Fault Tolerance

- Fault – cause of an error that might lead to failure; could be transient, intermittent, or permanent
- Fault tolerance – a system can provide its services even in the presence of faults
- Requirements
  - Availability – most likely working at any instant
  - Reliability – time interval between failures
  - Safety – no catastrophy in operation
  - Maintainability – ease of repair

Failure Models

- Crash/fail-stop: correct operation until system is unresponsive/halts
- Omission: request or response dropped
- Timing: outside specified real-time requirements
- Response failure: incorrect data or state transition
- Byzantine or arbitrary: malicious or incorrect

Failure Masking by Redundancy

- E.g., triple modular redundancy (TMR)

Agreement in Faulty Systems

- The two-army problem (attaining common knowledge)
- The Byzantine generals problem

Reliable Multicast

- Scalable reliable multicast
  - Return negative acknowledgements as feedback
  - Schedule a feedback message with some random delay
- Hierarchical feedback control

Distribution Protocols

- Permanent, server-initiated, or client-initiated replicas
- What is propagated?
  - Invalidation
  - Update
  - active replication (move the computation)
- When is it propagated?
  - Pull versus push
  - Leases
  - Epidemic protocols

Reliable Multicast in the Presence of Failures

- Virtual synchrony
  - Split up time into epochs with group membership G
  - A message m is delivered to every member of the group G before there is a view change allowed
  - If the sender crashes, message m can be delivered to all processes in the group or to none

Message Ordering

- Unordered multicast
- FIFO-ordered multicast
- Causally-ordered multicast
- Totally-ordered multicast
- Total order + virtual synchrony = atomic multicast

Checkpointing, Logging, and Rollback Recovery

- Approaches to reliability
  - Transactions: data-oriented applications
  - Group communication: abstraction of ideal communication system
  - Rollback recovery: long-running applications

A system recovers correctly if its internal state is consistent with the observable behacior of the system before the failure

Background

- Message-passing system with N processes
  - Possible to model shared memory using message passing
- Fail-stop failures possible at any time
- GOAL: recover all processes to some "consistent" state after one or more nodes have failed and then recovered (or been replaced)

Background and Definitions

- System model
  - Collection of application processes, communicating thru a network
  - Processes have access to a *stable storage* device, where recovery info is periodically saved during failure-free execution
  - Recovery info includes:
    - Checkpoints
    - logs of interactions with I/O devices
    - events that occur at each process
    - messages exchanged among processes
  - Protocols may assume the communication subsystem is reliable & FIFO, or unreliable (lost, duplicate, reordered messages)

Checkpointing

- Basic idea: If something goes wrong, we just pick up the pieces and put everything back where it was
- At regular intervals, dump all memory and resources associated with a process to persistent storage
- When a process fails, we reload the stored file into memory, restore all state, and restart the process from where it was when the checkpoint was taken

Concurrent Checkpointing

- Idea: trap writes to pages you haven't checkpointed, and copy the original pages to a buffer before allowing the write
- In filesystems, this is called “snapshotting”
- Advantage: the process may continue computing while the checkpointing takes place

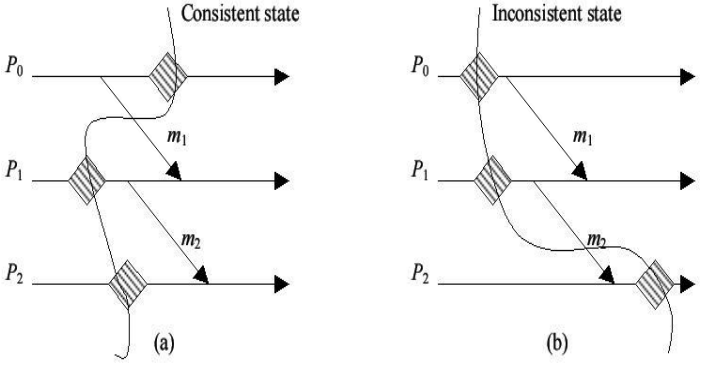
Incremental Checkpointing

- Idea: save only MODIFIED pages
- Best when used together with concurrent checkpointing
- Could even use differential storage to reduce space overhead of multiple checkpoints for a single process

Checkpointing in a Distributed Environment

- Consistency Issue: if P1 checkpoints and then sends a message to P2, you can no longer roll P1 back to before the message was sent unless P2 rolls back to before the message's receipt
- Issue: Checkpointing can be very expensive; you don't want to checkpoint more than necessary, but you also don't want to have to roll back too far
- Issue: Communication with the outside world doesn't get undone

Illustration of Consistency Problems



Uncoordinated Checkpointing

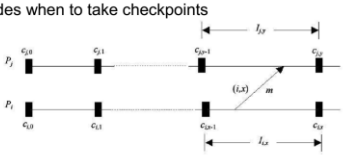
- Every once in a while, a process will checkpoint its own state
- For recovery, each process sends information on the checkpoints it has to some central point, which calculates the “recovery line” - the last set of checkpoints to create a globally consistent state

1. Uncoordinated checkpointing

-Each process independently decides when to take checkpoints

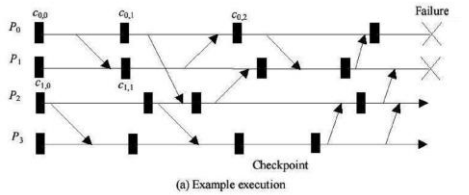
- $c_{i,x}$: x[th] checkpoint of process P_i
- $I_{j,y}$: checkpoint interval

Maximum number of useful checkpoints that must be kept on stable storage cannot exceed N(N+1) / 2



Recovering process	Other processes
Broadcasts *dependency request* →	Stop execution
	↓ Reply with dependency info (saved and current)
Calculates *recovery line* ←	
↓ Broadcasts *rollback request* containing recovery line →	If state belongs to recovery line, resume execution. Else, rollback to an earlier checkpoint

1. Uncoordinated checkpointing



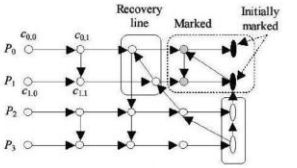
(a) Example execution

Rollback dependency graph

Directed edge drawn from $c_{i,x}$ to $c_{j,y}$ if either

(1) $i \neq j$, and a message m is sent from $I_{i,x}$ and received in $I_{j,y}$, or

(2) $i = j$ and $y = x + 1$



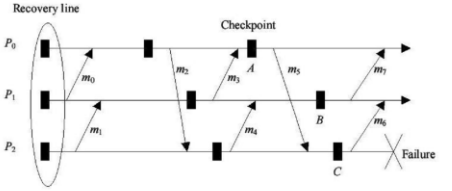
(b) rollback-dependency graph

1. Uncoordinated checkpointing

Advantage: each process may take checkpoint when most convenient

Disadvantages

- Domino effect



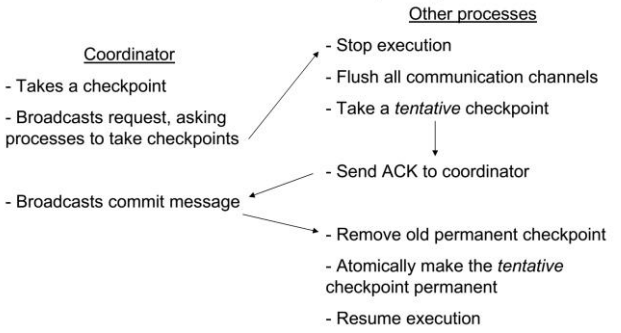
- Useless checkpoints
- Each process must maintain multiple checkpoints
- Garbage collector must be invoked periodically
- Not suitable for apps with frequent output commits

Coordinated Checkpointing

- Idea: all message-passing calls block while checkpointing takes place at the same time across all processes
- Checkpoints are only valid after it is known that all processes have successfully completed their own copy
- Advantage: only one checkpoint needs to be kept
- Advantage: recovery is just rolling back everything to THE checkpoint

2. Coordinated checkpointing

Straightforward approach:
Block communications while checkpointing executes



Problem: messages that could make a checkpoint inconsistent are also blocked

Nonblocking Checkpoint Coordination [e.g., Chandy&Lamport 1985 Distributed Snapshots]

- FIFO channels:
  - Precede 1st post-checkpoint message on each channel by a checkpoint request
  - Force each process to take a checkpoint upon receiving 1st checkpoint request
- Non-FIFO channels:
  - Checkpoint request piggybacked on every post-checkpoint message

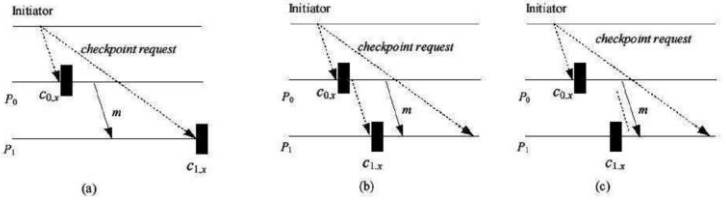


Figure 8. Non-blocking coordinated checkpointing: (a) checkpoint inconsistency; (b) with FIFO channels; (c) non-FIFO channels (short dashed line represents piggybacked *checkpoint request*).

Coordinated Checkpointing

- Advantages
  - Simplified recovery
  - Avoids domino effect
  - Less stable storage requirement (1 checkpoint / process)
  - No need for garbage collection
- Disadvantages
  - Large latency in committing output (may improve by minimal checkpoint coordination)

Logging as a Complement to Checkpointing

- The Piecewise Deterministic (PWD) Assumption
  - Any nondeterministic element of the system may be captured in such a way as to allow replaying it in a deterministic fashion at a later time
- Determinant – Information necessary to replay a nondeterministictic event during recovery, logged during failure-free operation
- OWP – A “process” whose incoming messages represent program output and whose outgoing messages are program input
- “In Transit” - a message sent but not received
- “Orphan” - a process whose checkpoint depends on a state that cannot be recreated

Pessimistic Logging

- Write determinant to stable storage before allowing further events
  - observable pre-failure state always recoverable
  - Recovery always starts from the most recent checkpoint
  - Effect of failure confined to the processes that fail
  - Simple garbage collection: reclaim everything before last checkpoint

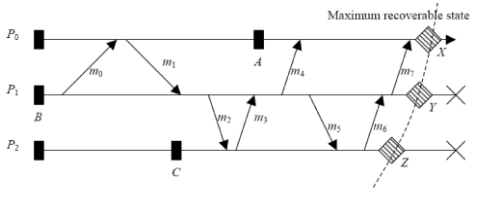


Figure 10. Pessimistic logging.