Compact Java Monitors

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Abstract

For scope and context, the idea we’ll describe below, Compact Java Monitors, is intended as a potential replacement implementation for the “synchronized” construct in the HotSpot JVM. The readers is assumed to be familiar with current HotSpot implementation.

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1 Introduction

Compact Java Monitors (CJM) are based on the Compact NUMA-Aware Locks (CNA) algorithm, but ignoring the NUMA-Aware property and focusing on the Compact aspect. CNA is itself a variation on the gold-standard MCS (Mellor-Crummey Scott) [13] queue-based lock algorithm 1.

Underlying much of the following design is our approach from Compact NUMA-Aware Locks (CNA) which was published in EuroSys 2019 [8, 5] and is being integrated into the Linux kernel as a replacement for the existing low-level qspinlock construct [2, 11], which is itself based on MCS. CNA is itself a variation on classic MCS. One of the key ideas in CNA is propagating values of interest from the MCS owner’s queue node into the successor, which allows the lock body to remain compact – just one word. Specifically, fields that would normally appear in the body of a lock are instead maintained in the owner’s queue node and, at unlock-time, conveyed to the successor in the queue. In the context of this discussion we’re not interested in NUMA-aware aspects of CNA, where we propagate the list of remote nodes isolated on a distinct chain, but instead the fact that the lock is compact. Taken to the extreme, our design shifts all the fields that’d normally reside in the classic HotSpot objectMonitor construct into the MCS queue nodes, so we can represent the abstract monitor with just a single pointer to the MCS tail.

1 If you’re unfamiliar with MCS, please see the appendix for a quick description.
2 Requirements for synchronized

Let's start with requirements for synchronized in Java. Taking some liberties, the API is basically lock (MONITORENTER), unlock (MONITOREXIT), wait, notify and notifyAll. As notifyAll is usually just a trivial variant of notify, we'll use the term notify to collectively refer to both flavors. For reasons I'll explain shortly, the identity hash code facility is also intimately convolved with synchronization, as they share the mark word (described below), so any subsystem redesign needs to take that into account. There are also JNI (Java Native Interface) equivalents for the above, which also need to be supported. The language demands that locking operations expressed via synchronized need to be lexically balanced. JNI locking operators, which mirror those above but are callable from C/C++, are slightly more liberal, but not to the point of any particular complication. Note that lexically balanced locking precludes such common idioms as hand-over-hand (coupled) locking. Relationally, the only way to acquire an arbitrary number of locks is via recursion, which imposes its own constraints because of stack growth. Empirically, from papers which characterize synchronization behavior, we believe that it is extremely rare for a thread to hold more than 3 distinct locks at any given time.

The unlock, notify and wait operators all require that the caller hold the lock in question, otherwise they're required to throw “Illegal Monitor State Exception”, abbreviated here as IMSX. Conceptually, you can think of Java monitors as melding a pthread condvar and mutex, but you can only use the condvar while holding that associated mutex. Recursive locking is required, so if you acquire a lock and then acquire it again, that's fine, and the JVM will track the recursion levels. (Recursive locks make sense in an object-oriented framework where some synchronized methods might call other publicly exposed synchronized accessor methods). The JIT is often able to detect recursive locking and discard the inner synchronization. JIT-based automatic inlining helps in this effort. It's also worth noting that since lock and unlock operations must be lexically paired, we can often relax the ownership check in the unlock operation. As JNI operations have not such language-level lexical constrains, we always must check ownership for JNI operations.

Our desiderata are the usual. We want good performance, which means low latency absent contention and good scaling under contention. We assume a spin-then-park waiting model, made loom-aware by omitting the spin phase as appropriate. Indefinite spinning or yielding isn't acceptable. We also need to provide wait morphing to accelerate wait/notify. Fairness is more interesting. The current implementation allows unbounded bypass. (It's worth noting that all the Java.util.Concurrent (JUC) constructs do as well, except one flavor of ReentrantLock where FIFO is explicitly selected). For loom, given that MCS

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2 There is no way to express imbalanced locking in the language itself, and the javac compiler will only emit bytecode that is balanced. Bytecode verification does not, however, require balanced locking, but the C2 JIT checks for balance, in order to assign stack slots for locking constructs, and any code that fails the balance check is banished to run in the interpreter.

3 Wait morphing is a performance optimization where notify simply moves threads from the waitset to the entryset – the MCS chain in our case – avoiding the need to immediately wake the notifyee at the point where notify executed. This avoids futile context switching where the notifyee might otherwise contend on the lock still held by the thread that called notify, and, critically, may shift expensive unpark operations – often thousands of cycles – out of the critical section. HotSpot’s current implementation provides wait morphing. The linux pthread_mutex and pthread_condvar implementation also provides wait morphing for pthread_cond_signal and pthread_cond_broadcast, when the runtime can establish that the signalling thread holds the same mutex specified by the waiter(s).
provides direct handoff, we can directly context switch the carrier thread to the successor, which usually provides good performance and responsiveness. We also care about less tangible qualities, such as simplicity. The current system is extremely complex, having evolved through accretion, which inhibits research and experimentation. Ideally, a new subsystem would be more malleable and comprehensible. In addition, the current subsystem is “marbled”[15] and tightly or overly coupled to other subsystems – disentangling such dependencies is highly desirable. We also want the lock and related structures to be compact to control footprint.

3 HotSpot : background

Briefly, HotSpot had, until recently, 3 locking modes: biased locking; stack locking; and inflated locks. Biased locking attempted to address the issue of expensive atomics. If a given lock was acquired and release repeatedly by just one thread, then, conceptually, we’d defer the unlock until contention arose at which point we’d release the lock. This optimization – which is a latency play, not a scalability improvement – made economic sense when atomics were expensive (particularly in the time of bus locking, before cache-based atomics) but changes in modern architectures have sped up CAS, etc., making biased locking obsolete and of little value. It was also complicated and made the code far more brittle. Thankfully, biased locking has been recently removed, leaving us with stack locking and inflated locks. Stack locking is typically used in uncontended operation. At the onset of contention, we’ll inflate an object and switch to inflated mode. (There are other reasons we inflate as well, but those aren’t really relevant to this discussion).

At this point we need a quick digression into the object header. In HotSpot each object has 2 header words. These words are accessible by the runtime, but not by application code. The 1st word is the so-called class pointer, which describes the type of the object. This is used for certain runtime casting checks, for garbage collection (GC) to determine the type and layout of the object for root processing, and, if necessary, it also contains information equivalent to a C++ vtable pointer. The 2nd word is the mark word, which is the focus of our interest. The mark is heavily overloaded – a single-word discriminated union, where the low-order bits act as a tag and describe what the other bits contain. The mark can variously hold the identity hashCode value, a pointer into the owner’s stack for stack locking mode, or a pointer to an inflated object monitor when in inflated state. In the latter two cases the hashCode value is said to be displaced and stored elsewhere. HotSpot assigns hashCodes on-demand, lazily, but once a hashCode is assigned to an object, the relationship must be stable and permanent for the lifetime of the object. It’s worth noting that the object header format is not dictated in any specifications and is at the whim of the implementer. The heavily overloaded and multiplexed mark word is a HotSpot-specific design decision. Since every object in the heap has a header, there’s pressure to keep the header size as small as possible.

Back to synchronization, the stack locking mode isn’t particularly interesting except to say that it adds complication and clutter, requiring triage of the mark word low-order bits and requiring the ability to shift from stack locked to inflated state upon contention. When inflated, the high order bits of the mark point directly to a native C++ objectMonitor structure. The objectMonitor, or simply “monitor” or “fat lock”, contains a lock; the identity of the owning thread, if any; recursion level; waitset pointer; a back-pointer to the
associated object; and a list of threads waiting on entry. An objectMonitor can be referred to and be associated with at most object at any given time.

Until recently, in HotSpot, once an object was inflated, it would stay inflated until at least the next safepoint. That is, the relationship between an object was stable except at certain points. This simplified the design, as once a thread has fetched from the mark and found a pointer to an objectMonitor, it can depend on that relationship holding unless the code passes through a safepoint. In some incarnations of HotSpot, the objectMonitors resided in type-stable memory (TSM). The downside to this design is that we can suffer rampant objectMonitor accumulation. It’s not uncommon to have 10s of thousands of extant objectMonitor instances, reflecting a significant footprint. Until recently deflation only occurred only at safepoints – monitor scavenging – which is undesirable, as safepoints are driven (for the purposes of this discussion) by GC activities. Specifically, deflation at safepoints is expensive, not highly parallel, and reflects an unwanted coupling between the GC and safepoint mechanism, and the synchronization subsystem. Recent versions of HotSpot have eliminated safepoint-time monitor scavenging and deflation, and deflate outside safepoints, partially addressing the issue of monitor accretion and footprint.

### 3.1 Historical Perspective: ExactVM

It’s worth mentioning that some JVMs deflate aggressively on the “last” unlock, when there are no waiting threads. Sun’s ExactVM used this strategy. While appealing, this adds extra synchronization to avoid races between arriving threads and the deflator. Specifically, let’s say object O’s mark refers to monitor instance M. At unlock-time, the owner does not observe any contending or waiting threads and wants to deflate and retire M – severing the linkage between the mark word and M – while some other thread is concurrently arriving to lock the object and has just read that mark word in the object header and is about to follow that pointer to M. Techniques are available to either prevent or detect and recover from this race, but they all involve extra synchronization and interlocks in the fast uncontended path, impacting performance. ExactVM used a simple test-and-set bit – the metalock[1] – in the mark word that threads had to acquire when enqueuing or deflating, so ultimately, under very high concurrent lock flux, we just shifted all the queueing and contention to that bit. Also, the arrival and deflation paths were longer because of the more involved protocol on that bit.

Furthermore, with aggressive early “ASAP” deflation, common producer-consumer idioms cause monitors to flow or migrate from one set of threads to another, presenting yet another memory management challenge. To improve scalability, ExactVM allocated monitors in bulk, moving monitors from a global free list to per-thread free lists. Each time a thread needed more monitors we’d double the allocation unit size for that thread, clamped to 64K monitors, and at safepoints we’d reset the bulk reprovisioning size for each thread back to 16, and also trim those local free lists that had accumulated excessive numbers of free monitors.

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4 ExactVM’s metalock is an example of an inner lock, which protects internal locking metadata such as queues. At high arrival rates, contention on the logical outer lock results in the inner lock becoming contended and acting as a bottleneck. For instance, contention in p<code>thread_mutex_lock</code> on Linux often translates into contention and waiting on the kernel’s <code>futex</code> per-bucket chain locks.
To reduce coherence traffic on the central lock-free free list, which proved to be a bottleneck, we added a *home* field to monitors to indicate their origin and added a lock-free per-thread free list where the associated thread could push and pop, and remote threads could only push, allowing monitors that had migrated between threads to be returned to their origin. This presumes that the direction of inter-thread monitor “flow” will persist and is not random, which, empirically, seems to be the case. That is, previous outflow predicts future outflow. The extra overhead imposed by lock-free operations added latency, however, so we instead provided each thread with a purely local free list as well as a lock-free *returning* list. In the unlock operator, if a thread deflated and recovered a foreign monitor, it would use CAS to push that monitor onto the lock-free remote returning stack associated with the monitor’s home thread. To allocate a monitor for inflation in the lock operator, a thread would first check its private local free list. If the local list was empty it would then revert to the returning list, using SWAP of null to detach the set of monitors en masse, and then move that string of recovered monitors back to the local free list. Failing all the above, the thread would resort to allocation from the global pool. ExactVM did not have thin locks or stack locks, so an initial uncontended lock operation needed to allocate a monitor and inflate, so reducing the latency of allocation was critical.

See Appendix-A for a comparison on legacy HotSpot, modern HotSpot, ExactVM and CJM.

4 Compact Java Monitors : construction – simple locking

We’ll now describe, incrementally, a different approach. Initially, we’ll ignore hashCodes, and *wait/notify*, and start out with classic MCS assuming we have the whole object mark word at our disposal to serve as a pointer to the MCS tail. Note that we now forego a classic objectMonitor, replacing that construct with a chain of MCS queue nodes. MCS is frugal and parsimonious, requiring only one queue element (“node”) for each lock a thread holds and one additional node if the thread is waiting, yielding a very tight bound. A simple per-thread free list of nodes suffices, grown on-demand and implemented as stack. (More on this below). Nodes are always returned to the free list of the thread that allocated and enqued the node, avoiding rampant footprint growth or inter-thread migration, as described above. There should be no need to trim free lists. MCS also deflate aggressively when the last thread departs, but without any complex or expensive mechanisms, such as HotSpot’s current deflation sentinel approach or ExactVM’s metalock. Recursive locking is tracked with a new *nesting* field in the owner’s queue node.

We also need the ability to efficiently determine if the current thread \( T \) has locked object \( O \) to implement IMSX checks in unlock, *wait* and *notify*, and to check ownership for recursive locking, and finally we must have a way for the unlock operator to quickly find the implicit head (owner) of the MCS chain, in order to provide succession and to reclaim that node. To that end, we augment the synchronization subsystem with a per-thread associative map from objects to installed MCS queue nodes. (It’s worth noting that some MCS implementations use a non-standard lock-unlock API and simply pass the installed

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\(^5\) If the need to trim arose, the implementation is trivial and a thread-local decision. Absent trimming, a thread’s free list plus active list will contain \( N + 1 \) elements where \( N \) is the maximum number of locks held at any given time by that thread, putting a tight bound on the number of extant elements.
queued node address from the lock site to the unlock site. Other implementations preserve the usual lock-unlock API but store the owner’s queue node address in the lock body itself, to convey the address from unlock to unlock. None of those options are readily available to us in HotSpot).

In practice, our associative map can be implemented as a trivial linked list of active queue nodes, arranged as a stack rooted in thread-local storage. Active in this case means enqueued on an MCS chain. Given the stack-like nature of synchronized, absent JNI, at unlock-time, the relevant queue node will be found at the top of the stack. We expect accesses via the map to be mostly constant-time. The queue nodes need to be extended to include an object reference field to validate the association. As such, those references must be strong GC roots and scanned for any garbage collection at safepoints. While undesirable, we expect the lists to be extremely short and note that threads are already visited for root processing. We can easily integrate the per-thread lists of free queue nodes and held nodes.

5 Compact Java Monitors: construction – wait and notify

Arguably, we now have Java-style lock and unlock implemented, but the design sketched above does not support hashCode or wait/notify, so we’ll now move on to address the latter. A thread can return from wait because (a) it was notified, (b) the timeout, if any, expired, or (c) pending interrupt exceptions. In CJM, threads blocked in wait continue to be represented by the queue node they used to originally obtain the lock. The waitset of an object (monitor) is a pointer to a linked list of such waiting queue nodes, and is stored in the owner’s queue node in a distinct waitset field. Borrowing heavily from CNA, the value of this field – and thus the waitset – is propagated from the owner to the successor at at unlock-time. When a thread calls wait, it must hold the lock, in which case it adds itself to its own waitset, installs that waitset into the successor on the primary MCS chain, and passes ownership to the successor. When a thread calls notify, it simply transfers threads from the waitset to the MCS chain, appending the element(s) with a single SWAP, providing efficient wait morphing. The lock itself protects the waitset from concurrent accesses – only the current owner can access the waitset. More precisely, other than appending new threads to the MCS chain upon arrival, only the current owner can edit the MCS chain or the waitset. It’s worth noting that the waitset field is only set in the head (owner’s) queue element. Non-head elements will always have their waitset field set to null.

The case where a thread calls wait and the MCS chain is otherwise empty – no successors exist on the chain – is subtle and deserves special attention. In this circumstance we leave that waiting thread at the head of the MCS chain as a placeholder but mark its status (a field in the queue node) accordingly. Threads subsequently enqueuing on the chain via lock must inspect the predecessor’s state, and, if it was waiting, take immediate ownership of the lock and shift that predecessor, and its waitset, if any, to the new owner’s queue node waitset. We call this usurping the lock. The special placeholder state is the only circumstance where a thread blocked in wait appears resident on the primary MCS chain, and it must be the only element on the chain, except briefly, when new threads arrive.

Threads also exit wait state via interrupts or timeout, presenting a more interesting challenge. The procedure to implement notify was simple, relatively, as the waitset was protected by the lock itself and the notifying thread simply moved the notifyp from one
list to another. For interrupts and timeout, a thread will return from park and notice either the timeout or the interrupt condition and must take direct actions itself to address the situation. Assuming the thread is on the waitset (and not in special waiting state), the thread then allocates and enqueues a 2nd MCS element – which we call the beta element – onto the MCS chain to acquire ownership. The thread then waits until either the original element or the beta makes its way to the head of the MCS chain and becomes the owner, at which point the thread removes the other element from either the waitset or the primary MCS chain, and finally returns. This step, of expunging the other node, may involve traversal operations on the MCS chain, and requires waiting for the next MCS links to resolve to non-null.

6 Compact Java Monitors: construction – hashCode

To recap, at this point we have lock, unlock, wait (with interrupt and timeout support) and notify. Next on the agenda is to add identity hashCode support. We’ll employ the usual approach of a displaced mark word (DMW). We require only one tag bit for the discriminated union in the mark. The mark word encoding is 0:0 for neutral initial state, H:1 for hashed and unlocked, where H is the hashCode value and 1 indicates the least-significant bit is set, and N:0 indicates that the object is locked and N points to the tail of the MCS chain in the expected fashion. To make things simple, we assign a hashCode to an object either on the first call to hashCode or the first time we lock an object. Generating a hashCode value is cheap. We store the DMW – containing the hashCode value – in a dedicated field in the MCS queue elements, and propagate the hashCode value through all elements of the MCS chain. That is, all elements of the MCS chain will carry the same DMW (hashCode) value.

Fetching or assigning the hashCode when the mark is in 0:0 or H:1 state is trivial, and similar to the scheme HotSpot uses today. We use CAS to assign and change from 0:0 to H:1 state, if necessary. If the object is locked, however, then the protocol become more interesting. As called out above, locked implies hashed, which simplifies the design. If the object is locked by the caller, we can simply reach through the per-thread map to find the owner’s queue node and access the DMW to fetch the hashCode. (Note that I’ve ignored the mark word’s GC age bits, but we’ll assume for the moment those can be handled, effectively, as part of the hashCode).

When the object is locked by some other thread then we need to use a more involved strategy to safely retrieve the hashCode value. In a sense, we’re trying to effect a consistent read of object → mark → DMW even though the mark word is subject to concurrent flux from threads arriving and departing on the MCS chain. I’ll sketch out one crude but perfectly workable variation. We provide a global array of locks, indexed by a hash on a queue node’s virtual address. Readers of the hashCode (assuming the object is locked by another thread) will read the mark word, acquire the associated lock, validate that the mark still refers to the same object, fetch the DMW, drop the lock, and returned the fetched DMW, which must encode a hashCode value. If validation fails, we just drop the lock and loop, retrying. Complementary code acquires and immediately releases the lock when we release a queue node back to the per-thread free lists. We could also defer that action until the node actually recycles. We might also use reader-writer locks instead of simple locks but there’s likely no benefit given that we expect this case to be fairly rare.
For the purposes of explication we described a method that uses locks, but we could also use an external array of reference counts, hashed by the element address, to pin a element to allow safe reading of the hashCode. Using an external array of locks or reference counts allows us to avoid type-stable memory of the elements. The reference counts act as a simple protection counter incremented and decremented with atomic fetch-and-add. This approach is likely the better for a real implementation. Reading the hashCode is then obstruction-free and threads attempting to recycle a node would need to wait for the value to be observed as 0.

As noted above, we require that the hashCode value be propagated through the entirety of the MCS chain, via the DMW field in the queue nodes, to allow potential readers to fetch the hashCode from tail queue element. Assuming contended locking and a non-trivial chain, a thread arrives and swaps its queue node \( N \) into the MCS tail, obtaining the address of the predecessor queue node, \( P \). Before installing \( N \), the locking thread sets \( N \)'s DMW value to 0 to indicate not-yet-present. After the atomic swap, but before setting \( P \)'s forward MCS chain next pointer to refer to \( N \), the thread waits for \( P \rightarrow DWM \) to become non-0. It then propagates that value into its own \( N \rightarrow DMW \) field and finally sets \( P \rightarrow Next = N \) in the normal MCS fashion. The MCS interlock between \( N \) and \( P \) – where \( P \)'s next field is not yet set to \( N \) – is usually considered undesirable, as \( P \), when calling unlock, may need to wait for \( P \rightarrow Next \) to resolve to \( N \). We, however, leverage this property to our benefit, “freezing” \( P \) briefly by inhibiting succession so we can safely read its \( DWM \) field.

Recapping, our approach propagates and pushes the waitset forward, at unlock-time, from owner to successor. And arriving threads in the lock operator pull the DMW (hashCode) from their predecessor (or the mark word) into their MCS node. This allows the hashCode value to be read from the MCS tail element, which is referred to directly by the mark word. All the key fields that otherwise reside in a classic “fat” object monitor are now conveyed through the MCS chain. We eliminate the centralized object monitor, replacing it with the MCS chain, augmented to convey additional information.

As a brief aside, it’s worth pointing out that CJM is also amenable to designs that might use just a single object header word. See https://wiki.openjdk.java.net/display/lilliput. In this case the single 64-bit header word contains type information (an encoded reference to class metadata), the hashCode, garbage collection “age” bits, and low-order discriminated union “tag” bits that indicates if the header word is displace via synchronization activities. We expect that class information is effectively immutable.

### 6.1 Example: CJM in use

Figure-1 depicts a set of threads synchronizing on object \( A \). \( L1, E2, E3, E4, E5, W6, W7 \) are MCS waiting elements (queue nodes) augmented for CJM. Each element is contributed by a distinct thread, \( T1 \rightarrow T7 \) respectively, and resides on that thread’s active list. Eventually, those elements will cycle back to their thread’s free list. Thread \( T1 \) contributed \( L1 \), which is in \( LOCKED \) state. \( L1 \) resides at the head of the chain, thus \( T1 \) holds \( A \). \( E1, E2, E3, E4, E5 \) reside on the MCS chain and are in \( ENTRY \) state, and their associated threads are stalled waiting to acquire \( A \). \( A \)'s mark word, which encodes the MCS tail, points to \( E5 \). If a new thread arrives to acquire \( A \), it enqueues after \( E5 \) and swings the MCS tail pointer. Elements \( W6 \) and \( W7 \) represent threads stalled in \( wait \) – in \( WAITING \) state. When notified, they will be removed from the waitset and appended to the tail of the MCS chain. Notify
operates in constant time. When $T_1$ calls `unlock(A)`, the implementation locates $L_1$ via its thread-local active list, passes the waitset pointer (to $W_6$ and $W_7$) to its successor, $E_2$, and finally passes ownership to $E_2$. $E_2$‘s associated thread, $T_2$, has a thread-local active list that associates $A$ with $E_2$ (not shown). $T_1$ then removes $L_1$ from its active list and places $L_1$ on its local free list, allowing the element to be reused in future operations. These last steps execute outside and after the critical section.

7 Variations

**Hashed External Waitset**  Instead of propagating the waitset through the MCS chain, we can, instead, using the object’s hashcode, hash into a shared array of waitset bucket elements, where each bucket contains a lock and a pointer to set of MCS nodes associated with active wait operations. Hash collisions are possible, so the chain may be mixed, with elements from different objects. The bucket lock protects operations that append, remove and pop elements from the chain. This approach, which significantly simplifies the implementation of `wait`, still allows wait morphing but at the expense of incurring extra locking operations. In particular, this approach obviates the need for the beta element and the special waiting placeholder state.

**Fissile Locks Optimization**  As described above, CJM provide FIFO/FCFS succession with direct handover, by virtue of its MCS lineage. While fair, FIFO can suffer reduced throughput compared to locks that allow so-called *barging*, where departing threads release or renounce ownership and arriving threads can *pounce* on the lock and bypass threads that were already waiting. (The current HotSpot synchronized implementation, as well as, for instance, the default pthread_mutex on linux, and the default Java.util.ConcurrentReentrantLock, allow unbounded bypass with unlimited starvation). We could strike a compromise by using *Fissile Locks* which allow bounded bypass, trading improved throughput against short-term unfairness. To use Fissile locks we’d need to claim 2
additional bits in the mark word to serve as the Fissile outer lock, while the traditional MCS chain would act as the Fissile inner lock. Fissile locks configured to use MCS as the inner lock require only one MCS queue element per thread, regardless of the number of locks held. And in fact that element can be allocated on-stack as it is only needed while waiting. But for use in CJM that particular benefit of fissile locks is not available as we need the queue element to track held locks.

**Mark-free Synchronization** Ignoring the hashCode value, it’s entirely possible to implement synchronized in a fashion that completely avoids using the mark word. Instead, we hash the object’s address (or better, use its hashCode) into a table of buckets where each bucket has a lock and a chain of prime CJM MCS elements. A prime element is the nominal head of the MCS chain for a given object. Prime elements, each associated with a distinct object, form the spine of the list, and individual entrysets and waitsets are linked from each prime, as ribs.

We’ve implemented the equivalent of this approach in LD_PRELOAD libraries that interpose on the pthread synchronization primitives, and, not surprisingly, found that latency for uncontended lock and unlock increases and scalability is impacted.

If we were willing to take 2 bits from the other header word, and use the IBM 2-bit hashCode technique, putting aside the issue of GC age bits, we could eliminate the mark word, but the price to pay in reduced synchronization performance is non-trivial.

### 8 Advantages

1. Compared to the existing implementation, simpler and less code.
2. Very little coupling between safepoints, garbage collection, and the synchronization subsystem.
3. No inter-thread migration of monitors or other elements
4. Tightly bounded footprint, with no need to scavenge monitors at safepoints.
5. MCS queue elements don’t require type-stable memory providing simple lifetime and lifecycle for queue nodes.
6. FIFO fair lock admission with more predictable performance.
7. All or most of the algorithm could be transliterated to Java instead of C++, allowing a mostly-in-java implementation except for calls to native park and unpark, although some new unsafe helpers and GC accommodation would be needed to deal with the mixed-type mark word. The result may be more friendly to project loom than the current implementation. Queue elements would then become first-class Java objects.
8. Loom may benefit from succession by direct handoff.
9. Eliminates the objectMonitor construct, presenting an opportunity to remove code.
10. Eliminates stack locking mode, reducing all synchronization operations to just one flavor.
11. Simplified mark word encoding with only 1 tag bit required
12. Still provides wait morphing.

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6 This has been a long sought-after goal with attempts made in various managed runtimes. See also [https://wiki.se.oracle.com/display/JPG/Java+Object+Monitors+in+Java](https://wiki.se.oracle.com/display/JPG/Java+Object+Monitors+in+Java)
13. All state transitions are subsumed into park.
14. Uncontended performance (latency) is on par what we have with what we have in stack locking in the existing implementation.
15. Lock-unlock performance is about the same as classic MCS, as we’re not accessing any additional cache lines (no additional concurrency traffic) despite the slightly more involved paths.
16. As a stretch goal we easily adapt the lock to be NUMA-aware via CNA
17. As we’ve seen with CNA, etc, we can be quite flexible regarding the admission order, and not necessarily constrained to FIFO.
18. MCS is well understood and widely used, and CJM is really just a variation on MCS.
19. Eliminates spurious wakeups in wait.
20. No tunable performance “knobs” or opaque heuristics

9 Disadvantages

1. Expunging objectMonitors and stack locks, while an admirable long-term goal to reduce technical debt, is a heavy lift, as those constructs have tendrils everywhere. Early prototypes could leave the defunct structures in place, however. Specifically, as an interim measure, it should be possible to leave a degenerate transitional objectMonitor class in place which contains just a references to the associated object.
2. FIFO (and more generally, succession by direct handoff) provide predictable performance but throughput and scalability is generally less than that achieved by schemes that allow barging (either unbounded or bounded bypass) [9]. This reflects the classic fairness vs throughput trade-off.
3. Under preemption, FIFO performance can be problematic as we risk handover to preempted threads, stalling progress. A viable work-around is to divert excess threads not needed to maintain saturation of the lock to side lists [3, 4, 6, 7].
4. FIFO and spin-then-park waiting – with simplistic fixed bounded spin durations – don’t usually work well together, as the immediate successor is likely to have waited the longest and, for constant spin durations, thus be most likely to have already parked, impacting lock hand-over latency. This may manifest as a surprising and abrupt non-linearity in performance when the system rapidly undergoes a phase change where most successor are found to be parked. Techniques such as culling parked threads from the chain, and anticipatory wakeup can be palliative.
5. Auxiliary services such as JVMTI/DI, etc would be impacted and likely require attention.
6. It is easy to tell if the current thread \(T\) holds \(O\), but harder, given just \(O\), to determine the owner of \(O\) or if some arbitrary other thread \(S\) holds \(O\). This may impact some support code. Relatedly, on-the-fly deadlock detection is more difficult.
7. Once an implementation has switched to a FIFO it can be difficult to go back as applications may inadvertently come to depend on the admission policy. We’ve encountered producer-consumer idioms, for instance, that poll or busy-wait via a lock, and one flavor can happen to be starved out. So switching to FIFO might be a one-way transition and limit our latitude in future designs.

7 Helpful for SLAs.
8. While the algorithm proper is relatively self-contained, the changes would likely be invasive and extensive.

9. Arrivals mutate the object’s mark word, as it serves as a pointer to the MCS tail element. This may result in additional false sharing between accesses to the mark and accesses to the rest of the object.

### A Monitor deflation and inflation strategies and lifecycle

**Legacy HotSpot**
- **Inflation**: On lock contention, wait, etc. Monitors are allocated one-at-a-time from a central pool, under a lock.
- **Deflation**: Lazily at safepoint time. This policy increases safepoint durations because of the scavenging phase, which is effectively serial, and degrades overall performance. There is no natural back-pressure to trigger scavenging.
- **Migration**: None
- **Accumulation**: Rampant monitor accumulation is possible and has been observed in the wild, with associated bug reports filed. The issue of memory pressure is exacerbated by the fact that monitors reside in type-stable memory.
- **Access protocol**: Simple with no overheads as the object:monitor relationship is stable except over safepoints.
- **Lifecycle**: Threads allocate `objectMonitors` from a central pool one-at-a-time. Eventually the safepoint scavenger determines that a monitor is idle, deflates the object, and places the monitor back on the central free list.

**Modern HotSpot**
- **Inflation**: On lock contention, wait, etc. Monitors are allocated one-at-a-time from a central pool, under a lock.
- **Deflation**: Deferred. Deflation and scavenging runs outside safepoints and is performed by a dedicated `MonitorDeflationThread`, improving safepoint pause times.
- **Migration**: None
- **Accumulation**: Improved relative to Legacy HotSpot, above, as deflation and safepoints are decoupled and we can run deflation more frequently to keep the number of extant circulating monitors in check. A lingering concern is rate-mismatch between inflation, and production of idle monitors, and the system’s ability to to deflate and recover those monitors. That is, can deflation keep up with inflation.
- **Access protocol**: Complex with overheads impacting normal lock and unlock operations. Races are possible between threads trying to reach a monitor from the mark word, and concurrent deflation. Uses a `SENTINEL` protocol to detect and recover from the race.

**ExactVM**
- **Inflation**: Aggressive and early – on initial lock operation
– **Deflation:** Early – ASAP at runtime by normal mutator threads when the unlock operator detects the monitor is idle with no threads in the waitset or entryset.
– **Migration:** Vulnerable – mitigations necessary
– **Accumulation:** Constrained
– **Access protocol:** Complex with overheads impacting normal lock and unlock operations. Races are possible between threads trying to reach a monitor from the mark word, and concurrent deflation. Uses the metalock to prevent the race.

▶ CJM
– **Inflation:** Immediate – all lock operations contribute a queue element to the chain, which is recovered in the corresponding unlock operation.
– **Deflation:** ASAP
– **Migration:** None. CJM avoids imbalanced flow that can occur in other implementations, where one thread inflates and other subsequently deflates. In addition, CJM avoids the use of reference counts as there is no central per-lock structure requiring inflation or deflation.
– **Accumulation:** Minimal
– **Access protocol:** Simple
– **Remarks:** No central monitor pool or locking thereof

### B A quick overview of MCS locks

**MCS:** The *MCS lock* [13], is the usual alternative to simple test-and-set-based locks, or ticket locks, performing better under high contention, but also having a more complex path and often lagging behind simple locks under no or light contention. In MCS, arriving threads use an atomic *SWAP* operation to append an element to the tail of a linked list of waiting threads, and then busy wait on a field within that element, avoiding global spinning as found in test-and-set locks. The list forms a queue of waiting threads. The lock’s tail variable is explicit and the head – the current owner – is implicit. When the owner releases the lock it reclaims the element it originally enqueued and sets the flag in the next element, passing ownership. To convey ownership, the MCS unlock operator must identify the successor, if any, and then store to the location where the successor busy waits. The list forms a multiple-producer-single-consumer (MPSC) queue where any thread can enqueue but only the current owner can dequeue itself and pass ownership. The handover path is longer than that of test-and-set locks and accesses more distinct shared locations.

MCS uses so-called *local waiting*[10] where at most one thread is waiting on a given location at any one time. As such, an unlock operation will normally need to invalidate just one cache line – the line underlying the flag where the successor busy waits – in one remote cache. (Lock algorithms that use local spinning are also trivially easy to convert to blocking via park-unpark). Under contention, the unlock operator must fetch the address of the successor element from its own element, and then store into the flag in the successor’s element, accessing two distinct cache lines, and incurring a dependent memory access to reach the successor. Absent contention, the unlock operator uses an atomic compare-and-swap (CAS) operator to try to detach the owner’s element and set the
tail variable to null.

MCS locks provide strict FIFO order. They are also compact, with the lock body requiring just a pointer to the tail of the chain of queue elements.

One MCS queue element instance is required for each lock a thread currently holds, and an additional queue element is required while a thread is waiting on a lock. Queue elements cannot be shared concurrently and can appear on at most one queue – be associated with at most one lock – at a given time. The standard POSIX `pthread_mutex_lock` and `pthread_mutex_unlock` operators do not require scoped or lexically balanced locking. As such, queue element cannot be allocated on stack. Instead, MCS implementations that expose a standard POSIX interface will typically allocate elements from thread-local free lists, populated on demand.

The standard POSIX interface does not provide any means to pass information from a lock operation to the corresponding unlock operator. As such, the address of the MCS queue element inserted by the owner thread is usually recorded in an additional field in the lock instance so it can be conveyed to the subsequent unlock operation to identify the successor, if any. That field is protected by the lock itself and accessed within the critical section. Accesses to the field that records the owner’s queue element address may themselves generate additional coherence traffic, although some implementations may avoid such accesses to shared fields by storing the queue element address in a thread-local associative structure that maps lock addresses to the owner’s queue element address.

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8 We note that the MCS “K42” variant [12, 14] allows queue elements to be allocated on stack – they are required only while a thread waits – but at the cost of a longer path with more accesses to shared locations.
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