Fault Tolerance

- Part 1: Agreement in presence of faults
  - Two army problem
  - Byzantine generals problem
- Part 2: Reliable communication
- Part 3: Distributed commit
  - Two phase commit
  - Three phase commit
- Next class:
  - Paxos and RAFT
  - Failure recovery
    - Checkpointing
    - Message logging

Fault Tolerance

- Single machine systems
  - Failures are all or nothing
    - OS crash, disk failures
- Distributed systems: multiple independent nodes
  - Partial failures are also possible (some nodes fail)
- *Question:* Can we automatically recover from partial failures?
  - Important issue since probability of failure grows with number of independent components (nodes) in the systems
  - Prob(failure) = Prob(Any one component fails)=1-P(no failure)

A Perspective

- Computing systems are not very reliable
  - OS crashes frequently (Windows), buggy software, unreliable hardware, software/hardware incompatibilities
  - Until recently: computer users were “tech savvy”
    - Could depend on users to reboot, troubleshoot problems
  - Growing popularity of Internet/World Wide Web
    - “Novice” users
    - Need to build more reliable/dependable systems
  - Example: what is your TV (or car) broke down every day?
    - Users don’t want to “restart” TV or fix it (by opening it up)
- Need to make computing systems more reliable
  - Important for online banking, e-commerce, online trading, webmail…

Basic Concepts

- Need to build *dependable* systems
- Requirements for dependable systems
  - Availability: system should be available for use at any given time
    - 99.999 % availability (five 9s) => very small down times
  - Reliability: system should run continuously without failure
  - Safety: temporary failures should not result in a catastrophic
    - Example: computing systems controlling an airplane, nuclear reactor
  - Maintainability: a failed system should be easy to repair

Basic Concepts (contd)

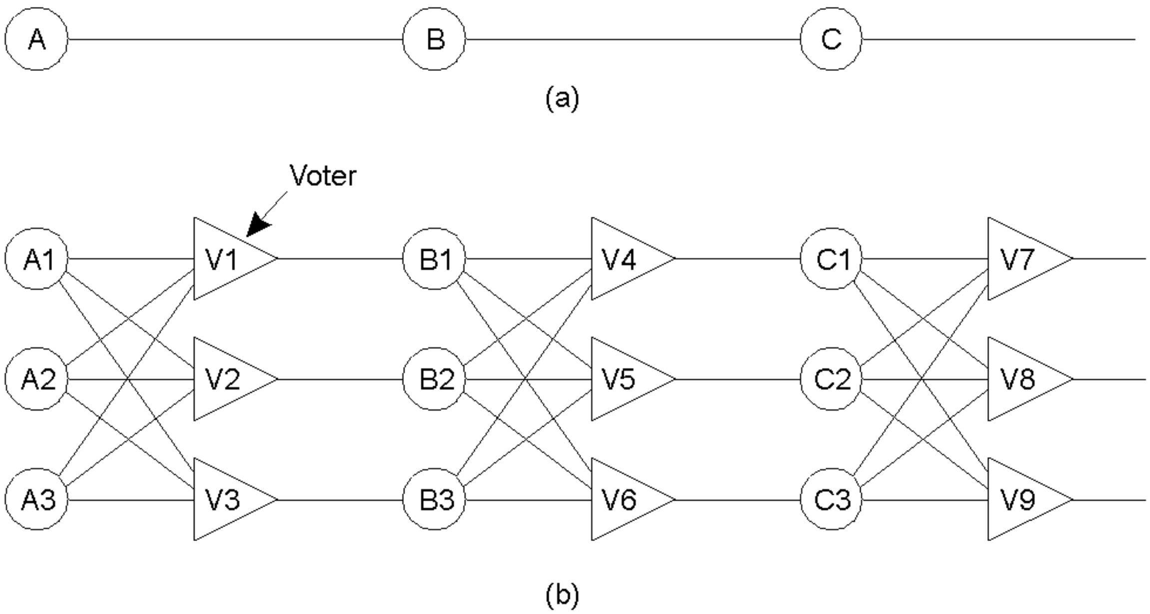
- Fault tolerance: system should provide services despite faults
  - Transient faults
  - Intermittent faults
  - Permanent faults

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

- Different types of failures.

Failure Masking by Redundancy



- Triple modular redundancy: can handle one failure in circuit

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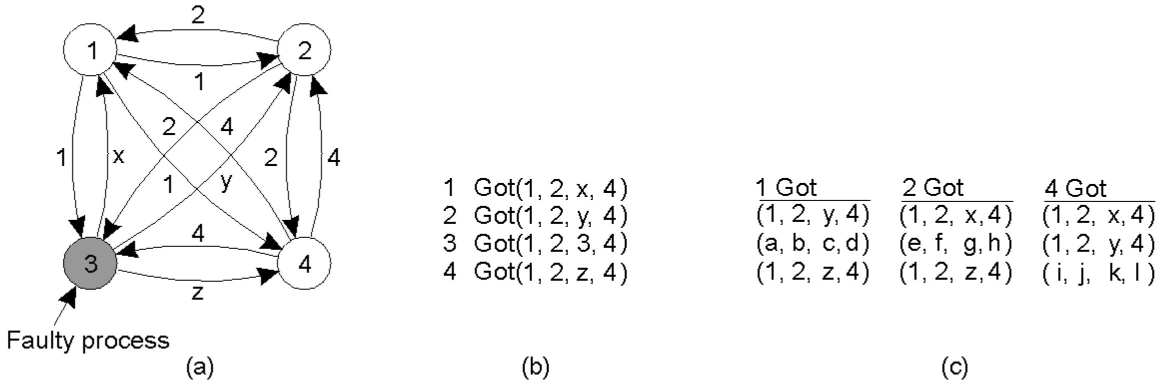
Agreement in Faulty Systems

- 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 Generals 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
  - Concept of **Common knowledge**
- **Byzantine generals problem**: Can N generals reach agreement with a perfect channel?
  - M generals out of N may be traitors

Byzantine Generals Problem



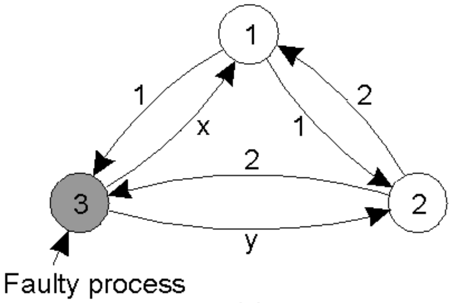
1 Got(1, 2, x, 4)
2 Got(1, 2, y, 4)
3 Got(1, 2, 3, 4)
4 Got(1, 2, z, 4)

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)

- 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 2*m*+1 processes function correctly out of 3*m*+1 total processes. [Lamport 82]
  - Need more than two-thirds processes to function correctly (for m=1, 3 out of 4 processes)

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

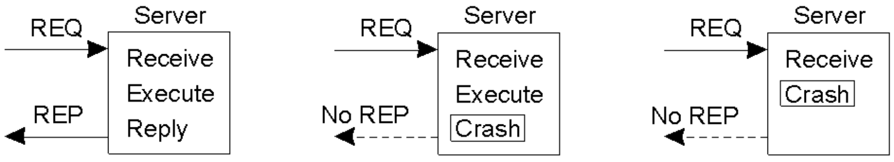
Reaching Agreement

- If message delivery is unbounded,
  - No agreement 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

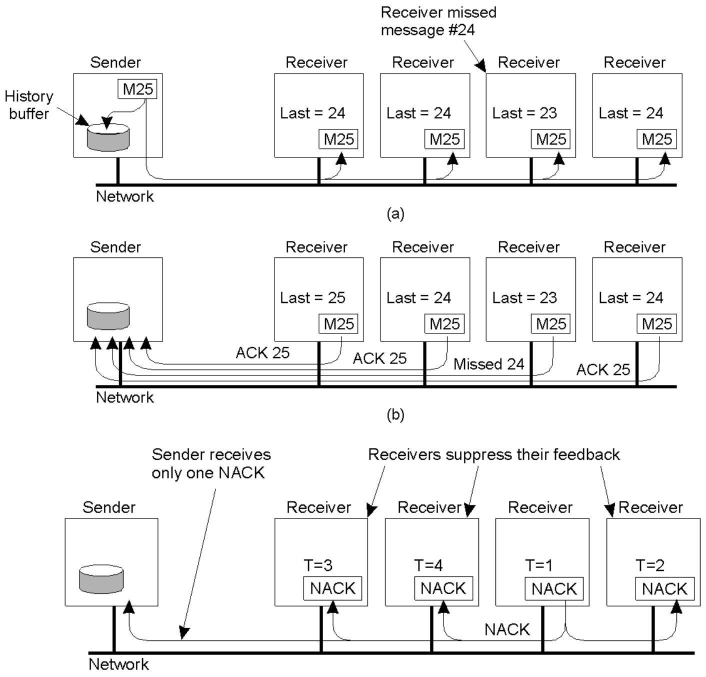
- Issues were discussed in Lecture 3
  - Use reliable transport protocols (TCP) or handle at the application layer
- RPC semantics in the presence of failures
- Possibilities
  - Client unable to locate server
  - Lost request messages
  - Server crashes after receiving request
  - Lost reply messages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



(a) (b) (c)

Reliable One-Many Communication

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

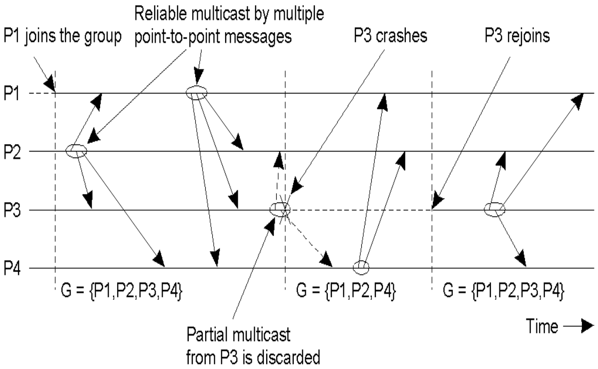


Broadcast Ordering

- Broadcast (or multicast) ordered important for replication
- FIFO broadcast: if a process sends m1 and then m2, all other processes receive m1 before m2
- Totally ordered: If a process receives m1 before m2 (regardless of sender), all processes receive m1 before m2
  - Does not imply FIFO, all processes just agree on order
- Causally ordered: if send(m1)->send (m2) => recv(m1)-> recv (m2)
- **State machine replication (SMR)**
  - Broadcast requests to all replicas using totally ordered broadcast; replicas apply requests in order.

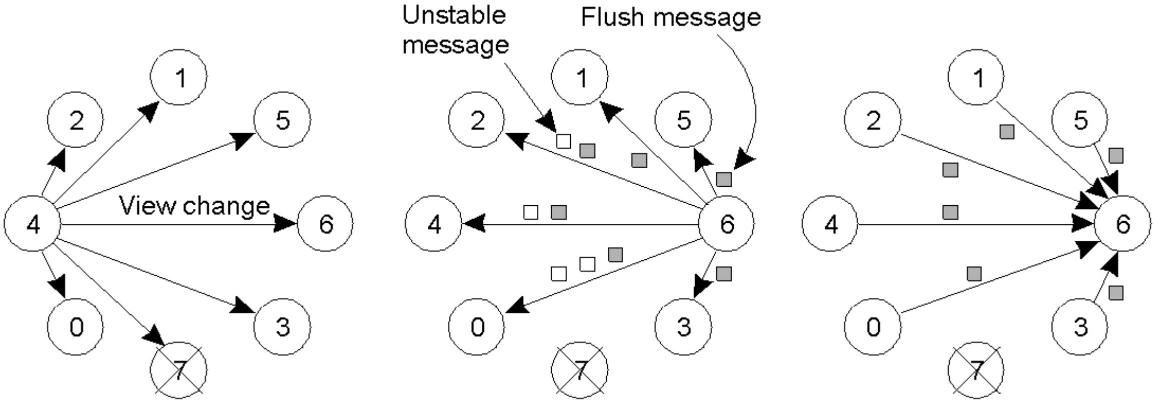
Atomic Multicast

- 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



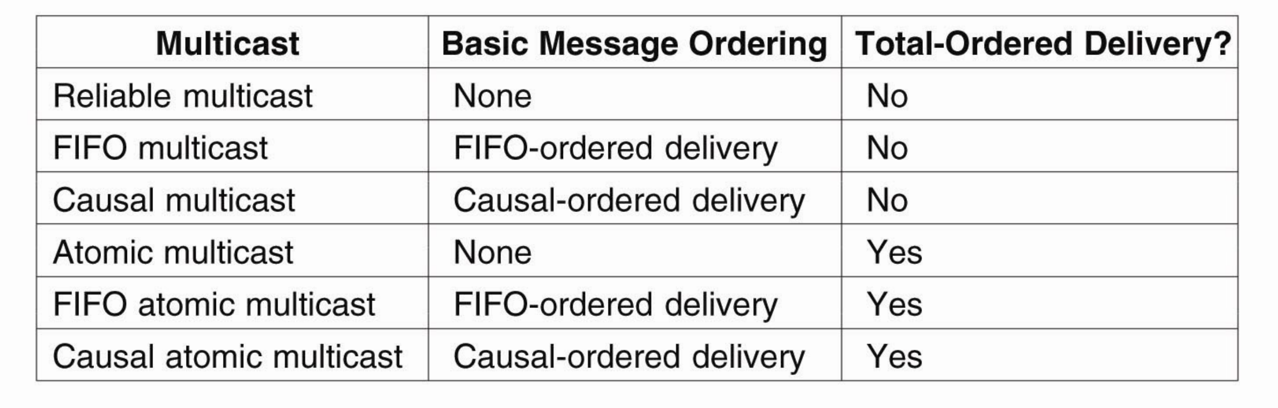
(a) (b) (c)

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



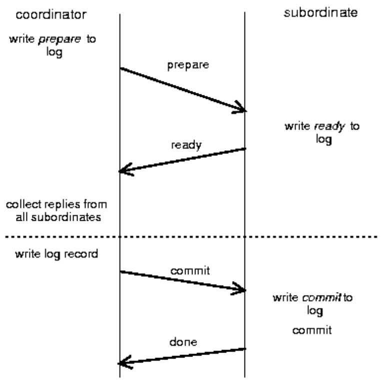
Multicast	Basic Message Ordering	Total-Ordered Delivery?
Reliable multicast	None	No
FIFO multicast	FIFO-ordered delivery	No
Causal multicast	Causal-ordered delivery	No
Atomic multicast	None	Yes
FIFO atomic multicast	FIFO-ordered delivery	Yes
Causal atomic multicast	Causal-ordered delivery	Yes

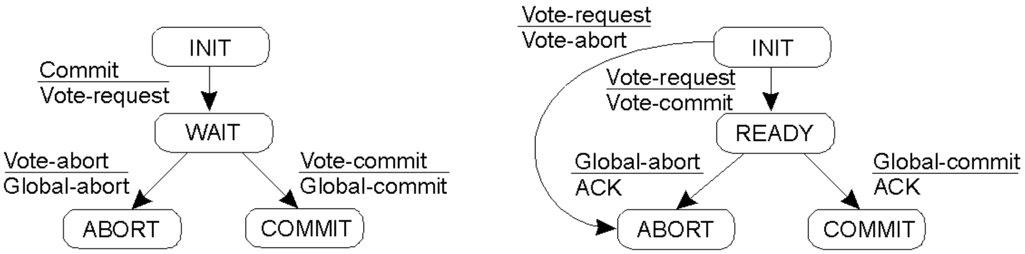
Distributed Commit

- 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:

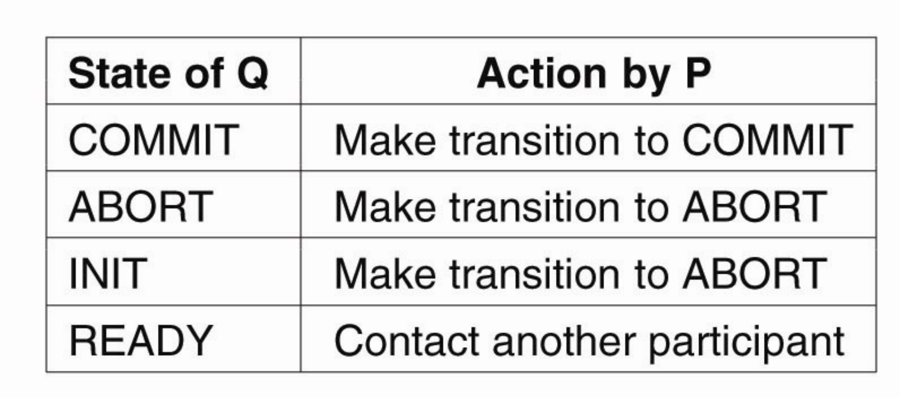
```
write INIT to local log;
wait for VOTE_REQUEST from coordinator;
if timeout {
    write VOTE_ABORT to local log;
    exit;
}
if participant votes COMMIT {
    write VOTE_COMMIT to local log;
    send VOTE_COMMIT to coordinator;
    wait for DECISION from coordinator;
    if timeout {
        multicast 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 */
```

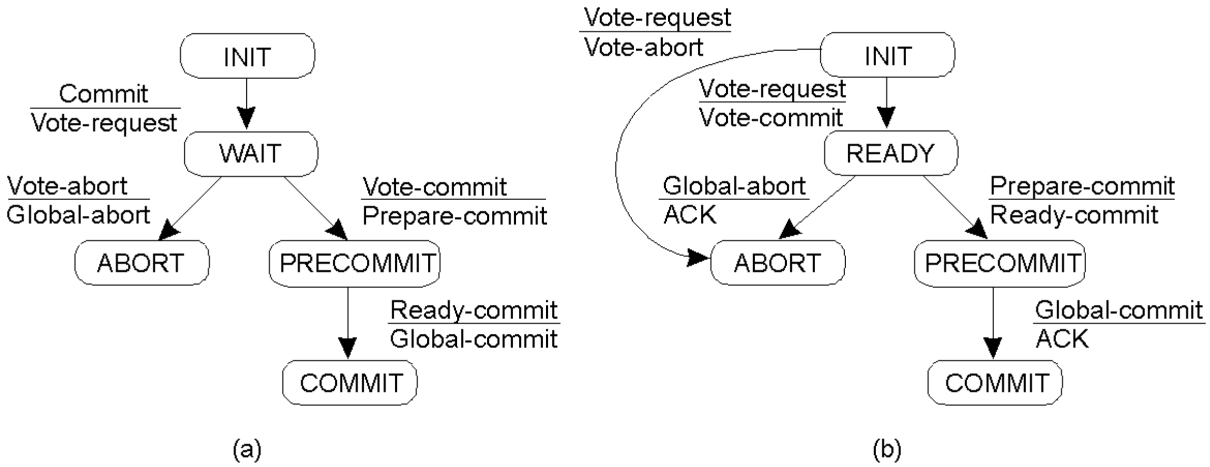
Recovering from a Crash

- 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

Replication for Fault Tolerance

- Basic idea: use replicas for the server and data
- Technique 1: split incoming requests among replicas
  - If one replica fails, other replicas take over its load
  - Suitable for crash fault tolerance (each replica produces correct results when it is us).
- Technique 2: send each request to all replicas
  - Replicas vote on their results and take majority result
  - Suitable for BFT (a replica can produce wrong results)
    - 2PC, 3PC, Paxos are techniques

Consensus, Agreement

- Consensus vs Byzantine Agreement vs Agreement
- Achieve reliability in presence of faulty processes
  - requires processes to agree on data value needed for computation
  - Examples: whether to commit a transaction, agree on identity of a leader, atomic broadcasts, distributed locks
- Properties of a consensus protocol with fail-stop failures
  - Agreement: every correct process agrees on same value
  - Termination: every correct process decides some value
  - Validity: If all propose v, all correct processes decides v
  - Integrity: Every correct process decided at most one value and if it decides v, someone must have proposed v.

2PC, 3PC Problems

- Both have problems in presence of failures
  - **Safety** is ensured but **liveness** is not
- 2PC
  - must wait for all nodes and coordinator to be up
  - all nodes must vote
  - coordinator must be up
- 3PC
  - handles coordinator failure
  - but network partitions are still an issue
- Paxos : how to reach consensus in distributed systems that can tolerate non-malicious failures?
  - majority rather than all nodes particpate

Paxos: fault-tolerant agreement

- Paxos lets nodes agree on same value despite:
  - node failures, network failures and delays
- Use cases:
  - Nodes agree X is primary (or leader)
  - Nodes agree Y is last operation (order operations)
- General approach
  - One (or more) nodes decides to be leader (aka proposer)
  - Leader proposes a value and solicits acceptance from others
  - Leader announces result or tries again
- Proposed independently by Lamport and Liskov
  - Widely used in real systems in major companies

Paxos Requirements

- Safety (Correctness)
  - All nodes agree on the same value
  - Agreed value X was proposed by some node
- Liveness (fault-tolerance)
  - If less than N/2 nodes fail, remaining nodes will eventually reach agreement
  - Liveness not guaranteed if steady stream of failures
- Why is agreement hard?
  - Network partitions
  - Leader crashes during solicitation or after deciding but before announcing results,
  - New leader proposes different value from already decided value,
  - More than one node becomes leader simultaneously....

Paxos Setup

- Entities: Proposer (leader), acceptor, learner
  - Leader proposes value, solicits acceptance from acceptors
  - Acceptors are nodes that want to agree; announce chosen value to learners
- Proposals are ordered by proposal #
  - node can choose any high number to try to get proposal accepted
  - An acceptor can accept multiple proposals
    - If prop with value v chosen, all higher proposals have value v
- Each node maintains
  - n_a, v_a: highest proposal # and accepted value
  - n_h : highest proposal # seen so far
  - my_n: my proposal # in current Paxos

Paxos operation: 3 phase protocol

- **Phase 1 (Prepare phase)**
  - A node decides to be a leader and propose
  - Leader chooses my_n > n_h
  - Leader sends <prepare, my_n> to all nodes
  - Upon receiving <prepare, n> at acceptor
    - If n < n_h
      - reply <prepare-reject> /* already seen higher # proposal */
    - Else
      - n_h = n /* will not accept prop lower than n */
      - reply <prepare-ok, n_a, v_a> /* send back previous prop, value/
      - /* can be null, if first */

Paxos operation

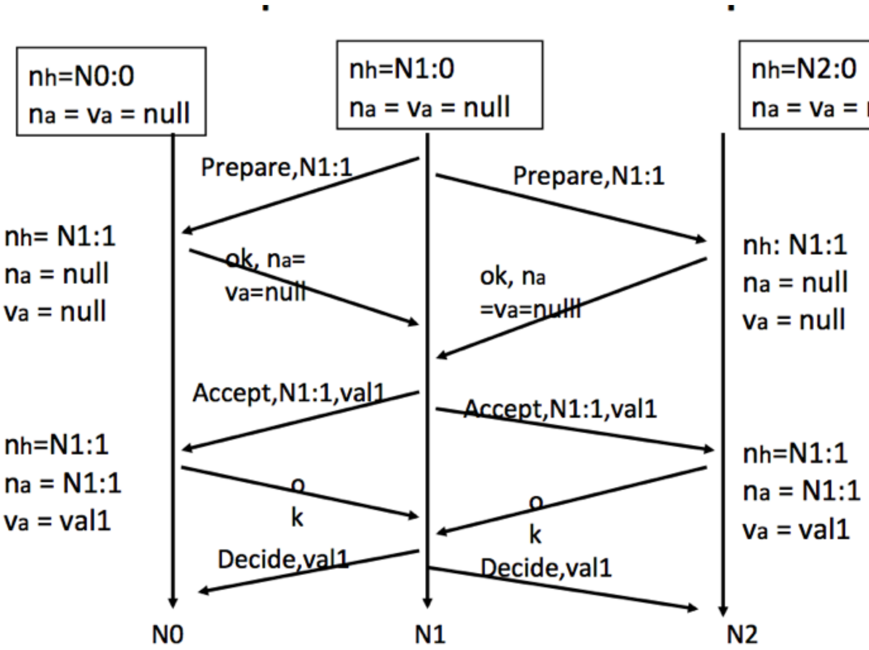
- **Phase 2 (accept phase)**
  - If leader gets prepare-ok from **majority**
    - V = non-empty value from highest n_a received
    - If V = null, leader can pick any V
    - Send <accept, my_n, V> to all nodes
  - If leader fails to get majority prepare-ok
    - delay and restart Paxos
  - Upon receiving <accept, n, V>
    - If n < n_h
      - reply with <accept-reject>
    - else
      - n_a=n ; v_a = V; n_h = h; reply <accept-ok>

Paxos Operation

- **Phase 3 (decide)**
  - If leader gets accept-ok from majority
    - Send <decide, v_a> to all learners
  - If leader fails to get accept-ok from a majority
    - Delay and restart Paxos

- **Properties**
  - P1: any proposal number is unique
  - P2: any two set of acceptors have at least one node in common
  - P3: value sent in phase 2 is value of highest numbered proposal received in responses in phase 1

Paxos Exampe



n_h=N0:0
n_a = v_a = null

n_h=N1:0
n_a = v_a = null

n_h=N2:0
n_a = v_a = null

Prepare,N1:1

Prepare,N1:1

n_h= N1:1
n_a = null
v_a = null

ok, n_a=
v_a=null

ok, n_a
=v_a=null

n_h: N1:1
n_a = null
v_a = null

Accept,N1:1,val1

Accept,N1:1,val1

n_h=N1:1
n_a = N1:1
v_a = val1

o
k

o
k

n_h=N1:1
n_a = N1:1
v_a = val1

Decide,val1

Decide,val1

N0

N1

N2

Issues

- Network partitions:
  - With one partition, will have majority on one side and can come to agreement (if nobody fails)
- Timeouts
  - A node has max timeout for each message
  - Upon timeout, declare itself as leader and restart Paxos
- Two leaders
  - Either one leader is not able to decide (does not receive majority accept-oks since nodes see higher proposal from other leader) OR
  - one leader causes the other to use it value
- Leader failures: same as two leaders or timeout occurs

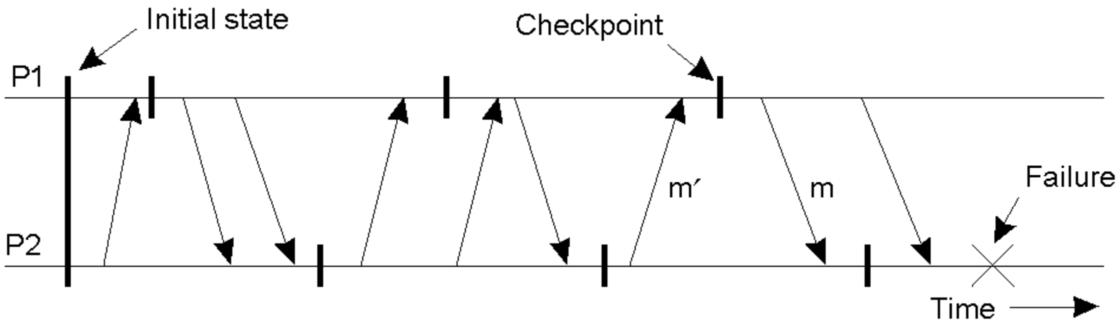
Raft Consensus Protocol

- Paxos is hard to understand (single vs multi-paxos)
- Raft - *understandable* consensus protocol
- **State Machine Replication (SMR)**
  - Implemented as a replicated log
  - Each server stores a log of commands, executes in order
  - Incoming requests —> replicate into logs of servers
  - Each server executed request log in order: stays consistent
- Raft: first elect a leader
- Leader sends requests (log entries) to followers
- If **majority** receive entry: safe to apply -> commit
  - If entry committed, all entries preceding it are committed

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

Logging

- Logging : a common approach to handle failures
  - Log requests / responses received by system on separate storage device / file (stable storage)
    - Used in databases, filesystems, ...
- Failure of a node
  - Some requests may be lost
  - Replay log to "roll forward" system state

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