Dynamic Allocation

Dynamic Memory Allocation

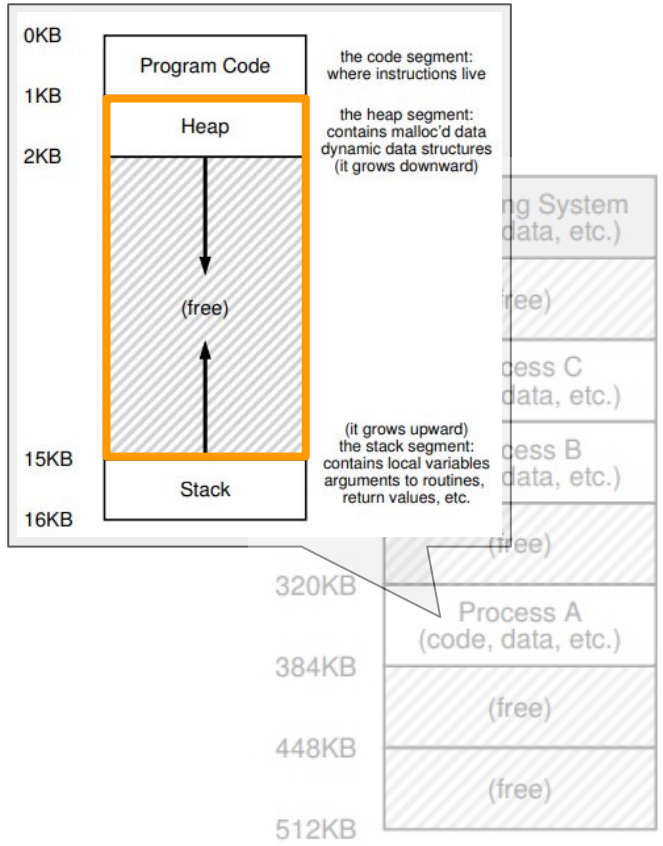
- Programmers use Dynamic Memory Allocation (malloc is an example) to request virtual memory during run-time.
  - We do this at runtime for structures, for which we cannot allocate at compile-time (e.g. a linked list)
    - Other languages like C++ or Java use ‘new’ to allocate memory
    - (Scripting languages do this behind the scenes for us)

```
1  #include <stdlib.h>

2  int main(){

3      int* array = (int*)malloc(500);

4      for(int i= 0; i < 500; ++i){
5          array[i] = i;
6      }

7      free(array);

8      return 0;
9  }
```

Note: We could allocate an array of ‘500’ integers at compile-time, this is just an example.

Dynamic Memory Allocation

- Dynamic memory allocators manage virtual memory in what is known as the *heap*
  - Each process has a heap segment of memory that can resize.
  - The heap consists of variable sized blocks
    - Each block can be marked as either:
      - allocated
      - free



Explicit vs Implicit Memory Allocation

- Explicit Allocator
  - The application(program) allocates and frees space
    - This is what we do in C with malloc and free
    - (or equivalently in C++ with *new* and *delete*)
- Implicit Memory Allocation
  - The application allocates, but does not free space
    - A **garbage collector** instead frees the memory for us.
    - e.g. The Java programming language has different garbage collectors to help us

Our focus in this class (since we use C) is to look at an explicit allocator

Malloc | Found in #stdlib.h or #malloc.h

- void* malloc(size_t size)
  - On Success
    - Returns a pointer to a memory block of at least size bytes
      - For x86 this memory is aligned to 8-byte boundaries
      - For x86-64 this memory is aligned to 16-byte boundaries
    - A size of 0 returns NULL
  - Unsuccessful allocation: returns NULL(0)
- void free(void *p)
  - Returns the block pointed at by p to pool of available memory
  - p must come from previous call to malloc (or realloc)
    - Note: Never use free with **delete** (used in C++), these are different allocators!

Other C Memory functions

C Library

- calloc
  - Similar to malloc, but initializes the allocated block to zero.
- realloc
  - Changes size of previously allocated block
- free
  - Reclaims memory allocated by malloc, calloc, or realloc.

System Calls

- sbrk
  - Use internally by allocators to grow or shrink the heap
  - This will be handy for implementing our own memory allocator!
- mmap
  - Creates a new mapping in virtual address space of calling process.

Malloc example

- Here is another annotated example of what is going on when we malloc properly.

```c
#include <stdio.h>
#include <stdlib.h>

int main(){

        // Allocate a block with 50 ints
        int* data = (int*)malloc(50*sizeof(int));

        // If our allocation fails, we get NULL back
        if(data==NULL){
                exit(0);
        }

        // Initialize allocated block
        int i;
        for(i=0; i < 50; ++i){
                data[i]=i;
        }

        // Return allocated block of size '50' to the heap
        free(data);

        return 0;
}
```

Malloc Performance

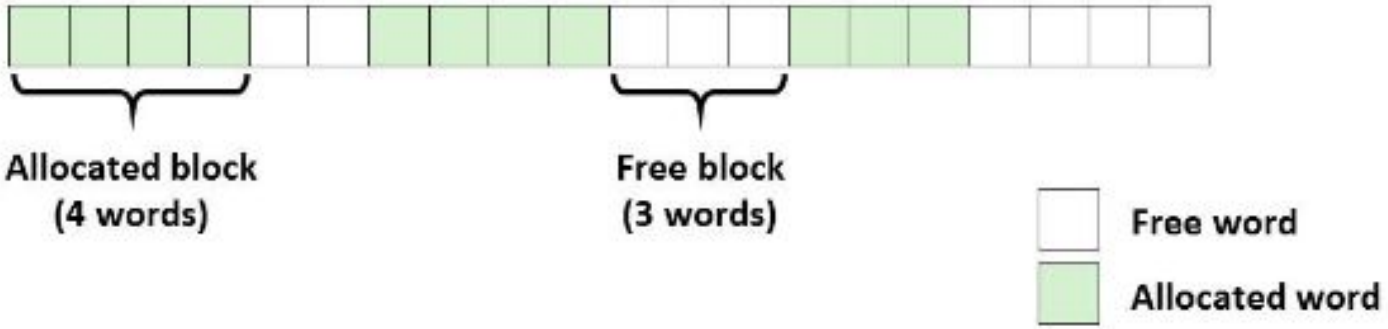
- Why is allocation expensive?
  ?

Malloc Performance

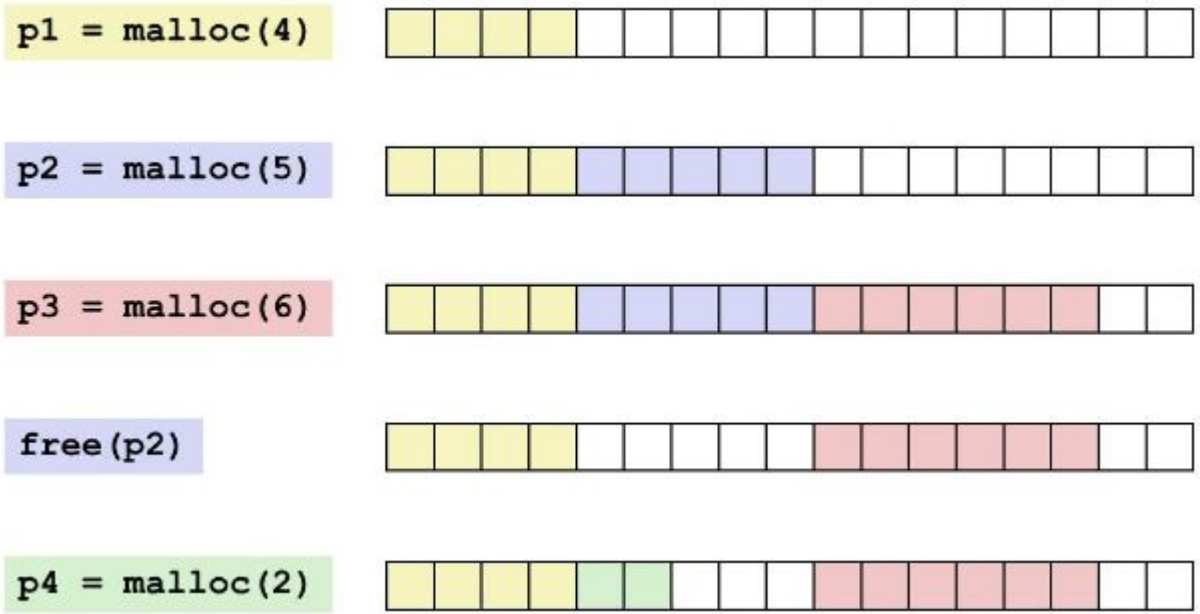
- Why is allocation expensive?
- A few answers:
  - One is that we have to find (perform some search) a block of memory that ‘fits’ in our heap.
    - If it does not fit then we have to make a system call to sbrk to extend our heap and find a block that fits
    - Anytime we have to call sbrk, that is a syscall
      - syscalls are expensive
      - They involve context switching (saving our registers state, moving to kernel mode, then swapping back)

Some ways to think about memory.

- You have some assortment of blocks
- Some are allocated, and some are free
  - (Assume 1 block here is 1 word or 32 bytes)



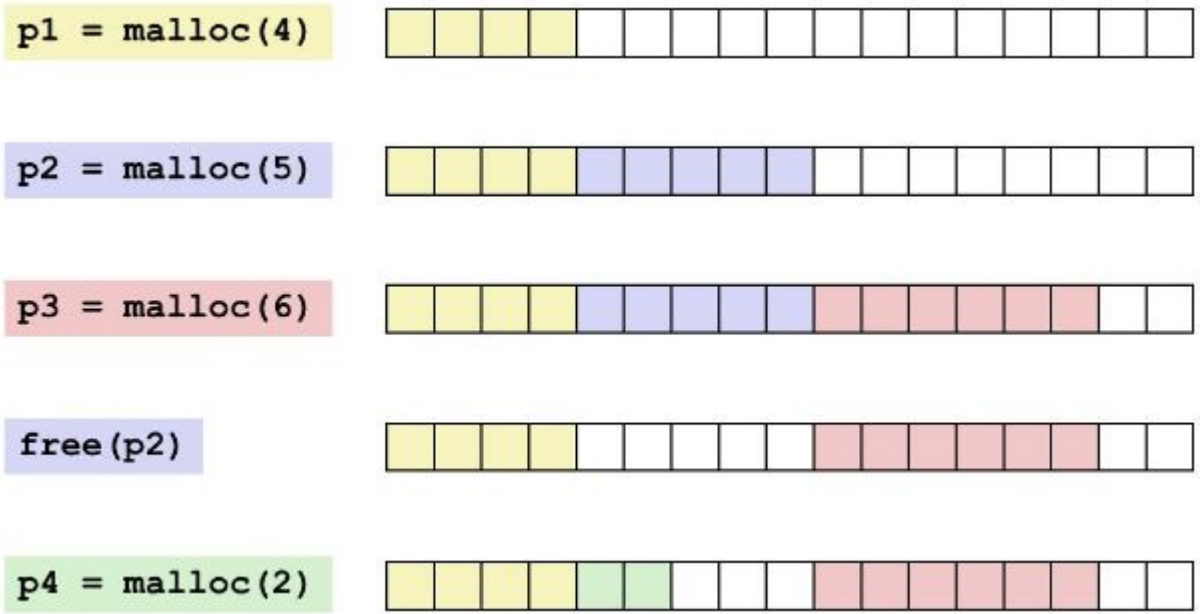
Allocation example visualization



Constraints (i.e. What makes memory allocation interesting?)

- You may not know how software will malloc or free
  - i.e. Patterns are not always predictable
- You can only free a malloc’d block
- Typically we try to keep our blocks aligned
  - x86 - 8-byte blocks
  - x86-64 - 16 byte blocks
- We are often trying to maximize speed and memory efficiency
  - i.e. when we malloc we want it to be fast
  - i.e. When we malloc, we do not want to constantly allocate new memory
    - (which would be the fastest thing to do)
  - We might measure this using a throughput measure
    - (i.e. how many mallocs and frees can I do in 10 seconds)

Ideally, we have no empty blocks ever

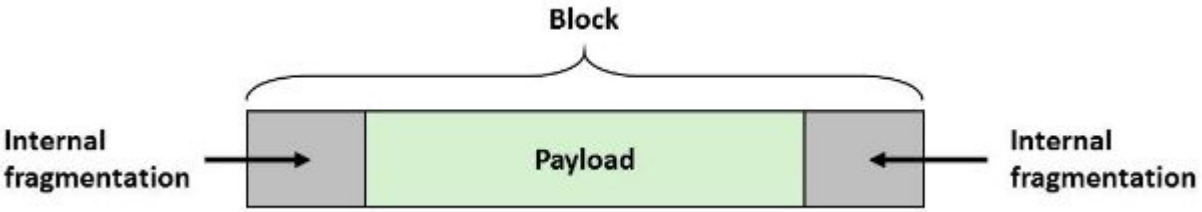


Poor memory utilization

- How we talk about this more formally
  a. Internal Fragmentation
  b. External Fragmentation

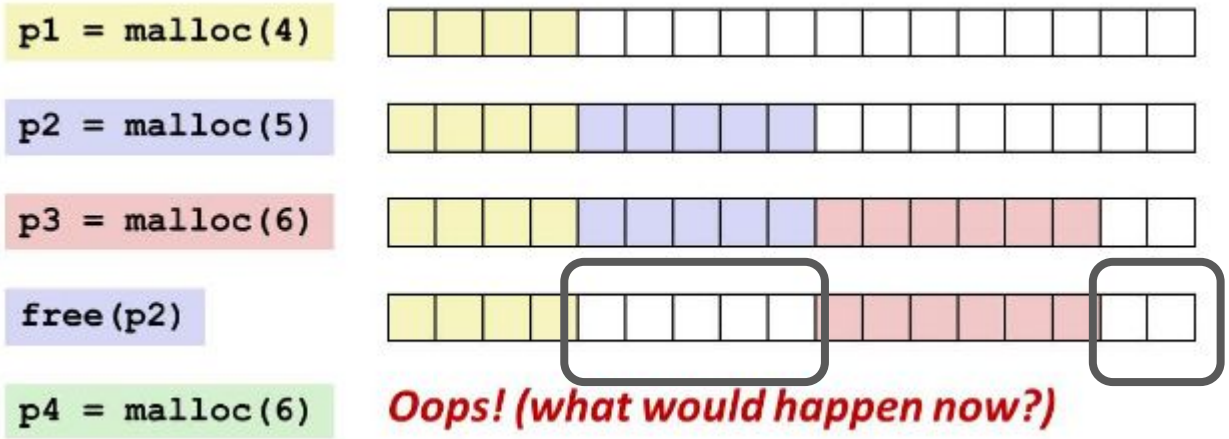
Internal Fragmentation

- e.g. we allocate structures smaller than our block size of 32 bytes (i.e. 1 char at a time)



External Fragmentation

- We have enough blocks (i.e. we don’t need to extend the heap), but they are not contiguous



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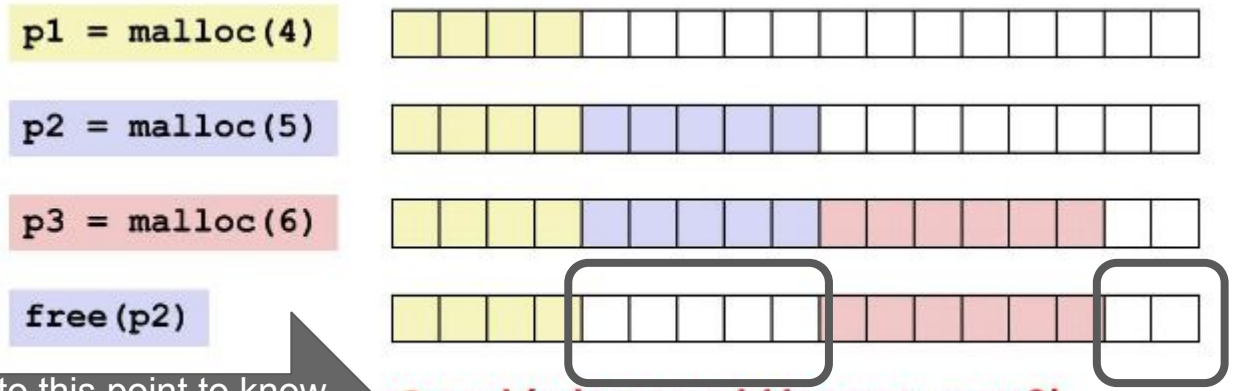

It is hard up to this point to know fragmentation will occur. We cannot always predict the future.

Implementation of an Allocator

- How do we know how much memory to free in a given pointer?
- How do we keep track of free blocks?
- What do we do with extra space when allocating structures smaller than the free block?
- How do we pick a block to use in allocation?
- How do we reinsert freed blocks?

How much do we free?

- Standard method
  - Keep the length of a block in the preceding block
    - (Often called the header)
  - This requires one extra word for every allocated block.

```
typedef long Align;  /* for alignment to long boundary */

union header {       /* block header: */
    struct {
        union header *ptr; /* next block if on free list */
        unsigned size;     /* size of this block */
    } s;
    Align x;         /* force alignment of blocks */
};

typedef union header Header;
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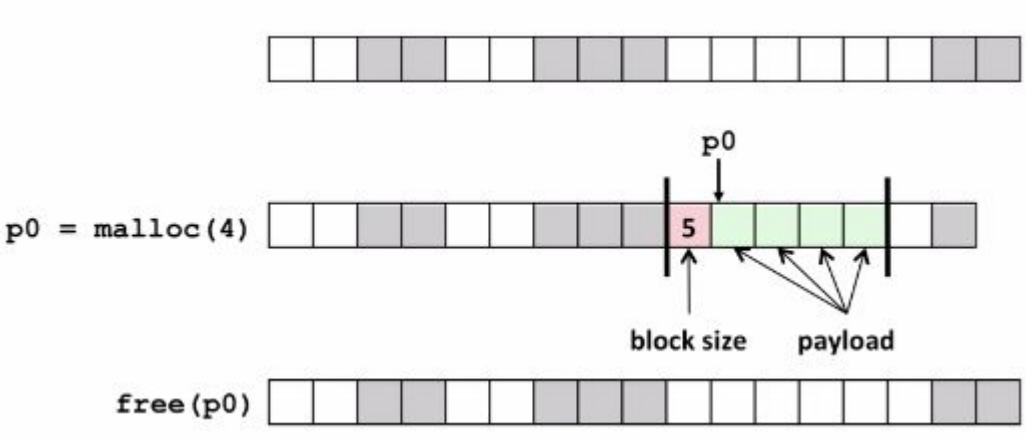

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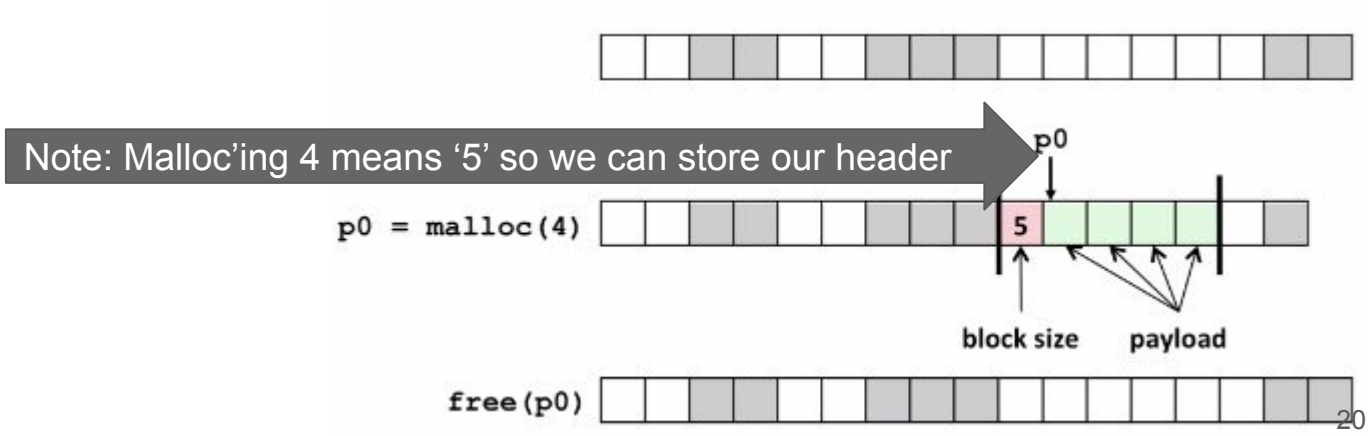
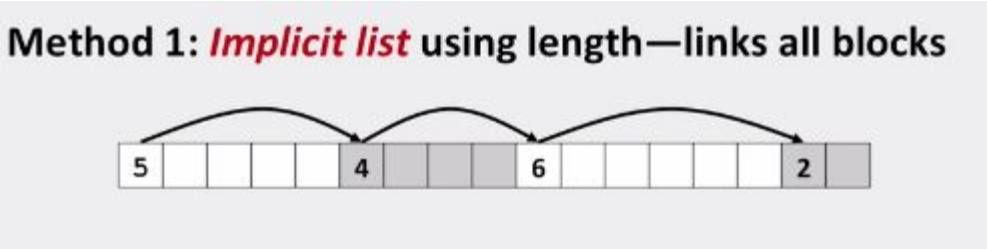


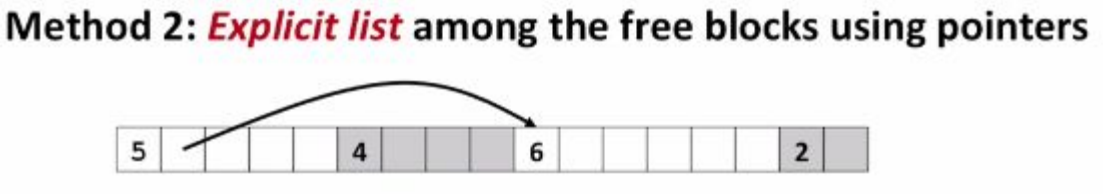
Keeping track of memory Strategy 1

- Keep track of everything we allocate
- If it is free, then we can reuse it.



Keeping track of memory Strategy 2

- Maintain another list that only points to free memory



Keeping track of memory Strategy 3 and Strategy 4

- Maintain a free list for different size classes
  - Perhaps all powers of 2
    - Or perhaps only allocate powers of 2
- Maintain a list that is sorted by size
  - Some balanced tree or binary tree structure

Implicit List: How to find a free block

- First fit strategy (Perhaps for our homework :))
  - Search from beginning of list
    - Choose first free block that fits
  - Takes linear time (O (number of allocated and freed blocks)

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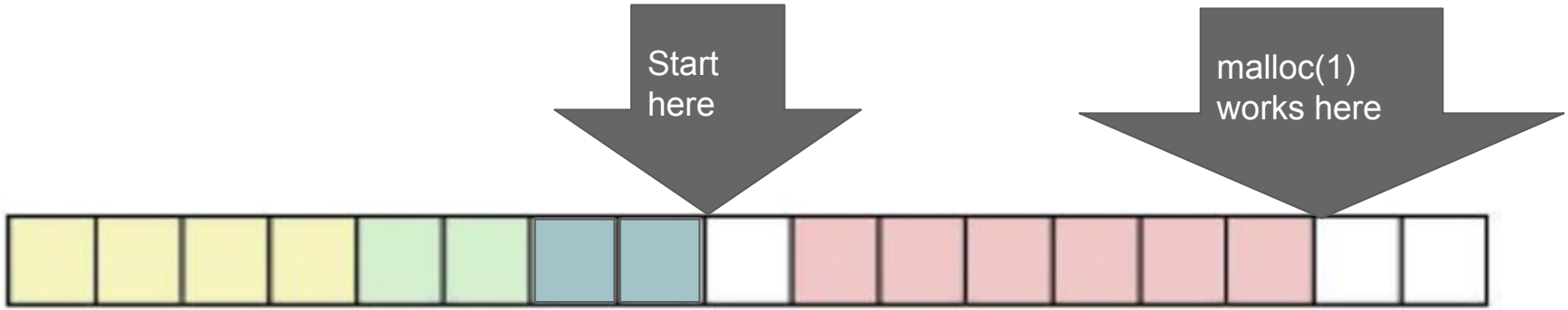
Implicit List: How to find a free block

- Next-fit strategy
  - Search from where you left off from your previous search
    - Choose first free block that fits
  - Takes linear time (O (number of allocated and freed blocks)
    - May be better, avoids re-scanning unhelpful blocks if you are doing many similar allocations
    - Could make fragmentation worse though!



Implicit List: How to find a free block

- Best-fit strategy
  - Scan for the block that fits best
    - i.e. fewest bytes left over
  - Keeps fragmentation small and improves memory utilization
  - Will typically run slower than first-fit (longer scan for optimal block)

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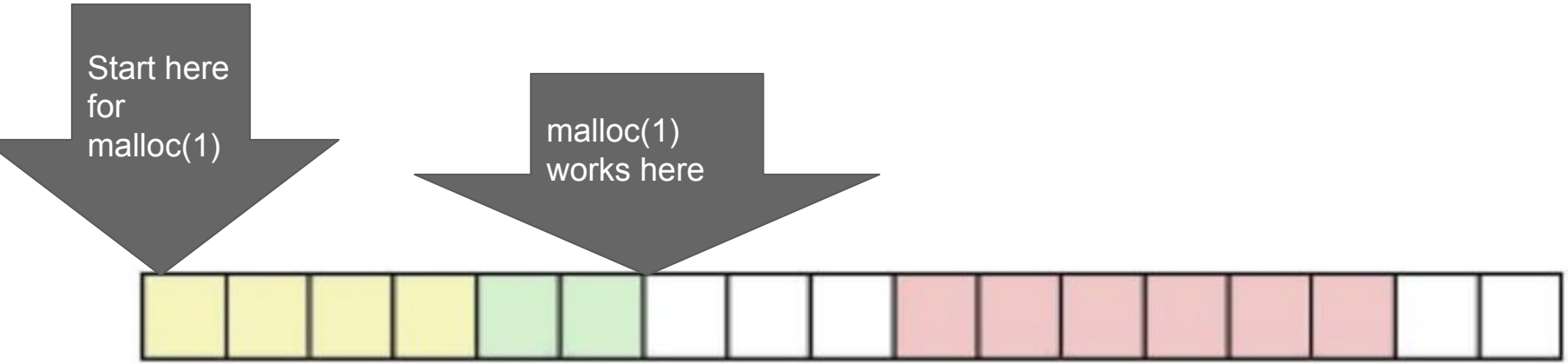

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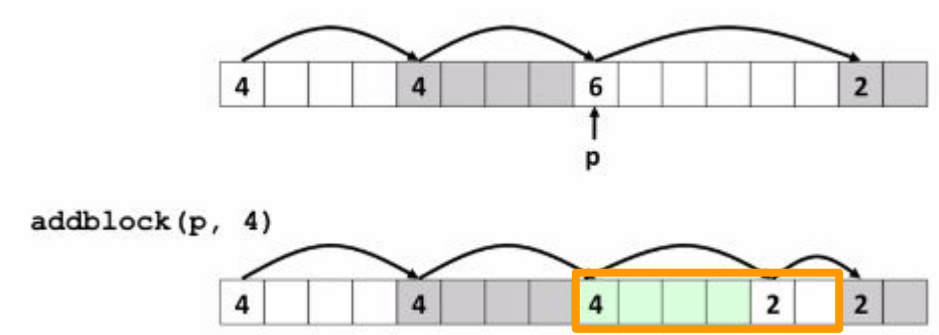
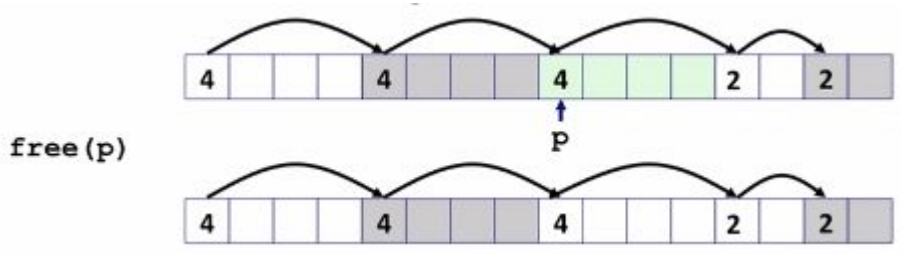
Implicit List: How allocate a free block?

- Depending on our strategy
  - We could allocate to the block found
    - i.e. we set a pointer to that block and size
    - We may want to also split that block
      - if there is room to do so (See example below)



Implicit List: How free block?

- Simply free a block by setting the free bit in the header
  - This will lead to fragmentation however!



Implicit List: How free block?

- Simply free a block by setting the free bit in the header
  - This will lead to fragmentation however!
    - It is suggested to coalesce these blocks (i.e. combine them)