Dynamo
Dynamo motivation

Fast, available writes
  - Shopping cart: always enable purchases

FLP: consistency and progress at odds
  - Paxos: must communicate with a quorum

Performance: strict consistency = “single” copy
  - Updates serialized to single copy
  - Or, single copy moves
Why Fast Available Writes?

Amazon study: 100ms increase in response time

=> 5% reduction in revenue

Similar results at other ecommerce sites

99.99% availability

=> less than an hour outage/year (total)

Amazon revenue > $300K/minute
Dynamo motivation

Dynamo goals

- Expose “as much consistency as possible”
- Good latency, 99.9% of the time
- Easy scalability
Dynamo consistency

Eventual consistency

- Can have stale reads
- Can have multiple “latest” versions
- Reads can return multiple values

Not sequentially consistent

- Can’t “defriend and dis”
External interface

get : key -> ([value], context)

- Exposes inconsistency: can return multiple values
- context is opaque to user (set of vector clocks)

put : (key, value, context) -> void

- Caller passes context from previous get

Example: add to cart

(carts, context) = get("cart-" + uid)
cart = merge(carts)
cart = add(cart, item)
put("cart-" + uid, cart, context)
Resolving conflicts in application

Applications can choose how to handle inconsistency:

- Shopping cart: take union of cart versions
- User sessions: take most recent session
- High score list: take maximum score

Default: highest timestamp wins

Context used to record causal relationships between gets and puts

- Once inconsistency resolved, should stay resolved
- Implemented using vector clocks
Dynamo’s vector clocks

Each object associated with a vector clock
  - e.g., [(node1, 0), (node2, 1)]

Each write has a coordinator, and is replicated to multiple other nodes
  - In an eventually consistent manner

Nodes in vector clock are coordinators
Dynamo’s vector clocks

Client sends clock with put (as context)

Coordinator increments its own index in clock, then replicates across nodes

Nodes keep objects with conflicting vector clocks
  - These are then returned on subsequent gets

If clock(v1) < clock(v2), node deletes v1
Dynamo Vector Clocks

Vector clock returned as context with get

- Merge of all returned objects’ clocks

Used to detect inconsistencies on write
node1

"1" @ [(node1, 0)]

node2

"1" @ [(node1, 0)]

node3

"1" @ [(node1, 0)]
node1

"1" @ [(node1, 0)]

get()

node2

"1" @ [(node1, 0)]

node3

"1" @ [(node1, 0)]

client
node1

"1" @ [(node1, 0)]

node2

"1" @ [(node1, 0)]

node3

"1" @ [(node1, 0)]

client
node1

"1" @ [(node1, 0)]

put("2", [(node1, 0)])
	node2

"1" @ [(node1, 0)]

tclient

node3

"1" @ [(node1, 0)]
node1

"1" @ [(node1, 0)]

"2" @ [(node1, 1)]

node2

"1" @ [(node1, 0)]

node3

"1" @ [(node1, 0)]

client
node1

"2" @ [(node1, 1)]

node2

"1" @ [(node1, 0)]

node3

"1" @ [(node1, 0)]
node1

"2" @ [(node1, 1)]

node2

"2" @ [(node1, 1)]

node3

"1" @ [(node1, 0)]

client
node1

"2" @ [(node1, 1)]

node2

"2" @ [(node1, 1)]

node3

"1" @ [(node1, 0)]
node1

"2" @ [(node1, 1)]

node2

"2" @ [(node1, 1)]

node3

"1" @ [(node1, 0)]

client

put("3", [(node1, 0)])
node1

"2" @ [(node1, 1)]

node2

"2" @ [(node1, 1)]

client

node3

"3" @ [(node1, 0), (node3, 0)]
node1

"2" @ [(node1, 1)]

node2

"2" @ [(node1, 1)]
"3" @ [(node1, 0), (node3, 0)]

node3

"3" @ [(node1, 0), (node3, 0)]
"2" @ [(node1, 1)]

"3" @ [(node1, 0), (node3, 0)]

"2" @ [(node1, 1)]

"3" @ [(node1, 0), (node3, 0)]

OK
node1

"2" @ [(node1, 1)]

node2

"2" @ [(node1, 1)]

"3" @ [(node1, 0), (node3, 0)]

node3

"3" @ [(node1, 0), (node3, 0)]
node1

"2" @ [(node1, 1)]

get()

node2

"2" @ [(node1, 1)]

"3" @ [(node1, 0), (node3, 0)]

node3

"3" @ [(node1, 0), (node3, 0)]

client
node1

"2" @ [(node1, 1)]

node2

"2" @ [(node1, 1)]

"3" @ [(node1, 0), (node3, 0)]

node3

"3" @ [(node1, 0), (node3, 0)]
node1

"2" @ [(node1, 1)]

node2

"2" @ [(node1, 1)]
"3" @ [(node1, 0), (node3, 0)]

node3

"3" @ [(node1, 0), (node3, 0)]
node1

"2" @ [(node1, 1)]

"2", "3", [(node1, 1), (node3, 0)]

node2

"2" @ [(node1, 1)]

"3" @ [(node1, 0), (node3, 0)]

node3

"3" @ [(node1, 0), (node3, 0)]

client
client must now run merge!
node1

"2" @ [(node1, 1)]

put("3", [(node1, 1), (node3, 0)])

node2

"2" @ [(node1, 1)]

"3" @ [(node1, 0), (node3, 0)]

node3

"3" @ [(node1, 0), (node3, 0)]

client
node1

"3" @ [(node1, 2), (node3, 0)]

node2

"2" @ [(node1, 1)]

"3" @ [(node1, 0), (node3, 0)]

node3

"3" @ [(node1, 0), (node3, 0)]

client
node1

"3" @ [(node1, 2), (node3, 0)]

node2

"3" @ [(node1, 2), (node3, 0)]

node3

"3" @ [(node1, 0), (node3, 0)]
"3" @ [(node1, 2), (node3, 0)]

node2

"3" @ [(node1, 2), (node3, 0)]

node3

"3" @ [(node1, 0), (node3, 0)]
node1

"3" @ [(node1, 2), (node3, 0)]

node2

"3" @ [(node1, 2), (node3, 0)]

node3

"3" @ [(node1, 2), (node3, 0)]
Where does each key live?

Goals:
- Balance load, even as servers join and leave
- Encourage put/get to see each other
- Avoid conflicting versions

Solution: consistent hashing
Detour: Consistent hashing

Node ids hashed to many pseudorandom points on a circle

Keys hashed onto circle, assigned to “next” node

Idea used widely:
- Developed for Akamai CDN
- Used in Chord distributed hash table
- Used in Dynamo distributed DB
Scaling Systems: Shards

Distribute portions of your dataset to various groups of nodes

Question: how do we allocate a data item to a shard?
Replicated, Sharded Database

Which keys are where?
Lab 4 (and other systems)

State machine

Paxos

Shard master

State machine

Paxos

State machine

Paxos
Replicated, Sharded Database

Shard master decides

- which group has which keys

Shards operate independently

How do clients know who has what keys?

- Ask shard master? Becomes the bottleneck!

Avoid shard master communication if possible

- Can clients predict which group has which keys
Recurring Problem

Client needs to access some resource
Sharded for scalability
How does client find specific server to use?
Central redirection won’t scale!
Another scenario

Google  Facebook  Netflix

Client
Another scenario

GET index.html
Another scenario

Google  facebook  NETFLIX

index.html

Client
Another scenario

Google | Facebook | Netflix

index.html

Links to: logo.jpg, jquery.js, ...

Client
Another scenario

GET logo.jpg

GET jquery.js
Another scenario

Google  Facebook  Netflix

Cache 1  Cache 2  Cache 3

GET logo.jpg  GET jquery.js

Client 2
Other Examples

Scalable shopping cart service
Scalable email service
Scalable cache layer (Memcache)
Scalable network path allocation
Scalable network function virtualization (NFV)
...
...
...
...
What’s in common?

Want to assign keys to servers w/o communication

Requirement 1: clients all have same assignment
Proposal 1

For $n$ nodes, a key $k$ goes to $k \mod n$

Cache 1
Cache 2
Cache 3

“a”, “d”, “ab”
“b”
“c”
Proposal 1

For $n$ nodes, a key $k$ goes to $k \mod n$

Cache 1: “a”, “d”, “ab”  
Cache 2: “b”  
Cache 3: “c”

Problems with this approach?
Proposal 1

For \( n \) nodes, a key \( k \) goes to \( k \mod n \)

Problems with this approach?

- Likely to have distribution issues
Requirements, revisited

Requirement 1: clients all have same assignment
Requirement 2: keys uniformly distributed
Proposal 2: Hashing

For \( n \) nodes, a key \( k \) goes to \( \text{hash}(k) \mod n \)

\[
\begin{align*}
\text{Cache 1} & \quad h(\text{"a"})=1 \\
\text{Cache 2} & \quad h(\text{"abc"})=2 \\
\text{Cache 3} & \quad h(\text{"b"})=3
\end{align*}
\]

Hash distributes keys uniformly
Proposal 2: Hashing

For $n$ nodes, a key $k$ goes to $\text{hash}(k) \mod n$

Hash distributes keys uniformly

But, new problem: what if we add a node?
Proposal 2: Hashing

For $n$ nodes, a key $k$ goes to $\text{hash}(k) \mod n$

- Cache 1
- Cache 2
- Cache 3
- Cache 4

$h(“a”) = 1 \quad h(“abc”) = 2 \quad h(“b”) = 3$

Hash distributes keys uniformly

But, new problem: what if we add a node?
Proposal 2: Hashing

For $n$ nodes, a key $k$ goes to $\text{hash}(k) \mod n$

<table>
<thead>
<tr>
<th>Cache 1</th>
<th>Cache 2</th>
<th>Cache 3</th>
<th>Cache 4</th>
</tr>
</thead>
</table>

$h(\text{“abc”})=2$  $h(\text{“a”})=3$  $h(\text{“b”})=\emptyset$

Hash distributes keys uniformly

But, new problem: what if we add a node?
Proposal 2: Hashing

For $n$ nodes, a key $k$ goes to $\text{hash}(k) \mod n$

- $h(\text{“abc”})=2$
- $h(\text{“a”})=3$
- $h(\text{“b”})=4$

Hash distributes keys uniformly

But, new problem: what if we add a node?

- Redistribute a lot of keys! (on average, all but $K/n$)
Requirements, revisited

Requirement 1: clients all have same assignment
Requirement 2: keys uniformly distributed
Requirement 3: can add/remove nodes w/o redistributing too many keys
Proposal 3: Consistent Hashing

First, hash the node ids
Proposal 3: Consistent Hashing

First, hash the node ids

Cache 1  Cache 2  Cache 3

0  \(2^{32}\)
Proposal 3: Consistent Hashing

First, hash the node ids

Cache 1

Cache 2

Cache 3

0

hash(1)

$2^{32}$
Proposal 3: Consistent Hashing

First, hash the node ids

Cache 1

Cache 2

Cache 3

$0 \quad \text{hash}(2) \quad \text{hash}(1) \quad 2^{32}$
Proposal 3: Consistent Hashing

First, hash the node ids

Cache 1

Cache 2

Cache 3

0 hash(2) hash(1) hash(3) $2^{32}$
Proposal 3: Consistent Hashing

First, hash the node ids

Cache 1  Cache 2  Cache 3
hash(1)  hash(2)  hash(3)

0  hash(2)  hash(1)  hash(3) $2^{32}$
Proposal 3: Consistent Hashing

First, hash the node ids

Cache 1  Cache 2  Cache 3

0  hash(2)  hash(1)  hash(3)  $2^{32}$

Keys are hashed, go to the “next” node
Proposal 3: Consistent Hashing

First, hash the node ids

```
Cache 1
Cache 2
Cache 3
```

```
0  hash(2)  hash(1)  hash(3)  2^{32}
```

“a”

Keys are hashed, go to the “next” node
First, hash the node ids

Keys are hashed, go to the “next” node
Proposal 3: Consistent Hashing

First, hash the node ids

Cache 1  Cache 2  Cache 3

0  hash(2)  hash(1)  hash(3)  $2^{32}$

“a”

Keys are hashed, go to the “next” node
Proposal 3: Consistent Hashing

First, hash the node ids

Cache 1
Cache 2
Cache 3

0 hash(2) hash(1) hash(3) $2^{32}$

“b”

Keys are hashed, go to the “next” node
Proposal 3: Consistent Hashing

First, hash the node ids

Cache 1

Cache 2

Cache 3

0  hash(2)  hash(1)  hash(3)  $2^{32}$

“b”

hash(“b”)

Keys are hashed, go to the “next” node
Proposal 3: Consistent Hashing

First, hash the node ids

Cache 1  

Cache 2  

Cache 3  

0  hash(2)  hash(1)  hash(3)  $2^{32}$

“b”

Keys are hashed, go to the “next” node
Proposal 3: Consistent Hashing
Proposal 3: Consistent Hashing

Cache 1

Cache 2

Cache 3

“a”

“b”
Proposal 3: Consistent Hashing

What if we add a node?
Proposal 3: Consistent Hashing

Cache 1

Cache 2

“a”

Cache 4

“b”

Cache 3
Proposal 3: Consistent Hashing

Only “b” has to move!
On average, K/n keys move
Proposal 3: Consistent Hashing

Cache 1

Cache 2

“a”

“b”

Cache 3

Cache 4
Proposal 3: Consistent Hashing

Cache 1

“a”

Cache 2

Cache 4

“b”

Cache 3
Proposal 3: Consistent Hashing

Only “b” has to move!
On average, K/n keys move but all between two nodes
Requirements, revisited

Requirement 1: clients all have same assignment

Requirement 2: keys evenly distributed

Requirement 3: can add/remove nodes w/o redistributing too many keys

Requirement 4: parcel out work of redistributing keys
Proposal 4: Virtual Nodes

First, hash the node ids to *multiple locations*

Cache 1  Cache 2  Cache 3

0  $2^{32}$
Proposal 4: Virtual Nodes

First, hash the node ids to *multiple locations*

Cache 1  Cache 2  Cache 3

0 1 1 1 1 1

$2^{32}$
Proposal 4: Virtual Nodes

First, hash the node ids to *multiple locations*

---

Cache 1

Cache 2

Cache 3

---

2^{32}
Proposal 4: Virtual Nodes

First, hash the node ids to *multiple locations*

As it turns out, hash functions come in families s.t. their members are independent. So this is easy!
Prop 4: Virtual Nodes

Cache 1

Cache 2

Cache 3
Prop 4: Virtual Nodes

Cache 1

Cache 2

Cache 3
Prop 4: Virtual Nodes

Cache 1

Cache 2

Cache 3
Prop 4: Virtual Nodes

Cache 1

Cache 2

Cache 3

Keys more evenly distributed and migration is evenly spread out.
Requirements, revisited

Requirement 1: clients all have same assignment

Requirement 2: keys evenly distributed

Requirement 3: can add/remove nodes w/o redistributing too many keys

Requirement 4: parcel out work of redistributing keys
Load Balancing At Scale

Suppose you have N servers

Using consistent hashing with virtual nodes:
  - heaviest server has x% more load than the average
  - lightest server has x% less load than the average

What is peak load of the system?
  - N * load of average machine? No!

Need to minimize x
Key Popularity

- What if some keys are more popular than others
- Consistent hashing is no longer load balanced!
- One model for popularity is the Zipf distribution
- Popularity of kth most popular item, $1 < c < 2$
  - $1/k^c$
- Ex: 1, 1/2, 1/3, ... 1/100 ... 1/1000 ... 1/10000
Zipf “Heavy Tail” Distribution

\[ \frac{1}{k^\alpha} \]

Popularity vs. Rank
Zipf Examples

• Web pages
• Movies
• Library books
• Words in text
• Salaries
• City population
• Twitter followers
• ...

Whenever popularity is self-reinforcing
Proposal 5: Table Indirection

Consistent hashing is (mostly) stateless

- Given list of servers and # of virtual nodes, client can locate key

- Worst case unbalanced, especially with zipf

Add a small table on each client

- Table maps: virtual node -> server

- Shard master reassigns table entries to balance load
Consistent hashing in Dynamo

Each key has a “preference list”—next nodes around the circle

- Skip duplicate virtual nodes
- Ensure list spans data centers

Slightly more complex:

- Dynamo ensures keys evenly distributed
- Nodes choose “tokens” (positions in ring) when joining the system
- Tokens used to route requests
- Each token = equal fraction of the keyspace
Replication in Dynamo

Three parameters: N, R, W

- N: number of nodes each key replicated on
- R: number of nodes participating in each read
- W: number of nodes participating in each write

Data replicated onto first N live nodes in pref list
- But respond to the client after contacting W

Reads see values from R nodes

Common config: (3, 2, 2)
Sloppy quorum

Never block waiting for unreachable nodes
  - Try next node in list!

Want get to see most recent put (as often as possible)

Quorum: $R + W > N$
  - Don’t wait for all $N$
  - $R$ and $W$ will (usually) overlap

Nodes ping each other
  - Each has independent opinion of up/down

“Sloppy” quorum—nodes can disagree about which nodes are running
Replication in Dynamo

Coordinator (or client) sends each request (put or get) to first $N$ reachable nodes in pref list

- Wait for $R$ replies (for read) or $W$ replies (for write)

Normal operation: gets see all recent versions

Failures/delays:

- Writes still complete quickly
- Reads eventually see
Ensuring eventual consistency

What if puts end up far away from first N?
  - Could happen if some nodes temporarily unreachable
  - Server remembers “hint” about proper location
  - Once reachability restored, forwards data

Nodes periodically sync whole DB
  - Fast comparisons using Merkle trees
Dynamo deployments

~100 nodes each
One for each service (parameters global)

How to extend to multiple apps?
Different apps use different (N, R, W)

- Pretty fast, pretty durable: (3, 2, 2)
- Many reads, few writes: (3, 1, 3) or (N, 1, N)
- (3, 3, 3)?
- (3, 1, 1)?
Dynamo results

Average *much* faster than 99.9%
  - But, 99.9% acceptable

Inconsistencies rare in practice
  - Allow inconsistency, but minimize it
Dynamo Revisited

Implemented as a library, not as a service

- Each service (eg shopping cart) instantiated a Dynamo instance

When an inconsistency happens:

- Is it a problem in Dynamo?
- Is it an intended side effect of Dynamo’s design?

Every service runs its own ops => every service needs to be an expert at sloppy quorum
Dynamo DB

Replaced Dynamo the library with DynamoDB the service

DynamoDB: strictly consistent key value store
  - validated with TLA and model checking
  - eventually consistent as an option
  - (afaik) no multikey transactions?

Dynamo is eventually consistent

Amazon is eventually strictly consistent!
Discussion

Why is symmetry valuable? Do seeds break it?

Dynamo and SOA
- What about malicious/buggy clients?

Issues with hot keys?

Transactions and strict consistency
- Why were transactions implemented at Google and not at Amazon?
- Do Amazon’s programmers not want strict consistency?