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HA NOI UNIVERSITY OF SCIENCE AND TECHNOLOGY
SCHOOL OF INFORMATION AND COMMUNICATION TECHNOLOGY

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Chapter 6: Fault Tolerance

Outline

1. Introduction to fault tolerance
2. Process resilience
3. Reliable client-Server Communication
4. Reliable Group Communication
5. Distributed Commit
6. Recovery

1. Introduction to fault tolerance

1.1. Basic concept

1.2. Failure models

1.3. Failure masking by redundancy

1.1. Basic concept

- Being *fault tolerant* related to ***Dependable systems*** *which cover:*
  - Availability
  - Reliability
  - Safety
  - Maintainability
- ***Fail/Fault***
- ***Fault Tolerance***
- ***Transient Faults***
- ***Intermittent Faults***
- ***Permanent Faults***

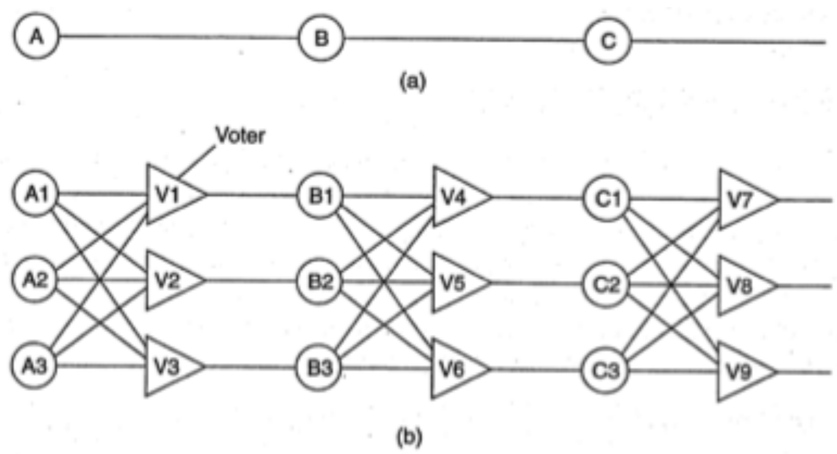
1.2. Failure models

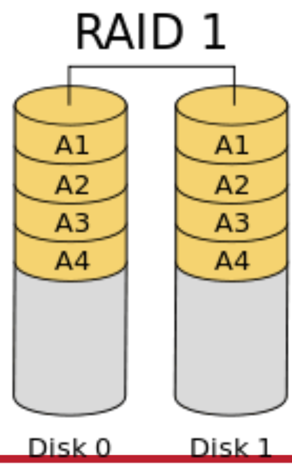
Different types of failures

Type of failure	Description
Crash failure	A server halts, but is working correctly until it halts
Omission failure	Aserver fails to respond to incoming requests
Receive omission	A server falls to receive incoming messages
Send omission	A server falls 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
Fail-stop failure	A server stops producing output and its halting can be detected by other systems
Fail-silent failure	Another process may incorrectly conclude that a server has halted
Fail-safe	A server produces random output which is recognized by other processes as plain junk

1.3. Failure masking by redundancy

- Three possible kinds for masking failure
  - ***Information redundancy***
  - ***Time redundancy***
  - ***Physical redundancy***
- Triple Modular Redundancy (***TMR***)
- RAID 1





2. Process resilience

2.1. Design issues

2.2. Failure masking and replication

2.3. Agreement in faulty system

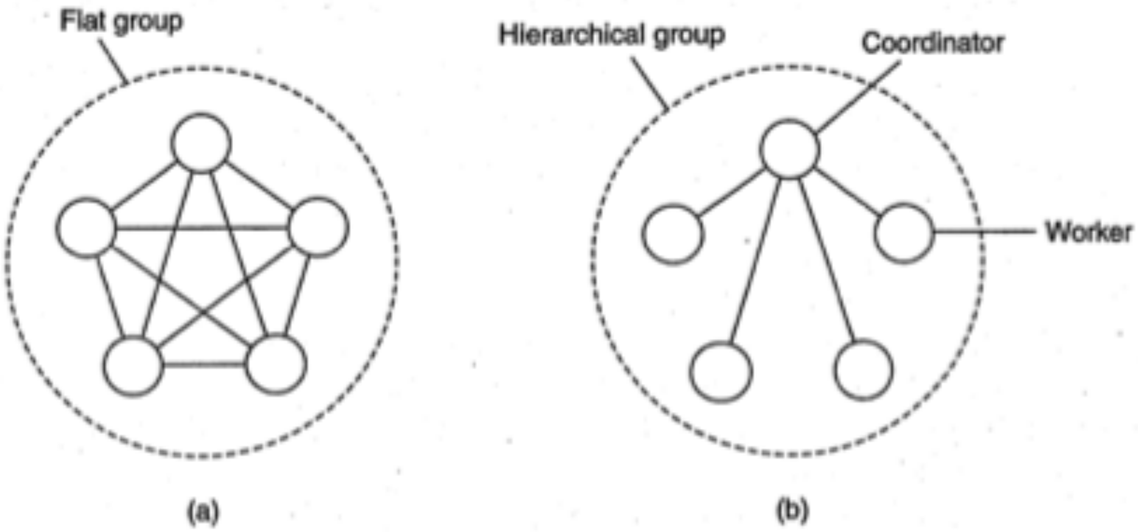
2.4. Failure detection

2.1. Design issues (1/3)

- ***Process group***
  - Key approach: organize several identical processes into a group
  - Key property: message is sent to the group itself and all members receive it
  - Dynamic: create, destroy, join or leave

2.1. Design issues (2/3)

- ***Flat Groups*** versus ***Hierarchical Groups***

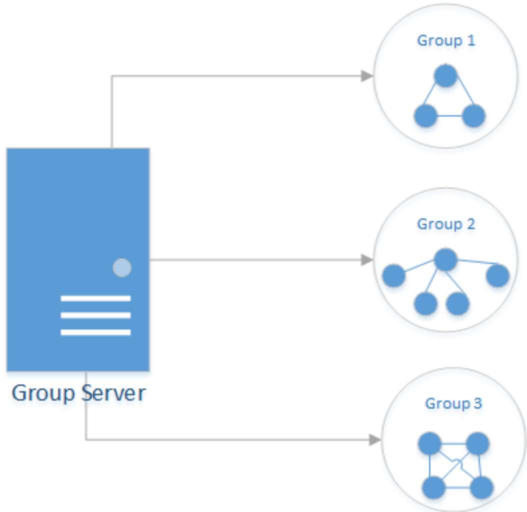


- Comparison

	Advantages	Disadvantages
Flat Groups	Symmetrical No single point of failure Group still continues while one of the processes crashes	Complicated decision making
Hierarchical Groups	Easy decision making	Loss of coordinator brings the group to halt

2.1. Group membership(3/3)

- ***Group Server***



Approach
- Send request
- Maintain databases of all groups
- Maintain their memberships

Disadvantages
- A single point of failure

- ***Distributed way***

Approach - each member communicates directly to all others
Disadvantages
- Fail-stop semantics are not appropriate
- Leaving and joining must be synchronous with data messages being sent

- ***Membership issues***

What happens when multiple machines crash at the same time?

2.2. Failure masking and Replication

- ***Primary-based protocols***
- Used in form of primary-backup protocol
- Organize group of processes in hierarchy
- Backups execute election algorithm to choose a new primary

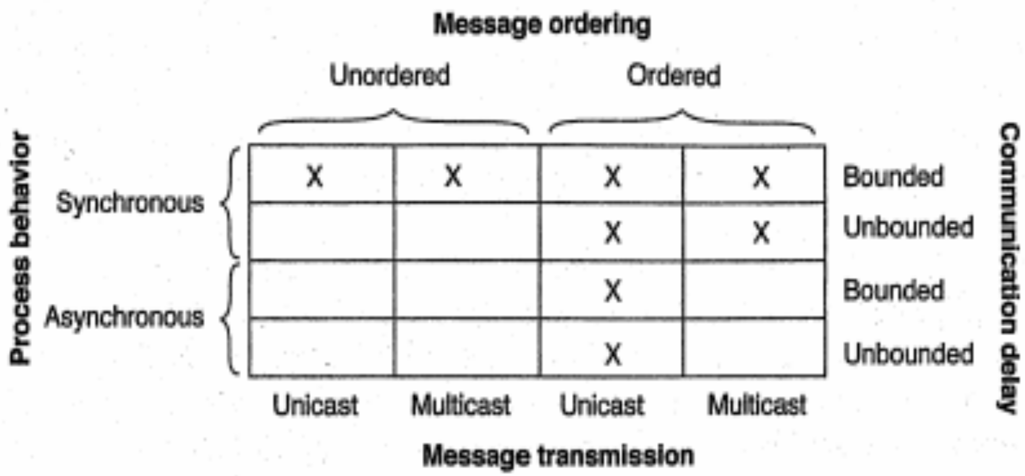
- ***Replicated-write protocols***
- Used in form of *active replication* or *quorum-based protocols*
- Organize a collection of identical processes into a flat group
- Called *'k fault tolerant'* if system can survive faults in k components.

2.3. Agreement in Faulty systems (1/3)

- ***Different cases***

1. Synchronous versus asynchronous system
2. Communication delay is bounded or not
3. Message delivery is ordered or not
4. Message transmission is done through unicasting or multicasting

- ***Circumstances under which distributed agreement can be reached***



2.3. Agreement in Faulty systems (2/3)

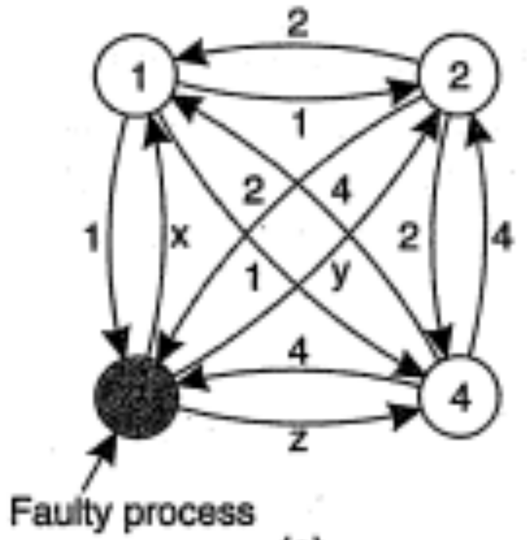
- ***Byzantine agreement***

Assuming N processes, each process i provides a value v_i

Goal: construct a vector V of length N

If i is nonfaulty then $V[i] = v_i$

- ***Example:*** $N = 4$ and $k = 1$



(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)

2.3. Agreement in Faulty systems (3/3)

- ***Lamport et al. (1982)*** proved that agreement can be achieved if
- *2k+1* correctly process for total of *3k + 1*, with *k* faulty processes

(or more than 2/3 correctly process with *2k+1* nonfaulty processes)

- ***Fisher et al. (1985)*** proved that where messages is not delivered within a known and finite time -> No possible agreement if even only one process is faulty because arbitrarily slow processes are indistinguishable from crashed ones

2.4. Failure Detection

- Two mechanisms - ***Active process and Passive Process***
- ***Timeout mechanism*** is used to check whether a process has failed. Main disadvantages:
  - Possible wrong detection when simply stating failure due to unreliable networks. Thus, generate false positives and a perfectly healthy process could be removed from the membership list
  - Failure detection is plain crude, based only on the lack of a reply to a single message
- How to ***design*** a failure ***detection subsystem***?
  - Through gossiping
  - Through probe
  - Regular information exchange with neighbors -> a member for which the availability information is old, will presumably have failed
- Failure detection ***subsystem ability***?
  - Distinguish network failures from node failures by letting nodes decide whether one of its neighbors has crashed
  - Inform nonfaulty processes about the failure detection using **FUSE** approach

3. Reliable Client-Server Communication

3.1. Point-to-Point Communication

3.2. RPC Semantics in the Presence of Failures

3.1. Point-to-Point Communication

- Point-to-point communication is established by using **reliable transport protocols**
  - TCP masks omission failures by using acknowledgments and retransmissions -> failure is hidden from TCP client

  - Crash failures cannot be masked because TCP connection is broken

    -> client is informed through exception raised

    -> Let the distributed system automatically set up a new connection

3.2. RPC Semantics in the Presence of Failures (1/5)

- **RPC (Remote Procedure Calls)** hides communication by remote procedure calls
- **Failures occur** when:
  - Client is unable to locate the server
  - Request message from the client to the server is lost
  - Server crashes after receiving a request
  - Reply message from the server to the client is lost
  - Client crashes after sending a request

3.2. RPC Semantics in the Presence of Failures (2/5)

- Client is unable to locate the server, e.g. the client cannot locate a suitable server, or all servers are down…

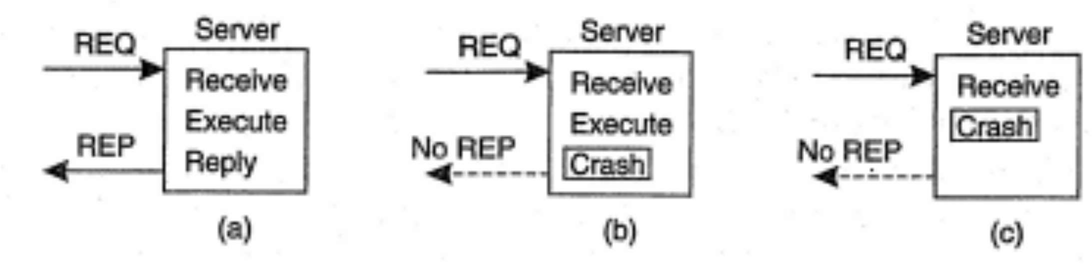
  -> Solution: raise **Exception**

  Drawbacks:

  - not every language has exceptions or signals.
  - Exception destroys the transparency
- Lost request Messages, detected by setting a timer
  - Timer expires before a reply or ack -> resend message
  - True loss -> no difference between retransmission and original
  - So many messages lost -> client gives up and concludes that the server is down, which is back to “Cannot locate server”
  - No message lost: let the server to detect and deal with retransmission

3.2. RPC Semantics in the Presence of Failures (3/5)

- <u>Server Crashes</u>



(a) Normal Case (b) Crash after execution (c) Crash before execution

Difficult to distinguish between (b) and (c)

- (b) the system has to report failure back to the client
- (c) need to retransmit the request

3 philosophies for servers:

- At least once semantics
- At most once semantics
- Exactly once semantics

4 strategies for the client

- Client decide to never reissue a request
- Client decide to always reissue a request
- Client decide to reissue a request only when no acknowledgment received
- Client decide to reissue a request only when receiving acknowledgment

3.2. RPC Semantics in the Presence of Failures (4/5)

- <u>Server Crashes (next)</u>

8 considerable combinations but none is satisfactory

- 3 events: M (send message), P (print text), C (crash)
- **6 orderings** **All possible combinations**

1. *M -> P -> C*
2. *M -> C (-> P)*
3. *P -> M -> C*
4. *P -> C –(> M)*
5. *C (-> P -> M)*
6. *C (-> M -> P)*

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

OK = Text is printed once
DUP = Text is printed twice
ZERO = Text is not printed at all

Conclusion

- The possibility of server crashes changes the nature of RPC and distinguishes single-processor systems from distributed systems
- In former case, a server crash also implies a client crash

3.2. RPC Semantics in the Presence of Failures (5/5)

- Lost Reply Messages
  - **Solution: rely on a timer** set by client's operating system

Difficulty -> The client is not really sure why there was no answer: lost or slow?

  - **Idempotent request:** asking for the first 1024 bytes of a file has no side effects and executing as often as necessary without any harm
  - **Assign sequence number:** server keeps track of the most recently received sequence number from each client and refuse to carry out any request a second time

- Client crashes
  - **Solution: activate computation called "orphan"**

Difficulty:

  - Waste CPU cycles
  - Lock files or tie up valuable resources
  - Confusion if the client reboots and does RPC again

- **Alternative solutions:**
  - Orphan extermination
  - Reincarnation
  - Gentle Reincarnation
  - Expiration

4. Reliable Group Communication

4.1. Basic Reliable – Multicasting Schemes

4.2. Scalability in Reliable Multicasting

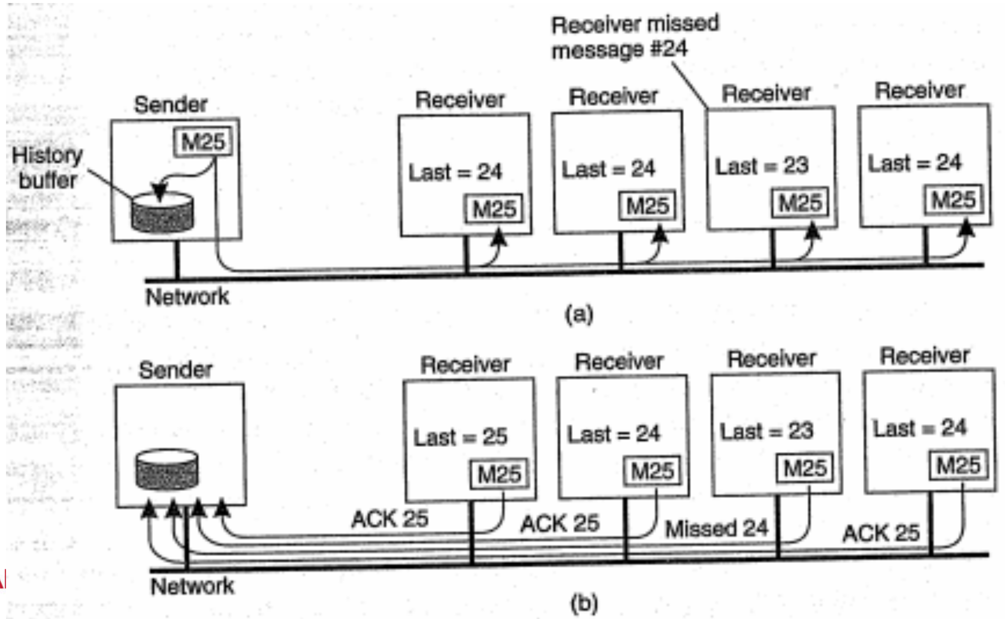
4.3. Atomic Multicast

4.1. Basic Reliable – Multicasting Schemes

- **Multicasting** means that a message sent to a process group, should be delivered to each member of that group
- **In presence of faulty process**: multicasting is reliable when all nonfaulty group members receive the message
- Solution to reliable multicasting when all receivers are known and assumed not to fail

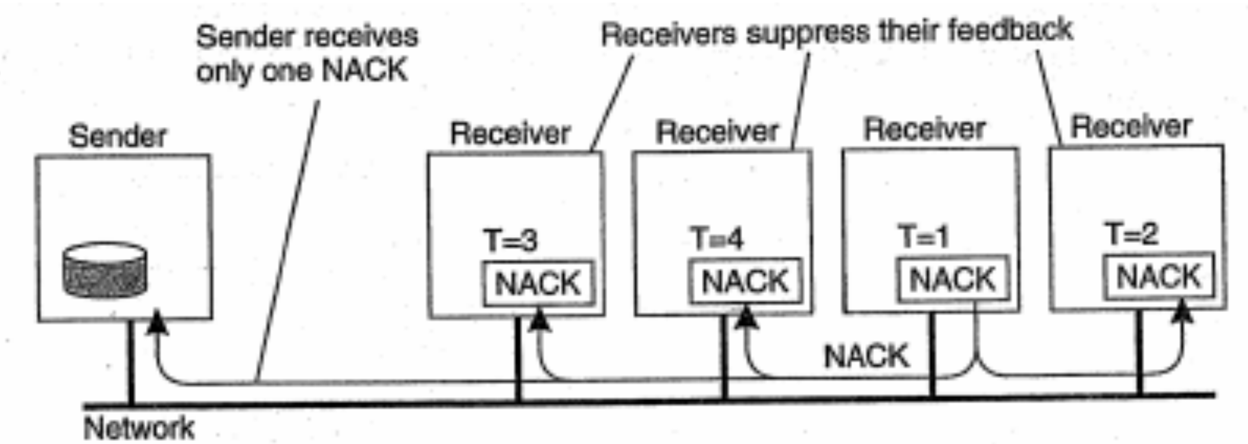
(a) Message Transmission

(b) Reporting feedback



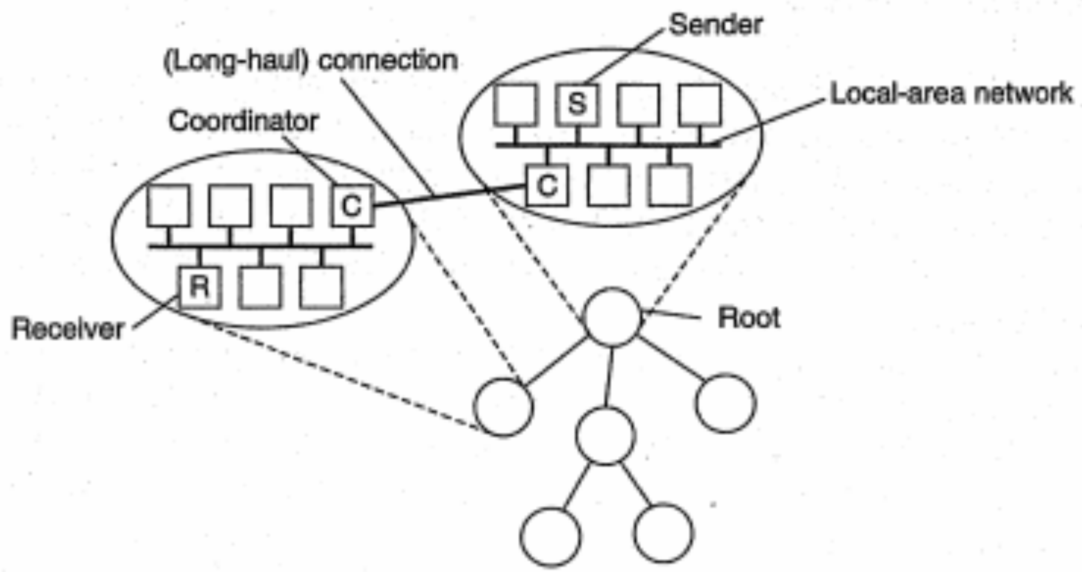
4.2. Scalability in Reliable Multicasting (1/2)

- **Problem of reliable multicast scheme** it that cannot support large numbers of receivers
- **Nonhierarchical feedback control**
  - Key: reduce the number of feedback messages returned
  - Model: feedback suppression which underlies the scalable reliable multicasting (SRM)
  - In SRM, receiver reports when missing message and multicasts its feedback to the rest of the group. Other group members will suppress its own feedback.



4.2. Scalability in Reliable Multicasting (2/2)

- **Hierarchical feedback control**
  - Achieving scalability for very large groups of receivers requires adopting hierarchical approaches
  - Each local coordinator forwards the message to its children and later handles retransmission requests



Main problem: construction of the dynamic is not easy

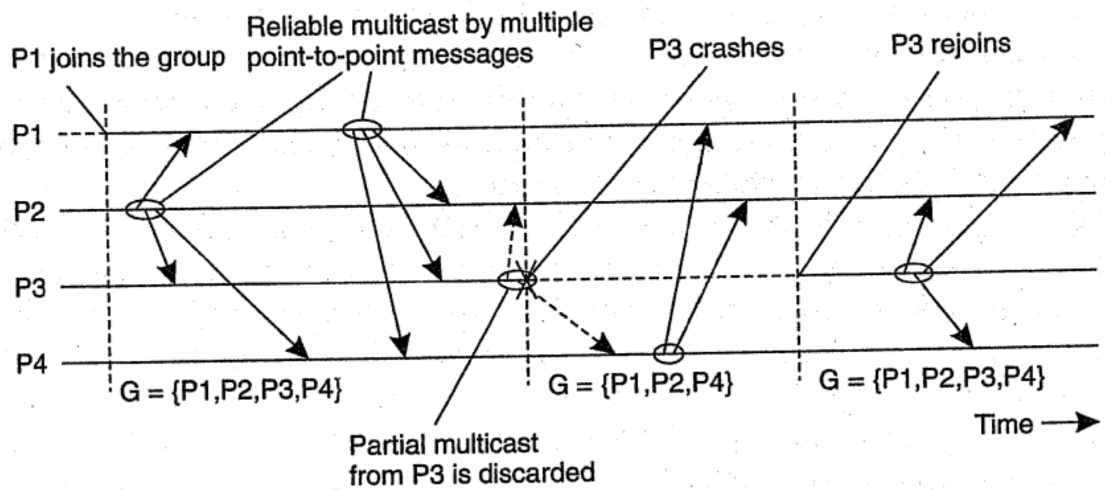
4.3. Atomic Multicast (1/6)

- **Atomic multicast:**
  - Guarantee that a message is delivered to either all processes or to non at all.
  - All messages are delivered in the same order to all processes
  - In non-atomic multicast, when there are multiple updates and a replica crashes, it is difficult to locate operations missing and the order these operations are to be performed
  - In atomic multicast, when replica crashes, it ensures that nonfaulty processes maintain a consistent view of the database and force reconciliation when a replica recovers and rejoins the group

4.3. Atomic Multicast (2/6)

- **Virtual Synchrony**

To distinguish between receiving and delivering message, adopt **distributed system model which consists of communication layer**



- Multicast message ***m*** **is associated with a list of processes** to which it should be delivered, named **group view**
- Each process on that list has the same view.
- Message m, group view G. While the multicast is taking place, another process joins or leaves the group -> **View change** – multicast a message *vc* announcing the joining or leaving of a process -> two multicast messages in transit: m and vc

4.3. Atomic Multicast (4/6)

- **Message Ordering**
  - Unordered multicasts

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

Sample of three communicating processes in the same group -> the ordering of events per process is shown along the vertical axis

  - FIFO-ordered multicasts

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

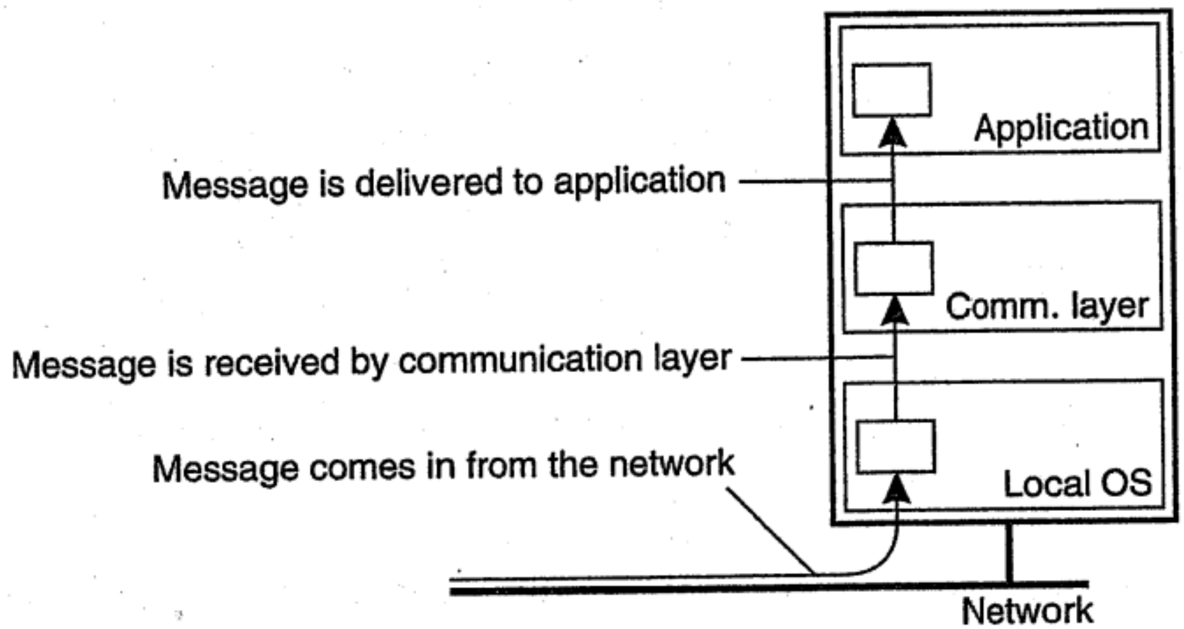
Sample of four processes in the same group with two different senders, and a possible delivery order of messages under FIFO-ordered multicasting

  - Causally-ordered multicasts
  - Totally-ordered multicasts

4.3. Atomic Multicast (5/6)

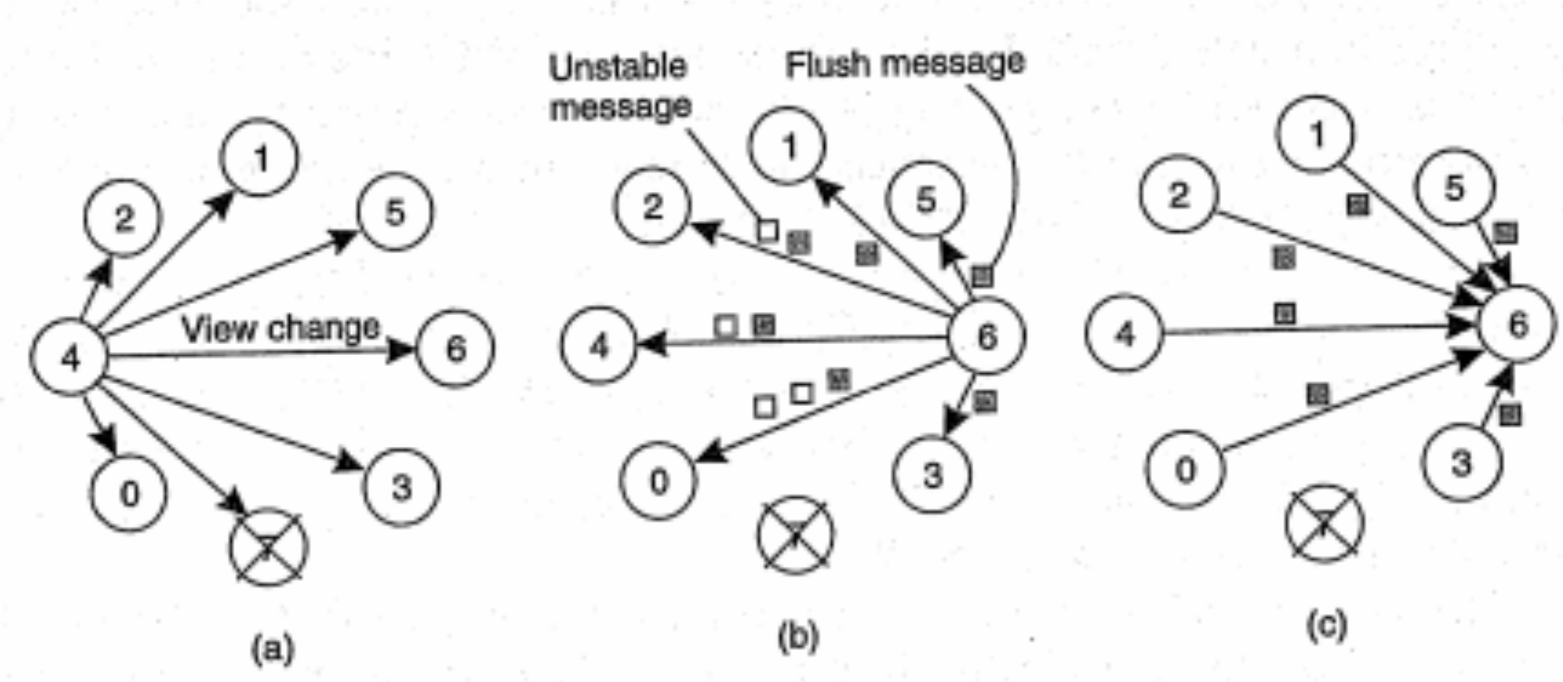
- **Implementing Virtual Synchrony**

- Goal: Guarantee that all messages sent to view G are delivered to all nonfaulty processes in G before the view change.
- Solution: Let every process in G keep m until it knows for sure that all members in G have received it.
- Stable message



4.3. Atomic Multicast (6/6)

- **Implementing Virtual Synchrony**
- Illustration of selecting stable message
  a) Process 4 notices that process 7 has crashed and sends a view change
  b) Process 6 sends out all its unstable messages and subsequently marks it as being stable, followed by a flush message
  c) Process 6 installs the new view when it has received a flush message from everyone else



5. Distributed Commit

5.1. Two-Phase Commit

5.2. Three-Phase Commit

About Distributed Commit

- Distributed commit involves **having an operation being performed by each member of a process group, or non at all**
  - Reliable multicasting: Operation = message delivery
  - Distributed transactions: Operation = transaction commit at the single site that takes part in the transaction
- Distributed commit is established by means of **coordinator**
- **One-phase commit protocol:** a simple scheme where a coordinator tells all other processes (called participants) whether or not to perform the operation in question.
- **Sophisticated schemes**: Two-phase commit or Three-phase commit

5.1. Two-Phase Commit - 2PC (1/5)

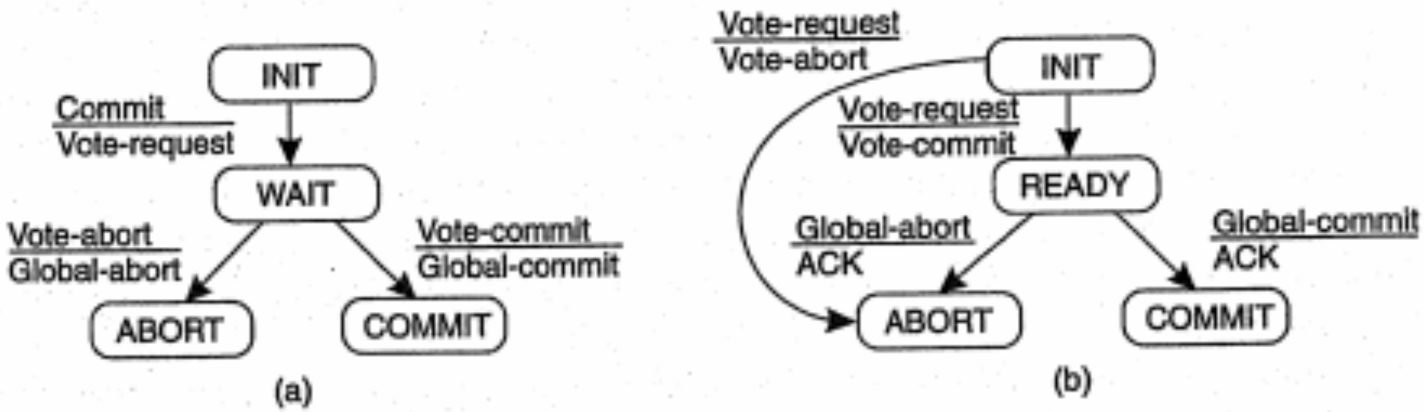
- Protocol consists **two phase**:

Phase 1

- ✓ Coordinator sends a VOTE_REQUEST message to all participants
- ✓ After receiving, participant returns VOTE_COMMIT or VOTE_ABORT message to the coordinator

Phase 2

- ✓ Coordinator collects all votes and send GLOBAL_COMMIT message or GLOBAL_ABORT message to participants
- ✓ Each participant that voted for a commit waits for the final reaction to commit or not the transaction



Coordinator **Participant**

5.1. Two-Phase Commit - 2PC (2/5)

- **Participant Solution:**
  - use timeout mechanism or let a participant P contact
  - Let a participant P contact another participant Q and decide what it should do. If P is in READY status, here are various options

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

5.1. Two-Phase Commit - 2PC (3/5)

- Sample of actions taken in place by the 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;
}
```

5.1. Two-Phase Commit - 2PC (4/5)

- Each participant should be prepared to accept requests for a global decision from other participants

```
Actions for handling decision requests: /* executed by separate thread */

while true {
    wait until any incoming DECISION_REQUEST is received; /* remain blocked */
    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 */
}
```

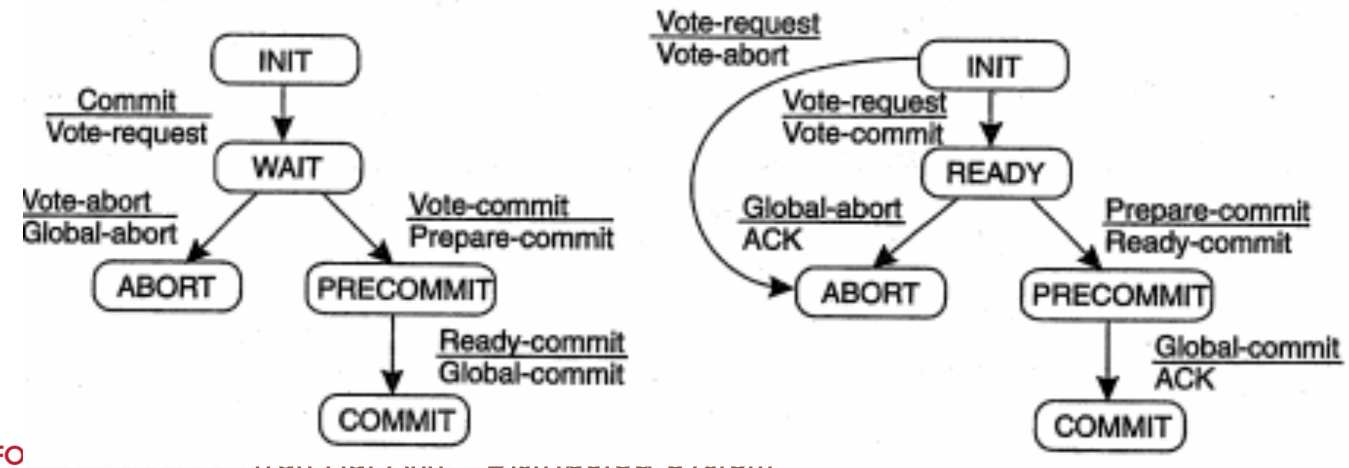
5.1. Two-Phase Commit - 2PC (5/5)

- **Coordinator solution**
  - Keep track of current state
  - Sample of actions taken in place by the coordinator:

```
write START_2PC to 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;
}
```

5.2. Three-Phase Commit (1/2)

- Two-phase problem: when the coordinator has crashed, participants may not be able make final decision
- Three-phase commit protocol (3PC) avoids blocking processes in when fail-stop crashes.
- Principle:
  - There is no single state from which it is possible to make a transition directly to either a COMMIT or an ABORT state
  - There is no state in which it is not possible to make a final decision, and from which a transition to a COMMIT state can be made
- Illustration



5.2. Three-Phase Commit (2/2)

- Actions taken by Participant in different cases

State of Participant P	State of Participant Q	State of all other participants	Action
INT			VOTE_ABORT
READY	INT		VOTE_ABORT
READY	READY	READY	VOTE_ABORT
READY	PRECOMMIT	PRECOMMIT	VOTE_COMMIT
PRECOMMIT	READY	READY	VOTE_ABORT
PRECOMMIT	PRECOMMIT	PRECOMMIT	VOTE_COMMIT
PRECOMMIT	COMMIT	COMMIT	VOTE_COMMIT

- Actions taken by Coordinator in different cases

State of Coordinator	Action
WAIT	GLOBAL_ABORT
PRECOMMIT	GLOBAL_COMMIT

- Main difference with 2PC: if any participant is in READY state, no crashed process will recover to a state other than INT, ABORT or PRECOMMIT

6. Recovery

6.1. Introduction

6.2. Checkpointing

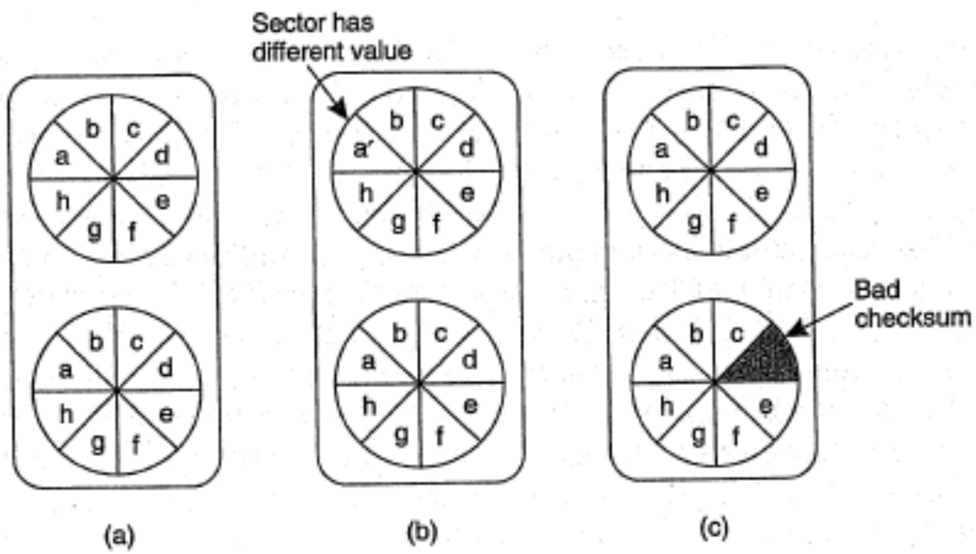
6.1. Introduction (1/2)

- **Backward recovery**: bring the system into a previously correct state.
  - Necessary to record the system's state, called checkpoint
  - Generally applied for recovering from failures in distributed systems
  - E.g. Reliable communication through packet retransmission
  - Drawback:
    - reduce performance
    - no guarantees that recovery has taken place
    - some states can never be rolled back to.
    - checkpoint could penalize performance and is cosly
  - Solution for checkpoint: combine with message logging or use receiver-based logging
- **Forward recovery**: bring the system in a correct new state from which it can continue to execute
  - E.g. Erasure correction- a missing packet is constructed from other; successfully delivered packets

6.1. Introduction (2/2)

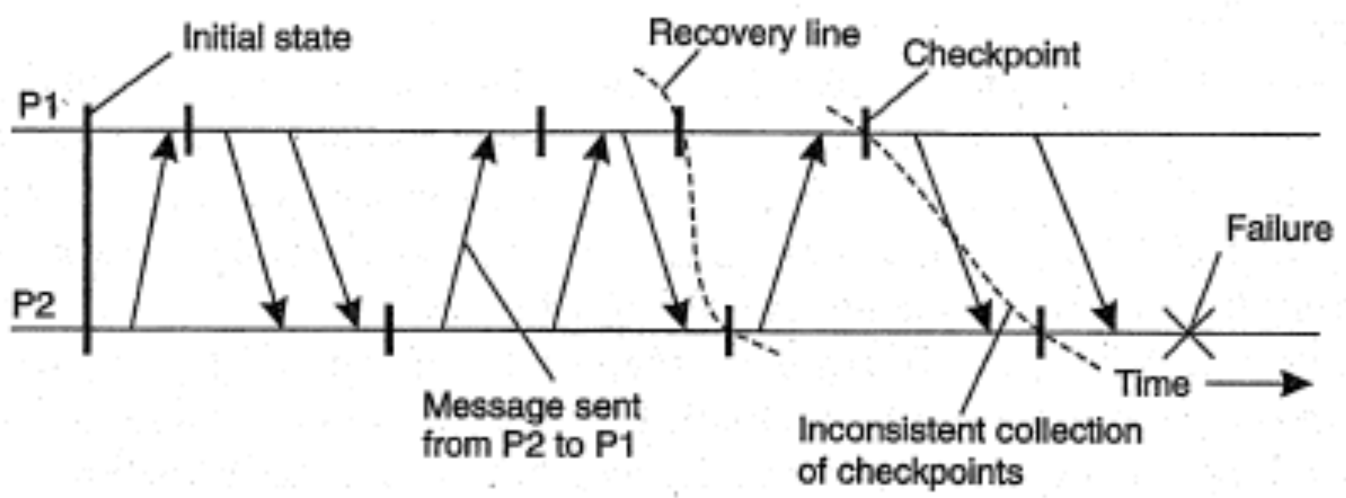
- **Stable Storage**
  - Information needed to enable recovery is safely stored in case of process crashes, site failures or various storage media failures
  - Three categories of storage: RAM memory, disk storage and stable storage
  - Sample of stable storage implementing with a pair of ordinary disk

(a) Stable storage
(b) Crash after drive 1 is updated
(c) Bad spot



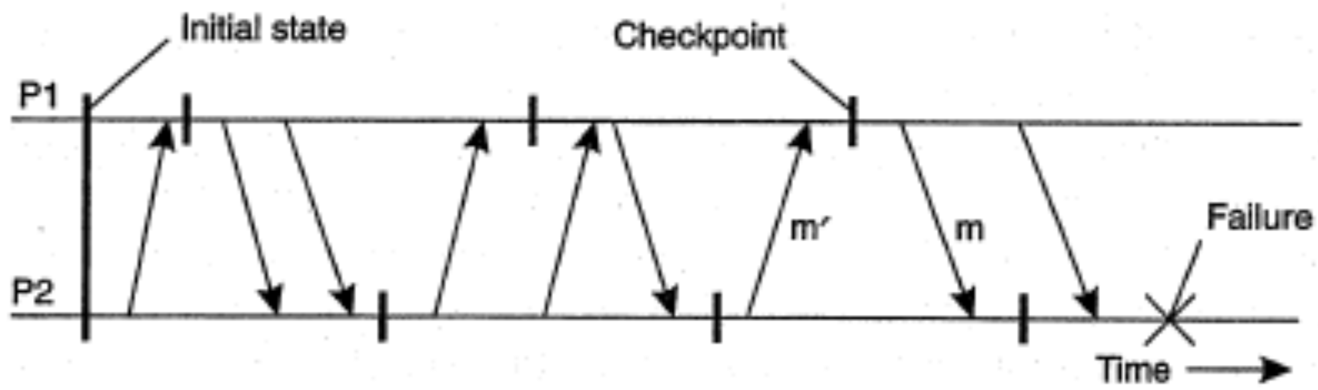
6.2. Checkpointing (1/3)

- **Distributed snapshot:** record a consistent global state.
  - If a process P records the receipt of a message, then there should also be a process Q that has recorded the sending of that message.
- **Recovery line**: recover to the most recent distributed snapshot



6.2. Checkpointing (2/3)

- **Independent Checkpointing**
  - Domino effect: process to find a recovery line via cascaded rollback



  - **Independent checkpointing**: processes take local checkpoints independent of each other.
  - **Disadvantages**: Introduction of performance problem, need of periodical cleaning for local storage, difficult problem in computing the recovery line

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Questions?