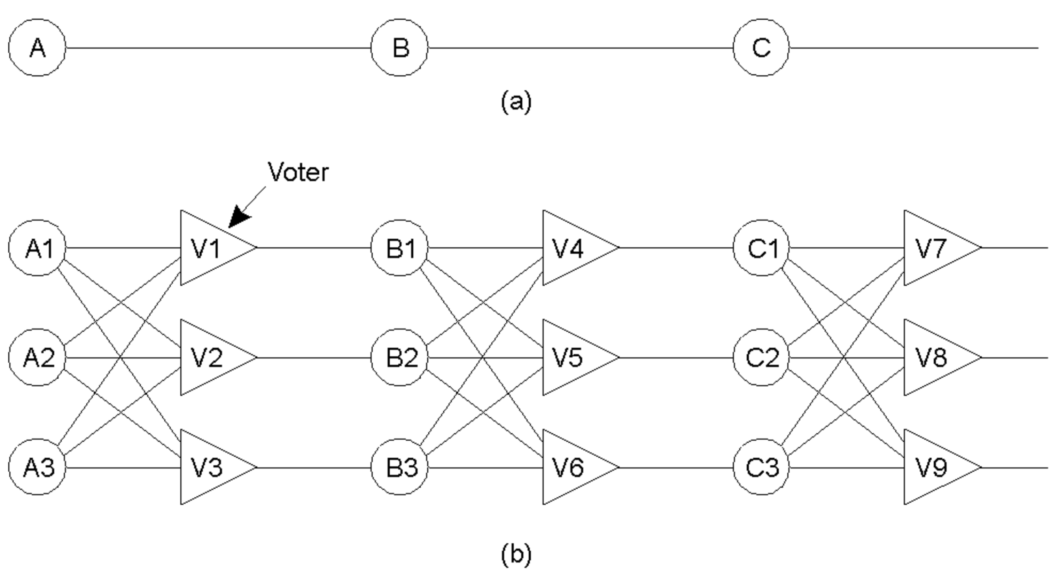
Today: Fault Tolerance

- Agreement in presence of faults
  - Two army problem
  - Byzantine generals problem
- Reliable communication
- Distributed commit
  - Two phase commit
  - Three phase commit
- Failure recovery
  - Checkpointing
  - Message logging

Failure Masking by Redundancy



- Triple modular redundancy.

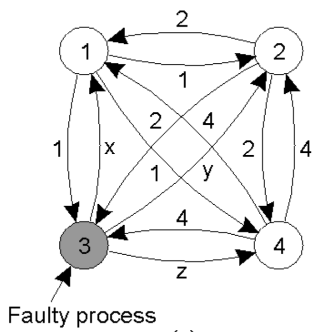
Agreement in Faulty Systems

- How should processes agree on results of a computation?
- *K-fault tolerant*: system can survive k faults and yet function
- Assume processes fail silently
  - Need (k+1) redundancy to tolerant k faults
- *Byzantine failures*: processes run even if sick
  - Produce erroneous, random or malicious replies
    - Byzantine failures are most difficult to deal with
  - Need ? Redundancy to handle Byzantine faults

Byzantine Faults

- Simplified scenario: two perfect processes with unreliable channel
  - Need to reach agreement on a 1 bit message
- Two army problem: Two armies waiting to attack
  - Each army coordinates with a messenger
  - Messenger can be captured by the hostile army
  - Can generals reach agreement?
  - Property: Two perfect process can never reach agreement in presence of unreliable channel
- Byzantine generals problem: Can N generals reach agreement with a perfect channel?
  - M generals out of N may be traitors

Byzantine Generals Problem



(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)

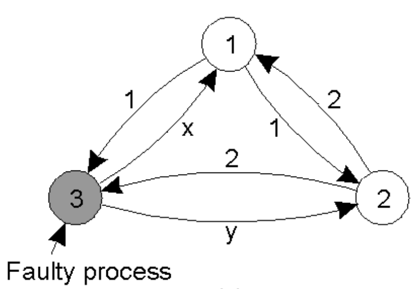
- Recursive algorithm by Lamport
- The Byzantine generals problem for 3 loyal generals and 1 traitor.

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.

Byzantine Generals Problem Example



(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)

- The same as in previous slide, except now with 2 loyal generals and one traitor.
- Property: With *m* faulty processes, agreement is possible only if $2m+1$ processes function correctly out of $3m+1$ total processes. [Lamport 82]
  - Need more than two-thirds processes to function correctly

Byzantine Fault Tolerance

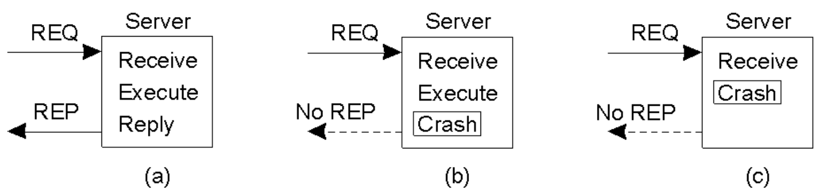
- Detecting a faulty process is easier
  - 2k+1 to detect k faults
- Reaching agreement is harder
  - Need 3k+1 processes (2/3rd majority needed to eliminate the faulty processes)
- Implications on real systems:
  - How many replicas?
  - Separating agreement from execution provides savings

Reaching Agreement

- If message delivery is unbounded,
  - No agreeement can be reached even if one process fails
  - Slow process indistinguishable from a faulty one
- BAR Fault Tolerance
  - Until now: nodes are byzantine or collaborative
  - New model: Byzantine, Altruistic and Rational
  - Rational nodes: report timeouts etc

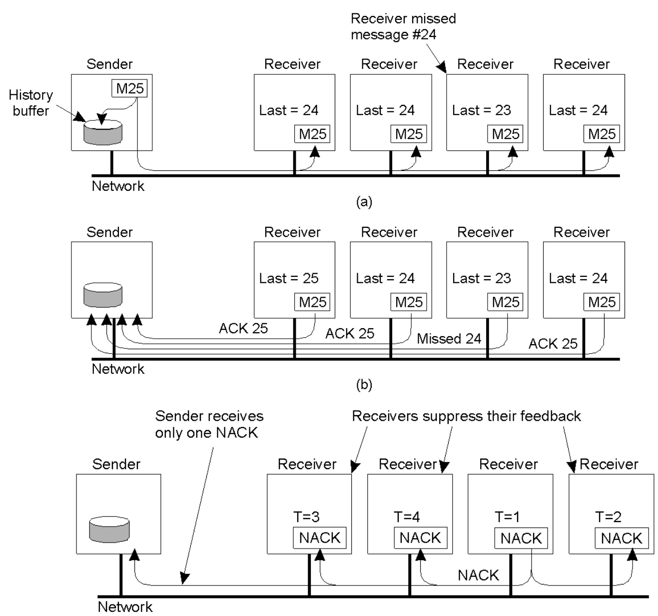
Reliable One-One Communication

- Issues were discussed in Lecture 3
  - Use reliable transport protocols (TCP) or handle at the application layer
- RPC semantics in the presence of failures
- Possibilities
  - Client unable to locate server
  - Lost request messages
  - Server crashes after receiving request
  - Lost reply messages
  - Client crashes after sending request



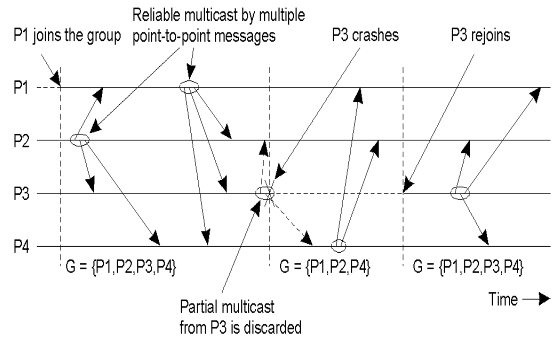
Reliable One-Many Communication

- Reliable multicast
  - Lost messages => need to retransmit
- Possibilities
  - ACK-based schemes
    - Sender can become bottleneck
  - NACK-based schemes



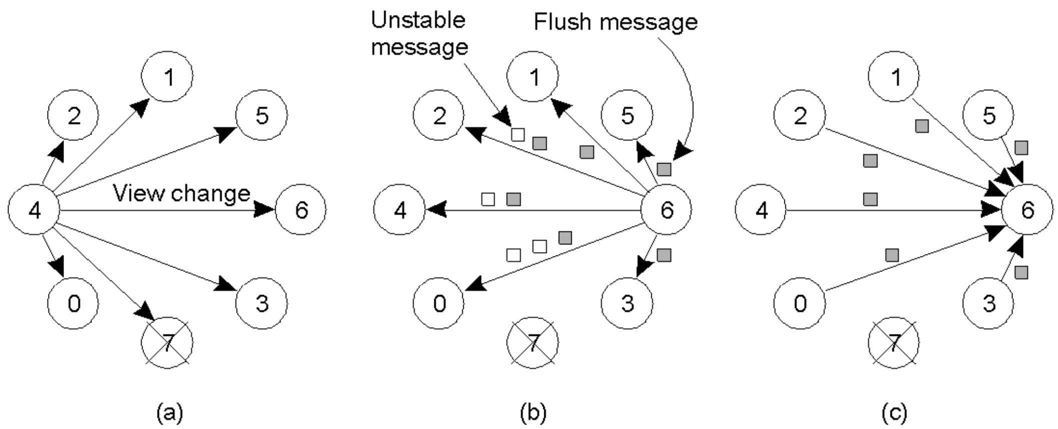
Atomic Multicast

- Atomic multicast: a guarantee that all process received the message or none at all
  - Replicated database example
  - Need to detect which updates have been missed by a faulty process
- Problem: how to handle process crashes?
- Solution: *group view*
  - Each message is uniquely associated with a group of processes
    - View of the process group when message was sent
    - All processes in the group should have the same view (and agree on it)



Virtually Synchronous Multicast

Implementing Virtual Synchrony in Isis



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

Implementing Virtual Synchrony

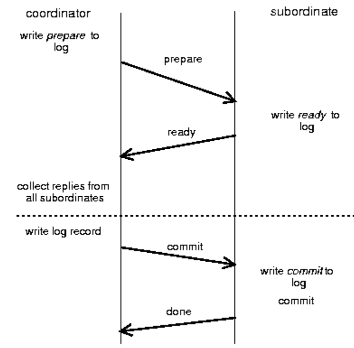
Multicast	Basic Message Ordering	Total-Ordered Delivery?
Reliable multicast	None	No
FIFO multicast	FIFO-ordered delivery	No
Causal multicast	Causal-ordered delivery	No
Atomic multicast	None	Yes
FIFO atomic multicast	FIFO-ordered delivery	Yes
Causal atomic multicast	Causal-ordered delivery	Yes

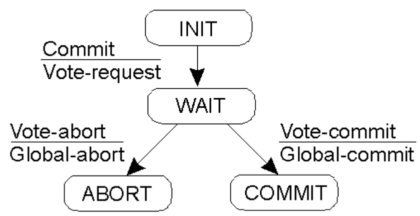
Distributed Commit

- Atomic multicast example of a more general problem
  - All processes in a group perform an operation or not at all
  - Examples:
    - Reliable multicast: Operation = delivery of a message
    - Distributed transaction: Operation = commit transaction
- Problem of distributed commit
  - All or nothing operations in a group of processes
- Possible approaches
  - Two phase commit (2PC) [Gray 1978]
  - Three phase commit

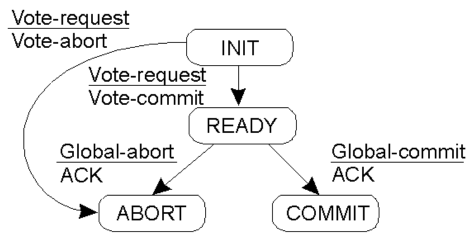
Two Phase Commit

- Coordinator process coordinates the operation
- Involves two phases
  - Voting phase: processes vote on whether to commit
  - Decision phase: actually commit or abort





(a)



(b)

Implementing Two-Phase Commit

actions by coordinator:

```
while 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 {
        while 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;
}
```

- Outline of the steps taken by the coordinator in a two phase commit protocol

Implementing 2PC

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;
}
```

actions for handling decision requests: /*executed by separate thread */

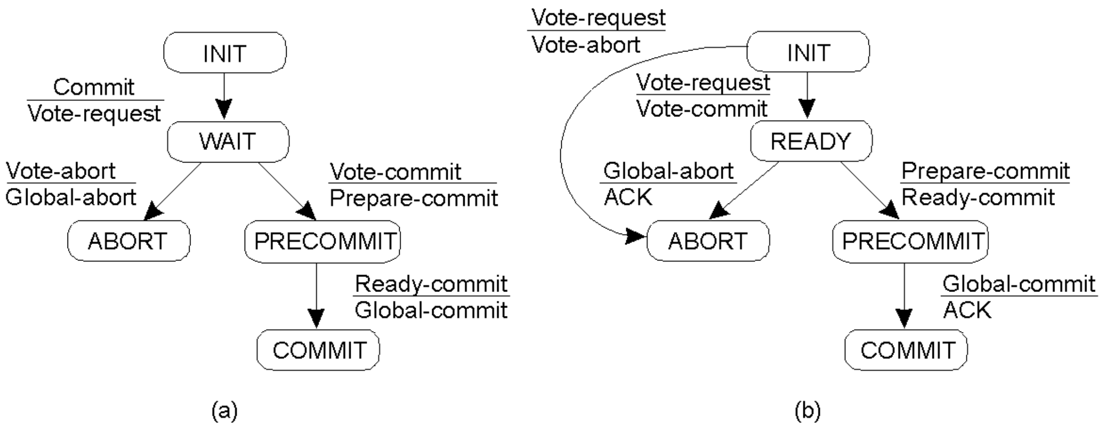
```
while true {
wait until any incoming DECISION_REQUEST
 is received; /* remain blocked */
   read most recently recorded STATE from the
local log;
   if STATE == GLOBAL_COMMIT
      send GLOBAL_COMMIT to requesting
            participant;
   else if STATE == INIT or STATE ==
            GLOBAL_ABORT
      send GLOBAL_ABORT to requesting
participant;
   else
      skip;  /* participant remains blocked */
```


Recovering from a Crash

- If INIT : abort locally and inform coordinator
- If Ready, contact another process Q and examine Q's state

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

Three-Phase Commit



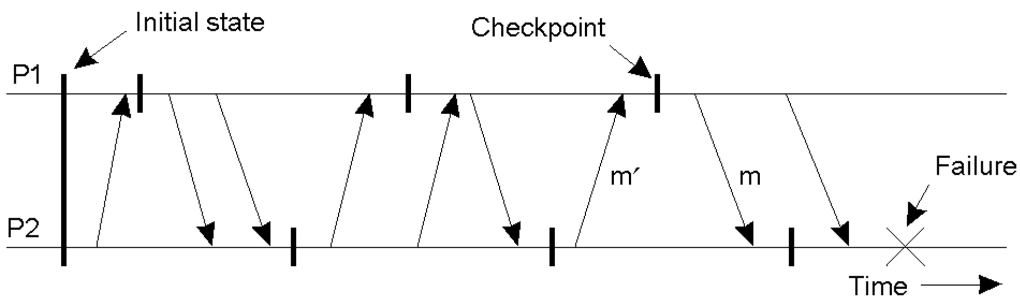
Two phase commit: problem if coordinator crashes (processes block)

Three phase commit: variant of 2PC that avoids blocking

Recovery

- Techniques thus far allow failure handling
- Recovery: operations that must be performed after a failure to recover to a correct state
- Techniques:
  - Checkpointing:
    - Periodically checkpoint state
    - Upon a crash roll back to a previous checkpoint with a *consistent state*

Independent Checkpointing



- Each processes periodically checkpoints independently of other processes
- Upon a failure, work backwards to locate a consistent cut
- Problem: if most recent checkpoints form inconsistenct cut, will need to keep rolling back until a consistent cut is found
- Cascading rollbacks can lead to a domino effect.

Coordinated Checkpointing

- Take a distributed snapshot [discussed in Lec 11]
- Upon a failure, roll back to the latest snapshot
  - All process restart from the latest snapshot

Message Logging

- Checkpointing is expensive
  - All processes restart from previous consistent cut
  - Taking a snapshot is expensive
  - Infrequent snapshots => all computations after previous snapshot will need to be redone [wasteful]
- Combine checkpointing (expensive) with message logging (cheap)
  - Take infrequent checkpoints
  - Log all messages between checkpoints to local stable storage
  - To recover: simply replay messages from previous checkpoint
    - Avoids recomputations from previous checkpoint