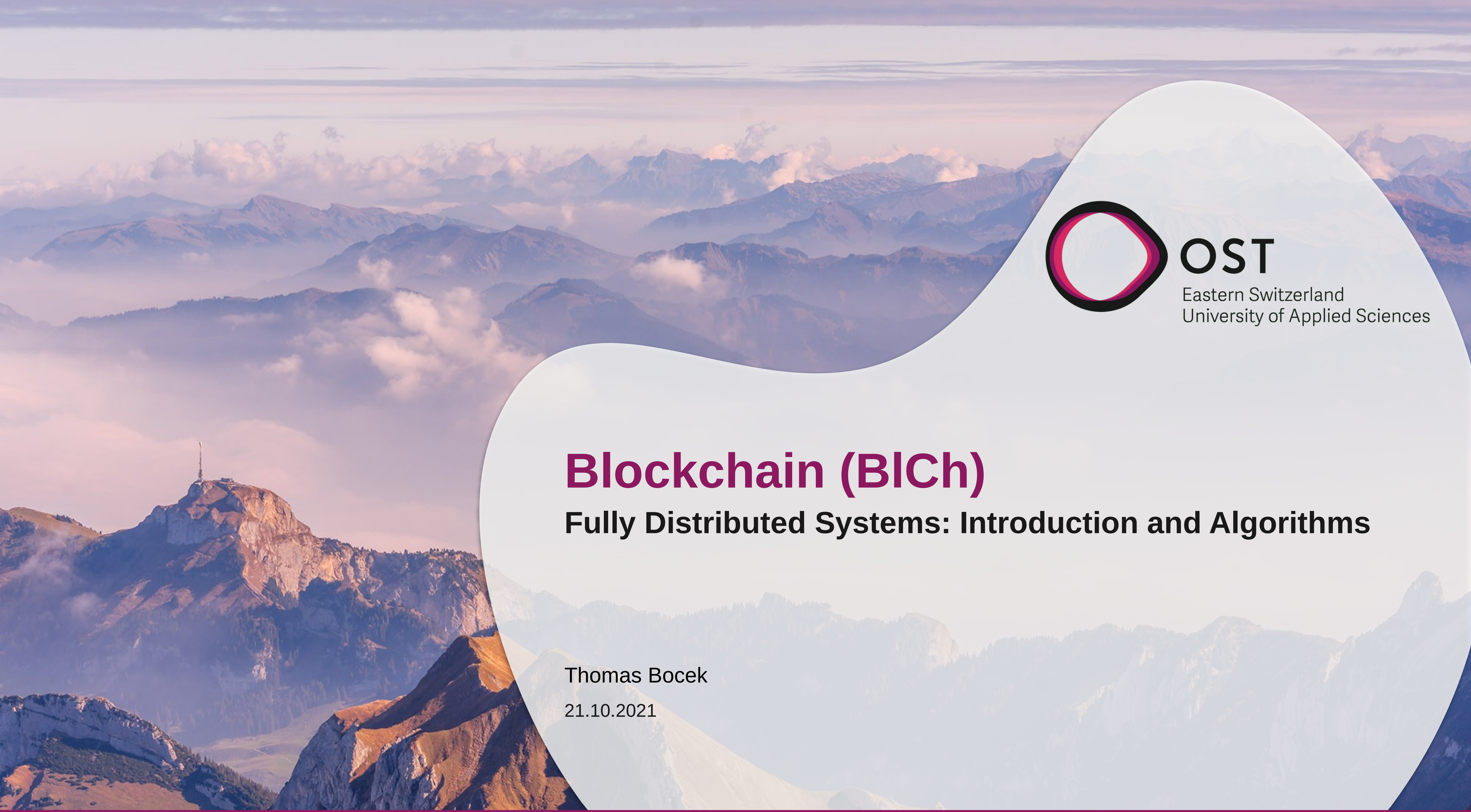


OST
Eastern Switzerland
University of Applied Sciences

Blockchain (BlCh)

Fully Distributed Systems: Introduction and Algorithms

Thomas Bocek

21.10.2021

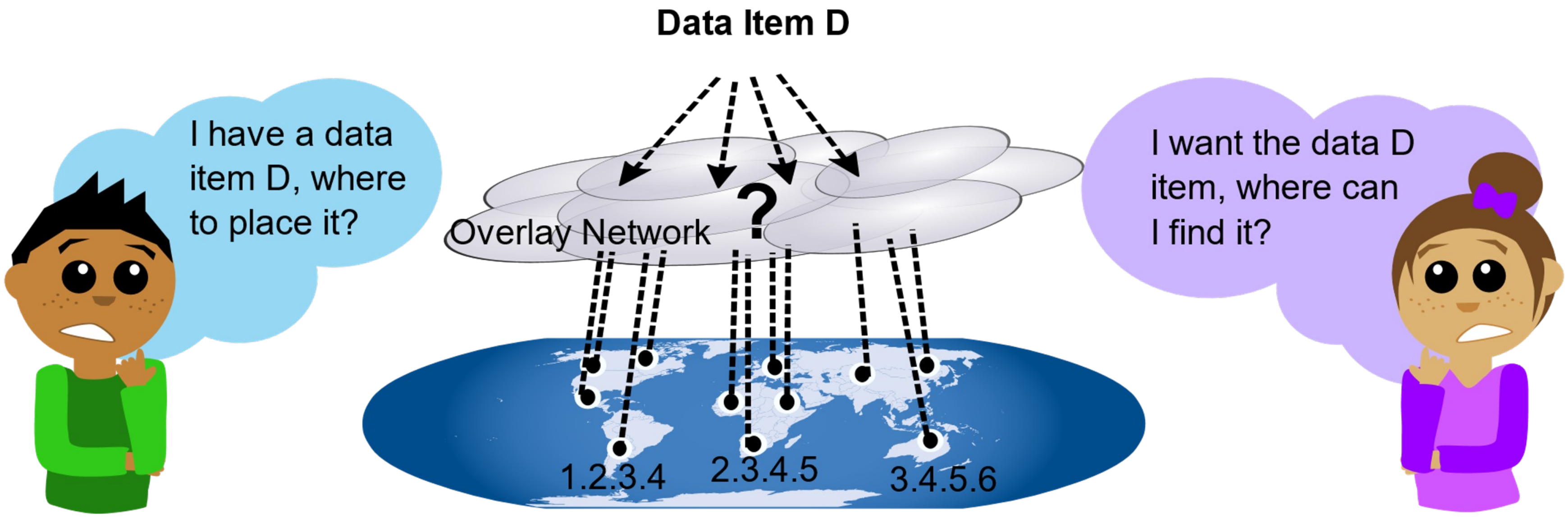
Recall Transparency Principles (DS1, FS21)

- Distributed system should hide its distributed nature
    - Location transparency – users should not be aware of the physical location
    - Access transparency - users should access resources in a single, uniform way
    - Replication transparency – users should not be aware about replicas, it should appear as a single resource
    - Concurrent transparency – users should not be aware of other users
    - ...

- More/other transparencies here, here, here

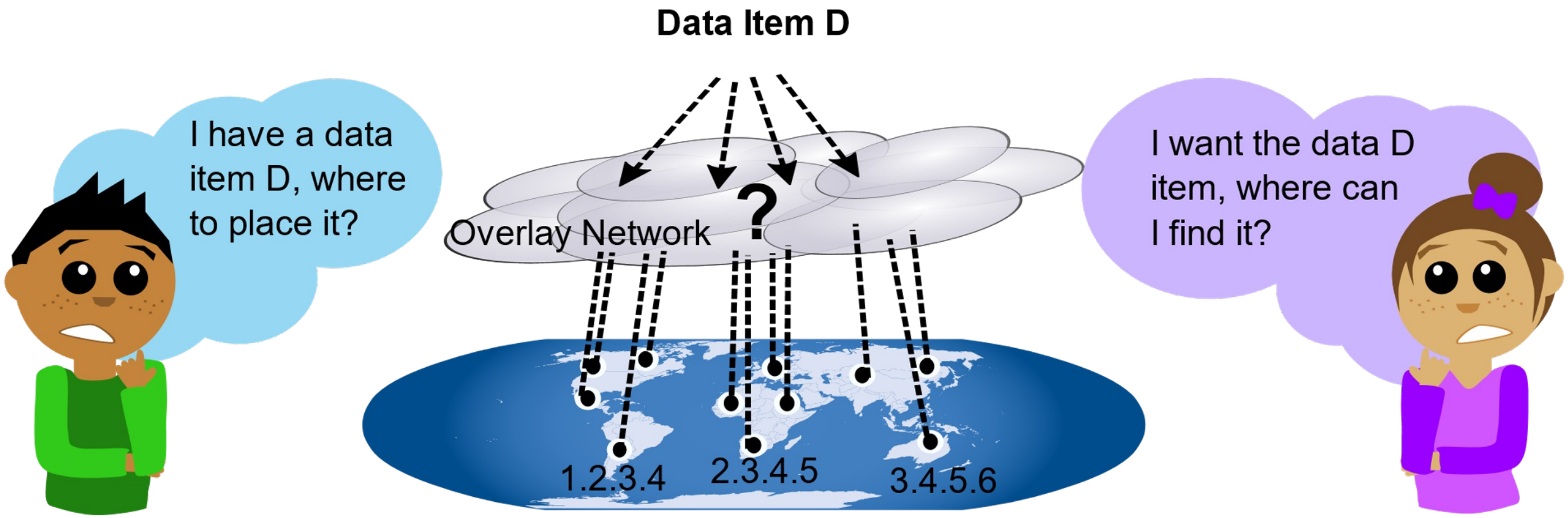
Distributed Management and Retrieval of Data

- Essential challenge in (most) distributed / P2P systems?
  - Location of a data item among systems distributed
    - Where shall the item be stored?
    - How can the item be found?
  - Scalability: keep the complexity for communication and storage scalable
  - Robustness and resilience in case of faults and frequent changes


Data Item D
I have a data item D, where to place it?
Overlay Network
?
I want the data D item, where can I find it?
1.2.3.4
2.3.4.5
3.4.5.6

Comparison of Strategies for Data Retrieval

- Strategies to store and retrieve data items in distributed systems
  - Central server (e.g., service registry, reverse proxy - although main use case is load balancing)
  - Flooding search (e.g., layer 2 broadcasting, wireless mesh networks, Bitcoin)
  - Distributed indexing (Tor, Bittorrent, IPFS, Apache Cassandra, Dynamo, Atek)


I have a data item D, where to place it?
Data Item D
?
Overlay Network
1.2.3.4
2.3.4.5
3.4.5.6
I want the data D item, where can I find it?

Central Server

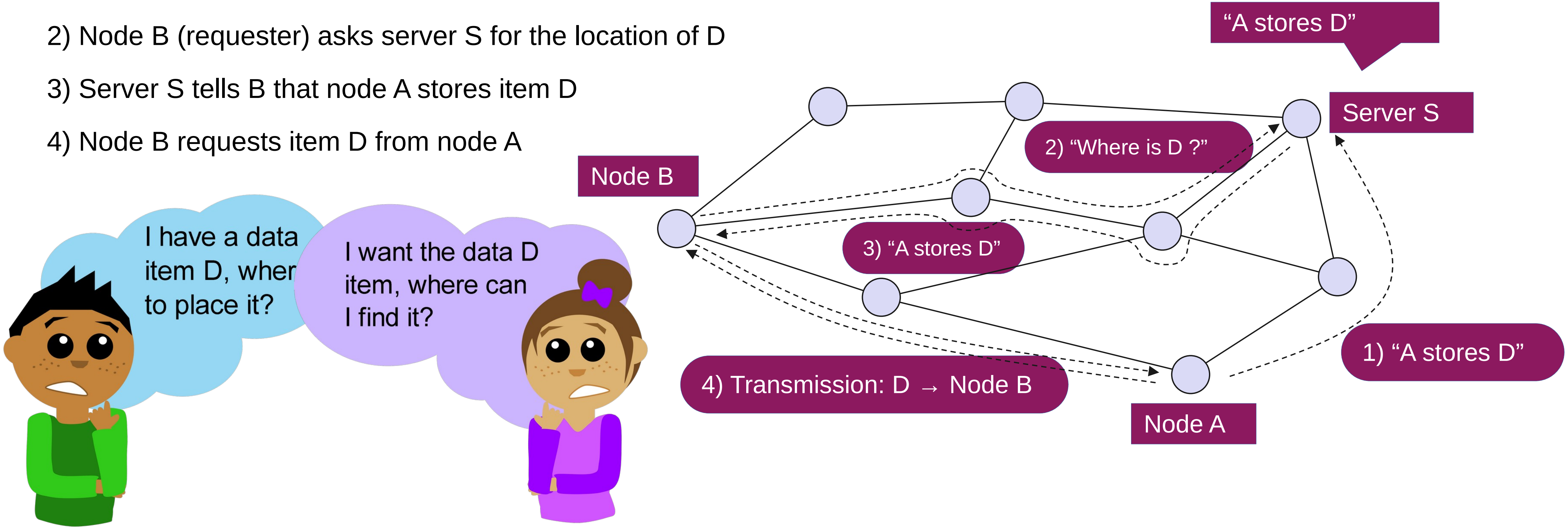
- Simple strategy: Central Server (can be powerful – vertical scaling!)
  - Server stores information about locations

    1) Node A (provider) tells server that it stores item D

    2) Node B (requester) asks server S for the location of D

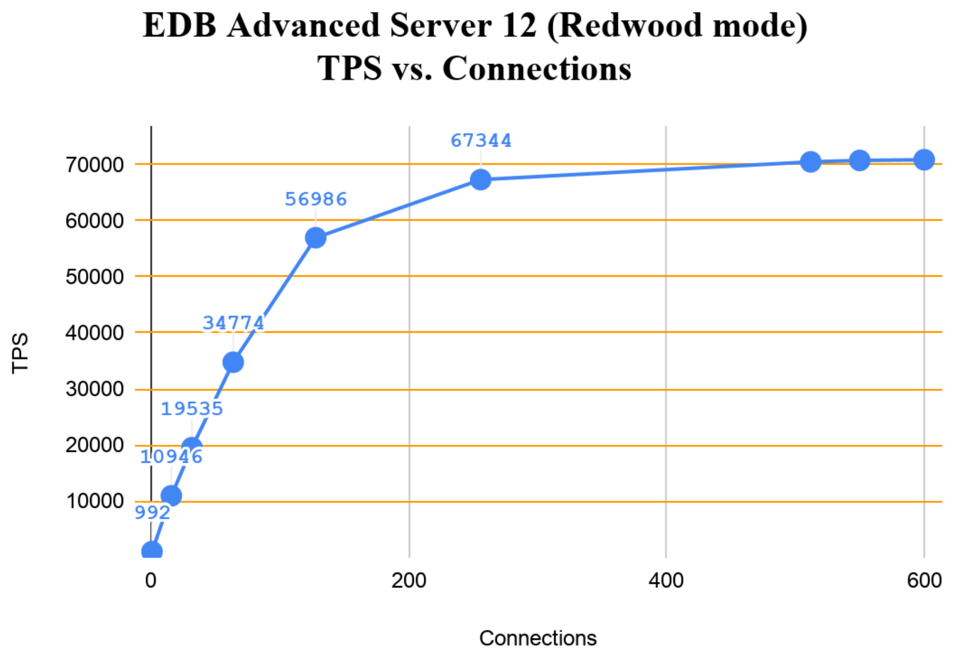
    3) Server S tells B that node A stores item D

    4) Node B requests item D from node A


I have a data item D, wher to place it?
I want the data D item, where can I find it?
“A stores D”
Server S
Node B
2) “Where is D ?”
3) “A stores D”
1) “A stores D”
4) Transmission: D → Node B
Node A

Approach I: Central Server

- 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
  - (Single) central server not suitable for systems with massive numbers of users
- But overall, …
  - Best principle for small and simple applications!

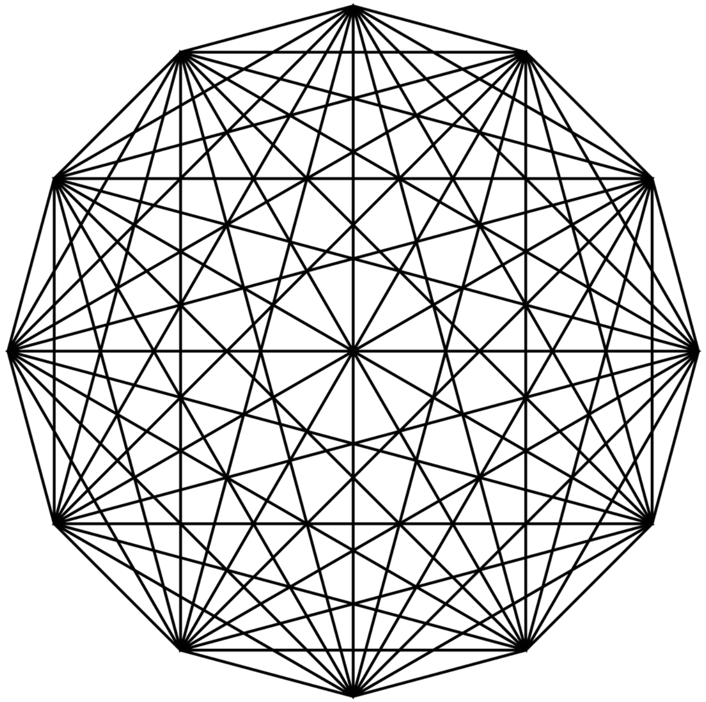


https://www.enterprisedb.com/blog/pgbench-performance-benchmark-postgresql-12-and-edb-advanced-server-12

- AMD EPYC: 48 core, 384GB RAM, 4xNVM SSD
  - ~70k TPS

Approach II: Flooding

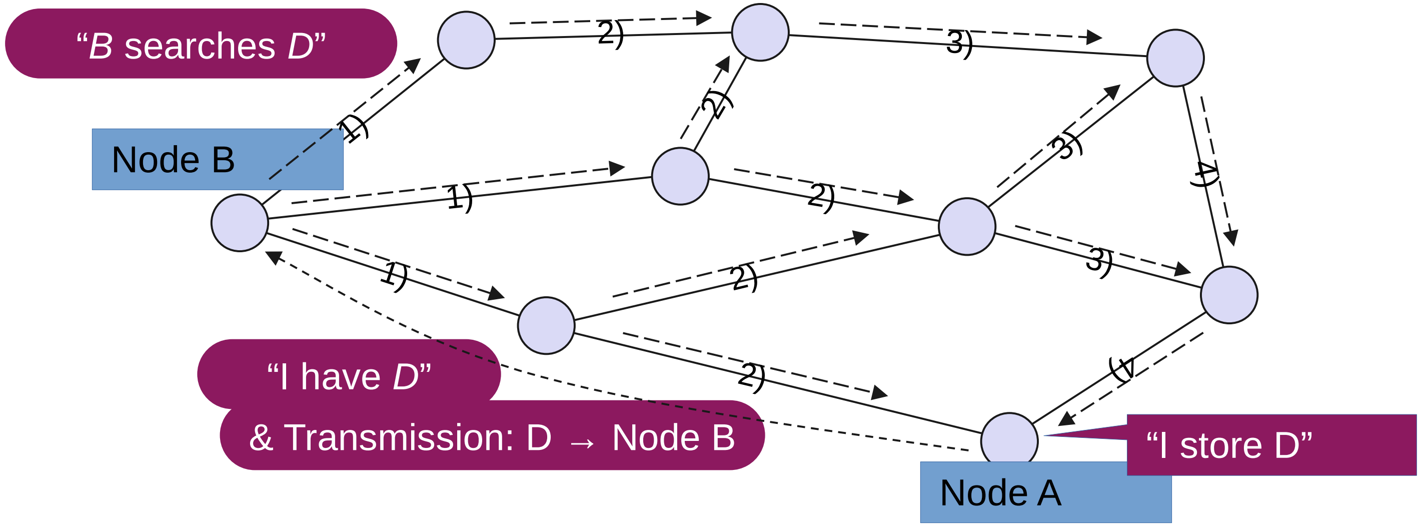
- Fully-distributed Approach
  - Opposite approach of approach I
  - No information on location of a content
- Retrieval of data
  - No routing information for content
  - Necessity to ask as much systems as possible / necessary
  - Approaches
    - Highest degree search: quick search through large areas
    - Random walk
  - Flooding: high traffic load on network, scalability issues (mechanism required to stop spamming, e.g. TX fee)
  - No guarantee to reach all nodes



Approach II: Flooding Search

- Fully Decentralized Approach: Flooding Search
  - No information about location of data in the intermediate systems
  - Flood with search term, or flood all the data (Bitcoin)
    - Flood all the data: search local

- 1) Node B (requester) asks neighboring nodes for item D
- 2-4) Nodes forward request to further nodes (breadth-first search / flooding)
- 5) Node A (provider of item D) sends D to requesting node B


“*B searches D*”

Node B

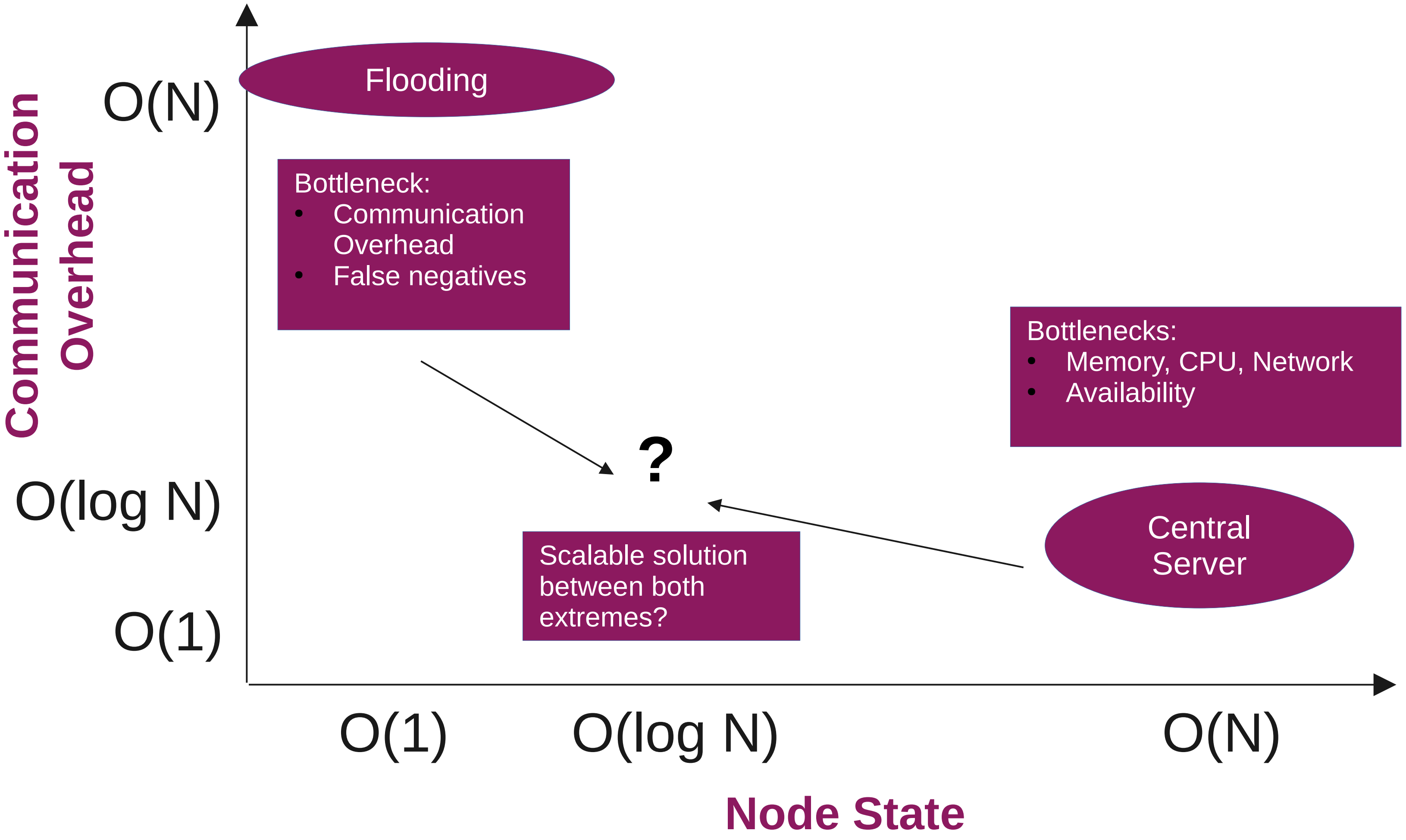
“I have *D*”

& Transmission: D → Node B

“I store D”

Node A

Motivation Distributed Indexing (1)



Bottleneck:

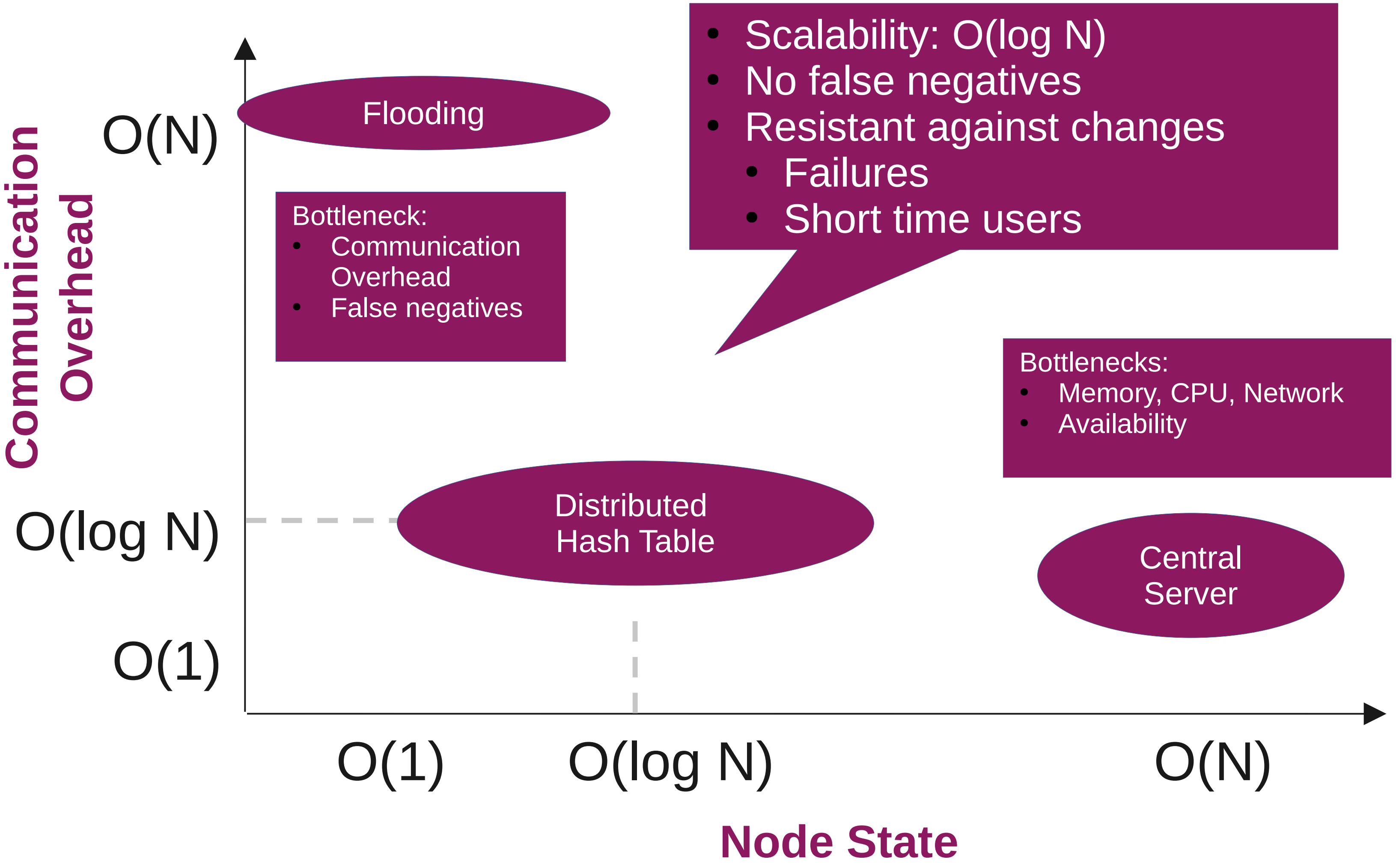
- Communication Overhead
- False negatives

Bottlenecks:

- Memory, CPU, Network
- Availability

Scalable solution between both extremes?

Motivation Distributed Indexing (1)



- Scalability: O(log N)
- No false negatives
- Resistant against changes
  - Failures
  - Short time users

Bottleneck:

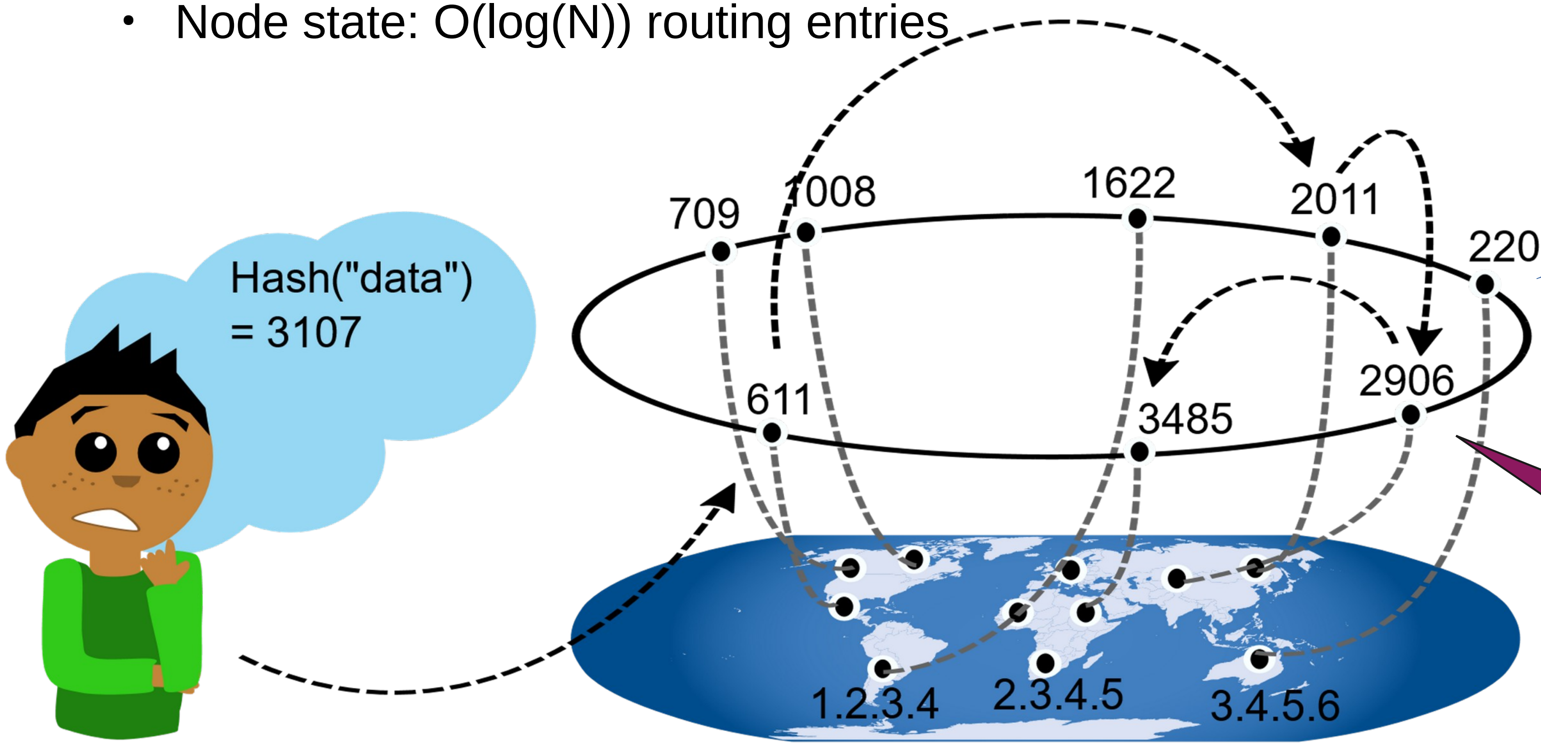
- Communication Overhead
- False negatives

Bottlenecks:

- Memory, CPU, Network
- Availability

Distributed Indexing (1)

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

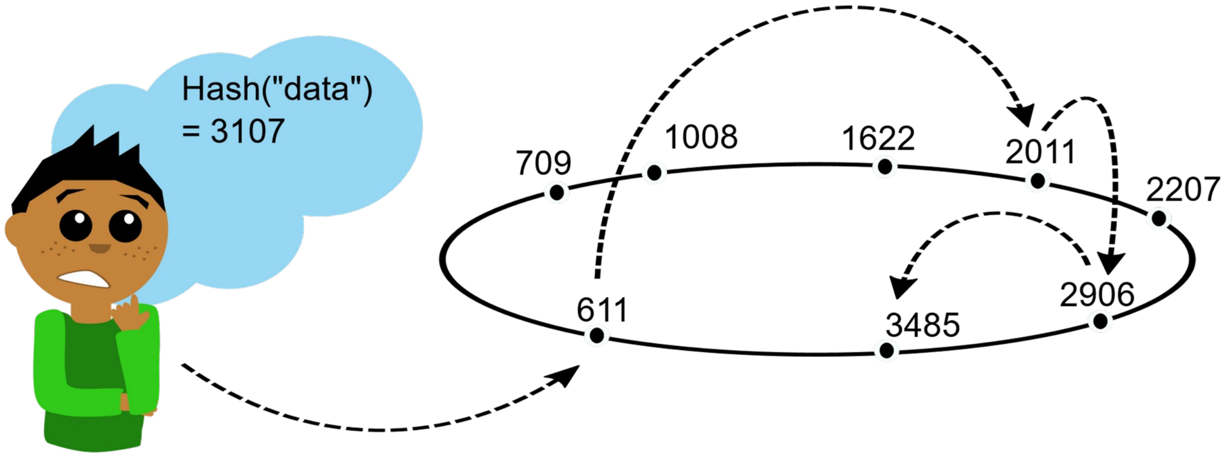


Routing in O(log(N)) steps to the node storing the data

Nodes store O(*log(N)*) routing information to other nodes

Distributed Indexing (2)

- Approach of distributed indexing schemes
  - Data and nodes are mapped into same address space
  - Nodes maintain routing information to other nodes
    - Definitive statement of existence of content
- Problems
  - Maintenance of routing information required
  - Fuzzy queries not primarily supported (e.g., wildcard searches)



Comparison of Lookup Concepts

- Big O notation: classify computer algorithms

System	Per Node State	Communication Overhead	Fuzzy Queries	No false negatives	Robustness / horizontal scalable
Central Server	O(N)	O(1)			( )
Flooding	O(1)	O(N)		( )	
Distributed Hash Tables	O(log N)	O(log N)	( )		

Fundamentals of Distributed Hash Tables

- Challenges for designing DHTs
  - Desired Characteristics
    - 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

- Distributed Hash Table
  - Consistent hashing → nodes responsible for hash value intervals
  - More peers = smaller responsible intervals
- Hash Table [link]
  - Modulo hashing
    - Bucket = hash(x) mod n
  - If n changes, remapping / bucket changes
  - N changes if capacity is reached
  - Remapping is expensive in DHT!
    - DHTs reassign responsibility

Distributed Management of Data

1. Mapping of nodes and data into same address space

- Peers and content are addressed using flat identifiers (IDs)
  - E.g., Address is public key (256bit) or SHA256 of public key. Content ID = SHA256(content)
- 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

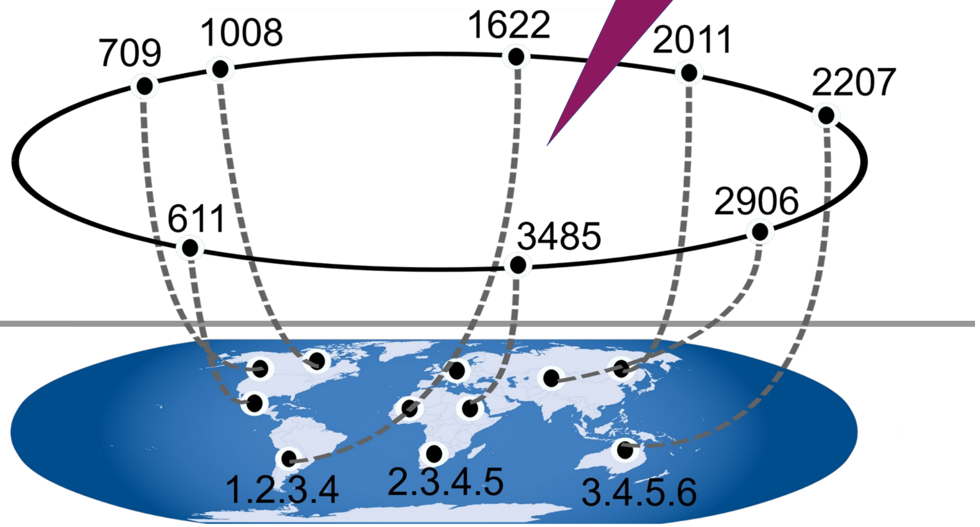
- Store data = first, search for responsible node
  - Not necessarily known in advance
- Search data = first, search for responsible node

Association of Address Space with Nodes

- 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 uncorrelated

Node 3485 is responsible for data items in range 2907 to 3485

(in case of a Chord-DHT)

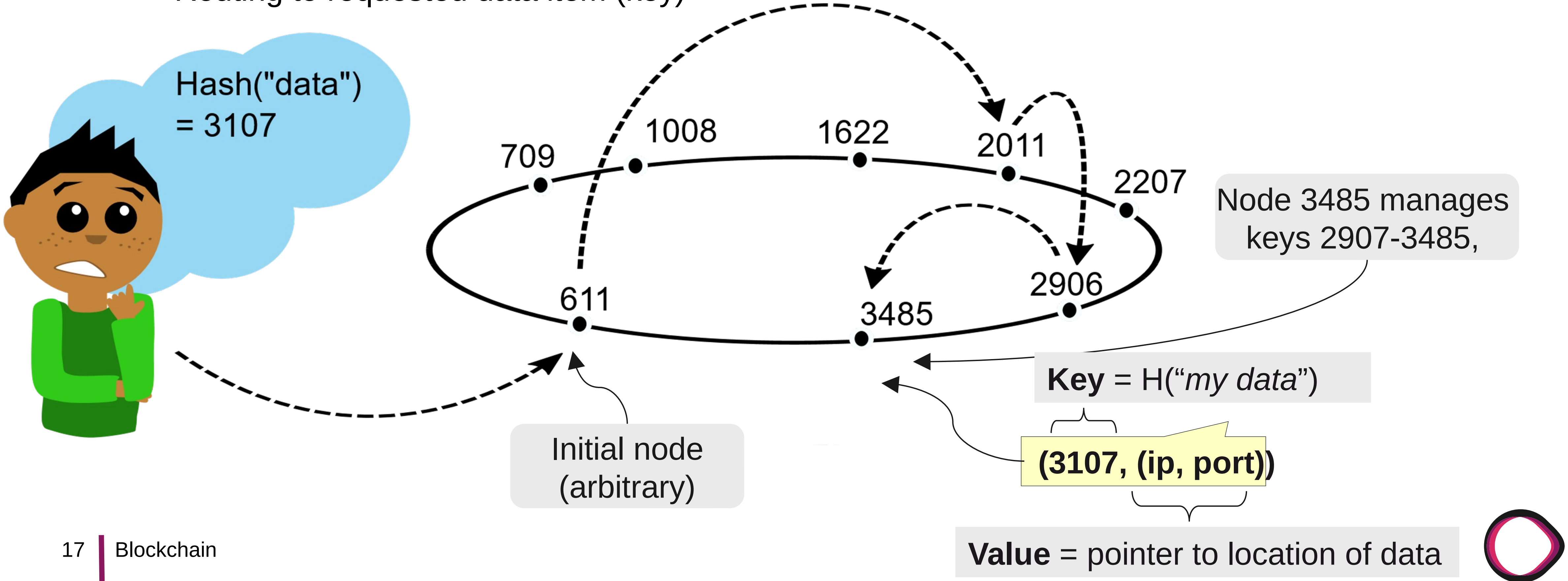


Logical view of the Distributed Hash Table

Mapping on the real topology

Routing to a Data Item

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



Node 3485 manages keys 2907-3485,

Initial node (arbitrary)

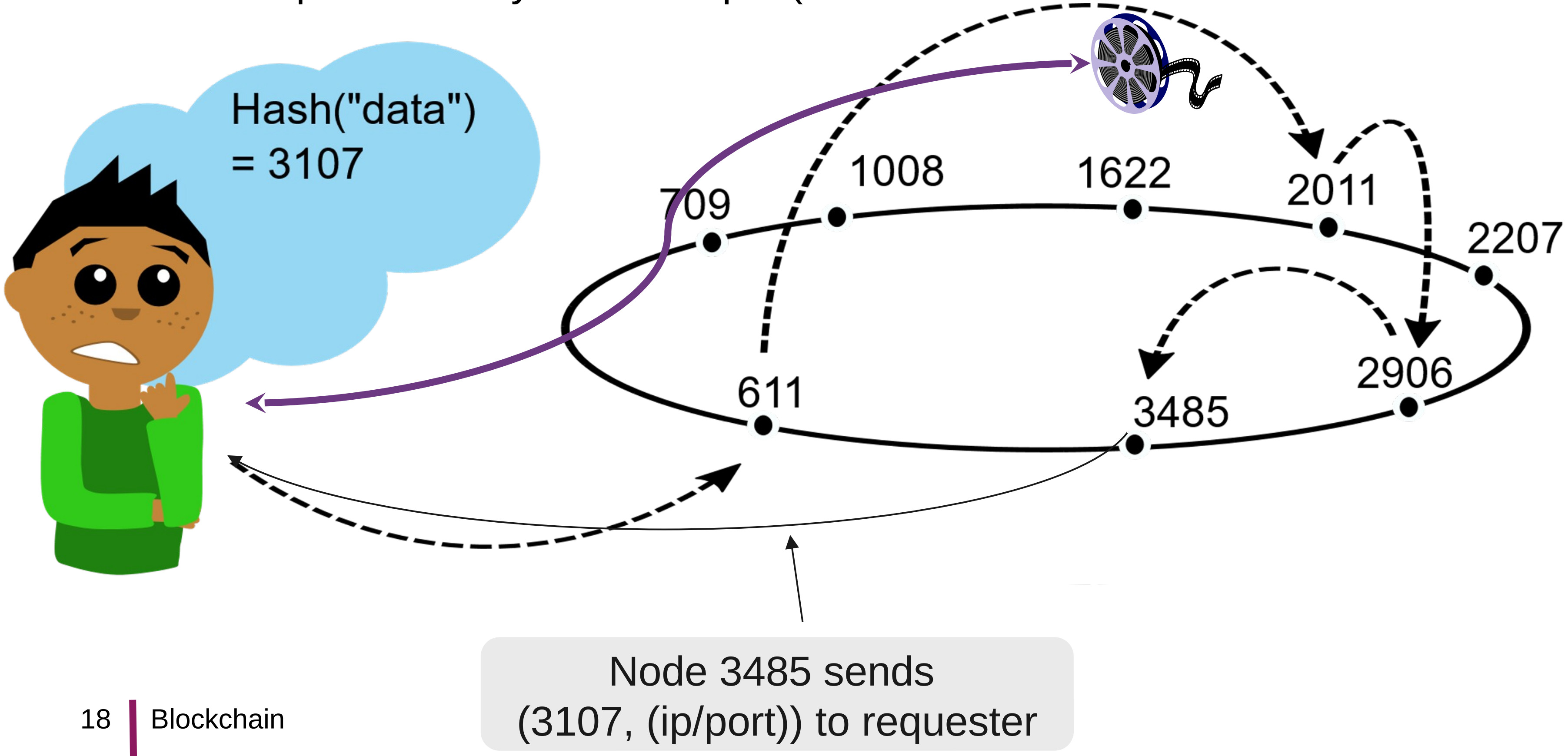
Key = H(“*my data*”)

(3107, (ip, port))

Value = pointer to location of data

Routing to a Data Item

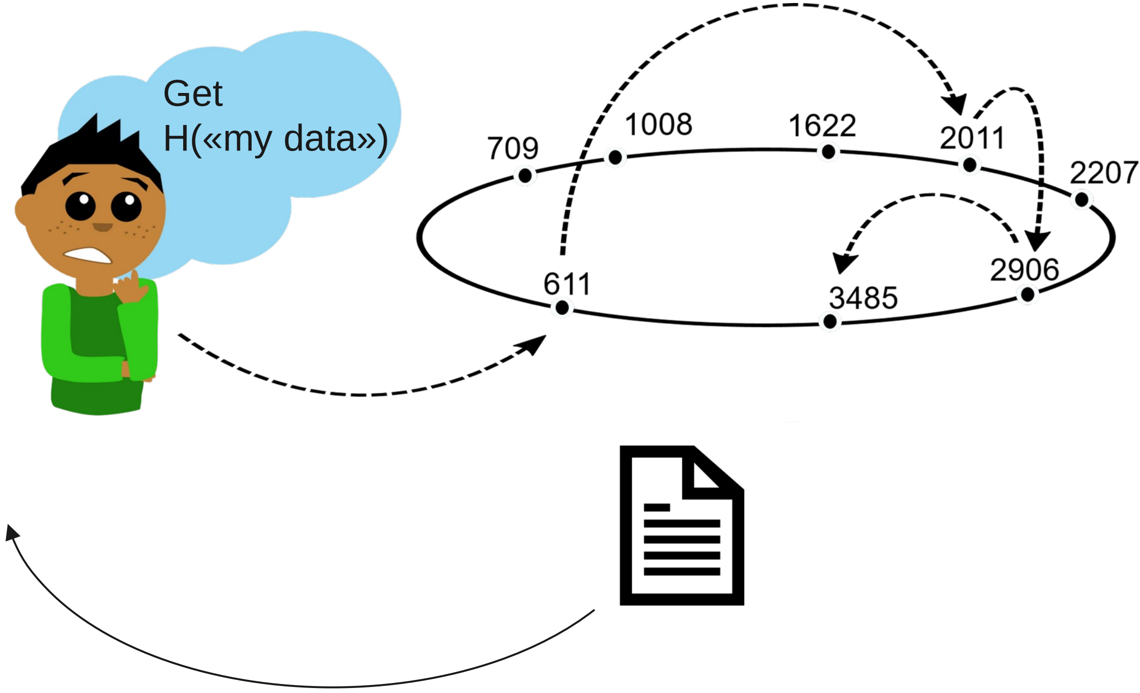
- Getting the content
  - K/V-pair is delivered to requester
  - Requester analyzes K/V-tuple (and downloads data from actual location – in case of indirect storage)



Node 3485 sends
(3107, (ip/port)) to requester

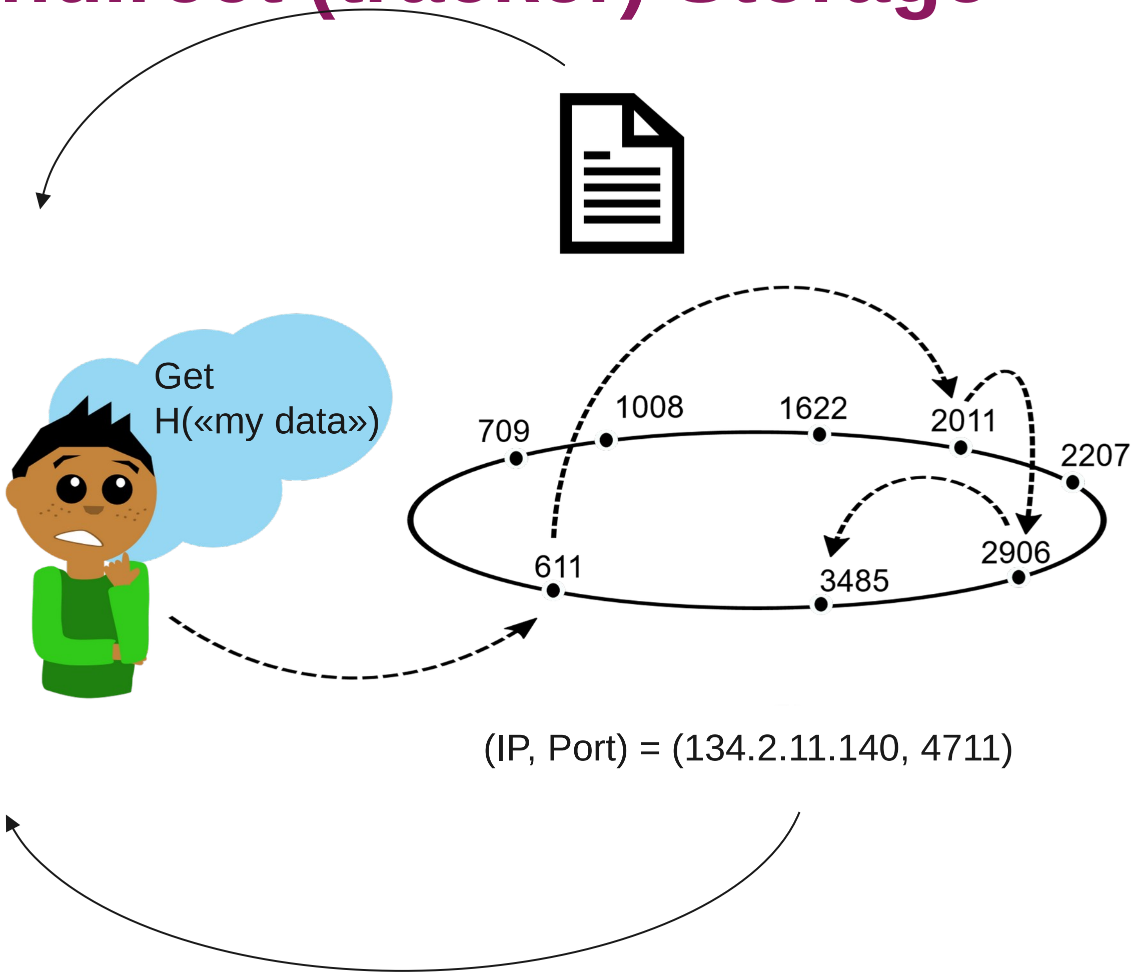
Association of Data with IDs – Direct Storage

- 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 (~KB) or used internally



Association of Data with IDs – Indirect (tracker) 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 for large data, but one step more to reach content

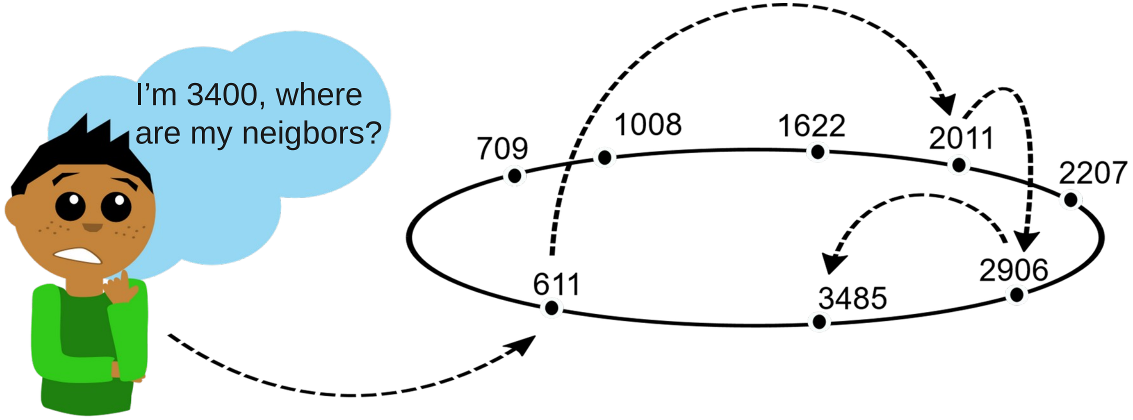


(IP, Port) = (134.2.11.140, 4711)

Join/Leave

- Joining of a new node
  1) Calculation of node ID (normally random / or based on PK)
  2) New node contacts DHT via arbitrary node (bootstrap node)
  3) Lookup of its node ID (routing)
  4) Copying of K/V-pairs of hash range (in case of replication)
  5) Notify neighbors
- 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
  - Copying of K/V pairs to corresponding nodes
    - Can be before or after unbinding
  - Friendly unbinding from routing environment
    - If unbinding is unfriendly, need for keep-alive messages



Kademlia

- Several approaches to build DHT
  - Distance metric as key difference
    - Chord, Pastry: numerical closeness
    - CAN: multidimensional numerical closeness
    - Kademlia: XOR metric
- Kademlia designed in 2002 by Maymounkov and Mazières
  - Many implementations, application specific
    - BitTorrent (tracker), IPFS, Tor Onion Services
- Parallel queries
  - For one query, α (alpha) concurrent lookups are sent
  - More traffic load, but lower response times
- Preference towards old contacts
  - Study has shown that the longer a node has been up, the more likely it is to remain up another hour
  - Resistance against DoS attacks by flooding the network with new nodes
- Network maintenance
  - In Chord: active fixing of fingers
  - In Kademlia: active maintenance
- DHT-based overlay network using the XOR distance metric
  - Symmetrical routing paths (A → B == B → A)
    - due to XOR(A,B) == XOR (B,A)

Construction of Routing Table

- Each Kademlia node and data item has unique identifier
  - 160 bit (SHA-1)
  - Nodes: Node ID (160bit)
    - Can be calculated from IP address or public key, and data item using secure hash function, or just random
  - Data items: Keys (160bit), hash of data item
- Keys are located on the node whose node ID is closest to the key
  - Knows neighbors well, further nodes not that much
  - Kademlia: 160 buckets with size 20 (8)
  - If distance can be represented in m bits, bucket m will be used

XOR Distance Calculation:

ID Node A: 110101
ID Node B: 010001

$d_{XOR}(A,B) = d(110101,010001)$

```
1 1 0 1 0 1
    XOR
0 1 0 0 0 1
       ↓
1 0 0 1 0 0
```

$d_{XOR}(A,B) = 1\ 0\ 0\ 1\ 0\ 0_2 = 36_{10}$

Kademlia Example

- 2^3, max size 8, #6 searches for 3

1	2	3
7	4 (or 5)	0 (or 1, 2)

Routing Table of #6
6 xor 3 = 101b

- Neighbors of 6, if k=1

1	2	3
1	2	4 (or 5, 6, 7)

Routing Table of #0
0 xor 3 = 11b

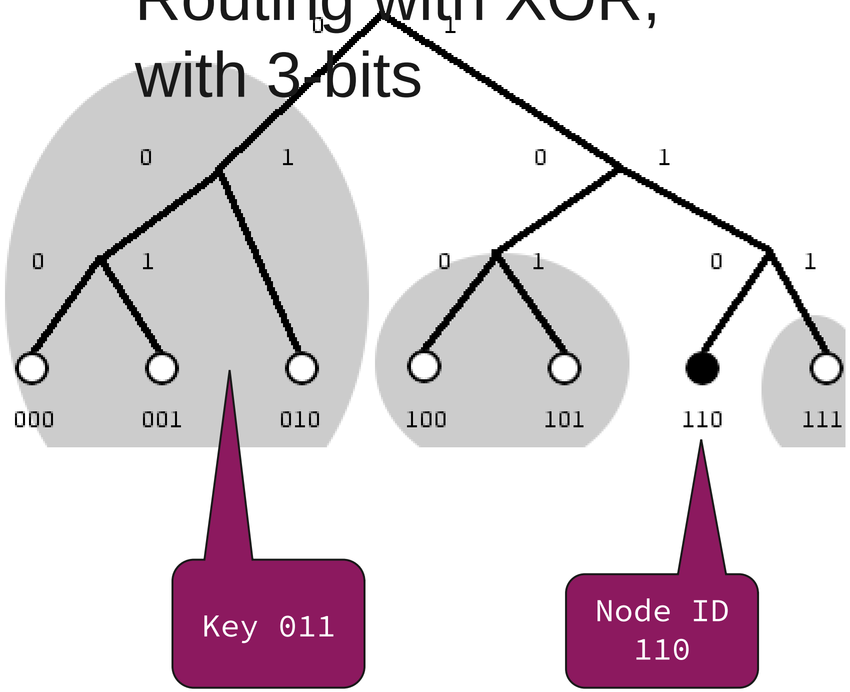
- Search for 3, ask 0, neighbors of 0
- Ask 2, neighbors of 2

1	2	3
-	0 (or 1)	4 (or 5, 6, 7)

Routing Table of #2
2 xor 3 = 1b

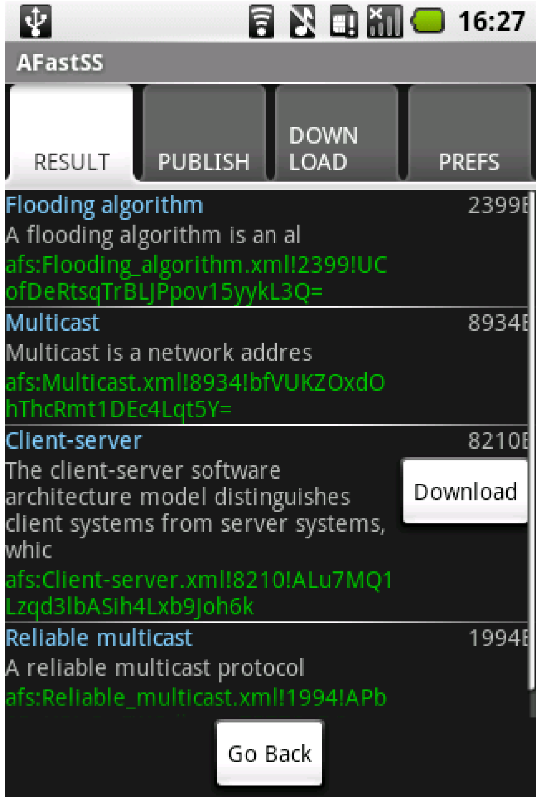
- Ask 2, 2 replies 0. 6 figures that there is no closer node, 2 is the closest one (2 xor 3 =1)

Routing with XOR, with 3 bits



TomP2P

- TomP2P is a P2P framework/library
  - Unmaintained ☹
  - Implements DHT (structured), broadcasts ([un]structured), direct messages (can implement super-peers)
  - NAT handling: UPNP, NATPMP, relays, hole punching (work in progress)
  - Direct / indirect (tracker / mesh) storage
  - Direct / indirect replication (churn prediction and ~rsync)
- Yes, this is the first Android device, HTC Dream, Sept. 2009


16:27

AFastSS

RESULT | PUBLISH | DOWN LOAD | PREFS

Flooding algorithm 2399E
A flooding algorithm is an al
afs:Flooding_algorithm.xml!2399!UCofDeRtsqTrBLJPpov15yykL3Q=

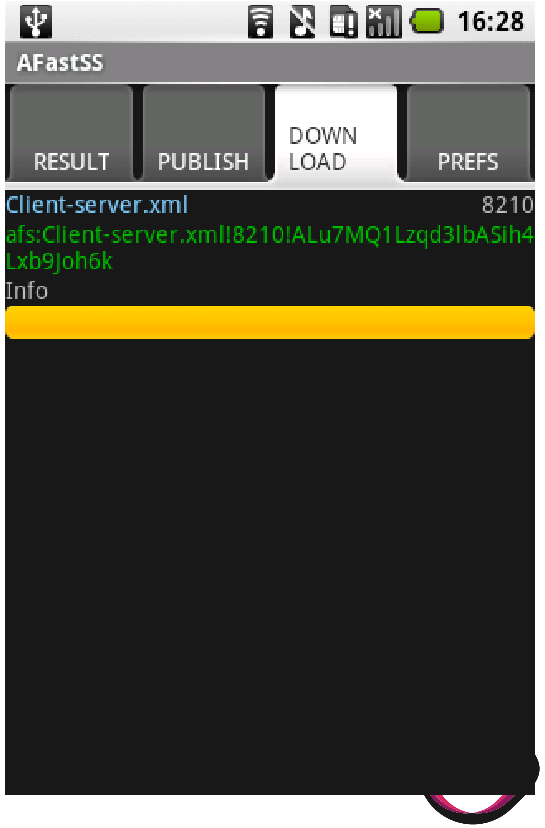
Multicast 8934E
Multicast is a network addres
afs:Multicast.xml!8934!bfVUKZOxdOhThcRmt1DEc4Lqt5Y=

Client-server 8210E
The client-server software architecture model distinguishes client systems from server systems, whic
afs:Client-server.xml!8210!ALu7MQ1Lzqd3lbASih4Lxb9Joh6k

Download

Reliable multicast 1994E
A reliable multicast protocol
afs:Reliable_multicast.xml!1994!APb

Go Back


16:28

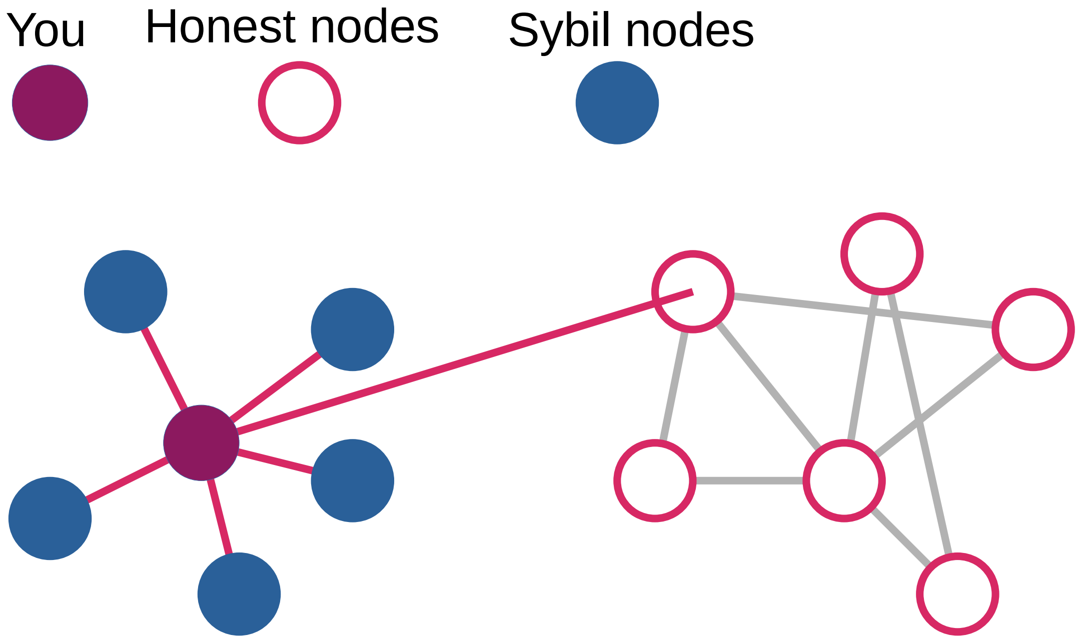
AFastSS

RESULT | PUBLISH | DOWN LOAD | PREFS

Client-server.xml 8210
afs:Client-server.xml!8210!ALu7MQ1Lzqd3lbASih4Lxb9Joh6k
Info

Fully Decentralized Systems

- Always consider Sybil attacks
  - TomP2P, BitTorrent, etc.
    - Data can always disappear
  - Know when data changed



- Sybil attack
  - Create large number of identities
  - Larger than honest nodes
    - Control “close” nodes in a DHT
    - Isolate nodes
- Prevention [source]
  - Creation of identities costs money
  - Always assume data from other nodes may be missing
    - Bitcoin – chain of block, if block is missing, you notice
  - Chain of trust / reputation

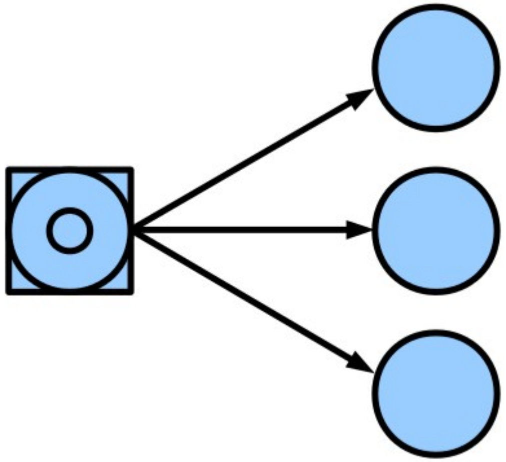
Attacking the DHT

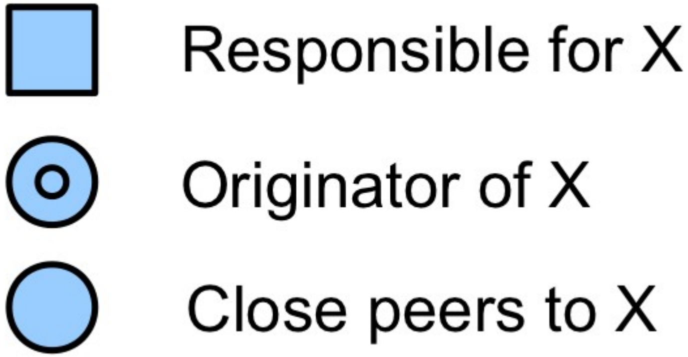
- Example
- Create a key for a data item close to the target:
  Number160.createHash(data).xor(new Number160(0)) – distance 0, perfect match
  Number160.createHash(data).xor(new Number160(1)) – distance 1
  Number160.createHash(data).xor(new Number160(2)) – distance 2
  …
- Or create key of node close to the target
  new PeerBuilder(new Number160(RND)).ports(port).start(), where RND is
  Number160.createHash(data).xor(new Number160(0))
  Number160.createHash(data).xor(new Number160(1))
  …
- Peer can then answer there is no data
- For previously known values / peers (known public key)
  - Cannot change data, but make it disappear

Redundancy in DHTs

- Replication
  - Enough replicas
  - Direct replication
    - Originator peer is responsible
    - Periodically refresh replicas
    - Example: tracker that announces its data

- Problem
  - Originator offline → replicas disappear. Content has TTL

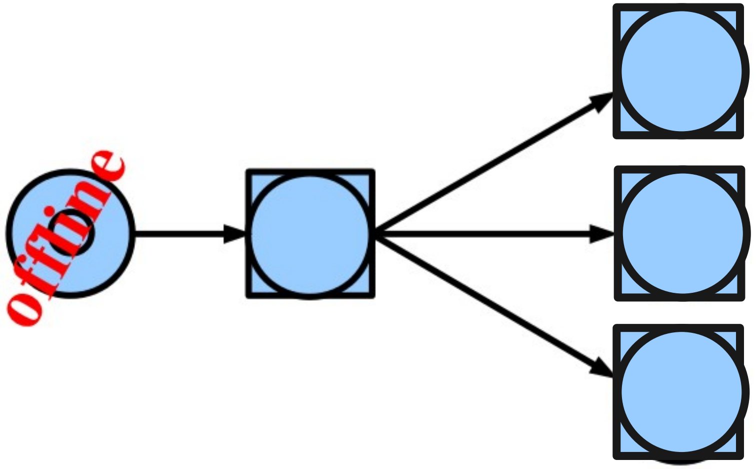




Redundancy in DHTs

- Indirect Replication
  - The closest peer is responsible, originator may go offline vs any close peers are responsible
    - Periodically checks if enough replicas exist
    - Detects if responsibility changes

- Problem
  - Requires cooperation between responsible peer and originator
  - Multiple peers may think they are responsible for different versions → eventually solved



closest vs any

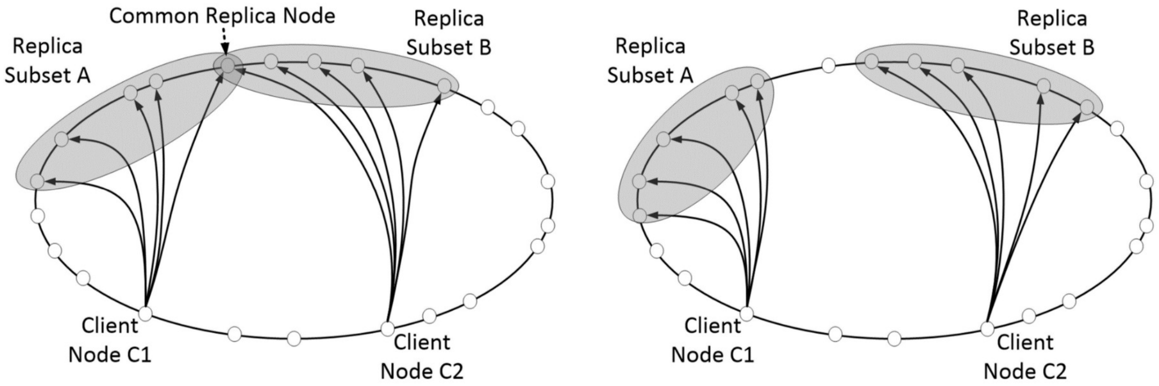
□ Responsible for X

◉ Originator of X

○ Close peers to X

Replication and Consistency

- DHTs have weak consistency
  - Peer A put X.1
  - Peer B gets X.1
  - Peer B modifies it puts B.2
- Same time (time in distributed systems):
  - Peer C gets X.1
  - Peer C modifies it puts C.2
- Replication makes it worse
  - Consistency: generic issue in distributed systems, requires typically coordinator
- Multi-Paxos, Raft, ZooKeeper → Leader Election



- vDHT: CoW, versions, 2PC, replication, software transactional memory (STM) → for consistent updates. Works for light churn
  - No locking, no timestamps (replication time may have an influence)
  - Every update – new version
    - get latest version, check if all replica peers have latest version, if not wait and try again
    - put prepared with data and short TTL, if status is OK on all replica peers, go ahead, otherwise, remove the data and go to step 1.
    - put confirmed, don’t send the data, just remove the prepared flag
  - Leader is the originator
  - In case of heavy churn, API user needs to resolve