Distributed Simulation and the Time Warp Operating System

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Introduction

- What is the problem?
  - They want to enable concurrent execution on a multiprocessor machine for discrete event simulation.
  - The system exhibits irregular causal and temporal behavior.
- What is new or different?
  - They developed an operating system with a complete commitment to optimistic execution and rollback.
- What are the contributions and limitation?
  - Performs synchronization with a distributed process rollback mechanism.
  - There is no dynamic creation of processes at runtime.
  - There is no migration of processes for load management.
Problem Details

- The system was specifically designed for military simulations.
  - Expensive computational tasks
  - Composed of many interacting subsystems
  - Highly irregular temporal behavior

- This was not intended as a general purpose operating system.

- Nevertheless, there are many applications:
  - Discrete event simulations
  - Large, distributed databases
  - Real time systems
  - Animation systems
Approach

- Develop a new operating system with complete commitment to optimistic execution and process rollback
  - Don’t treat rollback as a special case for exception handling, deadlock breaking, transaction abortion, etc.
  - Use rollback as frequently as other systems use blocking.
- But why a new OS?
  - Rollback forces a rethinking of all os issues (scheduling, synchronization, message queueing, flow control, memory management, error handling, I/O, and commitment.)
  - Building TW on top of an os would require two levels of synchronization, two levels of message queueing, etc.
Operating Environment

- TWOS was developed for the Mark III hypercube.
  - Mark III was developed between 1983 and 1987.
  - Composed of 32 nodes, or processing units, which together have peak speed of about 512 million floating point operations per second (flops).
  - Later upgraded to 128 nodes.
- It was a single user system.
- Supported distributed applications composed of processes communicating by messages.
Time Warp and Virtual Time

- Concept of *virtual time* used to organize and synchronize distributed systems [Jefferson 85].
- Virtual time is a global, temporal coordinate axis defined by the application as a measure of progress and as a scale against which to specify synchronization
  - Real values
  - Totally ordered
  - May or may not be connected to real time
- Virtual memory is to demand paging as virtual time is to the Time Warp mechanism.
Virtual Time Synchronization Problem

- Application is composed of many processes
- All messages are time-stamped
- All incoming messages are funneled into a single input queue
- How can the operating system control the execution of a process so that it receives its messages in nondecreasing time-stamp order and is guaranteed to make progress?
Time Warp Mechanism

- Takes an *optimistic* approach.
  - Assume the next message in the queue is the true next message.
- Messages may arrive asynchronously.
- When a message with time-stamp $t$ less than what has executed, Time Warp must:
  1. roll back the process to a time just before virtual time $t$
  2. execute the new message at virtual time $t$
  3. start re-executing messages with time-stamp greater than $t$, again in time-stamp order, canceling all effects of any output messages that were sent after $t$ during the last forward execution but were not re-sent in this one.
Antimessages

- How to support the cancellation described in (3)?
- Introduce the concept of antimessages
  - Every event, query, and reply message has a sign, + or -
  - Two messages identical in all fields with opposite signs are antimessages of each other
- How do antimessages behave?
  - \(-(-m) = m\)
  - \(\text{Insert(Insert(Q, m), -m)} = Q\)
How to use Antimessages

- When a process $P$ requests a message to be sent, TWOS creates a message-antimessage pair.
- The positive message delivered to the receiver’s input queue.
- The negative message is retained in $P$’s output queue.
- As long as there are no rollbacks, the negative message stays in the output queue and is eventually garbage collected.
To undo the affects of sending $m$ from $P$ to $Q$, remove $-m$ from $P$’s output queue, and send it to $Q$.

1. If $-m$ arrives in $Q$’s future, then it will annihilate with the $m$ in $P$’s input queue and the cancellation is finished.
2. If $-m$ arrives in $Q$’s past, it will cause $Q$ to roll back, but it will also annihilate with $-m$, so that when $Q$ executes forward again, neither $+m$ not $-m$ exist. $Q$ will not see either of them.
TWOS Programming Model

- Each process has a 20 character unique name
- Any process can send to any other process at any time
- No notion of a pipe, channel, or connection
TWOS Process

A TWOS Process is composed of 4 sections and state variables

- Initialization Section - executed once at initialization
- EventMessage Section - invoked when an event message is processed
- Query Message Section - invoked when a query message is processed
- Termination Section - invoked once at termination
Several system calls unique to TWOS:

- Me(MyName)
- Virtual Time(VTime)
- SendEventMessage(ReceiveTime, Receiver, Text)
- SendQueryMessage(Receiver, Text, Reply)
- SendReplyMessage(Text)
- MCount(n)
- ReadEventMessage(k, Text)
- ReadQueryMessage(Text)
Processor Scheduling

- Preemptive lowest virtual time first
- Arbitrary choice to break ties
- A process could run indefinitely
- If a new message arrives which causes a rollback, the process will be pre-empted
Process Synchronization

- A process only blocks if it has no unprocessed messages in its input queue, or if it is waiting for a reply to a query.
- Does a full rollback immediately (even if executing) if a message arrives with a lower time-stamp.
- A process can roll back out of a blocked state, then execute and re-enter the blocked state.
Flow Control Challenges

Flow Control is challenging in TWOS

- Not only do incoming messages fill up memory, but also outgoing and saved state
- No explicit channels, so flow control cannot be done on a per-channel basis
- Messages cannot be deleted when they are received because of rollback
- TWOS runs best when memory is almost completely full, which strains on storage and flow control mechanisms
Flow Control

Flow Control tool is *message sendback* [Gafni 85]

- Idea is that when memory is full, send a message back to make room, which may cause a rollback
- Communication analog of process rollback
Some operations are *irreversible* and therefore require commitment.

- Use Global Virtual Time (GVT)
- GVT is the minimum virtual time of any uncompleted event or message transmission in the system
- Once GVT is greater than some value \( t \), TW can commit all output requests at virtual time less than \( t \), and release all messages and state buffers with time less than \( t \), and report any error outstanding with time less than \( t \)
Performance

- Primary criteria is time to completion of benchmarks.
  - Game of Life
  - Military command and control model
- Note that since there is no dynamic process migration, there were many different assignments of processes to processors.
COMMO Benchmark

- COMMO is a military simulation
- The evaluation shows:
  - Little improvement after 16 processors, best time with 24 nodes
  - Maximum speedup of 10.66 using 24 processors
  - Number of rollbacks increases with the number of processors
  - Greater speedup occurs with more rollbacks (rollbacks aren’t in the bottleneck code)
  - About 33.4 % of messages were antimessages
Questions?