Programming of Distributed Systems

Topic V – Replication & Consistency

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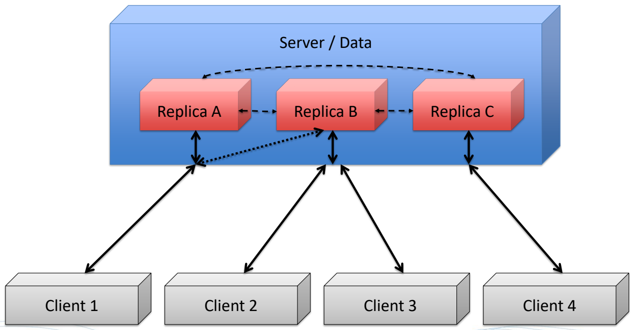
Reading Remarks

Reading Task:
Chapter 7

Replication Transparency



Reasons to Replicate

Dependability

- availability
  - there is always a server somewhere
- reliability
  - fault tolerance regarding data corruption and faulty operations

Performance

- response time
- throughput
- scalability

Problems with Replication

Changes to one replica have to be propagated to the other replicas in order to be consistent

→ What is meant by 'consistent'?

→ When to propagate modifications?

→ How to propagate modifications?

CAP theorem

Consistency

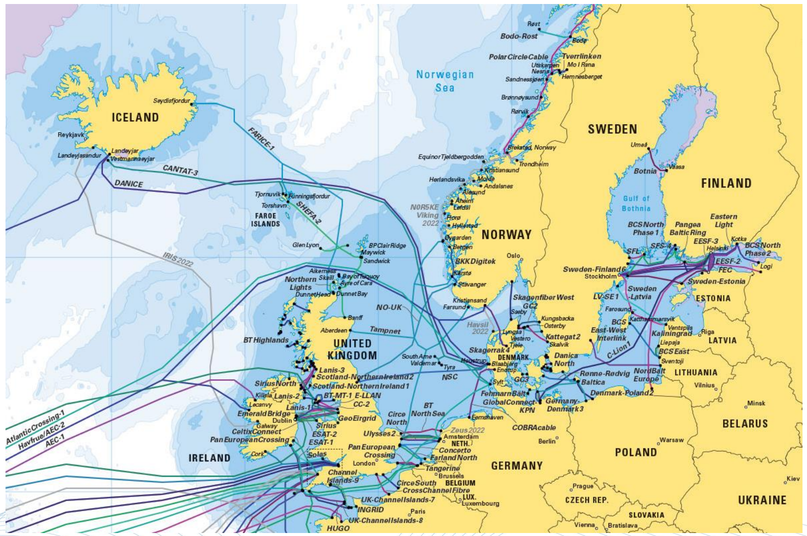
- Data items behave as if there is only one copy
- Cave-at: Similar to ACID's *atomicity*, not ACID's *consistency*!

Availibility

- Node failures do not prevent the system from continuing to operate

Partition-tolerance

- The system continues to operate in the presence of network partitions



Source: www.submarinecablemap.com

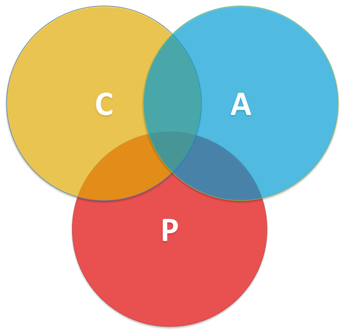
CAP theorem (2)

Simple (mis-)interpretation

- no system can have all 3 properties (in a very strict sense)

Somewhat better

In the presence of network partitions, one has to give up on either consistency (AP system) or availability (CP system)



AP – Best Effort Consistency

AP systems relax consistency in favor of availability, but are not totally inconsistent

Examples

- Caches
- Content Distribution Networks (CDN)
- Domain Name System (DNS)
- Conflict-free replicated data type (CRDT)

CP – Best Effort Availibility

CP systems sacrifice availability for consistency, but are not unavailable

Examples

- Majority protocols (Paxos, Raft, see end of lecture)
- Distributed locking (Chubby lock service)

Consistency

Intuitive definition

> A set of replicas is **consistent** when all the replicas are always the same.

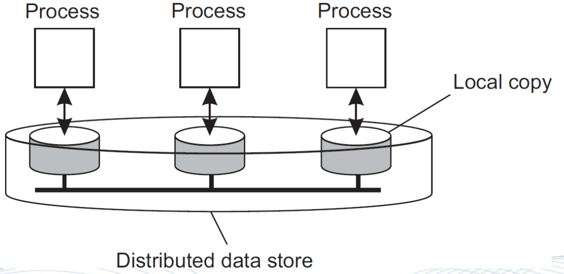
➔ all conflicting operations are done in the same order everywhere (*global synchronization*)

Danger of **disimprovements**! Performance improvements by introducing additional costs for replica management?

➔ Loose up the requirements to avoid global sychronous updates

A data-centric view

A **data store** is a physically distributed collection of storages that are replicated over multiple processes



Any operation that changes the data is considered a `write` operation.

Any other operation is a `read` operation.

Data-centric consistency models

Two types of conflicts

- `read-write`: concurrent read and write operations
- `write-write`: two concurrent write operations

→ Consistency means conflicting operations are done in the same order everywhere

Consistency models

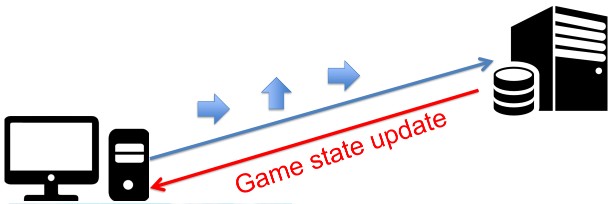
What is the guaranteed result of concurrent operations?

Degrees of consistency

Three different aspects of *loose* consistency

- replicas may differ in their (numerical) **values**
- replicas may differ in their **staleness**
- replicas may differ in their **order** of performed updates

Example: Consistency in an Online Game



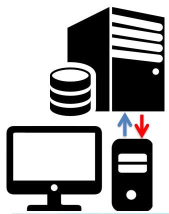
Game Server:

- state of the game (position of players on the map, inventory, etc)
- conflict resolution

Client:

- user interface
- Keyboard/mouse inputs
- partial game state

Example: Consistency in an Online Game



Local Game Server:

- state of the game

Two replicas of the game state that need to be consistent

Remote Game Server:

- state of the game (position of players on the map, inventory, etc)
- conflict resolution

Client:

- user interface
- Keyboard/mouse inputs
- partial game state

Example: Online 3D Shooter

Multiple Game States:

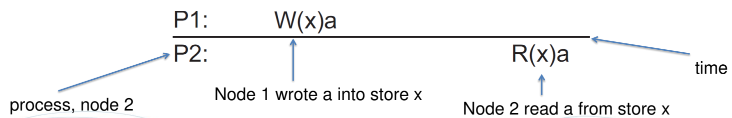
- Each one potentially different

➔ Inconsistencies can appear puzzling to players

Strict consistency

> Any read on data item returns a value corresponding to the result of the **most recent write** on that data item.

Notation from the book:



The Like-button 

Shared data item – social currency:

- number of likes for a video/picture/post on social media
- vector of likes resolved per country

Number of replicas for this data item:

- everyone accessing the post has a replica of the like counter
- several more replicas exist across the server infrastructure

Applying strict consistency: As soon as someone clicks like, no one else can until **all** copies are updated.

Sequential consistency

> The **order** of operations applied on each replica is the **same**. Operations from the same node follow the order given by its program.

Comments

- any order of reads and writes of different machines is acceptable, as long as they are the same for each replica (linearization of the concurrent processes)
- no notion of time (*most recent*), but we need a *total order*

Sequential consistency

P1:	W(x)a
P2:	W(x)b
P3:	R(x)b R(x)a
P4:	R(x)b R(x)a

sequentially consistent

P1:	W(x)a
P2:	W(x)b
P3:	R(x)b R(x)a
P4:	R(x)a R(x)b

sequentially not consistent

- Clicking the like-button does not block other likes anymore
- Updating a replica has to follow the distributed total order of like-events, but is not necessarily immediate
- The like from Japan has to update everywhere (e.g. observers in Sweden and the USA) before the like from Brazil

Example

Three variables `x, y, z` initialized with 0

Node 1
```
x = 1;
print(y,z)
```

Node 2
```
y = 1;
print(x,z)
```

Node 3
```
z = 1;
print(x,y)
```

→ 90 different valid execution sequences

Sequence 27
```
z = 1;
x = 1;
y = 1;
print(x,y)
print(y,z)
print(x,z)
```
Output
```
111111
```

Sequence 13
```
z = 1;
x = 1;
print(y,z)
print(x,y)
y = 1;
print(x,z)
```
Output
```
011011
```

Consistency model for sequential consistency allows any of those 90 sequences as correct results!

Causal consistency

> The order of **potentially causally related** write operations applied on each replica is the same. **Concurrent** write operations can have different order in each replica.

Comments

- weaker requirements than sequential consistency
- concurrent = not (potentially causally related)
- causal dependencies modelled with a graph → not trivial

Causal consistency

P1:	W(x)a W(x)c
P2:	R(x)a W(x)b
P3:	R(x)a R(x)c R(x)b
P4:	R(x)a R(x)b R(x)c

Concurrent!

causally consistent
not sequential consistent
not strict consistent

P1:	W(x)a
P2:	R(x)a W(x)b
P3:	R(x)b R(x)a
P4:	R(x)a R(x)b

- Causally unconnected events can update in any order: concurrent likes from Japan and Brazil may appear in different order in the USA and Sweden
- Connected events need to maintain the correct order

FIFO (or PRAM) consistency

Write operations from a single node are applied to each replica in the correct order but writes from different nodes may be applied to each replica in a different order.

Comments

- weaker requirements than causal consistency
  → only local orders apply [yet all of them are relevant], but no synchronization between nodes is required
- rather easy to implement

FIFO Consistency

Valid sequence of FIFO consistency

P1:	W(x)a						
P2:		R(x)a	W(x)b	W(x)c			
P3:					R(x)b	R(x)a	R(x)c
P4:					R(x)a	R(x)b	R(x)c

- [The like number example does not really work here – so let's chat for a moment …]
- Multiple users in a chat group write multiple messages concurrently, each person's messages are in the correct local order, but they might be interleaved between persons differently for each observer

Eventual consistency

If after some **point no further write operations** are performed the system will **eventually** end up in a **consistent** state.

→ lazy updates

→ busy systems (writes happening all the time) might never converge to a consistent state

Practically very relevant:

many systems have considerable more read than write operations and/or limited nodes that are allowed to perform write operations

Eventual consistency

BASE semantics:

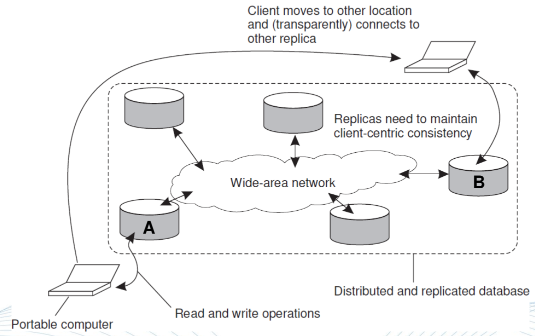
Basically Available, Soft-state, Eventually consistent

- AP system with no consistency guarantees
- Liveness guarantee, but no correctness guarantee
  → before convergence any value can be read

- Likes can be posted all the time, but different users will see different numbers; the number will only become consistent across all replicas once no more new likes are being posted

Client-centric consistency

- global view vs. local view on consistency



Only the states in A & B need to match, the state of the overall store is irrelevant for the user impression of consistency.

Replica & Content Placement

Goal

Find *k* 'good' servers to place items choosing from *n* options

Optimization criteria

- minimizing average latency between clients and replicas
- minimizing difference of bandwith utilization of replicas

Replica & Content Placement

Optimal solution

- NP hard → not feasible

'Good' approximate solutions using cluster analysis

- iterative/recursive procedures to form groups
- still to expensive / slow → > $O(n^2)$

Practical solutions based on heuristics

- allow real-time placement of replicas

Replica & Content Placement

Three different types of replicas

Permanent replicas

- node always having a replica

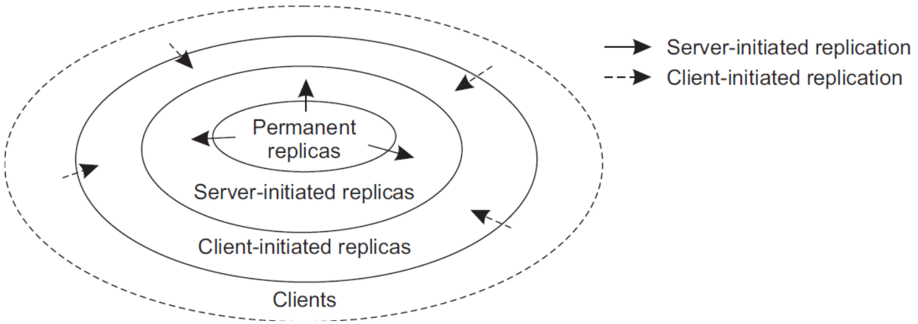
Server-initiated replica

- node that can dynamically host a replica on request of another server in the data store

Client-initiated replica

- node that can dynamically host a replica on request of a client

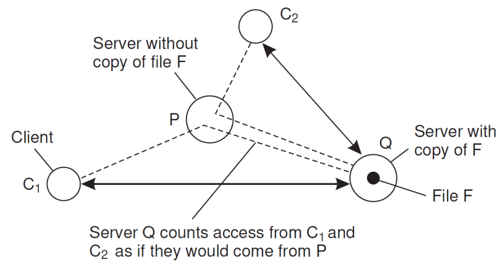
Replica & Content Placement



Server-initiated replica - example

Access counter at temporary replicas & thresholds

- Very low number of access operations → *drop data*
- Very high number of access operations → *replicate data*
- With known topology and requests coming from certain areas only → *migrate data*



Update propagation

Information

- update notifications
- updated data (passive replication)
- update operations (active replication)

Responsibility

- push → server propagates update unasked
- pull → client requests to be updated

Push vs. Pull protocols

Read-Write-ratio

- High → push
- Low → pull

Failures

- Push → use of stale (outdated) data
- Pull → known risk of using stale data
- Highly reliable systems → push + pull

Push vs. Pull protocols

Consistency model

- Strict(er) → push
- Loose(r) → pull

Cost vs. Quality-of-Service factors

- update rate & number of replicas ➔ maintainance workload
- bookkeeping for push servers
- response times
- traffic → updates vs. poll + maybe updates

Leases

Combining push and pull

- client pulls for a lease
- time interval in which the server pushes updates

Lease expiration

- fixed time
- age-based: the longer data is unchanged, the longer the lease
- renewal-frequency: the more often a clients needs data, the longer the lease
- server state based: longer leases, if server is idle

Propagation methods

Communication

- LAN: push & multicast, pull & unicast
- WAN: unicast

Algorithm & Information flow

- Overlay network (e.g. tree)
- Flooding (e.g. structured P2P architectures)
- Epidemic protocols

Epidemic protocols

Assumption

- no write-write conflicts → single server introduces changes
- eventual consistency model (lazy updates)
- replica passes updates only to a few neighbours

Two variants

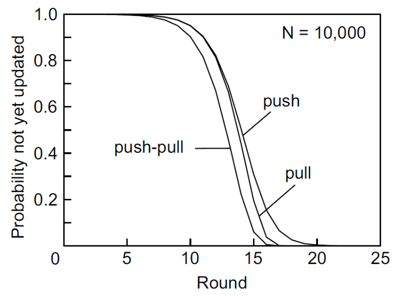
- anti-entropy
- rumor-spreading / gossiping

Epidemic protocols: Anti-entropy

Idea

Per round each replica randomly chooses another replica and either

- pulls updates from the contacted replica
- pushes updates to the contacted replica
- push+pull: both replicas update each other (consistency models!)



Epidemic protocols: Gossiping

Idea

In each round each updated (infected) replica contacts *k* replicas

- a replica stops participating (removed) with a probability of *s*/*k*, where *s* is the number of contacted replicas that are already updated, other replica are being updated (infected)
- large *k*: good coverage, large overhead
- small *k*: gossip dies out rather soon

➔ does not ensure eventual consistency

Consistency protocols

> A consistency protocols describes the implementation of a consistency model.

Approaches that are often relevant

- sequential consistency
- eventual consistency

Primary-based protocols

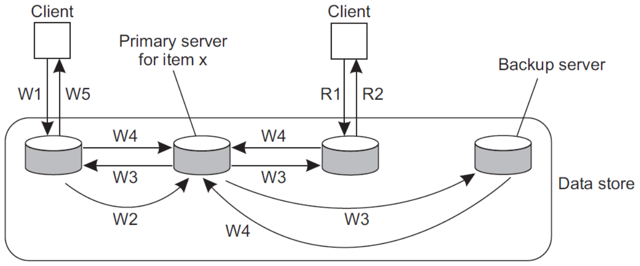
Purpose

Implementing sequential consistency

Idea

One replica acts as coordinator (primary) for all updates to a certain data item

Primary-based protocols



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

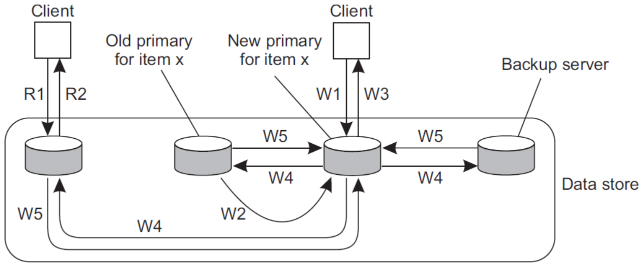
R1. Read request
R2. Response to read

Remote-write

- primary is fixed
- primary enforces global order
- mostly blocking, but non-blocking variants possible

→ Also read-your-writes consistent

Primary-based protocols



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

Local-write

- primary is migrating to the replica that initiated to last write
- non-blocking variant allows a sequence of local writes that are then propagated as a batch

Replicated-write protocols

Idea

Each read or write operation requires permission by a number (quorum) of replicas before execution, subject to the following constraints:

- $N_R + N_W > N$
- $N_W > N/2$

N: number of nodes / replicas

N_R: number of nodes necessary to contact for `read`

N_W: number of nodes necessary to contact for `write`

Replicated-write protocols

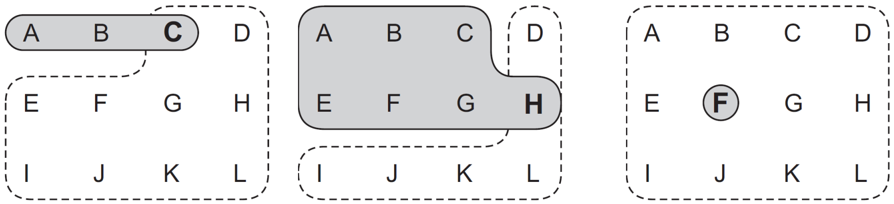
Read

- collect the read quorum
- read from any up-to-date replica (latest time stamp)

Write

- collect the write quorum
- update any out-of-date replicas in the quorum before write
- write on all replicas belonging to the quorum

Replicated-write protocols



$N_R = 3, \quad N_W = 10$ — valid choice

$N_R = 7, \quad N_W = 6$ — incorrect choice, write-write conflict possible

$N_R = 1, \quad N_W = 12$ — valid choice, read-one, write-all

Replicated-write protocols

Allows different levels of strictness

- Guaranteed-up-to-date: full quorum
- Limited guarantee: read does not require the full quorum
- Best effort: read/write without a quorum (requires another form of consistency checks)

Possibility to combine quorum-based methods with locks to implement a sequence/transaction mechanism

Summary

- Replication
- Consistency models and CAP theorem
- Distribution protocols
- Consistency protocols

RAFT (Replicated and Fault Tolerant)

Realistic consensus algorithm

- Exactly-once failure semantics
- RPCs
- Elections
- Quorums (Majority votes)

Go watch the online lecture about RAFT [soon]!
https://www.youtube.com/watch?v=YbZ3zDzDnrw