Distributed Systems

CS425/ECE428

April 12 2022

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Acknowledgements for some of the materials: Indy Gupta

Logistics

- HW5 is due tomorrow (not on Thursday!)
- HW6 will be released on Thursday.
- Final exam is on May 12th, 8-11am.
  - It will be fully online.
  - Same format as your midterm, but longer.
  - It will be comprehensive – everything covered in class.

Our agenda for the next 3-4 classes

- Brief overview of key-value stores

- Distributed Hash Tables
  - Peer-to-peer protocol for efficient insertion and retrieval of key-value pairs.

- Key-value stores in the cloud
  - How to run large-scale distributed computations over key-value stores?
    - Map-Reduce Programming Abstraction
  - How to design a large-scale distributed key-value store?
    - Case-study: Facebook's Cassandra

Our focus today

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The Key-value Abstraction

- (Business) Key → Value
  - (twitter.com) tweet id → information about tweet
  - (amazon.com) item number → information about it
  - (kayak.com) Flight number → information about flight, e.g., availability
  - (yourbank.com) Account number → information about it

The Key-value Abstraction (2)

- It's a dictionary data-structure.
  - Insert, lookup, and delete by key
  - E.g., hash table, binary tree
- But *distributed*.

Isn’t that just a database?

- *Yes, sort of.*
- Relational Database Management Systems (RDBMSs) have been around for ages
  - e.g. MySQL is the most popular among them
- Data stored in structured tables based on a *Schema*
  - Each row (data item) in a table has a primary key that is unique within that table.
- Queried using SQL (Structured Query Language).
  - Supports joins.

Relational Database Example

users table

user_id	name	zipcode	blog_url	blog_id
101	Alice	12345	alice.net	1
422	Charlie	45783	charlie.com	3
555	Bob	99910	bob.blogspot.com	2

↑ Primary keys ↓

↑ Foreign keys

blog table

id	url	last_updated	num_posts
1	alice.net	5/2/14	332
2	bob.blogspot.com	4/2/13	10003
3	charlie.com	6/15/14	7

Example SQL queries

1. SELECT zipcode
   FROM users
   WHERE name = "Bob"

2. SELECT url
   FROM blog
   WHERE id = 3

3. SELECT users.zipcode, blog.num_posts
   FROM users JOIN blog
   ON users.blog_url = blog.url

Mismatch with today's workloads

- Data: Large and unstructured
- Lots of random reads and writes
- Sometimes write-heavy
- Foreign keys rarely needed
- Joins infrequent

Key-value/NoSQL Data Model

- NoSQL = "Not Only SQL"
- Necessary API operations: get(key) and put(key, value)

- Tables
  - Like RDBMS tables, but …
  - May be unstructured: May not have schemas
    - Some columns may be missing from some rows
  - Don't always support joins or have foreign keys
  - Can have index tables, just like RDBMSs

Key-value/NoSQL Data Model

- Unstructured
- No schema imposed
- Columns missing from some Rows
- No foreign keys, joins may not be supported

Key

Value

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Distributed Hash Tables (DHTs)

- Multiple protocols were proposed in early 1990s.
    - Chord, CAN, Pastry, Tapestry
    - Initial usecase: Peer-to-peer file sharing
        - key = hash of the file, value = file
    - Cloud-based distributed key-value stores reuse many techniques from these DHTs.

- Key goals:
    - Balance load uniformly across all nodes (peers).
    - Fault-tolerance
    - Efficient inserts and lookups.

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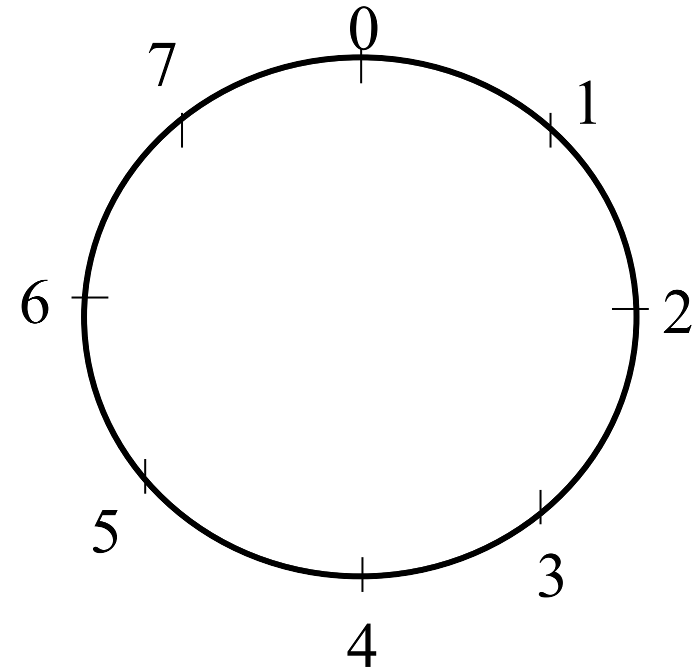
Chord

- Developed at MIT by I. Stoica, D. Karger, F. Kaashoek, H. Balakrishnan, R. Morris
- Key properties:
  - Load balance:
    - spreads keys evenly over nodes.
  - Decentralized:
    - no node is more important than others.
  - Scalable:
    - cost of key lookup is O(logN), N = no. of nodes.
  - High availability:
    - automatically adjusts to new nodes joining and nodes leaving.
  - Flexible naming:
    - no constraints on the structure of keys that it looks up.

Chord: Consistent Hashing

- Uses *Consistent Hashing* on node's (peer's) address
  - SHA-1(ip_address,port) → 160 bit string
  - Truncated to **m** bits (modulo 2^m)
  - 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



Circle for m = 3

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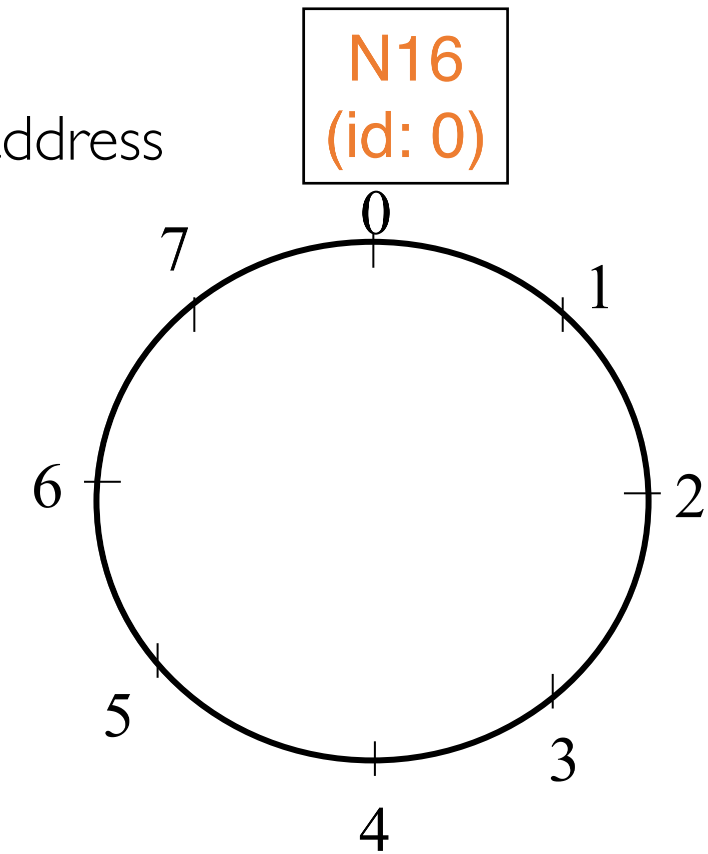

Circle for m = 3

Where will N16 be placed on this circle?

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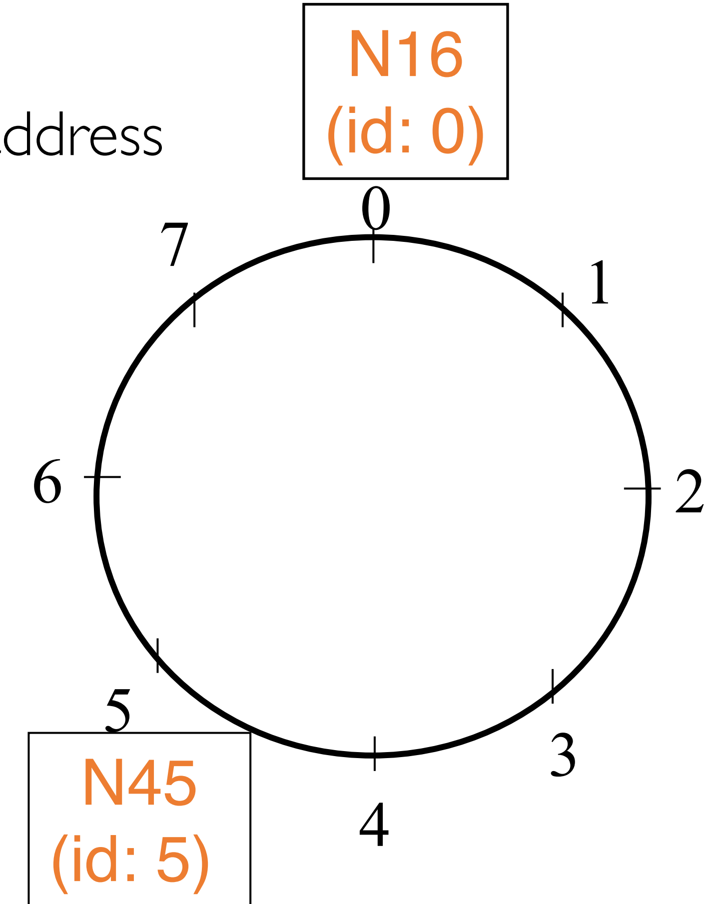
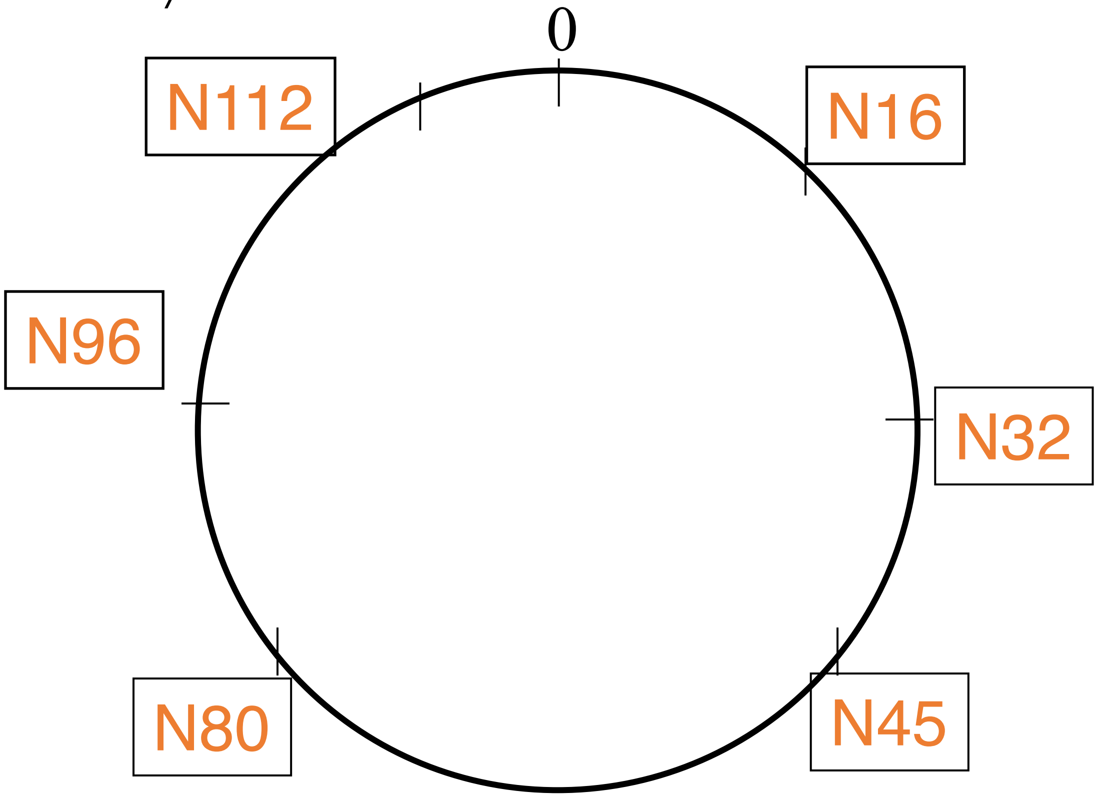


Circle for m = 3

Where will N45 be placed on this circle?

Ring of Peers: Running Example

- Say m=7 (128 possible points on the circle – not shown)
- 6 nodes in the system.

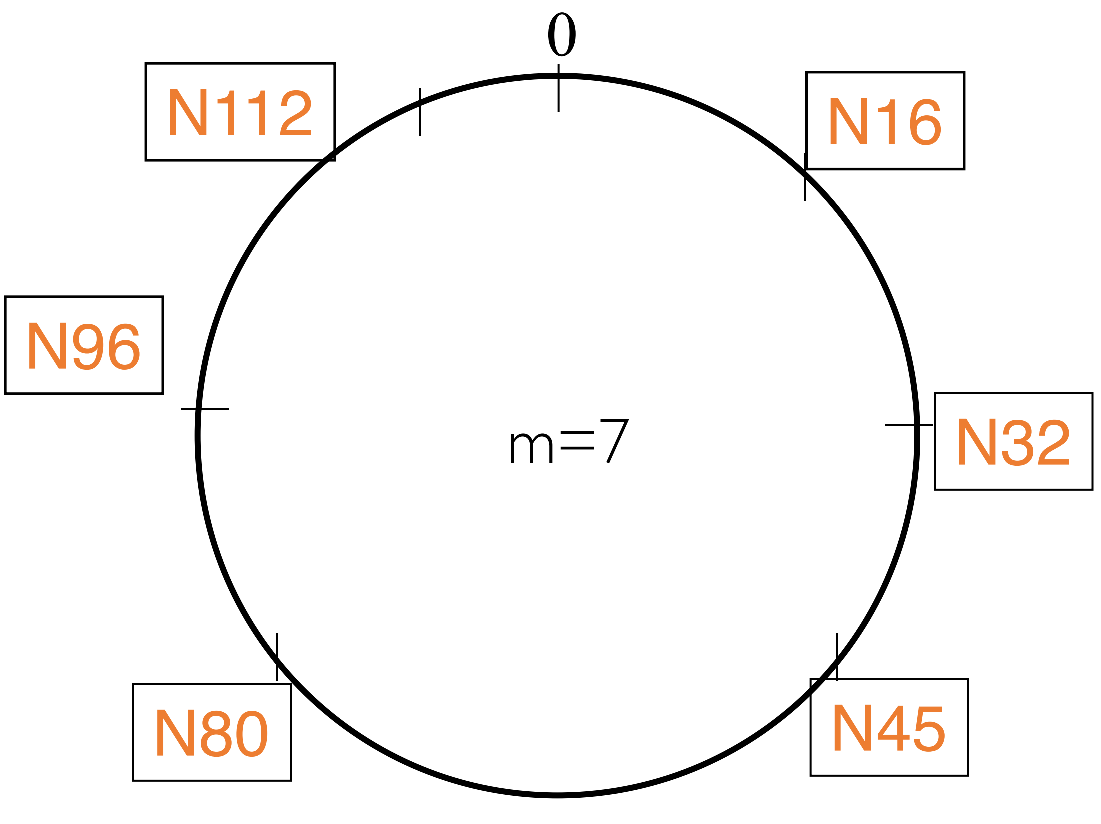


Mapping Keys to Nodes

- Use the same consistent hash function
    - SHA-1(key) → 160 bit string (key identifier)
        - Henceforth, we refer to SHA-1(key) as *key*.
    - The key-value pair stored at the key's *successor* node.
    - *successor(key) = first peer with id greater than or equal to (key mod 2^m)*
        - *Cross-over the ring when you reach the end.*
            - *0 < 1 < 2 < 3 …….. < 127 < 0 (for m=7)*

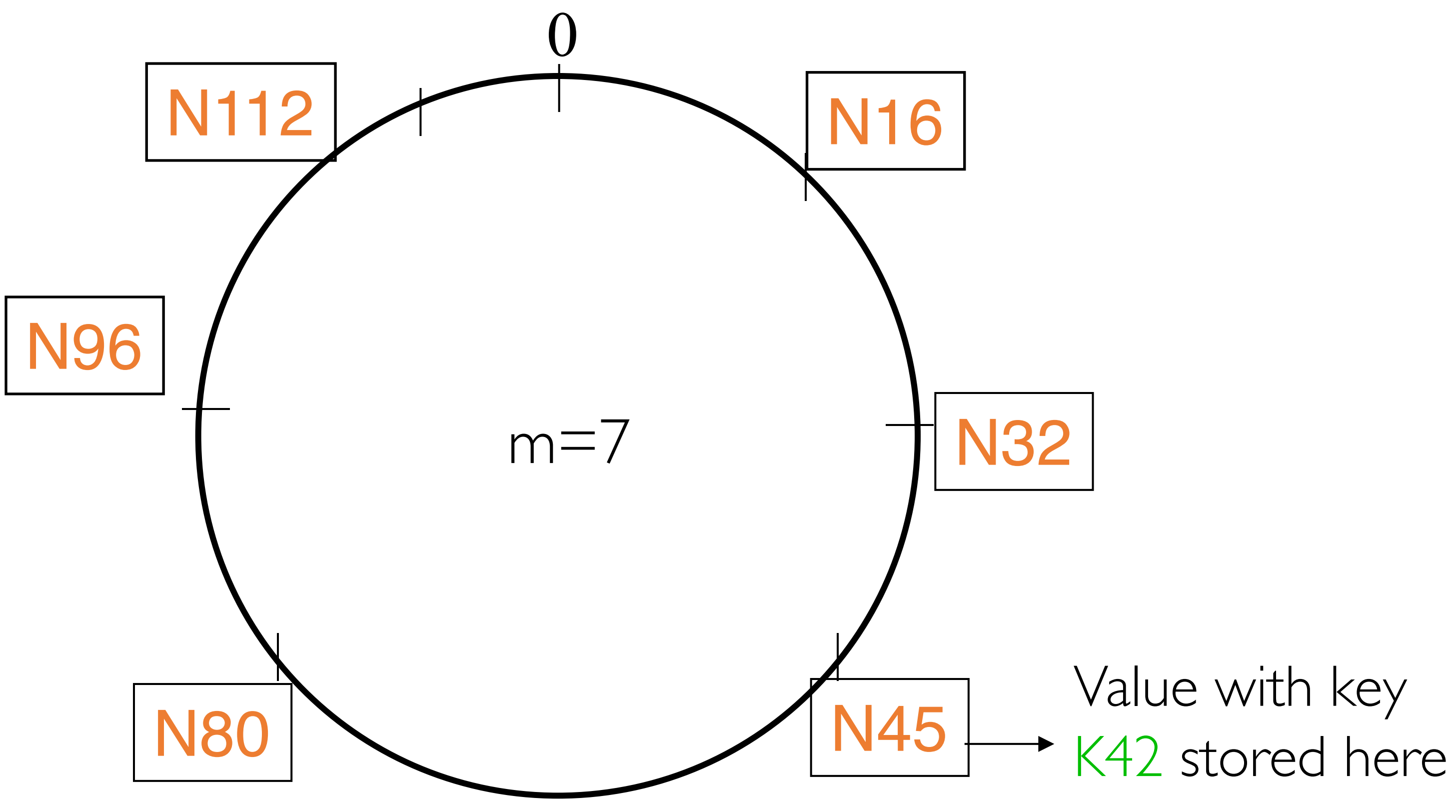
- Consistent Hashing => with K keys and N peers, each peer stores O(K/N) keys. (i.e., < c.K/N, for some constant c)

Ring of Peers: Running Example



Where will the value with key 42 be stored?

Ring of Peers: Running Example



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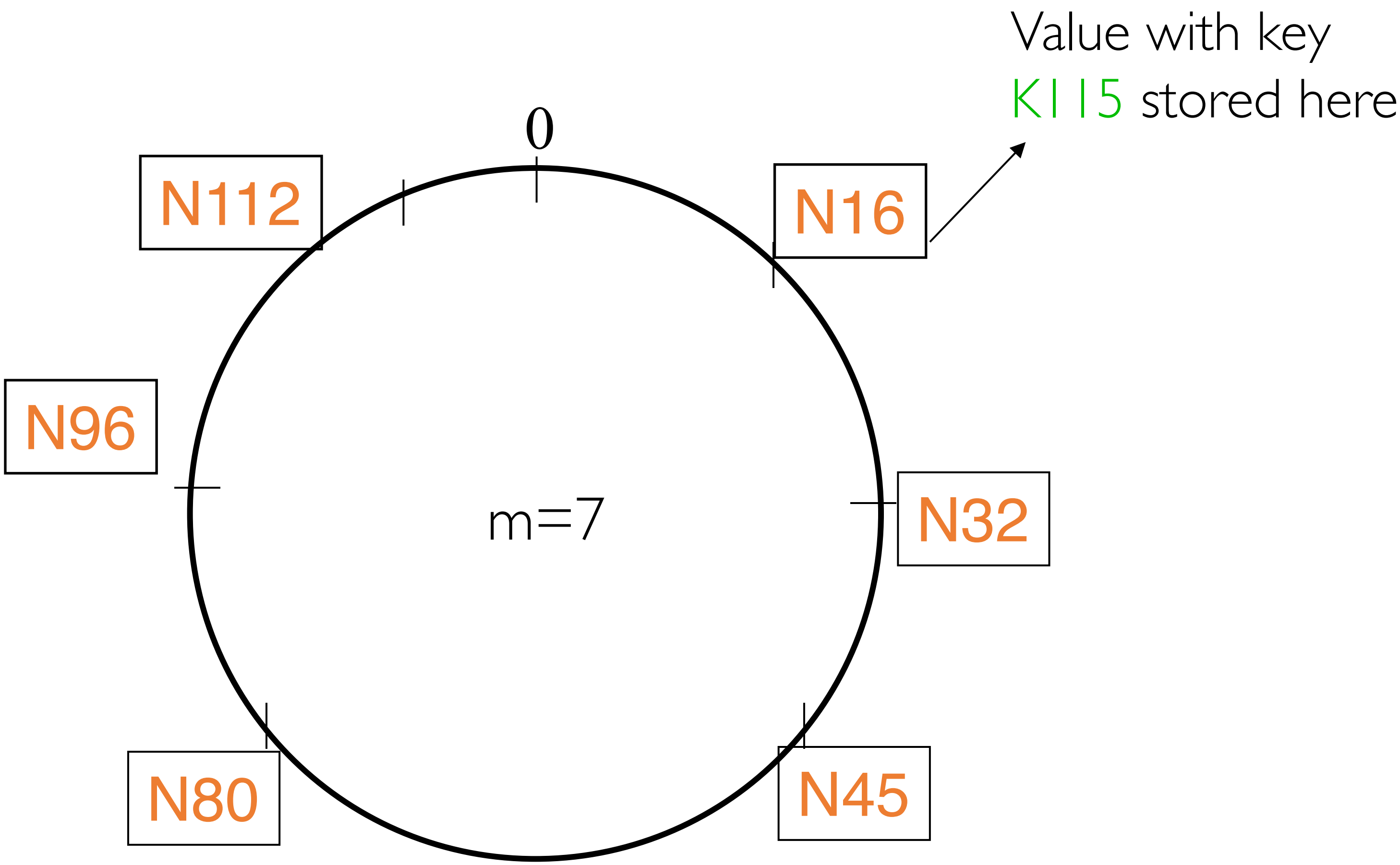
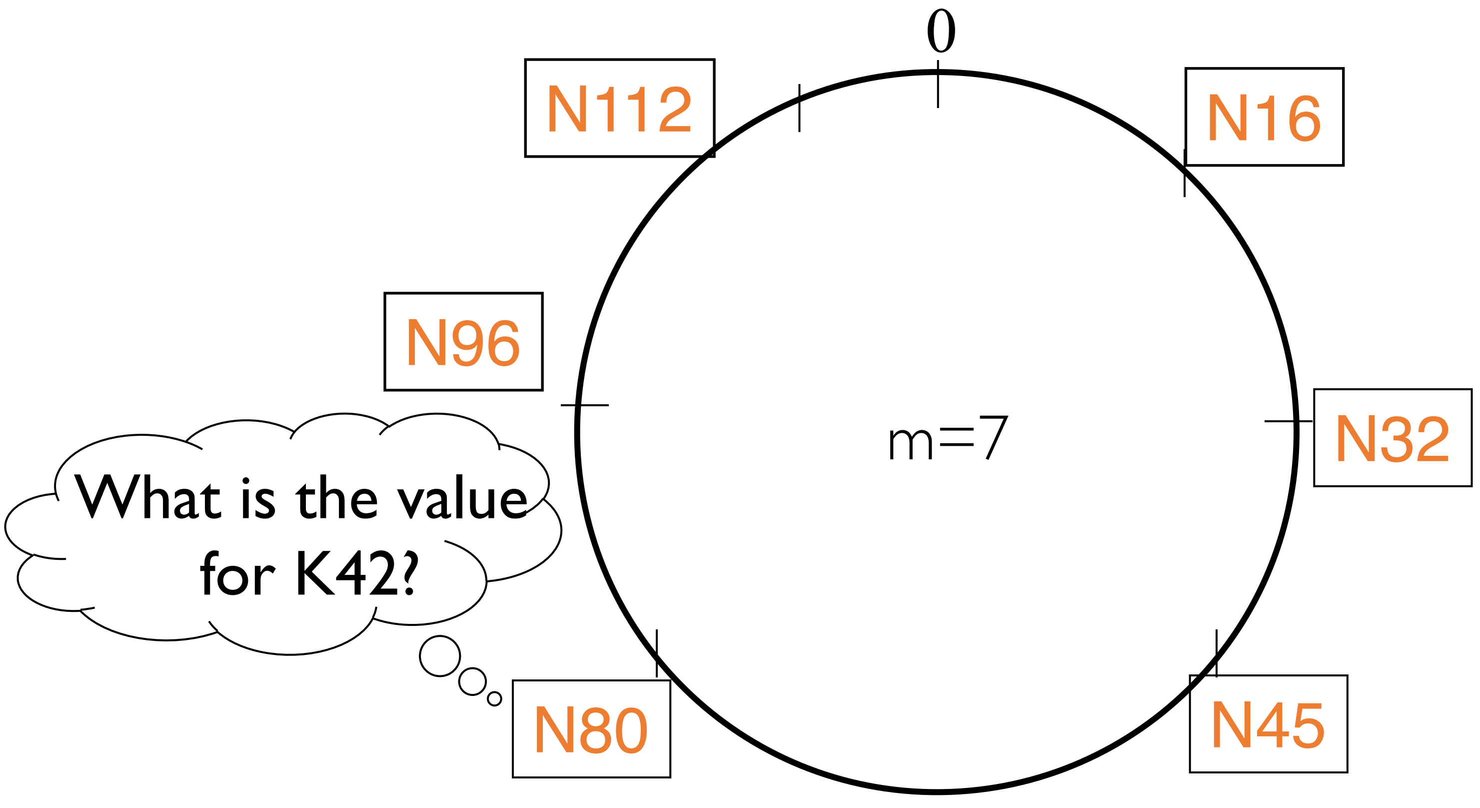


Where will the value with key 115 be stored?

Performing Lookups

Suppose N80 receives a request to lookup K42.



Need to ask the successor of K42!

Performing Lookups

- Option 1: Each node is aware of (can route to) any other node in the system.
  - Need a very large routing table.
  - Poor scalability with 1000s of nodes.
  - Any node failure and join will require a *necessary* update at all nodes.
- Option 2: Each node is aware of only its ring successor.
  - O(N) lookup. Not very efficient.
- Chord chooses a sweet middle-ground.

Performing Lookups

- Chord chooses a sweet middle-ground.
    - Each node is aware of **m** other nodes.
    - Maintains a *finger table* with **m** entries.
    - The ith entry of node n's finger table = successor($n + 2^i$)
        - i ranges from 0 to m-1

Finger Tables

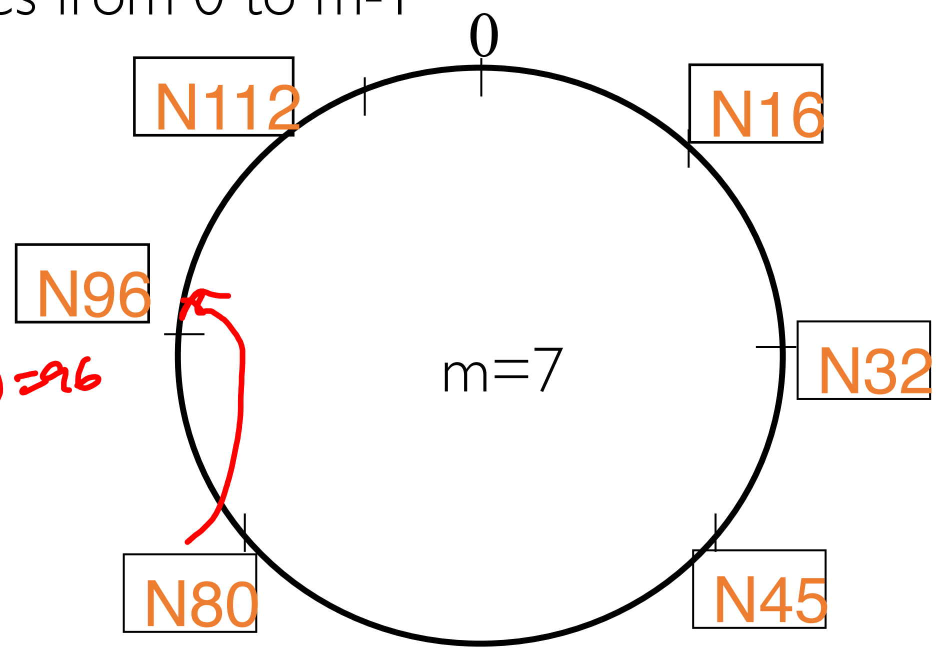
Compute the finger table for N80

ith entry of node n's finger table = successor(n + 2^i),

i ranges from 0 to m-1

i	
0	96
1	$s(80+2^1) = s(82) = 96$
2	96
3	96
4	96
5	112
6	16

$s(80+16) = s(96) = 96$

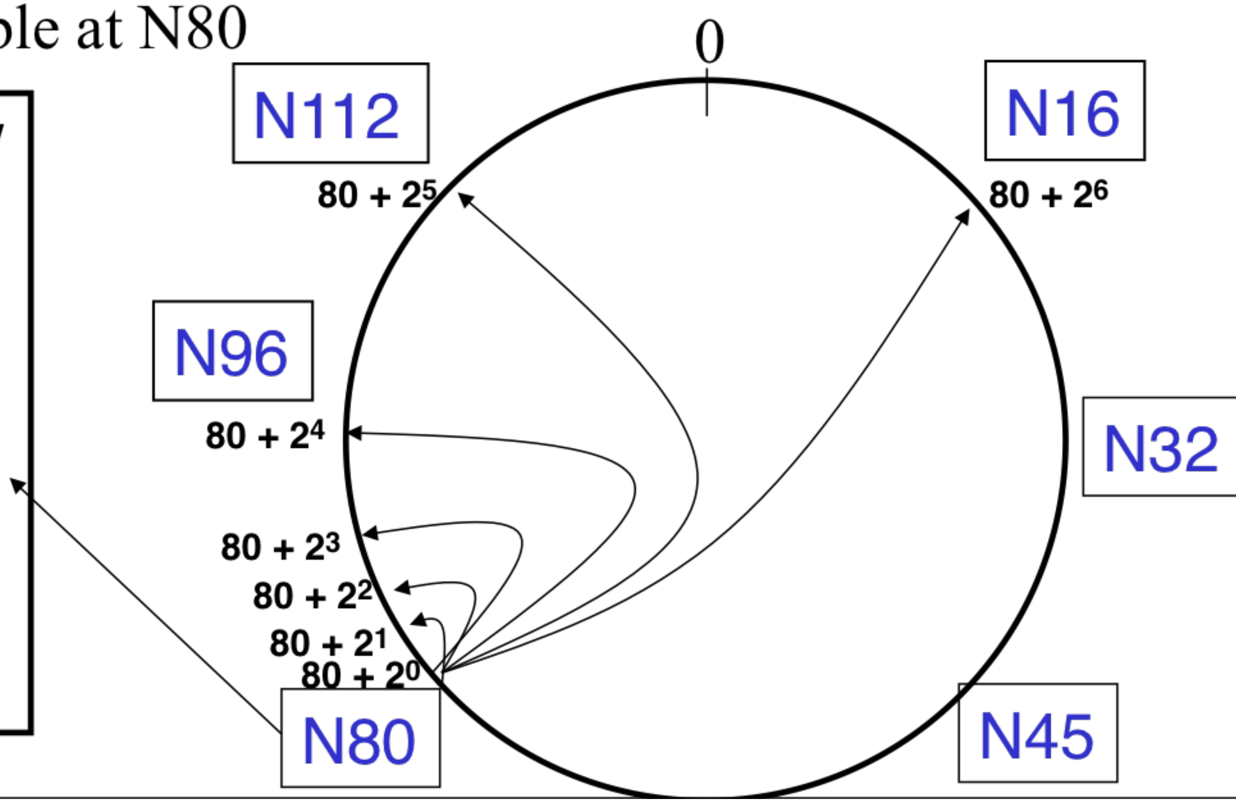


Finger Tables

Say m=7

Finger Table at N80

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



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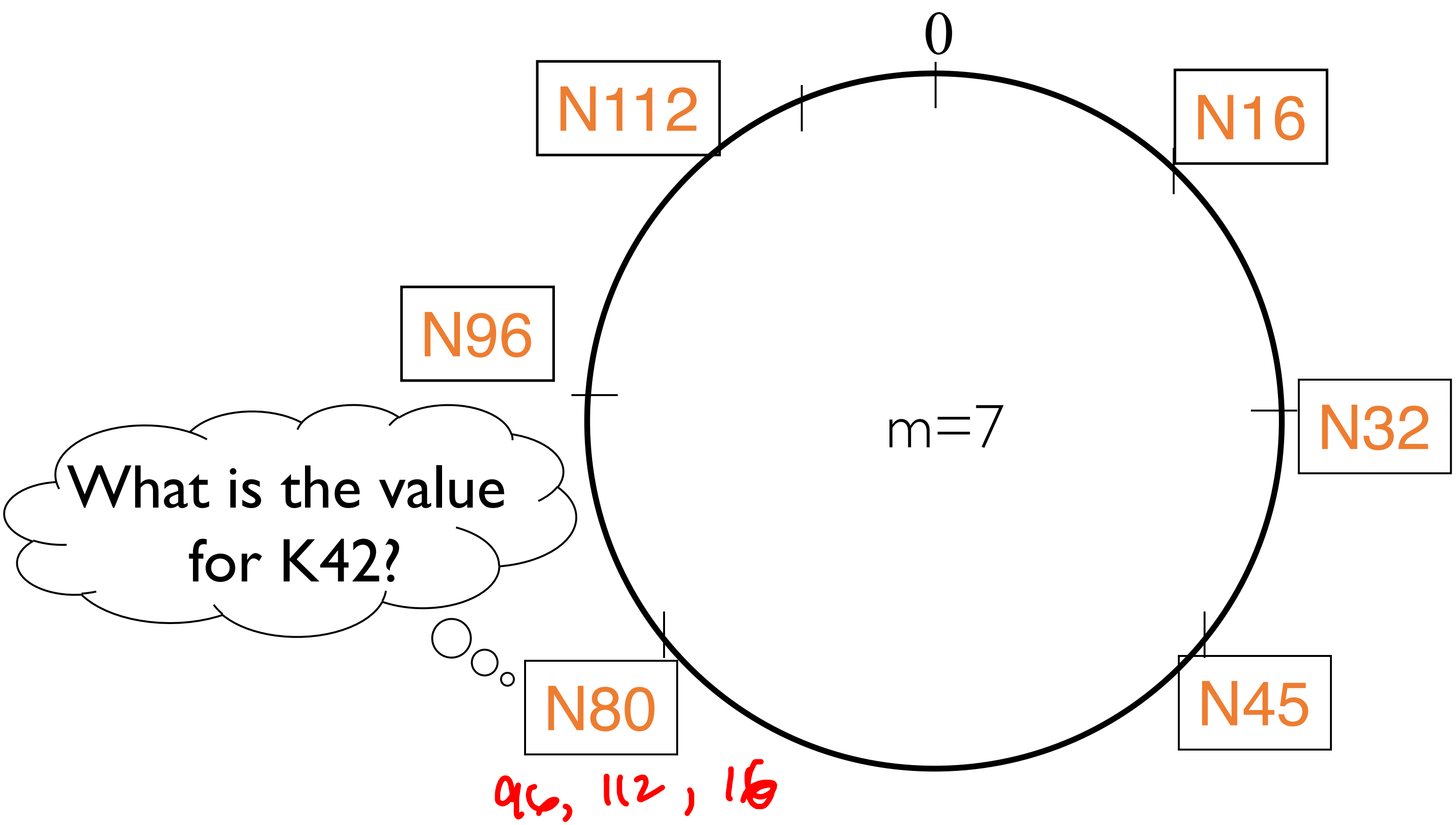

Need to locate successor of K42!

Which nodes is N80 aware of?

Say m=7

Finger Table at N80

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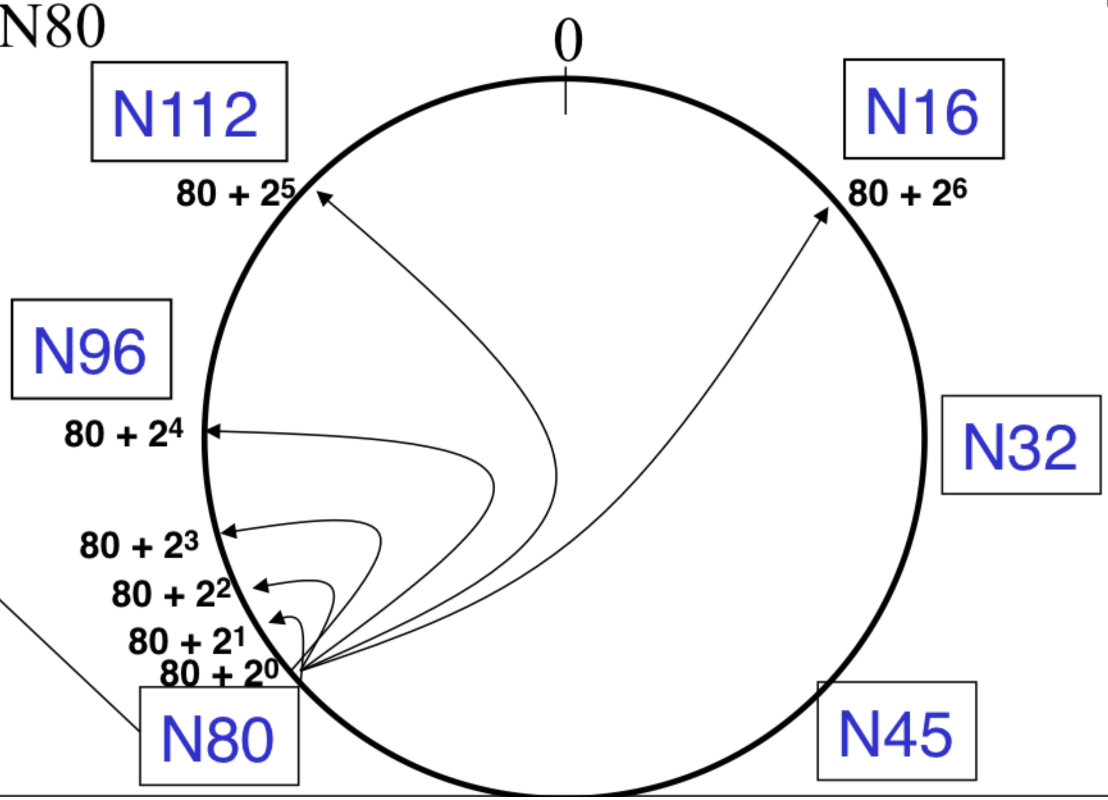

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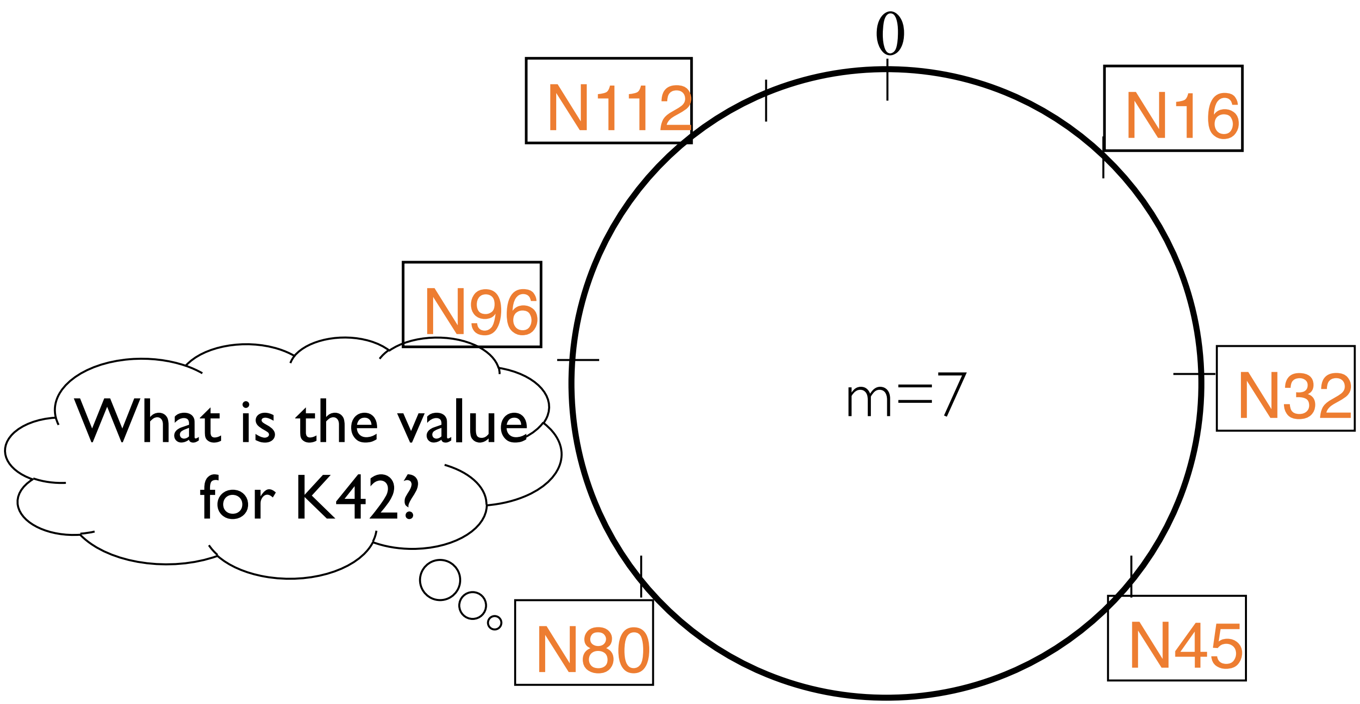


Need to locate successor of K42!

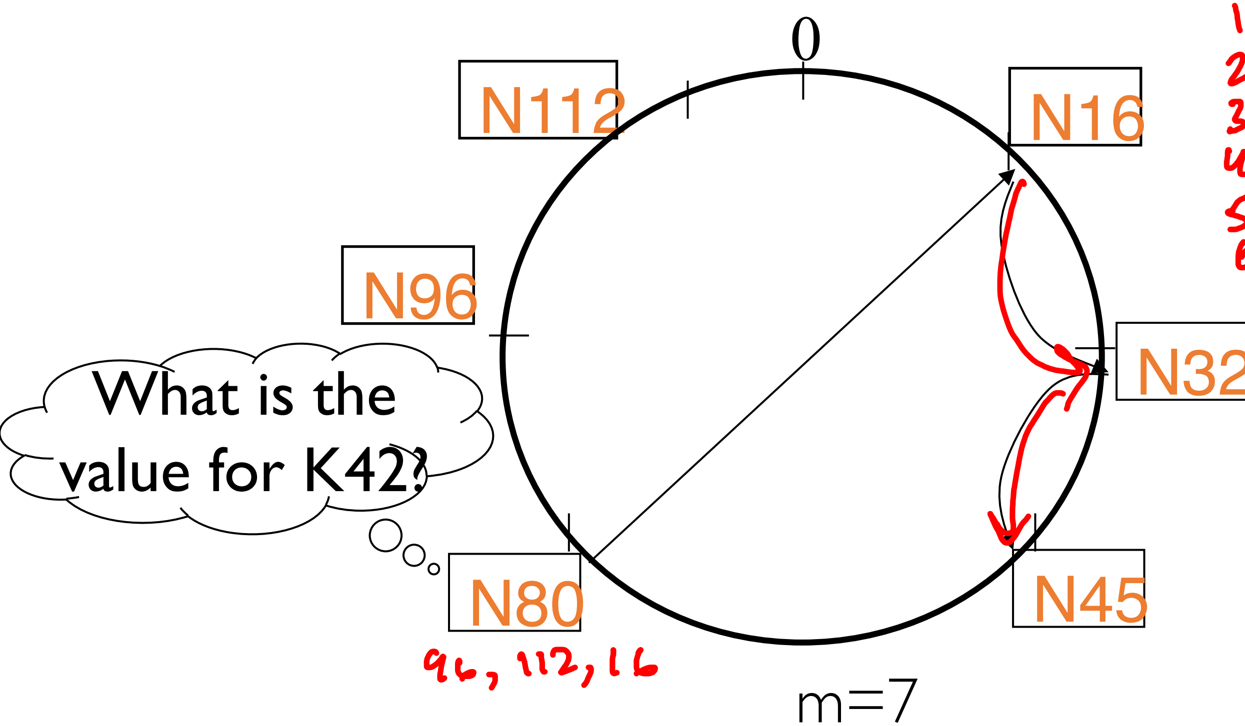
Forward the query to the most promising node you know of.

Search for key k at node n

At node n, if k lies in range (n, next(n)], where next(n) is n's *ring successor* then next(n) = successor(key). Send query to next(n)
Else, send query for k to largest finger entry <= k

$16 + 32 = 48$

0: 32
1: 32
2: 32
3: 32
4: 32
5: 80
6: 80

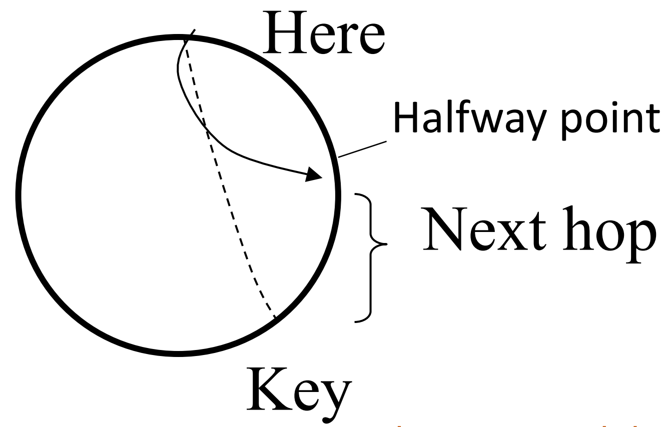


0: 45

$42 \in (32, 45]$

Analysis

$N \ll 2^m$



Search takes O(log(N)) time

Proof Intuition:

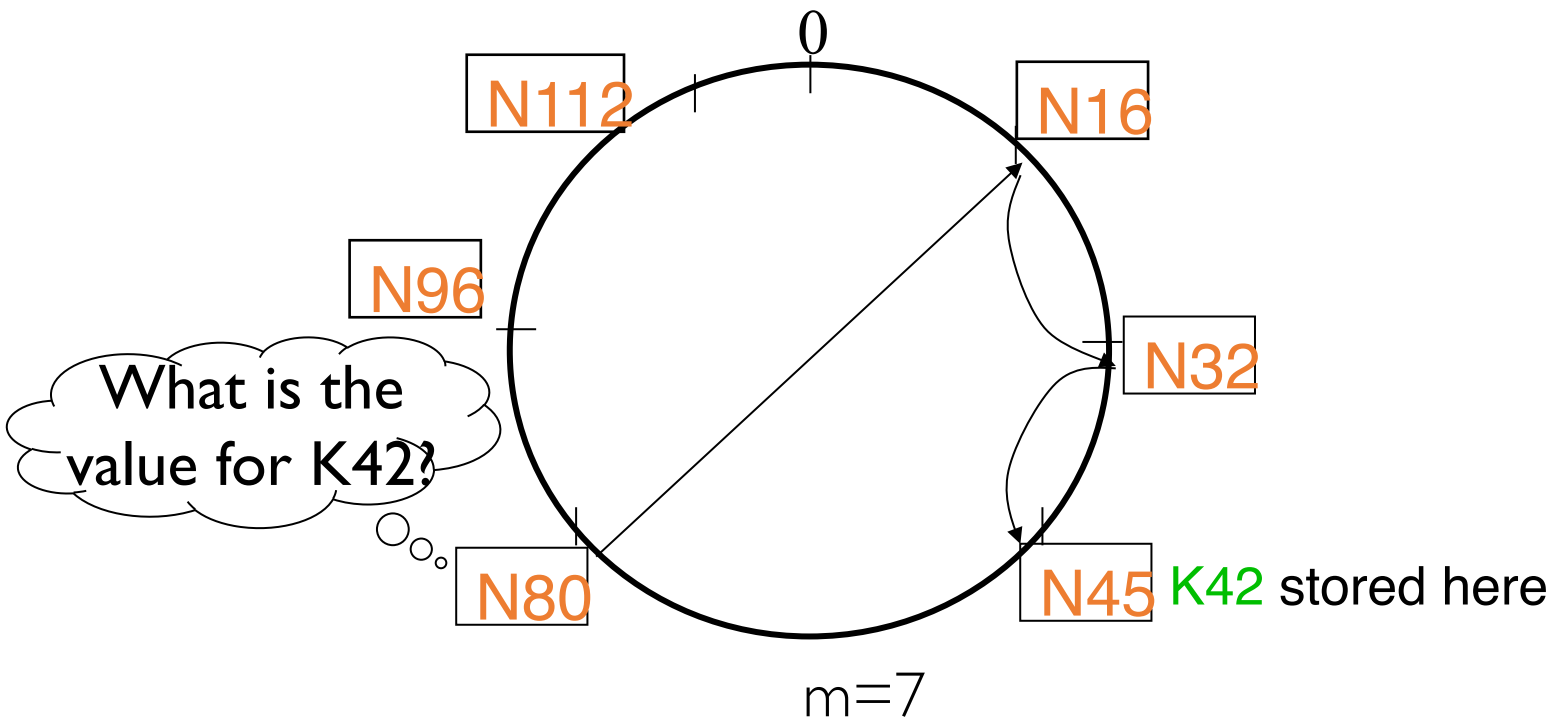
- (intuition): at each step, distance between query and peer-with-file reduces by a factor of at least 2 (why?)
- (intuition): after log(N) forwardings, distance to key is at most $2^m/2^{\log(N)} = 2^m / N$
- Expected number of node identifiers in a range of $2^m / N$:
  - ideally one
  - O(log(N)) with high probability (by properties of consistent hashing)

So using ring successors in that range will use another O(log(N)) hops. Overall lookup time stays O(log(N)).

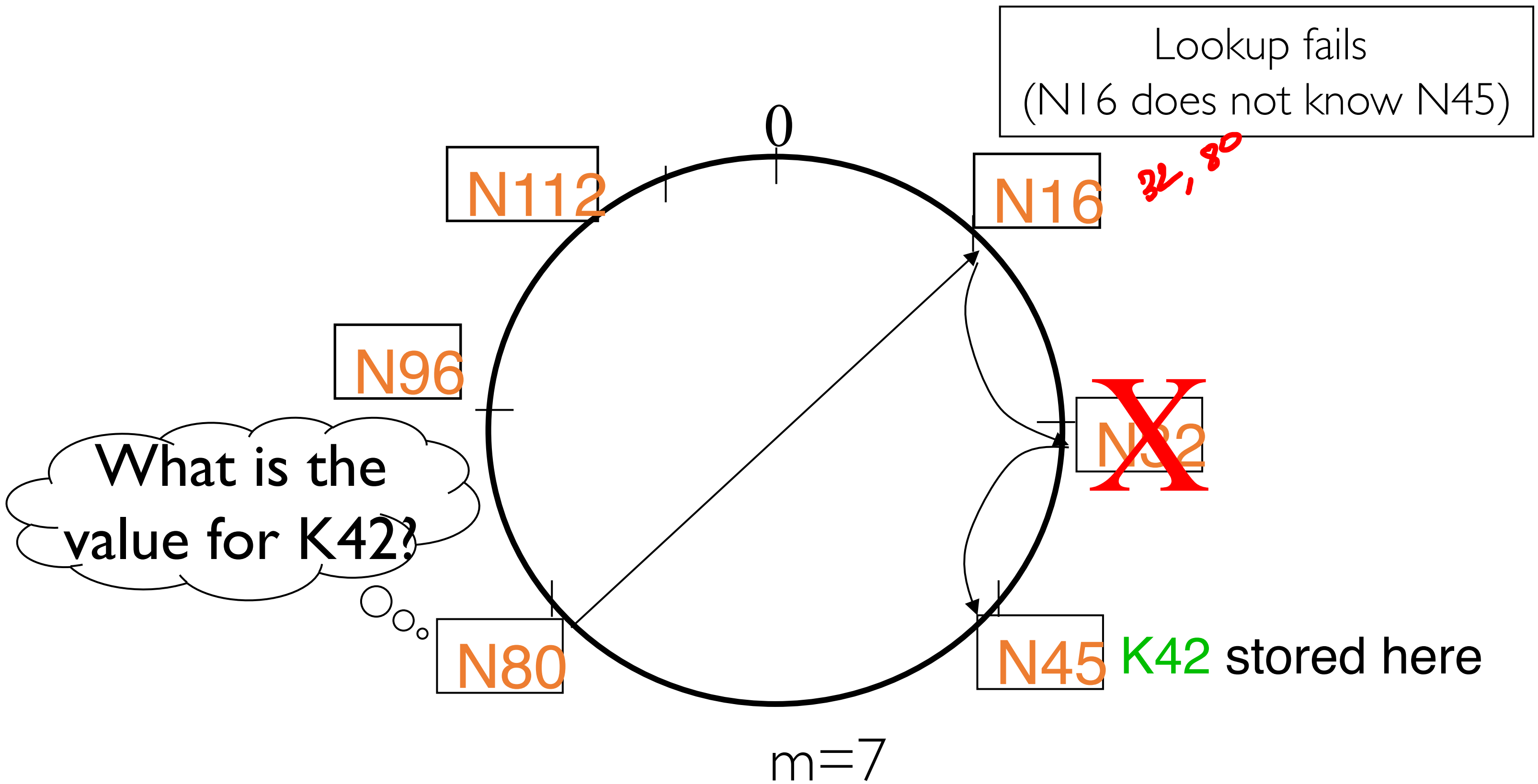
Analysis

- 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
    - Coming up next!

Search for key k at node n



If a node fails



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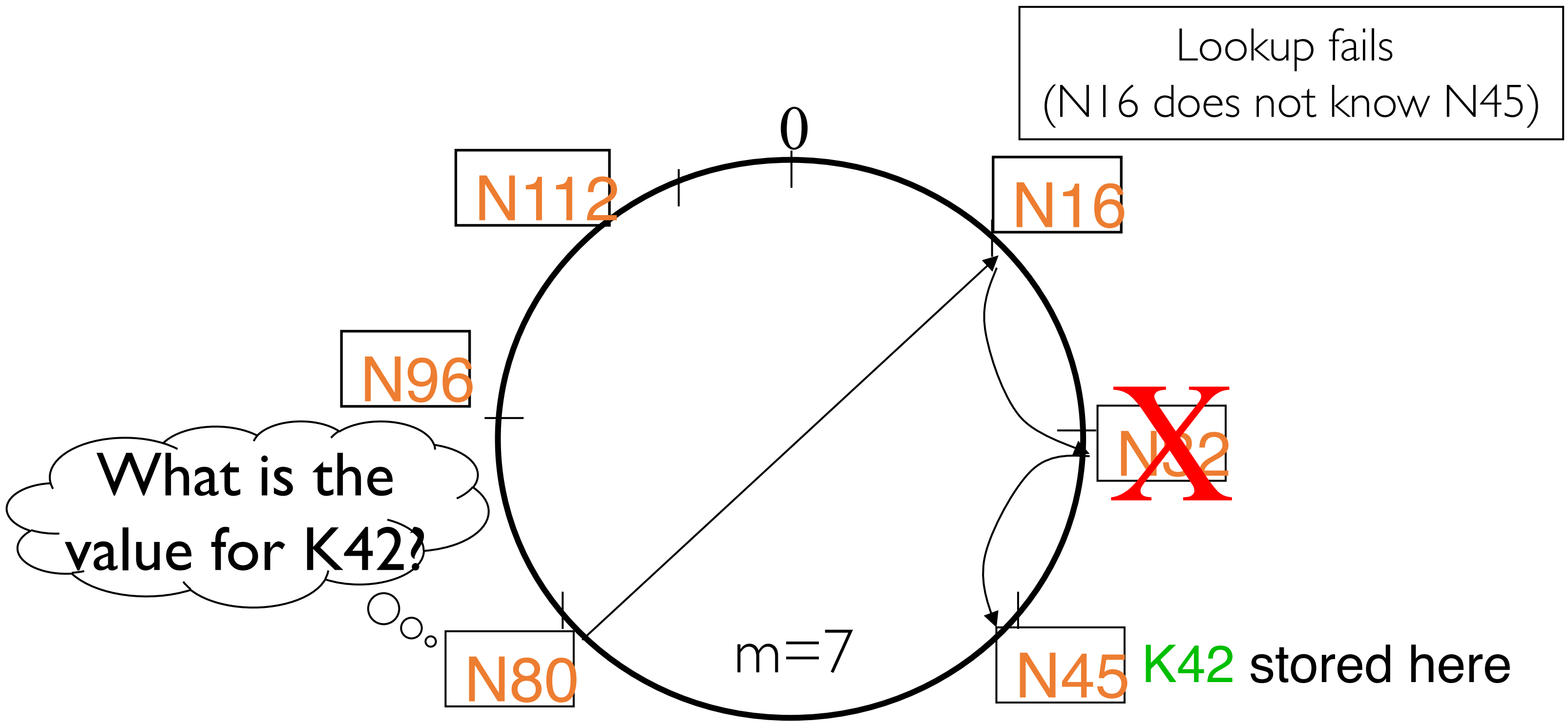
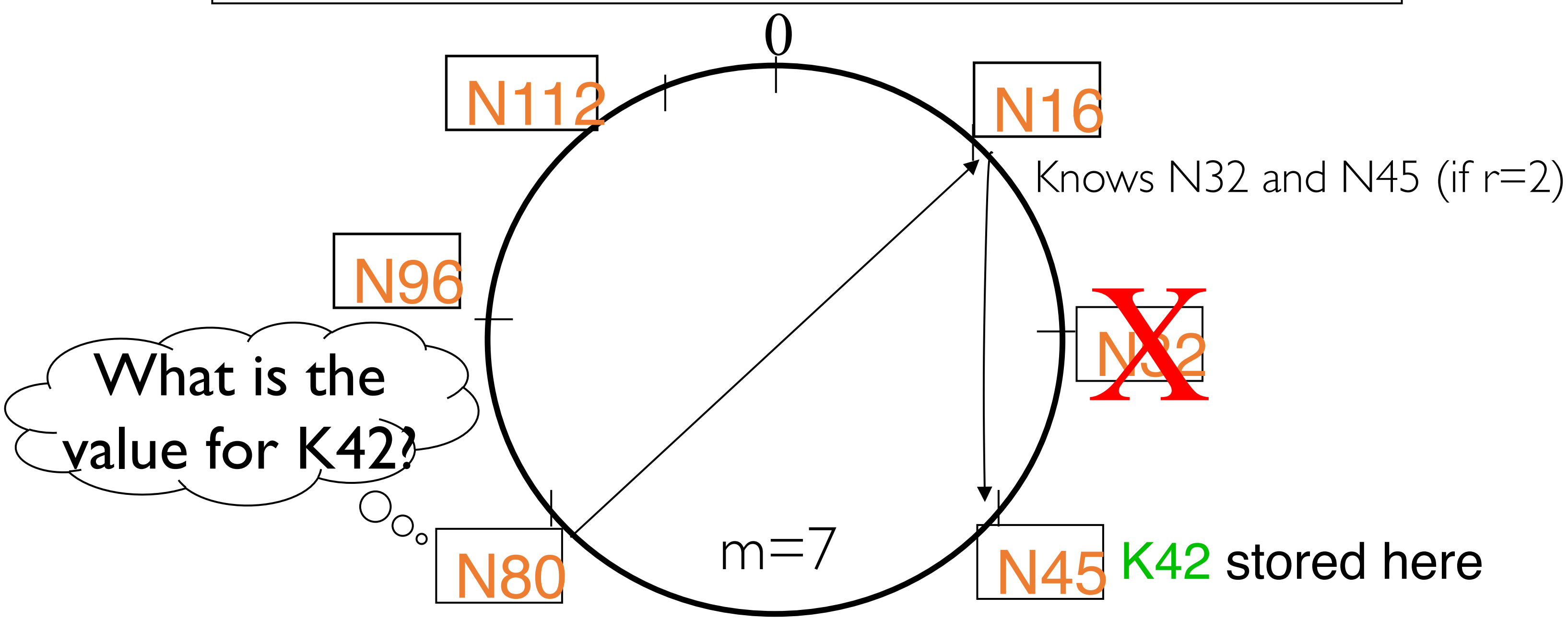


How do we handle this?

If a node fails

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



Search under node failures

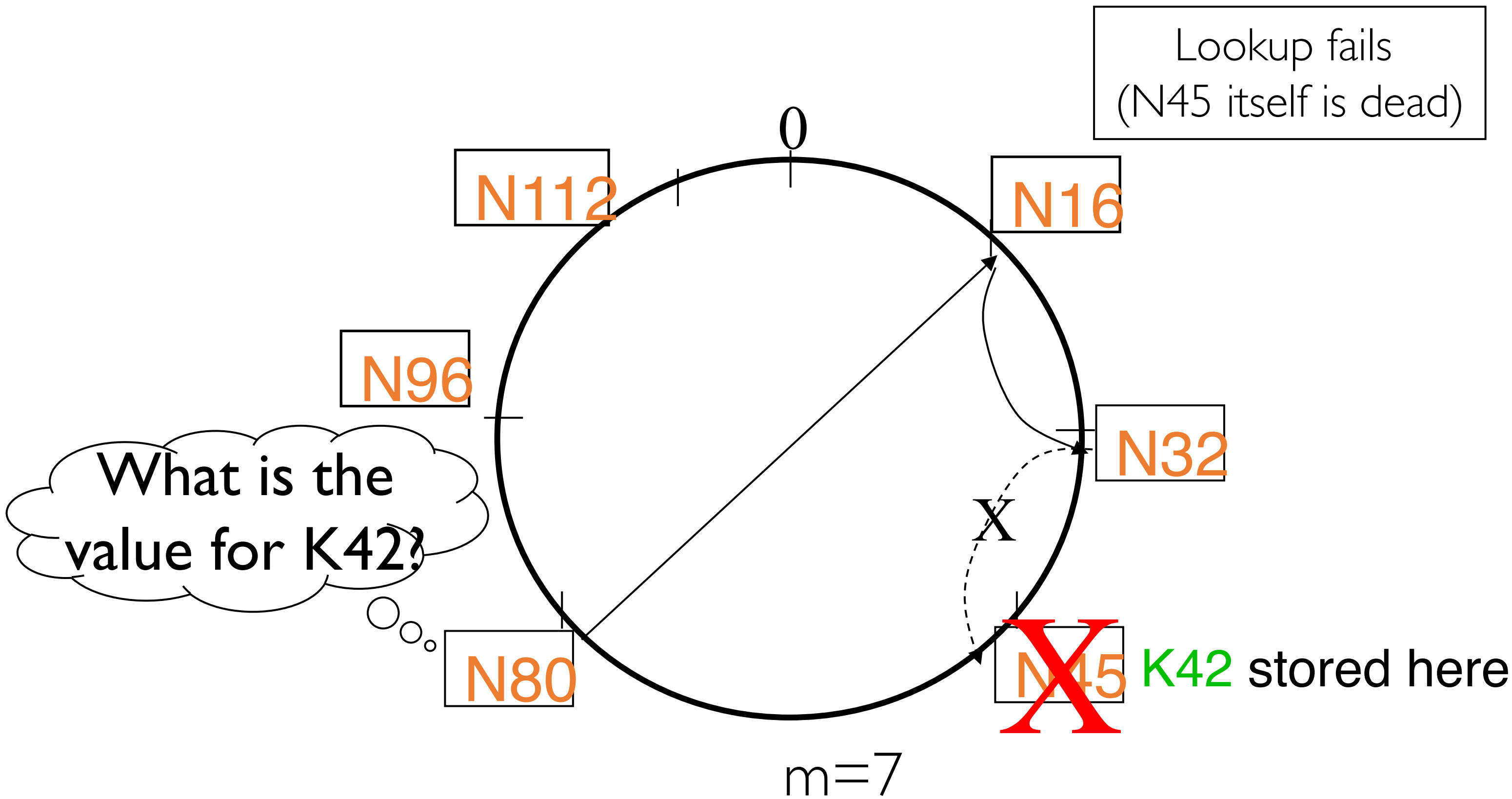
- If every node fails with probability 0.5, choosing r=2log(N) suffices to maintain lookup correctness (i.e. keep the ring connected) with high probability.
    - Intuition:
        - Pr(at given node, at least one successor alive)=

$$1-(\frac{1}{2})^{2\log N}=1-\frac{1}{N^2}$$

        - Pr(above is true at all alive nodes)=

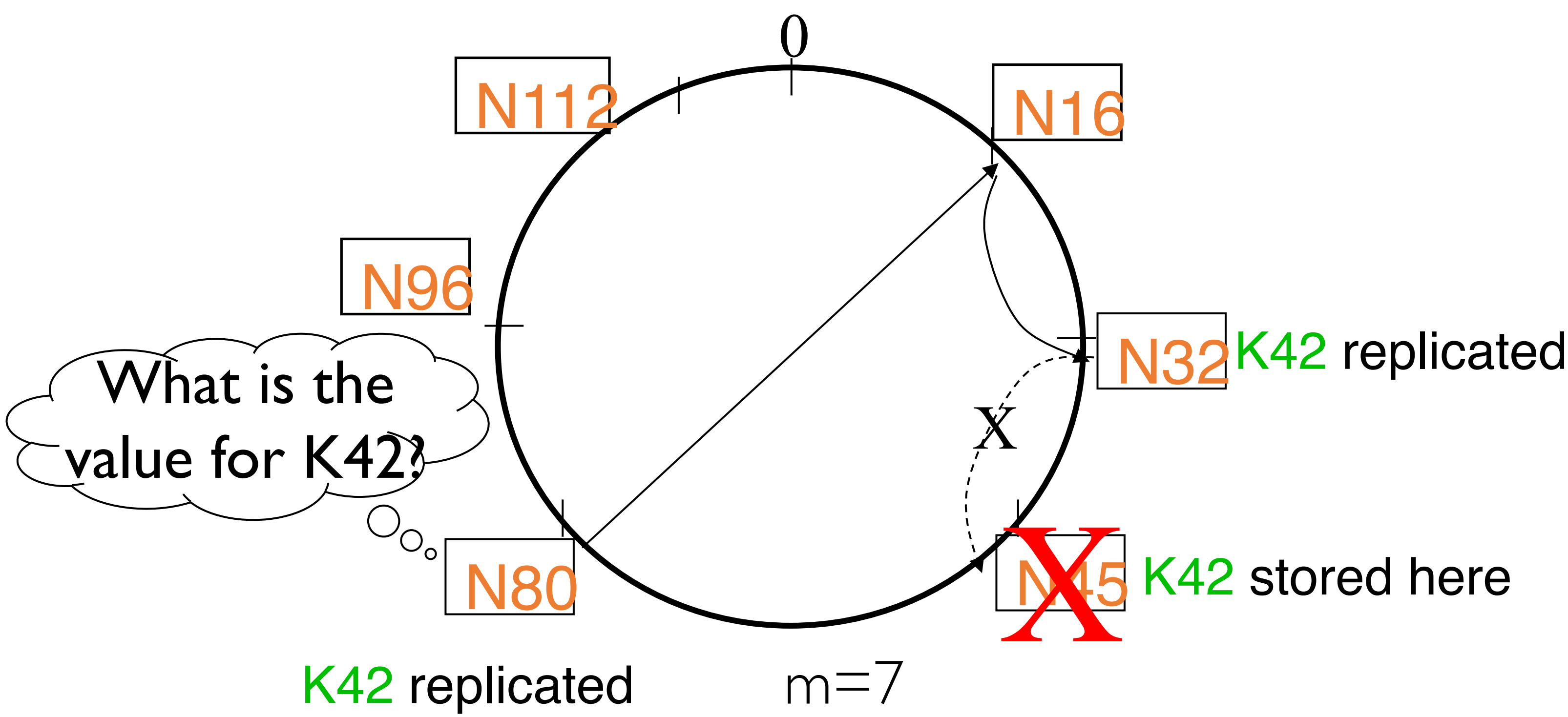
$$(1-\frac{1}{N^2})^{N/2}=e^{-\frac{1}{2N}}\approx 1$$

If a node fails



If a node fails

One solution: replicate key-value at r successors and predecessors



Need to deal with dynamic changes

- ✓ Nodes fail
- New nodes join
- Nodes leave

To be continued in next class!