EPITA - Practical Programming

08 - Memory Management

Overview

1. Multi-task And Memory Management
   a. Issues ?
   b. Virtual Memory
2. Processus Memory Organization
3. `malloc(3)`
   a. Heap Management ?
   b. A Simple First Fit Allocator
4. Other Kind Of Allocators

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Multi-Task And Memory

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Issues ?

- Sharing one memory with several processes
- Each process wants contiguous memory blocks
- We need confinement between processes
- How to deal with dynamic memory
- Binary program may not be relocatable
- ...

Solutions

- Fixed size memory partitions: *too much constraints*
- Full swapping: *way too slow …*
- Dynamics partitioning: *continuity issues and probably no possible confinement …*
- Relocatable code: *complex and risky*

Can we do better ?

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Virtual Memory

Virtual Memory *maps memory addresses used by a program, called* ***virtual addresses****, into* ***physical addresses*** *in computer memory.*

Virtual Memory

- All memory accesses are rewritten on the fly
- Each process has its own virtual address space
- Rewriting is done by the MMU (hardware)
- Rewriting tables are managed by the Kernel

Benefits

- Memory is always contiguous for each process
- Memory has a fixed layout for each process
- No swapping are required
- Each process is alone in its virtual address space

Virtual Memory provides a complete solution.

Mapping ?

- Can we do a one-to-one mapping ?
- A translation table needs 8 bytes (64bits) per translated address, let's do some math ...
- For n bytes of virtual memory, we need 8n bytes

To map the memory we need 8 times its size !

Frames and Pages

- Memory is splitted in blocks
- Block in physical memory is called **frame**
- Block in virtual memory is called **page**
- We only translate page base into fram base
- Page/Frame base addresses are shorter
- Usually, page/frame have fixed size

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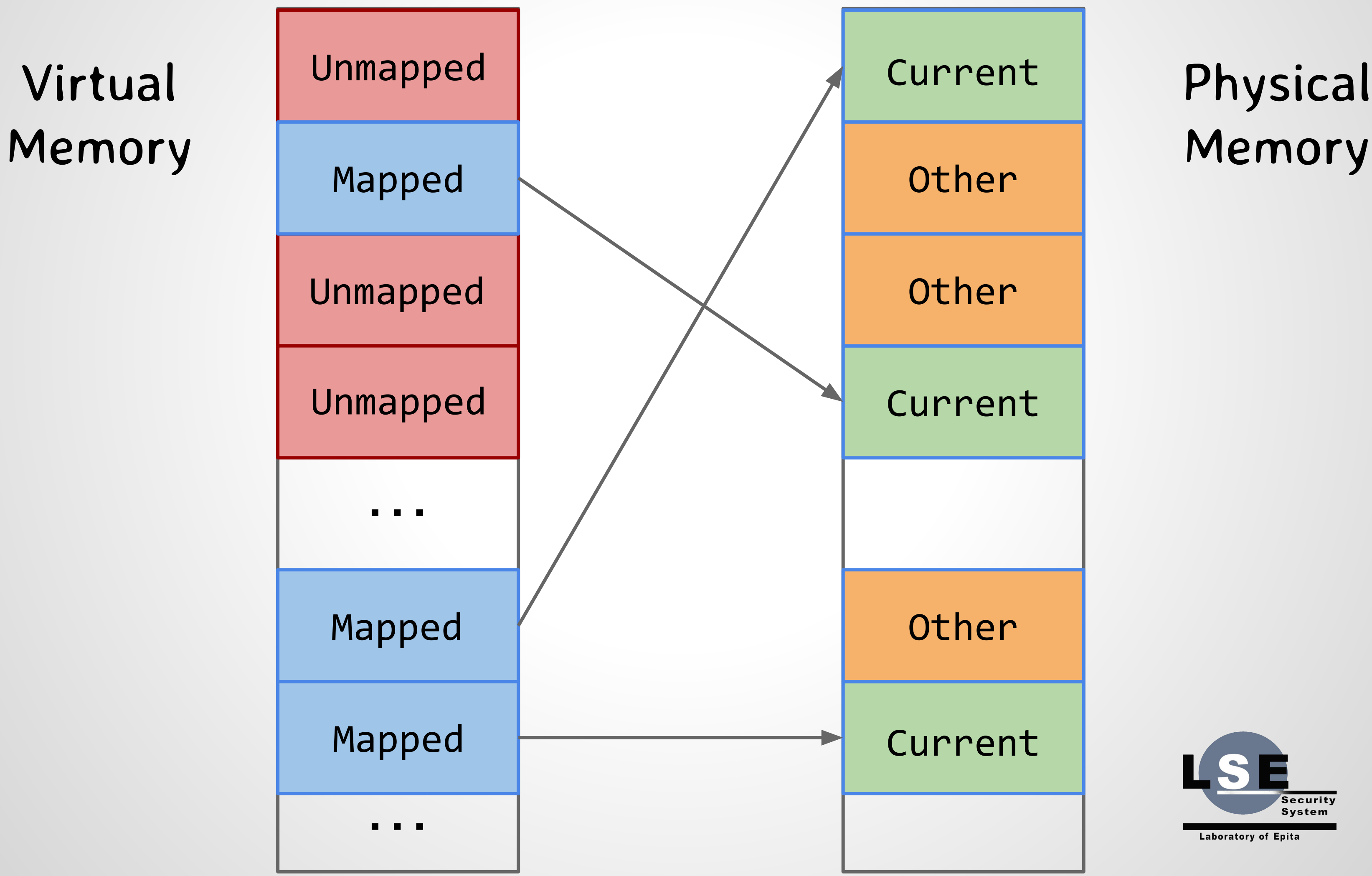
Virtual Memory



Pages Translation Example

Intel ia32 (32bits) schema:

- We use 4KB pages (12bits)
- Pages are grouped in **page directory**
- Translation is done in two step:
  1. Translate the page directory base address
  2. Translate the page base address
- The page directory table contains 1024 entry of 4 bytes each pointing to page table of the same size. A full mapping takes at most 4MB for 4GB.

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Process Memory

Memory Organization

- Each process has its own address space
- The memory is divided in *segments*:
  - **Text Segment**: the process image (code)
  - **Data Segment:** static initialized variables
  - **BSS Segment:** static uninitialized variables (fill with 0)
  - **Heap:** where dynamic allocation should take place
  - **Memory Mapping Segment:** mapped files, libs ...
  - **Stack:** process (main thread) stack
- The kernel is also mapped, in the higher part of the memory.

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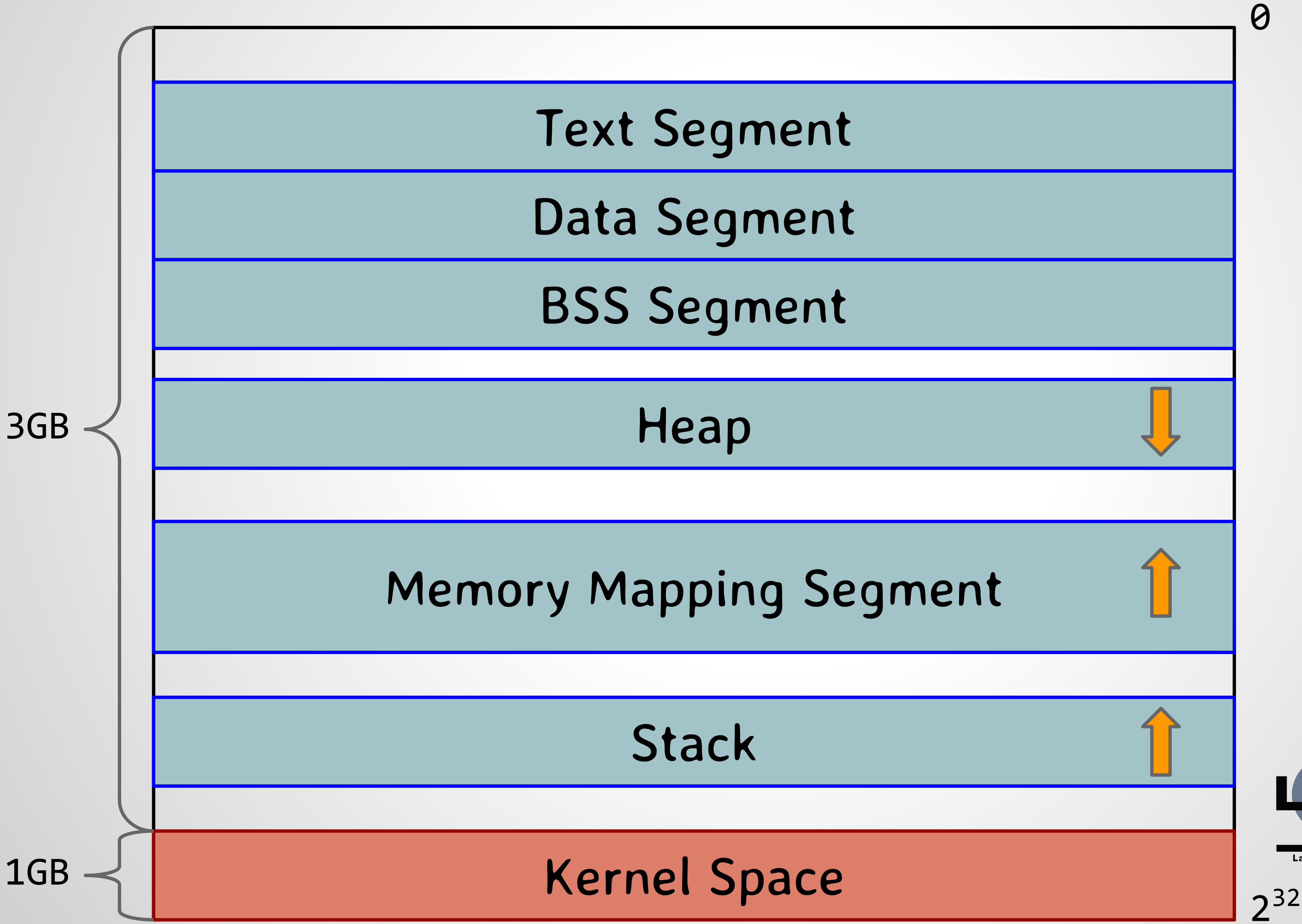
Process Layout (Linux 32bits)



Where're My Variables ?

- Global variables belongs to the BSS Segment
- Global constants belongs to the Data Segment
- Local variables are on the stack
- Dynamic allocation is done on the heap
- Parameters use registers, if possible, and the stack.

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Where're My Variables

```c
void f(int x) {
  // x is in a register but has
  // an address on the stack
  int   y;       // on the stack
  int   tab[8]; // on the stack
  char *s1 = "a constant string";
  // s1 is on the stack but points
  // to the Data segment
  char *s2 = malloc(32);
  // s2 is on the stack but points
  // to the heap
  char  s3[] = "a local string";
  // the string is on the stack
```

```c
  // Let's print some addresses
  printf("x    : %p\n",&x);
  printf("y    : %p\n",&y);
  printf("tab : %p\n",tab);
  printf("&tab: %p\n",&tab);
  printf("s1   : %p\n",s1);
  printf("s2   : %p\n",s2);
  printf("s3   : %p\n",s3);
  printf("&s3 : %p\n",&s3);
}
```

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Where're My Variables

```
x    : 0x7fffffffd5ec
y    : 0x7fffffffd5e8
tab  : 0x7fffffffd5c0
&tab: 0x7fffffffd5c0
s1   : 0x400732
s2   : 0x800c07040
s3   : 0x7fffffffd5b0
&s3  : 0x7fffffffd5b0
```

Static Arrays

```c
int    tab[8];
```

- Static arrays always verify: `(tab == &tab)`
- The address is not stored
- Address usage are replaced at compile time
- Static local string literals are similar

Mind Variables Lifetime

```c
struct list {
  struct list  *next;
  int           value;
};

struct list *
add(struct list *l, int x) {
  struct list  *r, tmp;
  tmp.next = l;
  tmp.value = x;
  r = &tmp;
  return r;
}
```

```c
int main() {
  struct list  *l = NULL;
  for (int i=0; i<10; ++i)
    l = add(l, i);
  assert(l != l->next);
  return 0;
}
```

```
Assertion failed:
  (l != l->next), function
  main, file stupid_list.c,
  line 23.
```

malloc(3)

malloc(3)

➢ C defines allocation functions: `malloc(3)`

> The `malloc()` function allocates size bytes of uninitialized memory. The allocated space is suitably aligned (after possible pointer coercion) for storage of any type of object.
>
> ...
>
> The `malloc()` and `calloc()` functions return a pointer to the allocated memory if successful; otherwise a NULL pointer is returned and errno is set to ENOMEM.
>
> *FreeBSD man page*

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malloc(3)

- The returned pointer points to a contiguous memory zone with a size superior or equal to the asked size.
- No further invocation of `malloc(3)` will return a pointer to an overlapping area.
- Memory acquire with `malloc(3)` can be release using `free(3)`.

Managing The Heap

- Dynamic allocation goes to the heap
- The heap start after the end of the BSS
- The actual end of the heap is called the **break**
- The break can be moved using brk(2) and sbrk(2)

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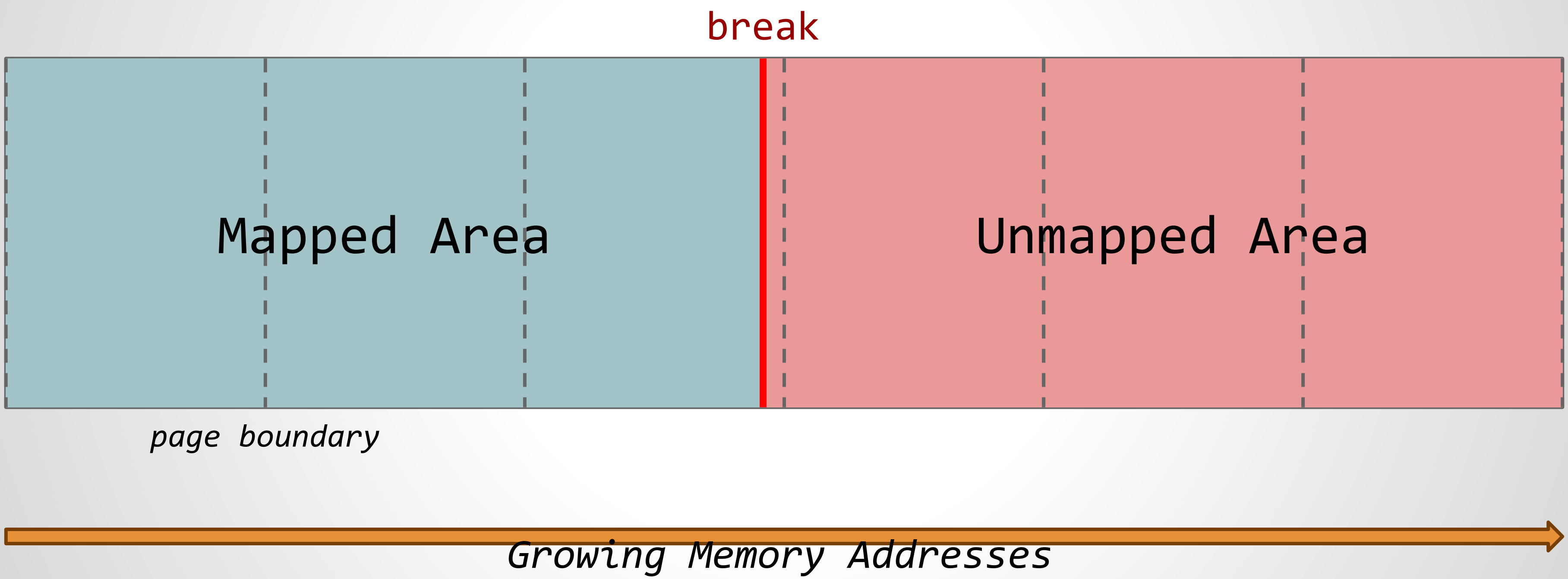
The Heap


break
Mapped Area
Unmapped Area
page boundary
Growing Memory Addresses

brk(2) and sbrk(2)

```c
int   brk(const void *addr);
void *sbrk(intptr_t incr);
```

- brk(addr) moves the break at address addr
  - returns 0 if successful
  - returns -1 and set errno otherwise
- sbrk(incr) moves the break by incr bytes
  - returns the address of the old break when succesful
  - returns (void*)(-1) and set errno otherwise

Simplest Allocator

```
void *malloc(size_t s) {
  void          *r;
  if ( (r = sbrk(s)) == (void*)(-1) )
    return NULL;
  return r;
}
```

Comments

Pros:

- ➢ Minimal cost (just the cost of `sbrk(2)`)
- ➢ No waste space and no overhead

Cons:

- ➢ Can't implement `free(3)`
- ➢ `realloc(3)` is unsafe

What Do We Need ?

- We need information about memory chunk:
  - start of the chunk
  - end of the chunk
  - availability (freed or not)
- We need to store those data
- We need to find available chunks of a given size

We need meta-data !

Strategy

- **First-Fit:** when searching for a given size returns the first chunk sufficiently large.
- **Best-Fit:** when searching for a given size returns the smallest chunk sufficiently large.
- Simple linear organization (linked list)
- More advanced structures (buddies, slab ...)

A First Fit Allocator

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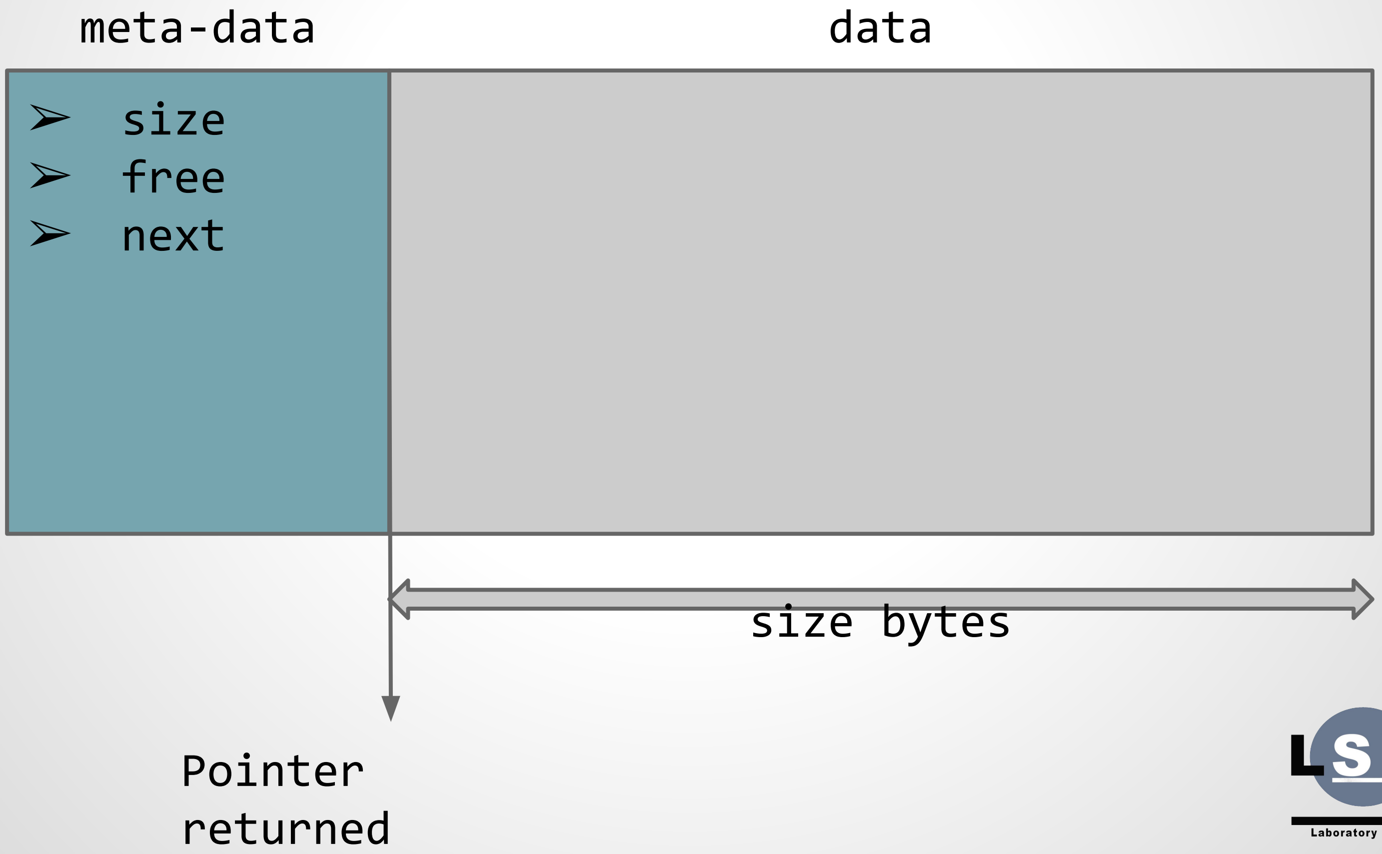
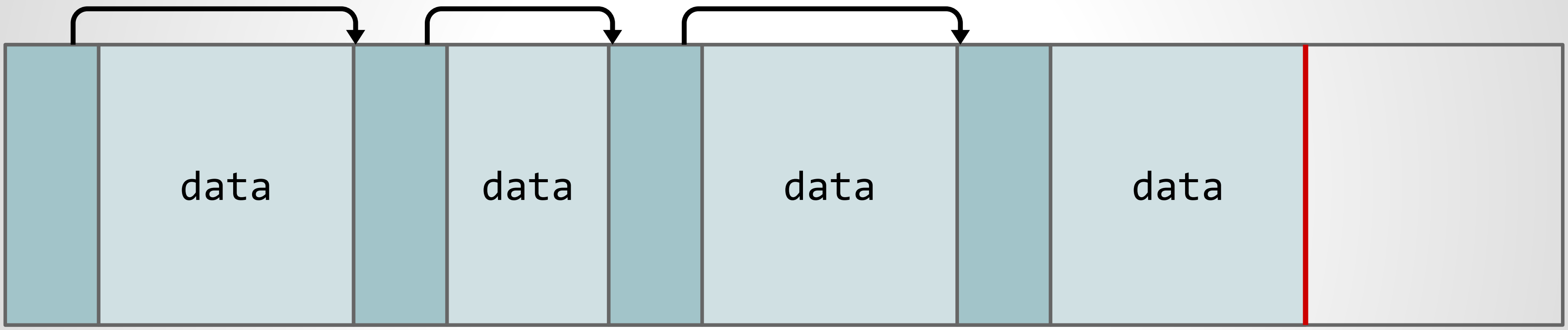
Meta-Data ?

- We add meta-data to each chunk
- we add the meta-data **before** the chunk
- We link chunk like a long linked list

Meta-data



Structured Heap



Meta-Data

```c
struct chunk {
  struct chunk *next;
  size_t        size;
  int           free;
};
```

- next is the list pointer
- we keep data size only
- free indicate chunk availability
- we may add information later

Construction Of `malloc`

- We need to manage the first call for init
- To enforce aligned addresses, we force size to be aligned too.
- When calling `malloc` with size `s`:
  - align the size (eventually force a minimal size)
  - scan the list of chunk for a free chunk sufficiently large
  - if none are available, extend the heap with `sbrk(2)`
  - mark the chunk as used and return a pointer just after the meta-data struct.
  - if it goes wrong, return `NULL`

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Heap Init

```c
void *base() {
  static struct chunk  *b = NULL;
  if (!b) {
    /* Initial call */
    b = sbrk(sizeof (struct chunk));
    if (b == (void*)(-1)) {
      /* error management */
      _exit(71 /* EX_OSERR */);
    }
    /* Build a sentinel */
    b->next = NULL;
    b->size = 0;
    b->free = 0;
  }
  return b;
}
```

- Get the base of the heap
- if not initialized:
  - add place for an empty chunk
  - save the old break
  - build a sentinel
- return the saved base
- if something goes wrong, die.
- We should probably test the initial address of the break for alignment

Searching For A Free Chunk

```
struct chunk *find(size_t s, struct chunk **heap) {
  struct chunk         *cur, *prev = NULL;
  for (cur=*heap; cur && (!cur->free || cur->size < s); cur=cur->next)
    prev = cur;
  *heap = prev;
  return cur;
}
```

- Basic list search
- If we don't find, return NULL and save last cell in heap

Adding New Chunk

```
struct chunk *new_chunk(size_t s,
                        struct chunk *prev)
{
  struct chunk          *b;
  b = sbrk(s + sizeof (struct chunk));
  if (b == (void*)(-1)) {
    if (errno == ENOMEM)
      return NULL;
    /* error management */
    _exit(71 /* EX_OSERR */);
  }
  prev->next = b;
  b->next = NULL;
  b->size = s;
  b->free = 1;
  return b;
}
```

- Used when no chunk are available
- Move the break of asked size plus meta-data size
- Old break points to the new chunk
- Init the new meta-data block
- In case of error:
  - If not enough mem: return NULL
  - Otherwise: die !

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free ?

free(p)

- First we need to verify p:
  - it must be between the base of the heap and its end
  - it must aligned on `sizeof (void*)`
- Then we must access the meta-data:
  - they lie (`sizeof (struct chunk)`) bytes before p
  - we just have to set the free field to 1

Valid call to free ?

- Is p a pointer returned by `malloc` ?
- We've done only the minimal tests
- Can we do better ?
  - traverse the list of chunk — expensive
  - add a magic number to the meta-data — not sure
  - available data can be verified some how ...

Tricks

- First add data address in the meta-data

```
struct chunk {
  struct chunk *next;
  size_t        size;
  int           free;
  void         *data; // pointer to data
};
```

- Then check for the address in free

```
struct chunk   *b = p;
b -= 1;
if (b->data == p)
  b->free = 1;
```

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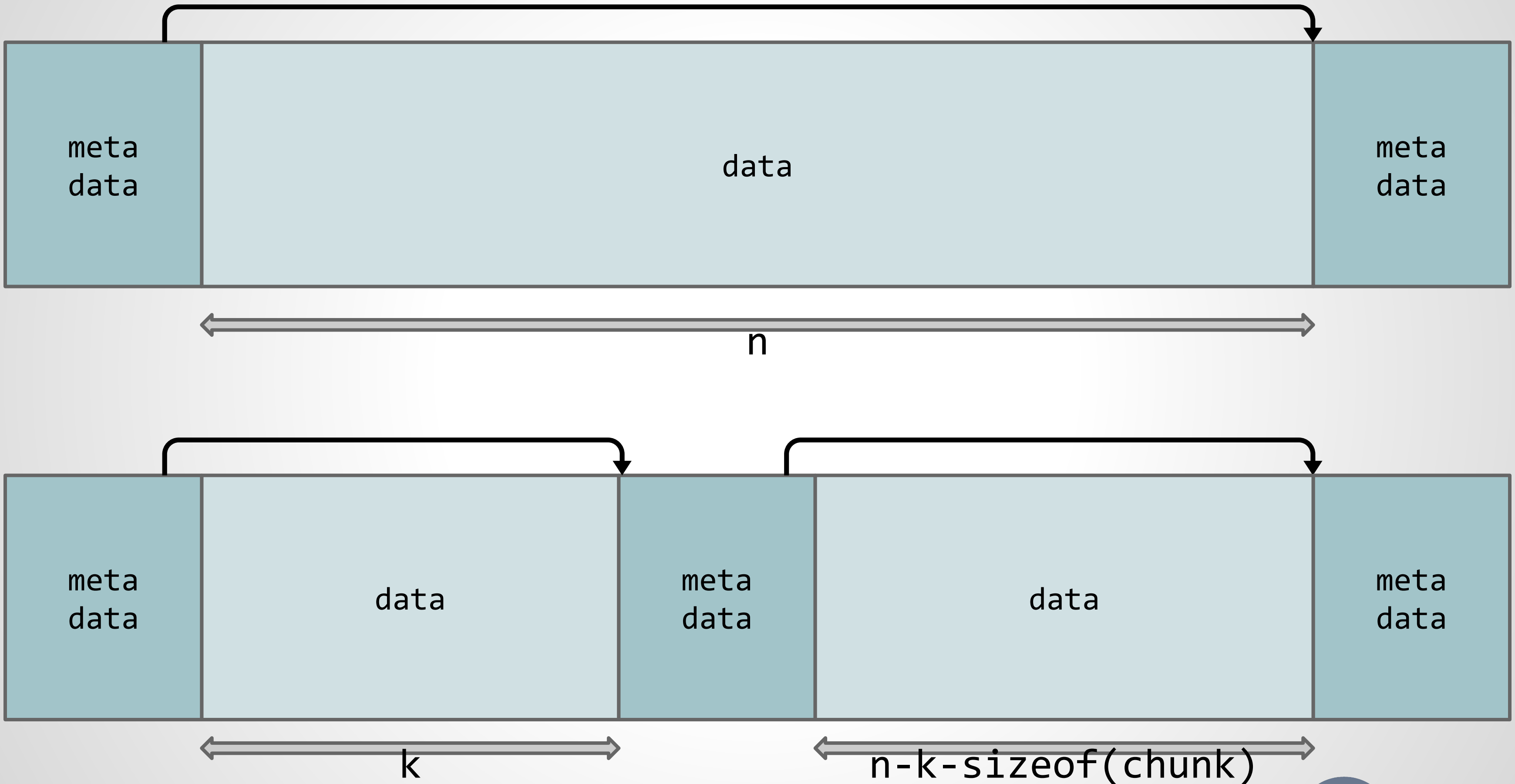
Wasted Space And Fragmentation

Wasted Space

- first-fit may choose ridiculously too large chunk
- best-fit requires clever storage for decent perf
- we should **split** chunk when they are too large:
  - if the founded check is larger than required
  - if the extra amount is enough to store meta-data
  - force a minimal size to avoid too small chunk
  - update the size of the chunk and populate meta-data

Split Chunk



meta data
data
meta data
n
meta data
data
meta data
data
meta data
k
n-k-sizeof(chunk)

Fragmentation

- **Internal Fragmentation:** wasted space → solved
- **External Fragmentation:** too many small chunks
  - after some round of malloc/free, all chunks are small
  - sum of free space is sufficient for large allocation
  - but no suitable chunk can be found
  - a lot of space is lost in meta-data

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Merge !

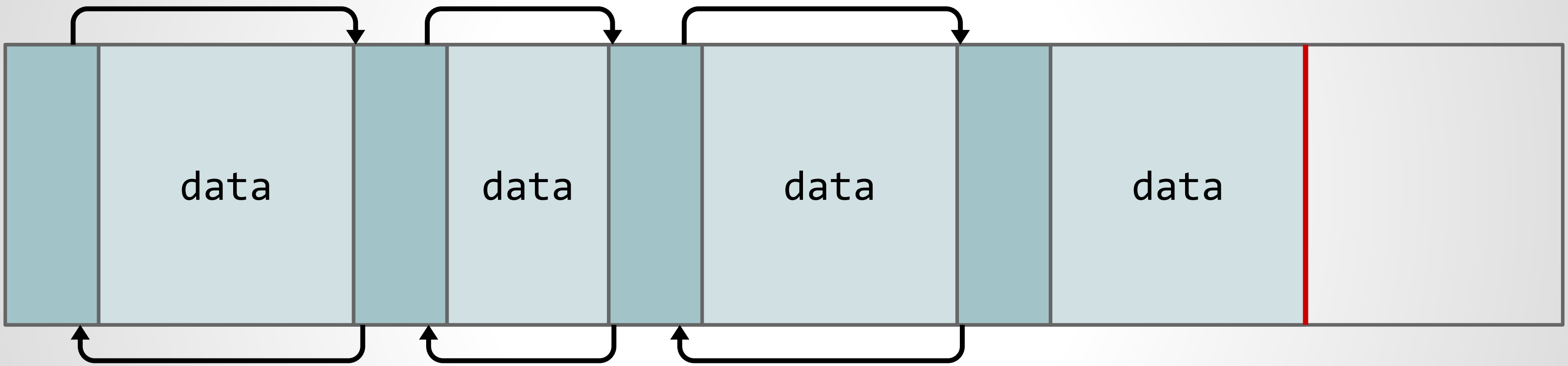
- The solution is to merge chunks
- When performing free:
  - if the next chunk is also free we can merge with it
  - we just update the size
  - and make next point to the next of the merged chunk
- Is it enough ?

Merge More ?

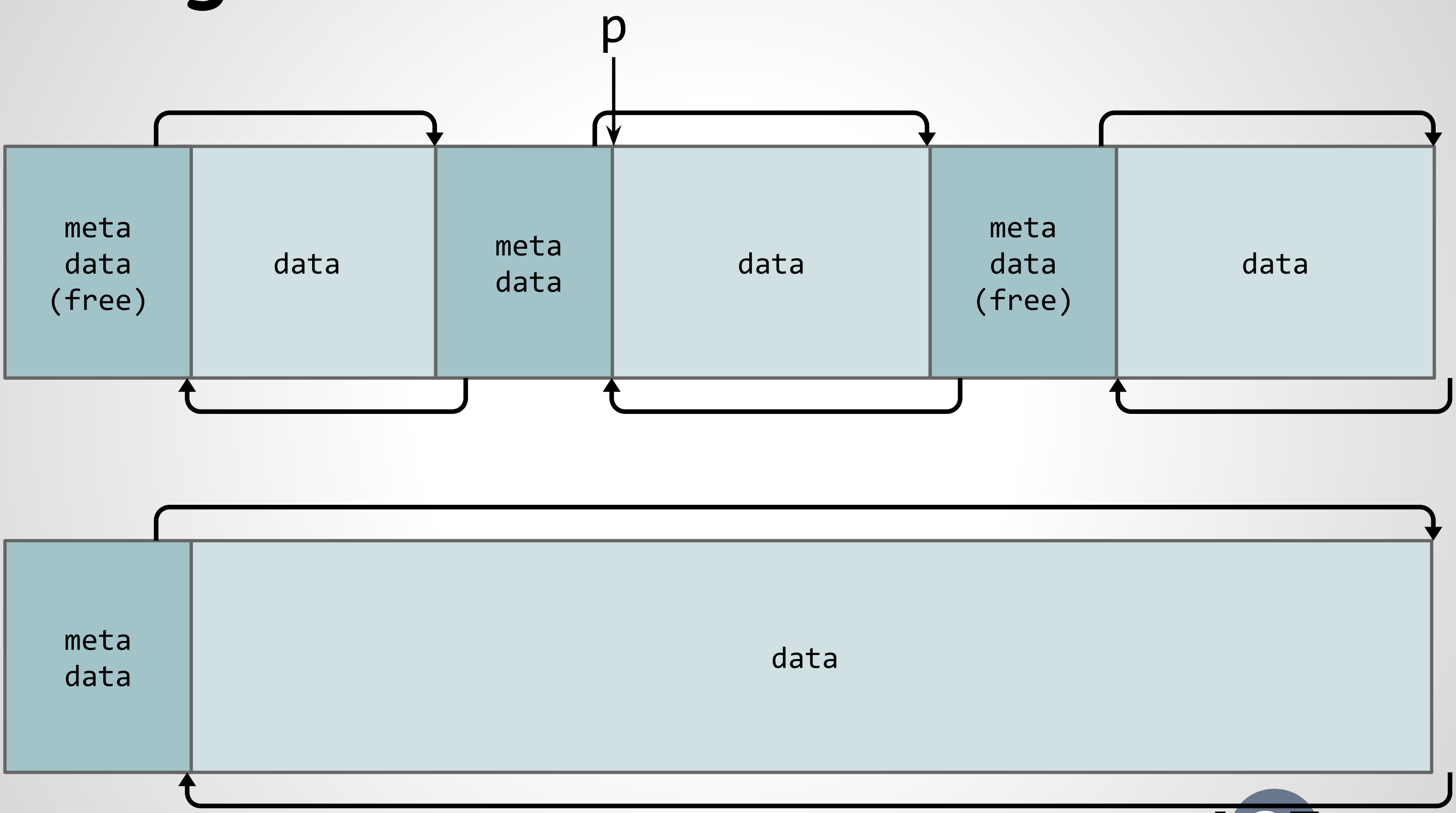
Sure that all adjacent free chunks are merged ?

- The next of the next ? No, to expensive !
- The previous chunk ? **Yes**
- If each time a chunk is freed we merge its previous and next chunk, we win !
- We need to access the previous chunk !

Double Link !



Merge


p
meta
data
(free)
data
meta
data
data
meta
data
(free)
data
meta
data
data

Doing Better ?

- Only link free chunks
- Embedded meta-data inside the chunk
- Using a best-fit ?
  - Finding the best chunk is expensive
  - Free chunk can be linked with chunks of the same size
  - **Buddy Algorithm:** chunks are split/merge by pair
  - **Slab Allocator:** pools of chunk of the same size
- Use `mmap(2)` with or instead of `sbrk(2)`

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More Allocators !

More Allocators ?

`malloc(3)` is highly constrained:

- Allocate any possible size
- Free chunk independently

For specific usage we may have better strategy

Allocate Many, Free Once

- Many programs can be sliced into stages
- Memory will be freed all at once at end of stage
- `malloc(3)` is not adapted to this case
  - we uselessly pay the cost of fine grain free
  - Freeing one by one can be difficult and expensive
- For that we can use a pool allocator !

Pool Allocator

- Allocate once and for all a huge single block
- Maintain an index of the currently used space
- Give chunk piece by piece as required
- Release memory by simply set the index to 0
- Allocation and release are in O(1)
- No overhead, no wasted space !

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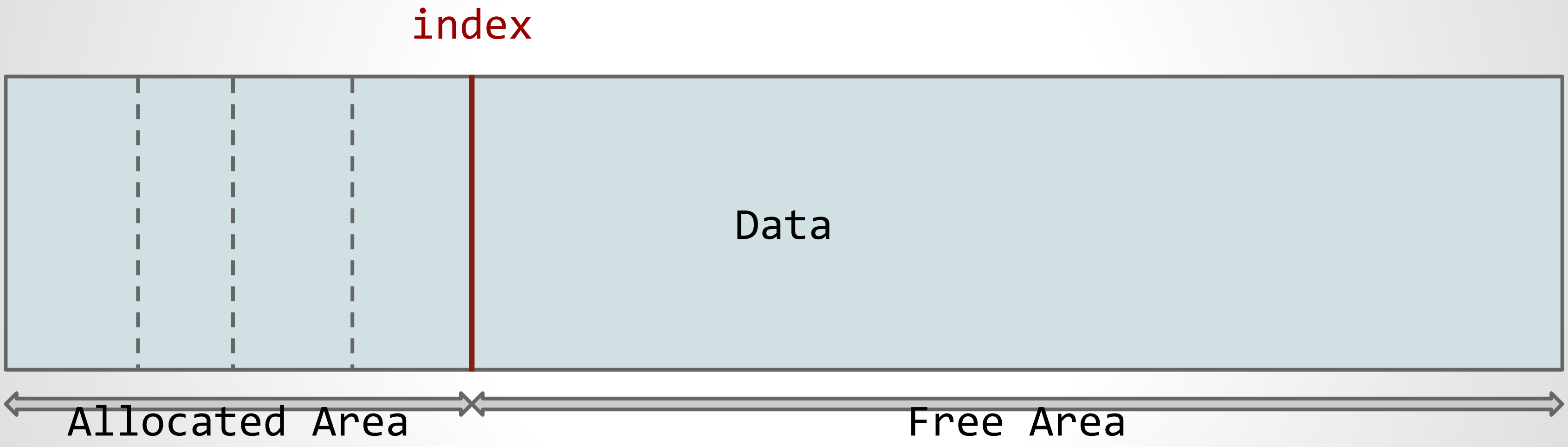
Pool Allocator



Pool Allocator

```
typedef struct pool {
  size_t         poolsize, index;
  char          *data;
}               *mempool;

void reset_pool(mempool mem) {
  mem->index = 0;
}

void *alloc_pool(mempool mem, size_t s) {
  void          *r = NULL;
  if (mem->index + s < mem->poolsize) {
    r = mem->data + mem->index;
    mem->index += s;
  }
  return r;
}
```

Recycling Pool

- We have a bunch of allocations of the same size
- We often allocate/free blocks
- We can use a pool for allocation
- Rather than really freed blocks, we reuse them !
- Again we have O(1) allocate and free !

Free List

- To provide easy reuse we add a free list
- We keep a list of free block
- When freeing a block:
  - we use the first word to store a pointer (our next field)
  - we bind the block to the free list (first place add)
  - we replace the entry of the free list by the block
- When allocate:
  - try to take the first element of the free list
  - take another chunk of the pool

Recycler

```
typedef struct rpool {
  size_t         poolsize, bsize, index;
  char          *data;
  void         **free_list;
}               *recycler;

void *alloc_rpool(recycler mem) {
  void          *r = NULL;
  if (mem->free_list) {
    r = mem->free_list;
    mem->free_list = *(mem->free_list);
  } else if (mem->index + mem->bsize < mem->poolsize) {
    r = mem->data + mem->index;
    mem->index += mem->bsize;
  }
  return r;
}

void free_rpool(recycler mem, void *p_) {
  void         **p = p_;
  *p = mem->free_list;
  mem->free_list = p;
}
```