CSCI 8220
Parallel & Distributed Simulation

PDES: Time Warp Mechanism

Other Mechanisms

Outline

- Rollbacks idiosyncrasies and remedies
  - » Error Handling
  - » Dynamic Memory Allocation
- Event Retraction
- Improving the cost of rollbacks
  - » Lazy Cancellation
  - » Lazy Re-Evaluation
- Memory Management
  - » Mechanisms
  - » Storage optimal protocols
  - » Artificial Rollback
- Other optimistic protocols

Optimistic Execution Questions

- How to handle error handling in an optimistic simulator?
  - » Why is this a problematic?
- How to manage dynamic memory allocations?
  - » Why is this problematic? Remedies?
- How to make rollbacks more efficient?

Error Handling

- *Typically Errors such as divide by zero, are handled by aborting program. Is this appropriate for TimeWarp simulations? Why or Why not?*
- **Problem**: What if an execution error is rolled back?
- **Solution**: Do not *abort* program until the error is committed (GVT advances past the simulation time when the error occurred).
  - » Requires Time Warp executive to "catch" (flag) errors when they occur
  - » Countermeasures depend on error type

Error Types

- Program detected
  - » Logic errors, e.g., some variables never negative
  - » Treat "abort" procedure like an I/O operation, prevent error from propagating and flag error to see if it erased by rollback.
- Infinite loops
  - » Interrupt mechanism to receive incoming messages
  - » Poll for messages in loop
- Benign errors
  - » Errors that impact only checkpointed state (e.g., divide by zero)
  - » Trap mechanism to catch runtime execution errors
- Destructive errors
  - » Difficult to detect these…
  - » Example: overwrite state of Time Warp executive)
  - » Runtime checks (e.g., array bounds)
  - » Strong type checking, avoid pointer arithmetic, etc.

Dynamic Memory Allocation

`malloc()` and `free()` How should they be handled?

Issues:

- Roll back of memory allocation (e.g., `malloc()`)
  - » **Problem**: Memory leak (when check pointing a pointer to a previously allocated memory location). Run out of memory…
  - » **Solution**: release memory if malloc rolled back
- Roll back of memory release (e.g., `free()`)
  - » **Problem**: Reuse memory that has already been released. The LP did not really mean to free the memory …
  - » **Solution**:
    - – Treat memory release like an I/O operation
    - – Only release memory when GVT has advanced past the simulation time when the memory was released

Event Retraction

- **Goal:**
  - » Need a primitive to un-schedule a previously scheduled event (application level primitive)
- **Example:**
  - » ORD Schedules an arrival at JFK
  - » Need to re-route aircraft to Boston (due to congestion at JFK)
- **Observation:**
  - » Cancellation retracts events at the 'simulation kernel level'
- **Problem:**
  - » Need a mechanism to *undo* event retraction (cancellation) if the event computation that invoked the retraction is rolled back.

Event Retraction Approaches

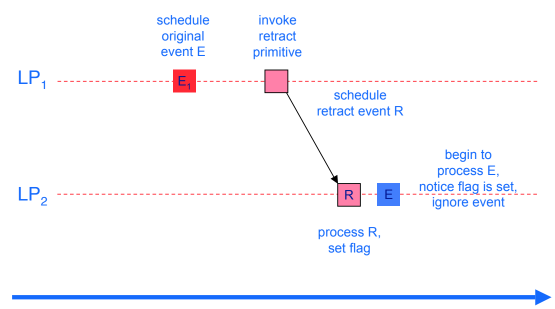
- **Application Level**
- **Kernel Level**

Event Retraction: Approach 1

Application Level Approach

1. Schedule a retraction event with time stamp earlier than (<) the event being retracted
2. Process retraction event: Set flag in LP state to indicate the event has been retracted.
3. Process event: Check if it has been retracted before processing any event

Example: Application Approach



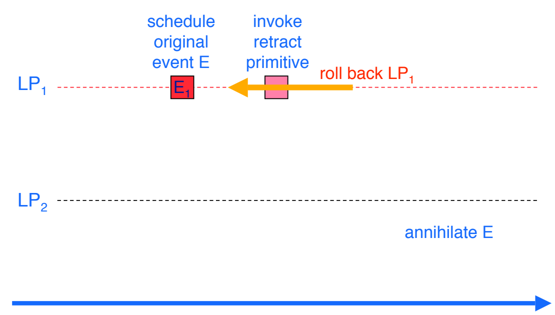
Retraction handled within the application

Event Retraction: Approach 2

Time Warp Executive Level Approach

- Retraction: **send anti-message to cancel the retracted event**
  - » Retraction: invoked by application program
  - » Cancellation: invoked by Time Warp executive (transparent to the application)
- Rollback retraction request
  - » Reschedule the original event
  - » Retraction: place positive copy of message being retracted in output queue
  - » Rollback: Send messages in output queue (same as before)

Example: Kernel Approach

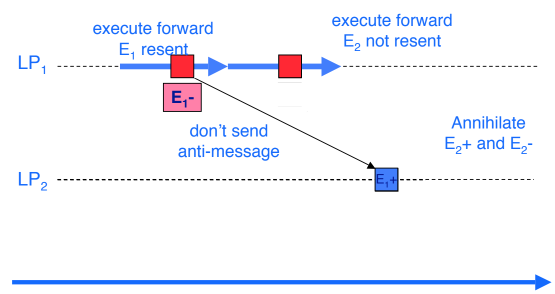


Retraction handled within Time Warp executive

Lazy Cancellation

- **Motivation**:
  - » re-execution after rollback may generate the same messages as the original execution
  - » in this case, need not cancel original message that were scheduled by rolled back event.
- **Mechanism**:
  - » rollback: do not immediately send anti-messages
  - » after rollback, recompute forward
  - » only send anti-message if recomputation does NOT produce the same message again

Example: Lazy Cancellation



Lazy cancellation avoids unnecessary rollback

Lazy Cancellation: Evaluation

- **Benefit**:
  - » avoid unnecessary message cancellations which in turn eliminate secondary rollbacks.
- **Liabilities:**
  - » extra overhead (message comparisons)
  - » delay in canceling wrong computations
    - – may allow erroneous computations to spread further. -> more computations may need to rollback when anti-message is finally sent
  - » more memory required (delayed memory reclamation)
- **Conventional wisdom**
  - » Lazy cancellation typically improves performance
  - » Empirical data indicate 10% improvement typical

Lazy Re-evaluation

- **Motivation**:
  - » re-execution of event after rollback may be produce same result (LP state) as the original execution
  - » in this case, original rollback was unnecessary
- **Mechanism**:
  - » rollback: do not discard state vectors of rolled back computations
  - » process straggler event, recompute forward
  - » during recomputation, if the state vector and input queue match that of the original execution, immediately "jump forward" to state prior to rollback.

Lazy Re-evaluation

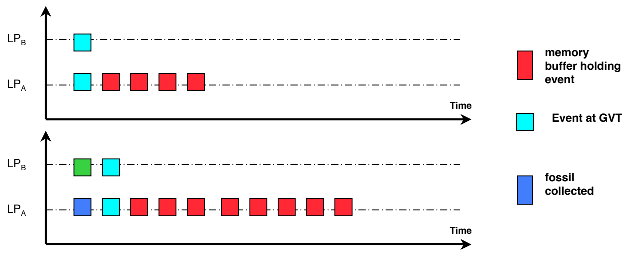
- **Benefit**:
  - » avoid unnecessary recomputation on rollback
  - » works well if straggler does not affect LP state (query events)
- **Liabilities**:
  - » extra overhead (state comparisons)
  - » more memory required
- **Conventional wisdom**
  - » Typically does not improve overall performance
  - » Useful in certain special cases (e.g., query events)

Memory Management in Time Warp

- Parallel execution using Time Warp tends to use much more memory than a sequential execution (even with fossil collection)
  - » State vector and event history
  - » Memory consumption can be unbounded because an LP can execute arbitrarily far ahead of other LPs
  - » "Overoptimism" lead to very long and frequent rollbacks, may waste computation time.

Memory Management in Time Warp

"Overoptimism" lead to very long and frequent rollbacks, may waste computation time.



Memory Consumption

- **Sequential Simulations:**
  - aborts
- **Parallel Simulations:**
  - abort?
  - more memory?
  - blocking?
  - Memory:
    1) positive and
    2) anti-messages and
    3) state vectors

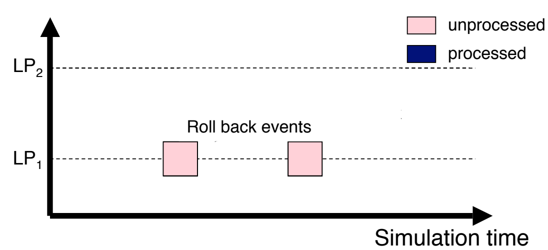
Memory Consumption Remedies

- **Infrequent / incremental**: state saving
- **Pruning**: dynamically release copy state saved memory
- **Blocking**: block certain LPs to prevent overly optimistic execution
- **Roll back** to reclaim memory
- **Message sendback**

Message Sendback

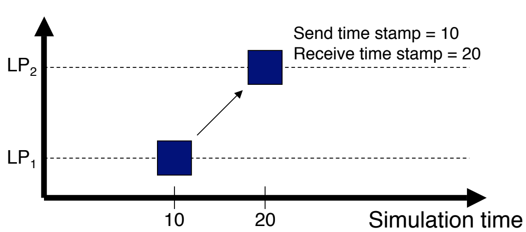
Basic Idea:

- Send time stamp
- Reclaim memory used by a message by returning it to the original sender
- Usually causes the sender to roll back



Event Time Stamps

- Receive time stamp: time stamp indicating when the event occurs (conventional definition of time stamp)
- Send time stamp of event E: time stamp of the LP when it scheduled E (time stamp of event being processed when it scheduled E)



Message Sendback

- Causes sender to roll back to the send time of event being sent back
- Can any message be sent back?
  - No! Can only send back messages with send time greater than GVT
- A new definition of GVT is needed

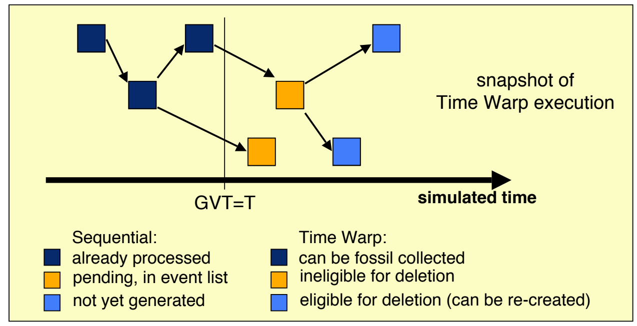
GVT(T) (GVT at wallclock time T) is the minimum among
- Receive time stamp of unprocessed and partially processed events
- Send time stamp of backward transient messages at wallclock time T

Storage Optimal Protocols

Storage Optimality: A memory management protocol is storage optimal iff it ensures that every parallel simulation uses memory O(M), where M is the number of units of memory utilized by the corresponding sequential simulation

- **Basic idea: if the Time Warp program runs out of memory**
  - **identify the events (message buffers) that would exist in a sequential execution at time T, where T is the current value of GVT**
  - **roll back LPs, possibly eliminating (via annihilation) all events except those that exist in the corresponding sequential execution.**

Classifying Events



Sequential execution: Which events occupy storage in a sequential execution at simulation time T?

Time Warp: For which events can storage be reclaimed?

Observations

- **In a sequential execution at simulation time T, the event list contains the events with**
  - **Receive time stamp greater than T**
  - **Send time stamp less than T.**
- **Time Warp can restore the execution to a valid state if it retains events with**
  - **Send time less than GVT and receive time stamp greater than GVT.**
  - **All other events can be deleted (as well as their associated state vector, anti-messages, etc.)**
- **Storage optimal protocols: roll back LPs to reclaim all memory not required in corresponding sequential execution**

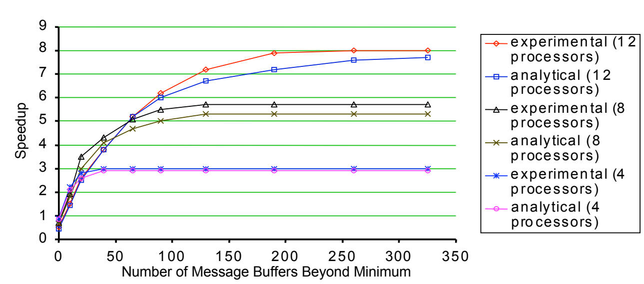
Cancelback

- **Shared memory machine mechanism**
- **Storage optimal**
- **Global pool to hold free buffers**
- **Uses Message Sendback mechanism (message TS > GVT)**
- **Requires:**
  - **GVT Computation**
  - **Fossil collection**
  - **Find and eligible event**
  - **Send back mechanism**
- **Batching – into a salvage parameter**

Other Memory Mechanisms

- **Prune-back**
- **Adaptive mechanisms: predicts memory the program needs on-line**
- **Trading performance and Memory**
  - **Performance may DECREASE if memory is increased further – poorly balanced workloads**
    - **limiting memory may provide a flow control mechanism that avoids overoptimistic execution.**

Effect of Limited Memory on Speedup



- **symmetric synthetic workload (PHold)**
- **one logical processor per processor**
- **fixed message population**
- **KSR-1 multiprocessor**
- **sequential execution requires 128 (4 LPs), 256 (8 LPs), 384 (12 LPs) buffers**
- **25% to 75% extra buffer and beyond minimum did not improve performance**

Performance Hazards

- Chasing Down Incorrect Computations
  - » incorrect computation spreads while correcting/canceling erroneous computations
  - » dog chasing its tail
- Rollback Echoes
  - » Expensive rollbacks may cause length of rollback to expand at an exponential rate. Cost of rollback:
    1. Antimessage to all cancelled events
    2. Restore State
    3. Pointer updates of input queue
  - » 1&2 suggest cost is proportional to #events being rolled back
  - » What if rolling back T units of simulated time takes twice as long as going forward by the same amount?
    - net rate of GVT progress decreases as the simulation proceeds!

Other Optimistic Algorithms

Principal goal: avoid excessive optimistic execution

A variety of protocols have been proposed:

- window-based approaches
  - » only execute events in a moving window (simulated time, memory)
- risk-free execution
  - » only send messages when they are guaranteed to be correct
- add optimism to conservative protocols
  - » specify "optimistic" values for lookahead

Other Optimistic Algorithms

Principal goal: avoid excessive optimistic execution

A variety of protocols have been proposed:

- introduce additional rollbacks
  - » triggered stochastically or by running out of memory
- hybrid approaches
  - » mix conservative and optimistic LPs
- scheduling-based
  - » discriminate against LPs rolling back too much
- adaptive protocols
  - » dynamically adjust protocol during execution as workload changes

Conservative Algorithms

Advantages:

- Good performance reported for many applications containing good lookahead (queuing networks, communication networks, war gaming)
- Relatively easy to implement
- Well suited for "federating" autonomous simulations, provided there is good lookahead

Disadvantages:

- Cannot fully exploit available parallelism in the simulation because they must protect against a "worst case scenario"
- Lookahead is essential to achieve good performance
- Writing simulation programs to have good lookahead can be very difficult or impossible, and can lead to code that is difficult to maintain

Optimistic Algorithms

Advantages:

- good performance reported for a variety of application
  - » queuing networks, communication networks, logic circuits, combat models
- offers the best hope for "general purpose" parallel simulation software
  - » not as dependent on lookahead as conservative methods
- "Federating" autonomous simulations
  - » avoids specification of lookahead
  - » caveat: requires providing rollback capability in the simulation

Disadvantages:

- state saving overhead may severely degrade performance
- rollback thrashing may occur (though a variety of solutions exist)
- Implementation:
  - » generally more complex and difficult to debug than conservative mechanisms; careful implementation is required or poor performance may result
  - » must be able to recover from exceptions (may be subsequently rolled back)

Summary

- Other Mechanisms
  - » Simple operations in conservative systems (dynamic memory allocation, error handling) present non-trivial issues in Time Warp systems
  - » Solutions exist for most, but at the cost of increased complexity in the Time Warp executive
- Event retraction
  - » Not to be confused with cancellation
  - » Application & kernel level solutions exist
- Optimizations
  - » Lazy cancellation often provides some benefit
  - » Conventional wisdom is lazy re-evaluation costs outweigh the benefits