# General announcement

- **Next Tuesday: Guest lecturer, recording unlikely, and probably highly relevant for projects & exam**
  - turn up in person!

# Structured **P2P** Networks

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# Distributed Hash Tables

- **DHTs are designed to be *infrastructure* for other applications**
- **General concept**
  - Assign peers IDs evenly across an ID space (e.g., [0, $2^n$-1])
  - Assign resources IDs in the same ID space, and associate resources with the closest (in ID space) peer
  - Distance = distance in ID space
  - Peers have **broad** knowledge of the network, and **deep** knowledge about their neighbourhood
  - Arrange peers in a network that they easily (iteratively or recursively) can be found
  - Searching for a resource and searching for a peer become the same

# Distributed Hash Tables

- **Challenges**
  - Routing information must be distributed – no central index
  - How is the routing information created and maintained?
  - How are peers inserted into the network? How do they leave? How are resources added?
  - Resources are stored at their closest peer
    - resources should be relatively small...

# Overview

- **Chord**
- **Pastry**
- **Kademlia**
- **Conclusions**

# Chord

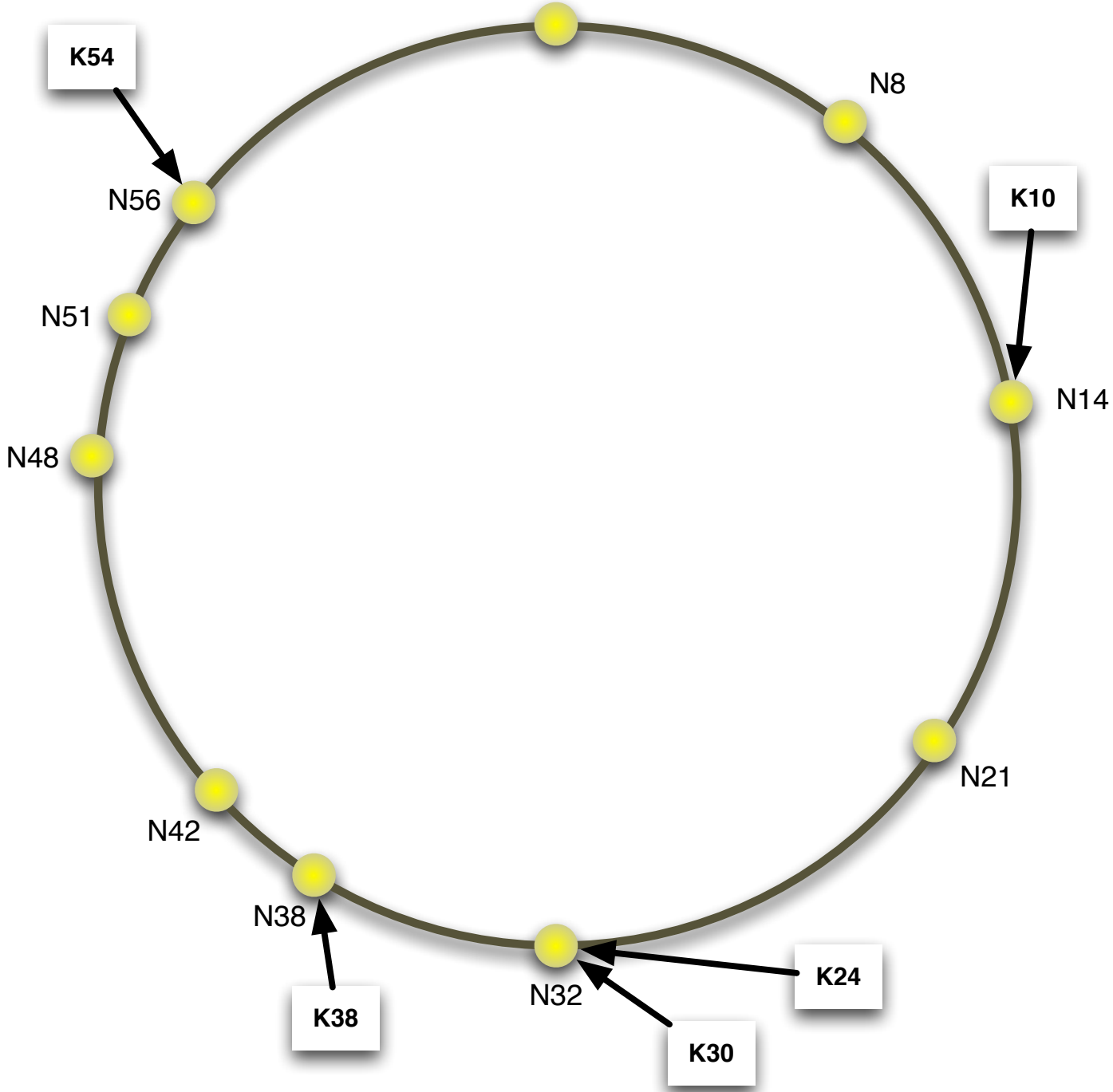
- **One operation:**
  - `IP address = lookup(key)`: Given a key, find node responsible for that key
- **Goals**
  - load balancing, decentralisation, scalability, availability, flexible naming
  - performance and space usage:
    - lookup in O(log N)
    - each node needs information about O(log N) other nodes

# Use of Hashing in Chord

- **Keys are assigned to nodes with hashing**
  - good hash function balances load
- **Nodes and keys are assigned m-bit identifiers**
  - using SHA-1 on nodes' IP addresses and on keys
  - m should be big enough to make collisions improbable
- **"Ring-based" assignment of keys to nodes**
  - identifiers are ordered on an identifier circle modulo $2^m$
  - a key $k$ is assigned to the first node $n$ where $ID_n \geq ID_k$: $n = \text{successor}(k)$

# Hash function?

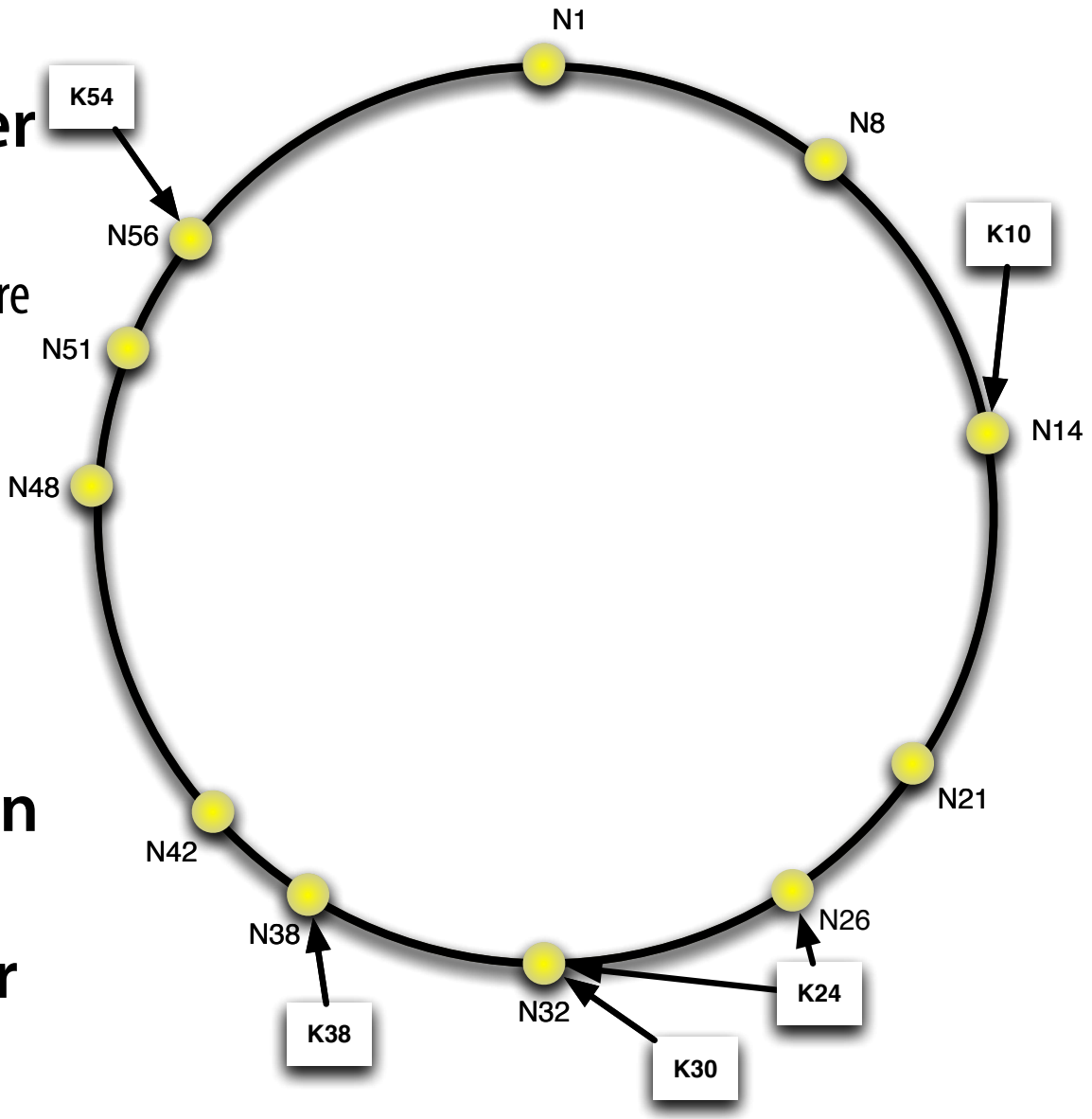
- *"A hash function is any function that can be used to map data of arbitrary size to data of fixed size"*
  - e.g., from some data to a number belonging to some range
  - good hash functions generate a uniform distribution of numbers across its range
- ***Cryptographic* hashes (such as SHA-1, SHA-256, etc) are excellent hash functions where it is *very* hard to guess the data that led to a specific hash value**
  - even tiny changes in data leads to dramatically different hash values
  - the range is usually *very* large, e.g. SHA-1 is $[0, 2^{160}=1{,}46\times10^{48}]$
  - (note that these days `SHA-1` is no longer considered safe, so use `SHA-256` instead)




A ring consisting of 10 nodes storing 5 keys

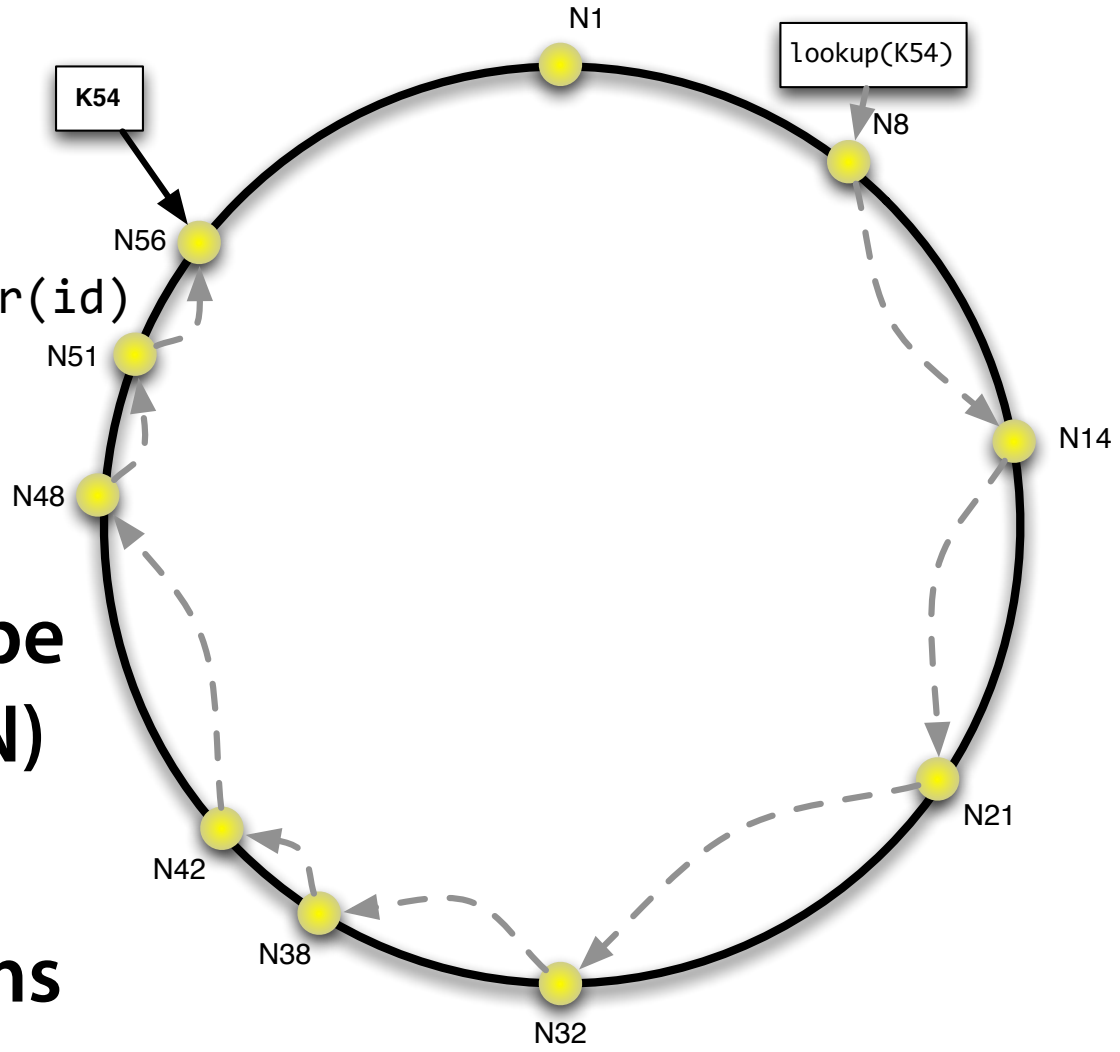
# Key Allocation in Chord

- **Designed to let nodes enter and leave network easily**
  - Node n leaves: all of n's assigned keys are assigned to successor(n)
  - Node n joins: keys k ≤ n assigned to successor(n) are assigned to n
  - Example: N26 joins ⇒ K24 becomes assigned to N26
- **Each physical node may run a number of virtual nodes, each with its own identifier to balance the load**



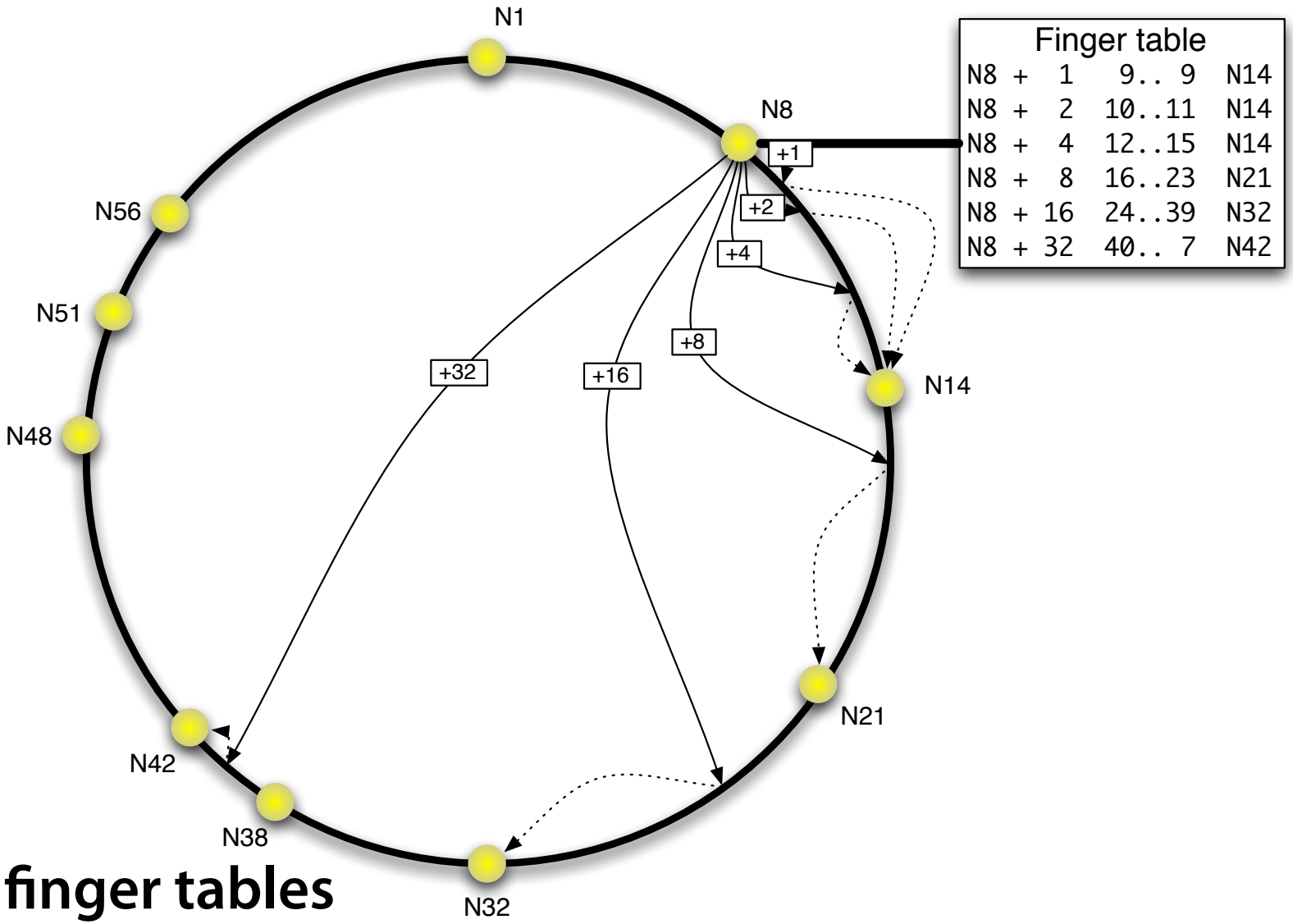
# Simple (Linear) Key Location

```
#ask node n to find the successor of id
n.find_successor(id)
  if n < id ≤ successor
    return successor
  else
    #forward query around circle
    return successor.find_successor(id)
```




- Simple key location can be implemented in time O(N) and space O(1)
- Example: Node 8 performs a lookup for Key 54

# Scalable Key Location

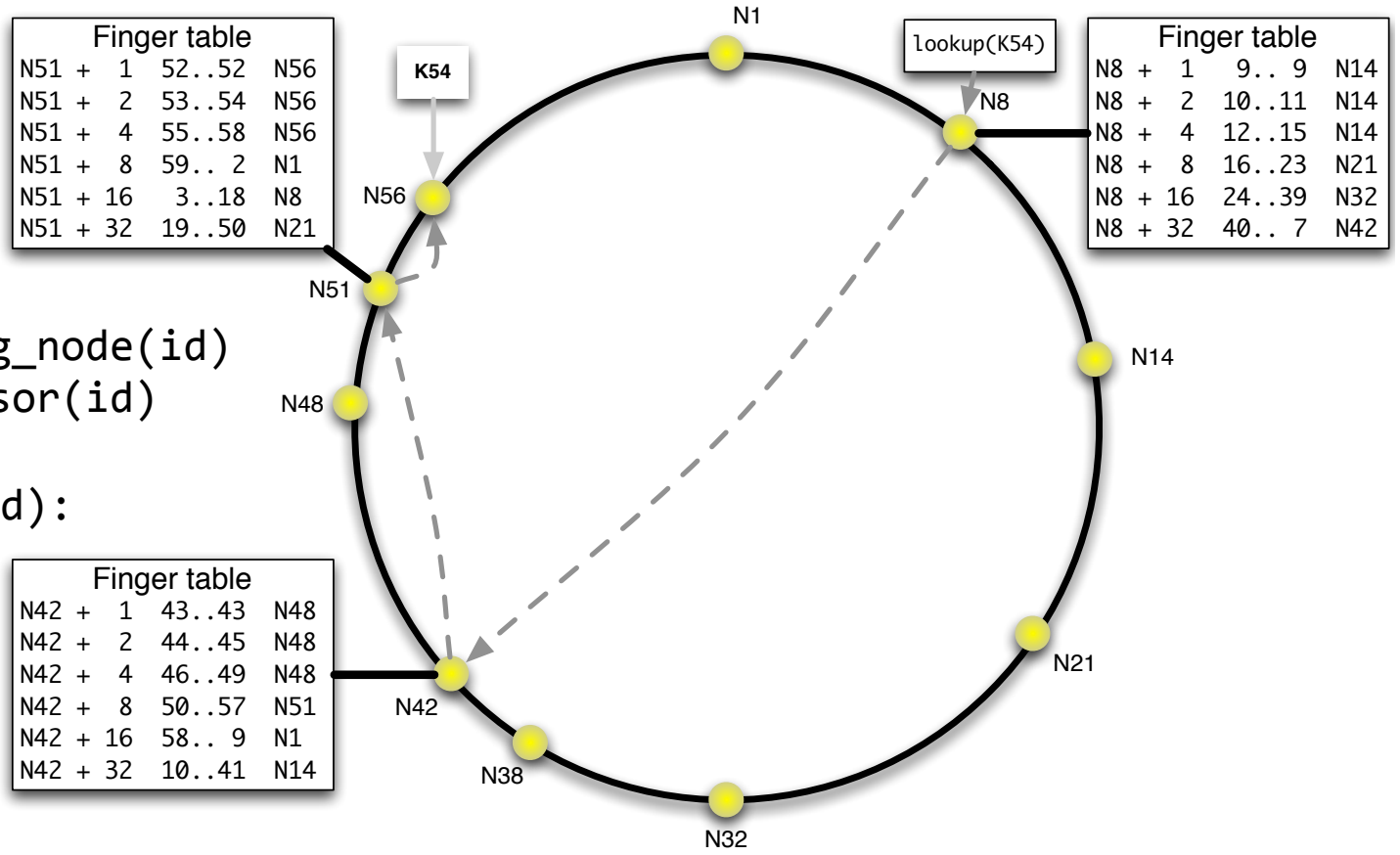



- **Uses finger tables**
  - $n.finger[i] = find\_successor(n + 2^{i-1}), 1 \leq i \leq m$

# Scalable Key Location

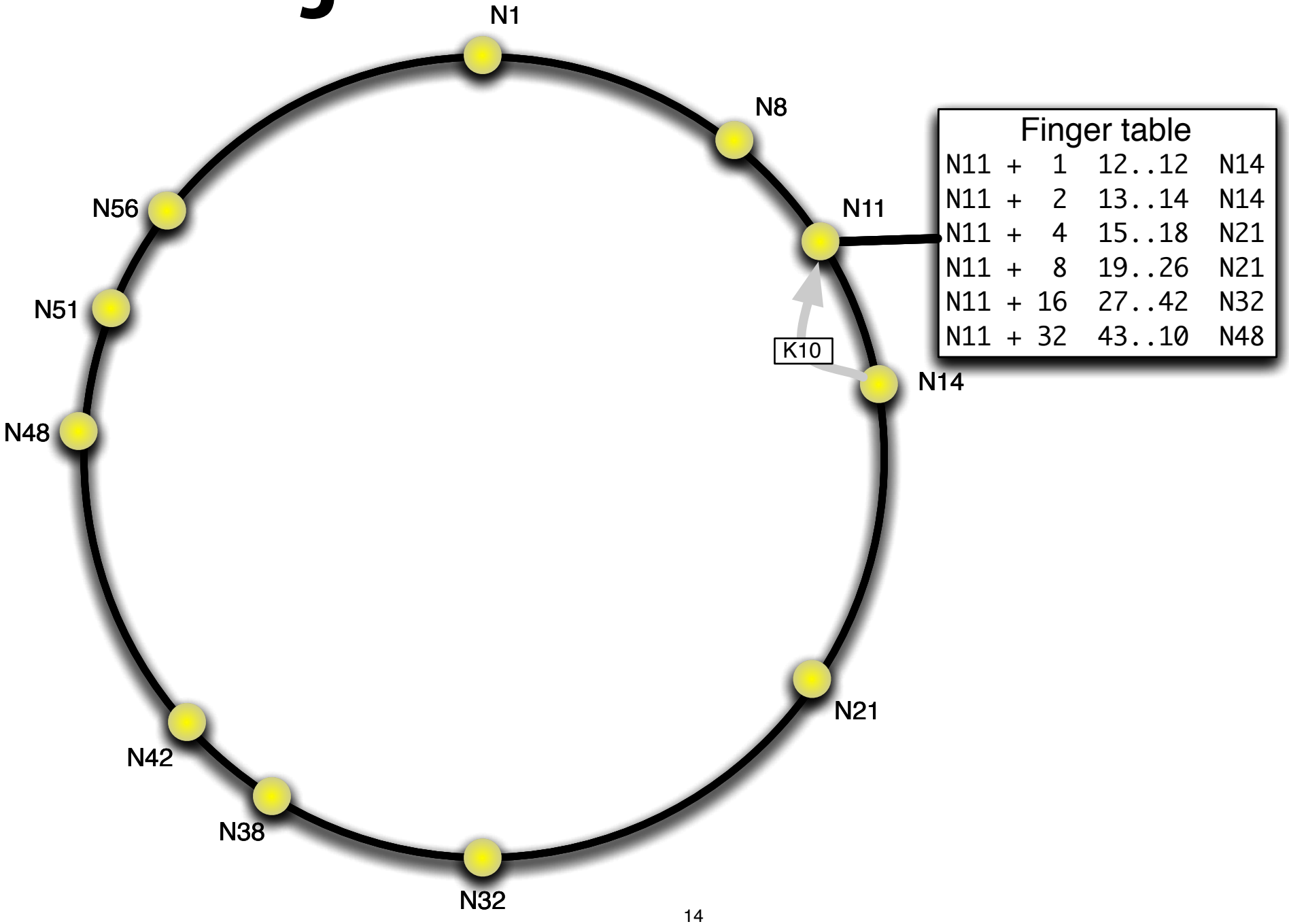
```
n.find_successor(id):
   if n < id ≤ successor
      return successor
   else
      n' = closest_preceding_node(id)
      return n'.find_successor(id)

n.closest_preceding_node(id):
   for i = m downto 1
      if n < finger[i] < id
         return finger[i]
   return n
```




- If successor not found, search finger table to find n' whose ID most immediately precedes id
- This node will know the most about n' of all nodes in the finger table

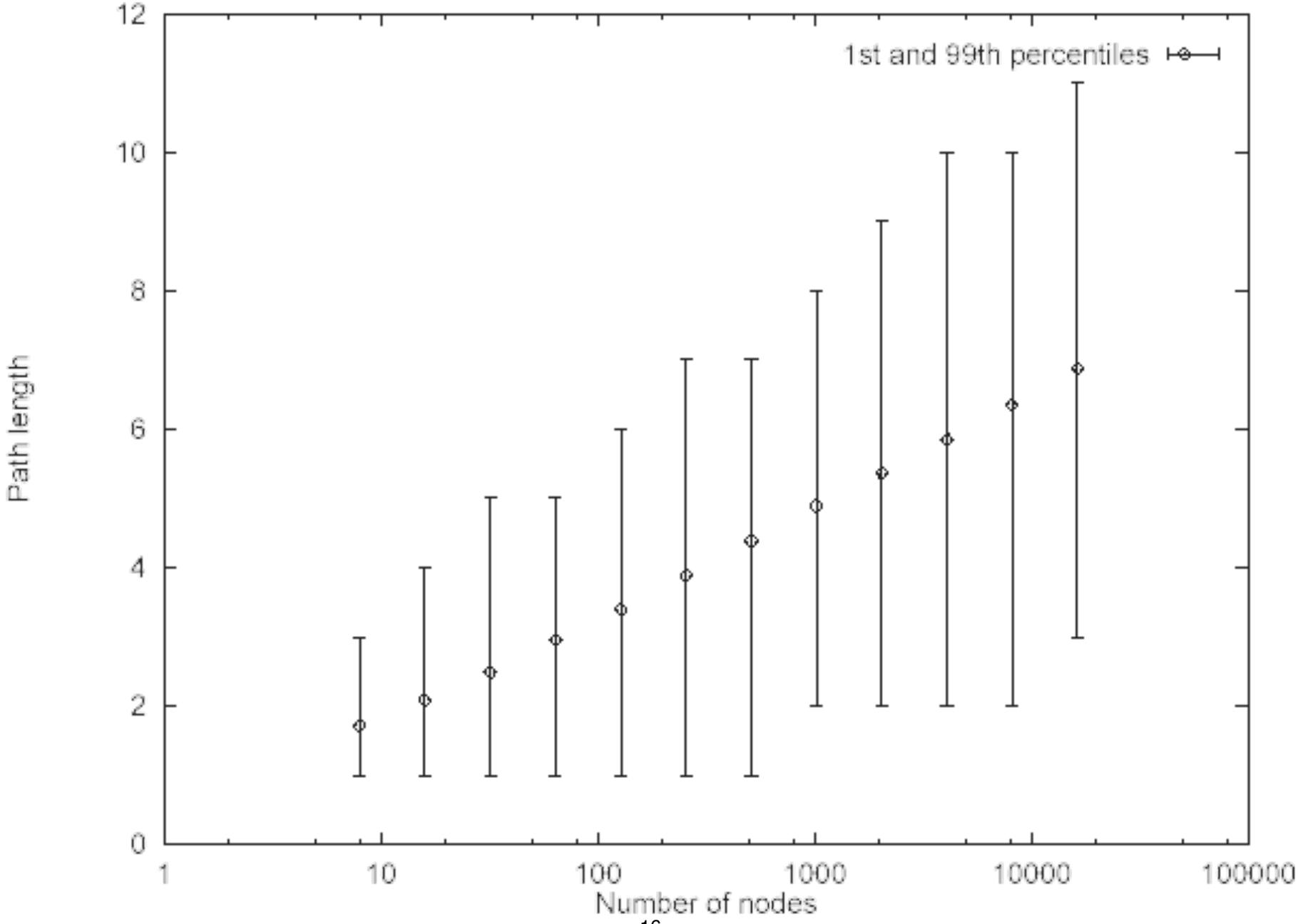
# Self organisation - new node arrival



# Self organisation - node failures

- **Chord maintains successor lists to cope with node failures**
  - node leaving could be viewed as a failure
  - if nodes leaves voluntarily, it may notify its successor and predecessor, allowing them to gracefully update their tables
  - otherwise, Chord can on demand use the successor lists to rebuild the information

# Results–Path Length/#Nodes



# Summary

- **Decentralised lookup of nodes responsible for storing keys**
  - based on distributed, consistent hashing
  - performance and space in O(log N) for stable networks
  - simple; provable performance and correctness
  - too simple; does not consider locality or strength of peers
    - though they do outline a solution using nearest (in IP space) nodes for finger tables rather than exact matches (in ID space)

# Overview

- Chord
- **Pastry**
- **Kademlia**
- **Conclusions**

# Pastry

- **Aim: Effective, distributed object location and routing substrate for P2P networks**
  - **Effective**: O(log N) routing hops
  - **Distributed**: no servers, routing and location distributed to nodes, only limited knowledge at nodes(routing tables size O(log N))
  - **Substrate**: not an application itself, rather it provides Application Program Interface (API) to be used by applications. Runs on all nodes joined in a Pastry network
  - Each node has a unique identifier (nodeId) (128 bits)

# Node Identifiers

- **Each node is assigned a 128 bit nodeId**
  - nodeIds are assumed to be uniformly distributed in the 128 bit ID space ⇒ numerically close nodeIds belong to diverse nodes
  - nodeId = cryptographic hash of node's IP address

# Assumptions and Guarantees

- Pastry can route to numerically closest node in $\log_{2^b} N$ steps (b is a configuration parameter)
- Unless |L|/2 (|L| being a configuration parameter) adjacent nodeIds fail concurrently, eventual delivery is guaranteed
  - such failure is *very* unlikely
- Join, leave in O(log N)
- Maintains locality based on application-defined scalar proximity metric

# Routing table

NodeId 10233102

Leaf set

| SMALLER | | LARGER | |
|---|---|---|---|
| 10233033 | 10233021 | 10233120 | 10233122 |
| 10233001 | 10233000 | 10233230 | 10233232 |

Routing table

| | | | |
|---|---|---|---|
| -0-2212102 | 1 | -2-2301203 | -3-1203203 |
| 0 | 1-1-301233 | 1-2-230203 | 1-3-021022 |
| 10-0-31203 | 10-1-32102 | 2 | 10-3-23302 |
| 102-0-0230 | 102-1-1302 | 102-2-2302 | 3 |
| 1023-0-322 | 1023-1-000 | 1023-2-121 | 3 |
| 10233-0-01 | 1 | 10233-2-32 | |
| 0 | | 102331-2-0 | |
| | | 2 | |

Neighborhood set

| | | | |
|---|---|---|---|
| 13021022 | 10200230 | 11301233 | 31301233 |
| 02212102 | 22301203 | 31203203 | 33213321 |

|L|/2 numerically closest smaller nodeIds

|L|/2 numerically closest larger nodeIds

ceiling($\log_{2^b} N$) rows with $2^b$-1 entries

each entry in row n shares a prefix of length n with the present node

nodes chosen according to proximetry metric

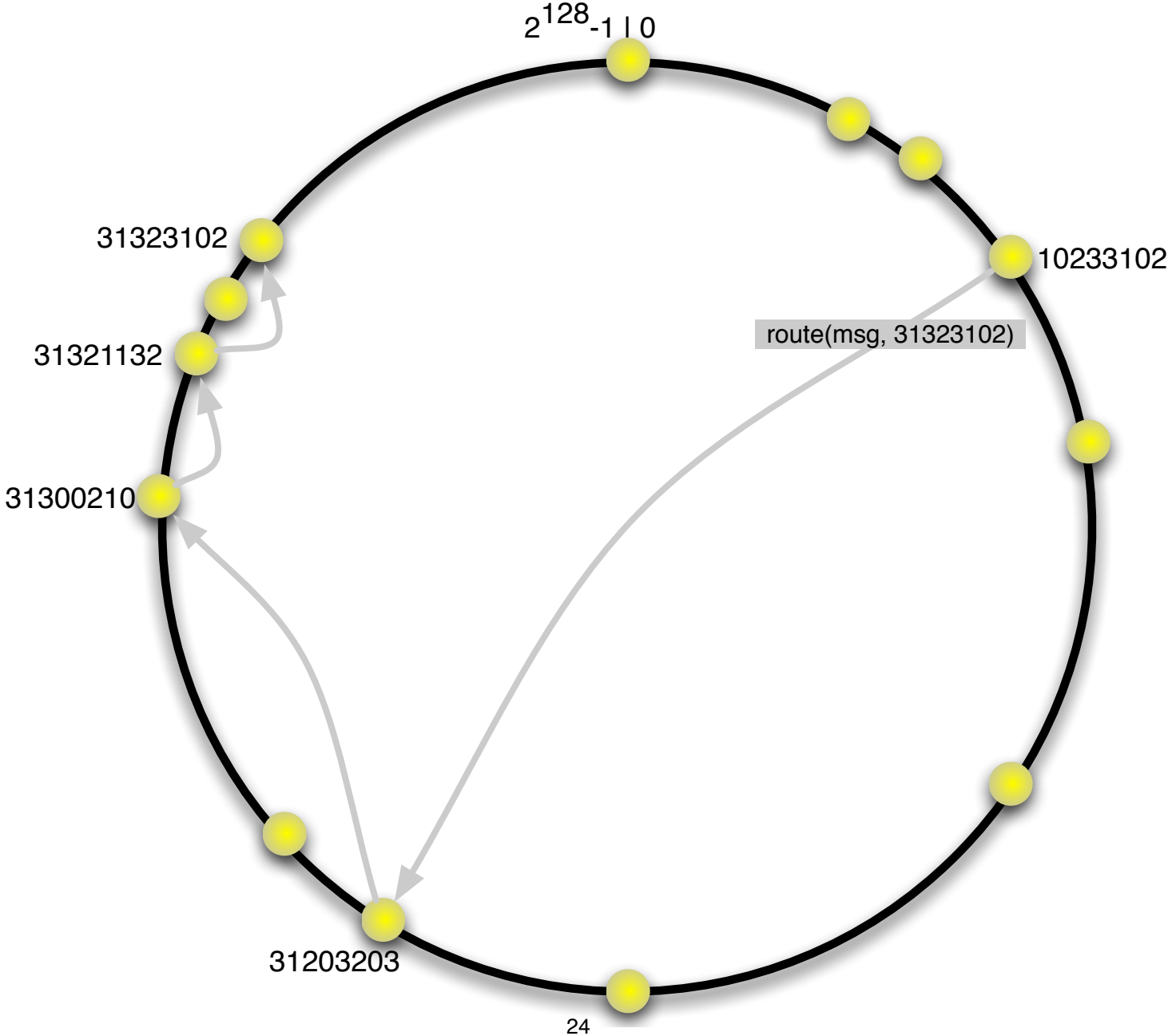
|M| closest nodes (according to proximetry metric)

b = 2; L = 8; M = 8

# Pastry routing

- **The node first checks if the key falls within the range of its leaf set. If yes, forward the message to the destination node.**
- **If not, use routing table to forward the message to a node that shares a common prefix with the key by at least one digit.**
- **In some rare cases, the appropriate entry is empty or unreachable, then the message will be forwarded to a known node**
  - that has a common prefix with the key at least as good as the local node (**and is numerically closer**)

# Routing in Pastry



# (Expected) Performance

1. Either: Destination one hop away
2. Or: The set of possible nodes with a longer prefix match is reduced by $2^b$ (i.e., one digit)
3. Or: Only one extra routing step is needed (with high probability)
   - given accurate routing tables, the probability for 3) is the probability that a node with the given prefix does not exist and that the key is not covered by the leaf set

# (Expected) Performance

- **Thus, expected performance is O(log N)**
  - The worst case routing step may be linear to N. (when many nodes fail simultaneously)
- **Eventual message delivery is guaranteed unless |L|/2 nodes with consecutive nodeIds fail simultaneously**
  - *highly* unlikely, as leafset nodes are widely distributed due to uniform hashing

# Self organisation – node arrival

- New node, X, needs to know existing, nearby node, A, (can be achieved using, e.g., multicast on local network)
- X asks A to route a “join” message with key equal to X
- Pastry routes this message to node Z with nodeId numerically closest to X
- All nodes en-route to Z returns their state to X

# Self organisation – node arrival

- X updates its state based on returned state:
  - neighbourhood set = neighbourhood set of A
  - leaf set is based on leaf set of Z (since Z has nodeId closest to nodeId of X)
  - rows of routing table are initialised based on rows of routing tables of nodes visited en-route to Z (since these share increasing common prefixes with X)
- X calibrates routing table and neighbourhood set based on data from the nodes referenced therein
- X sends its state to all the nodes mentioned in its leaf set, routing table, and neighbour list
- $O(\log_{2^b} N)$ messages exchanged

# Locality

- **Routing performance is based on small number of routing hops – and "good" locality of routing with respect to underlying network**
  - Pastry relies on a scalar proximity metric (e.g., number of IP routing hops, geographical distance, or available bandwidth)
- **Applications are responsible for providing proximity metrics**
- **Pastry assumes the triangle inequality holds**
- **Join protocol maintains locality invariant**

# Locality – Upon node arrival

- Assume the system holds locality property before the new node arrivals
- Assume A is actually near X, so the state updated from A should also hold the locality property
- The states updated from the routing path also tend to be close to X – at least in the beginning
  - as we progress, there will be fewer and fewer candidate nodes to choose from
- A second stage which updates node X's routing table with closer nodes is used to improve the locality property

# Self Organisation – Node Failure

- **Repair of leaf set**
  - contact the live node with the largest index on the side of the failed node and get leaf set from that node
  - returned leaf set will contain an appropriate node to insert
  - this works unless |L|/2 nodes with adjacent nodeIds have failed

# Self Organisation – Node Failure

- **Repair of routing table**
  - contact other node on the same row to check if this node has a replacement node (the contacted node may have a replacement node on the same row of its routing table)
  - if not, contact node on next row of routing table

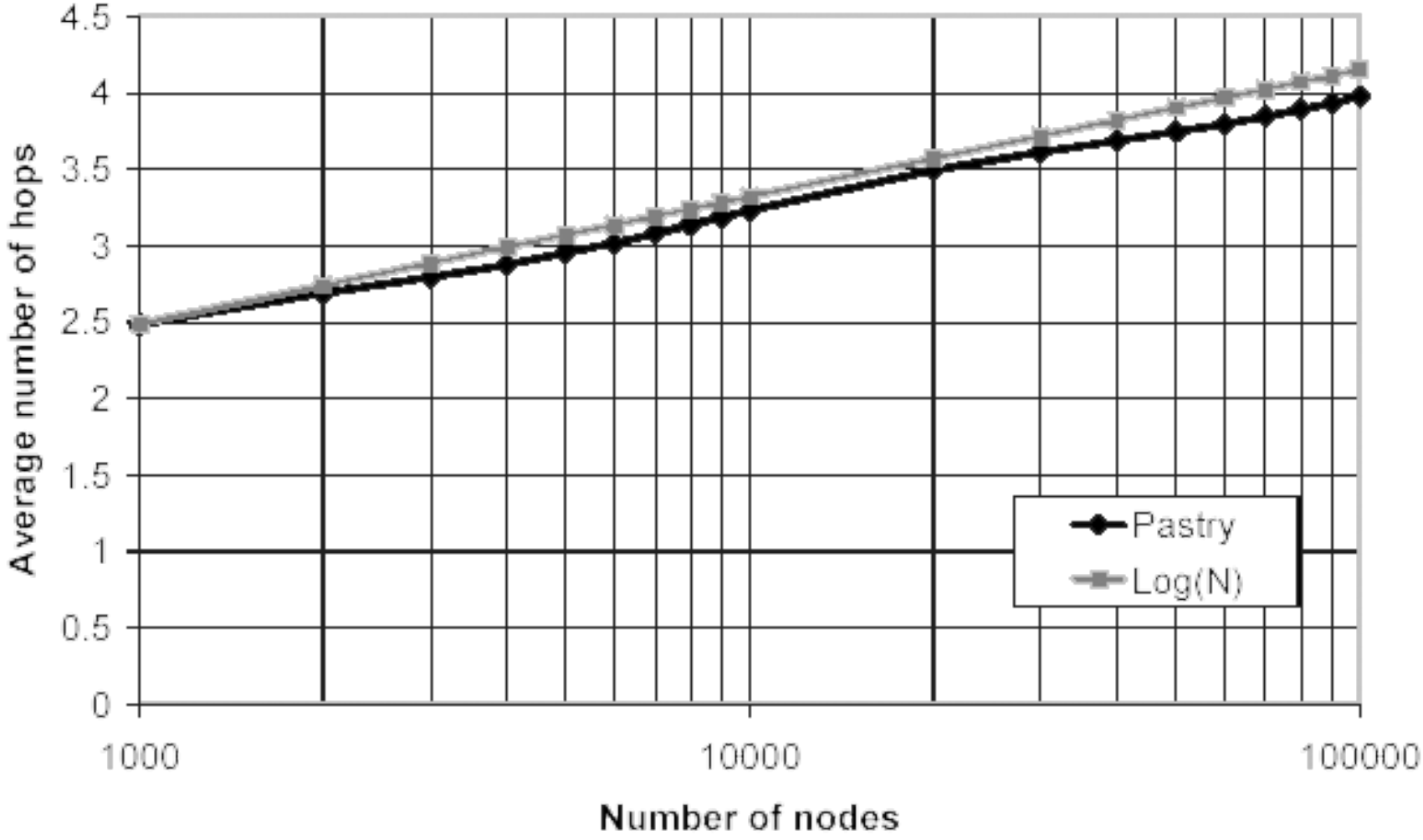
# Self Organisation – Node Failure

- **Repair of neighbourhood set**
  - neighbourhood set is normally not used in routing ⇒ contact periodically to check for liveness
  - if a neighbour is not responding, check with live neighbours for other close nodes

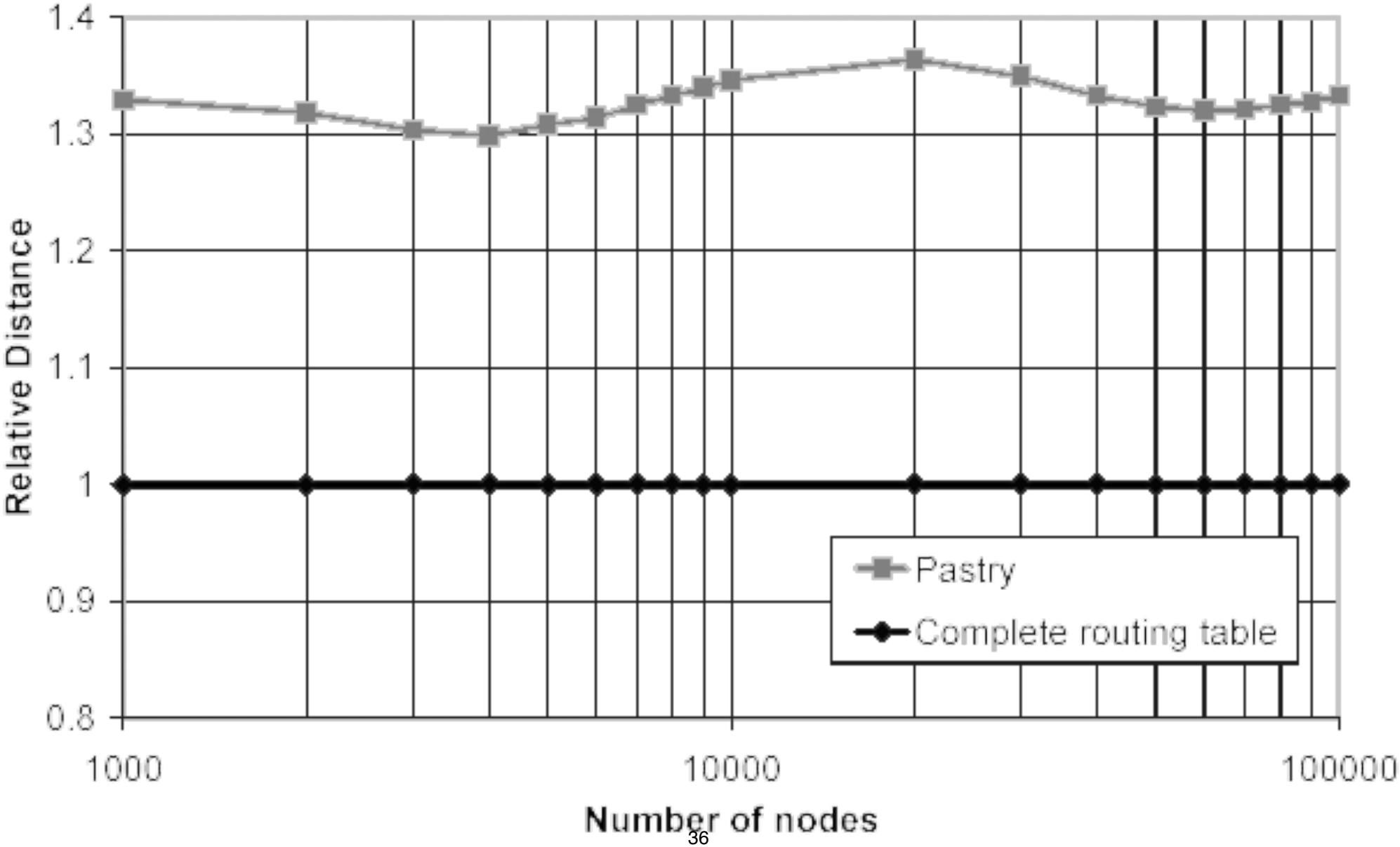
# Fault tolerance and malicious peers?

- **Choose *randomly* between nodes satisfying the criteria of the routing protocol**
- **A message can be forwarded to a node with longer common prefix or same common prefix but numerically closer**
  - randomly select a node from the nodes that satisfy the criterion described above
  - thus the routing is not deterministic, and it is possible to avoid bad nodes

# Routing Performance



# Routing Distance vs Optimal Routing



# Summary

- **Pastry is a P2P content location and routing substrate**
  - structured overlay network
  - usable for building various P2P application
- **Applications built on top of Pastry**
  - SCRIBE: group communication/event notification
  - PAST: archival storage
  - SQUIRREL: co-operative Web caching
- **Space and time requirements (expected) in O(log N), N = number of nodes in network**
- **Takes locality into account**

# Overview

- Chord
- Pastry
- **Kademlia**
- **Conclusions**

# Kademlia: A Peer-to-Peer Information System Based on the XOR Metric

- **Distributed Hash Table**
  - NodeIDs and keys based on SHA-1 (160 bits)
- **Routing done by halving the ID-space distance in each routing step**
  - Similar to Pastry's routing table routing (prior to leaf node)
- **Routing done in O(log N), space used O(log N)**

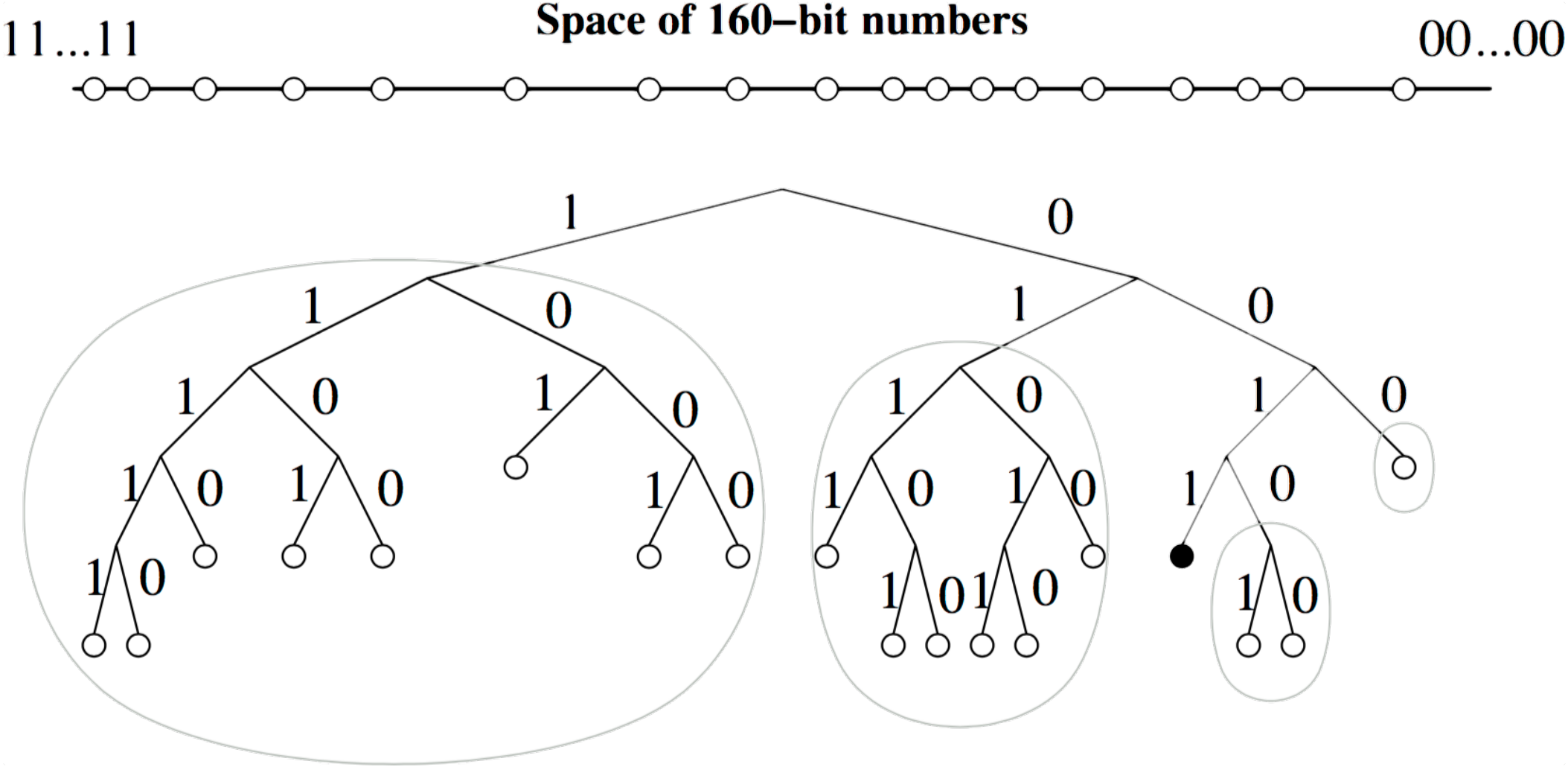
# Critique of other systems

- **Chord**
  - Finger tables only forward looking
  - I.e., messages arriving at a peer tell it nothing useful – knowledge must be gained explicitly
  - Separate track of control message exchanges
  - Rigid routing structure
  - Locality difficult to establish
- **Pastry**
  - Complex routing algorithm
  - First routing table, then leaf set
  - Maintains three different tables: leaf, routing and neighbour

# Aspects of Kademlia

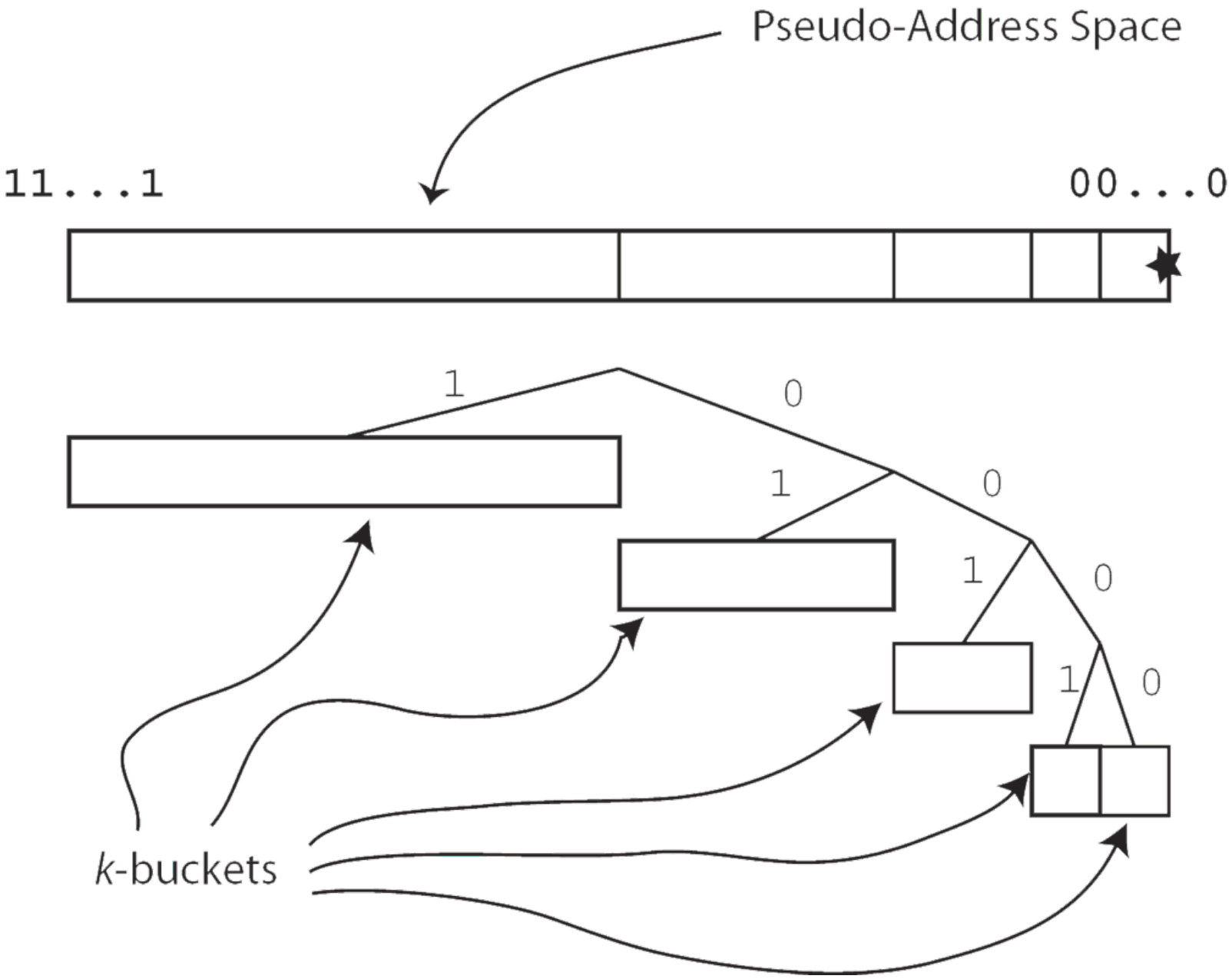
- **All IDs are 160 bits long, random or found with SHA-1**
  - i.e., uniform distribution, etc
- **To navigate this key space, Kademlia uses XOR**
  - $d(X, Y) = X \text{ XOR } Y$; $d(X, Y) = d(Y, X)$
  - intuition: higher order difference = longer distance
- **A Kademlia routing table stores 160 k-buckets**
  - the $i^{th}$ k-bucket contains nodes within a XOR distance of $2^i$ to $2^{i+1}$ from itself (so the $i^{th}$ bit is significant)
  - up to k nodes in each bucket, ordered by liveness (most recently seen at tail)
    - thus, once again, more complete knowledge of 'close' peers, but still knowledge about the rest of the world

# Kademlia routing table

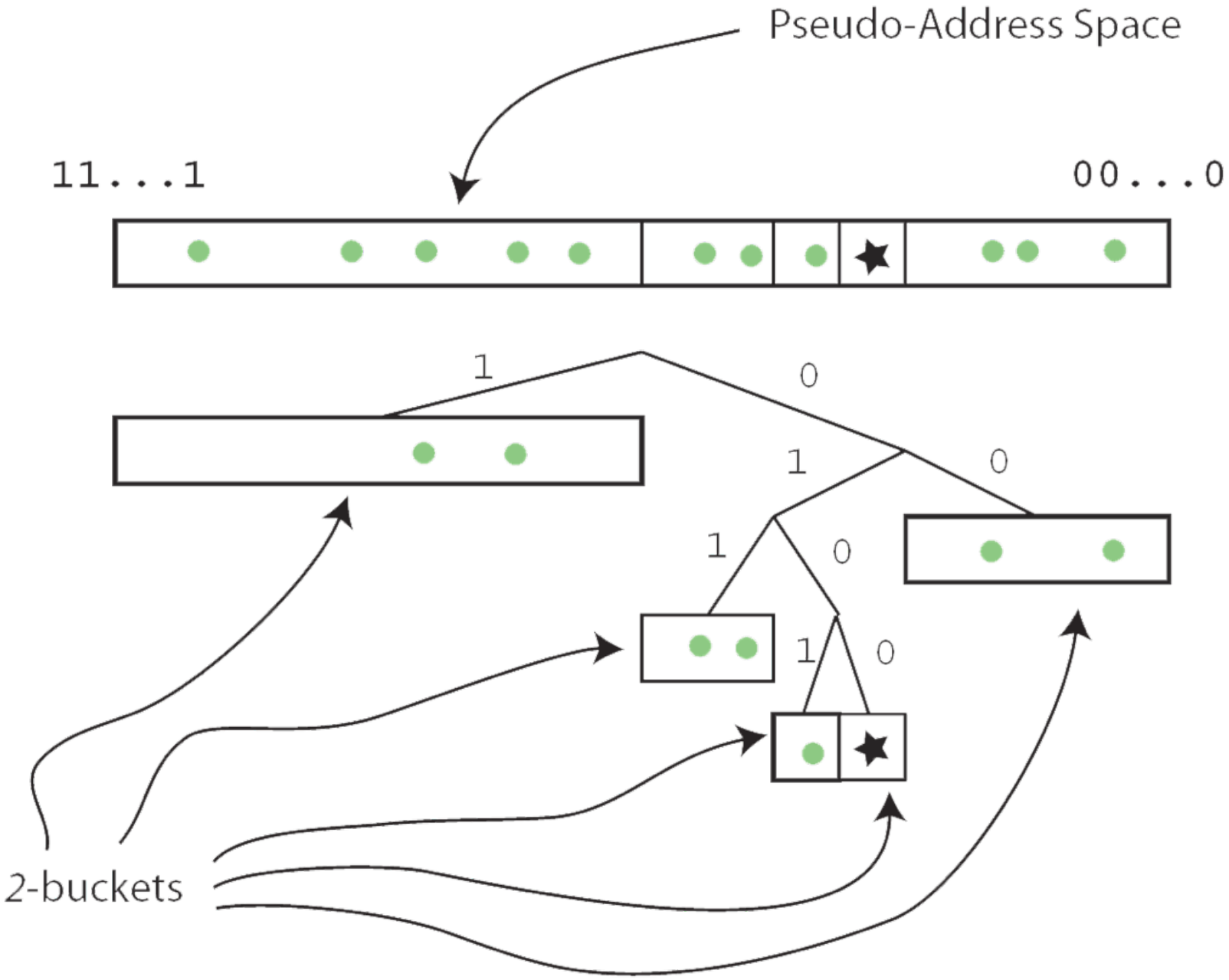



- **Peer 0011 (•) must know some peers in the highlighted groups — all different prefixes to itself**

# Kademlia routing table



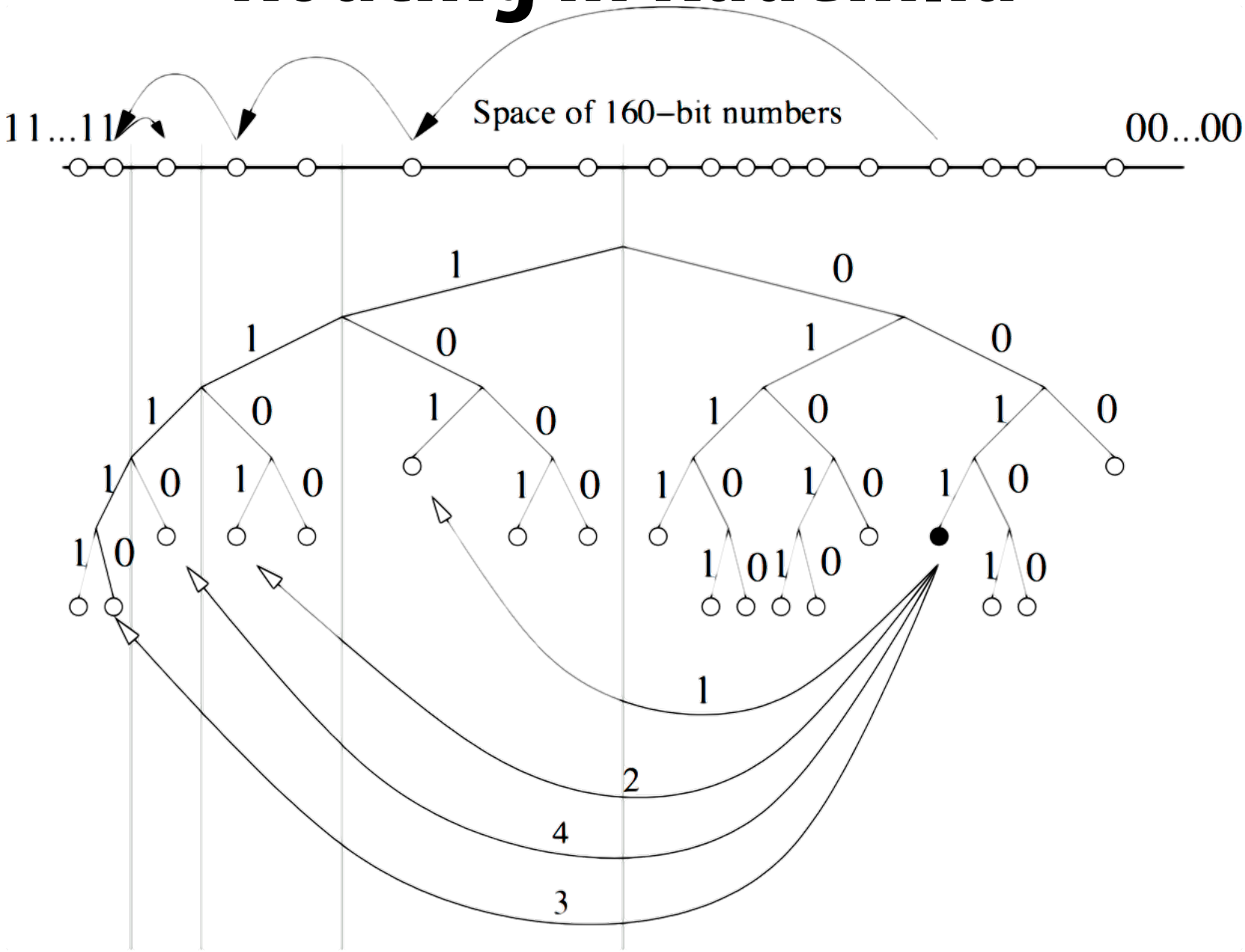
# Kademlia routing table



# Locating a destination

- Given a destination, use the (XOR) distance from ourselves to find the matching k-bucket
- Contact nodes in that k-bucket to get even closer nodes
  - if there are not enough nodes in the bucket, use the nearest
- Repeat until the k closest nodes have been found

# Routing in Kademlia




- Reaching 1110 from 0011. 0011 knows initially 101

# Operations in Kademlia

- **PING**
- **STORE**
- **FIND_NODE**
- **FIND_VALUE**

# FIND_NODE

- **FIND_NODE$_n$(id)**
  - returns the k closest nodes to an ID that n knows
- **Iterative process:**
  - $n_0$ = origin
  - $N_1$ = FIND_NODE$_{n_0}$(ID)
  - $N_2$ = FIND_NODE$_{n_1}$(ID)
  - …
  - $N_m$ = FIND_NODE$_{n_{m-1}}$(ID)
- **The node can choose any peer among the returned k nodes for the next step**
- **Lookup terminates when k closest nodes have responded**

# FIND_VALUE

- **FIND_VALUE$_n$(key)**
  - works like FIND_NODE, unless n knows the value in which case the value is returned
  - if one of the k closest nodes does not have the value, the requester will store it there

# Maintaining routing tables

- **Upon communication with another node**
  - Check the appropriate k-bucket
    - if already there, move to tail
    - if there is room, insert at tail
    - if new, and least recently seen node is unresponsive, replace with new node (and move to tail)
    - else: ignore node
  - Thus, the routing tables are populated, and old, active nodes are given preferential treatment
  - Implementation optimization: keep new peers in cache replacement list; replace only member of k-bucket if unresponsive during normal operations

# Maintaining routing tables

- **Why prefer old nodes?**
  - Studies show that the longer a peer *stays* online, the higher the probability is that it will *remain* online
  - Makes it difficult to flood the network with bogus peers
- **As SHA-1 is uniform, a Kademlia node will receive messages from nodes with IDs uniformly distributed across the key space**
  - Thus, all traffic is valuable and increase knowledge

# Parallelism in Kademlia

- At each step in the lookup process, `FIND_NODE`/`FIND_VALUE` queries α nodes in parallel
- The node can then choose the quickest peer and move on
- Ensures locality and takes advantages of the strongest peers
- The system does not have to wait until a node times out as with other systems

# Redundancy in Kademlia

- Each (key, value) pair is republished every hour and stored at k locations close to the key
- (key, value) expires after 24 hours, so old data is flushed
- But, original publisher republishes (key, value) every 24 hour, so valuable information is maintained
- Whenever a peer A observes a new peer B with ID closer to some of A's keys, A will replicate these keys to B

# Joining the network

- Compute an ID
- (Somehow) locate a peer in the network
- Add that peer to the appropriate k-bucket
- Find neighbours by doing `FIND_NODE` on own ID
- Populate the other k-buckets by performing `FIND_NODE`
- This process (due to the reflected nature of Kademlia) ensures that the new peer is known across the network

# Failure in Kademlia

- Unlikely: Routing tables are continually refreshed due to ordinary traffic
- As SHA-1 is uniform, the k-buckets will be evenly updated
- If there is no traffic, a peer will regularly explicitly refresh oldest k-bucket
- Parallelism in queries ensures that a failing peer is
  - detected
  - routed around

# Use of Kademlia

- **Kademlia is fairly widespread for file sharing purposes**
  - eDonkey2000, Overnet, eXeem, Kad
  - a number of BitTorrent clients use Kademlia to locate peers if the original tracker fails
  - IPFS uses an extended version of Kademlia, Coral DSHT
- **Files are stored using a hash of their contents**
- **File names**
  - are divided into keywords
  - the network stores (SHA-1(keyword), (file name, file hash)) for each keyword

# Summary

- Built on the experiences from earlier structured networks
- Ensures high performance through parallelism
- All traffic contributes to routing table upkeep
- In widest use of all structured networks

# Overview

- Chord
- Pastry
- Kademlia
- **Conclusions**

# Structured P2P: A Summary

- **"First generation"**
  - Largely application-specific
  - Few guarantees – worst case O(N)
  - Well suited for "fuzzy" searches
  - No particular overhead
- **"Second generation"**
  - Based on structured network overlays
  - Typically expected O(log N) time and space requirements
    - *...at the cost of overhead for maintaining network*
  - Usually, no "fuzzy" searches – this is exact matches only
    - *. . . but sometimes exact is good enough*
  - . . . *unless* we create an appropriate ID space for keyword matching!

# Conclusions

- **Scalability**
  - Much more scalable than unstructured P2P networks measured in number of hops for routing
  - However, churn results in control traffic; slow peers can slowdown entire system (especially in Chord); weak peers may be overwhelmed by control traffic
- **Fairness**
  - The load is evenly distributed across the network, based on the uniformness of the ID space
  - More powerful peers can choose to host several virtual peers

# Conclusions

- **Integrity and security**
  - Most systems have various provisions for maintaining proper routing and defending against malicious peers
  - A backhoe is unlikely to take out a major part of the system – at least if we store at k closest nodes
- **Anonymity, deniability, censorship resistance**
  - If we have the key, it is trivial to locate the matching hosts