LECTURE 10

DHTs and Amazon Dynamo
Scaling up

- Assumption so far: All replicas have entire state
  - Example: Every replica has value for every key

- What we need instead:
  - Partition state
  - Map partitions to servers
Partitioning state

- **Modulo hashing**
  - Apply hash function to key
  - Compute modulo to # of servers (N)
  - Store (key, value) pair at \(\text{hash}(key) \mod N\)

- **Example:**
  - Store student’s transcripts across 4 servers
  - Hash function = \((\text{Year of birth}) \mod 4\)
  - Hash function = \((\text{Date of birth}) \mod 4\)

- **Problem:** *Skew in load across servers*
Problem for modulo hashing: Changing number of servers

\[ h(x) = x + 1 \pmod{4} \]

Add one machine: \( h(x) = x + 1 \pmod{5} \)
Consistent Hashing

- Represent hash space as a circle

- Partition keys across servers
  - Assign every server a random ID
  - Hash server ID
  - Server responsible for keys between predecessor and itself

- How to map a key to a server?
  - Hash key and execute read/write at successor
Adding/Removing Nodes

- Minimizes migration of state upon change in set of servers
  - Server addition: New server splits successor’s shard
  - Server removal: Successor takes over shard
Virtual nodes

- Each server gets multiple (say v) random IDs
  - Each ID corresponds to a virtual node

- If N servers with v virtual nodes per server, each virtual node owns $1/(vN)^{th}$ of hash space

- Larger v $\rightarrow$ better load balancing
  - Vary v across servers to account for heterogeneity
Virtual nodes

- What happens upon server failure?
  - \( v \) successors take over
  - Each now stores \((v+1)/v \times 1/N\)th of hash space
How does client map keys to servers?

Front-ends must agree on set of active servers
Distributed Hash Table

- Scalable lookup of node responsible for any key
  - Scale to thousands (or even millions) of nodes
  - No one node knows all nodes in the system

- Example usage:
  - Trackerless BitTorrent
  - Key = File content hash
  - Value = IP addresses of nodes that have file content
Successor pointers

- If you don’t have value for key, forward to succ.

O(N) Lookup

Downside of approach?
Efficient lookups

- What’s required to enable $O(1)$ lookups?
  - Every node must know all other nodes

- Need to convert linear search to binary search

- Idea: Maintain $\log(N)$ pointers to other nodes
  - Called finger table
  - Pointer to node $\frac{1}{2}$-way across hash space
  - Pointer to node $\frac{1}{4}$-way across hash space
  - …
Finger tables

- i’th entry at node n points to successor of hash(n) + 2^i
  - # of entries = # of bits in hash value

- Binary lookup tree rooted at every node
  - Threaded through others’ finger tables
How to recursively use finger tables to locate node for key k?
Lookup with finger table

**Lookup** (key k, node n)

look in local finger table for highest f s.t. \(\text{hash}(f) < \text{hash}(k)\)

if f exists

    call Lookup(k, f)  //next hop

else

    return n's successor  //done
Lookups take $O(\log N)$ hops
Example

Resolving key 26 from node 1 and key 12 from node 28 using DHTs in Chord (using finger tables)
Is log(N) lookup fast or slow?

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

- Need to update finger tables upon addition or removal of nodes
- Hard to preserve consistency in the face of these changes
Dynamo: Amazon’s Highly Available Key-value Store

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ABSTRACT
Reliability at massive scale is one of the biggest challenges we face at Amazon.com, one of the largest e-commerce operations in

- Added to “Hall of Fame” at SOSP’17
- Rumored to be underpinning of Amazon S3’s architecture
Dynamo settings

- **Setting:**
  - Tens of millions of customers
  - Data spread across tens of thousands of servers

- **Example use case:** *Store shopping carts*

- **Goals:**
  - High availability
  - Low latency
    - Consistency takes a hit
Consistent Hashing in Dynamo

- Recall: Consistent hashing maps value for key to successor in hash space
- Replicate value for every key at $N$ nodes
  - $N$ clockwise successors of key
- Execution of writes
  - Write received by coordinator (successor of key)
  - Coordinator forwards to successors
Replication in Dynamo
Using Consistent Hashing

Client

Front-end

Front-end

Server

Server

Server
Consistent Hashing in Dynamo

What would it take to make this work?

Client

Server

Server

Server

Server

1-hop DHT
Gossip

- Once per second, each server contacts a randomly chosen other server
- Servers exchange their lists of known servers
  - Including virtual node IDs
Sloppy quorums

- N replicas for every key
  - Higher durability with greater N

- Serving reads and writes:
  - Coordinator forwards request to first \( N-1 \) reachable successors
  - Waits for response from R or W to replicas

- How to maximize availability/minimize latency?
  - Low R and/or low W

- How to ensure read sees last committed write?
  - \( R+W > N \)
Latency/availability over consistency

N = 3, W = 1, R = 1

Client1

Put(k, y)

Client2

Get(k)
Consistency over latency/availability

N = 3, W = 2, R = 2

How to tell which of R copies read is latest version?

Client 1

Client 2

A

B

C

Put(k, y)

Get(k)
Vector clocks

- Store a vector clock with each key-value pair
- What we have discussed previously:
  - Vector with # of components = # of servers
  - Not scalable

- Dynamo’s adaptation of vector clocks:
  - List of (coordinator node, counter) pairs
  - Example: [(A, 1), (B, 3), …]
Vector clocks

\[ N = 3, \ W = 2, \ R = 2 \]

\[ (A, 1) \]

\[ (A, [A, B], 1) \]

\[ (A, 1), (B, 1) \]

\[ \text{Put}(k, x) \]

\[ \text{Put}(k, y) \]
Vector clocks in Dynamo

- Consider following scenario:
  - Client1 executes PUT(k, v1)
  - Client2 executes GET(k) and gets v1
  - Client2 executes PUT(k, v2)

- How can vector clocks help in recognizing that okay to garbage collect v1?

- When responding to a GET, Dynamo returns the vector clock for value returned

- Client includes vector clock in subsequent PUT
Automatic conflict resolution

\[ v2 > v1, \text{ so Dynamo automatically drops } v1 \text{ at C} \]
App-specific conflict resolution

Client reads v2, v3; writes with [(A,1), (B,1), (C,1)]

v2 [(A,1), (B,1)]  v3 [(A,1), (C,1)]

v2 || v3, so client must perform reconciliation
Dynamo’s client interface

- **Client interface:**
  - Get(key) $\rightarrow$ value
  - Put(key, value)

- **Get(key) $\rightarrow$ List of <value, context> pairs**
  - Returns one value or multiple conflicting values
  - Context describes version(s) of value(s)

- **Put(key, value, context)**
  - Context indicates which versions this version supersedes or merges
Trimming version vectors

- Many nodes may process Puts to same key
  - Version vectors may grow arbitrarily long

- Dynamo’s clock truncation scheme
  - Dynamo stores time of modification with each version vector entry
  - When version vector > 10 nodes long, Dynamo drops node that least recently processed key

- Problems with truncation?
  - False concurrency
Impact of clock truncation

- **v1 [(A,1)]**
  - put handled by node A

- **v2 [(A,1), (B,1)]**
  - put handled by node B