Peer-to-Peer Networks

Pastry & Tapestry
4th Week

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Peer-to-Peer Networks

Pastry

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Pastry

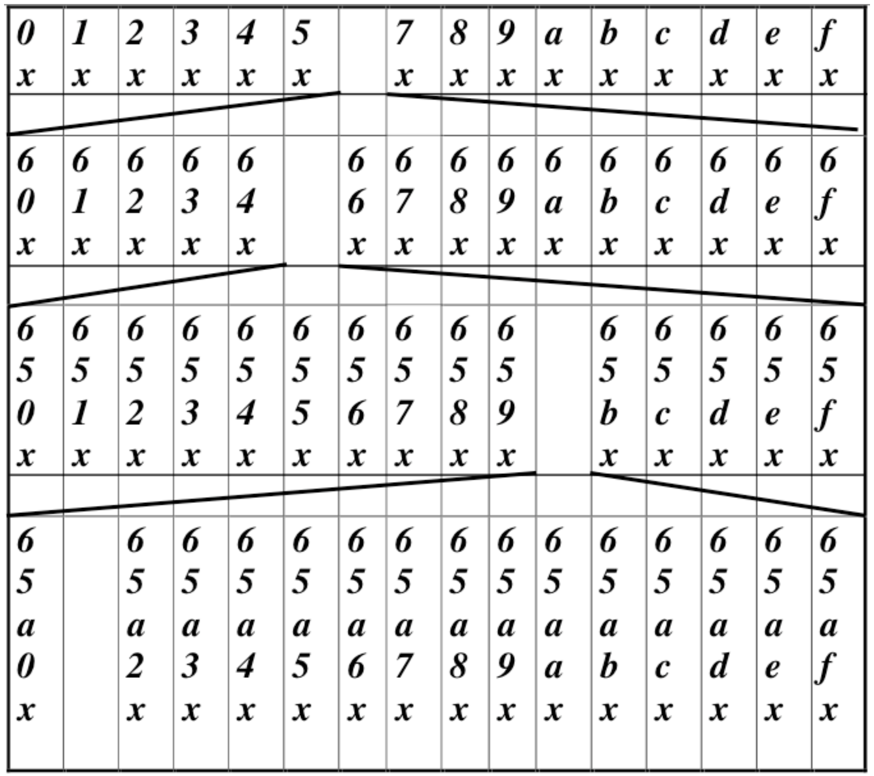
- **Peter Druschel**
  - Rice University, Houston, Texas
  - now head of Max-Planck-Institute for Computer Science, Saarbrücken/Kaiserslautern
- **Antony Rowstron**
  - Microsoft Research, Cambridge, GB
- **Developed in Cambridge (Microsoft Research)**
- **Pastry**
  - Scalable, decentralized object location and routing for large scale peer-to-peer-network
- **PAST**
  - A large-scale, persistent peer-to-peer storage utility
- **Two names one P2P network**
  - PAST is an application for Pastry enabling the full P2P data storage functionality

Pastry Overview

- **Each peer has a 128-bit ID: nodeID**
  - unique and uniformly distributed
  - e.g. use cryptographic function applied to IP-address
- **Routing**
  - Keys are matched to $\{0,1\}^{128}$
  - According to a metric messages are distributed to the neighbor next to the target
- **Routing table has $O(2^b(\log n)/b) + \ell$ entries**
  - n: number of peers
  - ℓ: configuration parameter
  - b: word length
    - typical: b= 4 (base 16), $\ell = 16$
    - message delivery is guaranteed as long as less than $\ell/2$ neighbored peers fail
- **Inserting a peer and finding a key needs O((log n)/b) messages**

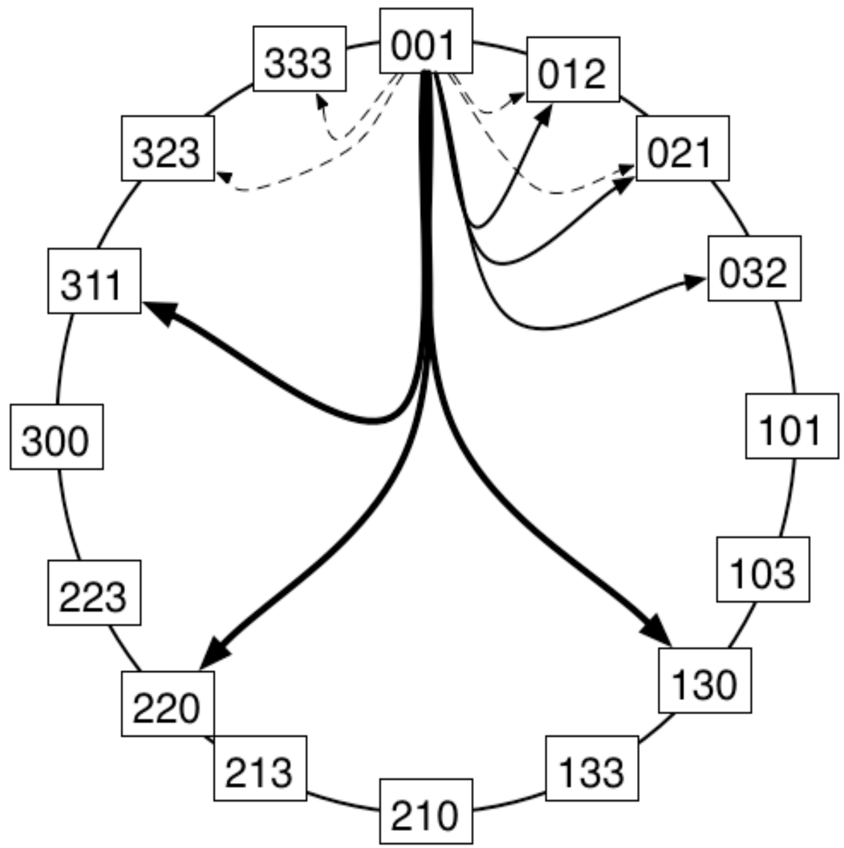
Routing Table

- **NodeId presented in base 2^b**
  - e.g. NodeID: 65A0BA13
- **For each prefix p and letter x ∈ {0,..,2^b-1} add an peer of form px* to the routing table of NodeID, e.g.**
  - b=4, 2^b=16
  - 15 entries for 0*,1*, .. F*
  - 15 entries for 60*, 61*,... 6F*
  - ...
  - if no peer of the form exists, then the entry remains empty
- **Choose next neighbor according to a distance metric**
  - metric results from the RTT (round trip time)
- **In addition choose ℓ neighors**
  - ℓ/2 with next higher ID
  - ℓ/2 with next lower ID



Routing Table

- **Example b=2**
- **Routing Table**
  - For each prefix p and letter x ∈ {0,..,2^b-1} add an peer of form px* to the routing table of NodeID
- **In addition choose ℓ neighors**
  - ℓ/2 with next higher ID
  - ℓ/2 with next lower ID
- **Observation**
  - The leaf-set alone can be used to find a target
- **Theorem**
  - With high probability there are at most O(2^b (log n)/b) entries in each routing table



Routing Table

- **Theorem**
  - With high probability there are at most O(2^b (log n)/b) entries in each routing table
- **Proof**
  - The probability that a peer gets the same m-digit prefix is

$$2^{-bm}$$

  - The probability that a m-digit prefix is unused is

$$(1-2^{-bm})^n \leq e^{-n/2^{bm}}$$

  - For m=c (log n)/b we get

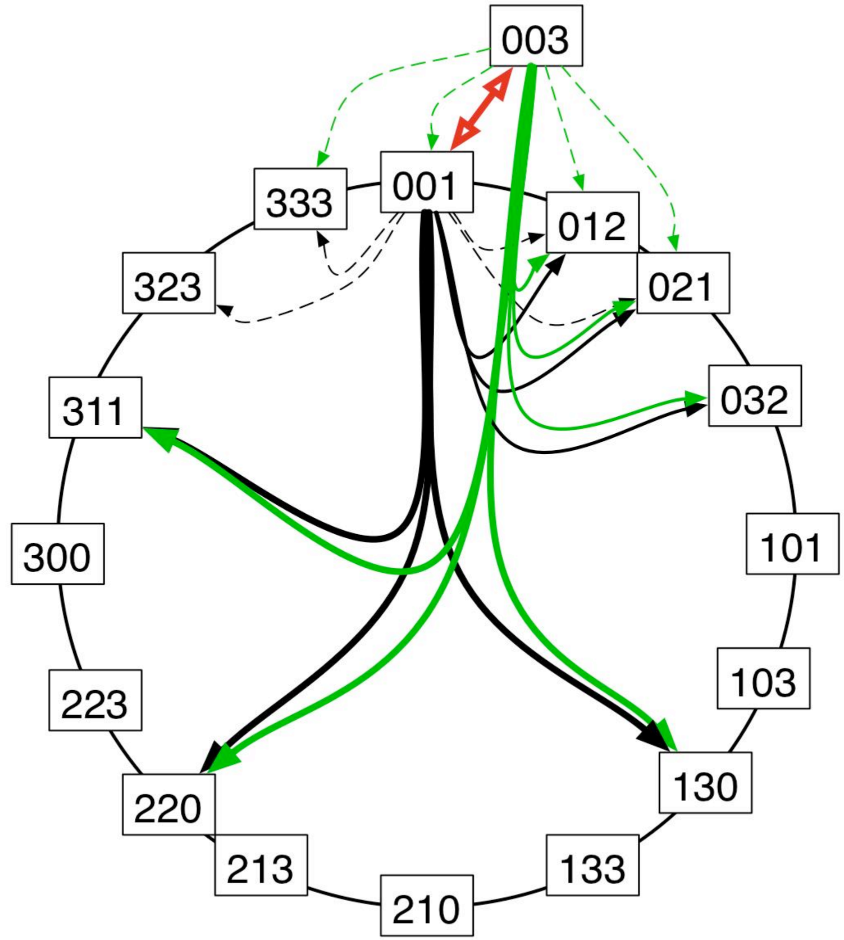
$$e^{-n/2^{bm}} \leq e^{-n/2^{c \log n}} \leq e^{-n/n^c} \leq e^{-n^{c-1}}$$

- With (extremely) high probability there is no peer with the same prefix of length (1+ε)(log n)/b
- Hence we have (1+ε)(log n)/b rows with 2^b-1 entries each

0x	1x	2x	3x	4x	5x		7x	8x	9x	ax	bx	cx	dx	ex	fx
60x	61x	62x	63x	64x		66x	67x	68x	69x	6ax	6bx	6cx	6dx	6ex	6fx
650x	651x	652x	653x	654x	655x	656x	657x	658x	659x		65bx	65cx	65dx	65ex	65fx
65a0x		65a2x	65a3x	65a4x	65a5x	65a6x	65a7x	65a8x	65a9x	65aax	65abx	65acx	65adx	65aex	65afx

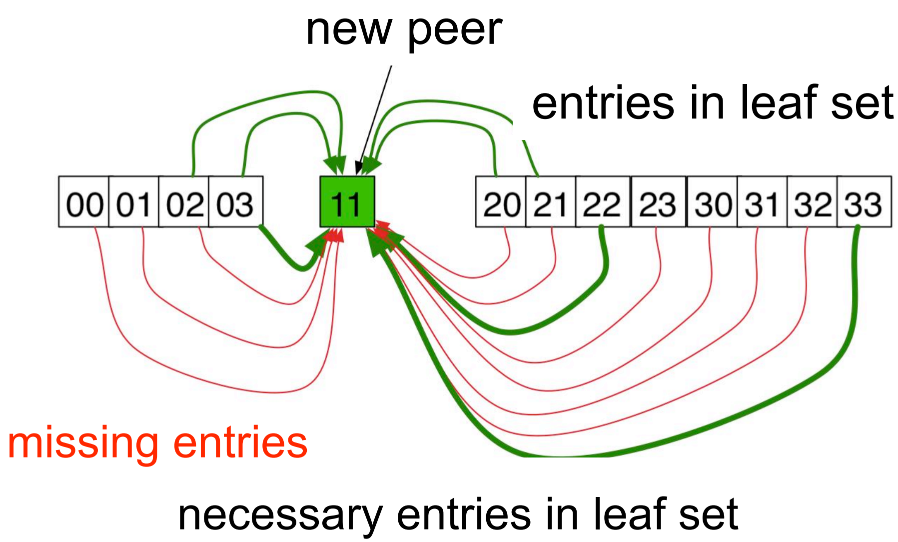
A Peer Enters

- **New node x sends message to the node z with the longest common prefix p**
- **x receives**
  - routing table of z
  - leaf set of z
- **z updates leaf-set**
- **x informs informiert ℓ-leaf set**
- **x informs peers in routing table**
  - with same prefix p (if $\ell/2 < 2^b$)
- **Numbor of messages for adding a peer**
  - ℓ messages to the leaf-set
  - expected (2^b - ℓ/2) messages to nodes with common prefix
  - one message to z with answer



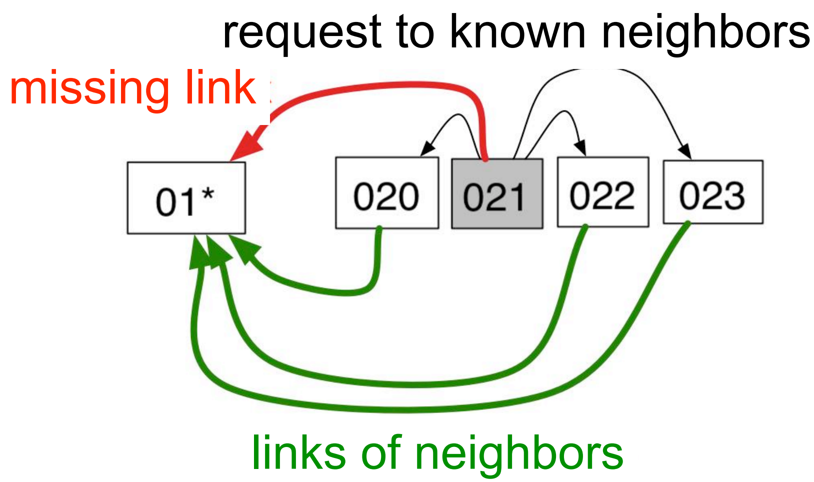
When the Entry-Operation Errs

- **Inheriting the next neighbor routing table does not allows work perfectly**
- **Example**
  - If no peer with 1* exists then all other peers have to point to the new node
  - Inserting 11
  - 03 knows from its routing table
    - 22,33
    - 00,01,02
  - 02 knows from the leaf-set
    - 01,02,20,21
- **11 cannot add all necessary links to the routing tables**



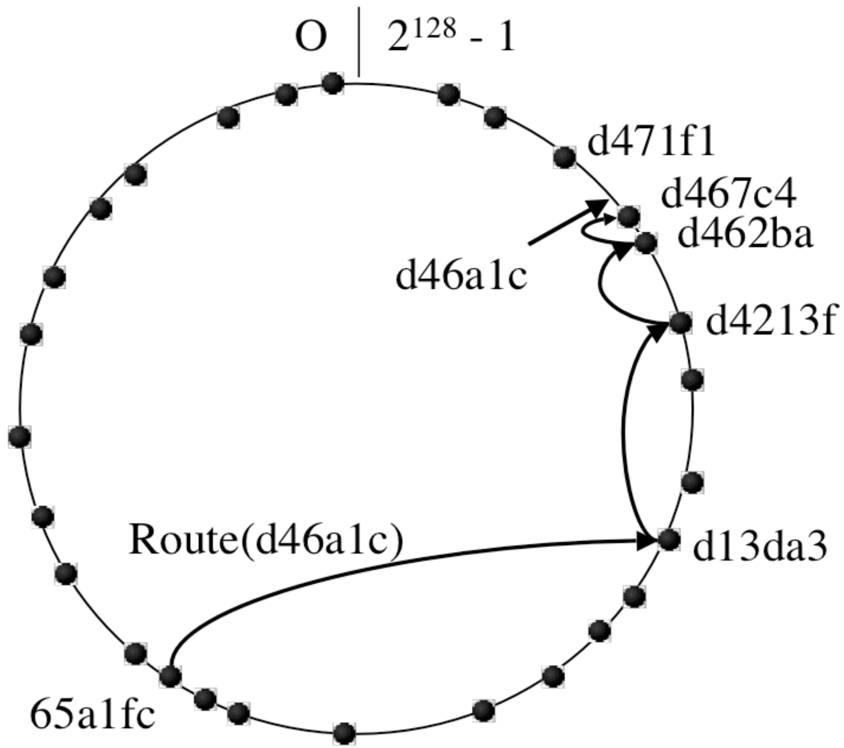
Missing Entries in the Routing Table

- **Assume the entry R_i^j is missing at peer D**
  - j-th row and i-th column of the routing table
- **This is noticed if message of a peer with such a prefix is received**
- **This may also happen if a peer leaves the network**
- **Contact peers in the same row**
  - if they know a peer this address is copied
- **If this fails then perform routing to the missing link**



Lookup

- **Compute the target ID using the hash function**
- **If the address is within the ℓ-leaf set**
  - the message is sent directly
  - or it discovers that the target is missing
- **Else use the address in the routing table to forward the mesage**
- **If this fails take best fit from all addresses**



Lookup in Detail

- **L:** **ℓ-leafset**
- **R:** **routing table**
- **M:** **nodes in the vicinity of D (according to RTT)**
- **D:** **key**
- **A:** **nodeID of current peer**
- **R^i_l:** **j-th row and i-th column of the routing table**
- **L_i:** **numbering of the leaf set**
- **D_i:** **i-th digit of key D**
- **shl(A):** **length of the larges common prefix of A and D (shared header length)**

if $(L_{-\lfloor |L|/2 \rfloor} \leq D \leq L_{\lfloor |L|/2 \rfloor})$ {
    // D is within range of our leaf set
    forward to L_i, s.th. $|D - L_i|$ is minimal;
} else {
    // use the routing table
    Let $l = shl(D, A)$;
    if $(R_l^{D_l} \neq null)$ {
        forward to $R_l^{D_l}$;
    }
    else {
        // rare case
        forward to $T \in L \cup R \cup M$, s.th.
            $shl(T, D) \geq l$,
            $|T - D| < |A - D|$
    }
}

Routing — Discussion

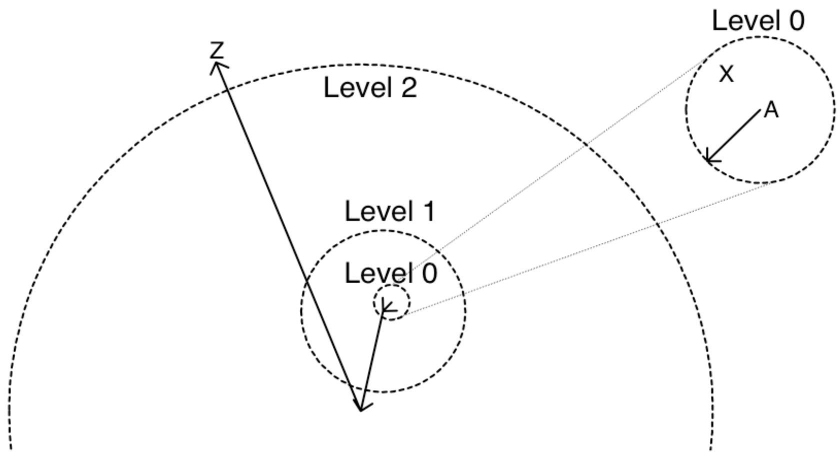
- **If the Routing-Table is correct**
  - routing needs O((log n)/b) messages
- **As long as the leaf-set is correct**
  - routing needs O(n/l) messages
  - unrealistic worst case since even damaged routing tables allow dramatic speedup
- **Routing does not use the real distances**
  - M is used only if errors in the routing table occur
  - using locality improvements are possible
- **Thus, Pastry uses heuristics for improving the lookup time**
  - these are applied to the last, most expensive, hops

Localization of the k Nearest Peers

- **Leaf-set peers are not near, e.g.**
  - New Zealand, California, India, ...
- **TCP protocol measures latency**
  - latencies (RTT) can define a metric
  - this forms the foundation for finding the nearest peers
- **All methods of Pastry are based on heuristics**
  - i.e. no rigorous (mathematical) proof of efficiency
- **Assumption: metric is Euclidean**

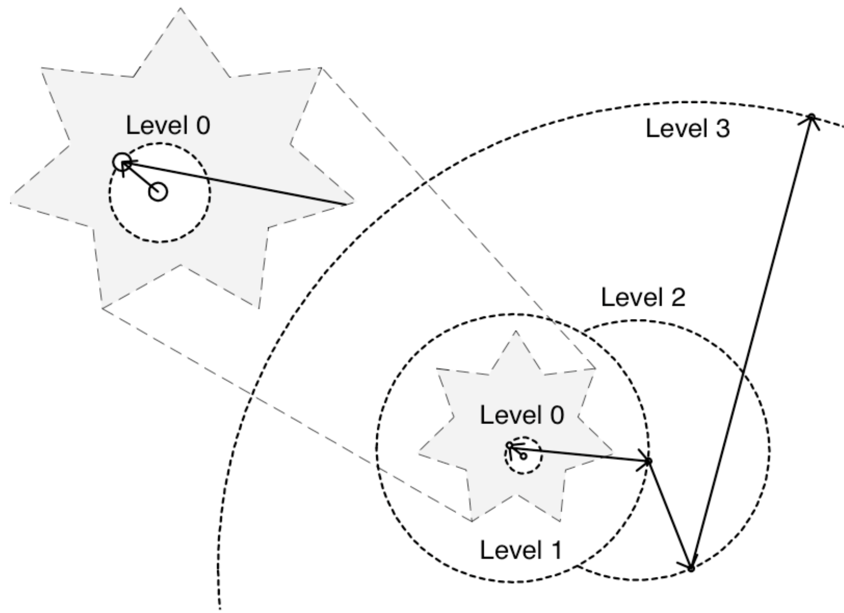
Locality in the Routing Table

- **Assumption**
  - When a peer is inserted the peers contacts a near peer
  - All peers have optimized routing tables
- **But:**
  - The first contact is not necessary near according to the node-ID
- **1st step**
  - Copy entries of the first row of the routing table of P
    - good approximation because of the triangle inequality (metric)
- **2nd step**
  - Contact fitting peer p‘ of p with the same first letter
  - Again the entries are relatively close
- **Repeat these steps until all entries are updated**



Locality in the Routing Table

- **In the best case**
  - each entry in the routing table is optimal w.r.t. distance metric
  - this does not lead to the shortest path
- **There is hope for short lookup times**
  - with the length of the common prefix the latency metric grows exponentially
  - the last hops are the most expensive ones
  - here the leaf-set entries help

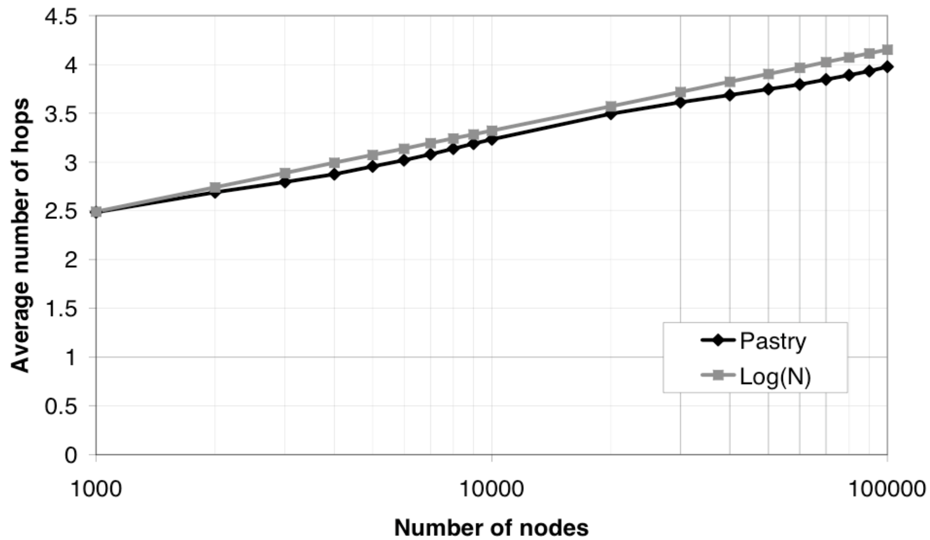


Localization of Near Nodes

- **Node-ID metric and latency metric are not compatible**
- **If data is replicated on k peers then peers with similar Node-ID might be missed**
- **Here, a heuristic is used**
- **Experiments validate this approach**

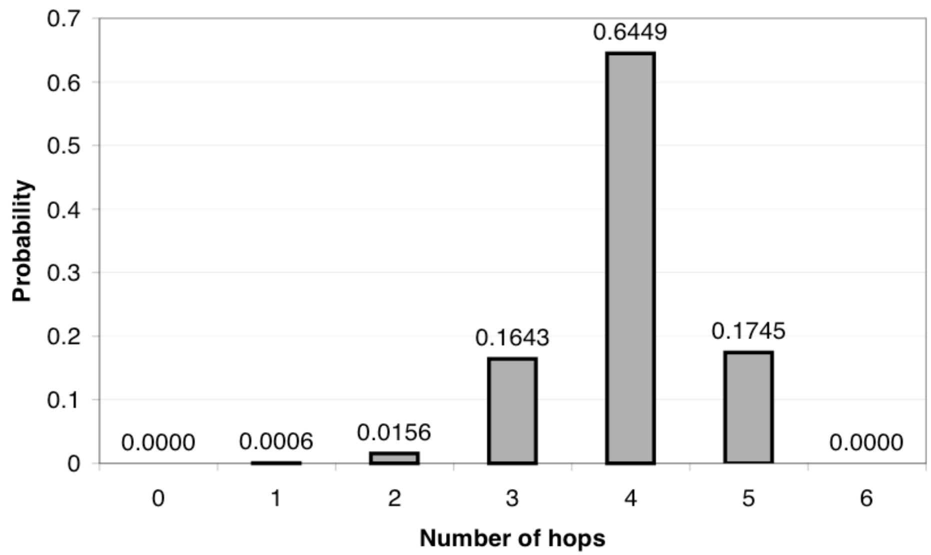
Experimental Results — Scalability

- **Parameter b=4, l=16, M=32**
- **In this experiment the hop distance grows logarithmically with the number of nodes**
- **The analysis predicts 4 log n**
- **Fits well**



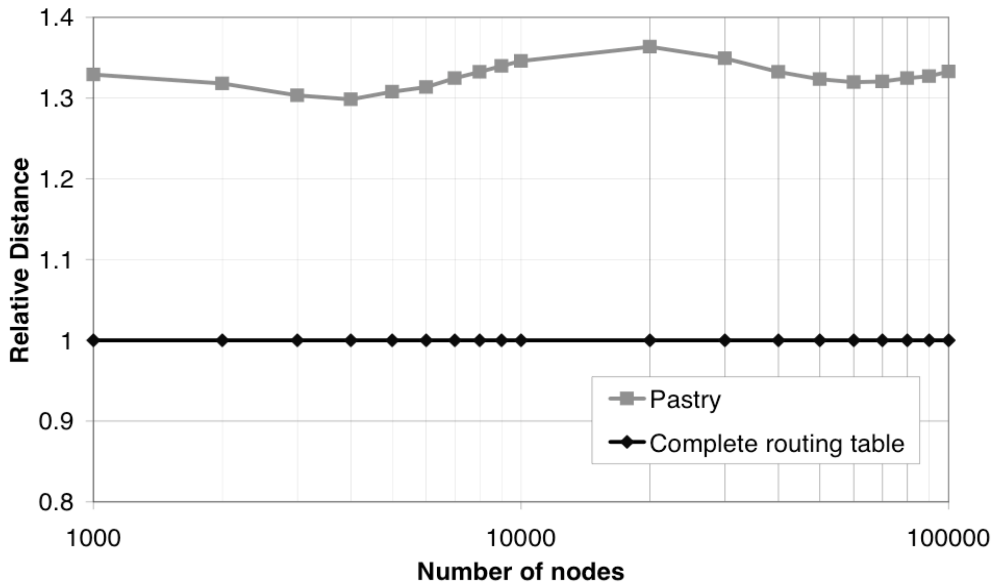
Experimental Results
Distribution of Hops

- **Parameter b=4, l=16, M=32, n = 100,000**
- **Result**
  - deviation from the expected hop distance is extremely small
- **Analysis predicts difference with extremely small probability**
  - fits well



Experimental Results — Latency

- **Parameter b=4, l=16, M=3**
- **Compared to the shortest path astonishingly small**
  - seems to be constant

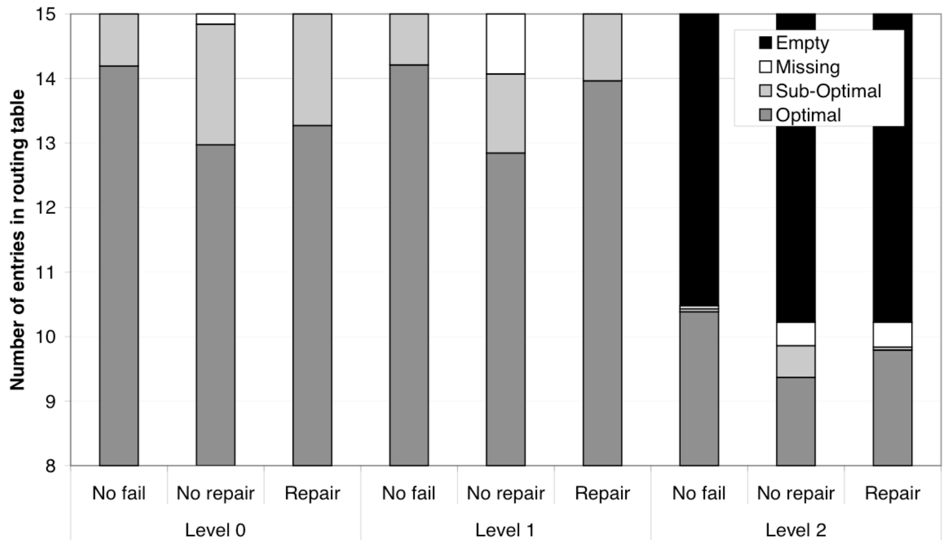


Critical View at the Experiments

- **Experiments were performed in a well-behaving simulation environment**
- **With b=4, L=16 the number of links is quite large**
  - The factor $2^b/b = 4$ influences the experiment
  - Example n= 100 000
    - $2^{b/}b \log n = 4 \log n > 60$ links in routing table
    - In addition we have 16 links in the leaf-set and 32 in M
- **Compared to other protocols like Chord the degree is rather large**
- **Assumption of Euclidean metric is rather arbitrary**

Experimentelle Untersuchungen
Knotenausfälle

- Parameter b=4, l=16, M=32, n = 5 000
- No fail: vor Ausfall
- No repair: 500 von 5000 Peers fallen aus
- Repair: Nach Reparatur der Routing-Tables



Peer-to-Peer Networks

Tapestry

Zhao, Kubiatowicz und Joseph (2001)

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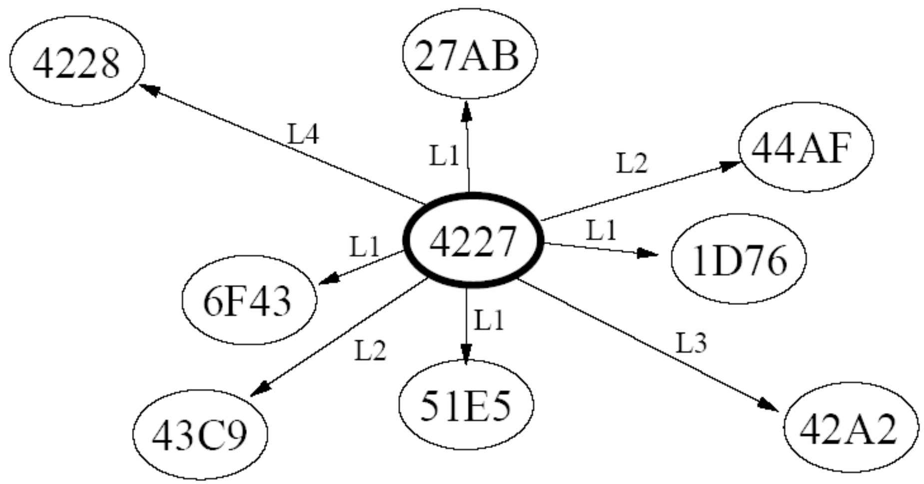
Tapestry

- **Objects and Peers are identified by**
  - Objekt-IDs (Globally Unique Identifiers GUIDs) and
  - Peer-IDs
- **IDs**
  - are computed by hash functions
    - like CAN or Chord
  - are strings on basis B
    - B=16 (hexadecimal system)

Neighborhood of a Peer (1)

- **Every peer A maintains for each prefix x of the Peer-ID**
  - if a link to another peer sharing this Prefix x
  - i.e. peer with ID B=xy has a neighbor A, if xy´=A for some y, y´
- **Links sorted according levels**
  - the level denotes the length of the common prefix
  - Level L = |x|+1



Neighborhood Set (2)

- **For each prefix x and all letters j of the peer with ID A**
  - establish a link to a node with prefix xj within the neighboorhood set $N^{A}_{x,j}$
- **Peer with Node-ID A has b |A| neighborhood sets**
- **The neighborhood set of contains all nodes with prefix sj**
  - Nodes of this set are denoted by (x,j)

Example of Neighborhood Sets

Neighborhood set of node 4221

	Level 4	Level 3	Level 2	Level 1
j=0	4220	420?	40??	0???
j=1	4221	421?	41??	1???
.	4222	422?	42??	2???
.	4223	423?	43??	3???
.	4224	424?	44??	4???
.	4225	425?	45??	5???
.	4226	426?	46??	6???
j=7	4227	427?	47??	7???

Links

- **For each neighborhood set at most k Links are maintained**

$$k \geq 1 : \left| N_{x,j}^{A} \right| \leq k$$

- **Note:**
  - some neighborhood sets are empty

Properties of Neighborhood Sets

- **Consistency**
  - If $N^{A}_{x,j} = \emptyset$ für any A
    - then there are no (x,j) peers in the network
    - this is called a hole in the routing table of level |x|+1 with letter j
- **Network is always connected**
  - Routing can be done by following the letters of the ID $b_1 b_2 \ldots b_n$

N^{A}_{ϕ, b_1} 1st hop to node A_1

$N^{A_1}_{b_1, b_2}$ 2nd hop to node A_2

$N^{A_2}_{b_1 o b_2, b_3}$ 3rd hop to node A_3

…

Locality

- **Metric**
  - e.g. given by the latency between nodes
- **Primary node of a neighborhood set** $N_{x,j}^A$
  - The closest node (according to the metric) in the neighborhood set of A is called the primary node
- **Secondary node**
  - the second closest node in the neighborhood set
- **Routing table**
  - has primary and secondary node of the neighborhood table

Root Node

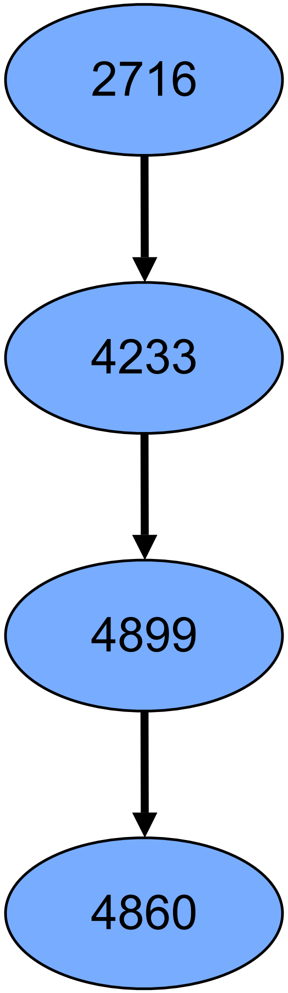
- **Object with ID Y should stored by a so-called Root Node with this ID**
- **If this ID does not exist then a deterministic choice computes the next best choice sharing the greatest commen prefix**

Surrogate Routing

- **Surrogate Routing**
  - compute a surrogate (replacement root node)
  - If (x,j) is a hole, then choose (x,j+1),(x,j+2),… until a node is found
  - Continue search in the next higher level

Example: Surrogate Routing

- **Lookup of 4666 by peer 2716**



Level 1, j=4

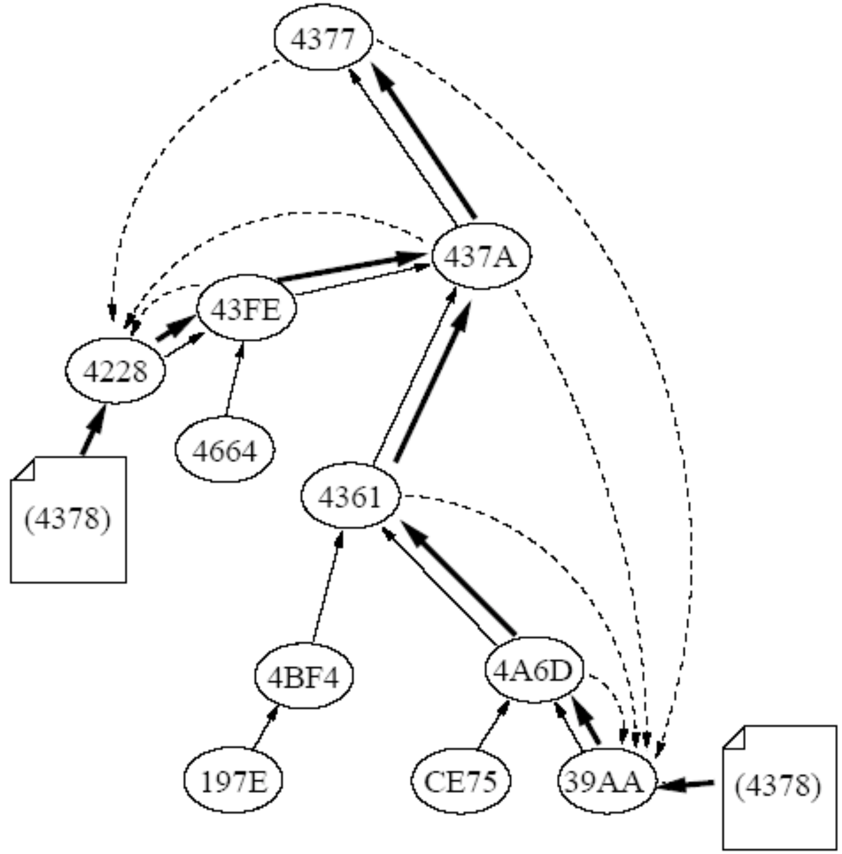
Level 2, j=6 does not exist, next link j=8

Level 3, j=6

Peer 4860 has no level 4 neighbors => end of search

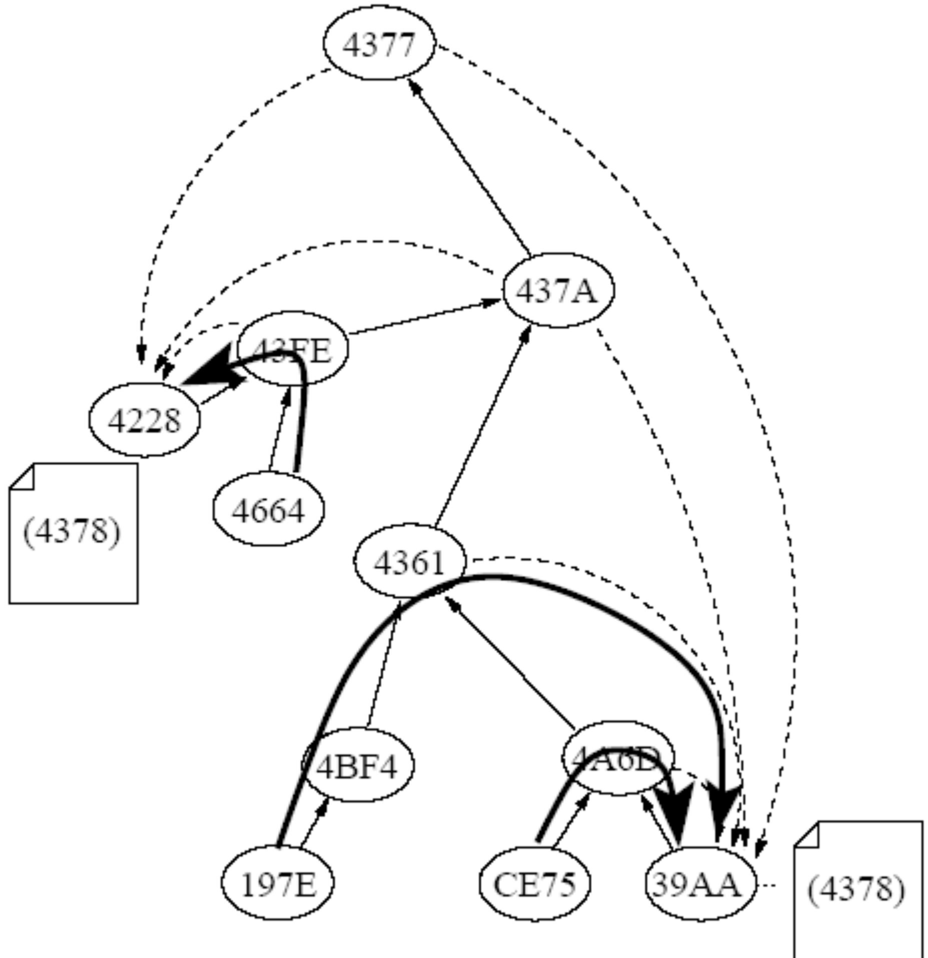
Publishing Objects

- **Peers offering an object (storage servers)**
  - send message to the root node
- **All nodes along the search path store object pointers to the storage server**



Lookup

- **Choose the root node of Y**
- **Send a message to this node**
  - using primary nodes
- **Abort search if an object link has been found**
  - then send message to the storage server



Fault Tolerance

- **Copies of object IDs**
  - use different hash functions for multiple root nodes for objects
  - failed searches can be repeated with different root nodes
- **Soft State Pointer**
  - links of objects are erased after a designated time
  - storage servers have to republish
    - prevents dead links
    - new peers receive fresh information

Surrogate Routing

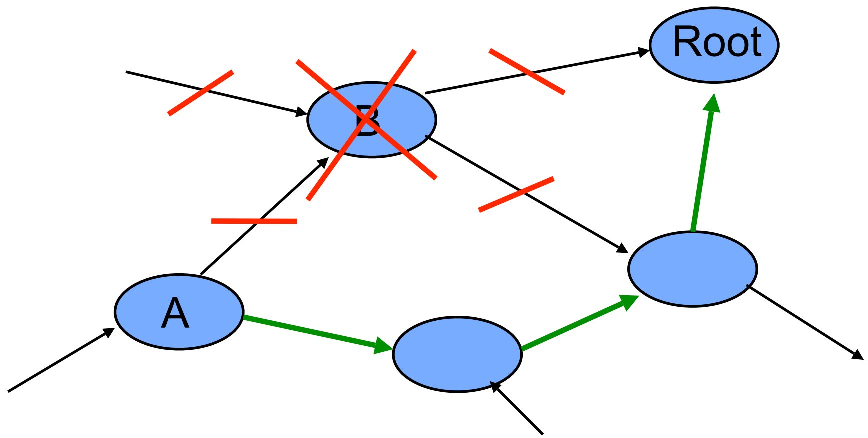
- **Theorem**
  - Routing in Tapestry needs O(log n) hops with high probability

Adding Peers

- **Perform lookup in the network for the own ID**
  - every message is acknowledged
  - send message to all neighbors with fitting prefix,
    - Acknowledged Multicast Algorithm
- **Copy neighborhood tables of surrogate peer**
- **Contact peers with holes in the routing tables**
  - so they can add the entry
  - for this perform multicast algorithm for finding such peers

Leaving of Peers

- **Peer A notices that peer B has left**
- **Erase B from routing table**
  - Problem holes in the network can occur
- **Solution: Acknowledged Multicast Algorithm**
- **Republish all object with next hop to root peer B**



Pastry versus Tapestry

- **Both use the same routing principle**
  - Plaxton, Rajamaran und Richa
  - Generalization of routing on the hyper-cube
- **Tapestry**
  - is not completely self-organizing
  - takes care of the consistency of routing table
  - is analytically understood and has provable performance
- **Pastry**
  - Heuristic methods to take care of leaving peers
  - More practical (less messages)
  - Leaf-sets provide also robustness

Peer-to-Peer Networks

End of 4th Week

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