Evaluation of Lockless Linked Lists Against Standard Lock Implementations

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1 Summary

We implemented three variations of linked lists: lock-free, fine-grained, coarse-grained. We also checked for correctness of these three implementations against a sequential linked list without locks. We found, after various tests, that our lock-free implementation had better performance than our fine-grained or coarse-grained linked lists.

2 Background

Lock-free data structures allow multiple threads to concurrently access shared data without using synchronization primitives like mutexes. This is especially impressive because correct lock-free code prevents deadlock from occurring. Lock-free data structures also fix problems that might otherwise occur with locks such as page faults, or preemption while a thread is in a critical section (creating deadlock.) However, it is very difficult to write correct lock-free code. Our lock-free linked list is based on the non-blocking implementation described in Harris' paper and supports inserting, removing, and finding a node. The correctness of Harris' lock-free algorithm is ensured by linearizability, meaning that operations appear to occur atomically. In order words, the invocation of each operation is followed immediately by its response (Harris).

3 Approach

Our linked list is implemented such that there is a head node to identify entry into the list and a tail node to identify the end of the list. We tested on a machine with maximum of 64 threads.

(i) coarse-grain

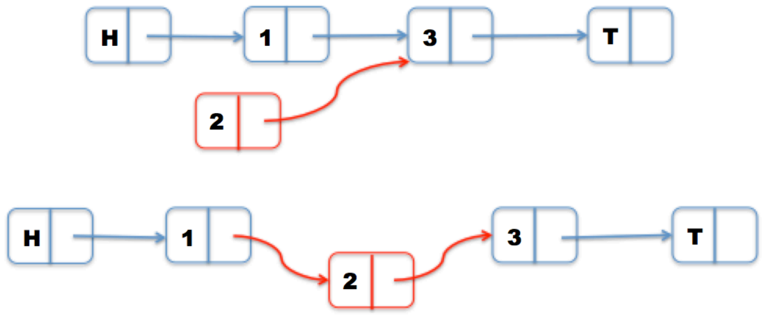
Our coarse-grain linked list was implemented with a mutex that was obtained before beginning an operation and released after.

(ii) fine-grain

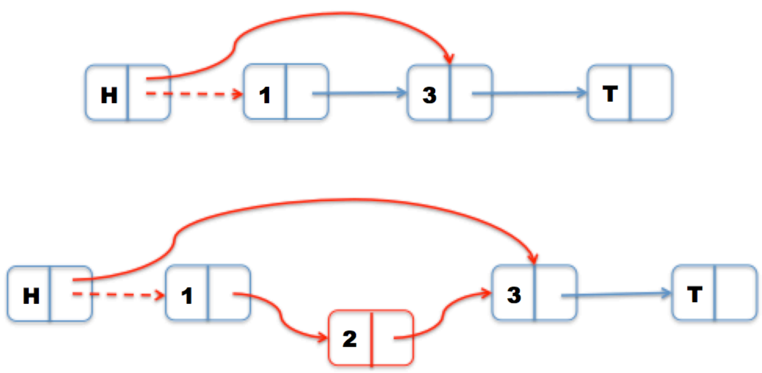
Our fine-grain linked list was implemented with hand-over-hand locking, where each list node included its own spinlock.

(iii) lock-free

We followed Harris' paper to implement a non-blocking linked-list, which guarantees system-wide progress. This means that even if some threads stop completely, the other threads will continue and maintain progress of the task.

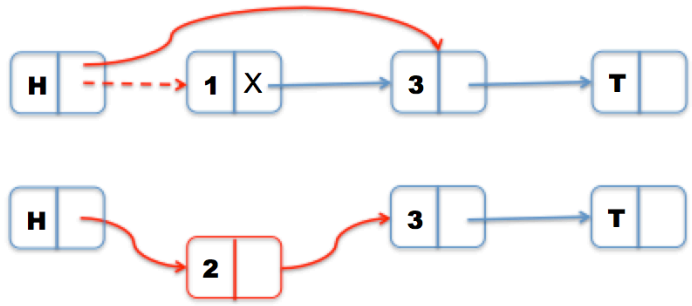


Insertion is pretty trivial. We simply find the appropriate spot for the inserted node (using a search function that finds the left and right nodes), and perform a compare and swap on the next field of the left node. This guarantees that no other thread has intercepted and changed the successor of left node. We use gcc's `__sync_bool_compare_and_swap` to atomically check that values are what we'd expect them to be.



Deletion is more complicated, however, so we can't use the same logic we would use in the sequential implementation of a linked list. Consider an example where we try to delete Node 1. Naively, we would just swing the head's next pointer to Node 3 using compare and swap. But if we concurrently insert Node 2, then our single compare and swap won't detect that a node has been inserted between Node 1 and Node 3. Thus, we would lose Node 2 when we delete Node 1.

Instead, as Harris proposes, we use two compare and swaps—the first logically deletes the node and the second physically deletes the node. We know a node is logically deleted if it is marked, meaning that its **next** field is marked. Since pointers in C++ are four-byte aligned, the last two bits of an address are unused. This means that we are free to change the last bit to a 1 to signal that it is "marked" and leave it as a 0 to signal that it is "unmarked." Even if an address has a 1, we can still access it in its unmarked state and traverse through the linked list normally.



Now, if Node 2 is being inserted while Node 1 is in the process of being deleted, Node 2 will see that Node 1 is logically deleted and physically delete Node 1 before inserting itself. Deletion was more troublesome to implement than insertion and we had a segfault in our code, which turned out to be because of a bad memory access. Marked fields give us addresses that don't make sense, so it's important to be careful with getting the correct unmarked form.

Harris' paper has a proof of correctness so we just assumed the algorithm we used is correct. Harris' algorithm, however, doesn't solve the "ABA problem."

We examined David Stolp's "Common Pitfalls in Writing Lock-Free Algorithms," which showed that a lock-free implementation of a stack with sleeps both increased throughput and decreased processor utilization. We wanted to try including sleeps in our lock-free linked list, but we didn't have time.

(iv) test suite

We wrote a python script that renders various trace files that test different use cases with defined behavior. For example, we test our linked lists on a large number of consecutive insertions, random insertions on a predefined range of values, alternating between a large block of insertions followed by a large block of deletions, and alternating between inserting at the beginning and end of the list. Each trace file was run on our three linked lists, as well as a basic sequential linked list. Performance time is measured using CycleTimer.h, where the total time is the sum of the time it takes to complete each operation. We used OpenMP to assign threads the appropriate work.

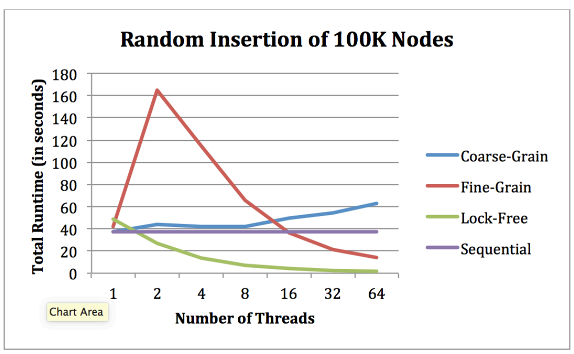
To test for correctness of our implementations, we compared the results obtained from various trace files on our fine-grain, coarse-grain, and lock-free lists using multiple threads against the results obtained from our sequential list. The behavior of multiple threads is undefined, which is to say that inserting Node x before removing Node x would give different results than vice versa. To account for this, we created trace files where each group of n operations (where n is the number of threads) would never include inserting and removing the same node if a node of the same value didn't already exist in the list. We used a barrier-like mechanism to do this. All threads must finish their appropriate work in a chunk of operations (chunk size is equal to number of threads) before moving on to the next chunk of the trace file. Our requirement for correctness was just that a resulting linked list has the same nodes in the same order as the sequential linked list.

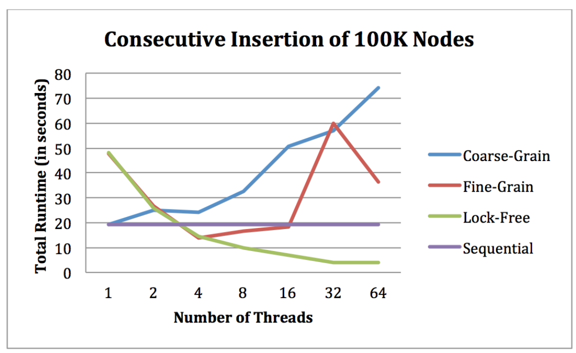
To test for performance we tried to come up with as many types of test cases as possible, some of which are described above. We tested each trace on various numbers of threads (up to 64 threads) in intervals of powers of 2.

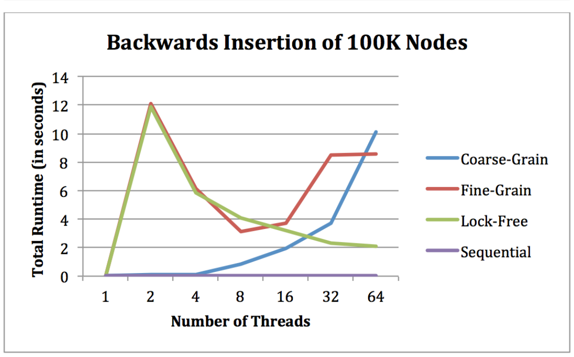
4 Results

We found that our lock-free linked list doesn't perform as well as our other implementations at small thread counts. We suspect that this is due to the overhead incurred by the compare and swap. However, at high thread counts our lock-free implementation performs really well.

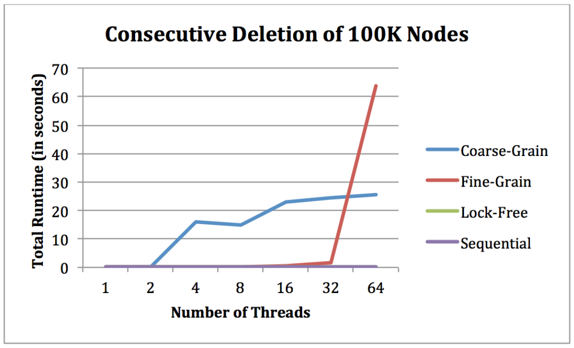
For our tests on insertions, we inserted 100,000 nodes in three ways: randomly, consecutively, and backwards. The lock-free implementation for consecutive and backwards inserts performed almost the same as the fine-grained implementation for 1-4 threads and started to significantly improve after 8 threads while the fine-grained got worse. The fine-grained implementation peaked at 32 threads for both of these tests. For random insertions, our lock-free implementation performed the best at all threads counts.

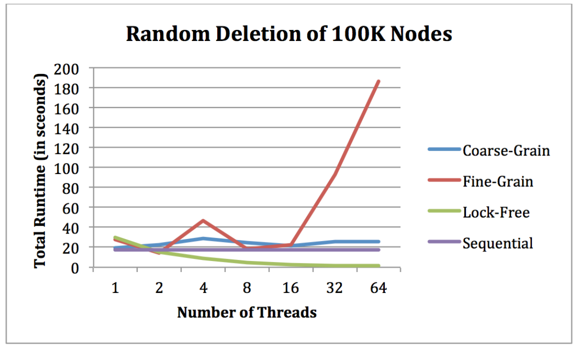


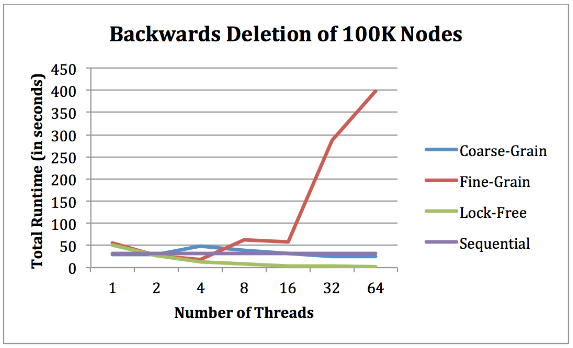




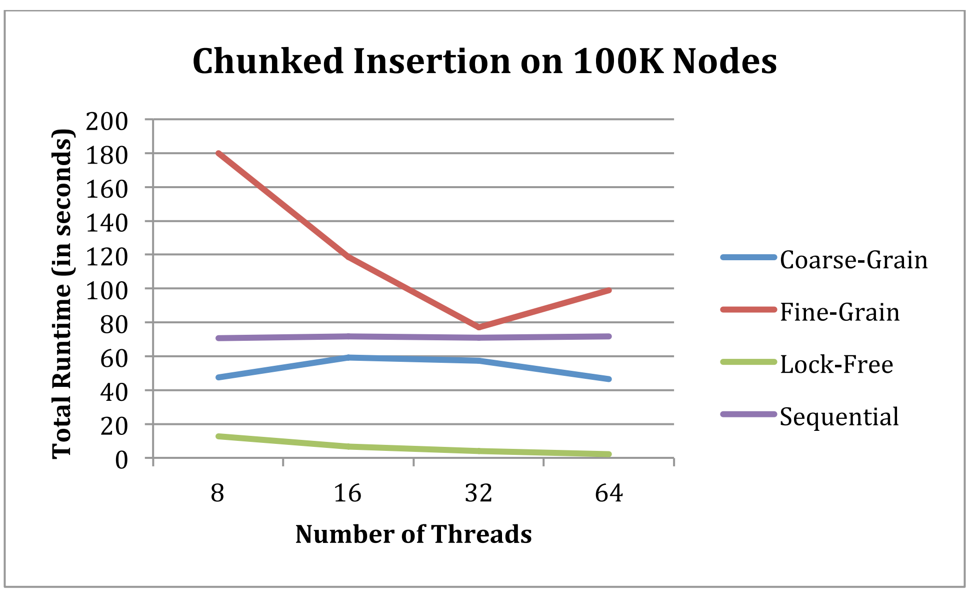
For our tests on deletions, we started with a linked list with 100,000 preexisting nodes (with values from 0 to 99999) and removed 100,000 nodes in the same three ways as we did for insertion (randomly, consecutively, and backwards.) Again, our lock-free implementation performed the best in all cases, and the fine-grained implementation significantly worsened at 32 and 64 threads.

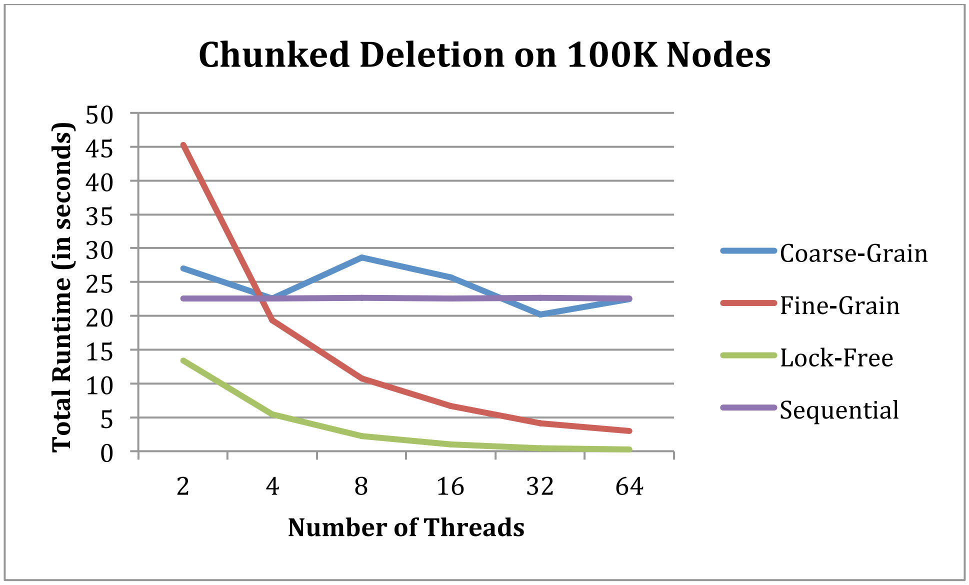




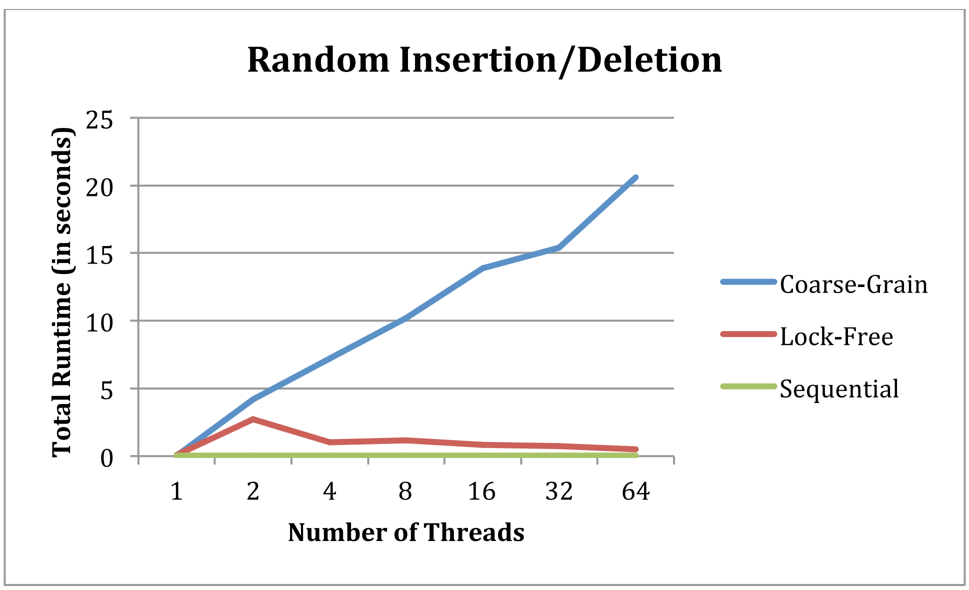


These tests were done only on multiple threads, so the single thread is not included in these graphs. For NUM_THREAD threads, we segmented the linked list into NUM_THREAD chunks, such that each thread would work only on its own segment at any given point. We performed insertions and deletions on a linked list with 100,000 preexisting nodes once again. We believe that this use case most clearly demonstrated the efficiency of our lock-free implementation because it benefits most from parallelism.





Our last test case was a trace file with random insertions and deletions, where there were 100,000 operations in total. We omitted the fine-grained linked list from this test, since it took an incredibly long time and we didn't want to wait for it to complete. For various NUM_THREADS values, lock-free didn't perform as well as the sequential implementation but came closer as NUM_THREADS increased.



We wanted to run on the latedays machines, but it was too inconvenient to learn how to compile in the specific way required.

5 References

http://www.contrib.andrew.cmu.edu/~sgbowen/15418/writeup.pdf
https://timharris.uk/papers/2001-disc.pdf

http://www.cs.rochester.edu/~scott/papers/1996_PODC_queues.pdf
http://blog.memsql.com/common-pitfalls-in-writing-lock-free-algorithms/
http://www.drdobbs.com/lock-free-data-structures/184401865

6 List of Work

We each divided the work equally.