Slide 1

DISTRIBUTED SYSTEMS (COMP9243)

Lecture 3a: Replication & Consistency

① Replication
② Consistency
- Models
- Protocols

③ Update propagation
④ Replica placement

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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)

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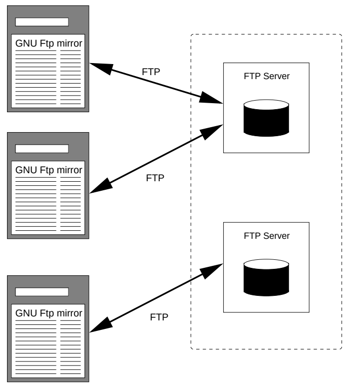
DATA VS CONTROL REPLICATION

Data Replication (Server Replication/Mirroring):



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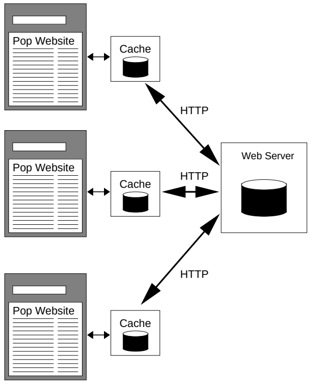
Data Replication (Caching):



What's the difference between mirroring and caching?

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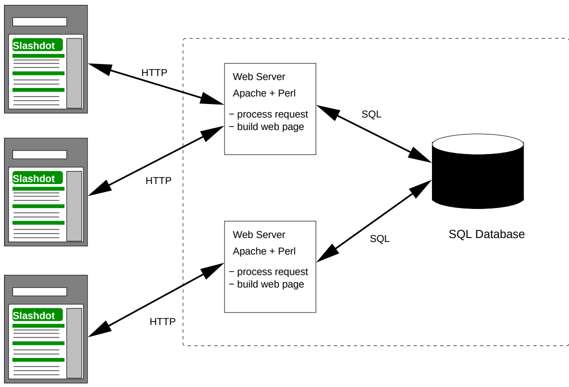
Control Replication:



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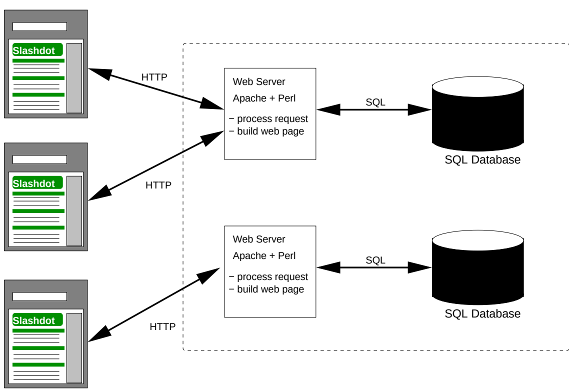
Data and Control Replication:



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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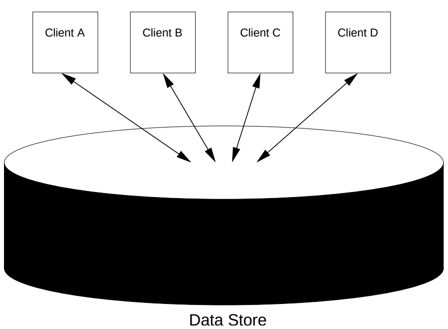
DISTRIBUTED DATA STORE

- ➜ data-store stores data items

Client's Point of View:



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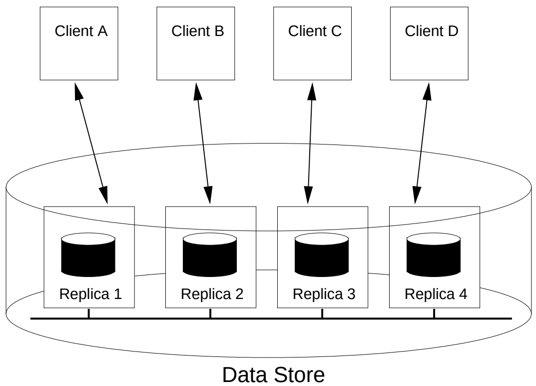
Distributed Data-Store's Point of View:



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Data Model:

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

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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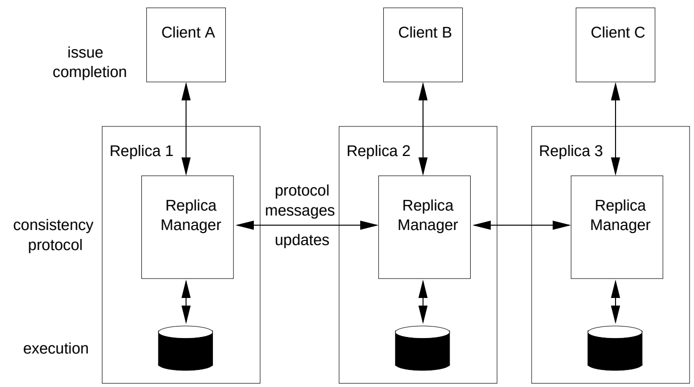
Replica Managers:



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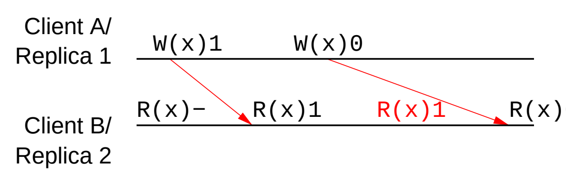
Timeline:



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Inconsistency

Staleness:

- ➜ How old is the data?
- ➜ How old is the data allowed to be?
  - Time
  - Versions

Operation order:

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

Conflicting Data:

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

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Consistency

Non-distributed data store:

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

Updates and concurrency result in conflicting operations

Conflicting Operations:

- ➜ Read-write conflict (only 1 write)
- ➜ Write-write conflict (multiple concurrent writes)

Consistency:

- ➜ The order in which conflicting operations are performed affects consistency
- ➜ partial order: order of a single client's operations
- ➜ total order: interleaving of all conflicting operations

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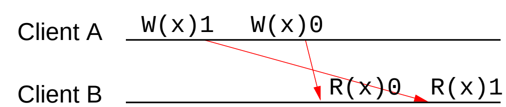
Example:

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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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

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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.

- ➜ Described consistency is experienced by all clients
- ➜ Multiple clients accessing the same data store
- ➜ 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 clients 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)b W(x)a W(x)c}`
- ➜ Weak, Release, Entry

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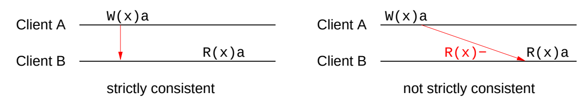
STRICT CONSISTENCY

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



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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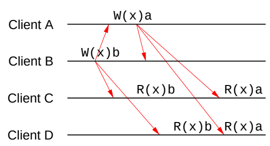
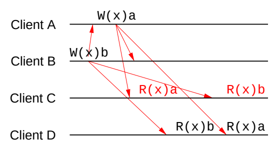
Sequential Consistency

All operations are performed in some sequential order

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



sequential



not sequential

Performance:

read time + write time >= minimal packet transfer time

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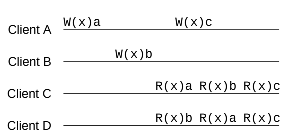
Causal Consistency

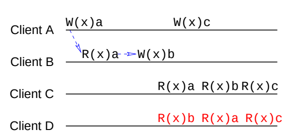
Potentially causally related writes are executed in the same order everywhere

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

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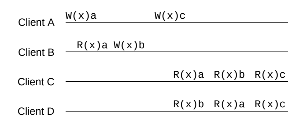
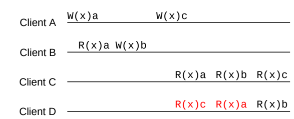
FIFO (PRAM) Consistency

Only partial orderings of writes maintained



FIFO consistent



not FIFO consistent

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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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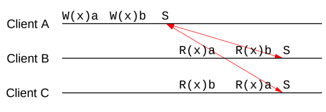
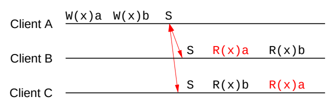
Example:

- ➜ `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

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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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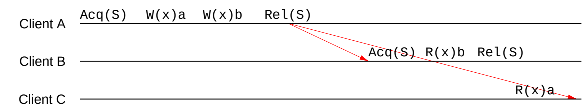

release consistent

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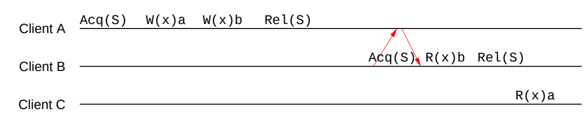
Lazy Release Consistency:

- ➜ 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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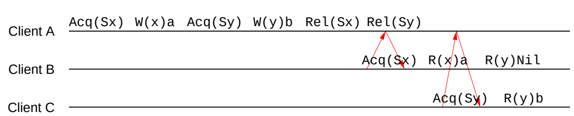
Properties:

➜ 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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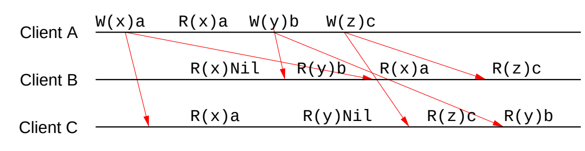
EVENTUAL CONSISTENCY

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 inconsistency (i.e., old data)

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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

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CAP Theory

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

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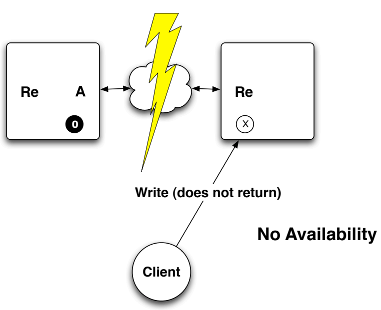
CAP Impossibility Proof:



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CAP Consequences

For wide-area systems:

➜ must choose: Consistency or Availability

➜ choosing Availability
- Eventual consistency

➜ choosing Consistency
- delayed (and potentially failing) operations

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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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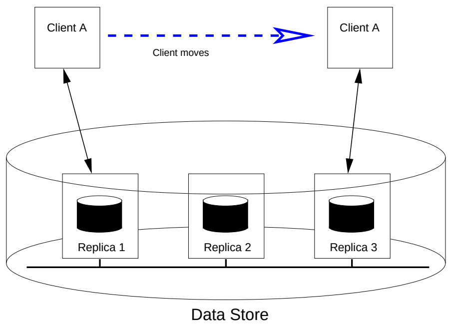
Data-Store Model for Client-Centric Consistency:



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

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Notation and Timeline for Client-Centric Consistency:

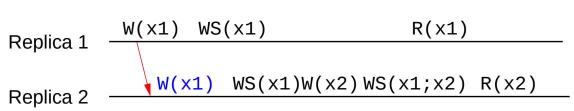
➜ `xi[t]`: version of x at replica i at time t

➜ 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)



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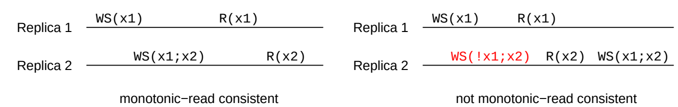
MONOTONIC READS

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



When is Monotonic Reads sufficient?

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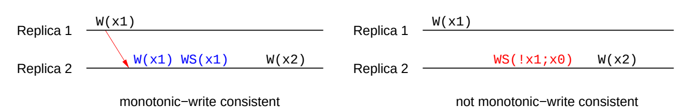
MONOTONIC WRITES

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.



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.

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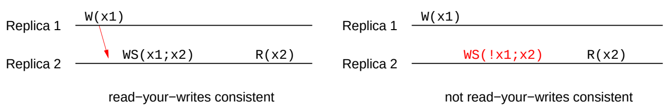
Read Your Writes

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



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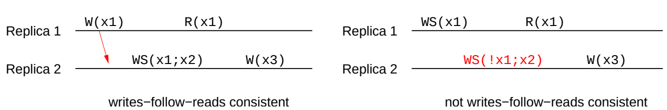
Write Follows Reads

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



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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

Consistency and Performance:

- ➜ Consistency requires extra work
- ➜ Consistency requires extra communication
- ✗ Can result in loss of overall performance

Consistency and Scalability:

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

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Consistency Protocols

Consistency Protocol: implementation of a consistency model

Primary-Based Protocols:

- ➜ Remote-write protocols
- ➜ Local-write protocols

Replicated-Write Protocols:

- ➜ Active Replication
- ➜ Quorum-Based Protocols

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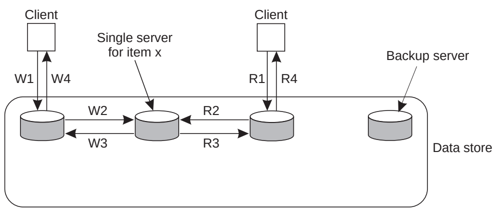
REMOTE-WRITE PROTOCOLS

Single Server:

- ➜ All writes and reads executed at single server
- ➜ No replication of data



W1. Write request
W2. Forward request to server for x
W3. Acknowledge write completed
W4. Acknowledge write completed

R1. Read request
R2. Forward request to server for x
R3. Return response
R4. Return response

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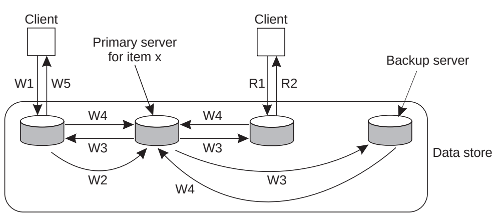
Primary-Backup:

- ➜ All writes executed at single server, Reads are local
- ➜ Updates block until executed on all backups
- ✗ Performance



W1. Write request
W2. Forward request to primary
W3. Tell backups to update
W4. Acknowledge update
W5. Acknowledge write completed

R1. Read request
R2. Response to read

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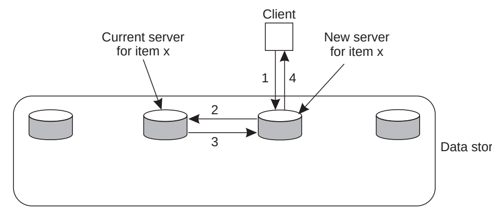
LOCAL-WRITE PROTOCOLS

Migration:

- ➜ Data item migrated to local server on access
- ➜ Distributed, non-replicated, data store



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

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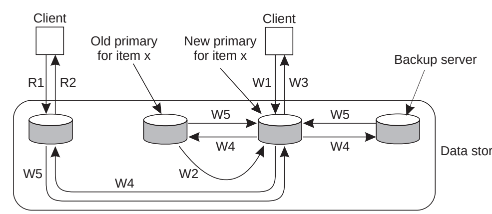
Migrating Primary (multiple reader/single writer):



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

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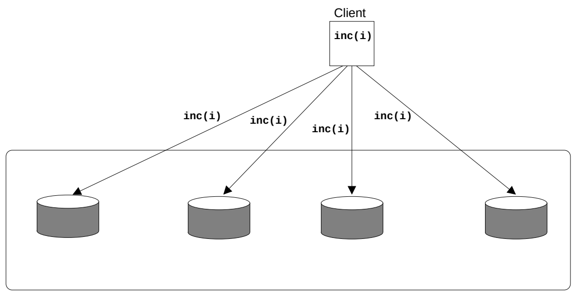
Active Replication

- ➜ Updates (write operation) sent to all replicas
- ➜ Need totally-ordered multicast
- ➜ e.g. sequencer/coordinator to add sequence numbers



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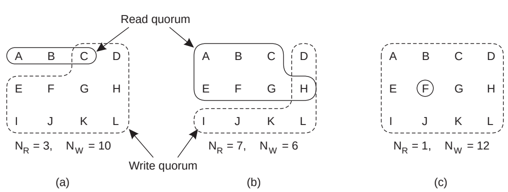
Quorum-Based Protocols

- ➜ Voting
- ➜ Versioned data
- ➜ Read Quorum: Nr
- ➜ Write Quorum: Nw
- ➜ Nr + Nw > N Why?
- ➜ Nw > N/2 Why?



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Update Propagation

What to propagate?

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

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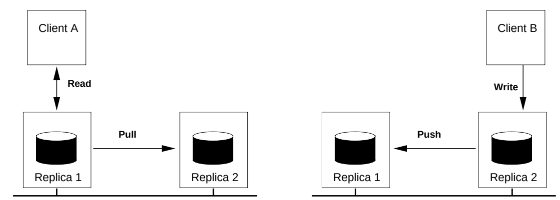
Push vs Pull



Pull:

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

Push:

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

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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

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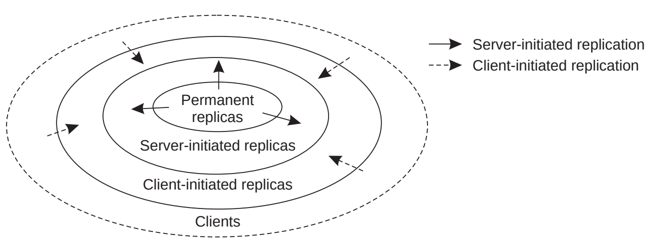
Replica Placement



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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
- ➜ Placed close to groups of clients
  - Manually
  - Dynamically

Client-Initiated Replicas:

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

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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
- ➜ Deletion threshold
- ➜ Replication threshold
- ➜ Migration threshold
- ➜ Clients always send requests to nearest server

Miscellaneous Implementation and Design Issues

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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

Reading List

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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.