CMSC 714
Lecture 15
Lamport Clocks and Race Conditions

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(with thanks to Chris Ackermann)

Notes

- MPI Project results sent
  - If you have questions, send me email
- OpenMP projects
  - Working on them, but no results until next week
- 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** → **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** → **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** → **b**
3. If **a** → **b** and **b** → **c** then **a** → **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 $C_i<\mathbf{a}> \; < \; C_i<\mathbf{b}>$
  - 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 $C_i<\mathbf{a}> \; < \; C_j<\mathbf{b}>$
- 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<**a**> < C_j<**b**>
  - C_i<**a**> = C_j<**b**> 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 $\mathscr{L}$

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

  if **a** ⇨ **b** then C<**a**> < C<**b**>

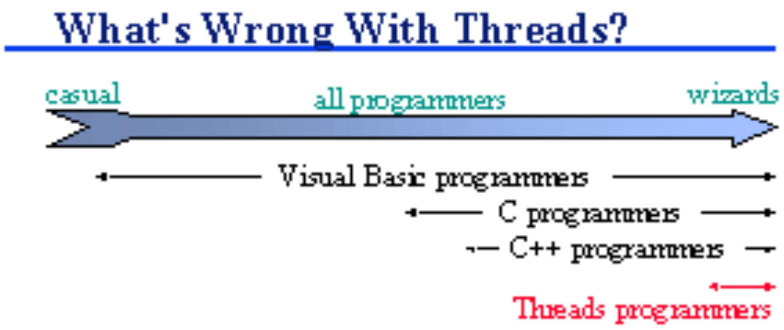
- Achieve strong clock condition with physical clocks

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 $(T_m + \mu_m)$

Race Conditions

- 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

Data Races

- Data Race
  - More than 1 thread has read or write access to a variable without synchronization, and at least one is doing a write
- Static race detection
  - Analyze the program code, so does not require that the program execute
  - Difficult analysis, if *sound* (does not produce false negatives) tends to produce many false positives (lack of *completeness*)
  - Getting both soundness and completeness is undecidable

Data Races (cont.)

- Dynamic race detection
  - Analyze the events from a single program execution to determine the occurrence of a race condition in one program execution
  - Can be sound and complete, but only for that execution
  - Want to have the *single input, single execution* (SISE) property, so that a single execution instance is sufficient to determine the existence of a data race for a given input.
  - Two basic kinds – based on happens-before (HB) relation (Lamport), and based on locksets (e.g, Eraser algorithm)

HB-based Dynamic Race Detection

- Inefficient since large amount of information is required
- Basic idea has 3 parts:
  - track the HB-relation within each thread
  - keep an access history as a sequence of logical timestamps for each shared resource (variable or memory location)
  - validate that, for every resource, critical accesses are ordered by the HB-relation
- While the analysis can be sound and complete, the article shows that with a more general notion of data races, the HB-based analysis does not report all possible data races so is not sound wrt that definition

Lockset-based Detection

- Targeted at programs that use *critical sections* as their primary synchronization model
- Validates that a program execution adheres to a programming policy, called a *locking discipline*
  - E.g., threads that access a common memory location must hold a mutual exclusion lock when performing the access
- Compliance with the locking discipline implies that executions don't have a data race
- Validation can be done with static or dynamic analysis, or both

Lockset-based algorithm

- Each thread tracks at run-time the set of locks it currently holds – i.e. via a shadow location for each variable that holds the current lockset
- On the first access to a shared variable, the shadow memory is initialized with the lockset of the current thread.
- On subsequent accesses, the lockset in shadow memory is updated by intersecting it with the lockset of the accessing thread.
- If the intersection is empty and the variable has been accessed by different threads, a potential data race is reported.
- Lockset-based detection is *sound*, and has the SISE property
- Detection is *incomplete*, since accesses that violate the locking discipline may be ordered by other means of synchronization – so can get false positives

Static Data Race Detection

- Pragmatic methods look for deviations from common programming practice
  - Examples include FindBugs for Java from UMD, RacerX for large OS codes
- Methods based on dataflow analysis
  - May-happen-in-parallel analysis (MHP) to compute the may-happen-in-parallel relation among statements in different threads
  - Inter-process precedence graph for determining anomalies in programs with post-wait synchronization
- Type-based methods
  - To model and express data protection and locking policies in data and method declarations
- Model checking
  - To explore every possible control flow-path and variable value assignment for undesired program behavior
  - Since that is computationally intractable, models of the data and program are explored