Slide 1

DISTRIBUTED SYSTEMS (COMP9243)

Lecture 6: Fault Tolerance

① Failure
② Reliable Communication
③ Process Resilience
④ Recovery

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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.

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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/`

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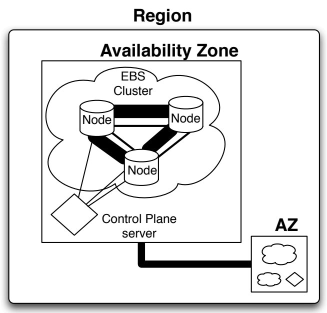
AWS EBS Overview:

- ➜ 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

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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

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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

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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

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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

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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*)

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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

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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

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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

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Failure Prevention

Make sure faults don't happen:

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

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Failure Prediction

Deal with expected faults:

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

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Failure Masking

Try to hide occurrence of failures from other processes

Mask:

① Communication Failure → Reliable Communication

② Process Failure → Process Resilience

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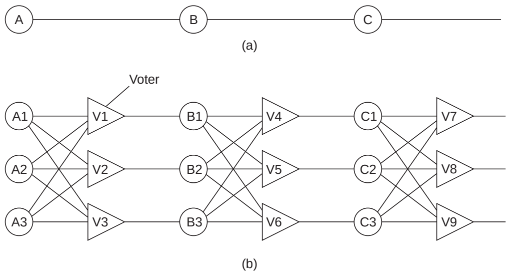
Redundancy:

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



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Reliable Communication

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

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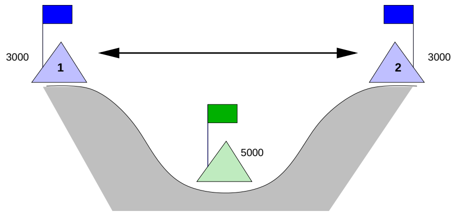
Two Army Problem:

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?

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Reliable Point-to-Point Communication

- ➜ Reliable transport protocol (e.g., TCP)
  - ☑ Masks omission failure
  - ✗ Not crash failure

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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?

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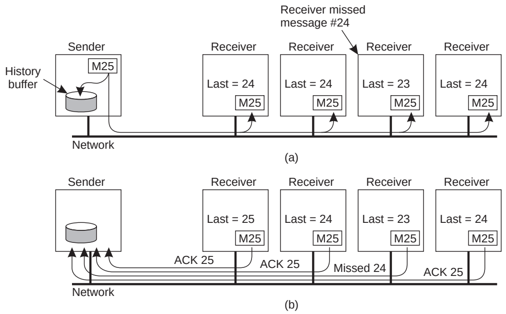
Reliable Group Communication



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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

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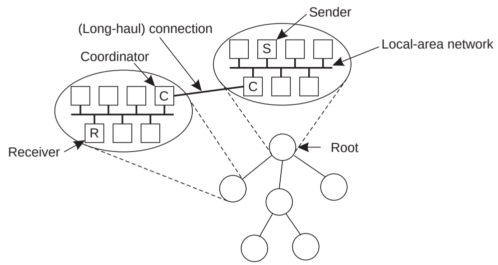
Hierarchical Multicast:



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Process Resilience

Protection against process failures

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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

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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

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STATE MACHINE REPLICATION

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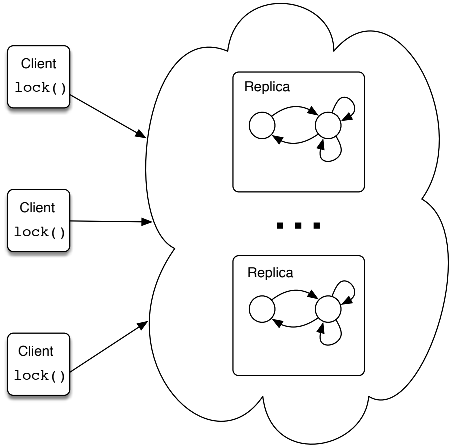

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Each replica executes as a state machine:

- *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?

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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

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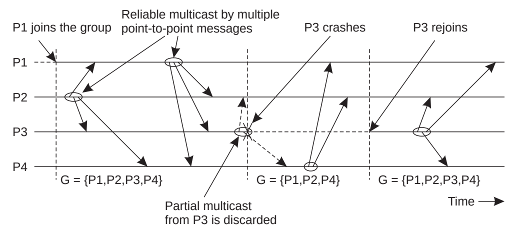
View Synchrony:

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?

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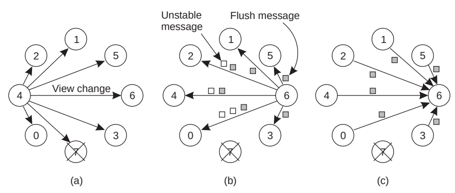
Implementing View Synchrony:

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



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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)

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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

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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

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CONSENSUS IN A SYNCHRONOUS SYSTEM

Assume:

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

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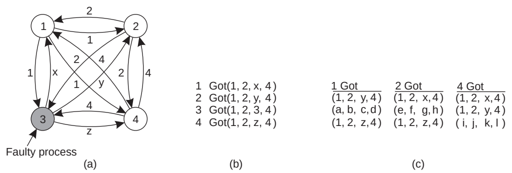
Byzantine Generals Problem:

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)



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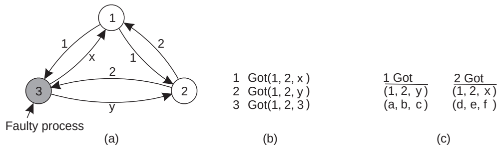
Byzantine Generals Impossibility:



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

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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

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CONSENSUS IN AN ASYNCHRONOUS SYSTEM

Assume:

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

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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

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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

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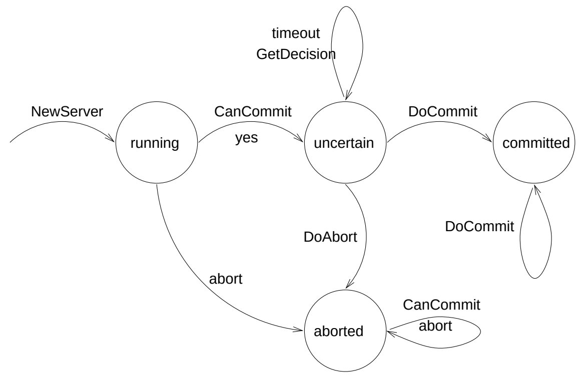
Two-phase commit with timeouts: Worker:



- ➜ On *timeout* sends `GetDecision`.

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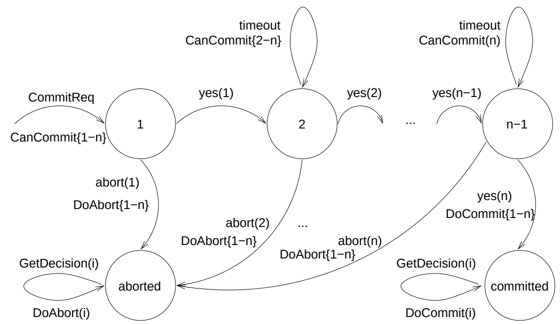
Two-phase commit with timeouts: Coordinator:



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

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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

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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?

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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

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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

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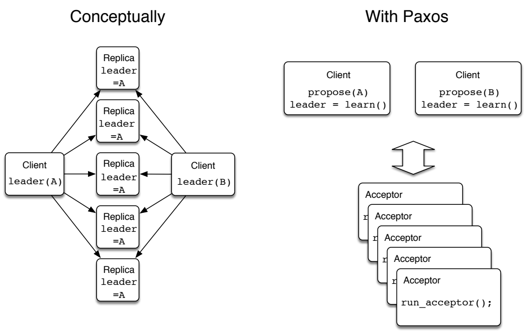
Example: Leader Election



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API:

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

Client: Proposer and Learner:

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

Replica: Acceptor:

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


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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*

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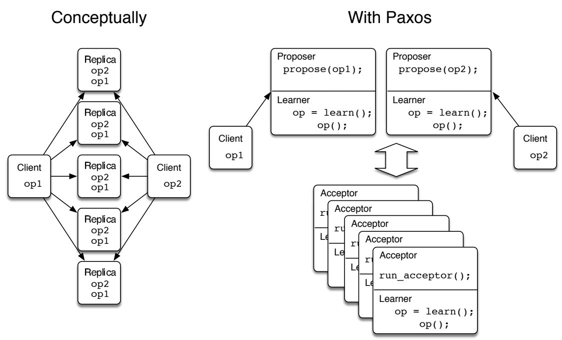
Example: State Machine Replication



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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);
}
```

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Replica: Proposer (leader):

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

Replica: Acceptor:

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

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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.

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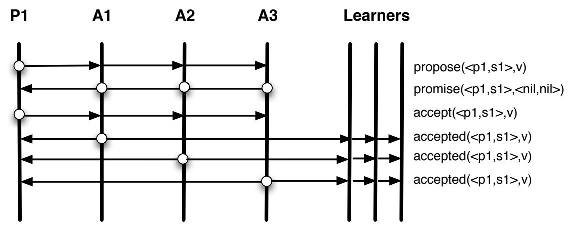
Simple Case



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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

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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.

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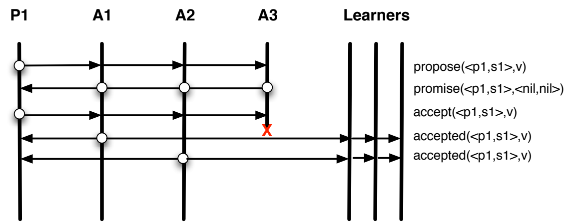
ACCEPTOR FAILS

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



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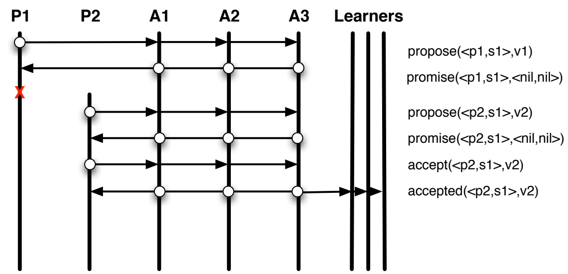
PROPOSER FAILS

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



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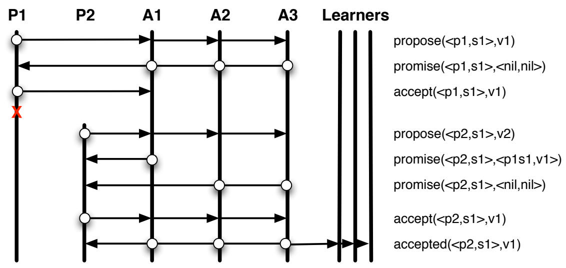

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MULTIPLE PROPOSERS

➜ For example: crashed proposer returns and continues

✗ Dueling proposers

✗ No guaranteed termination

☑ Heuristics to recognise situation and back off

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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.

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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

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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)

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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

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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

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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

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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*

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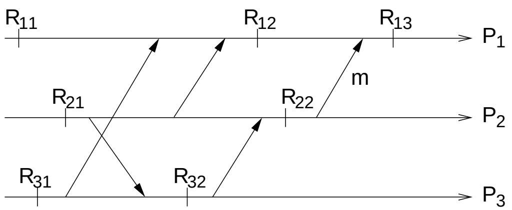
Domino Effect:



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

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

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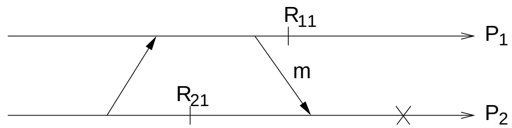
Message Loss:



- ➜ 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!
- → Require protocols resilient to message loss

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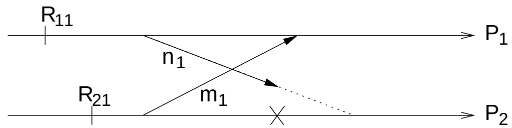
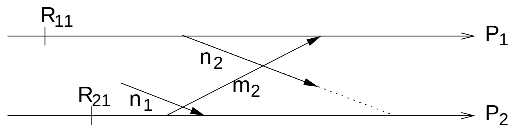
Livelock:



$P_2 \Downarrow \rightarrow P_2 \curvearrowright R_{21} \rightarrow P_1 \curvearrowright R_{11}$. 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

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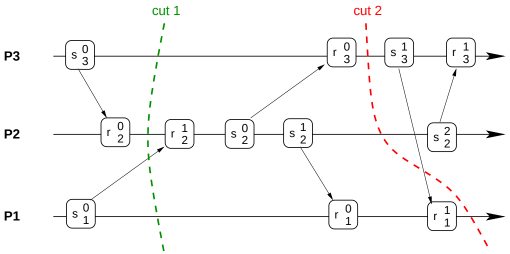
CONSISTENT CHECKPOINTING

Consistent Cut:



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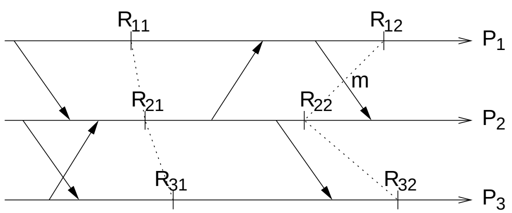
Idea: collect *local checkpoints* in a coordinated way.

- ➜ 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

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- ➜ **Strongly consistent checkpointing** requires quiescent system
  → 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!
- → Require some coordination during checkpointing

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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

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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

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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

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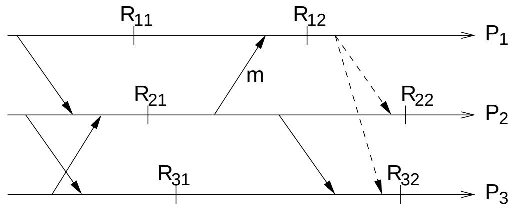
Redundant Checkpoints

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

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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

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Homework

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

Hacker's edition:

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

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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.