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- A distributed system should be able to recover automatically from partial failures without seriously affecting availability and performance.

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  - Maintainability
- **In-class Exercise**: How is is availability different from reliability? How about a system that goes down for 1 millisecond every hour? How about a system that never goes down but has to be shut down two weeks every year?

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- **In-class Exercise**: Give examples of each type of fault for your project!

Failure Models (1)

Type of failure	Description
Crash failure	A server halts, but is working correctly until it halts
Omission failure	A server fails to respond to incoming requests
Receive omission	A server fails to receive incoming messages
Send omission	A server fails to send messages
Timing failure	A server's response lies outside the specified time interval
Response failure	A server's response is incorrect
Value failure	The value of the response is wrong
State transition failure	The server deviates from the correct flow of control
Arbitrary failure	A server may produce arbitrary responses at arbitrary times

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  - Arbitrary failures where a server is producing output that it should never have produced, but which cannot be detected as being incorrect.
  - A faulty server may even be working with other servers to produce intentionally wrong answers!

Reliable Client-Server Communication

RMI semantics in the presence of failures.

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- The client crashes after sending a request.

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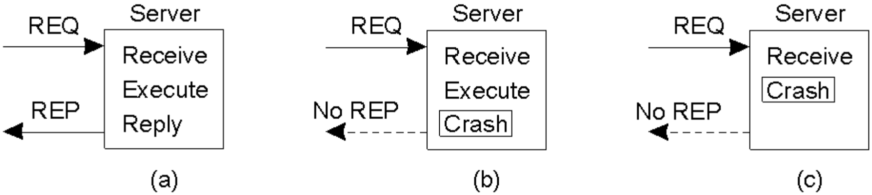
- Possible RPC semantics
  - Exactly once semantics
  - At least once semantics
  - At most once semantics
  - Guarantee nothing semantics

Server Crash (1)



- A server in client-server communication
  - (a) Normal case
  - (b) Crash after execution
  - (c) Crash before execution

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  - Reissue a request only if it has not received an acknowledgment of its print request.

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  - Print the text (P)
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- These events can occur in six different orderings:

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Server Crash (5)

Client	Server					
	Strategy M -> P			Strategy P -> M		
Reissue strategy	**MPC**	**MC(P)**	**C(MP)**	**PMC**	**PC(M)**	**C(PM)**
Always	DUP	OK	OK	DUP	DUP	OK
Never	OK	ZERO	ZERO	OK	OK	ZERO
Only when ACKed	DUP	OK	ZERO	DUP	OK	ZERO
Only when not ACKed	OK	ZERO	OK	OK	DUP	OK

- M: send the completion message, P: print the text, C: server crash
- OK (text is printed once), DUP (text is printed twice), ZERO (text is not printed at all)

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  - Expiration. Each RPC is given a quantum of time to finish its job. If it cannot finish, then it asks for another quantum. After a crash, a client need only wait for a quantum to make sure all orphans are gone.

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  - Have a bit in the message to distinguish between original and duplicate transmission

Reliable Group Communication

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- Atomic multicasting using Virtual Synchrony

Basic Reliable Multicasting Schemes (1)

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- Few processes: Set up reliable point-to-point channels. Inefficient for more processes.
- Issues in reliable multicasting:
  - What does reliable multicasting mean?
  - What if a process joins during the communication?
  - What happens if a sending process crashes during communication?
  - How to reach agreement on what does the group look like?

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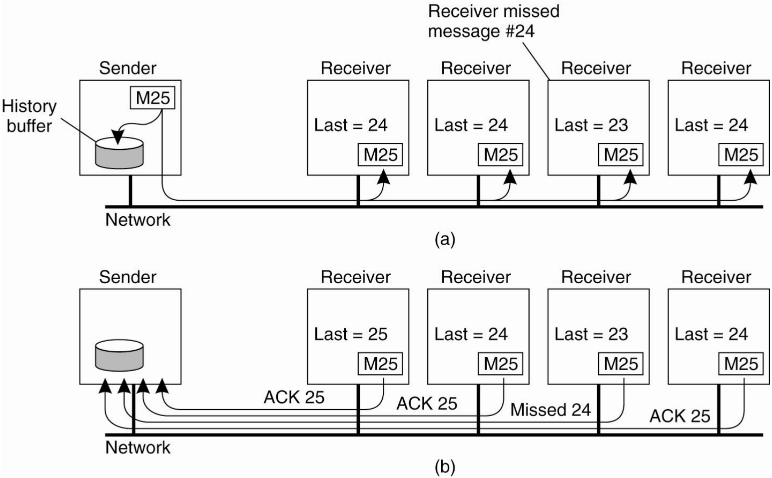
- Sender retransmits on a negative `Ack` or on timeout before all `Ack`s were received. `Ack`s can be piggy-backed. Retransmissions can be done with point-to-point communication.

Basic Reliable Multicasting Schemes (3)



- A simple solution to reliable multicasting when all receivers are known and are assumed not to fail.
- (a) Message transmission. (b) Reporting feedback.

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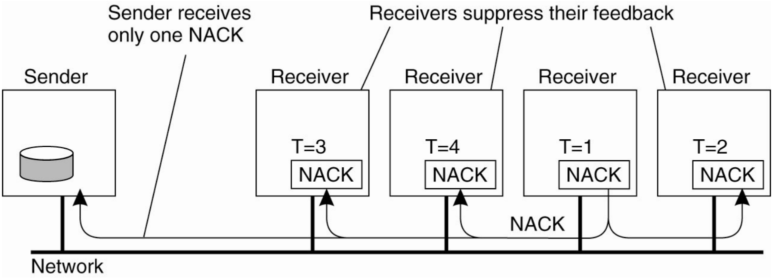
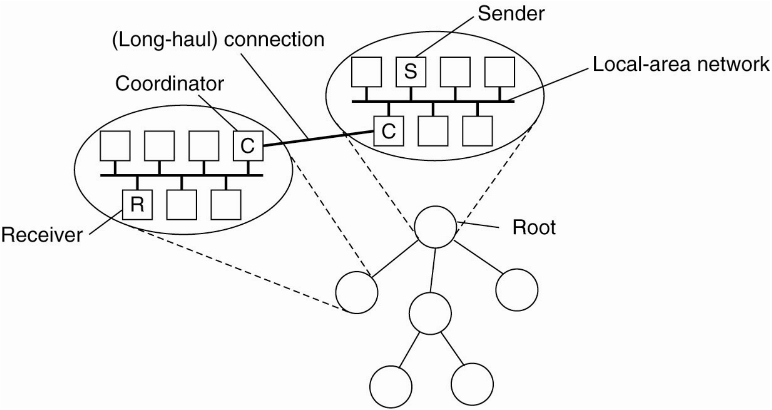
- Hierarchical feedback control: Use subgroups and coordinators in each subgroup.

Nonhierarchical Feedback Control



- Several receivers have scheduled a request for retransmission with random delays, but the first retransmission request leads to the suppression of others.

Hierarchical Feedback Control



- The essence of hierarchical reliable multicasting. Each local coordinator forwards the message to its children and later handles retransmission requests.

Reliable Atomic Multicast

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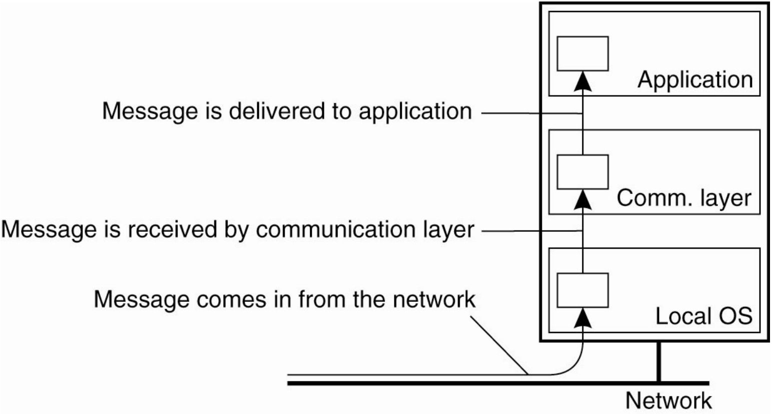
  - All messages are delivered in the same order to all processes.
- For example, this solves the problem of a replicated database on top of a distributed system.
  - Atomic multicasting ensures that non-faulty processes maintain a consistent view of the database, and forces reconciliation when a replica recovers and rejoins the group.

Virtual Synchrony (1)



- The logical organization of a distributed system to distinguish between message receipt and message delivery.

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- Note that m being not delivered is because the sender of m crashed.

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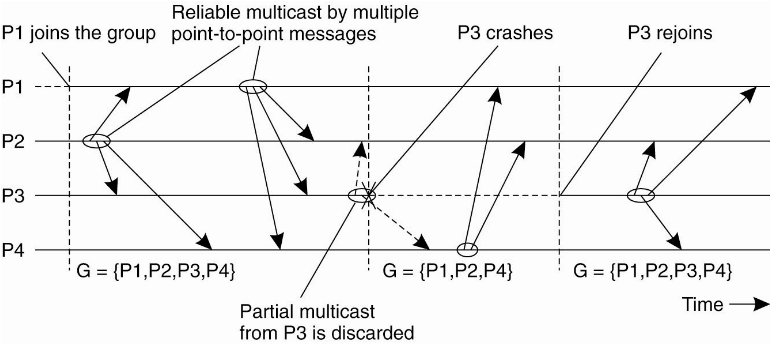
- The principle is that all multicasts take place between view changes.
- All multicasts that are in transit when a view change takes place are completed before the view change comes into effect.

Virtual Synchrony (4)



- The principle of virtual synchronous multicast.

Message Ordering in Multicasting (1)

Virtual synchrony allows us to think about multicasts as taking place in epochs. But we can have several possible orderings of the multicasts:

- Unordered multicasts
- FIFO-ordered multicasts
- Causally-ordered multicasts (requires vector timestamps)
- Totally-ordered multicasts

Message Ordering in Multicasting (2)

Process P1	Process P2	Process P3
sends m1	receives m1	receives m2
sends m2	receives m2	receives m1

- Three communicating processes in the same group. The ordering of events per process is shown along the vertical axis. This shows unordered multicasts.

Message Ordering in Multicasting (3)

Process P1	Process P2	Process P3	Process P4
sends m1	receives m1	receives m3	sends m3
sends m2	receives m3	receives m1	sends m4
	receives m2	receives m2	
	receives m4	receives m4	

- Four processes in the same group with two different senders, and a possible delivery order of messages under FIFO-ordered multicasting.

Message Ordering in Multicasting (4)

Multicast	Basic Message Ordering	Total-Ordered Delivery?
Reliable multicast	None	No
FIFO multicast	FIFO-ordered delivery	No
Causal multicast	Causal-ordered delivery	No
Atomic multicast	None	Yes
FIFO atomic multicast	FIFO-ordered delivery	Yes
Causal atomic multicast	Causal-ordered delivery	Yes

- Six different versions of virtually synchronous reliable multicasting.

Implementing Virtual Synchrony (1)

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- Assumes that no process crashes during a view change (although it can be generalized to handle that as well).

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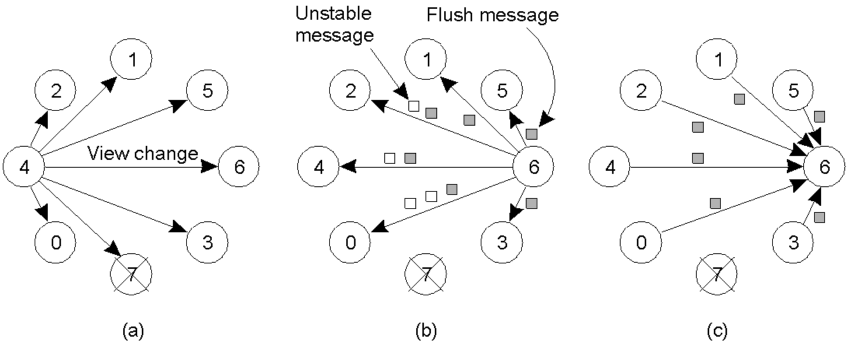

(a) Process 4 notices that process 7 has crashed, sends a view change.

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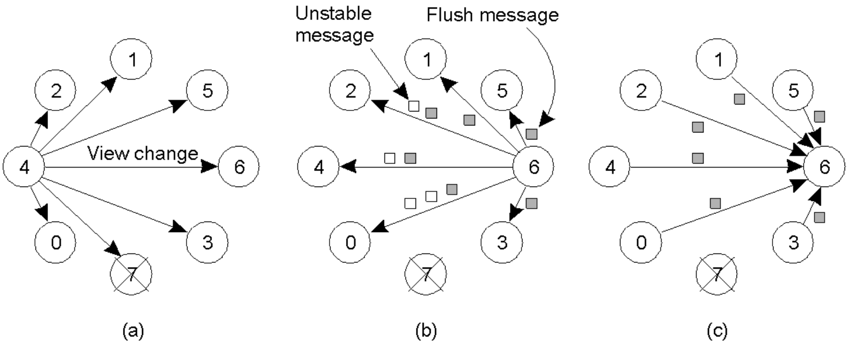

(a) Process 4 notices that process 7 has crashed, sends a view change.

(b) Process 6 sends out all its unstable messages, followed by a flush message.

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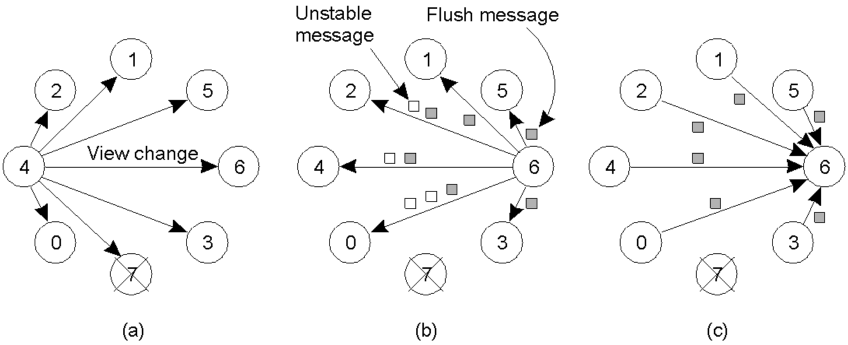


(a) Process 4 notices that process 7 has crashed, sends a view change.
(b) Process 6 sends out all its unstable messages, followed by a flush message.
(c) Process 6 installs the new view when it has received a flush message from everyone else.

Failure Masking by Redundancy

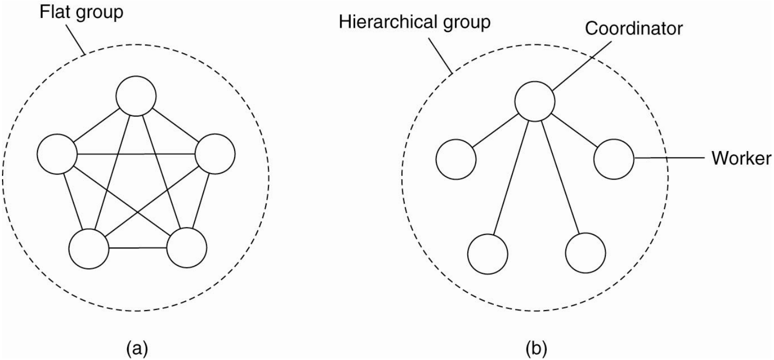
- Information Redundancy. For example, adding extra bits (like in Hamming Codes, see the book Coding and Information Theory) to allow recovery from garbled bits.
- Time Redundancy. Repeat actions if need be.
- Physical Redundancy. Extra equipment or processes are added to make the system tolerate loss of some components.

Process Resilience

Achieved by replicating processes into groups.

- How to design fault-tolerant groups?
- How to reach an agreement within a group when some members cannot be trusted to give correct answers?

Flat Groups Versus Hierarchical Groups



Failure Masking Via Replication

- *Primary-backup protocol*. A primary coordinates all write operations. If it fails, then the others hold an election to replace the primary.
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  - For *Byzantine failures*, at least $2k+1$ extra components are needed to achieve k fault tolerance.
  - Requires atomic multicasting: all requests arrive at all servers in same order. This can be relaxed to just be for write operations.

Consensus in Faulty Systems

The model: a very large collection of clients send commands to a group of processes that jointly behave as a single, highly robust process. To make this work, we need to make an important assumption:
In a fault-tolerant process group, each nonfaulty process executes the same commands, in the same order, as every other nonfaulty process.

- Flooding Consensus (for fail-stop failures)
- Paxos Consensus (for fail-noisy failures)
- Byzantine Agreement (for arbitrary failures)

Flooding Consensus

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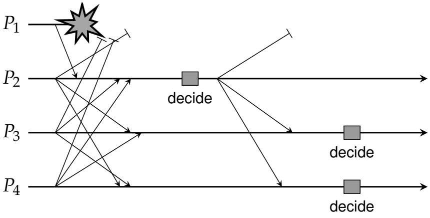

Example: Realistic Consensus: Paxos

- **Assumptions (rather weak ones, and realistic)**
  - A partially synchronous system (in fact, it may even be asynchronous).
  - Communication between processes may be unreliable: messages may be lost, duplicated, or reordered.
  - Corrupted message can be detected (and thus subsequently ignored).
  - All operations are deterministic: once an execution is started, it is known exactly what it will do.
  - Processes may exhibit crash failures, but not arbitrary failures.
  - Processes do not collude.

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  - Processes do not collude.
- Understanding Paxos
  - We will build up Paxos from scratch to understand where many consensus algorithms actually come from.

Paxos Organization

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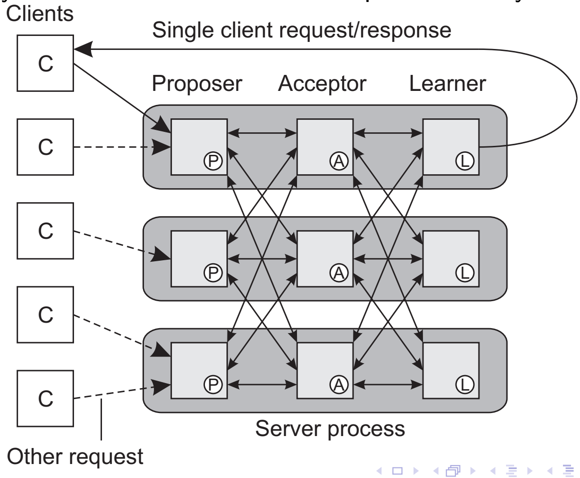
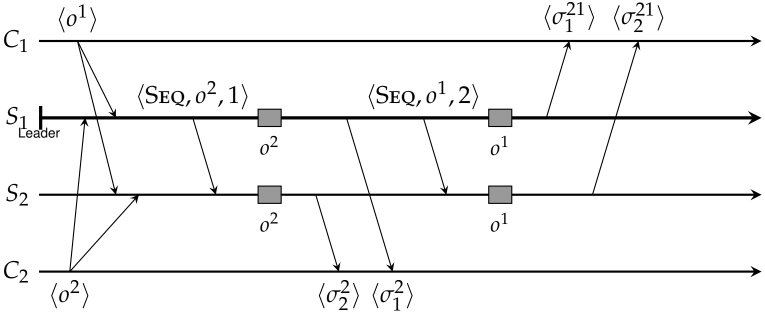


Two Server Situation



Subscripts designate processes, and superscripts designate operations and states.

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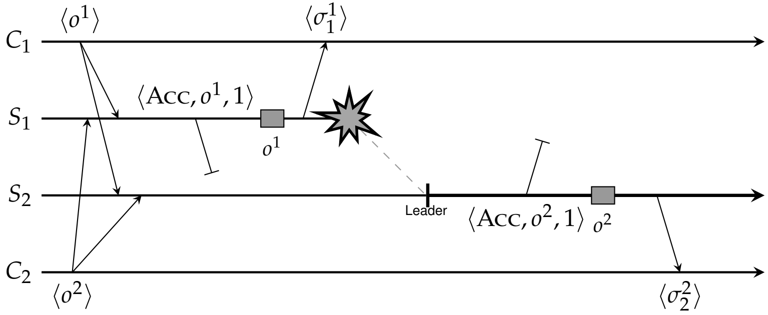
- Failing leader.

Handling lost messages

- Some Paxos terminology
  - The leader sends an accept message $\textsc{accept}(o, t)$ to backups when assigning a timestamp t to command o.
  - A backup responds by sending a learn message: $\textsc{learn}(o, t)$
  - When the leader notices that operation o has not yet been learned, it retransmits $\textsc{accept}(o, t)$ with the original timestamp.

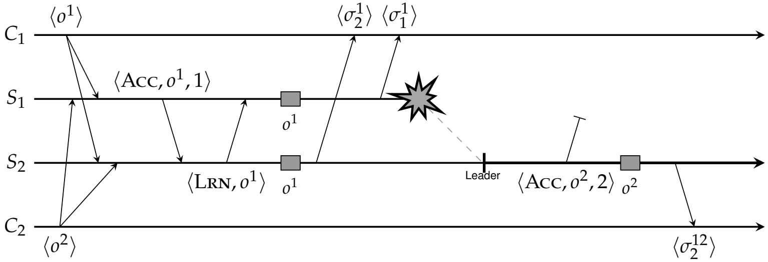
Two servers and one crash: problem



Problem:

- Primary crashes after executing an operation, but the backup never received the accept message.

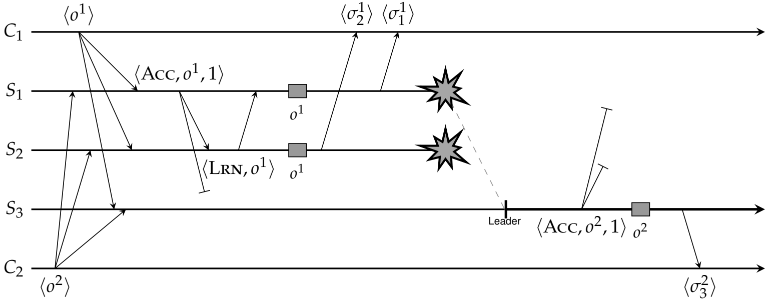
Two servers and one crash: solution



Solution:

- Never execute an operation before it is clear that is has been learned.

Three servers and two crashes: still a problem?



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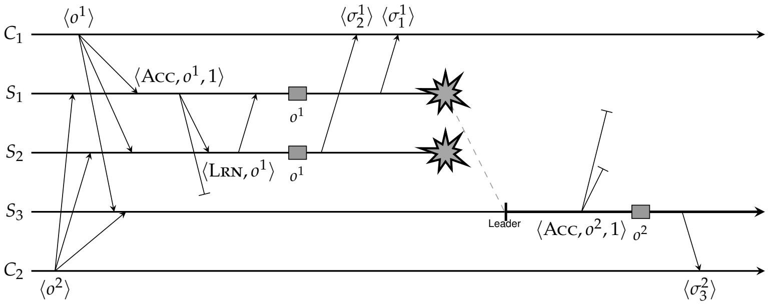

Scenario:

What happens when $\text{LEARN}(o^1)$ as sent by S_2 to S_1 is lost?

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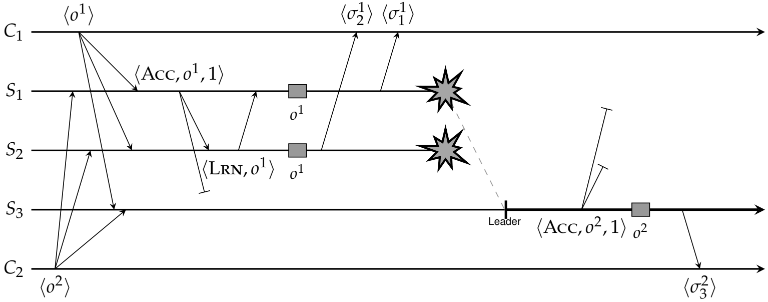

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Solution:

S_2 will also have to wait until it knows that S_3 has learned o^1.

Paxos: fundamental rule

General rule:
In Paxos, a server S cannot execute an operation o until it has received a $\textsc{learn}(o)$ from all other nonfaulty servers.

Failure detection

Practice:

- Reliable failure detection is practically impossible. A solution is to set timeouts, but take into account that a detected failure may be false.

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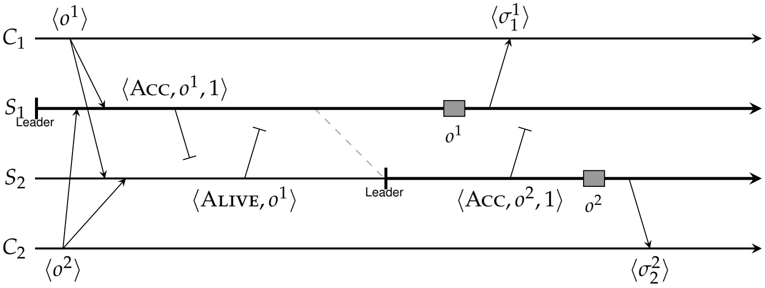

Required number of servers

Observation:

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Adapted fundamental rule:

- In Paxos with three servers, a server S cannot execute an operation o until it has received at least one (other) LEARN(o) message, so that it knows that a majority of servers will execute o.

Required number of servers (contd.)

Assumptions before taking the next steps:

- Initially, S_1 is the leader.
- A server can reliably detect it has missed a message, and recover from that miss.
- When a new leader needs to be elected, the remaining servers follow a strictly deterministic algorithm, such as $S_1 \rightarrow S_2 \rightarrow S_3$.
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Observation:

- If either one of the backups (S_2 or S_3) crashes, Paxos will behave correctly: operations at nonfaulty servers are executed in the same order.

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Leader crashes after sending ACCEPT(o^1, 1)

- S_3 is completely ignorant of any activity by S_1
  - As soon as S_2 announces that o^2 is to be accepted, S_3 will notice that it missed an operation and can ask S_2 to help recover.
- S_2 had missed ACCEPT(o^1, 1):
  - As soon as S_2 proposes an operation, it will be using a stale timestamp, allowing S_3 to tell S_2 that it missed operation o^1.

Leader crashes after sending $\text{ACCEPT}(o^1, 1)$

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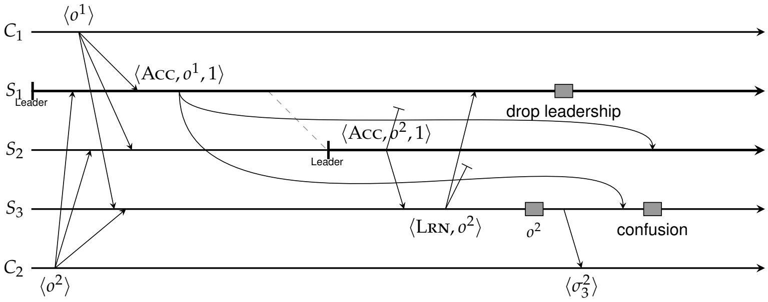
Observation:

- Paxos (with three servers) behaves correctly when a single server crashes, regardless when that crash took place.

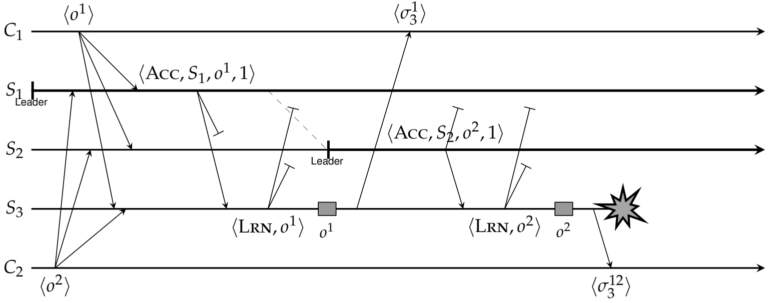
False crash detection



Problem and solution:

- S_3 receives ACCEPT$(o^1, 1)$, but much later than ACCEPT$(o^2, 1)$. If it knew who the current leader was, it could safely reject the delayed accept message $\Rightarrow$ leaders should include their ID in messages.

But what about progress (liveness)?



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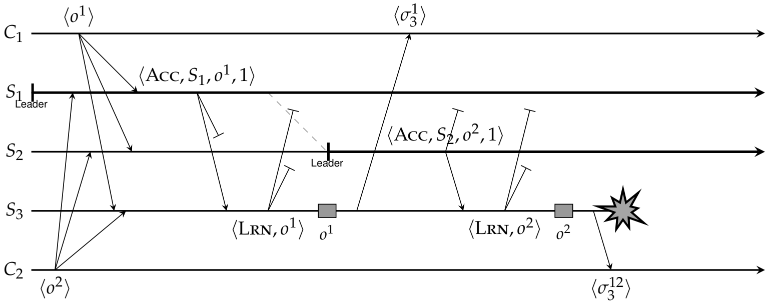
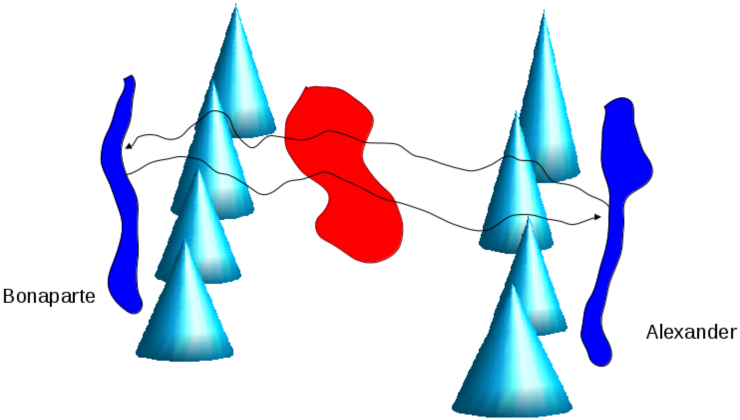


Essence of solution

- When S_2 takes over, it needs to make sure than any outstanding operations initiated by S_1 have been properly flushed, i.e., executed by enough servers. This requires an explicit leadership takeover by which other servers are informed before sending out new accept messages.

Consensus in Systems with Arbitrary Faults



- Two Army Problem
- Non-faulty generals with unreliable communication.

Byzantine Agreement Problem (1)

Problem:

- Red army in the valley, n blue generals each with their own army surrounding the red army.
- Communication is pairwise, instantaneous and perfect.
- However m of the blue generals are traitors (faulty processes) and are actively trying to prevent the loyal generals from reaching agreement. The generals know the value m.

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- However m of the blue generals are traitors (faulty processes) and are actively trying to prevent the loyal generals from reaching agreement. The generals know the value m.

Goal: The generals need to exchange their troop strengths. At the end of the algorithm, each general has a vector of length n. If ith general is loyal, then the ith element has their correct troop strength otherwise it is undefined.

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Conditions for a solution:

- All loyal generals decide upon the same plan of action
- A small number of traitors cannot cause the loyal generals to adopt a bad plan

Byzantine Agreement Problem (2)

Setup:

- Assume that we have n processes, where each process i will provide a value v_i to other processes. The goal is to let each process construct a vector of length n such that if process i is non-faulty, $V[i] = v_i$. Otherwise, $V[i]$ is undefined.
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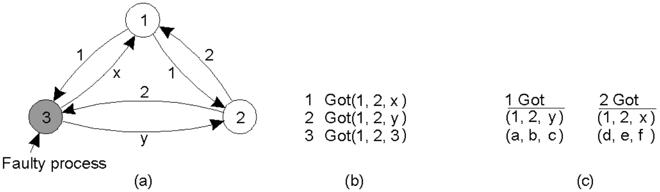
The goal of Byzantine agreement is that consensus is reached on the value for nonfaulty processes only.

Byzantine Agreement Example (1)



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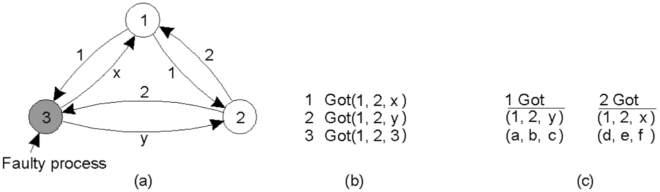

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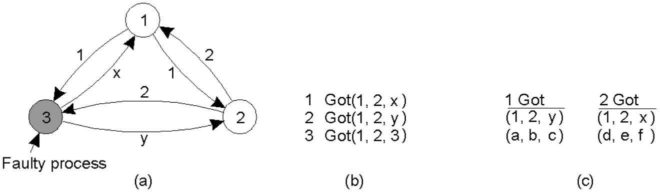

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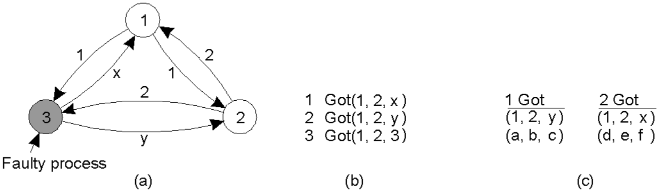

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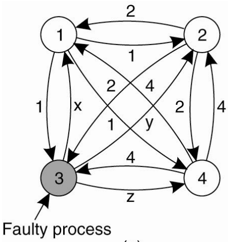
- Similarly, process 2 cannot ascertain the right value for $V[1]$. Hence, they cannot reach agreement.
- For m faulty processes, we need $2m + 1$ non-faulty processes to overcome the traitors. In total, we need a total of $3m + 1$ processes to reach agreement.



(a)

1	Got(1, 2, x, 4)
2	Got(1, 2, y, 4)
3	Got(1, 2, 3, 4)
4	Got(1, 2, z, 4)

(b)

1 Got	2 Got	4 Got
(1, 2, y, 4)	(1, 2, x, 4)	(1, 2, x, 4)
(a, b, c, d)	(e, f, g, h)	(1, 2, y, 4)
(1, 2, z, 4)	(1, 2, z, 4)	(i, j, k, l)

(c)

The Byzantine generals problem for 3 loyal generals and 1 traitor:

(a) The generals announce their troop strengths (let's say, in units of 1 kilo soldiers).

(b) The vectors that each general assembles based on previous step.

(c) The vectors that each general receives.

(d) If a value has a majority, then we know it correctly, else it is unknown. In this case, we can reach agreement amongst the non-faulty processes.

Limitations on Reaching Consensus (1)

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The general goal of distributed consensus algorithms is to have all the non-faulty processes reach consensus on some issue, and to establish that consensus within a finite number of steps. Possible cases:

- Synchronous versus asynchronous systems
- Communication delay is bounded or not
- Message delivery from the same sender is ordered or not
- Message transmission is done through unicasting or multicasting

Limitations on Reaching Consensus (2)

Process behavior	Communication delay	Message ordering: Unordered — Message transmission: Unicast	Unordered — Multicast	Ordered — Unicast	Ordered — Multicast
Synchronous	Bounded	X	X	X	X
Synchronous	Unbounded			X	X
Asynchronous	Bounded				X
Asynchronous	Unbounded				X

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- Most distributed systems in practice assume that processes behave synchronously, message transmission is unicast, and communication delays are unbounded.

The CAP Theorem

- CAP Theorem (aka *Brewer's Theorem*): states that it is impossible for a distributed computer system to simultaneously provide all three of the following guarantees:
  - **C**onsistency (all nodes see the same data at the same time)
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Brewer's CAP Theorem (Liberian.com)

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- Design around it!

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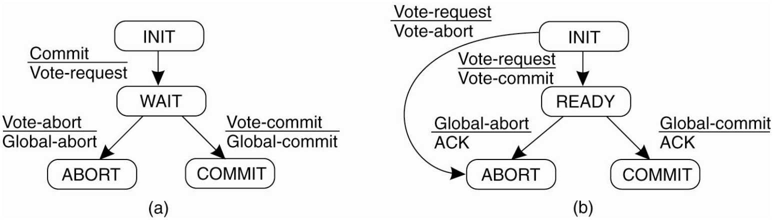
  - Three-phase commit: Can work even if the coordinator crashes, but rarely used in practice.

Two Phase Commit (1)



(a) The finite state machine for the coordinator in Two Phase Commit (2PC).

(b) The finite state machine for a participant.

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  - We can simply block until the coordinator recovers.
  - Or contact another participant Q to see if it can decide from Q's state what to do. Four cases to deal with here that are summarized on next slide.

Two Phase Commit (3)

State of Q	Action by P
COMMIT	Make transition to COMMIT
ABORT	Make transition to ABORT
INIT	Make transition to ABORT
READY	Contact another participant

- Actions taken by a participant P when residing in state READY and having contacted another participant Q.

Two Phase Commit (4)

- **actions by coordinator**

```
write START_2PC local log;
multicast VOTE_REQUEST  to all participants;
while not all votes have been collected {
    wait for any incoming vote;
    if timeout {
        write GLOBAL_ABORT to local log;
        multicast  GLOBAL_ABORT to all participants;
        exit;
    }
    record vote;
}
if all participants sent VOTE_COMMIT and coordinator votes COMMIT{
    write GLOBAL_COMMIT to local log;
    multicast GLOBAL_COMMIT to all participants;
} else {
    write GLOBAL_ABORT  to local log;
    multicast GLOBAL_ABORT to all participants;
}
```

Two Phase Commit (5)

- **actions by participant**

```
write INIT to local log;
wait for VOTE_REQUEST from coordinator;
if timeout {
    write VOTE_ABORT to local log;
    exit;
}
if participant votes COMMIT {
    write VOTE_COMMIT to local log;
    send VOTE_COMMIT to coordinator;
    wait for DECISION from coordinator;
    if timeout {
        multicast DECISION_REQUEST to other participants;
        wait until DECISION is received; /* remain blocked */
        write DECISION to local log;
    }
    if DECISION == GLOBAL_COMMIT
        write GLOBAL_COMMIT to local log;
    else if DECISION == GLOBAL_ABORT
        write GLOBAL_ABORT to local log;
} else {
    write VOTE_ABORT to local log;
    send  VOTE ABORT to coordinator;
}
```

Two Phase Commit (6)

- **actions for handling decision requests**

```
/* executed by separate thread */
while true {
    wait until any incoming DECISION_REQUEST is received; /* remain b
    read most recently recorded STATE from the local log;
    if STATE == GLOBAL_COMMIT
        send GLOBAL_COMMIT to requesting participant;
    else if STATE == INIT or STATE == GLOBAL_ABORT
        send GLOBAL_ABORT to requesting participant;
    else
        skip;  /* participant remains blocked */
}
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- Forward recovery. Bring the system to a correct new state from which it can continue execution. E.g. In an (n, k) block erasure code, a set of k source packets is encoded into a set of n encoded packets, such that any set of k encoded packets is enough to reconstruct the original k source packets.

Stable Storage

- We need fault-tolerant disk storage for the checkpoints and message logs. Examples are various RAID (Redundant Array of Independent Disks) schemes (although they are used for both improved fault tolerance as well as improved performance). Some common schemes:
  - RAID-0 block-level striping
  - RAID-1 mirroring
  - RAID-5 block-level striping with distributed parity
  - RAID-6 block-level striping with double distributed parity
  - RAID-10 stripes data across mirrored pairs

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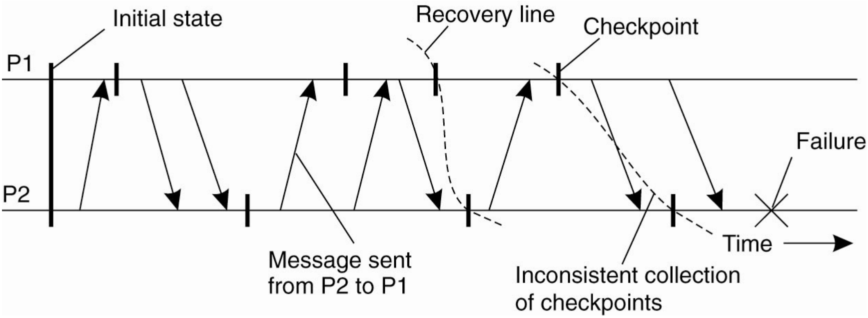
  - Message logging:
    - Optimistic message logging
    - Pessimistic message logging

Checkpointing and Recovery Line



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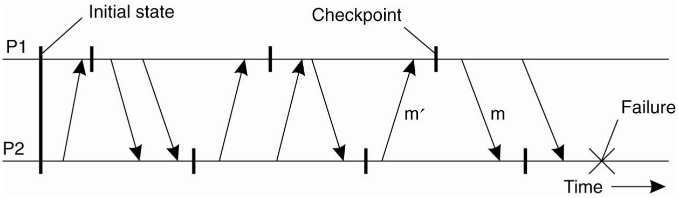
- To discover a recovery line requires that each process be rolled back to its most recently saved state. If these local states jointly do not form a distributed snapshot, further rolling is necessary. This can lead to a domino effect.
- Find the recovery line in the following timeline:



Coordinated Checkpointing (1)

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- Assumes a piece wise deterministic model, where deterministic intervals occur between sending/receiving messages. The deterministic interval starts with a non-deterministic event such as sending or receiving a message. Then the execution of the process is deterministic until the next non-deterministic event.
- An deterministic interval can be replayed with a known result, provided it is replayed starting with the same non-deterministic event as before. Hence if we record all non-deterministic events, it becomes possible to completely replay the entire execution of a process in a deterministic way.

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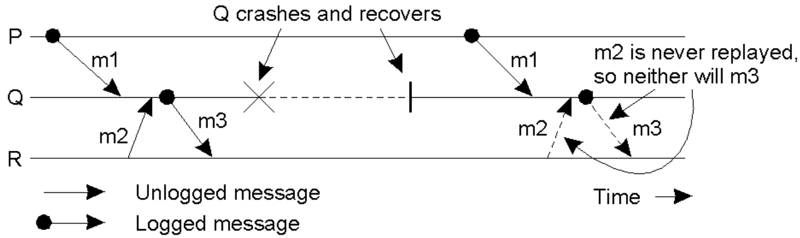

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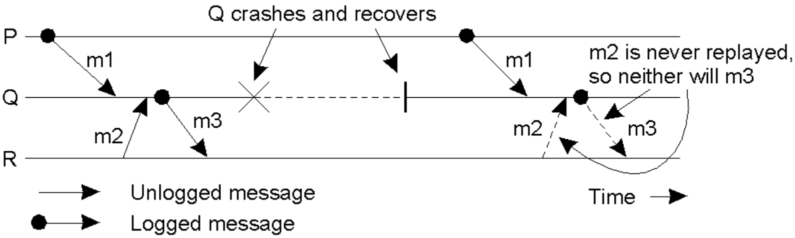

- How to deal with orphans?

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