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Chapter 5: Distributed Systems: Fault Tolerance

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Chapter Outline

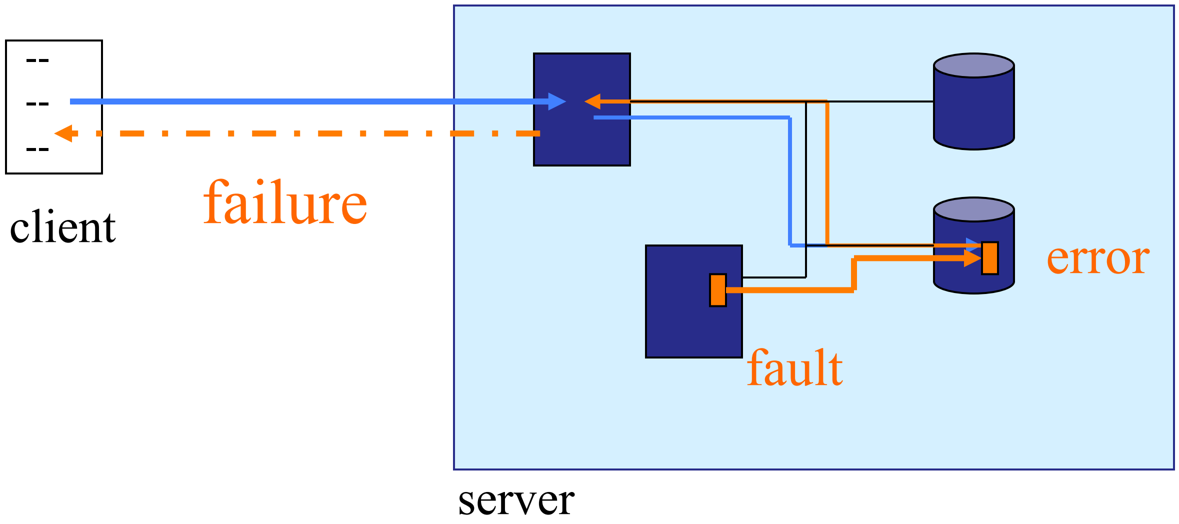
- Fault tolerance
- Process resilience
- Reliable group communication
- Distributed commit
- Recovery

Basic Concepts

Dependability includes

- Availability
- Reliability
- Safety
- Maintainability

Fault, error, failure



Failure Model

- Challenge: independent failures
- Detection
  - which component?
  - what went wrong?
- Recovery
  - failure dependent
  - ignorance increases complexity

  => taxonomy of failures

Fault Tolerance

- Detection
- Recovery
  - mask the error OR
  - fail predictably
- Designer
  - possible failure types?
  - recovery action (for the possible failure types)
- A fault classification:
  - transient (disappear)
  - intermittent (disappear and reappear)
  - permanent

Failure Models

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

Crash: fail-stop, fail-safe (*detectable*), fail-silent (*seems to have crashed*)

Failure Masking (1)

Detection

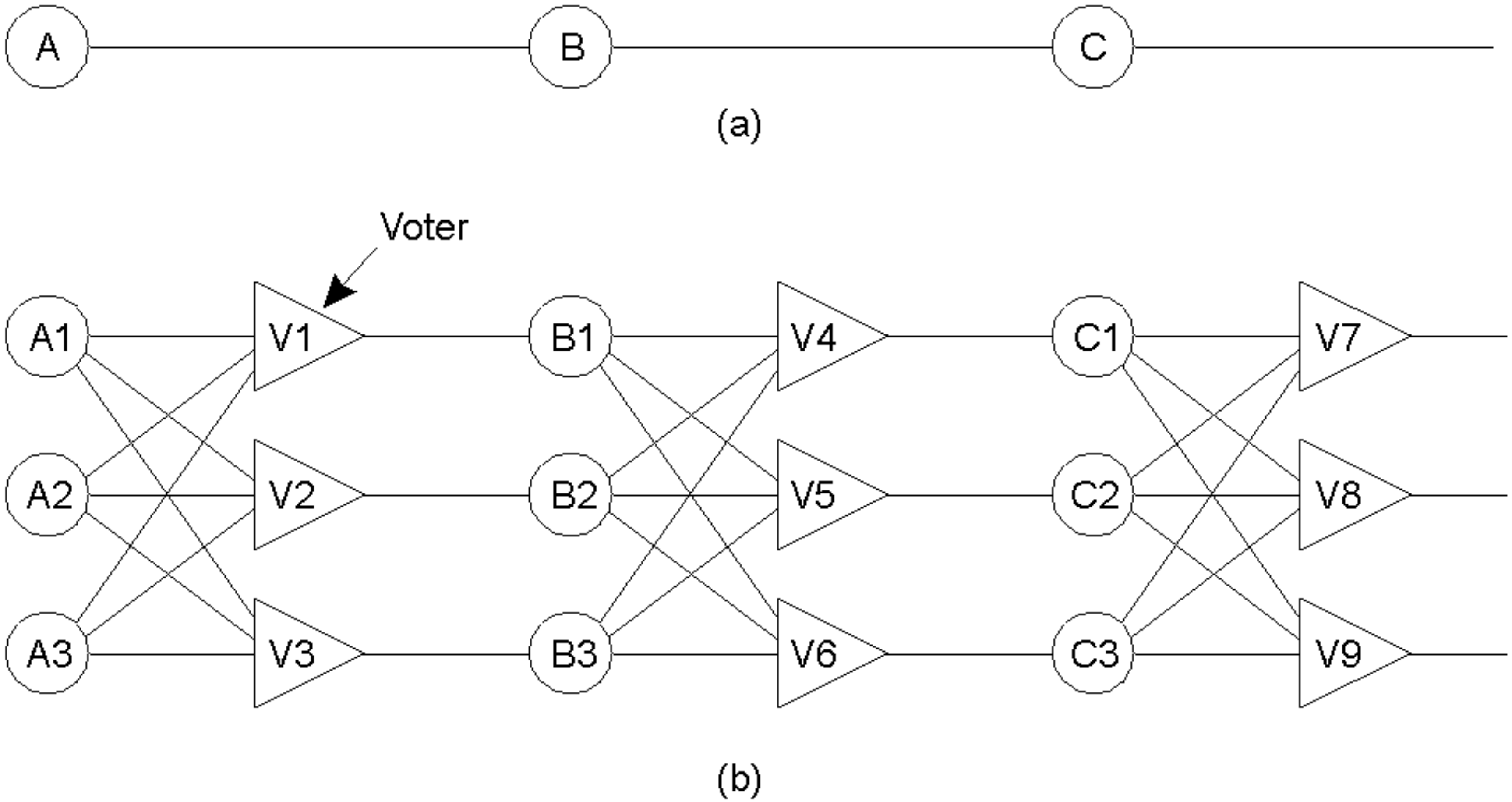
- redundant information
  - error detecting codes (parity, checksums)
  - replicas
- redundant processing
  - groupwork and comparison
- control functions
  - timers
  - acknowledgements

Failure Masking (2)

Recovery

- redundant information
  - error correcting codes
  - replicas
- redundant processing
  - *time redundancy*
    - retrial
    - recomputation (checkpoint, log)
  - *physical redundancy*
    - groupwork and voting
    - tightly synchronized groups

Example: Physical Redundancy



Triple modular redundancy.

Failure Masking (3)

- Failure models vs. implementation issues:

  the (sub-)system belongs to a class

  => certain failures do not occur

  => easier detection & recovery
- A point of view: forward vs. backward recovery
- Issues:
  - process resilience
  - reliable communication

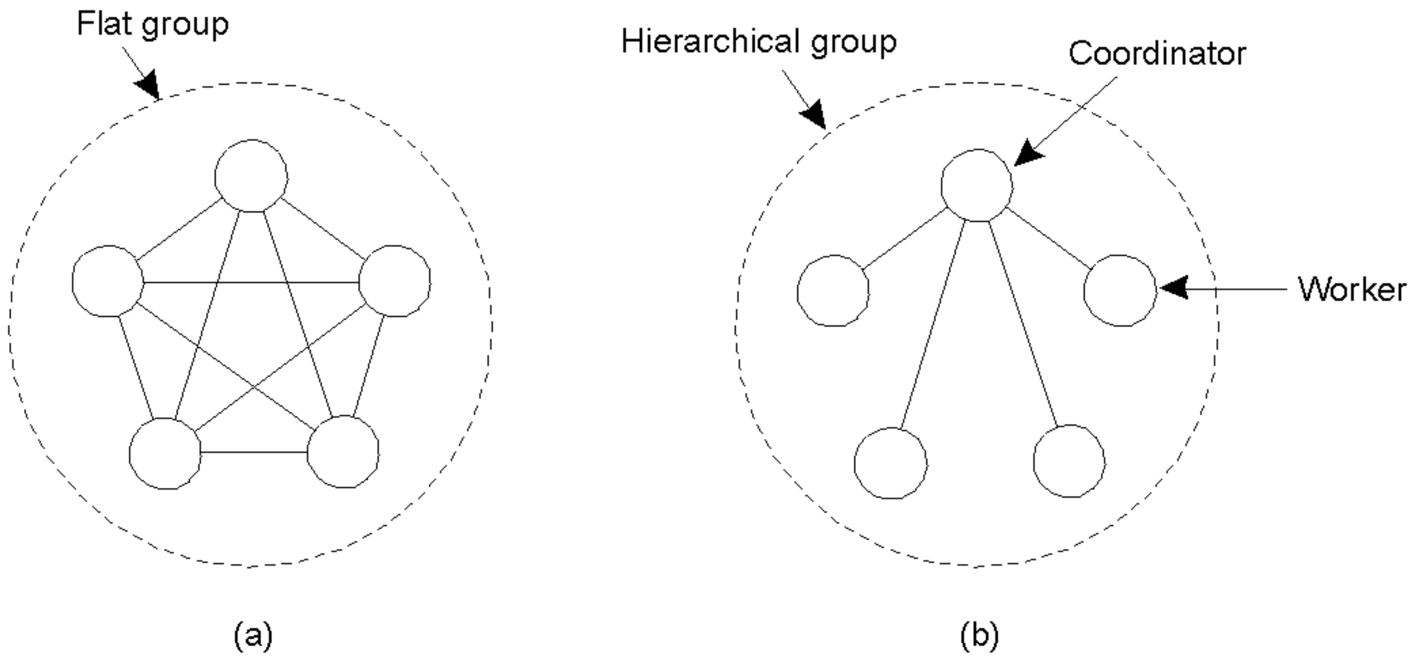
Process Resilience (1)

- Redundant processing: groups
  - Tightly synchronized
    - flat group: voting
    - hierarchical group:

      a **primary** and a **hot standby** (execution-level synchrony)
  - Loosely synchronized
    - hierarchical group:

      a **primary** and a **cold standby** (checkpoint, log)
- Technical basis
  - "group" – a single abstraction
  - reliable message passing

Flat and Hierarchical Groups (1)



Communication in a flat group.

Communication in a simple hierarchical group

Group management: a group server OR distributed management

Flat and Hierarchical Groups (2)

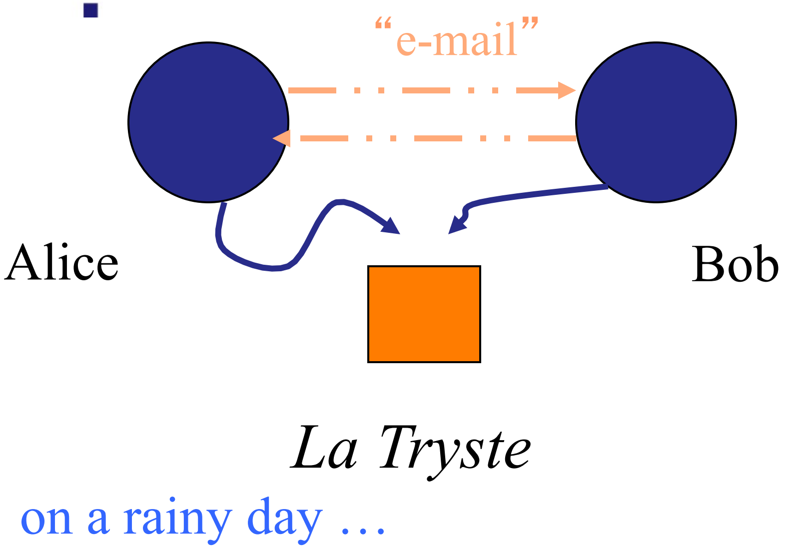
- Flat groups
  - symmetrical
  - no single point of failure
  - complicated decision making
- Hierarchical groups
  - the opposite properties

- Group management issues
  - join, leave;
  - crash (*no notification*)

Process Groups

- Communication vs management
  - application communication: message passing
  - group management: message passing
  - synchronization requirement:
    each group communication operation in a stable group
- Failure masking
  - **k fault tolerant**: tolerates k faulty members
    - fail silent: k + 1 components needed
    - Byzantine: 2k + 1 components needed
  - a precondition: **atomic multicast**
  - in practice: the probability of a failure must be "small enough"

Agreement in Faulty Systems (1)



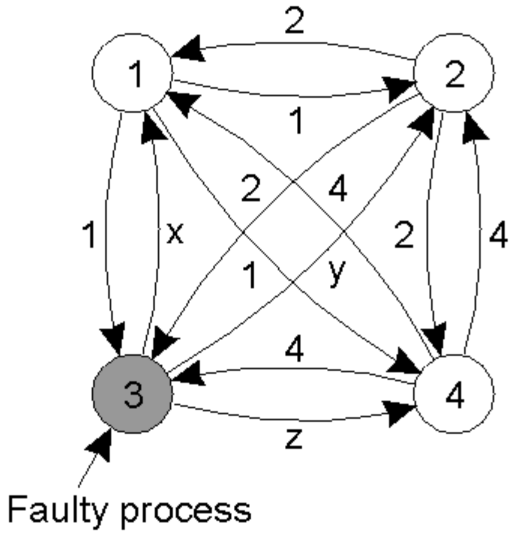
Requirement:
- an agreement
- within a bounded time

Faulty data communication: no agreement possible

Alice -> Bob *Let's meet at noon in front of La Tryste …*
Alice <- Bob *OK!!*
Alice: *If Bob doesn't know that I received his message, he will not come …*
Alice -> Bob *I received your message, so it's OK.*
Bob: *If Alice doesn't know that I received her message, she will not come …*
…

Agreement in Faulty Systems (2)

Reliable data communication, unreliable nodes



(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)

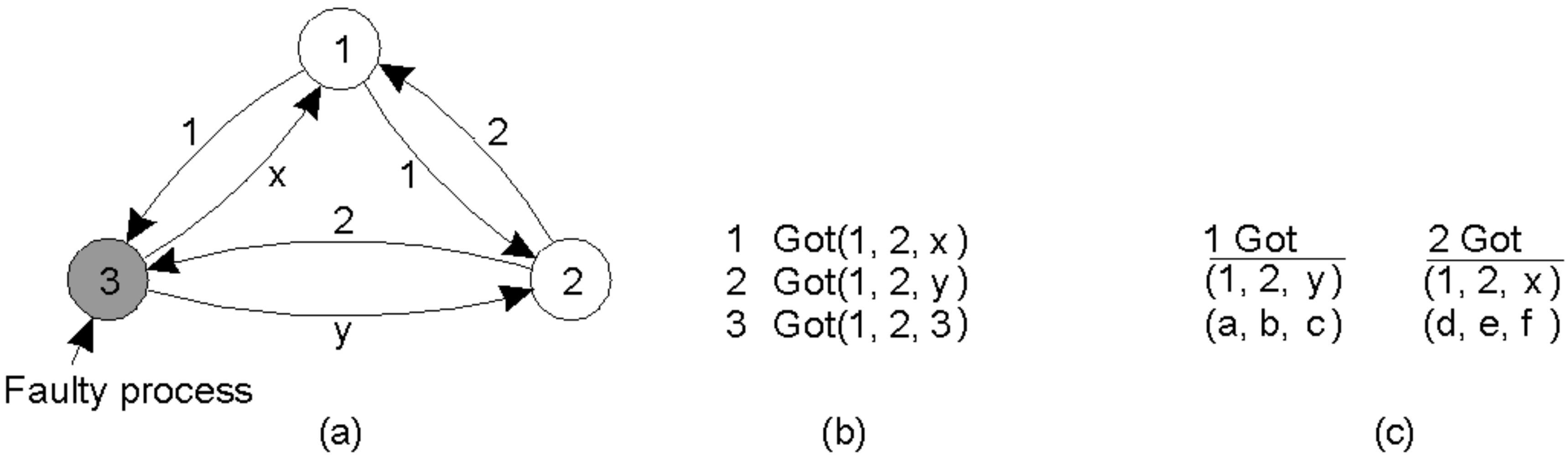
The Byzantine generals problem for 3 loyal generals and 1 traitor.

a) The generals announce their troop strengths (in units of 1 kilosoldiers).

b) The vectors that each general assembles based on (a)

c) The vectors that each general receives in step 3.

Agreement in Faulty Systems (3)



The same as in previous slide, except now with 2 loyal generals and one traitor.

Reliable Group Communication

- Lower-level data communication support
  - unreliable multicast (LAN)
  - reliable point-to-point channels
  - unreliable point-to-point channels
- Group communication
  - individual point-to-point message passing
  - implemented in middleware or in application
- Reliability
  - acks: lost messages, lost members
  - communication consistency ?

Reliability of Group Communication?

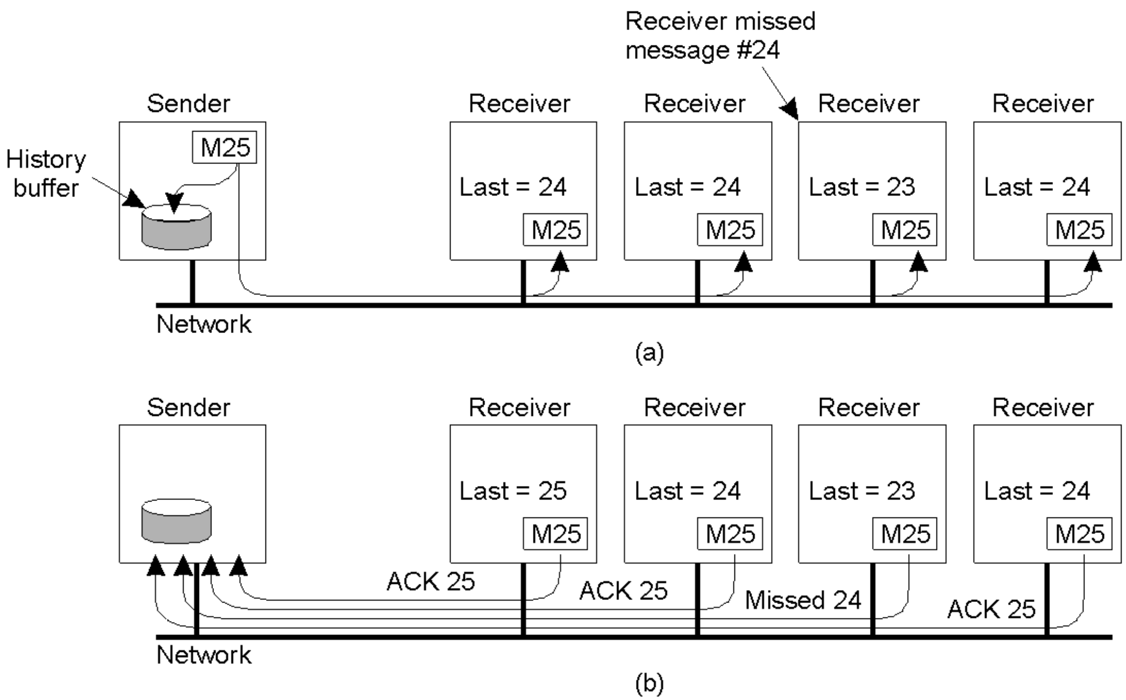
- A sent message is received by all members

  (acks from all => ok)
- Problem: during a multicast operation
  - an old member disappears from the group
  - a new member joins the group
- Solution
  - membership changes synchronize multicasting

  => during an MC operation no membership changes

  An additional problem: the sender disappears (remember: multicast ~ for (all P_i in G) {send m to P_i})

Basic Reliable-Multicasting Scheme



Message transmission

Reporting feedback

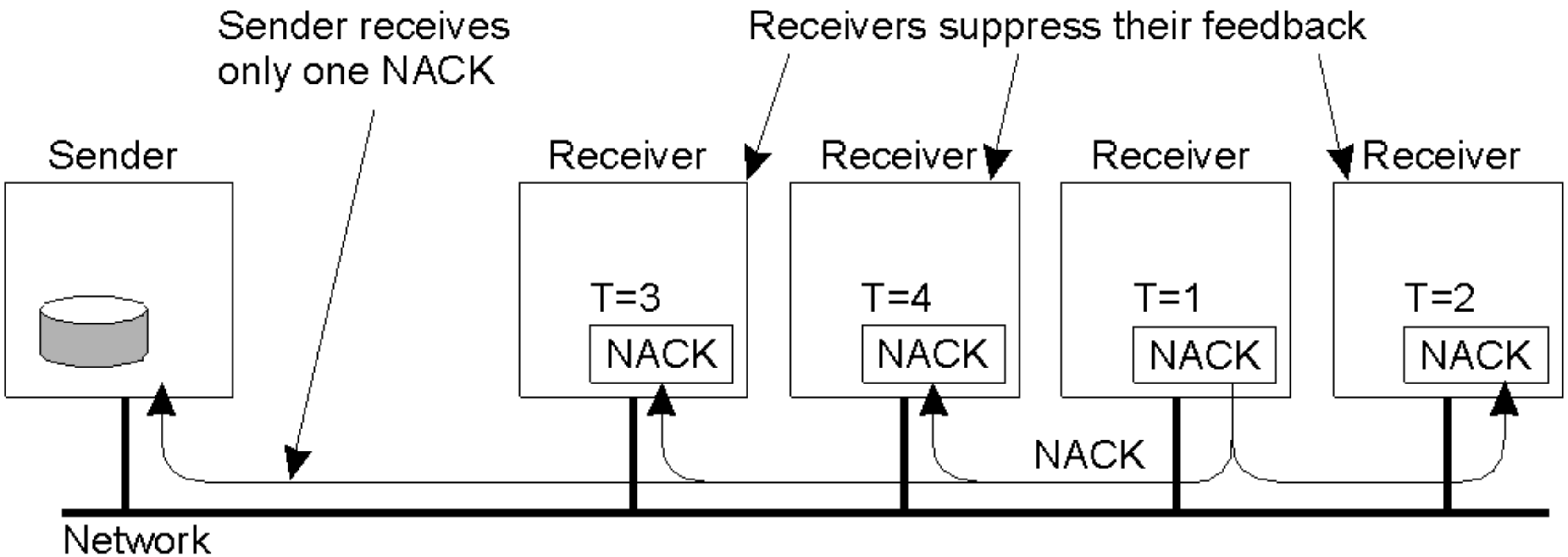
A simple solution to reliable multicasting when all receivers are known and are assumed not to fail

Scalability?

Feedback implosion !

Scalability: Feedback Suppression

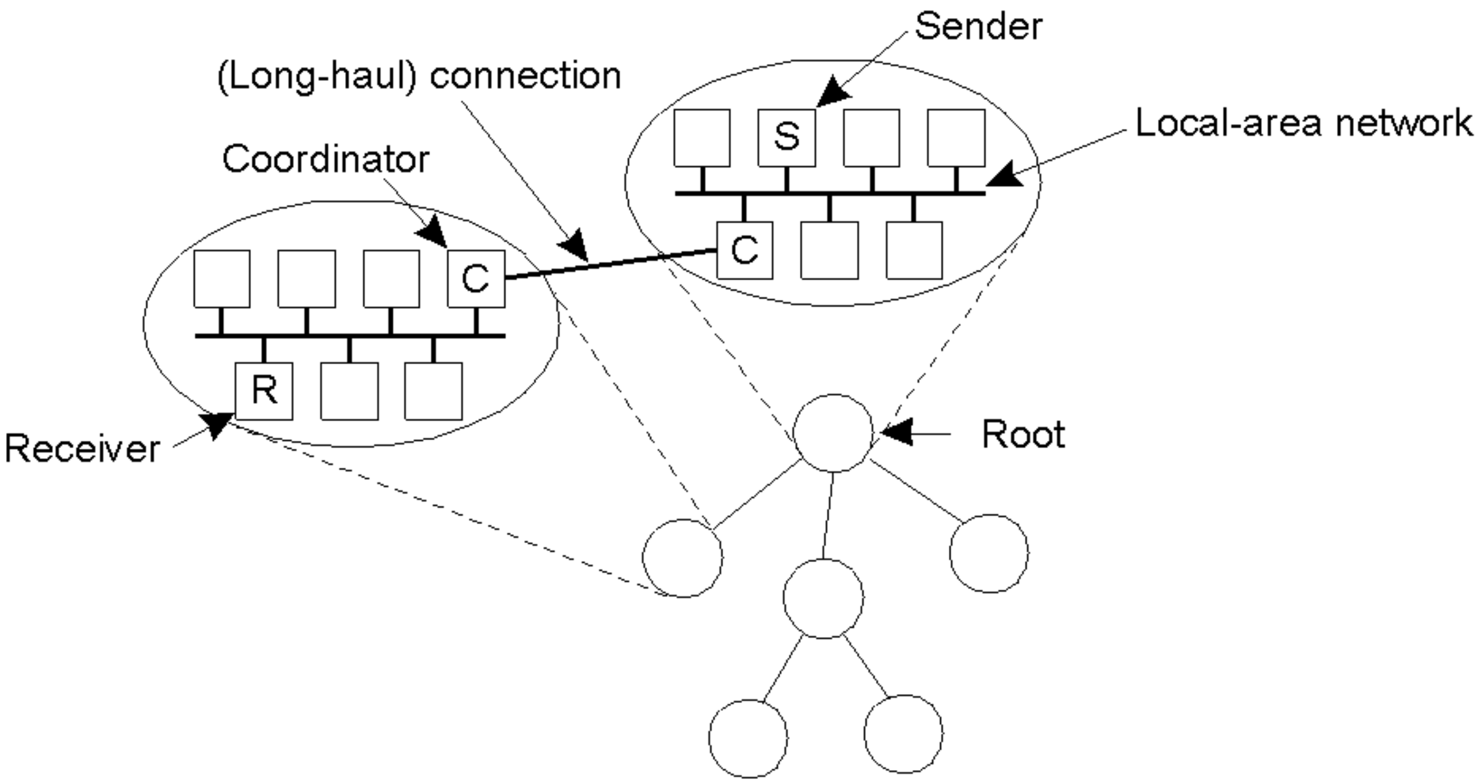
1. Never acknowledge successful delivery.



2. Multicast negative acknowledgements – suppress redundant NACKs

   Problem: detection of lost messages and lost group members

Hierarchical Feedback Control

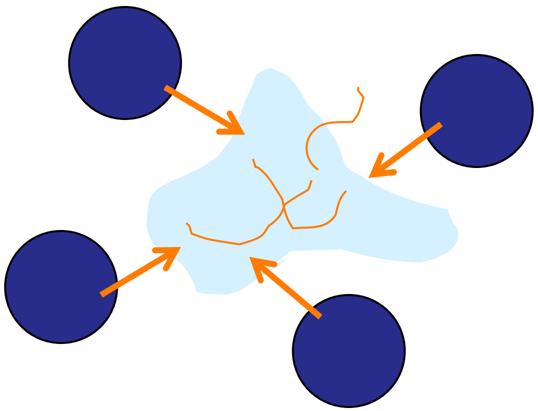


The essence of hierarchical reliable multicasting.

a) Each local coordinator forwards the message to its children.

b) A local coordinator handles retransmission requests.

Basic Multicast



Guarantee:

the message will eventually be delivered to all member of the group (during the multicast: a fixed membership)

Group view: G = {p_i}

"delivery list"

Implementation of *Basic_multicast(G, m)* :

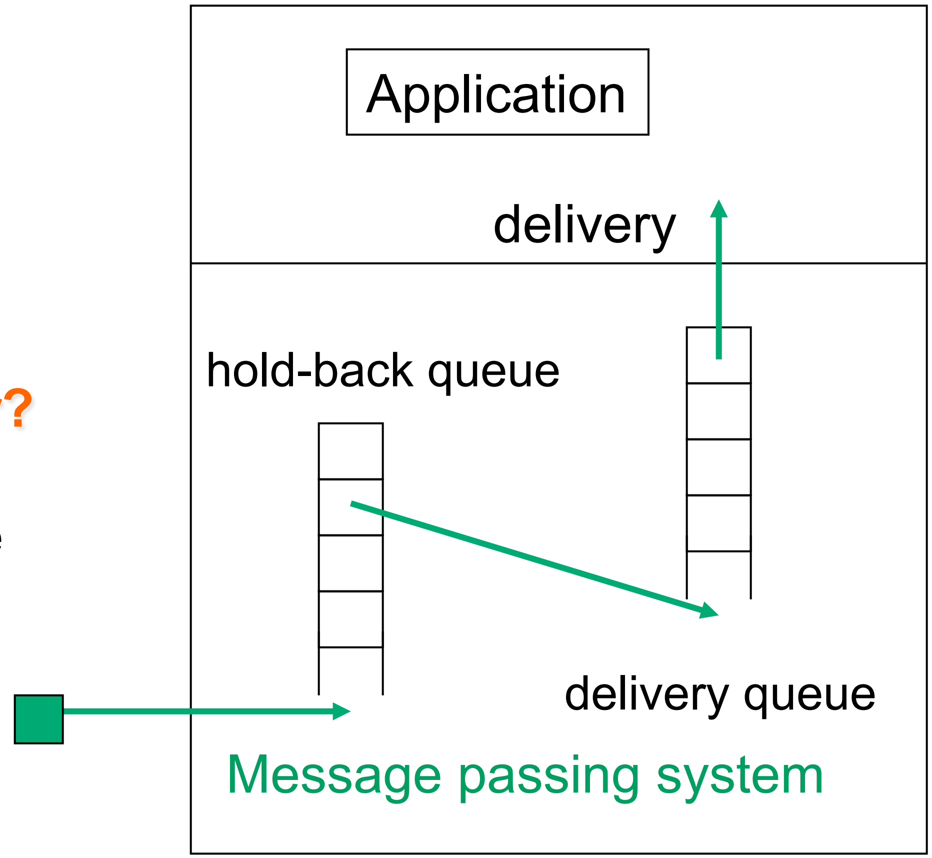
1. for each p_i in G: *send*(p_i,*m)* (a reliable one-to-one send)
2. on *receive(m)* at p_i : *deliver(m)* at p_i

Message Delivery

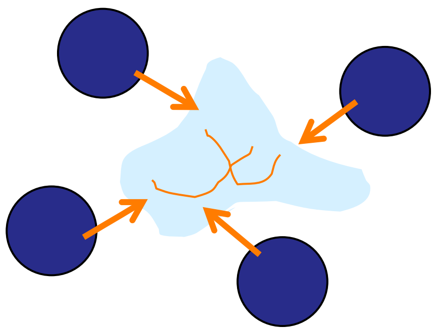
Delivery of messages

- new message => HBQ
- decision making
    - delivery order
    - **deliver or not to deliver?**

- the message is allowed to be delivered: HBQ => DQ
- when at the head of DQ: message => application (application: *receive* …)



Reliable Multicast and Group Changes



Assume

- reliable point-to-point communication
- group G={p_i}: each p_i : groupview

Reliable_multicast (G, m):

if a message is delivered to one in G, then it is delivered to all in G

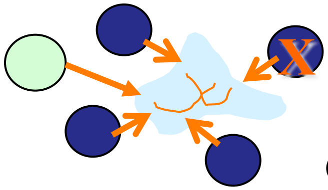
- Group change (join, leave) => change of groupview
- Change of group view: update as a multicast *vc*
- ***Concurrent group_change and multicast***

  => concurrent messages ***m*** and ***vc***

Virtual synchrony:

all *nonfaulty processes see* ***m*** *and* ***vc*** *in the same order*

Virtually Synchronous Reliable MC (1)



Group change: $G_i = G_{i+1}$

Virtual synchrony: "all" processes see m and vc in the same order

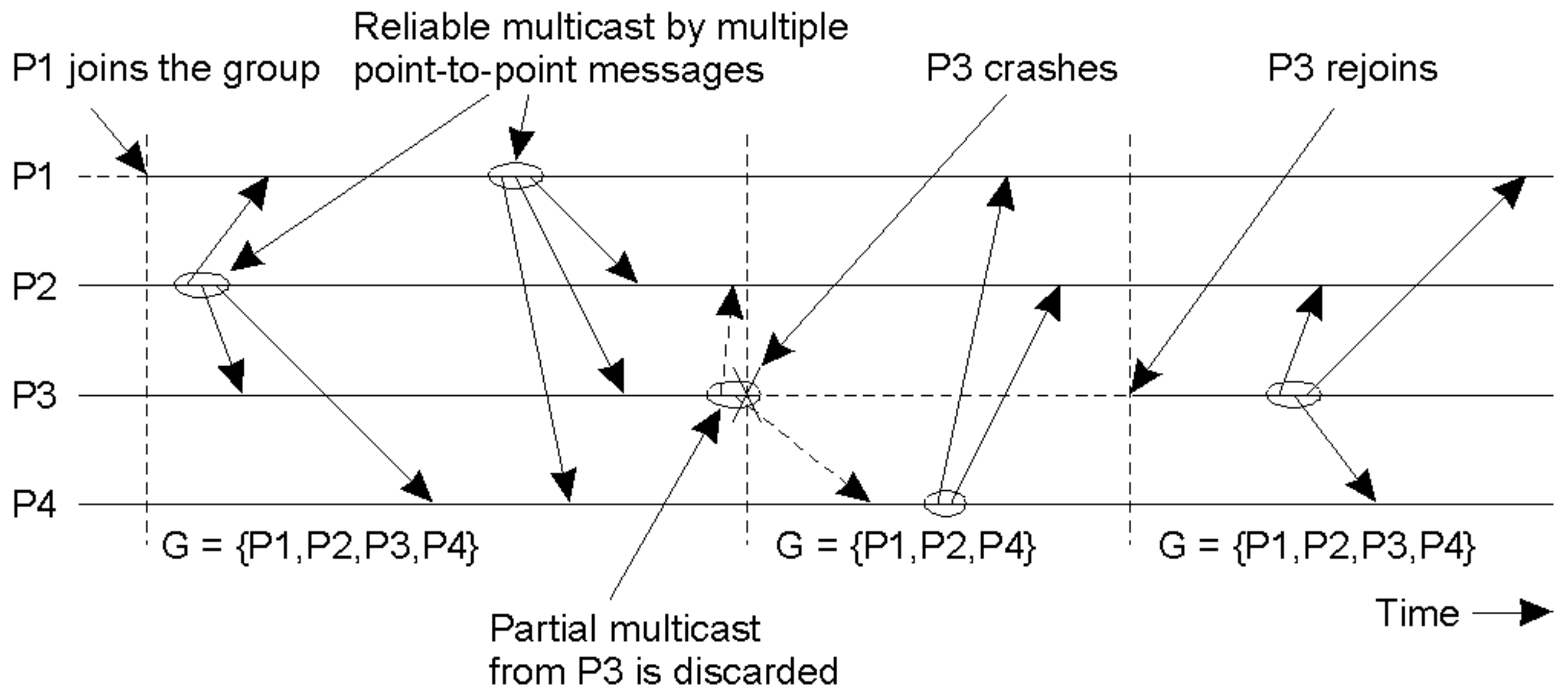
- m, vc => m is delivered to **all nonfaulty** processes in G_i (alternative: this order is not allowed!)
- vc, m => m is delivered to all processes in G_{i+1}
  (what is the difference?)

Problem: the sender fails *(during the multicast – why is it a problem?)*

Alternative solutions:

- m is delivered to all other members of G_i (=> ordering m, vc)
- m is ignored by all other members of G_i (=> ordering vc, m)

Virtually Synchronous Reliable MC (2)



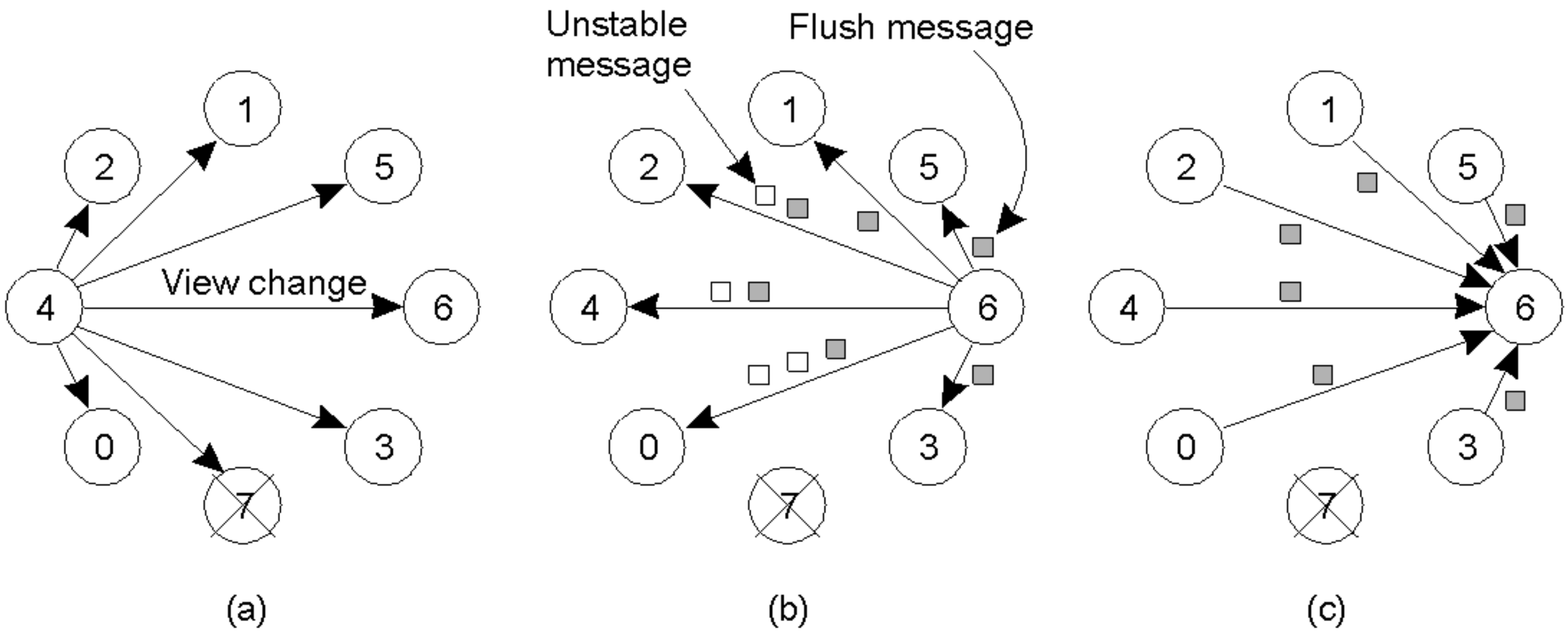
The principle of virtual synchronous multicast:

- a reliable multicast, and if the sender crashes
- the message may be delivered to all or ignored by each

Implementing Virtual Synchrony

- Communication: reliable, order-preserving, point-to-point
- Requirement: all messages are delivered to all nonfaulty processes in G
- Solution
  - each p_j in G keeps a message in the hold-back queue until it knows that all p_j in G have received it
  - a message received by all is called **stable**
  - only stable messages are allowed to be delivered
  - view change G_i => G_{i+1} :
    - multicast **all unstable messages** to all p_j in G_{i+1}
    - multicast a **flush message** to all p_j in G_{i+1}
    - after having received a flush message from all: install the new view G_{i+1}

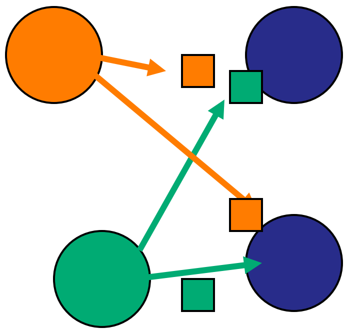
Implementing Virtual Synchrony



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

Ordered Multicast



Need:
all messages are delivered in the intended order

If p: multicast(G,m) and if (for any m')

- for **FIFO** multicast(G, m) **<** multicast(G, m')
- for **causal** multicast(G, m) **->** multicast(G, m')
- for **total** if at any q: deliver(m) < deliver(m')

then for all q in G : deliver(m) < deliver(m')

Reliable FIFO-Ordered Multicast

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

Virtually Synchronous Multicasting

Virtually synchronous 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

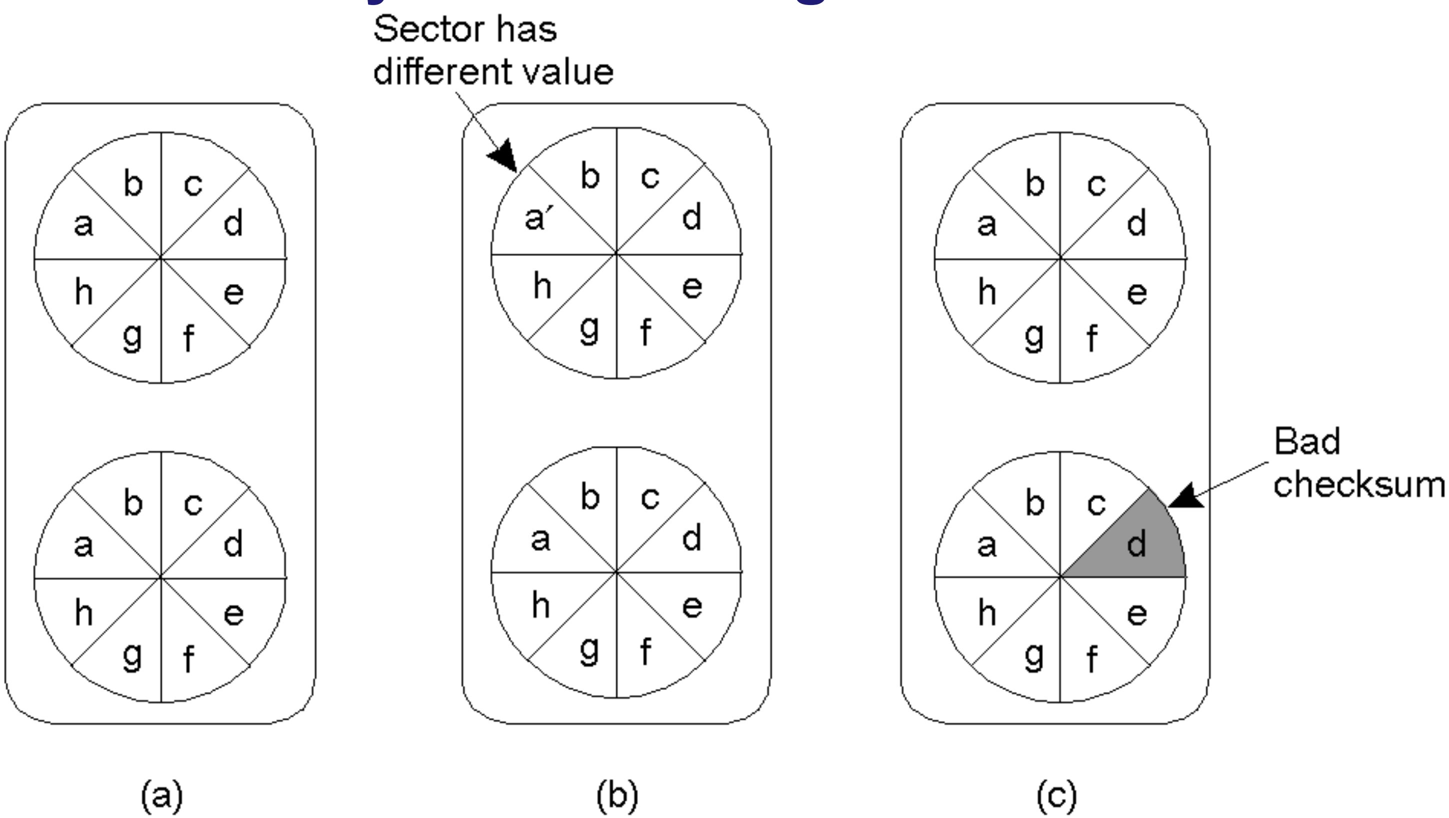
- virtually synchronous: everybody or nobody (members of the group) (sender fails: either everybody else or nobody)
- **atomic multicasting**: virtually synchronous reliable multicasting with totally-ordered delivery.

Recovery

- Fault tolerance: recovery from an error (erroneous state => error-free state)
- Two approaches
  - backward recovery: back into a previous correct state
  - forward recovery:
    - detect that the new state is erroneous
    - bring the system in a correct new state

    challenge: the possible errors must be known in advance
  - forward: continuous need for redundancy
  - backward:
    - expensive when needed
    - recovery after a failure is not always possible

Recovery Stable Storage



Stable Storage

Crash after drive 1 is updated

Bad spot

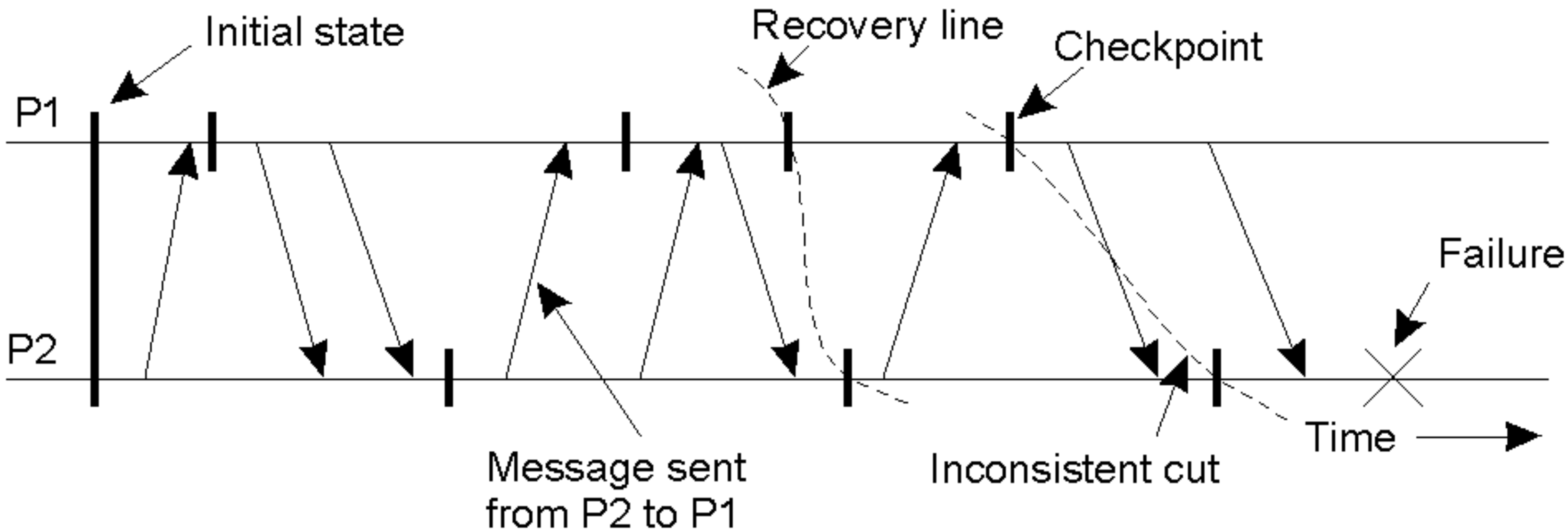
Implementing Stable Storage

- Careful block operations (fault tolerance: transient faults)
  - careful_read: {get_block, check_parity, error=> N retries}
  - careful_write: {write_block, get_block, compare, error=> N retries}
  - irrecoverable failure => report to the "client"
- Stable Storage operations (fault tolerance: data storage errors)
  - stable_get:

    {careful_read(replica_1), if failure then careful_read(replica_2)}
  - stable_put: {careful_write(replica_1), careful_write(replica_2)}
  - error/failure recovery: read both replicas and compare
    - both good and the same => ok
    - both good and different => replace replica_2 with replica_1
    - one good, one bad => replace the bad block with the good block

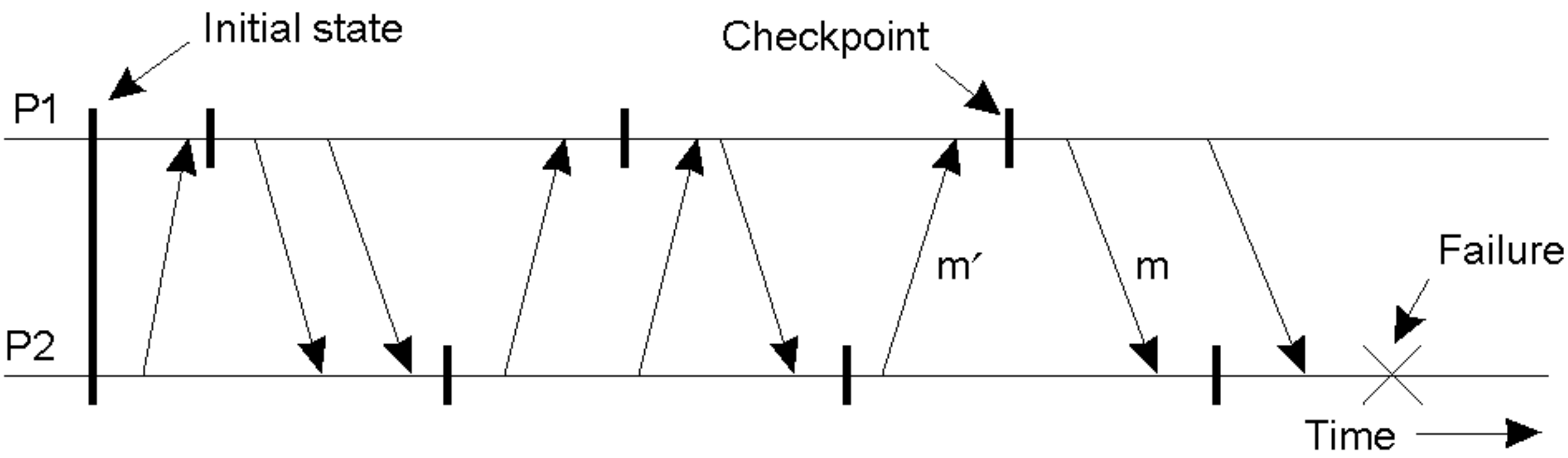
Checkpointing

Needed: a consistent global state to be used as a **recovery line**



A recovery line: the most recent distributed snapshot

Independent Checkpointing



Each process records its local state from time to time
⇒ difficult to find a recovery line

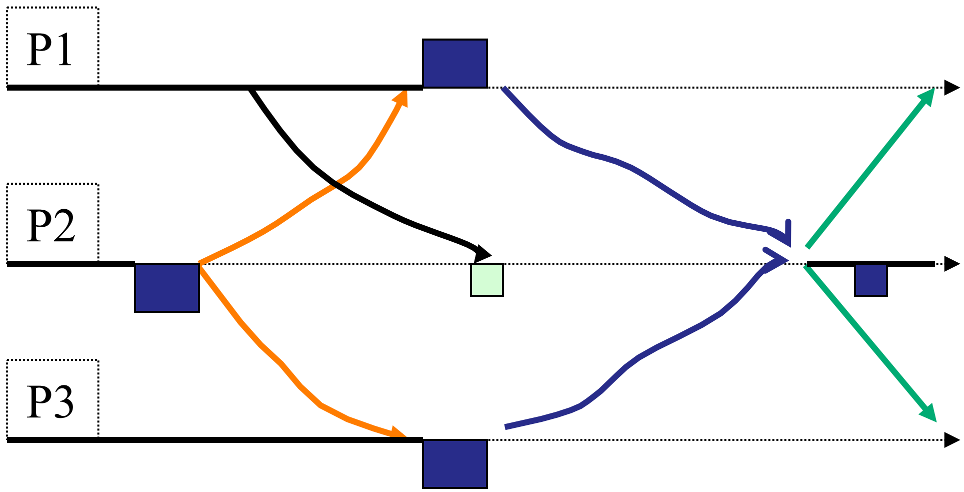
If the most recently saved states do not form a recovery line
⇒ rollback to a previous saved state (threat: the domino effect).

A solution: coordinated checkpointing

Coordinated Checkpointing (1)

- Nonblocking checkpointing
  - see: distributed snapshot
- Blocking checkpointing
  - coordinator: multicast CHECKPOINT_REQ
  - partner:
    - take a local checkpoint
    - acknowledge the coordinator
    - wait (and queue any subsequent messages)
  - coordinator:
    - wait for all acknowledgements
    - multicast CHECKPOINT_DONE
  - coordinator, partner: continue

Coordinated Checkpointing (2)

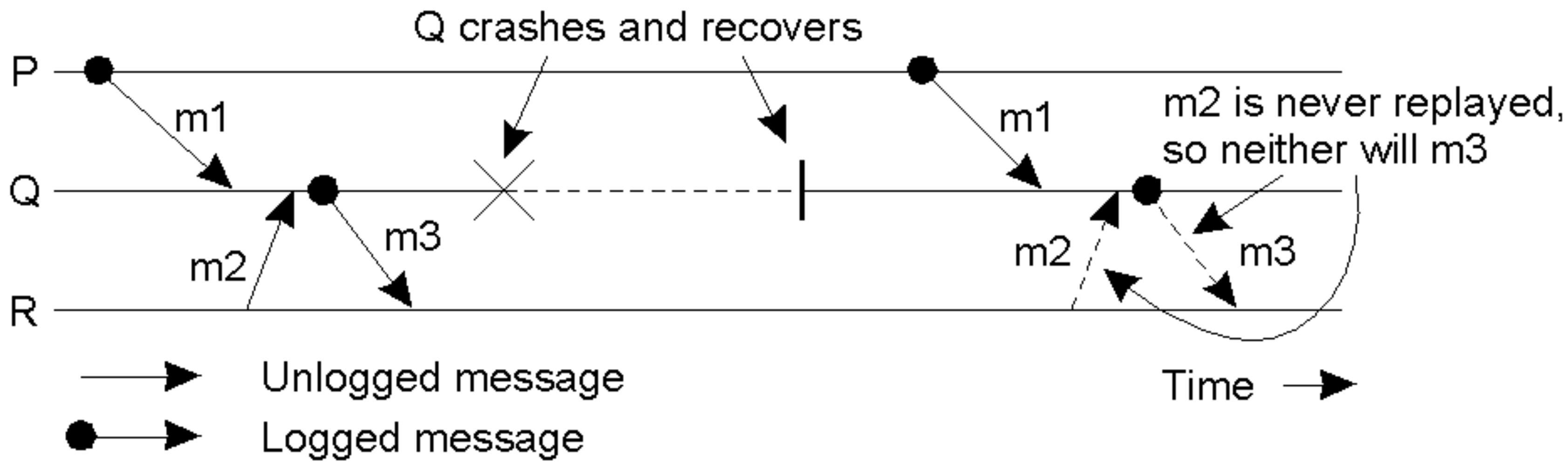


Message Logging

Improving efficiency: checkpointing and message logging

Recovery: most recent checkpoint + replay of messages

Problem: Incorrect replay of messages after recovery may lead to orphan processes.



Chapter Summary

- Fault tolerance
- Process resilience
- Reliable group communication
- Distributed commit
- Recovery