RECOVERY & CONSENSUS

CHECK POINTING AND ROLLBACK RECOVERY: INTRODUCTION

- Rollback recovery protocols restore the system back to a consistent state after a failure,
- It achieves fault tolerance by periodically saving the state of a process during the failure-free execution
- It treats a distributed system application as a collection of processes that communicate over a network

Checkpoints

The saved state is called a checkpoint, and the procedure of restarting from a previously check pointed state is called rollback recovery. A checkpoint can be saved on either the stable storage or the volatile storage

Why is rollback recovery of distributed systems complicated?

Messages induce inter-process dependencies during failure-free operation

Rollback propagation

The dependencies among messages may force some of the processes that did not fail to roll back.This phenomenon of cascaded rollback is called the domino effect.

Uncoordinated check pointing

If each process takes its checkpoints independently, then the system cannot avoid the domino effect – this scheme is called independent or uncoordinated checkpointing

Techniques that avoid domino effect

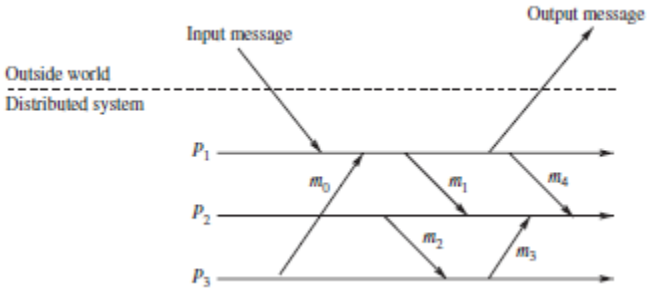
1. Coordinated checkpointing rollback recovery - Processes coordinate their checkpoints to form a system-wide consistent state
2. Communication-induced checkpointing rollback recovery - Forces each process to take checkpoints based on information piggybacked on the application.
3. Log-based rollback recovery - Combines checkpointing with logging of non-deterministic events • relies on piecewise deterministic (PWD) assumption.

BACKGROUND AND DEFINITIONS

System model

- A distributed system consists of a fixed number of processes, P1, P2,…_ PN , which communicate only through messages.

- Processes cooperate to execute a distributed application and interact with the outside world by receiving and sending input and output messages, respectively.
- Rollback-recovery protocols generally make assumptions about the reliability of the inter-process communication.
- Some protocols assume that the communication uses first-in-first-out (FIFO) order, while other protocols assume that the communication subsystem can lose, duplicate, or reorder messages.
- Rollback-recovery protocols therefore must maintain information about the internal interactions among processes and also the external interactions with the outside world.



An example of a distributed system with three processes.

A local checkpoint

- All processes save their local states at certain instants of time
- A local check point is a snapshot of the state of the process at a given instance
- Assumption
  - A process stores all local checkpoints on the stable storage
  - A process is able to roll back to any of its existing local checkpoints
- Ci,k – The kth local checkpoint at process Pi
- $Ci,0$ – A process Pi takes a checkpoint $Ci,0$ before it starts execution

Consistent states

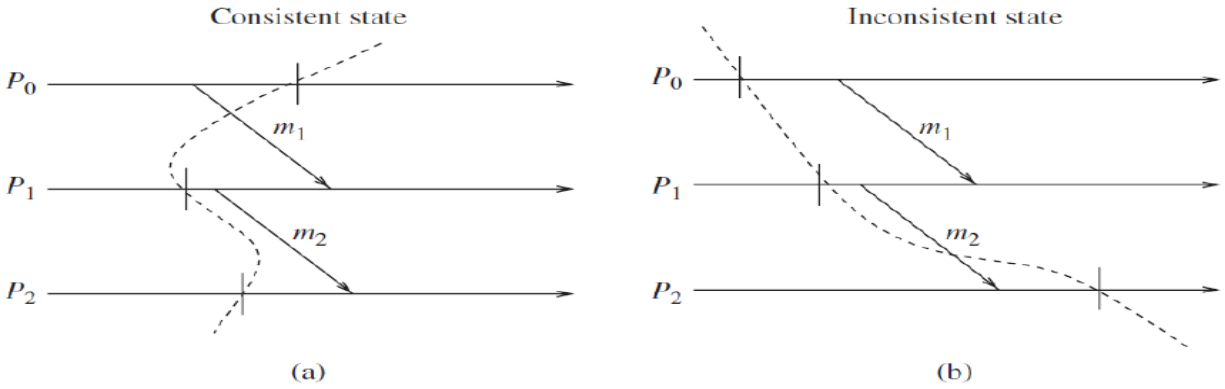
- A global state of a distributed system is a collection of the individual states of all participating processes and the states of the communication channels
- Consistent global state

– a global state that may occur during a failure-free execution of distribution of distributed computation

– if a process‟s state reflects a message receipt, then the state of the corresponding sender must reflect the sending of the message

- A global checkpoint is a set of local checkpoints, one from each process
- A consistent global checkpoint is a global checkpoint such that no message is sent by a process after taking its local point that is received by another process before taking its checkpoint.

Consistent states - examples



- For instance, Figure shows two examples of global states.
- The state in fig (a) is consistent and the state in Figure (b) is inconsistent.
- Note that the consistent state in Figure (a) shows message *m*1 to have been sent but not yet received, but that is alright.
- The state in Figure (a) is consistent because it represents a situation in which every message that has been received, there is a corresponding message send event.
- The state in Figure (b) is inconsistent because process *P*2 is shown to have received *m*2 but the state of process *P*1 does not reflect having sent it.
- Such a state is impossible in any failure-free, correct computation. Inconsistent states occur because of failures.

Interactions with outside world

A distributed system often interacts with the outside world to receive input data or deliver the outcome of a computation. If a failure occurs, the outside world cannot be expected to roll back. For example, a printer cannot roll back the effects of printing a character

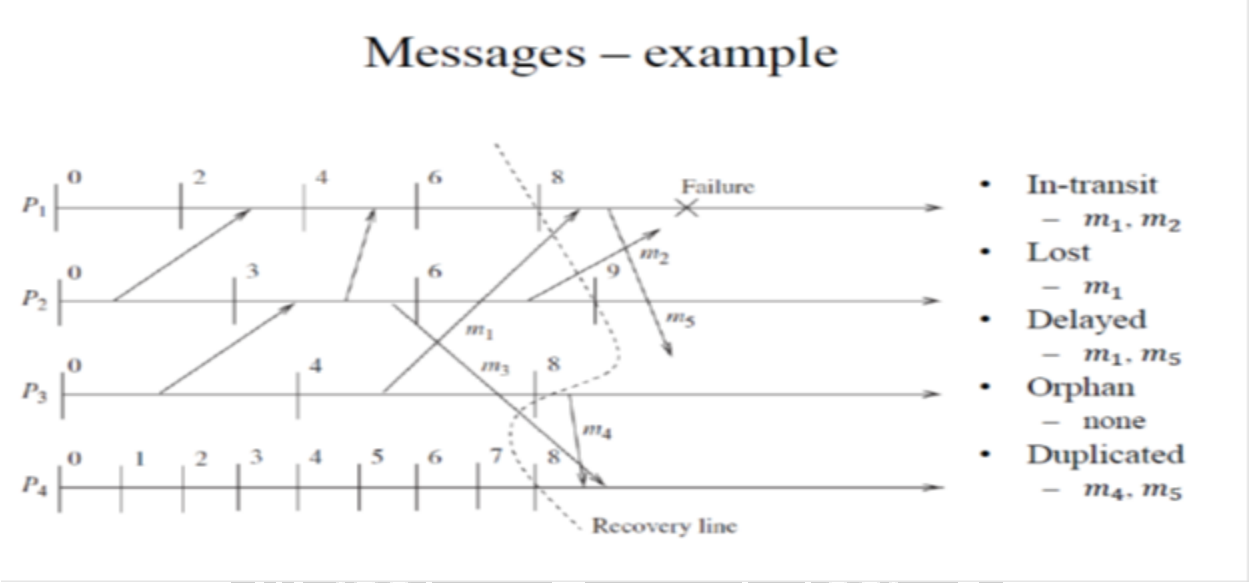
Outside World Process (OWP)

- It is a special process that interacts with the rest of the system through message passing.
- It is therefore necessary that the outside world see a consistent behavior of the system despite failures.
- Thus, before sending output to the OWP, the system must ensure that the state from which the output is sent will be recovered despite any future failure.

A common approach is to save each input message on the stable storage before allowing the application program to process it. An interaction with the outside world to deliver the outcome of a computation is shown on the process-line by the symbol "||".

Different types of Messages

1. In-transit message
    - messages that have been sent but not yet received
2. Lost messages
    - messages whose "send" is done but "receive" is undone due to rollback
3. Delayed messages
    - messages whose "receive" is not recorded because the receiving process was either down or the message arrived after rollback
4. Orphan messages
    - messages with "receive" recorded but message "send" not recorded
    - do not arise if processes roll back to a consistent global state
5. Duplicate messages
    - arise due to message logging and replaying during process recovery



In-transit messages

In Figure , the global state {C1,8 , C2, 9 , C3,8, C4,8} shows that message *m*1 has been sent but not yet received. We call such a message an *in-transit* message. Message *m*2 is also an in-transit message.

Delayed messages

Messages whose receive is not recorded because the receiving process was either down or the message arrived after the rollback of the receiving process, are called *delayed* messages. For example, messages m2 and m5 in Figure are delayed messages.

Lost messages

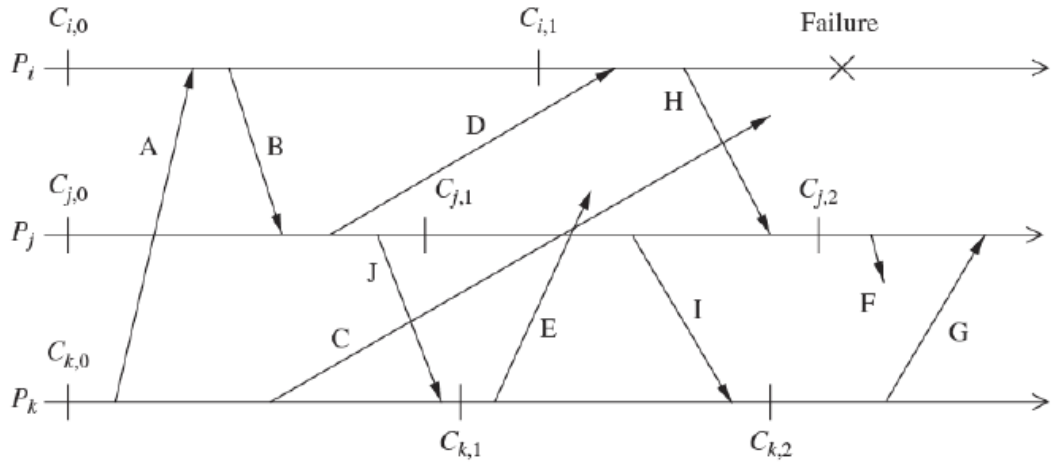
Messages whose send is not undone but receive is undone due to rollbackare called lostmessages. This type of messages occurs when the processrolls back to a checkpoint prior to reception of the message while the senderdoes not rollback beyond the send operation of the message. In Figure ,message m1 is a lost message.

Duplicate messages

- Duplicate messages arise due to message logging and replaying during process recovery. For example, in Figure, message m4 was sent and received before the rollback. However, due to the rollback of process P4 to C4,8 and process P3 to C3,8, both send and receipt of message m4 are undone.
- When process P3 restarts from C3,8, it will resend message m4.
- Therefore, P4 should not replay message m4 from its log.
- If P4 replays message m4, then messagem4 is called a duplicate message.

ISSUES IN FAILURE RECOVERY

In a failure recovery, we must not only restore the system to a consistent state, but also appropriately handle messages that are left in an abnormal state due to the failure and recovery



The computation comprises of three processes Pi, Pj , and Pk, connected through a communication network. The processes communicate solely by exchanging messages over fault-free, FIFO communication channels.

Processes Pi, Pj , and Pk have taken checkpoints

- Checkpoints : $\{C_{i,0}, C_{i,1}\}$, $\{C_{j,0}, C_{j,1}, C_{j,2}\}$, and $\{C_{k,0}, C_{k,1}, C_{k,2}\}$
- Messages : A - J
- The restored global consistent state : $\{C_{i,1}, C_{j,1}, C_{k,1}\}$

- The rollback of process Pi to checkpoint Ci,1 created an orphan message H
- Orphan message I is created due to the roll back of process Pj to checkpoint Cj,1
- Messages C, D, E, and F are potentially problematic
  - Message C: a delayed message
  - Message D: a lost message since the send event for D is recorded in the restored state for Pj, but the receive event has been undone at process Pi.
  - Lost messages can be handled by having processes keep a message log of all the sent messages
  - Messages E, F: delayed orphan messages. After resuming execution from their checkpoints, processes will generate both of these messages

CHECKPOINT-BASED RECOVERY

Checkpoint-based rollback-recovery techniques can be classified into three categories:

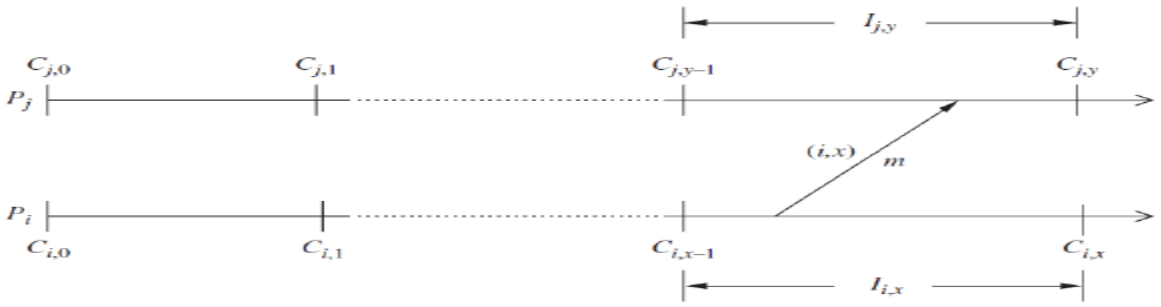
1. Uncoordinated check pointing
2. Coordinated check pointing
3. Communication-induced check pointing

1. Uncoordinated Check pointing

- Each process has autonomy in deciding when to take checkpoint
- Advantage: The lower runtime overhead during normal execution
- Disadvantages
    1. Domino effect during a recovery
    2. Recovery from a failure is slow because processes need to iterate to find a consistent set of checkpoints
    3. Each process maintains multiple checkpoints and periodically invoke a garbage collection algorithm
    4. Not suitable for application with frequent output commits
- The processes record the dependencies among their checkpoints caused by message exchange during failure-free operation
- The following direct dependency tracking technique is commonly used in uncoordinated check pointing.

Direct dependency tracking technique

- Assume each process Pi starts its execution with an initial checkpoint $Ci,0$
- Ii,x : checkpoint interval, interval between $Ci,x-1$ and Ci,x
- When Pj receives a message m during Ij,y , it records the dependency from Ii,x to Ij,y, which is later saved onto stable storage when Pj takes Cj,y



- When a failure occurs, the recovering process initiates rollback by broadcasting a dependency *request* message to collect all the dependency information maintained by each process.
- When a process receives this message, it stops its execution and replies with the dependency information saved on the stable storage as well as with the dependency information, if any, which is associated with its current state.
- The initiator then calculates the recovery line based on the global dependency information and broadcasts a rollback request message containing the recovery line.
- Upon receiving this message, a process whose current state belongs to the recovery line simply resumes execution; otherwise, it rolls back to an earlier checkpoint as indicated by the recovery line.

2. Coordinated Checkpointing

In coordinated check pointing, processes orchestrate their checkpointing activities so that all local checkpoints form a consistent global state

Types

1. Blocking Checkpointing: After a process takes a local checkpoint, to prevent orphan messages, it remains blocked until the entire checkpointing activity is complete
   Disadvantages: The computation is blocked during the checkpointing
2. Non-blocking Checkpointing: The processes need not stop their execution while taking checkpoints. A fundamental problem in coordinated checkpointing is to prevent a process from receiving application messages that could make the checkpoint inconsistent.

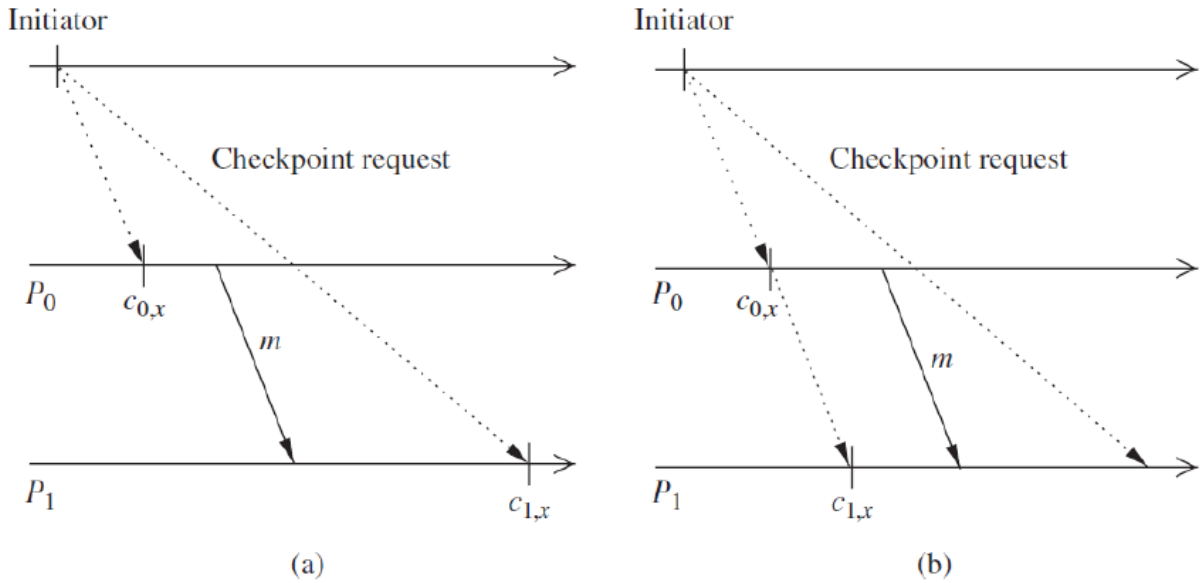
Example (a) : Checkpoint inconsistency

- Message m is sent by $P0$ after receiving a checkpoint request from the checkpoint coordinator
- Assume m reaches $P1$ before the checkpoint request
- This situation results in an inconsistent checkpoint since checkpoint $C1,x$ shows the receipt of message m from $P0$, while checkpoint $C0,x$ does not show m being sent from $P0$

Example (b) : A solution with FIFO channels

- If channels are FIFO, this problem can be avoided by preceding the first post-checkpoint message on each channel by a checkpoint request, forcing each process to take a checkpoint before receiving the first post-checkpoint message

Coordinated Checkpointing



Impossibility of min-process non-blocking checkpointing

- A min-process, non-blocking checkpointing algorithm is one that forces only a minimum number of processes to take a new checkpoint, and at the same time it does not force any process to suspend its computation.

Algorithm

- The algorithm consists of two phases. During the first phase, the checkpoint initiator identifies all processes with which it has communicated since the last checkpoint and sends them a request.
- Upon receiving the request, each process in turn identifies all processes it has communicated with since the last checkpoint and sends them a request, and so on, until no more processes can be identified.
- During the second phase, all processes identified in the first phase take a checkpoint. The result is a consistent checkpoint that involves only the participating processes.

- In this protocol, after a process takes a checkpoint, it cannot send any message until the second phase terminates successfully, although receiving a message after the checkpoint has been taken is allowable.

3. Communication-induced Checkpointing

*Communication-induced checkpointing*is another way to avoid the domino effect, while allowing processes to take some of their checkpoints independently. Processes may be forced to take additional checkpoints

Two types of checkpoints

1. Autonomous checkpoints
2. Forced checkpoints

The checkpoints that a process takes independently are called *local* checkpoints, while those that a process is forced to take are called *forced* checkpoints.

- Communication-induced checkpointing piggybacks protocol- related information on each application message
- The receiver of each application message uses the piggybacked information to determine if it has to take a forced checkpoint to advance the global recovery line
- The forced checkpoint must be taken before the application may process the contents of the message
- In contrast with coordinated checkpointing, no special coordination messages are exchanged

Two types of communication-induced checkpointing

1. Model-based checkpointing
2. Index-based checkpointing.

Model-based checkpointing

- Model-based checkpointing prevents patterns of communications and checkpoints that could result in inconsistent states among the existing checkpoints.
- No control messages are exchanged among the processes during normal operation. All information necessary to execute the protocol is piggybacked on application messages
- There are several domino-effect-free checkpoint and communication model.

- The MRS (mark, send, and receive) model of Russell avoids the domino effect by ensuring that within every checkpoint interval all message receiving events precede all message-sending events.

Index-based checkpointing.

- Index-based communication-induced checkpointing assigns monotonically increasing indexes to checkpoints, such that the checkpoints having the same index at different processes form a consistent state.

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