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Overlay and P2P Networks

Structured Networks and DHTs

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- Structured networks
- Foundations
- Cluster-based structures

Structured Overlays

Structured overlays are typically based on the notion of a **semantic free index**

They utilize **hashing** extensively to map data to servers

The **cluster**-based techniques typically can guarantee a very small number of hops to reach a given destination

The decentralized **DHTs** balance hop count with the size of the routing tables, network diameter, and the ability to cope with changes

Consistent hashing

Consistent hashing was first introduced in 1997 as a solution for distributing requests to a dynamic set of web servers

In this solution, incoming messages with keys were mapped to web servers that can handle the request

Consistent hashing has had dramatic impact on overlay algorithms

DHTs utilize consistent hashing to partition an identifier space over a distributed set of nodes. The key goal is to keep the number of elements that need to be moved at minimum

Consistent hashing continued

In most traditional hash tables a change in the number of array elements causes nearly **all keys** to be remapped

They are therefore useful for balancing load to a fixed collection of servers, but not suitable for dynamic server collections

Consistent hashing is a technique that provides hash table functionality in such a way that the addition or removal of an element does **not significantly change** the mapping of keys to elements

The technique requires only *K/n* keys to be remapped on average, where *K* is the number of keys, and *n* is the number of nodes

Ranged hash functions

Hashing applied to the distributed case

Ranged hash functions are hash functions that depend on the set of available buckets

A typical ranged hash function hashes items to positions in some space

Then assigns each item to the nearest available bucket

As the set of buckets changes, an item may move to a new nearest available bucket

Another view

A ranged hash function changes minimally as the range of the function changes

Range changes when a server is added or removed

Ranged hash with a ring

Items and buckets are mapped to a uniformly random place on continuous unit ring [0,1).

Each item is assigned to the closest possible bucket.

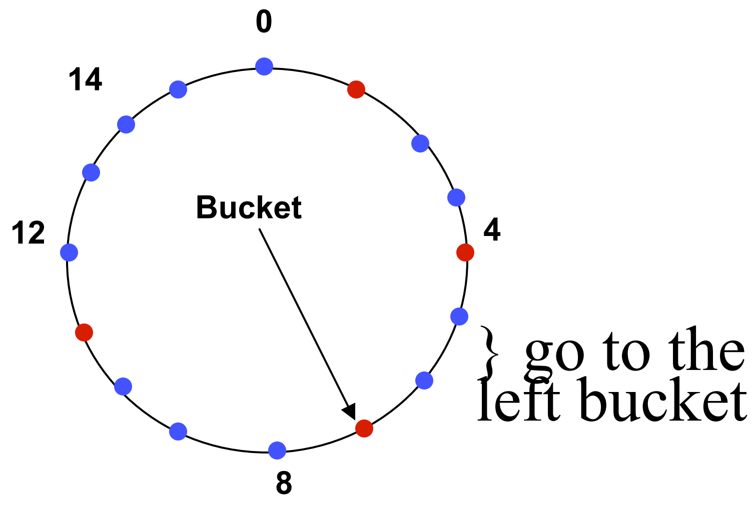
Bucket order determines placement on the ring.

Optimality proven for growth-restricted metric spaces
- Given point q and distance d, the number of points within distance 2d is at most constant factor larger than within distance d.

J. Aspnes at al. Ranged Hash Functions and the Price of Churn. SODA 2008.

Example of Consistent Hashing

- Creating the structure
  - Assign each of C hash buckets to random points on mod 2^n circle, where, hash key size = n
  - Map object to random position on circle
  - Hash of object = closest clockwise bucket



Problem

Having only one location for a bucket is not good

Does not ensure good spread

Solution: have multiple virtual locations for a bucket

Implication: when removing / adding a bucket, have to move data from several servers

Replication with virtual buckets

One point is not sufficient to characterize a bucket due to the required properties.

A bucket is replicated κ log(C) times, where C is the number of distinct buckets, and κ is a constant
The log(C) term comes from the theory, basically it is needed to get the good fraction O(1/|V|) of buckets to servers

When a new bucket is added, only those items are moved which are closest to one of its points. Similarly for the removal of a bucket.

Properties of ranged hash functions

Monotone

Each item has its own preference list and hashes to the first available bucket

This minimizes rearrangement cost

Multiple virtual locations for the item are possible

Can be described with a preference matrix

Items and the buckets

Properties of Consistent Hashing I

A **view** is a subset of the buckets (cache servers available from certain part of the network)

Consistent hashing uses a **ranged hash function** to specify an assignment of items to buckets for every possible view

A ranged hash family is said to be **balanced** if given a particular view, a set of elements, and a randomly chosen function from the hash family, with high probability the fraction of items mapped to each bucket is $O(1/|V|)$, where V is the view

In other words, items are uniformly distributed over the buckets of the view

Properties of consistent hashing II

Load: A balanced ranged hash function distributes load **evenly** across the buckets

Monotonicity is another important property for the hash function. This property says that some items can be moved to a new bucket from old buckets, but not between old buckets. The aim is to preserve an even distribution

Spread is about ensuring that at least a constant fraction of the buckets are visible to clients

Example of a ranged hash function (RHF)

Let I be the items, C the caches, and V the views. V_i is a subset of C.

RHF is a map that takes a view (all possible views $2^{C)}$ and hashes it to a cache in which the item can be found:
$h: 2^C \times I \rightarrow C$

For an item: pick a point r uniformly and independently at random

For the buckets: pick a set of κ log C points uniformly and independently at random.

For an item (V,i) map it to the first bucket b in V that is encountered clockwise starting from r.

Bad examples

Pick b in V at random: bad spread properties (needs to be the preference list of many buckets)

Take mod of the number of caches in a view: good balance but not smooth (e.g. problems when adding or removing a server)

```
public class ConsistentHash<T> {
  private final HashFunction hashFunction;
  private final int numberOfReplicas;
  private final SortedMap<Integer, T> circle =
    new TreeMap<Integer, T>();

  public ConsistentHash(HashFunction hashFunction,
    int numberOfReplicas, Collection<T> nodes) {
    this.hashFunction = hashFunction;
    this.numberOfReplicas = numberOfReplicas;

    for (T node : nodes) {
      add(node);
    }
  }
  public void add(T node) {
    for (int i = 0; i < numberOfReplicas; i++) {
      circle.put(hashFunction.hash(node.toString() + ":" + i),
        node);
    }
  }
  public void remove(T node) {
    for (int i = 0; i < numberOfReplicas; i++) {
      circle.remove(hashFunction.hash(node.toString() + ":"+ i));
    }
  }
  public T get(Object key) {
    if (circle.isEmpty()) {
      return null;
    }
    int hash = hashFunction.hash(key);
    if (!circle.containsKey(hash)) {
      SortedMap<Integer, T> tailMap =
        circle.tailMap(hash);
      hash = tailMap.isEmpty() ?
             circle.firstKey() : tailMap.firstKey();
    }
    return circle.get(hash);
  } }
```

This code does not move data between buckets!
Should be added here

http://www.lexemetech.com/2007/11/consistent-hashing.html

Wraps around the circle here

Main point in consistent hashing

The technique requires only *K/n* keys to be remapped on average, where *K* is the number of keys, and *n* is the number of nodes

Used in most DHT algorithms

Developed by Karger et al. at MIT

Somewhat involved for example in Chord

Used by CDNs and caches

- Akamai

Semantic free indexing I

With semantic free indexing in structured overlays, data objects are given unique identifiers called keys that are chosen from the same identifier space

Keys are mapped by the overlay network protocol to a node in the overlay network

The overlay network needs to then support scalable storage and retrieval (key, value) pairs

Semantic free indexing II

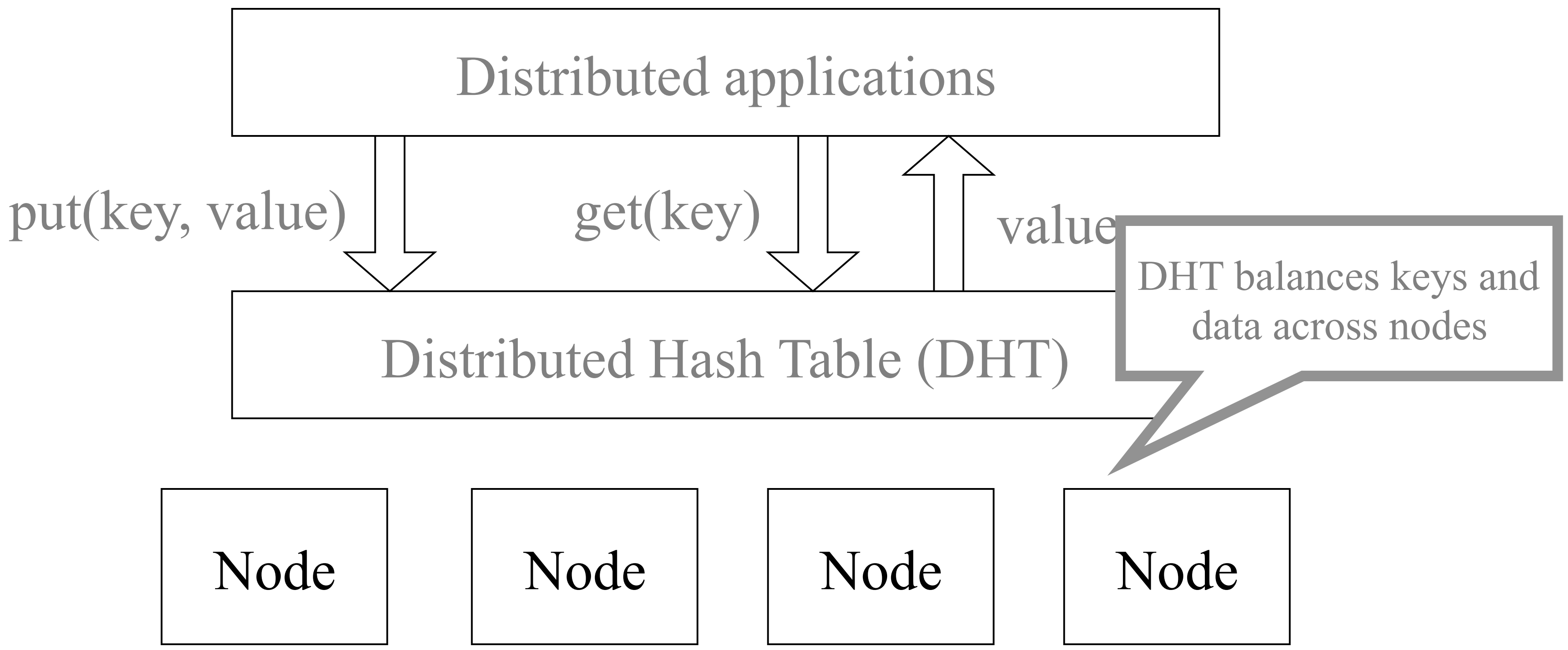
In order to realize the insertion, lookup, and removal of (key, value) pairs, each peer maintains a routing table that consists of its neighbouring peers (their node identifiers and IP addresses)

Lookup queries are then routed across the overlay network using the information contained in the routing tables

Typically each routing step takes the query or message closer to the destination

DHT interfaces

- DHTs offer typically two functions
  - put(key, value)
  - get(key) → value
  - delete(key)
- Supports wide range of applications
  - Similar interface to UDP/IP
    - Send(IP address, data)
    - Receive(IP address) → data
- No restrictions are imposed on the semantics of values and keys
- An arbitrary data blob can be hashed to a key
- Key/value pairs are persistent and global


Distributed applications
put(key, value)
get(key)
value
DHT balances keys and data across nodes
Distributed Hash Table (DHT)
Node
Node
Node
Node

Foundations of Structured Networks

We distinguish between a routing algorithm and the routing geometry. The algorithm pertains to the exact details of routing table construction and message forwarding.

Geometry pertains to the way in which neighbours and routes are chosen. Geometry is the foundation for routing algorithms

The key observation is that the geometry plays a fundamental part in the construction of decentralized overlays

Geometries

The five frequently used overlay topologies are:

- trees
- tori (k-ary n-cubes)
- butterflies (k-ary n-flies)
- de Bruijn graphs
- rings
- XOR geometry

The differences between some of the geometries are subtle

For example, it can be seen that the static DHT topology emulated by the DHT algorithms of Pastry and Tapestry are Plaxton trees; however, the dynamic algorithms can be seen as approximation of hypercubes.

Trees

The tree’s hierarchical organization makes it a suitable choice for efficient routing

In a tree geometry, node identifiers represent the leaf nodes in a binary tree of depth log n

The distance between any two nodes is the height of their smallest common subtree

One of the first DHT algorithms, the Plaxton’s algorithm, is based on this geometry (object rooted at a node)

For scalable networking, each node maintains a routing table with log *n* neighbours. In this table, the *i*th neighbour is at distance *i* from the current node. Greedy routing can then be used to forward a message to its destination on the network given the target identifier

Observations on Plaxton

Global ordering of nodes (only one root node possible)

Static configuration

Forest of trees where each server is a root

Populate routing table to reflect possible distances

- One suffix digit at a time

Plaxton’s algorithm: routing table of node 3642

Levels \ Entries	1 Primary neighbour	2	3	4
1	0642	X042	XX02	XXX0
2	1642	X142	XX12	XXX1
3	2642	X242	XX22	XXX2
4	**3642**	X342	XX32	XXX3
5	4642	X442	XX42	XXX4
6	5642	X542	XX52	XXX5
7	6642	X642	XX62	XXX6
8	7642	X742	XX72	XXX7

Wildcards are marked with X
Primary neighbour is one digit away

Example lookup

Node **3642** receives message for **2342**
- The common string is **XX42**
- Two shared digits, consult second column and choose the correct digit
- Send to node with one digit closer
- Fourth line with **X342**

Table size: base * address length
In this example octal base (8)
and 4 digit addresses

Each routing table is organized in routing levels and each entry points to a set of nodes closest in network distance to a node which matches the given suffix

Comparison to IP routing

IP routing is based on the longest matching prefix
- Keep a prefix data structure (ternary tree, TCAM)
- Find next hop based on the list (or the destination)

IP addresses are obtained through a local configuration
- process and/or BGP tables, default routes as well

For the Plaxton / DHT case we do not have the IP address
- semantics and mapping to the IP topology

The Plaxton/DHT topology is flat!

Hence the table structure with suffixes/prefixes.

Rings

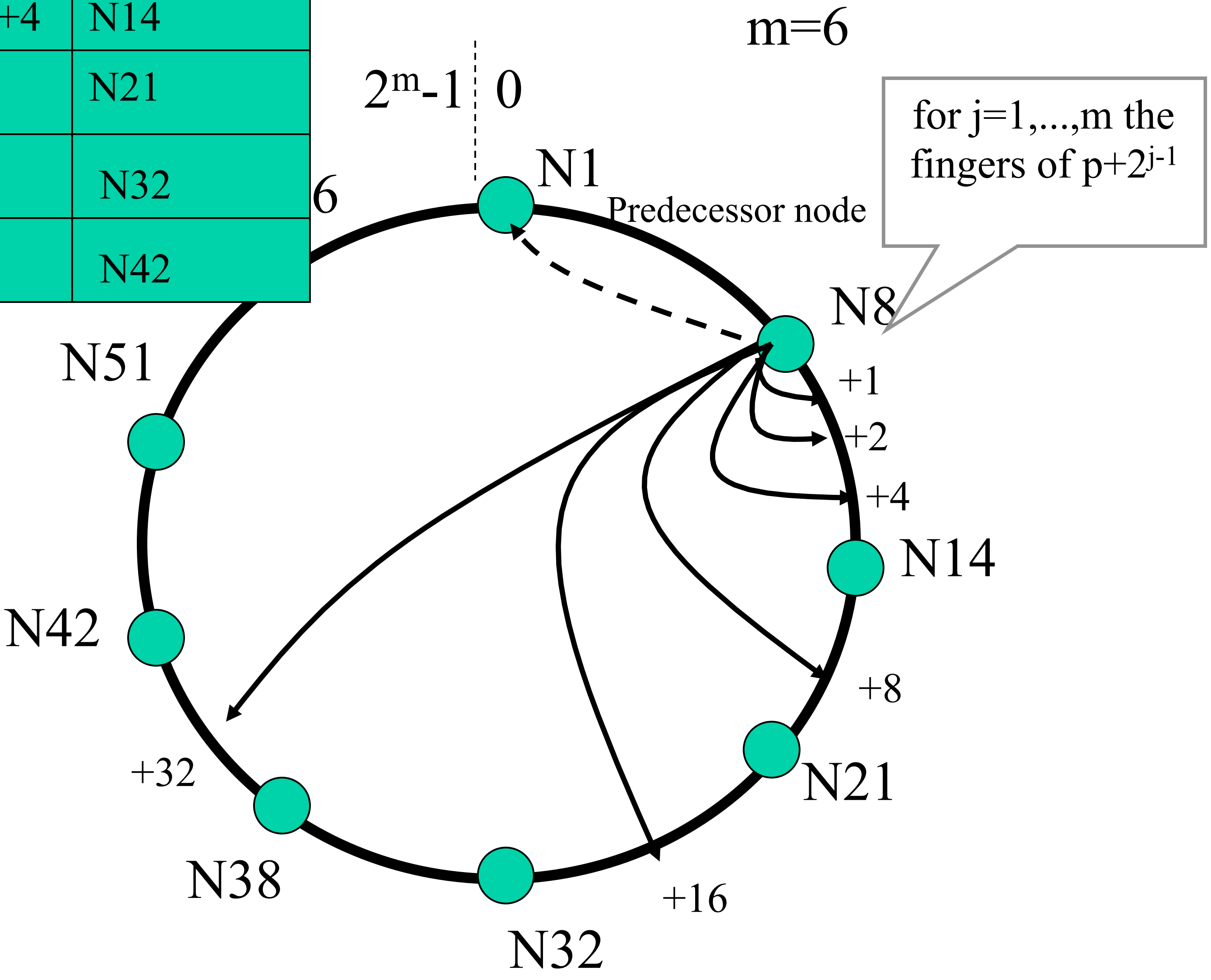
Rings are a popular geometry for DHTs due to their simplicity. In a ring geometry, nodes are placed on a one-dimensional cyclic identifier space. The distance from an identifier A to B is defined as the clockwise numeric distance from A to B on the circle

Rings are related with **tori** and **hypercubes**, and the 1-dimensional torus is a ring. Moreover, a k-ary 1-cube is a k-node ring

The Chord DHT is a classic example of an overlay based on this geometry.

Each node has a predecessor and a successor on the ring, and an additional routing table for pointers to increasingly far away nodes on the ring

Finger	Maps to	Real node
1,2,3	x+1,x+2,x+4	N14
4	x+8	N21
5	x+16	N32
6	x+32	N42



Hypercubes

The distance between two nodes in the **hypercube geometry** is the number of bits by which their identifier differ.

At each step a **greedy** forwarding mechanism corrects (or fixes) one bit to reduce the distance between the current message address and the destination.

Hypercubes are related to tori. In one dimension a line bends into a circle (a ring) resulting in a 1-torus. In two dimensions, a rectangle wraps into the two-dimensional torus, 2-torus. An n dimensional hypercube can be transformed into an n-torus by connecting the opposite faces together.

The Content Addressable Network (CAN) is an example of a DHT based on a d-dimensional torus.

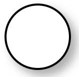
Differences

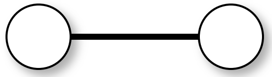
The main different between hypercube routing and tree routing is that the former allows bits to be fixed in any order

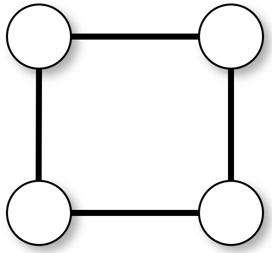
Tree routing requires that the bits are corrected in a strict order (digit by digit, still can be redundancy in the table)

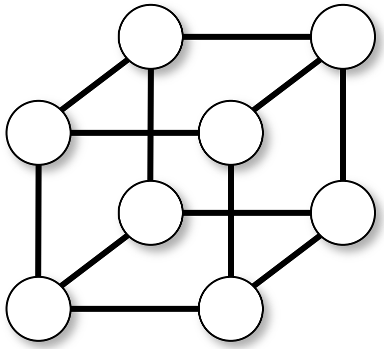
Thus hypercube is more restricted in selecting neighbours in the routing table but offers more possibilities for route selection!

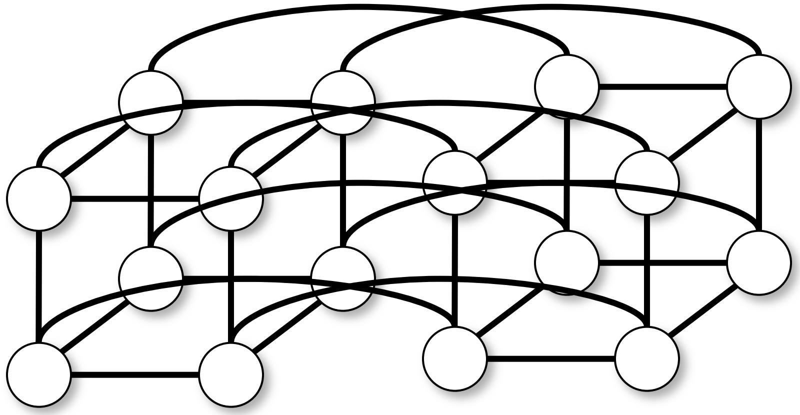
Hypercubes


$d = 0$
$N = 1$


$d = 1$
$N = 2$


$d = 2$
$N = 4$


$d = 3$
$N = 8$


$d = 4$
$N = 16$

Butterfly Geometry

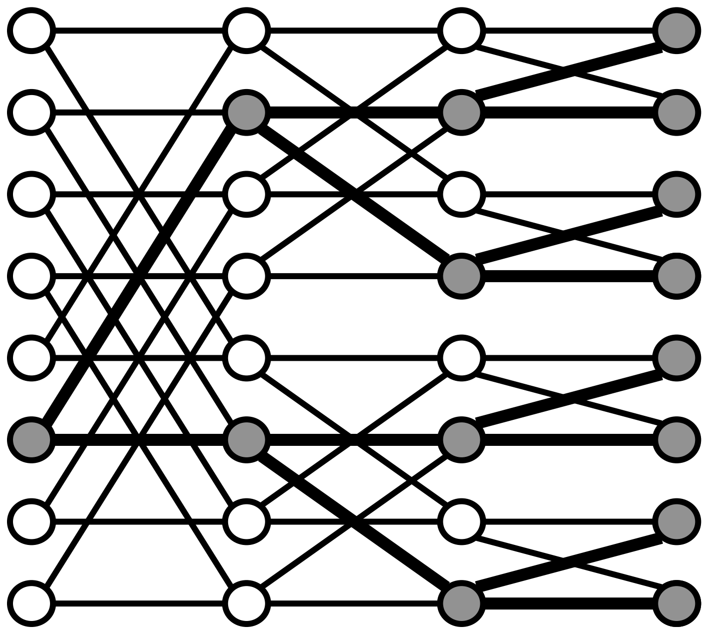
A ***k*-ary *n*-fly** network consists of k^n source nodes, n stages of k^{n-1} switches, and k^n destination nodes

The network is unidirectional and the degree of each switching node is $2k$

The diameter of the network is logarithmic to the number of source nodes. At each level l, a switching node is connected to the identically numbered element at level $l + 1$ and to a switching node whose number differs from the current node only at the lth most significant bit

The main drawback of this structure is that there is **only one path from a source to a destination**, in other words, there is no path diversity. In addition, butterfly networks do not have as good locality properties as tori

Butterfly network (with a tree)



De Bruijn Graph

An *n*-dimensional **de Bruijn** graph of *k* symbols is a directed graph representing overlaps between sequences of symbols. It has k^n vertices that represent all possible sequences of length *n* of the given symbols

In a *n*-dimensional de Bruijn graph with 2 symbols, there are 2^n nodes, each of which has a unique *n*-bit identifier.

Creating a de Bruijn graph

The node with identifier *i* is connected to nodes $2i \bmod 2^n$ and $2i + 1 \bmod 2^n$

A routing algorithm can route to any destination in *n* hops by successively shifting in the bits of the destination identifier.

Routing a message from node *m* to node *k* is accomplished by taking the number *m* and shifting in the bits of *k* one at a time until the number has been replaced by *k*

De Bruijn Graph

Consider a node n with identifier b1 b2 ...bk , bi ∈ {0, 1}

n has an out-edge to the nodes with identifier b2 ...bk 0 and b2 ...bk 1.

Node 0**0**: out edge to 00 and 01
Node 0**1**: out edge to 10 and 11
Node 1**0**: out edge to 00 and 01
Node 1**1**: out edge to 10 and 11

This adjacency scheme, based on shifting the identifier strings associated with a node yields a simple prefix based routing policy.

Constructing de Bruijn Graphs

De Bruijn graph for 2^m node network can be constructed in a recursive fashion from a 2^{m-1} node network.

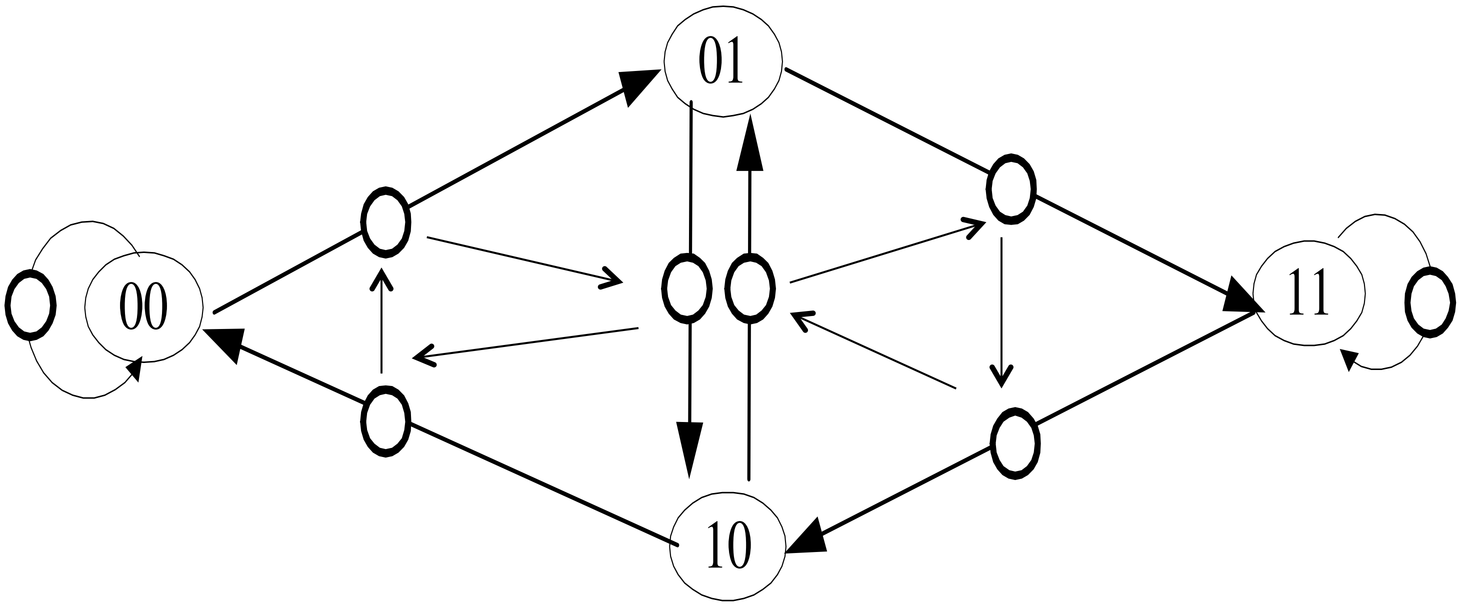
Take the edge of the 2^{m-1} node network

Add a node in the middle

Details:

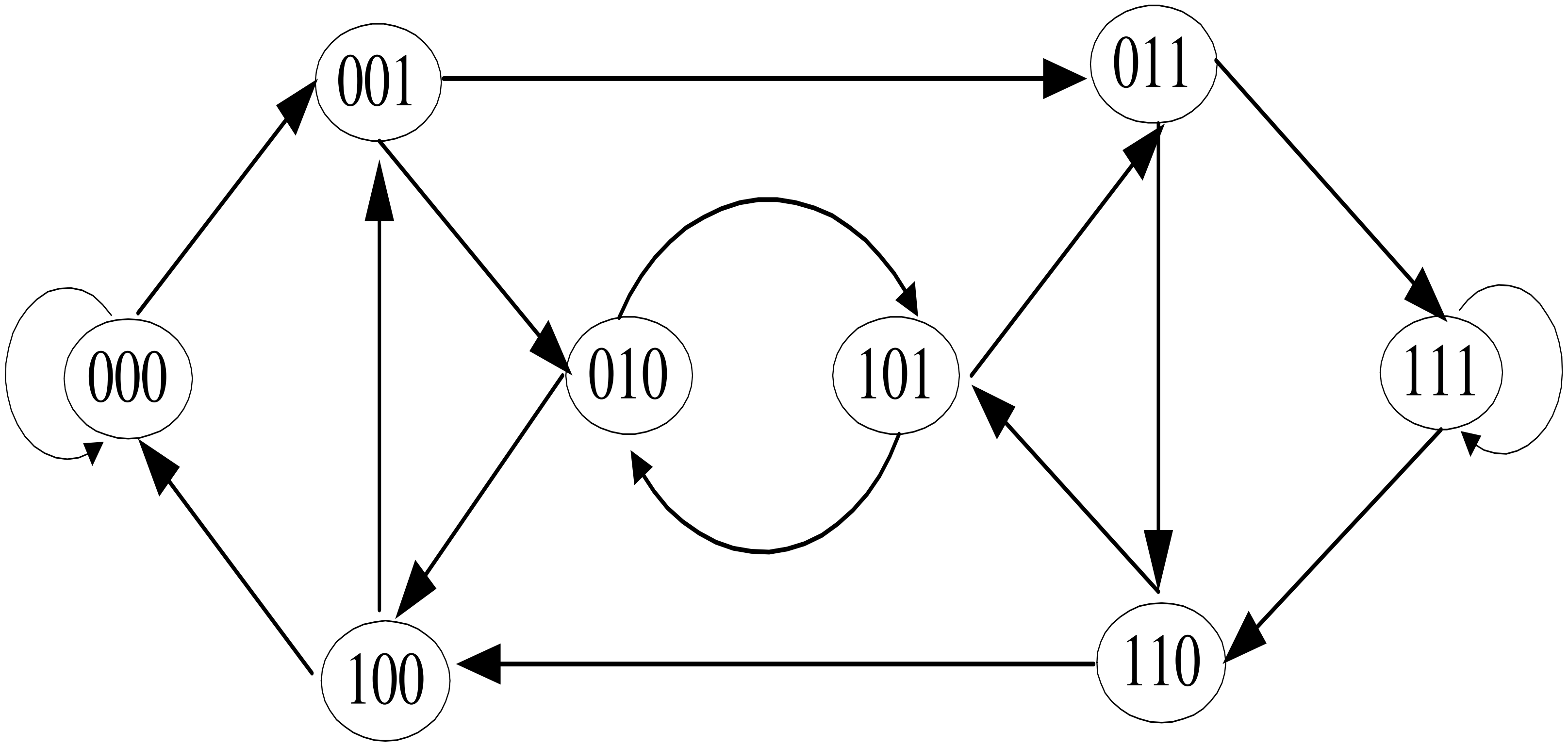
http://research.microsoft.com/en-us/um/people/nswamy/papers/halo-tr.pdf

Example: Adding a digit



Source: Jyh-Wen Mao The Coloring and Routing Problems on de Bruijn Interconnection Networks, PhD dissertation 2003.

Example: Adding a digit



Source: Jyh-Wen Mao The Coloring and Routing Problems on de Bruijn Interconnection Networks, PhD dissertation 2003.

The XOR Geometry

The Kademlia P2P system defines a routing metric in which the distance between two nodes is the numeric value of **the exclusive OR (XOR)** of their identifiers

The idea is to take messages closer to the destination by using the XOR distance d(x,y) = XOR(x,y) (taken as an integer)

The routing therefore ”fixes” high order bits in the current address to take it closer to the destination

Satisfies triangle property, symmetric, unidirectional

XOR Metric and Triangle Property

Triangle inequality property
$d(x,z) <= d(x,y) + d(y,z)$

Easy to see that XOR satisfies this

Useful for determining distances between nodes

Unidirectional:

For any given point x and a distance $D > 0$, there is exactly one point y such that $d(x,y) = D$. This means that lookups converge.

Comparing geometries

Gummadi et al. compared the different geometries, including the tree, hypercube, butterfly, ring, and XOR geometries.

Loguinov et al. complemented this list with de Bruijn graphs.

The conclusions of these comparisons include that the ring, XOR, and de Bruijn geometries are more flexible than the others and permit the choice of neighbours and alternative routes

The ring and XOR geometries were also found to be the most flexible in terms of choosing neighbours and routes

Only de Bruijn graphs allow alternate paths that are independent of each other

Comparison

Can you choose neighbours?

Can you choose routes?

Are there alternative routes?

Are there alternative routes without overlap?

Comparison

	Tree	Hypercube	Ring	Butterfly	XOR	De Bruijn
Neighbour selection	Yes	1	Yes	1	Yes	No
Route selection	1	Yes	Yes	1	Some	Yes
Sequential neighbours	No	No	Yes	No	No	Yes
Independent paths	No	No	No	No	No	Yes

Discussion

Based on previous table the ring looks pretty good

But this is partly due to the sequential neighbours property (predecessor and successor on the ring)

If sequential neighbours is added to other geometries, XOR and de Bruijn are also good

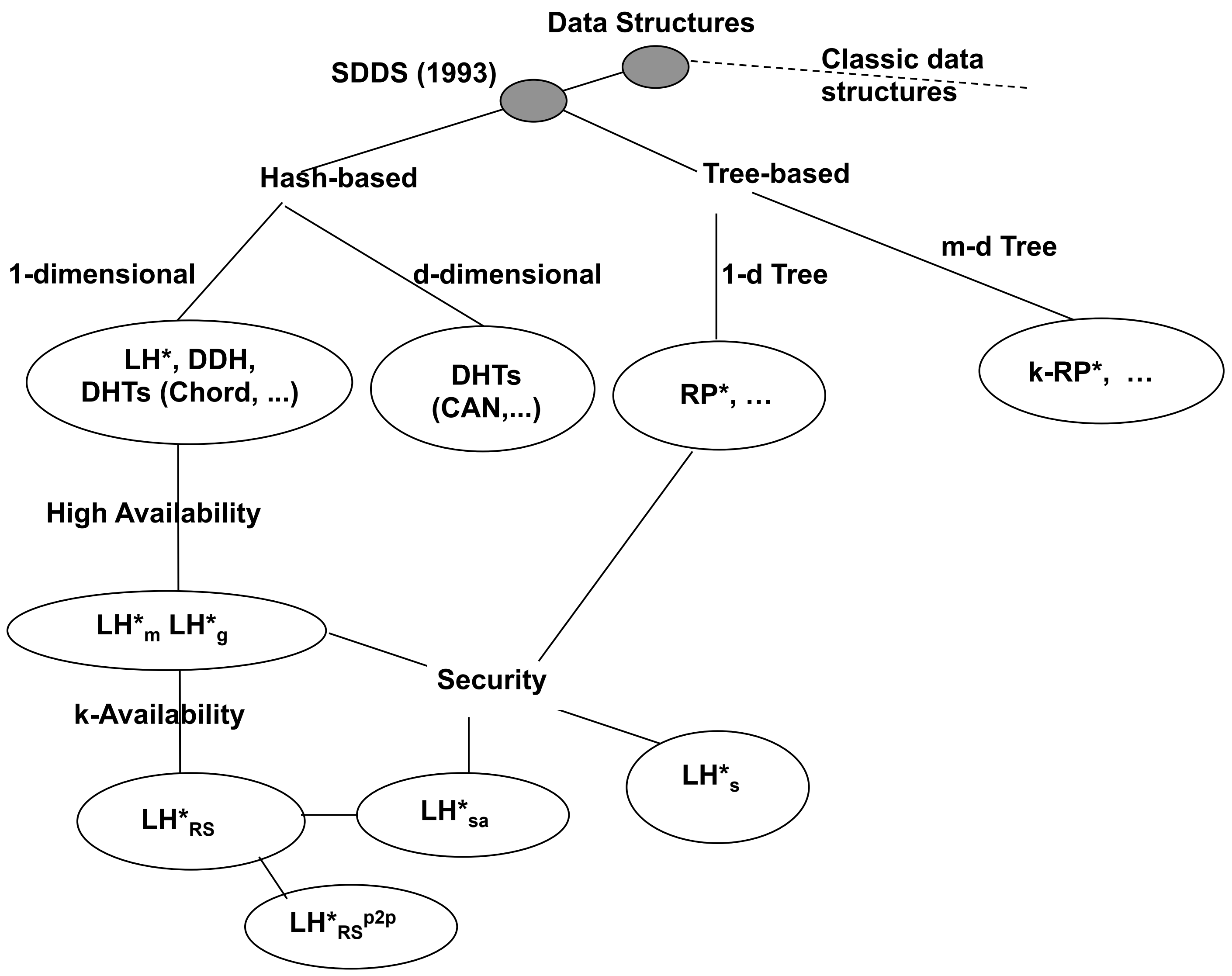
Distributed Data Structures (DDS)

- DHTs are an example of DDS
- DHT algorithms are available for clusters and wide-area environments
  - They are different!
- Cluster-based solutions
  - Ninja
  - LH* and variants
- Wide-area solutions
  - Chord, Tapestry, ..
  - Flat DHTs, peers are equal
  - Maintain a subset of peers in a routing table

Distributed Data Structures (DDS)

- Ninja project (UCB)
  - New storage layer for cluster services
  - Partition conventional data structure across nodes in a cluster
  - Replicate partitions with replica groups in cluster
    - Availability
  - Sync replicas to disk (durability)
- Other DDS for data / clusters
  - LH* Linear Hashing for Distributed Files
  - Redundant versions for high-availability

Taxonomy


Data Structures
SDDS (1993)
Classic data structures
Hash-based
Tree-based
1-dimensional
d-dimensional
1-d Tree
m-d Tree
LH*, DDH, DHTs (Chord, ...)
DHTs (CAN,...)
RP*, …
k-RP*, …
High Availability
$LH*_m$ $LH*_g$
Security
k-Availability
$LH*_{RS}$
$LH*_{sa}$
$LH*_s$
$LH*_{RS}^{p2p}$

Linear Hashing

Use a family of hash functions $\mathbf{h}_0$, $\mathbf{h}_1$, $\mathbf{h}_2$, ...

- Each function's range is twice that of its predecessor

- When all the pages at one level (the current hash function) have been split, a new level is applied

- Splitting occurs gradually
  Current hash function, then you know if a bucket has been split from a split counter

- Pages are split when overflows occur – but not necessarily the page with the overflow

- Splitting **a round robin** fashion

Linear Hashing II

Use a family of hash functions $\mathbf{h_0, h_1, h_2, ...}$

$h_i(\text{key}) = h(\text{key}) \bmod (2^i N)$

N = initial number of buckets

h is some hash function

h_{i+1} doubles the range of h_i

Keep track of the next bucket to split and the current level: half of a split bucket is moved to the new bucket

Linear Hashing III

Algorithm proceeds in rounds. Current round number is Level, Next = 0

There are N_{level} ($N * 2^{Level}$) buckets at round start

Buckets 0 to Next-1 have been split
Next to N_{Level} have not been split yet
Round ends when all initial buckets have been split (when Next = N_{Level}).

To start next round:
Level=Level+1
Next = 0

Linear Hashing III

Algorithm proceeds in rounds. Current round number is Level, Next = 0

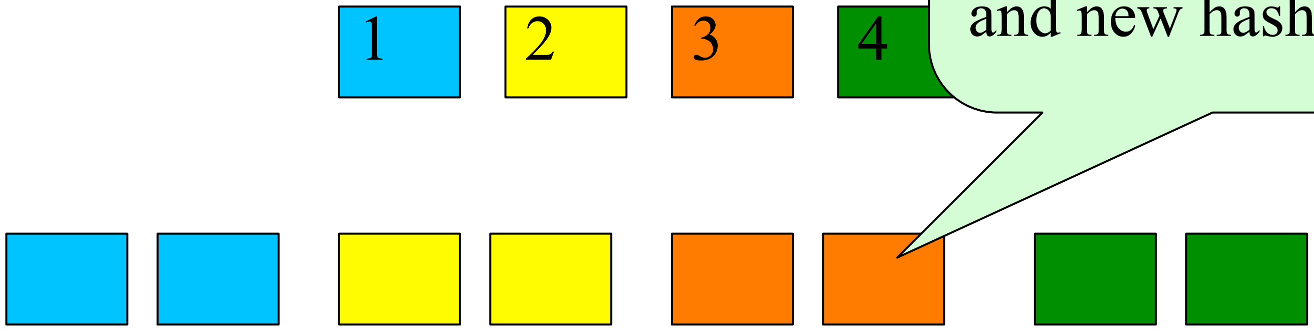
There are N_{level} ($N * 2^{Level}$) buckets at round start

Buckets 0 to Next-1 have been split
Next to N_{Level} have not been split yet
Round ends when all initial buckets have been split (when Next = N_{Level}).

To start next round:
Level=Level+1
Next = 0

Example

When splitting, half of the content is moved to the new bucket, just take this into account when looking up (old and new hash function)



Start: i =0, N = 4, next = 0

Overflow of 3: i =0, N = 4, next = 1

Overflow of 1: i =0, N = 4, next = 2

Overflow of 4: i =0, N = 4, next = 3

Overflow of 2: i =0, N = 4, next = 0

Next level: i =1, N = 4, next = 0

Now we have moved to the new hash function altogether, splitting starts again!

Read operation

Use h(level, key) if it is greater than or equal to the next counter

Otherwise use h(level+1, key), because they have been rehashed with the new level

Overflow of a bucket

What happens if there is no space, bucket overflows and it is not the next bucket to split?

Use overflow buckets, normal bucket has a pointer to the overflow bucket

Overflow bucket taken into account when the bucket in question is split (round robin)

Linear hashing

Spreads the cost of the expansion across insertion operations

Buckets split one at a time

LH* Linear Hashing for Distributed Files

LH* generalizes linear hashing to decentralized distributed operation

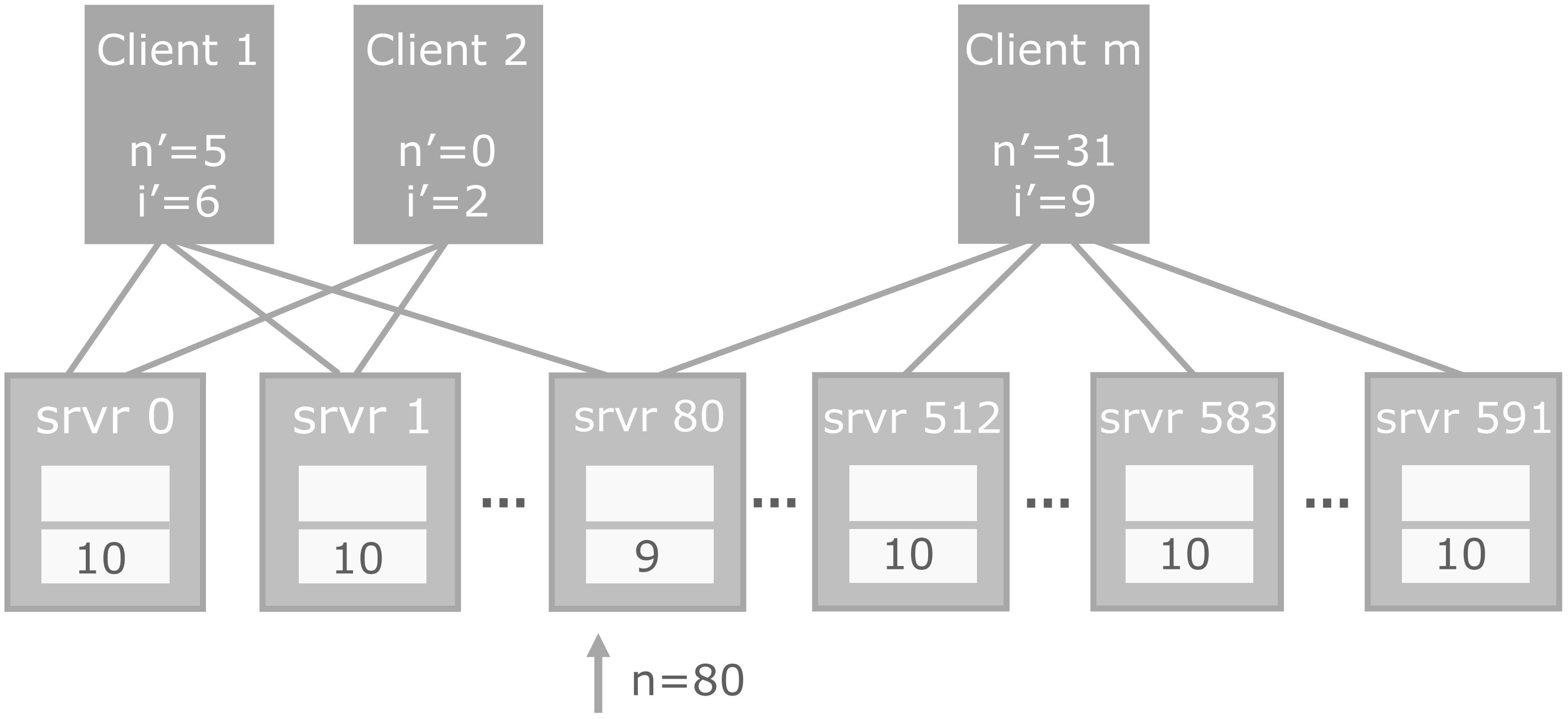
The system supports constant time insertion and lookup of data objects in a cluster.

Data items are hashed into buckets with each bucket residing on a server. New servers are incorporated into the system when a bucket overflows using a split operation

A **split controller** manages the split operation. When a split is performed, a new server is added to the system from a supply of servers and the hashing parameters are adjusted accordingly

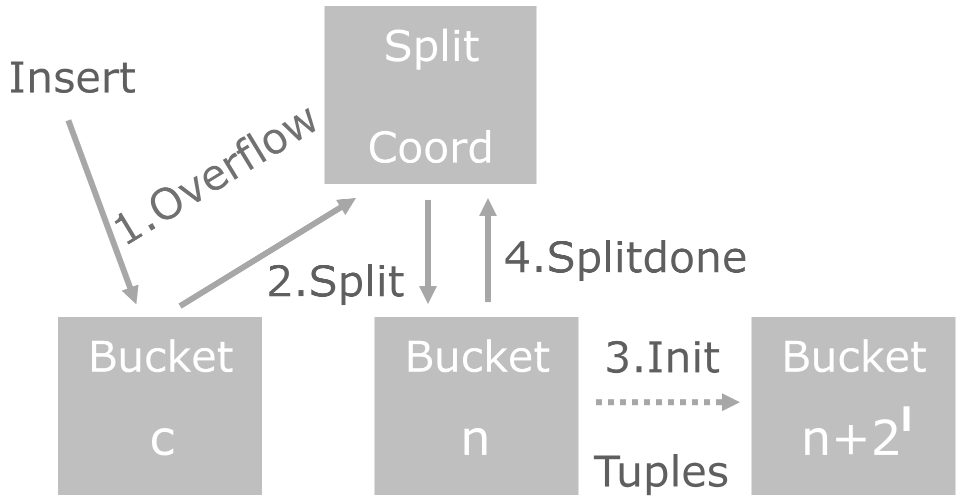
In a distributed environment, the clients have a **view** to these system parameters which in some cases maybe out of date. This requires **auto-correction** and **synchronization** mechanisms

LH* Example



Client 1
n′=5
i′=6
Client 2
n′=0
i′=2
Client m
n′=31
i′=9
srvr 0
10
srvr 1
10
…
srvr 80
9
…
srvr 512
10
…
srvr 583
10
…
srvr 591
10
n=80

LH* Bucket Split



Cluster-based Distributed Hash Tables (DHT)

- The NINJA project
- Directory for non-hierarchical data
- Several different ways to implement
- A distributed hash table
  - Each "brick" maintains a partial map
    - "local" keys and values
  - **Overlay addresses** used to direct to the right "brick"
    - "remote" key to the brick using hashing
- Resilience through **parallel**, unrelated mappings

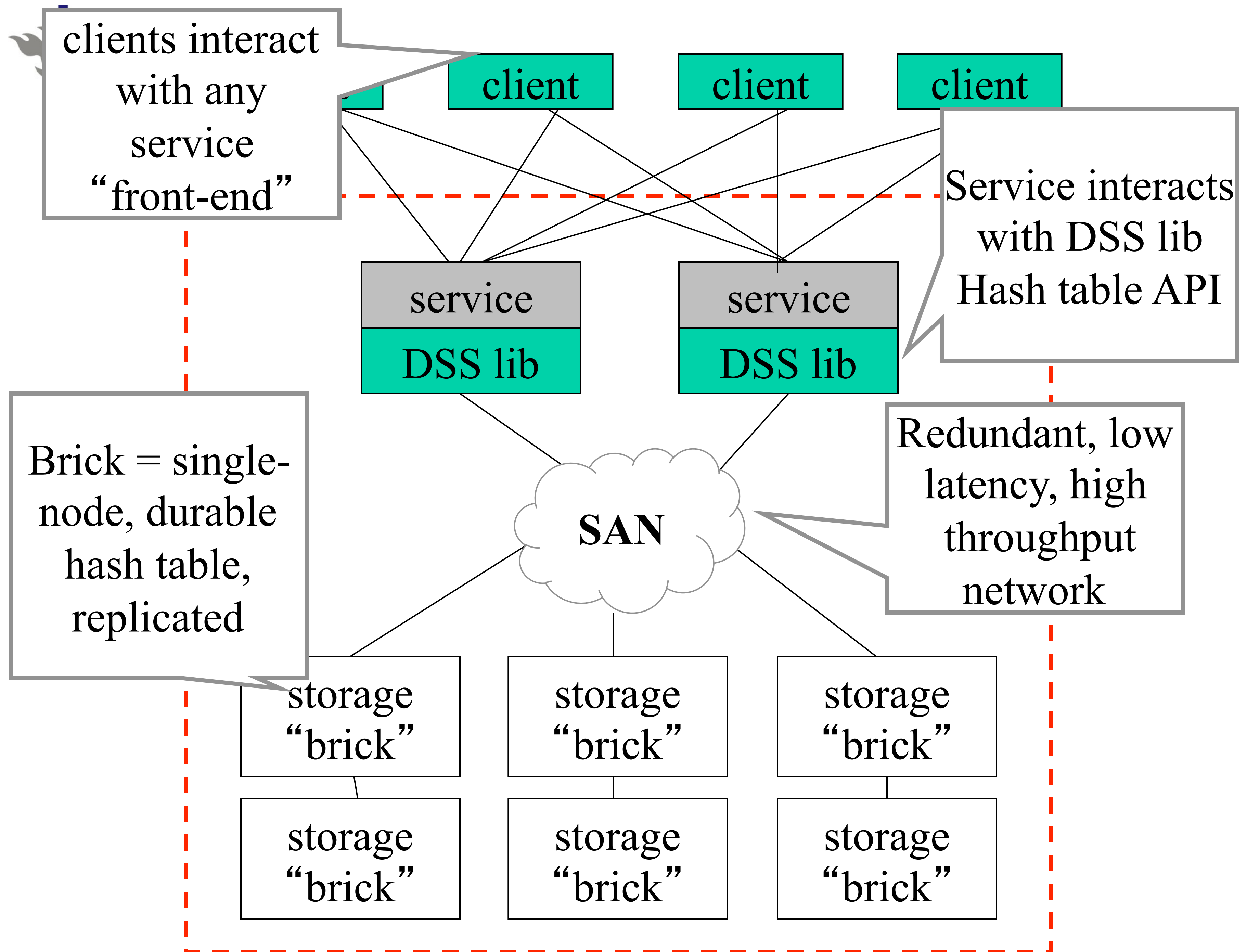
NINJA

The API provides services with *put()*, *get()*, *remove()*, *destroy()* operations on hash tables.

Behind the API the DDS needs to implement the mechanisms to access, partition, replicate, scale, and recover data

A distributed hash table was implemented as an example of the DDS concept in Ninja. All operations inside the distributed hash table are atomic meaning that a given operation is either performed fully or not at all. In order to ensure reliability

Elements are replicated within the DDS across multiple nodes called *bricks*. A **two-phase commit algorithm** is used to keep the replicas coherent. A brick consists of a buffer cache, a lock manager, a persistent chained hash table implementation, and an RPC communications system


clients interact with any service "front-end"
client
client
client
service
DSS lib
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Service interacts with DSS lib Hash table API
Brick = single-node, durable hash table, replicated
SAN
Redundant, low latency, high throughput network
storage "brick"
storage "brick"
storage "brick"
storage "brick"
storage "brick"
storage "brick"

Summary

Geometries form the basis of the structured overlay algorithms

A *Distributed Data Structure (DDS)* is a self-managing storage layer that runs on a cluster. The aim of the DDS is to support high throughput, high concurrency, availability, incremental scalability, offer strict consistency guarantees for the data

The LH* family of algorithms are scalable DDSes intended for clusters

Consistent hashing allows buckets to be added in **any order**, whereas Litwin’s Linear Hashing (LH*) scheme requires buckets to be added one at a time in sequence

The Ninja system was designed to support robust distributed Internet services. One key component of the system was a cluster of servers for scalable service