Peer-to-Peer Systems and Applications

Lecture 5: Selected Topics

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Chapter 5, 8, 21 and 33:

Part II: Unstructured P2P Systems
Part III: Structured Peer-to-Peer
Part VI: Search and Retrieval Systems
Part X: Advanced Issues

*Original slides provided by Ralf Steinmetz and Vasilios Darlagiannis (Technische Universität Darmstadt), and David Hausheer and Burkhard Stiller (University of Zürich)

0. Lecture Overview

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1. Selected DHT Algorithms: CAN

Design, Routing, Node Join,
Node Departure, References

*Based partially on original slides by Sylvia Ratnasamy et al. (UC Berkeley)

1.1. Design of CAN

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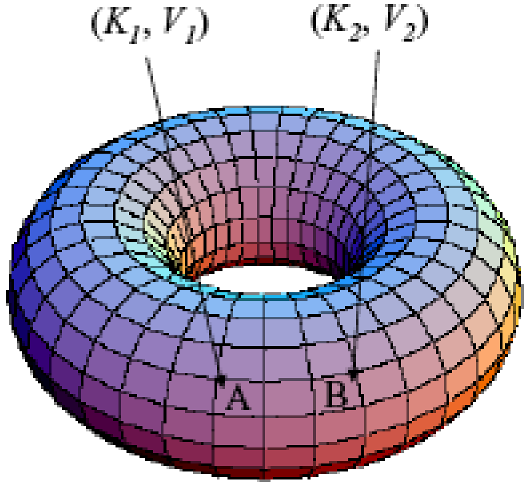
- CAN: A Scalable Content Addressable Network
  - Ratnasamy et al., SIGCOMM 2001

- *d*-dimensional Cartesian coordinate space (*d*-torus)

- Each node owns a *zone* on the torus

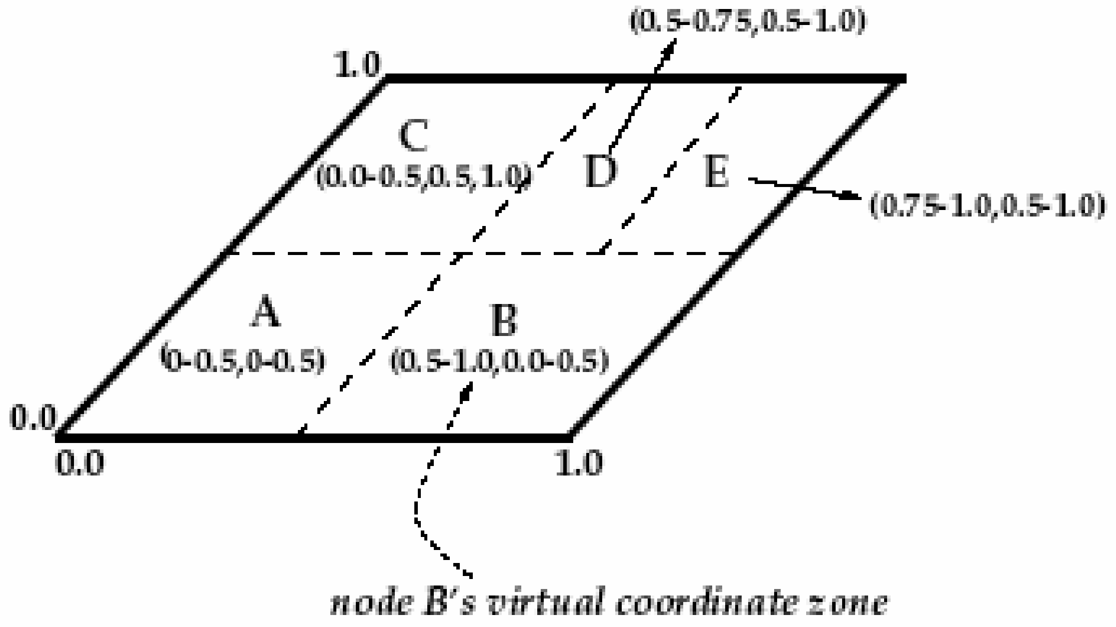
- To store key value pair (K_1, V_1),
  - K_1 mapped to point P_1 using uniform hash function
  - (K_1, V_1) stored at the node N that owns the zone containing P_1



2-torus

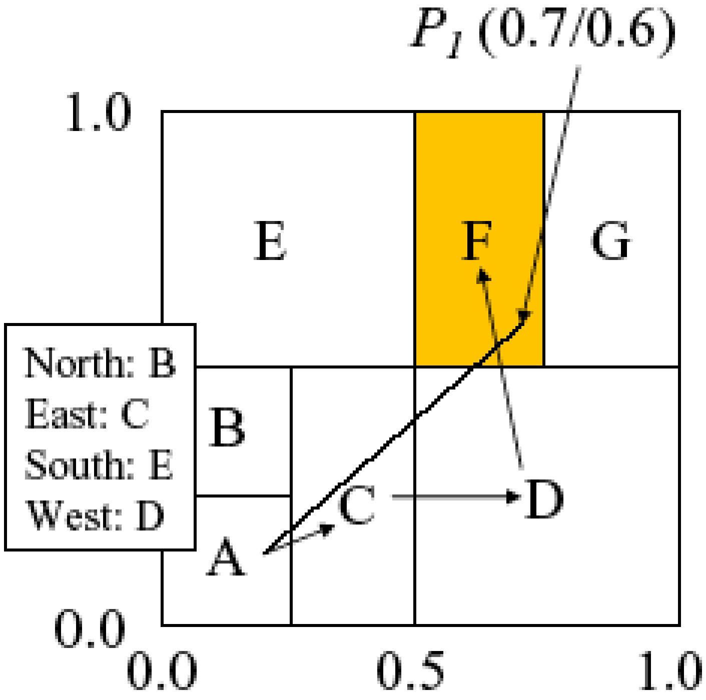
1.1. Design of CAN

- Each node stores IP address and coordinate zone of adjoining zones
- This set of neighbors is the node's routing table



1.2. CAN Routing

- How to route from node *A* to point P_1 at (0.7, 0.6)?
  - Draw straight line from point in *A*'s zone to P_1
  - Follow straight line using neighbor pointers



- For *d*-dimensional space partitioned into *n* equal zones, each node maintains 2*d* neighbors
  - Average routing path length:

$$\left(\frac{d}{4}\right)\left(n^{\frac{1}{d}}\right)$$

1.3. CAN: Node Join

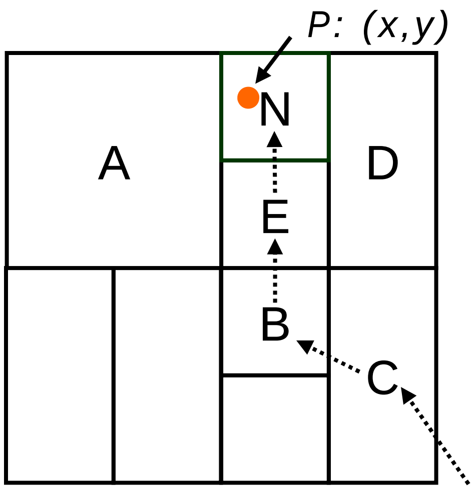
1. New node finds a node already in CAN

2. New node chooses random point P and sends JOIN message to node whose zone contains *P*, say node *N*

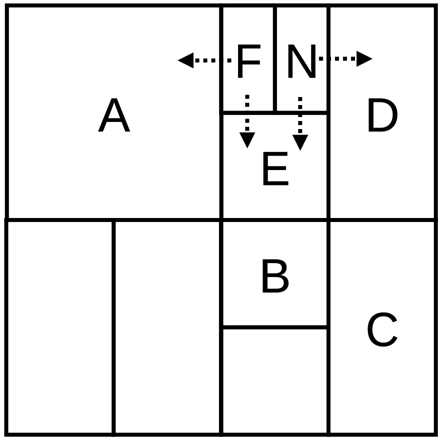
3. *N* splits its zone and allocates “half” to new node, transfer of (key,value) pairs

4. New node learns neighbor set from *N*

5. *N* updates its neighbor set to include new node



Routing path from node C to point (x,y)



1.3. CAN: Node Departure

- Graceful Node Departure
  - Node explicitly hands over zone and (key,value) pairs to one of its neighbors
  - Merge to form “valid” zone if possible
  - If not, two zones are temporarily handled by smallest neighbor

- Node Failures
  - Each node periodically sends messages to each of its neighbors
  - Nodes that detects failure initiates *takeover mechanism*
  - Takeover mechanism ensures node with smallest volume takes over the zone

1.4. References

- CAN
  - S. Ratnasamy, P. Francis, M. Handley, R. Karp, S. Shenker: A Scalable Content Addressable Network; In Proceedings of ACM SIGCOMM 2001, August 2001.
- Kademlia
  - P. Maymounkov and D. Mazieres: *Kademlia: A peer-to-peer information system based on the xor metric*; In Proceedings of IPTPS02, Cambridge, USA, March 2002.
- Viceroy
  - D. Malkhi, M. Naor, D. Ratajczak: *Viceroy: A scalable and dynamic emulation of the butterfly*; 21st ACM Symposium on Principles of Distributed Computing (PODC), 2002.
- P-Grid
  - Karl Aberer: *P-Grid: A Self-Organizing Access Structure for P2P Information Systems*; Sixth International Conference on Cooperative Information Systems (CoopIS), 2001.

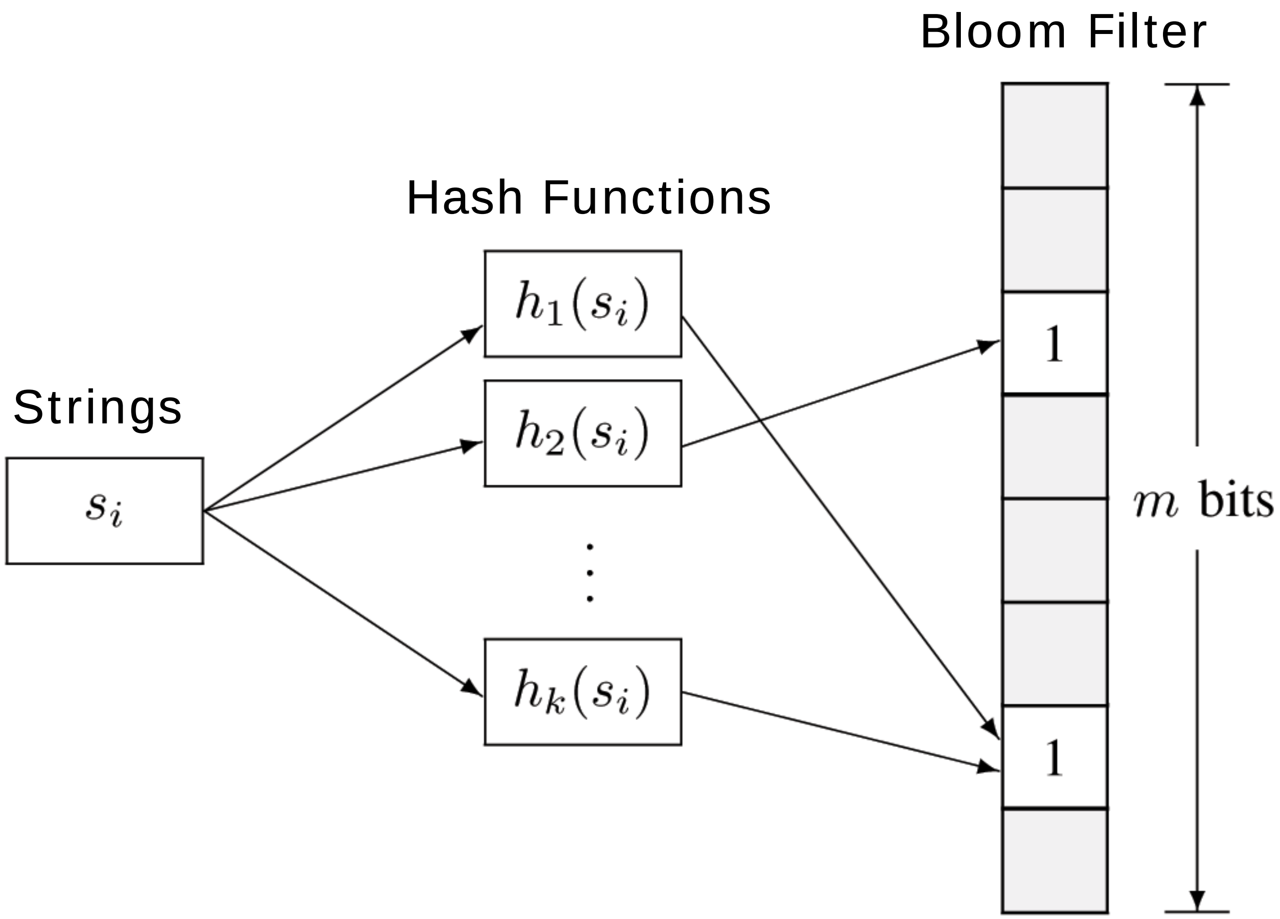
2. Bloom Filters

Traditional Bloom Filter, Attenuated Bloom Filter, References

2.1. Traditional Bloom Filter

- An array of *m* bits, initially all bits set to 0
- A bloom filter uses *k* independent hash functions
  - *h1, h2, ..., hk* with range {1, ..., m}
- Each key is hashed with every hash function
  - Set the corresponding bits in the vector
- Operations
  - Insertion
    - The bit A[hi(x)] for 1 < i < k are set to 1
  - Query
    - Yes if all of the bits A[hi(x)] are 1, no otherwise
  - Deletion
    - Removing an element from this simple Bloom filter is impossible

2.1. Insertion of an Element



2.1. Properties

- Space Efficiency
  - Any Bloom filter can represent the entire universe of elements
    - In this case, all bits are 1
- No Space Constraints
  - Add never fails
  - But false positive rate increases steadily as elements are added
- Simple Operations
  - Union of Bloom filters: bitwise OR
  - Intersection of Bloom filters: bitwise AND

2.1. False-Positive Probability

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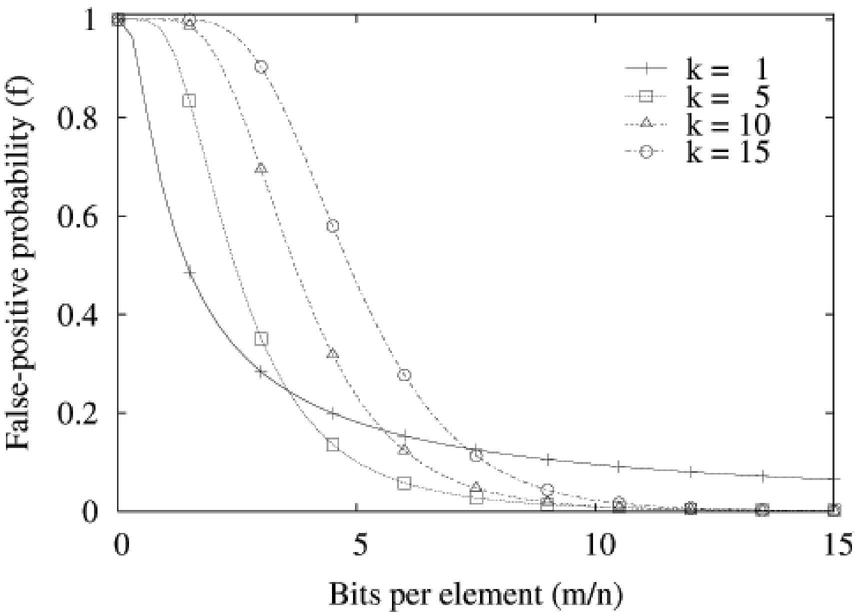
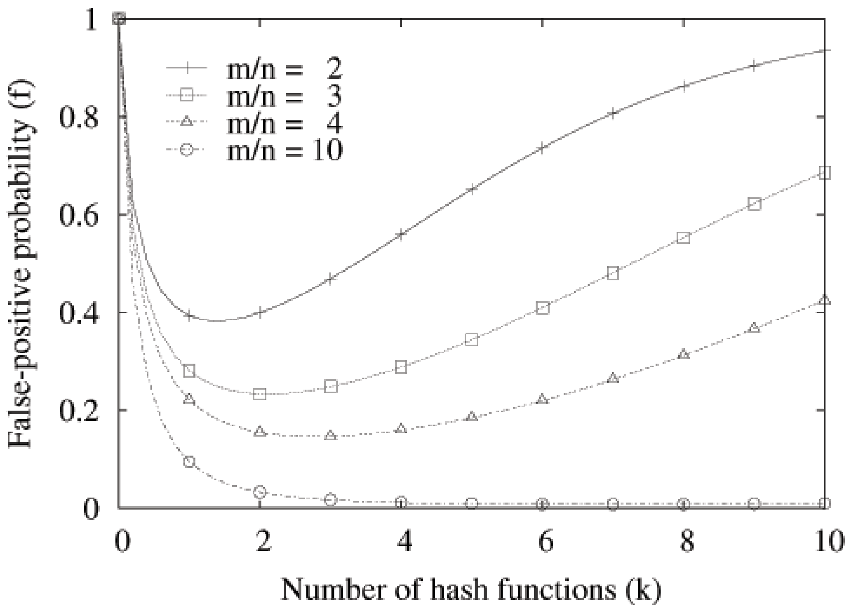
- No false negative, but false positive
- False-positive probability: $f = (1 - e^{-\frac{nk}{m}})^k$
  - *n* number of strings; *k* hash functions; *m*-bit vector



=> A longer bit vector and fewer insertions are always better



=> Given m/n, there is an optimal number of hash functions (f = 0.5^k) (when 50% of the bits are set)

2.1. Examples

- Application Example
  - Hash every attribute of a service description
  - Hash the query string
  - If the corresponding bits are set to 1, the query is satisfied

- Example for False-positives
  - Insertions
    - Hash („color printer“) => (1,4,6)
    - Hash („digital camera“) => (3,4,5)
  - Query
    - Hash („heat sensor“) => (3,4,6)
    - Matches since bits 3,4,6 are all set to 1

2.1. Applications

- Distributed Caching
- Collaboration in Overlay and Peer-to-Peer Networks
- Resource Routing
- Packet Routing
- Measurement Infrastructures
  - Traffic Flow Measurement
    - Space-Code Bloom Filter
  - Network Intrusion Detection
    - Packet Scanning
    - Identify malicious content, e.g. Internet worms and viruses

2.1. Bloom Filter Variants (1)

- Attenuated Bloom Filter
  - Use arrays of Bloom filters to store shortest path distance information
- Counting Bloom Filters
  - Each entry in the filter need not be a single bit but rather a small counter
  - Delete operation possible (decrementing counter)
- Spectral Bloom Filters
  - Extend the data structure to support estimates of frequencies
- Compressed Bloom Filters
  - When the filter is intended to be passed as a message
  - False-positive rate is optimized for the *compressed* bloom filter (uncompressed bit vector m will be larger but sparser)
  - Parameters can be adjusted to the desired trade-off between size and false-positive rate

2.1. Bloom Filter Variants (2)

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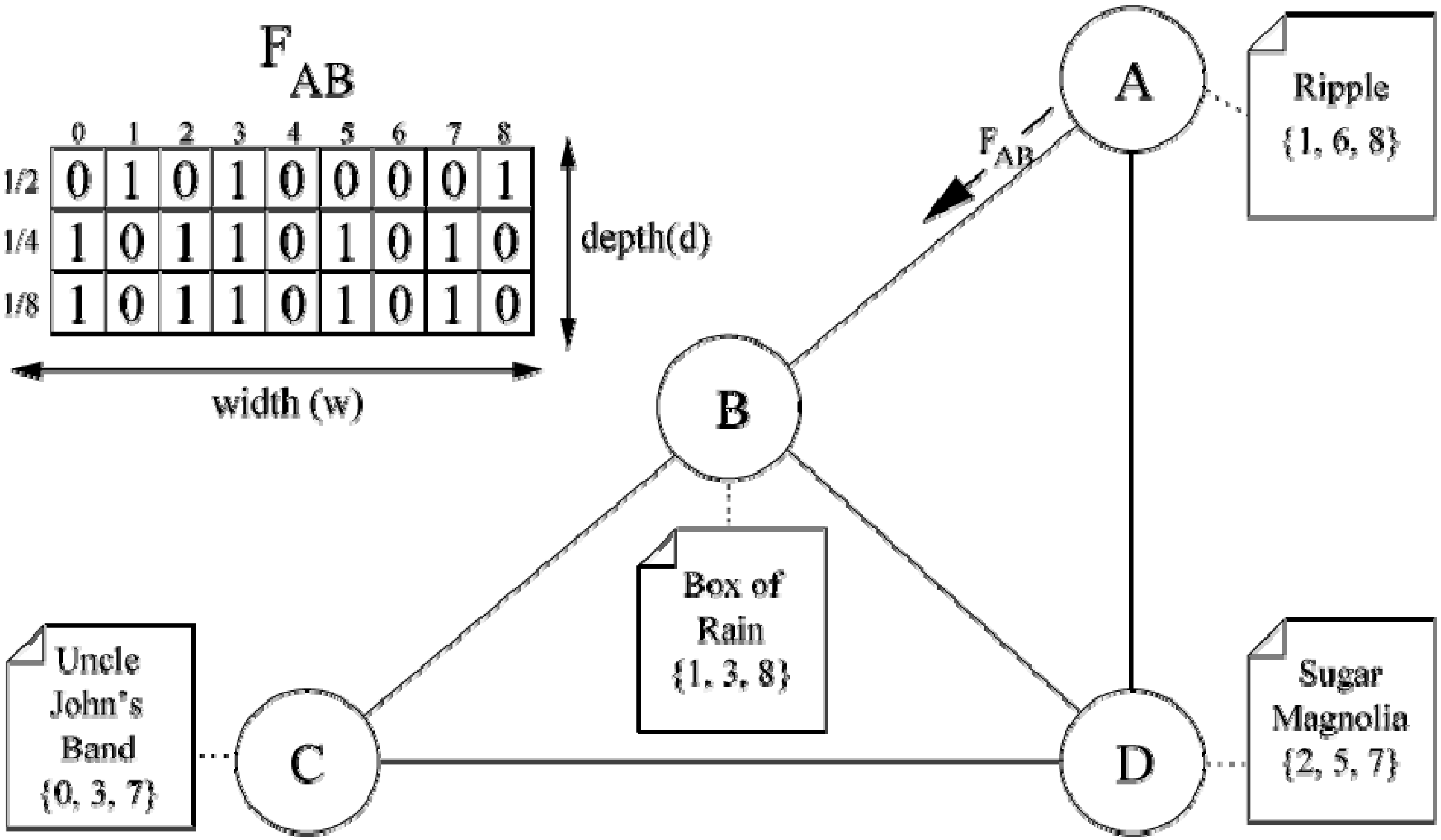
- Generalized Bloom Filter
  - Two type of hash functions *gi* (reset bits to 0) and *hj* (set bits to 1)
  - Start with an arbitrary vector (bits can be either 0 or 1)
  - In case of collisions between *gi* and *hj*, bit is reset to 0
  - Produces either false positives or false negatives
- Space-Code Bloom Filter
  - Made of l groups of hash functions, each group viewed as a traditional Bloom filter
    - **Insertion:**
      One group of hash function is selected, and the bits are set to 1
    - **Query:**
      Matches a group if all the bits of that group are set to 1; keeps track of the number of groups matched

2.2. Attenuated Bloom Filter

- Definition
  - An attenuated Bloom filter of depth *d* is an array of *d* normal Bloom filters
- Assumption
  - Each node has a set of overlay neighbors participating in the location algorithm
- Association
  - Each neighbor link is associated with an attenuated Bloom filter
- Construction
  - Bloom filter *k* is a union of objects at exactly *k* hops away

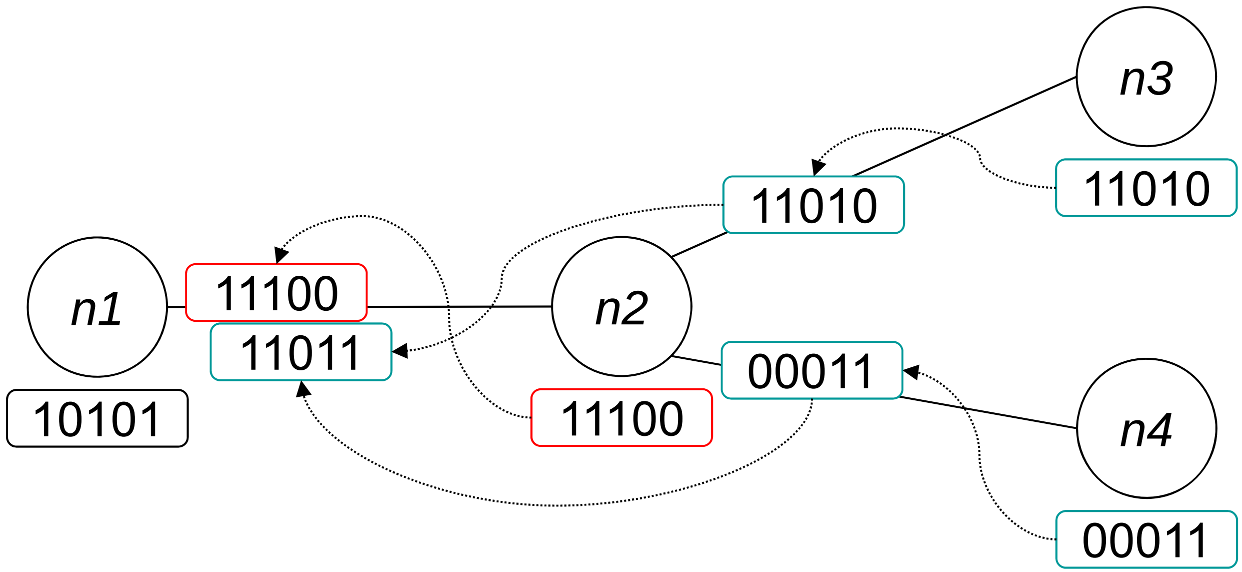
Sean C. Rhea, John Kubiatowicz: Probabilistic Location and Routing; Infocom 2002.

2.2. Example (1)

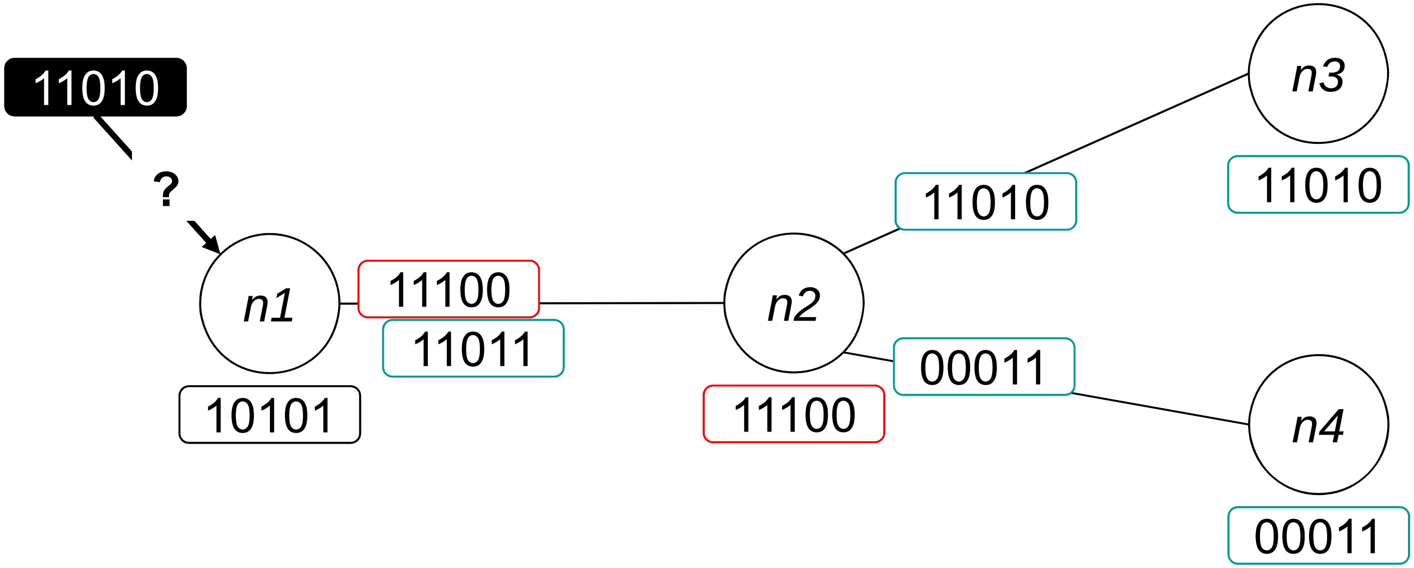


Sean C. Rhea, John Kubiatowicz: Probabilistic Location and Routing; Infocom 2002.

2.2. Example (2)



2.2. Query Routing Example



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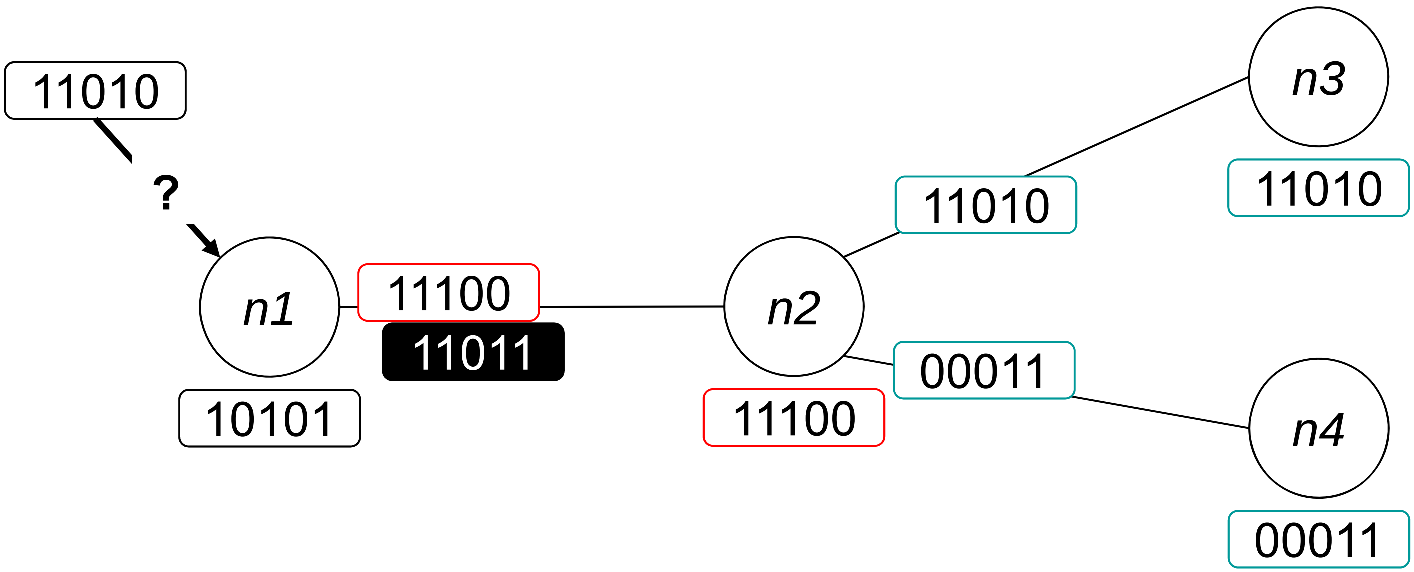

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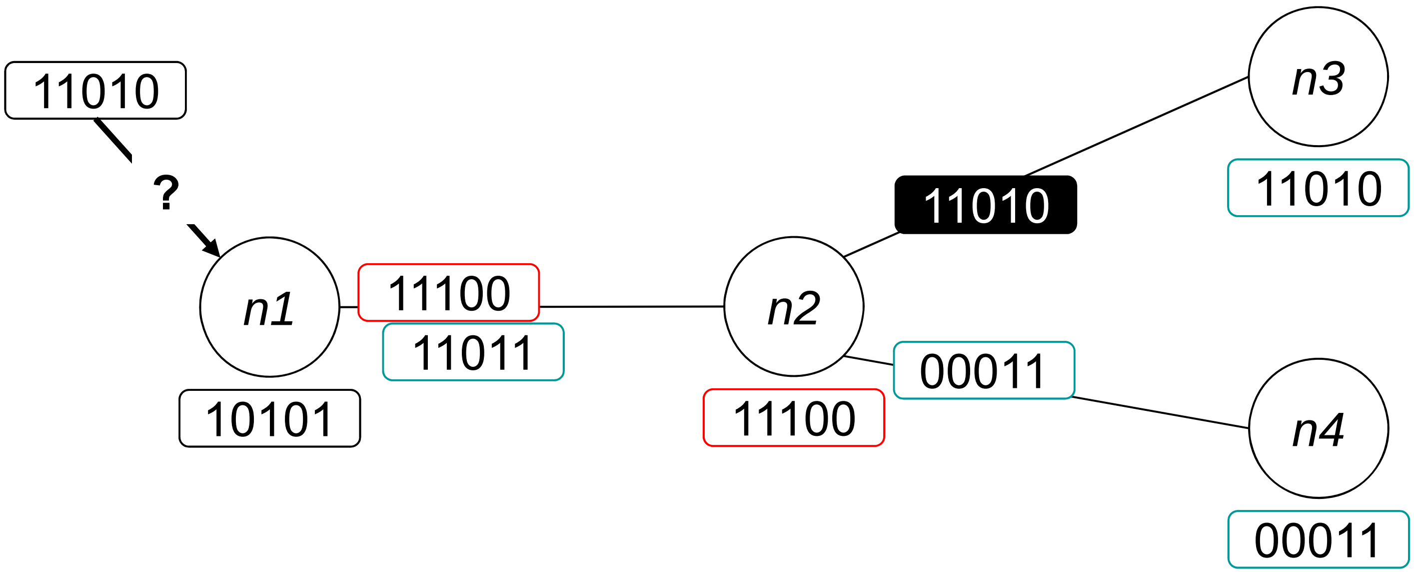
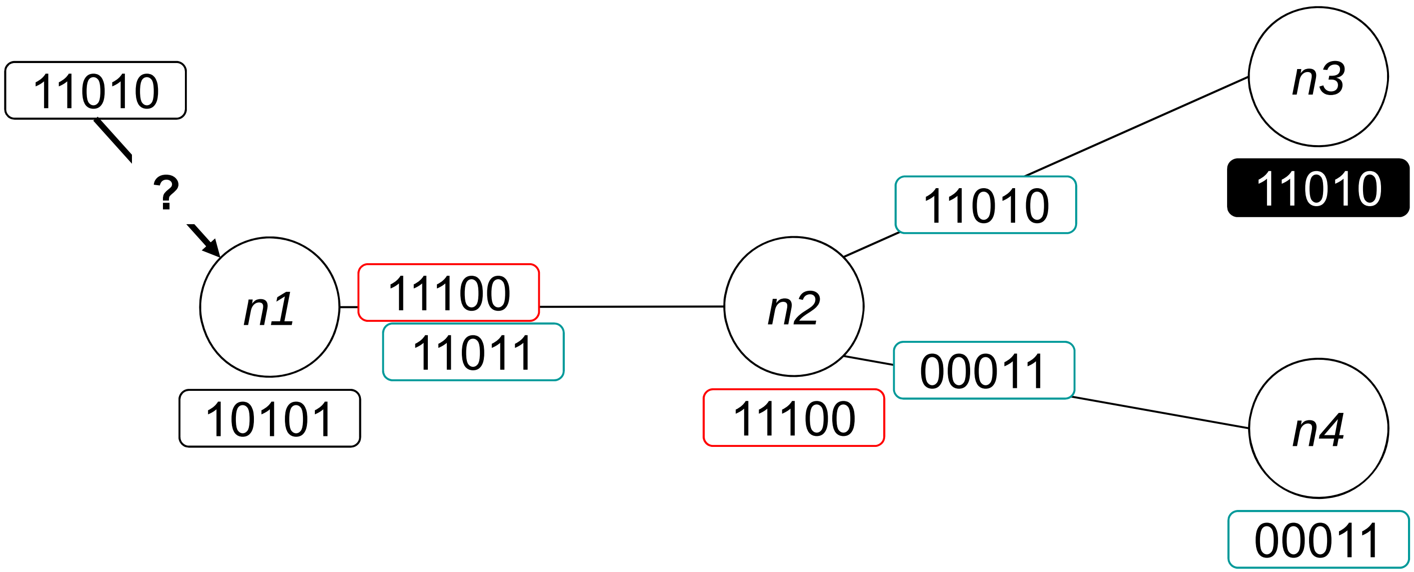


2.2. Query Routing Example



2.3. References

- Traditional Bloom Filter
  - Burton H. Bloom: *Space/Time Trade-offs in Hash Coding with Allowable Errors*; Communications of the ACM, Vol. 13(7), pp. 422-426, 1970.
- Attenuated Bloom Filter
  - S. C. Rhea and J. Kubiatowicz: *Probabilistic Location and Routing*; IEEE INFOCOM 2002, New York, NY, USA, pp. 1248-1257, June 2002.
- Bloomier Filter
  - B. Chazelle, J. Kilian, R. Rubinfeld, and A. Tal: *The Bloomier Filter: An Efficient Data Structure for Static Support Lookup Tables*; SODA 2004.
- Spectral Bloom Filters
  - S. Cohen, Y. Matias: *Spectral Bloom Filters*; SIGMOD 2003.
- Counting Bloom Filters
  - L. Fan, P. Cao, J. Almeida, A. Broder: *Summary Cache: A Scalable Wide-Area Web Cache Sharing Protocol*; IEEE/ACM Transactions on Networking, Vol. 8(3), pp. 281-293, June 2000.
- Compressed Bloom Filters
  - M. Mitzenmacher: *Compressed Bloom Filters*; IEEE Transactions on Networking, Vol. 10 (5), pp. 604-612, October 2002.

2.3. References

- A. Broder and M. Mitzenmacher: *Network Applications of Bloom Filters: A Survey*; 40th Annual Allerton Conference on Communication, Control, and Computing, pp. 636-646, 2002.
- T. Kocak, I. Kaya: *Low-Power Bloom Filter Architecture for Deep Packet Inspection*; IEEE Communications Letters, Vol. 10(3), pp. 210-212, March 2006.
- S. Dharmapurikar, P. Krishnamurthy, T. S. Sproull, and J. W. Lockwood: *Deep Packet Inspection using Parallel Bloom Filters*; IEEE Micro, Vol. 24 (1), pp. 52-61, January 2004.
- R. Laufer, P. Velloso, O. Duarte: *Generalized Bloom Filters*; Technical Report GTA-05-43, COPPE/UFRJ, September 2005.

3. Hypercube Networks

Construction, Routing, Properties, Limitations

3. Hypercube Networks

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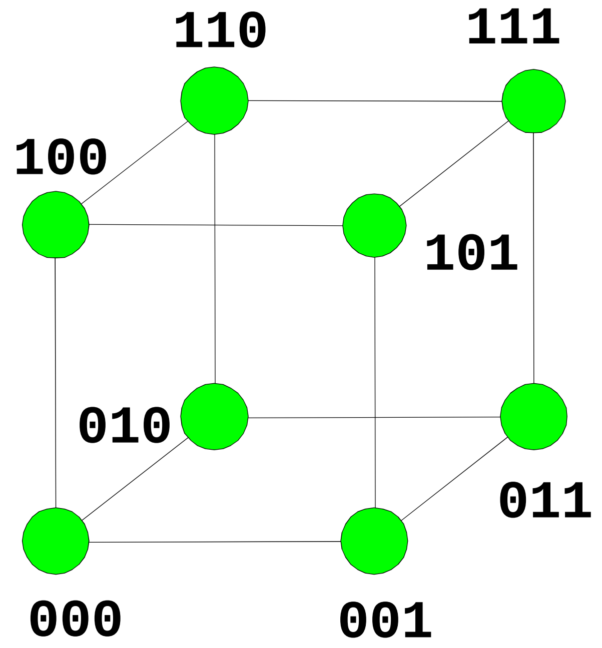
- Example:
  - 3-dimensional Hypercube Network

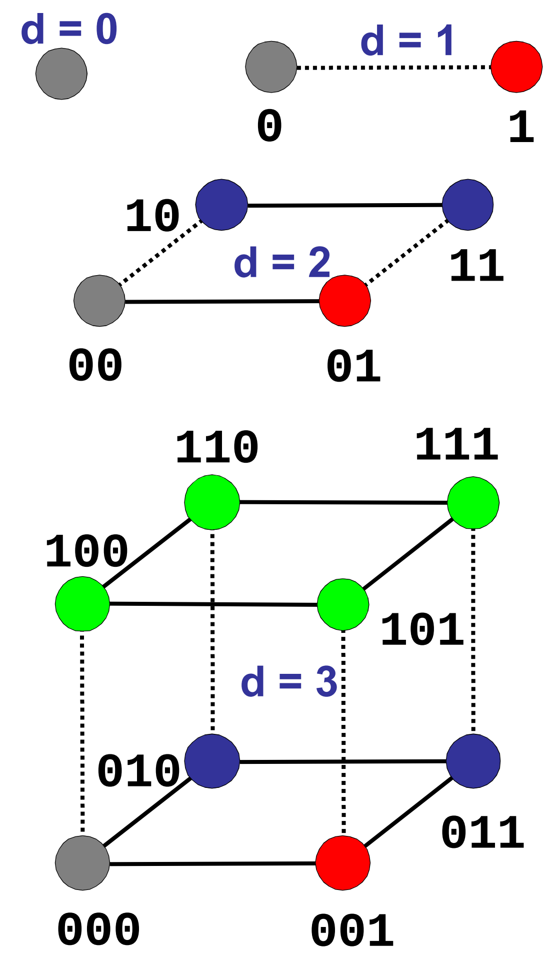


- d-dimensional binary hypercube definition
  - A d-dimensional binary hypercube network consists of 2^d
    - interconnected nodes
    - whose addresses are represented by d-bit binary numbers.
  - A node n has d adjacent nodes
    - whose addresses are obtained by reverting each bit of its address
    - fixed number of contacts per node!

3.1. Hypercube Networks: How to construct

- Construction algorithm
  - if (d == 0)
    draw a node
  - else
    - 1. draw two hypercubes of dimension (d-1)
    - 2. add arcs between
      - corresponding nodes of the two hypercubes

- Identification algorithm
  - 1. use the first bit
    - to decide which of the two sub-hypercubes the node is in.
  - 2. use the remaining d-1 bits as
    - an address within that sub-hypercube.



3.2. Hypercube Networks: Routing Algorithm

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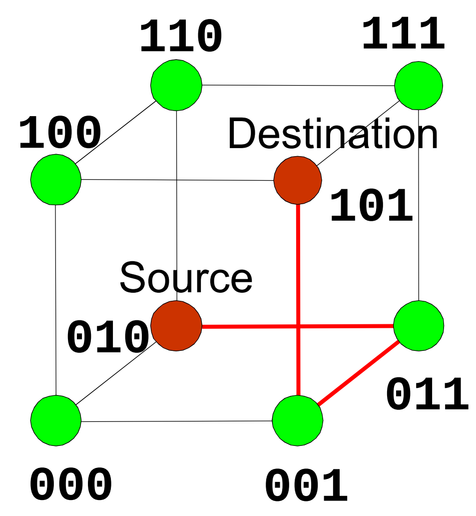
- A simple source-to-destination routing algorithm for binary hypercube networks
  - Node failure is ignored

- To route from node i to node j,
  - the bits of i which are different from those of j are changed,
    - traversing a link with each bit changed,
    - until j is reached.
  - Since each node has links corresponding to each of the n bit positions,
    - any bit can be changed at any step in the route;
  - →
    - the number of eligible links at each step equals the distance from the destination.

3.2. Hypercube Networks: Routing Example

- Route from 010 to 101
  - 010 has 3 options (000, 110, 011)
    - → distance = 3
    - Select 011 as the next hop
  - 011 has 2 options (001, 111)
    - → distance = 2
    - Select 001 as the next hop
  - 001 is direct neighbor
    - → distance = 1
    - Forward to destination

- IF
  - nodes fail
- THEN
  - alternative paths may be followed in dynamic environments



3.3. Hypercube Networks: Properties

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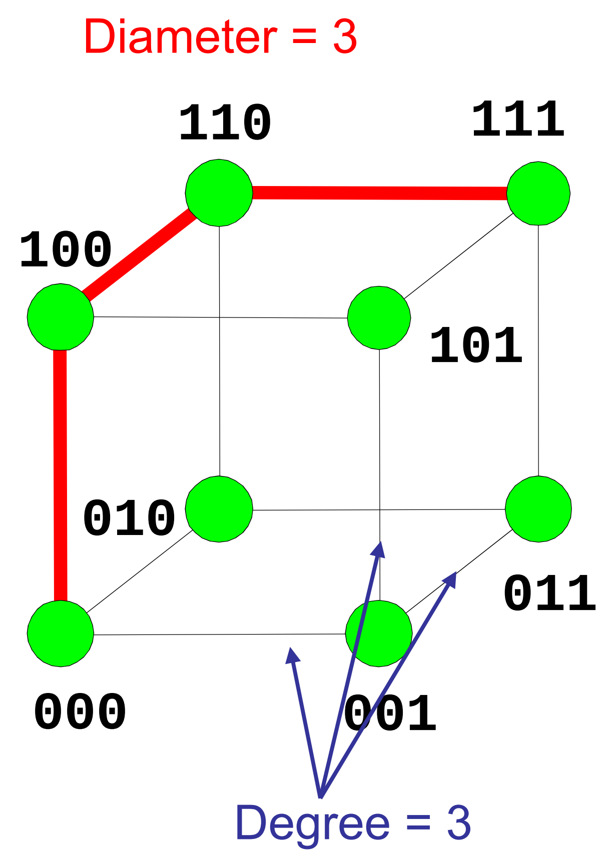
- Basic properties:

- diameter of the network
  - i.e. worst case node distance
  - increases logarithmically with respect to the network size
- node degree
  - i.e. number of neighbors
  - increases logarithmically with respect to the network size
- network is both
  - vertex- and
  - edge-symmetric graph

- hypercube is a hierarchically recursive network



3.4. Hypercube Networks: Limitations

- Exponentially expandable
  - Network size is defined only for 1, 2, 4, 8, ... nodes
    - for binary hypercubes
  - Not incrementally expandable
    - i.e. network cannot be defined for any arbitrary integer

- Node degree increases logarithmically with respect to the network size
  - → increasing the required maintenance cost

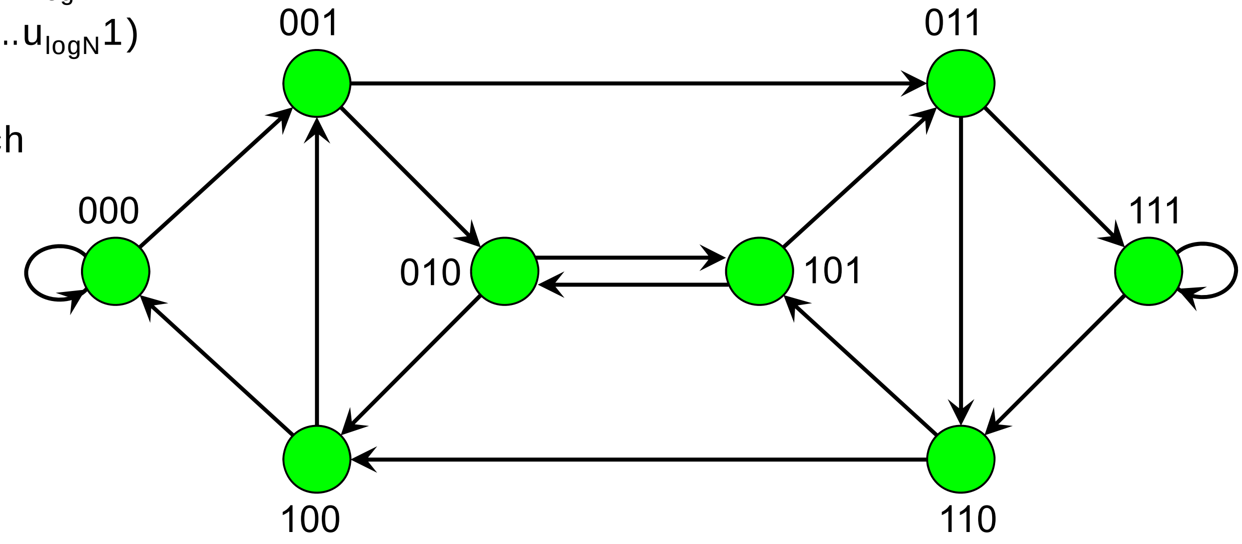
- Mostly appropriate for static environments
  - with infrequent joins and leaves

4. de Bruijn Networks

Construction, Routing, Properties, Limitations, Omicron

4. de Bruijn Networks

- r-dimensional binary de Bruijn digraph (directed graph) consists of
  - 2^r nodes
  - 2^{r+1} edges
- each node corresponds to
  - an r-digit binary string
- there is a directed edge
  - from each node $(u_1 u_2 \ldots u_{\log N})$
  - to $(u_2 \ldots u_{\log N} 0)$ and $(u_2 \ldots u_{\log N} 1)$
  - number of in and out edges per node: 2 each



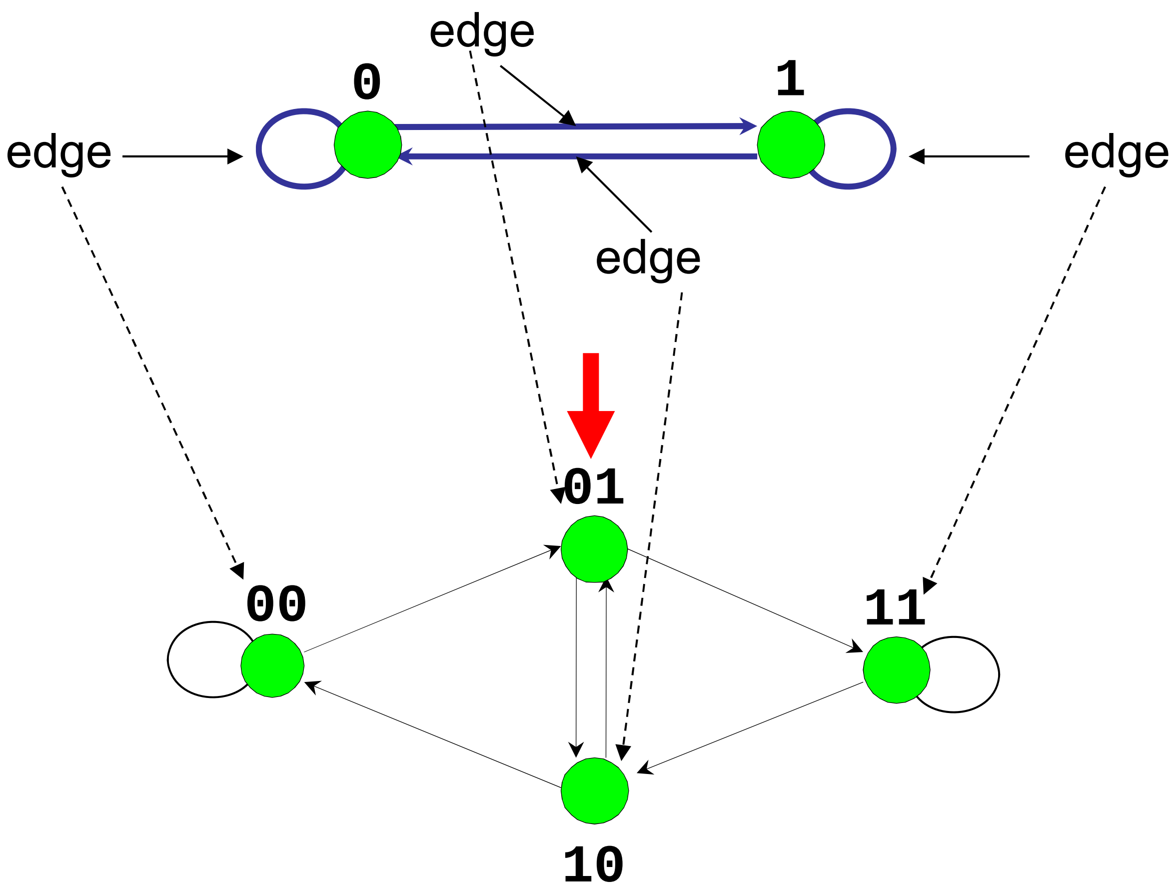
4.1. de Bruijn Networks: How to construct

- Partial Line Digraph Algorithm: recursive construction
  - The N-node graph can be obtained from the N/2 –node graph

- Algorithm description
  - Replace every edge of the N/2-node graph with a node
    - Edge($u_1 \ldots u_{logN-1}$, $u_2 \ldots u_{logN}$) → Node($u_1 \ldots u_{logN}$)
  - Insert a directed edge between pairs of nodes
    that correspond to consecutive directed edges in the N/2-node graph
    - Edge($u_1 \ldots u_{logN-1}$, $u_2 \ldots u_{logN}$) and
      Edge($u_2 \ldots u_{logN}$, $u_3 \ldots u_{logN+1}$)
    - Replaced by
      Edge($u_1 \ldots u_{logN}$, $u_2 \ldots u_{logN+1}$)

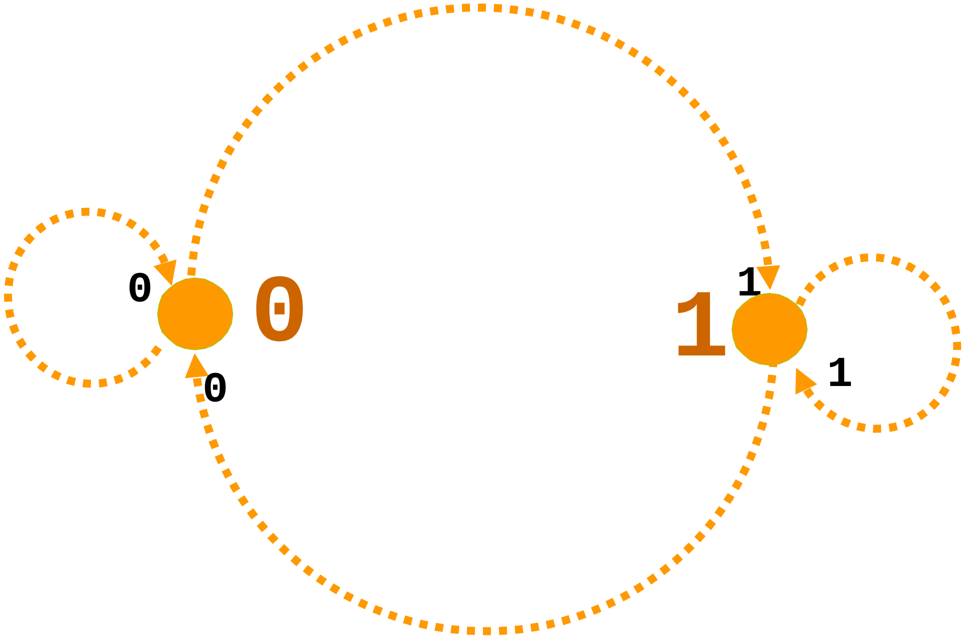
4.1. de Bruijn Networks: Construction Example

- N = 2
- N = 4



4.1. de Bruijn Networks: Construction Example

- N = 2



4.1. de Bruijn Networks: Construction Example

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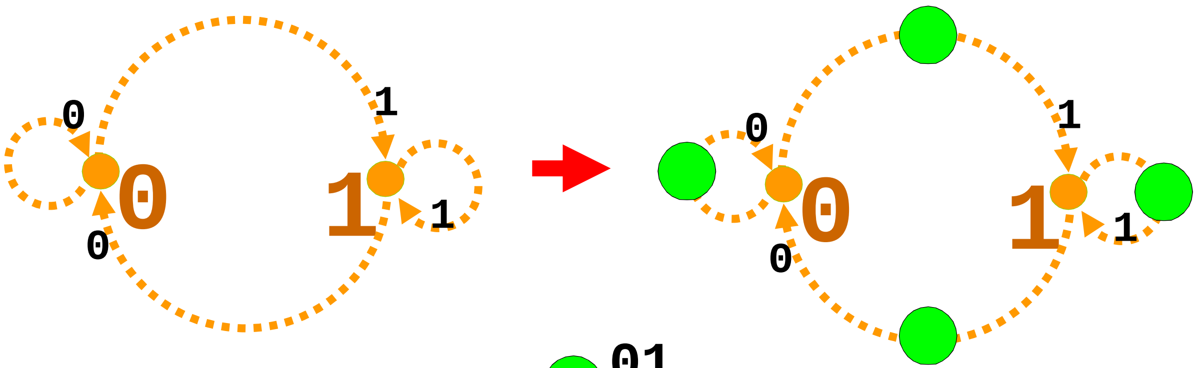
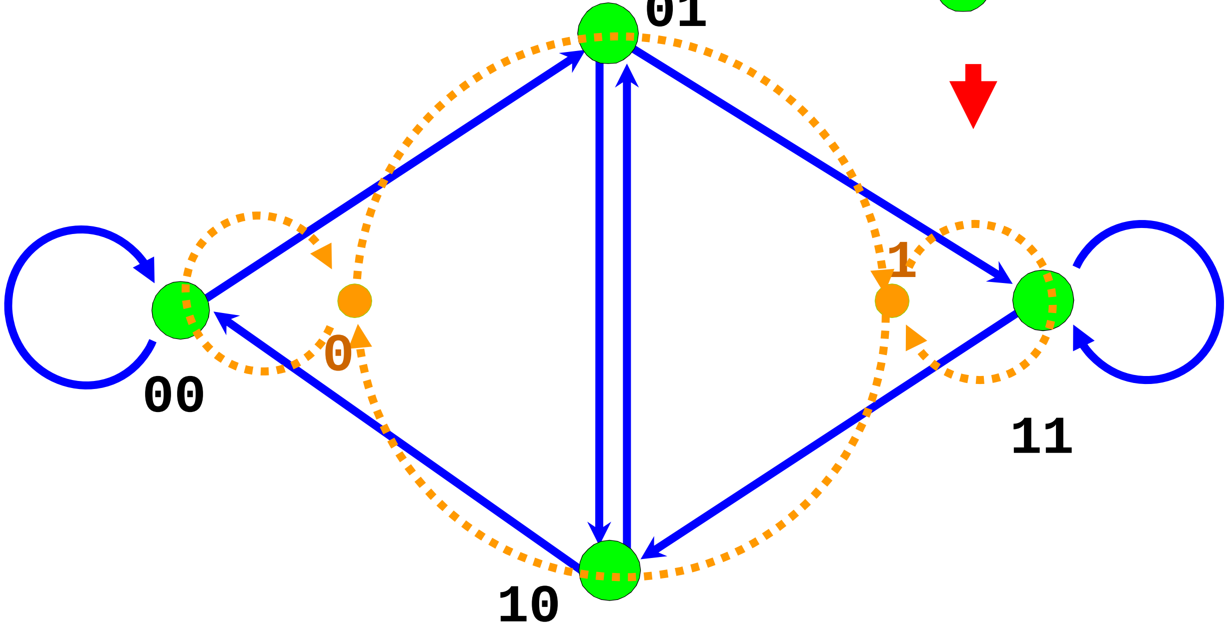


- N = 4



4.2. de Bruijn Networks: Routing Algorithm

- Operation: shift_match(shift, K, L), where 0 <= shift <= D
  - returns TRUE if and only if
    $k_{1+shift}k_{2+shift}...k_D = l_1 l_2 ... l_{D-shift}$
  - returns FALSE otherwise
- Operation: merge(shift, K, L), where 0 <= shift <= D.
  - returns the sequence of length (D + shift) given by
    $k_1 k_2 ... k_D l_{D-shift+1} l_{D-shift+2} ... l_D$

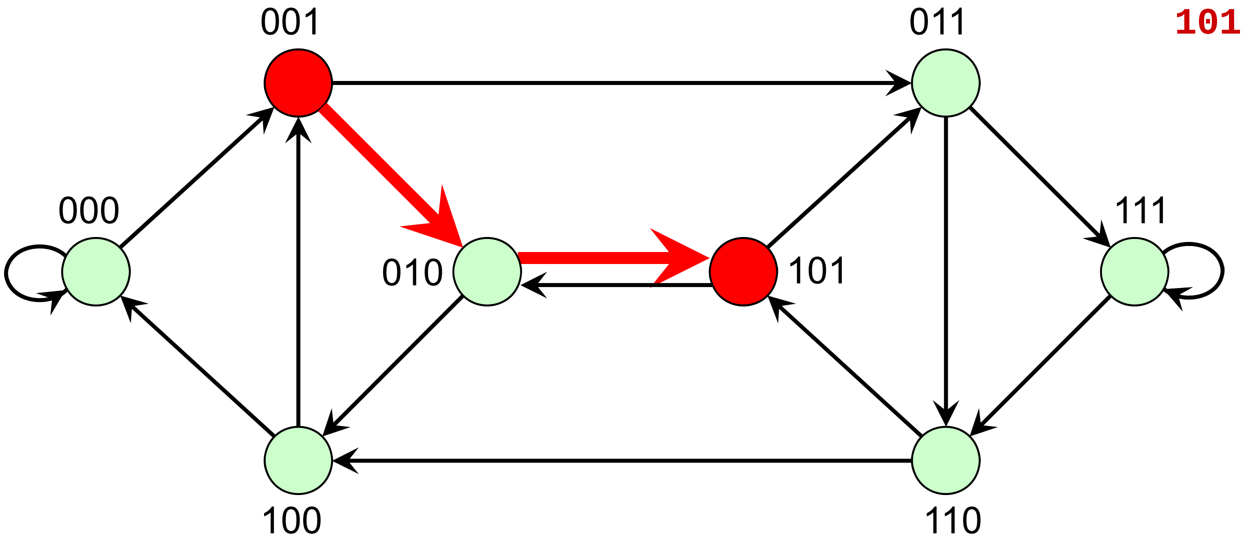
- Shortest-path algorithm (Sivarajan and Ramaswami)

```
shortest_path(K, L)
    shift = 0
    while (shift_match(shift, K, L) == FALSE and shift < D)
     do shift = shift + 1
    return merge(shift, K, L)
```

4.2. de Bruijn Networks: Routing Example

- Example: route
  - to node 101
  - from node with ID (GUID) 001

- Only shift left operation is allowed
  - i.e. only 2 entries in the routing table




```
Example
  to node   101
  from node 001

   ←← match by shift left
  101 destinations node
001       from
 010      via …
  101     to destination node
```

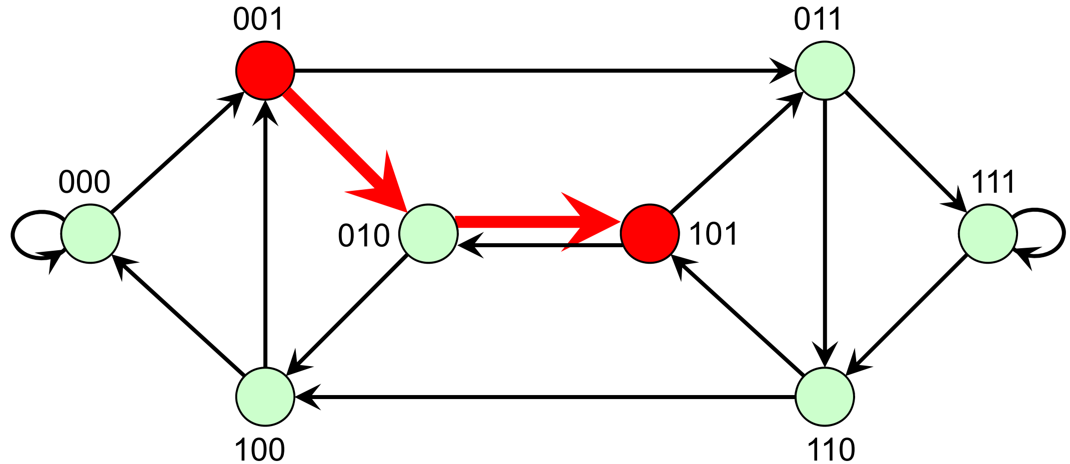
4.2. de Bruijn Networks: Routing Example

- i.e. Route message from source (001) to (101)

```
shift = 0
  shift_match(0, 001, 101) = FALSE  …  001 101
shift = 1
  shift_match(1, 001, 101) = FALSE  …    01   10
shift = 2
  shift_match(2, 001, 101) = TRUE   …     1    1

return merge (2, 001,101) = 00101   …         01
```

  - 2 forwarding steps



4.2. de Bruijn Networks: Routing Example

- We want
  - to route to node with ID (GUID) 101
  - coming from node 001
- Only shift left operation is allowed
  - i.e. only 2 entries in the routing table
- Procedure
  - 1 0 1 destinations node
  - 0 0 1 from
  - 0 1 0 via ...
  - 1 0 1 to destination node

And other example

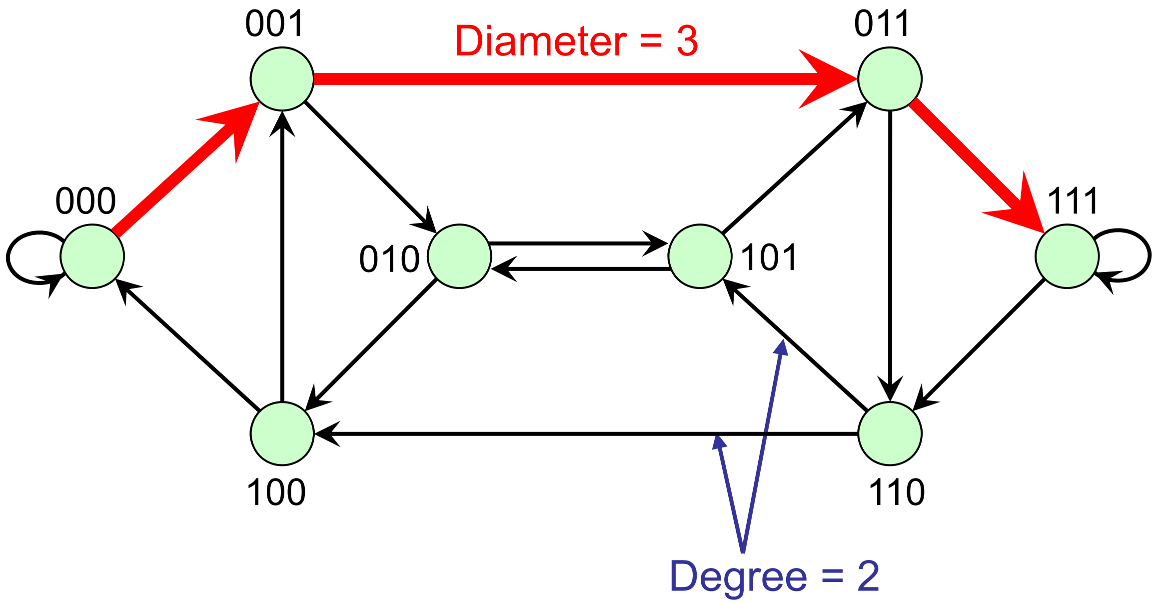
.. to node 01001

.. from 11111

```
     01001 destinations node
11111      from
 11110     via …
  11101
   11010
    10100
     01001 to destination node
```

4.3. de Bruijn Networks: Properties

- Basic characteristics
  - Average distance is very close to the diameter
  - Constant vertex degree
  - Logarithmic diameter
  - Adjacency is based on left shift by 1 position

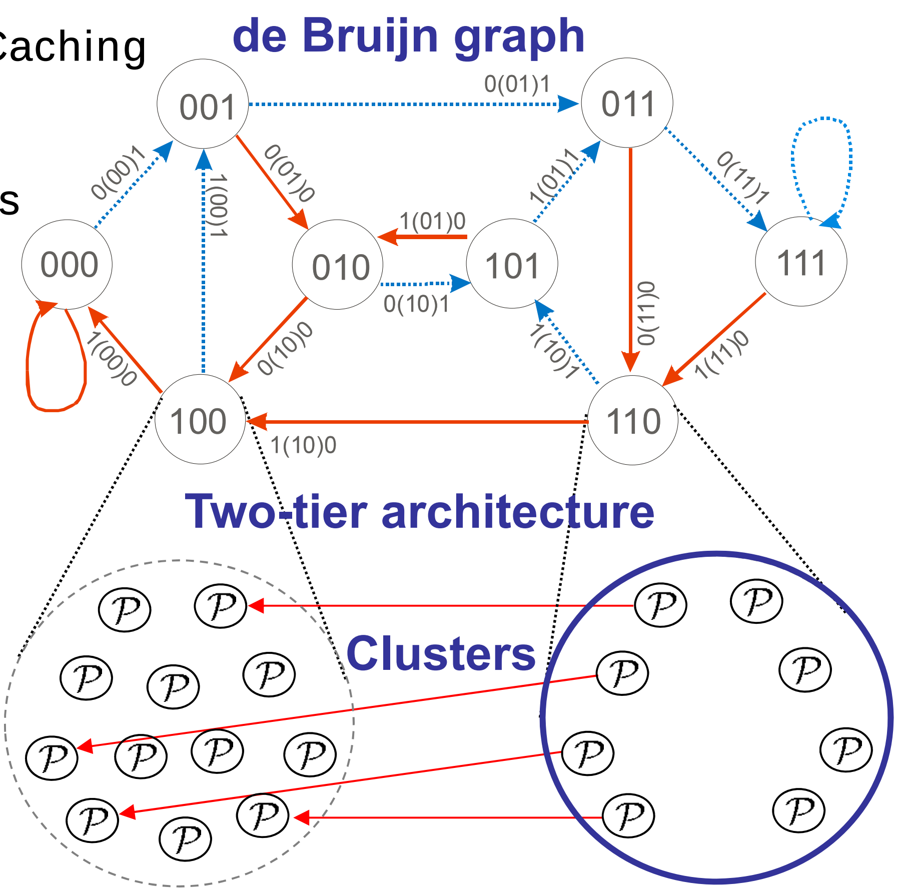


4.4. de Bruijn Networks: Limitations

- Limitations of de Bruijn networks
  - Exponentially expandable
    - Network size is defined only for 1, 2, 4, 8, ... nodes (for binary graphs)
    - Not incrementally expandable
      - i.e. basic network cannot be defined for any arbitrary integer
      - But, enhancements possible (see PhD Darlargiannis)
  - Mostly appropriate for static environments with infrequent joins and leaves

4.5. Omicron

- Omicron
  - Organized Maintenance, Indexing, Caching and Routing for Overlay Networks
  - Uses a hybrid DHT topology to deal with several conflicting requirements
    - Scalability, efficiency, robustness, heterogeneity and load-balance
- Structured macro level (de Bruijn)
  - Scalable
    - Asymptotically optimal Diameter and average node distance
    - Fixed node degree
  - Stable components required
- Clustered micro level
  - Redundancy and fault-tolerance
  - Locality aware
  - Finer load balance
  - Handling hot spots



4.5. Omicron Roles

- Common overlay network operations
  - Ⓜ **Maintainer:** Maintaining structure (topology)
  - Ⓘ **Indexer:** Indexing advertised items
  - Ⓒ **Cacher:** Caching popular items
  - Ⓡ **Router:** Routing queries