Πανεπιστήμιο Πατρών

Προχωρημένα Θέματα σε Κατανεμημένα Συστήματα

Distributed Hash Tables

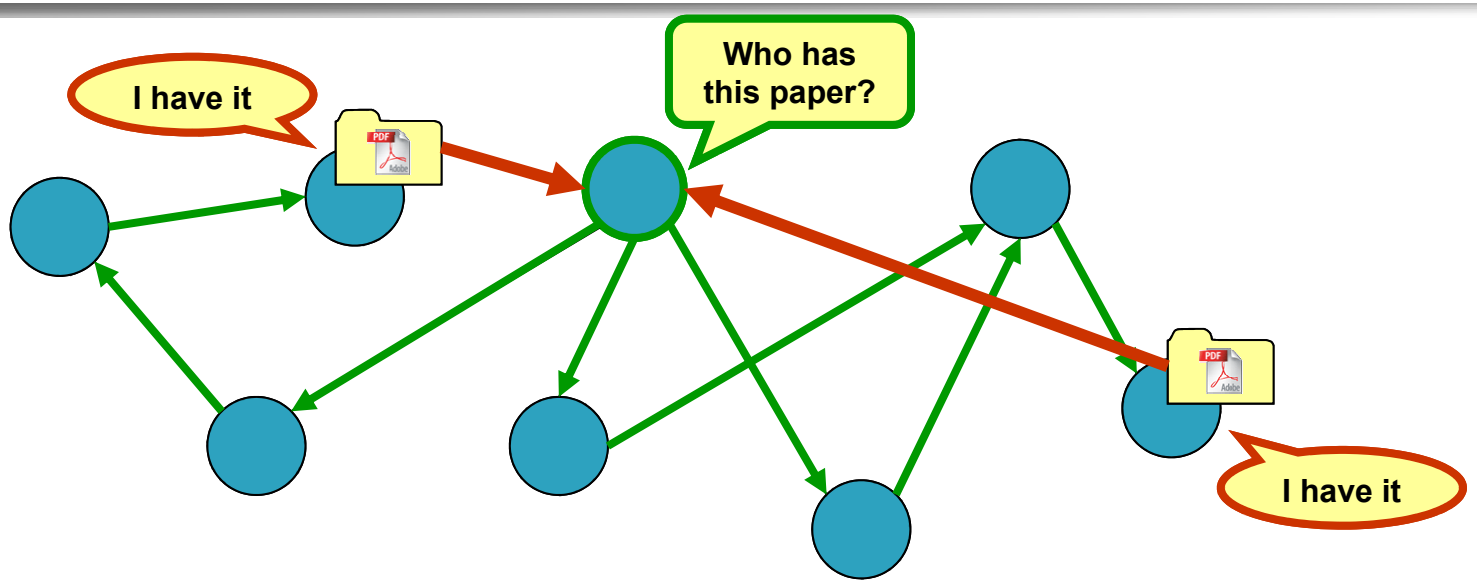
Σ.ΣΙΟΥΤΑΣ, Σ.ΒΟΥΛΓΑΡΗΣ

Today's Agenda

- What are DHTs?
  - Why are they useful?
- What makes a "good" DHT design
- Case studies
  - Chord
  - Pastry

Based on slides by Pascal

P2P challenge: Locating content



- Simple strategy: flood (e.g., expanding ring) until content is found
  - If ***R*** of ***N*** nodes have a replica, the expected search cost is at least ***N/R***, i.e., ***O(N)***
  - Need many replicas to keep overhead small
- Other strategy: centralized index (Napster)
  - Single point of failure, high load
- Goal: **Decentralize the index!**

Indexed Search

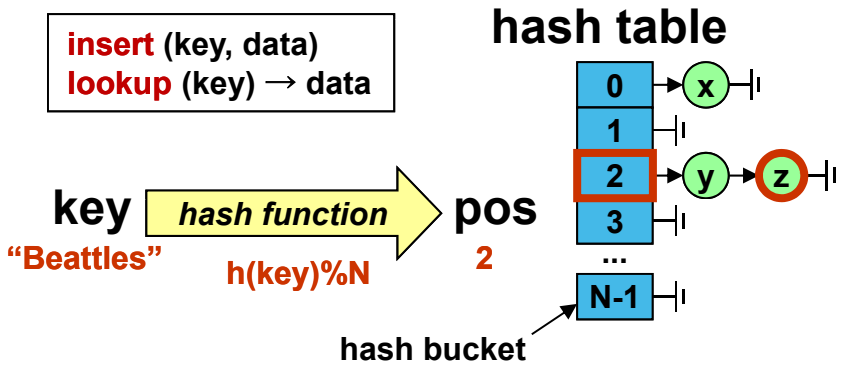
- Idea
  - Store **particular content** on **particular nodes**
    - alternatively: *pointers to content*
  - When a node wants this content, go to the node that is supposed to hold it (or knows where it is)

- Challenges
  - Avoid bottlenecks:

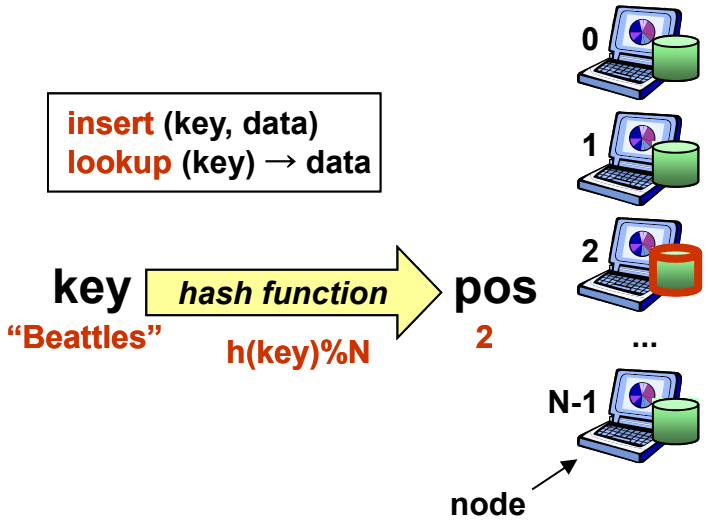
    Distribute the responsibilities "evenly" among the existing nodes
  - Self-organization w.r.t. nodes joining or leaving (or failing)
    - Give responsibilities to joining nodes
    - Redistribute responsibilities from leaving nodes
  - Fault-tolerance and robustness
    - Operate correctly also under failures

Idea: Hash Tables

- In a classic Hash Table:
  - Table has *N* buckets
  - Each data item has a key
  - Key is hashed to find bucket in hash table
  - Each bucket is expected to hold 1/N of the items, so storage is balanced



- In a Distributed Hash Table (DHT), nodes are the buckets
  - Network has *N* nodes
  - Each data item has a key
  - Key is hashed to find peer responsible for it
  - Each node is expected to hold 1/N of the items, so storage is balanced
  - Additional requirement: Also balance routing load!!



DHTs: Problems

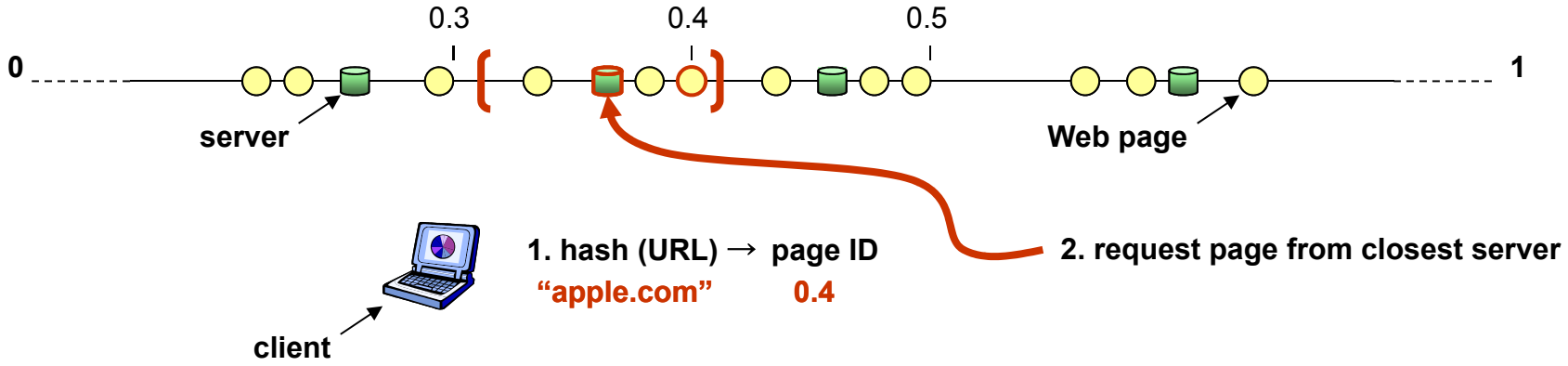
- Problem 1 (dynamicity): adding or removing nodes
  - With hash mod N, virtually every key will change its location!

$$h(k) \bmod m \neq h(k) \bmod (m+1) \neq h(k) \bmod (m-1)$$

- Solution: use consistent hashing
  - Define a fixed hash space
  - All hash values fall within that space and do not depend on the number of peers (hash bucket)
  - Peers have a hash value (ID)
  - Data items have hash values (KEY)
  - Each data items goes to peer with ID closest to its KEY

DHT Hashing

- Based on consistent hashing (designed for Web caching)
  - Each server is identified by an ID uniformly distributed in range [0, 1]
  - Each web page's URL is (via some hash function) associated with an ID which is uniformly distributed in [0, 1]
  - A page is stored to the closest server in the ID space
  - A client hashes the desired URL, retrieves page from appropriate server
  - Good load balancing: each server covers roughly equal intervals and stores roughly the same number of pages
  - Adding or removing a server invalidates few keys



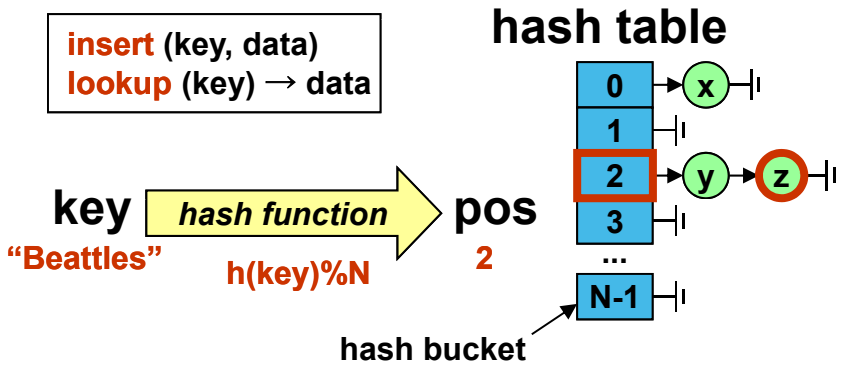
DHTs: Problems (cont'd)

- Problem 2 (size): all nodes must be known to insert or lookup data
  - Works with *small* and *static* server populations

- Solution: each peer has only a few "neighbors"
  - Messages are routed through neighbors via multiple hops (overlay routing)

DHTs: Routing Mechanisms

- In a classic Hash Table:
  - Table has *N* buckets
  - Each data item has a key
  - Key is hashed to find bucket in hash table
  - Each bucket is expected to hold 1/N of the items, so storage is balanced



- In a Distributed Hash Table (DHT), nodes are the buckets
  - Network has *N* nodes
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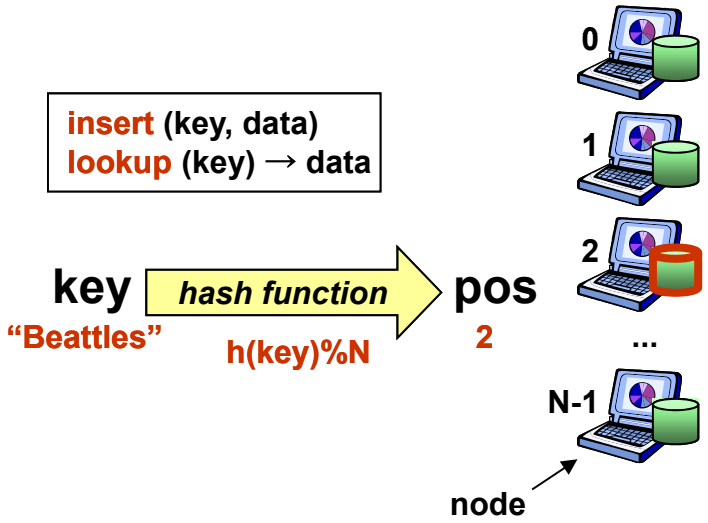
  - Additional requirement: Also balance routing load!!



What Makes a Good DHT Design?

- **Small diameter**
  - Should be able to route to any node in a few hops
  - Different DHTs differ fundamentally only in the routing approach
- **Load sharing**
  - DHT routing mechanisms should be decentralized
  - no **single point of failure**
  - no **bottleneck**
- **Small degree**
  - The number of neighbors for each node should remain “reasonable”
- **Low stretch**
  - To achieve good performance, minimize **ratio of DHT vs. IP latency**
- Should **gracefully handle nodes joining and leaving**
  - Reorganize the neighbor sets
  - Bootstrap mechanisms to connect new nodes into the DHT
  - Repartition the affected keys over existing nodes

DHT Interface

- Minimal interface (data-centric)

  Lookup(key) → IP address

- Generality: Supports a wide range of applications
  - Keys have no semantic meaning
  - Values are application dependent

- DHTs do **not** store the data
  - Data storage can be built on top of DHTs

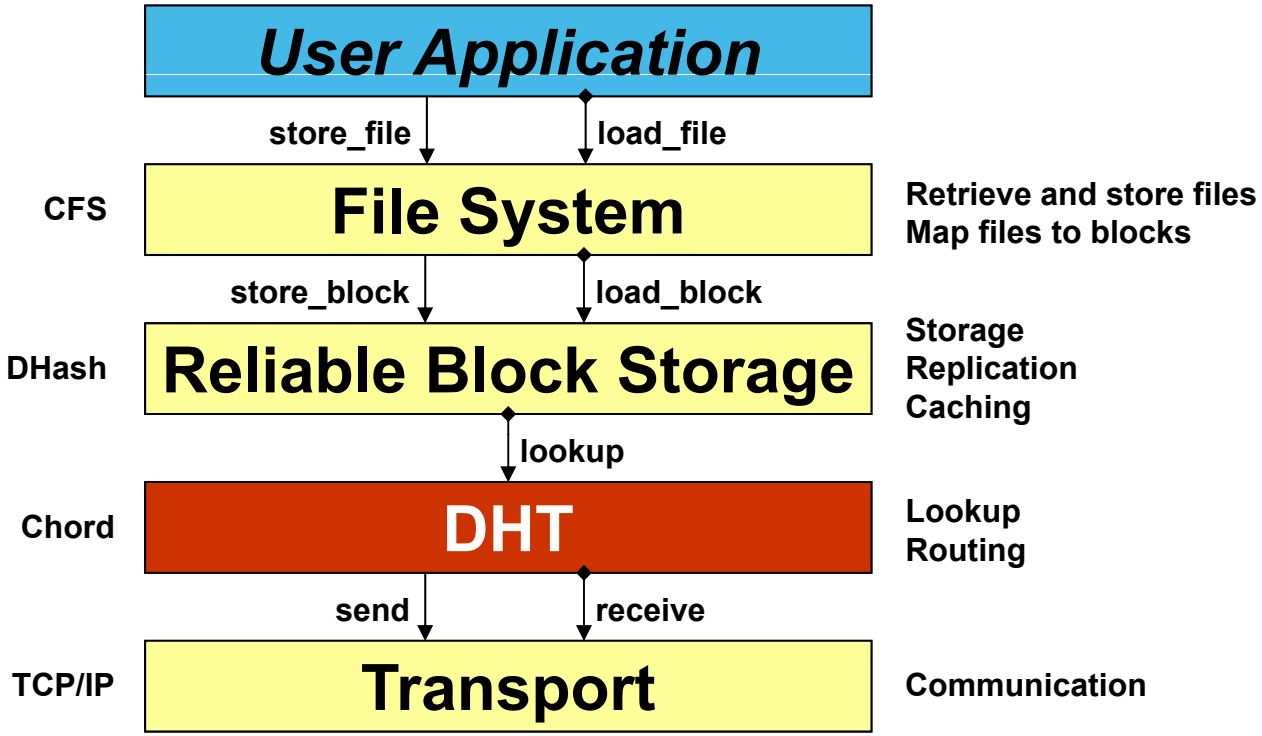
    Lookup(key) → data

    Insert(key, data)

Application spectrum

- DHTs support many applications:
  - Network storage [CFS, OceanStore, PAST, …]
  - Web cache [Squirrel, …]
  - E-mail [e-POST, …]
  - Query and indexing [Kademlia, …]
  - Event notification [Scribe]
  - Application-layer multicast [SplitStream, …]
  - Naming systems [ChordDNS, INS, …]
  - ...

DHTs in Context



Application spectrum

- DHTs support many applications:
  - Network storage [CFS, OceanStore, PAST, …]
  - Web cache [Squirrel, …]
  - Censor-resistant storage [Eternity, FreeNet, …]
  - Application-layer multicast [Narada, …]
  - Event notification [Scribe]
  - Naming systems [ChordDNS, INS, …]
  - Query and indexing [Kademlia, …]
  - Communication primitives [POST, …]
  - Backup store [HiveNet]
  - Web archive [Herodotus]

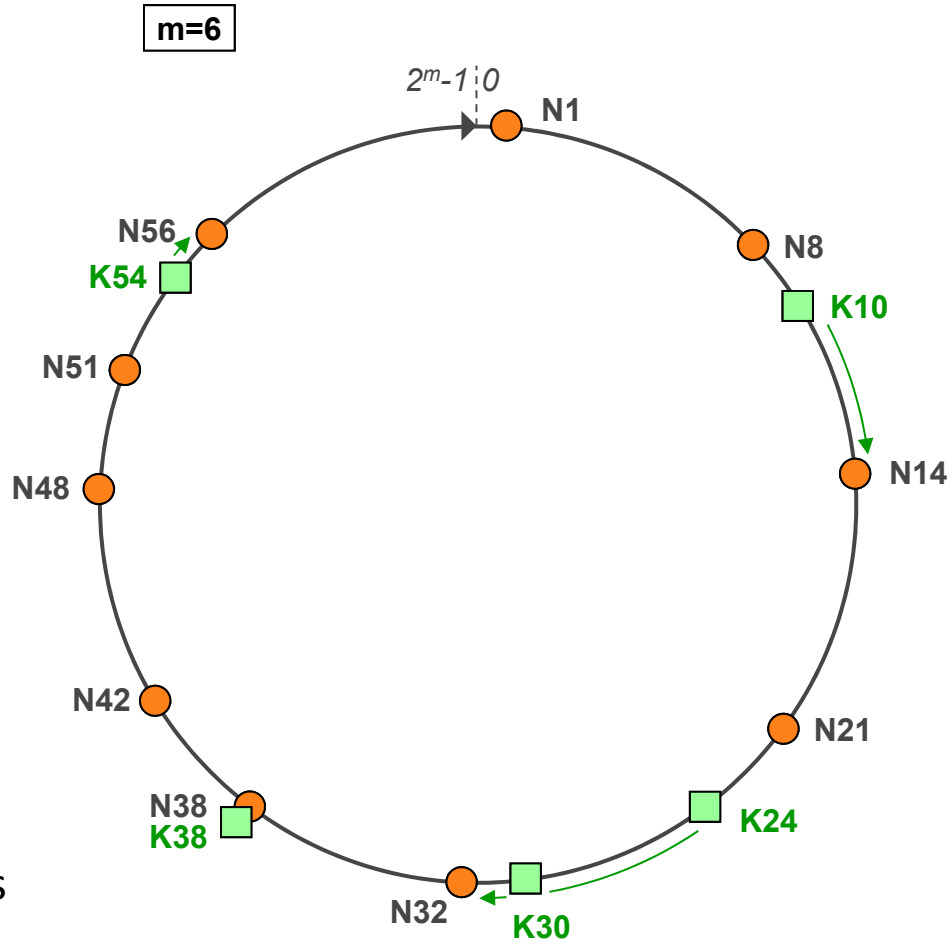
DHT Case Studies

- Case Studies
  - Chord
  - Pastry
- Questions
  - How is the hash space divided evenly among nodes?
  - How do we locate a node?
  - How do we maintain routing tables?
  - How do we cope with (rapid) changes in membership?

CHORD
(MIT)

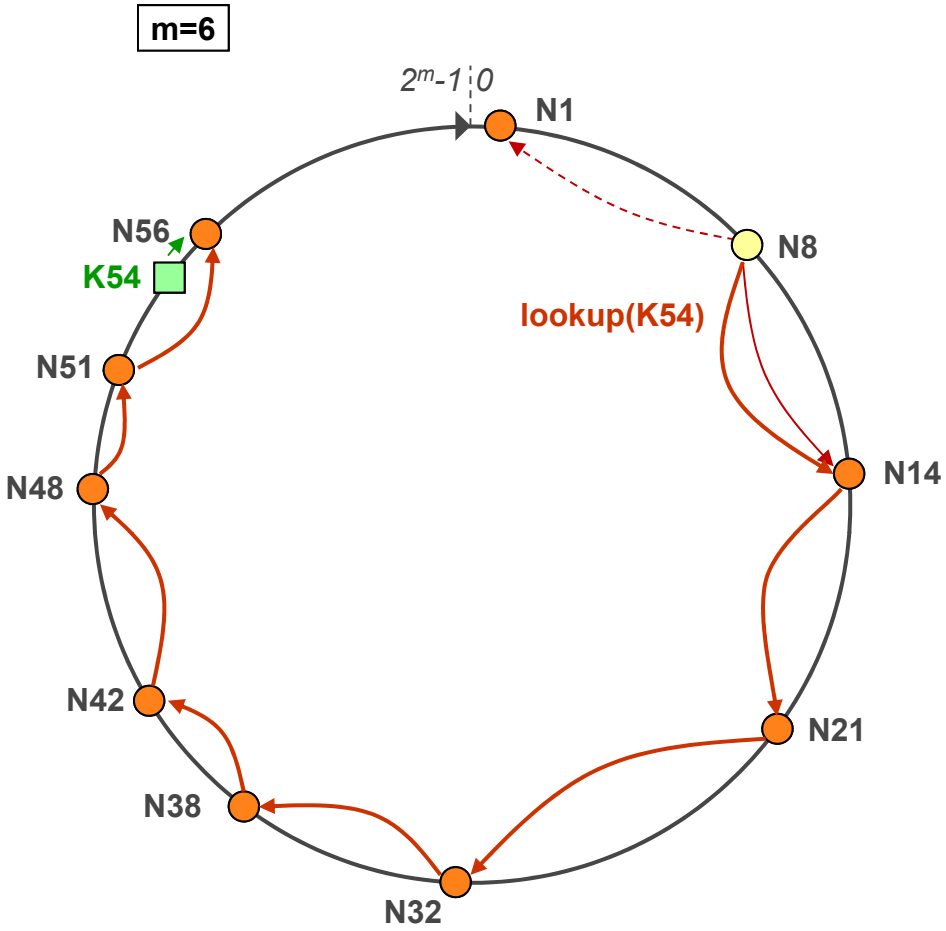
Chord (MIT)

- Circular *m*-bit ID space for both keys and node IDs
- Node ID = SHA-1(IP address)
- Key ID = SHA-1(key)
- Each key is mapped to its **successor** node
  - Node whose ID is equal to or follows the key ID
- Key distribution
  - Each node responsible for *O(K/N)* keys
  - *O(K/N)* keys move when a node joins or leaves



Basic Chord: State and Lookup

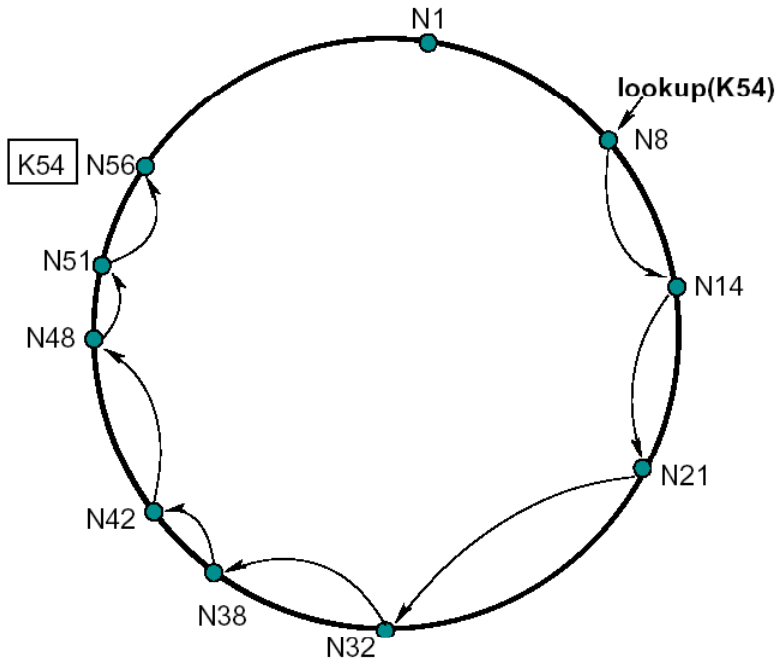
- Each node knows only two other nodes on the ring:
  - Successor
  - Predecessor (for ring management)
- Lookup is achieved by forwarding requests around the ring through successor pointers
  - Requires *O(N)* hops



Basic Chord: State and Lookup

```
// ask node n to find the successor of id
n.find_successor(id)
    if (id ∈ (n, n.successor])
        return n.successor;
    else
        // forward the query around the circle
        return successor.find_successor(id);
```

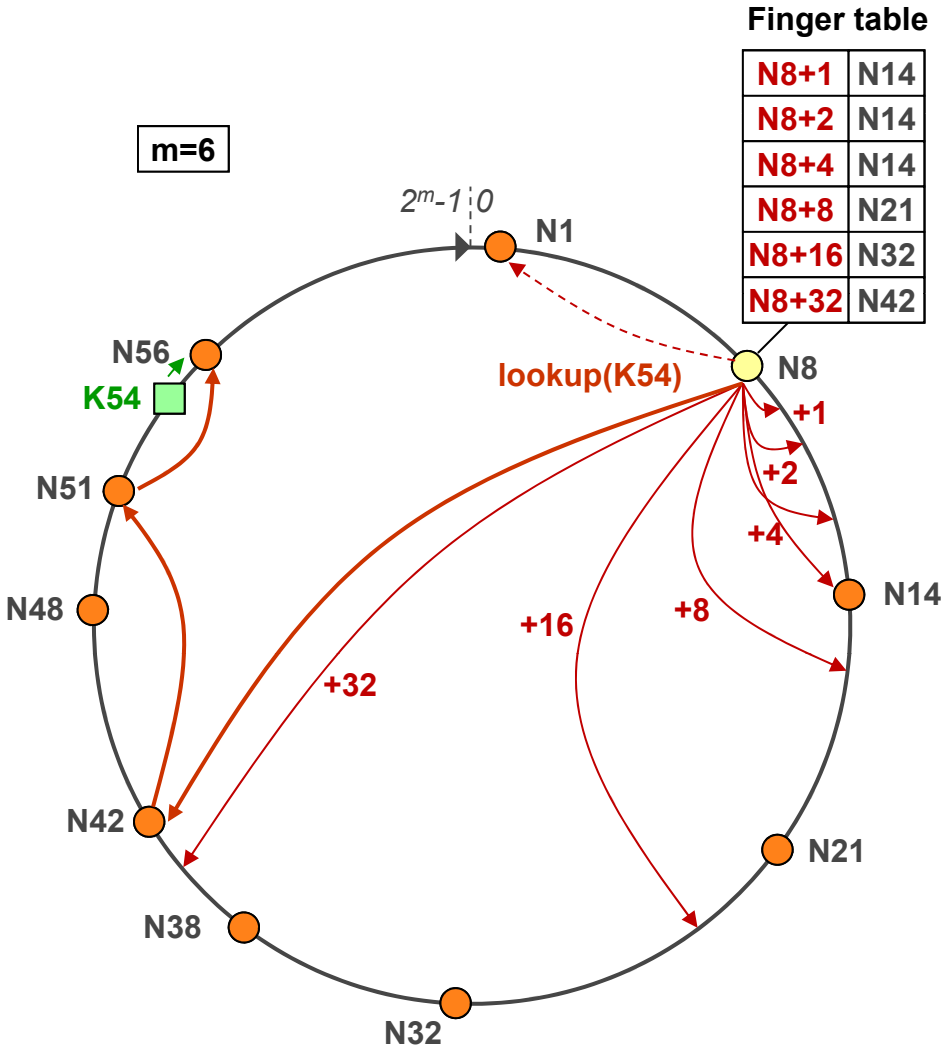
(a)



(b)

Complete Chord

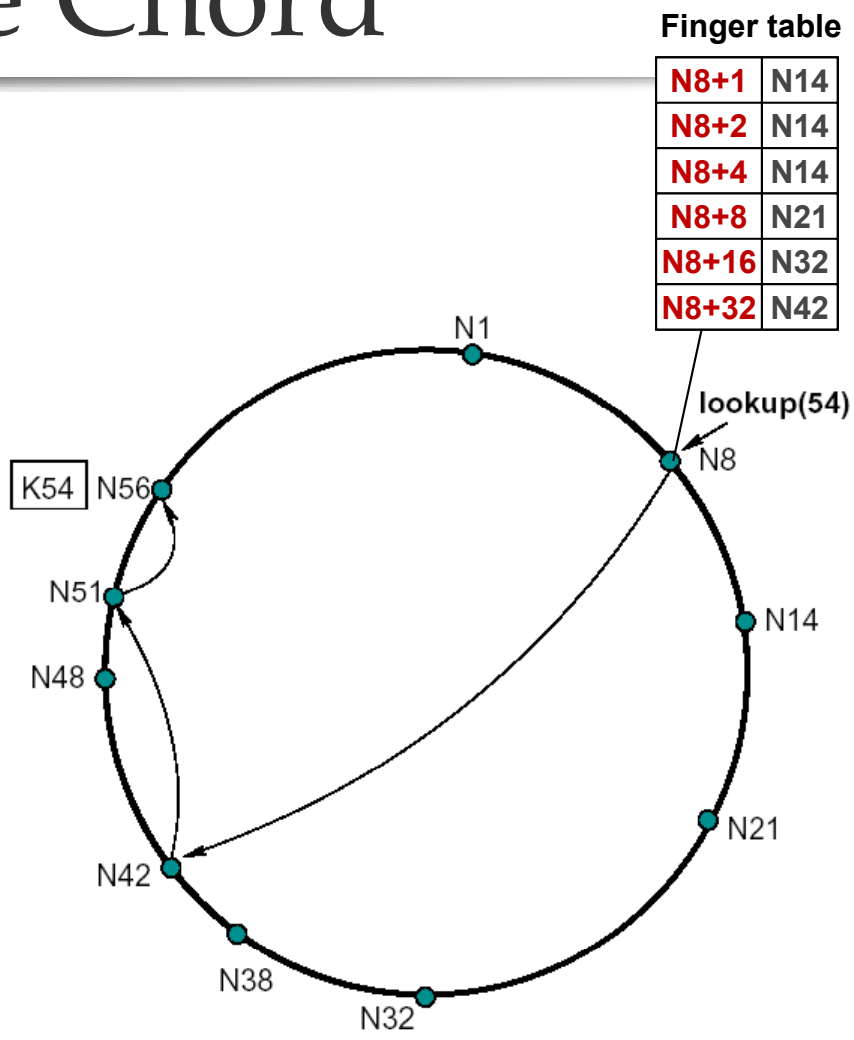
- Each node knows these two nodes:
  - Successor
  - Predecessor (for ring management)
- But also: Each node has *m* **fingers**
  - *n*.finger(*i*) points to node on or after 2^i steps ahead
  - *n*.finger(0) == *n*.successor
  - *O(log N)* state per node
- Lookup is achieved by following *longest preceding fingers*, then the successor
  - *O(log N)* hops



Complete Chord

```
// ask node n to find the successor of id
n.find_successor(id)
    if (key ∈ (n, n.successor])
        return n.successor;
    else
        n' = closest_preceding_node(id);
        return n'.find_successor(id);
```

```
// search the local table for the highest predecessor of id
n.closest_preceding_node(id)
    for i = m downto 1
        if (finger[i] ∈ (n, id))
            return finger[i];
    return n;
```



Chord Ring Management

- For **correctness**, Chord needs to maintain the following invariants
  - **Successors** are **correctly** maintained
  - For every key *k*, *succ(k)* is responsible for *k*
- **Fingers** are for **efficiency**, not necessarily correctness!
  - One can always default to successor-based lookup
  - Finger table can be updated lazily

Joining the Ring

- Three step process:

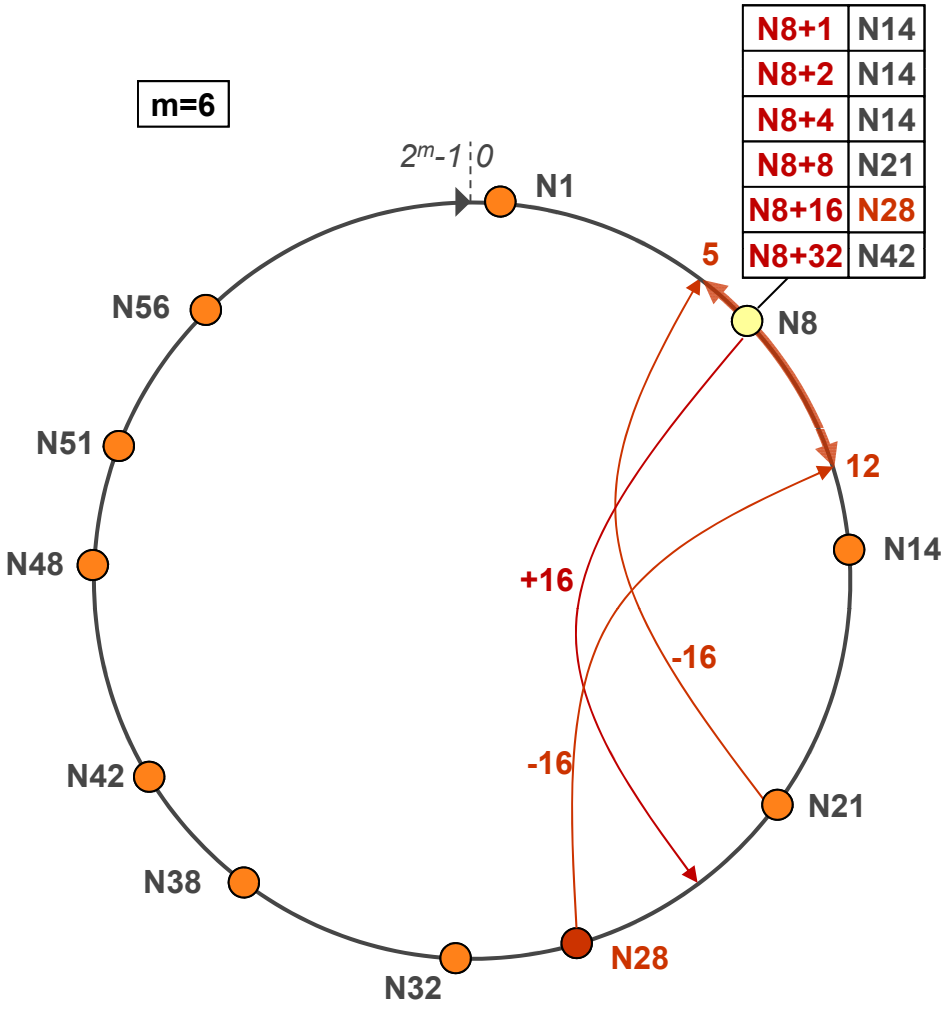
1. Outgoing links
   - Initialize predecessor and all fingers of new node
2. Incoming links
   - Update predecessors and fingers of existing nodes
3. Transfer some keys to the new node

Joining the Ring – Step 1

- Initialize the new node finger table
  - Locate any node *n* in the ring
  - Ask *n* to lookup the peers at $j+2^0$, $j+2^1$, $j+2^2$…
  - Use results to populate finger table of *j*

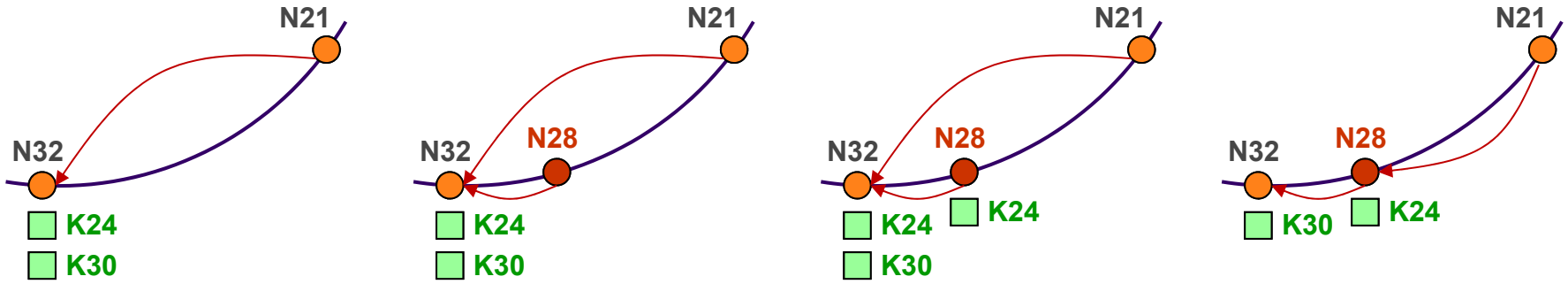
Joining the Ring — Step 2

- Updating fingers of existing nodes
  - New node *j* calls update function on existing nodes that must point to *j*
    - Nodes in the ranges $[j-2^i , pred(j)-2^i+1]$
  - *O(log N)* nodes need to be updated



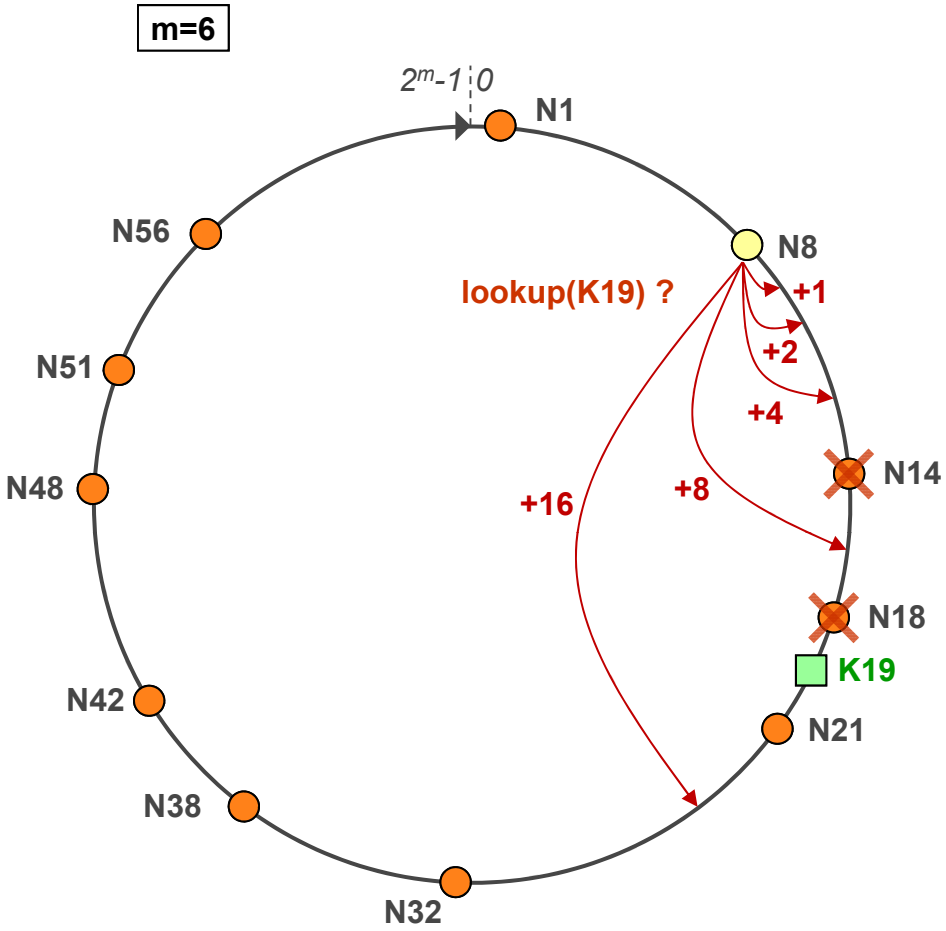
Joining the Ring — Step 3

- Transfer key responsibility
  - Connect to successor
  - Copy keys from successor to new node
  - Update successor pointer and remove keys



Leaving the Ring (or Failing)

- Node departures are treated as node failures
- Failure of nodes might cause incorrect lookup
  - N8 doesn't know correct successor, so lookup of **K19** fails
- Solution: **successor list**
  - Each node *n* knows *r* immediate successors
  - After failure, *n* contacts first alive successor and updates successor list
  - Correct successors guarantee correct lookups



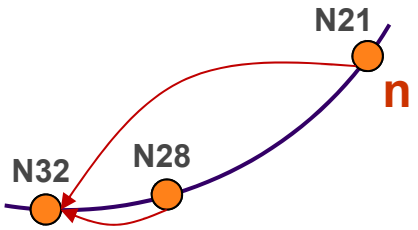
Leaving the Ring (or Failing)

- Successor lists guarantee correct lookup with some probability
  - Can choose *r* to make probability of lookup failure arbitrarily small

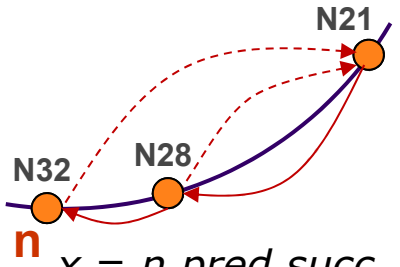
- Assume half of the nodes fail and failures are independent
  - *P(n.successorList all dead) = 0.5^r*
  - *P(n does not break the Chord ring) =* 1 - *0.5^r*
  - *P(no broken nodes) = $(1 - 0.5^r)^{N/2}$*
    - *r = 2log N* makes probability = *1 – 1/N*
    - With high probability (*1-1/N*), the ring is not broken

Stabilization

- Case 1: finger tables are reasonably fresh
- Case 2: successor pointers are correct, not fingers
- Case 3: successor pointers are inaccurate or key migration is incomplete — MUST BE AVOIDED!
- Stabilization algorithm periodically verifies and refreshes node pointers (including fingers)
  - Eventually stabilizes the system when no node joins or fails



x = n.succ.pred
if *x* in (*n*, *n.succ*)
n.succ = x



x = n.pred.succ
if *x* in (*n.pred*, *n*)
n.pred = x

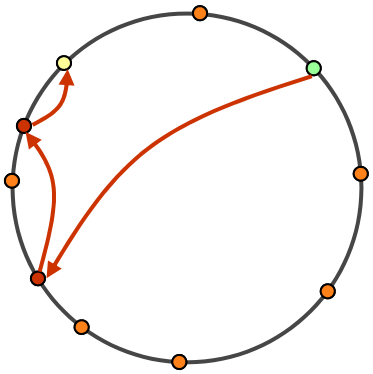
Evolution of P2P Systems

- Nodes leave frequently, so surviving nodes must be notified of arrivals to stay connected after their original neighbors fail

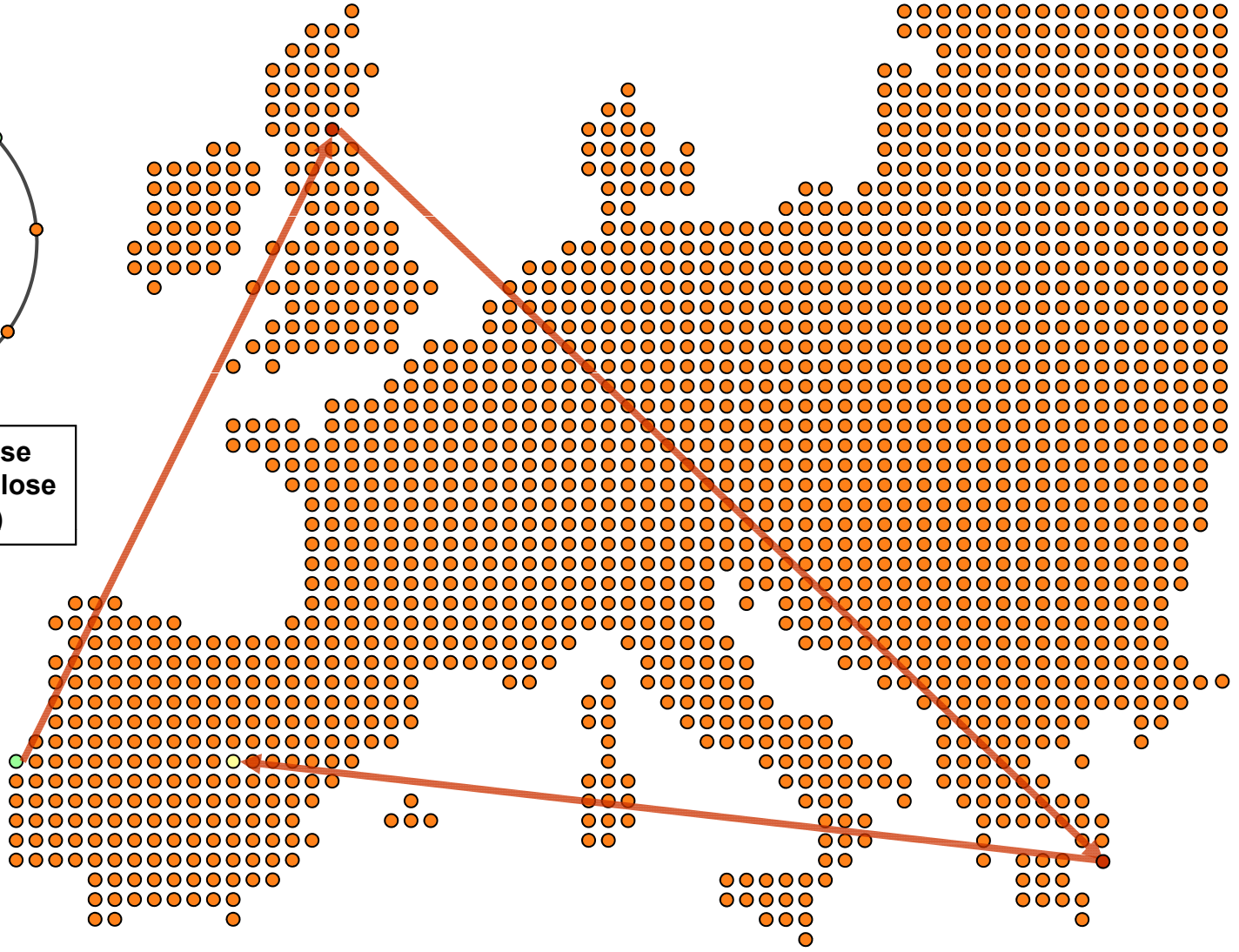
- Take time *t* with *N* nodes
  - Doubling time: time from *t* until *N* new nodes join
  - Halving time: time from *t* until *N* nodes leave
  - Half-life: minimum of halving and doubling time

- Theorem: there exist a sequence of joins and leaves such that any node that has received fewer than *k* notifications per half-life will be disconnected with probability at least $(1 - 1/(e-1))^k \approx 0.418^k$

Chord and Network Topology

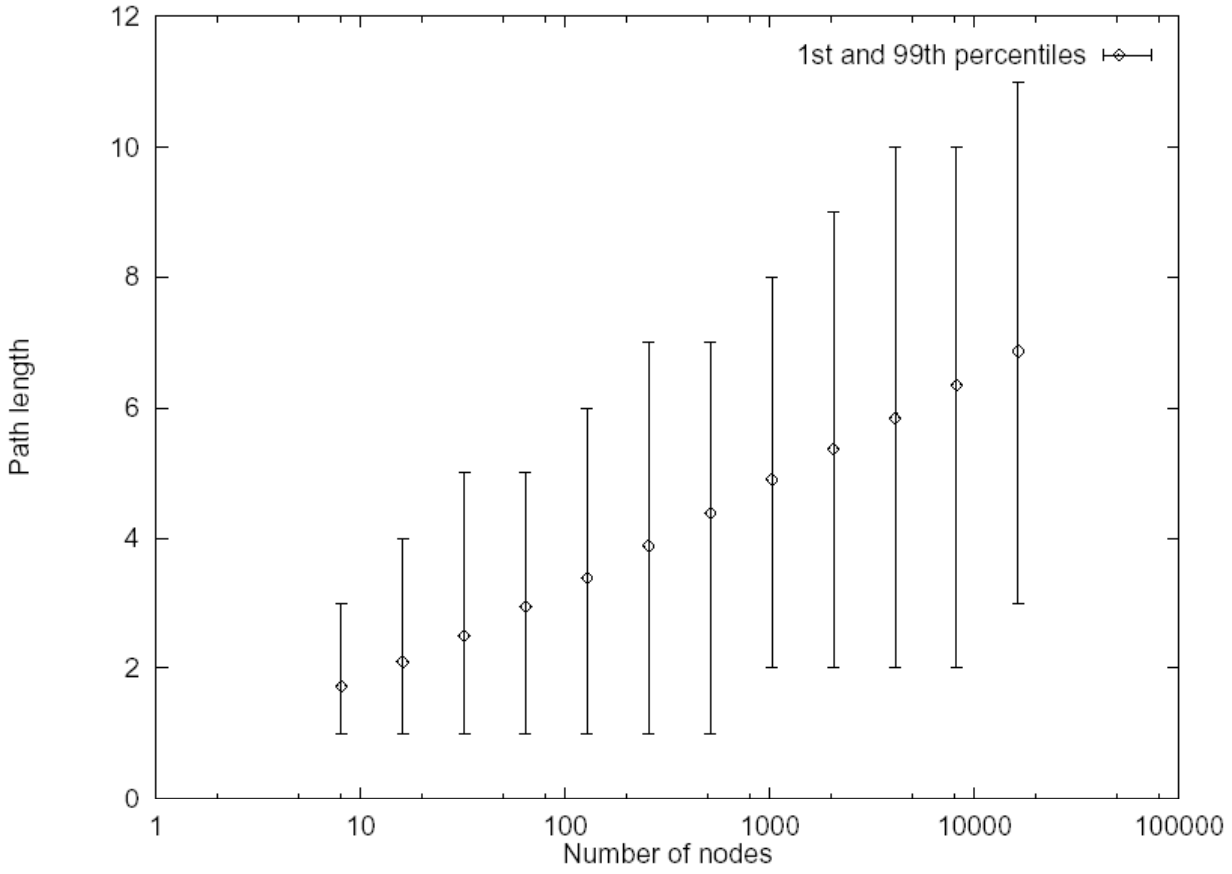


Nodes numerically-close are not topologically-close (1M nodes = 10+ hops)



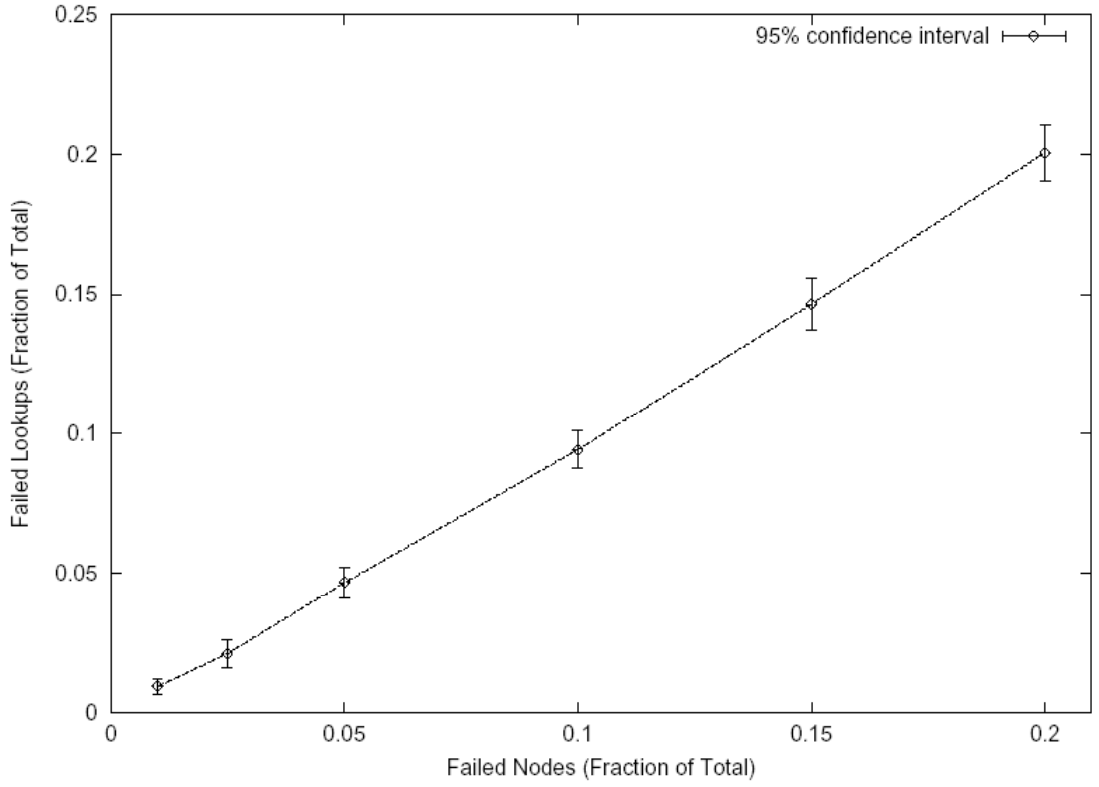
Cost of Lookup

- Cost is *O(log N)*, constant is 0.5



Robustness

- Simulation results: static scenario
- Failed lookup means original node with key failed (no replicas)



- Result impl

Chord Discussion

- Search types
  - Only equality
- Scalability
  - Diameter (search and update) in *O(log N)* w.h.p.
  - Degree in *O(log N)*
  - Construction: $O(\log^2 N)$ if a new node joins
- Robustness
  - Replication might be used by storing replicas at successor nodes
- Autonomy
  - IP address imposes a specific role for storage and routing
- Global knowledge
  - Mapping of IP addresses and data keys to common key space
  - Single origin (single initial node — cannot merge rings)

Chord Discussion

- Search types
  - Only equality
- Scalability
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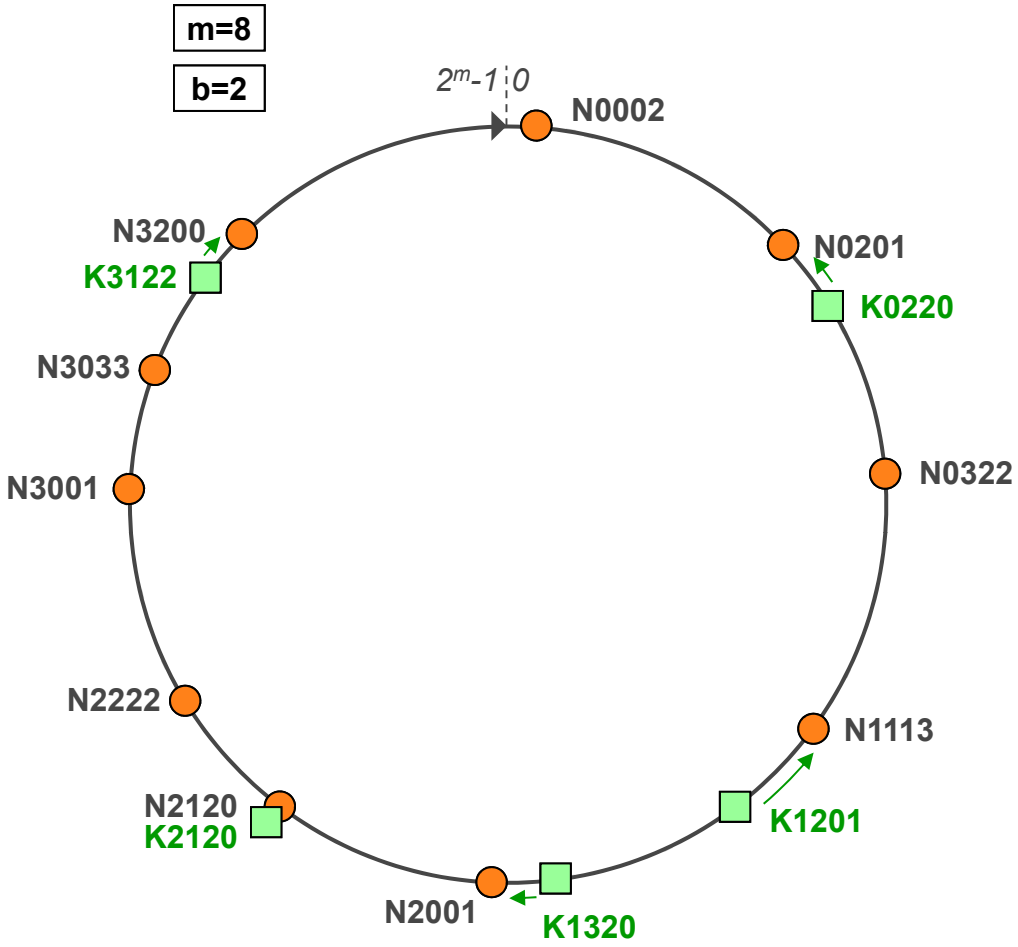
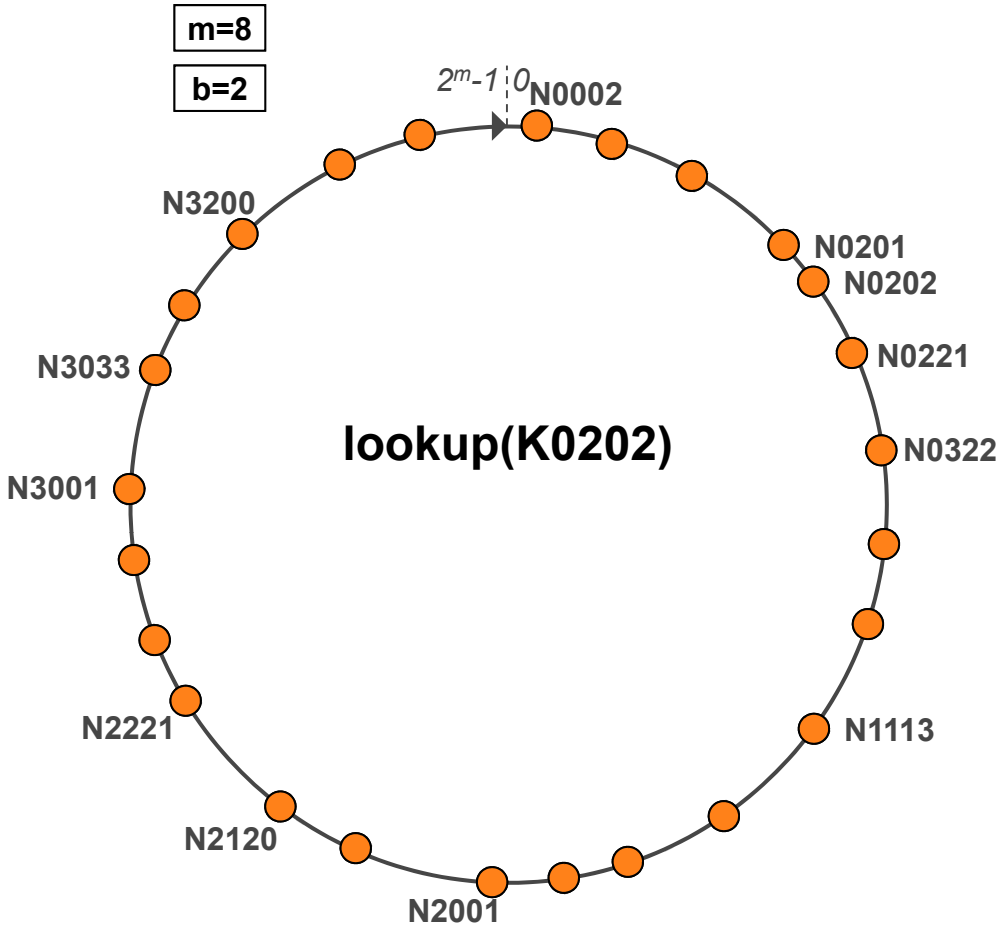
PASTRY
(MSR + Rice)

Pastry

- Circular *m*-bit ID space for both keys and nodes
- Addresses in base 2^b with *m/b* digits
  - Address: *m* bits
  - Digit: *b* bits
  - ==> Address: *m/b* digits
- Node ID = SHA-1(IP address)
- Key ID = SHA-1(key)
- A key is mapped to the node whose ID is **numerically-closest** to the key ID



Pastry Routing



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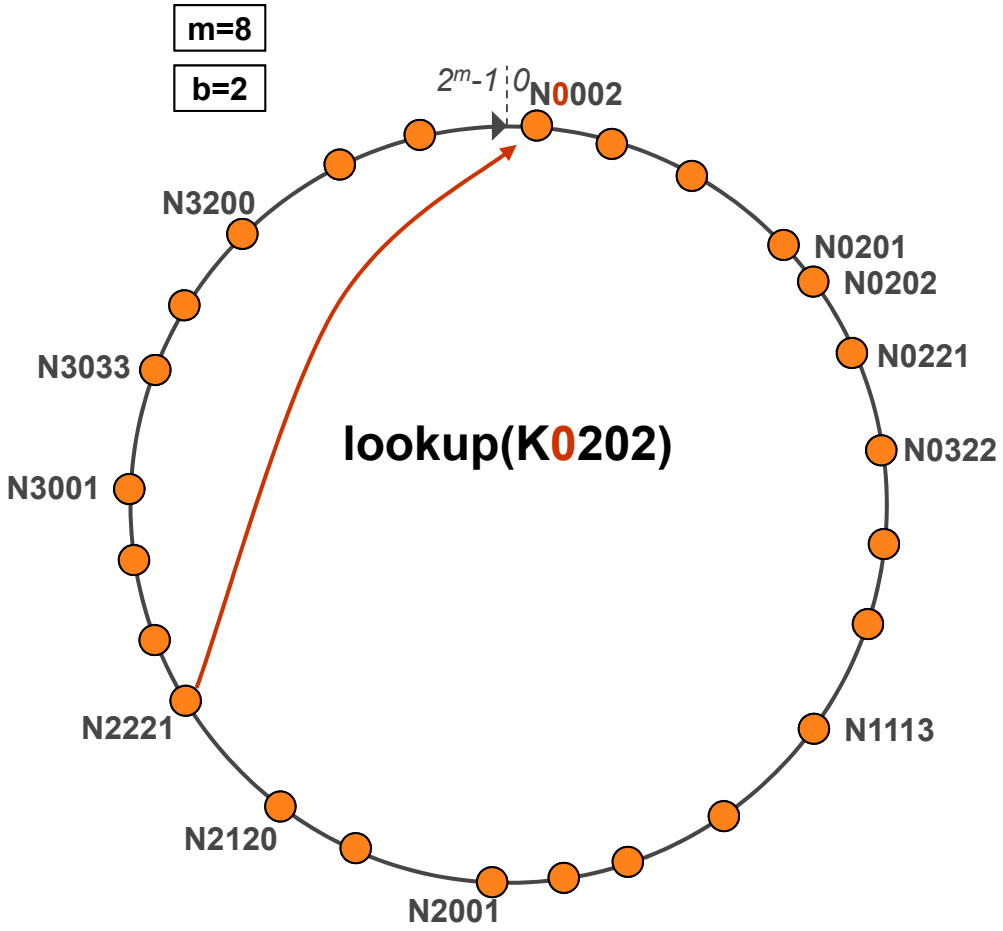

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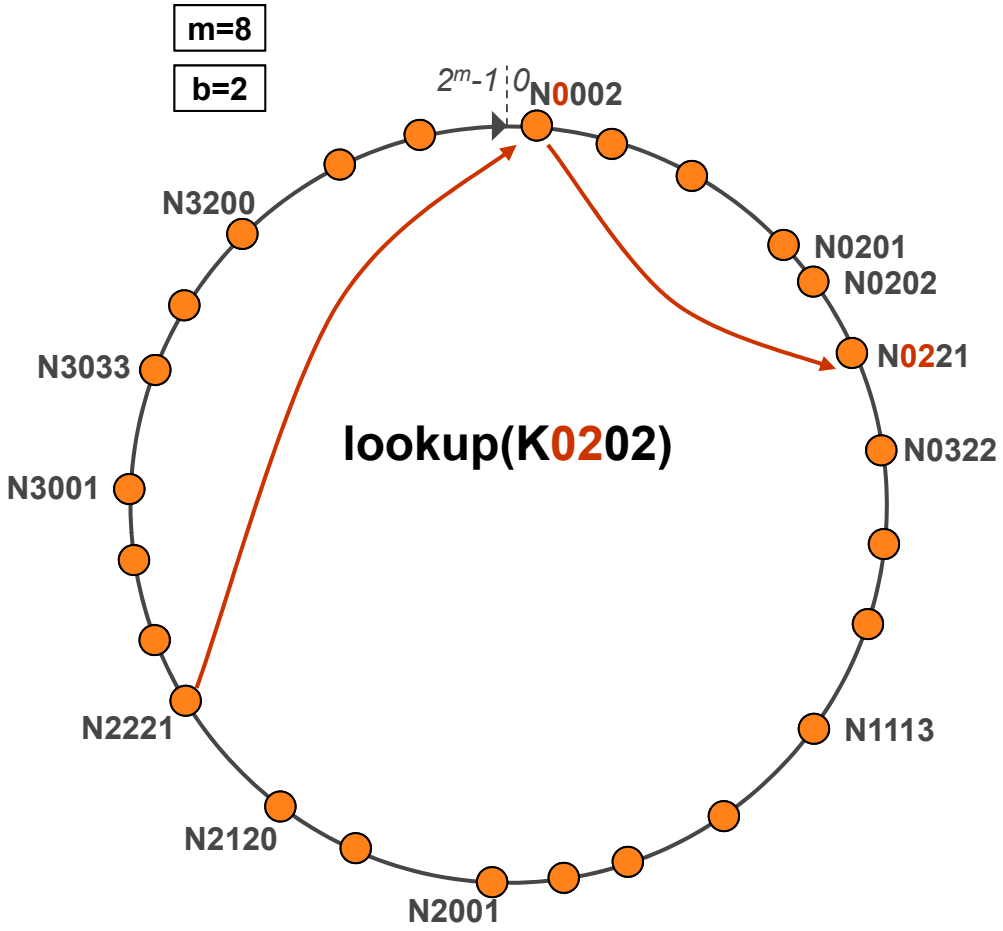
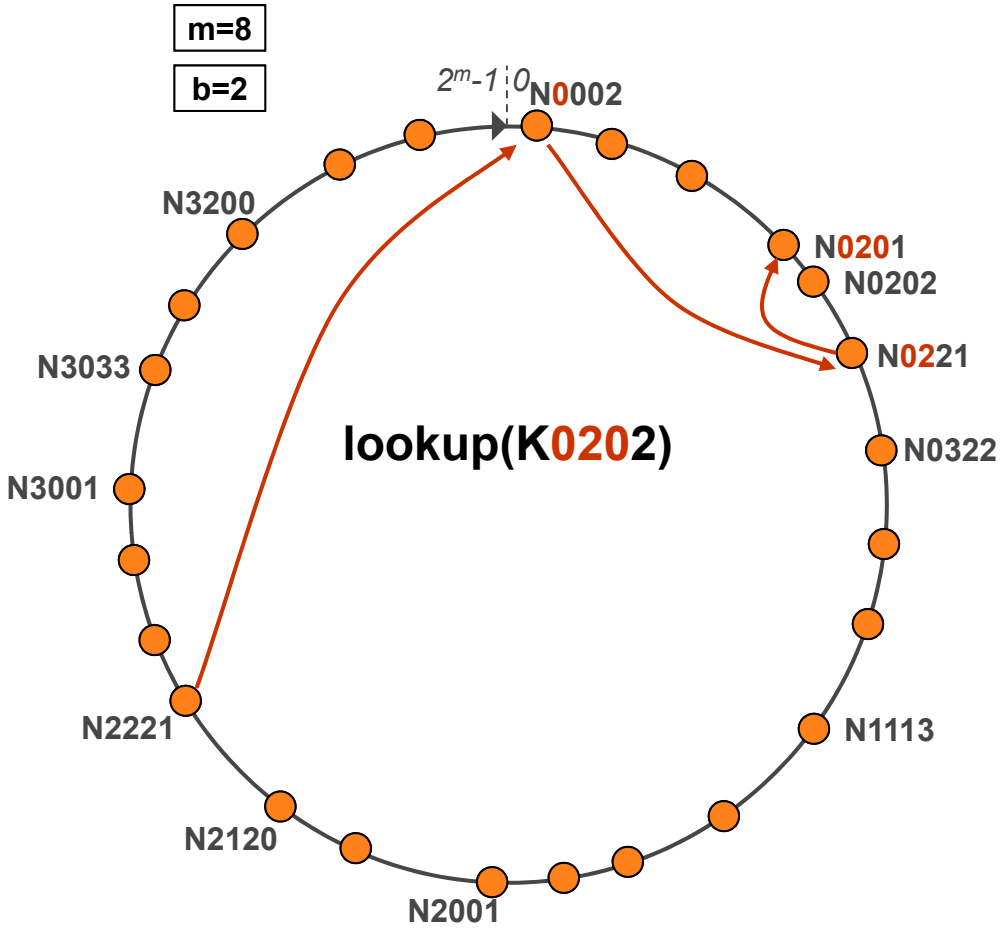
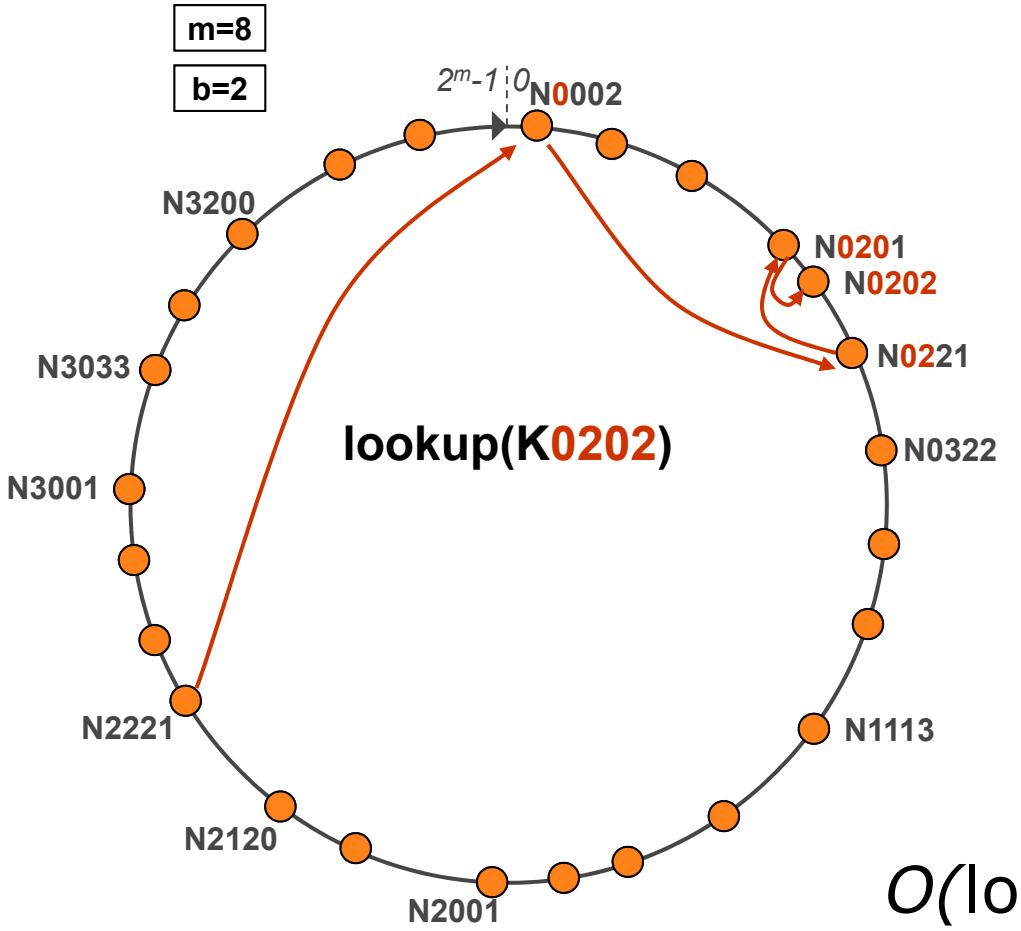


Pastry Routing



Pastry Routing



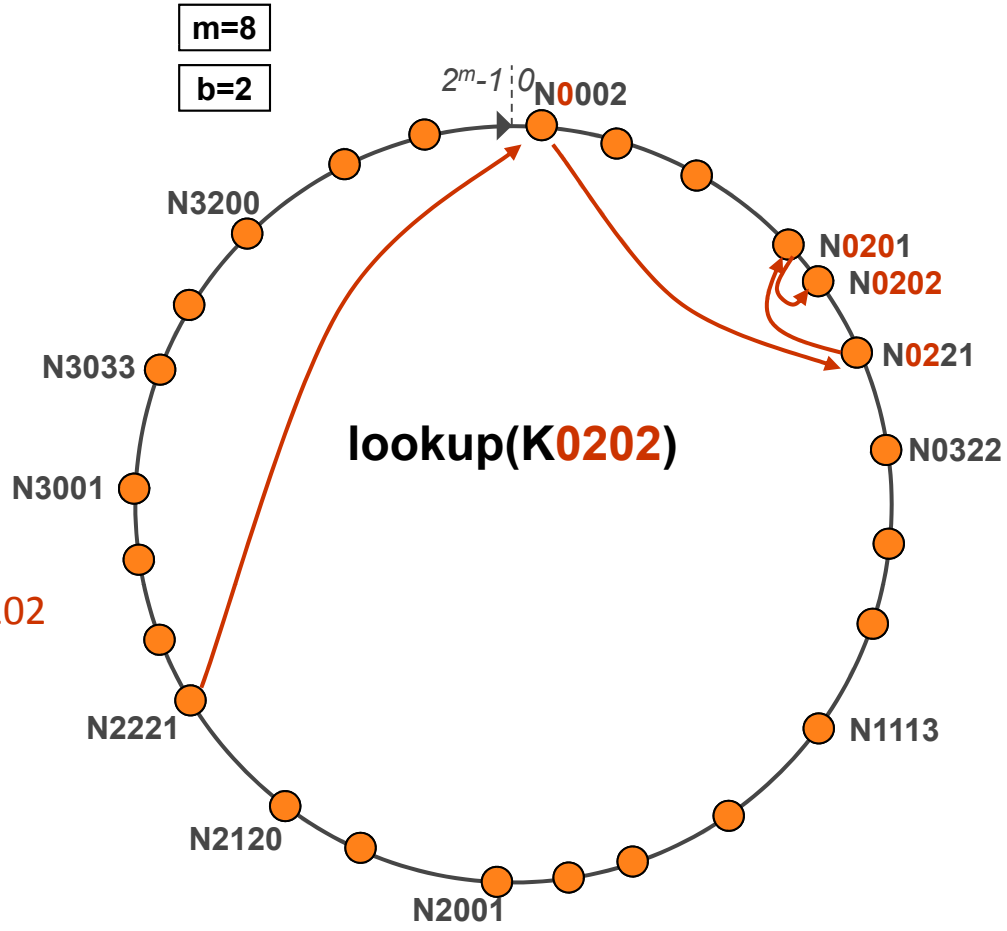
O(log*N*) hops

Pastry Routing

- O(log*N*) hops
- Route to 0202:

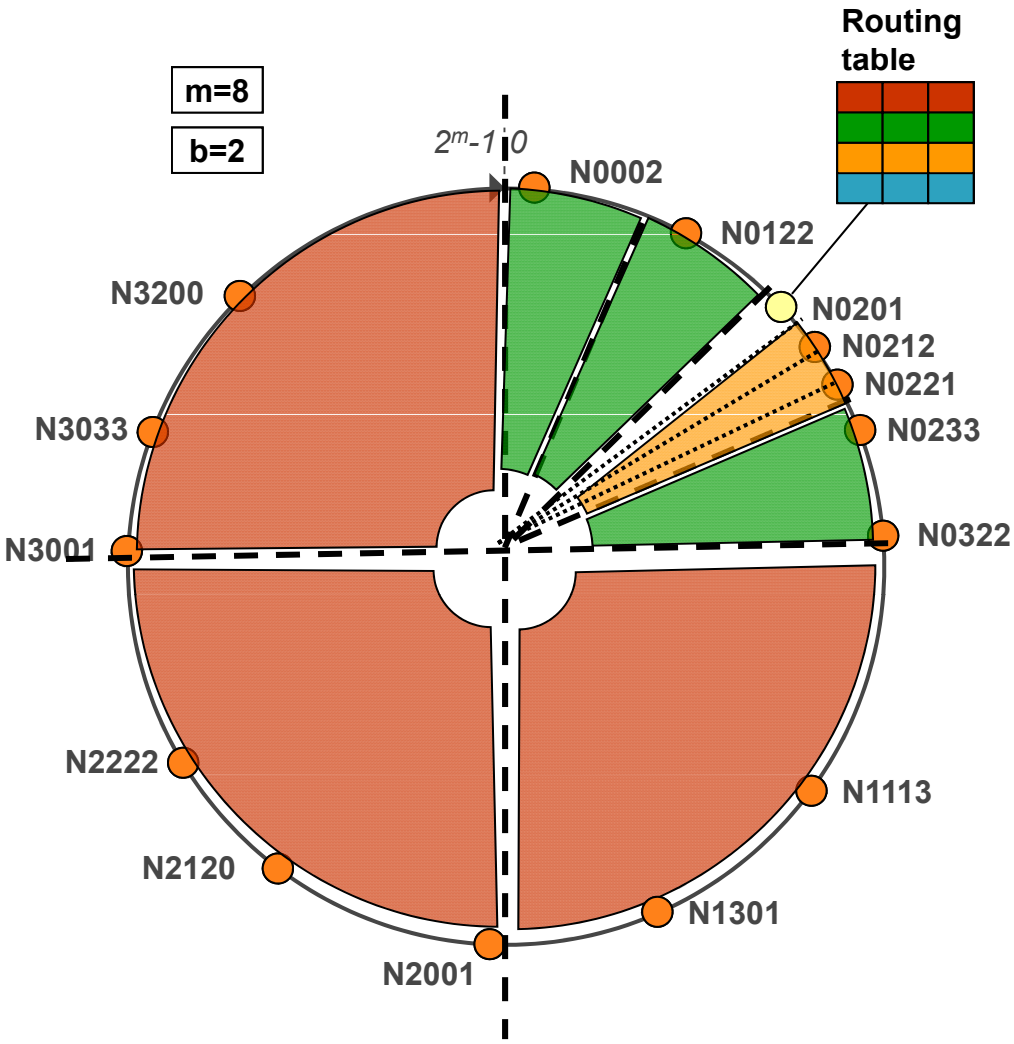
  2221 → 0002 → 0221 → 0201 → 0202
- If chain not complete, forward to numerically closest neighbor (successor)

  2221 → 0002 → 0221 → 0210 → 0201 → 0202

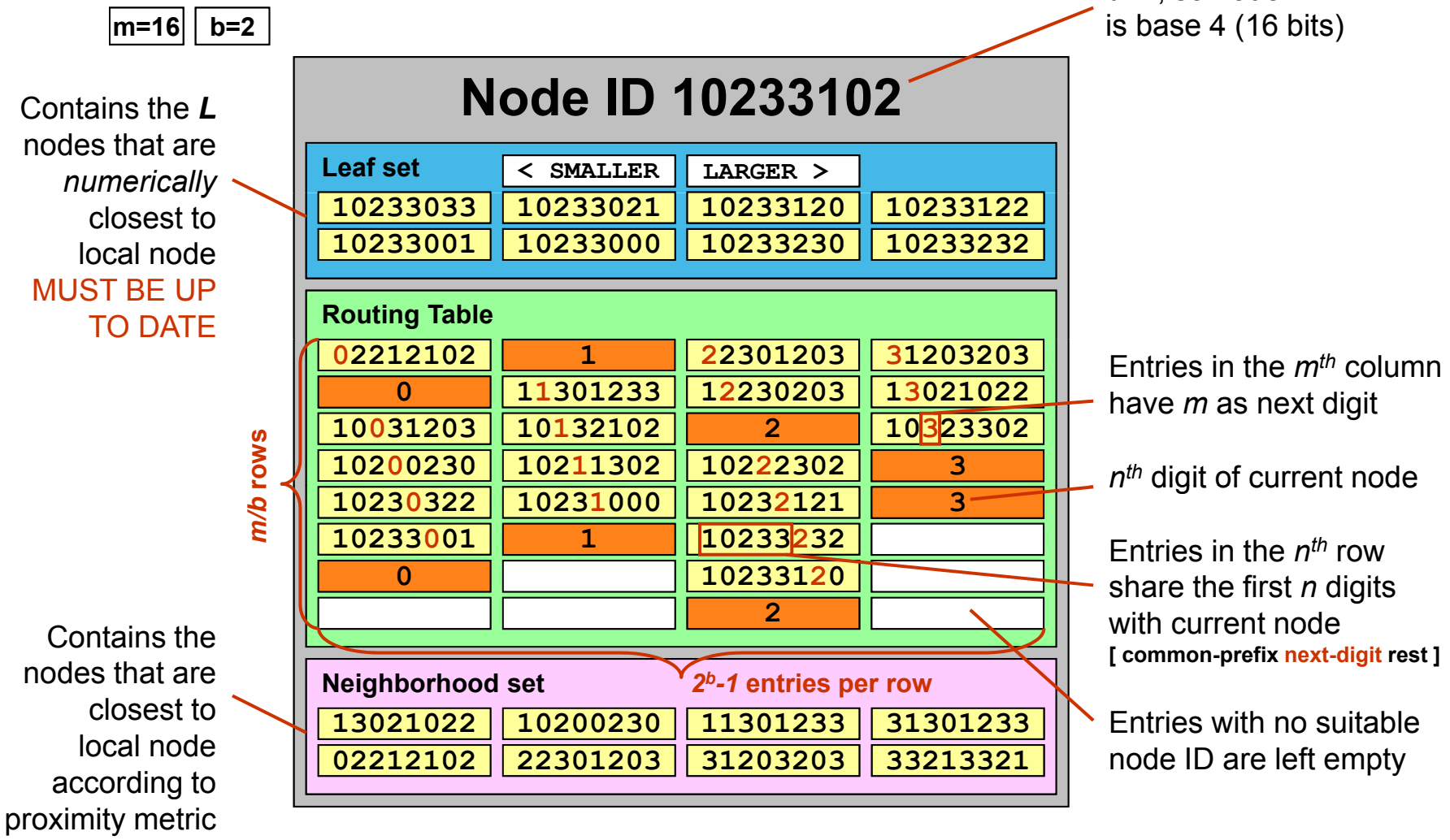


Pastry State and Lookup

- For each prefix, a node knows some other node (if any) with same prefix and different next digit
- For instance, N0201:
  - N-: N1???, N2???, N3???
  - N0: N00??, N01??, N03??
  - N02: N021?, N022?, N023?
  - N020: N0200, N0202, N0203
- When multiple nodes, choose topologically-closest
  - Maintain good locality properties (more on that later)



A Pastry Routing Table



Pastry Lookup (Detailed)

The routing procedure is executed whenever a message arrives at a node

1. IF (*key* in Leaf Set)
   1. If key is in leaf set, destination is 1 hop away, forward directly to destination.
2. ELSE IF (*key* in Routing Table)
   1. Forward to node that matches one more digit
3. ELSE
   1. Forward to a node numerically closer, from Leaf Set

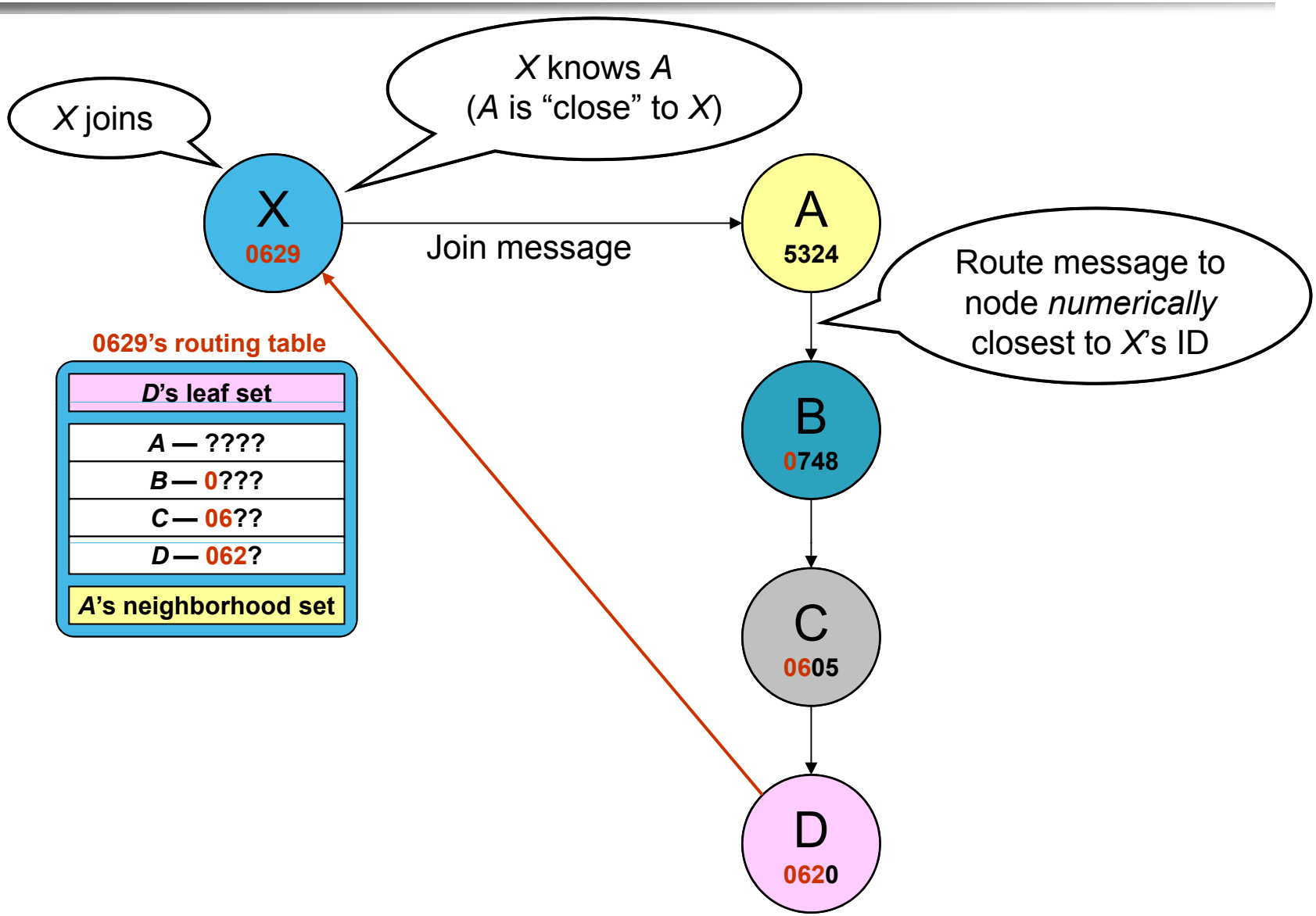
- **The procedure always converges!**

```
(1)  if (L_{-⌊|L|/2⌋} ≤ D ≤ L_{⌊|L|/2⌋}) {
(2)      // D is within range of our leaf set
(3)      forward to L_i, s.th. |D − L_i| is minimal;
(4)  } else {
(5)      // use the routing table
(6)      Let l = shl(D, A);
(7)      if (R_l^{D_l} ≠ null) {
(8)          forward to R_l^{D_l};
(9)      }
(10)     else {
(11)         // rare case
(12)         forward to T ∈ L ∪ R ∪ M, s.th.
(13)             shl(T, D) ≥ l,
(14)             |T − D| < |A − D|
(15)     }
(16) }
```

Lookup Performance

- If the key is within range of the leaf set, the destination node is at most one hop away
- If a message is forwarded using the routing table, the destination is reached in $\lceil log_{2^b} N \rceil$ steps
- The probability of the third case (empty entry in routing table) is less then 0.006 for $|L| = 2*2^b$
- In case of many simultaneous node failures, the number of routing steps can be close to N
- Eventually, message delivery is guaranteed unless $|L|/2$ nodes with consecutive node identifiers fail simultaneously

Joining


X joins
X knows A
(A is "close" to X)
X
0629
Join message
A
5324
Route message to
node numerically
closest to X's ID
0629's routing table
D's leaf set
A — ????
B — 0???
C — 06??
D — 062?
A's neighborhood set
B
0748
C
0605
D
0620

Locality

- Desired **proximity invariant**: all routing table entries refer to a node that is near the present node, according to proximity metric, among all live nodes with prefix appropriate for the entry

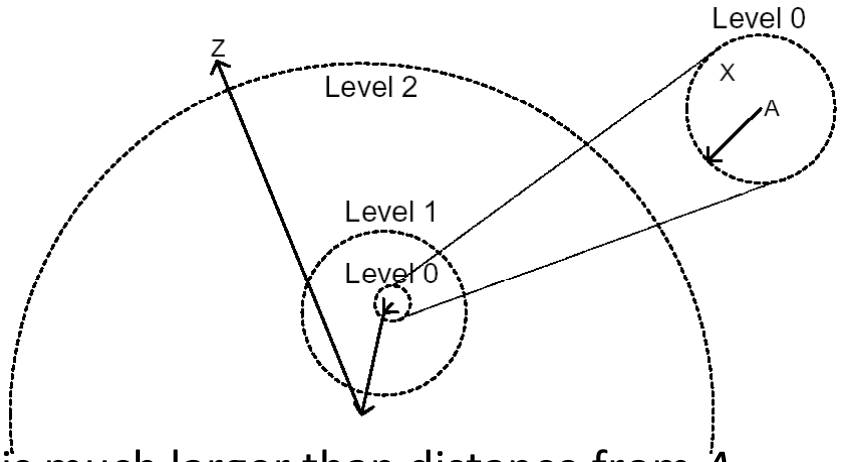
- Assumptions
  - Scalar proximity metric (e.g., ping delay, # IP hops)
  - A node can probe distance to any other node

- We assume this property holds prior to node X joining the system

- Show how we can maintain the property after X joins the system

Locality (cont' d)

- The joining phase preserves the locality property
  - First: *A* must be near *X*
  - Entries in row zero of *A*'s routing table are close to *A*, *A* is close to *X* $\Rightarrow$ X_0 can be A_0

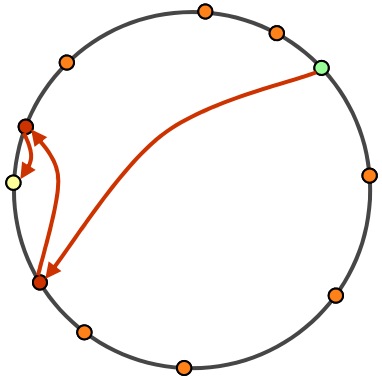


  - The distance from *B* to nodes from B_1 is much larger than distance from *A* to *B* (*B* is in A_0) $\Rightarrow$ B_1 can be reasonable choice for X_1, C_2 for X_2, etc.
  - To avoid cascading errors, *X* requests the state from each of the nodes in its routing table and updates its own with any closer node

Locality (cont' d)

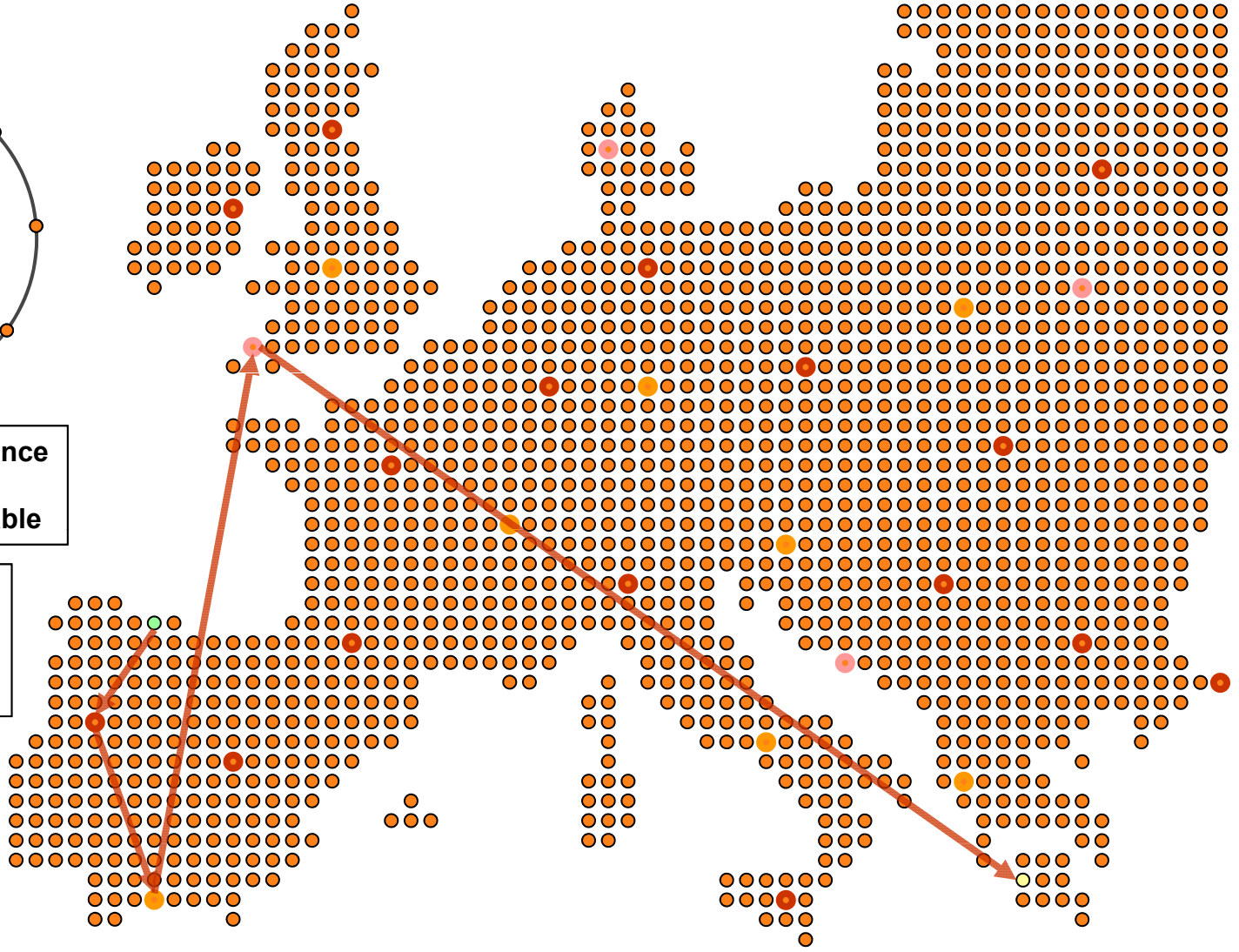
- This scheme works "pretty well" in practice
  - No guarantee for shortest path
  - Measured stretch around 2-3
- Since only local information is used, Pastry minimizes the distance of the next routing step with no sense of global direction
- Although it cannot be guaranteed that the distance of a message from its source increases monotonically at each step, a message tends to make larger and larger strides

Pastry and Network Topology



Expected node distance increases with row number in routing table

Smaller and smaller numerical jumps
Bigger and bigger topological jumps



Node Departure

- To replace a failed node in the leaf set, the node contacts the live node with the largest index on the side of the failed node, and asks for its leaf set
- To repair a failed routing table entry R^d_l, node contacts first the node referred to by another entry R^i_l, $i \neq d$ of the same row, and asks for that node's entry for R^d_l
- If a member in the *Neighbors* table is not responding, the node asks other members for their *Neighbors* table, check the distance of each of the newly discovered nodes, and updates its own *Neighbors* table

Average # Routing Hops

- 2 nodes selected randomly; a message is routed between
- Maximum route length is $\lceil log_{2^b} N \rceil$ (5 for N=100,000)

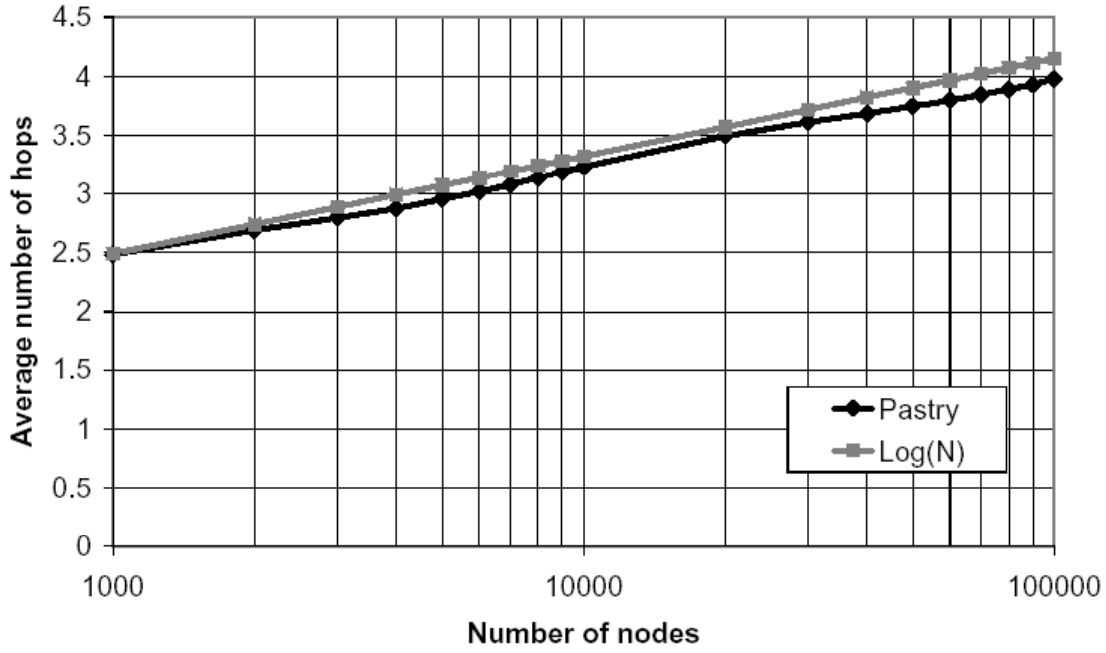


Fig. 4. Average number of routing hops versus number of Pastry nodes, $b = 4$, $|L| = 16$, $|M| = 32$ and 200,000 lookups.

Probability vs. # Routing Hops

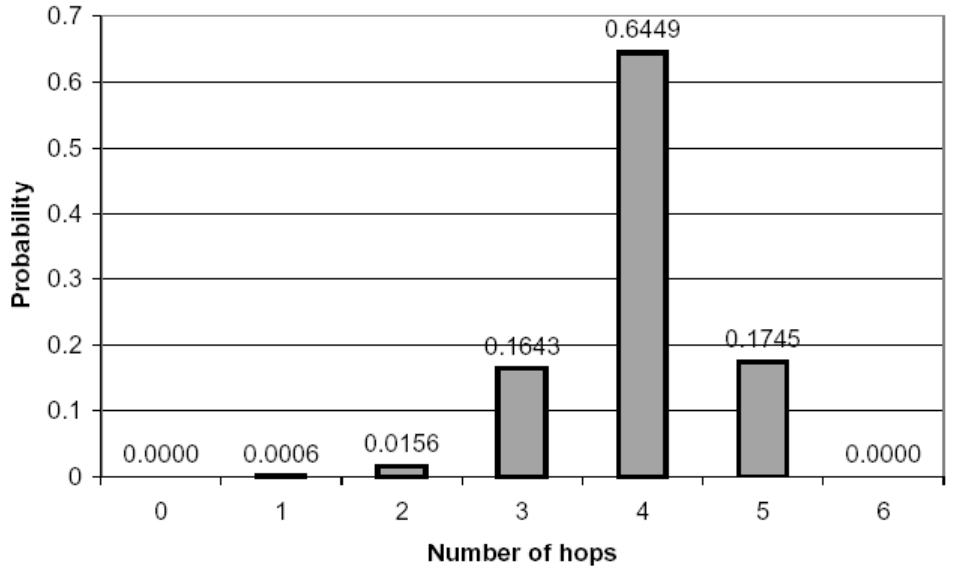


Fig. 5. Probability versus number of routing hops, $b = 4$, $|L| = 16$, $|M| = 32$, $N = 100,000$ and 200,000 lookups.

Route Distance vs. # Nodes

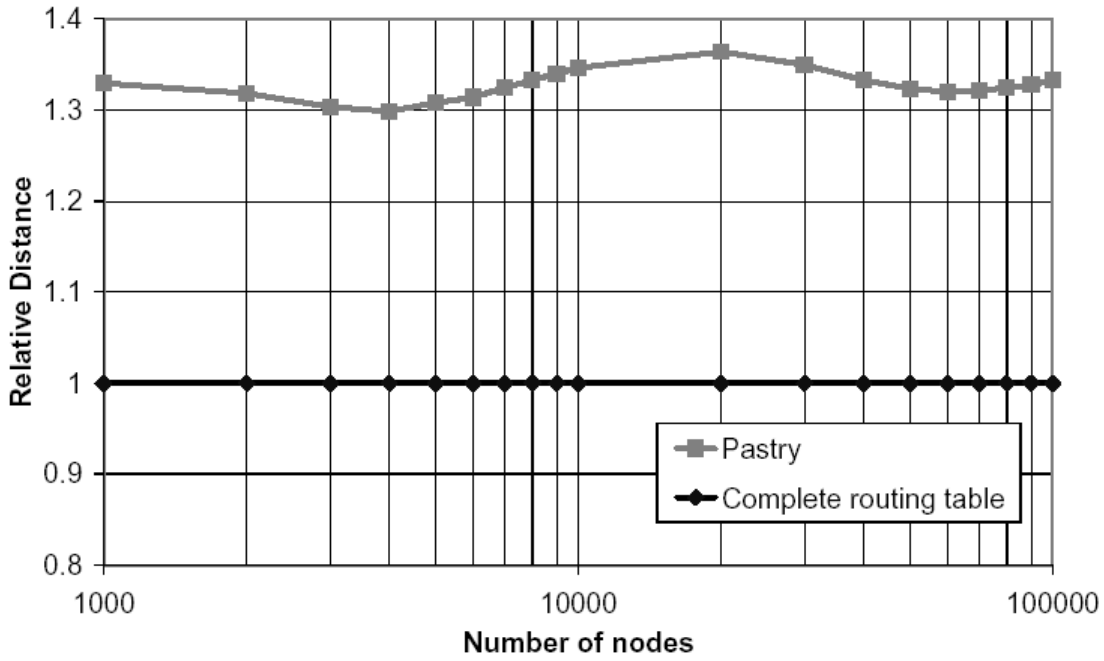


Fig. 6. Route distance versus number of Pastry nodes, $b = 4$, $|L| = 16$, $|M| = 32$, and 200,000 lookups.

Routing Hops vs. Node Failures

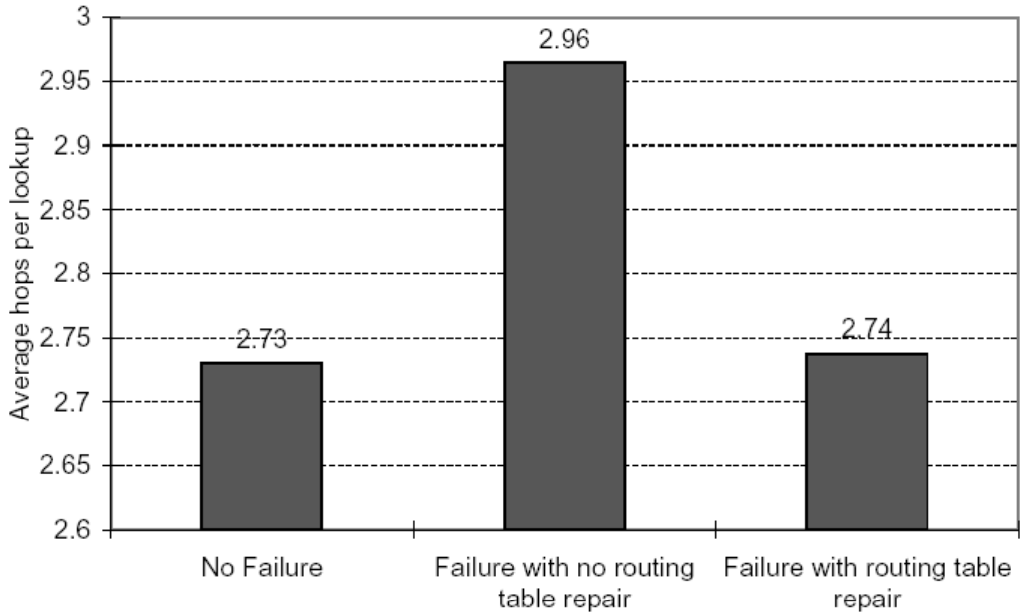


Fig. 10. Number of routing hops versus node failures, $b = 4$, $|L| = 16$, $|M| = 32$, 200,000 lookups and 5,000 nodes with 500 failing.

Pastry Discussion

- Search types
  - Only equality
- Scalability
  - Search $O(log_{2^b} N)$ w.h.p.
- Robustness
  - Can route around failures via nodes of leaf set
  - Replication might be used

Conclusion

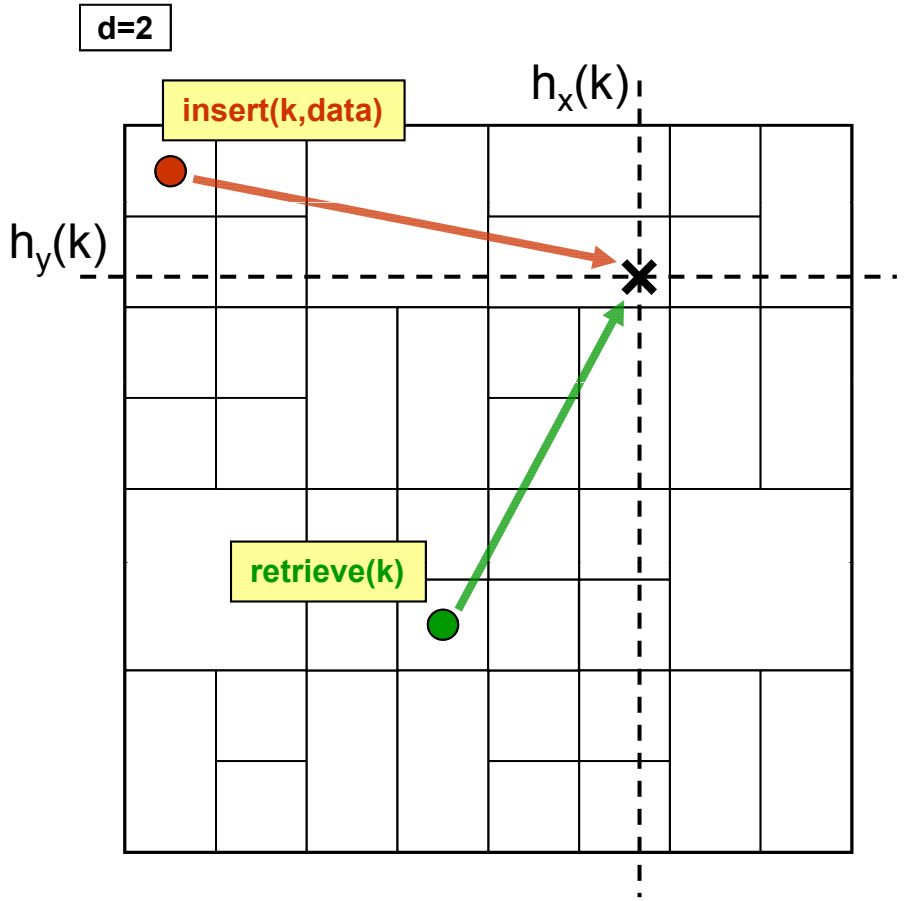
- DHTs are a simple, yet powerful abstraction
  - Building block of many distributed services (file systems, application-layer multicast, distributed caches, etc.)
- Many DHT designs, with various pros and cons
  - Balance between state (degree), speed of lookup (diameter), and ease of management
- System must support rapid changes in membership
  - Dealing with joins/leaves/failures is not trivial
  - Dynamics of P2P networks are difficult to analyze
- Many open issues worth exploring

Pastry Discussion

- Search types
  - Only equality
- Scalability
  - Search $O(log_{2^b} N)$ w.h.p.
- Robustness
  - Can route around failures via nodes of leaf set
  - Replication might be used
- Autonomy
  - IP address imposes a specific role for storage and routing
- Global knowledge
  - Mapping of IP addresses and data keys to common key space
  - Replication scheme (if any)
  - Single origin (single initial node)

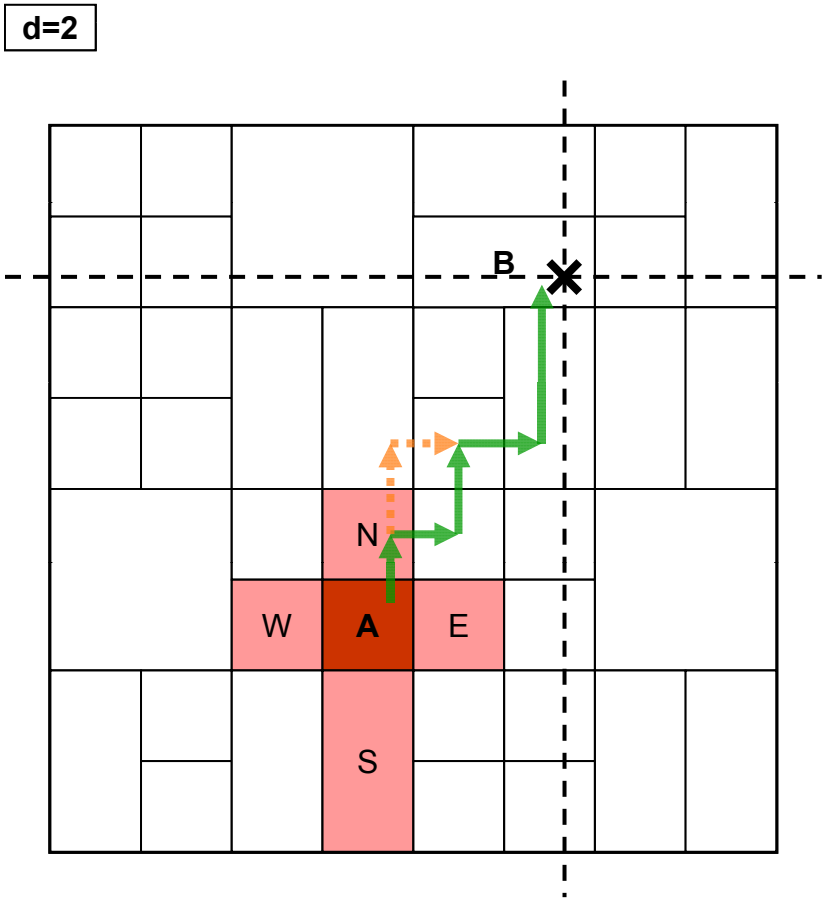
CAN (Berkeley)

- Cartesian space (*d*-dimensional)
  - Space wraps up: *d*-torus
- Incrementally split space between nodes that join
- Node (cell) responsible for key *k* is determined by hashing *k* for each dimension



CAN State and Lookup

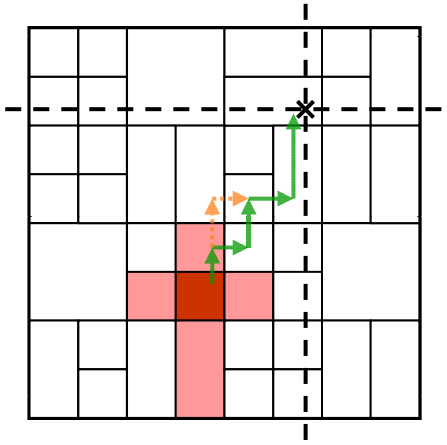
- A node *A* only maintains state for its immediate neighbors (*N*, *S*, *E*, *W*)
  - *2d* neighbors per node
- Messages are routed to neighbor that minimizes Cartesian distance
  - More dimensions means faster the routing but also more state
  - $(dN^{1/d})/4$ hops on average
- Multiple choices: we can route around failures



CAN Landmark Routing

- CAN nodes do not have a pre-defined ID
- Nodes can be placed according to locality
  - Use well known set of *m* landmark machines (e.g., root DNS servers)
  - Each CAN node measures its RTT to each landmark
  - Orders the landmarks in order of increasing RTT: *m!* possible orderings
- CAN construction
  - Place nodes with same ordering close together in the CAN
  - To do so, partition the space into *m!* zones: *m* zones on *x*, *m-1* on *y*, etc.
  - A node interprets its ordering as the coordinate of its zone

CAN and Network Topology



Use *m* landmarks to split space in *m!* zones

Nodes get random zone in their zone

Topologically-close nodes tend to be in the same zone