# What is the common most-accessed subroutine of all executed C&C++ programs?

**Transitively also of programs in Java, C# and .NETs, Python, Rust, JavaScript, LISPs, Haskell, MLs, Golang, R, PHP, Ruby, shells, …**

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`malloc()`

**(or a matching variant thereof)**

# CUSTOM RESTRICTED MEMORY ALLOCATOR

Assignment #1

Advanced C++ course, KSI MFF UK

# Intro

Memory management is a grave concern for implementation of programming languages and low-level programs.

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- Inner workings of the allocator are usually considered black magic.
- Studying the inner workings of commonly used allocators confirms the black magic.

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- Show that it is not that hard
  (on a slightly simplified, non-general case)

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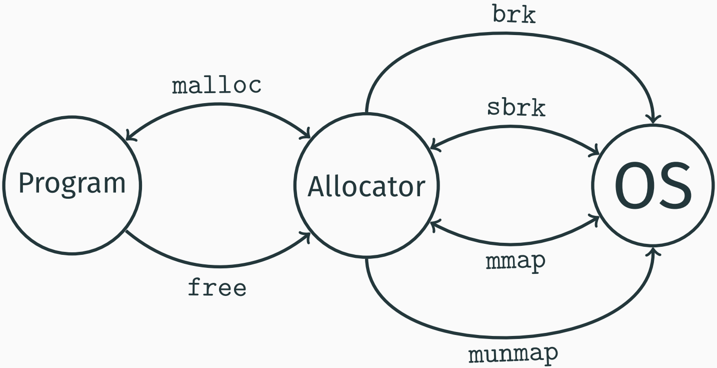
- Show that it is not that hard
  (on a slightly simplified, non-general case)
- Practice the *Allocator* named requirement of C++ classes
- Practice some common data structures used for implementing allocators
- Practice working with raw memory

# Some of the main concerns of memory allocator design

# AS AN ALGORITHM



# AS AN ALGORITHM

**Program interface** user asks for *non-overlapping memory blocks*

**OS interface** the allocator can obtain potentially infinite amount of memory using syscalls

**Middle layer problems** Mixed use of available memory
- constrol structures required for ensuring that the memory does not overlap
- memory blocks for the user

**Concerns**
- Consume the smallest possible amount of OS resources
- Once allocated, user blocks can not be moved
- Allocation/deallocation must be fast
- Syscalls are slow

# IMPLEMENTATIONS NOW

- glibc malloc internals: `https://sourceware.org/glibc/wiki/MallocInternals`
- Doug Lea's malloc (used before 2000): `http://g.oswego.edu/dl/html/malloc.html`
- jemalloc: `http://jemalloc.net/`
- SLAB/SLUB allocators in Linux kernel
- • • • ......

Common implementation concerns: Minimize space, time, and anomalies; maximize locality, allow tuning.

# SUPPORT STRUCTURES — BITMAPS

Bitmaps are the simplest (and reasonably powerful) way to store allocation information.

- Describing vacancy in $n$ blocks of memory takes $n$ bits
- For $n$ blocks of $b$ bits, we need $n \cdot (1 + b)$ bits

## SUPPORT STRUCTURES — BITMAPS

Operations:

**Find a free block** Scan the vacancy bits, return the position of the first clear bit

Possible size vs. speed tradeoffs:

- remember a position for starting the scan
- remember total vacancy

**Allocate a block** Set the bit

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Usual solution: Separate the bitmaps for small and big allocations.

# SUPPORT STRUCTURES — CHUNKS

To aid separation, memory is usually divided into *chunks*.

- Chunks form a double-linked list in the whole heap.
- Chunks contain
  - pointers to other chunks (the list may be circular)
  - memory for block allocation
    - bitmap
    - just a single block
  - extra helpful information
    - was the chunk mmap-ed or does it reside on heap?
    - how big is the chunk
    - what is the size of bitmap blocks
- Various alternative designs exist
  (layered/multi-arena chunks, interval trees, ...)

# CHUNK OPERATIONS

**Initialize** Find heap dimensions, store pointer to heap.

**Create a chunk of sufficient size**

1. Run through the linked list and find a free piece of space between adjacent nodes
2. If there is no free space, ask OS for more
3. Modify the linked list.

**Remove a free chunk**

1. Modify the linked list to skip the chunk.
2. Return free space to OS, if viable.

# OVERALL DESIGN

- Small chunks increase linked-list crawling overhead and fragmentation
- Large chunks possibly increase memory inefficiency

Usual solution: Set a threshold on small vs. big allocation.

- Small allocation:
  - Bucket the allocations according to $\log_2 \lceil \text{size} \rceil$
  - Use bitmaps of size smaller than the threshold
- Big allocation: Use separate chunk.

# ALLOCATION ALGORITHM FOR CHUNKS

1. Find the category of the allocation.
2. If the allocation is small, try to find a free bitmap of the size and add the allocation.
3. If the allocation is big or a new bitmap is needed, allocate a new chunk
4. If there is no space left, ask OS for space and retry
5. If OS refuses to give more memory, fail.

# DEALLOCATION ALGORITHM FOR CHUNKS

1. Crawl through the list to find a chunk that contains the pointer for deallocation
   (chunks are intervals!)
2. Determine whether the chunk is a bitmap or single-block
3. Erase the block from the bitmap (if it's a bitmap)
4. Erase the chunk if it is empty.

# Assignment

# ASSIGNMENT

Write an allocator that works on a static area of memory with known size.

- On initialization, the algorithm receives a continuous block of memory
- The algorithm sets up any required management structures on this memory
- For testing, the algorithm will be required to handle a set of `allocate`/`deallocate` requests from some simple algorithm.
- *No OS communication will be required.*
- Usual allocators are reentrant. *Your solution is not required to be reentrant.*

# INTERFACE

Use the standard C++ allocator interface.

```
std::vector<int, some_allocator<int>> v;
```

# INTERFACE — USING MORE THAN 1 HEAP

```
/* declare a static description of the heap object */
struct heap_holder {
  static inblock_allocator_heap heap;
};

/* create the heap (this does not allocate memory!) */
inblock_allocator_heap heap_holder::heap;

/* assign some memory */
heap_holder::heap(0x6437856328, 10*1024*1024);

/* use in code */
std::vector<int, inblock_allocator<int, heap_holder>> v1;
std::vector<int, inblock_allocator<int, hh2>> v2,v3,v4;
```

# INTERFACE – YOUR IMPLEMENTATION

```
class inblock_allocator_heap {
  // ...your static data here...
  void operator()(void*ptr, size_t n_bytes) { ... };
};

template<typename T, typename HeapHolder>
class inblock_allocator {
  // ...your solution here...
};
```

Wrap your solution in header file `inblock_allocator.hpp`.

If required, you can separate the solution into multiple header files and `.cpp` modules. Not required at all. Do not do it.

# ALLOCATORS WITH NON-STATIC PARAMETERS

You can also pass dynamic allocator parameters using prepared structures in containers:

```
explicit std::vector::vector
  (const allocator_type& alloc = allocator_type());
```

The static information will be copied among the allocators together with the allocator.

We will use the static approach.

# CRITERIA

- The algorithm **must only use the assigned memory area**
    - no `malloc`, `mmap`, `brk` or any other calls, from neither `inblock_allocator_heap` nor `inblock_allocator`
    - extra $\mathcal{O}(1)$ of static storage allowed e.g. for storing the pointer to the assigned memory

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    - result of `allocate` will not overlap any other allocated memory
    - `deallocate` will reliably make the memory available for further use
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  - all allocated addresses will be *aligned*
- Support data structures should be reasonably efficient
  - Avoid fragmentation
  - Avoid large support structures
  - Test programs will use peak 33% of the 'raw' memory volume of the assigned memory area

# HINTS

- **Do not try to beat the standard** `malloc()`.
  (but try not to be 1000× slower)
- Available memory 'heap' will be relatively small (even with the 300% overhead!), be careful with the thresholds.
- Various optimizations that can help the performance&efficiency:
  - Bitmaps may carry a pointer to the next bitmap of the same block size
  - Heuristic to save memory: bitmap sizes may grow exponentially from a relatively small number

# HINTS — ALLOCATOR

*Allocator named property* specifies the members of allocator-capable class that need to be present for the interoperation with rest of C++ library.

See `https://en.cppreference.com/w/cpp/named_req/Allocator`

You are not required to implement obsolete or optional members, including:

- `A::template rebind<U>` — used for allocating different types
- `A::is_always_equal` — used for optimizations in some containers
- `A::propagate_on_container_{move,copy,swap}` — used for controlling the lifetime of allocator object

# HINTS — ALIGNMENT

Various CPUs do *various weird things* if you access memory using unaligned pointers.

Pointer $p$ is aligned to $n$ iff

$$p \equiv 0 \mod n$$

Align all memory addresses to avoid trouble. Recommended alignment is 8 bytes.

# HINTS — HEURISTICS

Optimality of your solution depends on a lot of heuristics.

If going with big vs. small chunks,

- you don't know what is the optimal threshold to expect,
- any optimization on simple test cases can lead to problems with bigger cases.

Solution:

- Define the threshold as a constant so that we can change (and fix) it easily during testing.
- Aim for robustness, not optimality.

# HINTS — ALLOCATOR INTERFACE

Many containers require implementation of additional allocator methods!

- `A::operator==(const A&)`
  decide whether allocator instances are compatible (used when e.g. moving containers)
- `template<typename U> A(const A<U>&)`
  copy-construct from a same kind of allocator for different type (used e.g. when containers need multiple data types)

# Submit to ReCodex.

**You should be able to see (and enroll to) the Advanced C++ group.**

**The**
- **task description**
- **test programs**
- **copy of the slides**

**will appear in ReCodex ASAP.**

## EXTRA ADVICE — DEBUGGING

**In this assignment, you have a relatively high chance of getting segmentation faults because of memory corruption.**

**Memory corruptions caused by allocators are nearly impossible to debug using standard means.**

# EXTRA ADVICE — DEBUGGING

Time-saving advice: Write the program in small, simple steps; make sure that individual building blocks work correctly before progressing further.

For example:

1. The interface works, but cheats by only calling `malloc/free`.
2. The solution allocates consecutive blocks on the given memory heap, `deallocate` does not do anything.
3. The allocated blocks are formatted as chunks
4. The chunks may be found by a pointer and deallocated
5. Allocation can create bitmap chunks and select a viable bitmap chunk for adding new data, but bitmap chunks are never really removed
6. Bitmap chunks are correctly destroyed when the bitmap becomes empty.

# Evaluation

# EVALUATION CRITERIA — MUST-HAVE

- Program builds from source on major compilers
- Program does not crash, freeze, abort, hang, segfault, die, run into infinite loop, trigger OOM, throw an unhandled exception, cause undefined behavior, ...
- Program does not leak any memory
- Test programs return the same results as with standard allocator

# EVALUATION CRITERIA — CODE METRICS

- **<u>less code</u> is better**
- **easily <u>readable code</u> is better**
- consistent formatting (try `astyle` or `clang-format`)
- reasonable identifier names
- no magic constants
- comments
    - Hint: include a comprehensive "structure of solution" (SOS) comment on the top of the file
- C/C++-style efficiency measures
- `-Wall`, `cppcheck` (`valgrind` may not apply this time)
- portability to all major compilers

# EVALUATION CRITERIA — BONUS STUFF

You may use bonus points to patch up some amount of point loss from minor/pedantic issues.

Optional bonuses:

- Optimized finding of the next chunk
- Optimized sizing of bitmaps
- Measurable improvements in bitmap implementation (avoid wasting instructions on individual bits)
- Performance better or comparable to `std::allocator`
- Structure better than chunks+bitmaps
- *[insert your brilliant idea here]*

# Q&A