Peer-to-Peer Systems and Distributed Hash Tables

COS 518: *Advanced Computer Systems*
Lecture 16

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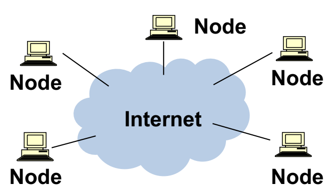
[Credit: Slides Adapted from Kyle Jamieson and Daniel Suo]

Today

1. **Peer-to-Peer Systems**
   – **Napster, Gnutella, BitTorrent, challenges**
2. Distributed Hash Tables
3. The Chord Lookup Service
4. Concluding thoughts on DHTs, P2P

What is a Peer-to-Peer (P2P) system?



- A **distributed** system architecture:
  - **No centralized control**
  - Nodes are **roughly symmetric** in function
- **Large** number of **unreliable** nodes

Why might P2P be a win?

- **High capacity for services** through parallelism:
  - Many disks
  - Many network connections
  - Many CPUs
- **Absence of a centralized server** may mean:
  - **Less chance** of service overload as load increases
  - Easier **deployment**
  - A single failure **won't wreck** the whole system
  - System as a whole is **harder to attack**

P2P adoption

Successful adoption in **some niche areas**

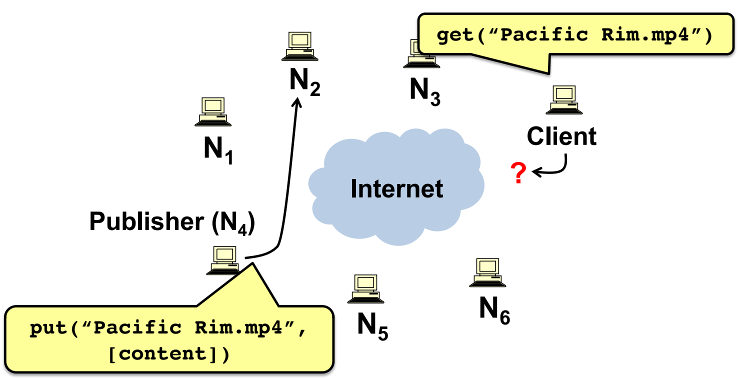
1. Client-to-client (legal, illegal) **file sharing**
2. **Digital currency:** no natural single owner (Bitcoin)
3. **Voice/video telephony:** user to user anyway
   – Issues: Privacy and control

Example: Classic BitTorrent

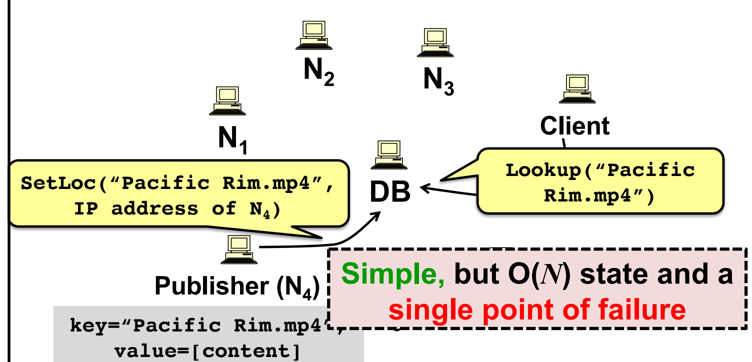
1. User clicks on download link
   – Gets ***torrent*** file with content hash, IP addr of ***tracker***
2. User's BitTorrent (BT) client talks to tracker
   – Tracker tells it **list of peers** who have file
3. User's BT client downloads file from peers
4. User's BT client tells tracker it has a copy now, too
5. User's BT client serves the file to others for a while

Provides huge download bandwidth, **without** expensive server or network links

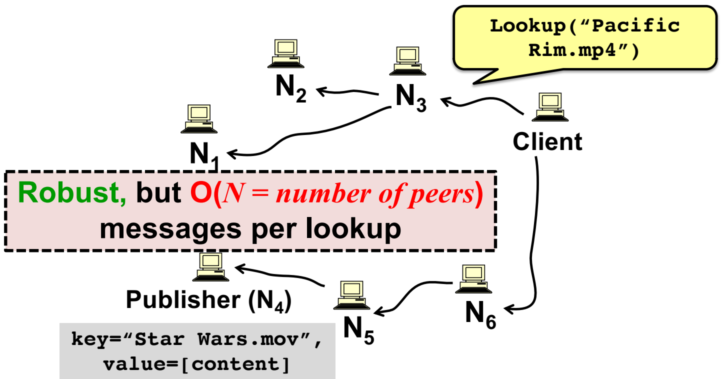
The lookup problem



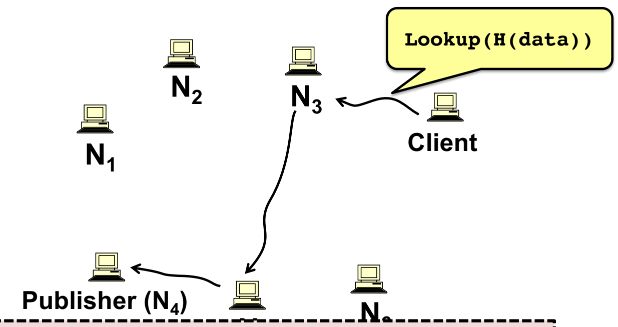
Centralized lookup (Napster)



Flooded queries (original Gnutella)



Routed DHT queries (Chord)



Can we make it **robust**, **reasonable state**, reasonable number of **hops**?

Today

1. Peer-to-Peer Systems
2. **Distributed Hash Tables**
3. The Chord Lookup Service
4. Concluding thoughts on DHTs, P2P

What is a DHT (and why)?

- Local hash table:

```
key = Hash(name)
put(key, value)
get(key) → value
```

- **Service:** Constant-time insertion and lookup

How can I do (roughly) this across millions of hosts on the Internet?
Distributed Hash Table (DHT)

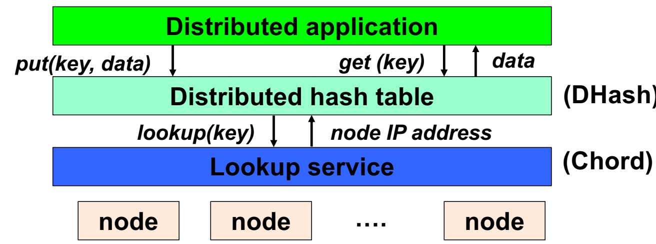
What is a DHT (and why)?

- Distributed Hash Table:

```
key = hash(data)
lookup(key) → IP addr (Chord lookup service)
send-RPC(IP address, put, key, data)
send-RPC(IP address, get, key) → data
```

- **Partitioning data** in **large-scale distributed systems**
  - Tuples in a global database engine
  - Data blocks in a global file system
  - Files in a P2P file-sharing system

Cooperative storage with a DHT



- App may be **distributed** over many nodes
- DHT **distributes data storage** over many nodes

BitTorrent over DHT

- BitTorrent can use DHT instead of (or with) a tracker
- BT clients use DHT:
  - Key = **file content hash** ("infohash")
  - Value = **IP address of peer** willing to serve file
    - Can store multiple values (*i.e.* IP addresses) for a key
- Client does:
  - `get(infohash)` to find other clients willing to serve
  - `put(infohash, my-ipaddr)` to identify itself as willing

Why might DHT be a win for BitTorrent?

- The DHT comprises a single giant tracker, less fragmented than many trackers
  - So peers more likely to **find each other**
- Classic tracker too exposed to **legal & © attacks**

Why the put/get DHT interface?

- API supports a wide range of applications
  - DHT imposes no structure/meaning on keys
- Key/value pairs are persistent and global
  - Can store keys in other DHT values
  - And thus build complex data structures

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Why might DHT design be hard?

- Decentralized: no central authority
- Scalable: low network traffic overhead
- Efficient: find items quickly (latency)
- Dynamic: nodes fail, new nodes join

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3. **The Chord Lookup Service**
   - **Basic design**
   - Integration with *DHash* DHT, performance

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Chord lookup algorithm properties

- **Interface:** lookup(key) → IP address
- **Efficient:** O(log N) messages per lookup
  - N is the total number of servers
- **Scalable:** O(log N) state per node
- **Robust:** survives massive failures
- **Simple to analyze**

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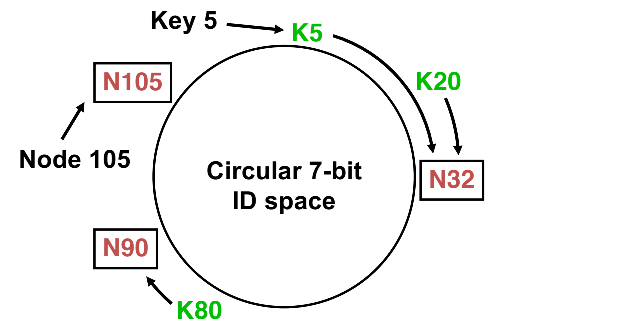
Chord identifiers

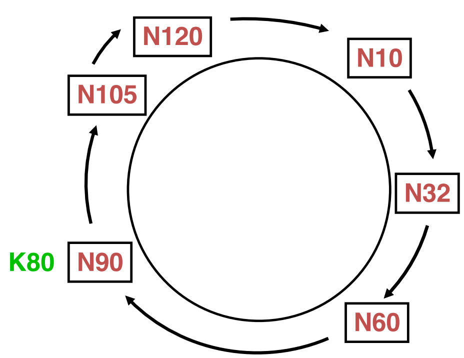
- **Key identifier** = SHA-1(key)
- **Node identifier** = SHA-1(IP address)
- SHA-1 distributes both uniformly
- ***How does Chord partition data?***
  – *i.e.*, map key IDs to node IDs

Consistent hashing [Karger '97]

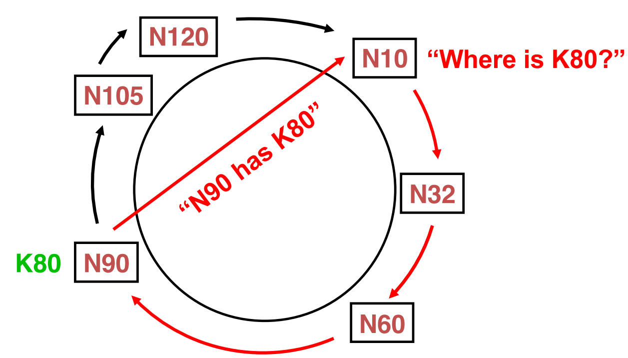


Key is stored at its **successor:** node with next-higher ID

Chord: Successor pointers



Basic lookup



Simple lookup algorithm

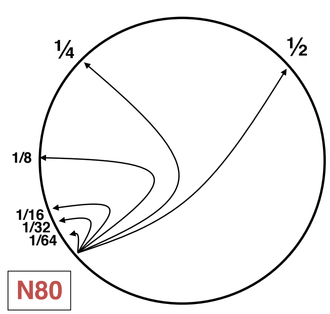
```
Lookup(key-id)
  succ ← my successor
  if my-id < succ < key-id    // next hop
    call Lookup(key-id) on succ
  else                        // done
    return succ
```

Correctness depends only on **successors**

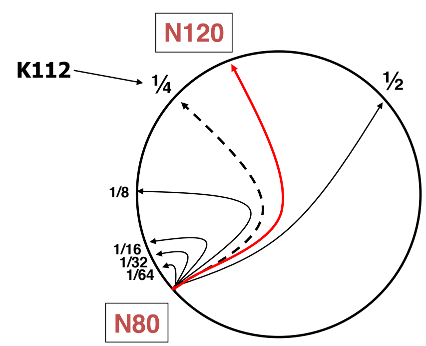
Improving performance

- **Problem:** Forwarding through successor is slow
- Data structure is a linked list: O(n)
- **Idea:** Can we make it more like a binary search?
  - Need to be able to halve distance at each step

"Finger table" allows log N-time lookups



Finger *i* Points to Successor of $n+2^i$



Implication of finger tables

- A **binary lookup tree** rooted at every node
  - Threaded through other nodes' finger tables
- Better than arranging nodes in a single tree
  - Every node acts as a root
    - So there's **no root hotspot**
    - **No single point** of failure
    - But a **lot more state** in total

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Lookup with finger table

```
Lookup(key-id)
  look in local finger table for
    highest n: 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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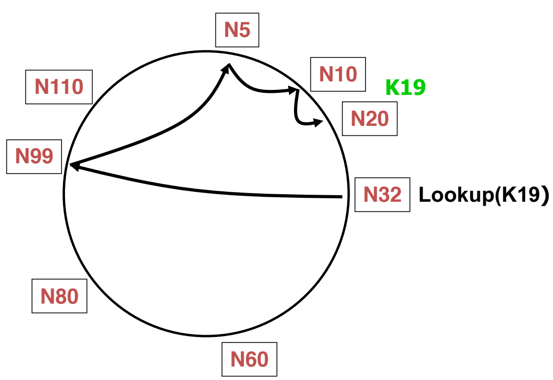
Lookups Take O(log *N*) Hops



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An aside: Is log(n) fast or slow?

- For a million nodes, it's 20 hops
- If each hop takes 50ms, lookups take **a second**
- If each hop has 10% chance of failure, it's a couple of timeouts
- So in practice log(n) is better than O(n) but **not great**

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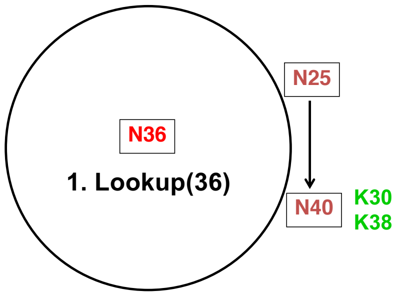
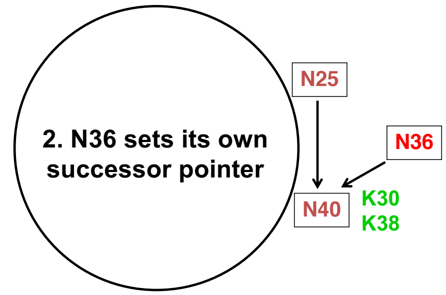
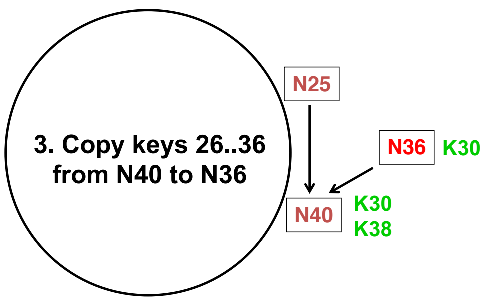
Joining: Linked list insert



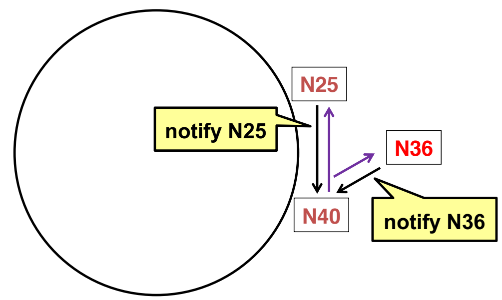
Join (2)



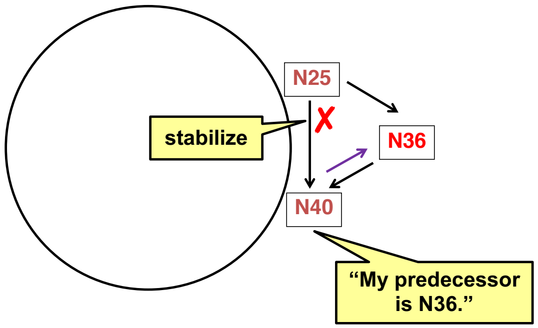
Join (3)



Notify maintains predecessors



Stabilize message fixes successor



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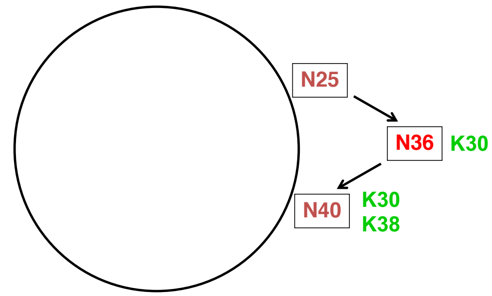
Joining: Summary



- Predecessor pointer allows link to new node
- Update finger pointers in the background
- Correct successors produce correct lookups

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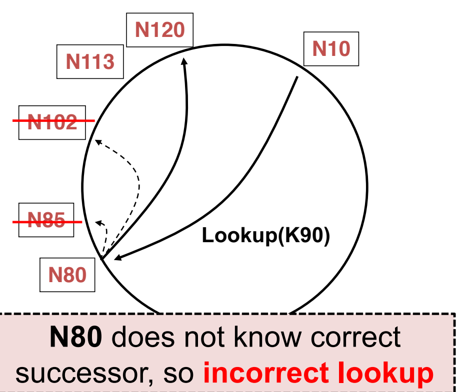
Failures may cause incorrect lookup



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Successor lists

- Each node stores a **list** of its r immediate successors
  - After failure, will know first live successor
  - **Correct successors** guarantee correct lookups
    - Guarantee is with some probability

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Choosing successor list length

- Assume **one half** of the nodes **fail**
- P(successor list all dead) = $(\frac{1}{2})^r$
  - *i.e.*, P(this node breaks the Chord ring)
  - Depends on independent failure
- Successor list of **size r = O(log N)** makes this probability 1/N: low for large N

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Lookup with fault tolerance

```
Lookup(key-id)
  look in local finger table and successor-list
    for highest n: 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 and/or
         successor list
      return Lookup(key-id)
  else
    return my successor    // done
```

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The DHash DHT

- Builds key/value storage on Chord
- **Replicates** blocks for availability
  - Stores ***k* replicas** at the ***k* successors** after the block on the Chord ring
- **Caches** blocks for load balancing
  - **Client** sends **copy of block** to each of the servers it contacted along the **lookup path**
- **Authenticates** block contents

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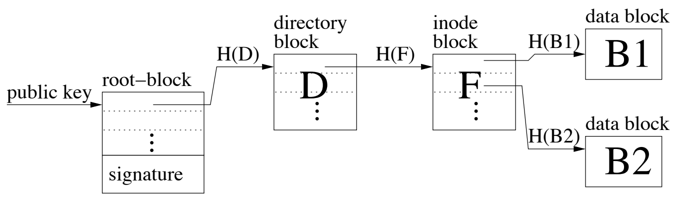
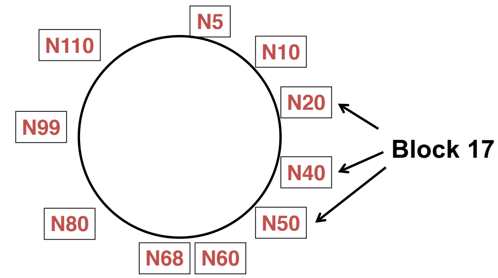
DHash data authentication

- Two types of DHash blocks:
  - **Content-hash:** key = SHA-1(data)
  - **Public-key:** Data signed by corresponding private key
- Chord File System example:



DHash replicates blocks at *r* successors



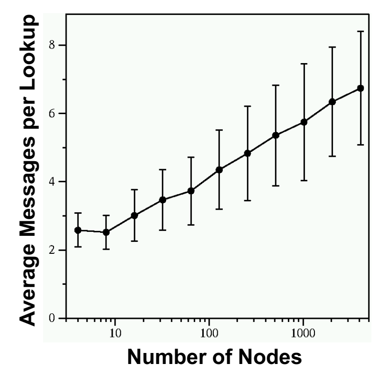
- **Replicas** are **easy to find** if successor fails
- Hashed node IDs ensure **independent failure**

Experimental overview

- **Quick lookup** in large systems
- Low **variation** in lookup costs
- **Robust** despite **massive failure**

Goal: Experimentally confirm theoretical results

Chord lookup cost is O(log N)



Constant is 1/2

Failure experiment setup

- Start **1,000 Chord servers**
  - Each server's **successor list** has 20 entries
  - Wait until they **stabilize**
- Insert 1,000 key/value pairs
  - **Five replicas** of each
- **Stop X%** of the servers, immediately make 1,000 lookups

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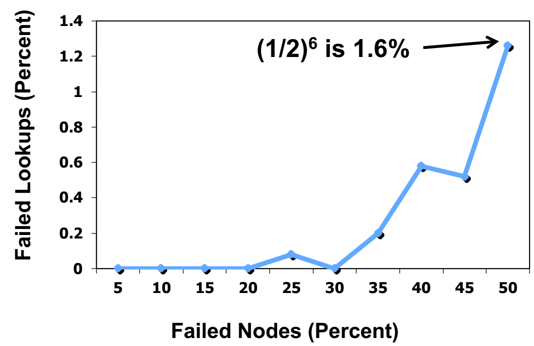
Massive failures have little impact



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DHTs: Impact

- Original DHTs (CAN, Chord, Kademlia, Pastry, Tapestry) proposed in 2001-02
- Next 5-6 years saw proliferation of DHT-based apps:
  - Filesystems (e.g., CFS, Ivy, OceanStore, Pond, PAST)
  - Naming systems (e.g., SFR, Beehive)
  - DB query processing [PIER, Wisc]
  - Content distribution systems (e.g., CoralCDN)
  - distributed databases (e.g., PIER)

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Why don't all services use P2P?

1. **High latency and limited bandwidth** between peers (vs. intra/inter-datacenter)

2. User computers are **less reliable** than managed servers

3. **Lack of trust** in peers' correct behavior
   - Securing DHT routing hard, unsolved in practice

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DHTs in retrospective

- Seem promising for finding data in large P2P systems
- Decentralization seems good for load, fault tolerance

- **But:** the **security problems** are difficult
- **But:** **churn** is a problem, particularly if log(n) is big

- DHTs have not had the hoped-for impact

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What DHTs got right

- **Consistent hashing**
  - Elegant way to divide a workload across machines
  - Very useful in clusters: actively used today in Amazon Dynamo and other systems
- **Replication** for high availability, efficient recovery
- **Incremental scalability**
- **Self-management:** minimal configuration
- **Unique trait:** no single server to shut down/monitor

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