SSC0146 – Sistemas Computacionais Tolerantes a Falhas

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Checkpointing

Failure During Program Execution

- Computers today are much faster, but applications are more complicated
- Applications which still take a long time -
  - (1) Database Updates
  - (2) Fluid-flow Simulation - weather and climate modeling
  - (3) Optimization - optimal deployment of resources by industry (e.g. - airlines)
  - (4) Astronomy - N-body simulations and modeling of universe
  - (5) Biochemistry - study of protein folding
- When execution time is very long - both probability of failure during execution and cost of failure become significant

Checkpointing - Definition

- A checkpoint is a snapshot of entire state of the process at the moment it was taken
  - all information needed to restart the process from that point
- Checkpoint saved on stable storage of sufficient reliability
- Most commonly used - Disks: can hold data even if power is interrupted (but no physical damage to disk); can hold enormous quantities of data very cheaply
- Checkpoints can be very large - tens or hundreds of megabytes
- RAM with a battery backup is also used as stable storage
- No medium is perfectly reliable - reliability must be sufficiently high for the application at hand

Overhead and Latency of Checkpoint

- Checkpoint Overhead: increase in execution time of application due to taking a checkpoint (i.e. time that the application is blocked from executing)
- Checkpoint Latency: time needed to save checkpoint
- In a simple system - overhead and latency are identical
- If part of checkpointing can be overlapped with application execution - overhead may be substantially smaller than latency
- Example: A process checkpoints by writing its state into an internal buffer - CPU can continue execution while the checkpoint is written from buffer to disk

Checkpointing Latency Example

```
for (i=0; i<1000000; i++)
    if (f(i)<min) {min=f(i); imin=i;}
for (i=0; i<100; i++) {
    for (j=0; j<100; j++) {
        c[i][j] += i*j/min;
    }
}
```

- 1st part - compute smallest value of f(i) for 0<i<1000000

  2nd part - multiplication followed by division

- Latency depends on checkpoint size - is program dependent and can change during execution
  - few kilobytes or as large as several gigabytes
- 1st part: small checkpoint - only program counter and variables min and imin
- 2nd part: checkpoint must include c[i][j] computed so far

Issues in Checkpointing

- At what level (kernel/user/application) should we checkpoint?
- How transparent to user should checkpointing be?
- How many checkpoints should we have?
- At which points during the program execution should we checkpoint?
- How can we reduce checkpointing overhead?
- How do we checkpoint distributed systems with/without a central controller?
- How do we restart the computation at a different node if necessary

Checkpointing at the Kernel Level

- Transparent to user; no changes to program
- When system restarts after failure - kernel responsible for managing recovery operation
- Every OS takes checkpoints when process preempted
  - process state is recorded so that execution can resume from interrupted point without loss of computational work
- But, most OS have little or no checkpointing for fault tolerance

Checkpointing at the User Level

- **A user-level library provided for checkpointing**
  - **Application programs are linked to this library**
- **Like kernel-level checkpointing, this approach generally requires no changes to application code**
- **Library also manages recovery from failure**

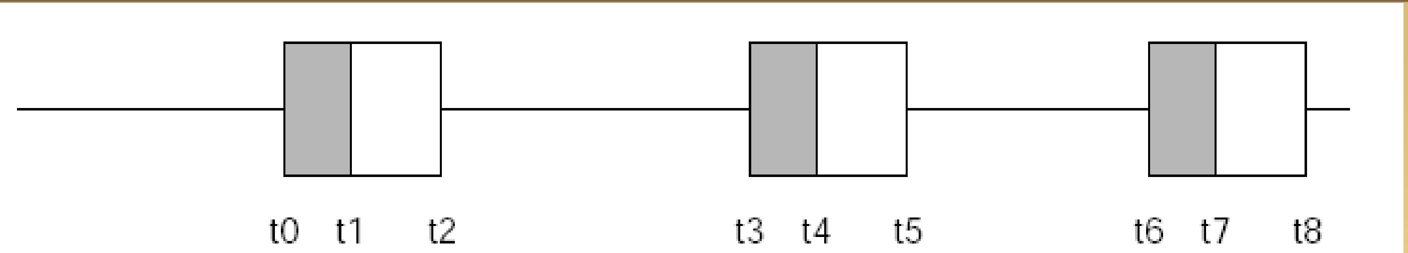
Checkpointing at the Application Level

- Application responsible for all checkpointing functions
- Code for checkpointing & recovery part of application
- Provides greatest control over checkpointing process
- Disadvantage - expensive to implement and debug

Comparing Checkpointing Levels

- Information available to each level may be different
- Multiple threads - invisible at the kernel
- User & application levels do not have access to information held at kernel level
  - Cannot assign process identifying numbers – can be a problem
- User & application levels may not be allowed to checkpoint parts of file system
  - May have to store names and pointers to appropriate files

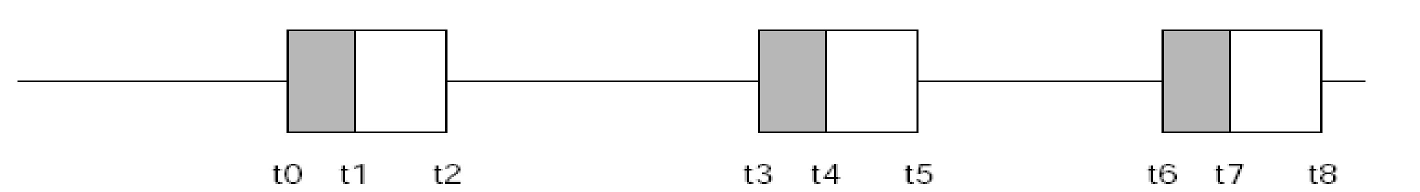
Optimal Checkpointing - Analytic Model



- Boxes denote latency; shaded part - overhead
- Latency –total checkpointing time
- Overhead - part of checkpointing not done in parallel with application execution - CPU is busy checkpointing

  application is blocked from executing due to checkpointing
- Overhead has a greater impact on performance than latency
- Latency Tlt = t2-t0=t5-t3=t8-t6
- Overhead Tov = t1-t0=t4-t3=t7-t6

Model Notations



- Checkpoint represents state of system at t0,t3,t6
- If a failure occurs in [t3,t5] - checkpoint is useless - system must roll back to previous checkpoint t0

Reducing Overhead - Buffering

- Processor writes checkpoint into main memory and then returns to executing application
- Direct memory access (DMA) is used to copy checkpoint from main memory to disk
  - DMA requires CPU involvement only at beginning and end of operation
- Refinement - copy on write buffering
- No need to copy portions of process state that are unchanged since last checkpoint
- If process does not update main memory pages too often - most of the work involved in copying pages to a buffer area can be avoided

Copy on Write Buffering

- Most memory systems provide memory protection bits (per page of physical main memory) indicating: (page) is read-write, read-only, or inaccessible
- When checkpoint is taken, protection bits of pages belonging to process are set to read-only
- Application continues running while checkpointed pages are transferred to disk
- If application attempts to update a page, an access violation is triggered
- System then buffers page, and permission is set to read-write
- Buffered page is later copied to disk
- This is an example of incremental checkpointing

Incremental Checkpointing

- Recording only changes in process state since the previous checkpoint was taken
- If these changes are few - less has to be saved per incremental checkpoint
- Disadvantage: Recovery is more complicated
- Not just loading latest checkpoint and resuming computation from there
- Need to build system state by examining a succession of incremental checkpoints

Reducing Checkpointing Overhead - Memory Exclusion

- Two types of variables that do not need to be checkpointed:
  - Those that have not been updated, and
  - Those that are "dead"
- A dead variable is one whose present value will never again be used by the program
- Two kinds of dead variables:
  - Those that will never again be referenced by program, and
  - Those for which the next access will be a write
- The challenge is to accurately identify such variables

Identifying Dead Variables

- The address space of a process has four segments: code, global data, heap, stack
  - Finding dead variables in code is easy: self-modifying code no longer used - code is read-only, no need to checkpoint
  - Stack segment equally easy: contents of addresses held in locations below stack pointer are obviously dead
  - Heap segment: many languages allow programmers to explicitly allocate and deallocate memory (e.g., malloc() and free() calls in C) - contents of free list are dead by definition
  - Some user-level checkpointing packages (e.g., libckpt) provide programmer with procedure calls (e.g., checkpoint_here()) that specify regions of memory that should be excluded from, or included in, future checkpoints

Reducing Latency

- Checkpoint compression - less written to disk
- How much is gained through compression depends on:
  - Extent of compression - application-dependent - can vary between 0 and 50%
  - Work required to execute the compression algorithm - done by CPU - adds to checkpointing overhead as well as latency
- In simple sequential checkpointing where $T_{lt} = T_{ov}$ - compression may be beneficial
- In more efficient systems where $T_{ov} \ll T_{lt}$ - usefulness of this approach is questionable and must be carefully assessed
- Another way of reducing latency is incremental checkpointing

CARER: Cache-Aided Rollback Error Recovery

- CARER scheme
  - Marks process footprint in main memory and cache as parts of checkpointed state
  - Reduces time required to take a checkpoint
  - Allows more frequent checkpoints
  - Reduces penalty of rollback upon failure
- Assuming memory and cache are less prone to failure than processor
- Checkpointing consists of storing processor's registers in main memory
- Includes processes' footprint in main memory + lines of cache marked as part of checkpoint

Checkpoint Bit For Each Cache Line

- Scheme requires hardware modification - an extra checkpoint bit associated with each cache line
- When bit is 1 - corresponding line is unmodifiable
  - Line is part of latest checkpoint
  - May not update without being forced to take a checkpoint immediately
- When bit is 0 - processor is free to modify word
- Process' footprint in memory + marked cache lines serve as both memory and part of checkpoint
  - Less freedom when deciding when to checkpoint
- Checkpointing is forced when
  - A line marked unmodifiable is to be updated
  - Anything in memory is to be updated
  - An I/O instruction is executed or an external interrupt occurs

Checkpointing and Roll Back

- Taking a checkpoint involves:
  - (a) Saving processor registers in memory
  - (b) Setting to 1 the checkpoint bit associated with each valid cache line
- Rolling back to previous checkpoint simple: restore registers, and mark invalid all cache lines with checkpoint bit = 0
- Cost:
  - A checkpoint bit for every cache line
  - Every write-back of a cache line into memory involves taking a checkpoint

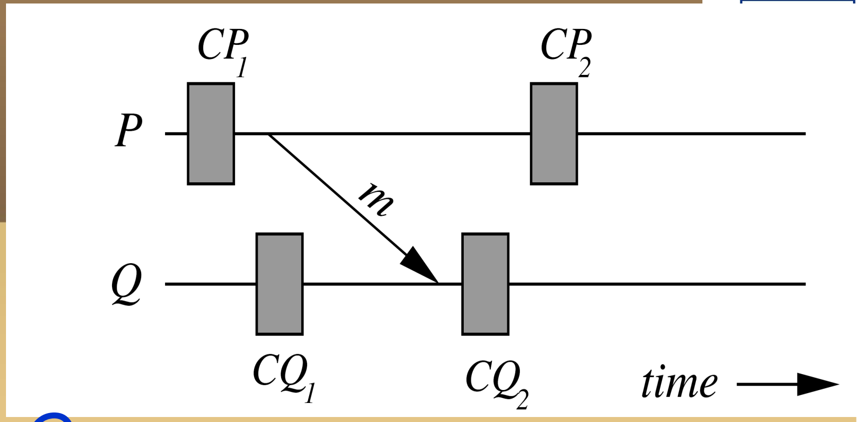
Checkpointing in Distributed Systems

- Distributed system: processors and associated memories connected by an interconnection network
  - Each processor may have local disks
  - Can be a network file system accessible by all processors
- Processes connected by directional channels -point-to-point connections from one process to another
  - Assume channels are error-free and deliver messages in the order received

Process/Channel/System State

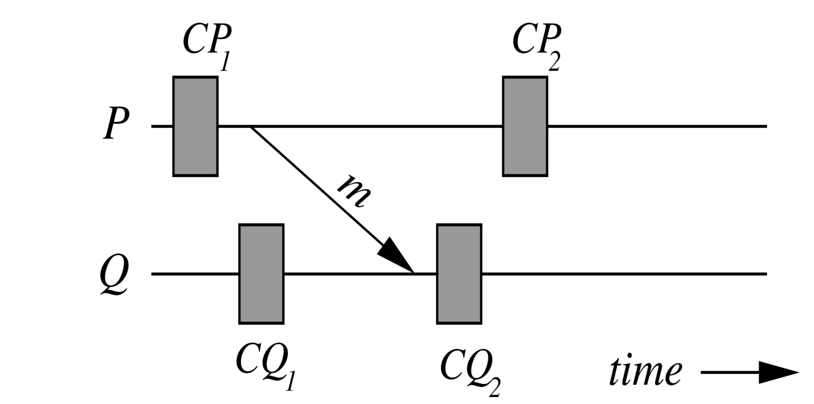
- The state of channel at t is
  - set of messages carried by it up to time t
  - order in which they were received
- State of distributed system: aggregate states of individual processes and channels
- State is consistent if, for every message delivery there is a corresponding message-sending event
- A state violating this - a message delivered that had not yet been sent - violates causality
  - Such a message is called an orphan
- The converse - a system state reflecting sending of a message but not its receipt - is consistent

Consistent/Inconsistent States



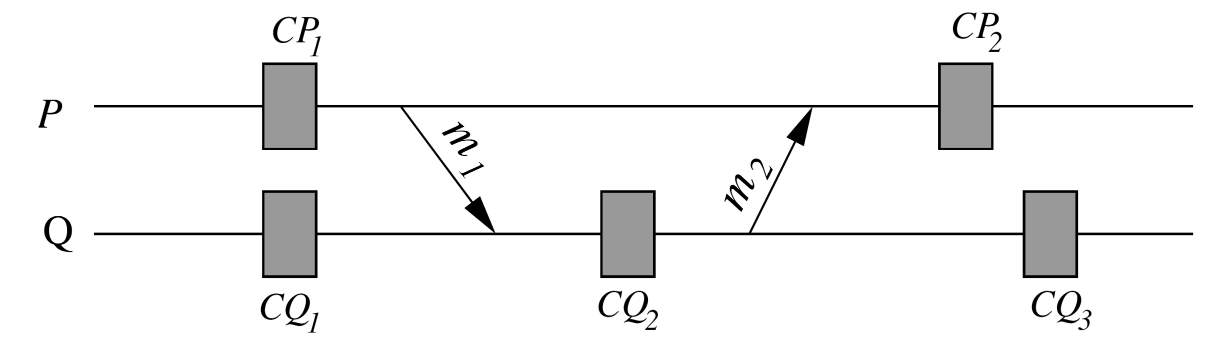
- Example:2 processes P and Q, each takes two checkpoints; Message m is sent by P to Q
- Checkpoint sets representing consistent system states:
  - * {CP_1,CQ_1}: Neither checkpoint knows about m
  - * {CP_2, CQ_1}: CP_2 indicates that m was sent; CQ_1 has no record of receiving m
  - * {CP_2,CQ_2}: CP_2 indicates that m was sent; CQ_2 indicates that it was received
- {CP_1,CQ_2} is inconsistent:
  - * CP_1 has no record of m being sent
  - * CQ_2 records that m was received
  - * m is an orphan message

Recovery Line



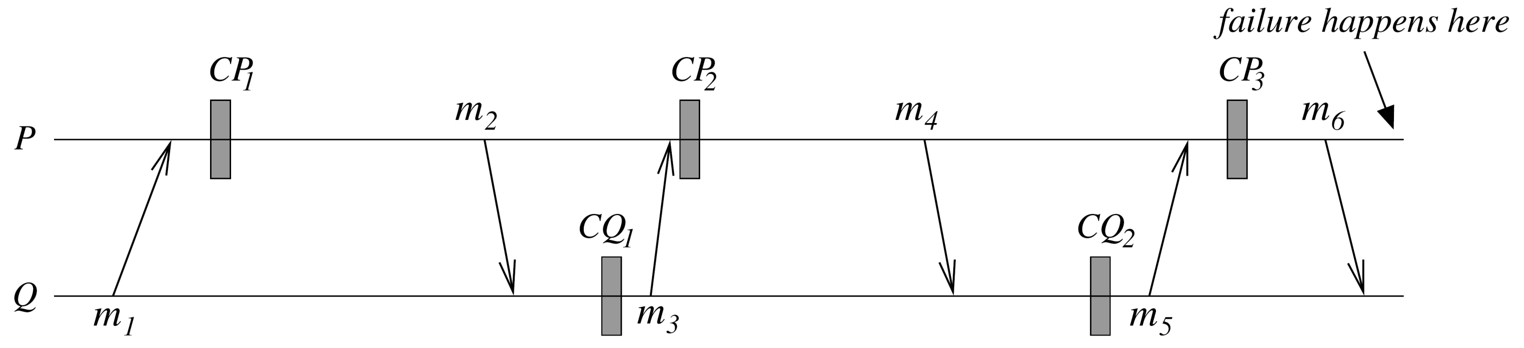
- Consistent set of checkpoints forms a recovery line- can roll system back to them and restart from there
- Example: {CP1,CQ1}
  - Rolling back P to CP1 undoes sending of m
  - Rolling back Q to CQ1 means: Q has no record of m
  - Restarting from CP1,CQ1, P will again send m
- Example: {CP2,CQ1}
  - Rolling back P to CP2 means: it will not retransmit m
  - Rolling back Q to CQ1: Q has no record of receiving m
- Recovery process has to be able to play back m to Q
  - Adding it to checkpoint of P, or
  - Have a separate message log which records everything received by Q

Useless Checkpoints



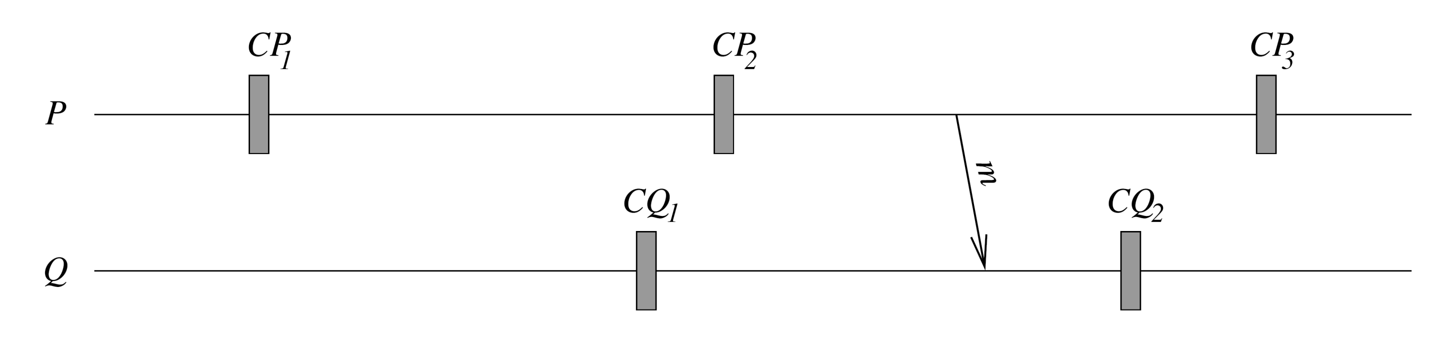
- Checkpoints can be useless
  - Will never form part of a recovery line
  - Taking them is a waste of time
- Example: CQ_2 is a useless checkpoint
- CQ_2 records receipt of m_1, but not sending of m_2
- $\{CP_1, CQ_2\}$ not consistent
  - otherwise m_1 would become an orphan
- $\{CP_2, CQ_2\}$ not consistent
  - otherwise m_2 would become an orphan

The Domino Effect



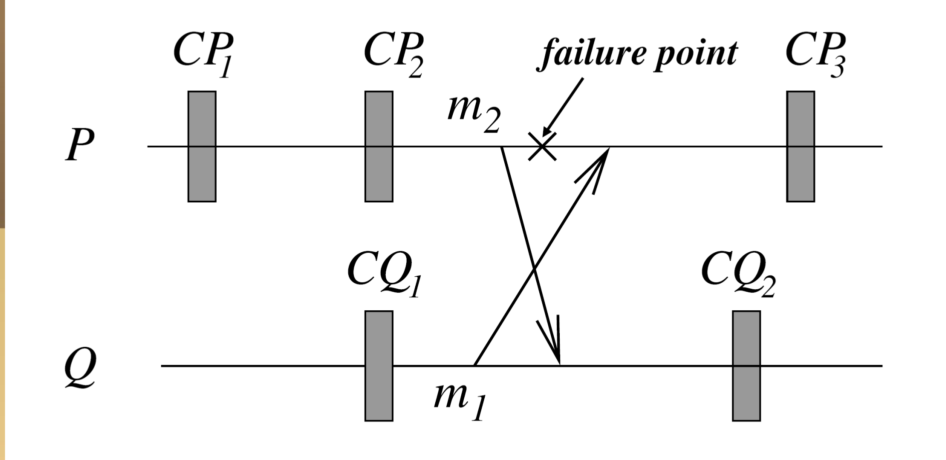
- A single failure can cause a sequence of rollbacks that send every process back to its starting point
- Happens if checkpoints are not coordinated either directly (through message passing) or indirectly (by using synchronized clocks)
- Example: P suffers a transient failure
  - Rolls back to checkpoint CP_3
  - Q rolls back to CQ_2 (so m_6 will not be an orphan)
  - P rolls back to CP_2 (so m_5 will not be an orphan)
  - This continues until both processes have rolled back to their starting positions

Lost Messages



- Suppose Q rolls back to CQ1 after receiving message m from P
- All activity associated with having received m is lost
- If P does not roll back to CP2 – the message was lost – not as severe as having orphan messages
- m can be retransmitted
- If Q sent an acknowledgment of that message to P before rolling back, then the acknowledgment would be an orphan message unless P rolls back to CP2

Livelock



- Another problem that can arise in distributed checkpointed systems
- Q sends P a message m1; P sends Q a message m2
- P fails before receiving m1
- Q rolls back to CQ1 (otherwise m2 is orphaned)
- P recovers, rolls back to CP2, sends another copy of m2, and then receives the copy of m1 that was sent before all the rollbacks began
- Because Q has rolled back, this copy of m1 is now orphaned, and P has to repeat its rollback
- This orphans the second copy of m2 and Q must repeat its rollback
- This may continue indefinitely unless there is some outside intervention

Wrapping up

- Chapter 6 – Fault tolerant systems by Israel Koren