This document exposes a bottom-up explanation of the implementation of the library density (https://github.com/giucamp/density). It does not reach the source-line level of detail, and does not cover trivial parts, but rather it covers the interesting parts.

The library deals with:

- page-based memory management
- lifo ordered allocation of heterogeneous objects, typical of stacks and generally used for thread-local temporary data
- fifo ordered allocation of heterogeneous objects, typical of queues and generally used for data shared between threads, in most case for communication.
- concurrency with constrained progression guarantee

Paged memory management

The library implements a page-based memory management. Grouping user data in large memory pages improves the access locality, and increases the granularity of every memory management based task, including ensuring that indirections in lock-free algorithms are safe.
Objects of heterogeneous types are allocated linearly in the same page and in the same order in which the user will access the objects (in *container order*). When the space in a page is exhausted, another page is allocated. We say that a *page switch* occurs. A page switch occurs also when destroying\consuming objects, when a page has no more objects allocated within. Allocation and deallocation in-page are considered the fast path in all the data structures, while a page switch is the slow path. The data structures of the library never cache pages. The page allocator may possibly do that.
There is no limit on the size of objects to allocate, so in case of objects too large all data structures fallback to legacy heap allocation. For this reason allocator types in the library are required to model two distinct concepts: *PagedAllocator* and *UntypedAllocator*.

Memory pages have an arbitrary constant size and a constant alignment. The alignment must be greater or equal to the size (and of course an integer power of 2). Given an address of a byte within a page, we are able to compute the start address of the page with a simple bitwise and. Since the size of pages can be less than the alignment, page allocators can store some metadata in a page footer struct. As example, by default the page allocator of density manages page aligned to `2^16`, with a page size of `2^16 - sizeof(AnInternalPageFooter)`. The page allocator must guarantee that the space between the end of a page and the next aligned page in the address space will not be used by any other allocator. This guarantee will show very useful for the implementation of lifo memory management.

To allow a safe access to pages in a lock-free context, the allocator supports page pinning. Pinning is a kind of reference counting: while a page is pinned (that is the reference count is non-zero), even if the page is deallocated, the allocator will not recycle it in an allocation function, and will not alter or read its content in any way.
Pinning a page that has been already deallocated is legal. Accessing such page, or doing anything but unpinning it, triggers an undefined behaviour. When encountering a pointer with value P in a data structure, a thread should pin it, and then check if P is still linked to the data structure. If not, it has to unpin and retry.

Sometimes we need the pages we allocate to have a zeroed content. Lock-free algorithms may exploit this constraint to make threads agree on an history of the allocated memory, which begins with the zero state. We define an allocator that can allocate pages with zeroed (rather than undefined) content.
When deallocating a page, we may tell to the allocator that the page is already zeroed. If the page is still pinned, the deallocating thread guarantees that the page will be zeroed when unpinned. This allows the allocator to return the page to the user as zeroed without having to memset it. The set of zeroed pages is not distinct from the set of normal pages: being zeroed is a transient property of a page.

Here is the PageAllocator synopsis:

```
class PageAllocator
{
public:
	static constexpr size_t page_size = ...;
	static constexpr size_t page_alignment = ...;

	static_assert(is_power_of_2(page_alignment)
		&& page_alignment >= page_size, "");

	void * allocate_page();
	void * try_allocate_page(progress_guarantee) noexcept;
	void * allocate_page_zeroed();
	void * try_allocate_page_zeroed(progress_guarantee) noexcept;
	void deallocate_page(void *) noexcept;
	void deallocate_page_zeroed(void *) noexcept;
	void pin_page(void *) noexcept;
	void unpin_page(void *) noexcept;
};
```

Allocation functions return a pointer to the first byte of the page. Functions taking a page as parameter always align the address, so the user can specify a pointer to any byte within the page.
The above page allocator and many data structures of the library expose a set of *try_* functions*. These functions have in common:

- return a boolean or a type convertible to a boolean. A true return value indicates success, while false return value indicates a failure with so observable side effects.
- are noexcept or at least exception neutral. Allocation try_* function are always noexcept, while put functions don't throw any exception but they pass through any exception raised by the constructor of an user defined type
- the first parameter has always the type:
  ```
  enum progress_guarantee { Progress_blocking, progress_obstruction_free,
  	progress_lock_free, progress_wait_free };
  ```
  If the implementation can't guarantee the completion with the specified progress guarantee, the function fails. A failure with a blocking progress guarantee generally indicates an out of memory.

Deallocation functions are required to be always wait-free. The rationale for this is that any lock-free CAS based deallocation algorithm, whenever it does not succeed to perform the operation in a finite

number of steps, can push the free page in a thread-local queue, and try later (or satisfy a subsequent request of the same thread).

The current implementation of lock-free and spin-locking queues has a defect related to page pinning. Page pinning and unpinning has an obvious implementation with atomic increment and decrement, that have a lock-free implementation on most modern architectures. Anyway, even when such operations are translated to a single instruction, it's unlikely that they can ever be wait-free. For this reason wait-free try_* operations are forced to fail when they would perform a page switch, even if a thread executes them in isolation.

This is a defect, since wait-free operation should never fail if tried by a thread in isolation. The planned solution for this problem is to extend the PageAllocator concept with two more functions:

```
bool try_pin_page(progress_guarantee, void *) noexcept;
void unpin_page(progress_guarantee, void *) noexcept;
```

The first function is expected to try a possibly successful CAS-based increment in case the argument is progress_wait_free, and an always successful atomic increment in all the other cases.
The second one can't fail by design, because the caller is unlikely to be able to handle the failure. In case of failure of a wait-free unpin, the allocator may push the page on its thread-local cache of pages, so that it can re-try the unpin operation later.

SingletonPtr

Since C++11 the initialization of static local objects is thread safe. Since global objects exhibit the initialization order fiasco, static locals are generally safer than globals to implement singletons. Anyway, unless zero or constant initialization is possible, the compiler introduces an hidden atomic initialization guard, so that only the first access will initialize the object. The cpu's branch predictor greatly reduces the cost of this branch, but in many cases it can be removed at all.

The implementation of density uses an internal class template to implement the singleton pattern:

```
template <typename SINGLETON> class SingletonPtr;
```

This class template has non-nullable pointer semantics. It is stateless (therefore immutable), copyable and thread safe. The actual singleton object is handled internally, allocated in the static storage at a fixed address. Since this address is constant there is no need to store it, and all the specialization of `SingletonPtr` are guaranteed to be empty (no non-static data members).
The singleton is actually initialized when the first `SingletonPtr`is constructed. When the last `SingletonPtr`is destroyed, the singleton is destroyed too (it uses an internal reference count). The cost of handling the lifetime of the singleton is paid only by the constructor and the destructor. This is an advantage when we can keep a stable pointer to the singleton, and use repeatedly. For example an allocator class may keep a `SingletonPtr` pointing to a memory manager. Everyone who has access to a `SingletonPtr` can safely access the singleton.
Internally every specialization of `SingletonPtr` declares an instance of itself in the static storage, so that the singleton is always constructed during the dynamic initialization. If another `SingletonPtr` is

constructed and destroyed before the initialization of this internal instance, the singleton is constructed, destroyed, and then constructed again. Similarly if a `SingletonPtr` is constructed after the destruction of the internal instance, the singleton is created again.
So `SingletonPtr` does not guarantee that only one instance of the singleton is created, but rather that in any moment at most one instance of the singleton exists. In case of contention between threads in the first access, if that happens during the dynamic initialization, a thread may spin-lock waiting for another thread to complete the initialization if the singleton. This is a limitation of the current implementation, and will be probably fixed in the next releases.

Raw atomics

Sometimes in lock free algorithms we can't use std::atomic, basically even if standard atomics are trivially default-constructible, they require a call to std::atomic_init to complete the initialization. So we introduce a minimal set of non-standard of functions for atomic operations on fundamental variables:

```
template <typename TYPE>
	TYPE raw_atomic_load(
		TYPE const volatile * i_atomic,
		std::memory_order i_memory_order) noexcept;

template <typename TYPE>
	void raw_atomic_store(
		TYPE volatile * i_atomic,
		TYPE i_value,
		std::memory_order i_memory_order) noexcept;

template <typename TYPE>
	bool raw_atomic_compare_exchange_weak(
		TYPE volatile * i_atomic,
		TYPE * i_expected,
		TYPE i_desired,
		std::memory_order i_success,
		std::memory_order i_failure) noexcept;

template <typename TYPE>
	bool raw_atomic_compare_exchange_strong(
		TYPE volatile * i_atomic,
		TYPE * i_expected,
		TYPE i_desired,
		std::memory_order i_success,
		std::memory_order i_failure) noexcept;
```

The default value for memory order parameters is omitted, and it is always `std::memory_order_seq_cst`. The current implementation deletes all the generic function templates, and specialize an implementation only for some integer.
These functions behave like the standard counterparts. Anyway raw variables are fully trivially constructible, and can be zero-initialized (for example with a memset). A second advantage of raw atomics is that in some (rare) cases we can mix non-atomic and atomic writes to the same variable, if we know for sure that the non-atomic access is synchronized in some way.

The implementation of `lf_heter_queue` we are going to describe requires raw atomics. If for a given compiler or OS raw atomics can't be implemented, the lock-free queues can't be used.

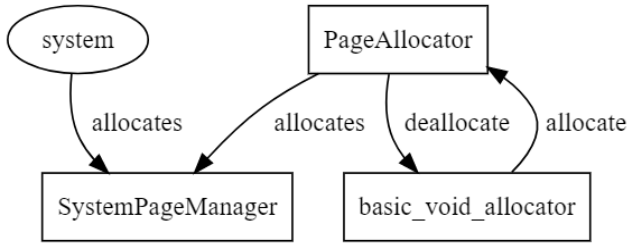
WF_PageStack

The implementation of the page allocator uses WF_PageStack, a wait-free queue specialized for pages.

```
namespace density
{
    namespace detail
    {
        class WF_PageStack
        {
        private:
            std::atomic<PageFooter*> m_first{ nullptr };

        public:

            bool try_push(PageFooter * i_page) noexcept;

            bool try_push(PageStack & i_stack) noexcept;

            PageFooter * try_pop_unpinned() noexcept;

            PageStack try_remove_all() noexcept;
        };

    } // namespace detail

} // namespace density
```

All the operation can fail in case of contention between threads. The function `try_pop_unpinned` temporary steals the whole stack, then search for the first page with zero pin count, and then restores the stack (with possibly one less page). Stealing the whole content is an easy and elegant way to avoid the ABA problem.

Implementation of the page allocator



The page management is mainly composed by 2 layers. The first layer is the `SystemPageManager`, that provides a public function that allocates a memory page, but provides no function to deallocate. So it provides an irreversible allocation service.

Internally the `SystemPageManager` allocates large memory regions from the system. Every region has a pointer to the next page to allocate. When a page is to be allocated, this pointer is advanced and its previous value is returned. When the current region is exhausted,

another region is created. If the `SystemPageManager` gets an out of memory from the system when allocating a region, it tries to allocate a smaller region. After a number of tries, it reports the failure to the caller.Memory regions are deallocated when the `SystemPageManager` is destroyed, that is when the program exits.

Anatomy of the queue

The storage of an lf_heter_queue is an ordered set of pages and possibly a set of legacy memory blocks. The first page is the *head page*, while the last is the *tail page*. A lf_heter_queue has two pointers: the *head pointer*, that points to a byte of the head page, and the *tail pointer*, that point to a byte of the tail page.
If the queue is not empty, the head pointer points to the first value of the queue. Values are stored as a null-terminated forward linked-list, and are allocated linearly, in container order, with a granularity specified by the internal constexpr s_alloc_granularity (usually 64). The pointer 'next' of the tail element is always zeroed.

A value is *alive* if it contains a valid element. The element of an alive value must be destroyed soon or later. A value is *dead* if it does not contain a valid element. Dead values arise from:

- canceled elements (including those whose constructor threw an exception)
- elements that have been consumed, but still have a storage
- raw allocations

The layout of a value is composed by:

- an instance of ControlBlock, an internal struct of the library. It is always present, and holds the pointer 'next' and the state flags of the value.
- possibly a type eraser, (usually) not present for raw allocations and for the *end-of-page* ControlBlock.
- possibly the user storage (the element or the raw block), not present for the *end-of-page* ControlBlock.

The bottom of the usable space of every page is reserved to the end-of-page control block. This block is allocated always at the same offset from the beginning of the page. Excluding the first control block of the page, all the other control blocks are allocated at variable offsets.
In the end-of-page control block, the pointer to the next control block always points to another page. In all other cases, the pointer to the next control block points to the same page.

There is an implementation defined limitation on the size and alignment of elements that can be allocated in a page. Whenever an element (or raw block) is too big, the queue inserts in the page just a pointer to a legacy heap memory block used as storage for the element.

If the queue is fully heterogeneous (that is the template argument COMMON_TYPE is void), a control block is composed only by an uintptr_t, that stores the pointer 'next':

```
struct ControlBlock
{
        volatile uintptr_t m_next;
```

```
};
```

If the queue is partially heterogeneous (that is the template argument COMMON_TYPE is not void), the control block includes a pointer to the element.
The least significant bits of m_next are used to store the control flags:

```
enum NbQueue_Flags : uintptr_t
{
        NbQueue_Busy = 1,
        NbQueue_Dead = 2,
        NbQueue_External = 4,
        NbQueue_InvalidNextPage = 8,
        NbQueue_AllFlags = NbQueue_Busy | NbQueue_Dead |
                NbQueue_External | NbQueue_InvalidNextPage
};
```

The flag 'Busy' is set to a value while a producer is producing it, or while a consumer is consuming it. The flag 'Dead' is set on values not alive. Consumers search for m_next that are not zeroed, and don't have heither 'Busy' or 'Dead'.
While an element is being produced (before commit is called on the put transaction), the element is busy, and not observable. If commit is not called, no one will ever observe any part of that element.
When a thread start consuming an element, it sets the flag 'Busy' on the element, which instantly becomes observable. If the consume operation is committed, the element is gone forever. Otherwise, if the consume operation is canceled, the element reappears in the queue (the busy flag is cleared). Since other consumers have observed the absence of the element between the beginning of the consume and the cancel, the consume is not a transaction[1].

Derivation chain

We are implementing the following class template:

```
template < typename COMMON_TYPE = void,
   typename RUNTIME_TYPE = runtime_type<COMMON_TYPE>,
   typename ALLOCATOR_TYPE = void_allocator,
   concurrent_cardinality PROD_CARDINALITY = concurrency_multiple,
   concurrent_cardinality CONSUMER_CARDINALITY = concurrency_multiple,
   consistency_model CONSISTENCY_MODEL = consistency_sequential>
      class lf_heter_queue;
```

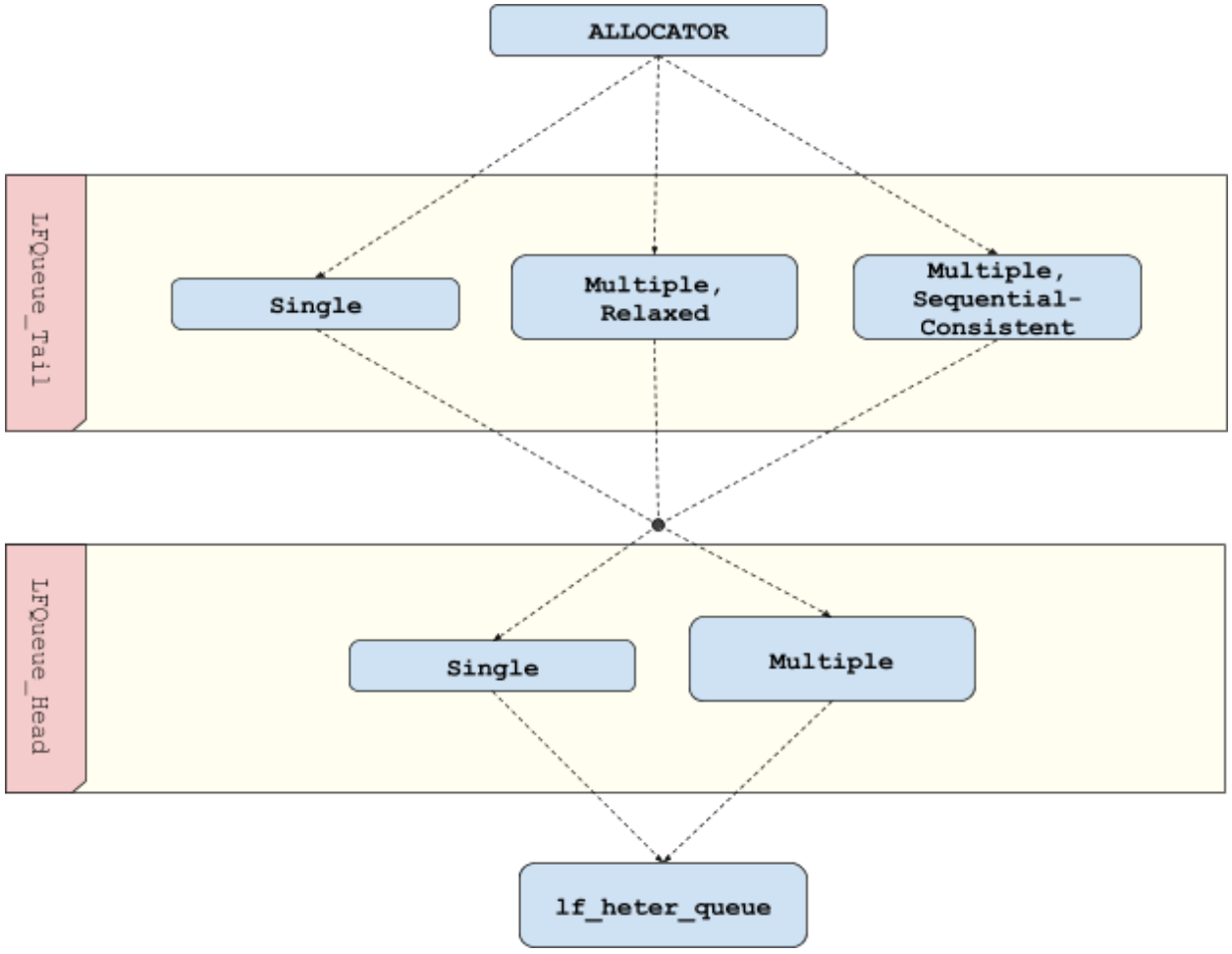
By default we provide the most general heterogeneous lock-free queue, but we allow the user to specify some limitations to have better performances.

Template parameter	Allowed values

[1] If we would consider consumes infallibile operations (just like destructors), they would be transactions. Anyway we expect the user to do non-trivial actions during a consume.

PROD_CARDINALITY	concurrency_multiple, concurrency_single
CONSUMER_CARDINALITY	concurrency_multiple, concurrency_single
CONSISTENCY_MODEL	consistency_sequential, consistency_relaxed

To handle such complexity, we split the implementation in 3 class templates. A lf_heter_queue has a four-level private hierarchy.



The queue is internally a null-terminated linked-list, and consumers can iterate it without accessing the tail for the termination condition. So the tail pointer is visible only to producers, and the head pointer is visible only to consumers. Beyond slightly less contention, this simplifies the implementation, and allows to better exploiting reduced cardinalities: if PROD_CARDINALITY is concurrency_single, the tail pointer is not an atomic variable. Similarly, if CONSUMER_CARDINALITY is concurrency_single, the head pointer is not an atomic variable.

Put operations

The first level is the allocator. In the second level we implement the tail pointer and the put operations in a class template:

```
namespace detail
{
  template < typename COMMON_TYPE, typename RUNTIME_TYPE,
    typename ALLOCATOR_TYPE,
    concurrent_cardinality PROD_CARDINALITY,
    consistency_model CONSISTENCY_MODEL >
      class LFQueue_Tail : protected ALLOCATOR_TYPE;
```

The general class template is not defined. The actual implementation is split in 3 template specializations:

- One for PROD_CARDINALITY = concurrency_single. This specialization allocates non-zeroed pages, and does not demand zeroing-before-deallocation to consumers.
- One for PROD_CARDINALITY = concurrency_multiple and CONSISTENCY_MODEL = consistency_relaxed. This specialization allocates zeroed pages, and does allow (but does not require) zeroing the memory at consume time. This is an optimization: consumers probably have that memory in their cache memories[2].
- One for PROD_CARDINALITY = concurrency_multiple and CONSISTENCY_MODEL = consistency_sequential. This specialization allocates zeroed pages, but does not allow zeroing the memory at consume time, because this would break the algorithm. In this case the cost of zeroing is up to the allocator, since zeroed pages are allocated, but non-zeroed pages are deallocated.

Every specialization of LFQueue_Tail provides this const boolean to communicate to the subsequent layers whether pages should be zeroed at consume time:

```
constexpr static bool s_deallocate_zeroed_pages = ...;
```

Queues that require zeroed pages return zeroed pages to the allocator. While this is not mandatory, it helps the allocator, that would have to write the whole content of the page before reusing it. In contrast the queue can zero the memory while it is probably still in the cache.

The constructor of LFQueue_Tail looks the same in all 3 specializations:

```
LFQueue_Tail() noexcept
        : m_tail(invalid_control_block()), m_initial_page(nullptr)
{
}
```

[2] At this time the advantage has not been verified and measured.

We delay the allocation of the first page, so that the default constructor and the move constructor can be noexcept. The value invalid_control_block() is such that it will always cause a page overflow in the first put. When the first page is allocated, it is set to m_initial_page, so that the consume layer can read it during its delayed initialization. After being set to the first allocated page, m_initial_page does not change anymore, even when the page it points to is deallocated.

The code below is the allocation function for an element or raw block in the case of single producer (and non-atomic m_tail).

```
// LFQueue_Tail<..., concurrency_single>::inplace_allocate
Block inplace_allocate(uintptr_t i_control_bits,
        bool i_include_type, size_t i_size, size_t i_alignment)
{
        if (i_alignment < min_alignment)
        {
                i_alignment = min_alignment;
                i_size = uint_upper_align(i_size, min_alignment);
        }

        auto tail = m_tail;
        for (;;)
        {
                // allocate space for the control block
                void * address = address_add(tail,
                        i_include_type ? s_element_min_offset : s_rawblock_min_offset);

                // allocate space for the element
                address = address_upper_align(address, i_alignment);
                void * const user_storage = address;
                address = address_add(address, i_size);
                address = address_upper_align(address, s_alloc_granularity);
                auto const new_tail = static_cast<ControlBlock*>(address);

                // check for page overflow
                auto const new_tail_offset = address_diff(new_tail,
                        address_lower_align(tail, ALLOCATOR_TYPE::page_alignment) );
                if (DENSITY_LIKELY(new_tail_offset <= s_end_control_offset))
                {
                        // Note: not an atomic store
                        new_tail->m_next = 0;

                        auto const control_block = tail;
                        auto const next_ptr =
                                reinterpret_cast<uintptr_t>(new_tail) + i_control_bits;

                        raw_atomic_store(&control_block->m_next,
                                next_ptr, detail::mem_release);

                        m_tail = new_tail;
                        return { control_block, next_ptr, user_storage };
                }
                else if (i_size + (i_alignment - min_alignment) <= s_max_size_inpage)
                {
```

```
                        tail = page_overflow(tail);
                }
                else
                {
                        /* this allocation would never fit in a page,
                                allocate an external block */
                        return external_allocate(i_control_bits, i_size, i_alignment);
                }
        }
}
```

The function LFQueue_Tail::inplace_allocate is the core of all put operations, and is the interface for subsequent layers. It is still a private and low-level function.
This is a good time to make 2 considerations valid for all 3 kinds of tail we are implementing:

1. We test for the page overflow in the domain of page offset to avoid having to handle the pointer arithmetic overflows.
2. Since most times all the arguments are compile time constants, an alternate overload template is always provided, to make sure all the possible simplifications are done:

```
template < uintptr_t CONTROL_BITS, bool INCLUDE_TYPE,
        size_t SIZE, size_t ALIGNMENT > Block inplace_allocate();
```

This is inplace_allocate for the case of multiple producers, but with relaxed consistency:

```
/* LFQueue_Tail<..., concurrency_multiple,
                consistency_relaxed>::inplace_allocate */
Block inplace_allocate(uintptr_t i_control_bits,
        bool i_include_type, size_t i_size, size_t i_alignment)
{
        if (i_alignment < min_alignment)
        {
                i_alignment = min_alignment;
                i_size = uint_upper_align(i_size, min_alignment);
        }

        auto tail = m_tail.load(detail::mem_relaxed);
        for (;;)
        {
                // allocate space for the control block
                void * new_tail = address_add(tail,
                        i_include_type ? s_element_min_offset : s_rawblock_min_offset);

                // allocate space for the element
                new_tail = address_upper_align(new_tail, i_alignment);
                void * const user_storage = new_tail;
                new_tail = address_add(new_tail, i_size);
                new_tail = address_upper_align(new_tail, s_alloc_granularity);

                // check for page overflow
                auto const new_tail_offset = address_diff(new_tail,
                        address_lower_align(tail, ALLOCATOR_TYPE::page_alignment));
                if (DENSITY_LIKELY(new_tail_offset <= s_end_control_offset))
                {
```

```
                        if (m_tail.compare_exchange_weak(tail,
                                static_cast<ControlBlock*>(new_tail),
                                detail::mem_acquire, detail::mem_relaxed))
                        {
                                auto const next_ptr = reinterpret_cast<uintptr_t>(
                                        new_tail) + i_control_bits;

                                raw_atomic_store(&tail->m_next, next_ptr,
                                        detail::mem_release);

                                return { tail, next_ptr, user_storage };
                        }
                }
                else if (i_size + (i_alignment - min_alignment) <= s_max_size_inpage)
                {
                        tail = page_overflow(tail);
                }
                else
                {
                        /* this allocation would never fit in a page,
                                allocate an external block */
                        return external_allocate(i_control_bits, i_size, i_alignment);
                }
        }
}
```

Unless a page overflow occurs, no page pinning is necessary on the producer side. The reason is that after that a producer allocates space (updating m_tail), that space can never be consumed until it unzeroes it and then removes the busy flag.

The are two reasons why this tail provides relaxed consistency instead of sequential consistency:

1) Every put updates the tail, and then writes the member m_next of the control-block it has just allocated (m_next is zero before the latter write). In the middle of these two writes, other producers may succesfull do other puts (they are not blocked), but for the consumers the queue is truncated to the first zeroed m_next. A put may be temporary not observable even to the thread that successfully has carried it.
2) Consumers are requested to zero the memory while consuming elements. In some cases of high contention a consumer may see an m_next zeroed by the other consumers, and incorrectly consider it an end-of-queue marker.

The last case of LFQueue_Tail::inplace_allocate is for multiple producers, and sequential consistent queue. Basically we have to solve the two problems above.
In this specialization of LFQueue_Tail we allocate in the pages only values requiring at most a number of bytes equal to the square of s_alloc_granularity. [3] All other values are allocated with a legacy heap allocation.

[3] We may avoid legacy allocations for values big up to the size of a page allocating such values in a secondary stream of pages. At the moment density is not doing that.

To solve the problem 1 we adopt a two phases tail update. To solve the problem 2 we just ask to consumers to not zero the memory. Here is the code of the put for sequential consistent queues:

```
Block inplace_allocate(uintptr_t i_control_bits, bool i_include_type,
        size_t i_size, size_t i_alignment)
{
        if (i_alignment < min_alignment)
        {
                i_alignment = min_alignment;
                i_size = uint_upper_align(i_size, min_alignment);
        }

        auto const overhead = i_include_type ? s_element_min_offset : s_rawblock_min_offset;
        auto const required_size = overhead + i_size + (i_alignment - min_alignment);
        auto const required_units = (required_size +
                        (s_alloc_granularity - 1)) / s_alloc_granularity;

        detail::ScopedPin<ALLOCATOR_TYPE> scoped_pin(this);

        bool const fits_in_page = required_units < size_min(s_alloc_granularity, s_end_control_offset / s_alloc_granularity);
        if (fits_in_page)
        {
                auto tail = m_tail.load(mem_relaxed);
                for (;;)
                {
                        auto const rest = tail & (s_alloc_granularity - 1);
                        if (rest == 0)
                        {
                                // we can try the allocation
                                auto const new_control =
                                        reinterpret_cast<ControlBlock*>(tail);
                                auto const future_tail = tail +
                                        required_units * s_alloc_granularity;
                                auto const future_tail_offset = future_tail -
                                        uint_lower_align(tail, page_alignment);
                                auto transient_tail = tail + required_units;
                                if (DENSITY_LIKELY(future_tail_offset <= s_end_control_offset))
                                {
                                        if (m_tail.compare_exchange_weak(tail,
                                                transient_tail, mem_relaxed))
                                        {
                                                raw_atomic_store(&new_control->m_next,
                                future_tail + i_control_bits, mem_relaxed);

                                                m_tail.compare_exchange_strong(transient_tail,
                                future_tail, mem_relaxed);

                                                auto const user_storage = address_upper_align(
                                address_add(new_control, overhead), i_alignment);

                                                return { new_control, future_tail +
                                                        i_control_bits, user_storage };
                                        }
                                }
                                else
                                {
                                        tail = page_overflow(tail);
                                }
                        }
                        else
                        {
```

```
                                        // an allocation is in progress, we help it
                                        auto const clean_tail = tail - rest;
                                        auto const incomplete_control =
                                                reinterpret_cast<ControlBlock*>(clean_tail);
                                        auto const next = clean_tail + rest * s_alloc_granularity;

                                        if (scoped_pin.pin_new(incomplete_control))
                                        {
                                                auto updated_tail = m_tail.load(mem_relaxed);
                                                if (updated_tail != tail)
                                                {
                                                        tail = updated_tail;
                                                        continue;
                                                }
                                        }

                                        uintptr_t expected_next = 0;
                                        raw_atomic_compare_exchange_weak(&incomplete_control->m_next,
                        &expected_next, next + detail::NbQueue_Busy, mem_relaxed);
                                        if (m_tail.compare_exchange_weak(tail, next, mem_relaxed))
                                                tail = next;
                                }
                        }
                }
                else
                {
                        return external_allocate(i_control_bits, i_size, i_alignment);
                }
}
```

A producer starts analyzing the value of m_tail. If it is multiple of s_alloc_granularity, then there is no other put in progress. So it:

- Adds to m_tail the required size in bytes divided by s_alloc_granularity. This is enough to make other consumers realize that a put is in progress, and how much memory this put is allocating.
- Setups the control block (that is sets m_next)
- Sets m_tail to point after the allocation

Otherwise, if the tail is not multiple of s_alloc_granularity, the thread first completes the put in progress, and then try to do its own put.