Memory management

Meltem Ozcelik (Concept: Amandine Gerard) / Daniil Shashenkov (Concept: Tooth Wu) / Joao Desager (Concept: Tan Zhi Hui)

Why?

- Trash the cache: hardware memory management
- This week: application memory management
  - Brace yourselves
- We skipped: operating system memory management

Why?

Memory management in its essence is

- Allocating memory (as fast as possible)
- Deallocating that same memory (as fast as possible)

Acquire heap memory with `malloc` or `new`
Free heap memory with `free` or `delete`

- Why do we bother with memory management?
- Why is it that in game software we find memory management important?

Fragmentation

Fragman-what-now?

Say this is the memory being managed by a *first fit allocator*:

Fragmentation

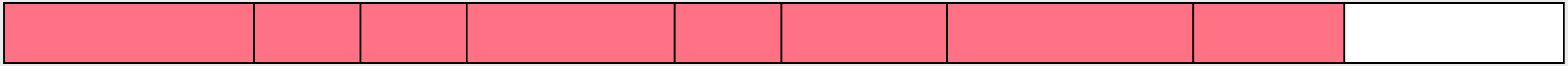
Fragman-what-now?

Let's allocate some memory:

Fragmentation

Fragman-what-now?

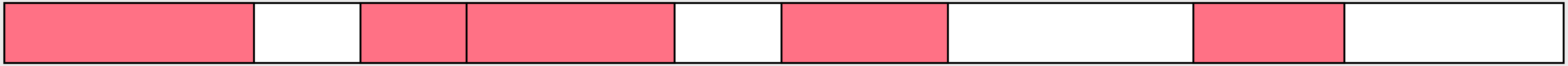
Let's allocate some more objects:



Fragmentation

Fragman-what-now?

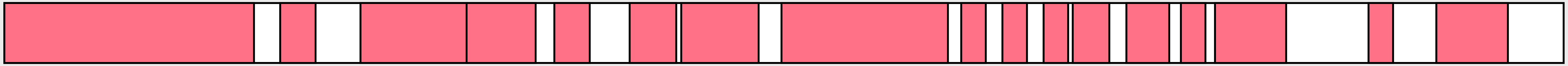
Now we release some memory:



Fragmentation

Fragman-what-now?

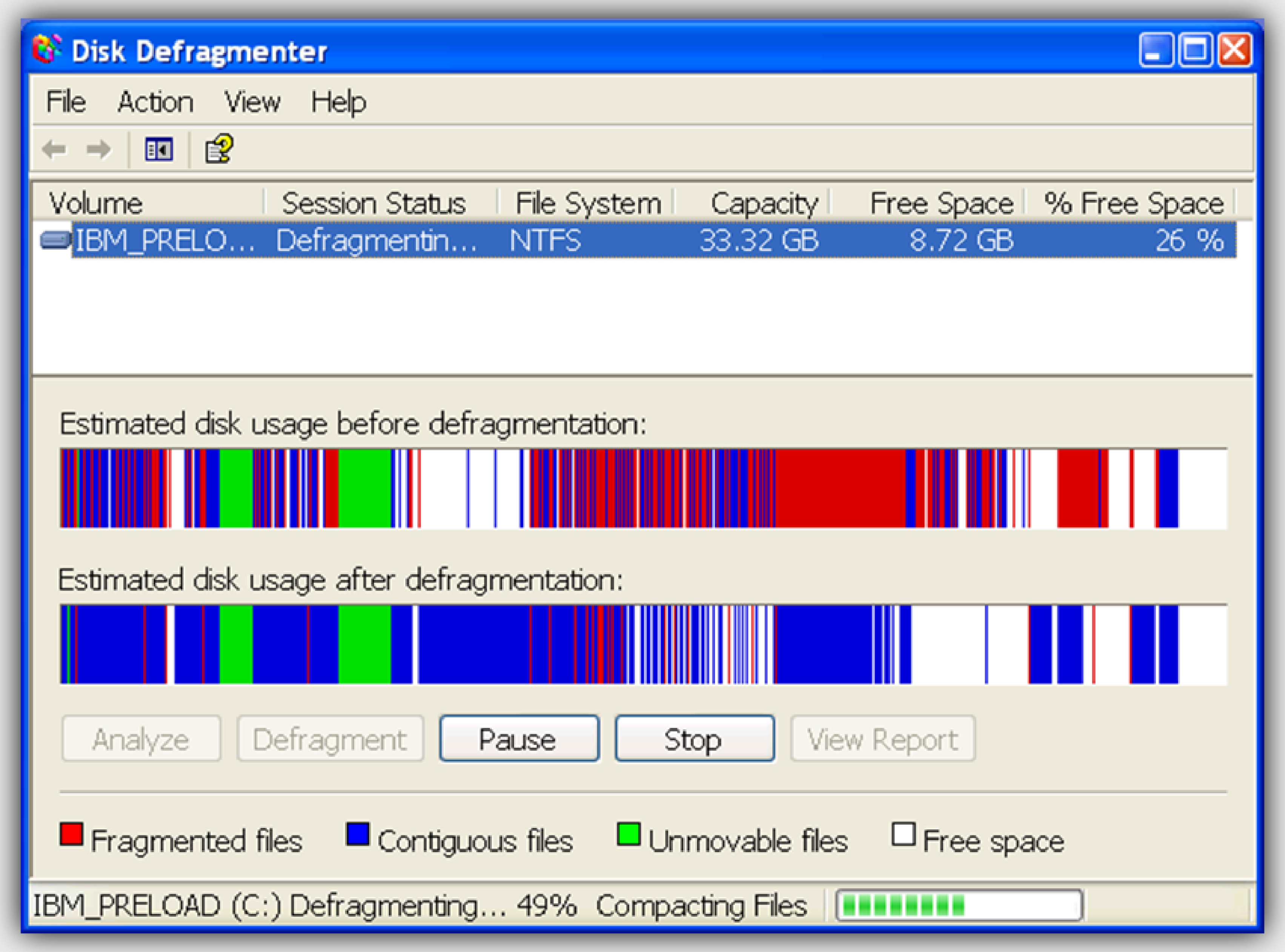
And we allocate and release some more, see the problem growing:



Why is it that games are often affected by this?

Fragmentation

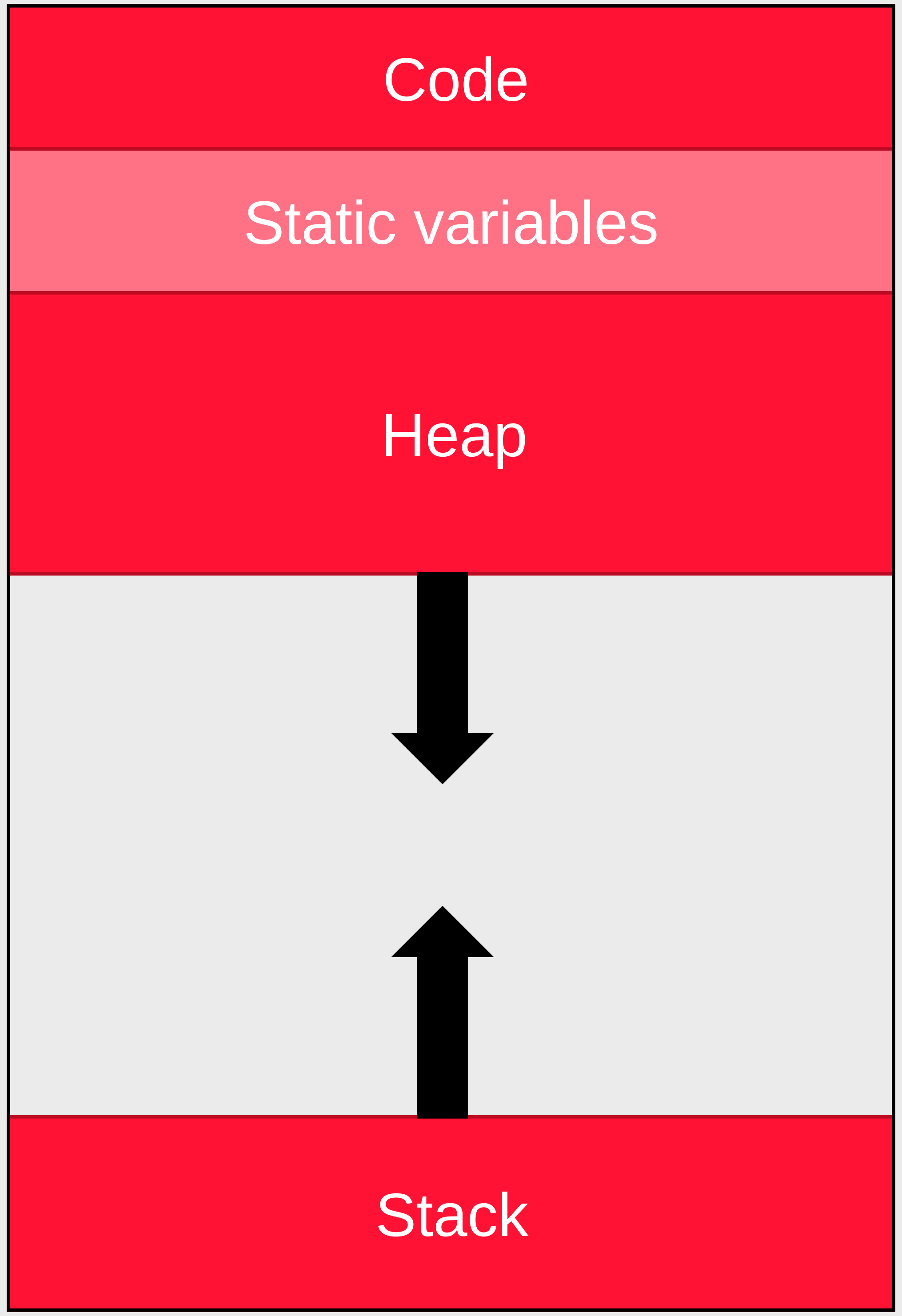
This is even valid for HDD's!



How are games affected by this on disk?

Memory segments

A program consists of several memory segments



Managed vs Unmanaged languages

Unmanaged languages: C++, Objective C, ...

- Programs run directly on the device
- Programs compile to machine code
- You’re on your own to manage your memory.
    - Standard memory managers aren't that bad, only use your own managers if there is a need!

Managed languages: C#, Java, …

- Programs run on a virtual machine (CLR, JVM)
- Programs compile to an intermediate language (IL, bytecode)
- Executed by a JIT compiler
- Memory is managed by the *garbage collector* (GC)

Garbage collector

No need to free any memory yourself.

- The GC checks whether objects are still referenced. If not, memory is freed.

Garbage collection occurs when one of the following conditions is true:

- The system has low physical memory
- Occupied memory surpasses an acceptable threshold. This threshold is continuously adjusted as the process runs.
- The `GC.Collect` method is called

Works on a managed heap

- Organized in 3 generations
- Young objects in generation 0 are checked more often
  - They age

Possible to perform defragmentation

Garbage collector

Cool! No more worries! Alas - “There ain't no such thing as a free lunch”

It’s still possible to leak memory.

- Dangling references
- Growing collections

Garbage collection can take a while

- Spike on your FPS counter
- Modern GC are getting better at this.
- So this rule remains: *no dynamic memory allocation on your* **hot code path**

Cache coherence still needed

- although the JIT compiler optimizes a lot

Memory allocators

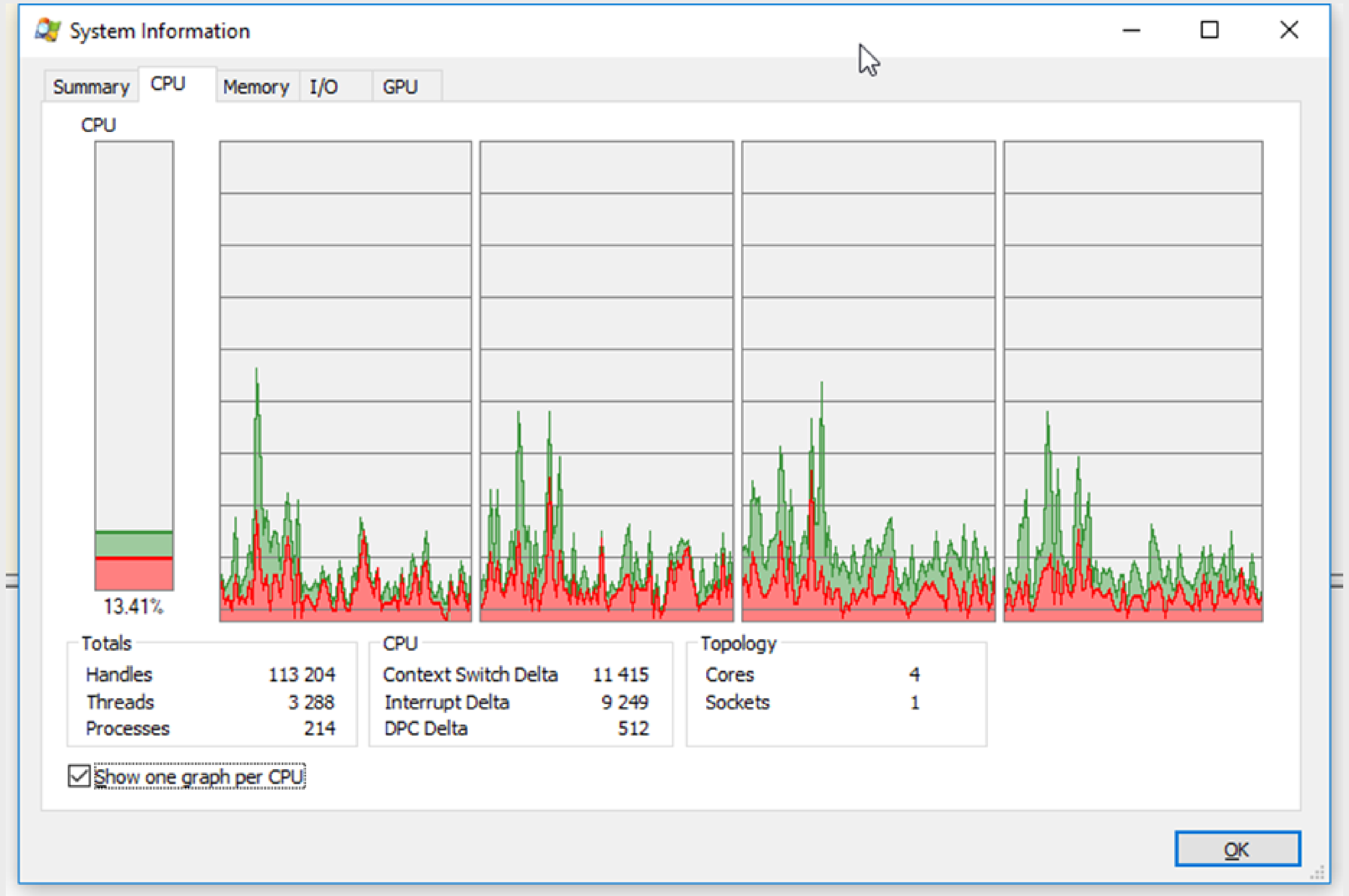
Acquire heap memory with `malloc` or `new`
Free heap memory with `free` or `delete`

Costly operations

- malloc and free might need to context-switch to go from user mode to kernel mode

Instead of doing this all the time, we could request a sufficiently sized chunk of memory and distribute that as required by the program/game

- Everything happens in user mode
- Better tweaked to the application's needs



Linked-list-based allocators

General purpose allocators

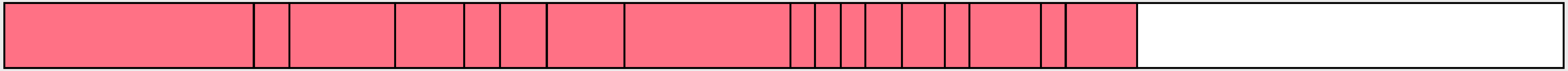
- Keep track of free memory, the “free list”
- Keep track of the size of each allocated block – why?

Linked-list-based allocators

General purpose allocators

- Keep track of free memory, the “free list”
- Keep track of the size of each allocated block – why?
    - When deleting/releasing memory we only provide the pointer to the memory that we want to release.

Suffer from fragmentation - but can we perform some defragmentation? Just sort all the allocated blocks up:

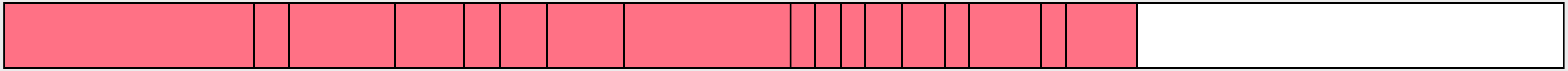


Linked-list-based allocators

General purpose allocators

- Keep track of free memory, the “free list”
- Keep track of the size of each allocated block – why?
  - When deleting/releasing memory we only provide the pointer to the memory that we want to release.

Suffer from fragmentation - but can we perform some defragmentation? Just sort all the allocated blocks up:



Can be a lengthy operation, but doesn’t have to be completed in one frame. We can spend some fixed time on this every frame until we’re done.

However: raw pointers become invalid

- Use (custom) smart pointers
- Use Handles – integer indices in a table that contains the actual pointers
- A handle is what every reference in C# or Java is

3rd party libraries might not be compatible

Free storage list

Let's look at a possible implementation of such an allocator.

- Divide a given buffer into blocks.
- Keep a linked list of free blocks
- Since that memory is not used by the program, we can store our node pointers there

count = # subsequent free blocks

Free storage list


```
struct Header
{
    size_t count;
};

struct Block : Header
{
    const static int size = 16;
    union
    {
        Block* next;
        char data[size - sizeof(Header)];
    };
};
```

Free storage list

Acquire

- Iterate over the list until you find a large enough space.
- Remove it from the list.
- Return pointer to that memory.

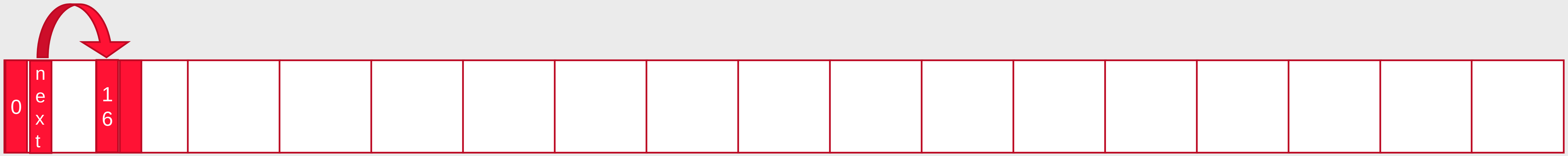
Release

- Find the first empty block before the block to release.
- Add into the list.
- Merge the blocks if adjacent.

This list must remain sorted

- Makes releasing memory costly O(n)

So what happens?

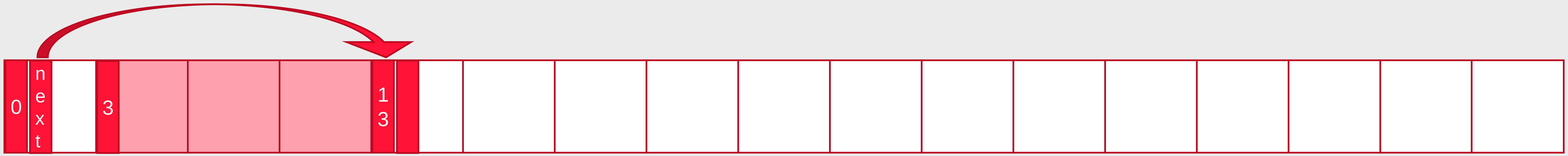


This is a buffer of 17 blocks.

- Max allocated size = (16*16b)-4b = 252b
    - (we allocate one extra block for the head)
    - We loose 4b for that counter in every first block

What happens when we allocate 40b?

So what happens?

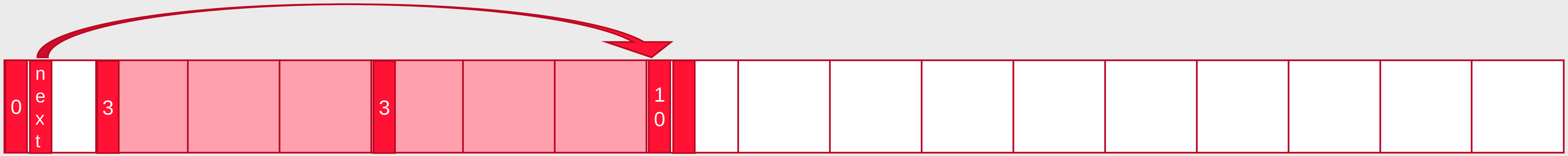


There are now 13 free blocks left.

- Max allocated size = 16*13-4 = 204

What happens when we allocate another 40 bytes?

So what happens?

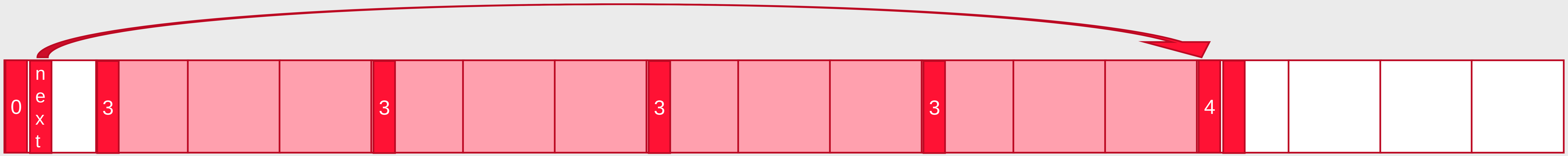


Now there are 10 free blocks.

- Max allocated size = 16*10-4 = 156

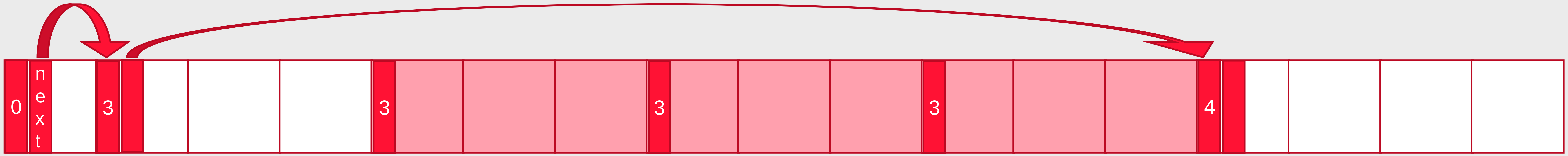
Let's allocate two more.

So what happens?



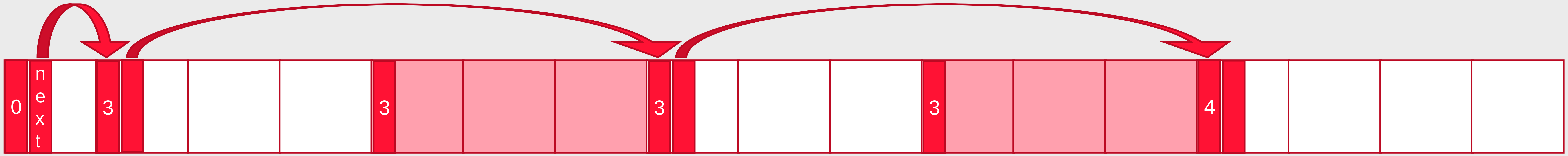
Fine, now let's free the 1st allocation we did

So what happens?



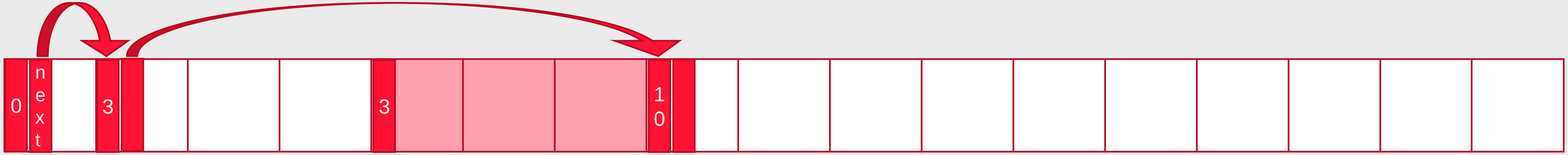
Now let's free the 3rd allocation we did

So what happens?



Finally free the 4th allocation we did

So what happens?



And we end up with this.

Overriding new and delete

```
namespace dae {
class MemoryAllocator;
}

void * operator new (size_t nbBytes);

void * operator new[] (size_t nbBytes);

void * operator new (size_t nbBytes, dae::MemoryAllocator* allocator);

void * operator new[] (size_t nbBytes, dae::MemoryAllocator* allocator);

void operator delete (void* pointerToBuffer) noexcept;

void operator delete[] (void* pointerToBuffer) noexcept;

void operator delete (void* pointerToBuffer, dae::MemoryAllocator* allocator);
```

Overriding new and delete

Let's use these

```
TEST_CASE("Test object 2")
{
    MyAllocator allocator(4096);
    Object* pObject = new (&allocator) Object();

    REQUIRE(pObject->m_integer == 0);
    REQUIRE(pObject->m_float == 0);

    delete pObject;
}
```

Look at that delete, it doesn't specify the allocator?

Overriding new and delete

Let's use these

```
TEST_CASE("Test object 2")
{
    MyAllocator allocator(4096);
    Object* pObject = new (&allocator) Object();

    REQUIRE(pObject->m_integer == 0);
    REQUIRE(pObject->m_float == 0);

    delete pObject;
}
```

Look at that delete, it doesn't specify the allocator?

Define a tag:

```
struct Tag
{
    MemoryAllocator* pool;
};
```

Overriding new and delete

And use it:

```
void * operator new (size_t nbBytes, MemoryAllocator* allocator)
{
    if (nbBytes == 0) nbBytes = 1;
    MemoryAllocator::Tag* const tag =
        reinterpret_cast<MemoryAllocator::Tag*>(
            allocator->Acquire(nbBytes + sizeof(MemoryAllocator::Tag))
        );
    tag->pool = allocator;
    return tag + 1;
}

void * operator new (size_t nbBytes)
{
    if (nbBytes == 0) nbBytes = 1;
    MemoryAllocator::Tag* const tag =
        reinterpret_cast<MemoryAllocator::Tag*>(
            malloc(nbBytes + sizeof(MemoryAllocator::Tag))
        );
    tag->pool = nullptr;
    return tag + 1;
}
```

Overriding new and delete

So the delete now can become:

```
void operator delete (void* pointerToBuffer, MemoryAllocator *allocator) noexcept
{
    if (pointerToBuffer != nullptr)
    {
        MemoryAllocator::Tag* const tag =
            reinterpret_cast<MemoryAllocator::Tag*> (pointerToBuffer) - 1;
        allocator->Release(tag);
    }
}

void operator delete(void * pointerToBuffer) noexcept
{
    if (pointerToBuffer != nullptr)
    {
        MemoryAllocator::Tag* const tag =
            reinterpret_cast<MemoryAllocator::Tag*> (pointerToBuffer) - 1;
        if (tag->pool != nullptr)
            tag->pool->Release(tag);
        else
            free(tag);
    }
}
```

Using them

When we create a new GameObject we write either

```
auto go(std::make_unique<GameObject>());
```

```
auto go(std::make_shared<GameObject>());
```

Override global new and delete?

- Ok, but then every allocation passes through our code
- Custom smart pointers

std::allocate_shared exists, but std::allocate_unique doesn’t

- Uses an Allocator (https://en.cppreference.com/w/cpp/named_req/Allocator)

Override Class-scope new/delete operator

- Can couple it to the required allocator.

std allocators

Downside: are passed as a class, not an instance.

See https://godbolt.org/z/7h8993bc5 as an example that illustrates this.

At EA this is one of the reasons to run their own stl (keep in mind, this is a page from 2007):
https://www.open-std.org/jtc1/sc22/wg21/docs/papers/2007/n2271.html#std_allocator

Often engines have their own container types that allow for custom allocators by instance.

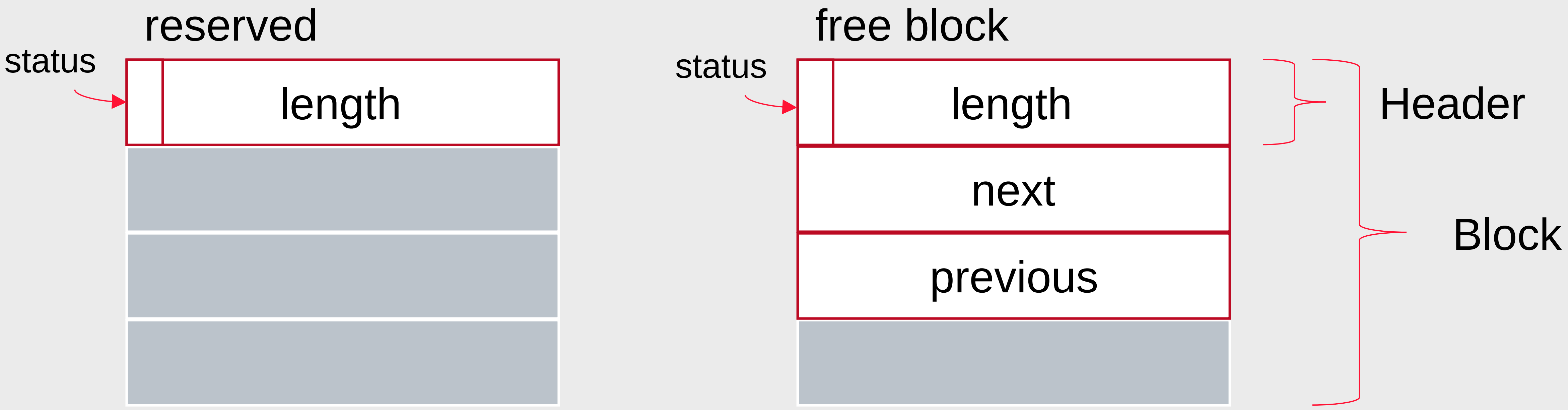
Doubly-linked free storage

Resembles the single linked list

- Just keep an extra pointer to the previous node too.
- To support coalescing, we add a status bit in the length field

When Releasing, just add it to the free list. This has become a *0(1) operation*

When Acquiring, while traversing the free list, coalesce free areas.



Doubly-linked free storage

Acquire

- Iterate over all nodes in free list.
    - For each node: if the next area is free, merge the two areas
    - If the area is big enough: break;
- Chop off an area sized as required and add the remaining to the free area list
- Set status flags (free or not)

Release

- Just add it to the list
- Set status flag

All purpose allocators

We saw two common all-purpose allocators.

Disadvantages:

- Slow O(n) operations on alloc and/or dealloc
- Fragmented memory

Advantages:

- No system calls
- We're in charge ourselves

Let's have a look at optimizations we can apply in games.

Stack-based allocators

Acquire memory

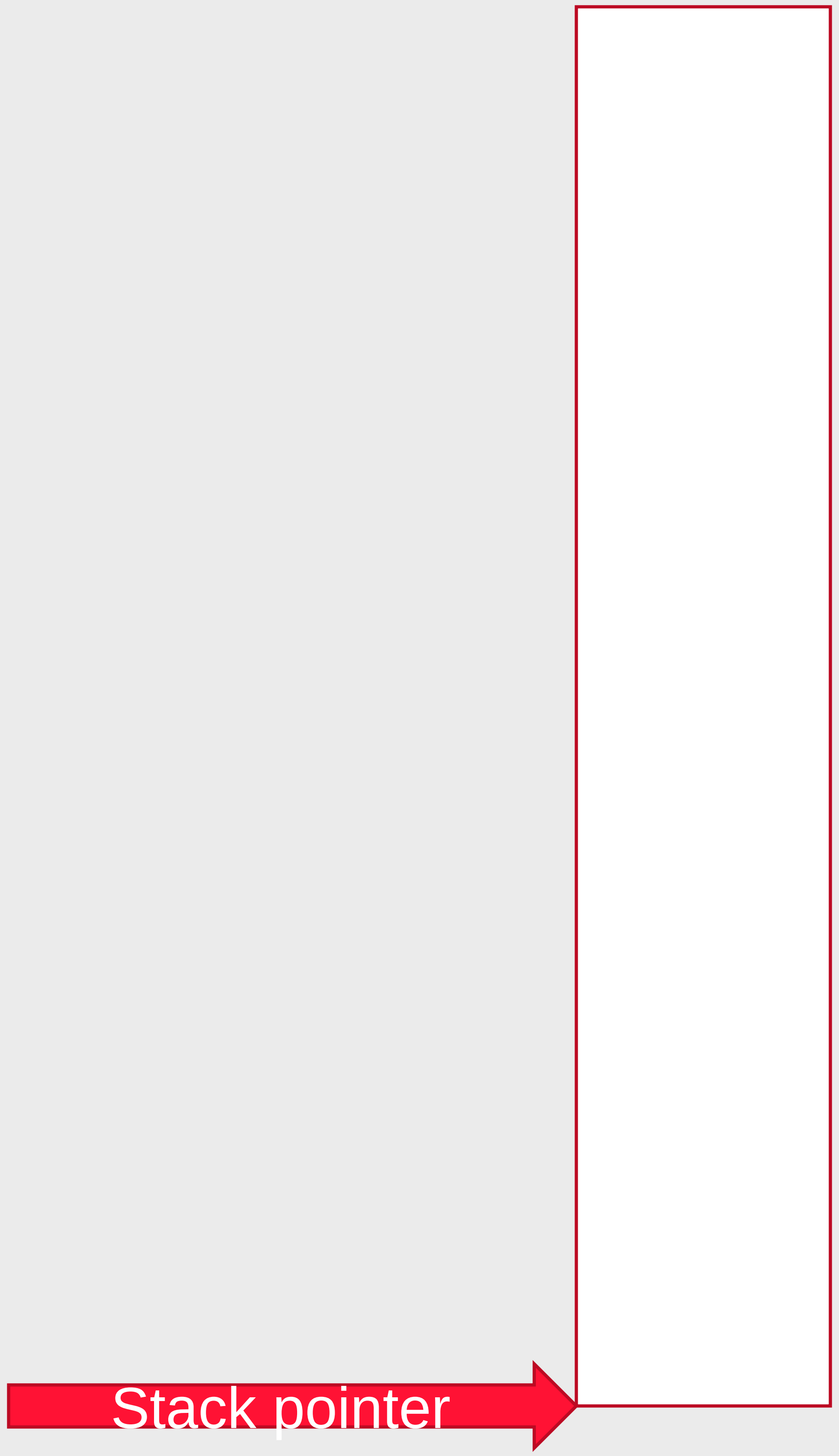
- Via malloc
- Or new
- Or with a global static buffer
  - (the data will reside in the static segment)

Easy implementation – just increment a pointer

- No fragmentation
- Downside: releasing memory must happen in reverse order
  - Better alternative: use markers to free entire blocks
  - Even better: don't release at all!

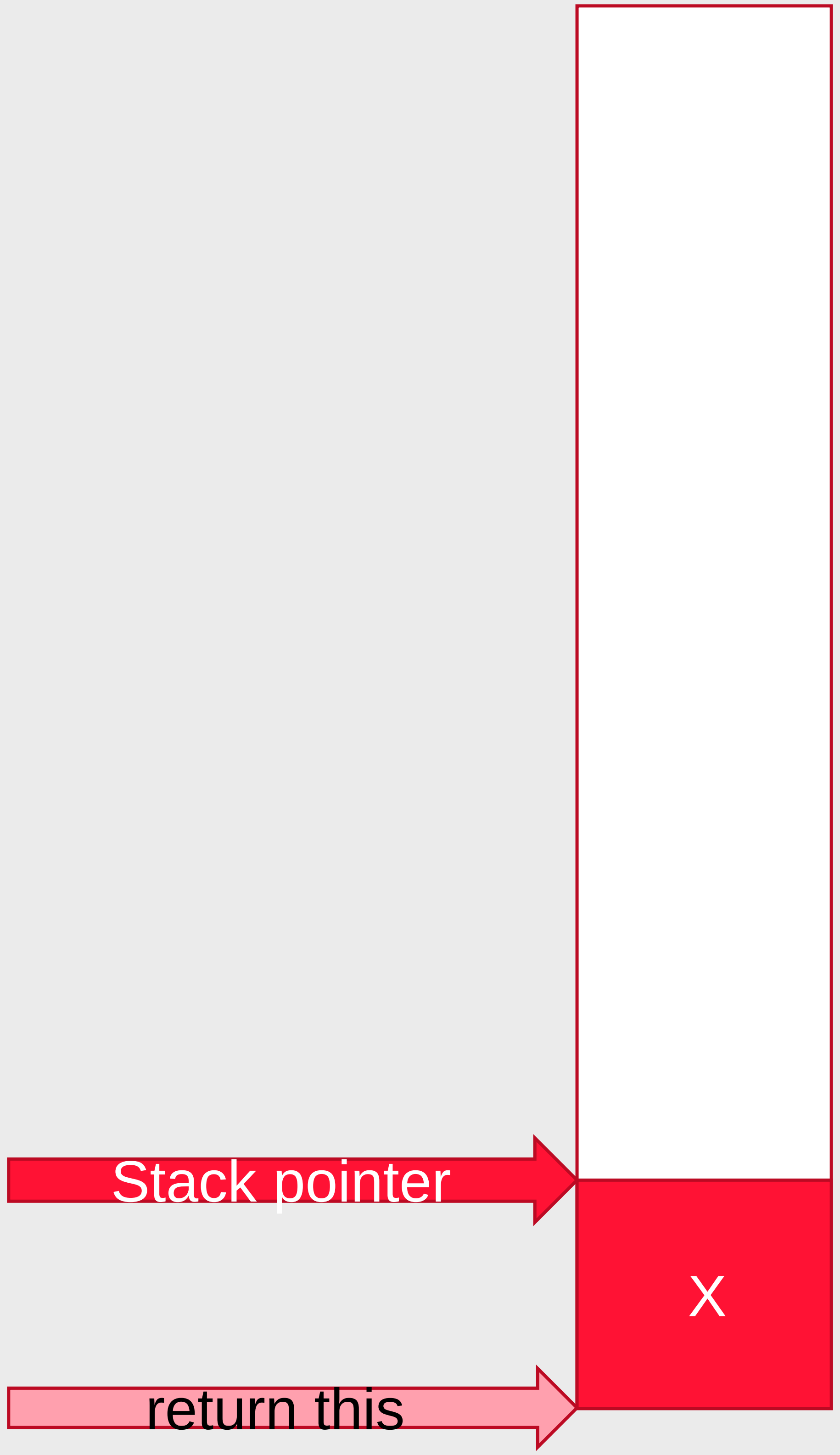
Stack allocator

Given en empty stack, from top to bottom.



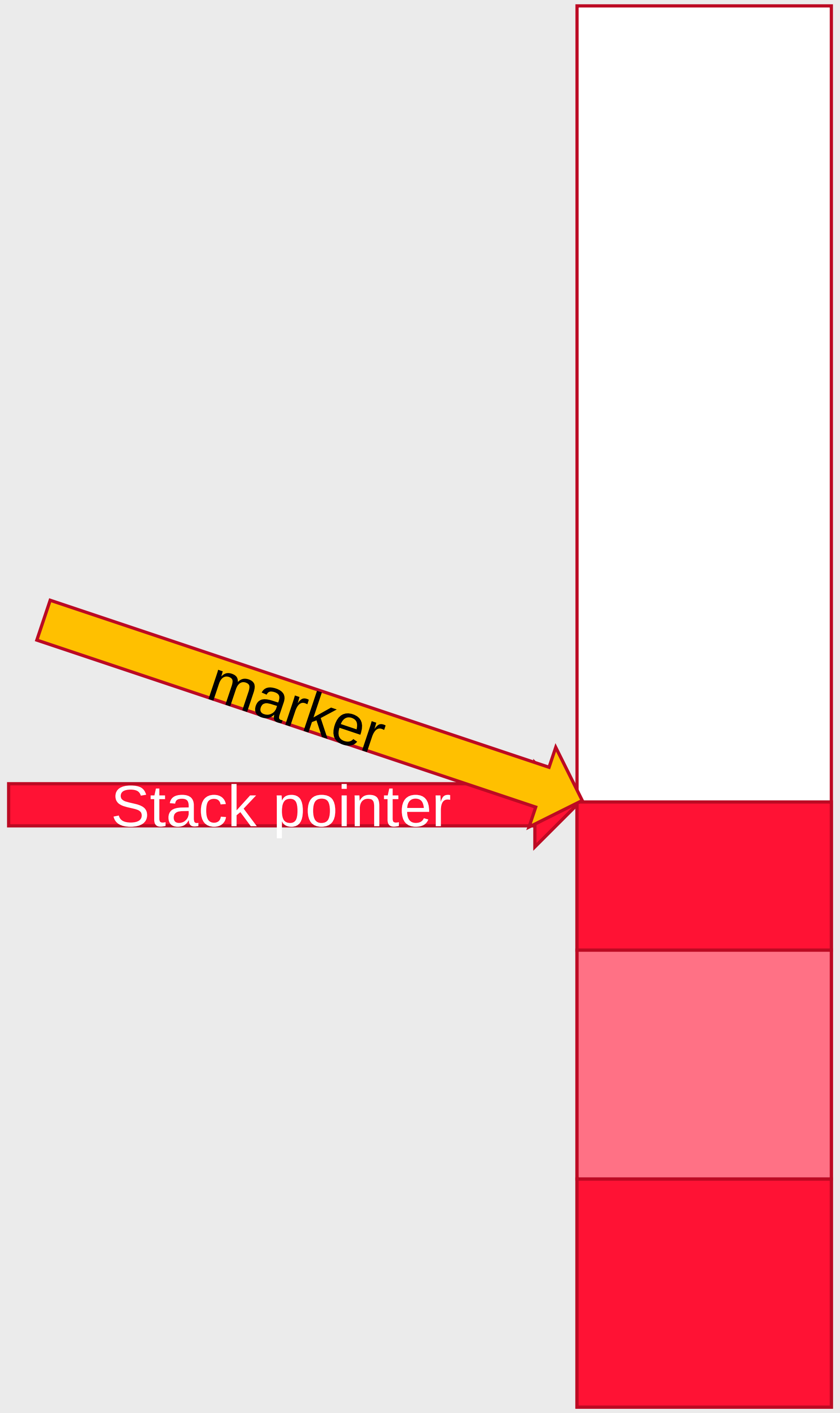
Stack allocator

Allocate x bytes



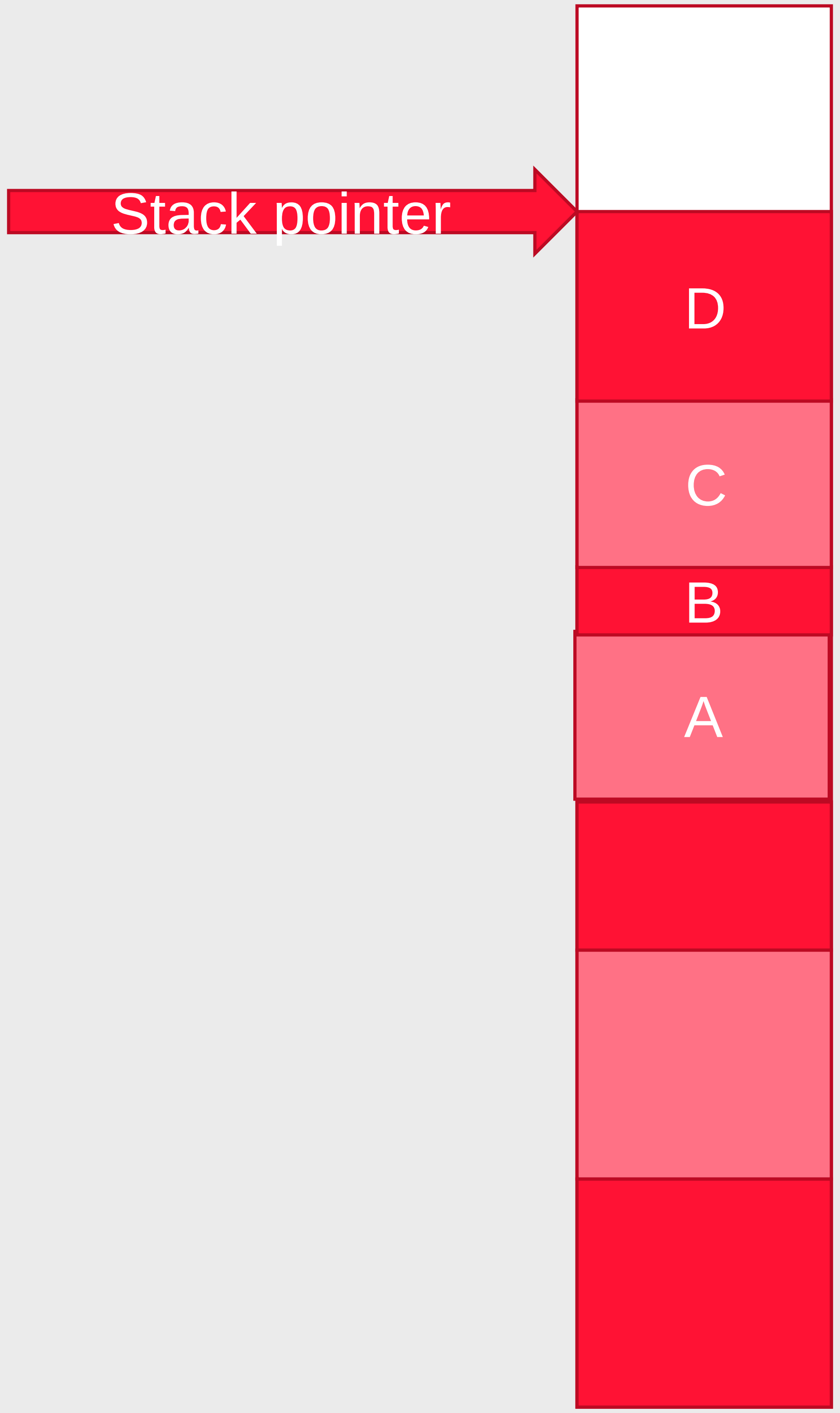
Stack allocator

Optionally: request a marker



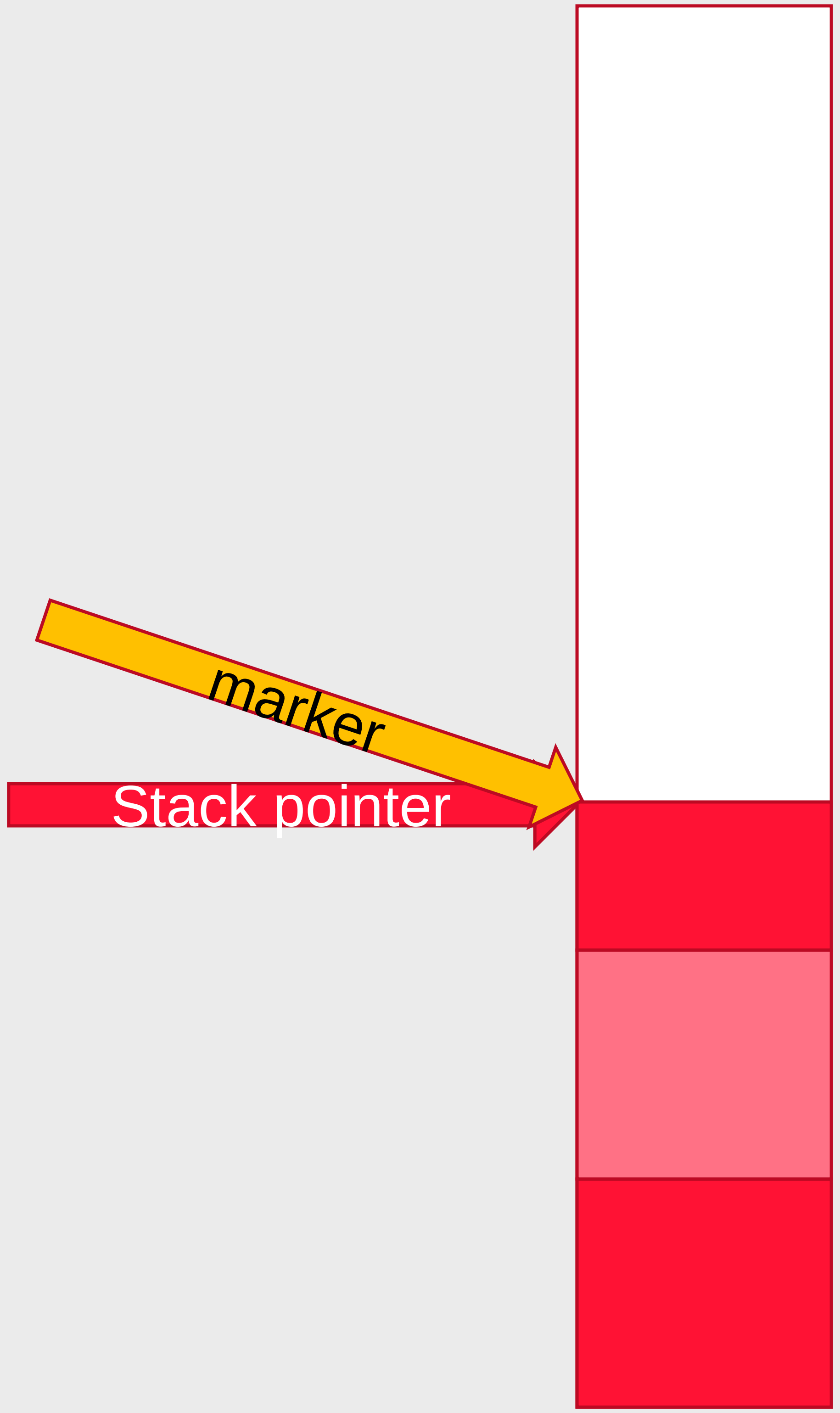
Stack allocator

Allocate some more



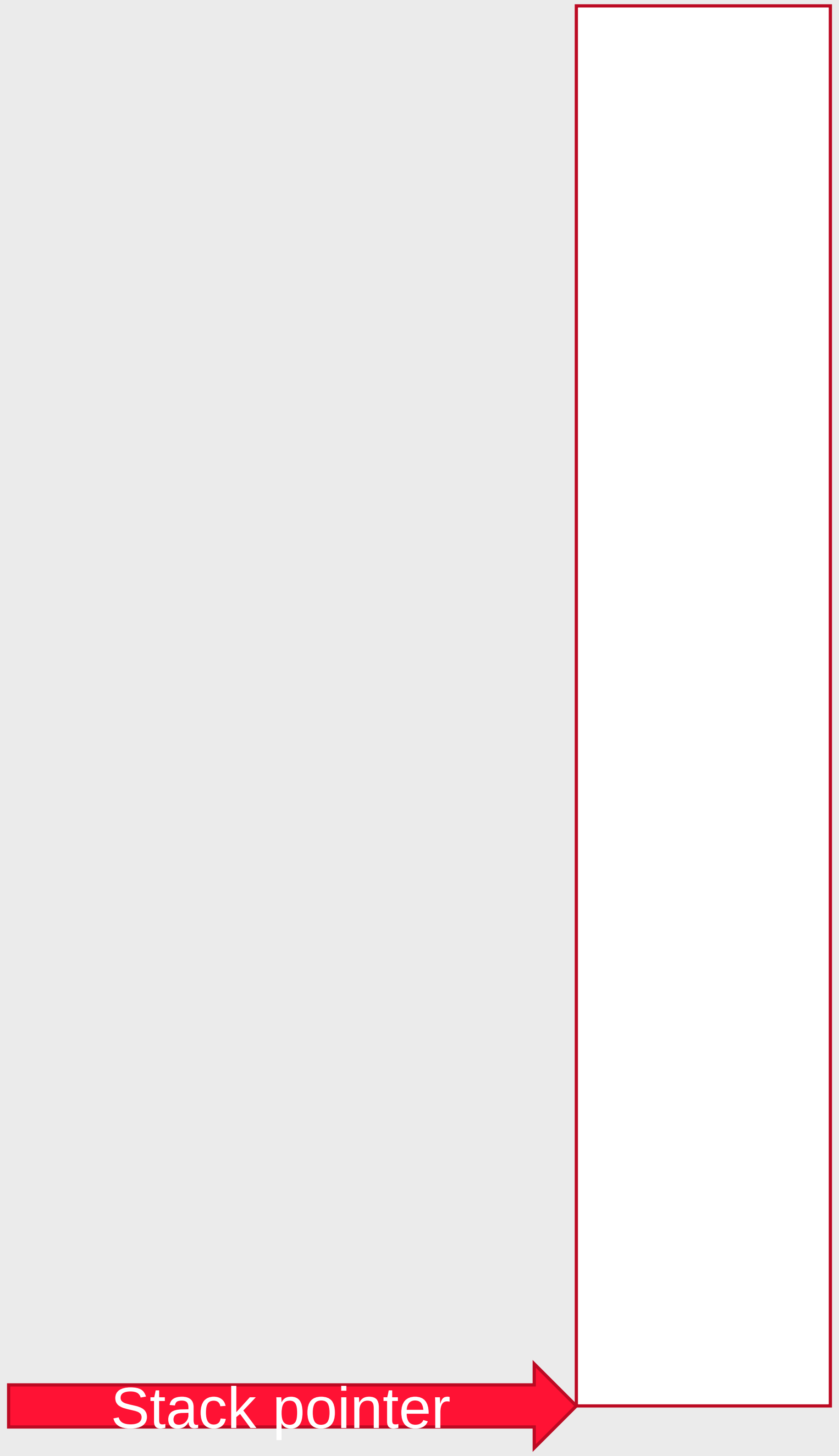
Stack allocator

Now free to marker



Stack allocator

Or just completely free the stack



Single frame allocators

Reserve a block of memory, manage it with a stack allocator.

At the start of the frame we reset the stack pointer to the bottom.

Pro's

- No need to free / delete the data
- Fast to allocate
- No fragmentation

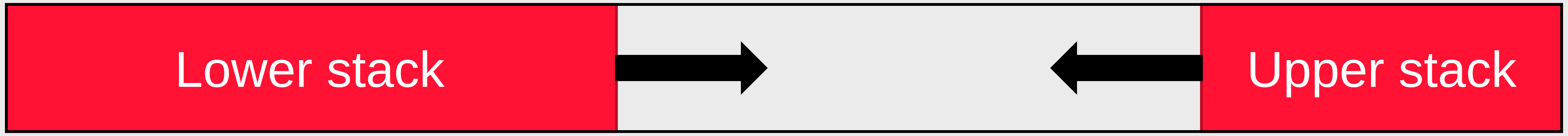
Con's

- Programmers must be well aware what they're doing
- No persistent pointers to this data possible!

Double-ended stack allocators

Use two stacks at each end.

Allocate a block and maintain a stack from both ends



For example:

- Use lower stack for level data – cleared every level.
- Use upper stack for frame data – cleared every frame.

Double-buffered stack allocators

These allow the data allocated in frame i to be used in frame i+1

Create two single frame stack allocators internally and ping-pong between the two.

Used to use results from the previous frame in the current one.

Object pools / Fixed size allocators

When

- You often create and destroy the same type of objects (bullets, particles, sounds, decals, etc.)
- The objects have the same size
- Allocating these on the heap leads to fragmentation

Or

- the objects encapsulate a resource via RAII that is costly to acquire/release (like a network connection, a thread or a database connection)

You could choose to use an Object Pool

- Allocate a bunch of them
- Request objects from the pool and return them when you don’t need them anymore.
- The underlying resource remains acquired

Object Pools/Fixed-size allocators

Possible waste of memory.

Possibly not enough memory.

- Prevent it (allocate max)
- Don’t create a new object
- Kill an existing object
- Grow

A reused object must be cleared – pay attention!

Small object allocator

Small objects cause the most fragmentation.

Create growing pool allocators for objects sized from 1 – 256 bytes, thus:

- A pool for objects of 1 byte,
- A pool for objects of 2 bytes,
- A pool for objects of 3 bytes,
- A pool for objects of 4 bytes,
- Etc...

Initialized with a size of 16 objects for each pool: takes ~500kb

How many bytes exactly?