Releasing Memory with Optimistic Access: A Hybrid Approach to Memory Reclamation and Allocation in Lock-Free Programs

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Abstract

Lock-free data structures are an important tool for the development of concurrent programs as they provide scalability, low latency and avoid deadlocks, livelocks and priority inversion. However, they require some sort of additional support to guarantee memory reclamation. The Optimistic Access (OA) method has most of the desired properties for memory reclamation, but since it allows memory to be accessed after being reclaimed, it is incompatible with the traditional memory management model. This renders it unable to release memory to the memory allocator/operating system, and, as such, it requires a complex memory recycling mechanism. In this paper, we extend the lock-free general purpose memory allocator LRMalloc to support the OA method. By doing so, we are able to simplify the memory reclamation method implementation and also allow memory to be reused by other parts of the same process. We further exploit the virtual memory system provided by the operating system and hardware in order to make it possible to release reclaimed memory to the operating system.

1 Introduction

With the recent developments in computer hardware focusing on the increase of parallelism as the main way to improve performance, it is key to have accompanying software capable of taking advantage of such hardware. Lock-free data structures provide one of the most fundamental building blocks for concurrent/parallel software, as the lock-freedom property promotes scalability and guarantees immunity to livelocks, deadlocks and priority inversion [10]. However, in comparison to their lock-based counterparts, lock-free data structures require additional support in order to manage memory reclamation. This can be delegated to a garbage collector, if the programming runtime being used provides one, but such a garbage collector is usually not lock-free causing the system as a whole to lose the lock-freedom property [18].

An alternative is to use a specific memory reclamation method. The most common methods, such as *pass the buck* [9] and *hazard pointers* [15], are based on the idea of threads advertising their coordinates in order to prevent other threads from reclaiming the memory they are using. This idea however requires every thread to constantly write its coordinates to memory and perform expensive memory barriers in order to ensure that such memory writes are visible. More sophisticated methods try to amortize the memory writes and consequent memory barrier usage. Some examples are *drop the anchor* [2], *hazard eras* [19], *interval based reclamation* [23], and *hazard hash and level* [17], among others. Dice et al. [7] also provide a mechanism to reduce the cost of memory barriers, but such mechanism requires hardware/operating system support.

Instead of having threads advertising their coordinates, a more recent strategy, called *optimistic access* (OA) [5], allows threads to optimistically access the memory they are traversing and only after verify if the access is valid. In order to be able to check the validity of a memory access, the OA method moves the responsibility to the reclaiming threads to advertise that memory reclamation has occurred. This no longer requires threads to constantly write to memory to advertise their locations, but only to do extra reads to check if memory reclamation has occurred. These extra reads are inexpensive, as they will target a cached memory location most of the time, and require less expensive memory barriers.

An important disadvantage of existing OA based methods is that they are unable to release memory to the memory allocator/operating system. This happens due to the fact that, at anytime, a thread may read memory that has already been reclaimed. To work around this problem, these methods implement a recycling mechanism to manage the memory being used. However, this prevents the memory used in this manner from being reused in other parts of the same process and from being released to the operating system.

In this work, we propose a solution to this problem without having to make the whole application aware of the memory reclamation method. Our proposal is to extend *LRMalloc* [12], a lock-free general purpose memory allocator, in such a way that we can guarantee memory allocations to be readable even after we free such allocations.

No guarantees are given about the content of the memory, or how it is reused by the rest of the application. This is a good match for OA because it already ensures that the contents of reads on possibly reclaimed memory are to be ignored, and that memory to be written is protected from reclamation by the use of hazard pointers.

We start by solving the problem at the memory allocator level, by adapting LRMalloc such that it does not release memory used by the OA method back to the operating system. This allows us to simplify the implementation of the OA memory reclamation method as we no longer need a recycling mechanism in order to manage the distribution of memory between threads. This task is now covered by the memory allocator as it was designed for this task in a general sense. We also gain the ability to reuse memory reclaimed by the OA method across the whole process. As we will see, all this is possible with minimal changes to the LRMalloc memory allocator.

Then, to complete our solution, and have the ability to release the memory used by the OA method to the operating system, we exploit how current operating systems/hardware use virtual memory. As we need the virtual addresses (pages) to remain accessible after they have been used by the OA method, but we do not care about the contents on the physical memory (frames) they are mapped to, we map all these multiple pages to the same frame. This allows us to free all the frames our pages were previously mapped to while keeping the pages still valid for access.

Modern operating systems apply similar strategies, e.g., when a memory request is made to the operating system, no frame is immediately reserved, only the pages are made valid by being all pointed to a single *copy on write* zero filled frame. Only when a memory write is attempted in these pages, is that the operating system copies the zero filled frame to a new free frame and maps the page to it. This all happens transparently to the application, which never notices that the memory given to it at the start was not actually backed by physical memory. One of the strategies we propose to implement the remapping of pages exploits this operation system behavior, while the other strategy will do the remapping in a more explicit fashion using the shared memory mechanisms of current operation systems.

The remainder of the paper is organized as follows. First, we introduce relevant background. Then, we present in detail the main ideas supporting our approach and discuss its current limitations. Next, we show a set of experiments comparing our model against the original OA method. At the end, we present conclusions and further work directions.

2 Background

This section briefly introduces relevant background about virtual memory and memory allocation systems and describes in more detail the LRMalloc memory allocator and the Optimistic Access (OA) method.

2.1 Virtual Memory

Virtual memory is a memory management system that works as an abstraction layer that allows for a multitude of optimizations in modern operating systems. The main idea is to have a translation layer between the memory addresses viewed by a user process and the actual physical addresses in main memory. The translation is done in hardware by the *memory management unit* (MMU) and relies on a cache named *translation lookaside buffer* (TLB). This introduces an overhead, as with virtual memory, when trying to access a memory location, one first needs to consult where the virtual address resides in physical memory. This requires extra memory accesses in order to obtain the physical memory location, however by the use of an efficient TLB this disadvantage is mostly mitigated. Modern systems define the granularity of a page/frame to be a power of 2, usually between 4KiB and 1GiB total size.

The main benefits provided by virtual memory are the ability for processes to oversubscribe memory allowing them to use more memory than what is physically available, the ability of multiple processes having the same address space, the ability to move unused pages from memory to persistent storage when under memory pressure, and the ability to block a process from accessing or modifying any memory that does not belong to it. Virtual memory also allows memory to be shared between processes, the most common case being shared libraries, so multiple processes can use the same copy of a library in physical memory but each have it in a different memory address. Another important use case is efficient inter-process communication, made possible having two or more processes mapping a single region of physical memory into their own address spaces.

Further optimizations include the ability to only load frames when they are needed, meaning that when a process is loaded into memory, it does not need to be entirely loaded, only the necessary frames are loaded as the corresponding pages are accessed. For example, an error routine that is never called would never actually be loaded into physical memory. When a process requests memory from the operating system, a similar optimization can be done, every page the process requests can be initially mapped to a single zero filled frame and only mapped to free memory frames when they are actually written to. As we will see later, this is one of the features that we will take advantage of for our proposal.

2.2 Memory Allocation

Memory allocators serve as an interface between processes and the operating system, satisfying memory requests of any size in such a way that processes waste as little additional memory and time as possible. To do so, a memory allocator starts by acquiring pages from the operating system that are then subsequently divided to satisfy smaller allocation requests, and later combined in order to give complete pages back to the operating system. Classic memory allocators [24] tended to use strategies like *best-fit*, in which they find the smallest block of contiguous memory that can satisfy the request and, if such a block is still too big, it is split to the right size so they can keep what remains to a future allocation. Another strategy is *first-fit*, in which instead of finding the smaller continuous block that satisfies a request, they simple use the first block found. This strategy has a speed advantage, but can increase memory waste.

A more modern strategy is to use *size classes*, where any request is met by rounding up to the nearest size class. Blocks of a size class are created by splitting a bigger block into many blocks of the same size. The size classes need to be carefully selected, therefore avoiding too many different classes and possibly allocations of large blocks that result in a limited amount of allocations from it, or too few classes and possibly wasting memory by having to provide a much larger allocation than needed due to the nonexistence of a large enough smaller size. Size classes are very time efficient and tend to improve memory locality, therefore also improve the global performance of applications beyond memory allocation.

With the advent of multi-core processors, in order to further improve performance and scalability, different proposals were adopted to minimize the amount of synchronization between threads. These gave origin to mechanisms such as *private heaps* [1], in which each thread has a private allocator implementing specific strategies to deal with frees that occur in threads different from the one where the memory was allocated. These strategies can be used to kept the free memory in the thread in which it was freed until it is allocated again; to immediately give back the free memory to the thread it was allocated on; or to give back only after a threshold is met. An alternative mechanism is to use a per thread cache on top of a shared heap [11].

2.3 LRMalloc

LRMalloc [12] is a modern lock-free memory allocator that uses size classes and thread caches as described above. It has three main components: (i) the *thread caches*, one per thread; (ii) the *heap*; and (iii) the *pagemap*. Figure 1 shows the relationship between these three components, the user's application and the operating system,

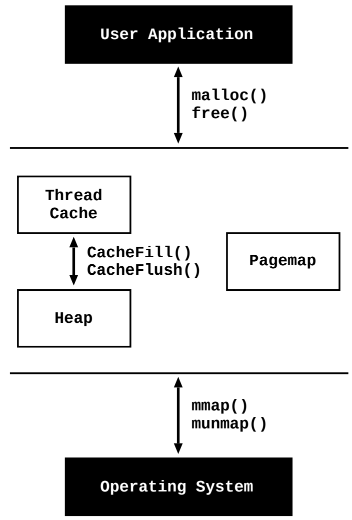


Figure 1: LRMalloc's overview

The thread caches use a stack for every size class, so that a memory request becomes simply a pop on the corresponding size class stack, and a memory free becomes a stack push. When a memory request is made and the corresponding stack is empty, then the stack is filled from the heap, and when a memory free happens and the stack is full, it is flushed back to the heap. The size of the stack is limited in order to prevent *blowup* [1]. The caches are local to a thread, so they only synchronize with other threads when a fill or flush from/to the heap occurs.

The heap is responsible for managing *superblocks*, which are large blocks of memory obtained from the operating system that are then divided into blocks of a size class to be given to the thread caches. Superblocks are managed through *descriptors*, an object that contains the superblock metadata and that is never reclaimed. When a superblock is released to the operating system, the associated descriptor is added to a recycling pool in order to be reused for a future superblock. The descriptor contains information, such as, where the superblock begins, its associated size class, the number of blocks it possesses, the index of the first free block and the number of free blocks.

Superblocks can be in one of three states: (i) *full*, if all its blocks are in use; (ii) *empty*, if all its blocks are available for allocation; or (iii) *partial*, if it has available and allocated blocks. The initial state of a superblock is always full, as all its blocks are immediately used to fill a cache. Then it becomes partial as some blocks are returned to it by cache flushes, at which point it can either become full again, if a threads uses it to fill its cache, or it can become empty, if all blocks are returned to it. When a superblock becomes empty, it cannot be used again and its memory is released back to the operating system. When threads try to fill their caches they give priority to partial superblocks and, if none is available, a new superblock is created by requesting memory from the operating system.

The pagemap is a simple lock-free data structure that stores metadata for each page in use. Taking into account that superblocks are always aligned with pages and have a size that is a multiple of the page size, blocks in the same page always belong to the same superblock. So this metadata includes the superblock that a page belongs to and its associated descriptor. The main usage of the pagemap is to allow finding the corresponding superblock for a block that is flushed from the cache, or to allow finding the appropriate cache (with the correct size class) when memory is receive from the application through a call to the *free()* procedure.

2.4 Optimistic Access

A memory reclamation method for a lock-free data structure is a mechanism that detects when an node removed from the data structure can no longer be referenced by any running thread, and thus uses such information to free the corresponding memory to the memory allocator/operating system. Usually, such methods require some sort of validation to avoid accessing memory that has been already reclaimed.

An alternative approach is the one followed by the *optimistic access* (OA) method [5], which, as the name implies, allows memory accesses before making sure the memory has not been reclaimed, and only then checks the validity of the access by reading a specific *warning-bit*. If the access corresponds to reclaimed memory, the result is ignored and the procedure is restarted from a memory location known to be valid. However, modifying operations cannot be performed in an optimistic manner as an optimistic CAS could incorrectly succeed due to an ABA problem [6]. For that, OA uses a hazard pointer strategy, so before performing any atomic CAS (*Compare-and-Swap*) update operation, it first protects all memory addresses involved by assigning hazard pointers to them and then performs a single additional validity check by reading the *warning-bit*, therefore ensuring that the memory was valid when it was protected by the hazard pointers. These hazard pointers are then used to prevent the recycling of the memory they are assigned to.

The OA memory recycling mechanism is composed by three pools: (i) the *ready pool* that contains all the nodes ready to be allocated, (ii) the *retire pool* to which nodes are added when they are retired from the data structure, and (iii) the *processing pool* that holds the nodes that are in the process of being recycled. The recycling mechanism works in phases, and a new phase is triggered when the ready pool is exhausted. At the start of a new phase, the nodes present in the retire pool before the phase stars are moved to the processing pool. Next, all threads are informed of the current recycling by their *warning-bit* being set. Finally, the nodes in the processing pool that are protected by hazard pointers are moved back to the retire pool, the ones not protected are moved to the ready pool. Threads that try to retire an node during the process of moving nodes from the retire pool to the processing pool need to help finish the move before retiring the node. Threads that try to start a new recycling phase while one is already in progress need to help finish the current phase before starting a new one.

While the recycling mechanism is complex and time consuming, it is rarely executed, which mitigates its cost. For the more frequent operations, such as the traversal of the data structure, this method only needs to perform an extra read per node traversed instead of a write, as it is the case for the hazard pointers memory reclamation method, and it also requires a much less expensive memory barrier, which in *total store ordering* (TSO) architectures like x86-64, translates to a simple compiler barrier and no additional hardware instructions are emitted. Also note that writing operations only require one validity check for setting multiple hazard pointers and consequentially only one expensive memory barrier, compared to the hazard pointers method which requires one per node. These characteristics make the optimistic access memory reclamation method extremely efficient and performant compared to the state-of-the-art, while also having low memory bounds and not requiring any specific support from the operating system.

A consequence of allowing optimistic accesses to possibly reclaimed nodes is that nodes need to remain accessible after being reclaimed. However, there is no need for the contents of the node to be maintained, as the result of the access will be ignored in the case it was invalid. To ensure the nodes are accessible after being reclaimed, the recycling mechanism is used, which allows nodes to be reused, but never released to the memory allocator or the operating system.

3 Our Approach

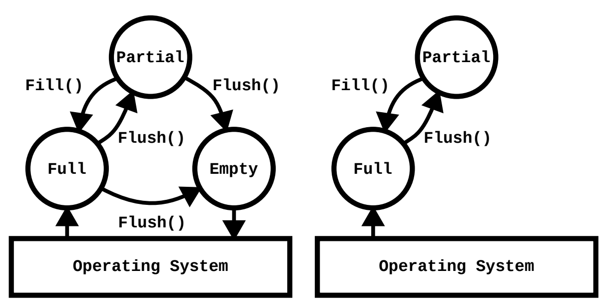
In this section, we start by introducing how we make LRMalloc compatible with the OA memory model and how we can use it to simplify the OA method. Next, we present how we can exploit virtual memory in order to allow memory to be released to the operating system.

3.1 Memory Recycling at the Allocator Level

As mentioned before, in a program using a lock-free data structure in combination with the OA memory reclamation method, the memory reclaimed can be reused by the data structure but it cannot be reused by other parts of the program, at least without extensive modifications both to the memory reclamation method and to the rest of the program.

Our solution is to handle this restriction at the memory allocator level by making sure that memory can be accessed even after being freed. The allocator would still not provide any guarantees of the contents of the freed memory, and we would not be allowed to write to it either, as it could lead to corruption if such memory was already reused in another allocation. To achieve this we extended LRMalloc with a new function that we named *palloc()* (*persistent alloc*).

To implement *palloc()*, we follow the same process as regular a allocation, but the *superblock* that contains the memory block being allocated is marked as *persistent*. This mark is then used to guarantee that persistent superblocks never reach the *empty* state, even if all its blocks are available. This change ensures that memory allocated with *palloc()* is never released to the operating system, but can still be reused by future allocations anywhere on the same process. Figure 2 shows the state diagram for superblocks before and after being marked as persistent.



(a) Non-persistent (b) Persistent

Figure 2: State diagram for superblocks

By having an allocator that satisfies these properties, we can now extensively simplify the memory reclamation method. As we no longer need the memory recycling mechanism employed originally in the OA method, we can use a much simper mechanism, similar to the one used by the hazard pointers memory reclamation method, as shown in Alg. 1.

Algorithm 1 Retire(Node N)

```
LimboList.add(N)
if LimboList.full() then
  for T in Threads do
    T.warning_bit.set()
  end for
  MemoryBarrier()
  for T in Threads do
    HPSet.add(T.hazard_pointers)
  end for
  for M in LimboList do
    if not HPSet.contains(M) then
      LimboList.remove(M)
      Free(M)
    end if
  end for
  HPSet.reset()
end if
```

The idea is as follows. When a node is retired, we add it to the reclaiming thread's *limbo list*, and when the list's size reaches a certain threshold, we perform the reclamation procedure. During such procedure, we only need to set all the other threads' *warning-bit* and then free all nodes that are not protected by a hazard pointer.

This mechanism however is not ideal for data structures with long chains, such as linked lists, since as we trigger more warnings, more restarts are needed. These restarts are inexpensive on data structures with short chains, such as hash tables, but not so much in linked lists, not only because the amount of work lost by a restart is high, but also because the beginning of the chain is most likely out of the L1 cache by the time of the restart.

To mitigate this issue, we implemented another warning mechanism that is based on the one used in the *Version Based Reclamation* (VBR) method [21]. In this mechanism instead of having a warning bit per thread, we have a monotonic global variable that we increment when we want to send a warning to all threads, and threads check for the warning by comparing the last value seen in the global variable with the current value. With this mechanism we can allow threads to piggy back of each other warnings, as we can forego sending a warning if one has happened since the time the nodes we want to reclaim was retired. Note that we not only take advantage of other threads warnings when we see the increment in the global variable, but also when we try to increment it with a CAS and it fails, what means that a warning was successfully fired by another thread and we can take advantage of it. Algorithm 2 shows the retire procedure and how it is able to piggy back of other threads. Note that this is not possible on the previous method as the warnings are not atomic with one *warning-bit* per thread. In this algorithm, the *GlobalClock* variable represents the global monotonic variable, the *LocalClock* is a local variable used to store the last seen value of the global variable, and the *LastRetireTime* is a local variable used to take advantage of the other threads warnings.

Algorithm 2 Retire(Node N)

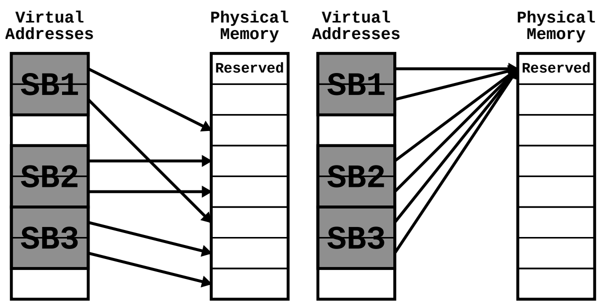
```
if LimboList.full() then
  if LastRetireTime = LocalClock then
    CAS(GlobalClock, LocalClock, LocalClock + 1)
    LocalClock ⇐ GlobalClock
  end if
end if
if LastRetireTime < LocalClock and LimboList.size() > X
then
  MemoryBarrier()
  for T in Threads do
    HPSet.add(T.hazard_pointers)
  end for
  for M in LimboList do
    if not HPSet.contains(M) then
      LimboList.remove(M)
      Free(M)
    end if
  end for
  HPSet.reset()
end if
LastRetireTime ⇐ LocalClock
LimboList.add(N)
```

As mentioned earlier, with this method we end up with memory that we can never release to the operating system throughout the lifetime of the process. In the case that a large amount of memory is allocated with *palloc()*, that memory will continue in the process even if the amount of memory it requires for the remainder of its lifetime is much lower. The main advantage of this mechanism is that it requires no additional features from the operating system or hardware compared to any other lock-free memory allocator.

3.2 Using Virtual Memory

Now that we have made the memory allocator compatible with the optimistic access model, we next focus on the interaction with the operating system. Remember that the memory allocator cannot release superblocks marked as persistent to the operation system because they need to remain accessible.

If we take a closer look to this problem, taking into account the virtual memory system, we can observe that what actually needs to remain accessible is the address range of the superblocks marked as persistent and not the backing physical memory, as there is no requirement regarding accessing the contents of the reclaimed memory. Thus, the problem can be solved if we can release the physical memory associated with such superblocks but maintain the addresses range accessible.[1] To do so, we can remap the address range of a persistent superblock becoming empty into a default pre-reserved frame. Thus, independently of how many empty superblocks we have, they will just consume a single frame of physical memory. This single frame could even be a frame already in use by the process, as long as we can ensure it will remain accessible throughout the lifetime of the process. Figure 3 illustrates this remapping process. In Fig. 3a we show multiple persistent superblocks using 2 pages each, with each page mapped to a different frame, and in Fig. 3b we show how the superblocks can be remapped in order to release all their frames while keeping the access to them valid.



(a) Before (b) After

Figure 3: Memory mappings before and after the remapping process

However, we need to be careful as the virtual address space is an abundant but limited resource. So, some mechanism to recycle the virtual addresses of the remapped superblocks still needs to be used. But this is almost already done by LRMalloc when it needs to recycle the *descriptors* that contain the metadata of a superblock. Remember that when a non-persistent superblock becomes empty, the superblock is unmapped and the descriptor is added to the recycling pool. Later, when a new superblock is requested, first, a descriptor is obtained from the recycling pool, then a superblock is mapped from the OS, and finally the metadata in the descriptor is rewritten with the metadata of the new superblock. So, if we use instead the address range stored in the descriptor obtained from the recycling pool to map the new superblock, we are effectively recycling the virtual address space by piggy backing on the descriptor. In the actual implementation, we added an additional recycling pool with this mechanism, which we give priority to obtain blocks from, and keep the original for descriptors originated from non-persistent superblocks. The reason for the second pool will become clearer in section 4.

For the actual remapping process, we propose 2 methods. The first method is to advise the operating system that the memory will not be needed. In Linux, this is accomplished by the use of the *madvise()* system call with the *MADV_DONTNEED* flag, which reverts the memory mapping to a state similar to when the superblock was first allocated, i.e., all pages are mapped to a single copy on write zero filled frame. This frees all physical memory previously associated with the map until it is written again. Note that reads to these ranges of memory do not cause a page fault, but only an actual read from the zero filled frame. With this method, when we get a descriptor from the recycling pool, we do not need to do any extra work for remapping as the original address range is already valid and ready to use.

This first method has the advantage of being simpler and more efficient, but has two main disadvantages. One disadvantage is that even though this system call and flag are defined in the POSIX standard, the standard itself does not imposes the behavior observed in Linux, which makes this method not portable. Another disadvantage is that some optimistic access derived methods, like VBR [21], use DWCAS (Double-Width Compare-and-Swap) on reclaimed memory, even though the DWCAS is certain to fail[2] as otherwise it would lead to corruption, the operating system is unable to ascertain that and faults a frame in through the copy on write mechanism. This does not cause a correctness issue but could lead to some memory leaking, as some pages would be reserved for unallocated superblocks.

The second method is to use the shared memory mechanism. We start by defining a shared memory region and then, when we want to deallocate a superblock, we map its address range to the shared memory region. We can choose a size for the shared memory region that varies from the size of a page to the size of a superblock, which can lead to different performance trade-offs as we need one system call to do the remap if we choose the size of a superblock, two system calls if we choose half the size of a superblock, and so on. Note that the physical memory associated with the shared memory region could be used to store something useful in the meantime. For example, it could be used to store the *descriptors*. Later, to reuse the virtual range of the superblock we need to remap it again to new memory. Note that this remap only requires one system call, independently of the size of the shared memory region. In Linux, this method is accomplished with the use of the *mmap()* system call with the flags *MAP_FIXED* and *MAP_SHARED* to release the physical memory, and *MAP_FIXED*, *MAP_PRIVATE* and *MAP_ANON* to reuse the superblock.

Although this method might look a bit abusive, it is supported by the POSIX standard. However, this support is not explicit and, in Linux, the memory statistics go haywire, as it counts all the ranges mapped to the shared mapping into the resident set size (RSS) of the process, even though it only uses one shared mapping of physical memory. This method can also be used in other operating systems outside the POSIX world, and does not lead to memory leakage when CAS instructions are used on reclaimed memory. It requires extra system calls but we were not able to measure any performance degradation caused by them.

[1] Note that now we are considering again that all superblocks can become empty, i.e., ready to be released to the operating system.

[2] It uses tagged pointers as an ABA prevention mechanism.

4 Limitations

The LRMalloc memory allocator uses a size class allocation strategy, which means that allocations up to a reasonable size (16KiB) are handled through this mechanism. For all size class allocations, LRMalloc uses superblocks of the same size (2MiB), which simplifies our remapping logic as we can reuse retired supeblock addresses to different size classes. This is ideal in most scenarios, as most allocations fall into the size class range. However, for allocations larger than the biggest size class, it requires a different mechanism. For such allocations, LRMalloc relies directly on the operating system, as other lock-free memory allocators do [16, 8, 20, 13]. Relying on the operating system for large allocations does not meaningfully impact performance as this kind of allocations are uncommon. Large allocations work similarly to size class allocations, but the thread caches are skipped and a superblock with the exact size needed is mapped to satisfy the allocation.

This way of dealing with large allocations is not ideal, as it requires a different mechanism in order to recycle the range of virtual addresses of such allocations. In this regard, we have chosen to restrict the persistent memory allocation to sizes that are compatible with the size classes. This is not a problem in most situations as lock-free data structures tend to either use small allocations for their internal structure, or the large allocations last the lifetime of the data structure and as such need no reclamation, one example being Michael's lock-free hash tables [14]. The exceptions are lock-free hash maps that use large arrays that are resizable, as during the resizing process they need to allocate a new array and reclaim the old one. Data structures with these mechanisms are rather uncommon as the resizing processes tend to be complex and synchronization heavy, which leads to performance loss. As such, we leave the resolution of this limitation to future work.

This limitation is also the reason why we need another recycling pool for descriptors when a superblock becomes *empty*. If the superblock is not marked as persistent[3], the superblock is unmapped and the descriptor is added to the pool with the original behavior. If the superblock is marked as persistent, we remap the superblock as shown in the previous section and add the descriptor to the new pool. When we need a new descriptor we try to obtain one using the following priority: (i) the new pool that already has the virtual range of the superblock associated with it and as such is only compatible with superblocks intended for size class allocations; (ii) the original pool that has generic descriptors; and finally, (iii) we allocate a new descriptor. We only go down the priority list if either the pool is incompatible or is exhausted.

5 Experimental Results

In order to evaluate the impact of our changes to the OA method, we compare the results of our two implementations of the OA method, the one with warning-bits and the one with the monotonic global variable, against the original OA method, and against no reclamation, in which memory is never reclaimed, reused or freed. From this point onwards, we will refer to our simplified OA method with the warning-bit per thread as *OA-BIT*, the alternative with the monotonic global variable as *OA-VER*, and the no reclamation alternative as *NR*.

5.1 Methodology

The hardware used was a machine with 2 AMD Opteron(TM) Processor 6274 with 16 cores each, 16KiB of L1 cache per core, 2MiB of L2 cache per pair of cores and 12MiB of usable shared L3 cache per CPU. It has a total of 32GiB of DDR3 memory.

We benchmarked the four methods with the commonly used Michael's lock-free hash tables [14] and Harris-Michael's lock-free linked lists [15]. For all benchmarks, we use LRMalloc as the memory allocator, and although for our simplified versions it uses the new *palloc()* procedure for allocation, for both the original OA and no reclamation it uses the regular *malloc()* procedure. Note that the OA method only uses the allocator to create its memory pool before the benchmark begins and performs no allocations during the benchmark itself.

The benchmarks were run with varying ratios of searches, inserts and removes, but we kept the ratio between inserts and removes at 1:1 in order to keep the size of the data structure constant throughout the benchmark. For linked lists, we ran the benchmarks with 5K nodes pre-inserted. For hash tables, we used both 10K and 1M nodes and a load factor of 0.75. The results are the mean of 10 runs of 1 second each, and we show the results in the form of throughput (number of operations per second) for every combination of threads from 1 to 32.

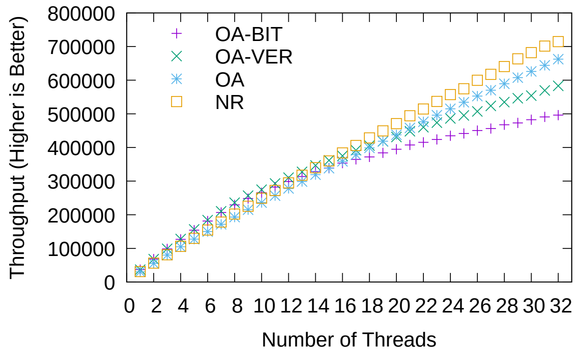
For all these experiments, we are not showing comparisons between the different approaches to memory remapping because we were unable to measure any difference in performance (outside a margin of error) between keeping the memory in the allocator, advising the operating system with *MADV_DONTNEED* and remapping with a shared memory region.

5.2 Results

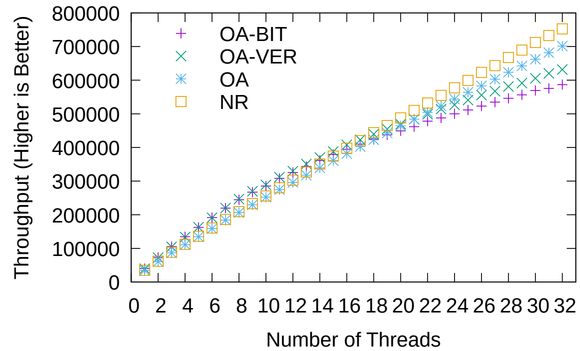
Figure 4 shows the results for the benchmark using linked lists with 5K nodes pre-inserted. Figure 4a shows the case with only modifying operations (50% inserts and 50% removes) and Fig. 4b shows a more balanced set of operations (50% searches, 25% inserts and 25% removes). Figures 5 and 6 then show the results for the benchmarks using hash tables with 10K nodes and 1M nodes, respectively. For both benchmarks, we also have the case with only modifying operations (50% inserts and 50% removes) and with a more balanced set of operations (50% searches, 25% inserts and 25% removes).

For linked lists with only modifying operations, the OA-VER method shows significant improvements to the OA-BIT method due to its ability to fire less warnings. This effect is somewhat reduced for linked lists with 50% searches, as there are less removes, and becomes negligible in both benchmarks using hash tables (Figs. 5 and 6) due to the much shorter chains.

[3] Note that only superblocks used for size class allocations can become persistent.

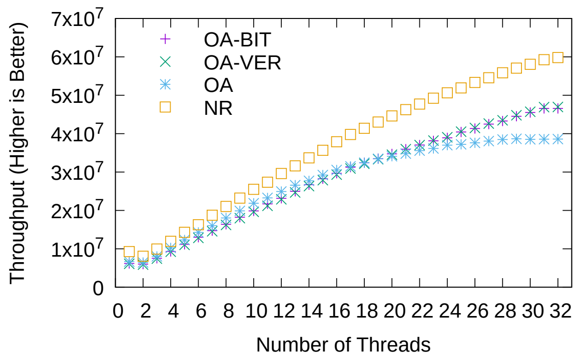


(a) 50% inserts and 50% removes

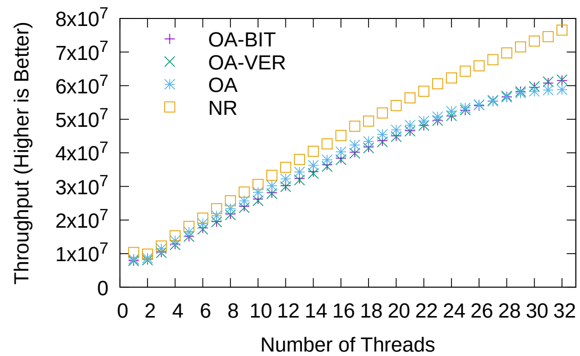


(b) 50% searches, 25% inserts and 25% removes

Figure 4: Linked lists with 5K nodes

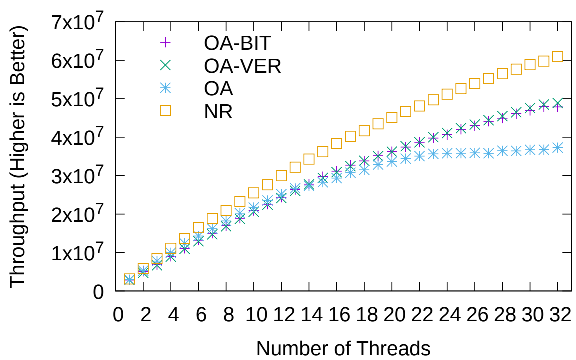


(a) 50% Inserts and 50% Removes

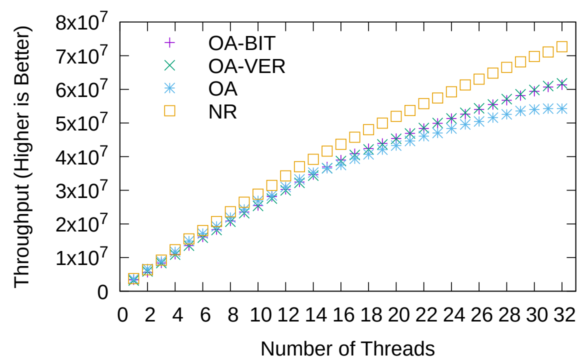


(b) 50% Searches, 25% Inserts and 25% Removes

Figure 5: Hash Table with 10K nodes



(a) 50% Inserts and 50% Removes



(b) 50% Searches, 25% Inserts and 25% Removes

Figure 6: Hash Table with 1M nodes

For low amounts of threads, we can see that both OA-BIT and OA-VER outperform the OA and even the NR method for linked lists. This happens because with low amounts of threads our methods use less memory, keeping most of the memory used in lower level caches. With increasing number of threads, our two methods start using more memory due to the per thread caches of LRMalloc and thus loose this advantage to the OA method that has a memory pool of a fixed size and to the NR method that suffers from less overhead caused by synchronisation between the many threads. A memory allocator with different characteristics could show a different behavior here. Linked lists are an unresting example to study the behavior of the system but they are not the ideal tool when performance matters due to their asymptotic complexity characteristics.

The benchmarks using hash tables show a kind of inversion of the results. In general, the OA method shows slightly better performance than our methods for low amounts of threads, but a clear lack of scalability for higher thread counts. Here, since we are working with much higher throughputs and larger amounts of memory, the weight of synchronization becomes much more relevant compared to memory usage and thus cache locality. The fixed size of the memory pool in the OA method proves detrimental as it requires much more recycling phases as the throughput and thread counts increase, causing synchronization to increase as well. In both our methods, we do not suffer from these drawbacks as the thread caches in the allocator and private limbo lists allow for less synchronization and thus better scalability.

Please remember that the main contribution of this paper is the added ability of releasing memory to the memory allocator/operating system and the simplification of the memory reclamation method, not the performance and scalability gains, even thought they are welcome.

6 Related and Future Work

Since the proposal of the OA method, some other proposals have been developed focusing on making OA easier to use and compatible with more data structures. One such example is the *Automatic Optimistic Access* (AOA) method [4], which allows the data structure programmer to forego the retire call by making use of garbage collector like techniques. A second example is the *Free Access* (FA) method [3] that requires the programmer to annotate the data structure functions, which then, through a combination of garbage collection techniques and compiler steps, is able to apply OA like memory reclamation to the data structure without the need for it be written in a normalized form [22]. Another example is the VBR method [21] that is able to extend OA to write operations through the use of DWCAS (Double-Width Compare-and-Swap) with tagged pointers.

We already discussed how our modifications to LRMalloc can be compatible with the optimistic DWCAS of VBR, so we leave it to future work the simplification and adaptation of VBR in order to also make it able to release memory back to the memory allocator/operating system. We could also use the extended LRMalloc in order to allow a dynamic resizing of the memory pool (in a garbage collector like manner) both in the AOA and FA methods, allowing the memory pool to be shrunk by releasing it to the memory allocator/operating system. Our results for the linked list benchmark show that this could also lead to performance improvements.

Further work also includes the removal of the limitation discussed in Section 4, which requires a mechanism capable of splitting and coalescing virtual address ranges in a lock-free manner.

7 Conclusion

Starting from a lock-free general purpose memory allocator named LRMalloc, we showed how to extend it to support the memory model required by the OA memory reclamation method in such a way that we can guarantee memory allocations to be readable even after we free such allocations. We were able to eliminate the major drawback of the OA method while ensuring that it remains one of the most efficient memory reclamation methods. While doing so, we were also able to simplify the implementation of the OA method, and obtain results showing performance improvements.

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