vaidya

Distributed System Organization

- Centralized
- Ring
- Clique
- How well do these work with 1M+ nodes?

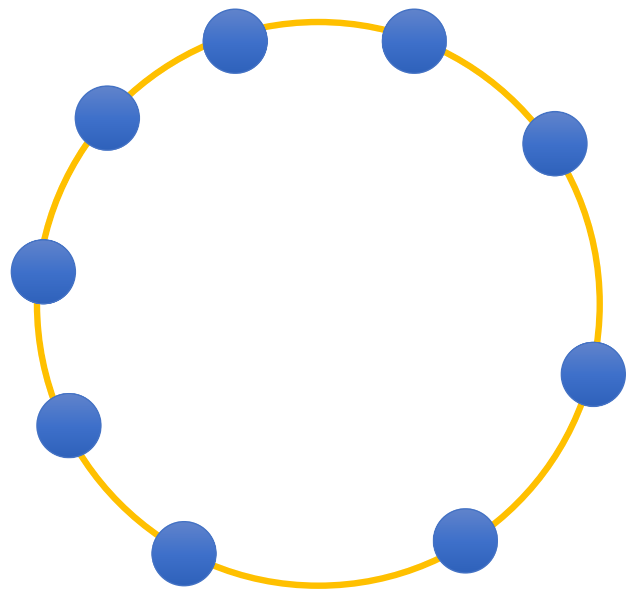
Centralized

- Problems?
- Leader a bottleneck
  - O(N) load on leader
- Leader election expensive



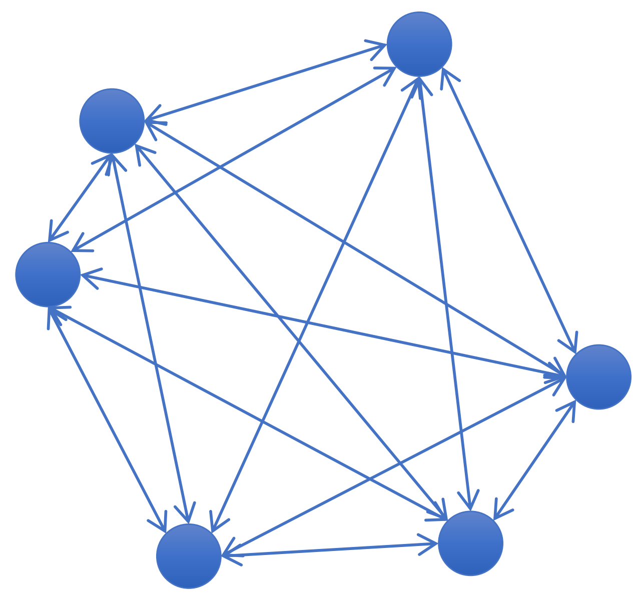
Ring

- Problems?
- Fragile
  - O(1) failures tolerated
- Slow communication
  - O(N) messages



Clique

- Problems?
- High overhead
  - O(N) state at each node
  - O(N^2) messages for failure detection



Distributed Hash Tables

- Middle point between ring and clique
- Scalable *and* fault-tolerant
  - Maintain O(log N) state
  - Routing complexity O(log N)
  - Tolerate O(N) failures
- Other possibilities:
  - State: O(1), routing: O(log N)
  - State: O(log N), routing: O(log N / log log N)
  - State: O(√N), routing: O(1)

Distributed Hash Table

- A hash table allows you to insert, lookup and delete objects with keys
- A *distributed* hash table allows you to do the same in a distributed setting (objects=files)
- DHT also sometimes called a key-value store when used within a cloud
- Performance Concerns:
  - Load balancing
  - Fault-tolerance
  - Efficiency of lookups and inserts

Chord

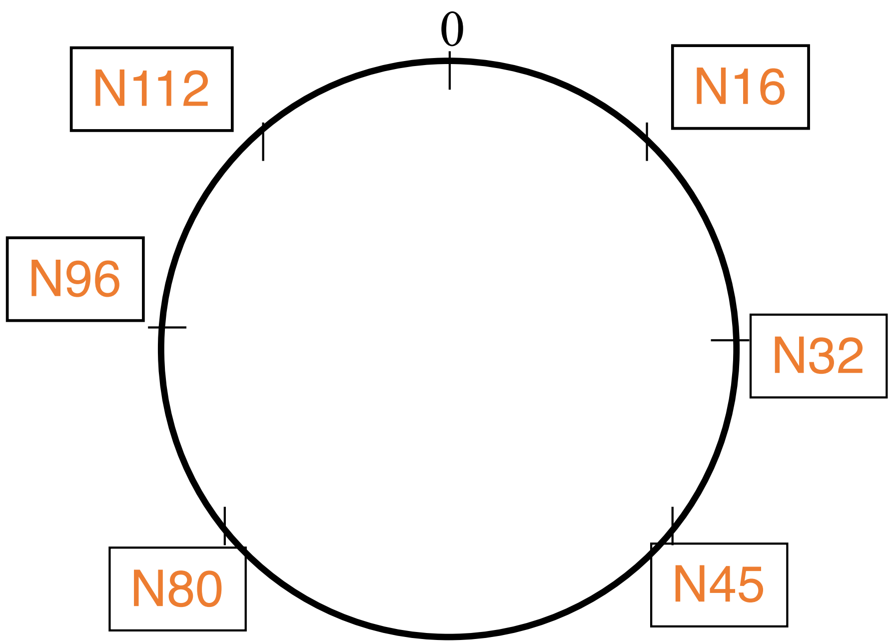
- Intelligent choice of neighbors to reduce latency and message cost of routing (lookups/inserts)

- Uses *Consistent Hashing* on node's (peer's) address
  - (ip_address,port) →hashed id (*m* bits)
  - Called peer *id* (number between 0 and $2^m - 1$)
  - Not unique but id conflicts very unlikely
  - Can then map peers to one of 2^m logical points on a circle

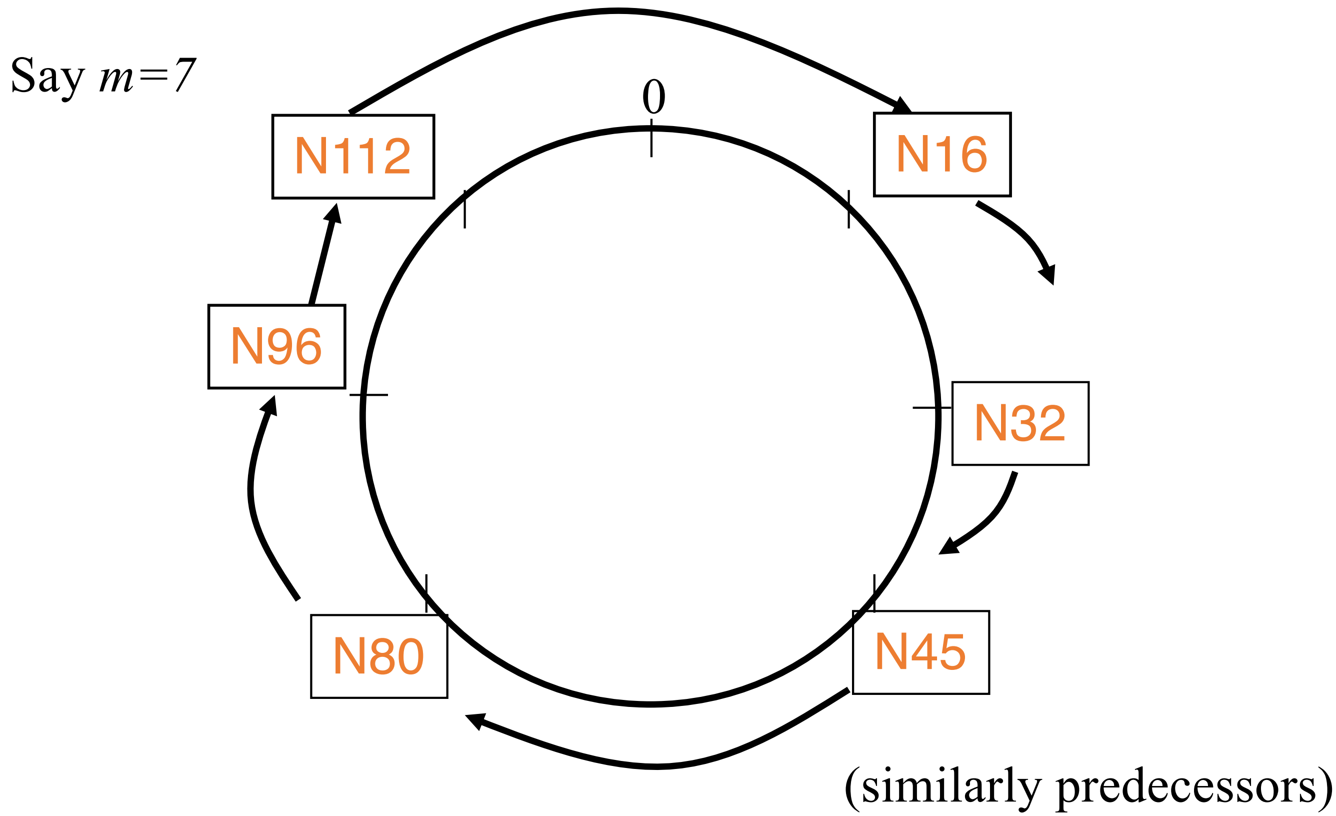
Ring of peers

Say $m=7$

6 nodes



Peer pointers (1): *successors*

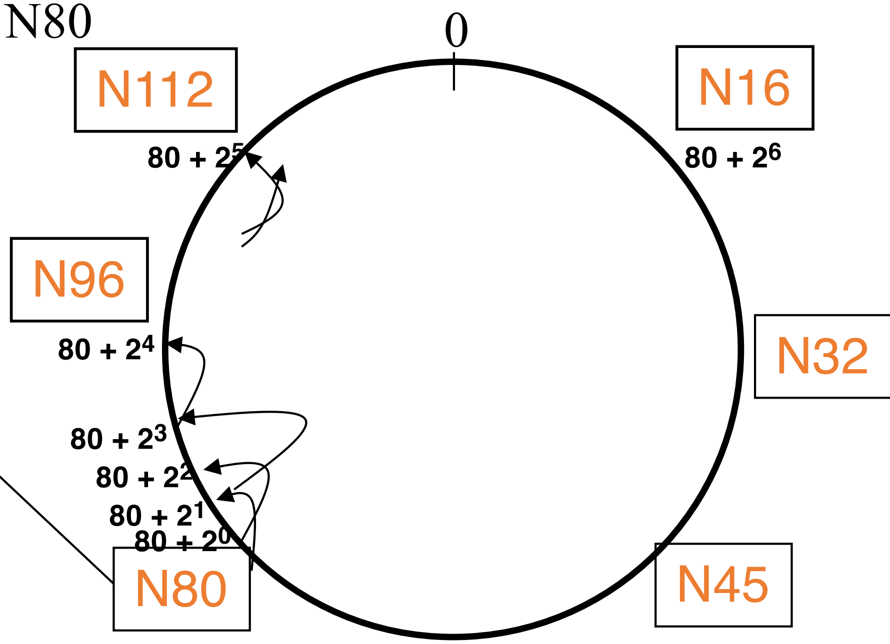


Peer pointers (2): *finger tables*

Say m=7

Finger Table at N80

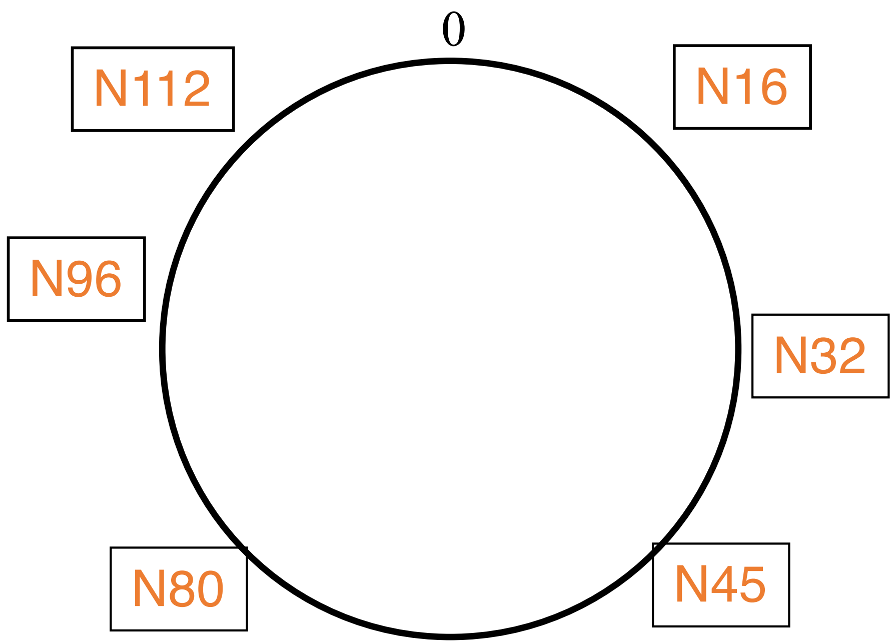
i	$ft[i]$
0	96
1	96
2	96
3	96
4	96
5	112
6	16



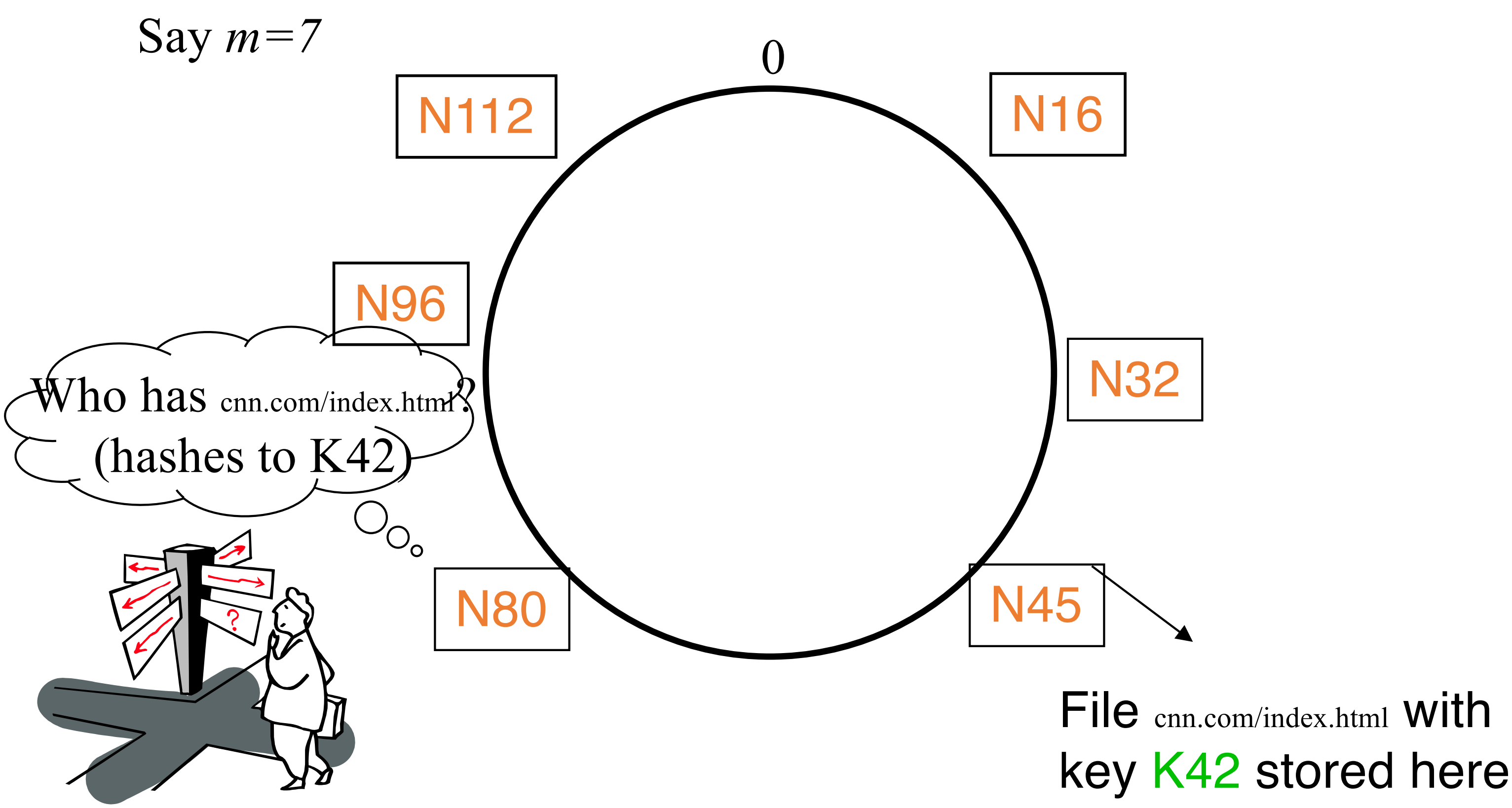
ith entry at peer with id n is first peer with id >= $n + 2^i \pmod{2^m}$

Mapping Values

- Key = hash(ident)
  - m bit string
- Value is stored at first peer with id greater than its key (mod 2^m)

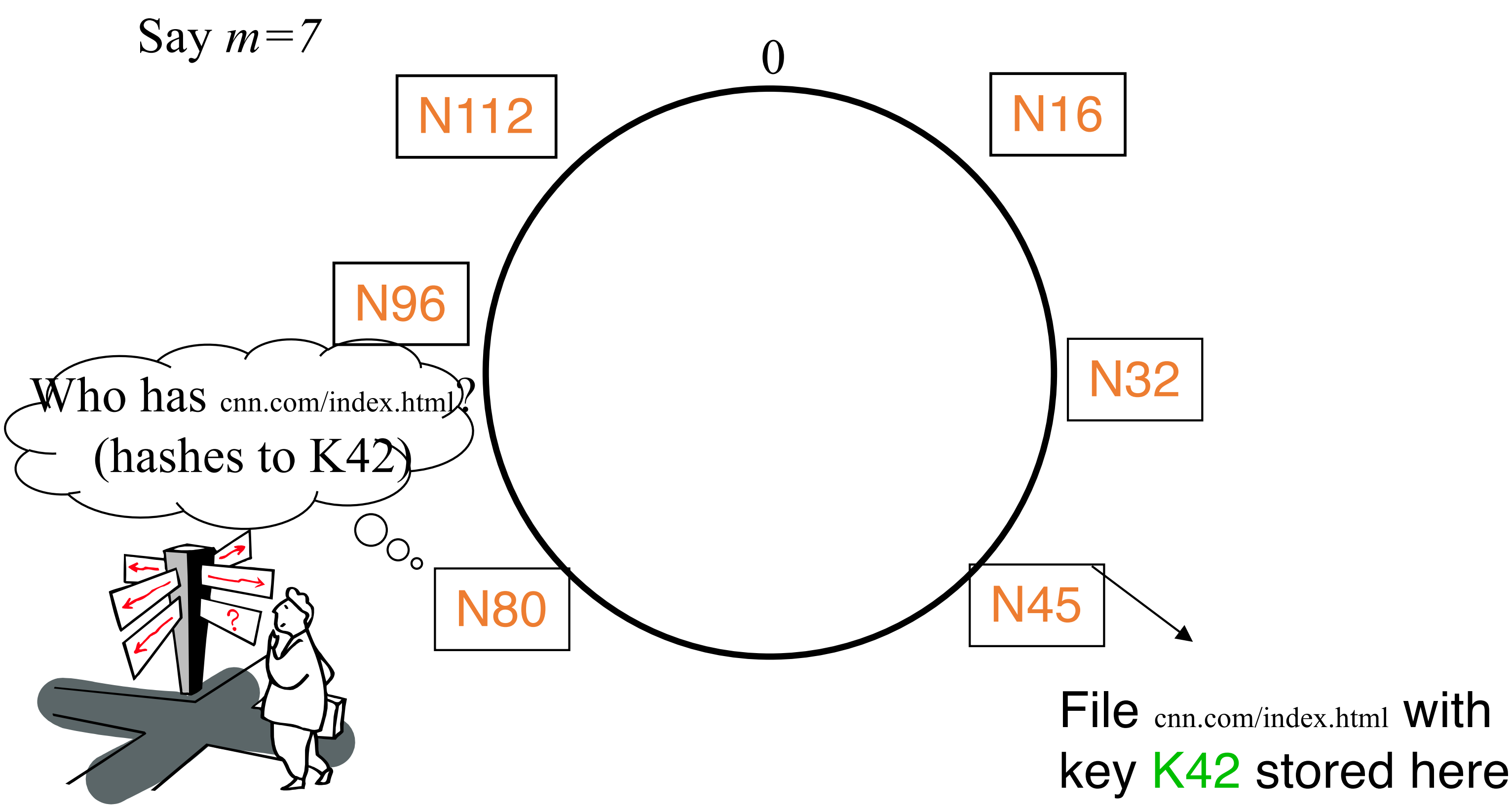


Search


Say m=7
0
N112
N16
N96
N32
Who has cnn.com/index.html?
(hashes to K42)
N80
N45
File cnn.com/index.html with
key K42 stored here

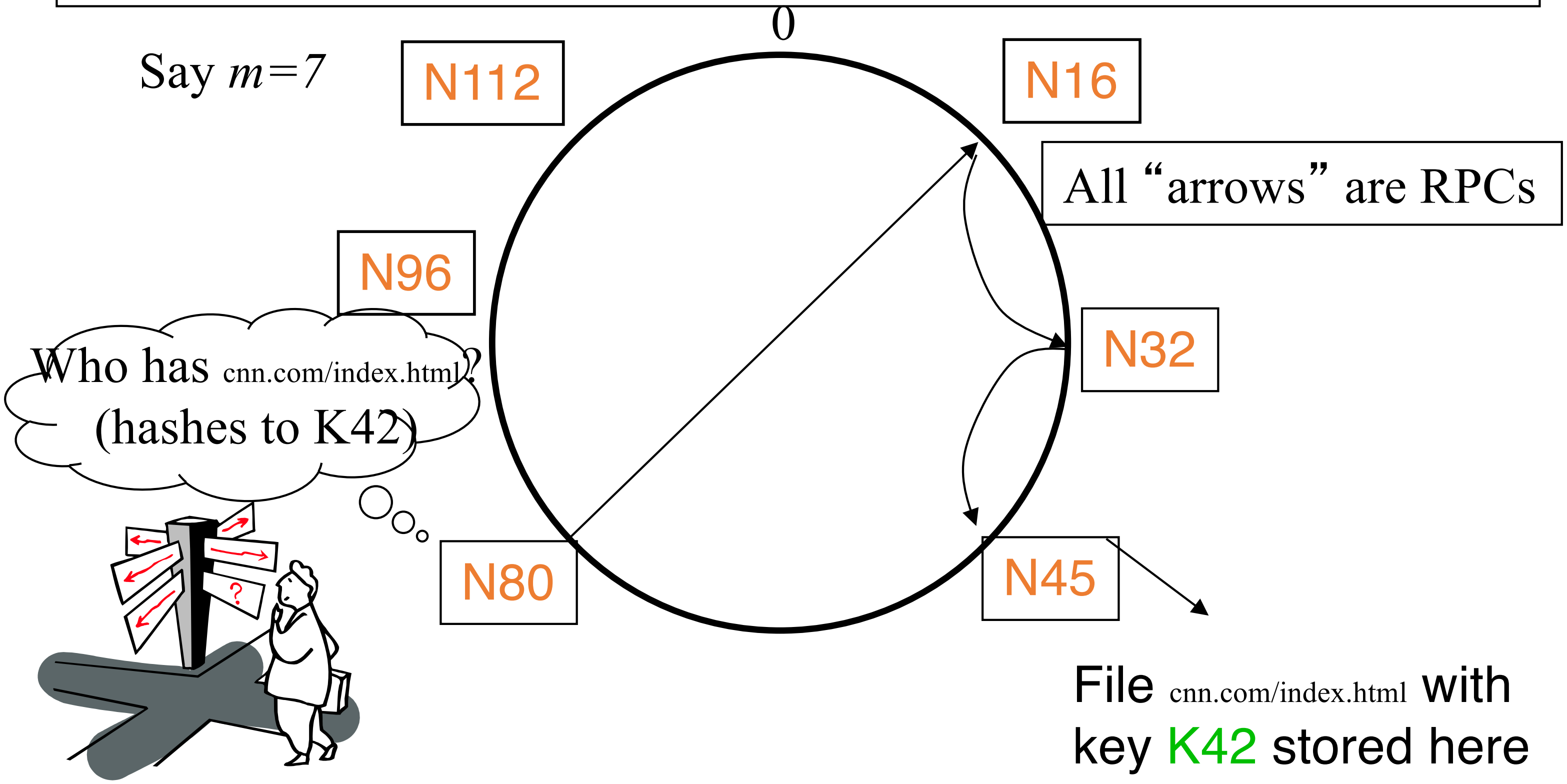
Search

At node *n*, send query for key *k* to largest successor/finger entry <= *k*
if none exist, send query to *successor(n)*

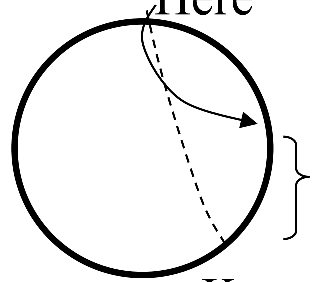


Search

At node *n*, send query for key *k* to largest successor/finger entry <= *k*
if none exist, send query to *successor(n)*



Analysis



Search takes *O(log(N))* time

Proof

- (intuition): *at each step, distance between query and peer-with-file reduces by a factor of at least 2* (why?)

  Takes at most *m* steps: 2^m is at most a constant multiplicative factor above *N,* lookup is *O(log(N))*
- (intuition): after *log(N)* forwardings, distance to key is at most $2^m / N$ (why?)

  Number of node identifiers in a range of $2^m / N$

  is *O(log(N))* with high probability (why?)

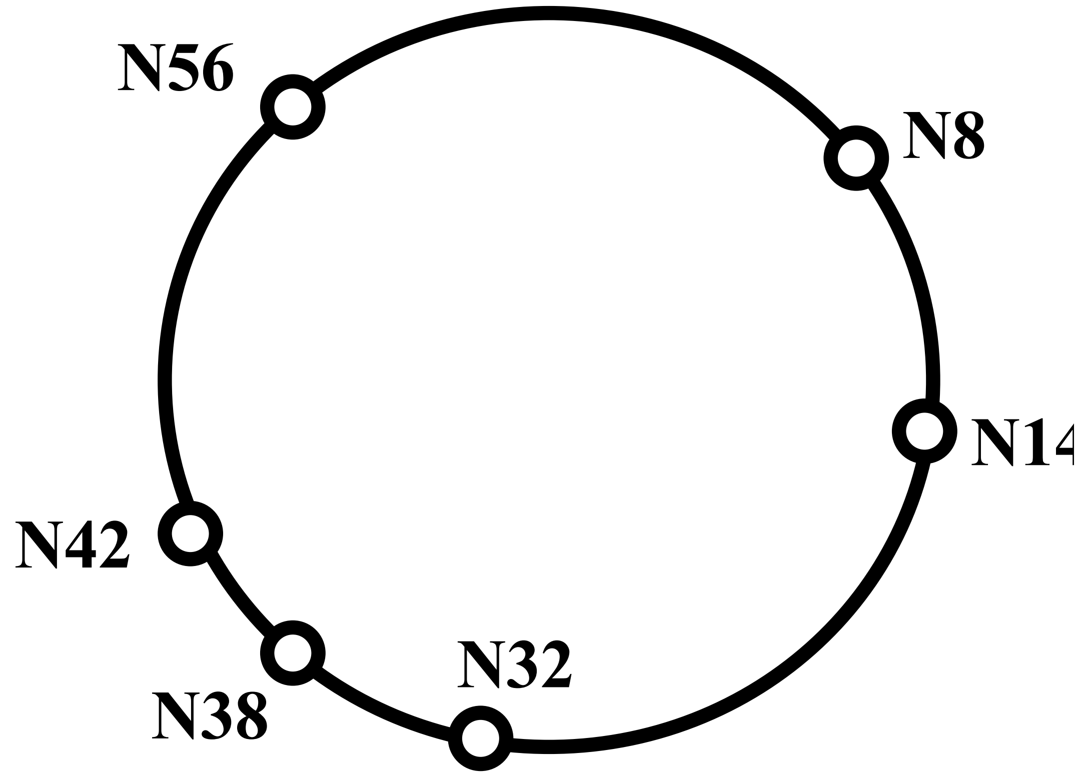
  So using *successor*s in that range will be ok

Analysis (contd.)

- *O(log(N))* search time holds for file insertions too (in general for *routing to any key*)
  - "Routing" can thus be used as a building block for
    - All operations: insert, lookup, delete
- *O(log(N))* time true only if finger and successor entries correct
- When might these entries be wrong?
  - When you have failures

Chord Recap

Each node has an identifier
id=H(address) in the range $[0,2^m)$



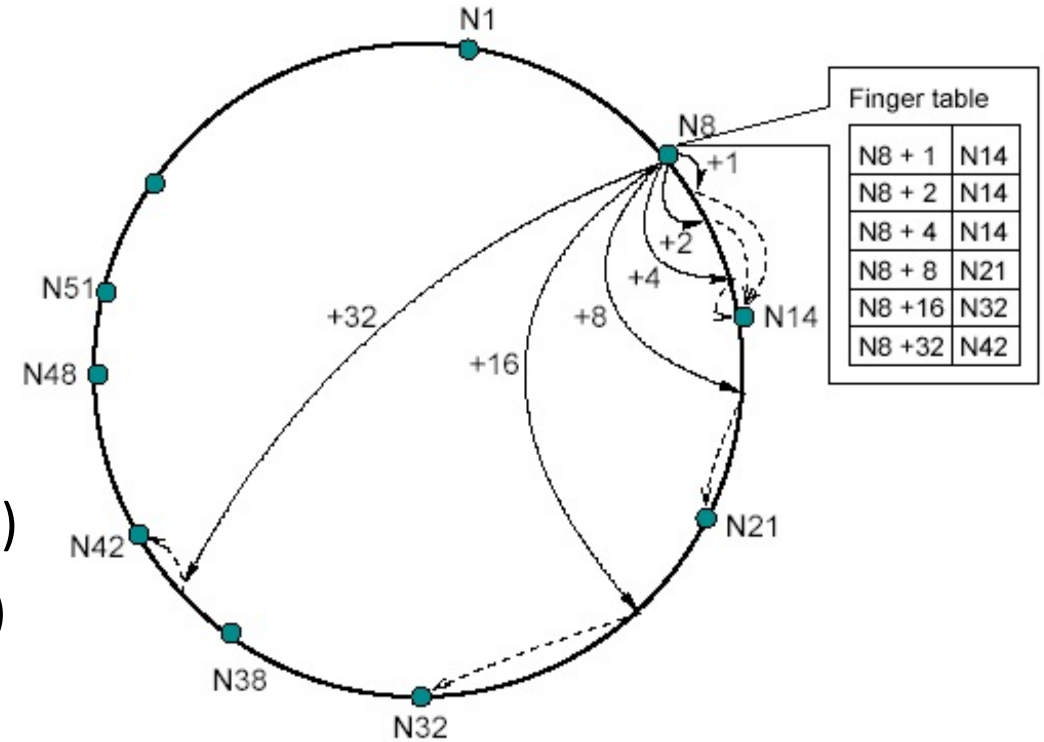
Chord Recap

Each node has an identifier id=H(address) in the range $[0,2^m)$

*succ(*n*)* = node with next largest ID > n, wrapping around mod 2^m

Node with id connects to:

- *succ*(id) (successor)
- *succ*($(id+2^i) \bmod 2^m$) (fingers)



Chord Recap

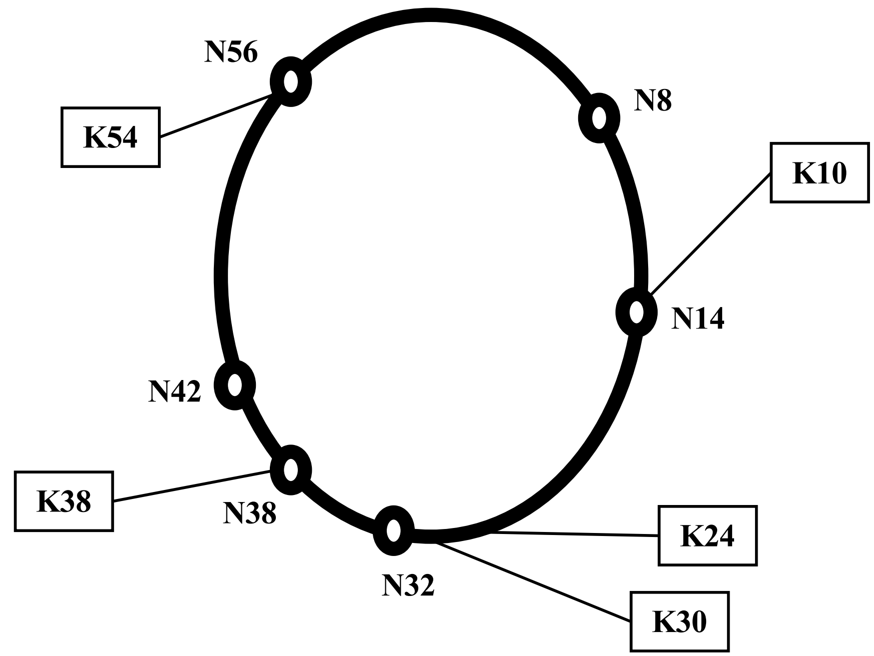
Each node has an identifier id=H(address) in the range $[0,2^m)$

*succ(*n*)* = node with next largest ID > n, wrapping around mod 2^m

Node with id connects to:

- *succ*(id) (successor)
- *succ*((id+2^i) mod 2^m) (fingers)

A key k is stored in succ(k)



Chord Recap

Each node has an identifier id=H(address) in the range $[0,2^m)$

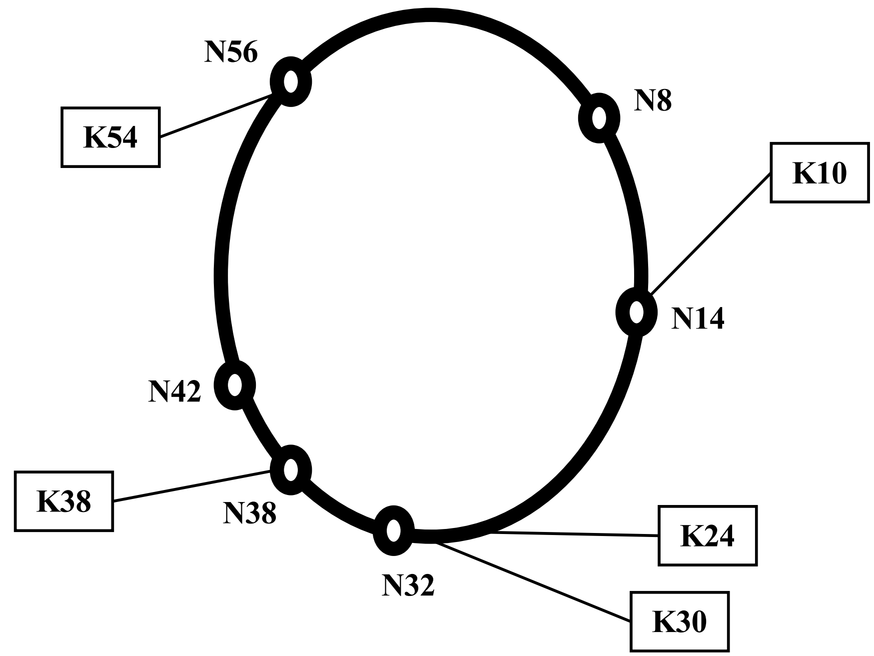
*succ(*n*)* = node with next largest ID > n, wrapping around mod 2^m

Node with id connects to:

- *succ*(id) (successor)
- *succ*((id+2^i) mod 2^m) (fingers)

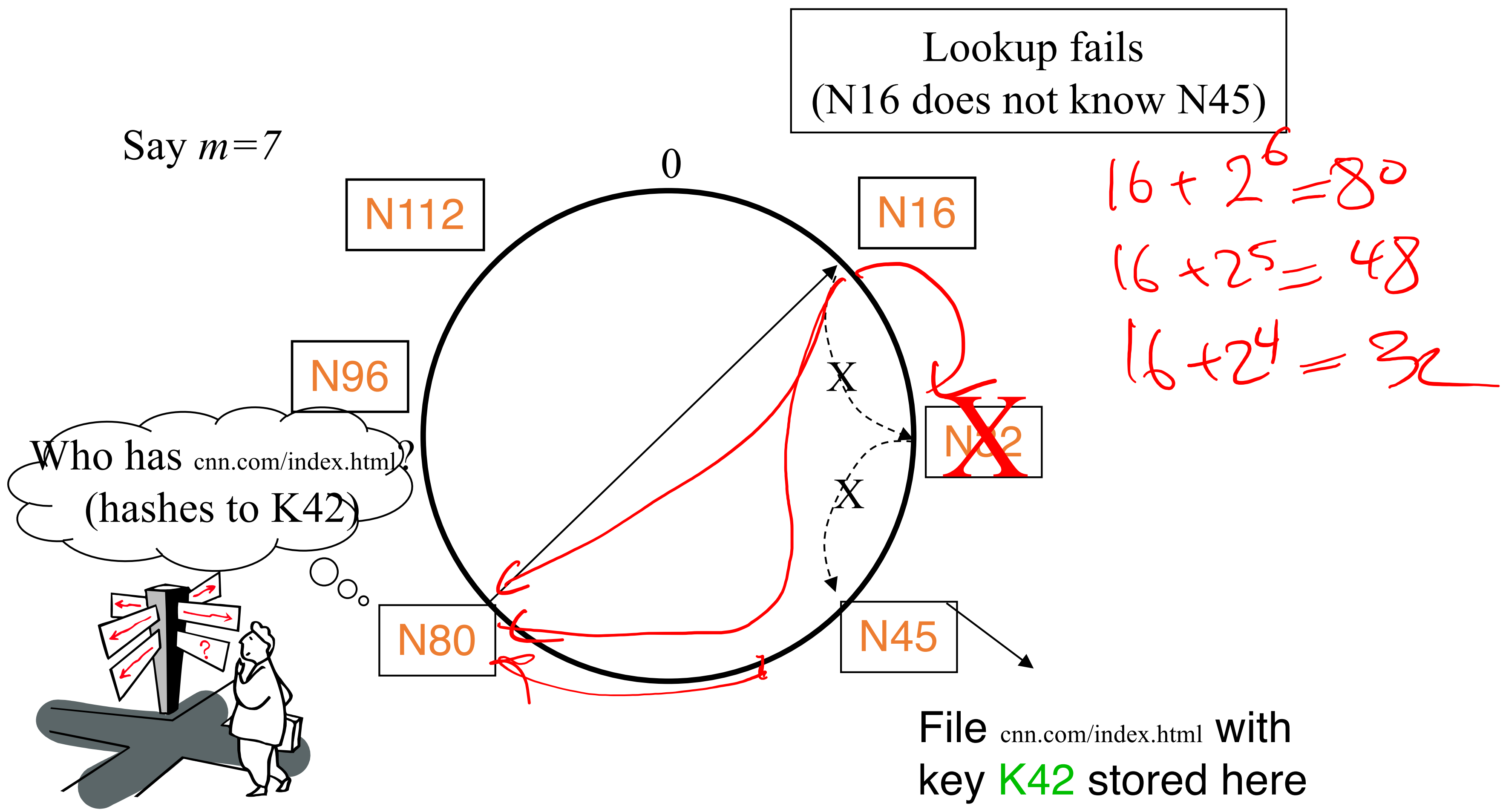
A key k is stored in succ(k)

To find key k, recursively follow the finger that gets you closest to k



Search under peer failures

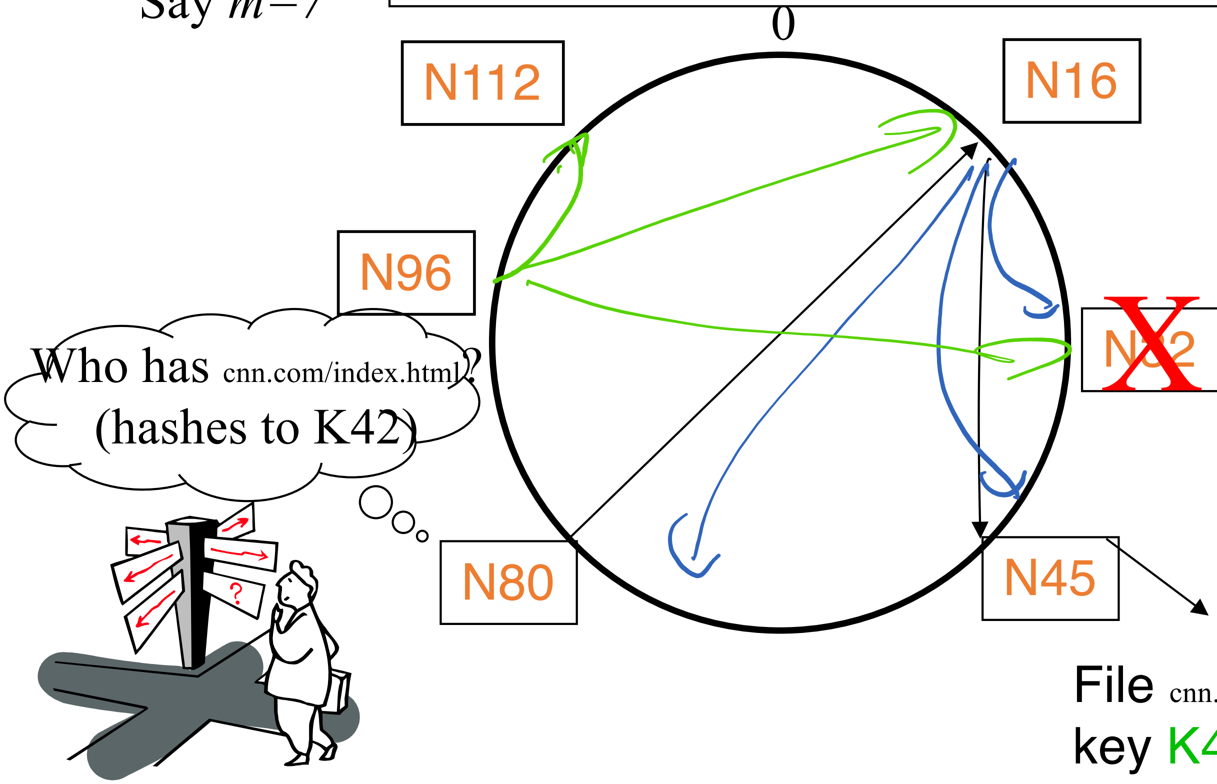
Say m=7



Search under peer failures

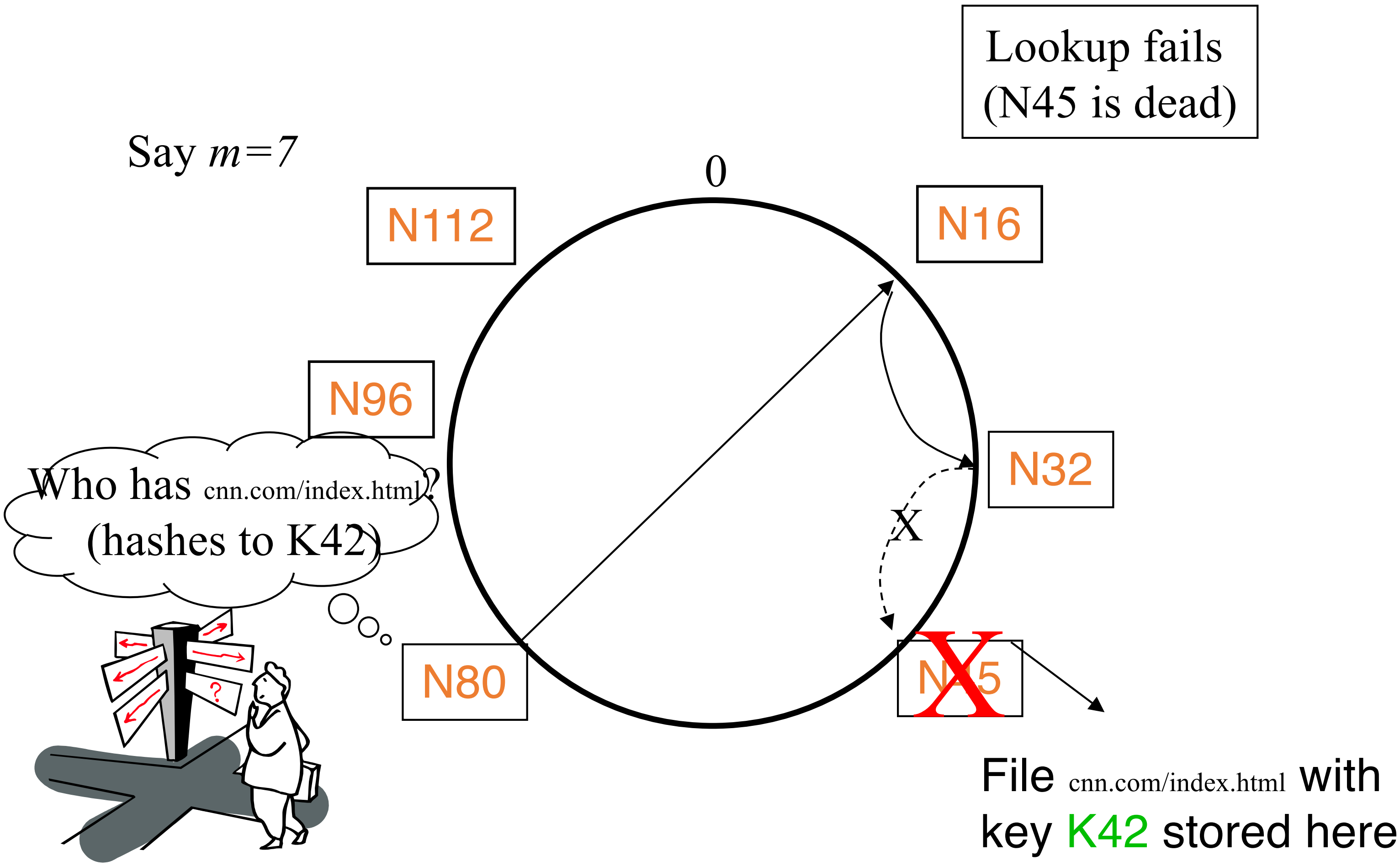
One solution: maintain *r* multiple *successor* entries
In case of failure, use successor entries

Say m=7



File cnn.com/index.html with key K42 stored here

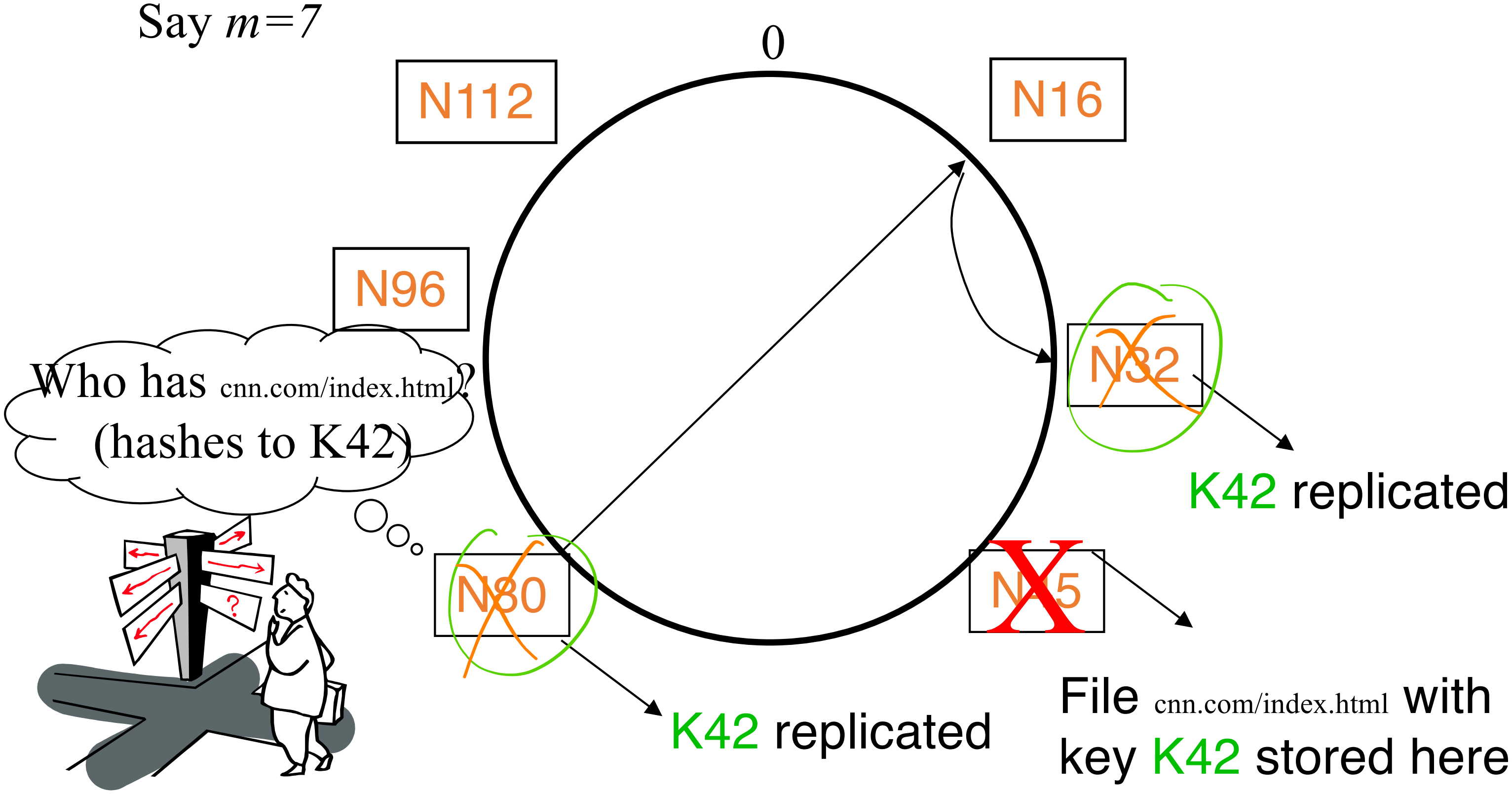
Search under peer failures (2)



Search under peer failures (2)

One solution: replicate file/key at *r* successors and predecessors

Say m=7



Need to deal with dynamic changes

✓Peers fail

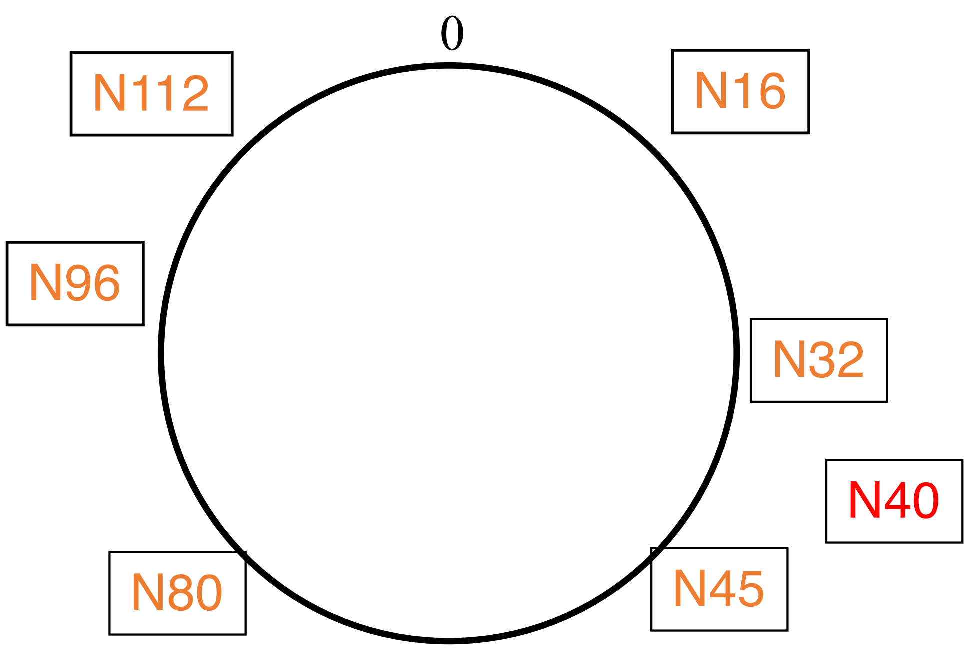
- New peers join
- Peers leave
  - P2P systems have a high rate of *churn* (node join, leave and failure)

→ Need to update *successor*s and *finger*s, and copy keys

New peers joining

Introducer directs N40 to N45 (and N32)
N32 updates successor to N40
N40 initializes successor to N45, and inits fingers from it

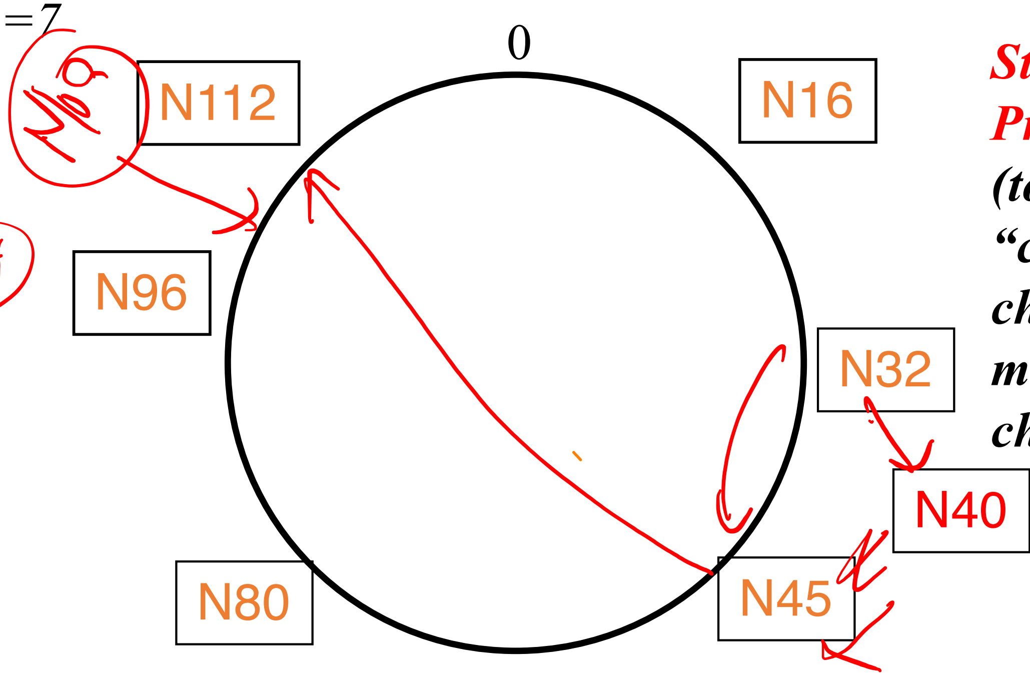
Say *m*=7



New peers joining

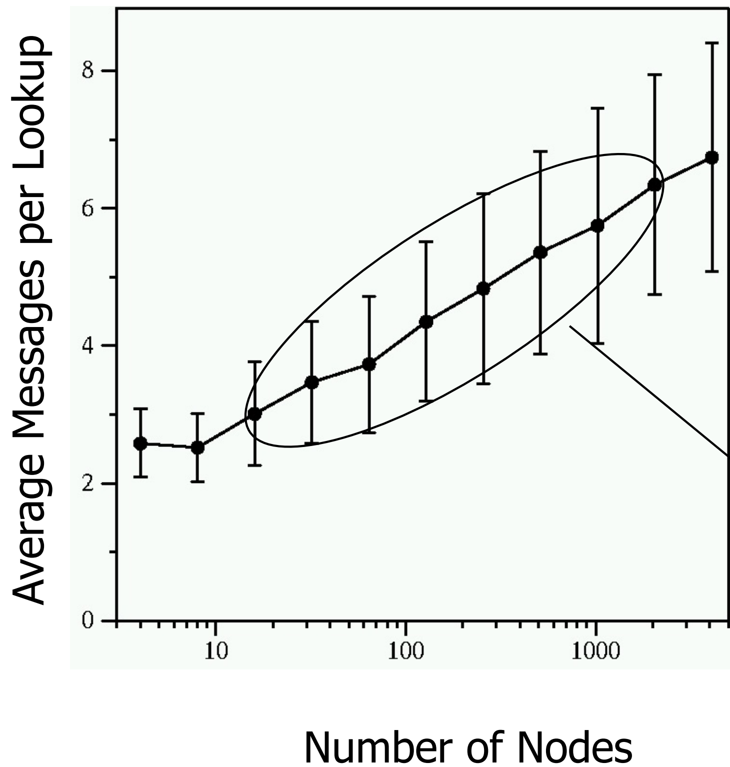
Introducer directs N40 to N45 (and N32)
N32 updates successor to N40
N40 initializes successor to N45, and inits fingers from it
N40 periodically talks to its neighbors to update finger table

Say $m=7$



Stabilization Protocol
(to allow for "continuous" churn, multiple changes)

Lookups



log N, as expected

Chord Protocol: Summary

- *O(log(N))* memory and lookup costs
- Hashing to distribute filenames uniformly across key/address space
- Allows dynamic addition/deletion of nodes

DHT Deployment

- Many DHT designs
  - Chord, Pastry, Tapestry, Koorde, CAN, Viceroy, Kelips, Kademlia, …
- Slow adoption in real world
  - Most real-world P2P systems unstructured
    - No guarantees
    - Controlled flooding for routing
  - Kademlia slowly made inroads, now used in many file sharing networks
- Distributed key-value stores adopt some of the ideas of DHTs
  - Dynamo, Cassandra, etc.