Peer-to-Peer Systems

DHT examples, part 2
(Pastry, Tapestry and Kademlia)

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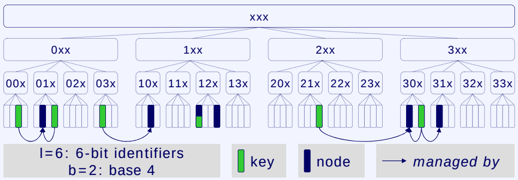
Plaxton routing

- Plaxton, Rajamaran and Richa: mechanism for efficient dissemination of objects in a network, published in 1997
  - Before P2P systems came about!
- Basic idea: prefix-oriented routing (fixed number of nodes assumed)
  - Object with ID A is stored at the node whose ID has the longest common prefix with A
    - If multiple such nodes exist, node with longst common suffix is chosen
  - Goal: uniform data dissemination
  - Routing based on pointer list (object - node mapping) and neigbor list (primary + secondary neighbors)
  - Generalization of routing on a hypercube
- Basis for well known DHTs Pastry, Tapestry (and follow-up projects)
  - Method adapted to needs of P2P systems + simplified

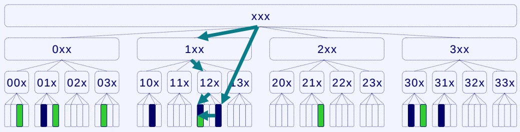
Pastry: Topology

- Identifier space:
  - 2^l-bit identifiers (typically: l = 128), wrap-around at 2^l - 1 ↔ 0
  - interpret identifiers to the base of 2^b (typically: b = 4, base 16)
  - prefix-based tree topology
  - leaves can be *keys* and *node IDs*
  - (key, value) pairs managed by numerically closest node



Pastry: Routing Basics

- Goal: find node responsible for k, e.g. 120
- Tree-based search for lookup(k)
  - Traverse tree search structure top-down
- Prefix-based routing for lookup(k)
  - Approximate tree search in distributed scenario
  - Forward query to known node with longest prefix matching k



Pastry: Routing Basics /2

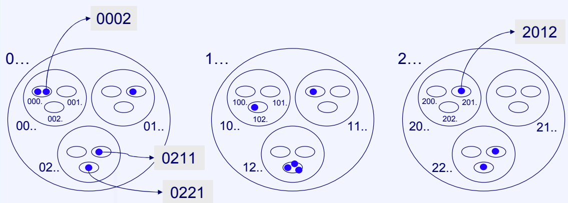
- Routing in Pastry:
  - In each routing step, query is routed towards "numerically" closest node
    - That is, query is routed to a node with a one character longer prefix (= b Bits)

    → $O(\log_{2^b} N)$ routing steps
  - If that is not possible:
    - route towards node that is numerically closer to ID

Destination: (b = 2)	012321
Start	321321
1. Hop	022222
2. Hop	013331
3. Hop	012110
4. Hop	012300
5. Hop	012322
Destination:	012321

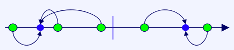
Pastry: Routing Basics /3

- Example:
  - Node-ID = 0221
  - Base = 3 (not power of 2, because it is easier to draw ;-))



Pastry: Routing Basics /4

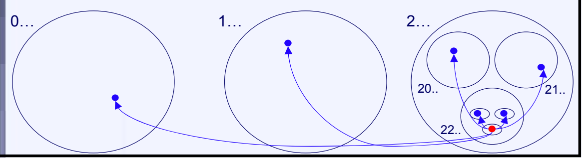
- Data (key-value-pairs) are managed in numerically closest node
  - keys → nodes:
    0002 →0002, 01** →0110



- Linking between Prefix-areas:
  - Nodes within a certain prefix area know IP addresses of each other
  - Each node in a prefix area knows one or more nodes from another prefix area
- From which prefix areas should a node know other nodes?
  - Links to shorter-prefix node areas on each prefix level

Pastry: Routing Basics /5

- Example:
  - Node in area 222* knows nodes from prefix areas 220*, 221* & 20**, 21** & 0***, 1***
  - Logarithmic number of links:
    - For prefix-length p: (base-1) links to other nodes with prefix length p, but with a different digit at position p
    - l/b different prefix-lengths: l ~ log(N)



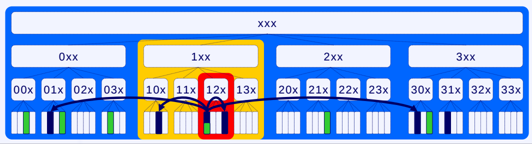
Pastry: Routing Information

- Challenges
  - Efficiently distribute search tree among nodes
  - Honor network proximity
- Pastry routing data per node
  - Routing table
    - Long-distance links to other nodes
  - Leaf set
    - Numerically close nodes
  - Neighborhood set
    - Close nodes based on proximity metric (typically ping latency)

Pastry: Routing Table

- Routing table
  - Long distance links to other prefix realms
  - l/b rows: one per prefix length
  - 2^b-1 columns: one per digit different from local node ID
  - Routing table for node 120:

?xx:	011	**1**	-	301
1?x:	102	-	**2**	-
12?:	**0**	-	-	123



Pastry: Routing Table

- $\lceil \log_{2^b} N \rceil$ rows with 2^b-1 entries each
  - row i: hold IDs of nodes whose ID share an i-digit prefix with node
  - column j: digit(i+1) = j
  - Contains topologically closest node that meets these criteria
- Example: b=2, Node-ID = 32101

Digit at position i+1

Shared prefix length with Node-ID

i \ j	0	1	2	3
0	01230	13320	22222	--
1	30331	31230	--	33123
2	32012	--	32212	32301
3	--	32110	32121	32131
4	32100	--	32102	32103

These entries match node 32101's ID

Topologically closest node with prefix length i and digit(i+1)=j

Possible node: **33**xyz
33123 is topologically closest node

Pastry: Routing Information

- Leaf set
  - contains numerically closest nodes (l/2 smaller and l/2 larger keys)
  - fixed maximum size
  - similar to Chord's succ/pred list
  - for routing and recovery from node departures

Node-ID = 32101

Smaller Node-IDs		higher Node-IDs	
32100	32023	32110	32121
32012	32022	32123	32120

- Neighbor set
  - contains *nearby* nodes
  - fixed maximum size
  - scalar proximity metric assumed to be available
    - e.g., IP hops, latency
  - irrelevant for routing
  - 'cache' of nearby candidates for routing table

Pastry Routing Algorithm

- Routing of packet with destination K at node N:
  1. Is K in Leaf Set, route packet directly to that node
  2. If not, determine common prefix (N, K)
  3. Search entry T in routing table with prefix (T, K) > prefix (N, K), and route packet to T
  4. If not possible, search node T with longest prefix (T, K) out of merged set of routing table, leaf set, and neighborhood set and route to T
     - This was shown to be a rare case
- Access to routing table O(1), since row and column are known
- Entry might be empty if corresponding node is unknown

Pastry: Routing Procedure

- Long-range routing
  - if key *k* not covered by leaf set:
  - forward query for *k* to
    - node with longer prefix match than self or
    - same prefix length but numerically closer

Node 103220

?xxxxx:	031120	1	201303	312201
1?xxxx:	0	110003	120132	132012
10?xxx:	100221	101203	102303	3
103?xx:		103112	2	103302
1032?x:		103210	2	
10322?:	0			
leaf set	103123	103210	103302	103330

lookup(102332)

→ 102303

Pastry: Routing Procedure

- Close-range routing
  - *k* covered by nodes IDs in leaf set
  - pick leaf node n_L numerically closest to *k*
  - n_L must be responsible for k → last step in routing procedure
  - return n_L as answer to query for *k*

Node 103220

?xxxxx:	031120	1	201303	312201
1?xxxx:	0	110003	120132	132012
10?xxx:	100221	101203	102303	3
103?xx:		103112	2	103302
1032?x:		103210	2	
10322?:	0			
leaf set	103123	103210	103302	103330

lookup(103312)

103302

Another example

Key = 01200
Common prefix:
32101
01200

0----

Key = 32200
Common prefix:
32101
32200

322--

Key = 33122
Common prefix:
32101
33122

33---

Key = 32102
Node is in range of Leaf-Set

Node-ID = 32101

i j	0	1	2	3
0	01234	14320	22222	--
1	30331	31230	--	33123
2	32012	--	32212	32301
3	--	32110	32121	32131
4	32100	--	32102	32103

Routing table

< Node-ID		> Node-ID	
32100	32023	32110	32121
32012	32022	32123	32120

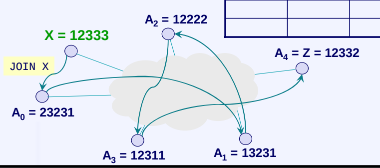
Leaf set

Arrival of a new node

- Node X wants to join Pastry DHT
  - Determine NodeID of X → 12333 (hash of IP address)
  - Initialize tables at node X
  - Send JOIN message to key 12333 via topologically nearest Pastry node
  - Node currently in charge of this key: z

i \ j	0	1	2	3
0				
1				
2				
3				
4				

< Node-ID		> Node-ID	



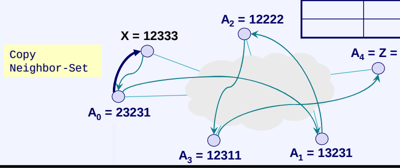
Arrival of a new node /2

- Node X wants to join Pastry DHT
  - Node X copies Neighbor-Set from node A0

32022	12300	01213	32123
00100	11001	21021	11213

i \ j	0	1	2	3
0				
1				
2				
3				
4				

< Node-ID		> Node-ID	



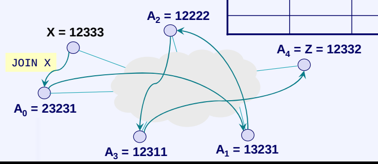
Arrival of a new node /3

- Node X wants to join Pastry DHT
  - Node A0 routes message to node Z
  - Each node sends row in routing table to X
  - Here A0

32022	12300	01213	32123
00100	11001	21021	11213

i \ j	0	1	2	3
0	02231	13231		32331
1				
2				
3				
4				

< Node-ID		> Node-ID	



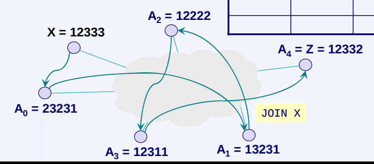
Arrival of a new node /4

- Node X wants to join Pastry DHT
  - Node A0 routes message to node Z
  - Each node sends row in routing table to X
  - Here A1

32022	12300	01213	32123
00100	11001	21021	11213

i \ j	0	1	2	3
0	02231	13231		32331
1	10122	11312	12222	
2				
3				
4				

< Node-ID		> Node-ID	



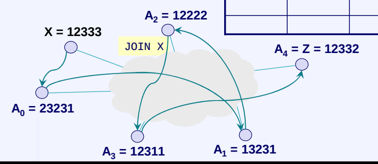
Arrival of a new node /5

- Node X wants to join Pastry DHT
  - Node A0 routes message to node Z
  - Each node sends row in routing table to X
  - Here A2

32022	12300	01213	32123
00100	11001	21021	11213

i \ j	0	1	2	3
0	02231	13231		32331
1	10122	11312	12222	
2	12033	12111		12311
3				
4				

< Node-ID		> Node-ID	



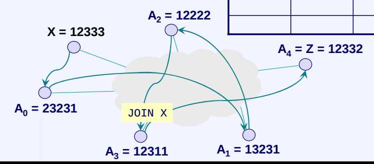
Arrival of a new node /6

- Node X wants to join Pastry DHT
  - Node A0 routes message to node Z
  - Each node sends row in routing table to X
  - Here A3

32022	12300	01213	32123
00100	11001	21021	11213

i \ j	0	1	2	3
0	02231	13231		32331
1	10122	11312	12222	
2	12033	12111		12311
3	12301		12320	12332
4				

< Node-ID		> Node-ID	



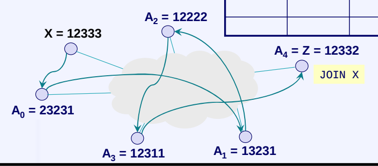
Arrival of a new node /7

- Node X wants to join Pastry DHT
  - Node A0 routes message to node Z
  - Each node sends row in routing table to X
  - Here A4

32022	12300	01213	32123
00100	11001	21021	11213

i \ j	0	1	2	3
0	02231	13231		32331
1	10122	11312	12222	
2	12033	12111		12311
3	12301		12320	12332
4	12330	12331		12333

< Node-ID		> Node-ID	



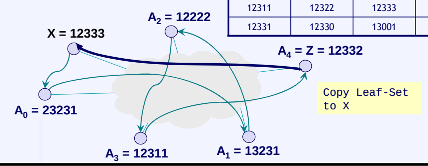
Arrival of a new node /8

- Node X wants to join Pastry DHT
  - Node Z copies its Leaf-Set to Node X

32022	12300	01213	32123
00100	11001	21021	11213

i \ j	0	1	2	3
0	02231	13231	-	32331
1	10122	11312	12222	-
2	12033	12111	-	12311
3	12301	-	12320	12332
4	12330	12331	-	12333

< Node-ID		> Node-ID	
12311	12322	12333	13000
12331	12330	13001	13003



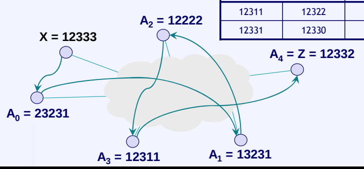
Arrival of a new node /9

- Some entries are doubtable
  - Entries pointing to "own-ID-positions" not required
- Some are missing
  - Take the node-IDs just visited

32022	12300	01213	32123
00100	11001	21021	11213

i \ j	0	1	2	3
0	02231	--	23231	32331
1	10122	11312	--	13231
2	12033	12111	12222	--
3	12301	12311	12320	--
4	12330	12331	12332	--

< Node-ID		> Node-ID	
12311	12322	12333	13000
12331	12330	13001	13003



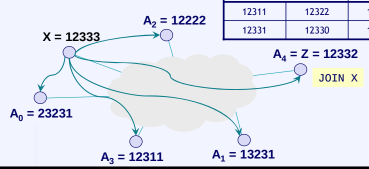
Arrival of a new node /10

- Node X wants to join Pastry DHT
  - Node x sends its routing table to each neighbor

32022	12300	01213	32123
00100	11001	21021	11213

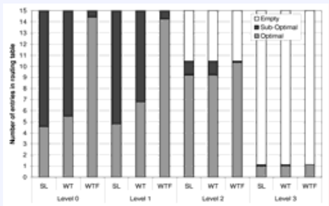
i \ j	0	1	2	3
0	02231		23231	32331
1	10122	11312		13231
2	12033	12111	12222	
3	12301	12311	12320	
4	12330	12331	12332	

< Node-ID		> Node-ID	
12311	12322	12333	13000
12331	12330	13001	13003



Arrival of a new node /11

- Efficiency of initialization procedure
  - Quality of routing table (b=4, l=16, 5k nodes)



SL: transfer only the i[th] routing table row of A_i

WT: transfer of i[th] routing table row of A_i as well as analysis of leaf and neighbor set

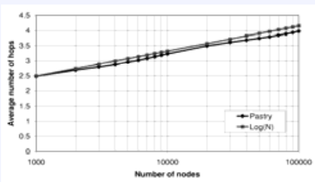
WTF: same as WT, but also query the newly discovered nodes from WT and analyse data

Failure of Pastry Nodes

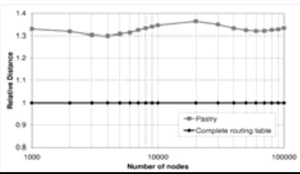
- Detection of failure
  - Periodic verification of nodes in Leaf Set
    - "Are you alive" also checks capability of neighbor
  - Route query fails
- Replacement of corrupted entries
  - Leaf-Set
    - Choose alternative node from Leaf (L) ∪ Leaf (±|L|/2)
    - Ask these nodes for their Leaf Sets
  - Entry $R_{x\,y}$ in routing table failed:
    - Ask neighbor node $R_{x\,i}$ (i≠y) of same row for route to $R_{x\,y}$
    - If not successful, test entry $R_{x{+}{+}\,i}$ in next row

Performance Evaluation

- Routing Performance
  - Number of Pastry hops (b=4, l=16, 2·10⁵ queries
  - O(log N) for number of hops in the overlay



  - Overhead of overlay
    (in comparison to route between two node in the IP network)
  - But:
    Routing table has only O(log N) entries instead of O(N)



Summary Pastry

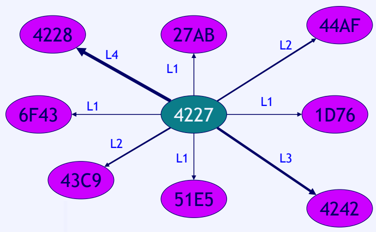
- Complexity:
  - O(log N) hops to destination
    - Often even better through Leaf- and Neighbor-Set: $O(\log_{2^b} N)$
  - O(log N) storage overhead per node
- Good support of locality
  - Explicit search of close nodes (following some metric)
- Used in many applications
  - PAST (file system), Squirrel (Web-Cache), …
  - Many publications available, open source implementation: FreePastry

Tapestry

- Tapestry developed at UC Berkeley
  - Different group from CAN developers
- Tapestry developed in 2000, but published in 2004
  - Originally only as technical report, 2004 as journal article
- Many follow-up projects on Tapestry
  - Example: OceanStore
- Like Pastry, based on work by Plaxton et al.
- Pastry was developed at Microsoft Research and Rice University
  - Difference between Pastry and Tapestry minimal
  - Tapestry and Pastry add dynamics and fault tolerance to Plaxton network

Tapestry: Routing Mesh

- (Partial) routing mesh for a single node 4227
  - Neighbors on higher levels match more digits

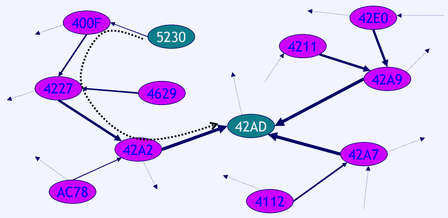


Tapestry: Neighbor Map for 4227

Level	1	2	3	4	5	6	8	A
1	1D76	27AB			51E5	6F43		
2			43C9	44AF				
3								42A2
4							4228	

- There are actually 16 columns in the map (base 16)
- Normally more entries would be filled (limited by a constant)
- Tapestry has multiple neighbor maps

Tapestry: Routing Example

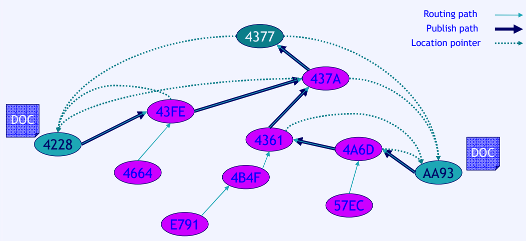


- Route message from 5230 to 42AD
- Always route to node closer to target
  - At n^{th} hop, look at $n+1^{th}$ level in neighbor map --> "always" one digit more
- Not all nodes and links are shown

Tapestry: Properties

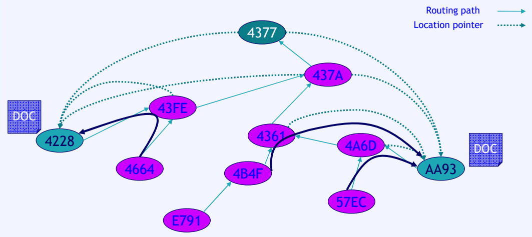
- Node responsible for objects which have the same ID
  - Unlikely to find such node for every object
  - Node also responsible for "nearby" objects (surrogate routing, see below)
- Object publishing
  - Responsible nodes only store pointers
    - Multiple copies of object possible
    - Each copy must publish itself
  - Pointers cached along the publish path
  - Queries routed towards responsible node
  - Queries "often" hit cached pointers
    - Queries for same object go (soon) to same nodes
- Note: Tapestry focuses on storing objects
  - Chord and CAN focus on values, but in practice no difference

Tapestry: Publishing Example



- Two copies of object "DOC" with ID 4377 created at AA93 and 4228
- AA93 and 4228 publish object DOC, messages routed to 4377
  - Publish messages create location pointers on the way
- Any subsequent query can use location pointers

Tapestry: Querying Example



- Requests initially route towards 4377
- When they encounter the publish path, use location pointers to find object
- Often, no need to go to responsible node
- Downside: Must keep location pointers up-to-date

Tapestry: Making It Work

- Previous examples show a Plaxton network
  - Requires global knowledge at creation time
  - No fault tolerance, no dynamics
- Tapestry adds fault tolerance and dynamics
  - Nodes join and leave the network
  - Nodes may crash
  - Global knowledge is impossible to achieve
- Tapestry picks closest nodes for neighbor table
  - Closest in IP network sense (= shortest RTT)
  - Network distance (usually) transitive
    - If A is close to B, then B is also close to A
  - Idea: Gives best performance

Tapestry: Fault-Tolerant Routing

- Tapestry keeps mesh connected with keep-alives
  - Both TCP timeouts and UDP "hello" messages
  - Requires extra state information at each node
- Neighbor table has backup neighbors
  - For each entry, Tapestry keeps 2 backup neighbors
  - If primary fails, use secondary
    - Works well for uncorrelated failures
- When node notices a failed node, it marks it as invalid
  - Most link/connection failures short-lived
  - Second chance period (e.g., day) during which failed node can come back and old route is valid again
  - If node does not come back, one backup neighbor is promoted and a new backup is chosen

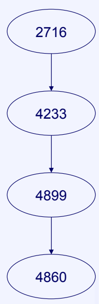
Tapestry: Fault-Tolerant Location

- Responsible node is a single point of failure
- Solution: Assign multiple roots per object
  - Add "*salt*" to object name and hash as usual
  - Salt = globally constant sequence of values (e.g., 1, 2, 3, …)
- Same idea as CAN's multiple realities
- This process makes data more available, even if the network is partitioned
  - With s roots, availability is $P \approx 1 - (1/2)^s$
  - Depends on partition
- These two mechanisms "guarantee" fault-tolerance
  - In most cases :-)
  - Problem: If the only out-going link fails…

Tapestry: Surrogate Routing

- Responsible node is node with same ID as object
  - Such a node is unlikely to exist
- Solution: surrogate routing
- What happens when there is no matching entry in neighbor map for forwarding a message?
  - Node (deterministically) picks next entry in neighbor map
    - If that one also doesn't exist, next of next … and so on
- Idea: If "missing links" are deterministically picked, any message for that ID will end up at same node
  - This node is the surrogate
- If new nodes join, surrogate may change
  - New node is neighbor of surrogate

Surrogate Routing Example



Peer 2716 searches for 4666:

Level 1, current digit j =4

Level 2, j=6 doesn't exist, next link: j=8

Level 3, j=6

Node 4860 doesn't have any level 4 neighbors => done

Tapestry: Performance

- Messages routed in $O(\log_b N)$ hops
  - At each step, we resolve one more digit in ID
  - N is the size of the namespace (e.g, SHA-1 = 40 digits)
  - Surrogate routing adds a bit to this, but not significantly
- State required at a node is $O(b \log_b N)$
  - Tapestry has c backup links per neighbor, $O(cb \log_b N)$
  - Additionally, same number of backpointers

Complexity comparison of DHTs so far

	CAN	Chord	Pastry	Tapestry
States per node	O(D)	O(log N)	O(log N)	O(log N)
Pathlength (Routing)	$O(\frac{D}{4} N^{\frac{1}{D}})$	O(log N)	O(log N)	O(log N)
Join of node	$O(DN^{\frac{1}{D}})$	$O(\log^2 N)$	O(log N)	O(log N)
Leave of node	?	$O(\log^2 N)$	?	?

Kademlia

- From New York University, 2002; used in eMule, Overnet, Azureus, …
- Routing idea similar to Plaxton's mesh: improve closeness one bit at a time
  - Nodes and Keys are mapped to m-bit binary strings
  - Distance between two identifiers: the XOR string, as a binary number

x = 0 1 0 1 1 0
y = 0 1 1 0 1 1
$x \otimes y$ = 0 0 1 1 0 1
d(x,y) = 13

  - If x and y agree in the first i digits and disagree in the (i+1) then $2^i \le d(x,y) \le 2^{i+1}-1$

x = 0 1 0 1 1 0
y = 0 1 1 1 1 0
$x \otimes y$ = 0 0 1 0 0 0
d(x,y) = 8

x = 0 1 0 1 1 0
y = 0 1 1 0 0 1
$x \otimes y$ = 0 0 1 1 1 1
d(x,y) = 15

Kademlia - Routing table

- Each node with ID x stores m k-buckets
  - a k-bucket stores k nodes that are at distance $[2^i, 2^{i+1}-1]$
    - K-buckets are ordered lists: least-recently used (LRU) at the end
    - default k: 20
    - empty bucket if no nodes are known
- Tables (k-buckets) are updated when lookups are performed
  - Query comes from node already in k-bucket: move entry to the end
  - Query comes from new node and k-bucket not full: add node at the end
  - Query comes from new node and k-bucket full: LRU node is removed
- Due to XOR symmetry a node receives lookups from the nodes that are in its own table
- Node Joins
  - contact a participating node and insert it in the appropriate bucket
  - perform a query for your own ID
  - refresh all buckets

Kademlia - Lookups

- Process is iterative:
  - everything is controlled by the initiator node
  - query in parallel the α nodes closest to the query ID
    - Parallel search: fast lookup at the expense of increased traffic
  - nodes return the k nodes closest to the query ID
  - go back to step 1, and select the α nodes from the new set of nodes
  - Terminate when you have the k closest nodes
- Node and key lookups are done in a similar fashion
- Underlying invariant:
  - If there exists some node with ID within a specific range then k-bucket is not empty
  - If the invariant is true, then the time is logarithmic
  - we move one bit closer each time
  - Due to refreshes the invariant holds with high probability

Kademlia vs. Chord and Pastry

- Comparing with Chord
  - Like Chord: achieves similar performance
    - deterministic
    - O(logN) contacts (routing table size)
    - O(logN) steps for lookup service
    - Lower node join/leave cost
  - Unlike Chord:
    - Routing table: view of the network
    - Flexible routing table
- Comparing with Pastry
  - Both have flexible routing table
  - Kademlia has better analysis properties (simpler)