Lock-Free Programming

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Update on December 12, 2023

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Part I

Theory

Chapter 1

Locks and Mutual Exclusion

Contents

1.1 Critical Sections

Definition 1.1 (Mutual exclusion property)**.** When only one thread executes at the same time.

Definition 1.2 (Critical section)**.** A block of code that must be executed under *mutual exclusion* among threads in order to guarantee program correctness.

If multiple threads interleave when executing a critical section, the program may fail. The standard way of securing mutual exclusion for a critical section is through the use of a `Lock`.

```
template <typename T>
concept LockConcept = requires (T t)
{
    { t.lock() };
    { t.unlock() };
};
```

Code 1: The Lock interface, using C++ 20 concepts.

We can evaluate the "goodness" of a `Lock` algorithm using the following three properties.

1. **Mutual Exclusion**
2. **Deadlock-free:** "If one or more threads try to acquire the lock, then some thread will succeed". Equivalently we can say "if there is a thread trying to acquire the lock, then it is not the case that no one gets it."
3. **Starvation-free:** "If a given thread tries to acquire the lock, then that thread will get the lock eventually". Equivalently, we can say "every call to `lock()` eventually returns".

Corollary 1.1. *L is a starvation-free lock* $\Rightarrow$ *L is a deadlock-free lock.*

It is worth pointing out that a program that uses only deadlock-free locks may still deadlock. TODO: give example.

1.2 2-Thread Locks

Let us progressively build a starvation-free lock for two threads.

1.2.1 Mutually exclusive, but deadlocks in concurrent lock() calls.

As a first (unsuccessful) attempt, consider an algorithm where the lock maintains one flag for each of the two threads. Thus, a thread sets its flag to true whenever it wants to acquire the lock; so a thread blocks while the other thread has the lock.

```
class BadTwoThreadedLock
{
public:
    void lock() {
        int this_thread_id = ThreadID.get();  // either 0 or 1
        int other_thread_id = 1 - this_thread_id;

        interested[this_thread_id] = true;
        while (interested[other_thread_id]) {}
    }

    void unlock() {
        int this_thread_id = ThreadID.get();
        interested[this_thread_id] = false;
    }

private:
    bool interested[2] = {false, false};
};
static_assert(LockConcept<BadTwoThreadedLock>);
```

Code 2: Simple but incorrect two threaded lock.

Let us evaluate `BadTwoThreadedLock`:

1. Does `BadTwoThreadedLock` satisfy mutual exclusion? Yes, proof left as an exercise to the reader.
2. Is `BadTwoThreadedLock` deadlock-free? No. If two threads call `lock()` at the same time, it may deadlock:
    - Thread-0 sets its own flag to true.
    - Thread-1 sets its own flag to true.
    - Thread-0 reads Thread-1's flag to be true, so it spins in the while loop.
    - Thread-1 reads Thread-0's flag to be true, so it spins in the while loop.

- `BadTwoThreadedLock` is in deadlock.

3. Is `BadTwoThreadedLock` starvation-free? No. Since it isn't deadlock-free, then it isn't starvation-free, by contrapositive of Corollary 1.1.

1.2.2 Mutually exclusive, but deadlocks in sequential lock() calls.

As a second (unsuccessful) attempt let's try to fix our first attempt; namely, let's make a lock that does not deadlock if two threads call `lock()` at the same time. This can be achieved via the following simple algorithm: when a thread wants to acquire the lock, it will first let the other thread acquire it.

```
class AnotherBadTwoThreadedLock
{
public:
    void lock() {
        int this_thread_id = ThreadID.get();
        waiter = this_thread_id;
        while (waiter == this_thread_id) {}
    }

    void unlock() {}

private:
    int waiter;
};
static_assert(LockConcept<BadTwoThreadedLock>);
```

Code 3: Another simple but incorrect two threaded lock.

Clearly, `AnotherBadTwoThreadedLock` satisfies mutual exclusion. However, it is not deadlock-free (so it also isn't starvation-free). Why? Think about what happens if only Thread-0 tries to acquire the lock and Thread-1 never does: it will wait forever to let Thread-1 go first. But this violates deadlock-freedom, since there is someone trying to acquire the lock but no one gets it.

1.2.3 Peterson Lock: a two-threaded starvation-free algorithm

Third time is the charm, so if we combine the ideas of our first two attempts we arrive at a starvation-free lock called the **Peterson Lock**.

```
class PetersonNaive {
public:
    void lock() {
        int thisID = ThreadID.get();  // either 0 or 1
        int otherID = 1 - thisID;

        interested[thisID] = true;
        waiter = thisID;
```

```
        while (interested[otherID] && waiter == thisID) {}
    }

    void unlock() {
        int thisID = std::this_thread::get_id() == firstThread.load();
        interested[thisID] = false;
    }

private:
    bool interested[2] = {false, false};
    int waiter{-1};
};
static_assert(LockConcept<PetersonNaive>);
```

Code 4: A simple, starvation-free lock algorithm. It also happens to be incorrect, since memory accesses are not sequentially consistent. See Exercise 1.3

Claim 1.1. *Peterson's Algorithm satisfies mutual exclusion.*

Proof. Left as an exercise to the reader. Hint: by contradiction. □

Claim 1.2. *Peterson's Lock is a starvation-free lock.*

Proof. Left as an exercise to the reader. Hint: by contradiction. □

Claim 1.3. *Peterson's Lock is a deadlock-free lock.*

Proof. Follows immediately from the fact that it is a starvation-free lock. □

1.3 Lamport's Bakery Algorithm: a fair, N-threaded lock

1.3.1 Fairness in locks

Informally speaking, a lock could be considered fair if it is first-come-first-served. Somewhat more precisely, if thread A calls `lock()` before thread B does, then thread A should enter the critical section before thread B. Let us formalize this notion.

First, some mathematical formalisms. Any call to `lock()` consists of two execution time intervals:

1. A doorway interval, whose execution consists of a bounded number of steps.

2. A waiting interval, whose execution may consist of an unbounded number of steps.

Now, we are ready to formally define fairness.

Definition 1.3 (First-come-first-served)**.** Consider two threads, A and B. A lock that is first-come-first-served guarantees that:

if A's doorway interval precedes B's doorway interval, then A's critical section interval precedes B's critical section interval.

1.3.2 Bakery Algorithm

Suppose there is a bakery. Whenever a client comes in, he takes a number. The next client to be served is the one with the lowest number that hasn't yet been served.

We can implement an n-threaded lock algorithm using the idea of the bakery. `interested[i]` is a flag indicating if thread i wants to acquire the lock, and `label[i]` is a number showing the relative order when threads first expressed interest in acquiring the lock. `label[i]` is assigned in two steps: scanning all previous labels, and incrementing the maximum by one. Note that, due to execution interleaving, ties are possible: multiple threads may end up with the same label. In such cases, ties are broken by deferring to the thread with lowest id.

```
class BakeryLock
{
public:
    BakeryLock(int num_threads) {
        n = num_threads;
        for (int i = 0; i < n; i++) {
            interested.push_back(false);
            label.push_back(0);
        }
    }

    void lock() {
        int this_thread = ThreadID.get();

        interested[this_thread] = true;
        label[this_thread] = max(label) + 1;

        // spin while there is another thread that is interested in
        // acquiring the lock AND arrived before this thread.
        while ((THERE EXISTS other_thread != this_thread) SUCH THAT
            (
                interested[other_thread] &&
                (
                    label[other_thread] < label[this_thread] ||
                    (
                        // break tie when two threads have same label
                        label[other_thread] == label[this_thread] && (other_thread < this_thread
                    )
                )
            )) {}

    void unlock() {
        interested[ThreadID.get()] = false;
    }

private:
    int n;
    std::vector<bool> interested;
```

```
    std::vector<bool> label;
};
static_assert(LockConcept<BakeryLock>);
```

Code 5: Pseudo-code for the simplest, best-known, starvation-free n-thread lock algorithm.

1.4 Theory digression

1.4.1 Bounded Timestamps

Note that the timestamps (labels) used in the Bakery Algorithm grow without a bound. This motivates the fundamental question: can we place a bound on the number of timestamps needed for a n-threaded deadlock-free lock algorithm?

Think about the two-threaded case. This can be achieved using three timestamps: 0,1,2 (as long as we agree that 2 comes before 0 and timestamps are consecutive). This notion can be generalized to the n-threaded case.

1.4.2 Lower Bounds on the Number of Read/Write Locations

Note that the Bakery algorithm requires reading and writing from $O(n)$ distinct locations, where n is the maximum number of concurrent threads. This motivates the following question: is there a clever lock algorithm, based solely on reading and writing memory, that avoids this overhead?

The answer is no. Any deadlock-free lock algorithm requires allocating and then reading or writing at least n distinct locations in the worst case. What does this mean for the design of modern multiprocessor machines? That we need synchronization operations stronger than read/write, and use them as the basis of our mutual exclusion algorithms.

The other important question is why this lower bound on the number of read/write locations an "immutable fact of nature"? The answer is based on the principle that any memory location written to by one thread may be overwritten without any other thread ever seeing it.

1.5 Algorithm

1.6 Exercises

Exercise 1.1. **(Herlihy & Shavit Chapter 2 Exercise #12)**

Solution. TODO check this answer.

Achieves mutual exclusion, but is not deadlock-free or starvation-free. □

Exercise 1.2. **(Herlihy & Shavit Chapter 2 Exercise #15)**

Solution. The `FastPath` lock does NOT satisfy the mutual exclusion property.

Consider two threads contending for the lock (calling `lock()` at the same time). Then the following interleaving may happen:

- Thread-0 sets $x \leftarrow 0$
- Thread-1 sets $x \leftarrow 1$
- Thread-0 reads $y == -1$ so it does not spin on the first while loop.
- Thread-1 also reads $y == -1$ so it also does not spin on the first while loop.

- Thread-0 sets $y \leftarrow 0$
- Thread-0 reads $x == 1$, so it enters IF statement, calls `lock.lock()`, and enters its critical section.
- Thread-1 sets $y \leftarrow 1$, reads $x == 1$, so it does not go inside the IF statement, and enters its own critical section.
- Both threads are in the critical section at the same time.

□

Exercise 1.3. Fixing the Peterson Lock implementation, see Code 1.2.3.

1. Write a program that consists of two threads. Each increments a shared counter, say half-a-million times, using the Peterson Lock for mutual exclusion. Does the shared counter add up to a million, as expected?
2. Explain what went wrong with Part 1.
3. Fix Part 1, the counter should be exactly one million.

Solution.
```
#include "Peterson.hpp"

int main() {
    int counter = 0;
    PetersonGood mutex;

    auto f = [&mutex, &counter]() {
        for (int i = 0; i < 500000; i++) {
            mutex.lock();
            counter++;
            mutex.unlock();
        }
    };

    std::thread thread1(f);
    std::thread thread2(f);

    thread1.join();
    thread2.join();

    std::cout << "Final result: " << counter <<  std::endl;
    return 0;
}
```
The counter adds up to around 970,000 but does not reach a million.

The problem is that memory accesses are not sequentially consistent, which causes access to the shared counter not to be mutually exclusive. Suppose the lines `interested[thisID] = true;` and `waiter = thisID;` were flipped. Then imagine the following interleaving:

- Thread B writes `waiter = B`
- Thread A writes `waiter = A`
- Thread A writes `interested[A] = true`
- Thread A reads `interested[B] = false`

- Thread A enters critical section.
- Thread B writes `interested[B] = true`
- Thread B reads `interested[A] = true`, but then also reads `waiter = A`.
- Thread B enters critical section before A has left it.

To avoid the memory accesses from being reordered, we can implement the Peterson Lock in the following way, and the counter does add up to a million.

```
class PetersonGood {
public:
    void lock() {
        std::thread::id currThreadID = std::this_thread::get_id();

        // mark first thread to acquire lock
        std::thread::id defaultID = std::thread::id();
        if (firstThread.compare_exchange_strong(defaultID,
                                                currThreadID,
                                                std::memory_order_seq_cst,
                                                std::memory_order_seq_cst)) {
            std::cout << "FIRST THREAD: " << firstThread << std::endl;
        }

        int thisID = currThreadID == firstThread.load();
        int otherID = 1 - thisID;
        interested[thisID].store(true);
        waiter.store(thisID);
        while (interested[otherID].load() && waiter.load() == thisID) {}
    }

    void unlock() {
        int thisID = std::this_thread::get_id() == firstThread.load();
        interested[thisID].store(false);
    }

private:
    std::atomic_bool interested[2] = {false, false};
    std::atomic_int8_t waiter{-1};
    std::atomic<std::thread::id> firstThread;
};
static_assert(LockConcept<PetersonGood>);
```

□

Chapter 2

Concurrent Objects

Contents

2.1 Concurrency and Correctness

2.1.1 Quiescent Consistency

2.1.2 Sequential Consistency

Think about the intuitive notion for sequential consistency in a single-threaded application: if the program defines a sequence of instructions a, b, c (called program order), then the order in which the instructions should be executed is a, b, c. This notion can be extended to multi-threaded applications.

Definition 2.1 (Sequential consistency in multi-threaded programs)**.** A sequentially consistent multi-threaded program is one where the program order of each individual thread is preserved.

Informally speaking, method calls of sequentially consistent objects may be re-ordered as long as the program order of every thread is preserved.

Note the (perhaps counter-intuitive) fact that sequential consistency allows for two calls from different threads that do not overlap to be re-ordered. This means that sequential consistency does not necessarily respect real-time ordering. This can be one motivation to introduce the stronger notion of Linearizability.

Lemma 2.1. *Sequential consistency is a non-blocking correctness condition, because for every pending invocation of a total method, there exists a sequentially consistent response.*

Lemma 2.2. *In general, composing multiple sequentially consistent objects does not result in a sequentially consistent system.*

2.1.3 Memory accesses are NOT sequentially consistent in modern multiprocessor architectures.

The order in which your code reads and writes memory is not necessarily the exact order in which memory ends up being actually read from or written to. This is the result of optimization tricks done by both the

CPU and the compiler. While these reorderings are invisible in single-threaded programs, they may result in unexpected behavior in multi-threaded programs.

Consider a two-threaded program with two variables initialized to $x \leftarrow 0$ and $y \leftarrow 0$.

```
# Thread 1
x = 42
y = 1

# Thread 2
while y == 0:
    continue
print x
```

Code 6: Pseudo-code for a two-threaded program. If the x,y variables were accessed in sequentially consistent order, the printed output should be 42. However, if thread 1's instructions are re-ordered, then there is an interleaving where the printed output is 0.

Why are memory accesses re-ordered, in the first place? Think about it from the perspective of multi-processor architectural design. When a processor writes to a variable, that change is reflected in the cache but eventually it must be reflected on main memory as well. The first option is that any writes done in one processor's cache is immediately applied to main memory as well. A better option (used in practice) is to temporarily queue them up in a *store buffer* (or *write buffer*); this provides at least two key benefits: writes to different addresses can be batched together and applied at once in a single trip to main memory, and multiple writes to the same address can be absorbed into one.

When you need sequential consistency, one option is to use *memory barriers* (or *fences*), which are CPU instructions that flush out write buffers. They can be expensive, though, using at least 10^2 cycles.

2.1.4 Linearizability

Definition 2.2 (Linearizability)**.** A *linearizable* concurrent object is one in which every call appears to happen instantaneously sometime between the invocation and response.

Lemma 2.3. *Linearizability is compositional: the result of composing linearizable objects is linearizable.*

Informally speaking, method calls of different threads can only be re-ordered if they are concurrent.

Lemma 2.4. *Linearizability* $\Rightarrow$ *sequential consistency.*

2.2 Concurrency and Progress

Fact 2.1. Unexpected thread delays are common in multiprocessors:

- A cache miss delays a processor for 10^2 cycles.
- A page fault delays a processor for 10^6 cycles.
- Preemption delays a processor for 10^8 cycles.

Definition 2.3 (Wait-free algorithm)**.** is one where every call finishes in a finite number of steps.

Definition 2.4 (Lock-free algorithm)**.** is one that guarantees that infinitely often some thread finishes in a finite number of steps. Note that this allows for some threads to starve.

Definition 2.5 (Obstruction-free algorithm)**.** It guarantees that when a thread executes in isolation it finishes in a finite number of steps.

Lemma 2.5. *Wait-free ⇒ lock-free ⇒ obstruction-free.*

2.3 The C++ Memory Model

A memory model describes the interactions of threads through memory and their shared use of the data.

2.4 A Wait-Free, Sequentially Consistent, Single-Producer-Single-Consumer Ring Buffer

---

```
#include <memory>  // unique_ptr
#include <atomic>

template <typename T>
class SPSCqueue
{
public:
    SPSCqueue(int capacity)
    : capacity_{capacity},
      head_{0},
      tail_{0}
    {
        ringBuffer_ = std::make_unique<T[]>(capacity);
    }

    void enqueue(T v) {
        if (tail_.load(std::memory_order_seq_cst) - head.load(std::memory_order_seq_cst) == capa
            throw std::exception("FullException");
        }
        int tail = tail_.load(std::memory_order_seq_cst);
        ringBuffer_[tail] = v;
        tail_.store((tail+1) % capacity_, std::memory_order_seq_cst);
        return;
    }

    T dequeue() {
        if (tail_.load(std::memory_order_seq_cst) == head.load(std::memory_order_seq_cst)) {
            throw std::exception("EmptyException");
        }

        int head = head_.load(std::memory_order_seq_cst);
        T v = ringBuffer_[head];
```

```
        head_.store((head+1) % capacity_, std::memory_order_seq_cst);
        return v;
    }

private:
    int capacity_;
    std::atomic_int head_;
    std::atomic_int tail_;
    std::unique_ptr<T[]> ringBuffer_;
};
```

Code 7: False sharing prevention isn't implemented. Looser memory ordering semantics can be used.

Part II

Practice

Chapter 3

Spin Locks and Contention

Contents

3.1 Peterson revisited

Recall the `PetersonNaive` 2-threaded starvation-free lock algorithm introduced in Section 1.2.3. It doesn't work in practice, despite our proof of correctness. To show this, consider the following experiment (in code block 3.1): write a simple program where two threads repeatedly acquire the `PetersonNaive` lock, increment a shared counter, and release the lock. If each thread does this acquire-increment-release process, say 500,000 times, then the counter should read 1,000,000 at the end. Let's see what happens in practice.

```
#include "Peterson.hpp"

int main() {
    int counter = 0;
    PetersonNaive mutex;

    auto f = [&mutex, &counter]() {
        for (int i = 0; i < 500000; i++) {
            mutex.lock();
            counter++;
            mutex.unlock();
        }
    };

    std::thread thread1(f);
    std::thread thread2(f);

    thread1.join();
```

```
    thread2.join();

    std::cout << "Final result: " << counter <<  std::endl;
    return 0;
}
```

Code 8: If PetersonNaive provided mutual exclusion as expected, then the output should be 1000000. However, I got 988,495 (exact output may vary from run to run).

3.2 Test-and-Set operation

One of the most basic *read-modify-write* (RMW) operations is test-and-set. It was the principal synchronization instruction used in the earlier multiprocessor architectures.

Algorithm 3.2.1: Test-and-Set operation. All of the following instructions occur in a single atomic step.

input : Binary value x
output: Binary value

```
1 t ← x;
2 x ← TRUE;
3 return t;
```

A (slightly) more general RMW operation is compare-and-swap

Algorithm 3.2.2: Compare-and-swap operation. Also referred to as compare-and-set and compare-exchange

input : A pointer p, an expected value e, a new value v
output: Boolean

```
// Performs the following atomically
1 if *p == e then
2 |   *p ← v;
3 |   return TRUE;
4 else
5 |   return FALSE;
6 .
```

From a x86 compiler perspective:
`cmpxchg src, dst` becomes `Movq e, %eax`

- Check if `%eax` contains the expected value.
  - If so, set the ZF-bit in EFLAGS and put `src` into `dst`
  - otherwise, put `dst` into `%eax`

Implementing a spin lock using the test-and-set operation

Declare a binary `flag` field that is set to true if and only if the lock is currently held by some thread. Then the `lock()` method would call `testAndSet(flag)` in a loop, and break once the return value is FALSE. The `unlock()` method simply `set(flag, FALSE)`. See Code 6 for an implementation.

```
#include <atomic>

class TASlock
{
public:
    void lock() {
        while (flag.exchange(true)) {}
    }

    void unlock() {
        flag.store(false);
    }

private:
    std::atomic_bool flag{false};
};
```

Code 9: Implementing a lock based on the test-and-set operation.

3.3 Array-based Locks

What is the main shortcoming of the `TTASlock`? It has excess *cache-coherence traffic*.

Definition 3.1 (Cache-coherence traffic)**.** Consider multiple threads reading from a shared location, each having a locally cached copy of the value. Suppose the value at that shared location changes. That means the locally cached copy of each thread has become *invalidated*. Thus, all threads must reload the value from memory into their cache.

Thus, one way to implement a better-performing spin lock is *local spinning*, where each thread spins on a different location. We can do this with an array-based lock.

3.3.1 Array-based Lock

The algorithm is simple. `ALock` has a boolean array `ready` with one entry for each thread. It has a shared counter `tail` specifying the index of the last entry in the queue. Each thread will get a *thread-local* "slot" number, which the thread will use to index into the boolean array. A thread is allowed to enter its critical section when `ready[slot]` == TRUE.

```
#ifndef ALOCK_HPP
#define ALOCK_HPP

#include <atomic>
```

```
#define MAX_NO_THREADS 8

class ALock {
public:
    ALock() {
        ready[0] = true;
    }

    /* Return's the slot acquired by the caller. Caller must
     * pass the returned 'slot' value to the corresponding unlock call. */
    int lock() {
        int slot = (tail++) % MAX_NO_THREADS;
        while (!ready[slot]) {}
        return slot;
    }

    void unlock(const int slot) {
        ready[slot] = false;
        ready[(slot+1) % MAX_NO_THREADS] = true;
    }

private:
    bool ready[MAX_NO_THREADS];
    std::atomic_int tail{0};
};

#endif
```

Code 10: An array-based lock implementation. Note how the interface changes slightly, and is specific to the implementation. TODO: dig deeper if there is a better way to do it, akin to Java's thread local storage.

While `ALock` solves the problem of having *all* threads spin on the same location, we claim that the implementation of `ALock` in Code 3.3.1 allows for multiple threads to effectively spin on shared locations. The problem is *false sharing*.

TODO better explanation of false sharing, also include diagram.

Definition 3.2 (False sharing)**.** The "units" or "building blocks" of a cache are *cache lines*, which span multiple bytes. This means that when address a is loaded from memory, it is not only the byte at address a that is loaded into the cache, but all the bytes between addresses a and $a + C_s$, where C_s is the cache line size. From the computer architecture point of view, this is a sensible design since memory accesses typically exhibit $spatiallocality$, namely that when a memory address is accessed it is likely that neighboring addresses will also be accessed next. However, this design choice allows for the possibility of *false sharing*. As an example, consider `ALock`. Suppose the cache line size spans three entries in the `ready` array. Imagine a situation where three threads A, B, C are contending for the lock, currently A is performing its critical section and B, C are queued; then the array is `ready`$= t, f, f$. Then A releases the lock, changing the array to `ready`$=f, t, f$. In principle, only B's cache entry should have been invalidated because `ready[B]` changed but not `ready[C]`. However, because both `ready[B]` and `ready[C]` fall into the same cache line, from C's point of view, its entry was invalidated, it was forced to reload `ready[C]` into the cache, only to find the actual value unchanged.

```
#ifndef CACHE_AWARE_ALOCK_HPP
#define CACHE_AWARE_ALOCK_HPP

#include <new>  // std::hardware_destructive_interference_size
#include <array>
#include <atomic>
#include <iostream>

#pragma GCC diagnostic push
#pragma GCC diagnostic ignored "-Winterference-size"

#define CACHE_LINE_SIZE std::hardware_destructive_interference_size
#define MAX_NO_THREADS 8

class CacheAwareALock {
public:
    CacheAwareALock() {
       ready[0] = {true};
    }

    int lock() {
        int slot = (tail++) % MAX_NO_THREADS;
        while (!ready[slot].flag) {}
        return slot;
    }

    void unlock(const int slot) {
        ready[slot] = {false};
        ready[(slot+1) % MAX_NO_THREADS] = {true};
    }

private:
    struct alignas(CACHE_LINE_SIZE) ArrElem {
        bool flag;
    };

    std::array<ArrElem, MAX_NO_THREADS> ready;
    alignas(CACHE_LINE_SIZE) std::atomic_int tail{0};
};

#pragma GCC diagnostic pop

#endif
```

Code 11: An array-based lock implementation that avoids false sharing.

3.3.2 Details of C++ and hardware

L1 cache line size in my Mac M1 is 128 bytes. TODO: for some reason, `std::hardware_interference_size` is 256. L1 cache is 65k bytes.

3.4 Exercises

Exercise 3.1. Comparison of TAS and TTAS lock.

1. Design a short critical section (such as incrementing a counter and/or logging) that each of n threads will execute.
2. Measure the average time difference between a thread's consecutive release and next acquire. Produce performance plot, with x-axis for number of threads and y-axis for time.
3. Challenge: Count number of cache misses for each.

Solution. 1. See Code 1

```
#include "TASlock.hpp"
#include <thread>
#include <chrono>
#include <iostream>

int main(int argc, char** argv) {
    if (argc != 2) {
        std::cerr << "Expected usage: "
                  << "'./scaling_counter NUM_THREADS'" << std::endl;
    }

    int counter = 0;
    TASlock mutex;
    int num_threads = std::stoi(argv[1]);
    int work_per_thread = 1000000 / num_threads;

    auto f = [&mutex, &counter, &work_per_thread]() {
        bool firstTime = true;
        std::chrono::time_point<std::chrono::high_resolution_clock> start;
        for (int i = 0; i < work_per_thread; i++) {
            mutex.lock();
            if (firstTime) {
                firstTime = false;
            } else {
                std::chrono::time_point<std::chrono::high_resolution_clock> end =
                    std::chrono::high_resolution_clock::now();
                std::chrono::microseconds duration =
```

```
                    std::chrono::duration_cast<std::chrono::microseconds>(end-start);

                std::cout << std::this_thread::get_id() << ","
                          << i << ","
                          << duration.count() << std::endl;
            }
            counter++;
            mutex.unlock();
            start = std::chrono::high_resolution_clock::now();
        }
    };

    // CSV header
    std::cout << "thread_id,counter,time" << std::endl;

    std::thread thread1(f);
    std::thread thread2(f);
    std::thread thread3(f);
    std::thread thread4(f);
    std::thread thread5(f);
    std::thread thread6(f);
    std::thread thread7(f);
    std::thread thread8(f);

    thread1.join();
    thread2.join();
    thread3.join();
    thread4.join();
    thread5.join();
    thread6.join();
    thread7.join();
    thread8.join();

    // if concurrent accesses to counter, it may not add up to 1M
    assert(counter == 1000000);

    return 0;
}
```

---

2. See Figure 3.1

□

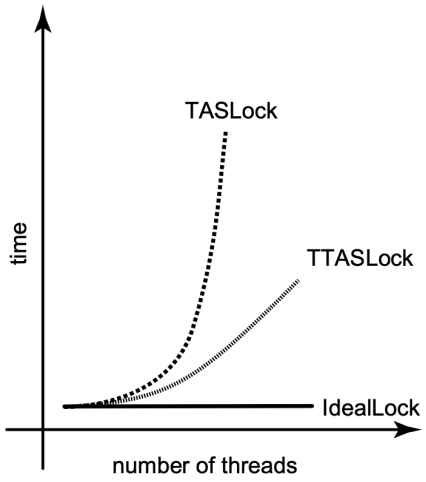
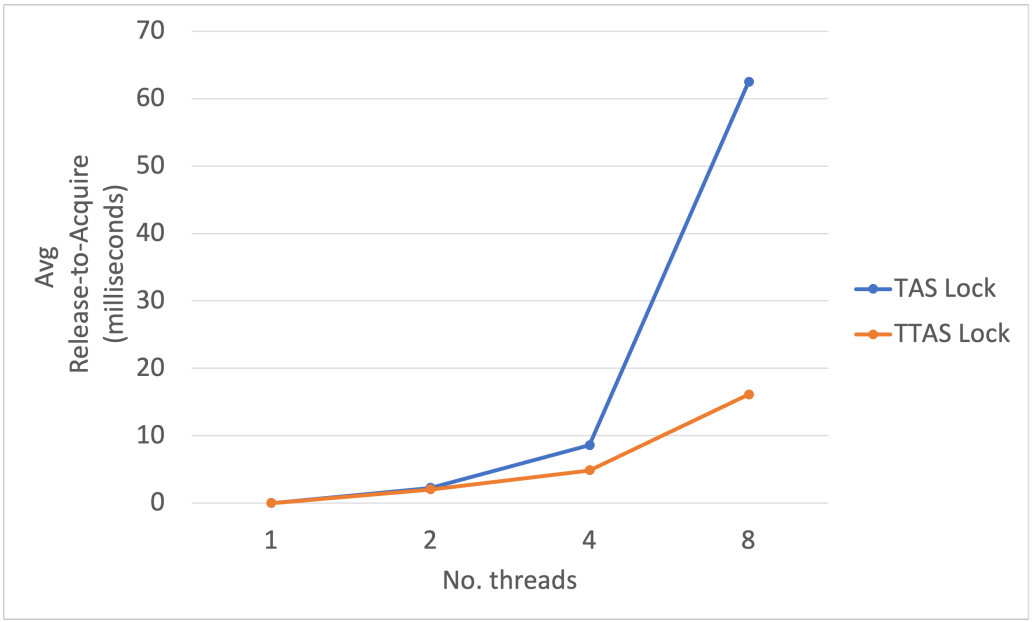


Figure 7.4 Schematic performance of a TASLock, a TTASLock, and an ideal lock with no overhead.

(a) Expected results



(b) Experimental results

Figure 3.1: Exercise 3.1 part 3

Chapter 4

Linked Lists

The problem of designing a concurrent Linked List boils down to the problem of synchronizing concurrent operations (add, remove, contains) on the list.

1. As a first idea, you can introduce a **single, global lock** that must be acquired when performing any operation.

   Problems:

   - Two distinct locations in the list cannot be modified at the same time.

2. To solve the above problem, you can **replace the single, global lock by one lock per node**. Then, performing an operation on the list consists of a hand-over-hand lock-acquiring traversal, and modifying the pred/curr nodes while locked.

   Problem:

   - Too many expensive lock acquisitions. This idea requires not only locking the pred/curr nodes being modified, but locking/releasing all the nodes in the list leading up to pred/curr while traversing.
   - If Thread T1 is modifying pred/curr, and Thread T2 wants to modify two other nodes beyond pred/curr, it won't be able to until T1 releases pred/curr and T2 can continue its hand-over-hand traversal to its target location.

3. To solve the above problems, you can **keep the one-lock-per-node but traverse without hand-over-hand locking and instead ONLY lock the two nodes pred/curr being actually modified.**

   Traversing without hand-over-hand locking comes at the price of having to traverse a second time. To see why, consider the steps in performing an operation.

   - Traverse without locking, starting from the head.
   - Lock pred/curr.

     Note that there is a small interval between when pred/curr were *found* and when they were *locked*, where any of three things could have gone wrong.

     - Another thread removed pred.
     - Another thread removed curr.
     - Another thread inserted a new node between pred/curr.
   - With pred/curr locked, check that none of the three things that could have gone wrong went wrong; otherwise, restart the operation.
     - Check that pred wasn't removed, by **traversing again from the head to pred**.

  - Check curr was not removed and that no node was inserted between pred/curr, by ensuring that pred.next == curr.

This approach only improves on the previous approach if the cost of traversing twice is less than the cost of traversing once while locking every node in the path.

Problems:

- The purpose of the second traversal is only to check that pred has not been removed. Can this same outcome be achieved without traversing twice?

4. **Every node will now have a "removed flag" in addition to a lock.**

   In a call to remove(), *before* unlinking the desired node from the list, its removed flag will be set. This means that in future calls to any operation, threads can check whether pred has been removed simply by testing its flag, rather than traversing from the head to check whether it's reachable.

   Problem:

   - Calls to contains() do not need any lock acquisitions (simply traverse to pred/curr and check that none of the possible things went wrong (listed above)). But add/remove still do need to acauire locks before modifying the nodes. Can we do without locks altogether?

5. Lock-free operations can be achieved by using an AtomicMarkableReference: if the removed flag and the next pointers can be accessed/modified atomically, then there is no need for locks.