CS 555: DISTRIBUTED SYSTEMS
[DYNAMO]

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Frequently asked questions from the previous class survey

- How can W=1 ever be fault tolerant?
- Are write-always systems eventually consistent?
- During partitions, how are major and minor partitions decided?

Topics covered in this lecture

- Amazon’s Dynamo

DYNAMO: AMAZON’S HIGHLY AVAILABLE KEY-VALUE STORE

Giuseppe DeCandia, Deniz Hastorun, Madan Jampani, Gunavardhan Kakulapati, Avinash Lakshman, Alex Pilchin, Swaminathan Sivasubramonian, Peter Vossahl, Werner Vogels: Dynamo: Amazon’s Highly Available Key-Value Store. SOSP 2007: 205-220

Storage technologies at Amazon

- Simple Storage Service (S3)
- SimpleDB
  - Distributed database
  - Written in Erlang
- Dynamo

Dynamo: Highlights

- Completely decentralized system
- Provides a key-value store
- Underlying technology for several core services
- Scales to extreme peak loads
  - Holiday shopping period
  - No downtimes
  - 3 million checkouts per day

Data From 2007

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But why not use an RDBMS?

- Would lead to inefficiencies
- Scaling and availability issues
  - ACID Guarantees
  - Difficult to scale-out
  - Difficult to have smart partitioning
- Most services only need primary-key access
  - No need for complex querying and management
  - $\\text{$$$$}$$

Many services in Amazon only need primary-key access to the data store

- Best seller lists
- Shopping carts
- Customer preferences
- Session management
- Product catalog

Techniques used by Dynamo

- Scalability and availability
  - Data partitioned and replicated
  - Consistent hashing
- Consistency among replicas
  - Decentralized, quorum protocol [sloppy quorums, hinted handoffs]
- Gossip protocols
  - Memberships
  - Failure detection

Dynamo: System Assumptions

Query Model

- read and write operations uniquely identified with key
- State stored as binary object (blob)
- Operations do not span multiple data items
  - No need for relational schema
- Target applications store small objects
  - Less than 1 MB

Dynamo: Primary research contributions

- How different distributed systems’ techniques can be combined
- Eventually consistent storage can be used in
  - Production & highly-demanding settings
Dynamo: System assumptions

ACID (Atomicity, Consistency, Isolation, Durability)

- If data is stored with ACID properties?
  - Poor availability
- Trade-off consistency for availability
  - Isolation?
    - Cannot access data modified during a transaction
    - That has not yet completed
  - No isolation guarantees in Dynamo

Dynamo: System Assumptions

Efficiency

- Must function on commodity hardware
- Stringent requirements:
  - Latency and throughput
  - Service Level Agreements (SLAs)
- Tradeoff space:
  - Performance, cost efficiency, availability, durability

Clients and services agree on Service Level Agreements (SLAs)

- Example SLA: Provide response
  - Within 300 milliseconds
  - For 99.9% of the requests
  - For up to a peak client load: 500 requests/second
- Rendering page requests in Amazon?
  - Construct response from 150 service requests
  - Each service in the call chain must meet contract

Design choices: Why strong consistency is out

- When there is uncertainty about data correctness?
  - Data is made unavailable
  - Must be absolutely certain, data is correct
- Not possible to have the A in CAP

Design considerations: Eventual consistency

- Increase availability using optimistic replication
  - Concurrent, disconnected updates allowed
- Conflicting changes must be:
  - Deleted
  - Resolved
- Conflict resolution:
  - When?
  - Who?
Conflict resolution in traditional stores:
Done during writes
- Read complexity is kept simple
- Writes may be rejected if data store cannot reach majority of the replicas
- At the same time

Conflict resolution in Dynamo:
When?
- Data store must be always writeable
  - Rejecting customer updates
    - Poor customer experience
    - $$$
  - Shopping cart edits must be allowed
    - Even during network and server failures
  - Complexity of conflict resolution pushed to reads

Conflict resolution in Dynamo:
Who?
- Data store?
  - Last write wins for conflicting updates
- Application?
  - Aware of the data schema
  - Decide on most suitable conflict resolution
  - E.g.: Application that maintains shopping carts?
    - Merge conflicting versions, and return unified cart

Dynamo: Other guiding design principles
- Incremental scalability
  - Scale out one server at a time
- Symmetry
  - Every node is a peer
- Decentralized
- Heterogeneity in infrastructure
  - No need to replace all nodes at same time
  - Add new nodes with higher capacity

System Interface
- Store objects with a key
  - getO and putO
  - get(key)
  - Locates objects replicas associated with key
  - Returns single or list of objects
  - Conflicting versions along with context
Context encodes system metadata about object

- Includes information about object version
- `put(key, context, object)`
  - Where should replicas of object be placed?
    - Based on 128-bit MD5 hash applied on key
    - Based on key
  - Context information stored with the object
  - Used to verify validity of put request

A key requirement is that Dynamo must scale incrementally

- **Dynamically partition** data over a set of storage nodes
- Uses **consistent hashing**
  - DHT
  - Data item identified by key
    - Assigned to node responsible for MD5-hash(key)

Dynamo uses a variant of consistent hashing

- Introduces the notion of **virtual nodes**
  - Virtual node looks like a real node
  - Each node is responsible for **more than 1** virtual nodes
    - A node is assigned **multiple positions** in the ring

Basic hashing scheme presents some challenges

- Random position assignment may lead to
  - Non-uniform data and load distribution
- Algorithm **oblivious** to heterogeneity of devices

Advantages of virtual nodes

- If a node becomes **unavailable**
  - **Load** handled by failed node, **dispersed** across remaining virtual nodes
- When node becomes available again
  - Accepts roughly the same amount of work from other nodes
  - **Number of virtual nodes** are decided based on machine’s capacity
Dynamo replicates data on multiple hosts

- Each data item is replicated at \( N \) hosts
- Coordinator is responsible for nodes that fall in its range
- Additionally, a coordinator replicates key at \( N-1 \) clockwise successor nodes

What does this mean?

- Each node is responsible for region between
  - itself and its \( N \)th predecessor
- List of nodes responsible for a key
  - Preference list
- A node maintains a list of more than \( N \) to account for failures
  - Account for virtual nodes
  - Make sure your list contains different physical nodes

Data versioning

- A put() may return before it is applied to all replicas
- If there are no failures
  - Upper bound on update propagation times
- If there are failures
  - Things take much longer

There are applications at Amazon that tolerate this

- Shopping carts
- Add to Cart can never be forgotten or rejected
- If most recent state of cart unavailable
  - Make changes to the older version
  - Divergent versions are reconciled later
Dynamo treats each modification as a new, immutable version of the data
- Multiple versions of data present at the same time
- Often new versions subsume old data
  - Syntactic reconciliation
- When an automatic reconciliation is not possible
  - Clients have to do it
  - Collapse branches into one
  - Manage your shopping cart

Dynamo uses vector clocks to capture causality
- A vector clock for each version of the object
- Two versions of object being compared
  - If \( VC_1 \leq VC_2 \) for all indices of the vector clock
    - \( O_1 \) occurred before \( O_2 \)
  - Otherwise, changes are in conflict
  - Need reconciliation

A client must specify which version it is updating
- Pass context from an earlier read operation
  - Context contains vector clock information
- Requests with branches that cannot be reconciled?
  - Returns all objects with versioning info in context
  - Update done using this context reconciles and collapses all branches

Execution of \( \text{get()} \) and \( \text{put()} \) operations
- Read and write operations involve the first \( N \) healthy nodes
- During failures, nodes lower in priority are accessed

To maintain consistency, Dynamo uses a quorum protocol
- Uses configurable settings for replicas that must participate in
  - Reads
  - Writes

Quorum-based protocols: When there are \( N \) replicas
- Read quorum \( N_R \)
  - To modify a file write-quorum \( N_W \)
  - \( N_R + N_W > N \)
  - Prevent read-write conflict
  - \( N_W > N/2 \)
  - Prevent write-write conflict
Quorum-based protocols:
Example

Upon receiving a put() request for a key
- Coordinator generates a vector clock for new version
- Sends new version to N highest-ranked reachable nodes
- If at least NW-1 nodes respond: write is successful

External Discovery: During node adds
- When A and B join, it might be a while before they know each other’s existence
  - Logical partitioning
- Use seed nodes that are known to all nodes
  - All nodes reconcile membership with seed

Popular reconciliation strategies
- Business logic specific
- Timestamp
  - Last write wins
- High performance read engine
  - High read rates
  - Small update rates
  - NR=1 and NW=N

DYNAMO: EXPERIENCES

Quorum-based protocols:
Example 2

Read Quorum: Write Quorum:
Common configuration of the quorum

- \( N_e = 2 \)
- \( N_w = 2 \)
- \( N = 3 \)

Balancing performance and durability

- Some services not happy with 300 ms SLA
  - Writes tend to be slower than reads
- To cope with this, nodes maintain **object buffer**
  - Main memory
  - Periodically written to storage

The contents of this slide-set are based on the following references

- Giuseppe DeCandio, Deniz Hastorun, Madan Jampani, Gunavardhan Kakulapati, Arivazhagan Lukeman, Alex Pilchin, Swaminathan Sivasubramonian, Peter Vosshall, Werner Vogels: Dynamo: Amazon’s Highly Available Key-value Store. SOSP 2007, 205-220