Overlay and P2P Networks

Structured Networks and DHTs

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Contents

• Today
  • DHTs continued
  • Discussion on geometries

• Next week
  • Shift to Applications
  • Dr. Samu Varjonen will talk about lookup services based on DHTs
Structured Overlays

Structured overlays are typically based on the notion of a semantic free index and consistent hashing. They are based on different routing geometries. The decentralized DHTs balance hop count with the size of the routing tables, network diameter, and the ability to cope with changes.

Geometries and DHTs
- Tree – Plaxton’s algorithm
- Ring – Chord
- Hypercubes – Pastry and Tapestry
- Tori – CAN
- XOR metric – Kademlia
Pastry I

- A DHT based on a circular flat identifier space
- Invariant: node with numerically closest id maintains object
- Prefix-routing
  - Message is sent towards a node which is **numerically closest** to the target node
  - Procedure is repeated until the node is found
  - Prefix match: number of identical digits before the first differing digit
  - Prefix match increases by every hop

- Similar performance to Chord
Pastry Routing

Pastry builds on consistent hashing and the Plaxton’s algorithm. It provides an object location and routing scheme and routes messages to nodes. It is a prefix based routing system, in contrast to suffix based routing systems such as Plaxton and Tapestry, that supports proximity and network locality awareness. At each routing hop, a message is forwarded to a numerically closer node. As with many other similar algorithms, Pastry uses an expected average of $\log(N)$ hops until a message reaches its destination. Similarly to the Plaxton’s algorithm, Pastry routes a message to the node with the nodeId that is numerically closest to the given key.
Pastry Routing Components

Leaf set
L/2 smaller and larger numerically closest nodes. L is a configuration parameter (typically 16 or 32)
To ensure reliable message delivery
To store replicas for fault tolerance

Routing table

Neighborhood set
M entries for nodes “close” to the present node (typically M = 32). Used to construct routing table with good locality properties
Leaf set is a ring

Leaf set is a ring:

If $L / 2 = 1$: each node has a pointer to its ring successor and predecessor

If $L / 2 = k$: each node has a pointer to its $k$ ring successors and $k$ predecessors

Ring breaks if $k$ consecutive nodes fail concurrently

$k - 1$ concurrent node failures can be tolerated
Pastry: Routing procedure

if (destination is within range of our leaf set)
   forward to numerically closest member
else
   let $l =$ length of shared prefix
   let $d =$ value of $l$-th digit in $D$’s address
   if ($R^d_i$ exists)
      forward to $R^d_i$
   else
      forward to a known node that
      (a) shares at least as long a prefix
      (b) is numerically closer than this node
Joining the Network

The join consists of the following steps:

- Create NodeID and obtain neighbour set from the topologically nearest node.
- Route message to NodeID.
- Each Pastry node processing the join message will send a row of the routing table to the new node. The Pastry nodes will update their long distance routing table if necessary (if numerically smaller for a given prefix).
- Receive the final row and a candidate leaf set.
- Check table entries for consistency. Send routing table to each neighbour.
Routing table of a Pastry node with nodeId 65a1x, b = 4. Digits are in base 16, x represents an arbitrary suffix.

The IP address associated with each entry is not shown.
Prefix-based
Route to node with shared prefix (with the key) of ID at least one digit more than this node.
Neighbor set, leaf set and routing table.

Pastry Routing Example
Proximity

The Pastry overlay construction observes proximity in the underlying Internet. Each routing table entry is chosen to refer to a node with low network delay, among all nodes with an appropriate nodeId prefix.

As a result, one can show that Pastry routes have a low delay penalty: the average delay of Pastry messages is less than twice the IP delay between source and destination.
Pastry Scalar Distance Metric

The Pastry proximity metric is a **scalar value** that reflects the distance between any pair of nodes, such as the round trip time.

It is assumed that a function exists that allows each Pastry node to determine the distance between itself and a node with a given IP address.

**Proximity invariant:** Each routing table entry refers to a node close to the local node (in the proximity space) among all nodes with the appropriate prefix.
Pastry: Routes in proximity space

NodeID space

Route(d46a1c)

Proximity space

Source: Presentation by P. Druschel et al. Scalable peer-to-peer substrates: A new foundation for distributed applications?
## Pastry and Tapestry

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<thead>
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<th>Pastry</th>
<th>Tapestry</th>
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<tr>
<td><strong>Foundation</strong></td>
<td>Plaxton-style mesh (hyper-cube)</td>
<td>Plaxton-style mesh (hyper-cube)</td>
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<tr>
<td><strong>Routing function</strong></td>
<td>Matching key and prefix in nodeID</td>
<td>Suffix matching</td>
</tr>
<tr>
<td><strong>System parameters</strong></td>
<td>Number of peers N, base of peer identifier B</td>
<td>Number of peers N, base of peer identifier B</td>
</tr>
</tbody>
</table>
| **Routing performance** | $O(\log_B N)$  
*Note similarity metric* | $O(\log_B N)$  
*Note surrogate routing* |
| **Routing state**   | $2B \log_B N$                               | $\log_B N$                                  |
| **Joins/leaves**    | $\log_B N$                                  | $\log_B N$                                  |
CAN and 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 difference 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

\[ \begin{align*}
    d &= 0 \\
    N &= 1
\end{align*} \]

\[ \begin{align*}
    d &= 1 \\
    N &= 2
\end{align*} \]

\[ \begin{align*}
    d &= 2 \\
    N &= 4
\end{align*} \]

\[ \begin{align*}
    d &= 3 \\
    N &= 8
\end{align*} \]

\[ \begin{align*}
    d &= 4 \\
    N &= 16
\end{align*} \]
Content Addressable Network (CAN)

The Content Addressable Network (CAN) is a DHT algorithm based on virtual multi-dimensional Cartesian coordinate space.

In a similar fashion to other DHT algorithms, CAN is designed to be scalable, self-organizing, and fault tolerant.

The algorithm is based on a \textit{d-dimensional torus} that realizes a virtual logical addressing space independent of the physical network location.

The coordinate space is dynamically partitioned into \textit{zones} in such a way that each node is responsible for at least one distinct zone.
**CAN performance**

For a $d$ dimensional coordinate space partitioned into $n$ zones, the average routing path length is $O(d \times N^{1/d})$ hops and each node needs to maintain $2d$ neighbours.

This means that for a $d$-dimensional space the number of nodes can grow without increasing per node state.

Another beneficial feature of CAN is that there are many paths between two points in the space and thus the system may be able to route around faults.
Logarithmic CAN

A logarithmic CAN is a system with $d = \log n$

In this case, CAN exhibits similar properties as Chord and Tapestry, for example $O(\log n)$ diameter and degree at each node
Joining a CAN network

In order for a new node to join the CAN network, the new node must first find a node that is already part of the network, **identify a zone that can be split**, and then **update** routing tables of neighbours to reflect the split introduced by the new node.

In the seminal CAN article the bootstrapping mechanism is not defined.

One possible scheme is to use a DNS lookup to find the IP address of a bootstrap node (essentially a rendezvous point).

Bootstrapping nodes may be used to inform the new node of IP addresses of nodes currently in the CAN network.
Leaving a CAN network

Node departures are handled in a similar fashion than joins. A node that is departing must **give up its zone** and the CAN algorithm needs to **merge** this zone with an existing zone. Routing tables need to be then updated to reflect this change in zones.

A node’s departure can be detected using heartbeat messages that are periodically broadcast between neighbours.

If a merging candidate cannot be found, the neighbouring node with the smallest zone will take over the departing node’s zone.

After the process the neighbouring nodes’ routing tables are updated to reflect the change in the zone responsibility.
Routing to point P

1. Node checks whether it or its neighbors contain the point P
2. If does not contain then
3. Node orders the neighbors by Cartesian distance between them and the point P
4. Forwards the search request to the closest one
5. Repeat step 1

6. When cannot repeat, return result to user
CAN: average path length

Total path length is given by the sum
0*1+1*2d+2*4d+3*6d...

Average path length is the total path length divided by the number of nodes

\[ P = 0 \times 1 + \sum_{i=1}^{n^{1/d} - 1} i \times 2id + \frac{n^{1/d}}{2} \times (n^{1/d} - 1)d + \sum_{i=n^{1/d}/2+1}^{n^{1/d}} i \times 2(n^{1/d} - i)d + n^{1/d} \times 1 \]

Avg. path length = \frac{TPL (Total path length)}{n (# of Nodes)} = d \times \frac{n^{1/d}}{4}

Source: www.mpi-inf.mpg.de/departments/d5/teaching/ws03_04/p2p-data/11-18-paper2.ppt
Virtual $d$-dimensional Cartesian coordinate system on a $d$-torus

Example: 2-$d$ $[0,1] \times [1,0]$

Dynamically partitioned among all nodes

Pair $(K,V)$ is stored by mapping key $K$ to a point $P$ in the space using a uniform hash function and storing $(K,V)$ at the node in the zone containing $P$

Retrieve entry $(K,V)$ by applying the same hash function to map $K$ to $P$ and retrieve entry from node in zone containing $P$

If $P$ is not contained in the zone of the requesting node or its neighboring zones, route request to neighbor node in zone nearest $P$
Peer Xs coordinate neighbor set = \{A, B, D, Z\}
New Peer Zs coordinate neighbor set = \{A, C, D, X\}

Z joins the system
Extensions

Increasing dimensions of the coordinate space reduces path length and latency with small routing table size increase.

Landmarks for topology sensitive construction
Nodes measure RTT to landmarks, order landmarks, partition coordinate space into m! equal sizes. Join nearest partition in landmark ordering.

Multiple hash functions

Realities. Multiple independent coordinate spaces.
## Content Addressable Network (CAN)

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<td><strong>Foundation</strong></td>
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<td><strong>Routing function</strong></td>
<td>Maps (key,value) pairs to coordinate space</td>
</tr>
<tr>
<td><strong>System parameters</strong></td>
<td>Number of peers N, number of dimensions d</td>
</tr>
<tr>
<td><strong>Routing performance</strong></td>
<td>$O(dN^{1/d})$</td>
</tr>
<tr>
<td><strong>Routing state</strong></td>
<td>$2d$</td>
</tr>
<tr>
<td><strong>Joins/leaves</strong></td>
<td>$2d$</td>
</tr>
</tbody>
</table>
Kademlia and the XOR geometry
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 \( d(x,y) = \text{XOR}(x,y) \) (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
\[ d(x,z) \leq d(x,y) + d(y,z) \]

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.
Kademlia is a scalable decentralized P2P system based on the XOR geometry.

The algorithm is used by the BitTorrent DHT MainLine implementation, and therefore it is widely deployed.

Kademlia is also used in kad, which is part of the eDonkey P2P file sharing system that hosts several million simultaneous users.
Kademlia

Relying on the XOR geometry makes Kademlia unique compared to other proposals.

Kademlia’s routing table results in the same routing entries as for tree geometries when failures do not occur, such as Plaxton’s algorithm.

When failures occur, Kademlia can route around failures due to its geometry.
Every node keeps touch with at least one node from each of its subtrees. Corresponding to each subtree, there is a k-bucket.
Kademlia Routing

In Kademlia, a node’s neighbours are called contacts. They are stored in buckets, each of which holds a maximum of $k$ contacts. These $k$ contacts are used to improve redundancy.

The routing table can be viewed as a binary tree, in which each node in the tree is a $k$-bucket.

The buckets are organized by the distance between the current node and the contacts in the bucket.
K-buckets

Every $k$-bucket corresponds to a specific distance from the node.

Nodes that are in the $n$th bucket must have a differing $n$th bit from the node’s identifier.

With an identifier of 160 bits, every node in the network will classify other nodes in one of 160 different distances (first $n$-1 bits need to match for the $n$th list)
Details

For each i (0 ≤ i < 160) every node keeps a list of nodes of distance between $2^i$ and $2^{(i+1)}$ from itself.

Call each list a k-bucket. The list is sorted by time last seen.

The value of k is chosen so that any given set of k nodes is unlikely to fail within an hour.

The list is updated whenever a node receives a message.
Kademlia Overview

The initiating node maintains a shortlist of \( k \) closest nodes These are probed to determine if they are active

The replies of the probes are used to improve the shortlist

Closer nodes replace more distant nodes in the shortlist.

This iteration continues until \( k \) nodes have been successfully probed and there subsequent probes do not reveal improvements

This process is called a node lookup and it is used in most operations offered by Kademlia
Joining the network

Find one active node

Insert the bootstrap node into one of the k-buckets

Lookup new node id to populate the other nodes’ k-buckets with the new node id and the joining node’s k-buckets

Lookup operation returns k-closest nodes of the receiver

Refresh k-buckets further away than the k-bucket with the bootstrap node. Refresh is a random lookup for a key within the range of a k-bucket
Kademlia

The lookup procedure can be implemented either using recursively or iteratively.

The current Kademlia implementation uses the iterative process where the control of the lookup is with the initiating node.

Leaving the network is straightforward and consistency is achieved by using leases.
Kademlia performance

The routing tables of all Kademlia nodes can be seen to collectively maintain one large binary tree.

Each peer maintains a fraction $O(\log(n)/n)$ of this tree.

During a lookup, each routing step takes the message closer to the destination requiring at most $O(\log n)$ steps.
Simple iterative lookup

Consult the k-bucket that has the smallest distance to destination
Kademlia

<table>
<thead>
<tr>
<th><strong>Foundation</strong></th>
<th>XOR metric</th>
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<td><strong>Routing function</strong></td>
<td>Matching key and nodeID</td>
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<tr>
<td><strong>System parameters</strong></td>
<td>Number of peers N, base of peer identifier B</td>
</tr>
<tr>
<td><strong>Routing performance</strong></td>
<td>$O(\log_B N) + \text{small constant}$</td>
</tr>
<tr>
<td><strong>Routing state</strong></td>
<td>$B \log_B N + B$</td>
</tr>
<tr>
<td><strong>Joins/leaves</strong></td>
<td>$\log_B N + \text{small constant}$</td>
</tr>
</tbody>
</table>
BitTorrent Mainline DHT

Each peer announces itself with the distributed tracker
Looking up the 8 nodes closest to the info-hash of the torrent and sending an announce message to them

Those 8 nodes will then add the announcing peer to the peer list stored at that info-hash

A peer joins a torrent by looking up the peer list at a specific info-hash

Nodes return the peer list if they have it
Summary

• Overlay networks have been proposed
  – Searching, storing, routing, notification,..
  – Lookup (Chord, Tapestry, Pastry), coordination primitives (i3), middlebox support (DOA)
  – Logarithmic scalability, decentralised,…

• Many applications for overlays
  – Lookup, rendezvous, data distribution and dissemination, coordination, service composition, general indirection support

• Deployment open. PlanetLab.
What is an address?

Base \(b\) with \(n\) digits

How to route efficiently?

Fix at least one digit per hop or take to the numerically closest destination based on routing table

How efficient is this?

\(\log_b N\) steps gives \(O(\log N)\) state and \(O(\log N)\) hops!
DHT: A General Approach

How to populate routing table?

Iterative nearest neighbour search to fill the routing table. Get enough information to be able to populate the routing table.
<table>
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<tr>
<th>Foundation</th>
<th>CAN</th>
<th>Chord</th>
<th>Kademlia</th>
<th>Koorde</th>
<th>Pastry</th>
<th>Tapestry</th>
<th>Viceroy</th>
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</thead>
<tbody>
<tr>
<td>Multi-dimensional space</td>
<td>Circular space</td>
<td>XOR metric</td>
<td>de Bruijn graph</td>
<td>Plaxton-style mesh</td>
<td>Plaxton-style mesh</td>
<td>Butterfly network</td>
<td></td>
</tr>
<tr>
<td>(d-dimensional torus)</td>
<td>(hyper-cube)</td>
<td></td>
<td></td>
<td>(hyper-cube)</td>
<td>(hyper-cube)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Routing function            | Maps (key,value) pairs to    | Matching key and nodeID       | Matching key and nodeID       | Matching key and prefix in   | Suffix matching               | Routing using levels of tree, |
|                            | coordinate space             |                               |                               | nodeID                        |                               | vicinity search               |

| System parameters           | Number of peers N, number   | Number of peers N,           | Number of peers N,           | Number of peers N,           | Number of peers N,           | Number of peers N             |
|                            | of dimensions d             | base of peer identifier B    | base of peer identifier B    | base of peer identifier B    | base of peer identifier B    |                               |

| Routing performance         | O(dN^{1/d})                  | O(log N)                      | O(log_B N) + small constant  | Between O(log log N) and O(log N), depending on state | O(log_B N)                    | O(log_B N)                    | O(log N)                     |

| Routing state               | 2d                            | log N                         | Blog_B N + B                 | From constant to log N       | 2Blog_B N                     | log_B N                       | Constant                     |

| Joins/leaves                | 2d                            | (log N)^2                      | log_B N + small constant     | log N                         | log_B N                       | log_B N                       | log N                         |
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

<table>
<thead>
<tr>
<th></th>
<th>Tree</th>
<th>Hypercube</th>
<th>Ring</th>
<th>Butterfly</th>
<th>XOR</th>
<th>De Bruijn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neighbour selection</td>
<td>Yes</td>
<td>1</td>
<td>Yes</td>
<td>1</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Route selection</td>
<td>1</td>
<td>Yes</td>
<td>Yes</td>
<td>1</td>
<td>Some</td>
<td>Yes</td>
</tr>
<tr>
<td>Sequential neighbours</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Independent paths</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>
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
Comparison: Geometries

We observe that the foundations differ across the algorithms, but result in similar scalability properties.

The foundations were considered earlier in the previous chapter and for the considered systems they are tori, ring, XOR metric, de Bruijn graph, hypercube, and butterfly network (note Koorde uses de Bruijn over Chord, not presented in the slides).

The conclusions of several comparisons of the geometries are that the ring, XOR, and de Bruijn geometries are more flexible than the others and permit the choice of neighbours and alternative routes.
Comparison: Routing

The routing tables of DHTs can vary from size $O(1)$ to $O(n)$. The algorithms need to balance between maintenance cost and lookup cost.

From the view point of routing state Chord, Pastry, and Tapestry offer logarithmic routing table sizes, whereas Koorde and Viceroy and support constant or near-constant sizes.

Churn and dynamic peers can also be supported with logarithmic cost in some of the systems, such as Koorde, Pastry, Tapestry, and Viceroy.

Recent analysis indicates that large routing tables actually lead to both low traffic and low lookup hops. These good design points translate into one-hop routing for systems of medium size and two-hop routing for large systems.
Comparison: Churn

Li et al. provide a comparison of different DHTs under churn. They examine the fundamental design choices of systems including Tapestry, Chord, and Kademlia. The insights based on this work include the following:

• Larger routing tables are more cost-effective than more frequent periodic stabilization

• Knowledge about new nodes during lookups may allow to eliminate the need for stabilization

• Parallel lookups result in reduced latency due to timeouts, which provide information about the network conditions
Comparison: Network Proximity

Support for network proximity is one key feature of overlay algorithms. The three basic models for proximity awareness in DHTs are:

- **Geographic Layout.** Node identifiers are created in such a way that nodes that are close in the network topology are close in the nodeId space.

- **Proximity Routing.** The routing tables do not take network proximity into account; however, the routing algorithm can choose a node from the routing table that is closest in terms of network proximity.

- **Proximity Neighbour Selection.** In this model, the routing table construction takes network proximity into account. Routing table entries are chosen in such a way that at least some of them are close in the network topology to the current node.
Asymptotic Tradeoffs

We analyze the asymptotic tradeoff curve between the routing table size and the network diameter. Analysis of the tradeoffs between the two metrics indicate that the routing table size of $\Omega(\log n)$ is a threshold point that separates two distinct state-efficiency regions. One can observe that this point is in the middle of the symbolic asymptotic curve. If the routing table size is asymptotically smaller or equal, the requirement for congestion-free operation prevents it from achieving the smaller asymptotic diameter. When the routing table size is larger, the requirement for congestion-free operation does not limit the system anymore.
Routing table size and network distance

Routing table size

n
log n
<= d
0

O(1) O(log n) O(n^{1/d}) O(n)

Worst-case distance

1 2 3 4
Criticism

There have been two main criticisms of structured systems. The first pertains to peer transience, which is an important factor in maintaining robustness. Transient peers result in churn, which is a current concern with DHTs.

The second criticism of structured systems stems from their foundation in consistent hashing, which makes it more challenging to implement scalable query processing than for unstructured systems. Given that the popular file-sharing applications rely extensively on metadata-based queries, simple exact-match key searches are not sufficient for them and additional solutions are needed on top of the basic DHT API.

It is also possible to combine structured and unstructured algorithms in so-called hybrid models.
Additional material

Butterfly networks and Viceroy

Skip graph

CANON: merging Chord rings

De Bruijn graph
Butterfly Geometry

A \textit{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 $l$th 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)
Viceroy

The key point in Viceroy is the emphasis on constant degrees. The primary motivation was to develop an algorithm that has constant linkage cost, logarithmic path length, and best achievable congestion under the constraints.

It generally has constant degree such as CAN. Its degree is smaller than in Chord, Tapestry, and Pastry.

Viceroy assumes a global ordering on all the nodes in the system, which may make practical deployments in decentralized environments challenging.
Viceroy network

The idea is to approximate a butterfly network

The butterfly network results in constant node degree and thus state

The algorithm is rather involved

Idea is to use the butterfly levels for routing and then vicinity search

Message is routed upwards to the butterfly network root, and then downwards towards the correct destination, a shortcut may be used to reduce the routing cost
# Viceroy

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<td><strong>System parameters</strong></td>
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<tr>
<td><strong>Routing performance</strong></td>
</tr>
<tr>
<td><strong>Routing state</strong></td>
</tr>
</tbody>
</table>
| **Joins/leaves** | $\log N$  
*Note: assumes global ordering of nodes* |
Skip graph I

A skip graph is a probabilistic structure based on the skip list data structure. The skip list has simple and easy insert and delete operations that do not require tree rearrangements. Thus the operations are fast. The skip list is a set of layered ordered linked lists. All nodes are part of the bottom layer 0 list. Part of the nodes take part in the layer 1 with some fixed probability. For each layer there is a probability for a node to be part of that layer. As a result the upper layers of a skip list are sparse. This means that a lookup can quickly go through the list by traversing the sparse upper layer until it is close to the target.
Skip graph II

The downside of this approach is that the sparse upper layer nodes are potential hotspots and single points of failure.

Skip graphs address this limitation and introduce multiple lists at each level to improve redundancy. Every node participates in one of the lists at each level.

On average $O(\log n)$ levels are needed in the structure, where $n$ is the number of nodes.
Skip Graph III

The skip graph is a distributed version of the skip list and its performance is comparable to the other DHTs.

Each node in a skip graph has average of log $n$ neighbours.

The main benefit of the structure comes from its ability to support **prefix** and **proximity** search operations. DHTs guarantee that a data can be located, but they do not typically guarantee where the data will be located.

Skip graphs are able to support location-sensitive name searches, because they use ordered lists.
CANON: Adding Hierarchy to DHTs

Most DHTs that have been proposed are flat and non-hierarchical structures. They thus contrast the traditional distributed systems, which have employed hierarchy to achieve scalability.

A hierarchical DHT can be constructed that retains the homogeneity of load and functionality of the flat DHTs. A generic construction called Canon has been shown to offer the same routing state and routing hops trade-off found in the flat DHT designs.

The benefits of this approach include fault isolation, adaptation to the underlying physical network and its organizational boundaries, and hierarchical storage of content and access control.
The nodes keep their original links.
Each node $m$ in one ring creates a link to a node $m'$ in the other ring if and only if:
- $m'$ is the closest node that is at least distance $2k$ away for some $0 \leq k \leq N$
- $m'$ is closer to $m$ than any node in the ring of $m$
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 $2i \mod 2^n$ and $2i + 1 \mod 2^n$.

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 $b_1 \ b_2 \ \ldots \ b_k$, $b_i \in \{0, 1\}$

$n$ has an out-edge to the nodes with identifier $b_2 \ \ldots \ b_k \ 0$ and $b_2 \ \ldots \ b_k \ 1$.

Node 00: out edge to 00 and 01
Node 01: out edge to 10 and 11
Node 10: out edge to 00 and 01
Node 11: 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:
Example: Adding a digit

Example: Adding a digit