Density 1.03 implementation

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1. Introduction

This document describes the implementation of the library density[1]. The exposition is bottom-up, from the most primitive functionalities to the public data structures. Trivial parts are not covered, while in the critical parts the exposition reaches the source-line level of detail. The document is at the same time an overview of the library, more technical than the one available in the documentation. This document assumes a basic knowledge of non-blocking programming. On Wikipedia there is an excellent introduction to this topic[2].

Density is a C++11 library that provides:

- Page-based memory management: rather than allocating many small blocks of heap memory, all the data structures of the library prefer allocating large memory pages from a page allocator. All the pages have the same size (by default around 64 kibibytes). In the unlikely case that a single object is too big to fit in a page, it is allocated on the legacy heap.

1 https://github.com/giucamp/density

2 https://en.wikipedia.org/wiki/Non-blocking_algorithm

- Lifo ordered allocation of heterogeneous objects, useful for thread-local temporary data. The library introduces the data-stack, a stack (parallel to the call-stack) in which the user can allocate dynamic arrays or raw buffers. The lifo memory management is built upon the paged-memory management, so the data stack is actually composed by memory pages. Allocating on the data-stack is fast almost like allocating on the call-stack with `_alloca`, but never results in a stack overflows. In case of out of system memory an `std::bad_alloc` is thrown.

- Fifo ordered allocation of heterogeneous objects, useful for exchanging messages between threads, or for asynchronous processing in both single-thread and multi-thread scenarios. The library provides a rich set of heterogeneous queues and function queues:

- Concurrency with parametric progress guarantee (blocking, obstruction-free, lock-free and wait-free). The user specifies a progress guarantee with a parameter, and the implementation does its best to successfully complete the operation respecting it. In case that the implementation can't respect the guarantee, the call fails and has no observable side effects.

This is the summary of the heterogeneous queues and function queues provided by the library:

Threading strategy	**Heterogeneous queue**	**Function queue**	**Producers cardinality**	**Consumers cardinality**
single-thread	`heter_queue`	`function_queue`	none	none
locking	`conc_heter_queue`	`conc_function_queue`	multiple	multiple
lock-free	`lf_heter_queue`	`lf_function_queue`	single or multiple	single or multiple
spin-locking	`sp_heter_queue`	`sp_function_queue`	single or multiple	single or multiple

Some miscellaneous notes about the library and the current implementation:

- The current implementation does not differentiate between obstruction-free and lock-free guarantees: when an obstruction-free operation is requested, the library tries to complete it in lock-freedom.

- Atomic operations are currently forced to be sequential consistent by a centralized constexpr switch. Future versions may exploit relaxed atomic operations.

- The library currently performs pointer arithmetic with `uintptr_t` addresses. While not portable, this is actually safe on most compilers and platforms. Anyway future versions may use `char*` instead of `uintptr_t`.

- All the data structures of the library provide the strong exception guarantee on all the operations.

The results of some benchmarks are available at http://giucamp.github.io/density/doc/html/lifo_array_benchmarks.html and http://giucamp.github.io/density/doc/html/function_queue_benchmarks.html.

Paged memory management

2. Overview of paged memory management

The library implements a page-based memory management. Grouping logically adjacent heterogeneous objects in large memory pages (instead of allocating each object in a separate heap block) improves the access locality, and increases the granularity of every memory-management related task, including safe indirections in lock-free algorithms.

Memory pages have a constant size and a constant alignment. The alignment must be greater or equal to the size (and of course an integer power of tow). Given an address of a byte within a page, we are able to compute the start address of the page applying a bitwise mask. 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 pages 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.

The data structures allocate many objects of heterogeneous types linearly in the same page and in the same order in which the user will access the them (in container order). When the free space in a page is exhausted, another page is allocated. In this case we say that a *page switch* occurs. A page switch occurs also when destroying\consuming objects, and a page has no more objects allocated within. *In-page* allocation and deallocation 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 free pages. The page allocator may possibly do that.

There is no limit on the size of objects the user can 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*. The first will be exposed in this paragraph, while the latter is just a legacy allocator supporting over-alignment with offset.

To allow safe access to pages in a lock-free context, the page allocator supports 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 for 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 behavior. When encountering a pointer with value P in a data structure, a thread should pin it, and then it should check whether P is still linked to the data structure. If not, it has to unpin and retry.

Sometimes we need that the pages we link to a data structure have a zeroed content. Lock-free algorithms may use initially zeroed pages to make threads agree on a history of the data which begins with the zeroed state. We introduce in our allocator functions to 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 page allocator and many data structures of the library expose a set of *try_* functions*. These functions have some common properties:

- they return a boolean or a type implicitly convertible to boolean. A true return value indicates success, while false return value indicates a failure with no observable side effects.

- they are noexcept or at least exception neutral. Allocation try_* function are always noexcept, while put try_* functions don't throw any exception, though they pass through any exception raised by the constructor of a 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[3]-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.

This is a defect, since any wait-free operation shouldn't fail indefinitely 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 first argument is `progress_wait_free`, and to do 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 CAS with wait-free progress guarantee, the allocator may push the page on a thread-local list of pages, so that it can re-try the unpin operation later.

3. SingletonPtr

Starting from 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 a 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 that implements 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 indirection of `SingletonPtr` just returns the address of the storage of the singleton.

3 Compare and set, `compare_exchange_weak` and `compare_exchange_strong` in C++11.

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 of the singleton. This is a defect of the current implementation, and will be probably fixed in a future release.

4. Raw atomics

Sometimes in lock free algorithms we can't use `std::atomic`, because even if standard atomics are trivially default-constructible, a default constructed atomic requires 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;
```

In the declarations above the default value for the memory order parameters is omitted (it is always `std::memory_order_seq_cst`). All the generic function template are deleted. The library specialize an implementation only for some integer types[4].

Raw-atomic functions behave like the standard counterparts. Anyway fundamental variables are fully trivially constructible, and can be zero-initialized. 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 library exploits this kind of mixed access in single-producer lock-free and spin-locking queues.

The implementation of `lf_heter_queue` we will describe requires raw atomics for `uintptr_t`. If for a given compiler or OS raw atomics aren't available, the lock-free queues can't be used.

5. WF_PageStack

The implementation of the page allocator uses `WF_PageStack`, a wait-free queue specialized for pages. The stack is implemented as an intrusive linked list.

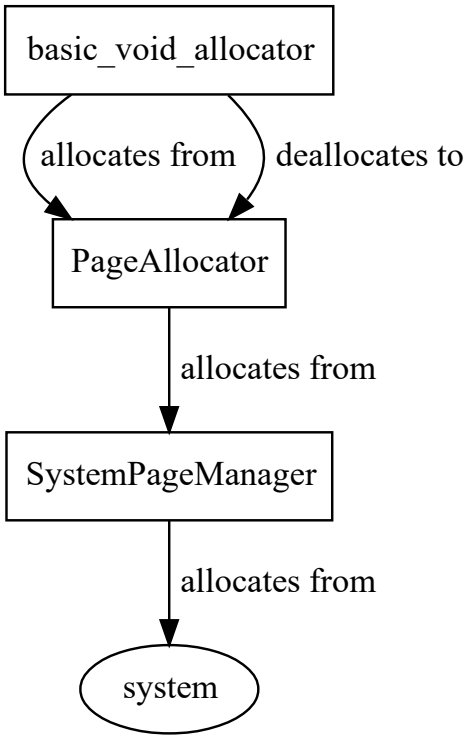
```
namespace density
{
    namespace detail
    {
        class WF_PageStack
        {
        private:
            std::atomic<PageFooter*> m_first{ nullptr };

        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;
        };
    }
}
```

The class `PageStack` (used for some member functions) is a non-concurrent stack of pages. All the operations on `WF_PageStack` 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 re-links the pages (with possibly one less) to the stack. Stealing the whole content is an easy and elegant way to avoid the ABA problem.

4 The reference documentation lists the supported types, anyway `uintptr_t` is always supported.

6. Implementation of the page allocator

The page management is composed by 3 layers. The lowest layer is the `SystemPageManager`, that exposes a public function to allocate a memory page, but no function to deallocate. So it provides an irreversible allocation service.



Internally the `SystemPageManager` allocates large memory regions from the system and slices them into pages. Every region has a pointer to the next page to allocate. When a page is to be allocated, this pointer is advanced by the size of a page, and then 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 failed tries with decreasing sizes, it reports the failure to the caller. Memory regions are deallocated when the `SystemPageManager` is destroyed, that is when the program exits.

The function of `SystemPageManager` that allocates a page is `try_allocate_page`:

```
void * SystemPageManager::try_allocate_page(
     progress_guarantee i_progress_guarantee) noexcept;
```

On success it returns a pointer to the first byte of the page, while in case of failure it returns null. The conditions under which this function fails depends on the requested progress guarantee, as illustrated in this table:

Progress guarantee	**Condition failure**
`progress_blocking`	Fails only in case of out of system memory
`progress_obstruction_free`	Fails if there is no free space in the memory regions already allocated, as the allocation of system memory is likely to be blocking.
`progress_lock_free`	
`progress_wait_free`	Fails if there is no free space in the memory regions already allocated or in case of contention between threads

The user of `SystemPageManager` may reserve in advance a capacity of memory usable in lock-freedom using the following function:

```
uintptr_t SystemPageManager::try_reserve_region_memory(
     progress_guarantee i_progress_guarantee,
     uintptr_t const i_size) noexcept;
```

The return value is the total memory (in bytes) allocated from the system after the call. If this memory would be less than the one specified by the second argument, and the caller has specified the blocking progress guarantee, it tries to allocate memory regions from the system until the total size is equal or greater than the second parameter. Note: the signature of this function does not respect the convention on try_ functions. Anyway it is an internal function, and it may change in the future.

The second layer is the `PageAllocator`, that provides reversible page allocation, with an interface similar to the PageAllocator concept. In this layer there are a (currently fixed) number of slot, each containing a `WF_PageStack` of free pages and a `WF_PageStack` of free and zeroed pages.

Furthermore the `PageAllocator` associates to every thread some local data:

- A pointer to the *current slot*
- A pointer to the *victim slot*
- A non-concurrent stack of free pages
- A non-concurrent stack of free and zeroed pages

When a new page is requested, the `PageAllocator` tries to satisfy the request executing an ordered sequence of steps until one of them is successful. More precisely the `PageAllocator`:

- Peeks the first non-pinned page from the local stack
- Peeks the first non-pinned page from the current slot
- Steals all the pages of the victim slot, pushing them to the current slot. Then peeks the first non-pinned page from the stolen stack
- Tries to allocate from the `SystemPageManager` in wait-freedom (no new system memory is allocated)
- Loops the pointer to the victim slot through all the slot, stealing all the pages from each of them. If a non-pinned page in found in a stolen stack, the loop is interrupted.
- Now, if the progress guarantee specified by the caller is not `progress_blocking`, the `PageAllocator` returns null to signal a failure. Otherwise it forwards the request to the `SystemPageManager`, that may try to allocate a new memory region.

To deallocate a page the `PageAllocator` loops the pointer to the current slot through all the slot. At every iteration it tries to push the page on the `WF_PageStack`. The push may fail only because of con-

tention with another thread. If the push fails on all the slots, the page is pushed on the thread-local stack.

The last layer of the page management is the `void_allocator`, that just forwards the requests to the `PageAllocator`. The layers before the `void_allocator` don't throw exceptions: they report a failure in allocating a page with a null return value. The `void_allocator` is the layer that, in case of failure of a non-try allocation function, throws an `std::bad_alloc`.

The user can use two functions of `void_allocator` e to reserve paged-memory to be used in lock-freedom:

```
static void reserve_lockfree_page_memory(size_t i_size,
     size_t * o_reserved_size = nullptr);

static bool try_reserve_lockfree_page_memory(
     progress_guarantee i_progress_guarantee,
     size_t i_size, size_t * o_reserved_size = nullptr) noexcept;
```

These functions make sure that the specified size is already been allocated from the system. In case of out of memory the first function throws an `std::bad_alloc`, while the second one, in case of failure, just returns false. The parameter `o_reserved_size` is to retrieve the total memory allocated from the system after the call.

Lifo memory management

7. The lifo allocator

The lifo memory management provided by the library is not thread safe, the reason being that it is supposed to be used mostly for thread-local data. It is built upon paged-memory management: the class template `lifo_allocator` adapts an allocator satisfying the requirements of both PagedAllocator and UntypedAllocator concepts to expose a LIFO constrained allocation service.

The LIFO order imposes that only the most recently allocated and living block can be resized or deallocated. If this constraint is violated the behavior is undefined. Dealing with the LIFO order without the help of the RAII idiom is extremely bug prone, and it's highly discouraged.

This is the signature of the class template:

```
class lifo_allocator {
     template < typename UNDERLYING_ALLOCATOR = void_allocator,
     size_t ALIGNMENT = alignof(void*)>
          class lifo_allocator;
```

To simplify the implementation of the allocator, the alignment is constant and the same for all the blocks.

The only non-static data member of is the a pointer to the end of the stack, that is the *top pointer*:

```
static constexpr uintptr_t s_virgin_top =
     uint_lower_align(page_alignment - 1, alignment);
uintptr_t m_top = s_virgin_top;
```

The top pointer usually points to the beginning of next block that will be allocated. It is an `uintptr_t` rather than a pointer to allow the default constructor to be constexpr (`reinterpret_cast` is not allowed in constant expressions).

The allocator is designed so that in the fast path, with the same conditional branch, it can redirect to the same slow execution path these 3 cases:

- the block to allocate is not too big, but the current page has not enough free space
- the block to allocate is too big, and it will not fit in a memory page
- the allocator is virgin, that is it has just been constructed and never used (after allocating a page the allocator will never return to the virgin state)

To allocate a block the allocator just adds the input size to the top pointer. If it detects that the updated top would lie past the end of the current page, it enters in the slow execution path. In the slow path it decides between a new page or an external block (that is a block allocated in the legacy heap). When allocating or deallocating external blocks the state of the allocator is not altered.

When a new page is allocated, a header is added at the beginning of the page. This header contains only a pointer to the previous page, and it is necessary for the deallocation.

```
void * allocate(size_t i_size)
{
     DENSITY_ASSERT(i_size % alignment == 0);

     auto const new_top = m_top + i_size;
     auto const new_offset = new_top -
          uint_lower_align(m_top, page_alignment);
     if (!DENSITY_LIKELY(new_offset < page_size))
     {
          // page overflow
          return allocate_slow_path(i_size);
     }
     else
     {
          // advance m_top
          DENSITY_ASSERT_INTERNAL(i_size <=page_size);
          auto const new_block = reinterpret_cast<void*>(m_top);
          m_top = new_top;
          return new_block;
     }
}
```

```
DENSITY_NO_INLINE void * allocate_slow_path(size_t i_size)
{
     DENSITY_ASSERT_INTERNAL(i_size % alignment == 0);
     if (i_size < page_size / 2)
     {
          // allocate a new page
          auto const new_page =
               UNDERLYING_ALLOCATOR::allocate_page();
          DENSITY_ASSERT_INTERNAL(new_page != nullptr);
          auto const new_header = new(new_page) PageHeader;
          new_header->m_prev_page = reinterpret_cast<void*>(
               m_top);
          m_top = reinterpret_cast<uintptr_t>(
               new_header + 1) + i_size;
          return new_header + 1;
     }
     else
     {
          // external block
          return UNDERLYING_ALLOCATOR::allocate(
               i_size, alignment);
     }
}
```

The function `allocate` requires that the size of the block is aligned, otherwise the behavior is undefined. `allocate` can allocate a block with size zero. Anyway there is a special allocation function that can be used when the size of the block is always zero:

```
void * allocate_empty() noexcept
{
     return reinterpret_cast<void*>(m_top);
}
```

This function does not alter the state of the queue, is faster and never throws. Note that it may return the virgin-allocator marker, but the user does not have to handle this as a special case.

The allocator uses a delayed deallocation strategy for the pages: a page is not deallocated when it owns no alive blocks, but rather when a block of the previous page is deallocated. With this strategy a user that occasionally allocates and deallocates a block will enter in the slow path (and will allocate a page) only the first time.

To deallocate a block, if the address is in the same page of the top pointer, the `lifo_allocator` just assigns the block to deallocate to the top pointer. Otherwise it enters the slow path, in which the allocator detects whether the top pointer is going to leave an empty page, or it has to deallocate an external block.

```
void deallocate(void * i_block, size_t i_size) noexcept
{
     DENSITY_ASSERT(i_block != nullptr && i_size % alignment == 0);

     // this check detects page switches and external blocks
```

```
     if (!DENSITY_LIKELY(same_page(i_block,
               reinterpret_cast<void*>(m_top))))
     {
          deallocate_slow_path(i_block, i_size);
     }
     else
     {
          m_top = reinterpret_cast<uintptr_t>(i_block);
     }
}

DENSITY_NO_INLINE void deallocate_slow_path(
     void * i_block, size_t i_size) noexcept
{
     DENSITY_ASSERT_INTERNAL(i_size % alignment == 0);

     if ((m_top & (page_alignment - 1)) == sizeof(PageHeader) &&
               same_page(reinterpret_cast<PageHeader*>(
               m_top)[-1].m_prev_page, i_block) )
     {
          // deallocate the top page
          auto const page_to_deallocate = reinterpret_cast<void*>(
               m_top);
          UNDERLYING_ALLOCATOR::deallocate_page(
               page_to_deallocate);
          m_top = reinterpret_cast<uintptr_t>(i_block);
     }
     else
     {
          // external block
          UNDERLYING_ALLOCATOR::deallocate(
               i_block, i_size, alignment);
     }
}
```

The allocator allows resizing a block, preserving its content up to the previous size, with the following function:

```
void * reallocate(void * i_block, size_t i_old_size, size_t i_new_size);
```

The implementation of this function is slightly more complex, but it is basically an exception safe mixing of `allocate` and `deallocate`, so it is not listed here.

8. The data-stack

The library keeps a private thread-local instance of `lifo_allocator`, called the *data-stack*. By design the constructor of `lifo_allocator` is constexpr, so that the data-stack does not need dynamic initialization by every thread. Threads may allocate the first page only when they uses the data-stack for the first time. Direct access to the data-stack is not allowed. Two data structures are provided instead to use indirectly the data-stack: `lifo_array` and `lifo_buffer`.

The class template `lifo_array` is very similar to an array. It has an immutable size specified at construction time. If no initializer is provided, `lifo_array` default-constructs the elements. This is a big difference with to `std::vector`, that uses value-initialization.

```
    // uninitialized array of doubles
    lifo_array<double> numbers(7);

    // initialize the array
    for (auto & num : numbers)
        num = 1.;

    // compute the sum
    auto const sum = std::accumulate(
           numbers.begin(), numbers.end(), 0.);
    assert(sum == 7.);

    // initialized array
    lifo_array<double> other_numbers(7, 1.);
    auto const other_sum = std::accumulate(
           other_numbers.begin(), other_numbers.end(), 0.);
    assert(other_sum == 7.);

    // array of class objects (default-constructed)
    lifo_array<std::string> strings(10);
    bool all_empty = std::all_of(strings.begin(), strings.end(),
      [](const std::string & i_str) {
                 return i_str.empty(); });
    assert(all_empty);
```

The constructor of `lifo_array` allows to specify any number of parameters to initialize the elements. Anyway they must be const l-value references: r-value are not supported, because they fit only to one-to-one initializations.

It's highly recommended to use `lifo_array` only on the automatic storage. Doing so there is no way to break the LIFO constraint. Any other used should be handled with caution.

The class `lifo_buffer` is very different from `lifo_array` mainly for 2 reasons:

- it handles raw memory rather than elements of a type known at compile-time
- it allows resizing (with content preservation) of the most recently constructed instance.

Resizing a `lifo_buffer` when another most recent `lifo_buffer` or `lifo_array` is alive causes undefined behavior.

Internally the default-contructor of `lifo_buffer` uses the function `allocate_empty` to allocate a block of size 0, so it is noexcept and very fast.

```
    void func(size_t i_size)
    {
```

```
        using namespace density;

        lifo_buffer buffer_1(i_size);
        assert(buffer_1.size() == i_size);

        lifo_buffer buffer_2; /* now buffer_1 can't be
                resized until buffer_2 is destroyed */
        assert(buffer_2.size() == 0);

        auto mem = buffer_2.resize(sizeof(int));
        assert(mem == buffer_2.data());
        *static_cast<int*>(mem) = 5;

        mem = buffer_2.resize(sizeof(int) * 20);
        assert(*static_cast<int*>(mem) == 5);

        lifo_array<int> other_numbers(7);
        // buffer_2.resize(20); ← other_numbers is more recent, so this
                            would be a violation of the lifo constraint!
    }
```

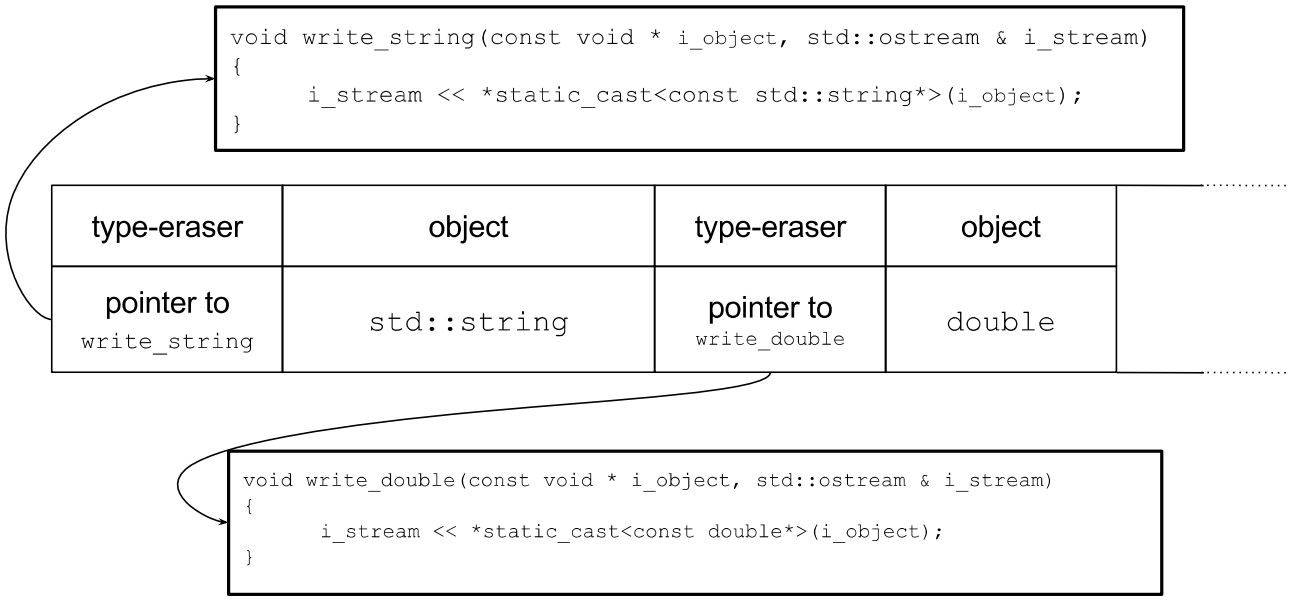
Heterogeneous and function queues

9. Introduction to type erasure

Type erasure is a well know technique to decouple actions on objects from their compile-time type. Let's consider the implementation of a heterogeneous sequence of objects. When we insert an object in the sequence probably we know the type at compile-time, so we can just call the constructor of the element. Anyway, when we iterate the sequence, we have no compile-time knowledge of the types of the objects. Type erasure solves this problem.

The type erasure used by density requires declaring in advance which features should be captured from the types. Let's suppose for example that we need to be able to write the objects of an heterogeneous sequence to an `std::ostream`. A very simple way to do that is prepending to every element a pointer to a function that is able to handle the specific object.

The memory layout of this sequence may be something like this:



In this example the type eraser is a pointer to a function with this signature:

```
void (*)(const void * i_object, std::ostream & i_stream);
```

A trivial consideration is that a universal implementation of the write function may be provided by a function template:

```
template <typename T>
	void write_string(const void * i_object, std::ostream & i_stream)
{
	i_stream << *static_cast<const T*>(i_object);
}
```

In a more realistic case we would need to add at least a pointer to a destroy function, so in this case our type erasure would be a struct containing two pointers to functions. We may even add a variable with the size of the type, and one with the alignment. If our type eraser has a considerable size, we may consider to add a level of indirection: the type eraser becomes a pointer to a static constexpr struct with the actual pointer to functions and data.

The above example is simplified, but is very similar to the type erasure used by density. Note that this technique is similar to the v-table used by the C++ compilers to implement virtual functions. The main advantages are:

- it's easily customizable. For example one may add data members (for example for the size and alignment of the target type), and even pointer to construction functions, while virtual static data and virtual constructors are currently not supported by the standard.

- it's not intrusive, while virtual function are a feature embedded in the type. A class can be type-erased without being modified.

Here follows a small digression on the advantages of using type erasure for polymorphism. The reader not interested may skip to the next paragraph.

Let's suppose we have a set of classes representing 2d shapes:

```
class Circle
{
public:

    bool IsPointInside(const Vector2d & i_point) const;

private:
    Vector2d m_center;
    float m_radius = -1.f;
};

class Box
{
public:

    bool IsPointInside(const Vector2d & i_point) const;

private:
    Vector2d m_center, m_size{-1.f, -1.f};
};
```

Now we want to implement a class `ComplexShape`, that represent a union of other shapes. `ComplexShape` provides a function `IsPointInside` that checks if the point is inside any of the child shapes. The classic OOP solution would be introducing a base class or an interface representing a shape, with a virtual function `IsPointInside`. Anyway interfaces and base classes have impact on both the design and the performances. Any instance of `Box` would have a pointer to a v-table as hidden member, even if polymorphous is not necessary for all the uses.

Instead of using polymorphism, we may implement `ComplexShape` using type erasure:

```
class ShapeReference
{
public:

    // ...

    bool IsPointInside(const Vector2d & i_point) const
    {
        return (*m_type->m_is_point_inside)(m_object, i_point);
    }

private:
    struct Type
    {
        bool (*m_is_point_inside)(void * const i_object,
                    const Vector2d & i_point);
        void (*m_destroy_func)(void * i_object);
    };
    void * m_object;
    Type * m_type;
```

```
};

class ComplexShape
{
    // ...
private:
    std::vector<ShapeReference> m_children;
};
```

With type-erasure, polymorphism is paid only when it's actually used.

10. The RuntimeType pseudo-concept

The heterogeneous queues provided by the library are not bound to a particular type-erasure. They have instead a type template-parameter that allows the user to specify a custom type erasure, provided that it models *RuntimeType*.

Here is the RuntimeType synopsis:

```
class RuntimeType
{
public:

    using common_type = ...;

    template <typename TYPE>
        static RuntimeType make() noexcept;

    template <typename TYPE>
        bool is() const noexcept;

    RuntimeType(const RuntimeType &);

    size_t size() const noexcept;

    size_t alignment() const noexcept;

    common_type * default_construct(void * i_dest) const;

    common_type * copy_construct(void * i_dest,
           const common_type * i_source) const;

    common_type * move_construct(void * i_dest,
           common_type * i_source) const;

    void * destroy(common_type * i_dest) const noexcept;

    const std::type_info & type_info() const noexcept;

    bool are_equal(const common_type * i_first,
```

```
            const common_type * i_second) const;

    bool operator == (
            const RuntimeType & i_other) const noexcept;

    bool operator != (
            const RuntimeType & i_other) const noexcept;
};
```

Most of these functions are optional, so RuntimeType strictly can't be a concept.

The static function template `make` performs the transition from a type known at compile-time to an instance of RuntimeType that has no compile-time dependence from the type. The type bound to a RuntimeType is the *target type*. If the type alias `common_type` is void, the target type can be any type. Otherwise the target type must be a user-defined type deriving from `common_type`.

The `*_contruct` functions take as parameter a pointer to the beginning of the storage of the object to construct (`i_dest`). If `common_type` is `void`, they return the same pointer. Otherwise they return a pointer to the `common_type` sub-object of the complete object. Symmetrically the function `destroy` takes a pointer to the `common_type` sub-object of the object, and returns a pointer to the complete object.

By default all the heterogeneous queues of the library use the class template `runtime_type` for type erasure. A `runtime_type` internally is just a pointer to a custom v-table containing data and pointer to functions to capture a set of features on the target type. This is the signature of the class template:

```
template <typename COMMON_TYPE = void,
  typename FEATURE_LIST =
     type_features::default_type_features_t<COMMON_TYPE> >
          class runtime_type;
```

`runtime_type` is highly customizable, as it allows to specify the set of feature to capture with the second template argument, which is a type list. The namespace `density::type_features` provides many common features ready to be used. The user may also define custom type features. This table enumerates the features that a `runtime_type` captures with the default feature list:

Feature	What allows on `runtime_type`
`type_features::size`	Allows to use the function `runtime_type::size` to get the size of the target type
`type_features::alignment`	Allows to use the function `runtime_type::alignment` to get the size of the target type
`type_features::rtti`	Allows to use the function `runtime_type::type_info` to get a `std::type_info` for the target type
`type_features::destroy`	Allows to use the function `runtime_type::destroy` to destroy an instance of the target type
`type_features::move_construct`	Allows to use the function `runtime_type::move_construct` to move-construct an instance of the target type from an instance

Feature	What allows on `runtime_type`
(only if the `comon_type` is `void` or is move constructible)	of the same type
`type_features::copy_construct` (only if the `comon_type` is `void` or is copy constructible)	Allows to use the function `runtime_type::move_construct` to copy-construct an instance of the target type from an instance of the same type

This example shows how to define a `runtime_type` customizing the captured features and how to use it:

```
using namespace type_features;
using MyRTType = runtime_type<void,
     feature_list<default_construct, destroy, size> >;
MyRTType type = MyRTType::make<std::string>();
void * buff = malloc(type.size());
type.default_construct(buff);
// now buff points to a valid std::string
*static_cast<std::string*>(buff) = "hello world!";
type.destroy(buff);
free(buff);
```

11. Overview of the heterogeneous queues

The library provides 4 heterogeneous queues:

- *heter_queue*: not thread safe
- *conc_heter_queue*: thread safe, blocking
- *lf_heter_queue*: thread safe, lock-free
- *sp_heter_queue*: thread safe, spin-locking

The first 3 template parameters of all the heterogeneous queues are:

- `COMMON_TYPE`, type parameter, by default `void`. An element of type `T` can be put in the queue only if `T*` is implicitly convertible to `COMMON_TYPE*`.
- `RUNTIME_TYPE`, type parameter, by default `runtime_type<>`. It's the type-eraser. It must have the member type alias `common_type` that matches `COMMON_TYPE`. A static assert checks that this requirement is met.
- `ALLOCATOR_TYPE`, type parameter, by default `void_allocator`. It must model both PageAllocator and UntypedAllocator.

The class template `lf_heter_queue` has these additional template parameters:

- `PRODUCER_CARDINALITY`, parameter of type `concurrency_cardinality`, the default value is `concurrency_multiple`. Specifies whether multiple threads are allowed to put in the queue concurrently.

- `CONSUMER_CARDINALITY`. parameter of type `concurrency_cardinality`, the default value is `concurrency_multiple`. Specifies whether multiple threads are allowed to consume from the queue concurrently.

- `CONSISTENCY_MODEL`, parameter of type `consistency_model`, the default value is `consistency_sequential`. Specifies whether the queue is linearizable, that is all the threads agree on a total ordering of all the operations on the queue.

The class template `sp_heter_queue` has these additional template parameters:

- `PRODUCER_CARDINALITY`. Like the homonymous parameter of `lf_heter_queue`.

- `CONSUMER_CARDINALITY`. Like the homonymous parameter of `lf_heter_queue`.

- `BUSY_WAIT_FUNC`. Type callable with the signature `void ()` that is called in the body of a busy wait. The default value is a function type that calls `std::this_thread::yield`.

An action on the queue is an *operation*. Some operations are executed by a single function call, while some others span more than one call. Every operation belongs to one of these classes:

- *put operations*: operations that inserts an element to the end of the queue.

- *consume operations*: operations that consume an element at the beginning of the queue, or that check if the queue is empty.

- *lifetime operations*: all the other functions, including constructors, destructors, assignments and swap.

Depending on the queue and on the template arguments, put and consume operations can be used concurrently. All the queues define a set of member constants that describe the concurrent capabilities of the queue:

Member constant	**Semantics**
`static constexpr bool concurrent_puts;`	Whether multiple threads are allowed to do put operations concurrently.
`static constexpr bool concurrent_consumes;`	Whether multiple threads are allowed to do consume operations concurrently.

Member constant	**Semantics**
`static constexpr bool concurrent_put_consumes;`	Whether put operations can be executed concurrently with consume operations.
`static constexpr bool is_seq_cst;`	Whether the queue is linearizable, that is all the threads agree on a total ordering of all the operations on the queue.

`heter_queue` is not concurrent, so all the above constants are `false`. `conc_heter_queue` is always fully concurrent, so all the above constants are `true`.

`lf_heter_queue` and `sp_heter_queue` always allows a single producer to run concurrently with a single consumer, so `concurrent_put_consumes` is always `true`. The values of `concurrent_puts` and `concurrent_consumes` depends on the template arguments `PRODUCER_CARDINALITY` and `CONSUMER_CARDINALITY`. The constant `is_seq_cst` is always true for `sp_heter_queue`, and depends on the template argument `CONSISTENCY_MODEL` for `lf_heter_queue`.

The simplest way to put an element in a queue is using `push` or `emplace`:

```
queue.push(19); // the parameter can be an l-value or an r-value
queue.emplace<std::string>(8, '*'); // pushes "********"
```

The type of the element is deduced from the argument in the case of `push`, but needs to be specified explicitly in the case of `emplace`.

Put functions containing `start_` in their name are *transactional*. They start a put, and return an object of type `put_transaction`, that can be used to *commit* or *cancel* the put.

```
auto put = queue.start_push(12);
put.element() += 2;
put.commit(); // commits a 14
```

A put transaction becomes observable only when it's committed. If it is canceled, it will never be observable.

An instance of `put_transaction` in any moment either is bound to a transaction, or is empty. When the functions `commit` or `cancel` are called, the `put_transaction` becomes empty. If the `put_transaction` is already empty, calling `commit` or `cancel` causes undefined behavior. When a non-empty `put_transaction` is destroyed, the transaction is canceled. `put_transaction` is movable but not copyable.

Transactional puts allow to associate a *raw block* with the element:

```
heter_queue<> queue;
struct MessageInABottle
{
```

```
    const char * m_text = nullptr;
};
auto transaction = queue.start_emplace<MessageInABottle>();
transaction.element().m_text = transaction.raw_allocate_copy("Hello!");
transaction.commit();
```

A raw block is an untyped and uninitialized range of contiguous memory, in which the user may store additional data associated to an element. An element may be associated to more than one block, but it should keep a pointer to every of them, because otherwise consumers would have no way to get these addresses.

Raw blocks can be allocated specifying a size and an alignment, a pair of iterators, or a range (like in the example). A raw block is automatically deallocated when the put of the associated element is canceled, or when the element is consumed. Accessing a deallocated raw block causes undefined behavior.

By default operations on queues are non-reentrant. During a non-re-entrant operation the queue is not in a consistent state for the calling thread (though it is in a consistent state for the other threads, provided that it is concurrency-enabled). So, in the example above, calling any member function on the queue between the `start_emplace` and the `commit` would cause undefined behavior. Even a single-call put may introduce re-entrancy:

```
// buggy code:
queue.emplace<ClassThatUsesTheQueueInTheConstructor>(12); <- UB!!!!
```

The operations that starts with a function containing `reentrant_` in their name support *re-entrancy*. Re-entrant operations can overlap each other.

```
auto put_1 = queue.start_reentrant_push(12);
auto put_2 = queue.start_reentrant_emplace<std::string>("Hello ");
auto put_3 = queue.start_reentrant_push(3.14f);
put_3.commit();
put_1.commit();
put_2.element() += "world!!!!";
put_2.cancel();
```

Non-re-entrancy allows to the implementation some optimizations and may alter thread synchronization. For example `heter_queue` starts non-re-entrant puts in the committed state, so that the actual `commit` becomes a no-operation (so the observable state of the queue is temporary wrong). A notable further example is `conc_heter_queue`, that keeps its internal non-recursive mutex locked during a non-re-entrant operation, while it locks its mutex twice for re-entrant operations. If the user starts an operation while a non-re-entrant one is still in progress, the mutex would be locked twice by the same thread, causing undefined behavior.

Put functions containing `dyn_` in their name are *dynamic*. Dynamic puts inserts elements of a type unknown at compile-time. The type of the element is specified by an instance of the type-eraser, passed as first argument. The element can be default-constructed, copy-constructed or move-constructed, provided that the type-eraser supports it.

```
using namespace type_features;
```

```
using MyRunTimeType = runtime_type<void, feature_list<
     default_construct, destroy, size, alignment>>;
heter_queue<void, MyRunTimeType> queue;
auto const type = MyRunTimeType::make<int>();
queue.dyn_push(type); // appends 0
```

One possible use of dynamic puts is for transferring one element from one queue to another, as shown in the following example:

```
using namespace type_features;
using MyRunTimeType = runtime_type<void, feature_list<
     move_construct, destroy, size, alignment>>;

heter_queue<void, MyRunTimeType> queue_1;
queue_1.emplace<std::string>("Hello!");

heter_queue<void, MyRunTimeType> queue_2;
auto consume = queue_1.try_start_consume();
queue_2.dyn_push_move(consume.complete_type(), consume.element_ptr());
consume.commit();

consume = queue_2.try_start_consume();
assert(consume && consume.complete_type().is<std::string>());
assert(consume.element<std::string>() == "Hello!");
consume.commit();

assert(queue_1.empty() && queue_2.empty());
```

Put functions containing `try_` in their name allows to specify the progression guarantee as first parameter, and returns a (possibly empty) `put_transaction`. Try put functions are supported only by `lf_heter_queue` and `sp_heter_queue`.

The set of put functions is orthogonal: every combination of transnational, re-entrant, dynamic and try_* is supported. This is a summary of the complete set:

- `[try_][start_][reentrant_]push`
- `[try_][start_][reentrant_]emplace`
- `[try_][start_][reentrant_]dyn_push`
- `[try_][start_][reentrant_]dyn_push_copy`
- `[try_][start_][reentrant_]dyn_push_move`

A *consume operation* is very similar to a put-transaction, but it's not a transaction. When the consume starts, the element is immediately removed by the queue, so that other consumers will not interfere. Actually the queue does not really move the element, but the other consumers will skip it. Whenever the consume operation is committed, the element is destroyed, and it's gone forever. Anyway if the consume is canceled the element will reappear in the queue, so that the consume can

be retried. This is the reason why consumes are not transactions: even when canceled, they have the observable effect of temporary removing the element.

```
    heter_queue<> queue;
    auto consume_1 = queue.try_start_consume();
    assert(!consume_1);
    queue.push(42);
    auto consume_2 = queue.try_start_consume();
    assert(consume_2);
    assert(consume_2.element<int>() == 42);
    consume_2.commit();
```

The following example shows how consumers can analyze the element and its type. Note that if the same action is needed for all the elements regardless of they type, a type feature would be a much better solution (there also is a built-in `type_feature::ostream` that can be used with `runtime_type`).

```
heter_queue<> queue;
queue.push(42);
queue.emplace<std::string>("Hello world!");
queue.push(42.);

while (auto consume = queue.try_start_consume())
{
    if(consume.complete_type().is<int>())
        std::cout << "Found an int: "
           << consume.element<int>() << std::endl;
    else if(consume.complete_type().is<std::string>())
        std::cout << "Found a string: "
           << consume.element<std::string>() << std::endl;
    consume.commit();
}
```

We may rewrite the consume loop in a similar way using another overload of `try_start_consume`:

```
heter_queue<>::consume_operation consume;
while (queue.try_start_consume(consume))
{
    ...
    consume.commit();
}
```

This overload takes as argument a reference to a `consume_operation`, and returns a boolean. If this boolean is true, after the call the consume operation is bound to an element. Otherwise it's cleared. In any case, if the consume operation was already consuming an element before the call, it is canceled first.

The overload of `try_start_consume` taking a `consume_operation` as parameter is functionally the same to the other one. Anyway, for lock-free and spin-locking queues, keeping a `consume_operation` alive may increase the performances of habitual consumers (the reason will be discussed later).

12. Anatomy of a queue

The storage of a heterogeneous 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*. The 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.

The layout of a *value* is composed by:

- the *control block*, an internal structure of the library. Every value has one, and contains a pointer to the next control block in the queue, that it's always in the same page except for the last value of the page. The least significant bits of this pointer are used to store some status flag:
  - *busy flag*: set whether a put or a consume is in progress on the value.
  - *dead flag*: set for values that don't have a valid element
  - *external flag*: set for values whose element (or raw block) was too big to be allocated in the page, so it has been is allocated externally

  If the queue is only partially heterogeneous (that is the template argument `COMMON_TYPE` is not `void`), the control block includes a pointer to the element. This pointer is necessary because up-casting a pointer in C++ is in general a non-trivial operation, especially (bu not only) in case of virtual base classes.
- optionally the run-time type object, not present for raw allocations.
- optionally the element or the raw block

While an element is being produced or consumed it has the busy-flag set. Consumers skip busy elements, as they are already being consumed, or they are being initialized.

If a value is dead, it has not a valid element. Dead values arise from:

- elements whose put was canceled (including those whose constructor threw an exception). Such elements occupy space on the page, until the page is deallocated by consumers.
- elements that have been consumed, but still have a storage
- raw blocks

If a value or a raw block is too large, it's allocated externally, and the external-flag is set on the control block. A struct containing a pointer to the external block is allocated in the page in place of the big element or block.

If the queue is not empty, the head pointer points to the first value of the queue. Values are stored as a forward linked-list, and are allocated linearly, in container order, with an implementation-defined granularity (which is the alignment guaranteed for the storage of the value).

To start a put, the tail pointer is advanced to make place for the new value. The newly initialized element is set to the busy state. When the put is committed or canceled, the busy-flag is removed. If the put is canceled, the element is destroyed, and the dead-flag is set.

To start a consume, all the values are scanned until the first non-dead and non-busy element is found. If no such element is found, the try-start-consume function returns an empty `consume_operation`. Otherwise the target element is marked as busy, so that the caller gets exclusive access on it. When a consume is committed, the head is advanced past all dead elements. When the head switches to a different page, the previous page is deallocated.

The storage of an element or a raw block is always properly aligned. Consumers can access the element using 3 member functions of the consume-operation:

1. The function `element<Type>()`, that returns a reference to the complete element, but requires to specify its type as template argument. If the actual element type does not match the one specified, the behavior is undefined. Consumers can use the member function `is<Type>()` to check if the type is exactly `Type`.

2. The function `element_ptr()`, that returns a pointer of type `common_type` (so in case of fully heterogeneous queues a `void` pointer). Conceptually `element` calls `element_ptr` and adds a `static_cast` and an indirection.

3. The function `unaligned_element_ptr()`, which is similar to `element_ptr`, but always returns a `void` pointer, which may not be the actual address of the element. To get a pointer to the element the caller must upper-align the returned address according to the type of the target value. Conceptually `element_ptr` calls `unaligned_element_ptr` and aligns the returned pointer, after retrieving the alignment from the runtime-type.

The third function is faster and, importantly, it does not access the runtime-type. If only `unaligned_element_ptr` is used, the runtime-type is not required to support the feature `alignment`. Anyway the pointer returned by `unaligned_element_ptr` must be aligned somehow. The point of exposing `unaligned_element_ptr` in the public interface is that a feature of the runtime-type that performs an action (for example that writes the object to an `std::ostream`) may embed the alignment step too. This is beneficial for two reasons:

- A feature of the runtime-type knows at compile time the alignment of the type, so it does not need to store and load it, and executes less instructions.

- Most times the runtime-type does not need to align the address at all. The reason is that the result of `unaligned_element_ptr` is guaranteed to be already aligned to a constant value, specified by the constant `min_alignment`, provided by all the heterogeneous queues. If the

actual type has an equal or smaller alignment, the alignment step can be skipped at compile time[5].

As shown later, function queues use only `unaligned_element_ptr`, because that they use a custom and simplified runtime-type.

13. The lock-free queue

This paragraph describes the details of `lf_heter_queue`. The implementations of the other queues are not covered because:

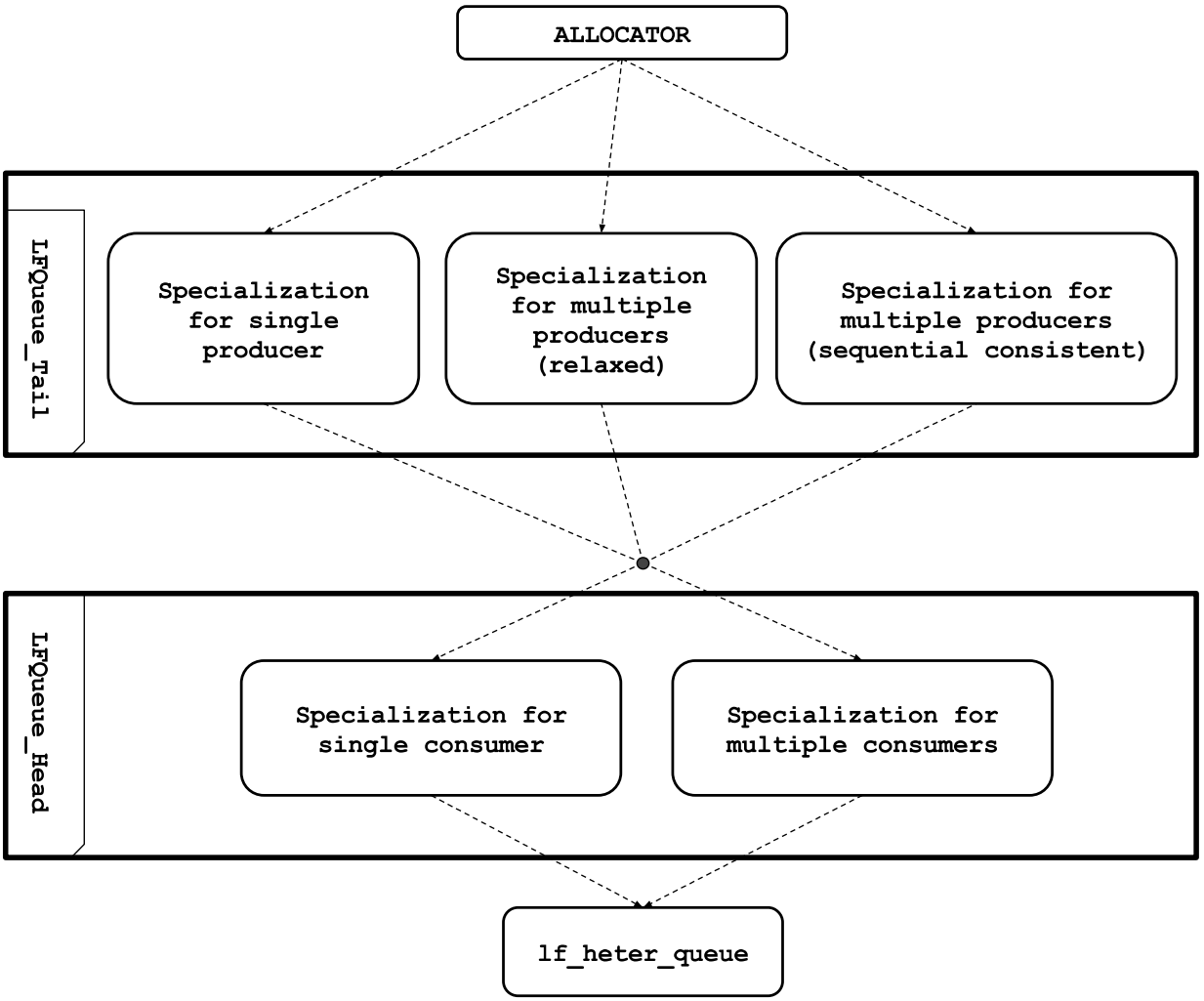
- `heter_queue` has an extremely similar layout, but a much simpler implementation.
- `conc_heter_queue` is just a wrapper of an internal `heter_queue` protected by an `std::mutex`.
- `sp_heter_queue` shares much of it implementation with `lf_heter_queue`. Only the producer layer and only in case of multiple producers is distinct.

This is the declaration of `lf_heter_queue`:

```
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;
```

The user may use the last 3 template parameters to set some restrictions on the functionalities and FIFO consistency. We should exploit these restrictions to provide a more efficient implementation. There are 2^3 = 8 possible assignments for these parameters, but fortunately we don't need to provide a different implementation for each of them. To handle the values of these template parameters `lf_heter_queue` has a four-level private hierarchy:

5 The features of runtime_type are not exploiting this constant because it is queue-specific. This may change in a future release.



- The first level is the allocator, that is a user provided type (by default `void_allocator`).
- The second level is `LFQueue_Tail`, an internal class template that implements put operations. Three partial specializations are provided.
- The third level is `LFQueue_Head`, that implements consume operations. Two partial specializations are provided.
- The fourth and last level is `lf_heter_queue`, the only one that defines public functions (it inherits privately from `LFQueue_Head`). `lf_heter_queue` uses functionalities from the underlying layers to provide the same interface of all the other queues. No partial specializations are defined for `lf_heter_queue`.

The queue is internally a null-terminated linked-list, so that consumers can iterate it without accessing the tail for the termination condition. The tail pointer is used only by producers, and the head pointer is used only by consumers. Beyond slightly less contention, this simplifies the implementation, and allows to better exploiting reduced cardinalities: if `PROD_CARDINALITY` is `concurrency_sin-`

gle, the tail pointer is not an atomic variable. Similarly, if CONSUMER_CARDINALITY is concurrency_single, the head pointer is not an atomic variable. The head and tail layers are aligned so that they should have their storage in two dinstict cache-lines.

The code below shows the definition of the control block and of the flags encoded in the least significant bits of the member m_next.

```
namespace detail
{
    template<typename COMMON_TYPE> struct LfQueueControl
    {
        uintptr_t m_next; // raw atomic
        COMMON_TYPE * m_element;
    };

    template<> struct LfQueueControl<void>
    {
        uintptr_t m_next; // raw atomic
    };

    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 busy-flag is set to a value while a producer is producing it, or while a consumer is consuming it. The dead-flag is set on values not alive. Consumers scan the queue until they find a m_next that is not zeroed, and is neither busy nor 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 starts consuming an element, it sets the busy-flag on the value. 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 the other consumers may have observed the absence of the element between the beginning of the consume and the cancel, the consume is not a transaction.

The class template LFQueue_Tail introduces and manages the tail pointer, and provides the function try_inplace_allocate, that is used by lf_heter_queue to implement the put and raw allocations:

```
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
{
     ...
     template <LfQueue_ProgressGuarantee PROGRESS_GUARANTEE,
               uintptr_t CONTROL_BITS, bool INCLUDE_TYPE,
               size_t SIZE, size_t ALIGNMENT>
          Block try_inplace_allocate();

     template<LfQueue_ProgressGuarantee PROGRESS_GUARANTEE>
          Block try_inplace_allocate(
               uintptr_t i_control_bits, bool i_include_type,
               size_t i_size, size_t i_alignment);
     ...
};
```

The above code is not actually present in the library, because the general class template is not defined. The first overload can be used for every non-dynamic put (that is when size and alignment are known at compile-time). The second is used for dynamic puts and raw allocations. The boolean `i_include_type` specifies whether a runtime-type should be allocated. `i_size` and `i_alignment` are the size and alignment of the element or raw allocation. The return type is a struct containing a possibly null pointer to the element (or the raw block), and a pointer to the control block.

Every specialization of `LFQueue_Tail` allocates either zeroed or non-zeroed memory pages, and provides a constexpr boolean to communicate to the subsequent layers whether pages should be zeroed at consume time:

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

Allocating zeroed pages and deallocating non-zeroed page is legal, but this forces the page allocator to `memset` a page before recycling it. Consumers, on the other side, can zero this memory while it is still hot on their cache.

The implementation of the producer layer is split in 3 partial specializations of `LFQueue_Tail`:

- One for `PROD_CARDINALITY` = `concurrency_single`, that allocates non-zeroed pages, and defines `s_deallocate_zeroed_page` as false.
- One for `PROD_CARDINALITY` = `concurrency_multiple` and `CONSISTENCY_MODEL` = `consistency_relaxed`, that allocates zeroed pages, and defines `s_deallocate_zeroed_page` as true.
- 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 the recycled memory falls to the allocator.

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

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

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, its address 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.

Currently the default constructor of this queue is not constexpr, because the function `invalid_control_block` performs a `reinterpret_cast`. This is a defect, because queues allocated in the static storage can't have constant initialization. To fix this, the tail pointer (`m_tail`) should be an `uintptr_t` rather than a pointer to a control-block (this technique is already used for `lifo_allocator`). Note that `invalid_control_block()` is already doing assumptions on the pointer representation.

14. Lock-free queue – the producer layer

The code below is the allocation function for an element or raw block in the case of single producer (`m_tail` is not an atomic in this case).

```
template <LfQueue_ProgressGuarantee PROGRESS_GUARANTEE, uintptr_t
CONTROL_BITS, bool INCLUDE_TYPE, size_t SIZE, size_t ALIGNMENT>
    Block try_inplace_allocate_impl()
        noexcept(PROGRESS_GUARANTEE != LfQueue_Throwing)
{
    auto guarantee = PROGRESS_GUARANTEE; /* used to avoid warnings
           about constant conditional expressions */

    constexpr auto alignment = size_max(ALIGNMENT, min_alignment);
    constexpr auto size = uint_upper_align(SIZE, alignment);
    constexpr auto can_fit_in_a_page =
           size + (alignment - min_alignment) <= s_max_size_inpage;
    constexpr auto over_aligned = alignment > min_alignment;

    auto tail = m_tail;
    for (;;)
    {
        DENSITY_ASSERT_INTERNAL(address_is_aligned(tail,
                                                   s_alloc_granularity));
        void * address = address_add(tail,
           INCLUDE_TYPE ? s_element_min_offset : s_rawblock_min_offset);

        // allocate space for the element
        if (over_aligned)
        {
            address = address_upper_align(address, alignment);
```

```
        }
        void * const user_storage = address;
        address = address_add(address, 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: while control_block->m_next is zero, no consumers
                may ever read this variable. So this does not need
                to be atomic store. */
            new_tail->m_next = 0;

            auto const control_block = tail;
            auto const next_ptr = reinterpret_cast<uintptr_t>(
                      new_tail) + CONTROL_BITS;
            raw_atomic_store(&control_block->m_next, next_ptr,
                      mem_release);

            m_tail = new_tail;
            return Block{ control_block, next_ptr, user_storage };
        }
        else if (can_fit_in_a_page)
        {
            tail = page_overflow(PROGRESS_GUARANTEE, tail);
            if (guarantee != LfQueue_Throwing)
            {
                if (tail == 0)
                {
                    return Block();
                }
            }
            else
            {
                DENSITY_ASSERT_INTERNAL(tail != 0);
            }
            m_tail = tail;
        }
        else
        {
            // this allocation would never fit in a page
            return external_allocate<PROGRESS_GUARANTEE>(
                           CONTROL_BITS, SIZE, ALIGNMENT);
        }
    }
}
```

This function is the core of all put operations, and is the interface for subsequent layers. It is still a private and low-level function. For the single-producer case, the function `page_overflow` is very easy to implement, so we will not discuss it.

The following code shows `try_inplace_allocate_impl` for the case of multiple producers with relaxed consistency:

```
template <LfQueue_ProgressGuarantee PROGRESS_GUARANTEE, uintptr_t
CONTROL_BITS, bool INCLUDE_TYPE, size_t SIZE, size_t ALIGNMENT>
    Block try_inplace_allocate_impl()
        noexcept(PROGRESS_GUARANTEE != LfQueue_Throwing)
{
    auto guarantee = PROGRESS_GUARANTEE; /* used to avoid warnings
           about constant conditional expressions /*

    constexpr auto alignment = size_max(ALIGNMENT, min_alignment);
    constexpr auto size = uint_upper_align(SIZE, alignment);
    constexpr auto can_fit_in_a_page =
           size + (alignment - min_alignment) <= s_max_size_inpage;
    constexpr auto over_aligned = alignment > min_alignment;

    auto tail = m_tail.load(mem_relaxed);
    for (;;)
    {
        void * new_tail = address_add(tail,
           INCLUDE_TYPE ? s_element_min_offset : s_rawblock_min_offset);

        if (over_aligned)
        {
            new_tail = address_upper_align(new_tail, alignment);
        }
        void * const user_storage = new_tail;
        new_tail = address_add(new_tail, 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))
        {
            /* No page overflow occurs with the new tail */
            if (m_tail.compare_exchange_weak(
                tail, static_cast<ControlBlock*>(new_tail),
                mem_acquire, mem_relaxed))
            {
                /* Assign m_next, and set the flags. This is very
                      important for the consumers, because they that
                      need this write happens before any other part of
                      the allocated memory is modified. */
                auto const control_block = tail;
                auto const next_ptr = reinterpret_cast<uintptr_t>(
```

```
                        new_tail) + CONTROL_BITS;
                raw_atomic_store(&control_block->m_next,
                        next_ptr, mem_release);

                return Block{ control_block, next_ptr, user_storage };
            }
            else
            {
                if (guarantee == LfQueue_WaitFree)
                {
                    return Block();
                }
            }
        }
        else if (can_fit_in_a_page)
        {
            tail = page_overflow(guarantee, tail);
            if (guarantee != LfQueue_Throwing)
            {
                if (tail == nullptr)
                {
                    return Block();
                }
            }
        }
        else
        {
            // this allocation would never fit in a page
            if (guarantee != LfQueue_Blocking
                && guarantee != LfQueue_Throwing)
            {
                return Block();
            }
            else
            {
                return external_allocate<PROGRESS_GUARANTEE>(
                        CONTROL_BITS, SIZE, ALIGNMENT);
            }
        }
    }
}
```

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

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

1. A put first updates the tail pointer, and then writes the member `m_next` of the control-block it has just allocated (`m_next` is zero before that). In the middle of these two writes, other producers may successful do other puts (they are not blocked), but for the consumers the queue

is truncated to the first zeroed `m_next`. So 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.

To implement the sequential consistent version of `try_inplace_allocate_impl` we have to solve the two problems above. For this case we allocate in the pages only values requiring at most a number of bytes equal to the square of `s_alloc_granularity` (64 by default, so the maximum size allocable in-page is 4 kibibytes). All other values are allocated with a legacy heap allocation.

To solve the first problem 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:

```
template <LfQueue_ProgressGuarantee PROGRESS_GUARANTEE, uintptr_t CONTROL_BITS,
                  bool INCLUDE_TYPE, size_t SIZE, size_t ALIGNMENT>
    Block try_inplace_allocate_impl()
        noexcept(PROGRESS_GUARANTEE != LfQueue_Throwing)
{
    auto guarantee = PROGRESS_GUARANTEE; /* used to avoid warnings
            about constant conditional expressions */

    constexpr auto alignment = size_max(ALIGNMENT, min_alignment);
    constexpr auto size = uint_upper_align(SIZE, alignment);
    constexpr auto overhead =
            INCLUDE_TYPE ? s_element_min_offset : s_rawblock_min_offset;
    constexpr auto required_size =
            overhead + size + (alignment - min_alignment);
    constexpr auto required_units = (required_size +
                  (s_alloc_granularity - 1)) / s_alloc_granularity;

    // this will pin a page when pin_new is called
    PinGuard<ALLOCATOR_TYPE> scoped_pin(this);

    bool 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, ALLOCATOR_TYPE::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 + 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), alignment);

                    return Block{ new_control,
                        future_tail + CONTROL_BITS, user_storage };
                }
                else
                {
                    if (guarantee == LfQueue_WaitFree)
                    {
                        return Block{};
                    }
                }
            }
            else
            {
                tail = page_overflow(guarantee, tail);

                if (guarantee != LfQueue_Throwing)
                {
                    if (tail == 0)
                    {
                        return Block();
                    }
                }
                else
                {
                    DENSITY_ASSERT_INTERNAL(tail != 0);
                }
            }
        }
        else
        {
            /* the memory protection currently used (pinning) is based on
                an atomic increment, that is not wait-free */
            if (guarantee == LfQueue_WaitFree)
            {
                return Block{};
            }

            // 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 + NbQueue_Busy, mem_relaxed);
                if (m_tail.compare_exchange_weak(tail, next, mem_relaxed))
                    tail = next;
            }
        }
    }
    else
    {
        return external_allocate<PROGRESS_GUARANTEE>(
            CONTROL_BITS, size, alignment);
    }
}
```

A producer starts analyzing the value of `m_tail`. If it is multiple of `s_alloc_granularity`, then there isn't another 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 tries to contribute to the put in progress by setupping the `m_next` member of the incomplete value and setting at the same time the busy-flag. Then, whether or not the help was successful, it retries its own put.

The producer layer has to allocate a new page when the last one is exhausted. Producers link the new page using a dead-value, the *end-of-page* value, that is the only value whose `m_next` can point to another page. Before a page is linked to the queue, the member `m_next` of its end-of-page value is set to the special value `NbQueue_InvalidNextPage`, so that producers can use a CAS to set the new page. To make all the threads agree on the status of this action, the end-of-page value is allocated always at the same offset from the beginning of the page. So, before allocating it, the producers first insert a padding dead value before the end-of-page value.

This is the complete put algorithm:

1. advance the tail pointer to make space for the new value. If the updated tail is in the same page of the previous tail, exit reporting success.

2. if the value would never fit in a page, allocate and return an external block

3. If there is unused space before the end-of-page value, try to allocate a padding dead-value, and then return to 1.

4. Perform a scoped pin on the current page, to prevent it from being recycled

5. If the member `m_next` of the end-of-page control block points to a new page, try to advance the tail pointer to this page.

6. Allocate a new page (initializing the `m_next` of the end-of-page control-block to `NbQueue_InvalidNextPage`)

7. Try to link the new page to the end-of-page control-block with a CAS on the `m_next` of the end-of-page control block

8. If the CAS of 7. has failed, deallocate the new page

9. Return to 1.

15. Lock-free queue – the consumer layer

The head pointer of every queue points to the first non-dead value. To start a consume, a thread searches for the first non-dead and non-busy value, starting from the head pointer. If no value is found, then it returns an empty consume operation. Otherwise it sets the busy flag to the value, and returns a consume operation bound to it.

When a consume is committed, the consumer clears the busy-flag, and sets the dead-flag. Then it tries to advance the head pointer to jump all the adjacent dead values, zeroing the memory at the same time, only if `s_deallocate_zeroed_page` is true. Whenever the head changes page, the old page is deallocated.

The consumer layer is implemented by the class template `LFQueue_Head`. Like for `LFQueue_Tail`, the general template is not defined. Two specializations are provided instead: one for the case of single producer, and one for multiple consumers.

The single-consumer layer does not need to pin pages, because in this case only one thread can deallocate them. The multiple-consumers layer needs to pin every page in order to access it, because pages may be deallocated by the other consumers in any moment. So the first step of a consume operation is pinning the head page. Every pinning or unpinning is a read-modify-write operation on a variable with high contention between consumers, so it is very costly.

Fortunately a consume operation object keeps its current page pinned regardless of whether it has a consume in progress. This is the reason why recycling a consume operation for multiple consumes is beneficial for lock-free and spin-locking queues: in this case consumers will do a pin and unpin only when a page switch actually occurs. In contrast, creating a consume operation object for each consume causes at least a pin\unpin pair every time.

Most of the code of `LFQueue_Head` is verbose and wouldn't add that much to the description above, so it is not listed here. The code below shows how consumers pin the head page.

```
    ControlBlock * head = i_queue->m_head.load();

    if (head == nullptr)
    {
        ... lazy initialization ...
    }

    while (!DENSITY_LIKELY(Base::same_page(m_control, head)))
    {
        i_queue->ALLOCATOR_TYPE::pin_page(head);

        if (m_control != nullptr)
        {
            i_queue->ALLOCATOR_TYPE::unpin_page(m_control);
        }

        m_control = head;

        head = i_queue->m_head.load();
    }
```

16. Function queues

Functions queues are queues of callable objects. The signature of the function is provided as template argument, similarly to `std::function`. A function queue may be seen as a queue of `std::function` objects.

```
// put a lambda
function_queue<void()> queue;
queue.push([] { std::cout << "Printing..." << std::endl; });

// we can have a capture of any size
double pi = 3.1415;
queue.push([pi] { std::cout << pi << std::endl; });

// now we execute all the functions
int executed = 0;
while (queue.try_consume())
    executed++;
```

Function queues have an interface very similar to heterogeneous queues: they support put-transactions, raw blocks, reentrant and non-reentrant operations, try-* operations. Anyway they don't support dynamic operations and start_* consume functions.

The library provides four function queues, each based on a heterogeneous queue:

- *function_queue*: not thread safe
- *conc_function_queue*: thread safe, blocking
- *lf_function_queue*: thread safe, lock-free
- *sp_function_queue*: thread safe, spin-locking

Function queues are always fully heterogeneous and don't allow to use a custom type for type erasure.

```
template < typename CALLABLE, typename ALLOCATOR_TYPE = void_allocator,
function_type_erasure ERASURE = function_standard_erasure >
    class function_queue;

template < typename CALLABLE, typename ALLOCATOR_TYPE = void_allocator,
function_type_erasure ERASURE = function_standard_erasure >
    class conc_function_queue;

template < typename CALLABLE, typename ALLOCATOR_TYPE = void_allocator,
        function_type_erasure ERASURE = function_standard_erasure,
        concurrency_cardinality PROD_CARDINALITY = concurrency_multiple,
        concurrency_cardinality CONSUMER_CARDINALITY = concurrency_multiple,
        consistency_model CONSISTENCY_MODEL = consistency_sequential >
    class lf_function_queue;

template < typename CALLABLE, typename ALLOCATOR_TYPE = void_allocator,
        function_type_erasure ERASURE = function_standard_erasure,
        concurrency_cardinality PROD_CARDINALITY = concurrency_multiple,
        concurrency_cardinality CONSUMER_CARDINALITY = concurrency_multiple,
        typename BUSY_WAIT_FUNC = default_busy_wait >
    class sp_function_queue;
```

Every function queue is implemented as an adapter of a heterogeneous queue. Function queues don’t use `runtime_type` for type erasure, but rather they implement a custom (and internal) type eraser. The layout of the type-eraser depends on the template argument `ERASURE`:

- `function_standard_erasure`. The type eraser contains two pointers to function: one that aligns, invokes and then destroys the function object, and another that aligns and then destroys the function object.
- `function_manual_clear`. The type eraser contains just a pointers to a function that aligns, invokes and then destroys the function object. Function queues with this type erasure can't be cleared. Furthermore they must be empty when they are destroyed, otherwise the behavior is undefined.

A value of a function queue is composed by:

- the control block: always an `uintptr_t`
- the type eraser: one or two pointers, depending on the template argument `ERASURE`.
- the capture, which may be empty

So, in queues that use `function_manual_clear`, a capture-less callable object (or a pointer to a function), consumes the space of two pointers. Anyway, in lock-free and pin-locking function queues, the size of values is aligned to the constant `concurrent_alignment` (usually 64 bytes).