Distributed Systems (COMP9243)

Lecture 6: Fault Tolerance

① Failure
② Reliable Communication
③ Process Resilience
④ Recovery

Dependability

Availability: system is ready to be used immediately

Reliability: system can run continuously without failure

Safety: when a system (temporarily) fails to operate correctly, nothing catastrophic happens

Maintainability: how easily a failed system can be repaired

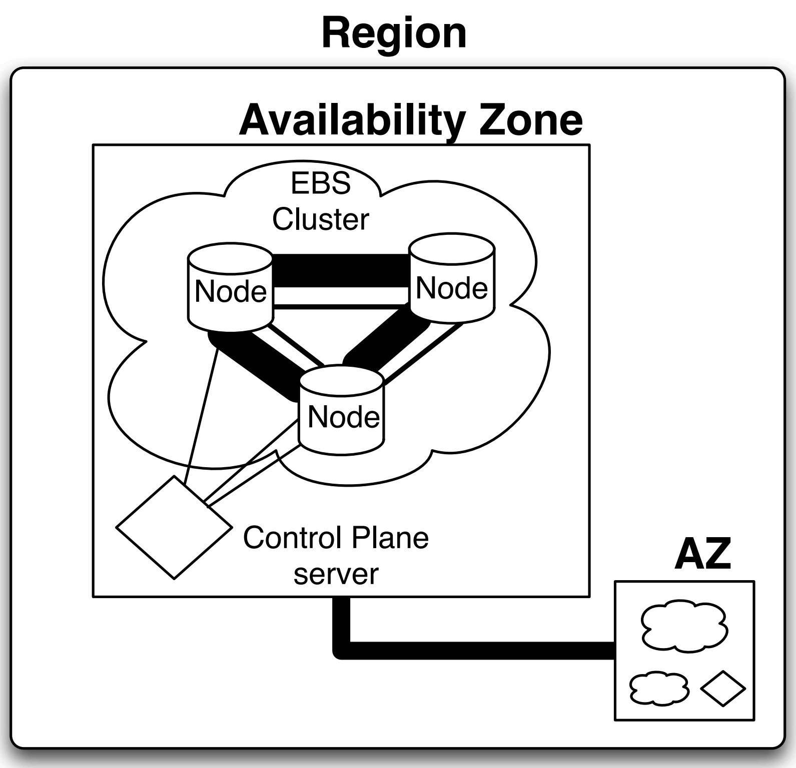
Building a dependable system comes down to controlling failure and faults.

CASE STUDY: AWS FAILURE 2011

- April 21, 2011
- EBS (Elastic Block Store) in US East region unavailable for about 2 days
- 13% of volumes in one *availability zone* got stuck
- led to control API errors and outage in whole region
- led to problems with EC2 instances and RDS in most popular region
- due to reconfig error and *re-mirroring storm*.
- `http://aws.amazon.com/message/65648/`

AWS EBS Overview:

- ➜ Region → Availability Zones
- ➜ Clusters → Nodes → Volumes
- ➜ Volume: replicated in cluster
- ➜ Control Plane Services: API for volumes for whole region
- ➜ Networks: primary, secondary



What happened?:

- ➜ network config problem
- ➜ re-mirroring storm
- ➜ CP API thread starvation
- ➜ node race condition
- ➜ CP election overload

FAILURE

Terminology:

Failure: a system fails when it does not meet its promises or cannot provide its services in the specified manner

Error: part of the system state that leads to failure (i.e., it differs from its intended value)

Fault: the cause of an error (results from design errors, manufacturing faults, deterioration, or external disturbance)

Recursive:

- ➜ Failure can be a fault
- ➜ Manufacturing fault leads to disk failure
- ➜ Disk failure is a fault that leads to database failure
- ➜ Database failure is a fault that leads to email service failure

TOTAL VS PARTIAL FAILURE

Total Failure:

All components in a system fail

- ➜ Typical in nondistributed system

Partial Failure:

One or more (but not all) components in a distributed system fail

- ➜ Some components affected
- ➜ Other components completely unaffected
- ➜ Considered as *fault* for the whole system

Categorising Faults and Failures

Types of Faults:

Transient Fault: occurs once then disappear

Intermittent Fault: occurs, vanishes, reoccurs, vanishes, etc.

Permanent Fault: persists until faulty component is replaced

Types of Failures:

Process Failure: process proceeds incorrectly or not at all

Storage Failure: "stable" secondary storage is inaccessible

Communication Failure: communication link or node failure

FAILURE MODELS

Crash Failure: a server halts, but works correctly until it halts

- **Fail-Stop:** server will stop in a way that clients can tell that it has halted.
- **Fail-Resume:** server will stop, then resume execution at a later time.
- **Fail-Silent:** clients do not know server has halted

Omission Failure: a server fails to respond to incoming requests

- **Receive Omission:** fails to receive incoming messages
- **Send Omission:** fails to send messages

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

Timing Failure: a server's response lies outside the specified time interval

Arbitrary Failure: a server may produce arbitrary response at arbitrary times (aka *Byzantine failure*)

DETECTING FAILURE

Failure Detector:

- ➜ Service that detects process failures
- ➜ Answers queries about status of a process

Reliable:

- ➜ *Failed* – crashed
- ➜ *Unsuspected* – hint

Unreliable:

- ➜ *Suspected* – may still be alive
- ➜ *Unsuspected* – hint

Synchronous systems:

- ➜ Timeout
- ➜ Failure detector sends probes to detect crash failures

Asynchronous systems:

- ✗ Timeout gives no guarantees
- ➜ Failure detector can track *suspected* failures
- ➜ Combine results from multiple detectors
- ✗ How to distinguish communication failure from process failure?
- ➜ Ignore messages from suspected processes
- ✓ Turn an asynchronous system into a synchronous one

Fault Tolerance

Fault Tolerance:

- ➜ System can provide its services even in the presence of faults

Goal:

- ➜ Automatically recover from partial failure
- ➜ Without seriously affecting overall performance

Techniques:

- ➜ **Prevention**: prevent or reduce occurrence of faults
- ➜ **Prediction**: predict the faults that can occur and deal with them
- ➜ **Masking**: hide the occurrence of the fault
- ➜ **Recovery**: restore an erroneous state to an error-free state

Failure Prevention

Make sure faults don't happen:

- ➜ Quality hardware
- ➜ Hardened hardware
- ➜ Quality software

Failure Prediction

Deal with expected faults:

- ➜ Test for error conditions
- ➜ Error handling code
- ➜ Error correcting codes
  - checksums
  - erasure codes

Failure Masking

Try to hide occurrence of failures from other processes

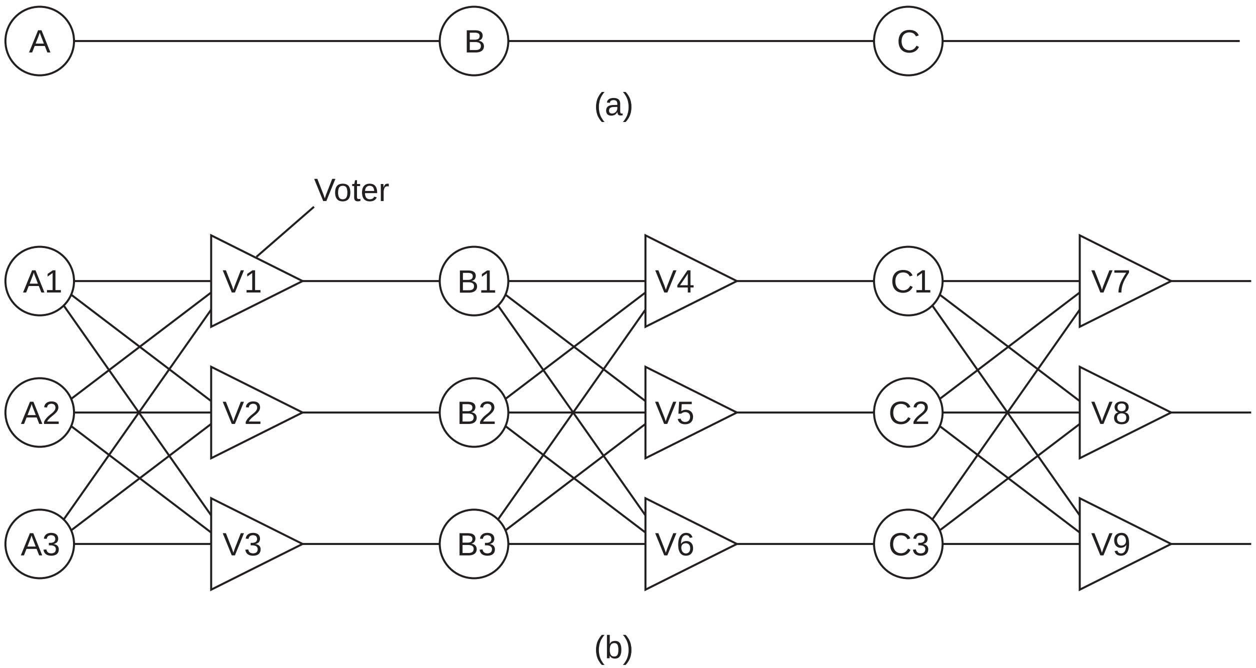
Mask:

① Communication Failure → Reliable Communication

② Process Failure → Process Resilience

Redundancy:

- ➜ Information redundancy
- ➜ Time redundancy
- ➜ Physical redundancy

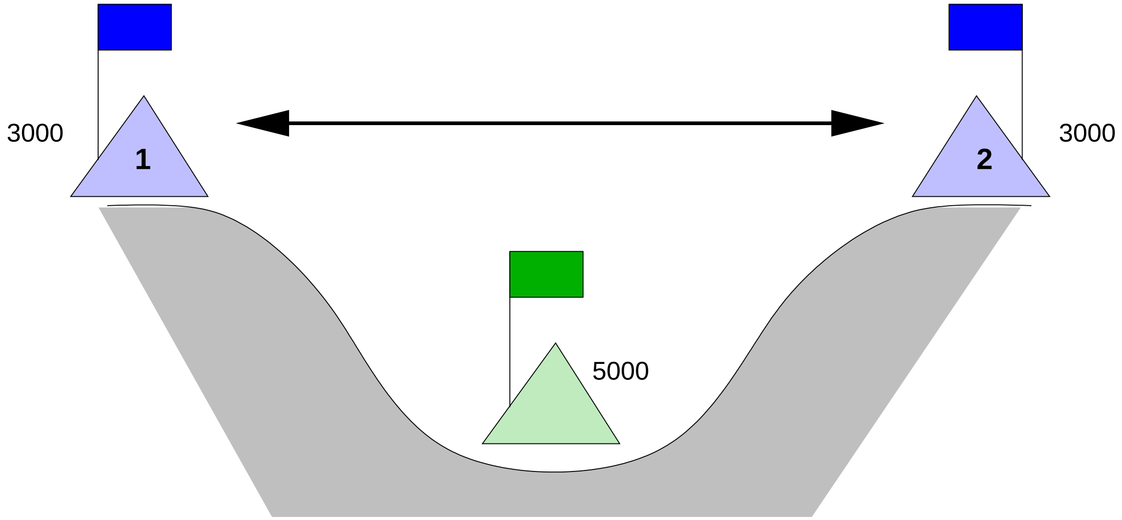


RELIABLE COMMUNICATION

- ➜ Communication channel experiences failure
- ➜ Focus on masking crash (lost/broken connections) and omission (lost messages) failures

Two Army Problem:

Non-faulty processes but lossy communication.



- $1 \rightarrow 2$ attack!
- $2 \rightarrow 1$ ack
- 2: did 1 get my ack?
- $1 \rightarrow 2$ ack ack
- 1: did 2 get my ack ack?
- etc.

Consensus with lossy communication is impossible.

Why does TCP work?

RELIABLE POINT-TO-POINT COMMUNICATION

➜ Reliable transport protocol (e.g., TCP)

- ☑ Masks omission failure
- ☒ Not crash failure

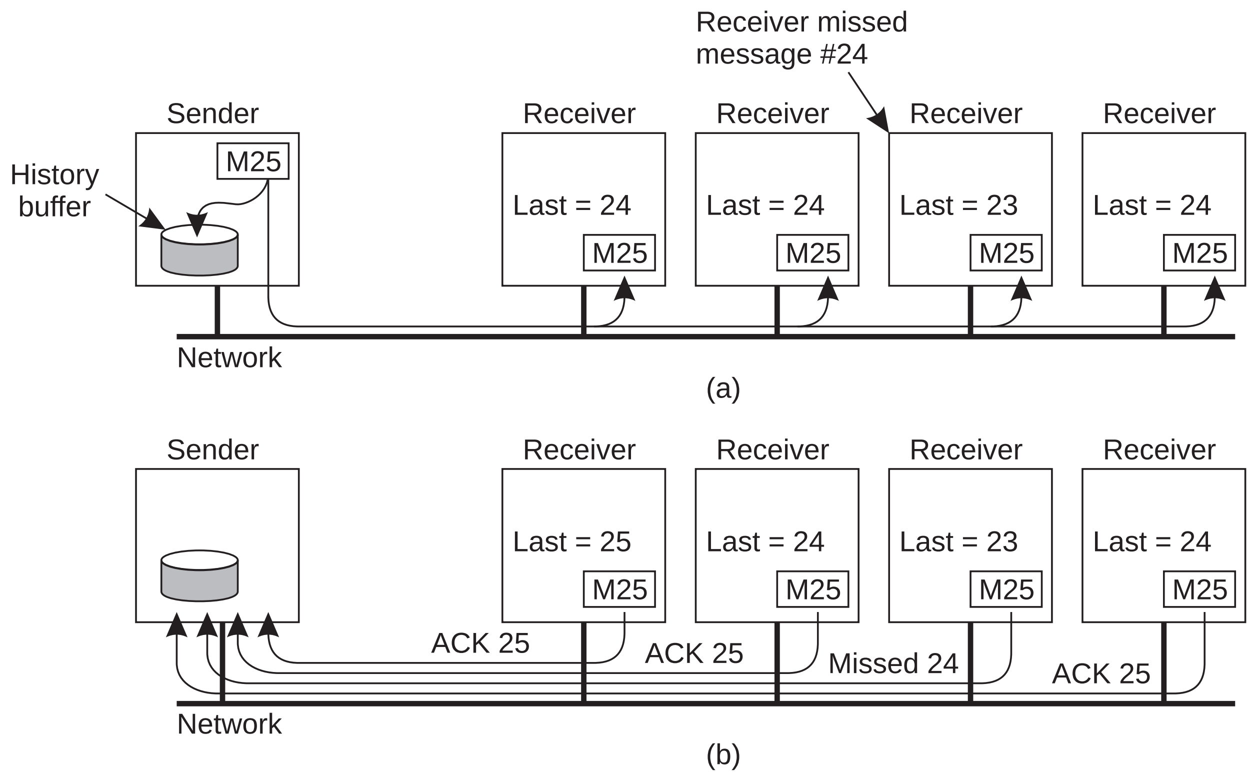
Example: Failure and RPC:

Possible failures:

- ➜ Client cannot locate server
- ➜ Request message to server is lost
- ➜ Server crashes after receiving a request
- ➜ Reply message from server is lost
- ➜ Client crashes after sending a request

How to deal with the various kinds of failure?

Reliable Group Communication



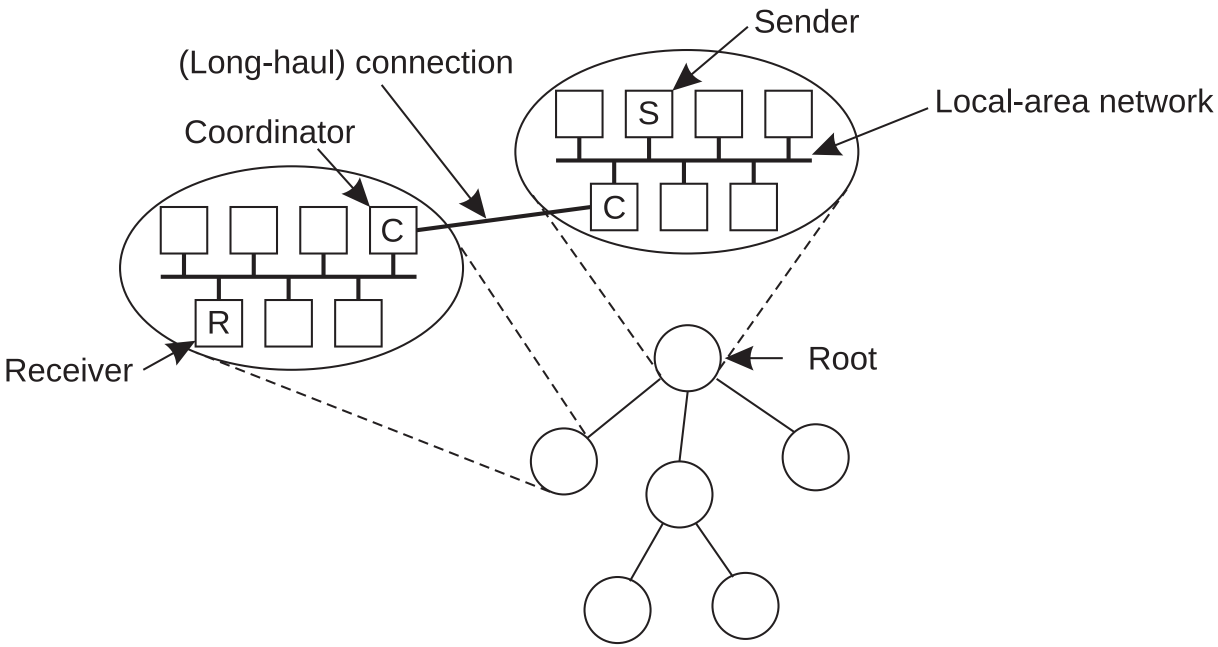
Scalability of Reliable Multicast

Feedback Implosion: sender is swamped with feedback messages

Nonhierarchical Multicast:

- ➜ Use NACKs
- ➜ Feedback suppression: NACKs multicast to everyone
- ➜ Prevents other receivers from sending NACKs if they've already seen one.
- ☑ Reduces (N)ACK load on server
- ☒ Receivers have to be coordinated so they don't all multicast NACKs at same time
- ☒ Multicasting feedback also interrupts processes that successfully received message

Hierarchical Multicast:



Process Resilience

Protection against process failures

Groups:

- ➜ Organise identical processes into groups
  - Process groups are dynamic
  - Processes can be members of multiple groups
  - Mechanisms for managing groups and group membership
- ➜ Deal with all processes in a group as a single abstraction

Flat vs Hierarchical Groups:

- ➜ Flat group: all decisions made collectively
- ➜ Hierarchical group: coordinator makes decisions

Replication

Create groups using replication

Primary-Based:

- ➜ Primary-backup
- ➜ Hierarchical group
- ➜ If primary crashes others elect a new primary

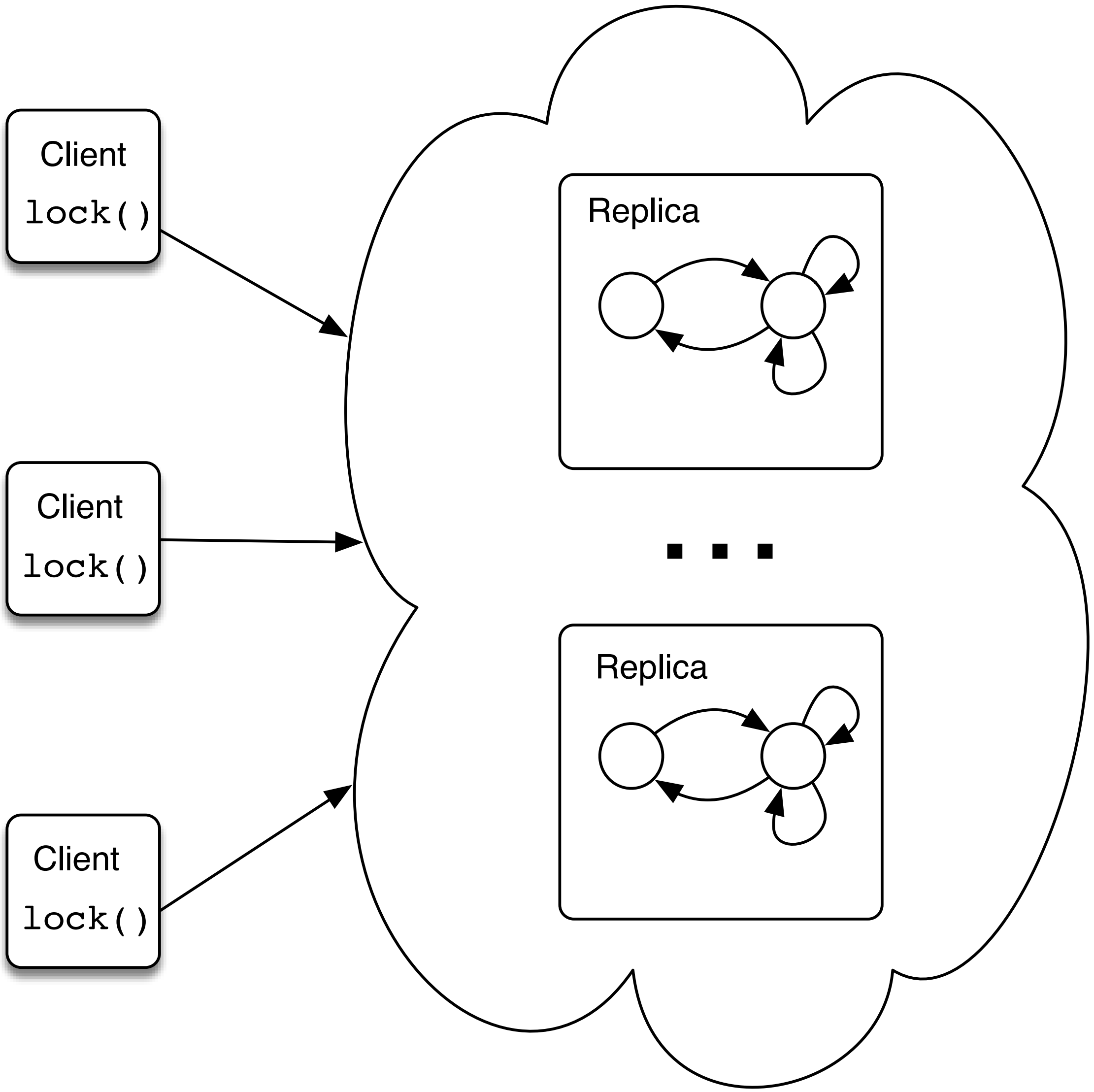
Replicated-Write:

- ➜ Active replication or Quorum
- ➜ Flat group
- ➜ Ordering of requests (atomic multicast problem)

k Fault Tolerance:

- ➜ can survive faults in k components and still meet its specifications
- ➜ $k + 1$ replicas enough if fail-silent (or fail-stop)
- ➜ $2k + 1$ required if if byzantine

State Machine Replication


Client
lock()
Client
lock()
Client
lock()
Replica
...
Replica

Each replica executes as a state machine:

- ➜ *state + input -> output + new state*
- ➜ All replicas process same input in same order
- ➜ Deterministic: All correct replicas produce same output
- ➜ Output from incorrect replicas deviates

Input Messages:

- ➜ All replicas agree on content of input messages
- ➜ All replicas agree on order of input messages
- ➜ Consensus (also called Agreement)

What can cause non-determinism?

Atomic Multicast

A message is delivered to either all processes, or none

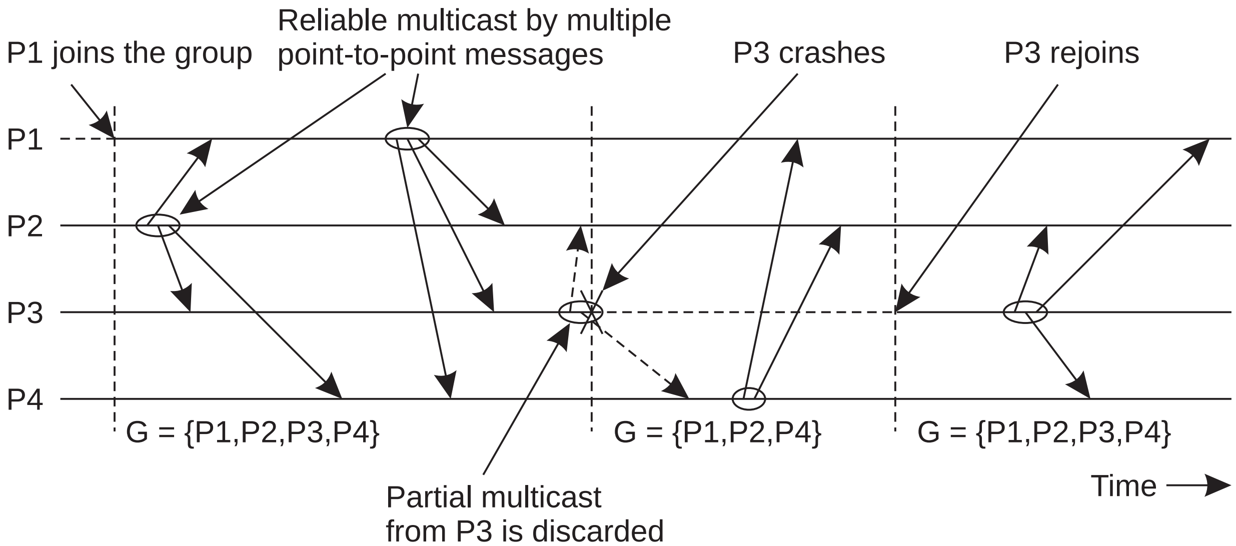
Requires agreement about group membership

Process Group:

- ➜ Group view: view of the group (list of processes) sender had when message sent
- ➜ Each message uniquely associated with a group
- ➜ All processes in group have the same view

View Synchrony:

A message sent by a crashing sender is either delivered to all remaining processes (crashed after sending) or to none (crashed before sending).

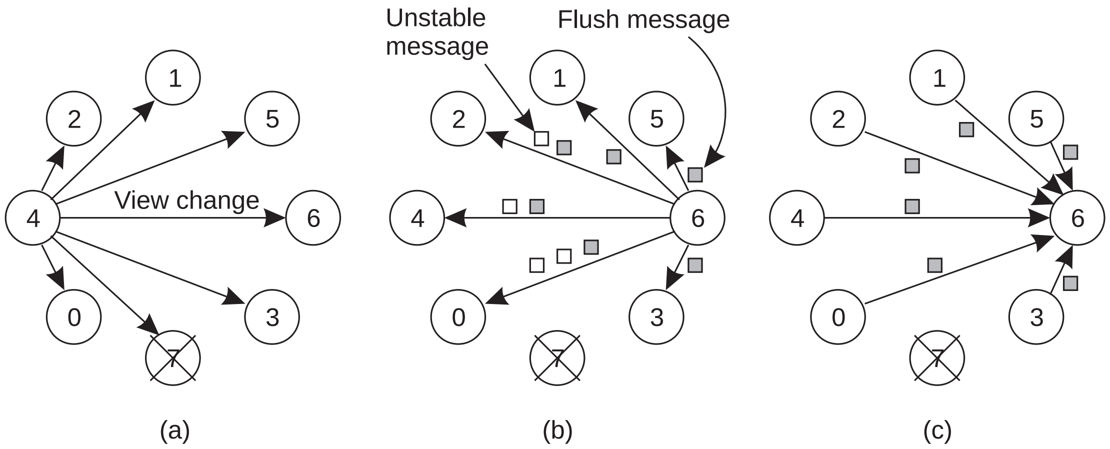


➜ view changes and messages are delivered in total order Why?

Implementing View Synchrony:

stable message: a message that has been received by all members of the group it was sent to.

- ➜ Implemented using reliable point-to-point communication (TCP)
- ➜ Failure during multicast → only some messages delivered



AGREEMENT

Examples: Election, transaction commit/abort, dividing tasks among workers, mutual exclusion

- ➜ Previous algorithms assumed no faults
- ➜ What happens when processes can fail?
- ➜ What happens when communication can fail?
- ➜ What happens when byzantine failures are possible

We want all nonfaulty processes to reach and establish agreement (within a finite number of steps)

VARIANTS OF THE AGREEMENT PROBLEM

Consensus:

- each process proposes a value
- communicate with each other...
- all processes decide on same value
- for example, the maximum of all the proposed values

Interactive Consistency:

- all processes agree on a decision *vector*
- for example, the value that each of the processes proposed

Byzantine Generals:

- commander proposes a value
- all other processes agree on the commander's value

Correctness of agreement:

Termination all processes eventually decide

Agreement all processes decide on the same value

Validity C the decided value was proposed by one of the processes

IC the decided value is a vector that reflects each of the processes proposed values

BG the decided value was proposed by the commander

Consensus in a Synchronous System

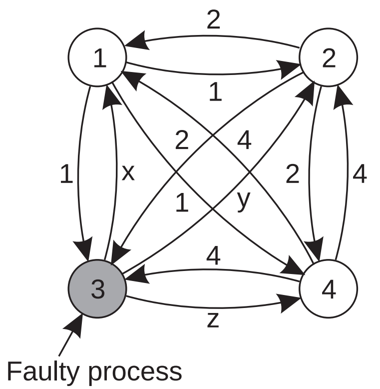
Assume:

- ➜ Execution in rounds
- ➜ Timeout to detect lost messages

Byzantine Generals Problem:

Reliable communication but faulty processes.

- ➜ n generals (processes)
- ➜ m are traitors (will send incorrect and contradictory info)
- ➜ Need to know everyone else's troop strength g_i
- ➜ Each process has a vector: $\langle g_1, ...g_n \rangle$
- ➜ (Note: this is actually interactive consistency)



(a)

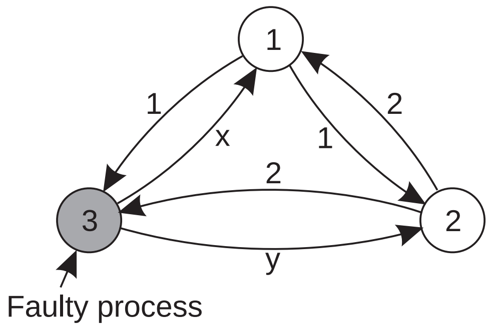
1	Got(1, 2, x, 4)
2	Got(1, 2, y, 4)
3	Got(1, 2, 3, 4)
4	Got(1, 2, z, 4)

(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)

Byzantine Generals Impossibility:



(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)

➜ If m faulty processes then $2m + 1$ nonfaulty processes required for correct functioning

Byzantine agreement with Signatures:

- ➜ Digitally sign messages
- ➜ Cannot lie about what someone else said
- ➜ Avoids the impossibility result
- ➜ Can have agreement with 3 processes and 1 faulty

Consensus in an Asynchronous System

Assume:

- ➜ Arbitrary execution time (no rounds)
- ➜ Arbitrary message delays (can't rely on timeout)

Impossibility of Consensus with One Failure

Impossible to guarantee consensus with ≥ 1 faulty process

Proof Outline:

- ➜ Fischer, Lynch, Patterson (FLP) 1985
- ➜ *the basic idea is to show circumstances under which the protocol remains forever indecisive*
- ➜ bivalent (any result is possible) vs univalent (only single result is possible) states

1. There is always a bivalent start state
2. Always possible to reach a bivalent state by delaying messages

$\rightarrow$ no termination

In practice we can get close enough

Consensus in Practice

Two Phase Commit:

➜ Original assumption: No failure

Failures can be due to:

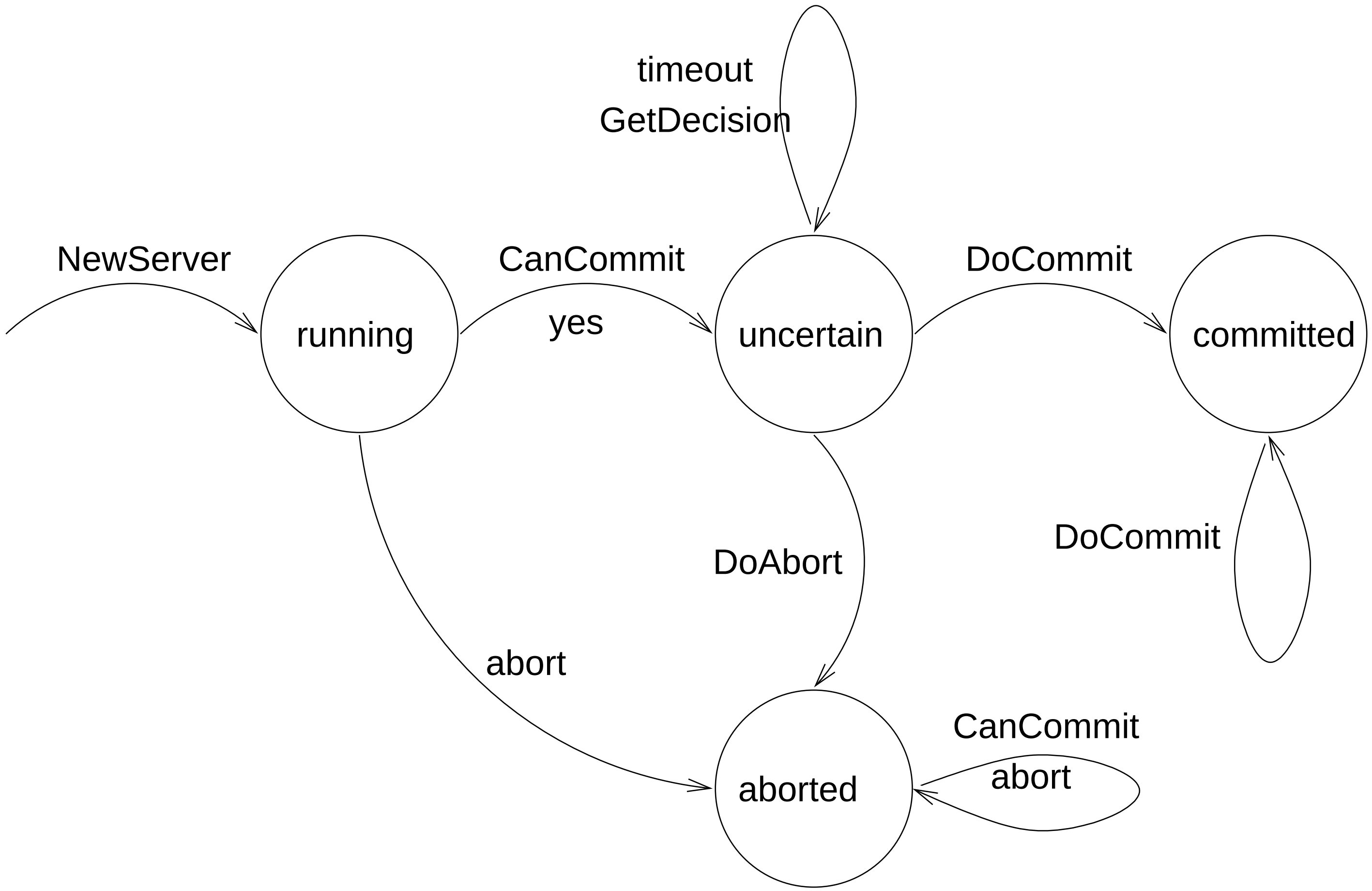
➜ **Failure of communication channels:**

- use timeouts

➜ **Server failures:**

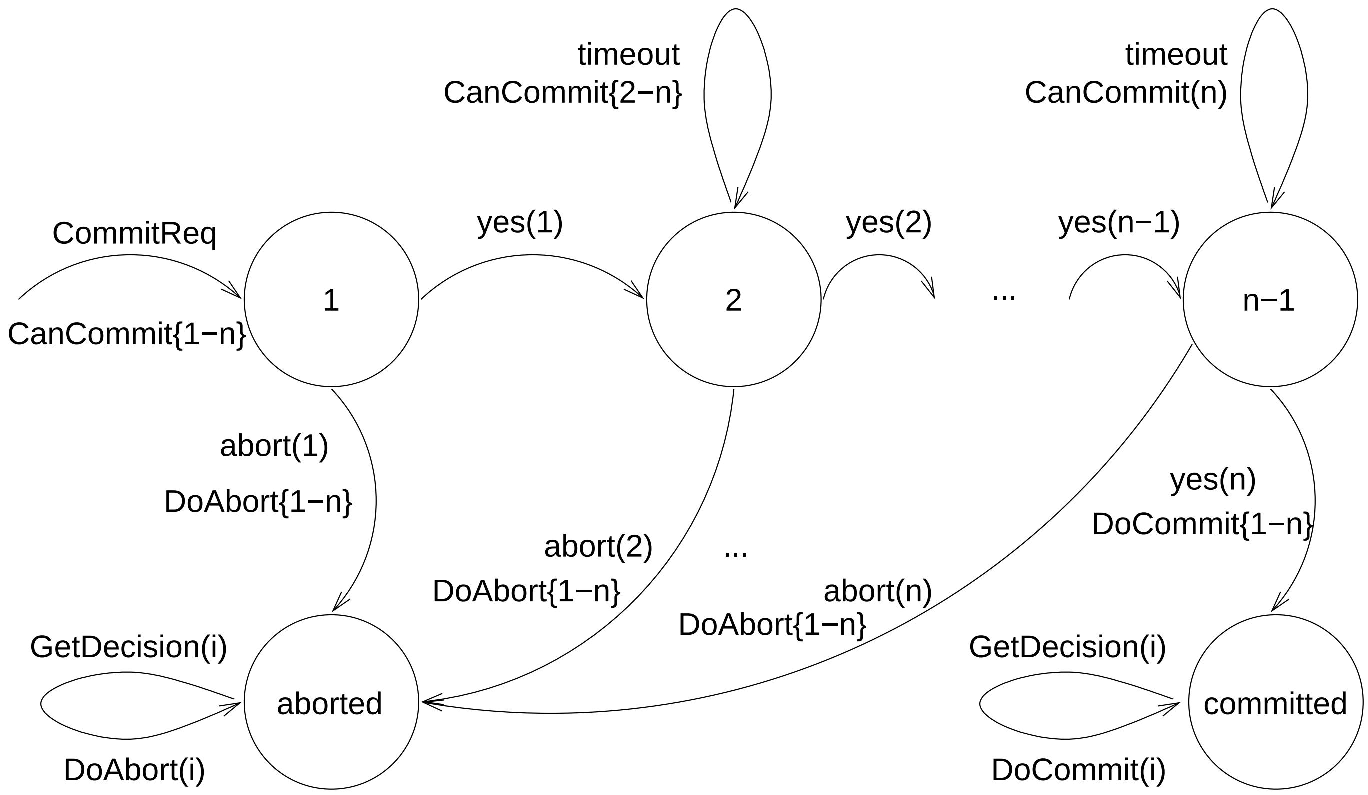
- potentially blocking

Two-phase commit with timeouts: Worker:



➜ On *timeout* sends `GetDecision`.

Two-phase commit with timeouts: Coordinator:



➜ On *timeout* re-sends `CanCommit`, On *GetDecision* repeats decision.

Coordinator failure:

- ➜ When coordinator crashes start a new recovery coordinator
- ➜ Learn state of protocol from workers (what did they vote, what did they learn from coordinator)
- ➜ Finish protocol

Coordinator and Worker failure: Blocking 2PC:

- ➜ Recovery coordinator can't distinguish between
  - All workers vote *Commit* and failed worker already committed
  - Failed worker voted *Abort* and rest of workers voted *Commit*
- ➜ So can't make a decision

Three Phase Commit

① Vote: as in 2PC

② Pre-commit: coordinator sends vote result to all workers, workers acknowledge

③ Commit: coordinator tells workers to perform vote action

Why does this work?

PAXOS

Goal: a collection of processes chooses a single proposed value In the presence of failure

Proposer proposes value to choose (leader)

Acceptor accept or reject proposed values

Learner any process interested in the result (*chosen value*) of the consensus

Chosen Value: value accepted by majority of acceptors

Properties:

- ➜ Only proposed values can be learned
- ➜ At most one value can be learned
- ➜ If a value has been proposed then eventually a value will be learned

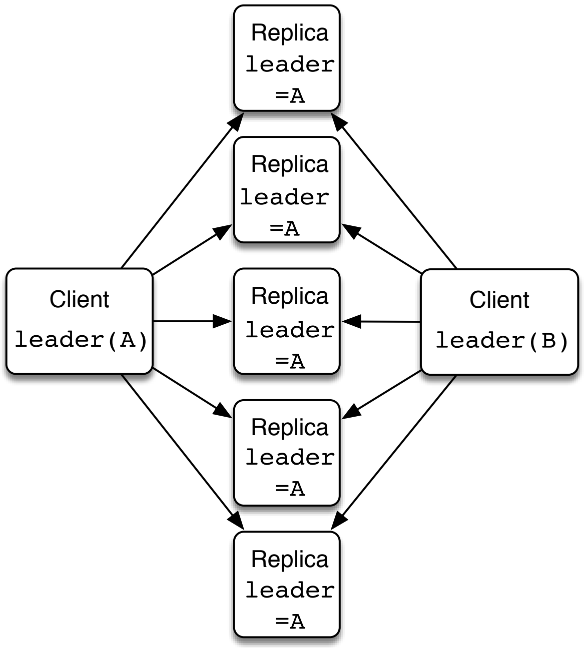
USING PAXOS

Use Paxos for:

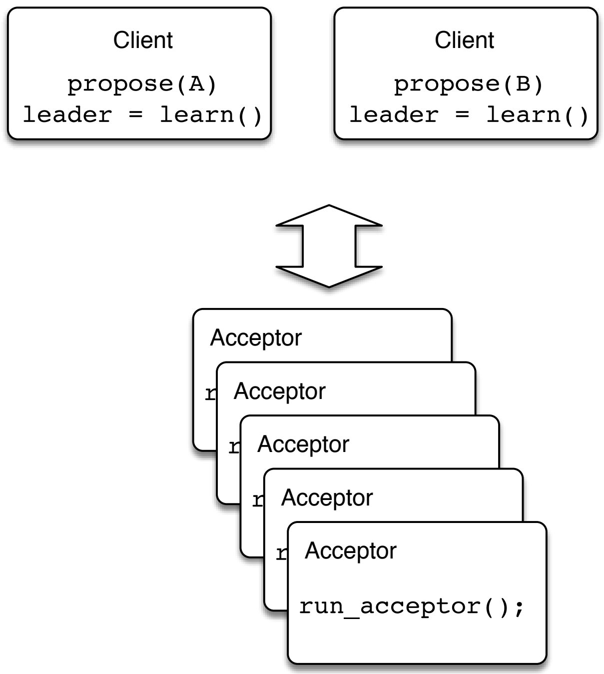
- ➜ Leader election: choose a leader id
  - single paxos instance. elections starter(s) propose leader id. result in an agreed upon leader.
- ➜ View synchrony: order view changes
  - one paxos instance per view change: result in a view change order sequence number
- ➜ Total order multicast: order messages
  - one paxos instance per message: result in a message sequence number
- ➜ State machine replication: order operations
  - one paxos instance per operation: result in an operation sequence number

Example: Leader Election

Conceptually



With Paxos



API:

```
val propose(proposed_val)
run_acceptor()
val learn()
```

Client: Proposer and Learner:

```
propose("A");
leader = learn();
```

Replica: Acceptor:

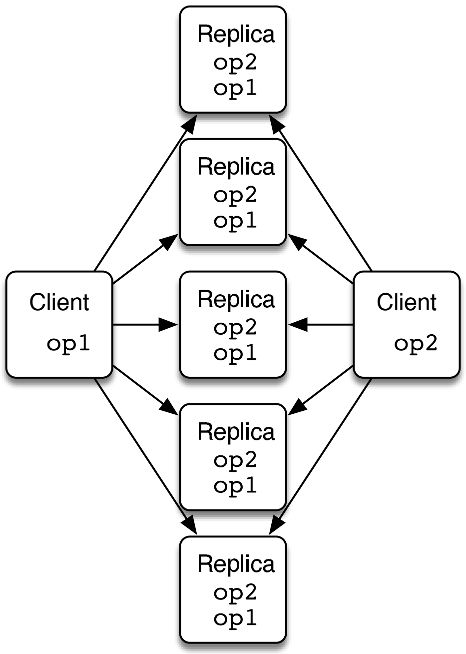
```
while(1) {
  run_acceptor();
}
```

Multi Paxos

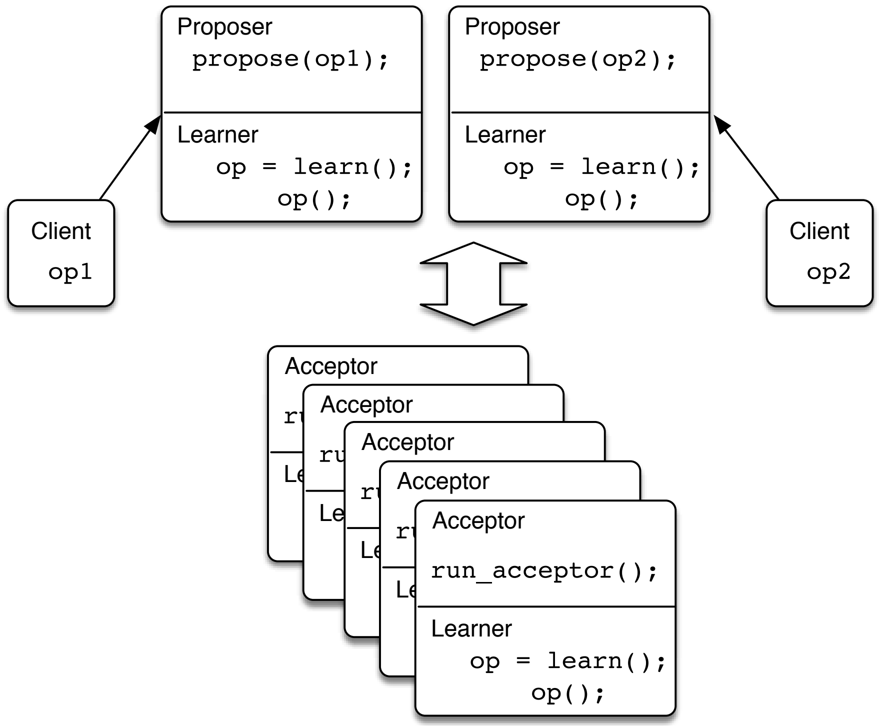
- Paxos allows you to agree on one value
- But, typically need to choose multiple values
  - agree on values
  - agree on order of values
- Run multiple *instances* of Paxos in sequence
- Each instance to choose a single value
- Add *instance id* to algorithm
- Track completed instances
- On failure, restart or join *last completed instance +1*

Example: State Machine Replication

Conceptually



With Paxos



API:

```
val run_proposer(iid, proposed_val)
run_acceptor(iid)
val learn(iid)
```

Client:

```
while (1){
 ...
 send(leader, nextop);
 ...
}
```

Replica: Learner:

```
while(1) {
  op = learn(i++); exec_op(op);
}
```

Replica: Proposer (leader):

```
while(1) {
  receive op
  do {    chosen = run_proposer(i++, op);  } while (chosen != op)
}
```

Replica: Acceptor:

```
while(1) {
  run_acceptor(i++);
}
```

Paxos Algorithm: 3 Phases

Assuming no failures

Phase 1: Propose:

① Propose: send a proposal *<seq, value>* to $\geq N/2$ acceptors

② Promise: acceptors reply.

- *accept* (include last accepted value). *promised* = seq.

Phase 2: Accept:

① Accept: when $\geq N/2$ *accept* replies, proposer sends value (as received from acceptor or arbitrary):

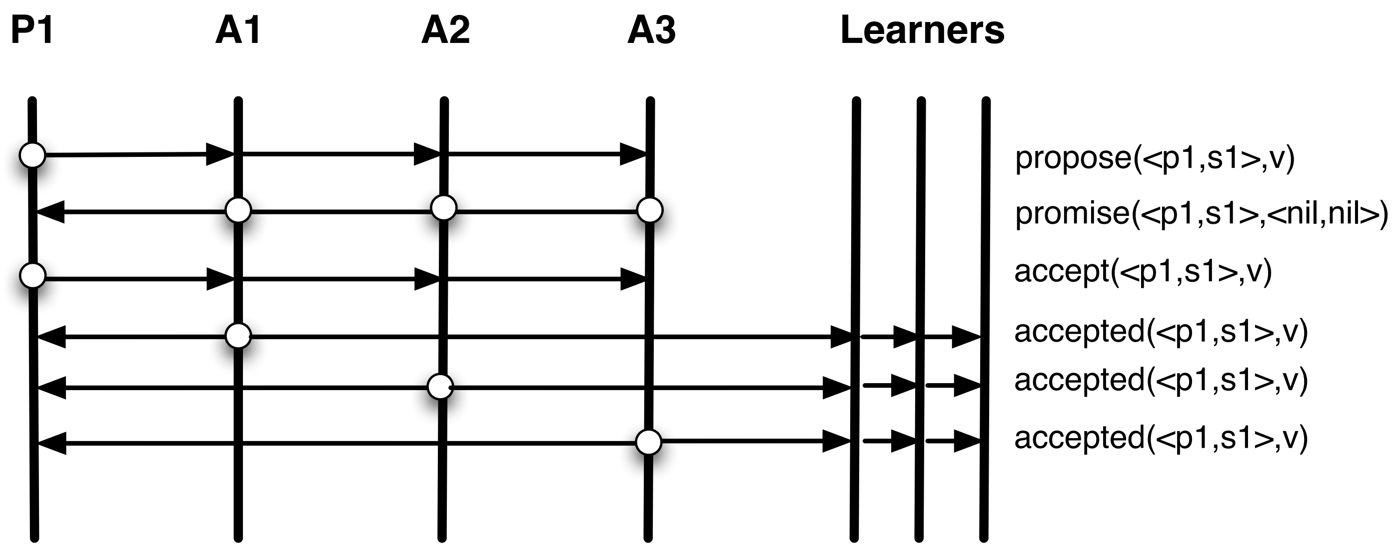
② Accepted: acceptors reply

- *accepted*. Remember accepted value.

Phase 3: Learn:

① Propagate value to Learners when $\geq N/2$ *accepted* replies received.

Simple Case


P1
A1
A2
A3
Learners
propose(<p1,s1>,v)
promise(<p1,s1>,<nil,nil>)
accept(<p1,s1>,v)
accepted(<p1,s1>,v)
accepted(<p1,s1>,v)
accepted(<p1,s1>,v)

FAILURES

What can go wrong before agreement is reached?

Failure Model:

channel : lose, reorder, duplicate message

process : crash (fail-stop, fail-resume)

Failure Cases:

① Acceptor fails

② Acceptor recovers/restarts

③ Proposer fails

④ Multiple proposers

- ➜ New proposer
- ➜ Proposer recovers/restarts

Paxos Algorithm: 3 Phases

With Failures!

Phase 1: Propose:

① Propose: send a proposal <*seq, value*> to $\geq N/2$ acceptors

② Promise: acceptors reply.

- *reject* if seq $<$ seq of previously accepted value
- else *accept* (include last accepted value). *promised* = seq.

Phase 2: Accept:

① Accept: when $\geq N/2$ *accept* replies, proposer sends value (as received from acceptor or arbitrary):

② Accepted: acceptors reply

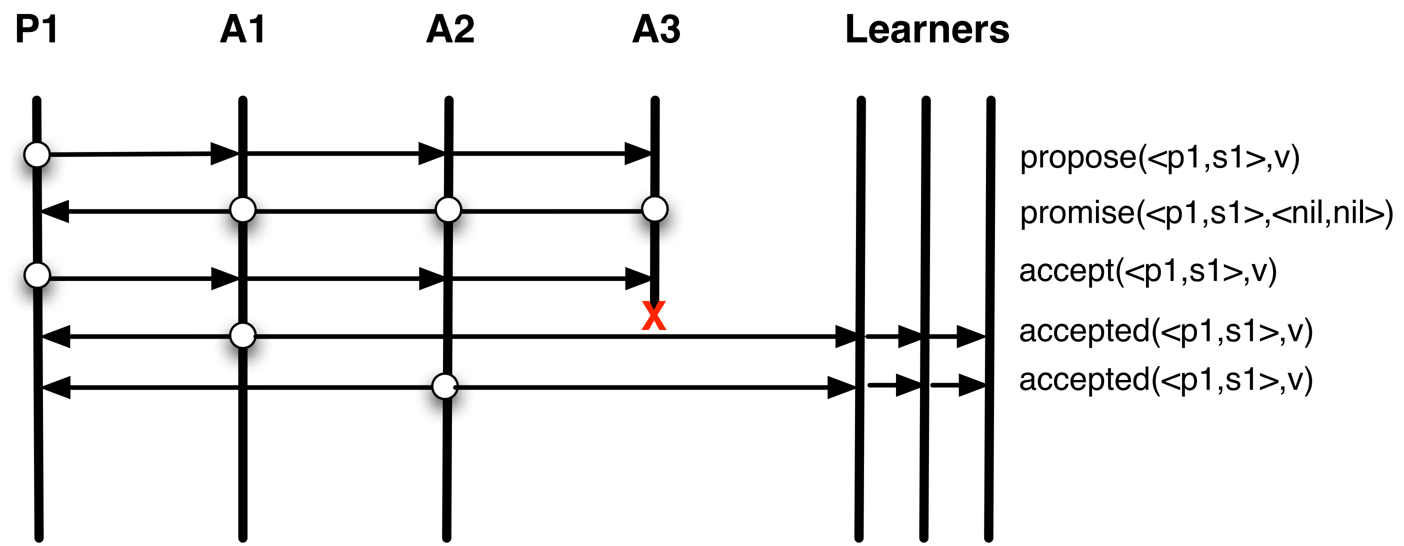
- *reject* if seq $<$ promised.
- else *accepted*. Remember accepted value.

Phase 3: Learn:

① Propagate value to Learners when $\geq N/2$ *accepted* received.

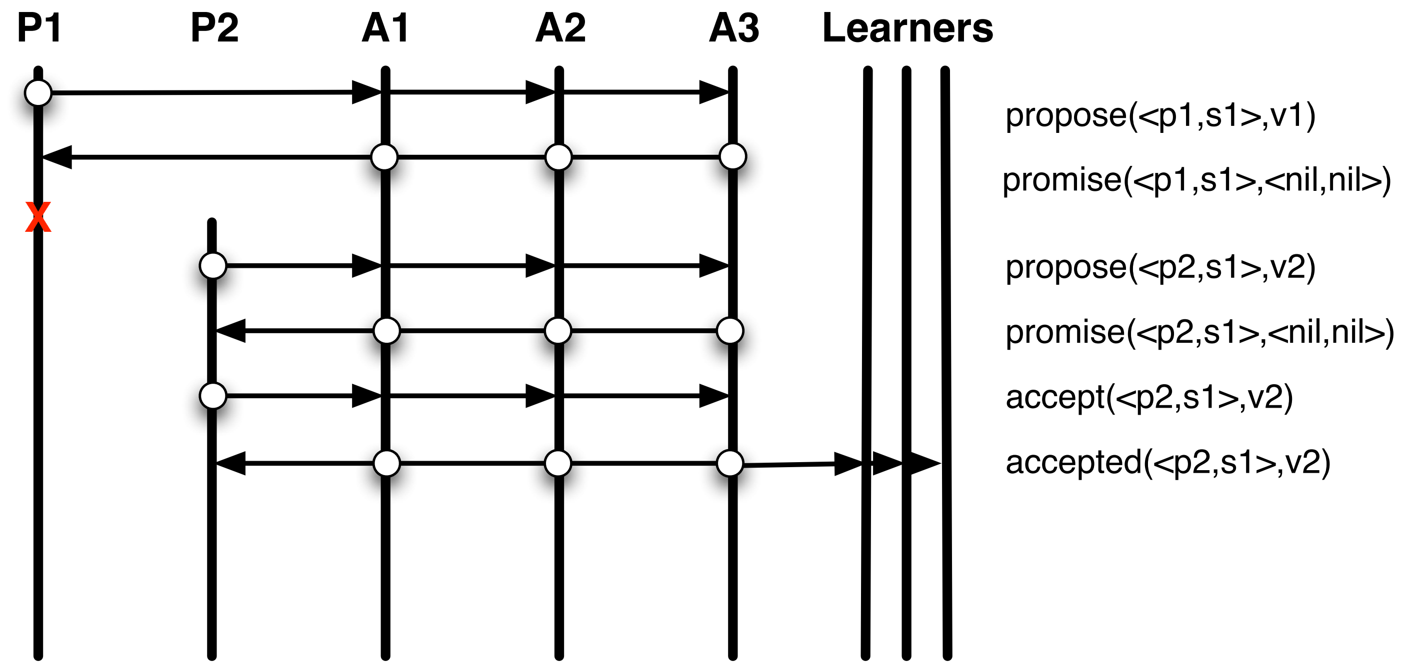
Acceptor Fails

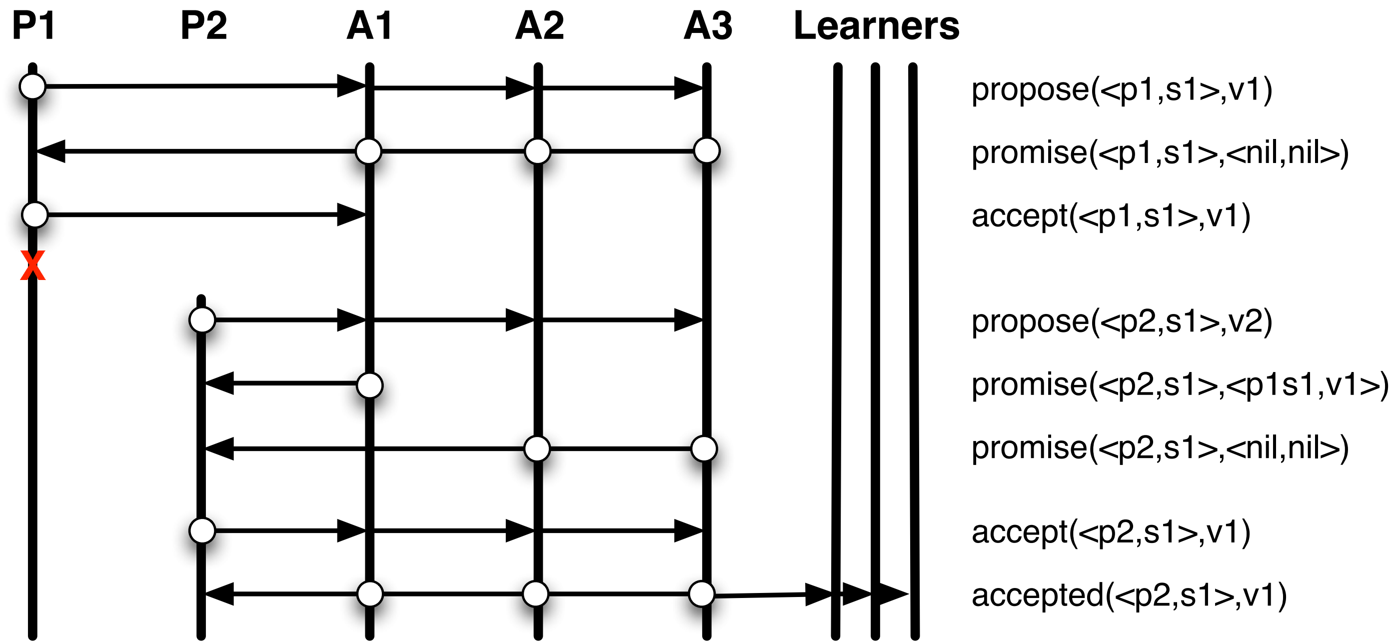
- ☑ As long as a quorum still available
- ➜ Restart: Must remember last accepted value(s)



Proposer Fails

- ➜ Elect a new leader
- ➜ Continue execution
- ☑ New proposer will choose any previously accepted value




P1
P2
A1
A2
A3
Learners
X
propose(<p1,s1>,v1)
promise(<p1,s1>,<nil,nil>)
accept(<p1,s1>,v1)
propose(<p2,s1>,v2)
promise(<p2,s1>,<p1s1,v1>)
promise(<p2,s1>,<nil,nil>)
accept(<p2,s1>,v1)
accepted(<p2,s1>,v1)

Multiple Proposers

- ➜ For example: crashed proposer returns and continues
- ✗ Dueling proposers
- ✗ No guaranteed termination
- ✓ Heuristics to recognise situation and back off

Optimisation and More Information

Opportunities for optimisation:

➜ Reduce rounds

- Phase 1: reject: return highest accepted seq
- Phase 2: reject: return promised seq

➜ Reduce messages

- Piggyback multiple requests and replies
- Pre-propose multiple instances (assumes Proposer rarely fails)

More information:

Paxos Made Live - An Engineering Perspective Experiences implementing Paxos for Google's Chubby lock server. It turns out to be quite complicated.

Failure Recovery

Restoring an erroneous state to an error free state

Issues:

- ➜ **Reclamation of resources:**
  locks, buffers held on other nodes
- ➜ **Consistency:**
  Undo partially completed operations prior to restart
- ➜ **Efficiency:**
  Avoid restarting whole system from start of computation

Forward vs. Backward Error Recovery

Forward Recovery:

- ➜ Correct erroneous state without moving back to a previous state.
- ➜ Example: erasure correction - missing packet reconstructed from successfully delivered packets.
- ✗ Possible errors must be known in advance

Backward Recovery:

- ➜ Correct erroneous state by moving to a previously correct state
- ➜ Example: packet retransmission when packet is lost
- ✓ General purpose technique.
- ✗ High overhead
- ✗ Error can reoccur
- ✗ Sometimes impossible to roll back (e.g. ATM has already delivered the money)

Backward Recovery

General Approach:

➜ Restore process to *recovery point*

➜ Restore system by restoring all active processes

Specific Approaches:

Operation-based recovery :

- Keep *log* (or audit trail) of operations (like transactions)
- Restore to recovery point by reversing changes

State-based recovery :

- Store complete state at recovery point (checkpointing)
- Restore process state from checkpoint (rolling back)

Log or checkpoint recorded on *stable* storage

State-Based Recovery - Checkpointing:

Take frequent checkpoints during execution

Checkpointing:

- ➜ Pessimistic vs Optimistic
  - *Pessimistic*: assumes failure, optimised toward recovery
  - *Optimistic*: assumes infrequent failure, minimises checkpointing overhead
- ➜ Independent vs Coordinated
  - *Coordinated*: processes synchronise to create global checkpoint
  - *Independent*: each process takes local checkpoints independently of others
- ➜ Synchronous vs Asynchronous
  - *Synchronous*: distributed computation blocked while checkpoint taken
  - *Asynchronous*: distributed computation continues while checkpoint taken

Checkpointing Overhead:

- ✗ Frequent checkpointing increases overhead
- ✗ Infrequent checkpointing increases recovery cost

Decreasing Checkpointing Overhead:

Incremental checkpointing: Only write changes since last checkpoint:

- ➜ Write-protect whole address space
- ➜ On write-fault mark page as dirty and unprotect
- ➜ On checkpoint only write dirty pages

Asynchronous checkpointing: Use copy-on-write to checkpoint while execution continues

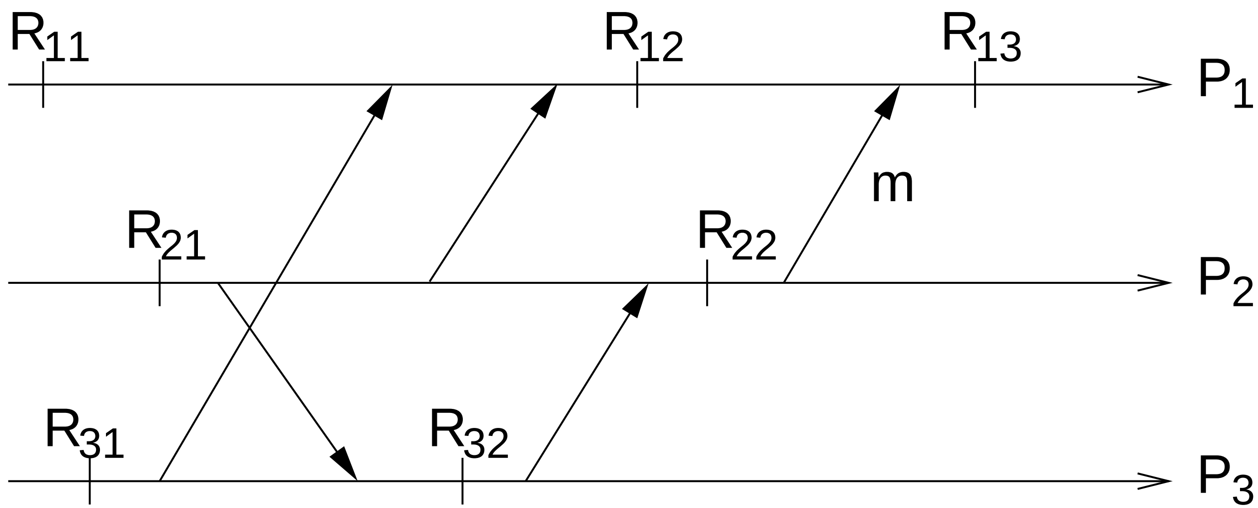
- ➜ Easy with UNIX fork()

Compress checkpoints: Reduces storage and I/O cost at the expense of CPU time

Recovery in Distributed Systems

- ➜ Failed process may have *causally affected* other processes
- ➜ Upon recovery of failed process, must undo effects on other processes
- ➜ Must roll back all affected processes
- → All processes must establish recovery points
- ➜ Must roll back to a *consistent global state*

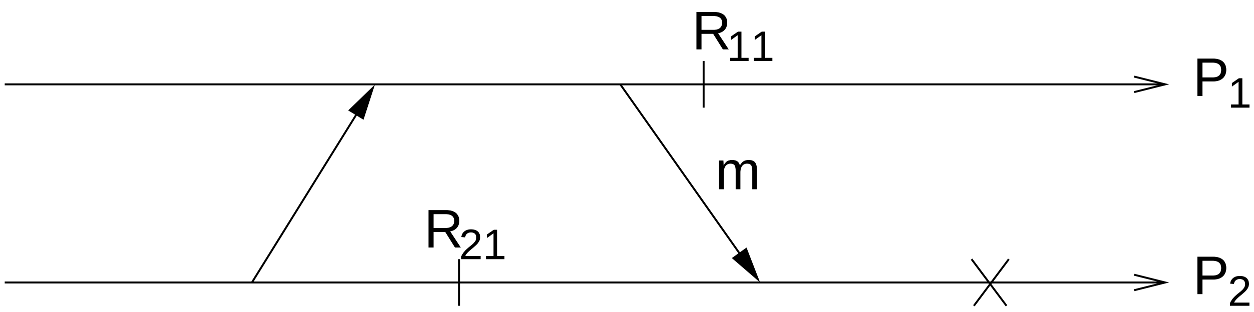
Domino Effect:



- ➜ P_1 fails $\rightarrow$ roll back: $P_1 \curvearrowright R_{13}$
- ➜ P_2 fails $\rightarrow P_2 \curvearrowright R_{22}$
  Orphan message m is received but not sent $\rightarrow P_1 \curvearrowright R_{12}$
- ➜ P_3 fails $\rightarrow P_3 \curvearrowright R_{32} \rightarrow P_2 \curvearrowright R_{21} \rightarrow P_1 \curvearrowright R_{11}, P_3 \curvearrowright R_{31}$

Messaging dependencies plus independent checkpointing may force system to roll back to initial state

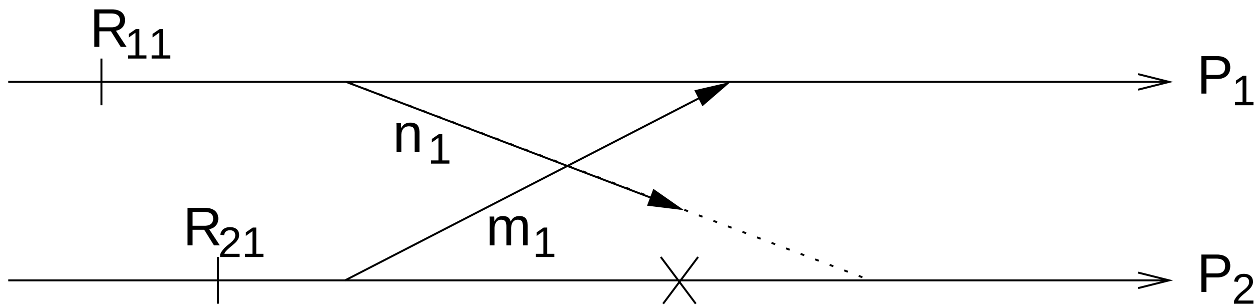
Message Loss:



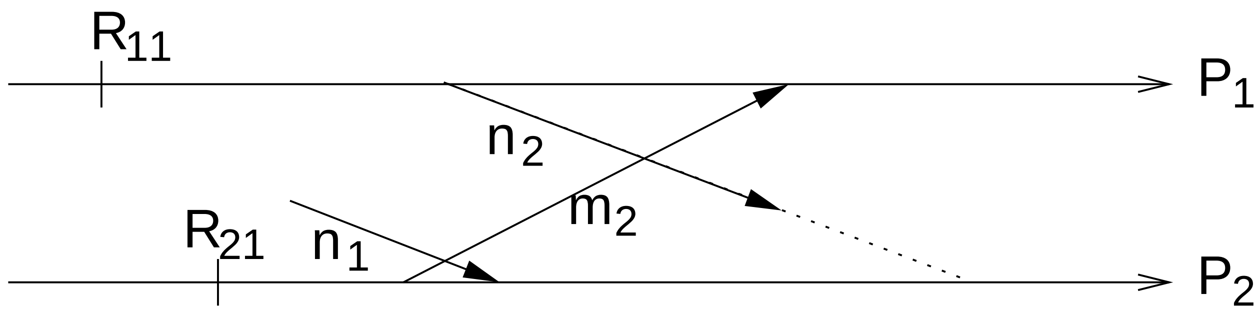
- ➜ Failure of $P_2 \rightarrow P_2 \curvearrowright R_{21}$
- ➜ Message m is now recorded as sent (by P_1) but not received (by P_2), and m will never be received after rollback
- ➜ Message m is *lost*
- ➜ Whether m is lost due to rollback or due to imperfect communication channels is indistinguishable!

$\rightarrow$ Require protocols resilient to message loss

Livelock:



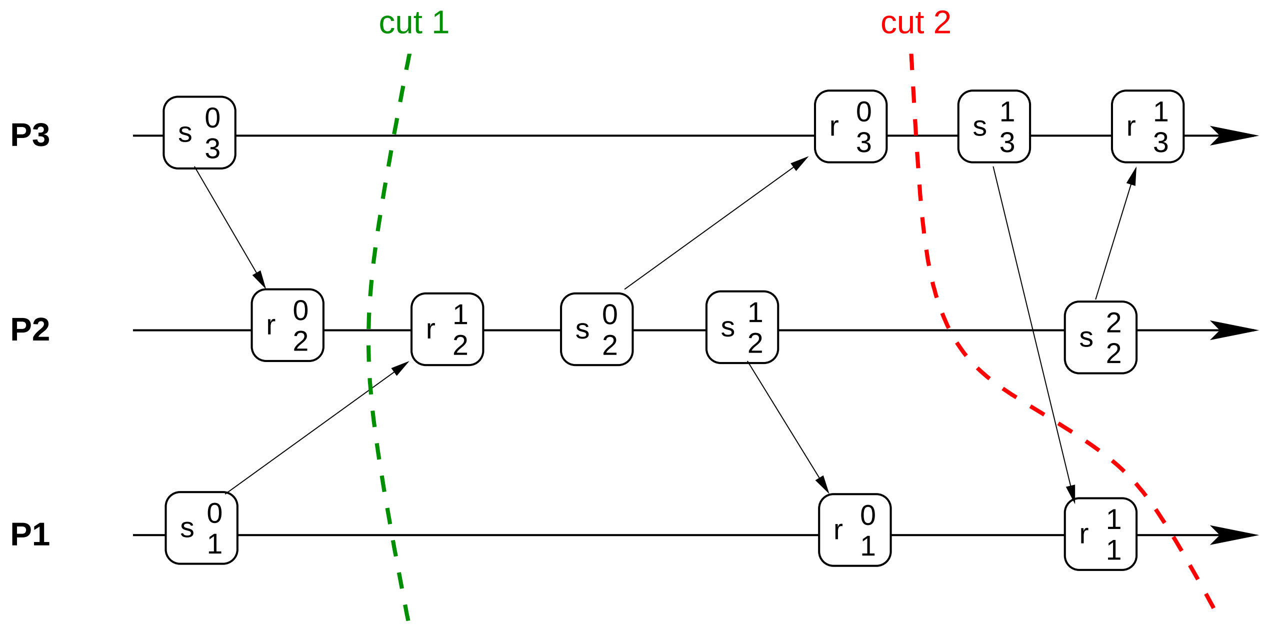
$P_2 \Downarrow \rightarrow P_2 \curvearrowright R_{21} \rightarrow P_1 \curvearrowright R_{11}$. Note: n_1 in transit



- ➜ Pre-rollback message n_1 is received after rollback
- ➜ Forces another rollback $P_2 \curvearrowright R_{21}, P_1 \curvearrowright R_{11}$, can repeat indefinitely

Consistent Checkpointing

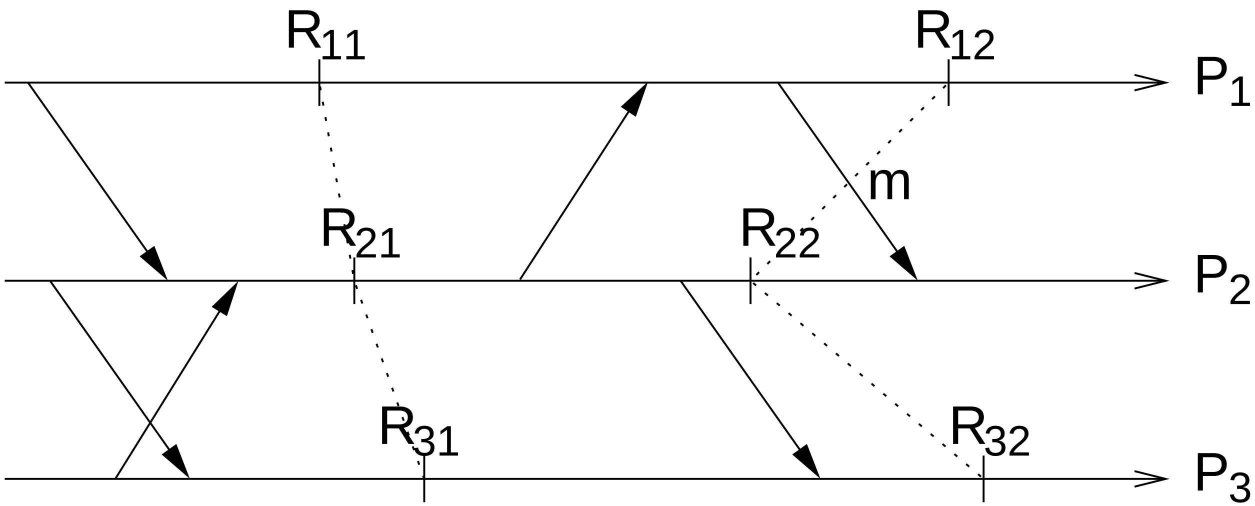
Consistent Cut:



Idea: collect *local checkpoints* in a coordinated way.

➜ Set of local checkpoints forms a *global checkpoint*.

➜ A global checkpoint represents a *consistent system state*.



➜ $\{R_{11}, R_{21}, R_{31}\}$ form a *strongly consistent checkpoint*:

- No information flow during checkpoint interval

➜ $\{R_{12}, R_{22}, R_{32}\}$ form a *consistent checkpoint*:

- All messages recorded as received **must be** recorded as sent

- **Strongly consistent checkpointing** requires quiescent system
  $\rightarrow$ Potentially long delays during *blocking checkpointing*
- **Consistent checkpointing** requires dealing with message loss
  - Not a bad idea anyway, as otherwise each lost message would result in a global rollback
  - Note that a consistent checkpoint may not represent an actual past system state

How to take a consistent checkpoint?:

- Simple solution: Each process checkpoints immediately after sending a message
- ✗ High overhead
- Reducing this to checkpointing after n messages, $n > 1$, is **not** guaranteed to produce a consistent checkpoint!

$\rightarrow$ Require some coordination during checkpointing

Synchronous Checkpointing

Processes coordinate local checkpointing so that most recent local checkpoints constitute a consistent checkpoint

Assumptions:

- ➜ Communication is via FIFO channels.
- ➜ Message loss dealt with via
  - Protocols (such as sliding window), or
  - Logging of all sent messages to stable storage
- ➜ Network will not partition

Local checkpoints:

permanent: part of a global checkpoint

tentative: may or may not become permanent

Synchronous Algorithm

- ➜ Global checkpoint initiated by a single *coordinator*
- ➜ Based on 2PC

First Phase:

① Coordinator P_i takes tentative checkpoint

② P_i sends t message to all other processes P_j to take tentative checkpoint

③ P_j reply to P_i whether succeeded in taking tentative checkpoint

④ P_i receives $true$ reply from each P_j $\rightarrow$ decides to make permanent

P_i receives at least one $false$ $\rightarrow$ decides to discard the tentative checkpoints

Second Phase:

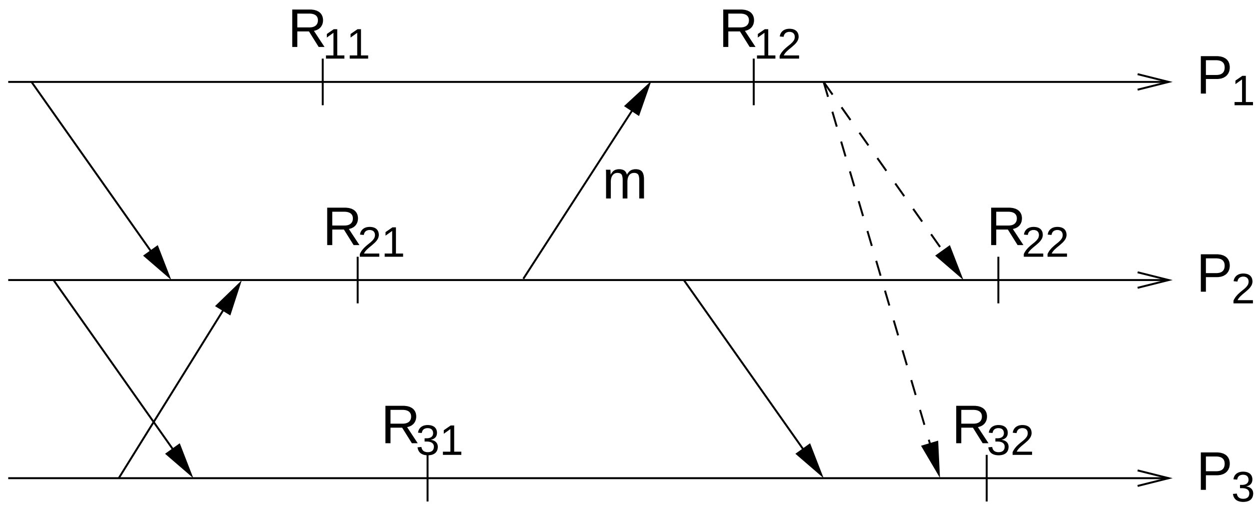
① Coordinator P_i informs all other processes P_j of decision

② P_j convert or discard tentative checkpoints accordingly

Consistency ensured because no messages sent between two checkpoint messages from P_i

Redundant Checkpoints

Algorithm performs unnecessary checkpoints



- ➜ $\{R_{11}, R_{21}, R_{31}\}$ form a (strongly) consistent checkpoint
- ➜ Checkpoint $\{R_{12}, R_{22}, R_{32}\}$ initiated by P_1 is strongly consistent
- ➜ R_{32} is redundant, as $\{R_{12}, R_{22}, R_{31}\}$ is consistent

Rollback Recovery

First Phase:

1. Coordinator sends "r" messages to all other processes to ask them to roll back
2. Each process replies $true$, unless already in checkpoint or rollback
3. **If** all replies are $true$, coordinator decides to roll back, otherwise continue

Second Phase:

1. Coordinator sends decision to other processes
2. Processes receiving this message perform corresponding action

HOMEWORK

➜ Find a Paxos library and implement a replicated state machine using it.

Hacker's edition:

➜ Implement the Paxos library (e.g., in Erlang).

Reading List

Optional

Paxos Made Live - An Engineering Perspective Experiences implementing Paxos for Google's Chubby lock server. It turns out to be quite complicated.