Fault Tolerance

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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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  - Safety
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- **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?

Fault Tolerance: Basic Concepts (2)

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

Failure Models

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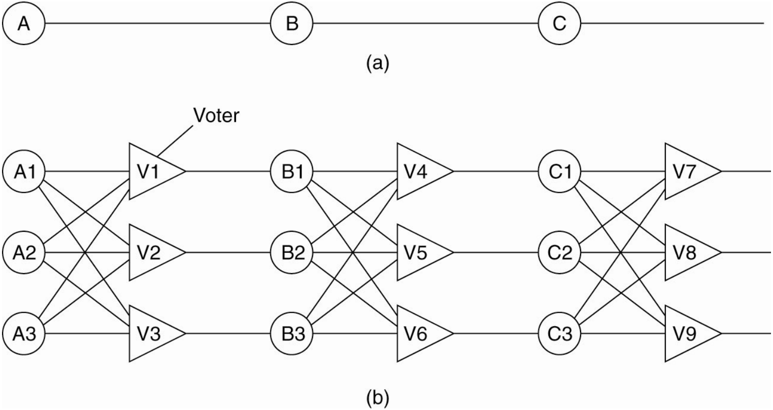
- Fail-stop versus fail-silent.
- Byzantine Failures:
  - Arbitrary failures where a server is producing output that it should never have produced, but which cannot be detected as being incorrect.
  - A faulty server may even be working with other servers to produce intentionally wrong answers!

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.

Failure Masking by Physical Redundancy

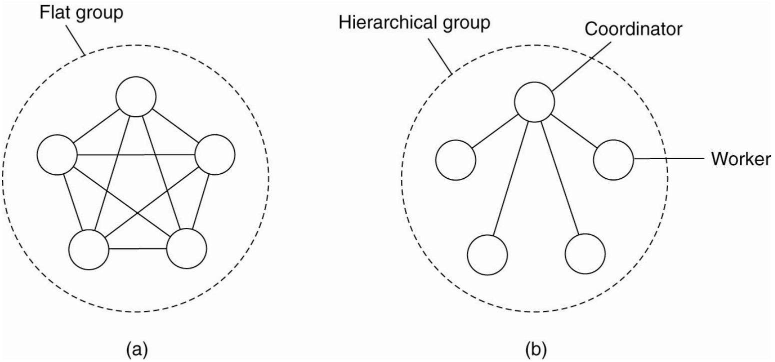


Process Resilience

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.
- *Replicated-write protocols*. Active replication as well as quorum based protocols. Corresponds to a flat group.

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    - For *fail-silent* components, $k+1$ are enough to be k fault tolerant.
    - 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.

Agreement in Faulty Systems (1)

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The general goal of distributed agreement 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

Agreement in Faulty Systems (2)

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

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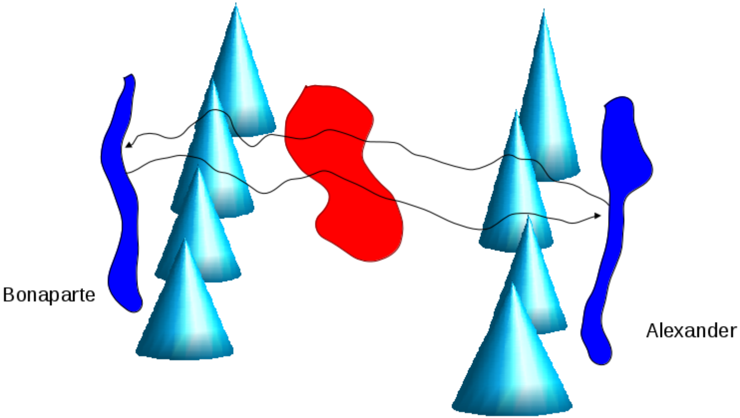
Synchronous	Bounded			X	
Synchronous	Unbounded			X	
Asynchronous	Bounded	X	X	X	X
Asynchronous	Unbounded			X	X

Message ordering: Unordered / Ordered; Message transmission: Unicast / Multicast

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

Agreement in Faulty Systems (3)



- 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 read 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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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.
- We assume that there are at most m faulty processes.

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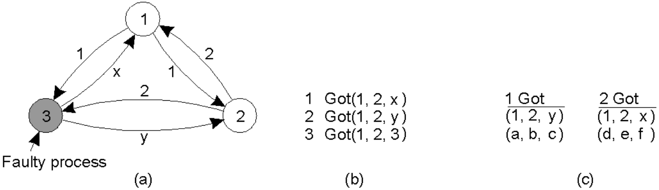

- We have 2 loyal generals and one traitor.

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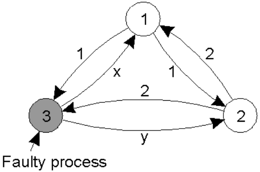

(a)

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

(b)

1 Got	2 Got
(1, 2, y)	(1, 2, x)
(a, b, c)	(d, e, f)

(c)

- We have 2 loyal generals and one traitor.
- Note that process 1 sees a value of 2 from process 2 (process 2 vector) but sees a value of *b* for process 2 (process 3 vector). But process 1 has no way of knowing whether process 2 or process 3 is a traitor. So it cannot decide the right value for $V[2]$.

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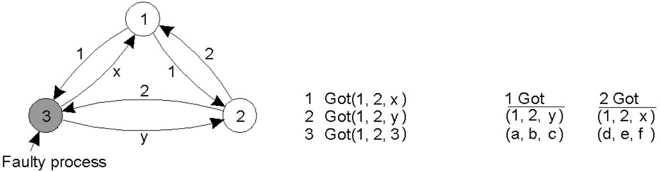

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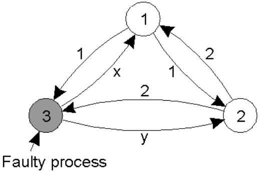

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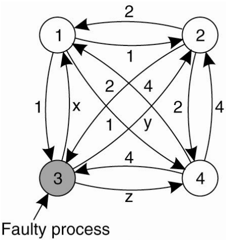
- Similarly, process 2 cannot ascertain the right value for $V[1]$. Hence, they cannot reach agreement.
- For m faulty processes, we need $2m+1$ non-faulty processes to overcome the traitors. In total, we need a total of $3m+1$ processes to reach agreement.

Byzantine Agreement Example (2)



(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.

Reliable Client-Server Communication

RMI semantics in the presence of failures.

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RPC Semantics in the Presence of Failures

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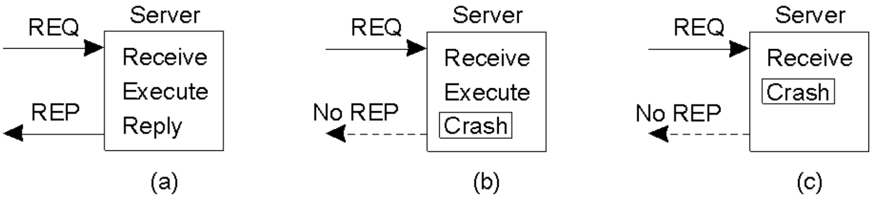
- Possible RPC semantics
  - Exactly once semantics
  - At least once semantics
  - At most once semantics
  - Guarantee nothing semantics

Server Crash (1)



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

Server Crash (2)

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  - Reissue a request only if it did not receive an acknowledgment of its request being delivered to the server.
  - Reissue a request only if it has not received an acknowledgment of its print request.

Server Crash (3)

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  - Send the completion message (M)
  - Print the text (P)
  - Crash (C)

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

Server Crash (4)

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4. $P \to C(\to M)$: The text printed, after which a crash occurs before the completion message could be sent.

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4. $P \rightarrow C(\rightarrow M)$: The text printed, after which a crash occurs before the completion message could be sent.
5. $C(\rightarrow P \rightarrow M)$: A crash happens before the server could do anything.

Server Crash (4)

1. $M \rightarrow P \rightarrow C$: A crash occurs after sending the completion message and printing the text.
2. $M \rightarrow C(\rightarrow P)$: A crash happens after sending the completion message, but before the text could be printed.
3. $P \rightarrow M \rightarrow C$: A crash occurs after sending the completion message and printing the text.
4. $P \rightarrow C(\rightarrow M)$: The text printed, after which a crash occurs before the completion message could be sent.
5. $C(\rightarrow P \rightarrow M)$: A crash happens before the server could do anything.
6. $C(\rightarrow M \rightarrow P)$: A crash happens before the server could do anything.

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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  - Use a sequence number with each request so server can detect duplicates. But now the server needs to keep state for each client....
  - Have a bit in the message to distinguish between original and duplicate transmission

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- Atomic multicasting using Virtual Synchrony

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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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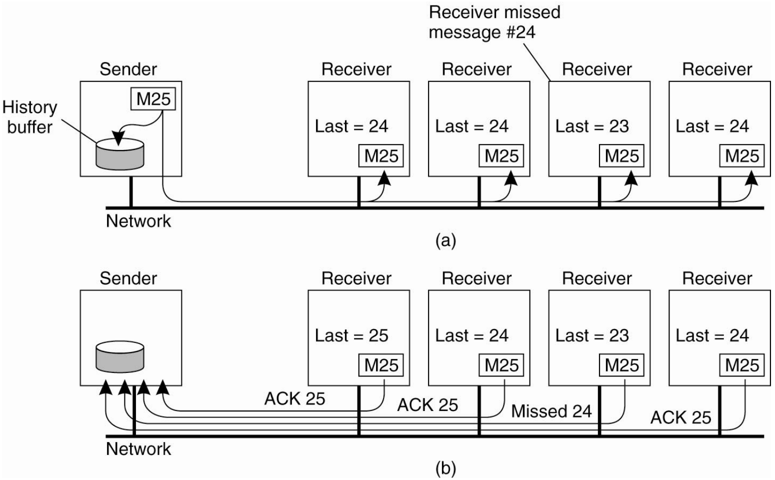
- Each multicast message is kept in a history buffer at the sender. Assuming that the sender knows the receivers, the sender simply keeps the message until all receivers have returned the acknowledgment (`Ack`).
- Sender retransmits on a negative `Ack` or on timeout before all `Ack`s were received. `Ack`s 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.

Scalability in Reliable Multicasting

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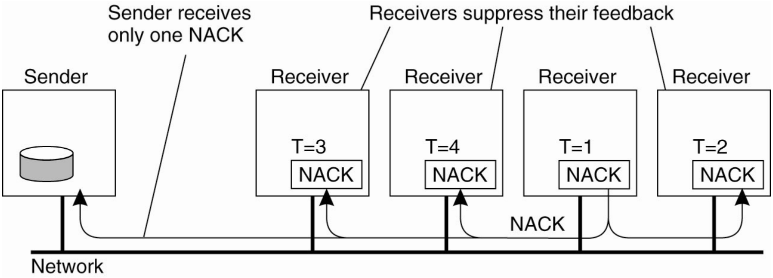
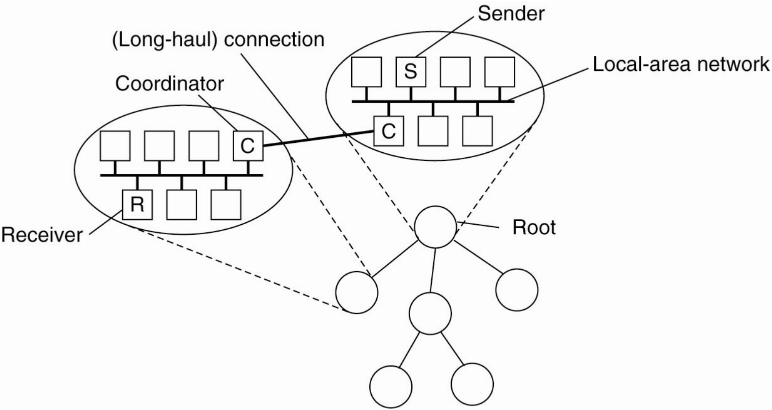
- Nonhierarchical feedback control: Feedback suppression via multicasting of negative feedback.
- Hierarchical feedback control: Use subgroups and coordinators in each subgroup.

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

- The atomic multicast setup to achieve reliable multicasting in the presence of process failures requires the following conditions:
  - A message is delivered to all processes or to none at all.
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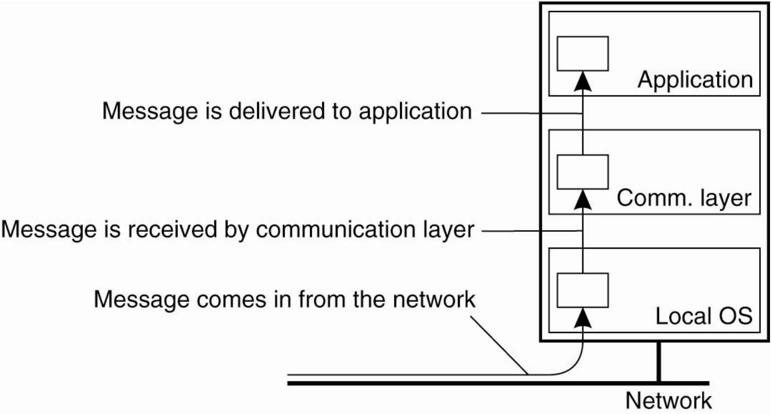
  - A message is delivered to all processes or to none at all.
  - All messages are delivered in the same order to all processes.
- For example, this solves the problem of a replicated database on top of a distributed system.
  - Atomic multicasting ensures that non-faulty processes maintain a consistent 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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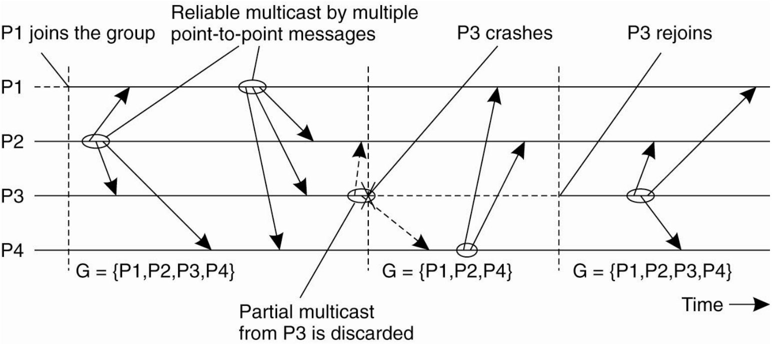
- All multicasts that are in transit when a view change takes place are completed before the view change comes into effect.

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.

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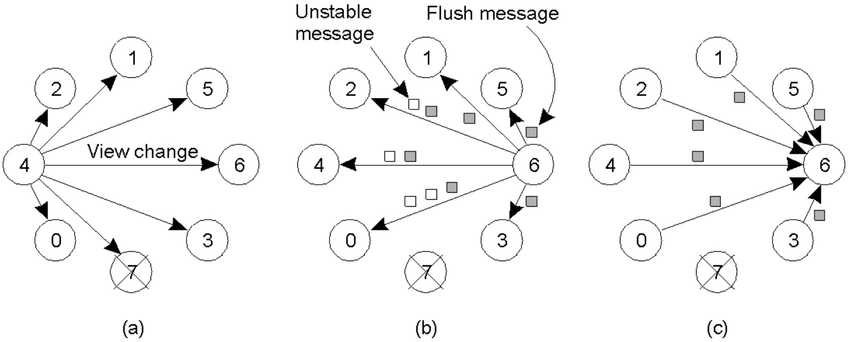
- Assumes that no process crashes during a view change (although it can be generalized to handle that as well).

Implementing Virtual Synchrony (2)



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

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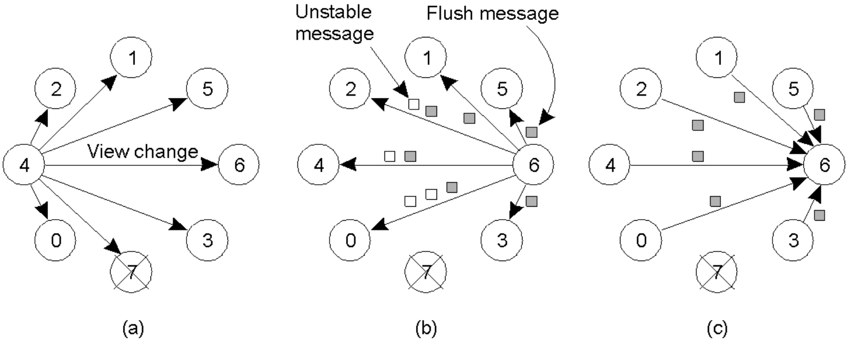

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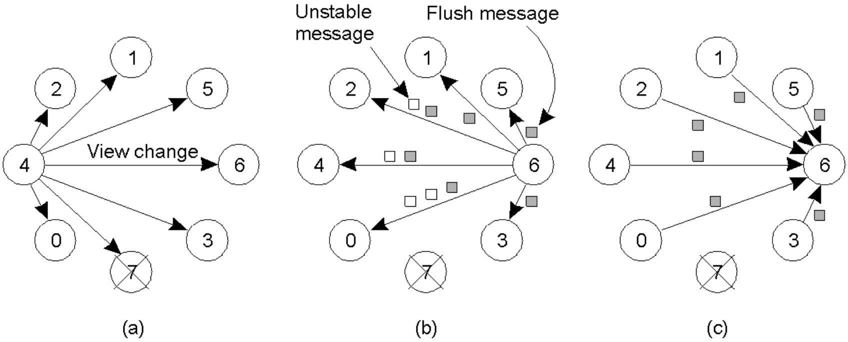

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(c) Process 6 installs the new view when it has received a flush message from everyone else.

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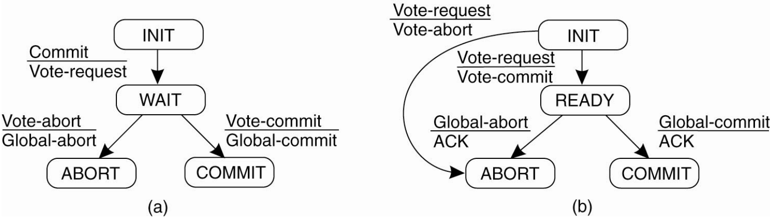
  - Three-phase commit: Can work even if the coordinator crashes, but rarely used in practice.

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 bl
    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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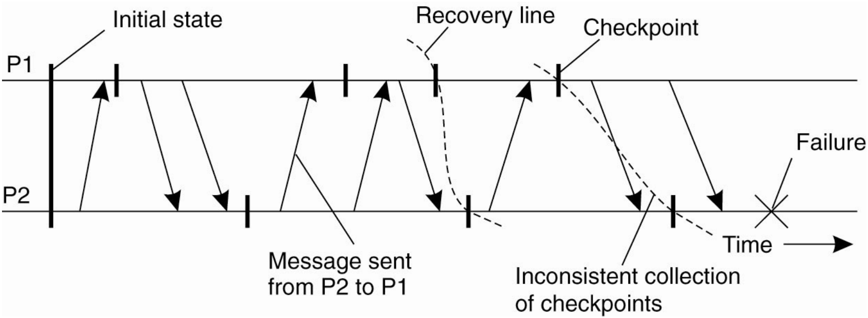
Checkpointing and Recovery Line



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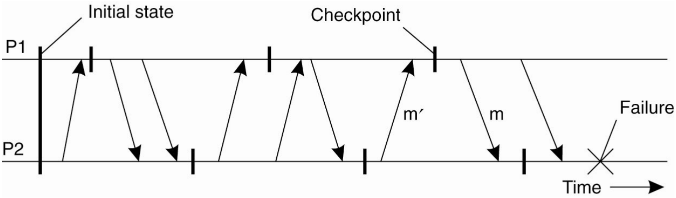
- Find the recovery line in the following timeline:



Coordinated Checkpointing (1)

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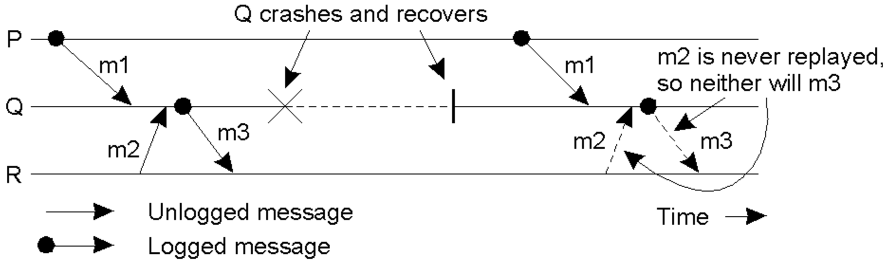
- Assumes a piece wise deterministic model, where deterministic intervals occur between sending/receiving messages. The deterministic interval starts with a non-deterministic event such as sending or receiving a message. Then the execution of the process is deterministic until the next non-deterministic 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.

Orphan Process



- An orphan process is a process that has survived the crash of another process, but whose state is inconsistent with the crashed process after its recovery.
- The figure above shows an incorrect replay of messages after recovery, leading to an orphan process. Which one is the orphan process?

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- Optimistic logging protocol: After a crash, orphan processes are rolled back until they are not in DEP(m). Much more complicated than pessimistic logging.

The CAP Theorem

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Brewer's CAP Theorem (julianbrowne.com)

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- Design around it!

References

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