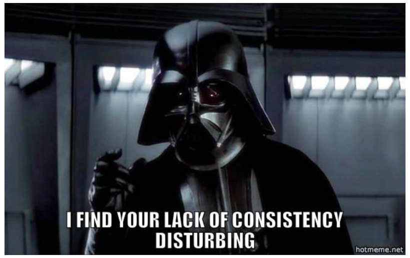
Slide 1

Distributed Systems (COMP9243)

Lecture 5: Replication & Consistency



① Replication
② Consistency
- Models vs Protocols

③ Update propagation

Slide 2

Replication

Make copies of services on multiple machines.

Why?:

➜ Reliability
- Redundancy

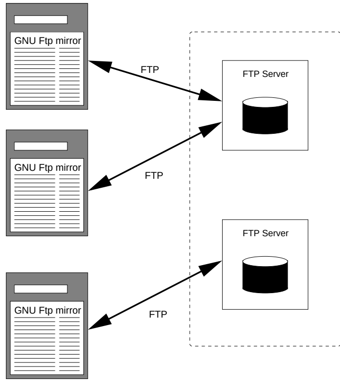
➜ Performance
- Increase processing capacity
- Reduce communication

➜ Scalability (prevent centralisation)
- Prevent overloading of single server (*size* scalability)
- Avoid communication latencies (*geographic* scalability)

Slide 3

Data vs Control Replication

Data Replication (Server Replication/Mirroring):



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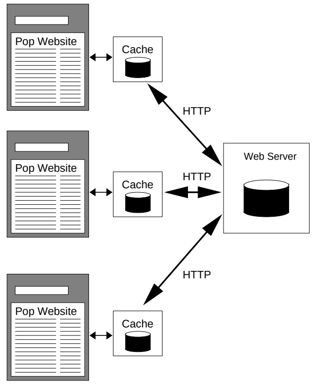
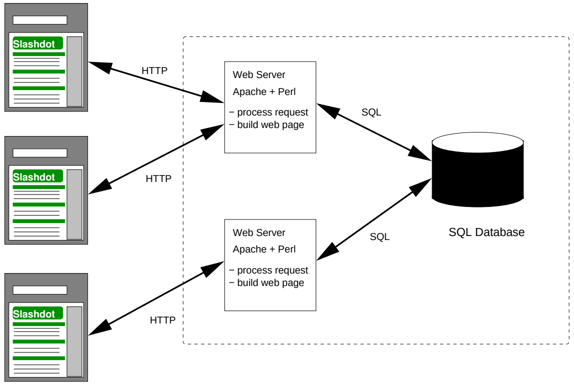
Data Replication (Caching):



What's the difference between mirroring and caching?

Slide 5

Control Replication:



What are the challenges of doing this?

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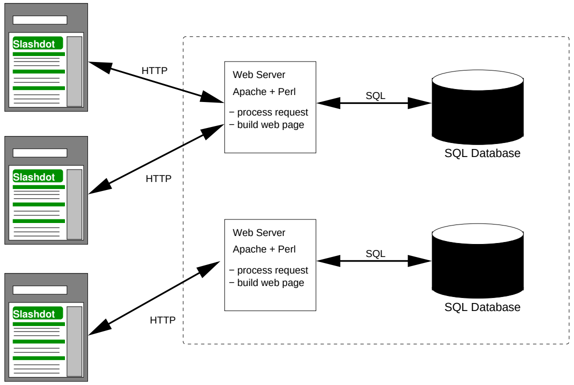
Data and Control Replication:



We will be looking primarily at data replication
(including combined data and control replication).

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Replication Issues

Updates

➜ Consistency (how to deal with updated data)

➜ Update propagation

Replica placement

➜ How many replicas?

➜ Where to put them?

Redirection/Routing

➜ Which replica should clients use?

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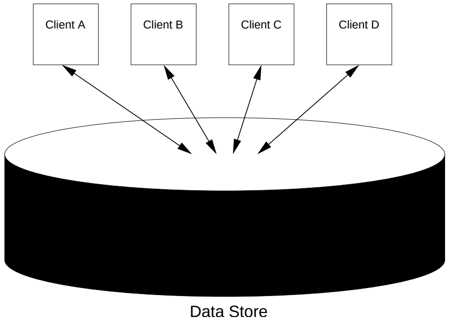
Distributed Data Store

➜ data-store stores data items

Client's Point of View:



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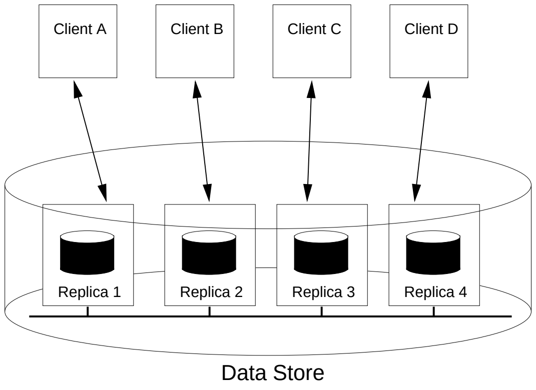
Distributed Data-Store's Point of View:



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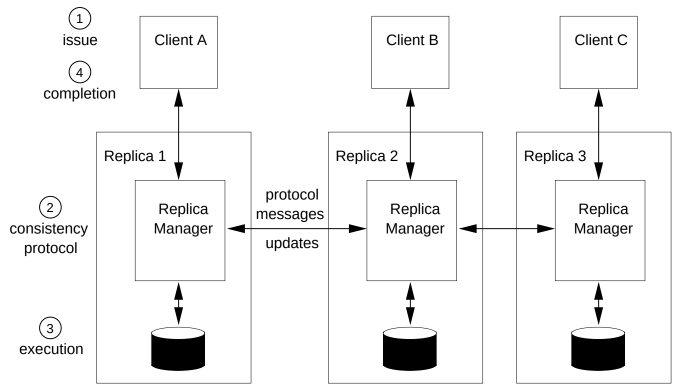
Replica Managers:



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Data Model:

- ➜ data item: simple variable
- ➜ data item values: explicit `(0, 1)`, abstract `(a,b)`
- ➜ data store: collection of data items

Operations on a Data Store:

- ➜ Read. `Ri(x)b` Client i performs a read for data item `x` and it returns `b`
- ➜ Write. `Wi(x)a` Client i performs write on data item `x` setting it to `a`
- ➜ Operations not instantaneous
  - Time of issue (when request is sent by client)
  - Time of execution (when request is executed at a replica)
  - Time of completion (when reply is received by client)
- ➜ Coordination among replicas

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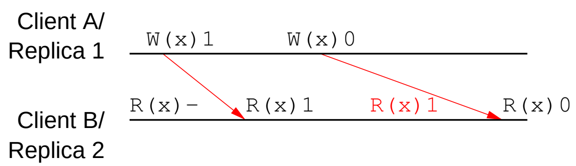
Timeline:

- ➜ ClientA/Replica1: `WA(x)1, WA(x)0`
- ➜ ClientB/Replica2: `RB(x)-, RB(x)1, RB(x)1, RB(x)0`



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CONSISTENCY

Conflicting Data:

- ➜ Do replicas have exactly the same data?
- ➜ What differences are permitted?

Consistency Dimensions:

- ➜ Time and Order

Time:

- ➜ How old is the data (staleness)?
- ➜ How old is the data allowed to be?
  - Time, Versions

Operation order:

- ➜ Were operations performed in the right order?
- ➜ What orderings are allowed?

Real world examples of inconsistency?

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ORDERING

Updates and concurrency result in conflicting operations

Conflicting Operations:

- ➜ Read-write conflict (only 1 write)
- ➜ Write-write conflict (multiple concurrent writes)
- ➜ The order in which conflicting operations are performed affects consistency

Partial vs Total Ordering:

- ➜ partial order: order of a single client's operations
- ➜ total order: interleaving of all conflicting operations

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Example:

Client A: `x = 1; x = 0;`

Client B: `print(x); print(x);`

Possible results:
--, 11, 10, 00
How about 01?

What are the conflicting ops? What are the partial orders? What are the total orders?

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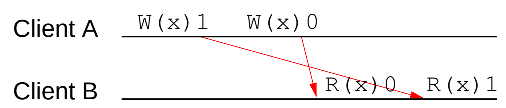
Example:

Client A: `x = 1; x = 0;`

Client B: `print(x); print(x);`

Possible results:
--, 11, 10, 00
How about 01?

What are the conflicting ops? What are the partial orders? What are the total orders?



Can you sanely use a system like this?

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Consistency Model

Defines which interleavings of operations are valid (admissible)

Consistency Model:

- ➜ Concerned with consistency of a data store.
- ➜ Specifies characteristics of *valid total orderings*

A data store that implements a particular model of consistency will provide a total ordering of operations that is valid according to the model.

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Data Coherence vs Data Consistency:

Data Coherence ordering of operations for single data item

- ➜ e.g. a read of x will return the most recently written value of x

Data Consistency ordering of operations for whole data store

- ➜ implies data coherence
- ➜ includes ordering of operations on other data items too

Non-distributed data store:

- ➜ Data coherence is respected
- ➜ Program order is maintained

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Data-Centric Consistency Model

A contract, between a distributed data store and clients, in which the data store specifies precisely what the results of read and write operations are in the presence of concurrency.

- ➜ Multiple clients accessing the same data store
- ➜ Described consistency is experienced by all clients
  - Client A, Client B, Client C see same kinds of orderings
- ➜ Non-mobile clients (replica used doesn't change)

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Strong Ordering vs Weak Ordering

Strong Ordering (tight):

- ➜ All writes must be performed in the order that they are invoked
- ➜ Example: all replicas must see: `W(x)a W(x)b W(x)c`
- ➜ Strict (Linearisable), Sequential, Causal, FIFO (PRAM)

Weak Ordering (loose):

- ➜ Ordering of *groups* of writes, rather than individual writes
- ➜ Series of writes are grouped on a single replica
- ➜ Only results of grouped writes propagated.
- ➜ Example: `{W(x)a W(x)b W(x)c}` == `{W(x)a W(x)c}` == `{W(x)c}`
- ➜ Weak, Release, Entry

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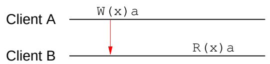
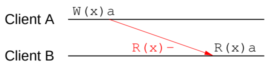
Strict Consistency

Any read on a data item x returns a value corresponding to the result of the most recent write on x

Absolute time ordering of all shared accesses



strictly consistent



not strictly consistent

What is *most recent* in a distributed system?

- ➜ Assumes an absolute global time
- ➜ Assumes instant communication (atomic operation)
- ➜ Normal on a uniprocessor
- ✗ Impossible in a distributed system

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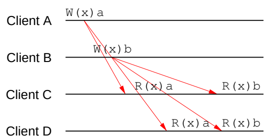
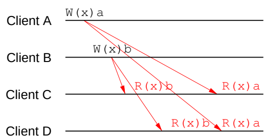
Linearisable Consistency

All operations are performed in a single sequential order

- ➜ Operations ordered according to a global (finite) timestamp.
- ➜ Program order of each client maintained



linearisable



not linearisable

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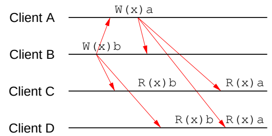
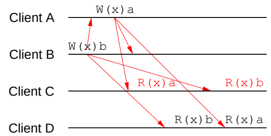
Sequential Consistency

All operations are performed in some sequential order

- ➜ More than one correct sequential order possible
- ➜ All clients see the *same* order
- ➜ Program order of each client maintained
- ➜ Not ordered according to time Why is this good?



sequential



not sequential

Performance:

read time + write time >= minimal packet transfer time

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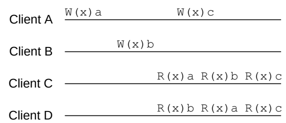
Causal Consistency

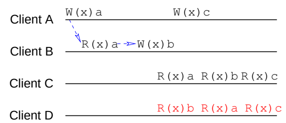
Potentially causally related writes are executed in the same order everywhere

Causally Related Operations:

- ➜ Read followed by a write (in same client)
- ➜ `W(x)` followed by `R(x)` (in same or different clients)



causally consistent



not causally consistent

How could we make this valid?

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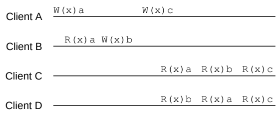
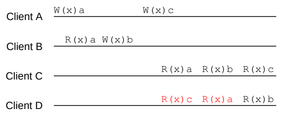
FIFO (PRAM) Consistency

Only partial orderings of writes maintained



FIFO consistent



not FIFO consistent

How could we make this valid?

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Weak Consistency

Shared data can be counted on to be consistent only after a synchronisation is done

Enforces consistency on a *group of operations*, rather than single operations

- ➜ Synchronisation variable (`S`)
- ➜ Synchronise operation (`synchronise(S)`)
- ➜ Define 'critical section' with synchronise operations

Properties:

- ➜ Order of synchronise operations sequentially consistent
- ➜ Synchronise operation cannot be performed until all previous writes have completed everywhere
- ➜ Read or Write operations cannot be performed until all previous synchronise operations have completed

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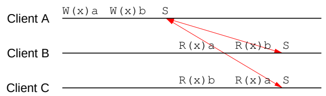
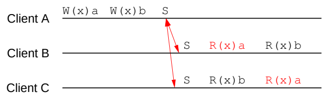
Example:

- ➜ `synchronise(S) W(x)a W(y)b W(x)c synchronise(S)`
- ➜ Writes performed locally
- ➜ Updates propagated only upon synchronisation
- ➜ Only `W(y)b` and `W(x)c` have to be propagated



weak consistent



not weak consistent

How could we make this valid?

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Release Consistency

Explicit separation of synchronisation tasks

- ➜ `acquire(S)` - bring local state up to date
- ➜ `release(S)` - propagate all local updates
- ➜ acquire-release pair defines 'critical region'

Properties:

- ➜ Order of synchronisation operations are FIFO consistent
- ➜ Release cannot be performed until all previous reads and writes done by the client have completed
- ➜ Read or Write operations cannot be performed until all previous acquires done by the client have completed

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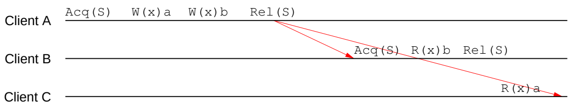

release consistent

What is an example of an invalid ordering?

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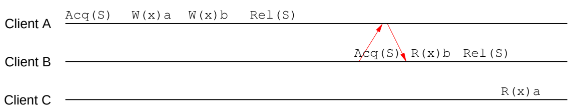
Lazy Release Consistency:

- ➜ Don't send updates on release
- ➜ Acquire causes client to get newest state
- ➜ Added efficiency if acquire-release performed by same client (e.g., in a loop)



lazy release consistent

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ENTRY CONSISTENCY

Synchronisation variable associated with specific shared data item (guarded data item)

- ➜ Each shared data item has own synchronisation variable
- ➜ `acquire()`
  - Provides ownership of synchronisation variable
  - Exclusive and nonexclusive access modes
  - Synchronises data
  - Requires communication with current owner
- ➜ `release()`
  - Relinquishes exclusive access (but not ownership)

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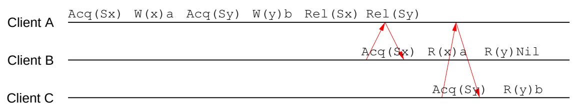
Properties:

- ➜ Acquire does not complete until all guarded data is brought up to date locally
- ➜ If a client has exclusive access to a synchronisation variable, no other client can have any kind of access to it
- ➜ When acquiring nonexclusive access, a client must first get the updated values from the synchronisation variable's current owner



entry consistent

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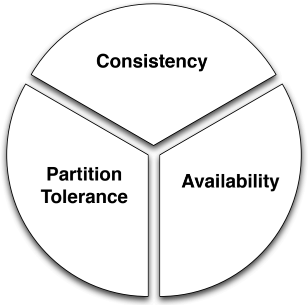
CAP Theory

C: Consistency: Linearisability
A: Availability: Timely response
P: Partition-Tolerance: Functions in the face of a partition



You can only choose two of C A or P

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CAP Theory

C: Consistency: Linearisability
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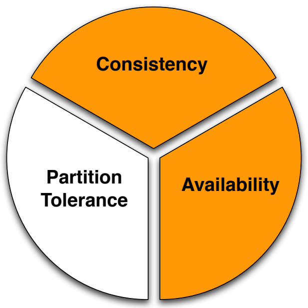

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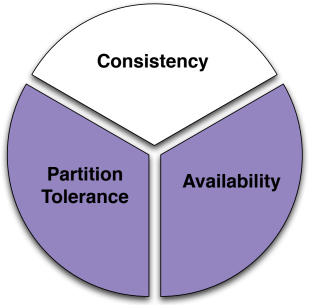

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Slide 36

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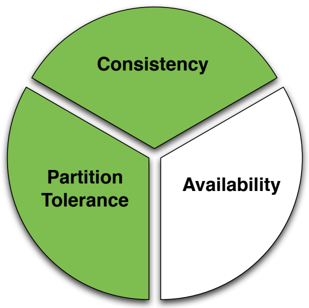

You can only choose two of C A or P

CAP Impossibility Proof:

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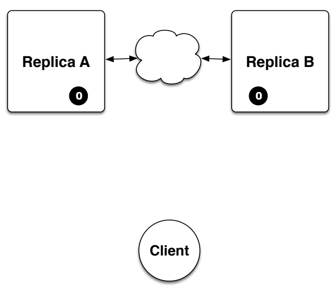

CAP Impossibility Proof:

Goal: Consistency and Availability
No Partition: It works!

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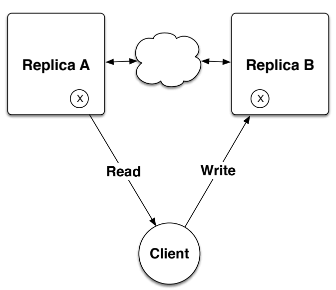

CAP Impossibility Proof:

Partition: no messages between A and B

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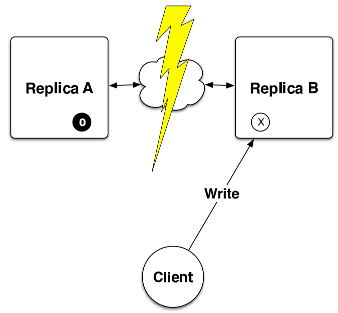

CAP Impossibility Proof:

Assume: Availability and Partition Tolerance

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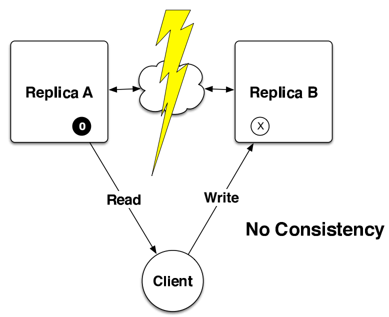

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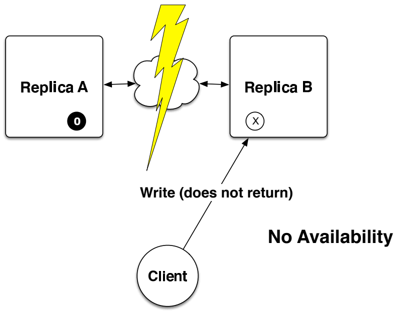
CAP Impossibility Proof:

Assume: Consistency and Partition Tolerance



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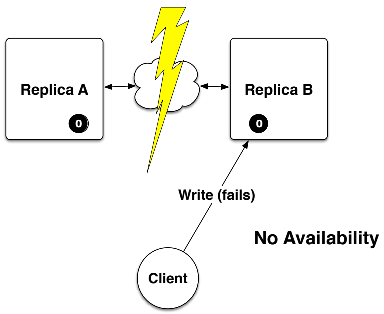
CAP Impossibility Proof:

Assume: Consistency and Partition Tolerance



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CAP Consequences

For wide-area systems:

- ➜ Must choose: Consistency or Availability
- ➜ Choosing Availability
  - Give up on consistency?
  - Eventual consistency
- ➜ Choosing Consistency
  - No availability
  - delayed (and potentially failing) operations

Why can't we choose C and A and forget about P?

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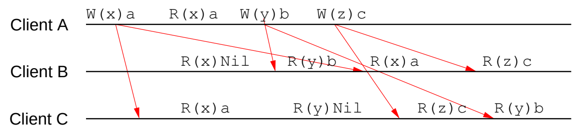
Eventual Consistency

If no updates take place for a long time, all replicas will gradually become consistent



eventual consistent

Requirements:

- ➜ Few read-write conflicts (R » W)
- ➜ Few write-write conflicts
- ➜ Clients accept time inconsistency (i.e., old data)
- ➜ What about ordering?

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Examples:

➜ DNS:
- no write-write conflicts
- updates slowly (1-2 days) propagate to all caches

➜ WWW:
- few write-write conflicts
- mirrors eventually updated
- cached copies (browser or proxy) eventually replaced
- manual merging for write-write conflicts

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CLIENT-CENTRIC CONSISTENCY MODELS

Provides guarantees about ordering of operations for a single client

➜ Single client accessing data store

➜ Client accesses different replicas (modified data store model)

➜ Data isn't shared by clients

➜ Client A, Client B, Client C may see different kinds of orderings

In other words:

➜ The effect of an operation depends on the client performing it

➜ Effect also depends on the history of operations that client has performed.

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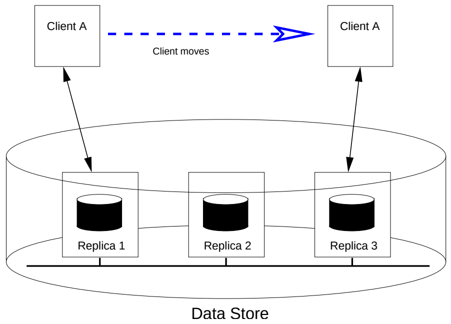
Data-Store Model for Client-Centric Consistency:



- Data-items have an owner
- No write-write conflicts

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Notation and Timeline for Client-Centric Consistency:

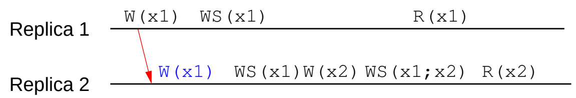
➜ `xi[t]`: version of x at replica i at time t

➜ Write Set: `WS(xi[t])`: set of writes at replica i that led to xi(t)

➜ `WS(xi[t1];xj[t2])`: WS(xj(t2)) contains same operations as WS(xi(t1))

➜ `WS(!xi[t1];xj[t2])`: WS(xj(t2)) does not contain the same operations as WS(xi(t1))

➜ `R(xi[t])`: a read of x returns xi(t)



Monotonic Reads

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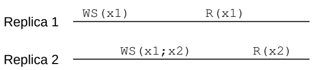
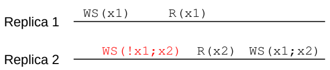
If a client has seen a value of x at a time t, it will never see an older version of x at a later time



monotonic−read consistent



not monotonic−read consistent

When is Monotonic Reads sufficient?

Monotonic Writes

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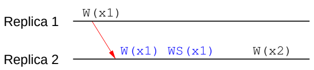
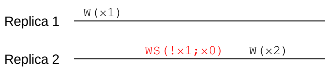
A write operation on data item x is completed before any successive write on x by the same client

All writes by a single client are sequentially ordered.



monotonic−write consistent



not monotonic−write consistent

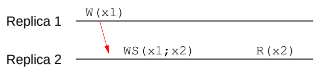
How is this different from FIFO consistency?

- ➜ Only applies to write operations of single client.
- ➜ Writes from clients not requiring monotonic writes may appear in different orders.

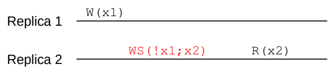
Read Your Writes

Slide 51

The effect of a write on x will always be seen by a successive read of x by the same client



read−your−writes consistent



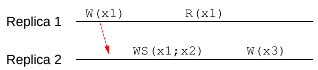
not read−your−writes consistent

When is Read Your Writes sufficient?

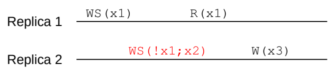
Write Follows Reads

Slide 52

A write operation on x will be performed on a copy of x that is up to date with the value most recently read by the same client



writes−follow−reads consistent



not writes−follow−reads consistent

When is Write Follows Reads sufficient?

Choosing the Right Model

Trade-offs

Consistency and Redundancy:
- ➜ All copies must be strongly consistent
- ➜ All copies must contain full state
- ➜ Reduced consistency → reduced reliability

Slide 53

Consistency and Performance:
- ➜ Consistency requires extra work and communication
- ✗ Can result in loss of overall performance
- ☑ Weaker consistency possible

Consistency and Scalability:
- ➜ Implementation of consistency must be scalable
  - don't take a centralised approach
  - avoid too much extra communication

Consistency Protocols

Slide 54

Consistency Protocol: implementation of a consistency model (e.g. sequential consistency)

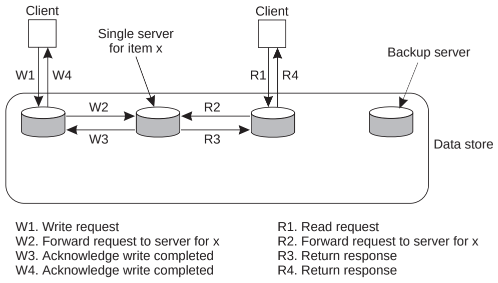
Primary-Based Protocols:
- ➜ Remote-write protocols
- ➜ Local-write protocols

Replicated-Write Protocols:
- ➜ Active Replication
- ➜ Quorum-Based Protocols

Remote-Write Protocols

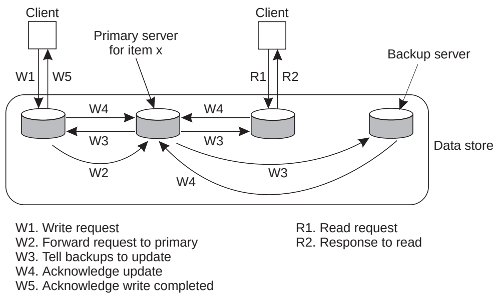
Slide 55

Single Server (single reader/single writer):
- ➜ All writes and reads executed at single server
- ✗ No replication of data



Slide 56

Primary-Backup (multiple reader/single writer):
- ➜ All writes executed at single server, Reads are local
- ➜ Updates block until executed on all backups
- ✗ Performance



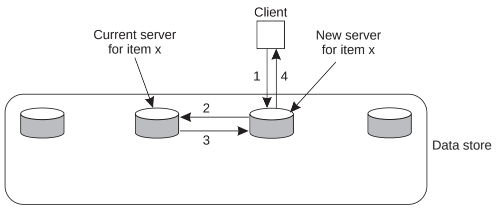
LOCAL-WRITE PROTOCOLS

Migration (single reader/single writer):

➜ Data item migrated to local server on access

☑ Performance (when not sharing data)

Slide 57



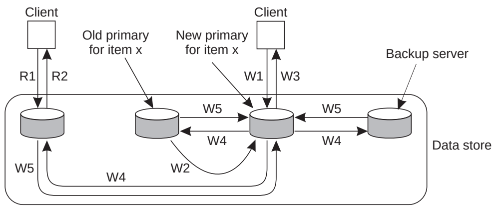
1. Read or write request
2. Forward request to current server for x
3. Move item x to client's server
4. Return result of operation on client's server

Migrating Primary (multiple reader/single writer):

☑ Performance for concurrent reads

✗ Performance for concurrent writes

Slide 58



W1. Write request
W2. Move item x to new primary
W3. Acknowledge write completed
W4. Tell backups to update
W5. Acknowledge update

R1. Read request
R2. Response to read

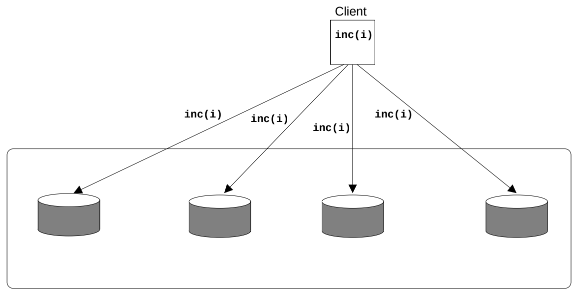
ACTIVE REPLICATION

➜ Updates (write operation) sent to all replicas

➜ Need totally-ordered multicast (for sequential consistency)

➜ e.g. sequencer/coordinator to add sequence numbers

Slide 59



QUORUM-BASED PROTOCOLS

➜ Voting

➜ Versioned data

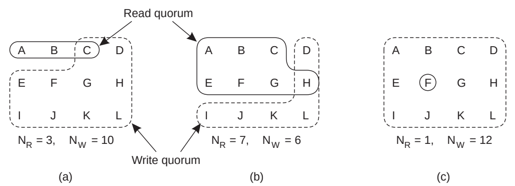
➜ Read Quorum: Nr

➜ Write Quorum: Nw

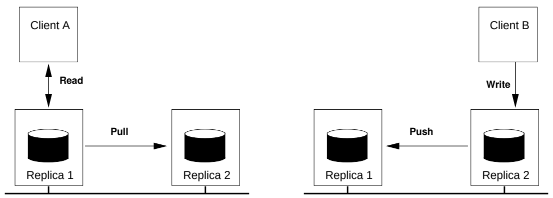
➜ Nr + Nw > N Why?

➜ Nw > N/2 Why?

Slide 60



Push vs Pull



Slide 61

Pull:

- ➜ Updates propagated only on request
- ➜ Also called *client-based*
- ➜ R/W low (W » R)
- ✗ Polling delay

Push:

- ➜ Push updates to replicas
- ➜ Also called *server-based*
- ➜ When low staleness required
- ➜ R/W high (R » W)
- ✗ Have to keep track of all replicas

Slide 62

Push Update Propagation:

What to propagate?

- ➜ Data
  - R/W high
- ➜ Update operation
  - low bandwidth costs
- ➜ Notification/Invalidation
  - R/W low

Slide 63

Compromise: Leases:

Server promises to push updates until lease expires

Lease length depends on:

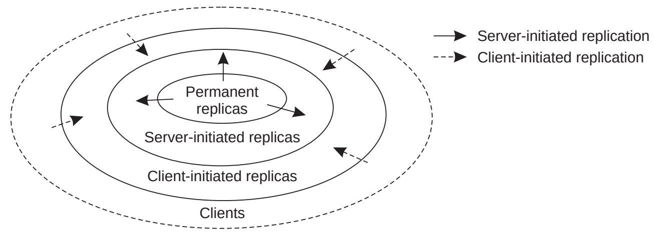
age: Last time item was modified

renewal-frequency: How often replica needs to be updated

state-space overhead: lower expiration time to reduce bookkeeping when many clients

Replica Placement

Slide 64



Slide 65

Permanent Replicas:

- ➜ Initial set of replicas
- ➜ Created and maintained by data-store owner(s)
- ➜ Allow writes

Server-Initiated Replicas:

- ➜ Enhance performance
- ➜ Not maintained by owner
- ➜ May or may not allow writes
- ➜ Placed close to groups of clients
  - Manually vs Dynamically

Client-Initiated Replicas:

- ➜ Client caches
- ➜ Temporary
- ➜ Owner not aware of replica
- ➜ Placed close to client
- ➜ Maintained by host (often client)

Slide 66

Dynamic Replication

Situation changes over time

- ➜ Number of users, Amount of data
- ➜ Flash crowds
- ➜ R/W ratio

Dynamic Replica Placement:

- ➜ Network of replica servers
- ➜ Keep track of data item requests at each replica
- ➜ Thresholds:
  - Deletion threshold
  - Replication threshold
  - Migration threshold
- ➜ Clients always send requests to nearest server

Slide 67

Miscellaneous Implementation and Design Issues

End-to-End argument:

- ➜ Where to implement replication mechanisms?
- ➜ Application? Middleware? OS?

Policy vs Mechanism:

- ➜ Consistency models built into middleware?
- ➜ One-size-fits-all?

Determining Policy:

- ➜ Who determines the consistency model used?
  - Application, Middleware
  - Client, Server

Keep It Simple, Stupid:

- ➜ Will the programmer understand the consistency model?

Slide 68

Reading List

Brewer's Conjecture and the Feasibility of Consistent, Available, Partition-Tolerant Web Services An overview of the CAP theorem and its proof.

Eventual Consistency An overview of eventual consistency and client-centric consistency models.

Slide 69

Homework

Consistency Models:

- ➜ Research consistency models used in existing Distributed Systems
- ➜ Why are those models being used?
- ➜ In the systems you looked at, could other models have been used? Would that have made the system better?

Hacker's Edition:

- ➜ Find a system that provides Eventual Consistency
  - ➜ (alternatively, implement (possibly in Erlang) a system that provides Eventual Consistency)
- ➜ Replicate some data and perform queries. How often do you get inconsistent results?
- ➜ If you can tweak replication parameters, how do they affect the consistency of results?