CMSC 714
Lecture 15
Lamport Clocks and Eraser

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(with thanks to Chris Ackermann)

Notes

- OpenMP project scores posted
  - Ask Swati if you have questions about grading
- Research project questions?

Lamport Clocks

- Distributed systems are inherently concurrent, asynchronous, and nondeterministic, so executing programs on multiple machines requires coordination
- Lamport introduce methods to define an ordering of events
- Want to create a partial ordering of events (instructions, message passing, or whatever)
- Define a *happens before* relation: **a** $\rightarrow$ **b**
  - event **a** happened before event **b**
  - event **a** can causally affect event **b**

Happens Before Relation

1. If a and b are events in the same process, and a comes before b, then a $\rightarrow$ b
2. If a is sending of a message by one process and b is the receipt of the same message by another process, then a $\rightarrow$ b
3. If a $\rightarrow$ b and b $\rightarrow$ c then a $\rightarrow$ c (transitivity)

- Partial Order: Unordered events are *concurrent*

Logical Clocks

- Clock Condition: For any events **a, b**: if **a → b** then **C<a> < C<b>**
- Holds if C1 and C2 are satisfied:
  - C1. If a and b are events in Process P_i, and a comes before b, then $C_i<a> \; < \; C_i<b>$
  - C2. If a is the sending of a message by process P_i and b is the receipt of that message by process P_j, then $C_i<a> \; < \; C_j<b>$
- Implementation
  - IR1. Each process P_i increments C_i between any two successive events
  - IR2a. If event a is the sending of a message m by Process P_i, then the message m contains a timestamp $T_m = C_i<a>$.
  - IR2b. Upon receiving a message m, process P_j sets C_j greater than or equal to its present value and greater than T_m.

Total Ordering

- Partial ordering not always enough
- Prioritize processes $P_i \prec P_j$
- Total ordering $a \Rightarrow b$:

  If a is in P_i and b is in P_j, then $a \Rightarrow b$ iff
  - $C_i\langle a\rangle < C_j\langle b\rangle$
  - $C_i\langle a\rangle = C_j\langle b\rangle$ and $P_i \prec P_j$

Logical Clocks

- Issues with physical clocks (clock drift, etc.)
- For many purposes, it is sufficient to know the order in which events occurred
- BUT: Logical clocks cannot be used to order events outside the system

Strong Clock Condition

- Approach does not take into account external events

- Define new set of events $\mathcal{L}$

- *Strong Clock Condition*: For any events a, b in $\mathcal{L}$:

  if a ⇨ b then C<a> < C<b>

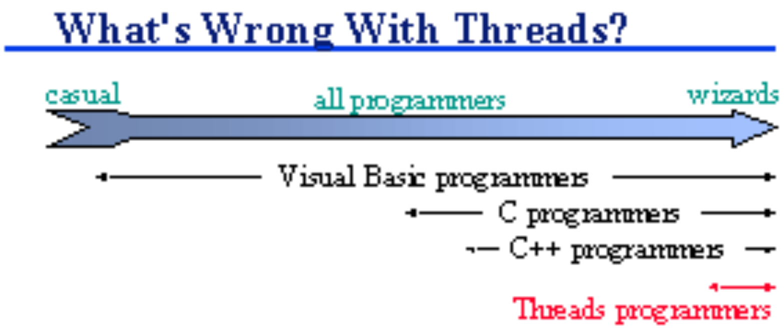
- Achieve strong clock condition with physical clocks

Physical Clocks

- Run continuously
- PC1. Clocks must run at approximately the correct rate
  - $\exists k.\ k << 1$, $|dC_i(t)/dt - 1| < k$
- PC2. Clocks must be synchronized
  - $|C_i(t) - C_j(t)| < \varepsilon$
- Minimum message delay μ
  - $C_i(t+\mu) - C_j(t) > 0$
- Satisfying Strong Clock Condition:
  - IR1: Each event occurs at a precise instant
  - IR2:
    - If P_i sends a message m at physical time t, then m contains a timestamp $T_m = C_i(t)$.
    - Upon receiving a message m at time t', process P_j sets $C_j(t')$ equal to the maximum of $C_j(t')$ and $(T_m + \mu_m)$

Eraser

- What is the problem?
  - Implementing multi-threaded programs is difficult and error prone



- Who cares?
  - Developers (and users) of multi-threaded systems
- What is the approach?
  - Provide tool support to automatically verify synchronization

Eraser

- Dynamic data race detection tool
- Supports only lock-based synchronization
- Claim: Simpler, more efficient, and more thorough than approaches based on *happens before*
- Lock
  - Synchronization object used for mutual exclusion
  - Only the owner of a lock may release it (not like a semaphore)
- Data Race
  - More than 1 thread has read or write access to a variable without synchronization, and at least one is doing a write

Other Approaches

- Monitors by Hoare
  - Do not account for dynamically allocated data
- Static race detection
  - Difficult analysis, if sound (does not produce false negatives) tends to produce many false positives
- Race detection based on *Happens Before*
  - Inefficient since large amount of information is required

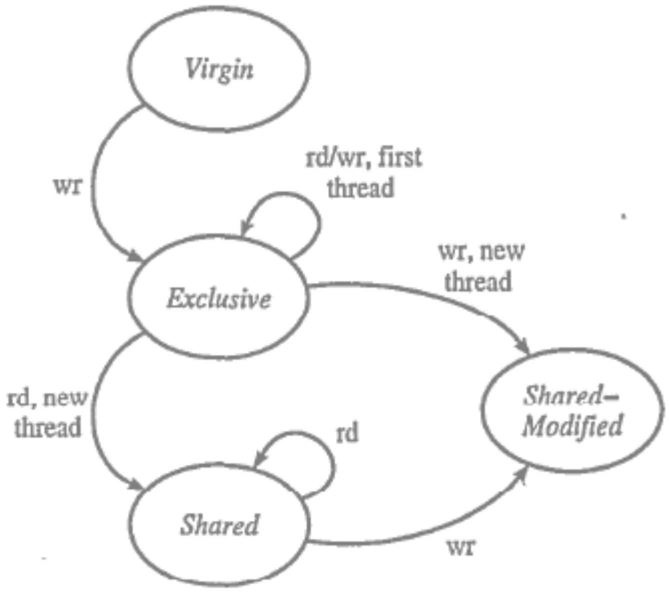
Lockset Algorithm

- First version: Enforces simple locking discipline
  - Each shared variable is protected by at least one lock
- Problem: Eraser doesn't know which lock is for which variables
- Solution: Infer protection relation from execution history
- Set C(v) of candidate locks for each shared variable v
  - Holds the locks that have protected a variable during execution
- Intuition:
  - Every time a thread t accesses a shared variable v it must hold at least one lock *l*
- Algorithm:
  - Initialize C(v) with all locks
  - $C(v) := C(v) \cap \text{locks\_held}(t)$
  - $C(v) = \{\} \rightarrow$ issue warning

Improvements

- Relax locking discipline
- Initialization: Shared variables initialized w/o holding lock
  - Algorithm “pauses” until variable is accessed by a second thread
- Read-shared data: Variables written during init only and read-only thereafter
  - No races are reported until a second thread writes to variable
- Read-write locks: Multiple readers can access a shared variable but only one writer at a time.
  - Keep track separately of write locks

States of Memory Locations



- Virgin:
  - New data, not referenced
- Exclusive
  - Accessed by one thread
- Shared
  - One write and multiple read accesses
- Shared-Modified
  - Multiple write accesses

Implementation

- Developed for DIGITAL Unix OS
  - now known as Tru64 UNIX (by HP)
- Input: Unmodified program binary
- Output: Instrumented binary that is functionally identical but includes calls to Eraser
- Race report:
  - file + line
  - list of stack frames
  - thread ID, memory address, type of access

Maintaining and Representing Lock Sets

- To maintain C(v)
  - Instrumented each call to storage allocator to init C(v) for dynamically allocated data
  - Instrument each load/store instruction
- To maintain lock_held(t)
  - Instrument each lock acquire/release (+ initialize/finalize)
- Each 32-bit word on heap or global data is possible shared variable
- List of lock sets for each memory location inefficient
  - Use hash tables to avoid duplicate lock sets
- Shared variables represented by *Shadow Words*
  - 30 bits for lockset index (or thread ID in exclusive state)
  - 2 bits for state condition

Evaluation

- Effectiveness
  - Eraser more efficient than manual validation
- Sensitivity
  - Not sensitive to the number of threads
- Extension to detecting deadlocks possible

Problems

- Slows down program by a factor of 10 to 30
- Removing false positives might be time consuming

Current Status

- Helgrind implements the Lockset algorithm (current web page says it implements *happens before*)
  - http://valgrind.org/docs/manual/hg-manual.html
- CheckSync implements Eraser for Java
  - For a CMSC433 class in 2004, web page no longer active
- Microsoft was working on RaceTrack
  - https://www.microsoft.com/en-us/research/publication/racetrack-efficient-detection-of-data-race-conditions-via-adaptive-tracking/
- Intel Inspector – not clear what algorithm is used
  - https://software.intel.com/en-us/articles/use-intel-parallel-inspector-to-find-race-conditions-in-openmp-based-multithreaded-code