Application-level Checkpointing of Parallel Programs

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Outline

- Motivation & Background
- Shared memory programs
- Distributed memory programs
- References

Motivation

- Trends in parallel computer systems:
  - Number of processors is increasing
  - Shift towards low-cost clusters
  - Running time of many applications is longer than the MTBF of hardware
- Must tolerate hardware faults in parallel systems…

Common Solutions

- Message Logging
  - All messages sent between processes are logged
  - On recovery, surviving processes replay messages to the failed process
  - **Advantage:** Restarts computation on failed process only, other processes continue
  - **Disadvantage:** Overhead is overwhelming, parallel programs communicate more than distributed programs
- Checkpointing
  - Periodically save state to stable storage
  - On recovery, all processes rolled back to the last checkpoint
  - **Advantage:** Time between checkpoints can be varied depending on reliability requirements
  - **Disadvantage:** All processes must roll back, state can be very large in massively parallel systems

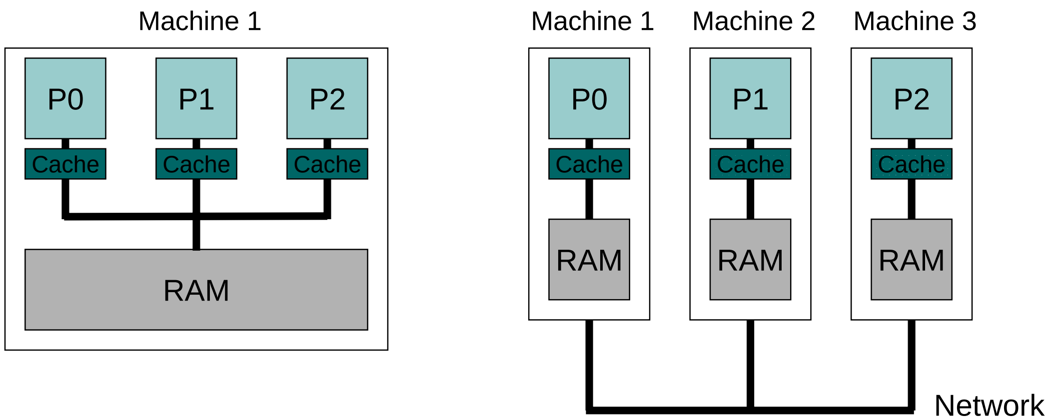
Checkpointing Techniques

- System-level or Application-level
  - **System-level:** Entire state of the system is saved (impractical for massively parallel systems)
  - **Application-level:** Necessary state of the application is saved (complicates coding of application)
- Uncoordinated or Coordinated
  - Uncoordinated
    - No coordination among processes
    - Possible exponential rollback on restart
  - Coordinated
    - **Blocking:** All processes brought to a halt before taking the checkpoint
    - **Non-blocking:** All processes participate in taking each checkpoint while computation continues, requires coordination protocol

Fault Model

- Two common classes
  - Stopping (fail-stop)
    - Faulty process stops and fails to respond, does not send/receive messages
  - Byzantine
    - Process makes computational errors at random and continues to function

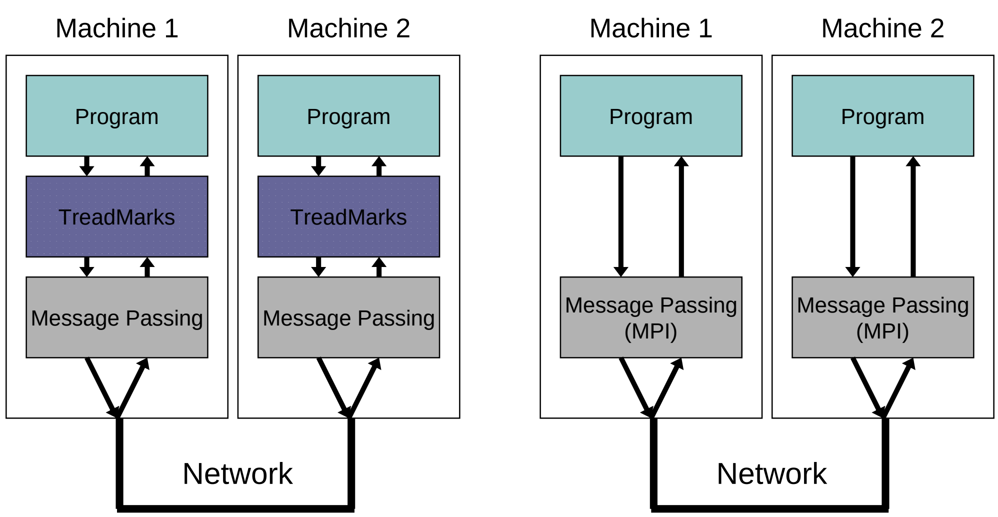
Shared vs. Distributed Memory



Shared Memory

Distributed Memory

Distributed Memory Systems



Software DSM

Message Passing System

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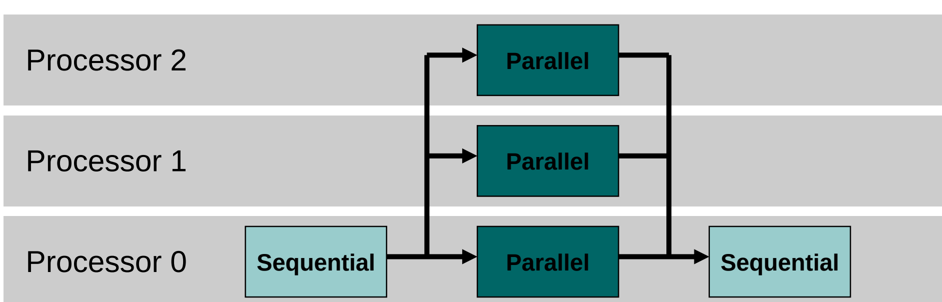
- **Shared memory programs**
- Distributed memory programs
- Conclusion

OpenMP in a Nutshell

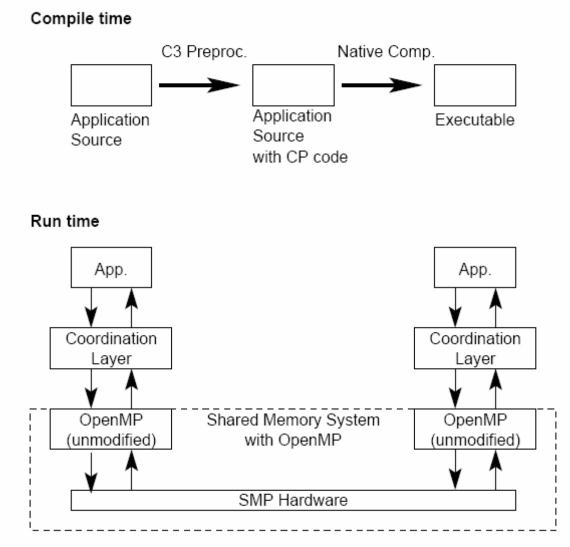
- Fork/join model



- All variables are either shared or private
  - **Shared:** All threads read from one address
  - **Private:** Each thread has a local copy

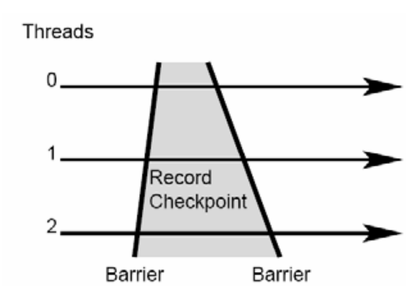
C^3 for OpenMP: System Overview

- Programmer annotates possible checkpoint locations
  - Call to `potentialCheckpoint()`
- C^3 pre-compiler transforms source code to include checkpointing code
- Compiled with native compiler, linked with coordination layer library
  - Layer sits between app and OpenMP
  - No modification to OpenMP



Blocking Protocol

- Checkpointing:
  - Each thread calls a barrier
  - Each thread saves its private state, thread 0 saves the system's shared state
  - Each thread calls a second barrier



- Recovery:
  - All threads restore private variables to their checkpointed values, thread 0 restores all the shared addresses to their checkpointed values
  - Every thread calls a barrier
  - Every thread continues execution

Saving Application State

- Heap
  - Custom heap library tracks memory that is allocated and freed
- Call stack
  - **Location Stack (LS):** Tracks sequence of function calls which lead to place where checkpoint was taken
  - **Variable Description Stack (VDS):** Records local variables in these function invocations that must be saved
  - On recovery:
    - LS is used to re-execute sequence of function calls and re-create stack frames
    - VDS is used to restore variables into stack
- Global Variables
  - Similar approach to VDS

Example #1

```
main() {
	int a;
	VDS.push(&a, sizeof(int));
	if(restart)
		load LS;
		copy LS to LS_Old;
		jump dequeue(LS_Old);
	...
	func1();
	…
	LS.push(label_0);
label_0:
	func2();
	LS.pop();
	…
	omp_set_num_threads(read_original_num_threads());
	#pragma omp parallel
		{ parallel code }
	...
	VDS.pop();
}
```

```
func1() {
	…
}

func2() {
	int b;
	VDS.push(&b, sizeof(int));
	if(restart)
		jump dequeue(LS.old);
	…
	LS.push(label_1);
	potentialCheckpoint();
label_1:
	if(restart)
		load VDS;
		restore variables;
	LS.pop();
	…
	VDS.pop();
}
```

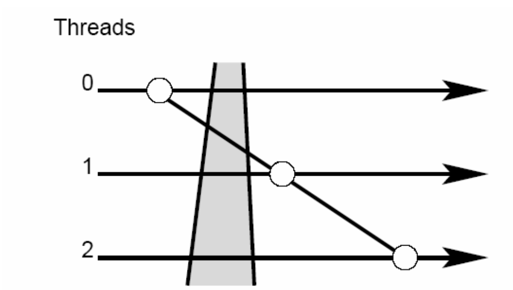
Example #2

```
main() {
    int a;
    VDS[0].push(&a, sizeof(int));
    if(restart)
        load LS[0];
        copy LS[0] to LS_Old[0];
        jump dequeue(LS_Old[0]);
    ...
```

```
    LS[0].push(label_0);
label_0:
    omp_set_num_threads(read_original_num_threads());
    #pragma omp parallel
    {
        int b;
        VDS[thread_num].push(&b, sizeof(int));
        if(restart)
            jump dequeue(LS_Old[thread_num]);
        …
        LS[thread_num].push(label_2);
        potentialCheckpoint();
    label_2:
        if(restart)
            load VDS[thread_num];
            restore variables;
        LS[thread_num].pop();
        …
        VDS[thread_num].pop();
    }
    LS[0].pop();
    ...
    VDS[0].pop();
}
```


Synchronization: Barriers

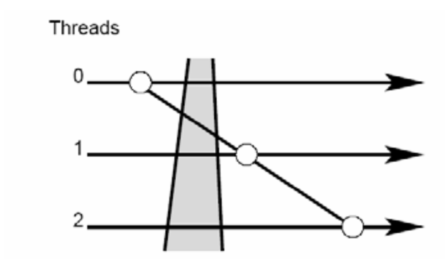
- OpenMP barriers will match calls in threads even if not at the same source code location
- In example, threads 1 & 2 take a checkpoint while thread 0 continues computing
- On recovery, OpenMP barrier semantics violated

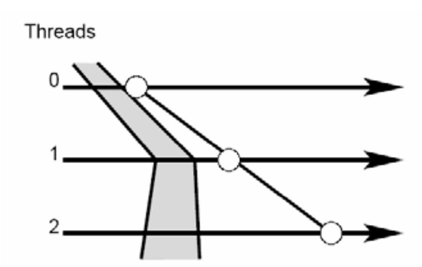


Solution for Barriers

- Ensure no checkpointing region ever crosses an application barrier
  - Associate a **`potentialCheckpoint()`** call with every call to an application barrier
- Problem: By the time a thread decides to take a checkpoint, thread 0 may already be blocked on its application barrier
  - Introduce a global **`checkpointFlag`** variable

Solution for Barriers (Cont.)





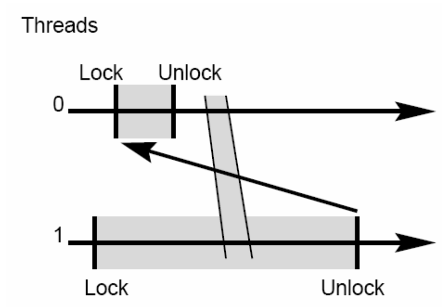

```
ccc_barrier(){
   #pragma omp barrier
   while(checkpointFlag){
      // only do this if checkpoint started while
      // waiting on application barrier
      save application state
      checkpointFlag=FALSE
      #pragma omp barrier

      // trying to wait on application barrier again
      #pragma omp barrier
   }
}

potentialCheckpoint(){
   // update checkpointFlag
   #pragma omp flush(checkpointFlag)
   // if time to checkpoint or others checkpointed
   if (checkpointFlag or initiateCheckpoint()){
      checkpointFlag = true;
      #pragma omp barrier
      save application state
      checkpointFlag = FALSE
      #pragma omp barrier
   }
}
```

Synchronization: Locks

- Problem is similar to that of barriers
  - Additional complexity: threads holding locks at checkpoint time must hold the same locks on recovery



Solution for Locks

- Associate a **`lockCheckpointFlag`** with every lock
- Before first barrier of checkpoint, thread will:
  - Set each lock's **`lockCheckpointFlag`** to TRUE
  - Remember which locks it is holding and release them
- Upon lock acquisition, thread will check value of the lock's **`lockCheckpointFlag`**
  - If FALSE, lock acquired normally
  - If TRUE, must take a checkpoint
- On recovery:
  - All **`lockCheckpointFlag`** set to FALSE
  - Each thread reacquires the locks it had before the checkpoint

Solution for Locks (Cont.)

```
ccc_set_lock(lock){
   omp_set_lock(lock)
   while(lock.lockCheckpointFlag){
      // only do this if checkpoint started while
      // waiting to acquire lock
      #pragma omp barrier
         for all held locks
            lock.lockCheckpointFlag=TRUE
         record which locks are being held
         release all locks

         save application state
         save lock state
         for all locks that were held
            reacquire lock
            lock.lockCheckpointFlag=FALSE
      #pragma omp barrier

      // try to acquire the lock again
      omp_set_lock(lock)
   }
}
```

```
potentialCheckpoint(){
   #pragma omp barrier
      for all held locks
         lock.lockCheckpointFlag=TRUE
      remember which locks are held
      release all locks

      save application state
      save lock state
      for all locks that were held
         reacquire lock
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   #pragma omp barrier
}
```
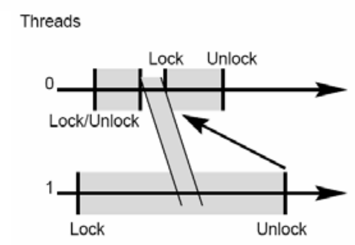
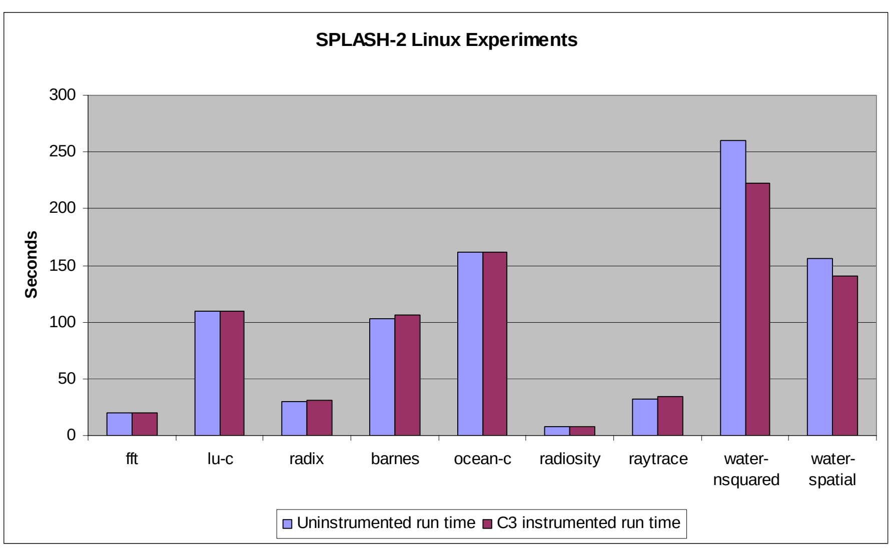
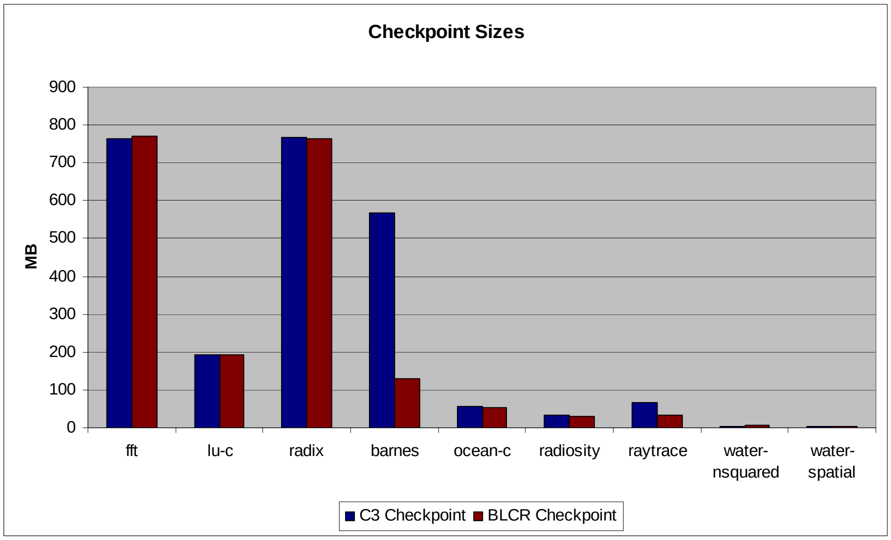



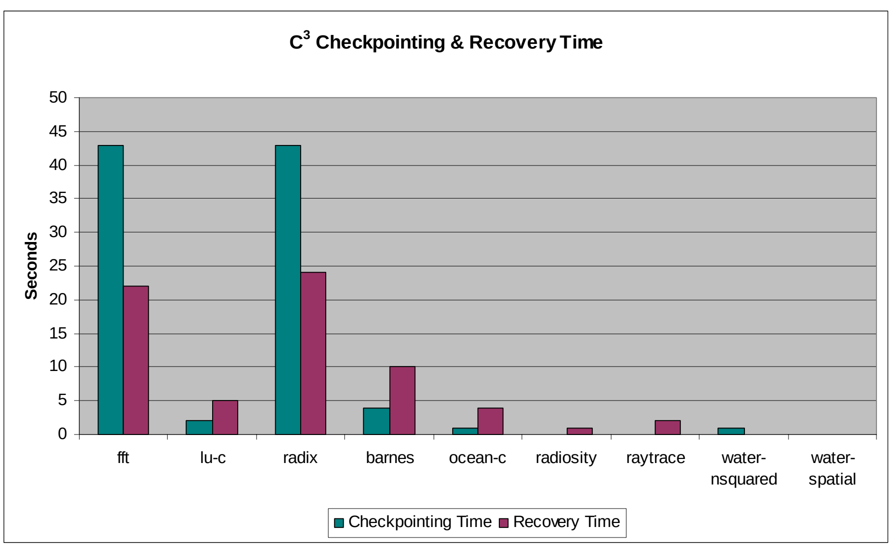
Execution Time Overhead



Checkpoint Sizes



Checkpointing & Recovery Time



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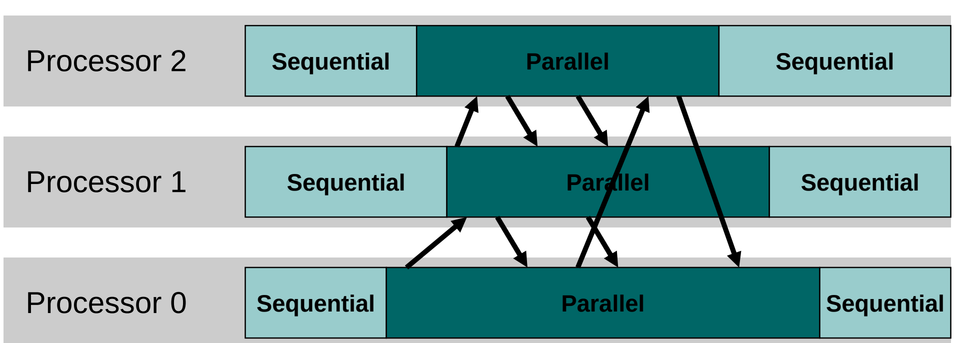
MPI in Nutshell

- All processors execute the same program
  - Only communication is via message passing



C3 for MPI: System Overview

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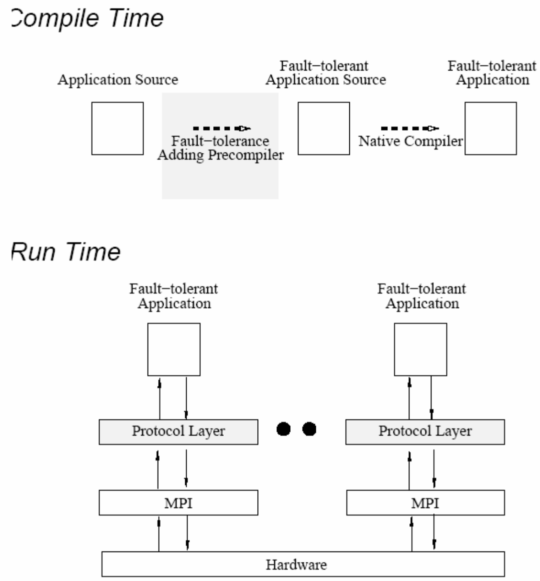
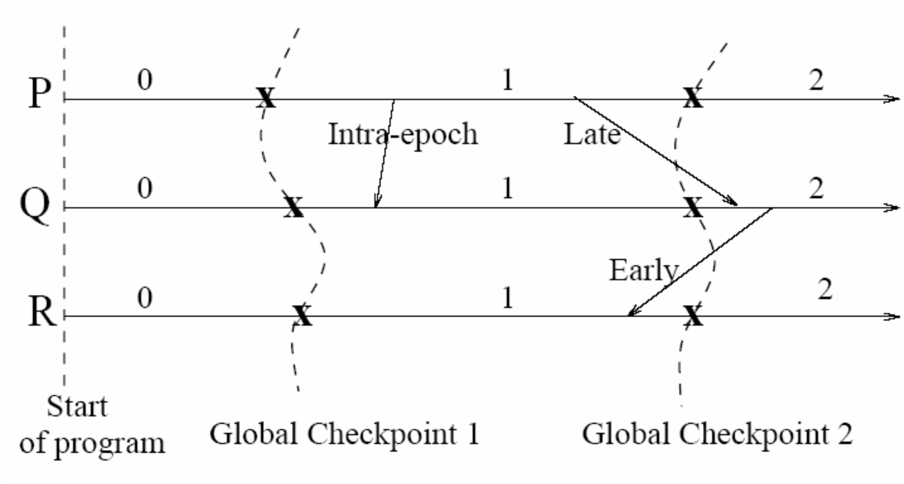


Assumptions

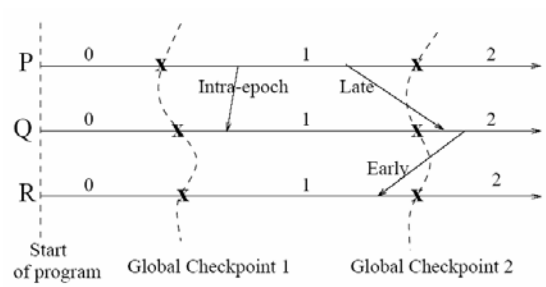
- Fail-stop fault model
- Reliable communication channels
- Communication channels are not FIFO at the application level
  - MPI processes can use tag matching

Epochs & Message Classification



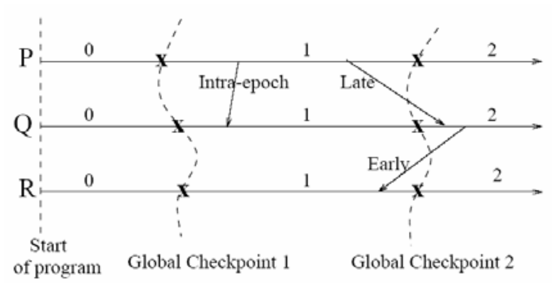
Delayed State Saving

- System-level checkpoints may be taken at any time
  - Use scheduling to avoid early messages
- Application-level checkpoint can only be taken at **`potentialCheckpoint()`** calls
  - Checkpoint delayed until call to **`potentialCheckpoint()`** reached
  - Must handle both early and late messages



Late and Early Messages

- P will not resend late message to Q
  - Identify late messages and save them with the checkpoint
  - Replay late messages to receiving process during recovery
- Q will resend early message to R
  - Identify early messages
  - Ensure early messages are not resend during recovery
  - Problem with non-deterministic events



Non-blocking Protocol

- **Phase 1:** Initiator process sends control message *pleaseCheckpoint* to all processes
- **Phase 2:** At some point each process takes a checkpoint
  - Saves local state & early messages
  - Starts logging all late messages received and all non-deterministic decisions it makes
  - Once all late messages received, sends control message *readyToStopLogging* back to initator, but keeps logging non-deterministic decisions

Non-blocking Protocol (Cont.)

- **Phase 3:** When initiator process receives control message *readyToStopLogging* from all processes, it sends control message *stopLogging* to all processes
- **Phase 4:** All processes stops logging
  - Occurs when either:
    - A process receives control message *stopLogging* from the initiator
    - A process receives a message from another process that it has stopped logging
  - All processes send control message *stoppedLogging* to initiator
  - Once initiator receives *stoppedLogging* message from the all processes, it terminates the protocol

Piggybacked Information on Messages

- Values piggybacked on all messages:
  - **epoch** (integer): The current epoch that the process is in
  - **amLogging** (boolean): True when the process is logging, false otherwise
  - **nextMessageID** (integer)
    - Initialized to 0 at beginning of each epoch
    - Incremented for each message sent
    - Uniquely identifies messages sent by a given process in a given epoch

How do we know when all late messages are received?

- In each epoch
  - Process P maintains how many messages sent to every other process Q: **sendCount(P →Q)**
  - Process Q maintains how many messages it received from every other process P: **receiveCount(Q ←P)**
- P sends a *mySendCount* message to other process upon taking a checkpoint
  - Contains number of message sent to them in previous epoch
  - Q compares with value of **receiveCount(Q ←P)**

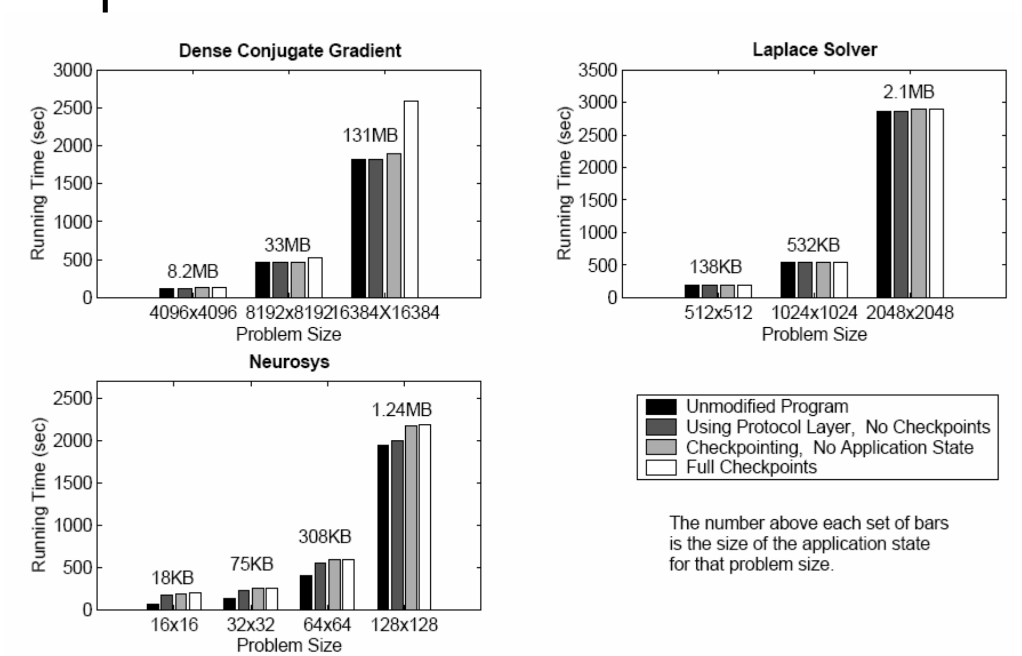
How do we suppress early messages on recovery?

- A process determines a message is early by comparing epoch numbers
  - Logs the pair <sender,messageID> at each checkpoint
  - Retrieved from storage on recovery by the receivers
  - Senders are informed of the messageIDs so that resending can be suppressed

Saving State

- Technique to take local checkpoints is independent of the coordination protocol
- Almost identical to technique for shared memory (OpenMP)
  - No shared variables
  - MPI library state
    - Use level of indirection & *pseudo-handles*
    - Different techniques for *transient* and *persistent* objects

Execution Time Overhead



Reducing Checkpoint Size

- Avoid saving dead and read-only variables
- Detect distributed redundant data
- Re-compute instead of saving

References

- G. Bronevetsky, D. Marques, K. Pingali, and P. Stodghill. Automated application-level checkpointing of MPI programs. In *Principles and Practices of Parallel Programming (PPoPP)*, June 2003.
- G. Bronevetsky, M. Schulz, P. Szwed, D. Marques, and K. Pingali. Application-level Checkpointing for Shared Memory Programs. *Conference on Application Support for Programming Languages and Operating Systems (ASPLOS)*, October 2004.
- G. Bronevetsky, D. Marques, K. Pingali, and P. Stodghill. C3: A System for Automating Application-level Checkpointing of MPI Programs. *International Workshop on Languages and Compilers for Parallel Computing*, October 2003.