# Distributed Systems
# Master of Science in Engineering in Computer Science

# AA 2020/2021

## LECTURES 15: SOFTWARE REPLICATION

# Motivation

- Fault Tolerance
  - Guarantee the availability of a service (also called object) despite failures

- Assuming p the failure probability of an object O. O’s availability is 1-p.

- Replicating an object O on n nodes and assuming p the failure probability of each replica, O’s availability is $\underbrace{1- p^{n}}_{\text{for n nodes}}$ (considering independent failures probability)

# System Model

The system is composed of a set of processes (clients)

Messages will never be lost, no injection, no duplication

- Processes are connected through Perfect point-to-point links
- Processes may fail by crash

Processes interacts wit a set of objects X located at different sites managed managed by processes

- Each object has a state accessed trough a set of operations
- An operation by a process $p_i$ on an object $x \in X$ is a pair invocation/response
  - The operation invocation is noted [*x* op(arg) $p_i$] where arg are the arguments of the operation op
  - The operation response is noted [x ok(res) $p_i$] where res is the result returned
  - The pair invocation/response is noted [x op(arg)/ok(res) $p_i$]
- After issuing an invocation a process is blocked until it receives the matching response

# Replication: requirements

In order to tolerate process crash failures a logical object must have several physical replicas located at different sites of the distributed system

- replicas of an object *x* are noted $x^1, x^2, \ldots x^l$
- Invocation of replica $x^j$ located on site s is handled by a process $p_j$ also located on s
- We assume that $p_j$ crashes exactly when $x^j$ crashes

Replication is transparent to the client processes

Considering all the replicas, we have the logical object, from POV of the user is the unique objects the replicas are the objects in the database
If the replica crashes we assume that the process
The main requirement is transparency
We consider pj failure as xj failure as well.

# Consistency criteria

A consistency criterion defines the result returned by an operation

- It can be seen as a contract between the programmer and the system implementing replication

Given that a exist multiple replicas and object is just one state
Discuss what we expect from the interaction with the object

Three main consistency criteria are defined in literature

- Linearizability
- Sequential consistency
- Causal consistency

Strong Consistency

Weak Consistency

The three consistency criteria differ however in the definition of the most recent state

# Linearizability

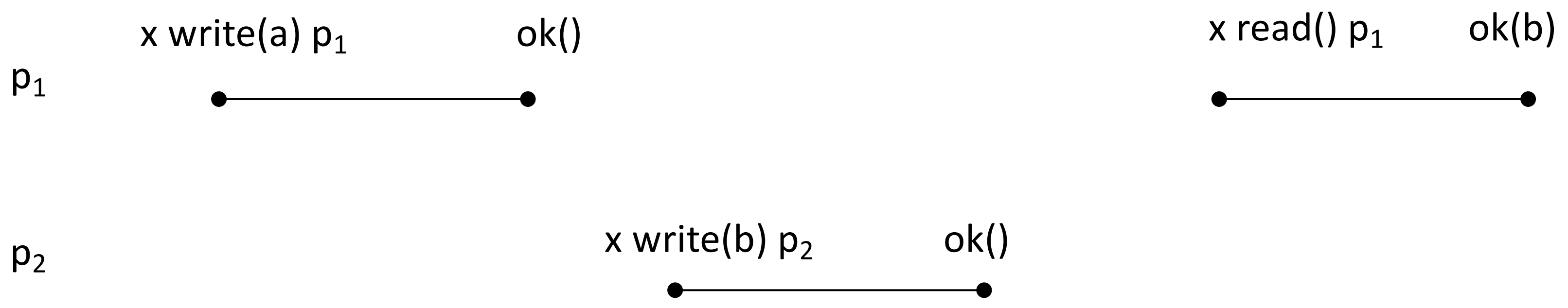
Let us consider the precedence relation ( denoted $\prec$) and the concurrency relation (denoted | |) defined between two operations.

An execution E is linearizable if there exists a unique sequence S including all operations of E such that the following two conditions hold:

1. for any two operations $O_1$ and $O_2$ such that $O_1 \prec O_2$, $O_1$ appears before $O_2$ in the sequence S
2. the sequence S is *legal* i.e., for every object x the subsequence of S of which operations are on x belongs to the sequential specification of x.

# Example: simple variable

1. LINEARIZZABILE



$p_1$

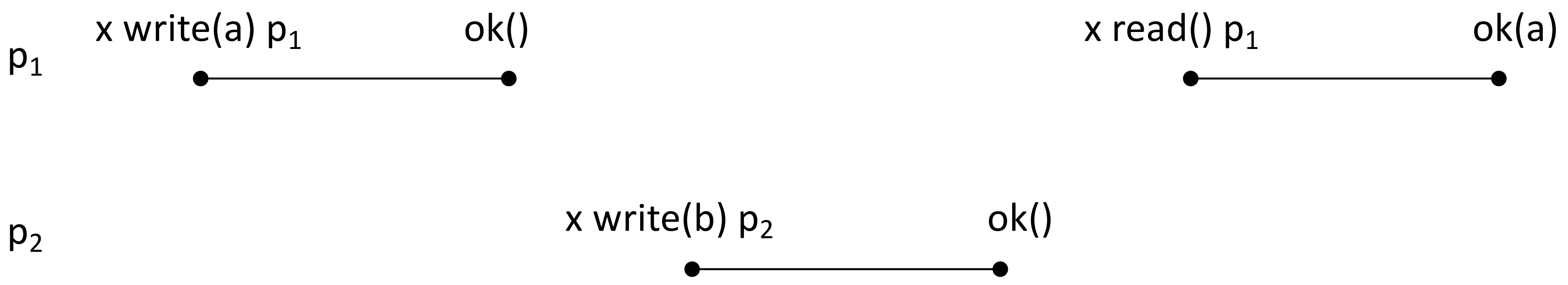
x write(a) $p_1$ ok()

x read() $p_1$ ok(b)

$p_2$

x write(b) $p_2$ ok()

2. NON LINEARIZZABILE



$p_1$

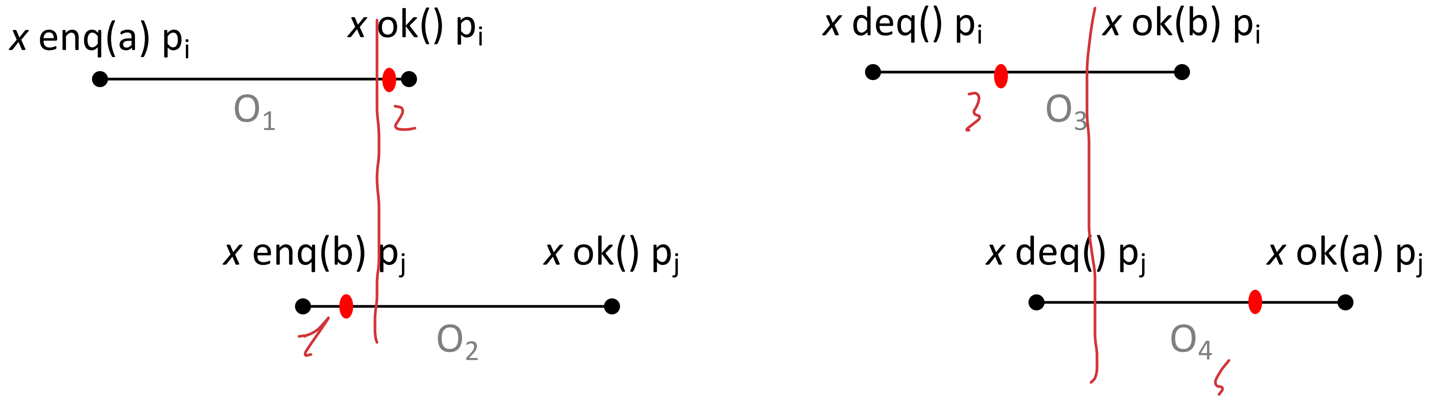
x write(a) $p_1$ ok()

x read() $p_1$ ok(a)

$p_2$

x write(b) $p_2$ ok()

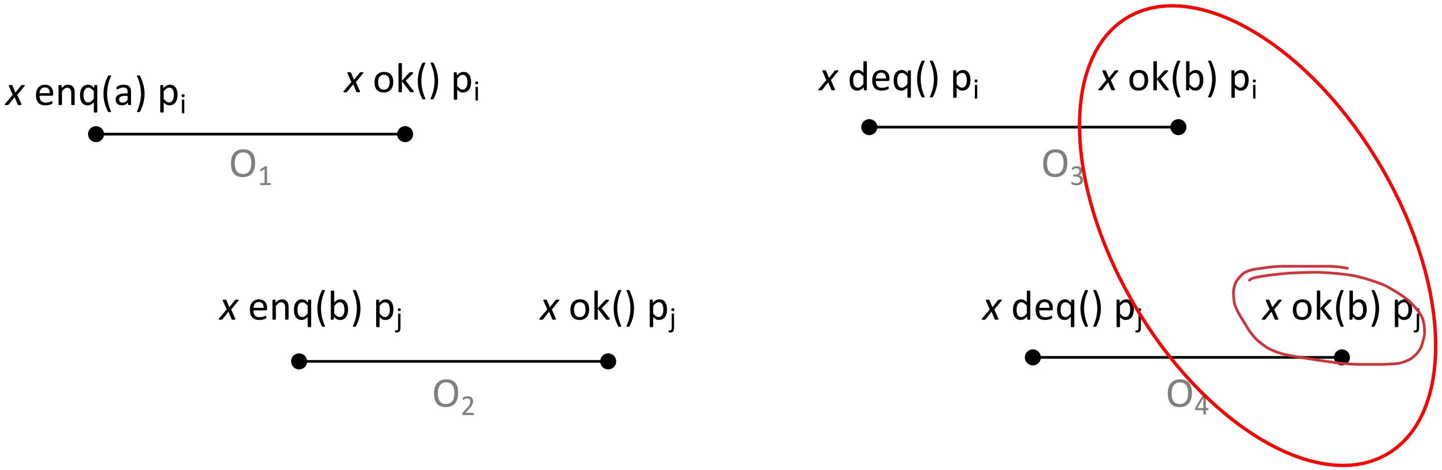
# Example: FIFO Queue



Linearizable

S= {O2, O1, O3, O4}

# Example: FIFO Queue



*x* enq(a) $p_i$

*x* ok() $p_i$

$O_1$

*x* enq(b) $p_j$

*x* ok() $p_j$

$O_2$

*x* deq() $p_i$

*x* ok(b) $p_i$

$O_3$

*x* deq() $p_j$

*x* ok(b) $p_j$

$O_4$

Not Legal wrt the sequential specification of a FIFO queue

NON-Linearizable

# A Sufficient Condition for Linearizability

*Replicas must agree on the set of invocations they handle and on the order according to which they handle these invocations*

**Atomicity:** Given an invocation [*x* op(arg) $p_i$], if one replica of the object x handles this invocation, then every correct replica of x also handles the invocation [*x* op(arg) $p_i$].

**Ordering:** Given two invocations [*x* op(arg) $p_i$] and [*x* op(arg) $p_j$] if two replicas handle both the invocations, they handle them in the same order

# Replication Techniques

Two main techniques implementing linearizability:

- Primary Backup (Passive Repl)
- Active Replication

# Passive Replication

PRIMARY-BACKUP

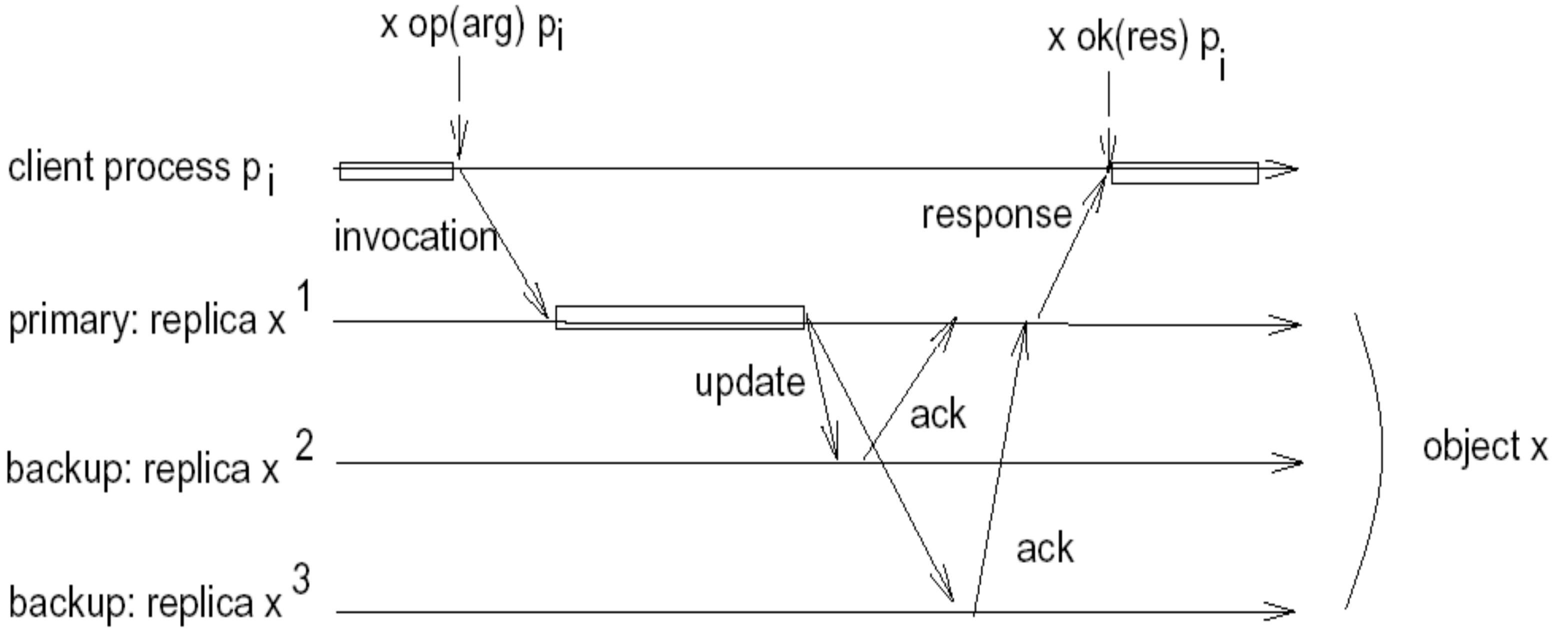
# Primary Backup

- *Primary*:
  - Receives invocations from clients and sends back the answers.
  - Given an object x, *prim(x)* returns the primary of x.

- *Backup:*
  - Interacts with *prim(x)*
  - is used to guarantee fault tolerance by replacing a primary when crashes

# Primary Backup Scenario

Need of leader election to know who is the primary



# Primary Backup:
# the case of no crash

1. When update messages are received by backups, they update their state and send back the ack to prim(x).
2. prim(x) waits for an ack message from each correct backup and then sends back the answer, res, to the client.

How to guarantee Linearizability: the order in which prim(x) receive clients' invocations define the order of the operation on the object.

# Primary Backup: Presence of Crash

Three scenarios :

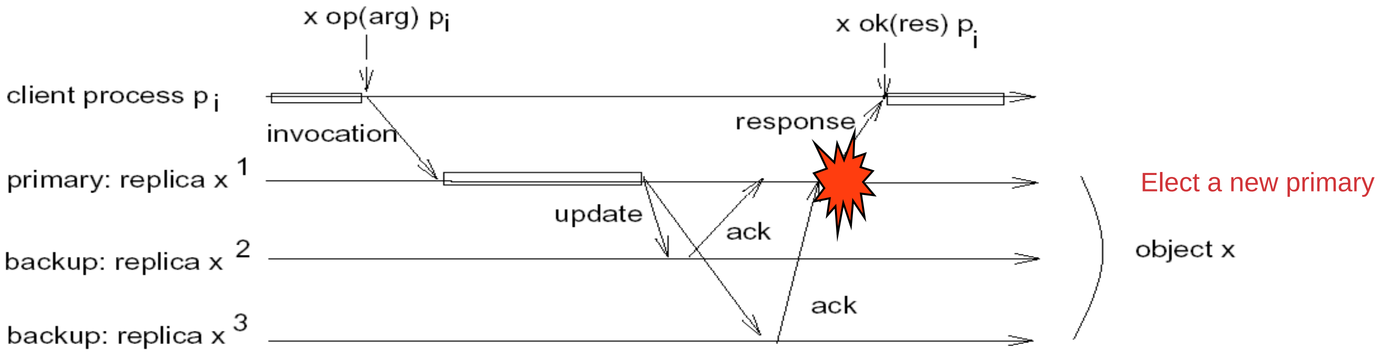
- **Scenario 1**: Primary fails after the client receives the answer.

- **Scenario 2**: Primary fails before sending update messages

- **Scenario 3**: Primary fails after sending update messages and before receiving all the ack messages.

In all cases there is the need of electing a new leader.

# Scenario 1
# Primary fails after sending the answer

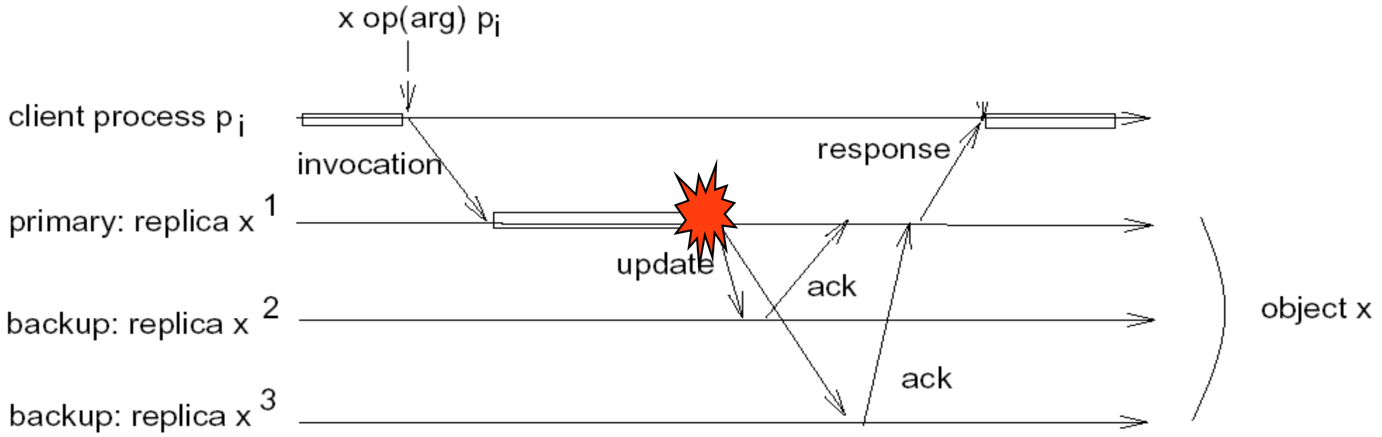


Two cases

1. Client does not receive the response due to perfect point-to-point link. If the response is lost, client retransmits the request after a timeout
2. Client receives the answer, everybody is happy (but the primary ☺)

The new primary will recognize the request re-issued by the client as already processed and sends back the result without updating the replicas

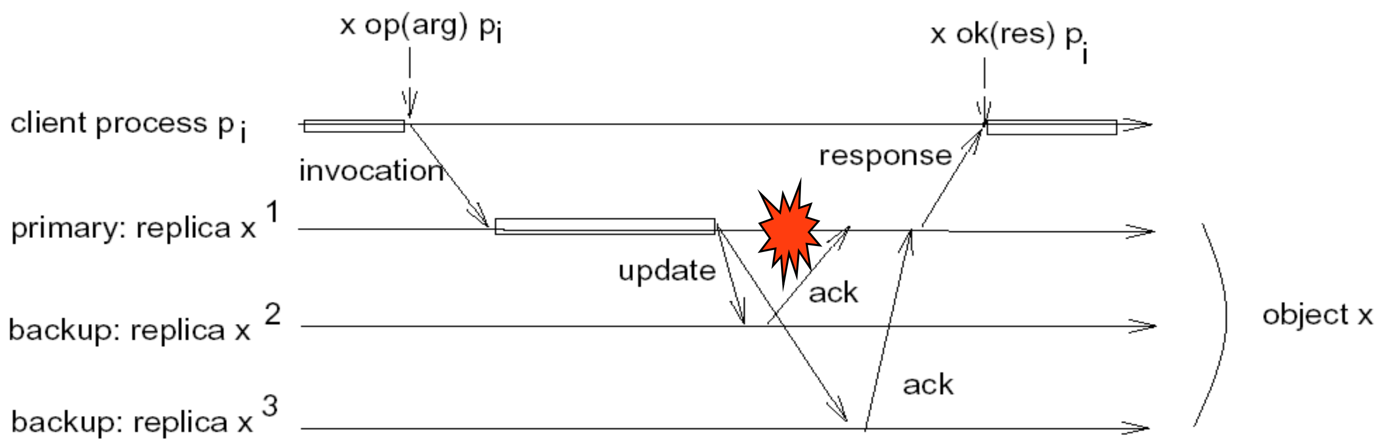
# Scenario 2
Primary fails before sending update messages



Client does not get an answer and resends the requests after a timeout

The new primary will handle the request as new

# Scenario 3
# Primary fails after sending update messages and before receiving all the ack messages



**How to Guarantee atomicity?** update it is received either by all or by no one.

When a primary fails there is the need to elect another primary among the correct replicas

# Active Replication

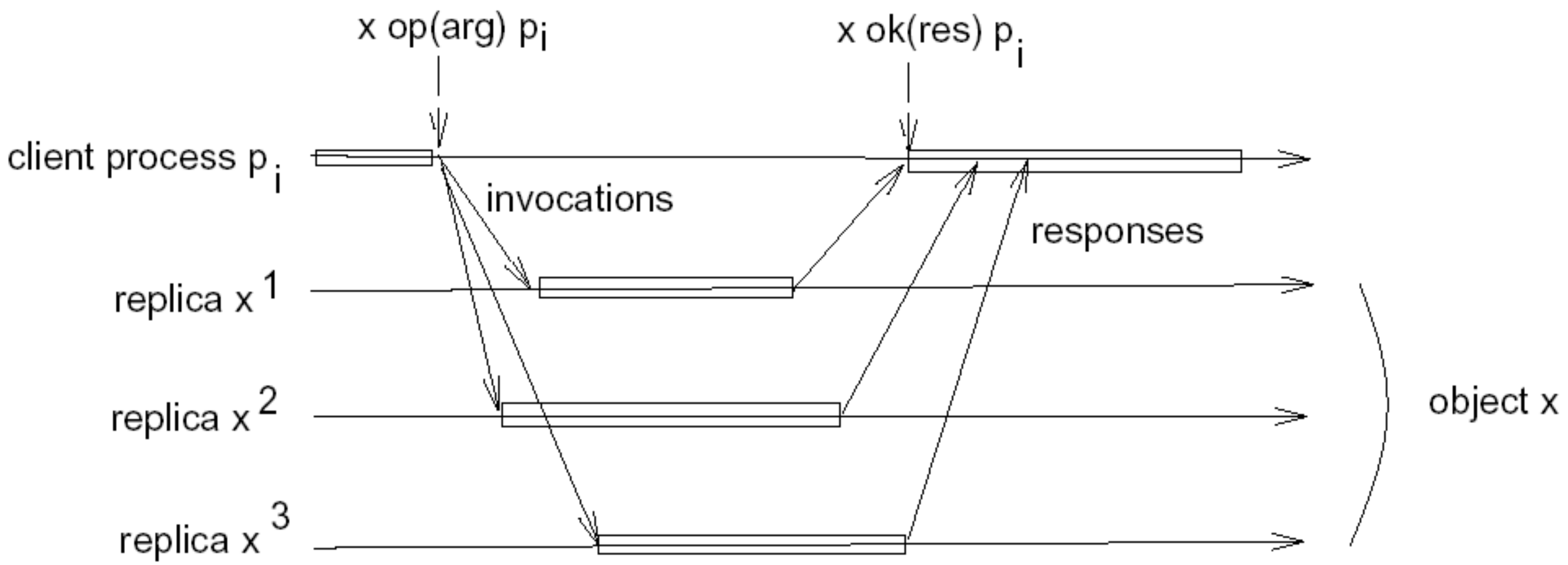
# Active Replication

There is no coordinator all replicas have the same role

Each replica is deterministic. If any replica starts from the same state and receives the same input, they will produce the same output

As a matter of fact clients will receive the same response one from each replica

# Active Replication



# Active Replication
# How to Guarantee Linearizability

To ensure linearlizability we need to preserve:

- Atomicity: if a replica executes an invocation, all correct replicas execute the same invocation.
- Ordering: (at least) no two correct replicas have to execute two invocations in different order.

We need: TOTAL ORDER Broadcast

- INCLUDING THE CLIENTS!

# Active Replication Crash

Active Replication does not need recovery action upon the failure of a replica

Faster but with more messages

# References

Rachid Guerraoui and André Schiper: *“Fault-Tolerance by Replication in Distributed Systems”*. In *Proceedings of the 1996 Ada-Europe International Conference on Reliable Software Technologies* (Ada-Europe '96).