COMPSCI 630 Systems **Spring 2017**

Lecture 18: April 28

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18.1 Times, Clocks, and Stuff Like That

One of the major issues in distributed systems is dealing with time because the assumption (made in everyday activites) that time is universal doesn't hold true. This is because latency in communication can cause non-deterministic ordering of events and clocks to fall out of sync.

If we could attach a *perfect* timestamp to each event occurence, we could obtain a *total order* on those events. Unfortunately, perfect timestamps are infeasible in distributed systems because the latency of message passing communication and clock drift forces the loss of synchronization.

18.1.1 How are clocks synchronized?

1. Atomic Clocks - The most accurate time measuring device. Uses the frequency of transmission of atoms under some light in the electromagnetic spectrum as a frequency standard for timekeeping. These are expensive (costs $25000) and are not practical for large or personal deployments.

2. Quartz Crystal - Quartz is known to vibrate at a certain frequency under some electronic oscillator. This creates a precise signal that produces a much more accurate clock than digital clocks, but less accurate than atomic clocks. The synchronization problem still persists, and several quartz clocks can drift further and further apart.

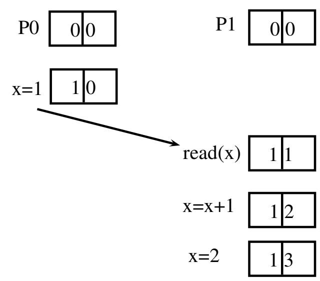
The time delay in synchronizing these clocks is nondeterministic. The *Network Time Protocol* (NTP) is a common standard for synchronizing the clocks of moder distributed servers. However, this synchronization is coarse-grained (i.e. clocks may be guaranteed to be within a day, hours, minutes, or seconds of sync with one another, but not fine-grained enough to guarantee against inversions in the perceived order of events).

Lamport described a way to determine a global ordering of events in a distributed system by defining a "happens-before" relationship between two events, establishing a *total order*. Lamport used *logical clocks* (a.k.a. Lamport clocks), which are essentially global counters (as opposed to perfect timestamps) that increment each event and are transmitted to all parts of a distributed system in every communication.

18.1.2 Vector Clocks

Vector clocks generalize Lamport clocks by maintaining essentially a vector of logical clocks, one for each thread or process in the distributed system. A vector clock must be maintained for *each* variable in the program. They encode the happens-before relation on all variable accesses/modifications, establishing a total order on these events.

Consider the following example.



In this example, two processes (P_0 and P_1) operate on a shared variable x. Each process maintains a vector clock of size 2 (since there are two processes) intialized to $[0|0]$. After operation $x = 1$ in P_0, its vector clock is updated to $[1|0]$ and at this point P_1 takes over execution. P_0 passes its vector clock $[1|0]$ to P_1. Before P_1 executes any instructions, it compares its vector clock $[0|0]$ against P_0's vector clock $[1|0]$. As the entry in P_1's vector clock for P_0 is less than or equal to the entry of P_0 in its vector clock (i.e. $0 \leq 1$), there is no race condition. In general, if there does not exist a happens-before relation between two events there could be a potential race. Logical and vector clocks detect such race conditions.

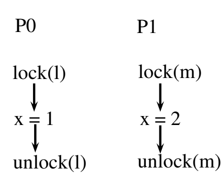
18.1.3 Race Detection

The happens-before relation can be used to detect potential race conditions in variable accesses and modifications. Vector clocks encode this relationship, so they lend to a *precise* notion of race-detection (i.e. if a race were to occur, it would be detected, and any races it detects are legitimate, potential races).

With the precision of vector clocks comes performance overhead. They require $O(n)$ space (linear in the number of threads/processes) per variable and vector clock operations (comparisons to determine ordering) are $O(n)$ time as as they require a linear traversal of the vectors.

18.1.4 Alternative Approaches to Race Detection

To address the performance overhead of vector clocks, some techniques sacrifice precision. ERASER is a Java race detector that uses such an approach, employing a *LockSet* analysis algorithm to detect potential races (potentially giving false-positives). The key insight here is that if multiple processes work on a shared variable without holding a lock, then there is a potential race. As an example, consider the two processes below:



Initially, we consider the LockSets for each process to be empty (i.e. $LS(P_0) = LS(P_1) = \emptyset$). After P_0 and P_1 acquire the locks l and m respectively, the lock-sets for the variable assignment on each process will be $LS(P_0) = \{l\}$ and $LS(P_1) = \{m\}$. Since $LS(P_0) \cap LS(P_1) = \emptyset$, there is a potential race condition. In general, the LockSet analysis reports a potential race whenever the intersection is empty.

Why is this a *potential* race?

1. The race could be benign, if for instance both threads assign the same value to x.
2. Note that if programs use alternative means of establishing ordering (rather than locking primitives), LockSet cannot detect that they may remain mutually exclusive.

18.1.5 FastTrack - Prof. Stephen Freund Guest Lecturer

FastTrack gives the precision of vector clocks without the space/time overhead required by that technique. Freund exploited the realization that in the majority of scenarios, we only need to remember the *very last write* to a shared variable instead of a vector clock encoding its entire history. As long as a race has yet to be detected, there is still a total order on writes, and so FastTrack replaces linear-sized vector clocks with an *epoch* encoding the thread id and counter of the last write to a variable. This preserves the happens-before relation before any races have occured, so FastTrack guarantees that it will precisely detect at least the first race to occur on a variable.

18.1.6 Improving Upon FastTrack

How can we perform better? We could:

1. Sample windows for potential races instead of every variable access. This has the downside of not being precise.
2. Use LockSet analysis until you would report a potential race, then switch to FastTrack to verify it is not a false positive. Results were not as promising as one might hope.
3. Reduce redundancy in consistency checks. This approach is taken in *RedCard*. If a variable is accessed multiple times inside a locked critical section that respects the happens-before relation, we can perform just a single check instead of checking at each access. Static analysis can be used to improve a dynamic detector by recognizing these cases.
4. Looping over an entire array checks accesses to every element in the array. If all your program ever does is loop over the entire array, a single check can be performed on the array itself, instead of requiring checks on every element within it. This involves recognizing access patterns and optimizing shadow representations of the happens-before relation.
5. Don't perform the check exactly when the access occurs. This can do things like hoist a check out of a loop so it's only done once instead of linearly in the number of the iterations.