Queue Delegation Locking

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Abstract—The scalability of parallel programs is often bounded by the performance of synchronization mechanisms used to protect critical sections. The performance of these mechanisms is in turn determined by their sequential execution time, efficient use of hardware, and ability to avoid waiting. In this article, we describe queue delegation (QD) locking, a family of locks that both delegate critical sections and enable detaching execution. Threads delegate work to the thread currently holding the lock and are able to detach, i.e., immediately continue their execution until they need a result from a previously delegated critical section. We show how to use queue delegation to build synchronization algorithms with lower overhead and higher throughput than existing algorithms, even when critical sections need to communicate results back immediately. Experiments when using up to 64 threads to access a shared priority queue show that QD locking provides 10 times higher throughput than Pthreads mutex locks and outperforms leading delegation algorithms. Also, when mixing parallel reads with delegated write operations, QD locking outperforms competing algorithms with an advantage ranging from 9.5% up to 207% increased throughput. Last but not least, continuing execution instead of waiting for the execution of critical sections leads to increased parallelism and better scalability. As we will see, queue delegation locking uses simple building blocks whose overhead is low even in uncontended use. All these make the technique useful in a wide variety of applications.

Index Terms—Locking, Synchronization, Delegation, Detached execution, Multi-core, NUMA

1 INTRODUCTION

Lock-based synchronization is a simple way to ensure that shared data structures are always in a consistent state. Threads synchronize on a lock, and only the current holder can execute a critical section on the protected data. To be efficient, locking algorithms aim to minimize the time required to acquire and release locks when not contended and the lock handover time when locks are contended.

Queue-based locks, like MCS [28] and CLH [7], [27], try to minimize the handover time by reducing cache coherence traffic. However, these locks strictly order the waiting threads, which harms performance when thread preemption is common. Moreover, on NUMA systems MCS and CLH are outperformed by less fair locks that exploit the NUMA structure, e.g., the HBO lock [33], the hierarchical CLH lock [26] or more recently the Cohort lock [9]. These locks let threads on a particular NUMA node execute critical sections for longer periods of time without interference from threads on other nodes. This avoids expensive coherence traffic between NUMA nodes for the lock and the memory it protects, but not between the cores within a node.

In this article we focus on a different approach, which sends critical sections to the lock data structure instead of transferring the lock. This way, a single thread can execute multiple critical sections without transferring the data between caches of different cores or NUMA nodes. This locking approach is called delegation, and the thread performing other threads’ critical sections is called helper. Put simply, delegation lets the operation come to the data while traditional locks let the data come to the operation. This can result in reduced cache misses since delegation makes it possible to let many operations on the shared data execute one after another on a single processor core. Besides these benefits, some algorithms employ detached execution, i.e., they allow threads to continue execution before the delegated critical section has been executed. In its original form [31], the detaching algorithm has some overhead and severe starvation issues for the helper thread. Newer approaches, like flat combining [17] or remote core locking [25], steered away from detached execution favor of faster delegation and in order to provide a simpler semantics. As we show in this article, in contrast to these earlier approaches our locking mechanism allows efficient delegation while it also permits detaching execution without starving the helper thread.

Main Ideas. We introduce Queue Delegation (QD) locking, a new efficient delegation algorithm whose idea is simple. When a lock is contended, the threads do not wait for the lock to be released. Instead, they try to delegate their operation to the thread currently holding the lock (helper). If successful, the helper is responsible for eventually executing the operation. The threads may either wait for the operation to complete or alternatively continue their execution immediately, possibly delegating more operations.

Delegated operations are placed in a delegation queue. As the queue preserves FIFO order, the correct order of operations is maintained, and QD locking ensures linearizability. The linearization point is the successful enqueuing into the delegation queue. However, the enqueuing can fail when the lock holder is not accepting any more operations. This allows the helper to limit the amount of work it performs, providing starvation freedom for the helper, and ensures that no operations are accepted when the lock is about to be released. If delegation fails, a thread has to retry until it succeeds to either take the lock itself or delegate its operation to a new lock holder. The QD locking algorithm thus puts the burden of executing operations on the thread that succeeds in taking the lock. After performing its own operation, this thread must perform, in order, all operations it finds in the delegation queue. When it eventually finds no more operations in the delegation queue, it must make sure that no further enqueue call succeeds before the lock is released.

To communicate return values from a delegated operation

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to the thread that delegated it, the operation may pass an address to store the return value as well as the address of a flag. The helper then has to store the return value before setting the flag, on which the delegating thread is waiting. This also means that, optionally, threads that do not require a return value can continue their execution immediately after a successful delegation. We refer to the former option as delegate and wait and the latter option plainly as delegate.

All requirements for QD locking are met by assembling two simple components: (i) a mutual exclusion lock to determine which thread is executing operations, and (ii) a queue to delegate operations to the lock holder. By using a reader indicator as an optional third component it is also possible to allow multiple readers to efficiently execute in parallel.

Contributions. The main contribution of this article is a detailed description of a new delegation algorithm that we call QD locking. It is novel in that it efficiently delegates operations while also allowing to detach the delegation from the eventual execution. We discuss its prerequisites and properties in detail, introduce multi-reader QD locks which allow multiple parallel readers, and a hierarchical QD locking variant which targets NUMA systems. Last but not least, we quantify the performance and scalability aspects of QD locking by comparing them against state-of-the-art scalable synchronization mechanisms. As we will see, QD locking offers performance that is on par and often much better than that of existing synchronization algorithms.

Overview. The rest of the article is structured as follows. The next section reviews the necessary background in mutual exclusion algorithms and related work. The following four sections present the different QD locking variants (Section 3), their implementation (Section 4), their properties (Section 5), as well as how the algorithm is extended to support reader-writer locking semantics (Section 6). Subsequently, QD locking is compared with related synchronization mechanisms on the experimental level (Section 7), and the article ends with some concluding remarks.

2 BACKGROUND AND RELATED WORK

This section discusses various algorithms that can be used to implement mutual exclusion. Starting with the most simple locking algorithms, we take a look at their abilities step by step. Furthermore, we showcase other algorithms that employ helper threads to improve performance, highlighting their respective features and limitations.

2.1 Locking

Locking (also called mutual exclusion), has been introduced by Dijkstra in 1965 [11]. Since then it has been a dominating synchronization mechanism for concurrent programming with shared memory. The most basic algorithm is the test-and-set (TAS) lock, which uses a simple flag to indicate the state of the lock and functions lock() and unlock() to modify this state as shown in Fig. 1. Atomic test-and-set is used to ensure that only one thread can take the lock at a time. Two additional functions are commonly also available. The first, is_locked(), returns true if the lock is currently taken and false otherwise. The second, try_lock(), takes the lock if it is available and then returns true, but does not wait (block) when it is unavailable; instead it simply returns false.

![Fig. 1. The test-and-set (TAS) and the test-and-test-and-set (TATAS) lock.](image1)

While the TAS lock is a functionally correct locking algorithm, its performance is lacking: When multiple threads try to take the lock at the same time, i.e., there is contention for the lock, each thread will repeatedly issue write-accesses to the locked flag. This causes the flag to be removed from any other private caches it may currently be in, and thereby causes lots of cache coherence traffic. This traffic can be reduced by first checking the flag before writing to it. The resulting test-and-test-and-set (TATAS) algorithm, also shown in Fig. 1, avoids repeatedly writing when the lock is taken, but will still cause traffic by the waiting threads whenever the lock is unlocked. However, when locks are usually uncontended this algorithm provides decent performance [1].

![Fig. 2. The futex lock.](image2)
wake up the thread when the lock is released, which on Linux is used by glibc’s implementation of the ubiquitous Pthreads mutex lock [12], [15], [16]. Fig. 2 shows how this can be implemented using the (Linux-specific) futex syscall. This futex lock uses three internal states: free, taken and contended. It only involves the operating system when there is contention, which causes the state to be set to contended. Otherwise it functions as the TAS and TATAS locks, using free and taken as the flag’s values. As syscalls can be expensive, another option is to attempt to take the lock multiple times before going into the contended state. This allows higher performance if the waiting time is expected to be low at a limited computational cost [15].

### 2.3 Fairness

All locking algorithms described so far lack fairness: When a lock is released, all threads waiting for it have a chance of obtaining the lock. The probability of obtaining the lock is largely dependent on the hardware properties, but there is markedly no upper limit for the time a thread may have to wait until it obtains the lock.

A simple way of obtaining fairness is to issue tickets to threads by fetch-and-incrementing a field in the lock [28]. A thread has obtained the lock when the number it received matches a second field representing the next ticket to be called. On unlock(), threads simply increment this second field, allowing the next thread to proceed. However, this approach is memory intensive: All threads waiting need to fetch the next ticket field whenever it is updated, but only one of them will be allowed to proceed.

This issue is solved by queue-based locks that allow each thread to wait on a separate memory address instead. The earliest such locks are MCS [28] locks, which have a queue node per thread. The threads compare-and-swap their node’s pointer with an initially null field when calling lock(). The first thread obtains null as the previous value and is allowed to proceed its critical section, while subsequent threads obtain the previous thread’s node pointer instead. They then reset a flag in their own node and set a next-pointer in the previous thread’s node. When unlocking, the thread tries to compare-and-swap the MCS lock field back to null, which fails if another thread arrived in the meantime. In that case, the thread follows its node’s next-pointer to set the flag in the next thread’s node, waking only that thread.

A further improvement of this scheme is the CLH [7], [27] lock, which does not require a swap operation for unlocking. (It takes a spare node from the lock which is not returned, but reused as the thread’s node on the next lock() operation.)

Queue-based schemes improve performance over ticket locks due to the lower cache coherence traffic. However, the strict ordering of waiting threads can harm performance when thread preemption is common: The next thread to execute may have to wait for processing time first. In Fig. 3 the performance of CLH is compared with the ubiquitous Pthreads lock and the Cohort lock, which is described below. Note that, in all graphs, the x-axis (# threads) is in log scale.

### 2.4 NUMA-aware Algorithms

On Non-Uniform Memory Access (NUMA) systems, the strict FIFO ordering of threads using CLH locks becomes a performance bottleneck. The locking algorithm needs to synchronize the lock’s state between the thread unlocking the lock and the one subsequently locking it. Such synchronization slows down when information needs to be communicated to another processor chip. It thus follows that hierarchical approaches are required for faster lock handovers in NUMA systems, at the cost of a potentially lower degree of fairness. Several NUMA-aware locking algorithms that exploit the hierarchical structure of NUMA systems exist by now [8], [26], [33]. Recently Dice et al. have proposed lock cohorting as a general mechanism to create NUMA-aware hierarchical locks [9]. A Cohort lock has one lock for every NUMA node in the system and an additional global lock. The holder of the global lock and a local lock has the right to execute a critical section and hand over the local lock to a waiting thread, if there is one, provided that the hand-over limit has not been reached. This reduces the number of expensive memory transfers that have to be done between NUMA nodes. The performance of the Cohort lock is also shown in Fig. 3. Chabbi et al. recently generalized Cohort locks for deep NUMA hierarchies [5]. The resulting hierarchical MCS (HMCS) lock allows to take advantage of locality within each different NUMA level individually.

NUMA-aware approaches are much more efficient on NUMA machines under high contention than traditional locks. However, their performance is inferior to other approaches, such as those based on delegation, when operating within only one NUMA node (cf. Fig. 4 in Section 2.6).

### 2.5 Detached Execution

The poor cache locality due to data transfers between private caches was identified by Oyama et al. [31] back in 1999 as a major bottleneck for locking algorithms. To improve this, they suggested that threads should not execute critical sections themselves, but they should be detached from their execution. While the threads lose control over the execution of their critical section, the scheme allows a single thread to execute critical sections efficiently due to the ability to exploit data locality. The algorithm for detached execution by Oyama et al. stores critical sections in a LIFO queue-based on a linked
list. A thread that successfully executes a compare-and-swap (CAS) instruction on a lock word that also functions as head of the LIFO queue becomes the helper.

Not discussed by Oyama et al. is that their detached critical sections cannot directly return data to the thread detaching them. If threads require knowledge about the success of a critical section or need to read data in a critical section to guarantee consistency, the scheme requires additional synchronization. For example, a communication variable could be defined, which can then be used store the desired information. Read-spinning on and writing to this communication variable must still ensure consistency.

Another problem in the algorithm by Oyama et al. is that the helper continues executing requests that are put by other threads as long as the LIFO queue is not empty. Therefore, it is possible for the helper to starve while executing requests for other threads. Furthermore, threads delegate operations by performing a CAS operation on the pointer to the LIFO queue. As noted by other researchers [14], [17], this pointer can become a contented hot spot which limits scalability. The original algorithm also suffers from the cost of memory management of LIFO queue nodes, which can be mitigated by pre-allocation of nodes. The resulting variant of the algorithm of Oyama et al. is called DetachExec in this article.

Despite these known problems, DetachExec can achieve some performance benefits through the ability to detach worker threads from the execution of their critical sections: If the programmer does not explicitly synchronize with the end of a critical section, threads will continue with their execution immediately after storing their operation in the LIFO queue.

### 2.6 Delegation Algorithms

The idea of a single thread executing many critical sections without any need for synchronization in between has been used by a number of approaches, which we call delegation algorithms. For consistent terminology, we say that worker threads delegate their critical sections to a helper thread. The following algorithms all differ from DetachExec in that they ensure that threads continue execution only when the delegated critical section has been executed.

#### Flat Combining

One approach to coalesce operations on a shared data structure into a single thread is flat combining (FC) [17]. Flat combining uses a lock and a list of request nodes L. Each thread has a single request node that can be put into L. To perform an operation on the shared data structure, the operation is first published on the thread’s request node. Subsequently, the thread spins in a loop that switches between checking whether the response value has been written back to its request node and trying to take the lock. A thread that successfully acquires the lock becomes the helper (in FC also called combiner), traverses the list of requests (a number of times), and performs the requests it finds there. The FC algorithm also has a way of removing nodes that have not been used for a long time from the list of requests. A thread that is waiting for a response has to occasionally check that its node is still in the list and put it back with a CAS operation if it has been removed. Flat combining’s delegation mechanism has been shown to perform better than the original algorithm of Oyama et al. for contended workloads [14], [17], but these comparisons do not consider an optimized variant of the algorithm, like DetachExec, that is better suited for modern machines.

#### Synch Algorithms

CC-Synch, DSM-Synch, and H-Synch are queue-based delegation algorithms developed by Fatourou and Kallimanis [14]. In all three algorithms, a thread T announces an operation by inserting its queue node, which contains the operation, at the tail of the request queue. T then needs to wait on a flag in the queue node until the flag is unset. If T then sees that the operation is completed it can continue normal execution, otherwise T becomes the helper. A helper thread first performs its own operation and then traverses the queue performing all requests until it reaches the end of the queue or a limit is reached.

The queue in the CC-Synch algorithm is based on the CLH lock [7], [27], while the queue in DSM-Synch is based on the MCS lock [28]. CC-Synch is slightly more efficient than DSM-Synch, but DSM-Synch is expected to also work well on systems without cache coherence. H-Synch is in spirit similar to lock cohorting, and has one CC-Synch data structure on every NUMA node and an additional global lock. Threads put their queue node in the Synch data structure located at their local NUMA node and a helper needs to take the global lock before starting to execute operations.

The Synch algorithms have been shown to perform better than flat combining for implementing queues and stacks [14].

#### Dedicated Core Locking

Locking mechanisms where cores are dedicated to only execute critical sections for specified locks have been studied both from a hardware and a software angle. Suleman et al. have proposed hardware support for the execution of critical sections [35]. Their suggested hardware has an asymmetric multi-core architecture where fat cores are dedicated to critical sections and have special instructions to execute them. Remote core locking [25] is a software locking scheme where one processor core is dedicated to execution of critical sections. The dedicated core spins in a loop checking a request array for new requests. All seen requests are executed and the response value or acknowledgment is written back in a provided memory location. Compared to delegation mechanisms, dedicated core locking has the disadvantage that the programmer has to decide which locks shall have a dedicated core and the cores that should be used for this. Furthermore, dedicated core locking is not well-suited for applications that have different phases where the lock is sometimes contented and sometimes not. Finally, remote core locking suffers from the same kind of overhead that flat combining has in that it needs to scan request nodes even when they are empty.

#### Hardware Message Passing

Recently, several algorithms using hardware message passing to optimize cache coherence interactions have been proposed [32]. The algorithms include an MCS lock variant called HybLock and two delegation algorithms, called mp-server and HybComb. While mp-server uses dedicated cores for execution of critical sections, HybComb promotes an existing thread to execute critical sections, similar to FC and CC-Synch. All three algorithms rely on a hardware message queue to avoid negatively affecting performance through the cache coherence protocol.

#### Delaying Updates

In update-heavy scenarios it can be beneficial to not update the global state until there is a read that needs to see the updates. OpLog [3] is such an approach. It uses core cycle timestamps provided by the
3 Queue Delegation Locks

This section describes the different QD locking variants. We start with the necessary components, and then use them to assemble a basic QD lock. We also show that QD locks can be used in a way that gives programmers more flexibility and allows them to achieve better performance than the one using only basic QD locks. Then we extend the algorithm to a multi-reader QD locking variant that allows multiple read-only operations to execute in parallel. Last, we sketch how QD locks can also provide the functionality of traditional mutual exclusion locks.

3.1 Building Blocks

Queue delegation locks are built from two main components: a mutual exclusion lock and a delegation queue.

The mutual exclusion lock is used to determine whether the lock is free or taken. QD locks can use most locking algorithms, as long as they provide a try_lock function in addition to the standard lock/unlock mechanisms.1 We also use the is_locked function of the mutual exclusion lock when we later build a multi-reader QD lock.

The other building block, the delegation queue, is required to store delegated operations. Semantically, it is a tantrum queue as described by Morrison and Afek [30]. Calls to its enqueue operation are not guaranteed to succeed, but can return a closed value instead. This allows the QD lock to stop accepting more operations. The required interface for the delegation queue consists of only three functions: open, enqueue and flush. The first two are simple: open resets the queue from closed state to empty, and enqueue adds an element to the queue. The flush function is used instead of a dequeue operation: it dequeues all elements (performing their operation) and changes the queue’s state to closed.

1. In fact, the lock mechanism for taking the lock unconditionally is not strictly required. Still, lock is useful in order to provide stronger guarantees and makes it easier to adapt legacy code to use QD locking.

3.2 Queue Delegation Lock

We use the building blocks outlined above to assemble a QD lock. A thread attempting to execute an operation under the QD lock first attempts to lock (using try_lock) the mutual exclusion lock. If this succeeds, the thread will first open the delegation queue (which then accepts other threads’ operations). Then the operation will be executed, followed by a flush operation on the delegation queue. Finally, the mutual exclusion lock is unlocked again. However, if the try_lock fails, the thread instead attempts to enqueque its operation into the delegation queue. When this succeeds, the thread has detached the critical section. At that point, the thread can either wait for the critical section to complete or continue its execution (and possibly wait for the result of the critical section at a later point). The resulting QD lock therefore accepts operations even when the mutual exclusion lock is locked; threads only need to retry if the mutual exclusion lock is locked and the queue is closed.

An operation that can be submitted to QD locks is semantically a self-contained function, which means it needs to store all required parameters from the local scope when delegated, similar to a closure. For implementation details of this mechanism, see Fig. 6 and 7.

The basic QD lock interface only consists of a delegate_and_wait function which takes an operation as an argument. It also creates a flag (initially set to false) and augments the operation with a final step that sets the flag to true. The call to delegate_and_wait then waits until this flag is true. This is semantically equivalent to the way the delegation algorithms in Section 2.6 operate.

However, the delegate_and_wait function can also be separated into delegate and wait functions, which can be called individually. It is then still guaranteed that the delegated operation will be executed before any operations from subsequent calls to delegate are executed, but the execution is detached until wait is called. Additional performance can be leveraged by a thread that delegates multiple operations before waiting for them. Finally, if the operation has no return value that needs to be obtained, the wait call can be omitted entirely. In this case it is also not required to create and set a flag that can be waited on, which further reduces the overhead incurred by the algorithm.

This separation of delegate and wait can be explained using the semantics of futures [2]. Namely, the value is not returned immediately, but the delegate call can promise to provide the value at a specific location upon the execution of the operation, i.e., it returns a future. When the calling thread needs to read the return value, it has to wait until it is available. The waiting can be done by the programmer by calling wait, or by hiding the call in a wrapper that does it automatically when the value is read.

3.3 Multi-Reader Queue Delegation Lock

Readers-writer locks can be built from mutual exclusion locks in a generic way. This is applicable to QD locking as well. For Multi-Reader QD (MR-QD) locks, which is our variant of readers-writer locks, a third building block is required: an indicator that shows whether there are any threads currently holding the lock in reading mode. Note that it is not necessary to count the readers. Instead, all we...

Fig. 4. Throughput for the same priority queue benchmark as in Fig. 3 with various delegation algorithms. Note that the y-axis scale has changed.
We will now describe how QD locks can be realized by way to wait for taking the lock. Our implementation works write contention on the lock. The basic algorithm only uses wait until it is safe to write.

A reader indicator extends QD locks to MR-QD locks, which allow many concurrent readers that efficiently execute in parallel when there is no writer or when the writer releases the lock. The interface of an MR-QD lock contains the additional functions rlock and runlock that work as in traditional readers-writer locks.

3.4 Queue Delegation Locks with a Wider Interface
We can easily extend the interface of QD and MR-QD locks to allow critical sections that are not delegated or to offer other functionality provided by mutual exclusion locks. To do so, we only need to expose the functions from the mutual exclusion lock component. This interface may be required for critical sections that need to lock multiple locks and release them in an order other than last in, first out, or because a critical section needs to run in a specific thread. We do not further discuss or evaluate this kind of extended QD locks, as their performance depends mostly on the performance of the mutual exclusion lock.

4 IMPLEMENTATION
We will now describe how QD locks can be realized by presenting our implementation. However, we note that the range of possible implementations of QD locking is not restricted to the ones we describe in this article. In fact, the components we use can be replaced by other ones providing the required interface. The ones we chose to base our implementation on may not be the “best” (whatever that means), but are easy to understand and, as we will see, provide good performance and scalability.

4.1 Mutual Exclusion Lock
The mutual exclusion lock component is not as important for QD locking as one might expect. As delegating operations is preferred over waiting for the lock, there is virtually no write contention on the lock. The basic algorithm only uses try_lock, while locking algorithms mainly differ in their way to wait for taking the lock. Our implementation works very well with the TATAS lock, whose implementation was shown in Fig. 1. However, as we will show in Section 5, the guarantees of the lock used here can be used to extend similar guarantees to the entire QD lock. Thus, for our implementation, we chose the MCS-futex lock, whose implementation is shown in Fig. 5. It is a simple extension of MCS locks that use futex syscall to wait for their turn instead of spin-waiting. Additionally, there is a try_lock function (equivalent to the one in the futex lock), which does not provide fairness. There is also a function try_lock_or_wait, which acts similar to try_lock but before returning false also makes threads sleep until the helper finishes all operations delegated to it and calls unlock. This allows spin-waiting for a limited period before sleep-waiting, which is a common optimization.

This MCS-futex lock provides a lock function, which is used in Section 5 to provide starvation freedom. It can also be used in the QD lock interface to deal with situations where delegation is not possible, like unlocking in an order other than last in, first out as mentioned in Section 3.4.

4.2 Delegation Queue
On the other hand, the delegation queue component is important for QD locking since it is used by all contending threads. It therefore must be fast when enqueueing operations.

Our delegation queue implementation, shown in Fig. 6, uses a fixed-size buffer array to store operations. A counter is used to keep track of how many elements are already in the queue. The queue is defined to be closed when the counter is greater than or equal to the size of the array. Initially, the counter is set to a value greater than the size of the array and thus the queue is in closed state. The enqueue function increases the counter using an atomic fetch_and_add instruction2 (line 10), which gives each delegated operation

```c
class mcsfutex_lock {
    thread local static std::map<mcs_futex_lock*, mcs_node*> mcs_node_store; // each thread gets one node per lock
    static atomic<mcs_node*> linked_list;
    void lock() {
        mcs_node* mynode = &mcs_node_store[this];
        mynode->next = NULL;
        mcs_node* c = this->locked.exchange(mynode);
        if(c != NULL) {
            mynode->is_locked = true;
            c->next = mynode;
        }
        while(mynode->is_locked) {
            sys_futex.wait(&mynode->is_locked, true);
        }
        void unlock() {
            mcs_node* mynode = &mcs_node_store[this];
            mcs_node* c = mynode;
            if(mynode->next == NULL) {
                if(this->locked.compare_exchange_strong(c, NULL)) {
                    if(this->sleep) {
                        this->sleep = false;
                        sys_futex.wake(&this->sleep);
                    }
                    return;
                }
                while(mynode->next == NULL) { /* wait for next pointer */
                    mynode->next = is_locked = false;
                    sys_futex.wake(&mynode->next->is_locked);
                }
            }
            if(this->locked.compare_exchange_strong(c, NULL)) {
                if(this->sleep) {
                    this->sleep = false;
                }
                sys_futex.wait(&this->sleep, true);
            }
            return false;
        }
    }
};
```

Fig. 5. The MCS-futex lock.

2. As not all platforms have a fetch_and_add (FAA) instruction, we've also done experiments where FAA is simulated with a CAS loop (Sect. 7).
its index in the buffer array. This way, the queue automatically closes when the buffer fills up, and can also be closed by atomically changing the counter field with a CAS or a swap instruction (as in line 35). The flush function repeatedly reads the counter and dequeues operations until the queue has been put to closed state by an enqueue function (line 38 detects this) or because the counter has not been updated since the last check (line 34).

Special care is needed when writing and reading the delegated operation; i.e., in lines 12–16 and 43–49. First of all, the operation needs to be self-contained: besides the operation, all parameters needed to execute it must be provided. In our implementation, we use a function pointer in the entries array, a size field and a variable-sized parameter field for each operation. Each function pointer entry is associated with a fixed amount of buffer space in the parameter array. If more space is needed, multiple entries can be used for a single function. The amount of required entries is stored in the size field, which always comes at the beginning of the associated buffer space. To ensure that no partially-written operations are used, the function pointer is written last and read first. The entries array content is reset to all zero (line 54) after the delegated operations have been executed. This allows to wait in the next iteration of the for loop until the function pointer entry contains a valid value. As the function pointer entry is written last, the entire operation can be read safely when the function pointer entry has a non-zero value.

The observant reader may wonder whether the counter field in the delegation queue could also be used for deciding which thread becomes the helper. While this is possible and gives high performance, it is then not possible to use the additional properties (fairness and sleeping while waiting) provided by an MCS-futex lock. When such properties are desired, a separation of lock and delegation queue allows simplified reasoning about them, as we will see in Section 5.

4.3 Queue Delegation Lock Implementation

With the mutual exclusion lock and the tantrum queue available, only the actual delegation functions have to be provided to build a QD lock. The delegate_and_wait function provides an interface that enforces the stronger semantics of most other locking algorithms. It extends the operation with a flag that will be set after the operation has been executed. This flag will be waited on before delegate_and_wait returns. The extended operation is handled by the delegate function, which can also be used by the programmer directly. As can be seen in Fig. 7, this function initially checks whether the lock is contended (line 5), so that it can avoid overheads if there is no contention. It then alternates between trying to delegate the operation (line 11) and trying to acquire the lock (lines 12–18) until one of them succeeds or the maximum number of tries is reached. If the enqueue function call succeeds, it is guaranteed that the operation will be executed and the delegate function can return. As described earlier, a delegate caller that does not need a return value from the operation can just continue execution at this point. An operation that requires a return value needs to write this value to a location that the caller of delegate can wait on. If the try_lock call succeeds, the thread opens the queue, executes its own operation and all enqueued operations until the queue is closed. Finally it unlocks the mutual exclusion lock. However, if the maximum number of tries is reached (in line 10) then the algorithm reverts to using the mutual exclusion lock directly (line 27), which will achieve progress if a starvation-free lock is used.

5 Properties

Let us now discuss some of the properties of QD locking; most notably starvation freedom and linearizability. We also show how to extend QD locking to be better suited for NUMA systems, and discuss issues related to how QD locks can be used for practical programming.
class qd_lock {
    mcsfutex.lock lock;
    delegation.queue queue;
    void delegate(Function f, Parameters p) {
        if(lock.try_lock()) {/* check for contention */
            f(p);
            lock.unlock();
            return;
        }
        for(int i = 1; i <= MAX_TRIES; i++) {
            if(queue.enqueue(f,p)) return;
            bool lock_acquired;
            if(i % (TRIES_WITHOUT_WAIT + 1) != 0) {
                lock.acquired = lock.try_lock();
            } else {
                lock.acquired = lock.try_lock_or_wait();
            }
            if(lock.acquired) {
                queue.open();
                f(p);
                queue.flush();
                lock.unlock();
            } else {
                return;
            }
        }
    }
    ReturnType delegate_and_wait(Function f, Parameters p) {
        std::atomic<bool> flag = false;
        ReturnType r;
        Function waiting_op = [&r,&flag](Parameters p) {
            r = f(p);
            flag = true;
        };
        delegate(waiting_op, p);
        while(!flag) {/* wait */
            return r;
        }
    }
};

Fig. 7. The delegate function and its waiting counterpart.

5.1 Starvation Freedom
The delegate function implementations shown in Fig. 7 and 12 are starvation free, meaning that a thread cannot get starved while executing them. When a thread fails too many times in both try_lock and enqueue calls, the algorithm uses lock as a fair fallback. This can happen if a thread always executes the enqueue function when the queue is closed and the try_lock function when the mutual exclusion lock is locked. According to our experience this does not seem to be a problem in practice, and experiments (in Section 7) show that the additional code does not harm performance severely.

However, one can easily replace the internal locking algorithm and remove the limit for retrying try_lock and enqueue to gain a little bit higher performance. As long as this limit exists and the mutual exclusion lock is starvation free, it is easy to see that the whole delegate function is also starvation free. This is because, in the worst case, the delegate function only does a fixed amount of work in the retry loop before it acquires the starvation free mutual exclusion lock unconditionally.

5.2 Linearizability
Linearizability [18] is a correctness criterion for concurrent data structures. Methods on a linearizable concurrent object appear as if they happen atomically at a linearization point during the methods’ execution. We discuss linearization of QD locking algorithms here, dealing with the problem that detached execution allows continuing to work even before critical sections have been executed. Still, if all accesses to a data structure are protected using a lock of the QD lock family, the resulting data structure is linearizable as we argue below.

Up front we note that the delegation queue is linearizable. The enqueue function, if successful, linearizes delegated operations exactly in the order in which they appear in the queue. When delegate enqueues successfully, linearization of operations is therefore given by the linearization of the delegation queue. When try_lock is successful, the linearization point is just before the opening of the queue (the point between lines 18 and 19 in Fig. 7). This is true because try_lock can only succeed when the lock is free, which implies that any previous holder must have executed all previously delegated operations. Likewise, concurrent delegate calls cannot succeed before the queue is opened, thus their operations must have a linearization point later on.

For completeness, we note that delegate returns a future of the operation’s result, not the actual result. This allows the linearization point of reading the return value to be distinct from the operation’s linearization point. This linearization point is after the actual execution of the operation, right after the return value has been written successfully. It should be noted that the returned value is still consistent with the linearization of the operations and does not reorder them. This linearization model has been independently described as strong future linearizability [22], albeit in that paper it is restricted to data structures and does not support general critical sections. However, when queue delegation is used with operations that have side effects outside the data structure protected by the lock, linearizability is not guaranteed. In such code, the program may have to wait for the result of the future before it is safe to depend on the actual execution of the operation.

5.3 NUMA Awareness
In this section, we present a NUMA-aware hierarchical queue delegation lock called hierarchical QD lock (or HQD lock for short). The HQD lock is derived from the QD lock in a way that is in spirit similar to how Cohort locks [9] are constructed from traditional mutual exclusion locks and to how the H-Synch algorithm is constructed from CC-Synch [14]. An HQD lock uses one mutual exclusion lock and one delegation queue per NUMA node. Additionally, the lock contains a global mutual exclusion lock that is used to determine which NUMA node is allowed to execute operations. We have chosen an MCS lock [28] as both the global lock and the per-node mutual exclusion lock. MCS is a fair queue-based lock that provides starvation freedom. These choices guarantee that all NUMA nodes will be able to execute operations in a reasonably fair order at high performance. (We have not used futex syscalls to deal with threads that spin-wait, as this hierarchical algorithm is highly sensitive to the timing between handovers and operating system calls are too expensive in this scenario.)

The implementation for the HQD lock algorithm is shown in Fig. 8. As with other hierarchical locking approaches each
thread needs to know which NUMA node it is running on (see line 5). The delegate function is using the lock and delegation queue of the local NUMA node to perform the QD locking algorithm. Additionally, it needs to take the global lock before opening its delegation queue in line 23. The same lock must also be acquired in all code paths that perform only a single critical section (lines 7 and 33). Constructed this way, the amount of expensive communication between the NUMA nodes can be significantly reduced. This allows HQD locks to perform better under high contention as we will see in Section 7. On the other hand, when the contention is low, a QD lock can perform better than an HQD lock on NUMA systems. QD locks can achieve higher parallelism at a higher communication cost compared to HQD locks. Threads on other NUMA nodes have to wait instead of delegating and continuing with their local work, which itself can limit performance. Also, it means there are less workers supplying the lock holder with additional work, which can mean the lock is released and taken again instead of the lock holder helping other threads. It is therefore not the case that HQD is always a better choice than QD on NUMA systems.

5.4 More Threads than Hardware Supports

In high-performance applications, programs often spawn exactly as many worker threads as the hardware can efficiently run at the same time. However, a general purpose mutual exclusion algorithm should also consider the case where there are more threads contending for the lock than hardware supports. In this case, locking algorithms need to cooperate with the operating system by putting themselves to sleep while waiting, in order to avoid that threads waiting to access the lock prevent execution of the thread holding it. In QD locking, this is not an issue as long as delegations succeed. However, once the delegation queue is filled up, the other threads can waste resources by repeated attempts to delegate, which are bound to fail until the helper finishes with its current workload. To limit the extent of spinning, the implementation of QD locks can use try_lock_or_wait the implementation of QD locks can use try_lock_or_wait. Measurements have shown that the performance impact of this extension is reasonably small, but can increase performance significantly when there are more threads than cores, especially when threads are not pinned to cores. However, this ability does not extend to the spinning done by threads waiting for return values, as waking them up individually causes significant overheads. Fortunately, each of them spins on its own flag which can be cached and therefore interferes little with the rest of the system as long as there is only a limited number of threads spin-waiting for a return value.

5.5 Usage Examples

The use of QD locks is straightforward. A comparison with lock/unlock-based critical sections is shown in Fig. 9. The critical section is turned into a lambda function, so that it can be delegated to a QD lock. By using delegate_and_wait the code guarantees that the critical section has completed. To also benefit from detached execution, the example in Fig. 10 uses delegate in conjunction with a boolean flag f to signal availability of the return value v1. The lambda function

Fig. 8. The delegate function in the HQD lock.

Fig. 9. Code transformation of a regular lock to a QD lock.

Fig. 10. Code transformation with detached execution using a QD lock.
captures both f and v1 by reference so that it can write to
them. This allows the lookup in the critical section lambda
(line 8) and an expensive computation (line 12) to be executed
in parallel when the operation is delegated to another thread.
Waiting on the flag (line 14) immediately before the value is
needed guarantees that v1 has been written to by the helper
thread. If the current thread happens to become a helper, the
execution would still be serial, but this will only affect one
thread at a time, benefitting all other worker threads.

5.6 Structured Locking and Practical Considerations
In many situations one may need to use structured locking
with multiple nested locks. For QD locking, the case of
delegating to one lock while executing a critical section
under another lock is not problematic. If there is already a
helper for the inner lock, the critical section will be delegated.
When both locks are required for an operation, the outer
lock’s helper thread issues the inner lock’s operation and
then just needs to wait for its execution, thus ensuring no
other operation is executed under the outer lock. However,
this does not cause any additional delays over classical
locking algorithms, as with them the thread would stall
until it acquires the inner lock as well. In the case where
there is no helper yet, the thread issuing the operation
will become a helper for the inner lock as well, helping
any additionally delegated calls before resuming the help
session on the outer lock. This can be seen as starving the
helper thread, as the maximum amount of work during
the outermost help session increases exponentially with
the locking depth. If this becomes a problem, mitigation
is possible by spawning additional threads to become helpers.
Alternatively, a flag could be passed to `delegate_and_wait'
and `delegate' to indicate that the call should not become a
helper. This would allow benefitting from existing helpers,
but fall back to `lock/unlock' if there is no helper available.
However, with this flag the performance of a call that never
helps becomes harder to predict and having too many such
calls can cause the scheme to degrade in performance.

More discussion on porting existing applications to use
QD locks and programmability aspects of QD locking can be
found in a paper describing our QD locking libraries [21].

5.7 Comparison with Other Delegation Algorithms
QD locking provides a broader set of functionality than other
delegation algorithms, and there is a number of differences
regarding the limitations of and choices by these algorithms.

When DetachExec by Oyama et al. executes critical sec-
tions, there is no upper limit for how many critical sections
can be executed by the thread, causing starvation of the
helper. This is not the case for QD locking which uses a
tantrum queue with limited size. DetachExec has a potential
hot spot where critical sections are delegated, and QD locking
has a similar potential hot spot. However, it is less of an
issue as we use a fetch-and-add instruction instead of a
CAS loop to synchronize between threads, which reduces
the already small impact of the hot spot. A final difference
between DetachExec and QD locking is that in order to make
DetachExec linearizable, the LIFO queue of operations needs
to be reversed, which also imposes extra cost.

Compared to flat combining, the QD locking approach
is offloading work to the lock’s holder and does not need
to wait for the critical section’s execution. FC cannot easily
detach execution because of happens-before relations: An-
other thread could synchronize with the detaching thread
and issue an operation to FC, which then might be executed
before the detached operation. Also, unlike FC, the helper in
QD locking does not need to traverse empty request nodes
which potentially can become a performance problem for FC
when the number of threads is big but contention is low.

Compared to CC-Synch, DSM-Synch and H-Synch, QD
locking has two advantages. First, it does not require
threads to wait until an operation has been applied to the
data structure that is protected by the lock. Instead, the
programmer can specify if and when a return value is needed,
allowing for the same strict or more relaxed semantics. If the
Synch algorithms were to be extended to support detached
execution, significant changes in their implementation would
be required to maintain starvation freedom. Second, our
implementations are using a queue that is based on an array
buffer. This approach causes fewer cache misses (external
loads fed from other cores) than the Synch based algorithms.
Since the operations are stored continuously in the array
buffer, several operations can be loaded per cache miss
compared to the Synch algorithms that require one cache
miss per loaded operation.

6 Multi-Reader Queue Delegation Locks
All locking algorithms reduce the amount of available
parallelism, which can become a bottleneck even if the
locking algorithm itself is very efficient. The most common
way to mitigate this problem is to allow limited parallelism
even when accessing shared data. By using readers-writer
locks, programmers can allow multiple read-only critical
sections to execute in parallel. This section describes how
QD locks can be extended to also support parallel read-only
critical sections. But let us start with some background.

The extension of mutex locks to readers-writer locks
was first proposed by Courtois et al. in 1971 [6]. Since then,
the idea has been used numerous times to extend various
algorithms [4], [10], [23], [29], [34]; in particular, it has been
employed on top of plain queue locks as well as other locking
algorithms mentioned in Section 2. A readers-writer (RW)
lock is an extension to the mutual exclusion lock that offers
two levels of locking: 1) The `read' lock level is usually used
for critical sections that do not modify shared data. Several
read critical sections protected by the same lock can execute
concurrently. 2) The `write' lock level is usually used for critical
sections that modify shared data. If a thread is inside a write
critical section, all other accesses (read and write) must wait
for it to complete before they can proceed. Since read critical
sections can execute concurrently, an RW lock can offer better
performance than a mutual exclusion lock for applications
that frequently execute read-only critical sections.

Calciu et al. described a general method to extend mutual
exclusion locks to RW locks [4]. This method can be adapted
to QD locks as well by applying the construction to `delegate.'
The chosen write-preference policy extends the interface of
QD locks by `rlock/runlock' functions, which neither dele-
gate nor detach read-only critical sections. Instead, read-only
critical sections are executed in the thread requesting them, potentially in parallel. Write-preference (up to a limit) aims to execute delegated operations (i.e., write critical sections) first, so that there is more time for read-only critical sections to arrive and execute in parallel once the mutual exclusion lock is released. The preference is limited to avoid starvation.

There are two transitions that need to be explained in some detail: (i) going from executing delegated operations to parallel reading, and (ii) going from parallel reading to a thread becoming a helper. We use the internal mutex lock’s status to determine whether there is a helper thread currently executing delegated operations. If there is, all reads will defer to delegated operations unless their patience limit is reached. When a thread reaches the patience limit, it will set a barrier that prevents further delegate calls from proceeding, which means that only delegated operations that have been delegated before will be executed. Therefore, delegated operations are preferred over read-only critical sections, but there is no starvation of readers. For the opposite transition of parallel read-only critical sections being executed and a thread calling delegate, we use a reader indicator (as mentioned in Section 3.3) to wait until all read-only critical sections have been completed before executing the delegated operation. The internal mutex lock will still be locked before waiting, which guarantees that further rlock calls will wait until this delegate call has completed. Furthermore we can open the delegation queue before waiting, as this guarantee also ensures correct order of operations, even if a thread delegates an operation and then calls rlock.

We use a simple reader indicator algorithm; see Fig. 11. Its rationale is to not have a single counter for the readers, which would be a bottleneck, but to split that counter into several cache lines. This reduces write contention on the counter significantly, and is easy to implement. By having at least as many counters as threads, the counters become simple flags, and there is no contention at all. Checking this reader indicator requires iterating over all counters to check that they are all zero, which is relatively expensive. That cost notwithstanding, we chose this algorithm because it performed better in our experiments than the ingress-egress counter used by Calciu et al. [4]. The third available algorithm, SNZI [13], was not used due to its complexity. For sufficiently large systems it may be a better choice.

The implementation of multi-reader QD locks (Fig. 12) is derived from the writer-preference readers-writer lock algorithm [4]. In fact, functions rlock and runlock are unchanged; we include them just for completeness and refer the reader to that paper [4] for their explanation. The queue delegation algorithm itself requires only two changes to allow multiple parallel readers; refer to Fig. 12. The first is on line 7 where execution can be blocked on a write barrier to avoid starvation of readers. The second change is on line 11 where the code waits for all readers to leave their critical section.

One might be wondering why the delegation queue can be opened on line 10 while readers still can be active. With this code a read critical section can execute during the same time that one or more delegate calls are issued. However, this is not a problem because the delegated operations can never be executed while there are active readers; the loop in line 11 ensures this. Likewise, the lock used by the helper will prevent any readers from becoming active before all successfully delegated critical sections have been executed.

The main advantage of multi-reader QD locks compared to traditional readers-writer locks is that a writer does not need to wait for the readers. This makes it possible for writers to continue doing useful work after delegating their critical section whereas they would have to wait if a traditional readers-writer lock was used. This can also have the effect of making more read critical sections bulk up, which can increase parallelism even further.

7 Evaluation

Having compared queue delegation locking with other synchronization mechanisms on the algorithmic level, we now compare its performance experimentally. For this, we
use two synthetic benchmark sets and a benchmark program from the Kyoto Cabinet, which is a library of routines for managing a database and an application of considerable size and code complexity. The program we use is the kccachetest benchmark, which exercises an in-memory database that is designed to be used as a cache (cf. Section 7.3). We will compare QD lock variants mostly against the latest implementations of three state-of-the-art delegation algorithms as provided by their authors: flat combining, CC-Synch and H-Synch. We will also compare against our own implementation of DetachExec, based on the pseudocode by Oyama et al. [31]. The main difference between the original code and DetachExec is that the latter preallocates 4,096 thread local queue nodes. The queue nodes have a free flag that is changed before a queue node is delegated and after it has been executed so that they can be reused. In order to put performance numbers into perspective, we also include measurements for Pthreads, CLH and Cohort locks. The implementation of the CLH lock is taken from the Synch repository; the Cohort lock one is written by us. In the data structure benchmark we also use a recently proposed lock-free implementation of the priority queue data structure [24].

Parameters. All delegation algorithms except that by Oyama et al. have a help_limit constant that limits the number of operations that can be performed by a helper during a help session. We use the term help session to refer to the period of time from when a thread starts executing delegated operations to the time when it hands over this responsibility. The original flat combining (FC) implementation has two additional parameters: num_rep and rep_threshold. The num_rep constant decides the maximum number of traversals of the request list per help session. After every request list traversal the lock is handed over to another thread if less than rep_threshold operations have been performed. We also added a condition to FC that will hand over the lock to another thread if help_limit or more operations have been helped during the help session. The help_limit was set to 4,096 in all experiments that we present graphs for in this article. For FC, num_rep was set to 4,096 and rep_threshold was set to 1. We found these parameters to work well with all algorithms; increasing the value further gave only a very small increase in throughput.

Benchmark Environment. All benchmarks were run on a Dell server with four Intel(R) Xeon(R) E5-4650 CPUs (2.70GHz), eight cores each, with simultaneous multithreading (SMT) and TurboBoost (up to 3.30GHz) enabled. I.e., the system has a total of 64 SMT-threads running on 32 cores. The machine ran Debian Linux 3.16.0-4-amd64 and had 128GB of RAM. The two synthetic benchmarks are written in C, Kyoto Cabinet in C++, and the lock implementations in C and C++. All code was compiled using GCC version 4.9.2-10 with -O3. The duration of runs for all synthetic benchmarks was two seconds and we took measurements five times. The graphs show the average of these five runs, and bars for the minimum and maximum values we observed.

Thread Pinning. We pin threads to SMT-threads for two reasons. First, in order to avoid arbitrary thread migrations as a source of unreliability in the measurements. Second, pinning allows us to both show the performance on a single processor chip and a NUMA system in the same graph. Our pinning policy first fills all SMT-threads on one NUMA node, then on two NUMA nodes, and so on. The pinning policy on a NUMA node level aims to achieve the best performance that our machine can give when running a low number of threads: It first pins a thread to a core without any previously pinned thread (i.e., it first uses all physical cores of the NUMA node) and then fills the SMT-threads without any previously pinned thread (i.e., it then uses the hyperthreads). Measurements with up to eight threads will therefore run on the eight physical cores on a single chip on our machine. Up to 16 threads will run on a single chip with all SMT-threads occupied, up to 32 threads will run on two chips, and so on.

7.1 Data Structure Benchmark

This benchmark, also used in other papers [14], [17], is used to evaluate QD locking as a way of constructing concurrent data structures. Both FC and the Synch algorithms have been shown to perform very well for this kind of task [14], [17]. Delegation is especially beneficial for data structures such as queues, stacks, and priority queues, whose operations cannot be parallelized easily. The data structure we have chosen is a priority queue implemented using a pairing heap. This is a high-performance implementation of a priority queue that, when using flat combining, has been shown to outperform the best previously proposed concurrent implementations as well as the then fastest lock-free implementation [17]. We verify this by comparing against a more recent lock-free priority queue implementation [24], using the implementation provided by its authors. A priority queue is well-suited for comparing synchronization algorithms for a concurrent data structure because it has a natural mix of operations that do not return a value (insert) and operations that return one (extract_min). However, both are write operations.

The benchmark measures throughput: the number of operations that \( N \) threads can perform during \( t \) seconds. All \( N \) threads start at the same time and execute a loop until \( t \) seconds have passed. The loop body consists of some amount of thread-local work and a global operation (either insert or extract_min) which is selected randomly with equal probability. The seed for the random number generator is thread-local to avoid false sharing between threads. The thread-local work uses a thread-local array \( L \) with 64 integer entries. Each local work unit consists of randomly selecting two of the 64 entries of \( L \), an additional random integer \( I \), adding \( I \) to the value stored in the first entry, and subtracting \( I \) from the value of the second entry.

Figures 13 through 17 show the results of the benchmark for different thread counts and different amount of work between the operations. We use four scenarios in total: the case with no local work, and the cases with 32, 64 and 128 units of local work between each two accesses to the lock.

In Fig. 13, QD locks are compared with DetachExec, FC, and CC-Synch, as well as the standard CLH lock, the Pthreads mutex lock and the lock-free priority queue implementation. The graph at the top left corner shows the case with no local work. All algorithms except the lock-free one show a big performance drop when going from the sequential case to two threads. For all delegation

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The lock-free algorithm scales best until eight cores are used, but does not benefit from additional SMT-threads as much as delegation algorithms. Again, performance drops significantly when using more than one NUMA node in this setting. CC-Synch performs better than FC on a single NUMA node, which is reversed with more threads, but neither is designed for NUMA systems.

The graph in the top right corner of Fig. 13 shows results for 32 units of local work between the operations. In this scenario, there is some amount of thread-local work between critical sections which benefits from parallelization. Thus, the single-threaded case is no longer the optimal choice. The lock-free algorithm scales best until eight cores are used, but does not benefit from additional SMT-threads as much as delegation algorithms. Again, performance drops significantly when using multiple NUMA nodes and again the algorithms are affected roughly the same by this.

The two graphs at the bottom of Fig. 13 show a different picture. Performance between different algorithms up to 16 threads becomes more similar, and in the bottom right graph even CLH locks perform well up to 16 threads. In the bottom left graph, algorithms other than QD locks still somewhat drop in performance when using more than 16 threads while QD locks maintain their performance. Even more striking, no delegation algorithm drops in performance in the bottom right graph, but only QD locking continues to scale with more threads.

Figure 14 shows how hierarchical algorithms deal with NUMA effects. Here we see that Cohort locks maintain their performance when going beyond 16 threads, albeit at a lower level than delegation algorithms. The hierarchical delegation algorithms, HQD lock and H-Synch, outperform the other algorithms when using more than one NUMA node in the zero local work case. This is due to their ability to reduce the amount of memory transfers between NUMA nodes.

The reason why the HQD lock performs better than H-Synch and the QD lock performs better than FC and CC-Synch is twofold: First, the QD and HQD locks can delegate their insert operations without having to wait for them to be applied to the underlying data structure. Second, the QD and HQD locks can have fewer cache misses because approximately 50% of the operations do not need a value written back and the helper can read several operations from the delegation queue with one cache miss. This is because the operations are stored one after the other in an array buffer so that several operations can fit in a single cache line. Both flat combining and the Synch algorithms require at least one cache miss for the helper thread to read an operation and one cache miss for the thread issuing the operation to read the response value or an acknowledgment. Due to the cost of transferring the data structure between the cores on the same NUMA node, the Cohort lock is not able to perform
A Deeper Look into QD Locking’s Performance

The graphs in Fig. 16 and 17 investigate the performance effect of different implementation aspects of QD and HQD locks. Lines for QD and HQD locks are included in these graphs as reference points, while the other lines correspond to implementations with a twist. QD (MCS) refers to a QD lock that uses a standard MCS lock instead of an MCS-futex lock internally, while HQD (futex) refers to an HQD lock that uses an MCS-futex lock instead of an MCS lock. The QD (MCS) lock performs very similar to the standard QD lock, showing that in the scenarios measured there is no worrisome overhead for using MCS-futex locks. For the HQD (futex) lock this is different: Using an MCS-futex lock causes HQD locks to drop in performance drastically when more NUMA nodes are added. The cause here is that only one NUMA node is active at a time in HQD locks, which causes the MCS-futex locks on all other nodes to enter the sleep state. However, this means the eventual lock contention is not high enough.

This problem is clearly illustrated in the graphs in Fig. 15. The graphs to the left of this figure show performance with varied amount of local work units. The graphs to the right show the average number of helped operations per help session instead of performance. Note that we have excluded the DetachExec lines from the graphs to the right because of different implementation aspects of QD and HQD locks compared to the other locking algorithms because of the ability to delegate insert operations without needing to wait for a response. Because QD locks allow for more parallelism, they benefit from this effect more strongly than HQD locks. Therefore, when there is not enough contention, QD locks can outperform hierarchical algorithms.

In the top right scenario in Fig. 14, the QD lock performs better than H-Synch even when using more than one NUMA node. The reason for this is again twofold: First, the QD lock’s ability to delegate insert operations without waiting is more beneficial in this scenario. A thread that delegates an insert operation is guaranteed to be able to execute at least 32 units of work until it executes another global operation again (and possibly waits). In the zero local work scenario, there is 50% chance that a thread needs to wait for the result of an extract_min operation almost directly after completing an insert operation. Second, the drop in performance of H-Synch when using more than one NUMA node shows a problem with the hierarchical delegation approaches when contention is not high enough.

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Fig. 14. Same benchmark as in Fig. 13, but showing hierarchical algorithms.

well compared to delegation algorithms on this workload. This downside of Cohort locks could potentially be mitigated by HMCS locks [5], which also aim to reduce data transfers between cores.

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This problem is clearly illustrated in the graphs in Fig. 15. The graphs to the left of this figure show performance with varied amount of local work units. The graphs to the right show the average number of helped operations per help session instead of performance. Note that we have excluded the DetachExec lines from the graphs to the right because of the lack of support for limiting the number of helped operations per help session in the algorithm. This means the helper thread is starved with the method by Oyama et al. It is clear that the drop in number of operations that are helped per help session drops earlier for the hierarchical variants than the non-hierarchical ones. The reason for this is easy to understand if one considers that the contention on a NUMA node level is lower than on the system level. The drop in operations that are helped per help session correlates well with the drop in performance for the hierarchical variants which can be explained with the increased traffic between the nodes. The two graphs at the bottom part of Fig. 14 can also be explained with a similar reasoning: More work between the operations is more beneficial for QD locks and HQD locks compared to the other locking algorithms because of the ability to delegate insert operations without needing to wait for a response. Because QD locks allow for more parallelism, they benefit from this effect more strongly than HQD locks. Therefore, when there is not enough contention, QD locks can outperform hierarchical algorithms.

A Deeper Look into QD Locking’s Performance

The graphs in Fig. 16 and 17 investigate the performance effect of different implementation aspects of QD and HQD locks. Lines for QD and HQD locks are included in these graphs as reference points, while the other lines correspond to implementations with a twist. QD (MCS) refers to a QD lock that uses a standard MCS lock instead of an MCS-futex lock internally, while HQD (futex) refers to an HQD lock that uses an MCS-futex lock instead of an MCS lock. The QD (MCS) lock performs very similar to the standard QD lock, showing that in the scenarios measured there is no worrisome overhead for using MCS-futex locks. For the HQD (futex) lock this is different: Using an MCS-futex lock causes HQD locks to drop in performance drastically when more NUMA nodes are added. The cause here is that only one NUMA node is active at a time in HQD locks, which causes the MCS-futex locks on all other nodes to enter the sleep state. However, this means the eventual lock contention is not high enough.

This problem is clearly illustrated in the graphs in Fig. 15. The graphs to the left of this figure show performance with varied amount of local work units. The graphs to the right show the average number of helped operations per help session instead of performance. Note that we have excluded the DetachExec lines from the graphs to the right because of the lack of support for limiting the number of helped operations per help session in the algorithm. This means the helper thread is starved with the method by Oyama et al. It is clear that the drop in number of operations that are helped per help session drops earlier for the hierarchical variants than the non-hierarchical ones. The reason for this is easy to understand if one considers that the contention on a NUMA node level is lower than on the system level. The drop in operations that are helped per help session correlates well with the drop in performance for the hierarchical variants which can be explained with the increased traffic between the nodes. The two graphs at the bottom part of Fig. 14 can also be explained with a similar reasoning: More work between the operations is more beneficial for QD locks and HQD locks compared to the other locking algorithms because of the ability to delegate insert operations without needing to wait for a response. Because QD locks allow for more parallelism, they benefit from this effect more strongly than HQD locks. Therefore, when there is not enough contention, QD locks can outperform hierarchical algorithms.
handover takes significantly longer, resulting in overall worse performance. For the lines identified as QD (CAS based) and HQD (CAS based), the `fetch_and_add` call in the enqueue function (line 10 of Fig. 6) is simulated with a CAS instruction. We did this to find out how QD locking would perform in processors without a `fetch_and_add` (FAA) instruction. It is clear that FAA is beneficial for QD locking’s implementation. It is also clear that even without using the FAA instruction, QD and HQD perform similar or better than the other algorithms we compare against. The implementations labeled QD (nodetach) and HQD (nodetach) have `insert` calls that wait for an acknowledgment from the delegated operation, even when the return value is not used. From these lines, it is clear that a large part of QD locking’s performance advantage in this benchmark comes from the ability to do detached execution. However, QD locking still performs slightly better than other algorithms even without detached critical sections. Finally, QD (TATAS) and HQD (TATAS) refer to implementations that use a simple TATAS lock internally and do not set a limit for retries to avoid starvation. This leads to at most a minuscule advantage in performance, which shows that the cost of avoiding starvation is not severe.

Further experiments with combinations of the above variants as well as with padding delegation queue entries to entire cachelines have not shown much deviation from the results shown here and are thus omitted from the figures.

### 7.2 Readers-Writer Benchmark

To evaluate our multi-reader QD lock implementations and compare them to other readers-writer locks we use a benchmark especially designed for RW locks. The benchmark is implemented from the description of RWBench that has been presented by Calciu et al. [4]. RWBench is similar to our data structure benchmark in that it measures throughput: the number of critical sections that \( N \) threads, which alternate between critical section work and thread-local work, can execute during \( t \) seconds. A shared array \( A \) with 64 integer entries is used for the protected shared memory. According to a specified probability for reading, it is determined randomly whether the critical section is a read or a write operation.

The read critical section work is placed inside a loop that iterates for four times. Inside this loop, the values of two random array slots from the shared array \( A \) are loaded.

The loop iteration count is also 4 for the write critical section. In the loop body, two of the 64 entries of \( A \) are updated in the following way: The two entries are randomly selected and an additional random integer \( I \) is generated.
Then \( I \) is added to the value stored in the first entry and subtracted from the value of the second entry. Thus, the sum of all array elements should be zero after the benchmark completes and can be used as a sanity check.

The thread-local work uses the same loop as the write operation, but writes in a thread-local array instead. One iteration in this loop is defined as one unit of thread-local work. This thread-local work is also used in the data structure benchmark (Section 7.1).

We compare our multi-reader QD lock (MR-QD) and its hierarchical variant (MR-HQD) with the DR-MCS and WPRW-Cohort algorithms of Calciu et al. [4]. All locks are constructed using the same algorithm; see Section 6. DR-MCS is a readers-writer variant of the MCS queue lock and WPRW-Cohort is based on a Cohort lock. For comparison we also show the performance of a mutual exclusion Cohort lock. The benchmark was run with different combinations of read probability and thread-local work. Figure 18 shows the results for 50\%, 80\% and 95\% reads combined with 0, 32 and 128 thread-local work loop iterations.

The left column shows the somewhat unrealistic scenario of no thread-local work. Under such high contention, all algorithms perform best when operating on a single chip, but only the QD locking algorithms scale when there are many write operations. In the right column, with a high amount of thread-local work, it can be seen that with 50\% and 80\% readers only MR-QD continues to scale when running on multiple chips. Overall, it can be seen that MR-QD and MR-HQD outperform the other algorithms on a single processor chip when there is high contention or many write sections. Furthermore, MR-QD outperforms all other algorithms when running on multiple chips. MR-HQD, on the other hand, does not work as well on multiple chips. We reason that this is because the contention on the delegation queue drops too low, and therefore the lock is released frequently.

With only 50\% read operations and 64 threads the mutual exclusion Cohort lock performs better than DR-MCS and comparably to WPRW-Cohort. This shows that our algorithms, which perform better when enough contention is maintained, can be used efficiently in scenarios with many writers. Established readers-writer locks have been limited to applications with very high amounts of readers to amortize the additional cost over mutual exclusion locks. Fewer readers are required for multi-reader QD locks to amortize their cost and be useful in applications traditionally not considered for readers-writer locking. But even with high amounts of readers, MR-QD consistently outperforms the other algorithms. In our experiments this is true even for 99\% readers, albeit the difference becomes less pronounced. With only readers all four algorithms use only the read indicator, and therefore behave identically.

### 7.3 Kyoto Cabinet Benchmark

We also tested our multi-reader QD locks on the kccachetest program from the Kyoto Cabinet (version 1.2.76, compiled with -O2) to evaluate the feasibility of using it in existing software and how well it performs compared to other algorithms. The kccachetest uses CacheDB, an in-memory database designed for use as a cache. In particular, we run 100,000 iterations of the wicked workload, which uses a user-defined amount of workers to perform operations on a CacheDB. As the workload is changed depending on the number of threads, it is not easily possible to compare performance with different numbers of workers. However, a comparison of different algorithms running with the same number of workers is possible.
We have also employed QD locking in two bigger systems. Written to it. With these tools ready, the porting itself was postponed until at least
64 numbers of worker threads. The row labeled Pthreads RW shows the performance of the original code of Kyoto Cabinet. The kccachetest is a kind of worst case scenario for our algorithms. It is designed to act as a benchmark but also to test the database. Therefore it always checks return values immediately to verify correctness. Besides that, outside the critical sections it only generates random numbers to decide which database operation to perform next. To make better use of delegation, we also patched the benchmark itself. For the two rows marked with (p) some error-checking has been postponed until at least 64 return values can be checked in bulk. This patch did not affect performance of the non-QD locking algorithms. Even without this patch, the results show that MR-QD and MR-HQD perform slightly better than other readers-writer locks. In contrast to Section 7.2, here MR-QD performs only slightly better than MR-HQD. This benchmark benefits less from detached execution as return values still need to be read for error checking and memory needs to be transferred to read the return value.

All in all, this shows that QD locks can be used in real applications for immediate benefit. Even better results are achieved when utilizing the time between a delegation and the use of return values.

All benchmark programs are available at http://www.it.uu.se/research/group/languages/software/qd_lock_lib.

7.4 Experience from Two Use Cases

We have also employed QD locking in two bigger systems. The first of them is in the implementation of the Erlang Term Storage (ETS). ETS is Erlang’s in-memory key-value store and is the only shared memory between Erlang processes. Being shared memory, ETS has become a scalability concern on multicore machines [20]. As ETS tables are protected by locks, QD locks were used to improve performance. Using our C QD locking library to gradually transform the code [21], we first used MR-QD locks without detaching execution (MRQD-wait). Then, we passed all required parameters in an allocated struct to the algorithm so detaching execution was possible (MRQD-malloc). Finally, we wrote a version that passes the parameters directly into the MR-QD lock instead of allocating an object on the heap (MRQD-copy). It was shown [21] that all three versions significantly outperform the existing ETS implementation in contended scenarios. While MRQD-copy performed best under most circumstances, the cost of copying parameters made MRQD-malloc more efficient for large parameter sizes (above 150 bytes per critical section).

The second use case for QD locking is in the Argo Distributed Shared Memory System [19]. ArgoDSM provides a shared memory layer for running applications on multiple cluster computer nodes. There, traditional locking does not perform due to the enormous communication cost even for spin-waiting on values. Thus HQD locks were chosen as a provider for mutual exclusion, as they allow the single-node performance to be available in such systems.

For more information on these use cases, we refer the readers to these two publications [19], [21].

8 Concluding Remarks

We have presented the details of a novel synchronization mechanism called queue delegation locking and variations to support multiple readers as well as NUMA systems. Our experiments show that QD locking can outperform current state-of-the-art delegation algorithms such as flat combining, CC-Synch and H-Synch. A key advantage of QD locking is its ability to delegate operations without waiting for a response, its simplicity and its small communication cost. Our results also suggest that multi-reader QD locks can be a better performing alternative to readers-writer locks for some use cases, especially with workloads that frequently require a full exclusive lock but still can exploit some read-only parallelism. It remains as future work to look into is how QD locking can be used for data structures with fine-grained locking such as hash tables. Finally, an important practical issue to investigate is how tools can help programmers in migrating from traditional synchronization mechanisms and get the highest benefit possible from queue delegation locking.

References


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