Algorithms and Distributed Systems 2019/2020 (Lecture Eight)

MIEI - Integrated Master in Computer Science and Informatics
Specialization block

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Lecture structure:

- Strong Consistency
- Eventual Consistency
- Dynamo (From Amazon)

Recently: State Machine Replication and Paxos

- Replication Strategy that from the outside of the system provides a behavior that:
  - Is like operations being executed over a non-replicated data object (Replication is hidden from Applications)
  - The state of the system evolves having all operations being ordered (in an order that respects real-time)

- This is known as **Linearizability**.
- Can we be more precise?

Atomicity

- Given a trace of a system, there exists for each operation a serialization point, between the start and the end of the operation. If we consider that the operation has happened at that point, then the state of the system follows the effects of all operations.
- If an operation never returns a reply to the client, then such an operation might or might not have a serialization point.

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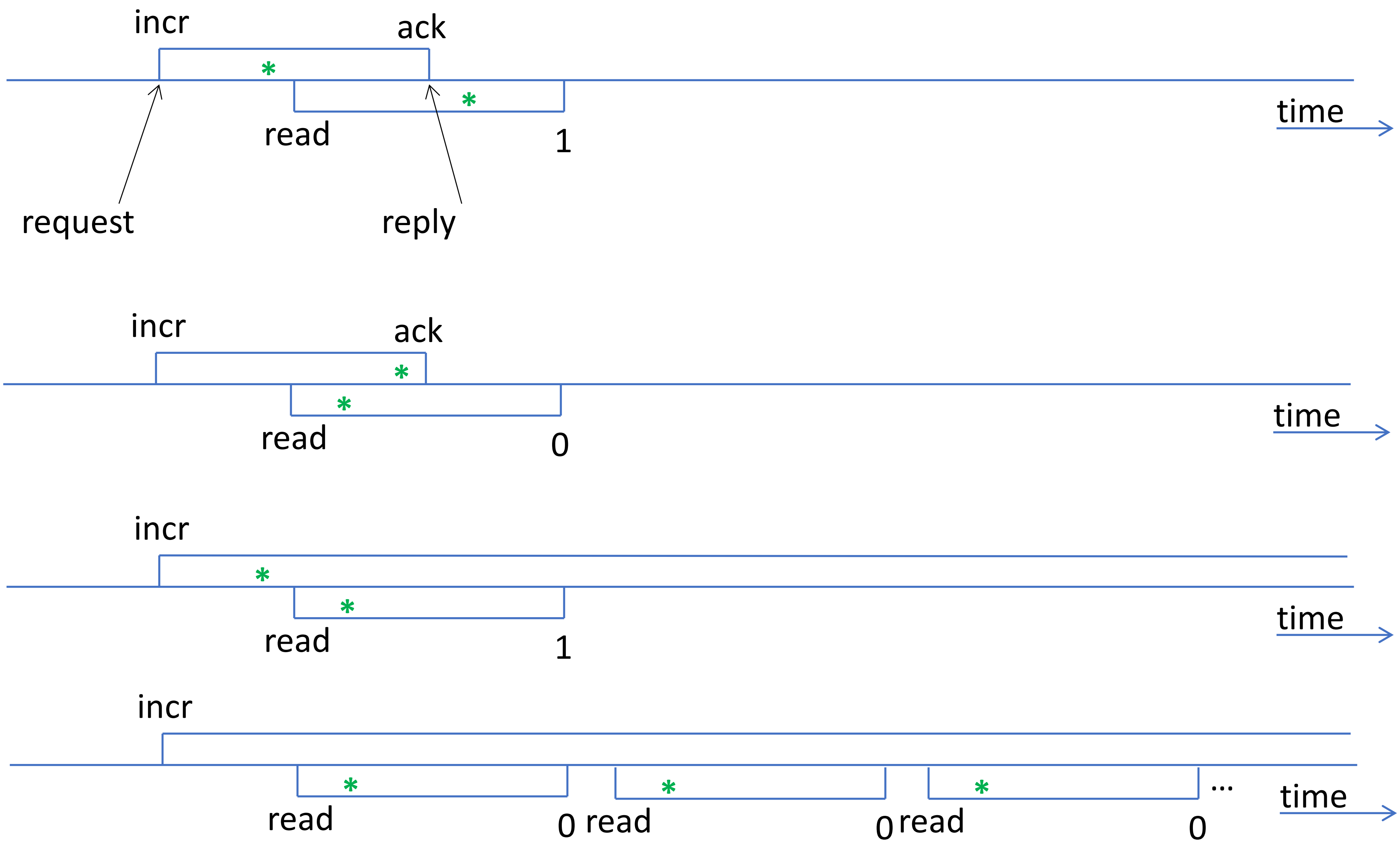
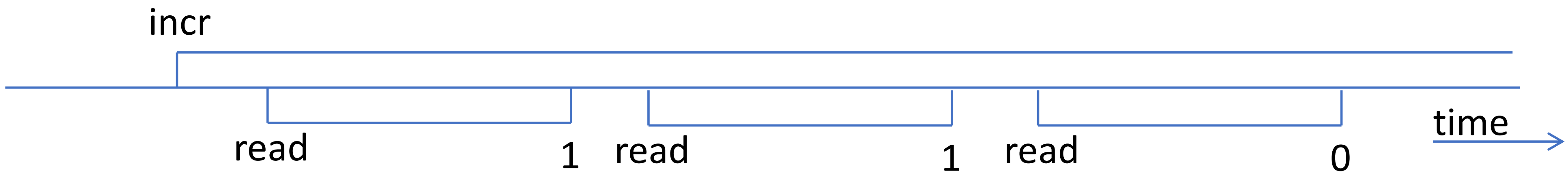
- E.g.,: A replicated counter (initial value zero) where increment operations can be executed.

Atomic Executions over a Counter



Non-Atomic Execution



Strong Consistency

- Systems that provide this notion of a strict evolution of state across all replicas (and hence Atomicity) are said to offer **Strong Consistency**.

- Multiple consistency models that fit Strong Consistency:
  - Linearizability.
  - Serializability.

Lineazibility

- *Linearizability is a guarantee about single operations on single objects.* It provides a real-time (i.e., wall-clock) guarantee on the behavior of a set of single operations (often reads and writes) on a single object (e.g., distributed register or data item).
- Under linearizability, writes should appear to be instantaneous. Informally, once a write completes, all later reads (where "later" is defined by a global wall-clock start time) should return the value generated by that write or the value of a later write. Once a read returns a concrete value, all later reads should either return that value or a value produced by a later write.

Serializability

- *Serializability is a guarantee about groups of one or more operations over one or more objects (usually called transactions).* It guarantees that the execution of a set of transactions (usually containing read and write operations) over multiple data objects is equivalent to *some* serial execution (total ordering) of the transactions.
- Unlike linearizability, serializability does not—by itself—impose any real-time constraints on the ordering of operations. It only requires a single order across all replicas (that might be different from the order of operations in relation to a global wall clock).

Why is it that we like Strong Consistency?

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- Mainly because it makes it easy to reason about the evolution of the state of a replicated system (since all replicas evolve across the same set of states in the same order).

- Some operations over the state of a replicated system require strong consistency to ensure that replicas converge to the same state (non-commutative operations for instance).

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  - Geo-Replicated Systems (high latency between replicas in different continents)
  - Systems where there is poor connectivity between clients and server replicas (e.g., mobile applications).
  - Systems with strict requirements of perfomance (Service Level Aggrements) such as maximum latency for an operation.

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- Well evidently if there is Strong Consistency…
- ...there is also Weak Consistency!

Weak Consistency Solution

- Contrary to strong consistency replication solutions, operations are only executed in a small (smaller than a quorum, i.e., without intersection guarantees) set of replicas, eventually only one.
- Operations are then propagated between replicas in background.
- Clients obtain their answer before replication mechanisms are executed (i.e., relies on some form of asynchronous replication).

Weak Consistency Solution (cont)

- What are the problems that can arise from this strategy?

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- Replicas will diverge (while operations are happening and being propagated among replicas, each replica might have a different value from all the others).

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- Replicas will diverge (while operations are happening and being propagated among replicas, each replica might have a different value from all the others).

- We have to find ways to explicitly deal with
  replica divergence.

Weak Consistency Models

- Similar to Strong Consistency, there are multiple consistency models that fit within what is generally refered as **Weak Consistency (recently renamed to Available Consistency)**.

- A consistency Model effectively defines a set of **safety conditions for a replication algorithm** that (usually) restricts the state of the system that a client can observe given the history of the system and his own local history (i.e., the operations that the client itself has executed before)

Weak Consistency Models

- Eventual Consistency.

- Causal Consistency.

(Many many others that we would need an entire course just to cover them and understand the differences).

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- Eventual Consistency. <- Today
- Causal Consistency. <- Next Friday
- (Many many others that we actually would need an entire course just to cover all of them and understand the differences).

Weak Consistency: *Eventual Consistency*

- Used in practice in many systems available now-a-days.
- Popularized by Amazon in the Dynamo System
  - Dynamo is a distributed and replicated data storage system.
  - Dynamo is used for many amazon services, including the shopping car.
  - Dynamo features multiple replicas, across different data centers. Operations execute by contacting only a very small number of replicas.
  - Clients are application servers (i.e., proxies) that operate within the Amazon datacenters.

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  - Clients are application servers (i.e, proxies) that operate within the Amazon datacenters.
- Also used in many mobile systems:
  - Clients execute their operations (offline) over a local copy (i.e., replica) of the (relevant) application state.
  - In background (typically when connectivity is available) they synchronize with servers.

Eventual consistency

- What are the safety guarantees enforced by the eventual consistency model?

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- Actually, none... This is the weakest form of weak consistenty that exists.

- So what does eventual consistency promises effectively?

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- Eventual consistency only promises that:
  eventually, when no write operations happen, all replicas of the system will converge to the same state.

- Is this safety or liveness?
- Effectively this is a liveness property.

- This has generated some debate, where some people in the community argue that eventual consistency is no consistency model at all.

Eventual Consistency

- Since there are no safety properties, the key aspect of Eventual Consistency replication strategies is to enforce the convergence of state.

- How can we do this?

Divergence Reconciliation

- Multiple Possibilities:
  - "***last writer wins***" Policy:
    - We define an order among any concurrent write operations.
    - We lose the effects of all operations (over a given data object) except for the last one (given that order).

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  - We expose the divergence to clients (for instance by returning multiple values upon the execution of a read operation) and the client merges these values and write the new value back to the system (***application-dependent policy***)

Eventual consistency

- There are some variants of eventual consistency (after all, we have no strict safety properties) that depend on implementation.
- We are going to focus on Dynamo (Amazon)

Dynamo: Amazon’s Highly Available Key-value Store

Giuseppe DeCandia, Deniz Hastorun, Madan Jampani, Gunavardhan Kakulapati, Avinash Lakshman, Alex Pilchin, Swaminathan Sivasubramanian, Peter Vosshall and Werner Vogels

Amazon.com

Valid Question: Why are we focusing on an Amazon system?

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A long long time ago (early 2000) before being popular for the Amazon Echo and now for making a Lord of the Rings TV Show (still maybe).

Valid Question: Why are we focusing on an Amazon system?

- Amazon was the first world-scale online seller…
- And hence, they had problems that no one had before, such as: how to build a database for global operation?

Valid Question: Why are we focusing on an Amazon system?

- They were the first to break with the SQL paradigm and proposed Dynamo that had a much simpler No-SQL Interface (Key-Value Store).

amazon
DynamoDB

Valid Question: Why are we focusing on an Amazon system?

- They were the first to break with the SQL paradigm and proposed Dynamo that had a much simpler No-SQL Interface (Key-Value Store).
- This in turn had a profound impact on how distributed system are built today…

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- Geographical replication with high performance and availability.
- Write operations can be executed without being aware (i.e, observe the effect of) other write operations.
  - Two users are allowed to buy (”at the same time”) the last available ticket for a plane.
- Eventually, all operations are propagated among all replicas of the system.
  - And the state converges, in the previous example, the list of all passengers in a plane would become visible everywhere and we would observe overbooking… How to address this?

Dynamo Requirements for Eventual Consisttency (intuitive definition)

- Starting Point:
  - Key-Value Store offering two operations
  - Read and Write operations (get/put)
    - get(key) → returns "value"
    - put(key,value) → returns "ack"

Dynamo Requirements for Eventual Consisttency (intuitive definition)

- To deal with concurrent writes, Dynamo extends this interface.
- Add metadata that allows to associate a **put** operation to the previous **get** of **that same client.**
  - This allows to infer that a given put operation already reflects the effects of a set of previous put operations (those that were observed by the get operation).
- Get operations can return multiple values (if divergence is detected).

Dynamo: interface

- **get(key) → returns <list of values,context>**
  - Returns a list containing the values written by the most recent put operations (that have not yet observed the effects of each other). This ensures that effects of concurrent writes are not lost.
  - **Context** describes the set of put operations that are reflected in the returned list of values.
- **put(key,value,context) → returns "ack"**
  - Writes the new value for data object identified by key.
  - Provides the context of the most recent get executed by that client.

Dynamo: Implementation

- To simplify, lets just consider operations over a single key, and a fixed set of replicas N.

- In fact Dynamo deals with faults, and partitioning of data:
  - One-hop DHT.
  - Consistent hashing.
  - Specifies the protocol to deal with faults.
    - More information in the paper (available in Clip)

Dynamo: Implementation

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- **Operations are executed in a single step:**
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  - **Replica propagates the get or put request to N replicas.**
  - **Waits for the answer of R or W replicas before returning to the client (incluiding itself)**
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- **How do we know if two put operations were concurrent?**

Concurrency Detection

- Possibility: return in the context the list of puts that form the complete story of the data object identified by that key.

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- The context is sent alongside the put operation, and stored by Dynamo along side the data.

Concurrency Detection

- Example: replicas A,B,C; clients: c1,c2,c3; W=1,R=2
  - **Client c1** executes ***get*** of the initial version of K **in A,B** and executed ***put*** **D1** in **A** (empty context).
  - **Client c2** executed ***get*** of the initial version of K **in B,C** and executed ***put D2*** in **B** (empty context).
  - **Client c3** executes ***get*** **in A,B → detects that A and B have not seen the effects of the last write in each other, therefore these writes are concurrent.**
    - **Get returns a list with values {D1,D2}, and context {D1,D2}**
  - **Client c3 executes put of D3**, **and sends context {D1,D2} (reconciliation has been achieved).**

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In this perfect?

  - C [illegible] executed ***put* D2** in **B** (empty context)
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- **Intuition**: what if we attribute a sequence number to put operations, and memorize only the most recent one?
  - This however requires that only a single replica processes write operations and propagates to the other replicas (we would have to abandon the multi-master model).

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- The solution that we saw works perfectly, but it does present a huge overhead in terms of metadata. **Is there a way to compress this information?**
- **Intuition**: what if we attribute a sequence number to put operations, and memorize only the most recent one?
  - This however requires that only a single replica processes write operations and propagates to the other replicas (we would have to abandon the multi-master model).
- **Use of vector clocks.**
- **Each write has associated a clock value, that is composed by an entry for each replica.**
  - **The replica entry has the sequence number of the most recent put operation that was processed by that replica.**

Example: Vector Clocks

- Client c1 executes get of the initial value [0,0,0] in A,B and executes put D1 in A (with context [0,0,0])
  - Replica A associates vector clock [1,0,0] to D1

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- Client c1 executes get of version [1,0,0] in A and [0,0,0] in B executing put operation D2 in A (with context [1,0,0])
  - Replica A associates vector clock [2,0,0] to D2

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  - Replica A associates vector clock [2,0,0] to D2
- Client c1 executes get of version [2,0,0] in A and [0,0,0] in B executing put operation D3 in B (with context [2,0,0])
  - Replica B associates vector clock [2,1,0] to D3

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  - Replica A associates vector clock [2,0,0] to D2
- Client c1 executes get of version [2,0,0] in A and [0,0,0] in B executing put operation D3 in B (with context [2,0,0])
  - Replica B associates vector clock [2,1,0] to D3
- Client c2 executes get of version [2,0,0] in A and [0,0,0] in C executing put operation D4 in C (with context [2,0,0])
  - Replica C associates [2,0,1] to D4

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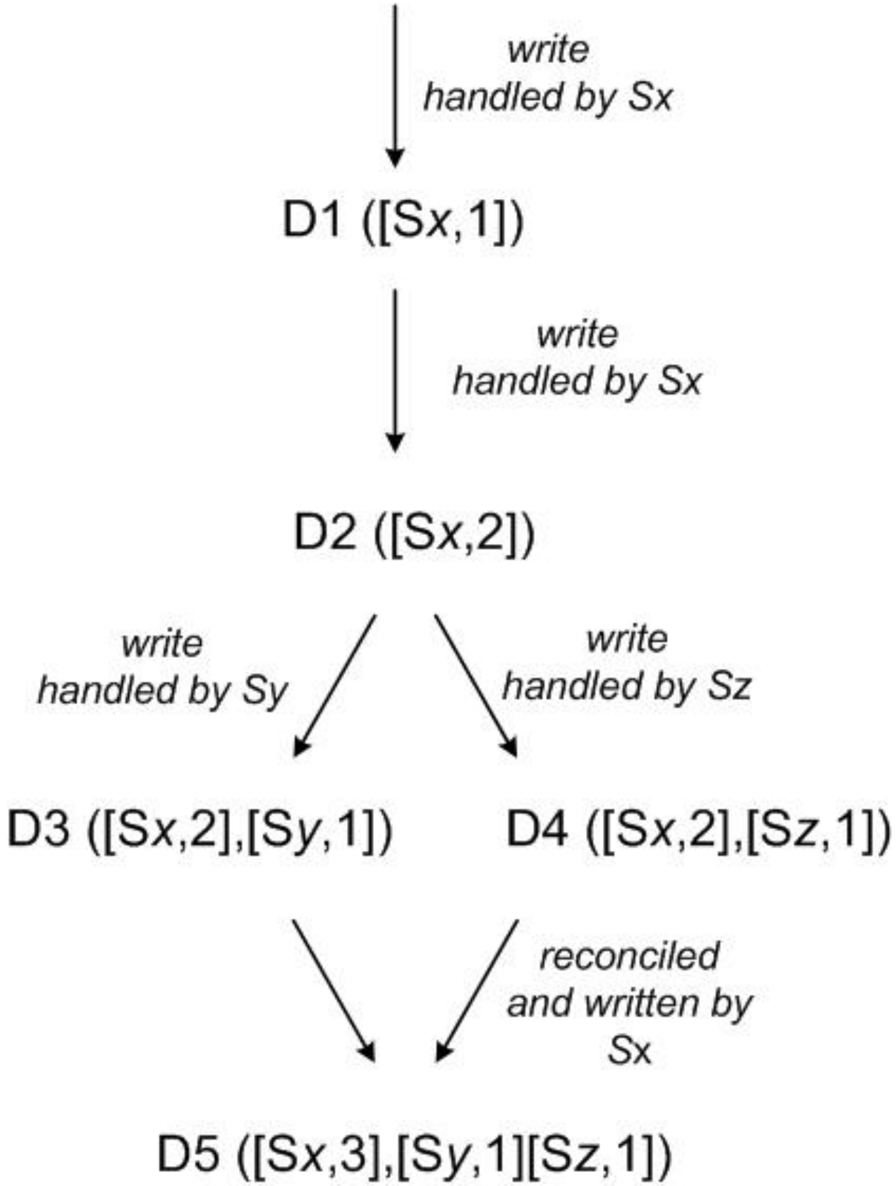
  - Replica B associates vector clock [2,1,0] to D3
- Client c2 executes get of version [2,0,0] in A and [0,0,0] in C executing put operation D4 in C (with context [2,0,0])
  - Replica C associates [2,0,1] to D4
- Client c3 executes get of version [2,1,0] in B and [2,0,1] in C → these vector clocks are incomparable, and hence reflect concurrent writes
  - Get return both {D3,D4} values and context [2,1,1]
  - Client application is responsible for merging these values and executes a put operation of D5 with [2,1,1], on replica A.
  - Replica A associates[3,1,1] to D5

Vector Clocks in Practice...



Fonte: G. DeCandia et al., “Dynamo: Amazon's Highly Available Key-Value Store”, in the Proceedings of the 21st ACM Symposium on Operating Systems Principles, Stevenson, WA, October 2007.

Dynamo: so how do we deal with concurrency?

- **Through the use of vector clocks**: one entry per replica
  - i^{th} entry representes the number of write operations reflected in the state (i.e., accepted) by replica i.
- If two replicas move their vector clocks independently, then both writes are concurrent.
- **Comparing vector clocks R1 e R2:**
  - **R1>=R2 if and only if R1[i]>=R2[i]** for all positions i of the vector clock
- **If neither R1>=R2 nor R2>=R1 then R1 e R2 are incomparable**
  - **Which means that the state of those replicas reflects concurrent (write) operations.**

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- Cassandra: "***last writer wins***":
    - **Concurrent updates are ordered in a deterministic way.**
    - **All concurrent updates are lost except one**

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- Dynamo: client resolution
- Cassandra: “***last writer wins***”:
    - Concurrent updates are ordered in a deterministic way.
    - All concurrent updates are lost except one
- Alternative: Conflict-free replicated data types (CRDTs) by N. Preguiça et. al.

Homework 4:

- Not this week…