CSE 444: Database Internals

Lectures 26

NoSQL: Key Value Stores

Announcements

- Lab 6 is new (first time at full scale)
  - Tackle it with an adventurous mind!
  - Consider the simplest extension: performance study
- Final project milestone is due on Wednesday
  - Show good progress on implementation
  - Start the final report (any non-empty file will get credit)
- Final project due June 8th
  - Code and final report
  - Absolutely no extensions!

References

- **Scalable SQL and NoSQL Data Stores**, Rick Cattell, SIGMOD Record, December 2010 (Vol. 39, No. 4)
- **Dynamo: Amazon's Highly Available Key-value Store**. By Giuseppe DeCandia et. al. SOSP 2007.
- Online documentation: **Amazon DynamoDB**.

NoSQL Motivation

- Originally motivated by Web 2.0 applications
- Goal is to scale simple OLTP-style workloads to thousands or millions of users
- Users are doing both updates and reads

Why NoSQL as the Solution?

- Hard to scale ***transactions***
  - Need to partition the database across multiple machines
  - If a transaction touches one machine, life is good
  - If a transaction touches multiple machines, ACID becomes extremely expensive! Need two-phase commit

- Replication
  - Replication can help to increase throughput and lower latency
  - Create multiple copies of each database partition
  - Spread queries across these replicas
  - Easy for reads but writes, once again, become expensive!

NoSQL Key Feature Decisions

- Want a data management system that is
  - Elastic and highly scalable
  - Flexible (different records have different schemas)

- To achieve above goals, willing to give up
  - Complex queries: e.g., give up on joins
  - Multi-object transactions
  - ACID guarantees: e.g., *eventual consistency* is OK
    - Eventual consistency: If updates stop, all replicas will *converge* to the same state and all reads will return the same value
    - BASE (Basically Available, Soft state, Eventually consistent)
  - *Not all NoSQL systems give up all these properties*

All updates *eventually* reach all replicas

Cattell, SIGMOD Record 2010

NoSQL

“Not Only SQL” or “Not Relational”.

Six key features:

1. Scale horizontally “simple operations”
2. Replicate/distribute data over many servers
3. Simple call level interface (contrast w/ SQL)
4. Weaker concurrency model than ACID
5. Efficient use of distributed indexes and RAM
6. Flexible schema

Data Models

- Tuple = row in a relational db
- Key-value = records identified with keys have values that are opaque blobs
- Extensible record = families of attributes have a schema, but new attributes may be added
- Document = nested values, extensible records (XML, JSON, protobuf, attribute-value pairs)

Cattell, SIGMOD Record 2010

Different Types of NoSQL

Taxonomy based on data models:

Today

- Key-value stores
  - e.g., Project Voldemort, Memcached, Redis
- Extensible Record Stores
  - e.g., HBase, Cassandra, PNUTS
- Document stores
  - e.g., SimpleDB, CouchDB, MongoDB
- Most recently: Graph databases
- New types of RDBMSs.. not really NoSQL
  - Next lecture

Key-Value Store: Dynamo

- **Dynamo: Amazon’s Highly Available Key-value Store**. By Giuseppe DeCandia et. al. SOSP 2007.

- Main observation:
  - “There are many services on Amazon’s platform that only need **primary-key access** to a data store.”
  - Best seller lists, shopping carts, customer preferences, session management, sales rank, product catalog

Basic Features

- **Data model**: (key,value) pairs
  - Values are binary objects (blobs)
  - No further schema
- **Operations**
  - Insert/delete/lookup by key
  - No operations across multiple data items
- **Consistency**
  - Replication with eventual consistency
  - Goal to NEVER reject any writes (bad for business)
  - Multiple versions with conflict resolution during reads

Operations

- **get(key)**
  - Locates object replicas associated with *key*
  - Returns a single *object*
  - Or a list of objects with conflicting versions
  - Also returns a *context*
    - Context holds metadata including version
    - Context is opaque to caller
- **put(key, context, object)**
  - Determines where replicas of object should be placed
  - Location depends on key value
  - Data stored persistently including context

Storage: Distributed Hash Table

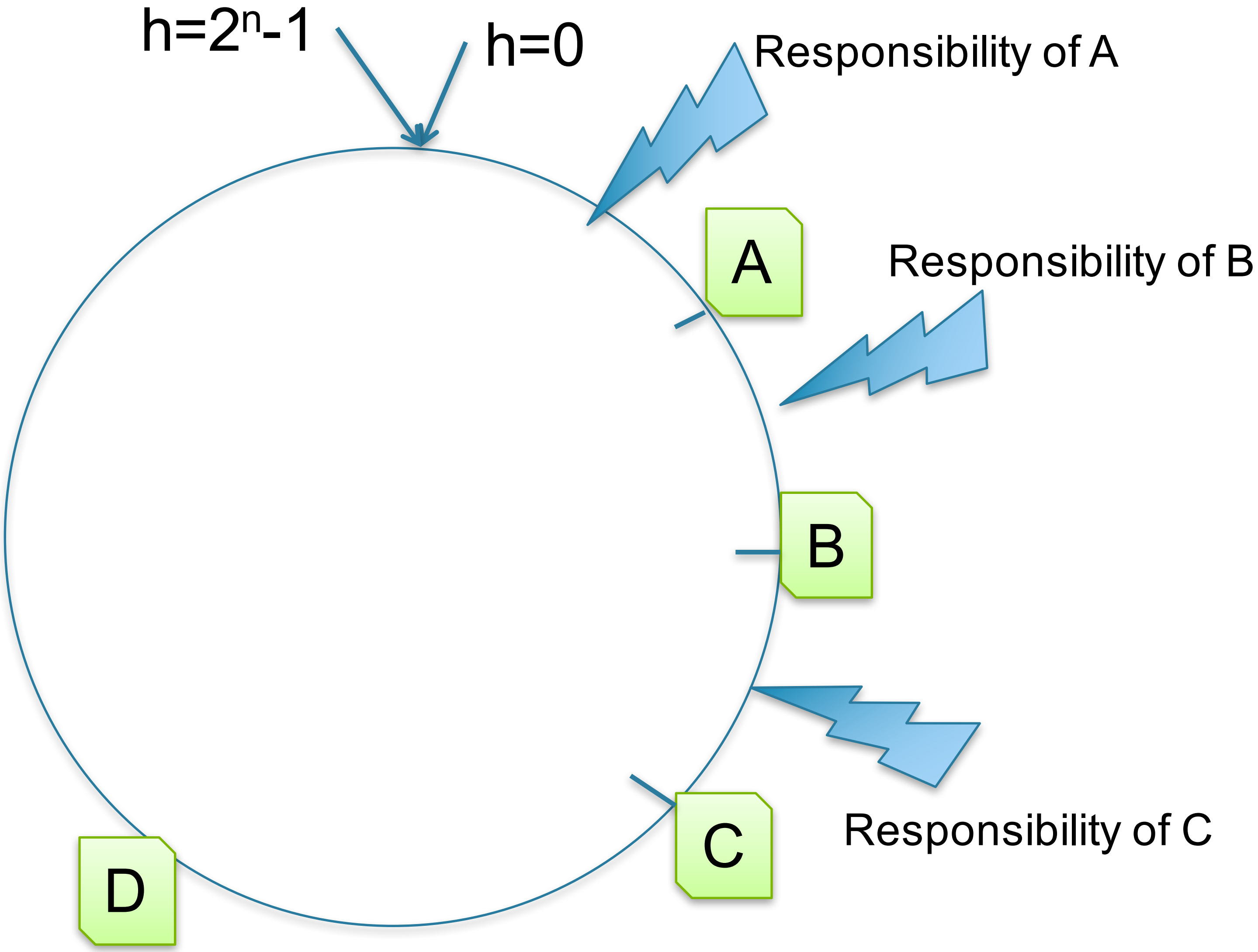
Implements a distributed storage

- Each key-value pair (k,v) is stored at some server h(k)
- API: write(k,v); read(k)

Use standard hash function: service key k by server h(k)

- Problem 1: a client knows only one server, doesn't know how to access h(k)
- Problem 2. if new server joins, then N → N+1, and the entire hash table needs to be reorganized
- Problem 3: we want replication, i.e. store the object at more than one server

Distributed Hash Table



Distributed Hash Table Details

- This type of hashing called “**consistent hashing**”

- Basic approach leads to load imbalance
  – Solution: Use V virtual nodes for each physical node
  – Virtual nodes provide better load balance
  – Nb of virtual nodes can vary based on capacity

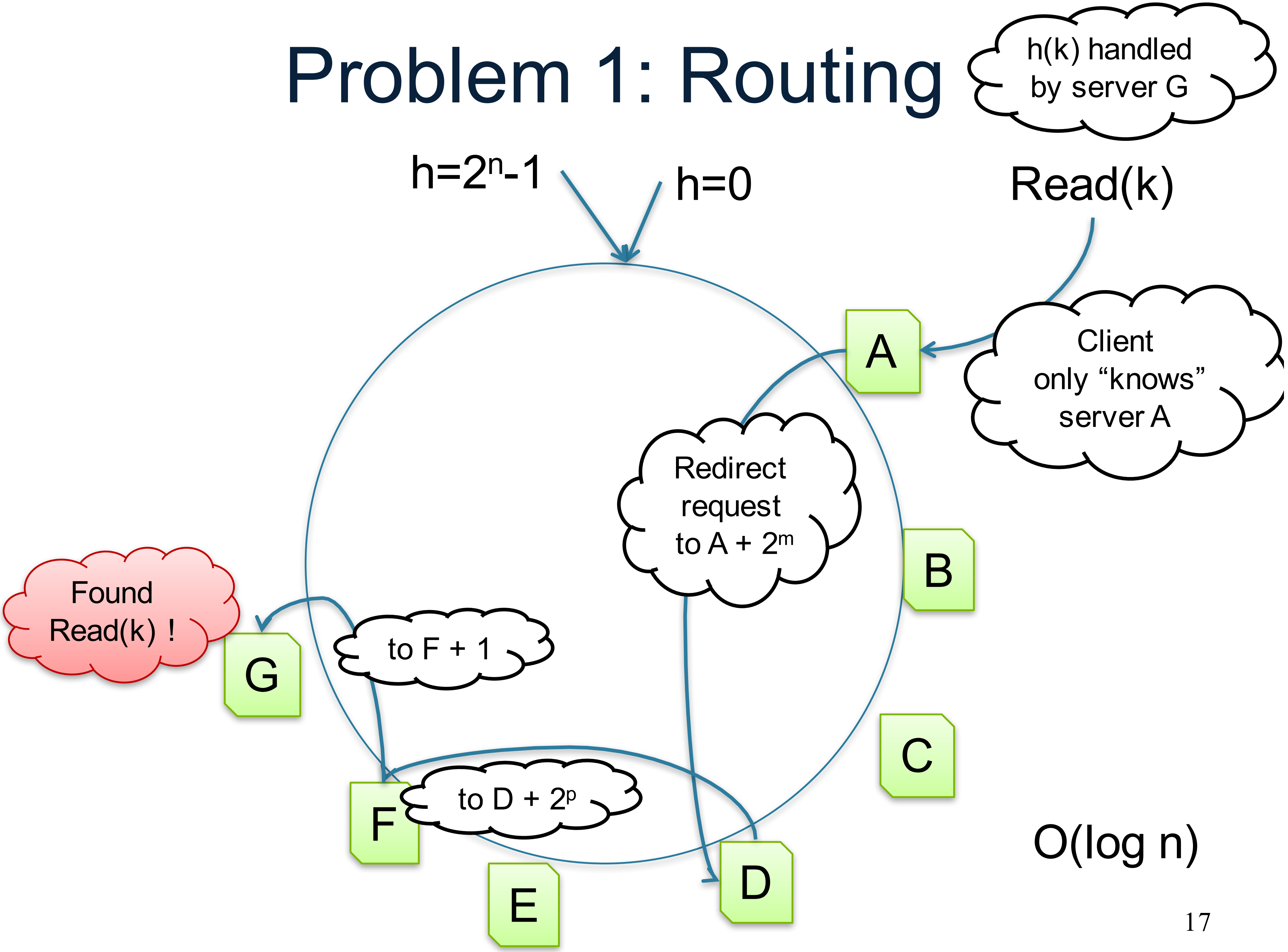
Problem 1: Routing

A client doesn't know server h(k), but some other server

- Naive routing algorithm:
  - Each node knows its neighbors
  - Send message to nearest neighbor
  - Hop-by-hop from there
  - Obviously this is O(n), so no good

- Better algorithm: "finger table"
  - Memorize locations of other nodes in the ring
  - a, a + 2, a + 4, a + 8, a + 16, ... a + 2^n – 1
  - Send message to closest node to destination
  - Hop-by-hop again: this is log(n)

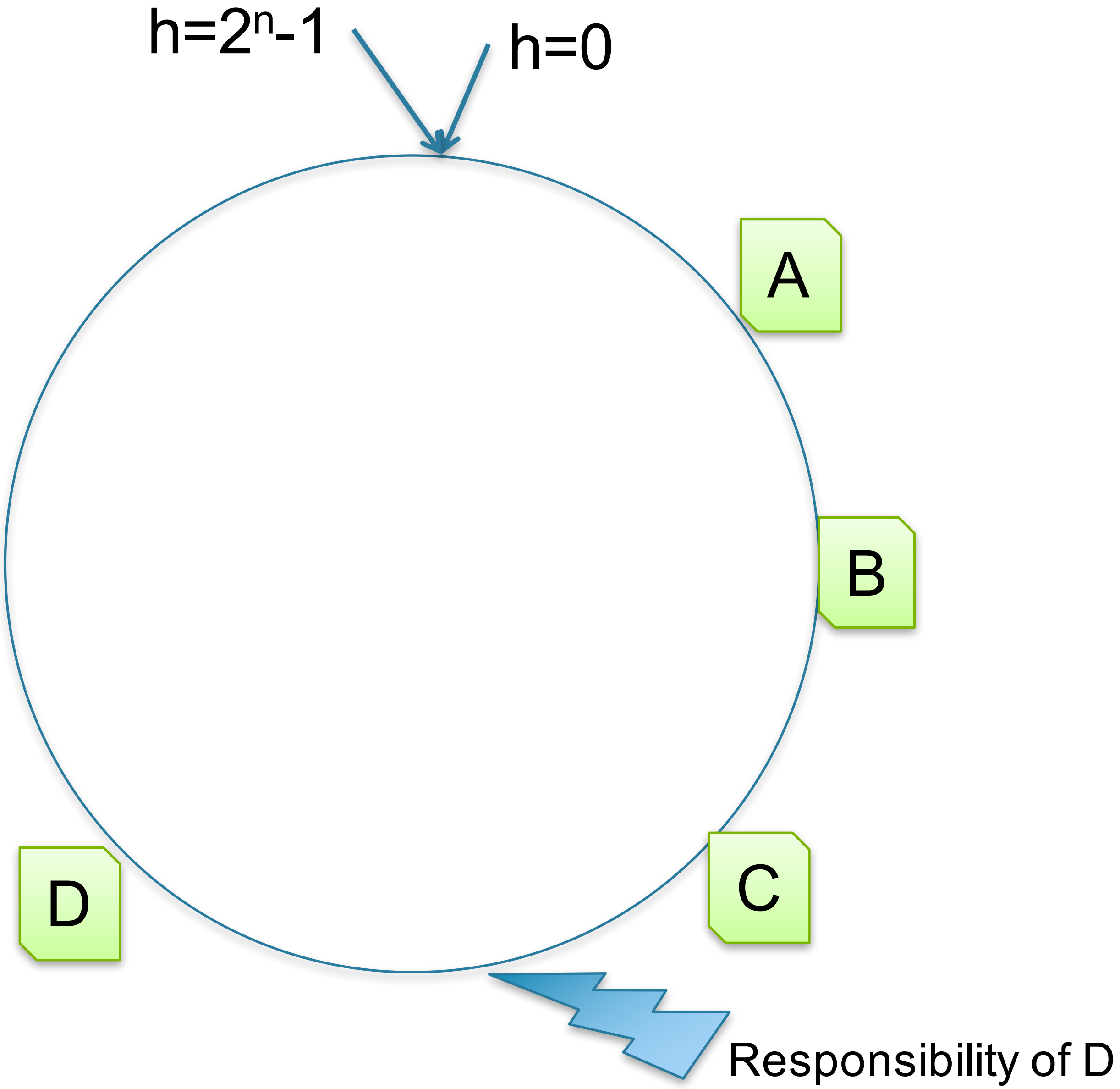
Problem 1: Routing



O(log n)

Problem 2: Joining

When X joins:
select random ID



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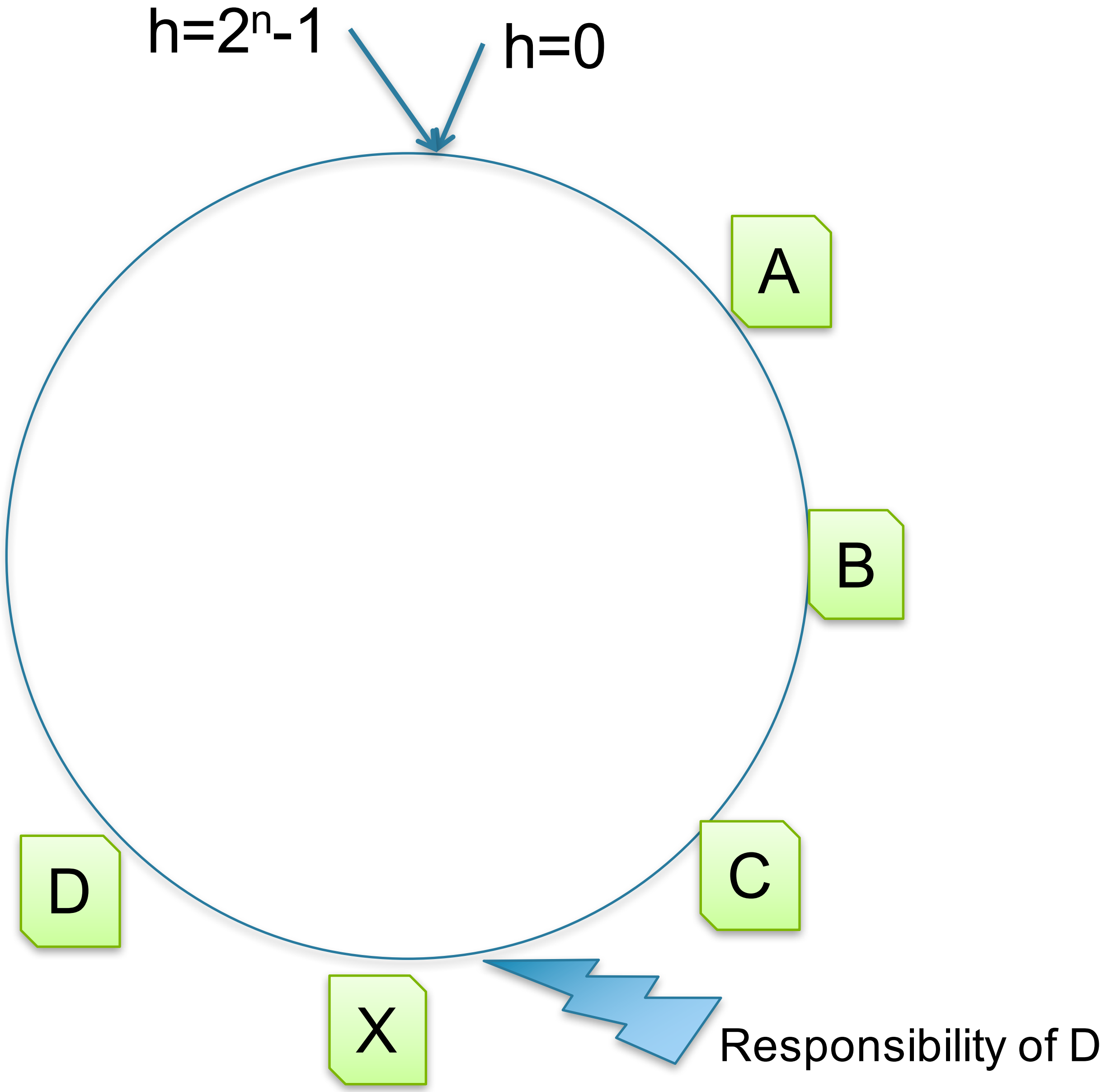
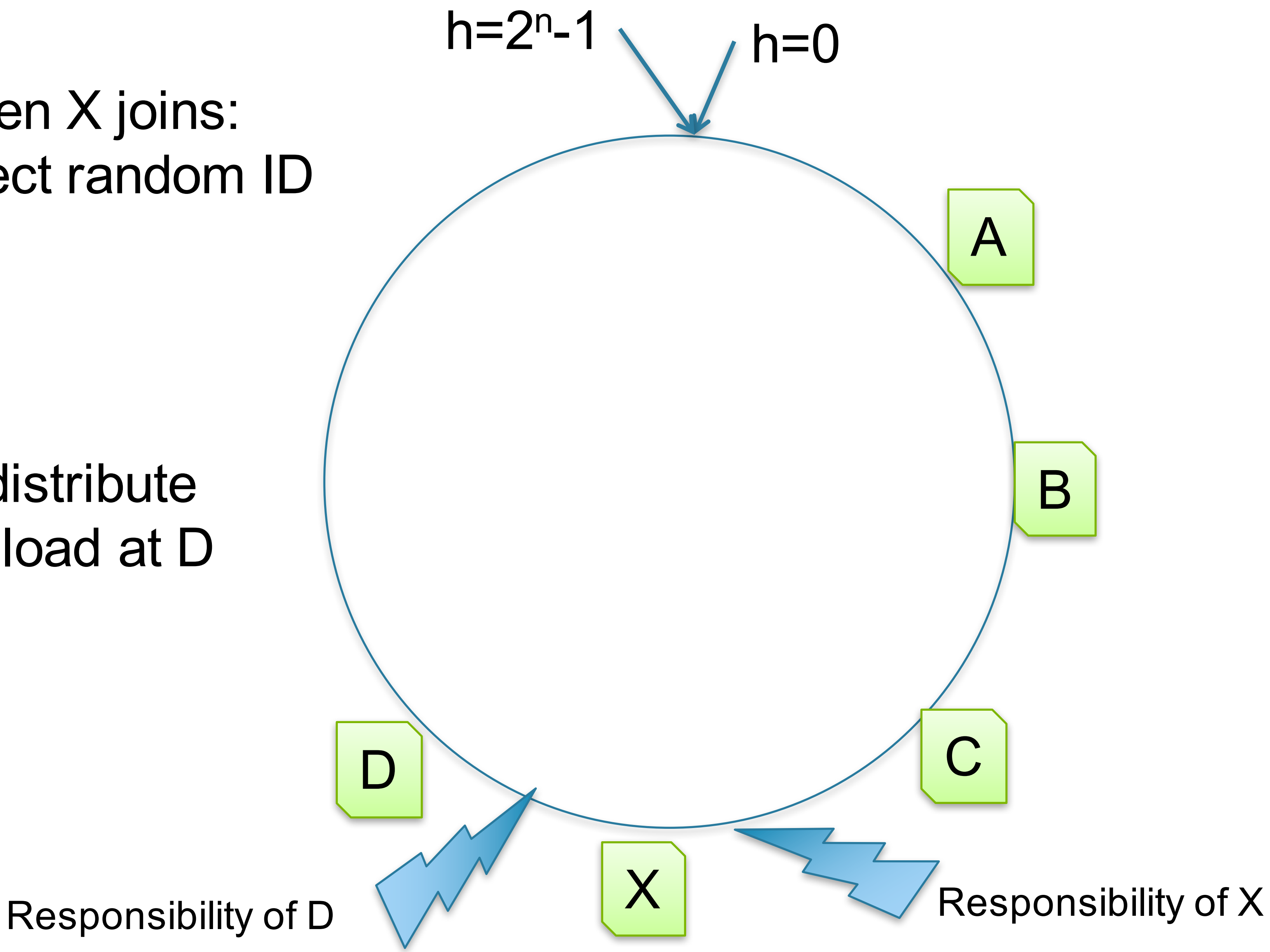
When X joins:
select random ID



Problem 2: Joining

When X joins:
select random ID

Redistribute
the load at D



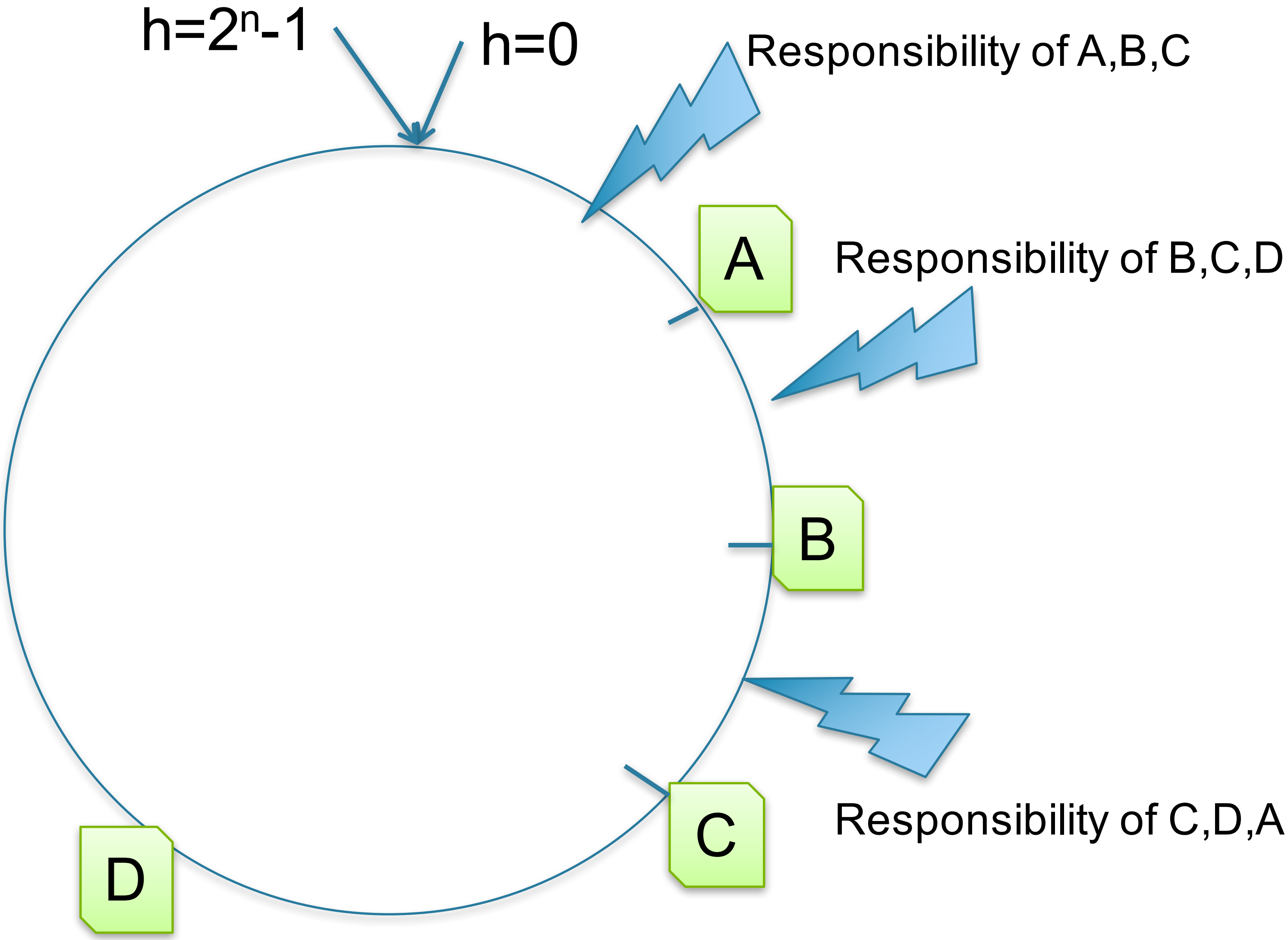
Problem 3: Replication

- Need to have some degree of replication to cope with node failures

- Let N=degree of replication

- Assign key k to h(k), h(k)+1, …, h(k)+N-1

Problem 3: Replication



Additional Dynamo Details

- Each key assigned to a *coordinator*
- Coordinator responsible for replication
  - Replication skips virtual nodes that are not distinct physical nodes
- Set of replicas for a key is its *preference list*
- One-hope routing:
  - Each node knows preference list of each key
- "Sloppy quorum" replication
  - Each update creates a new version of an object
  - Vector clocks track causality between versions

Vector Clocks

- An extension of Multiversion Concurrency Control (MVCC) to multiple servers

- Standard MVCC:
  each data item X has a timestamp t:
  $X_4, X_9, X_{10}, X_{14}, \ldots, X_t$

- Vector Clocks:
  X has set of [server, timestamp] pairs
  X([s1,t1], [s2,t2],…)

Dynamo:2007

Vector Clocks

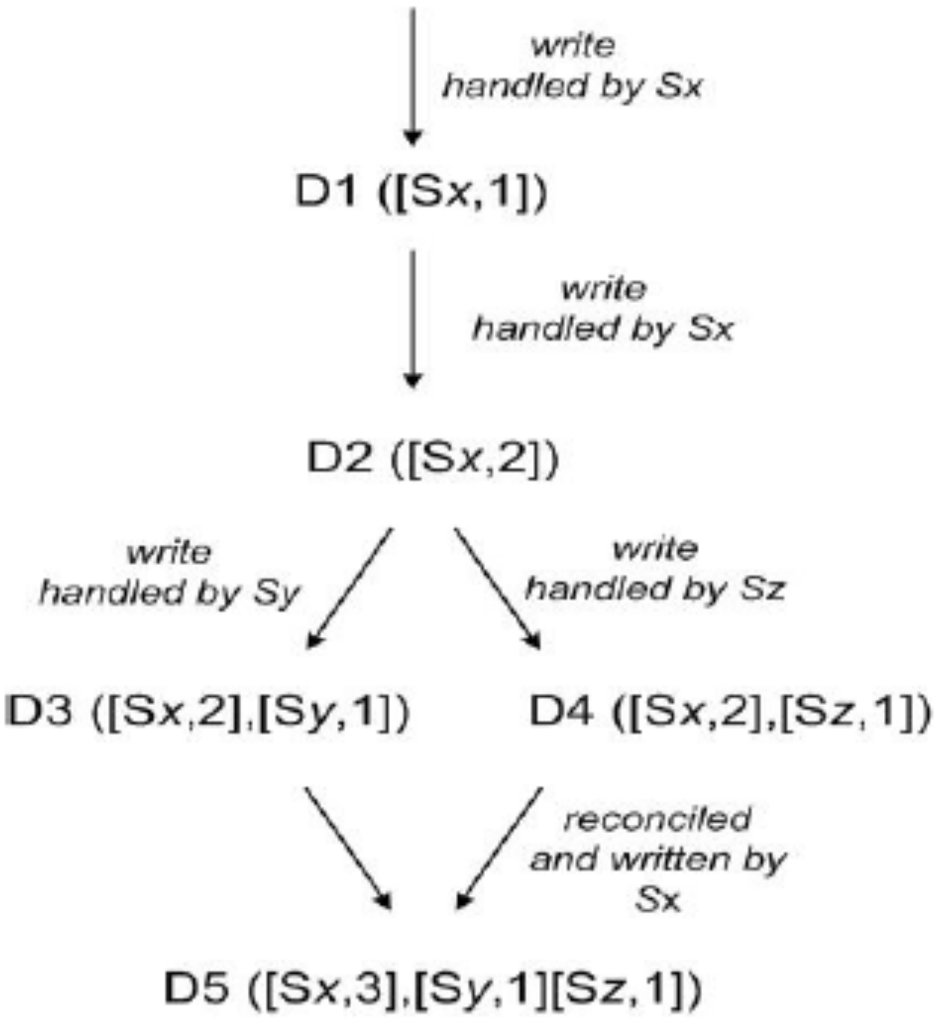


Figure 3: Version evolution of an object over time.

Vector Clocks: Example

- A client writes D1 at server SX:

  D1 ([SX,1])
- Another client reads D1, writes back D2; also handled by server SX:

  D2 ([SX,2]) (D1 garbage collected)
-
-
-

Vector Clocks: Example

- A client writes D1 at server SX:
  D1 ([SX,1])
- Another client reads D1, writes back D2; also handled by server SX:
  D2 ([SX,2]) (D1 garbage collected)
- Another client reads D2, writes back D3; handled by server SY:
  D3 ([SX,2], [SY,1])
-
-

Vector Clocks: Example

- A client writes D1 at server SX:

  D1 ([SX,1])
- Another client reads D1, writes back D2; also handled by server SX:

  D2 ([SX,2]) (D1 garbage collected)
- Another client reads D2, writes back D3; handled by server SY:

  D3 ([SX,2], [SY,1])
- Another client reads D2, writes back D4; handled by server SZ:

  D4 ([SX,2], [SZ,1])
-

Vector Clocks: Example

- A client writes D1 at server SX:

  D1 ([SX,1])
- Another client reads D1, writes back D2; also handled by server SX:

  D2 ([SX,2]) (D1 garbage collected)
- Another client reads D2, writes back D3; handled by server SY:

  D3 ([SX,2], [SY,1])
- Another client reads D2, writes back D4; handled by server SZ:

  D4 ([SX,2], [SZ,1])
- Another client reads D3 and D4: CONFLICT !

Vector Clocks: Meaning

- A data item D[(S1,v1),(S2,v2),…] means a value that represents version v1 for S1, version v2 for S2, etc.
- If server Si updates D, then:
  - It must increment vi, if (Si, vi) exists
  - Otherwise, it must create a new entry (Si,1)

Vector Clocks: Conflicts

- A data item D *is an ancestor* of D’ if for all (S,v)$\in$D there exists (S,v’)$\in$D’ s.t. v ≤ v’
- Otherwise, D and D’ are on parallel branches, and it means that they have a conflict that needs to be reconciled semantically

Vector Clocks: Conflict or not?

Data 1	Data 2	Conflict ?
([SX,3],[SY,6])	([SX,3],[SZ,2])	

Vector Clocks: Conflict or not?

Data 1	Data 2	Conflict ?
([SX,3],[SY,6])	([SX,3],[SZ,2])	Yes

Vector Clocks: Conflict or not?

Data 1	Data 2	Conflict ?
([SX,3],[SY,6])	([SX,3],[SZ,2])	Yes
([SX,3])	([SX,5])	

Vector Clocks: Conflict or not?

Data 1	Data 2	Conflict ?
([SX,3],[SY,6])	([SX,3],[SZ,2])	Yes
([SX,3])	([SX,5])	No

Vector Clocks: Conflict or not?

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([SX,3],[SY,6])	([SX,3],[SZ,2])	Yes
([SX,3])	([SX,5])	No
([SX,3],[SY,6])	([SX,3],[SY,6],[SZ,2])	

Vector Clocks: Conflict or not?

Data 1	Data 2	Conflict ?
([SX,3],[SY,6])	([SX,3],[SZ,2])	Yes
([SX,3])	([SX,5])	No
([SX,3],[SY,6])	([SX,3],[SY,6],[SZ,2])	No

Vector Clocks: Conflict or not?

Data 1	Data 2	Conflict ?
([SX,3],[SY,6])	([SX,3],[SZ,2])	Yes
([SX,3])	([SX,5])	No
([SX,3],[SY,6])	([SX,3],[SY,6],[SZ,2])	No
([SX,3],[SY,10])	([SX,3],[SY,6],[SZ,2])	

Vector Clocks: Conflict or not?

Data 1	Data 2	Conflict ?
([SX,3],[SY,6])	([SX,3],[SZ,2])	Yes
([SX,3])	([SX,5])	No
([SX,3],[SY,6])	([SX,3],[SY,6],[SZ,2])	No
([SX,3],[SY,10])	([SX,3],[SY,6],[SZ,2])	Yes

Vector Clocks: Conflict or not?

Data 1	Data 2	Conflict ?
([SX,3],[SY,6])	([SX,3],[SZ,2])	Yes
([SX,3])	([SX,5])	No
([SX,3],[SY,6])	([SX,3],[SY,6],[SZ,2])	No
([SX,3],[SY,10])	([SX,3],[SY,6],[SZ,2])	Yes
([SX,3],[SY,10])	([SX,3],[SY,20],[SZ,2])	

Vector Clocks: Conflict or not?

Data 1	Data 2	Conflict ?
([SX,3],[SY,6])	([SX,3],[SZ,2])	Yes
([SX,3])	([SX,5])	No
([SX,3],[SY,6])	([SX,3],[SY,6],[SZ,2])	No
([SX,3],[SY,10])	([SX,3],[SY,6],[SZ,2])	Yes
([SX,3],[SY,10])	([SX,3],[SY,20],[SZ,2])	No

(Sloppy) Quorum Read/Write

- Parameters:
  - N = number of copies (replicas) of each object
  - R = minimum number of nodes that must participate in a successful read
  - W = minimum number of nodes that must participate in a successful write
- Quorum: R+W > N
- Sloppy Quorum (Dynamo): allow R+W ≤ N

Operation Execution

- Write operations
  - Initial request sent to coordinator
  - Coordinator generates vector clock & stores locally
  - Coordinator forwards new version to all N replicas
  - If at least W-1 < N-1 nodes respond then success!
- Read operations
  - Initial request sent to coordinator
  - Coordinator requests data from all N replicas
  - Once gets R responses, returns data
- Sloppy quorum: Involve first N *healthy* nodes

Amazon DynamoDB

Additional functionality:

- Both document and key-value store models
- Offers secondary indexes to enable queries over non-key attributes
  - So can support selection and projection queries
- Offers choice of eventual consistent vs strongly consistent read

Try Amazon DynamoDB

http://aws.amazon.com/dynamodb/

Amazon DynamoDB Data Model

- Tables containing Items
  - Items are described with attributes
  - One attribute must be the primary key
    - Primary key can be a single partition key attribute
    - Or a pair of (partition key k1, sort key k2)
      - Items partitioned across nodes on k1
      - Sorted within the node on k2

Amazon DynamoDB Querying

- Selection and projection queries
  - Equality predicates on primary key
  - Must create secondary indexes to query other attributes. Also equality predicates
  - Can specify attributes to return (projection)
  - Can specify path notation for document attributes

Amazon DynamoDB Consistency

- Eventually consistent read
  - "When you read data from a DynamoDB table, the response might not reflect the results of a recently completed write operation. The response might include some stale data. However, if you repeat your read request after a short time, the response should return the latest data."
- Strongly consistent read
  - "When you request a strongly consistent read, DynamoDB returns a response with the most up-to-date data, reflecting the updates from all prior write operations that were successful. Note that a strongly consistent read might not be available in the case of a network delay or outage."