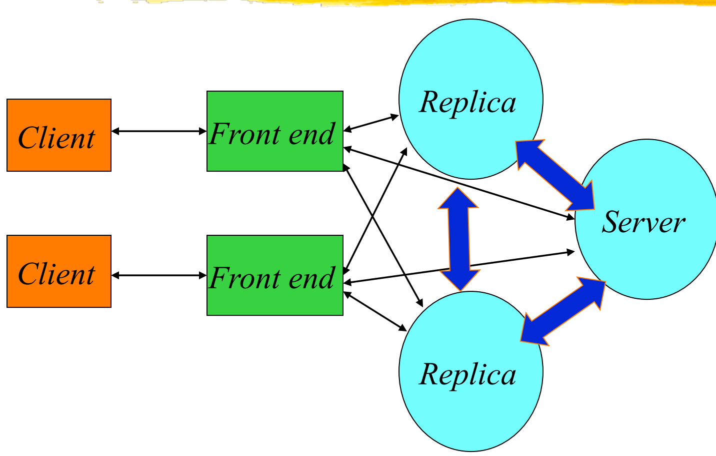
Replication in Distributed Systems

INF 5040 autumn 2015

lecturer: Roman Vitenberg

Replication architecture



Why replication I?

- Better performance
  - Multiple servers offer the same service – parallel processing of client requests
  - Geographical distribution
    - Creating copies of data/objects closer to the clients leads to smaller network delay and possibly reduced network traffic

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Why replication II?

- Better availability (continuous operation despite failures of individual components)
  - For many services it is important that availability with acceptable response time approaches 100%, despite that …
    - Server processes may fail
    - Parts of the network may fail
    - Data may get corrupted
- Example: 5% chance of a server failure within a given period - two independent servers give 99.75% availability

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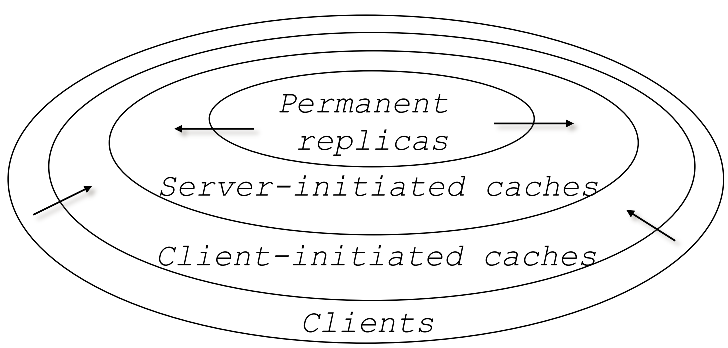
Challenges of replication

- Complex mechanisms
  - Placement of replicas (and search for them)
  - Propagation of data (e.g., updates) among the replicas
  - Consistency maintenance
  - Monitoring and failover mechanisms
- These protocols also consume bandwidth
- Some of this complexity is exposed to the clients
  - Impossible to achieve complete replication transparency

Placement of replicas



Placement of replicas

- Permanent replicas
  - Clusters of servers
  - Geographically dispersed web mirrors (Akamai)
- Server-initiated caches
  - Placement of hosting servers
  - Placement of caches
    - Flash crowds in the Web
- Client-initiated caches
  - Enterprise proxies or web browser caches

Propagation of updates among the replicas

- Push-based propagation
  - A replica pushes the update to the others
  - May push the new data or parameters of the update operation
- Pull-based propagation
  - A replica requests another replica to send the newest data it has

Issue	Push-based	Pull-based
State at the server	List of client caches	A server to pull data
Messages sent	Update	Poll and update
Freshness of replicas	Eager propagation	By demand

Propagation of updates among the replicas

- Pushing data vs pushing updates
  - Pushing updates reduces traffic
  - Requires more processing power on each replica
  - Requires deterministic operations
- Hybrid push-pull approaches
  - Lease-based propagation
  - Pushing invalidations
    - A replica that performs the update notifies other replicas
    - A replica informed that a newer version is available will fetch the new version at a later point

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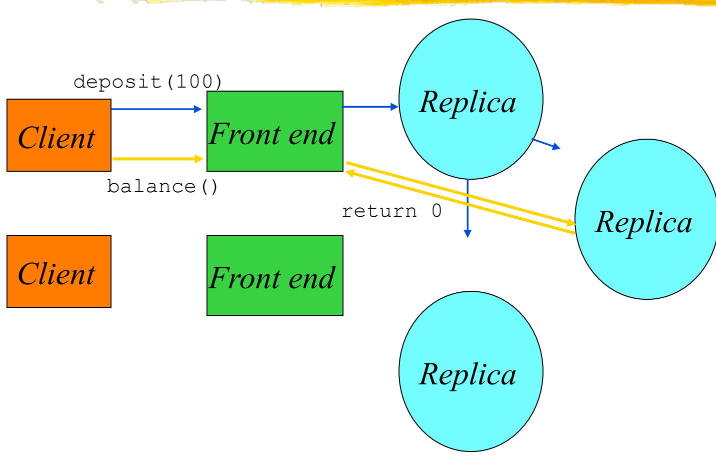
Lack of consistency



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Lack of consistency

Client 1

$deposit_B(x, 100)$

$deposit_A(y, 100)$

Client 2

$balance_A(y) \longrightarrow 100$

$balance_A(x) \longrightarrow 0$

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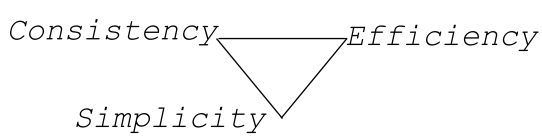
Consistency

- A contract between the client developer and a provider of the replicated service
  - The provider guarantees that the data will be updated according to some consistency criteria
  - The application developer will need to devise applications with these criteria in mind
- "Ideal consistency": system behavior is indistinguishable from a non-replicated system
- The consistency-efficiency-simplicity triangle



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Sequential consistency

- A system consists of a number of servers and a number of objects replicated on those servers
- Objects have well-defined interfaces
- An execution consists of events
  - Each event is an invocation of an operation on one of the replicas at one of the servers (with input and output values)
  - For each object, it is defined whether a sequence of ops makes sense (i.e., fulfills the specification of a single object copy)
- Sequential consistency: for each possible global history produced by system execution there should exist a linearization that fulfills the specification of each object

Example revisited

Client 1	***Client 2***
$deposit_B(x, 100)$	
$deposit_A(y, 100)$	
	$balance_A(y) \longrightarrow 100$
	$balance_A(x) \longrightarrow 0$

This is not sequentially consistent, because there is no corresponding sequential execution of a non-replicated system

More examples

C1	C2
Deposit(a, 50)	Balance(a) = empty
	Balance(a) = 50

C1
Deposit(a, 50) Balance(a) = empty

C1	C2
Deposit(a,50)	Balance(a) = 50
	Balance(a) = empty

C1	C2	C3	C4
Bal(b)=30	Bal(a)=50	Dep(a,50)	Dep(b,30)
Bal(a)=em	Bal(b)=em		

Active replication (replicated state machine)

- The idea:
  - Every replica sees exactly the same set of messages in the same order and will process them in that order
- Benefits:
  - Every server is able to respond to client queries with updated data
  - Immediate fail-over
- Limitations:
  - Waste of resources, since all replicas are doing the same
  - Update propagation only, which requires determinism
- Different implementation levels
  - Machine instruction level (or VM), e.g., Tandem™
  - Logical state (software-based active replication)

Passive replication (primary-backup replication)

- One server plays a special primary role
  - Performs all the updates
  - May propagate them to backup replicas eagerly or lazily
  - Maintains the most updated state
- Backup servers may take off the load of processing client requests but only if stale results are ok
- Implementable without deterministic operations
- Typically easier to implement than active replication
- Less network traffic during the normal operation but longer recovery with possible data loss
- Several sub-schemes (cold backup, warm backup, hot standby)

Primary-backup replication (cold backup)

- Only the primary is active
- Periodically checkpoints its state to backup storage
  - Stable storage or shared storage (SAN)
- When the primary fails, the backup is initiated, it loads the state from storage, and takes over
  - Slow recovery
    - Need to start the backup (run applications, obtain resources, etc.)
    - Either the backup replays the last actions from a log file, or it may miss the last updates since the most recent checkpoint
  - Most resource-efficient
- It is possible to have several backups to survive multiple failures

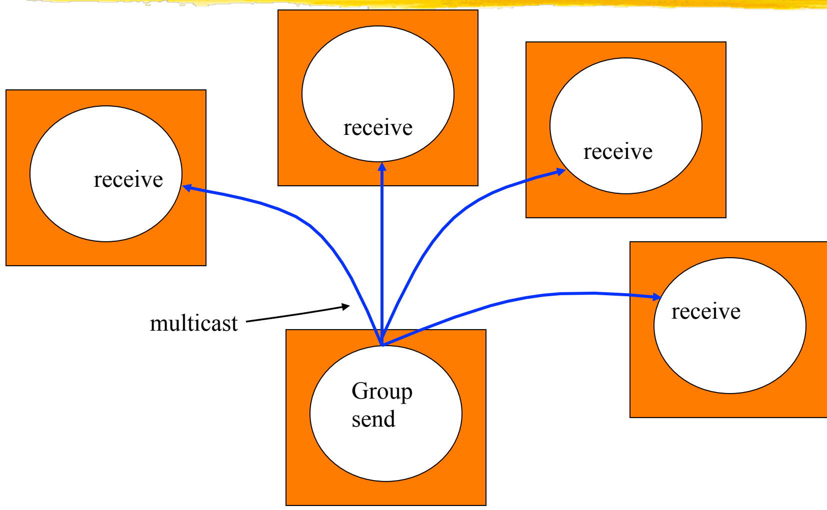
Primary-backup replication (other than cold backup)

- Warm backup
  - In this case, the backup is (at least) partially alive, so the recovery phase is faster
    - But typically still requires some replaying of last transactions, or losing the last few updates
- Hot standby (leader/follower)
  - The backup is also up, and is constantly updated about the state of the primary
- Local-write scheme
  - The primary migrates between the servers
  - Commonly used in mobile systems

Quorum-based replication

- Typically used with data-replacing updates
  - Such updates can be performed on old non-updated replicas
- An update is performed on a majority of replicas
- A query is sent to a majority of replicas
  - Replies include both versions and values
  - A client picks a reply with the highest version
  - The replica that sent such a reply is guaranteed to be the most updated one
- The scheme can be generalized
  - Write quorum $Sw = \{Sw_1, \ldots, Sw_n\}$, Sw_i is a set of replicas
  - $\forall i,j$, $Sw_i \cap Sw_j \neq \emptyset$
  - A client picks *i* and performs the update on all replicas in Sw_i
  - Read quorum $Sr = \{Sr_1, \ldots, Sr_n\}$, $\forall i,j$, $Sr_i \cap Sw_j \neq \emptyset$

From multicast to reliable group communication

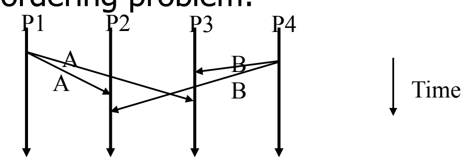


From multicast to reliable group communication

- Group membership service
  - Dynamic maintenance of groups
  - Failure detection
  - Distributes information about changes in the membership
  - Address expansion – an address for multicast to the entire group
- Reliable delivery
  - Acknowledgement of message reception
  - Message retransmissions
- Stability detection
  - Learning when all members of the group have received the message

What is still missing for active replication support?

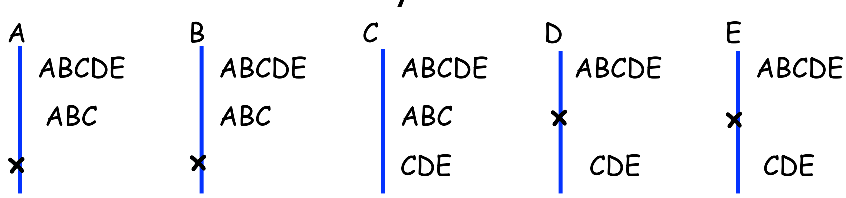
- Replicas should receive the same events in the same order
- Problem: synchronization between membership changes and message delivery
  - P1 receives m before it learns about a membership change
  - P2 receives m after it learns about a membership change
- Message ordering problem:



- Group communication provides view synchrony & ordered delivery

View synchrony

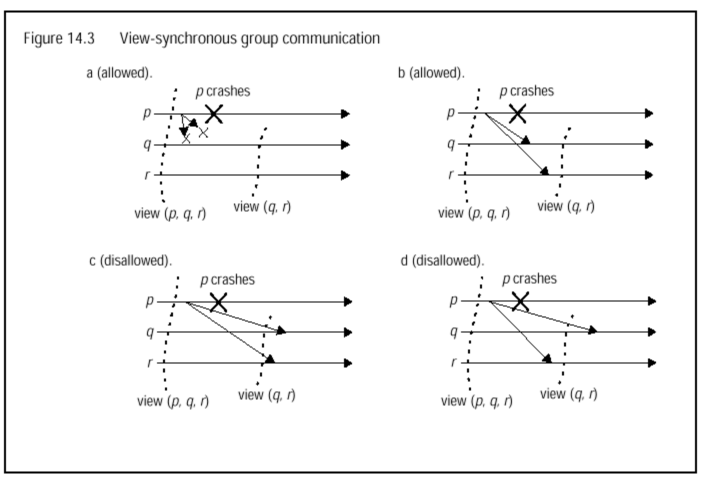
- View: epoch of system evolution between two consecutive changes of membership
- The evolution of the system can be seen as a global sequence of views
- Illusion of a static system in each view



View synchrony

- Synchronization:
  - Processes deliver views and messages in the same sequence of events
  - If two different processes deliver *m*, they do it in the same view
- Delivering the same set of messages:
  - If the process *p* delivers *m* in *v(g)* and later delivers *v(g')*, then every process *q* that delivers both *v(g)* and *v(g')* delivers *m* in *v(g)*
  - This implies retransmitting missing messages
  - If *p* delivers *m* in *v(g)*, and a process *q* does not deliver *m* in *v(g)*, the next view *p* delivers will not include *q*

Illustration (from the book)



Ordered message delivery

- Some rule (binary relation) that establishes that two messages m1 & m2 sent in the system are ordered: m1 < m2
  - Standard relation properties
- Two variants of ordered message delivery
  - Unreliable ordered delivery: if a process delivers m1 and m2, it should deliver m2 after m1
  - Reliable ordered delivery: if a process delivers m2, it should have already delivered m1
    - Delay message delivery until earlier messages arrive
    - To implement, one may need a lot of space for message buffering

Commonly used orderings

- FIFO
- Causal: two messages are ordered if related by the happen-before relation
  - Many applications require message delivery in an order that preserves cause and effect
    - Publish/subscribe (netnews), email, control systems, root cause determination
- Total: all messages will be received in the same order by all the processes in the group
  - Useful towards implementing the state machine abstraction

Implementing ordered delivery

The implementation does not deliver messages before it knows that consistent requirements are satisfied.