Distributed Hash Tables: Chord

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CS M038 / GZ06
12th February 2014
Today: DHTs, P2P

• Distributed Hash Tables: a building block
• Applications built atop them

• Your task: “Why DHTs?”
  – vs. centralized servers? (we’ll return to this question at the end of lecture)
  – vs. non-DHT P2P systems?
What Is a P2P System?

- A distributed system architecture:
  - No centralized control
  - Nodes are symmetric in function
- Large number of unreliable nodes
- Enabled by technology improvements
The Promise of P2P Computing

• High capacity through parallelism:
  – Many disks
  – Many network connections
  – Many CPUs

• Reliability:
  – Many replicas
  – Geographic distribution

• Automatic configuration

• Useful in public and proprietary settings
What Is a DHT?

• Single-node hash table:
  
  key = Hash(name)
  put(key, value)
  get(key) -> value

  – Service: $O(1)$ storage

• How do I do this across millions of hosts on the Internet?
  
  – *Distributed* Hash Table
What Is a DHT? (and why?)

Distributed Hash Table:
key = Hash(data)
lookup(key) -> IP address (Chord)
send-RPC(IP address, PUT, key, value)
send-RPC(IP address, GET, key) -> value

Possibly a first step towards truly large-scale distributed systems
- a tuple in a global database engine
- a data block in a global file system
- rare.mp3 in a P2P file-sharing system
DHT Factoring

- Application may be distributed over many nodes
- DHT distributes data storage over many nodes
Why the `put() / get()` 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
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
- General-purpose: flexible naming
The Lookup Problem

• At the heart of all DHTs
Motivation: Centralized Lookup (Napster)

SetLoc(“title”, N4)
Publisher@N4
Key=“title”
Value=file data...

N1 N2 N3 DB N4 N5 N6 N7 N8

Client
Lookup(“title”)

Simple, but $O(N)$ state and a single point of failure
Motivation: Flooded Queries (Gnutella)

Robust, but worst case $O(N)$ messages per lookup
Motivation: FreeDB, Routed DHT Queries (Chord, &c.)

Publisher → N₄
Key=H(audio data)
Value={artist, album title, track title}

Lookup(H(audio data))

Client → N₃

N₁ → N₂ → N₃

N₄ → N₁

N₆ → N₇ → N₈

N₉
DHT Applications

They’re not just for stealing music anymore...

– global file systems [OceanStore, CFS, PAST, Pastiche, UsenetDHT]
– naming services [Chord-DNS, Twine, SFR]
– DB query processing [PIER, Wisc]
– Internet-scale data structures [PHT, Cone, SkipGraphs]
– communication services [i3, MCAN, Bayeux]
– event notification [Scribe, Herald]
– File sharing [OverNet]
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
Chord IDs

• Key identifier = SHA-1(key)
• Node identifier = SHA-1(IP address)
• SHA-1 distributes both uniformly

• How to map key IDs to node IDs?
Consistent Hashing [Karger 97]

A key is stored at its successor: node with next higher ID
Basic Lookup

“N90 has K80”

“Where is key 80?”

N90 -> N10

N10 -> N120

N120 -> N32

N32 -> N60

N60 -> N105

N105 -> K80

K80 -> N90
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
“Finger Table” Allows log(N)-time Lookups
Finger $i$ Points to Successor of $n+2^i$
Lookup with Fingers

Lookup(my-id, key-id)
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
Lookups Take $O(\log(N))$ Hops
Joining: Linked List Insert

1. Lookup(36)
Join (2)

2. N36 sets its own successor pointer
Join (3)

3. Copy keys 26..36 from N40 to N36
Join (4)

4. Set N25’s successor pointer

Predecessor pointer allows link to new host
Update finger pointers in the background
Correct successors produce correct lookups
Failures Might Cause Incorrect Lookup

N80 doesn’t know correct successor, so incorrect lookup
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
Choosing Successor List Length

- Assume 1/2 of nodes fail
- \( P(\text{successor list all dead}) = (1/2)^r \)
  - i.e., \( P(\text{this node breaks the Chord ring}) \)
  - Depends on independent failure
- \( P(\text{no broken nodes}) = (1 - (1/2)^r)^N \)
  - \( r = 2\log(N) \) 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
Experimental Overview

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

Experiments confirm theoretical results
Chord Lookup Cost Is $\mathcal{O}(\log N)$

Constant is $1/2$
Failure Experimental Setup

- Start 1,000 CFS/Chord servers
  - 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 perform 1,000 lookups
DHash Replicates Blocks at $r$ Successors

- Replicas are easy to find if successor fails
- Hashed node IDs ensure independent failure
Massive Failures Have Little Impact

Failed Lookups (Percent)

Failed Nodes (Percent)

$(1/2)^6$ is 1.6%
DHash Properties

• Builds key/value storage on Chord
• Replicates blocks for availability
  – What happens when DHT partitions, then heals? Which \((k, v)\) pairs do I need?
• Caches blocks for load balance
• Authenticates block contents
DHash Data Authentication

- Two types of DHash blocks:
  - Content-hash: key = SHA-1(data)
  - Public-key: key is a cryptographic public key, data are signed by that key

- DHash servers verify before accepting put(key, value)

- Clients verify result of get(key)

- Disadvantages?
DHTs: A Retrospective

• Original DHTs (CAN, Chord, Kademlia, Pastry, Tapestry) proposed in 2001-02
• Following 5-6 years saw proliferation of DHT-based applications:
  – filesystems (e.g., CFS, Ivy, Pond, PAST)
  – naming systems (e.g., SFR, Beehive)
  – indirection/interposition systems (e.g., i3, DOA)
  – content distribution systems (e.g., Coral)
  – distributed databases (e.g., PIER)
  – &c....
DHTs: A Retrospective

Have these applications succeeded—are we all using them today?

**Have DHTs succeeded as a substrate for applications?**

- filesystems (e.g., CFS, Ivy, Pond, PAST)
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- content distribution systems (e.g., Coral)
- distributed databases (e.g., PIER)
- &c....
What DHTs Got Right

• Consistent Hashing
  – simple, elegant way to divide a workload across machines
  – very useful in clusters: actively used today in Dynamo, FAWN-KV, ROAR, ...

• Replication for high availability, efficient recovery after node failure

• Incremental scalability: “add nodes, capacity increases”

• Self-management: minimal configuration
What DHTs Got Right

• Consistent Hashing – simple, elegant way to divide a workload across machines – very useful in clusters: actively used today in Dynamo, FAWN-KV, ROAR, …

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• Incremental scalability: “add nodes, capacity increases”

• Self-management: minimal configuration

Unique trait: no single central server to shut down, control, or monitor

...well suited to “illegal” applications, be they sharing music or resisting censorship

Dynamo, FAWN-KV, ROAR, …
DHTs’ Limitations

- High latency between peers
- Limited bandwidth between peers (as compared to within a cluster)
- Lack of centralized control: another sort of simplicity of management
- Lack of trust in peers’ correct behavior
  - securing DHT routing hard, unsolved in practice