CompSci 356: Computer Network Architectures
Lecture 24: Overlay Networks
Chap 9.4

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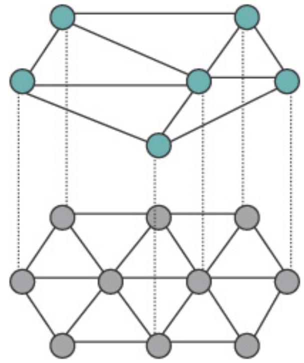
Overview

- What is an overlay network?

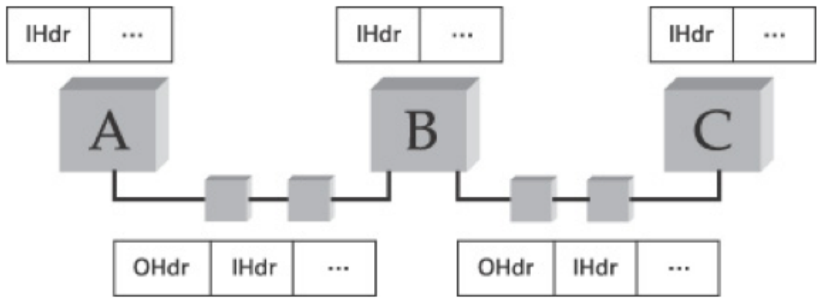
- Examples of overlay networks
  - End system multicast
  - Unstructured
    - Gnutella, BitTorrent
  - Structured
    - DHT

What is an overlay network?



- A logical network implemented on top of a lower-layer network
- Can recursively build overlay networks
- An overlay link is defined by the application
- An overlay link may consist of multi hops of underlay links

Ex: Virtual Private Networks



- Links are defined as IP tunnels
- May include multiple underlying routers

Other overlays

- The Onion Router (Tor)
- Resilient Overlay Networks (RoN)
  - Route through overlay nodes to achieve better performance
- End system multicast

Unstructured Overlay Networks

- Overlay links form random graphs
- No defined structure
- Examples
  - Gnutella: links are peer relationships
    - One node that runs Gnutella knows some other Gnutella nodes
  - BitTorrent
    - A node and nodes in its view

Peer-to-Peer Cooperative Content Distribution

- Use the client's upload bandwidth
  - infrastructure-less
- Key challenges
  - How to find a piece of data
  - How to incentivize uploading

Data lookup

- Centralized approach
  - Napster
  - BitTorrent trackers

- Distributed approach
  - Flooded queries
    - Gnutella
  - Structured lookup
    - DHT

Gnutella

- All nodes are true peers
  - A peer is the publisher, the uploader, and the downloader
  - No single point of failure
- A node knows other nodes as it neighbors
- How to find an object
  - Send queries to neighbors
  - Neighbors forward to their neighbors
  - Results travel backward to the sender
  - Use query IDs to match responses and to avoid loops

Gnutella

- Challenges
  - Efficiency and scalability issue
    - File searches span across many nodes → generate much traffic
  - Integrity (content pollution)
    - Anyone can claim that he publishes valid content
    - No guarantee of quality of objects
  - Incentive issue
    - No incentive for cooperation → free riding

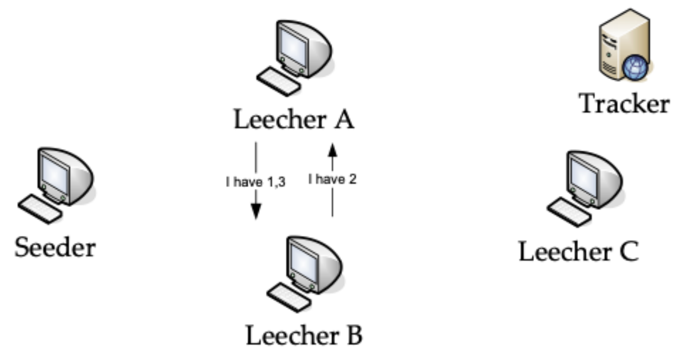
BitTorrent

- Designed by Bram Cohen
- Tracker for peer lookup
  - Later trackerless
- Rate-based Tit-for-tat for incentives

Terminology

- Seeder: peer with the entire file
  - Original Seed: The first seed
- Leecher: peer that's downloading the file
  - Fairer term might have been "downloader"
- Piece: a large file is divided into pieces
- Sub-piece: Further subdivision of a piece
  - The "unit for requests" is a sub piece
  - But a peer uploads only after assembling complete piece
- Swarm: peers that download/upload the same file

BitTorrent overview



- A node announces available chunks to their peers
- **Leechers** request chunks from their peers (**locally rarest-first**)

- Leechers A and B also announce to their peers which chunks they possess

- Now we show BitTorrent's incentive

mechanism, which is also known as rate-based tit-for-tat

In this case, leecher A makes the first step and offers to unconditionally upload for 10 seconds chunks to leecher B. In BT lingo, this step is called optimistic unchoking

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Optimistic Unchoking

- Discover other faster peers and prompt them to reciprocate
- Bootstrap new peers with no data to upload

Scheduling: Choosing pieces to request

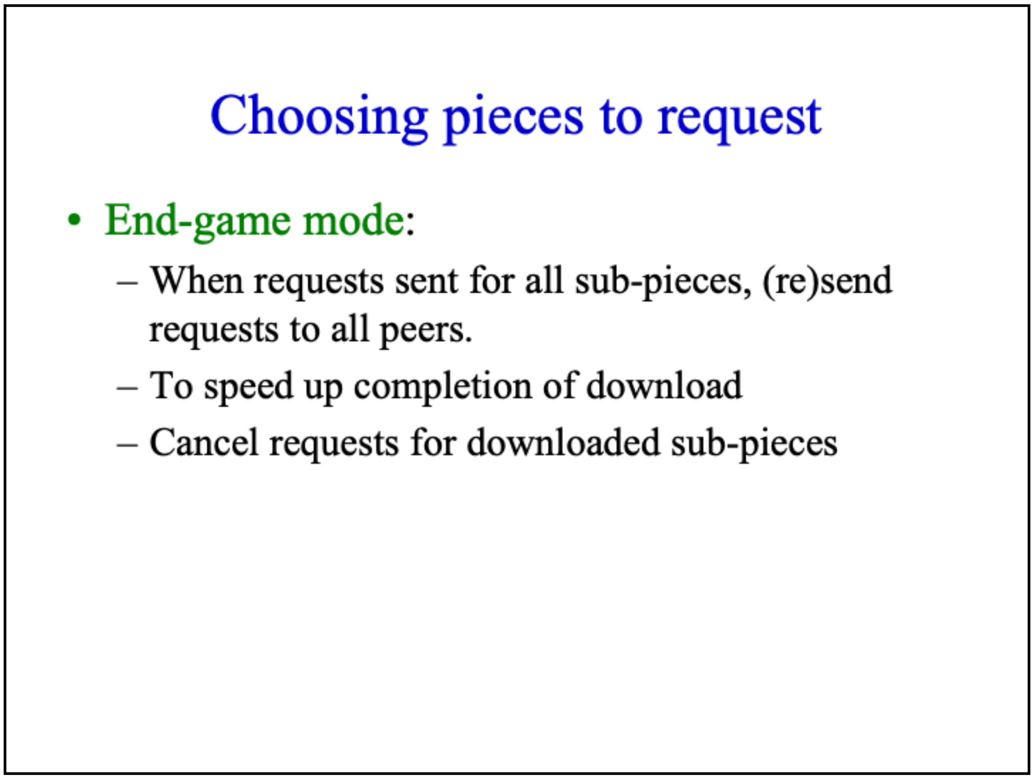
- Rarest-first: Look at all pieces at all peers, and request piece that's owned by fewest peers
  1. Increases diversity in the pieces downloaded
     - avoids case where a node and each of its peers have exactly the same pieces; increases throughput
  2. Increases likelihood all pieces still available even if original seed leaves before any one node has downloaded the entire file
  3. Increases chance for cooperation

- Random rarest-first: rank rarest, and randomly choose one with equal rareness

Start time scheduling

- Random First Piece:
  - When peer starts to download, request random piece.
    - So as to assemble first complete piece quickly
    - Then participate in uploads
    - May request sub pieces from many peers
  - When first complete piece assembled, switch to rarest-first

the rarest may be in only one peer
so it picks a random instead which may be at many peers
and downloads subpieces in SGM from multiple peers
like in EGM
but in the other modes he only downloads it
subpieces from the same peer



The End Game is the name for the final download strategy – there is a tendency for the last few pieces of a torrent to download quite slowly. To avoid this, many BitTorrent implementations issue requests for the same remaining blocks to all its peers. When a block comes in from one peer, you send CANCEL messages to all the other peers requested from, in order to save bandwidth. Its cheaper to send a CANCEL message than to receive the full block and just discard it.

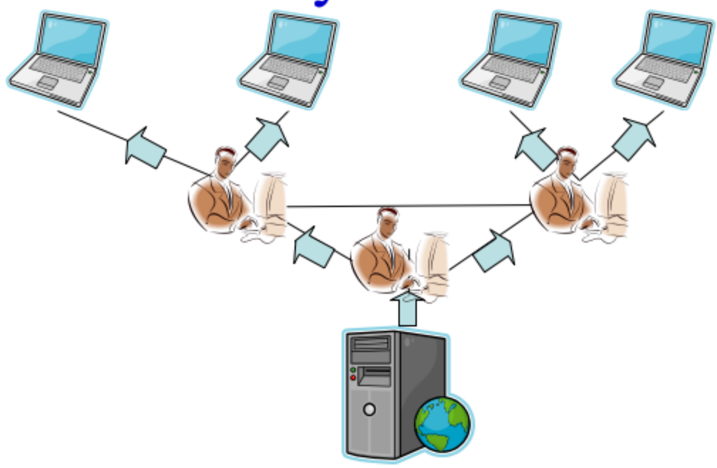
However, there is no formal definition of when to enter End Game Mode. I found two popular definitions:

1. All blocks have been requested
2. Number of blocks in transit is greater than number of blocks left, and no more than 20

Overview

- Overlay networks
  - Unstructured
  - Structured
    - End systems multicast
    - Distributed Hash Tables

End system multicast



- End systems rather than routers organize into a tree, forward and duplicate packets
- Pros and cons

+ less infrastructure requirement

- Single point of failure

- Node joins and leaves causing much chain

- one node may still be congested

- packets may traverse the same link twice

Structured Networks

- A node forms links with specific neighbors to maintain a certain structure of the network
- Pros
  - More efficient data lookup
  - More reliable
- Cons
  - Difficult to maintain the graph structure
- Examples
  - Distributed Hash Tables
  - End-system multicast: overlay nodes form a multicast tree

DHT Overview

- Used in the real world
  - BitTorrent tracker implementation
  - Content distribution networks
  - Many other distributed systems including botnets
- What problems do DHTs solve?
- How are DHTs implemented?

Background

- A hash table is a data structure that stores (key, object) pairs.
- Key is mapped to a table index via a hash function for fast lookup.
- Content distribution networks
  - Given an URL, returns the object

Example of a Hash table: a web cache

http://www.cnn.com	Page content
http://www.nytimes.com	…….
http://www.slashdot.org	…..
…	…
…	…

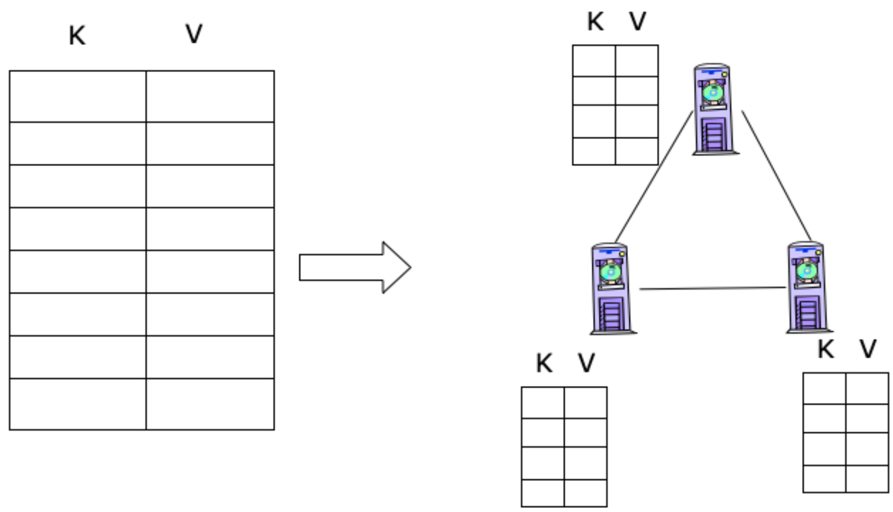
- Client requests http://www.cnn.com
- Web cache returns the page content located at the 1st entry of the table.

DHT: why?

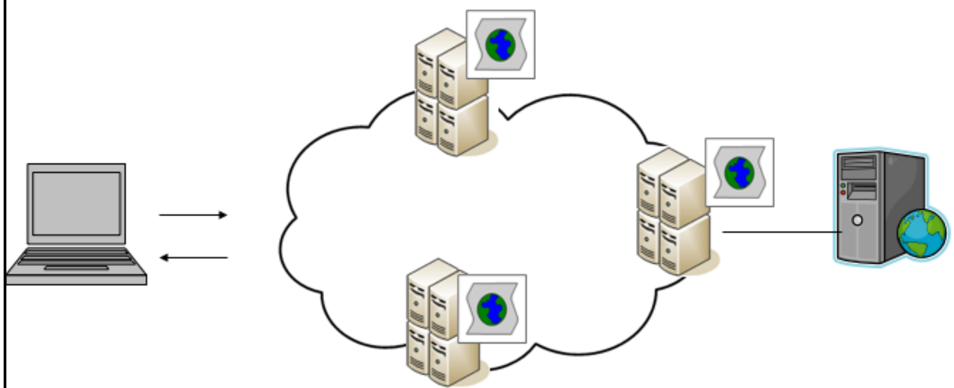
- If the number of objects is large, it is impossible for any single node to store it.

- Solution: distributed hash tables.
  - Split one large hash table into smaller tables and distribute them to multiple nodes

DHT



A content distribution network

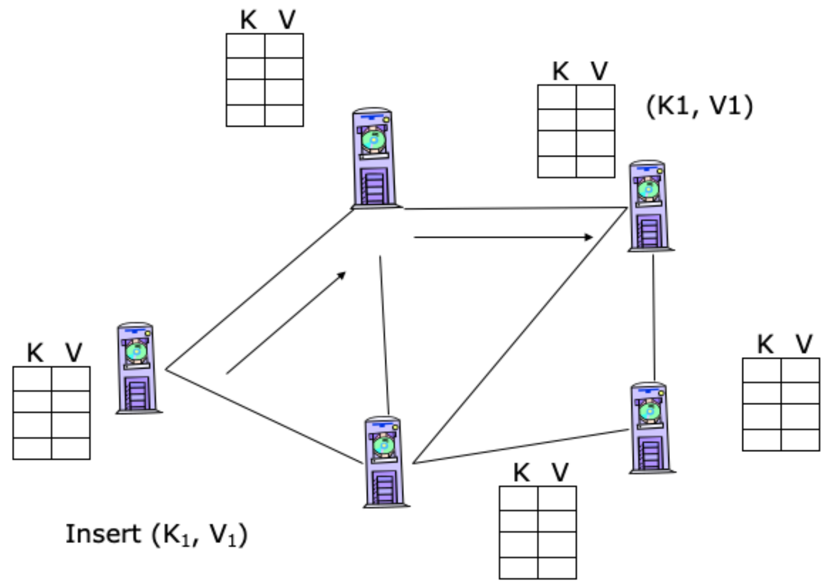


- A single provider that manages multiple replicas
- A client obtains content from a close replica

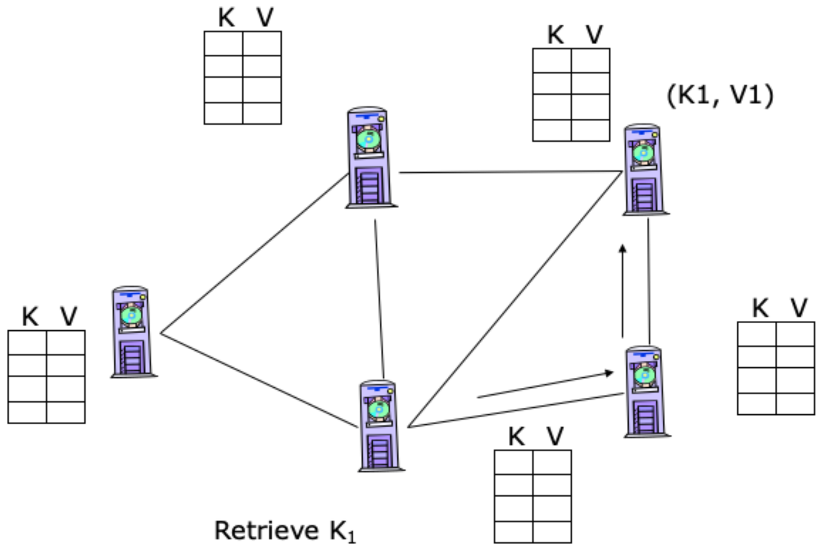
Basic function of DHT

- DHT is a “virtual” hash table
  - Input: a key
  - Output: a data item
- Data Items are stored by a network of nodes
- DHT abstraction
  - Input: a key
  - Output: the node that stores the key
- Applications handle key and data item association

DHT: a visual example



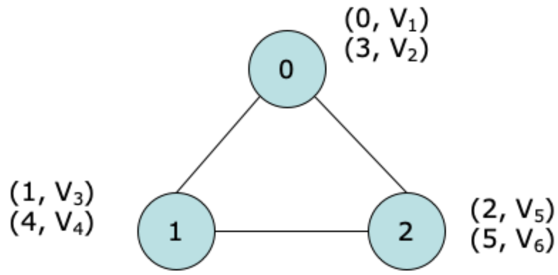
DHT: a visual example



Desired goals of DHT

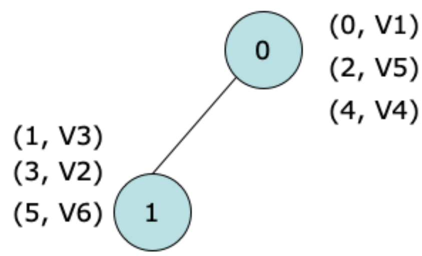
- Scalability: each node does not keep much state
- Performance: small look up latency
- Load balancing: no node is overloaded with a large amount of state
- Dynamic reconfiguration: when nodes join and leave, the amount of state moved from nodes to nodes is small.
- Distributed: no node is more important than others.

A straw man design



- Suppose all keys are integers
- The number of nodes in the network is n
- id = key % n

When node 2 dies



- A large number of data items need to be rehashed.

Fix: consistent hashing

- A node is responsible for a range of keys
  - When a node joins or leaves, the expected fraction of objects that must be moved is the minimum needed to maintain a balanced load.
  - All DHTs implement consistent hashing
  - They differ in the underlying "geometry"

Basic components of DHTs

- Overlapping key and node identifier space
  - Hash(www.cnn.com/image.jpg) → a n-bit binary string
  - Nodes that store the objects also have n-bit string as their identifiers
- Building routing tables
  - Next hops (structure of a DHT)
  - Distance functions
  - These two determine the geometry of DHTs
    - Ring, Tree, Hybercubes, hybrid (tree + ring) etc.
  - Handle nodes join and leave
- Lookup and store interface

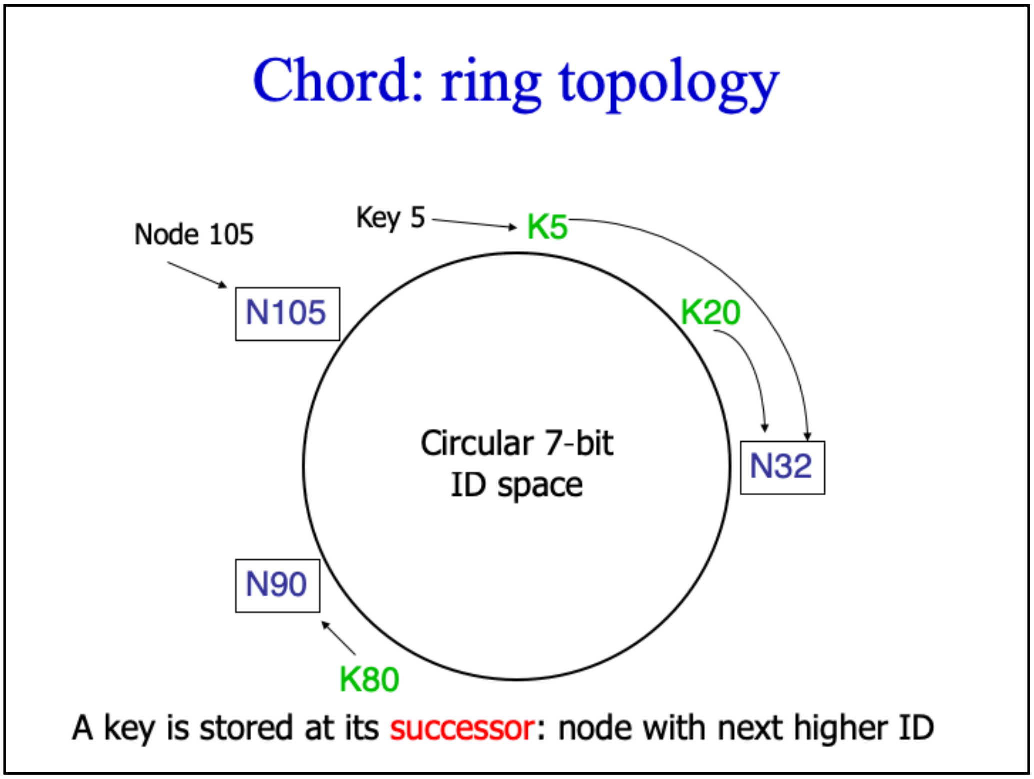
Case study: Chord

Note: textbook uses Pastry

Chord: basic idea

- Hash both node id and key into a m-bit one-dimension circular identifier space

- Consistent hashing: a key is stored at a node whose identifier is closest to the key in the identifier space
  - Key refers to both the key and its hash value.

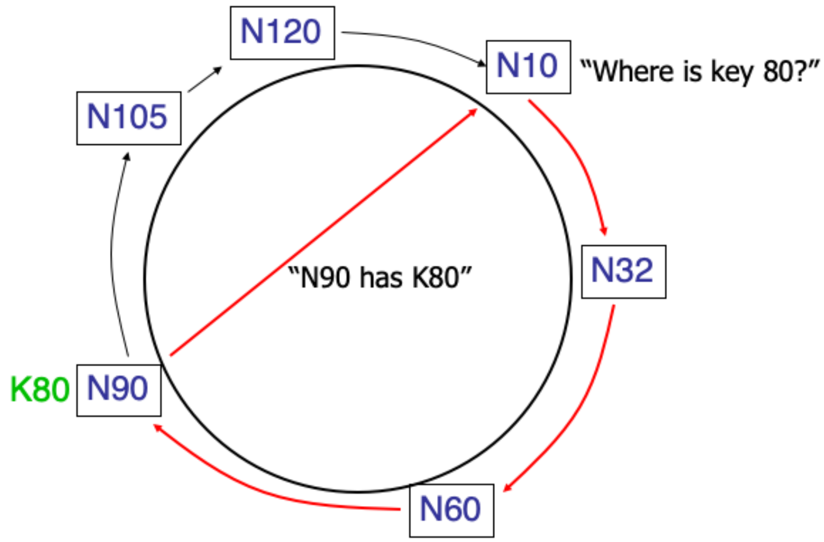


Ids live in a single circular space.

Chord: how to find a node that stores a key?

- Solution 1: every node keeps a routing table to all other nodes
  - Given a key, a node knows which node id is successor of the key
  - The node sends the query to the successor
  - What are the advantages and disadvantages of this solution?

Solution 2: every node keeps a routing entry to the node's successor (a linked list)



Simple lookup algorithm

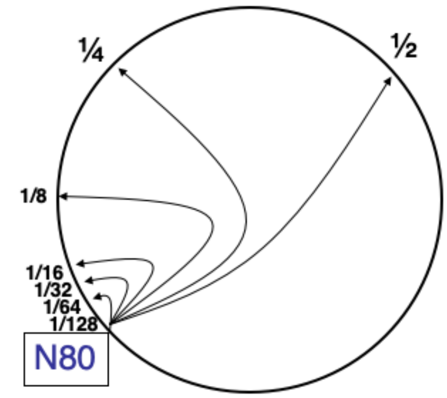
```
Lookup(my-id, key-id)
   n = my successor
   if my-id < n < key-id
        call Lookup(key-id) on node n   // next hop
   else
        return my successor              // done
```

- Correctness depends only on successors
- Q1: will this algorithm miss the real successor?
- Q2: what's the average # of lookup hops?

Always undershoots to predecessor. So never misses the real successor.

Lookup procedure isn't inherently log(n). But finger table causes it to be.

Solution 3: "Finger table" allows log(N)-time lookups



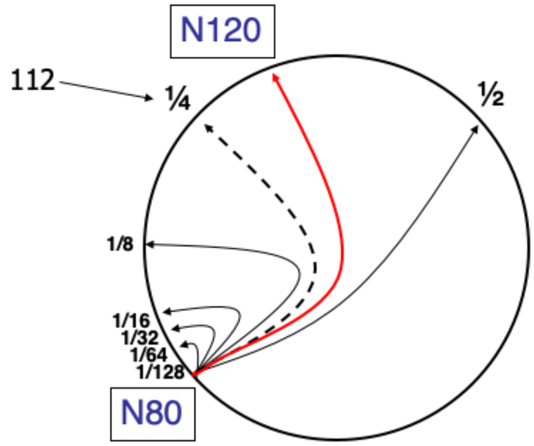
- Analogy: binary search

Small tables, but multi-hop lookup. Table entries: IP address and Chord ID.

Navigate in ID space, route queries closer to successor. Log(n) tables, log(n) hops.

Route to a document between ¼ and ½ …

Finger i points to successor of $n+2^{i-1}$



- The ith entry in the table at node n contains the identity of the *first* node s that succeeds n by at least 2^{i-1}
- A finger table entry includes Chord Id and IP address
- Each node stores a small table log(N)

Small tables, but multi-hop lookup. Table entries: IP address and Chord ID.

Navigate in ID space, route queries closer to successor. Log(n) tables, log(n) hops.

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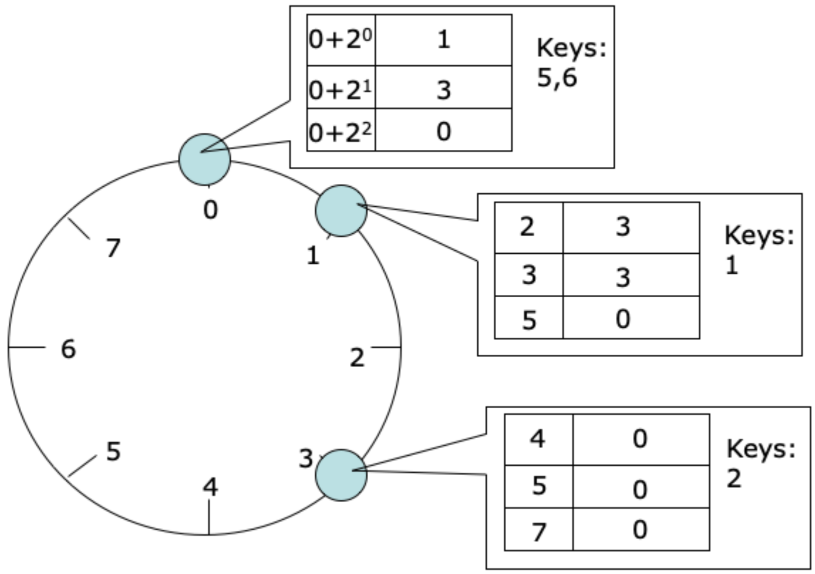
Chord finger table example



Lookup with fingers

```
Lookup(my-id, key-id)
  If key-id in my storage
      return my-value;
  else
      look in local finger table for
            highest node n s.t. my-id < n < key-id
      if n exists
      call Lookup(key-id) on node n  // next hop
  else
      return my successor              // done
```

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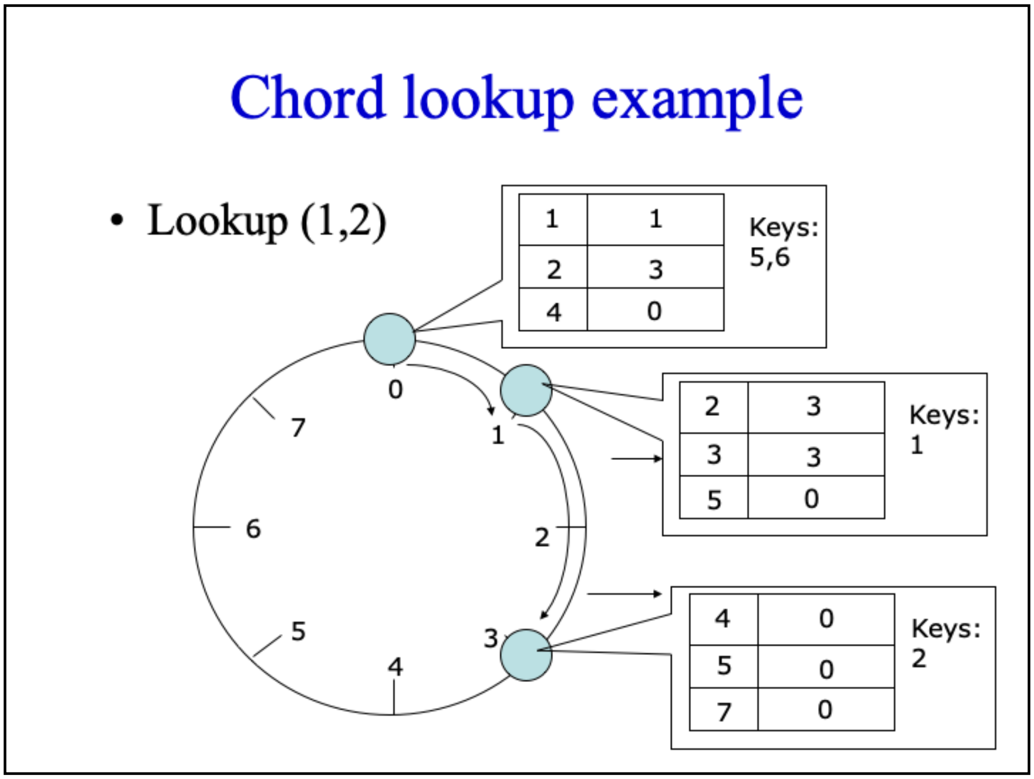


Look up key 2 at node 1. key 2 < successor. So send to successor directly.

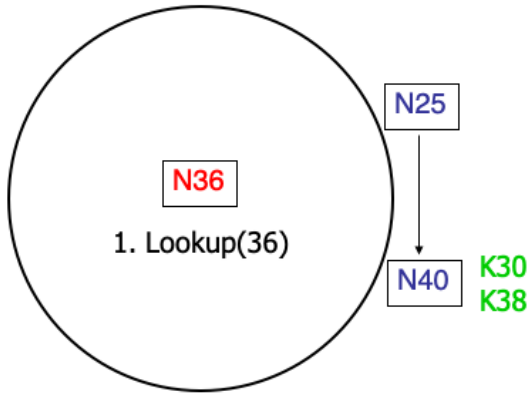
Node join

- Maintain the invariant
  1. Each node' successor is correctly maintained
  2. For every node k, node successor(k) answers for key k. It's desirable that finger table entries are correct

- Each nodes maintains a predecessor pointer

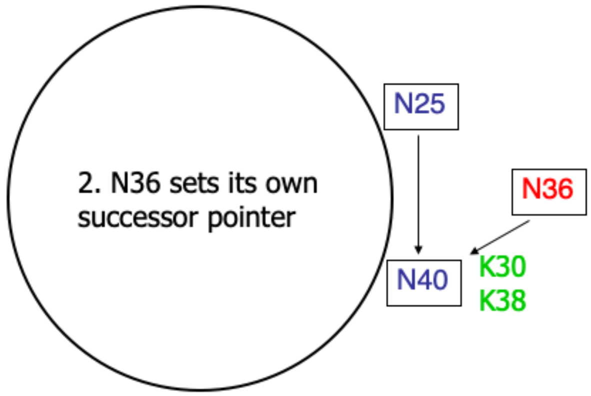
- Tasks:
  - Initialize predecessor and fingers of new node
  - Update existing nodes' state
  - Notify apps to transfer state to new node

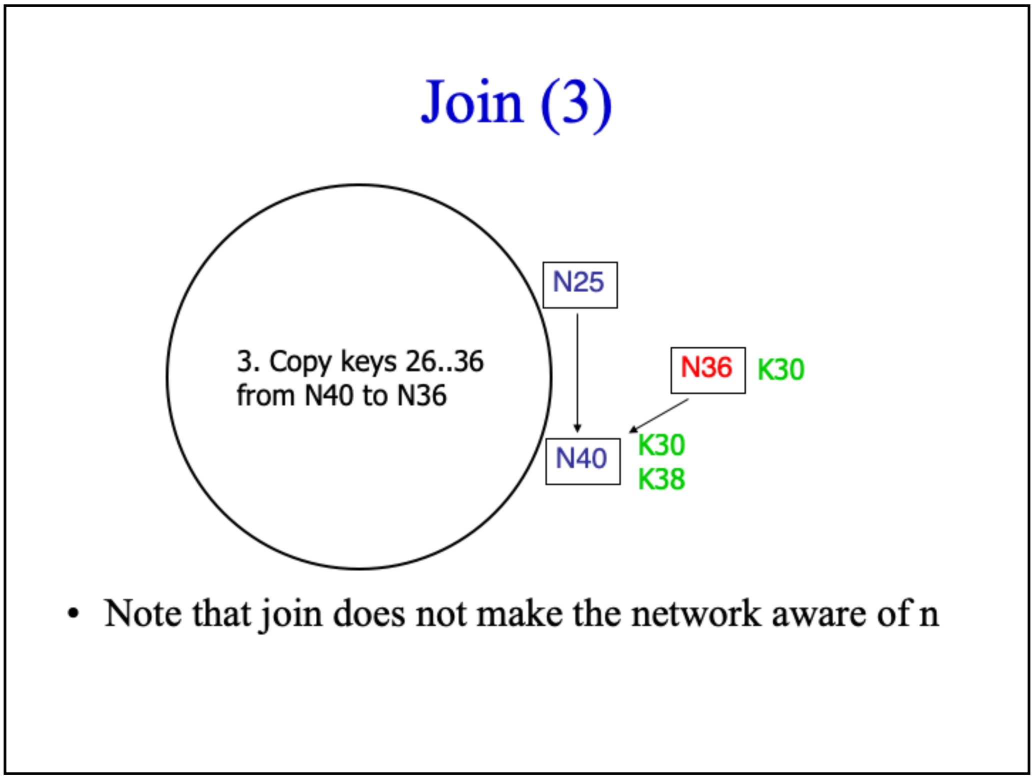
Chord Joining: linked list insert



- Node n queries a known node n' to initialize its state
- Look up for its successor: lookup (n)

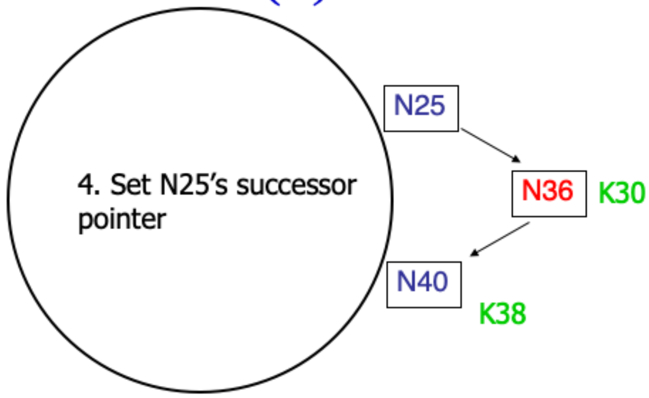
Join (2)





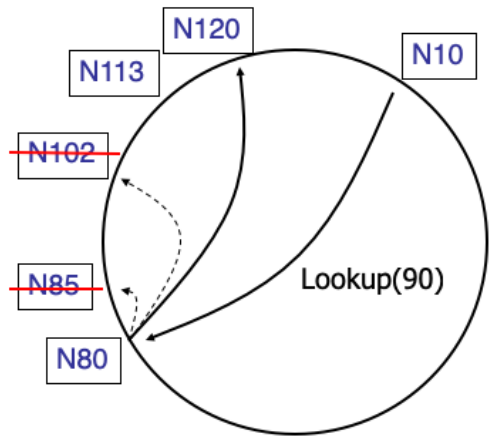
Concurrent join and stabilization are provably consistent eventually.

Join (4): stabilize



- Stabilize 1) obtains a node n's successor's predecessor x, and determines whether x should be n's successor 2) notifies n's successor n's existence
  - N25 calls its successor N40 to return its predecessor
  - Set its successor to N36
  - Notifies N36 it is predecessor
- Update finger pointers in the background periodically
  - Find the successor of each entry I
- Correct successors produce correct lookups

Failures might cause incorrect lookup



N80 doesn't know correct successor, so incorrect lookup

No problem until lookup gets to a node which knows of no node < key.

There's a replica of K90 at N113, but we can't find it.

Solution: successor lists

- Each node knows *r* immediate successors
- After failure, will know first live successor
- Correct successors guarantee correct lookups

- Guarantee is with some probability

- Higher layer software can be notified to duplicate keys at failed nodes to live successors

Choosing the successor list length

- Assume 1/2 of nodes fail
- P(successor list all dead) = $(1/2)^r$
  - I.e. P(this node breaks the Chord ring)
  - Depends on independent failure
- P(no broken nodes) = $(1 - (1/2)^r)^N$
  - $r = 2log(N)$ makes prob. = $1 - 1/N$

Lookup with fault tolerance

```
Lookup(my-id, key-id)
   look in local finger table and successor-list
        for highest node n s.t. my-id < n < key-id
   if n exists
        call Lookup(key-id) on node n   // next hop
        if call failed,
                remove n from finger table
                return Lookup(my-id, key-id)
   else return my successor               // done
```

Always undershoots to predecessor. So never misses the real successor.

Lookup procedure isn't inherently log(n). But finger table causes it to be.

Chord performance

- Per node storage
  - Ideally: K/N
  - Implementation: large variance due to unevenly node id distribution
- Lookup latency
  - O(logN)

Comments on Chord

- ID distance ≠ Network distance
  - Reducing lookup latency and locality
- Strict successor selection
  - Can't overshoot
- Asymmetry
  - A node does not learn its routing table entries from queries it receives
- Later work fixes these issues

Conclusion

- Overlay networks
  - Structured vs Unstructured

- Design of DHTs
  - Chord