Slide 1

Distributed Systems (COMP9243)

Lecture 7: 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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Failure

Terminology:

Failure: a system fails when it fails to 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

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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

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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

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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

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

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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

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

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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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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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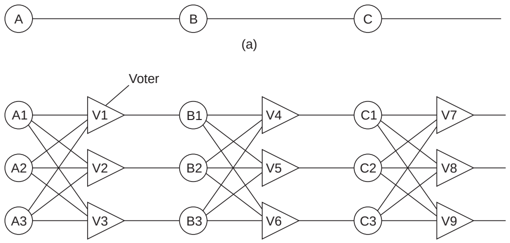
Failure Masking

Try to hide occurrence of failures from other processes

Redundancy:

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



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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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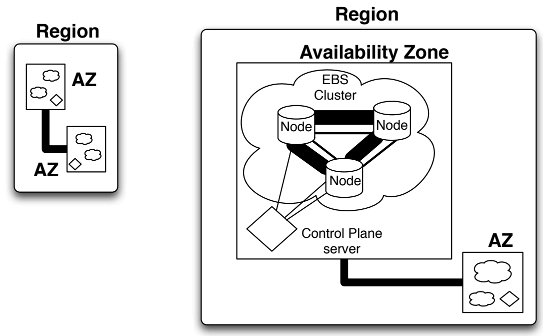

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Reliable Communication

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

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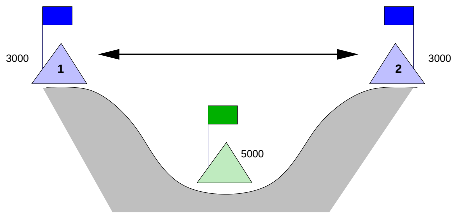
Two Army Problem:

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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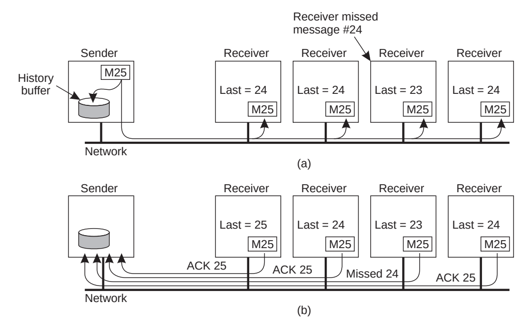
RELIABLE GROUP COMMUNICATION



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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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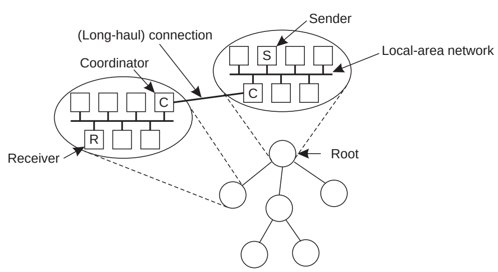
Hierarchical Multicast:



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Process Resilience

Protection against process failures

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

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)

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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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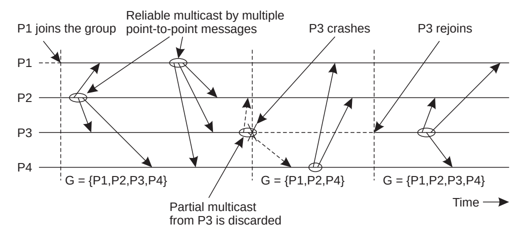
View Synchrony:

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

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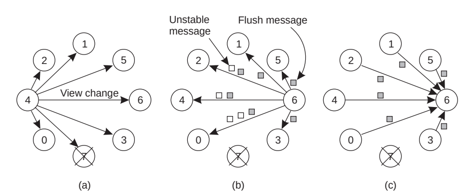
Implementing View Synchrony:

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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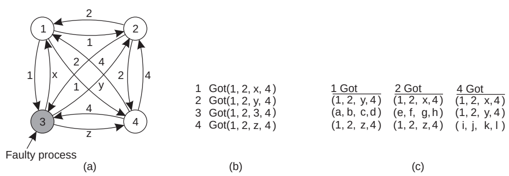
Byzantine Generals Problem:

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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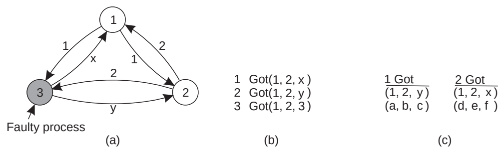
Byzantine Generals Impossibility:



- ➜ 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 vs univalent 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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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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Paxos Algorithm: 3 Phases

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* replies received.

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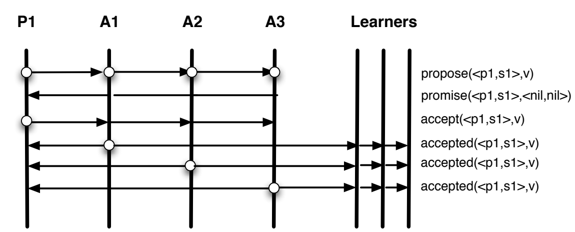
Simple Case



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Failures

Failure Model:

channel : lose, reorder, duplicate message
process : crash (fail-stop, fail-resume)

Failure Cases:

① Acceptor fails
② Proposer fails
③ Multiple proposers

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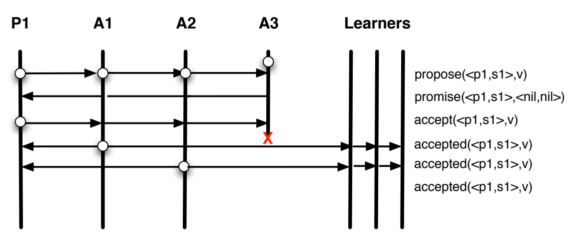
Acceptor Fails

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



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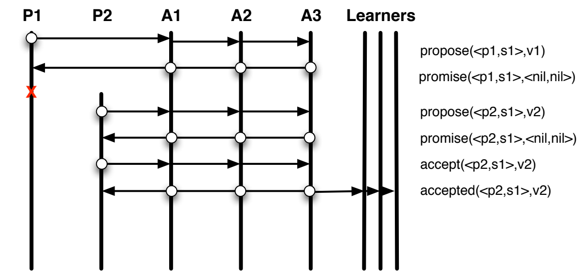
Proposer Fails

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



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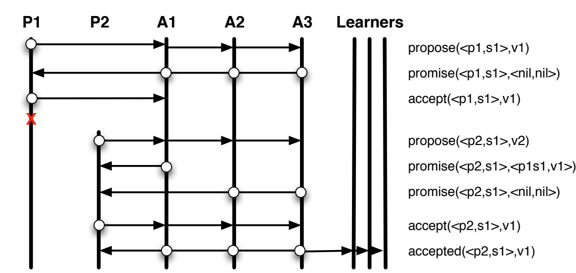

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Multiple Proposers

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

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Multi Paxos

- ➜ 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 competed instances
- ➜ On failure, restart or join *last completed instance +1*

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Using Paxos

Use Paxos for:

- ➜ Total order multicast: order messages
- ➜ State machine replication: order operations
- ➜ Leader election: choose a leader id
- ➜ Replicated storage: order writes
- ➜ View synchrony: order view changes

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Example: State Machine Replication

API:

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

Client:

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

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Replica: Proposer:

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

Replica: Acceptor:

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

Replica: Learner:

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

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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
- 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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Operation-Based Recovery - Logging:

Update in-place together with write-ahead logging

- ➜ Every change (update) of data is recorded in a log, which includes:
  - Data item name (for identification)
  - Old data item state (for *undo*)
  - New data item state (for *redo*)
- ➜ Undo log is written *before* update (write-ahead log).
- → Transaction semantics

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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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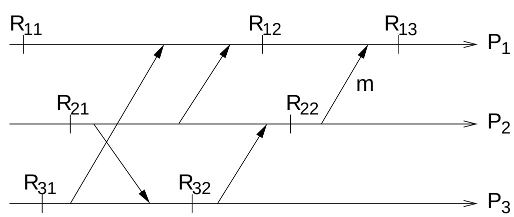
Domino Effect:



- ➜ 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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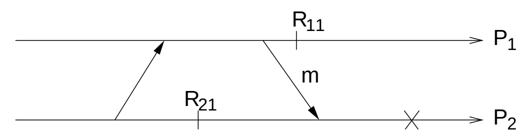
Message Loss:



- ➜ 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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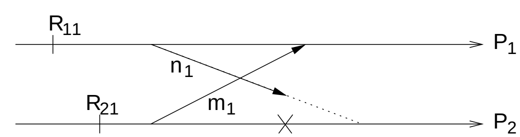
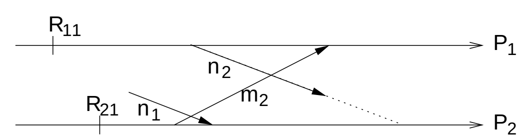
Livelock:



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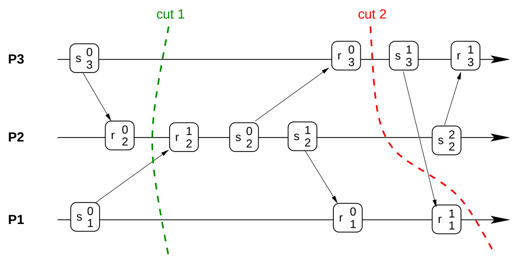
Consistent Checkpointing

Consistent Cut:



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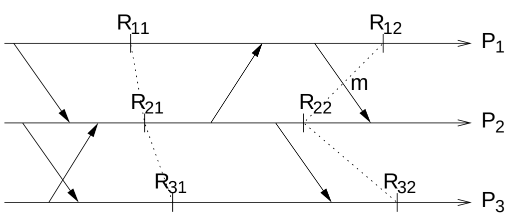
Idea: collect *local checkpoints* in a coordinated way.

- ➜ 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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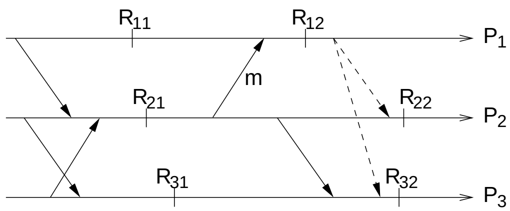
Redundant Checkpoints

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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Avoiding Redundant Checkpoints

Keep track of messages sent to avoid redundant checkpoints

- ➜ Associate each message m with *label* $m.l$, incremented at each message
- ➜ Each process maintains three vectors:
  - $last\_rec_i[j] := m.l$, where m is last msg m received by P_i from P_j since last checkpoint ($last\_rec_i[j] = 0$ if none)
  - $first\_sent_i[j] := m.l$, where m is first msg m sent by P_i to P_j since last checkpoint ($first\_sent_i[j] = 0$ if none)
  - $cohort_i := \{j | last\_rec_i[j] > 0\}$, set of processes from which P_i has received a message since last checkpoint
- ➜ P_j only needs to take a checkpoint after receiving a control message t ("take tentative checkpoint") from i if $last\_rec_i[j] \geq first\_sent_j[i] > 0$

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Checkpointing Algorithm

Messages:

➜ t: take tentative, p: make permanent, u: undo checkpoint

Initialisation: Each P sets $OK := true$, $first\_sent = \{0, 0, \cdots, 0\}$

Coordinator, P_i:

① $\mathrm{send}(t, i, last\_rec_i[j])$ to all $P_j \in cohort_i$

② **if** all replies are $true$, $\mathrm{send}(p)$ to all $P_j \in cohort_i$
else $\mathrm{send}(u)$ to all $P_j \in cohort_i$

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Others, P_j: upon receiving $(t, i, last\_rec_i[j])$

① **if** OK_j **and** $last\_rec_i[j] \geq first\_sent_j[i] > 0$

② take tentative checkpoint

③ $\mathrm{send}(t, j, last\_rec_j[k])$ to all $P_k \in cohort_j$

④ **if** all replies are $true$, $OK := true$ **else** $OK := false$

⑤ $\mathrm{send}(OK, j)$ to i

Others, P_j: upon receiving message $x \in \{p, u\}$ from P_i:

① **if** $x = p$ make permanent **else** discard tentative checkpoint

② $\mathrm{send}(x, j)$ to all $P_k \in cohort_j$

Note: $O(n^2)$ messages

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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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Redundant Rollbacks

Processes may roll back unnecessarily

➜ Can be avoided by keeping track of messages received

Avoiding Redundant Rollbacks:

➜ Message labelling as before

➜ Two additional vectors:

  ➜ $last\_sent_i[j] := m.l$, where m is *last* msg m sent by i to j since last checkpoint ($last\_sent_i[j] = \infty$ if none)

  ➜ $r\_cohort_i := \{j | i$ communicates with $j\}$

➜ P_i only needs to roll back after receiving message $(r, j, last\_sent_j[i])$ if $last\_rec_i[j] > last\_sent_j[i]$

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Rollback Recovery Algorithm

Messages:

- ➜ r: rollback request, d: do rollback, c:continue

Initialisation: Each P sets

- ➜ $resume := true$
- ➜ $last\_rec = \{\infty, \infty, \cdots, \infty\}$
- ➜ W according to willingness to roll back

Initiator, P_i:

① $\text{send}(r, i, last\_sent_i[j])$ to all $P_j \in r\_cohort_i$

② **if** all replies are $true$, $\text{send}(d)$ to all $P_j \in cohort_i$
else $\text{send}(c)$ to all $P_j \in cohort_i$

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Others, P_j: upon receiving $(r, i, last\_sent_i[j])$

① **if** W_j **and** $last\_rec_j[i] > last\_sent_i[j]$ **and** $resume_j$:

② $resume_j = false$,

③ $\text{send}(r, j, last\_sent_j[k])$ to all $P_k \in r\_cohort_j$,

④ **if** all replies are $true$, $W_j :=true$ **else** $W_j :=false$,

⑤ $\text{send}(W_j, j)$ to i.

Others, P_j: upon receiving message $x \in \{c, d\}$ from P_i:

① **if** $x = d$ roll back **else** continue,

② $\text{send}(x, j)$ to all $P_k \in r\_cohort_j$.

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Asynchronous Checkpointing

Let processes checkpoint independently (unsynchronised) and construct a consistent state during recovery.

- ➜ Source of inconsistencies are *orphan messages*.
- ➜ Consistent state can be obtained by:
  - ① Restarting failed process from latest checkpoint, and
  - ② *rolling forward* the restarted process past the point where the last message was sent prior to failure
- ➜ All send operations during roll-forward are suppressed.
- ➜ Except for timing, the result is indistinguishable from restarting from a (non-existent) checkpoint taken after the last send.
- ➜ Works as long as no message was lost.

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Message Logging

- ➜ Suppressing outgoing messages during roll-forward requires knowledge of the number of messages the failed process had sent prior to failure.
  - *Log* the send count in *stable storage*.
- ➜ Any attempted receive of a lost message will terminate roll-forward.
  - Log all *incoming* messages in stable storage
  - During roll-forward replay incoming messages from log

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Problems with Message Logging:

Roll-forward assumes *deterministic behaviour* of all processes

- ➜ Possible dependence of behaviour on uncontrollable factors (resident set).
- ➜ Possible inconsistencies between process IDs (different ID after restart!)
- ➜ Interrupt processing imposes time constraint, interrupts are *asynchronous* wrt. program messages.
  - May need to checkpoint before handling any interrupt!
- ➜ Multithreaded processes introduce a degree of non-determinism.

Require careful implementation and appropriate OS support.

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Optimistic Checkpointing

Asynchronous Logging:

- ➜ Log messages to volatile memory
- ➜ Flush to stable store asynchronously
- ➜ On failure, unflushed log is lost, resulting in inconsistent state
- ➜ Construct consistent state by rolling back orphan processes

Do synchronisation required between checkpointing and logging

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Assumptions:

Communication Channels

- ➜ Reliable
- ➜ Ordered (FIFO)
- ➜ Infinite buffer size
- ➜ Finite (but arbitrary) delays

Event-Driven Computation

- ➜ Event is receipt of message
- ➜ Process waits for message
- ➜ Upon receipt sends 0 or more messages
- ➜ Each event logged to volatile storage as $\{e, m, msgs\_sent\}$, where $msgs\_sent$ is set of messages sent
- ➜ Log is flushed to stable storage asynchronously.

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Optimistic Checkpoint Recovery

- ➜ Each process P_i keeps track of:
  - $n\_rcvd_{i \leftarrow j}(E)$: # messages received from P_j (up to event E),
  - $n\_sent_{i \rightarrow j}(E)$: # messages sent to P_j (up to event E).
- ➜ Upon restart, compare local message count with that of neighbours:
  - neighbour P_j is orphan if $n\_rcvd_{j \leftarrow i} > n\_sent_{i \rightarrow j}$,
  - must roll back until $n\_rcvd_{j \leftarrow i} \leq n\_sent_{i \rightarrow j}$.
- ➜ P_j's rollback may orphan other processes ($\rightarrow$ domino rollback).

Optimistic Checkpoint Recovery Algorithm

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Recovery is initiated by restarting process broadcasting its failure.

- ➜ restarting process P_i sets
  E_i := *latest event on stable log*,
- ➜ process P_j receiving failure messages sets
  E_j := *latest event that happened at* P_j.

Processor P_i (initiator or not) performs following steps:

① **for** $k := 1$ **to** N **do** /* N *is number of processes* */
② **for** each neighbour j **do**
③ $\text{send}(r, i, n\_sent_{i \to j}(E_i))$;
④ **wait** for r messages from all neighbours;
⑤ **for** each message (r, j, s) received **do**
⑥ **if** $n\_rcvd_{i \leftarrow j}(E_i) > s$ **then** /* *have orphan* */
⑦ $E_i :=$ *latest* E *suchthat* $n\_rcvd_{i \leftarrow j}(E) = s$;

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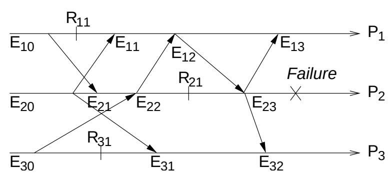
Example:



① $P_2 : recover\,from R_{21};\ E_2 := E_{22};\ \text{send}(r, P_2, 2) \to P_1;\ \text{send}(r, P_2, 1) \to P_3$;
② $P_1 \leftarrow P_2; E_1 := E_{13};\ n\_rcvd_{1 \leftarrow 2}(E_{13}) = 3 > 2 :\ E_1 := E_{12};\ \text{send}(r, P_1, 2) \to P_2$;
③ $P_3 \leftarrow P_2;\ E_3 := E_{32};\ n\_rcvd_{3 \leftarrow 2}(E_{32}) = 2 > 1 :\ E_3 := E_{31};\ \text{send}(r, P_3, 1) \to P_2$;
④ $P_2 \leftarrow P_1;\ n\_rcvd_{2 \leftarrow 1}(E_{22}) = 1 \leq 2;$ *no change*; $\text{send}(r, P_2, 2) \to P_1$;
⑤ $P_2 \leftarrow P_3;\ n\_rcvd_{2 \leftarrow 3}(E_{22}) = 1 \leq 1;$ *no change*; $\text{send}(r, P_2, 1) \to P_3$;

Recovery state $\{E_{12}, E_{22}, E_{31}\}$, roll back to $\{R_{11}, R_{21}, R_{31}\}$.

Reading List

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