Peer-to-Peer Systems and Applications

Lecture 2: Distributed Hash Tables (1)

Chapter 7 and 8:

Part III: Structured
Peer-to-Peer Systems

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0. Lecture Overview

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    4. Distributed indexing
    5. Comparison of lookup concepts
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1. Distributed Management and Retrieval of Data

Comparison of Strategies:
Central Server, Flooding, Distributed Indexing

1. Distributed Management and Retrieval of Data

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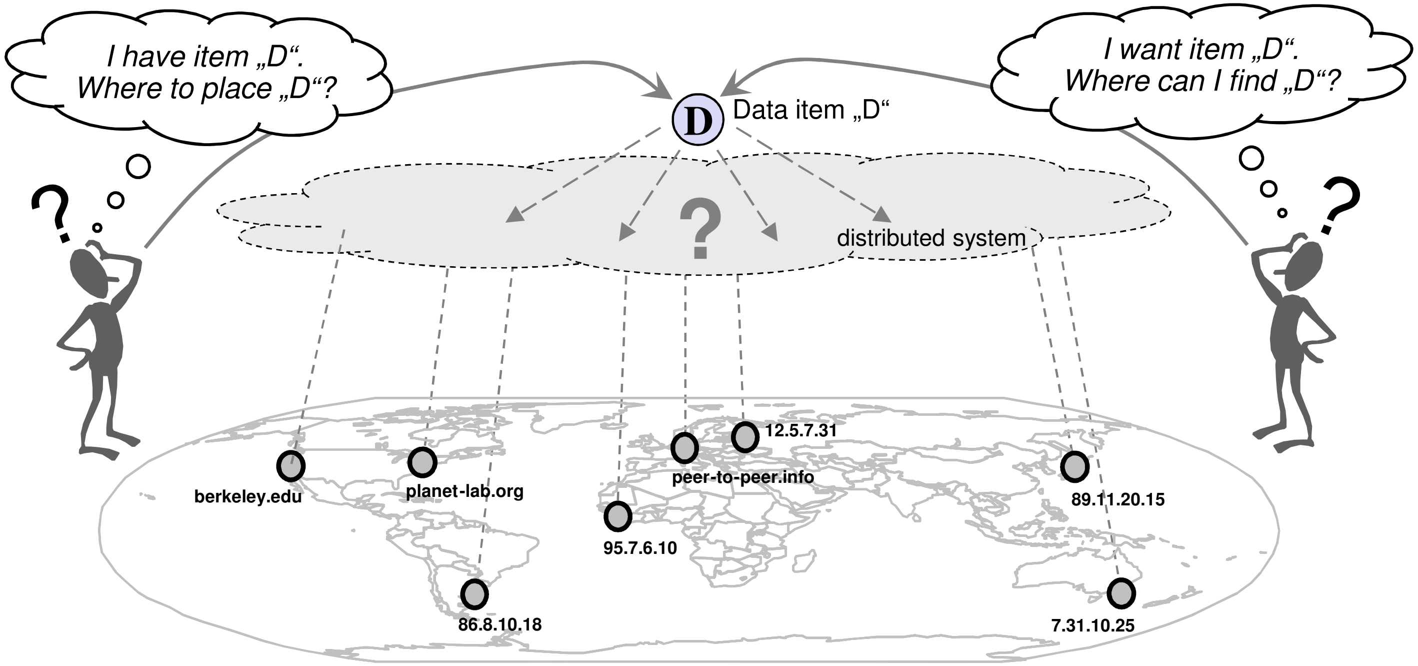

- Essential challenge in (most) Peer-to-Peer systems?
  - Location of a data item among systems distributed
    - Where shall the item be stored by the provider?
    - How does a requester find the actual location of an item?
  - Scalability: keep the complexity for communication and storage scalable
  - Robustness and resilience in case of faults and frequent changes

1.1. Comparison of Strategies for Data Retrieval

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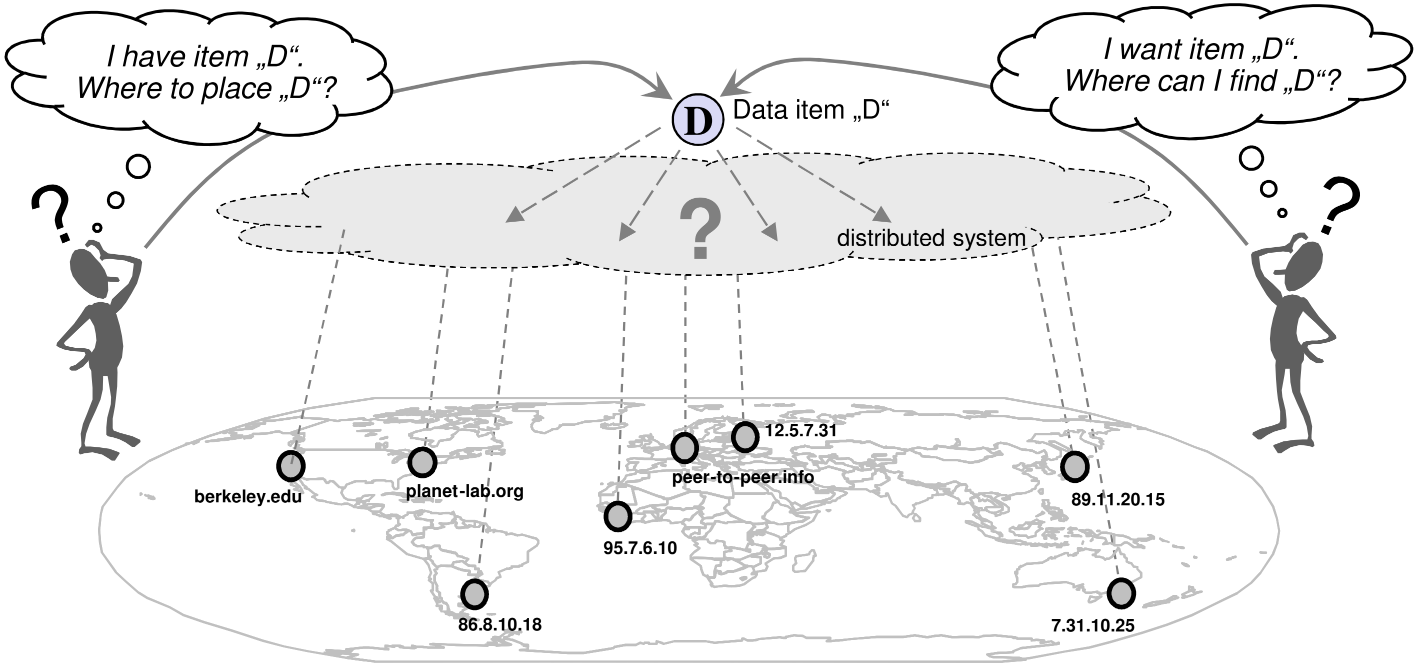

- Strategies to store and retrieve data items in distributed systems
  - Central server
  - Flooding search
  - Distributed indexing

1.2. Approach I: Central Server (1)

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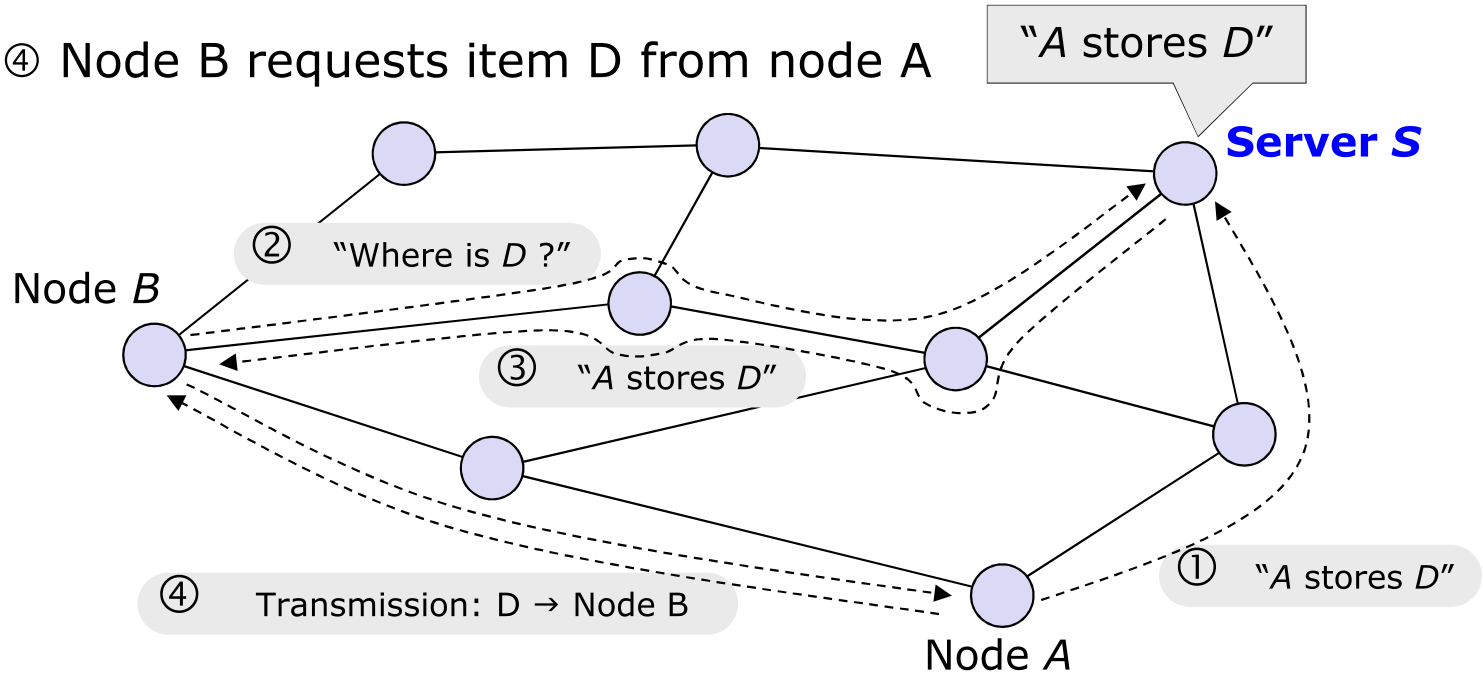
- Simple strategy: Central Server
  - Server stores information about locations
    - ① Node A (provider) tells server that it stores item D
    - ② Node B (requester) asks server S for the location of D
    - ③ Server S tells B that node A stores item D
    - ④ Node B requests item D from node A



1.2. Approach I: Central Server (2)

- Advantages
  - Search complexity of O(1) – *"just ask the server"*
  - Complex and fuzzy queries are possible
  - Simple and fast
- Problems
  - No Scalability
    - O(N) node state in server
    - O(N) network and system load of server
  - Single point of failure or attack (also for law suites ;-)
  - Non-linear increasing implementation and maintenance cost
    (in particular for achieving high availability and scalability)
  - Central server not suitable for systems with massive numbers of users
- But overall, …
  - Best principle for small and simple applications!

1.3. Approach II: Flooding Search (1)

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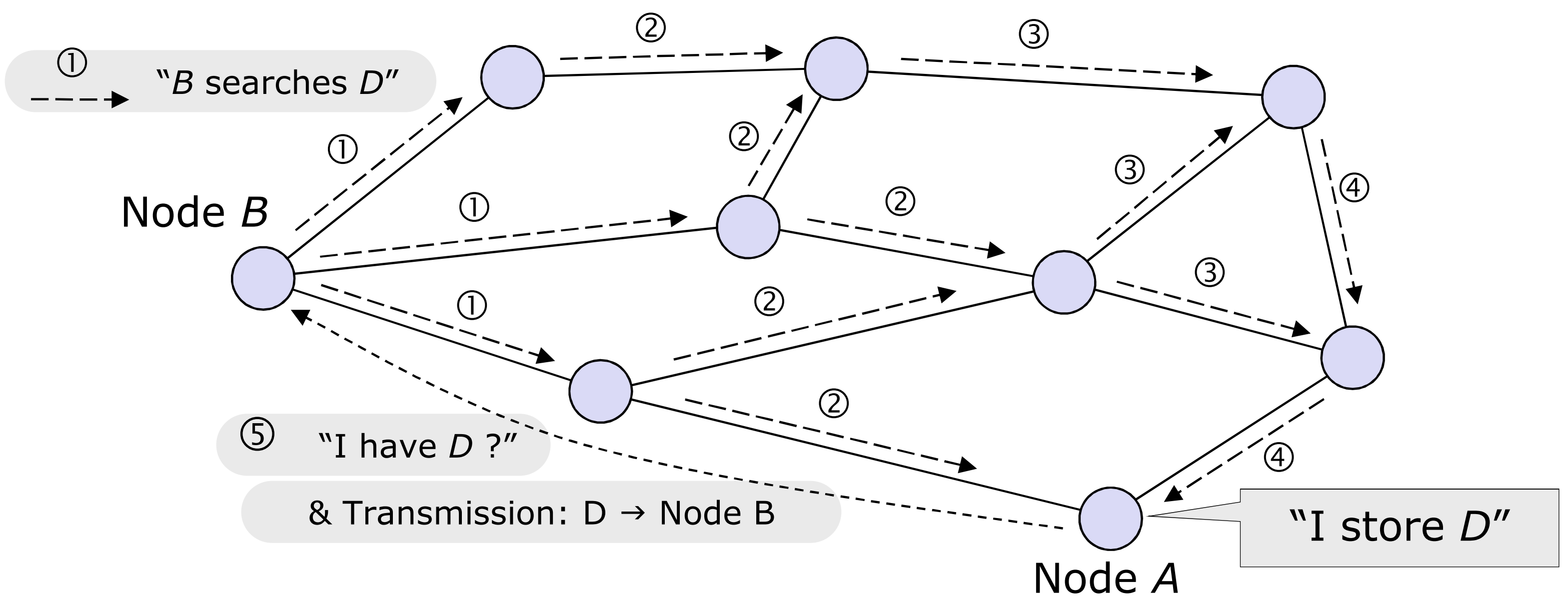
- Fully Distributed Approach
  - Central systems are vulnerable and do not scale
  - Unstructured Peer-to-Peer systems follow opposite approach
  - No information on location of a content
  - Content is only stored in the node providing it

- Retrieval of data
  - No routing information for content
  - Necessity to ask as much systems as possible / necessary
  - Approaches
    - Flooding: high traffic load on network, does not scale
    - Highest degree search: quick search through large areas – large number of messages needed for unique identification

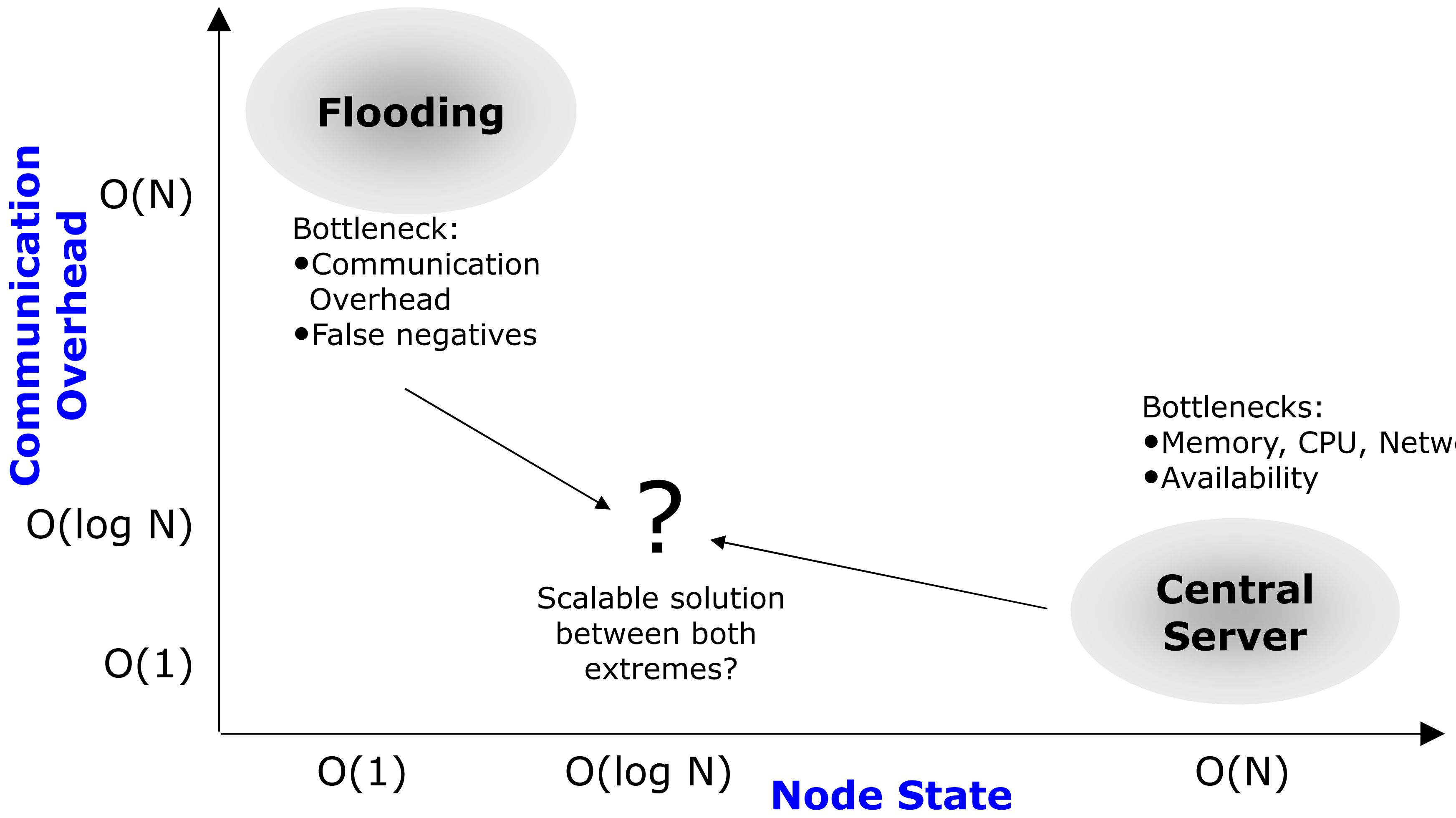
1.3. Approach II: Flooding Search (2)

- Fully Decentralized Approach: Flooding Search
  - No information about location of data in the intermediate systems
  - Necessity for broad search
    - ① Node B (requester) asks neighboring nodes for item D
    - ②-④ Nodes forward request to further nodes (breadth-first search / flooding)
    - ② Node A (provider of item D) sends D to requesting node B



1.4. Motivation Distributed Indexing (1)

- Communication overhead vs. node state



1.4. Motivation Distributed Indexing (2)

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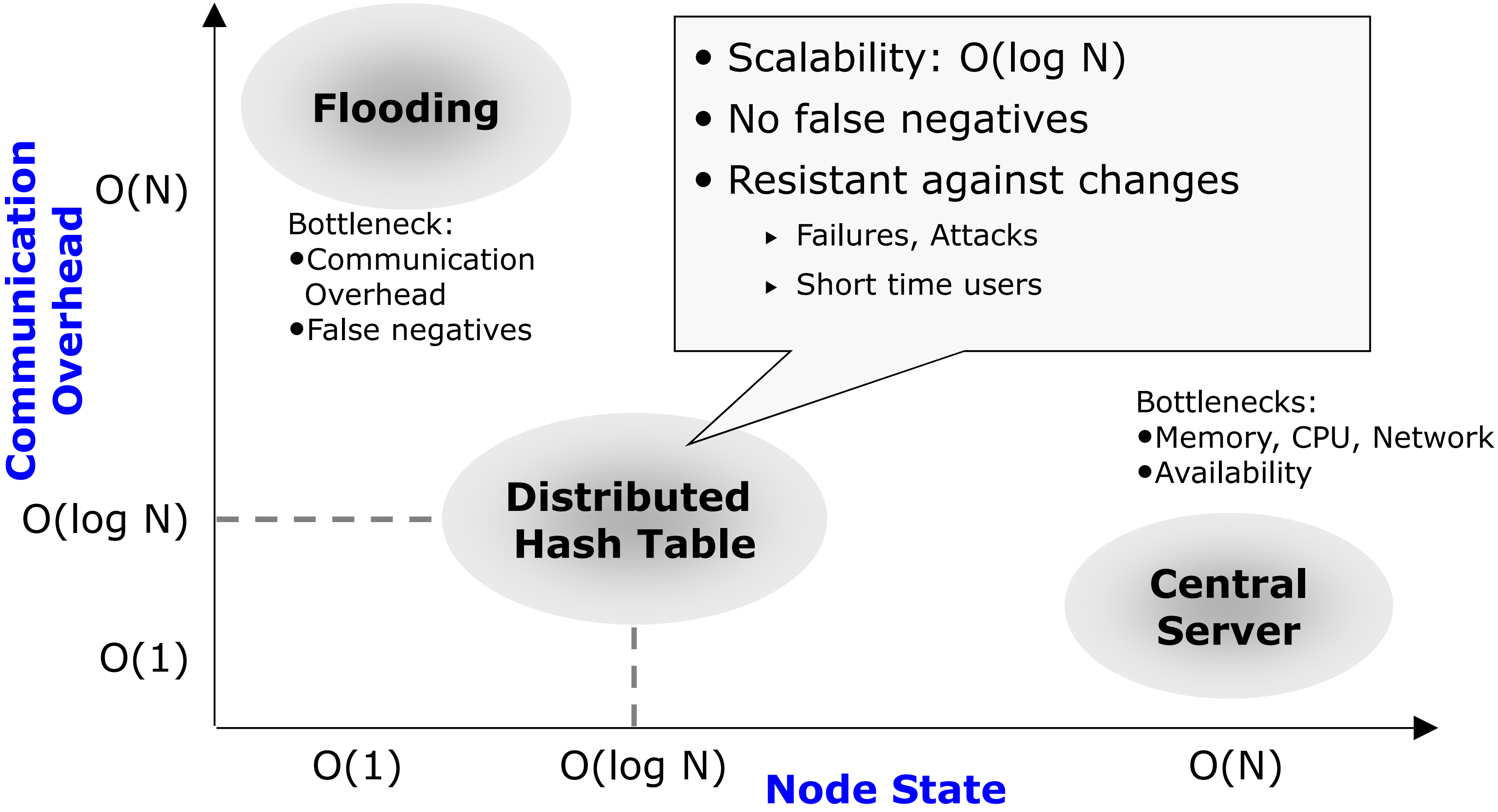
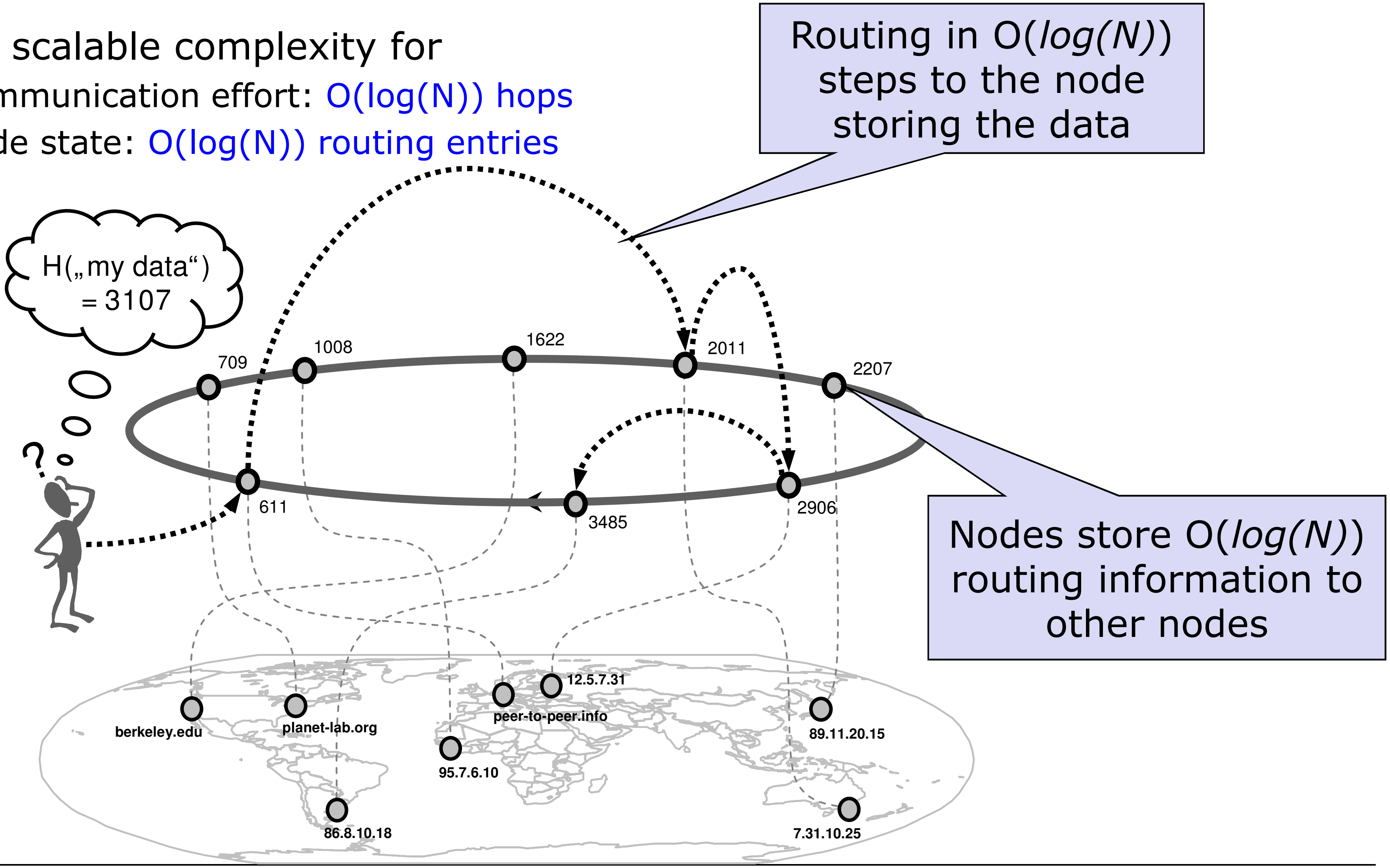
- Communication overhead vs. node state



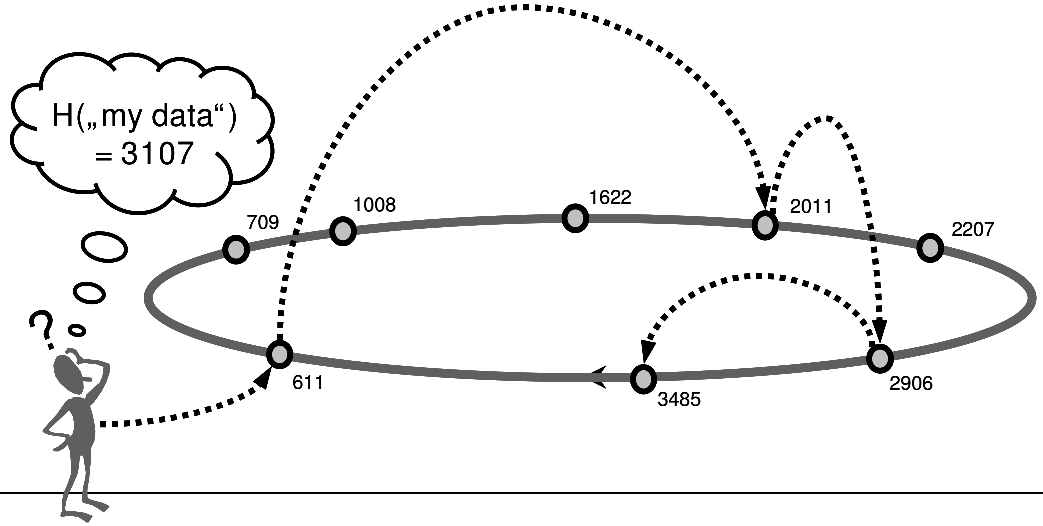
1.4. Distributed Indexing (1)

- Goal is scalable complexity for
  - Communication effort: O(log(N)) hops
  - Node state: O(log(N)) routing entries



1.4. Distributed Indexing (2)

- Approach of distributed indexing schemes
  - Data and nodes are mapped into same address space
  - Intermediate nodes maintain routing information to target nodes
    - Efficient forwarding to „destination“ (content – not location)
    - Definitive statement of existence of content
- Problems
  - Maintenance of routing information required
  - Fuzzy queries not primarily supported (e.g, wildcard searches)



1.5. Comparison of Lookup Concepts

System	Per Node State	Communi-cation Overhead	Fuzzy Queries	No false negatives	Robust-ness
Central Server	O(N)	O(1)	✓	✓	✗
Flooding Search	O(1)	O(N²)	✓	✗	✓
Distributed Hash Tables	O(log N)	O(log N)	✗	✓	✓

2. Fundamentals of Distributed Hash Tables

Distributed Data Management
Addressing, Routing, Data Storage

2. Fundamentals of Distributed Hash Tables

- Challenges for designing DHTs
  - Desired Characteristics
    - Flexibility
    - Reliability
    - Scalability
  - Equal distribution of content among nodes
    - Crucial for efficient lookup of content
  - Permanent adaptation to faults, joins, exits of nodes
    - Assignment of responsibilities to new nodes
    - Re-assignment and re-distribution of responsibilities in case of node failure or departure

2.1. Distributed Management of Data

Sequence of operations

1. Mapping of nodes and data into same address space
   - Peers and content are addressed using flat identifiers (IDs)
   - Common address space for data and nodes
   - Nodes are responsible for data in certain parts of the address space
   - Association of data to nodes may change since nodes may disappear

2. Storing / Looking up data in the DHT
   - Search for data = routing to the responsible node
     - Responsible node not necessarily known in advance
     - Deterministic statement about availability of data

2.2. Addressing in Distributed Hash Tables

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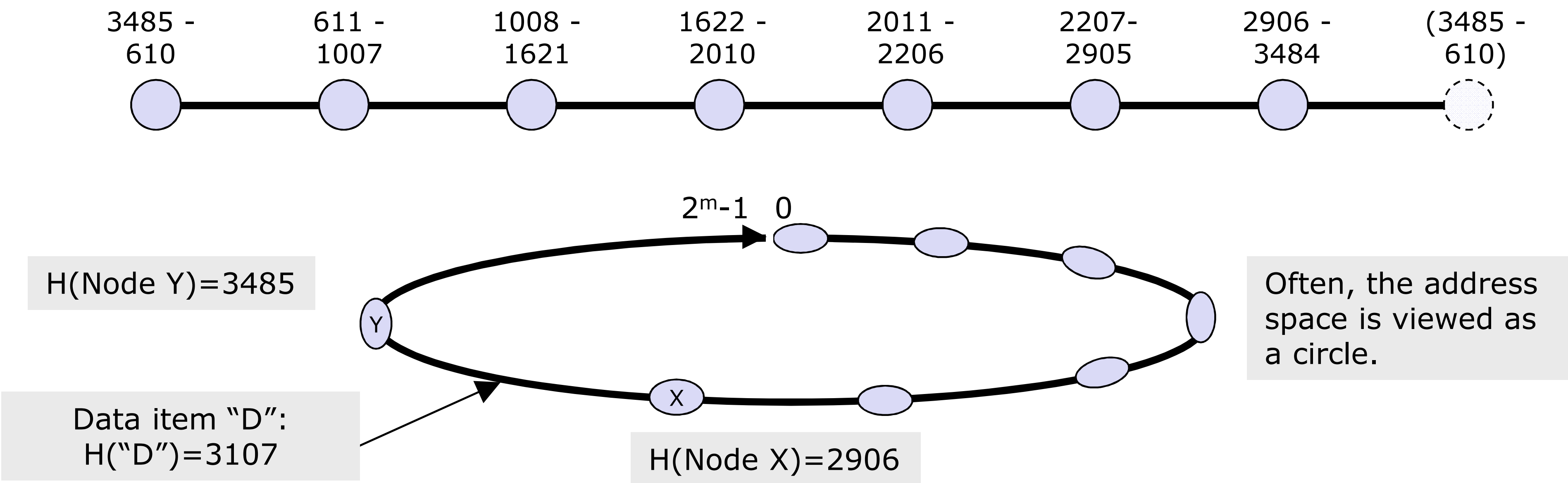
- Step 1: Mapping of content/nodes into linear space
  - Usually: 0, …, 2^m-1 >> number of objects to be stored
  - Mapping of data and nodes into an address space (with hash function)
    - E.g., Hash(*String*) mod 2^m: H(„*my data*") → 2313
  - Association of parts of address space to DHT nodes



2.2. Association of Address Space with Nodes

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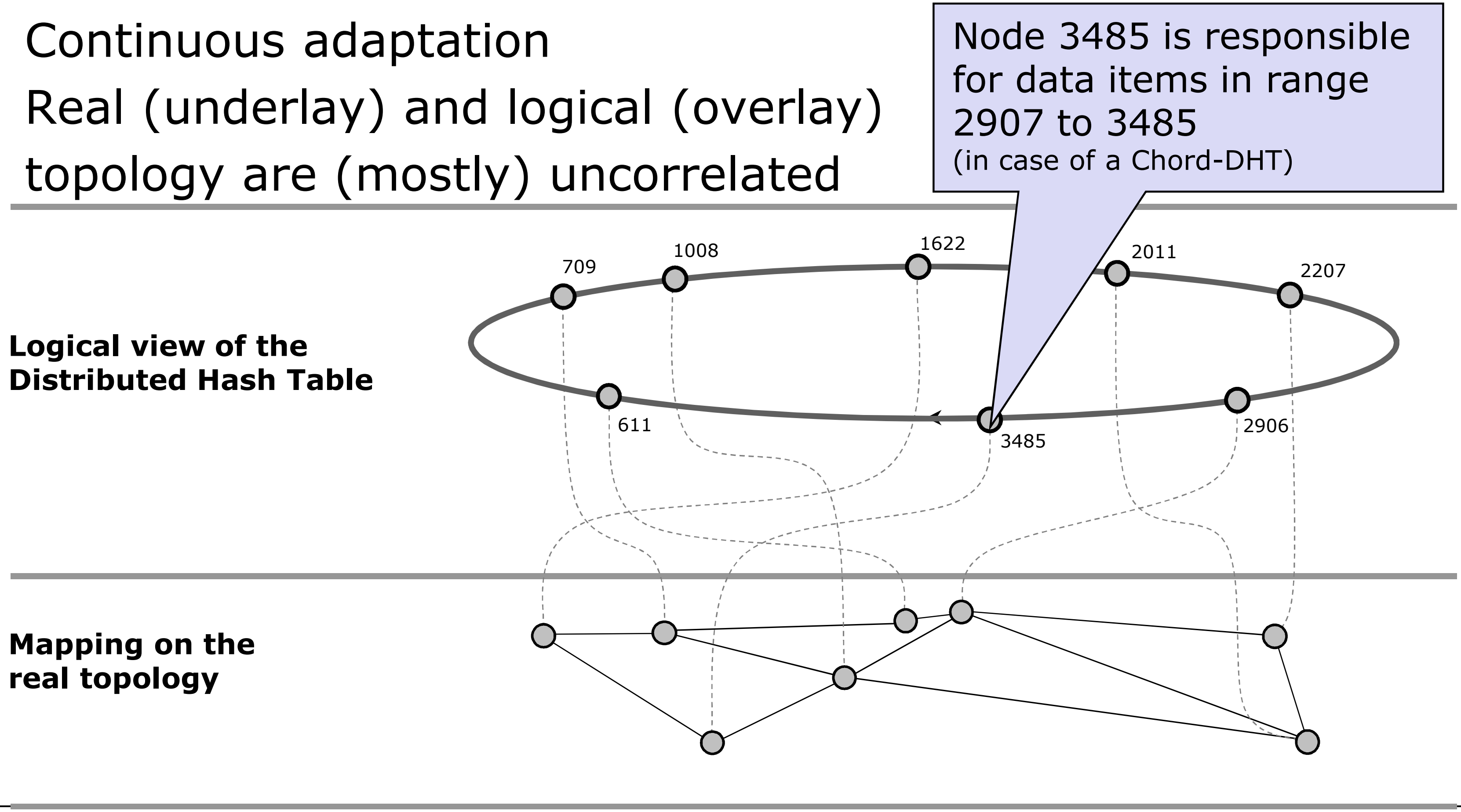
- Each node is responsible for part of the value range
  - Often with redundancy (overlapping of parts)
  - Continuous adaptation
  - Real (underlay) and logical (overlay) topology are (mostly) uncorrelated



2.3. Step 2: Routing to a Data Item (1)

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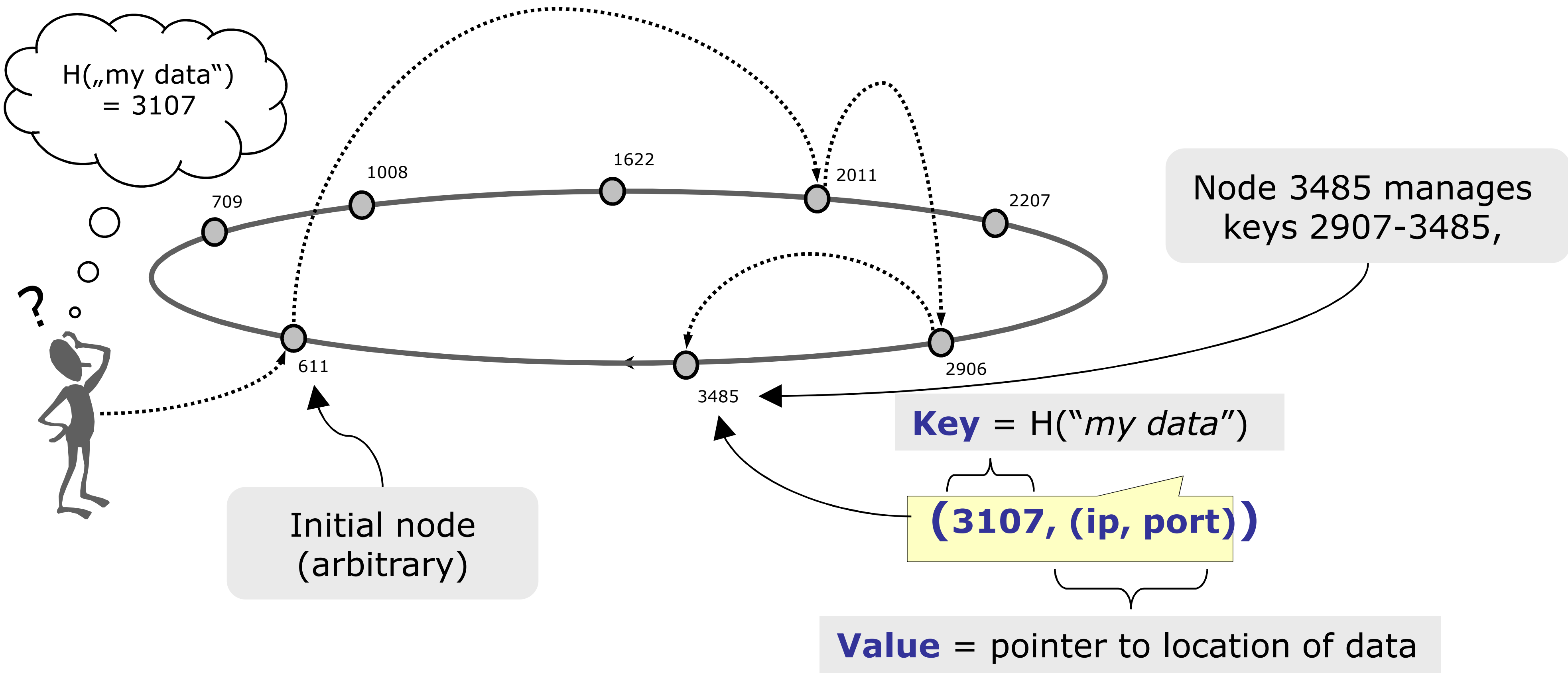
- Step 2:
  Locating the data (content-based routing)

- Goal: Small and scalable effort
  - O(1) with centralized hash table
    - But:
      Management of a centralized hash table is very costly (server!)
  - Minimum overhead with distributed hash tables
    - O(log N): DHT hops to locate object
    - O(log N): number of keys and routing information per node
      (N = # nodes)

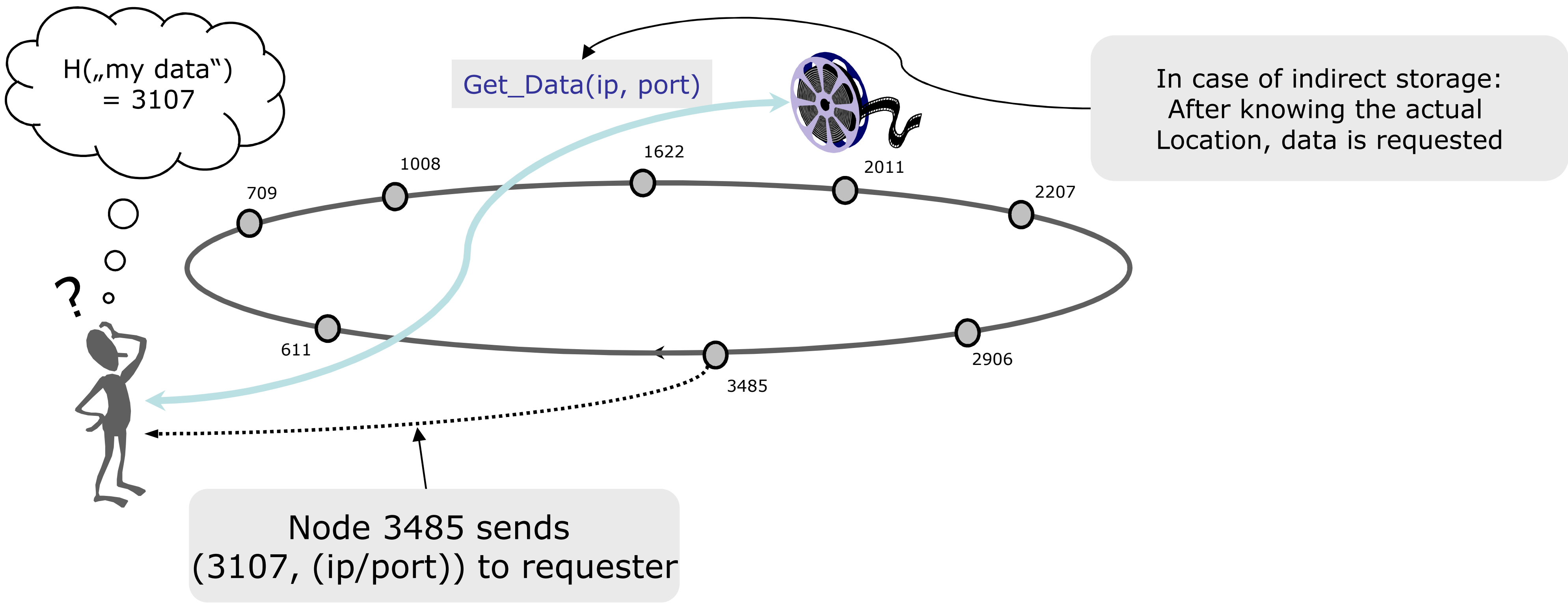
2.3. Step 2: Routing to a Data Item (2)

- Routing to a K/V-pair
  - Start lookup at arbitrary node of DHT
  - Routing to requested data item (key)



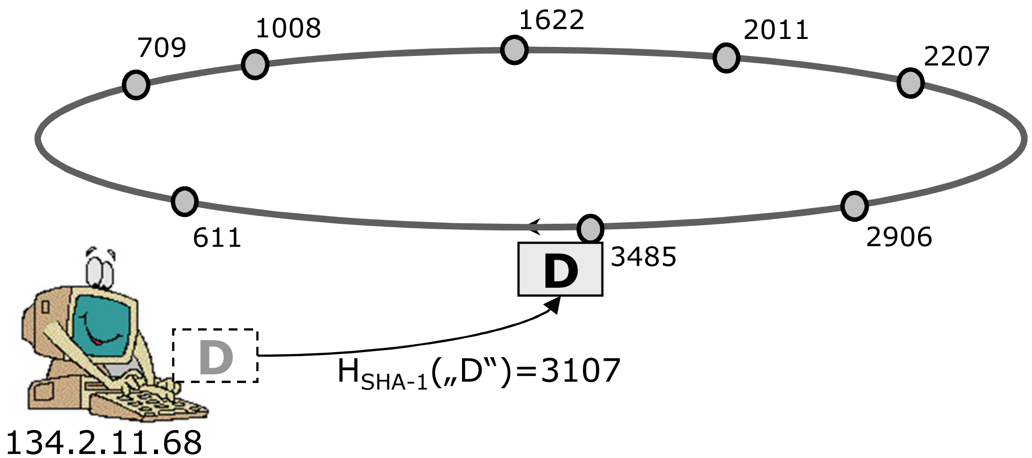
2.3. Step 2: Routing to a Data Item (3)

- Getting the content
  - K/V-pair is delivered to requester
  - Requester analyzes K/V-tuple
    (and downloads data from actual location – in case of indirect storage)



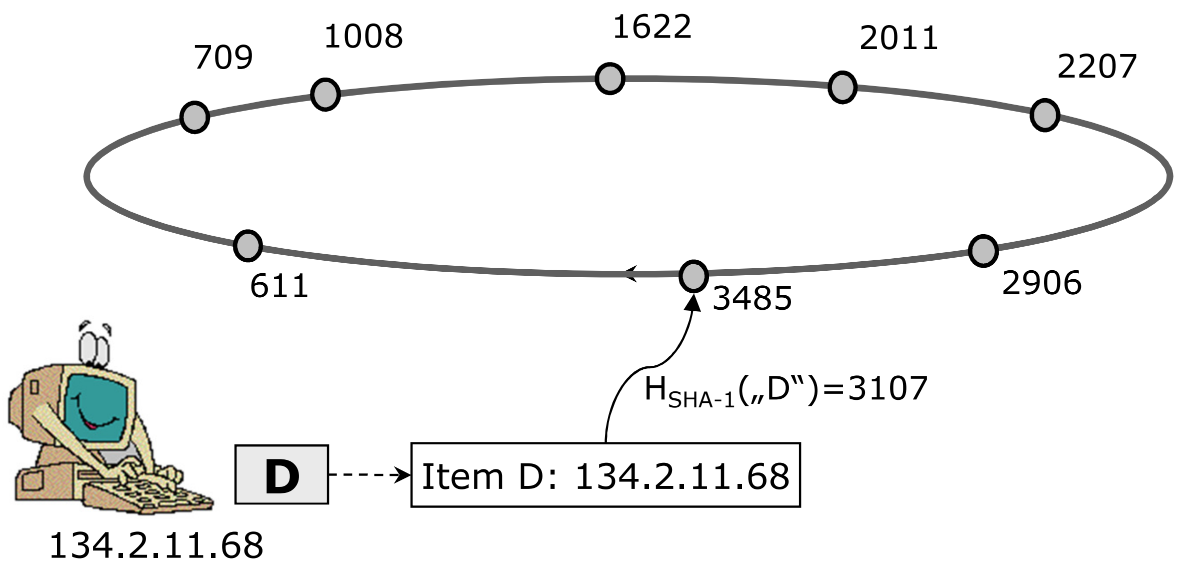
2.4. Association of Data with IDs – Direct Storage

- How is content stored on the nodes?
  - Example:
    H("*my data*") = 3107 is mapped into DHT address space
- Direct storage
  - Content is stored in responsible node for H("*my data*")
    → Inflexible for large content – o.k., if small amount data (<1KB)



2.4. Association of Data with IDs – Indirect Storage

- Indirect storage
  - Nodes in a DHT store tuples like (key,value)
    - Key = Hash(„*my data*”) → 2313
    - Value is often real storage address of content:
      (IP, Port) = (134.2.11.140, 4711)
  - More flexible, but one step more to reach content

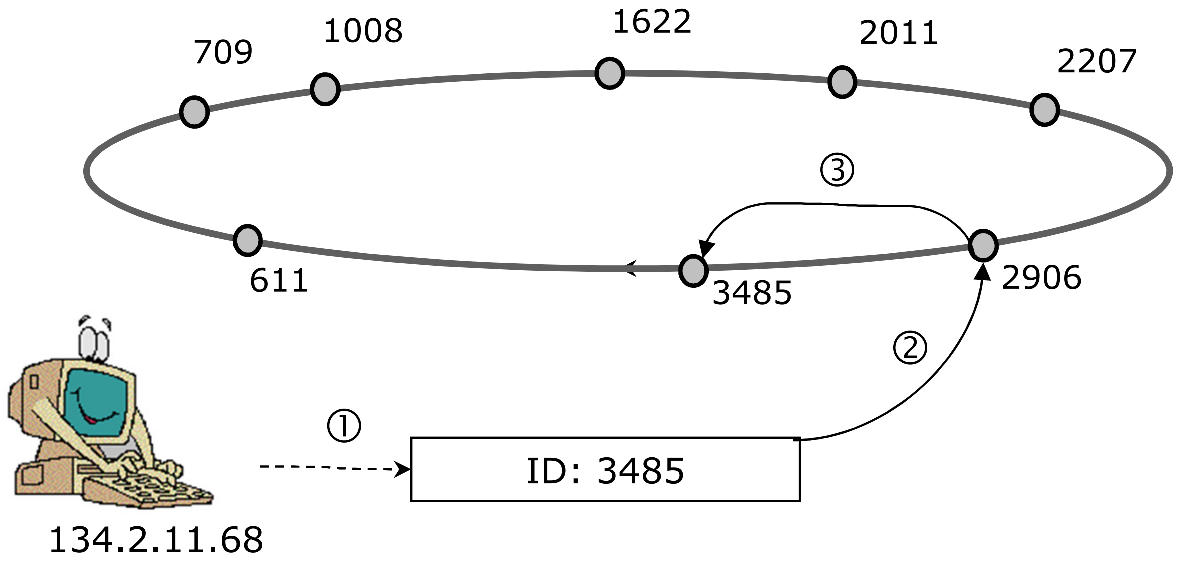


3. DHT Mechanisms

Node Arrival
Node Failure / Departure

3.1. Node Arrival

- Joining of a new node
  1. Calculation of node ID
  2. New node contacts DHT via arbitrary node
  3. Assignment of a particular hash range
  4. Copying of K/V-pairs of hash range (usually with redundancy)
  5. Binding into routing environment



3.2. Node Failure / Departure

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- Failure of a node
  - Use of redundant K/V pairs (if a node fails)
  - Use of redundant / alternative routing paths
  - Key-value usually still retrievable if at least one copy remains

- Departure of a node
  - Partitioning of hash range to neighbor nodes
  - Copying of K/V pairs to corresponding nodes
  - Unbinding from routing environment

4. DHT Interfaces

Comparison: DHT vs. DNS

Summary: Properties of DHTs

4. DHT Interfaces

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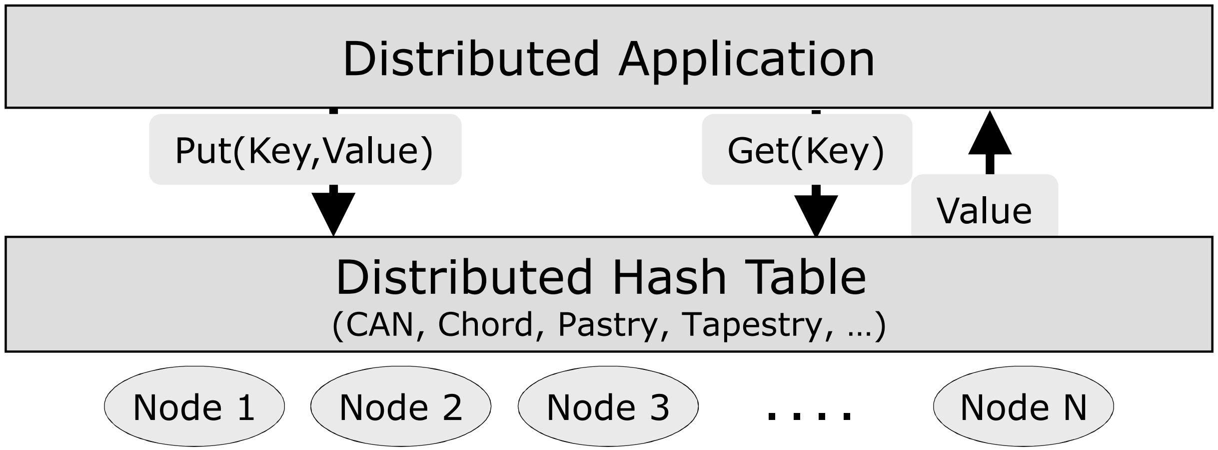
- Generic interface of distributed hash tables
  - Provisioning of information
    - Publish(key,value)
  - Requesting of information (search for content)
    - Lookup(key)
  - Reply
    - value
- DHT approaches are interchangeable (with respect to interface)



4.1. Comparison: DHT vs. DNS (1)

- Comparison DHT vs. DNS
  - Traditional name services follow fixed mapping
    - DNS maps a logical node name to an IP address
  - DHTs offer flat / generic mapping of addresses
    - Not bound to particular applications or services
    - „*value*“ in *(key, value)* may be
      - an address
      - a document
      - or other data …

4.1. Comparison: DHT vs. DNS (2)

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Domain Name System

- Mapping:
  Symbolic name → IP address
- Is built on a hierarchical structure with root servers
- Names refer to administrative domains
- Specialized to search for computer names and services

Distributed Hash Table

- Mapping: key → value can easily realize DNS
- Does not need a special server
- Does not require special name space
- Can find data that are independently located of computers

4.2. Summary: Properties of DHTs

- Use of routing information for efficient search for content
- Keys are evenly distributed across nodes of DHT
  - No bottlenecks
  - A continuous increase in number of stored keys is admissible
  - Failure of nodes can be tolerated
  - Survival of attacks possible
- Self-organizing system
- Simple and efficient realization
- Supporting a wide spectrum of applications
  - Flat (hash) key without semantic meaning
  - Value depends on application

Next …

- Specific examples of Distributed Hash Tables
  - Pastry
    Microsoft Research, Rice University
  - Chord
    UC Berkeley, MIT
  - Tapestry
    UC Berkeley
  - CAN
    UC Berkeley, ICSI
  - P-Grid
    EPFL Lausanne

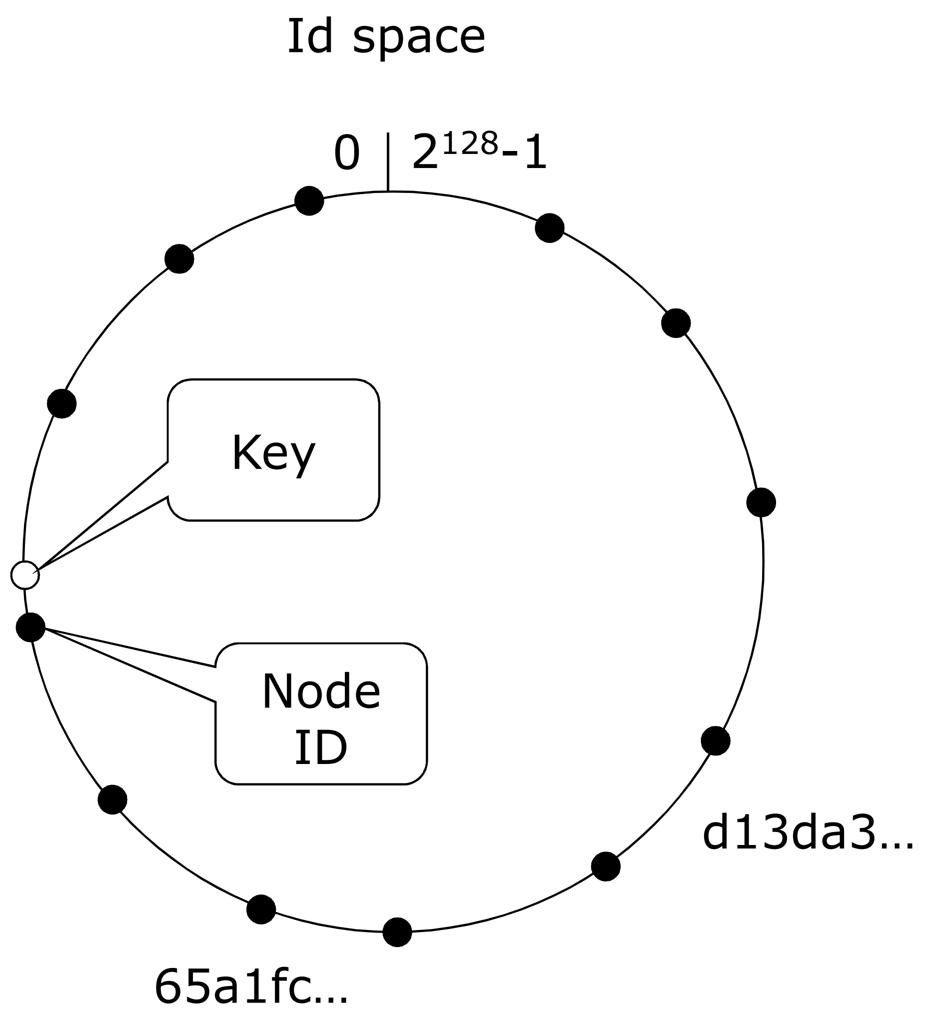
- … and there are plenty of others: Kademlia, Symphony, Viceroy, …

5. Selected DHT Algorithm: Pastry

Identifier Space, Routing Information, Routing Procedure, **Node Addition and Failure,** Common API, FreePastry Demo

5.1. Identifier Space

- Each node and data item has unique l-bit identifier
  - l typically 128
  - Nodes: Node ID
  - Data items: Key
  - Can be calculated from IP address or public key, and data item using secure hash function
- Keys are located on the node whose node ID is numerically closest to the key
- Pastry identifiers are strings of digits to the base 2^b
  - b typically 4
  - E.g. 65a1fc...



5.2. Routing Information

- Leaf Set L
  - Nodes close in the ID space
  - |L|/2 numerically closest larger nodeIds, and |L|/2 numerically closest smaller nodeIds
  - |L| typically 16
- Routing Table R
  - l/b rows with 2^b - 1 entries
  - Row n: Nodes that share an n-digit prefix, but whose n+1th digit is different
  - On average only $\log_{2^b}(N)$ rows are populated
- Neighborhood Set M
  - Nodes close in network locality

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	

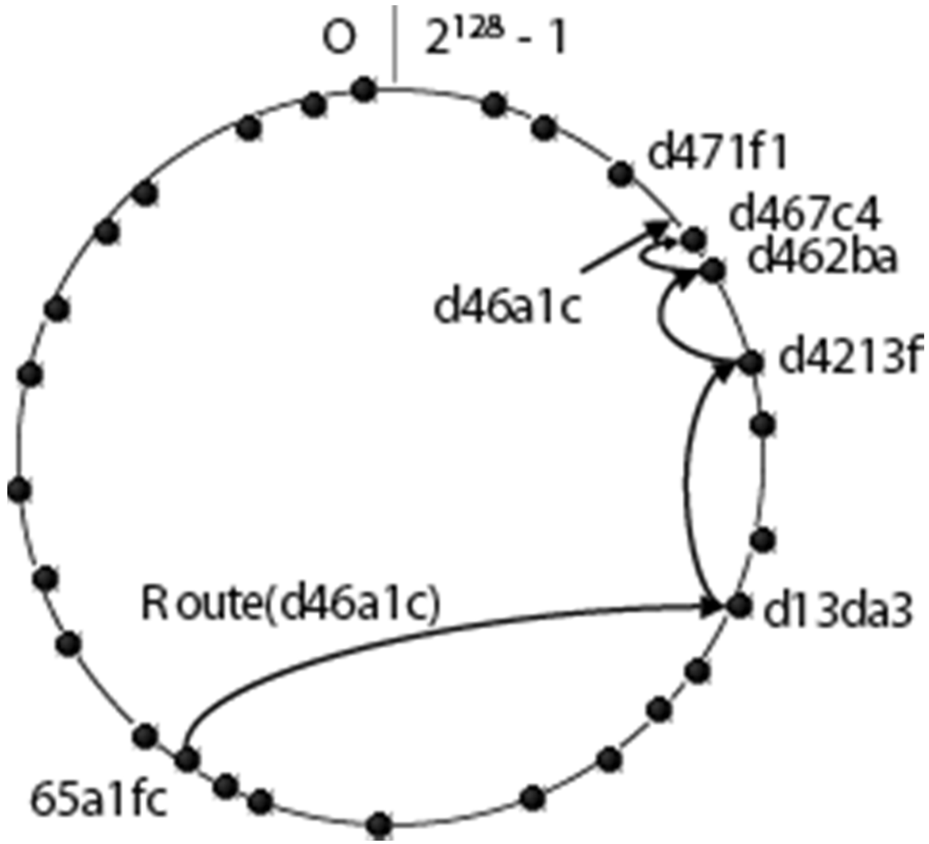
Neighborhood set

13021022	10200230	11301233	31301233
02212102	22301203	31203203	33213321

Pastry node with nodeId 10233102
b = 2, *l* = 16, |L| = 8

5.3. Routing Procedure

- Step 1
  - Forward message to a node who shares with the key a *prefix* that is at least *one digit (b bits) longer* than the prefix that the key shares with the current node
  - If no such nodes exists, forward message to a node who is numerically closer to the key
- Step 2
  - Forward message to a node in the leafset who is numerically closest to the key



Routing of a message from node 65a1fc with key d46a1c

5.4. Node Addition and Failure

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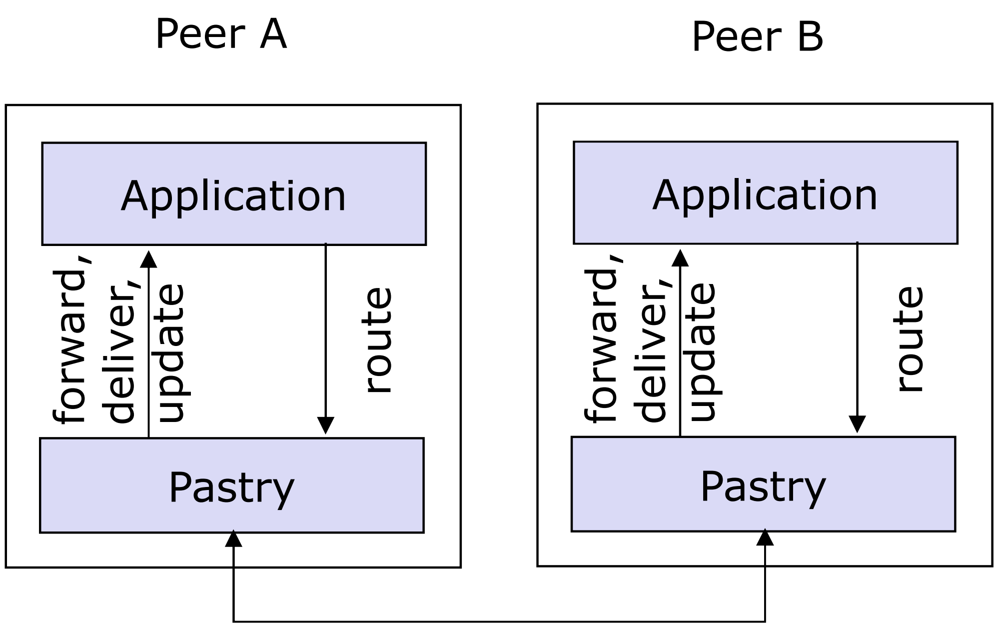
- Node state (routing information) has to be maintained efficiently
- Node Arrivals
  - New node with nodeId X asks nearby node A (bootstrap node) to route a special message to key X
  - Message is routed to node Z, X obtains leaf set from Z and i-th row of routing table from i-th node along the route from A to Z
- Node Failures
  - Leaf set nodes periodically exchange keepalive messages
  - If a node does not respond for a time T, it is declared dead
  - Members of the leaf set are notified and update their leaf set

5.5. Common API for Structured P2P Overlays

- Standardized interface between applications and overlays
  - Implemented by Pastry, others implement it too (Chord, Tapestry, CAN)
- forward(RouteMessage)
  - Called just before a message is forwarded
  - Message could be changed or dropped
- deliver(Id, Message)
  - Called when a message is received
- update(NodeHandle, boolean)
  - Called when a node‘s leafset changes (node joined or left)
- route(Id, Message, NodeHandle)
  - Send a message to a node numerically closest to an Id (key)
  - NodeHandle can serve as a hint



5.6. FreePastry Demo

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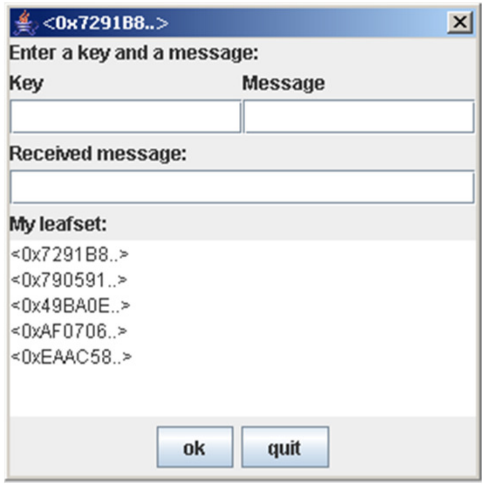

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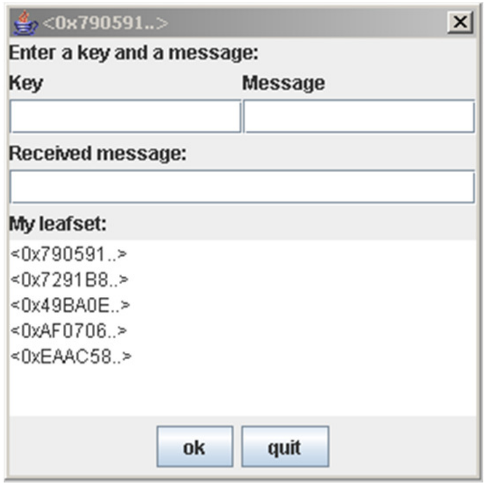

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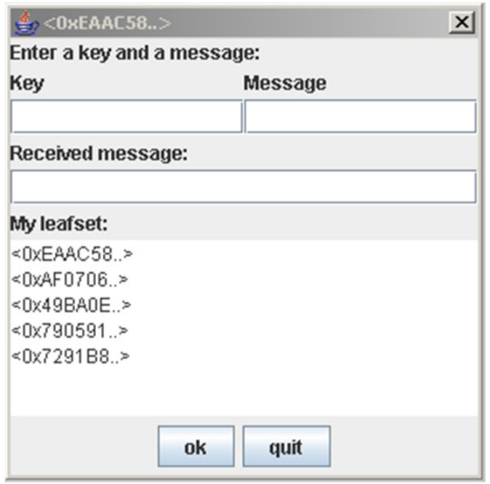

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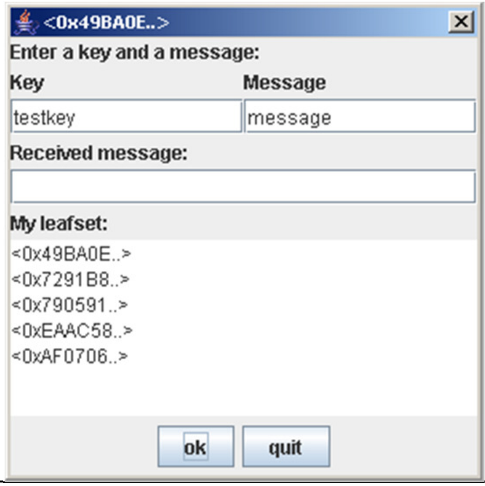

Key: testkey
Message: message

Key maps to
Id <B6B809..>

<0xAF0706..>