Lecture 14: Dynamic Memory

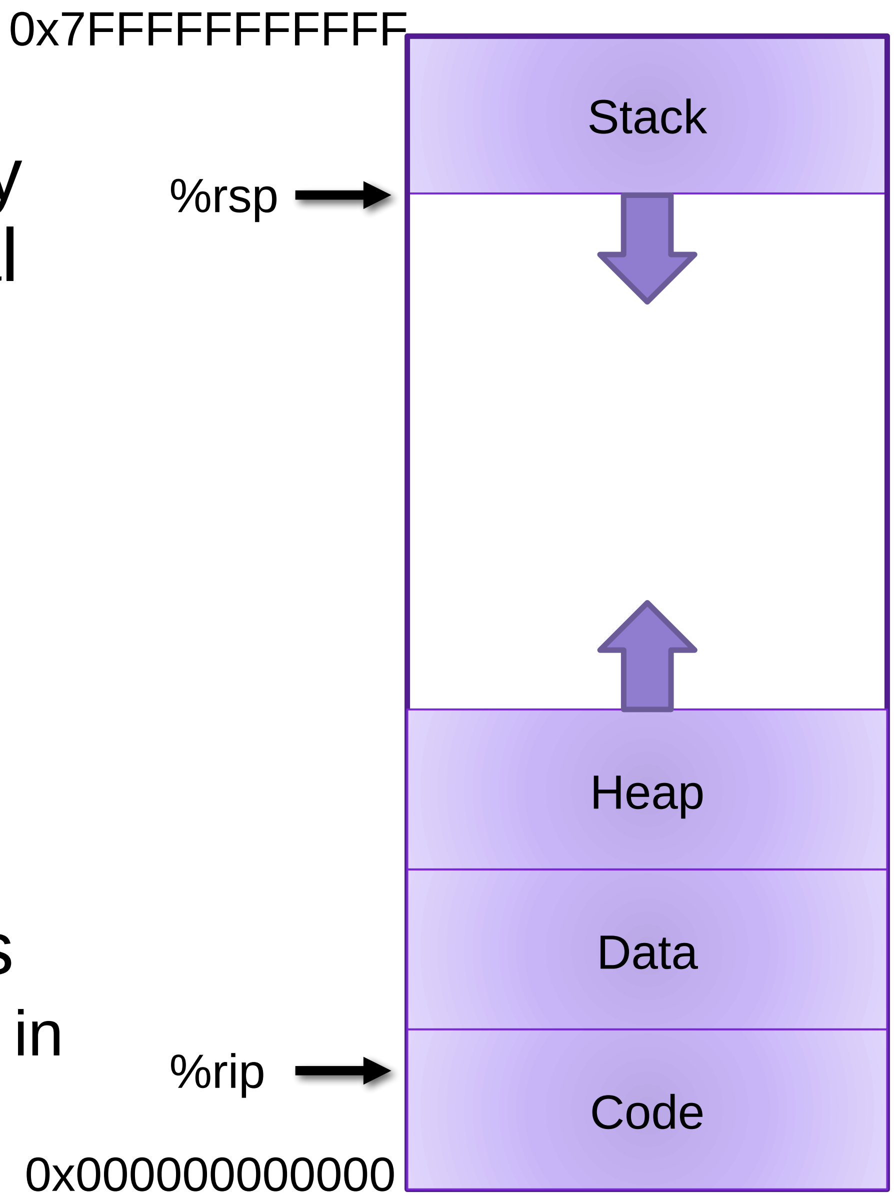
CS 105

Fall 2025

Memory

- byte addressable array made up of four logical segments
- attempt to access uninitialized address results in exception (segfault)

- **stack** provides local storage for procedures
  - "top" of the stack stored in register %rsp



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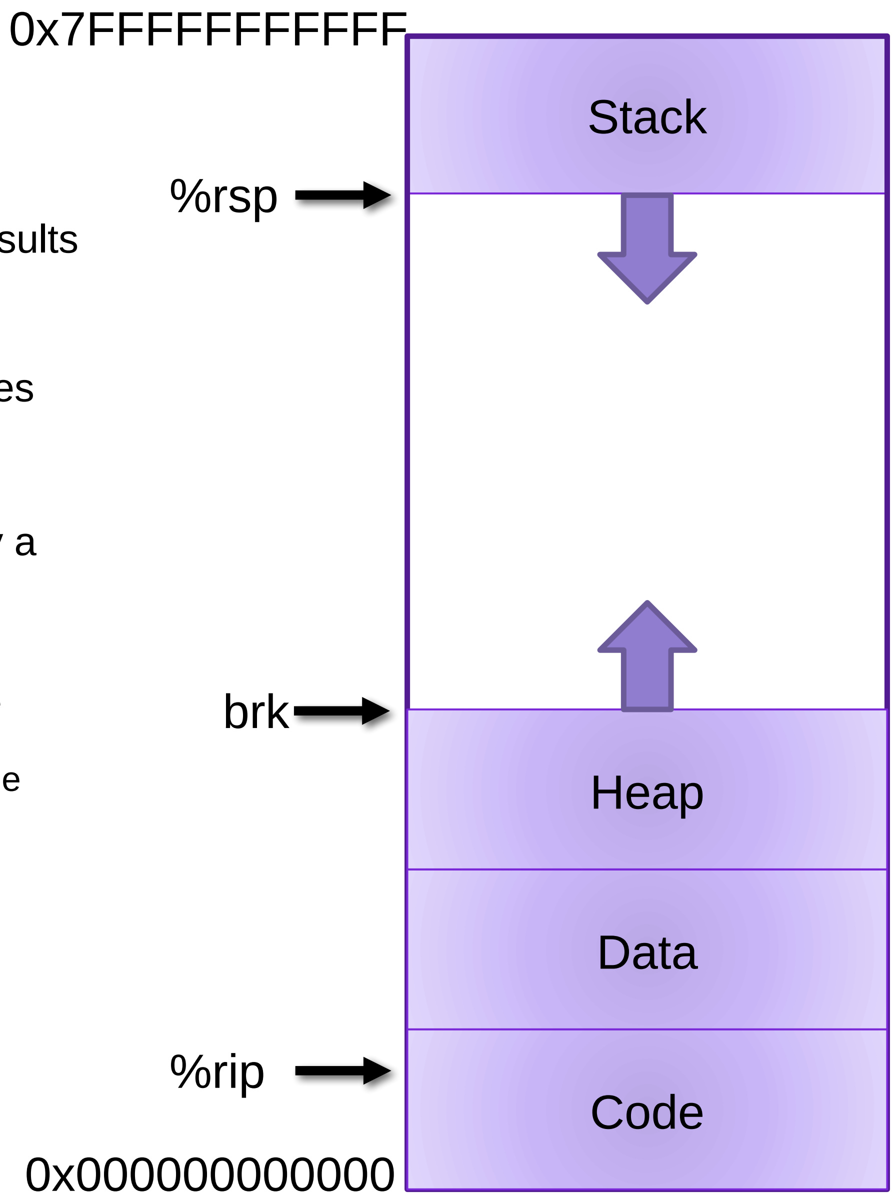
- **heap** is an area of memory maintained by a dynamic memory allocator
  - operating system maintains variable brk that points to the top of heap
  - program can dynamically allocate/deallocate heap memory
  - program can use system call sbrk() to change size of heap

- **data** stores global variables

- **code** stores program instructions



Dynamic Memory Allocation

Dynamic memory allocator

- Manages the heap
  - organizes the heap as a collection of (variable-size) **blocks**, each of which is either **allocated** or **free**
  - allocates and deallocates memory
  - may ask OS for additional heap space using system call sbrk()
- Part of the process’s runtime system
  - Linked into program

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Example dynamic memory allocators

- **`malloc`** and **`free`** in C
- **`new`** and **`delete`** in C++
- object creation & garbage collection in Java
- object creation & garbage collection in Python

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- object creation & garbage collection in Java
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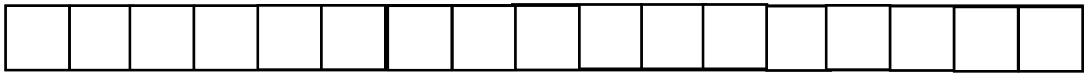
- object creation & garbage collection in Java
- object creation & garbage collection in Python

implicit allocators

Allocation Example using **malloc**

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

void foo(int n) {

    /* Allocate a block of n ints */
    int* p = (int*) malloc(n * sizeof(int));
    if (p == NULL) {
        perror("malloc");
        exit(0);
    }

    /* Initialize allocated block */
    for (int i=0; i<n; i++){
            p[i] = i;
    }

    /* Return allocated block to the heap */
    free(p);
}
```

Allocation Example



Assume each diagram block depicts 4 bytes

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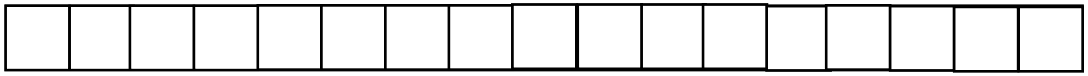

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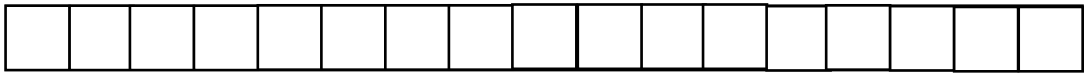

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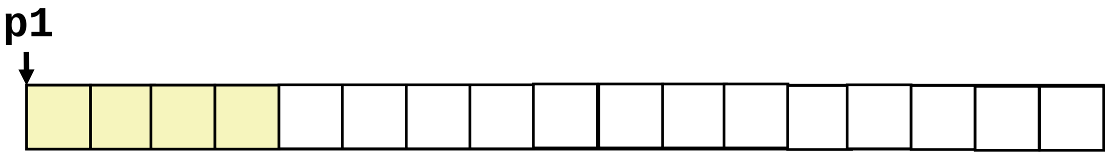

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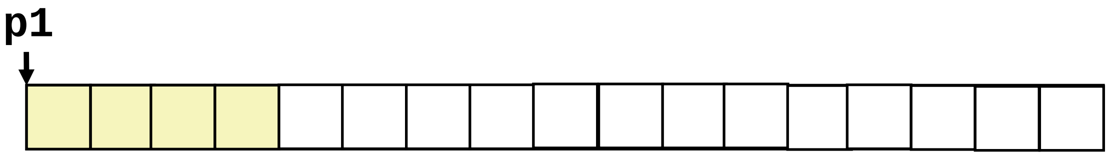

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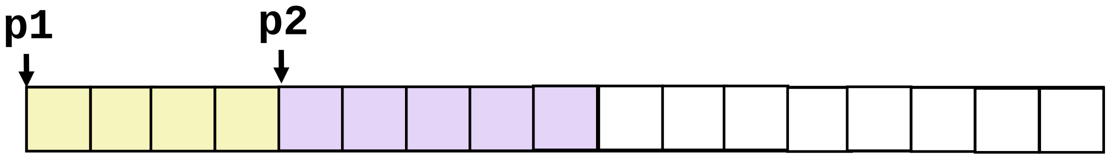

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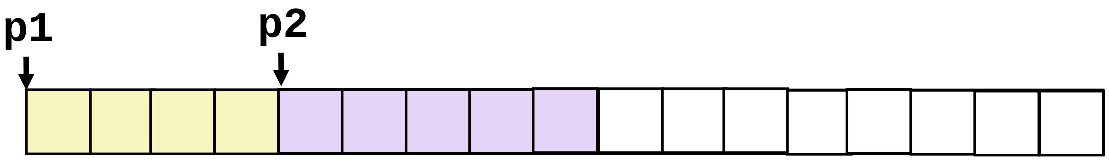

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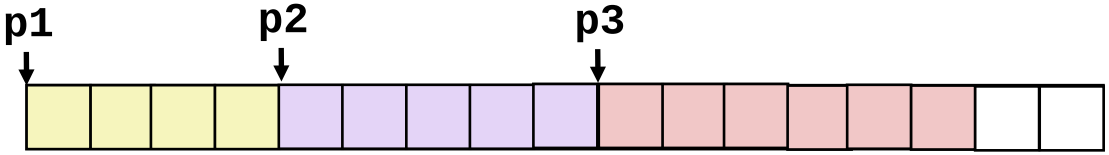

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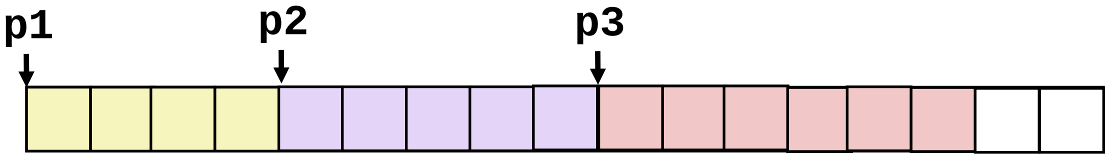

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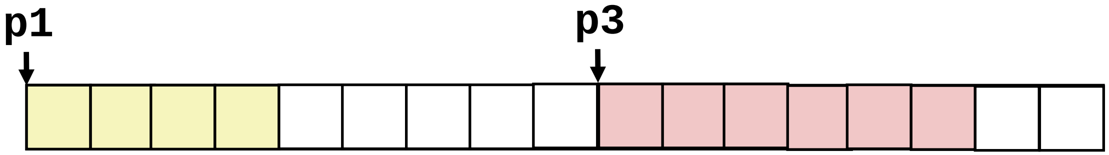

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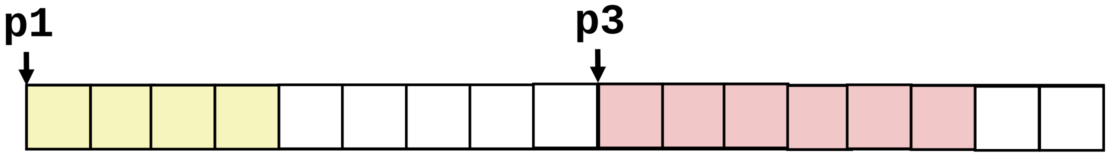

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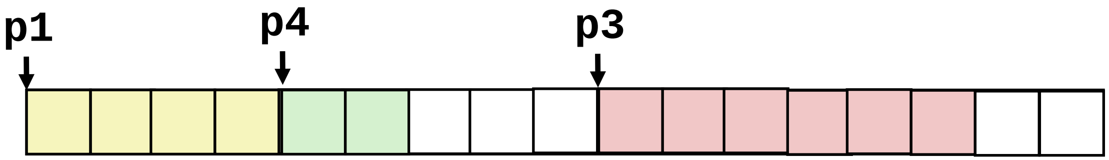

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5) **Must only use the heap:**
   - any data structures used by the allocator must be stored in the heap

First Example: A Simple Allocator

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void* malloc (size_t size) {
  return sbrk(align(size));
}

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  // do nothing
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Advantages

- Simple
- Blazing fast

Disadvantages

- Memory is never recycled
- Wastes a lot of space

Allocator Goals

-

- **Throughput:** number of requests completed per time unit
  - Make allocator efficient
  - Example: if your allocator processes 5,000 `malloc` calls and 5,000 `free` calls in 10 seconds then throughput is 1,000 operations/second

- **Memory Utilization:** fraction of heap memory allocated
  - Minimize wasted space
  - Peak Memory Utilization $U_t = \frac{\max_{i \leq t} space\ allocated\ at\ time\ i}{size\ of\ heap\ at\ time\ t}$

- These goals are often conflicting

Exercise: Memory Utilization

- Recall that Peak Memory Utilization $U_t = \frac{\max_{i \le t} space\ allocated\ at\ time\ i}{size\ of\ heap\ at\ time\ t}$

- What is the Peak Memory Utilization at time $t = 2$?
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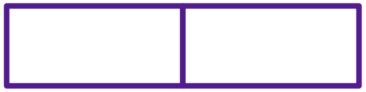

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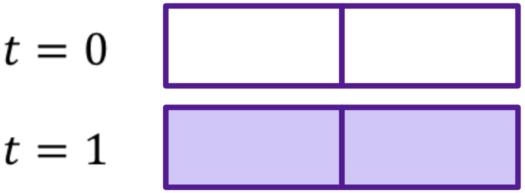

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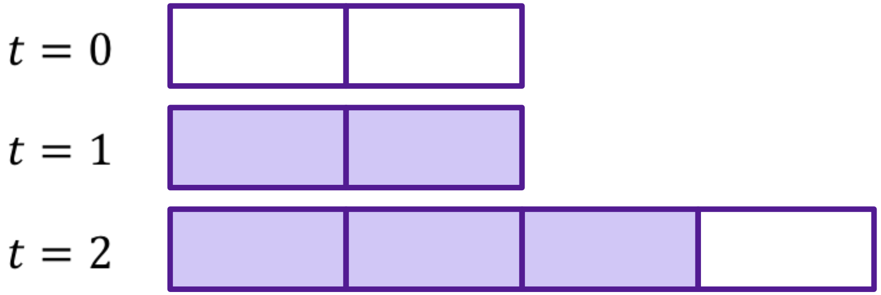

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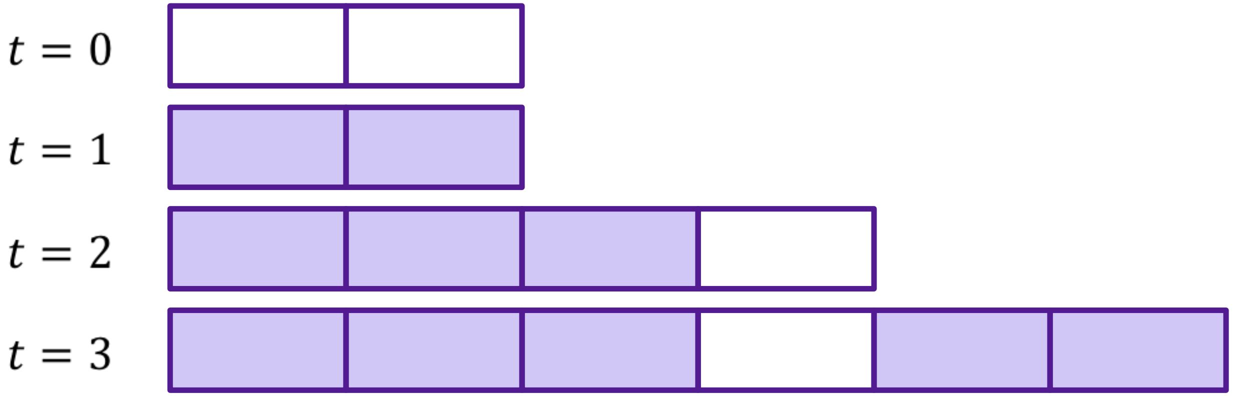

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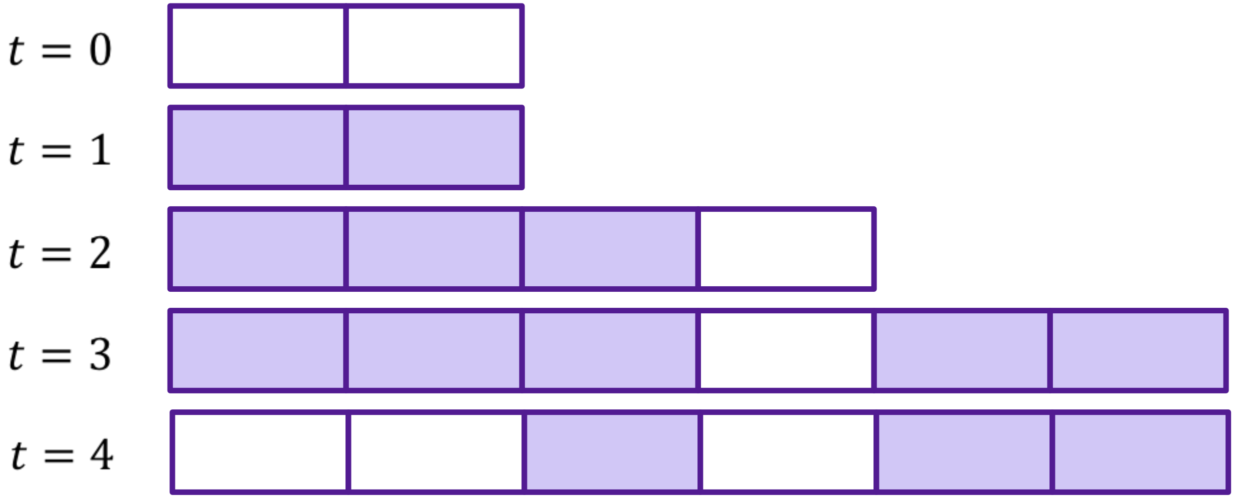

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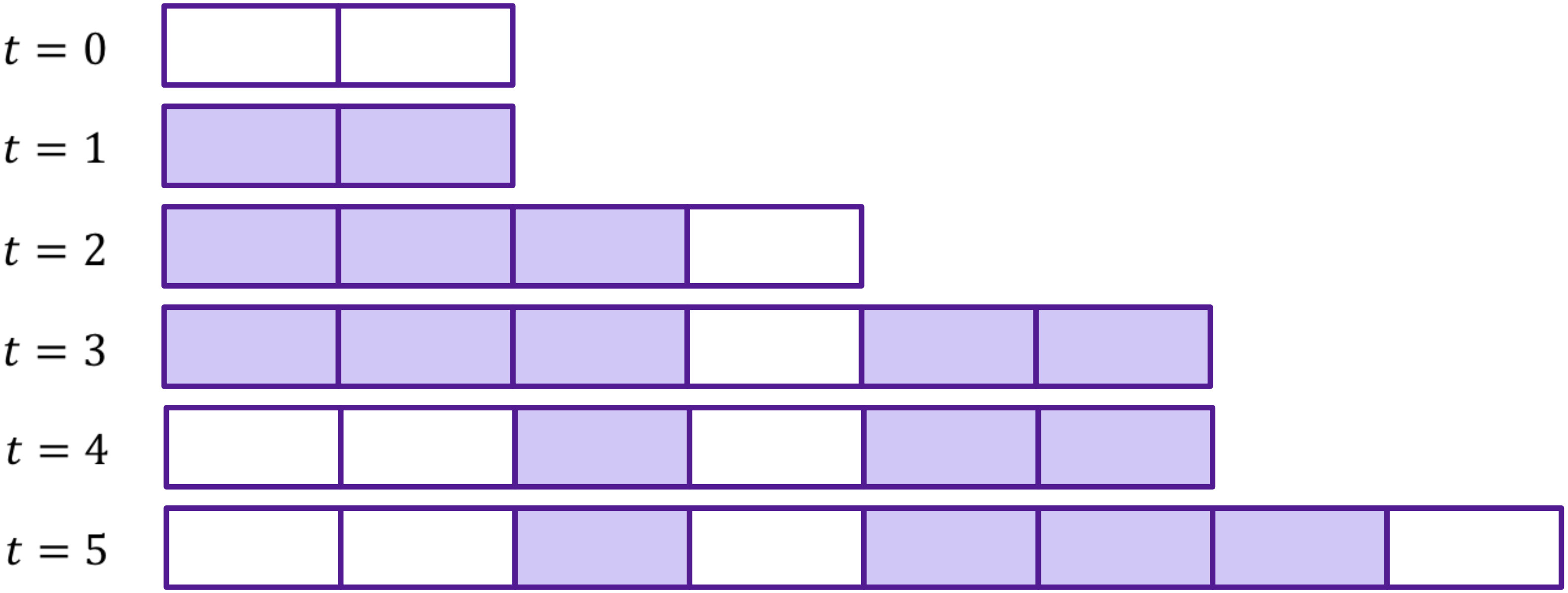

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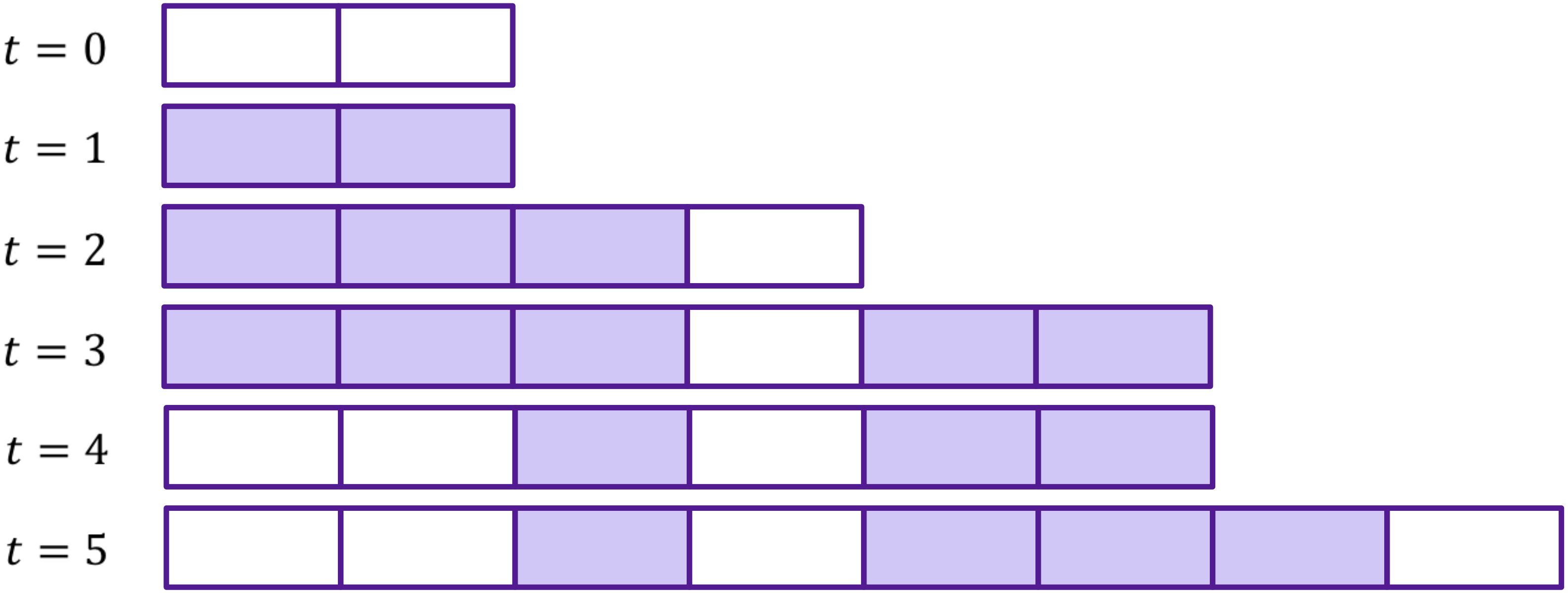

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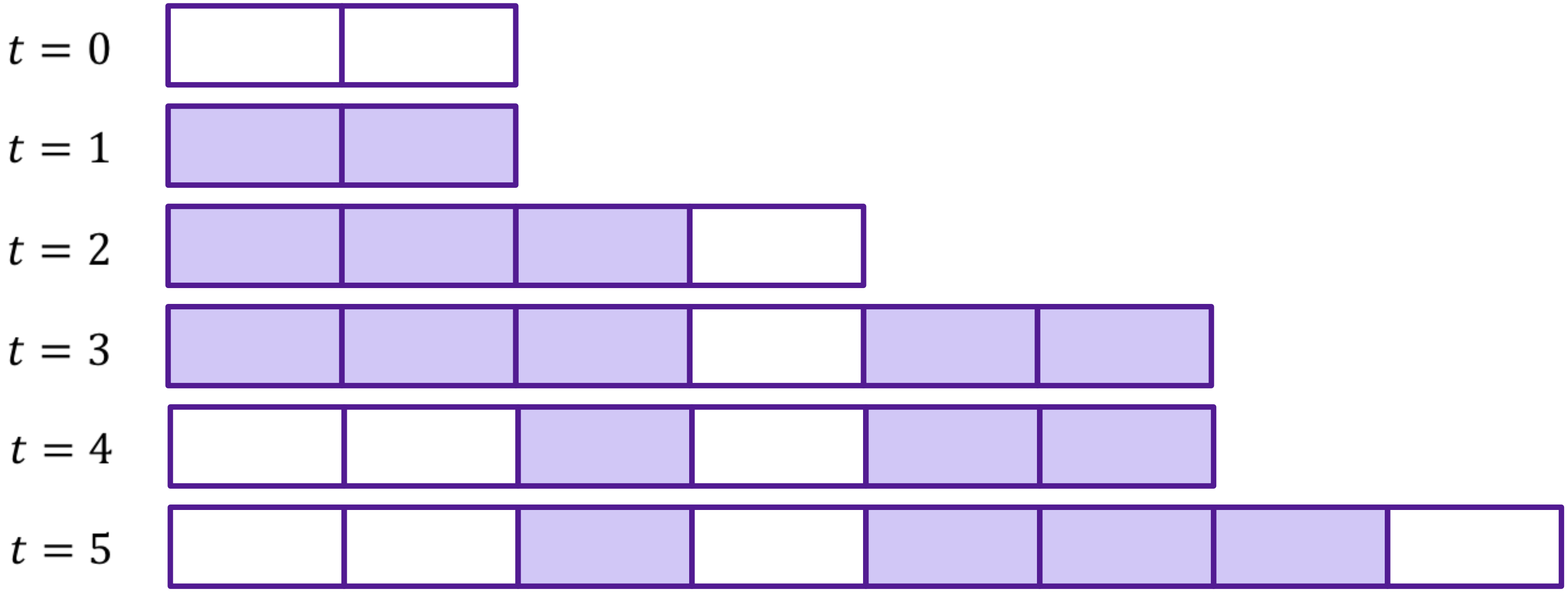

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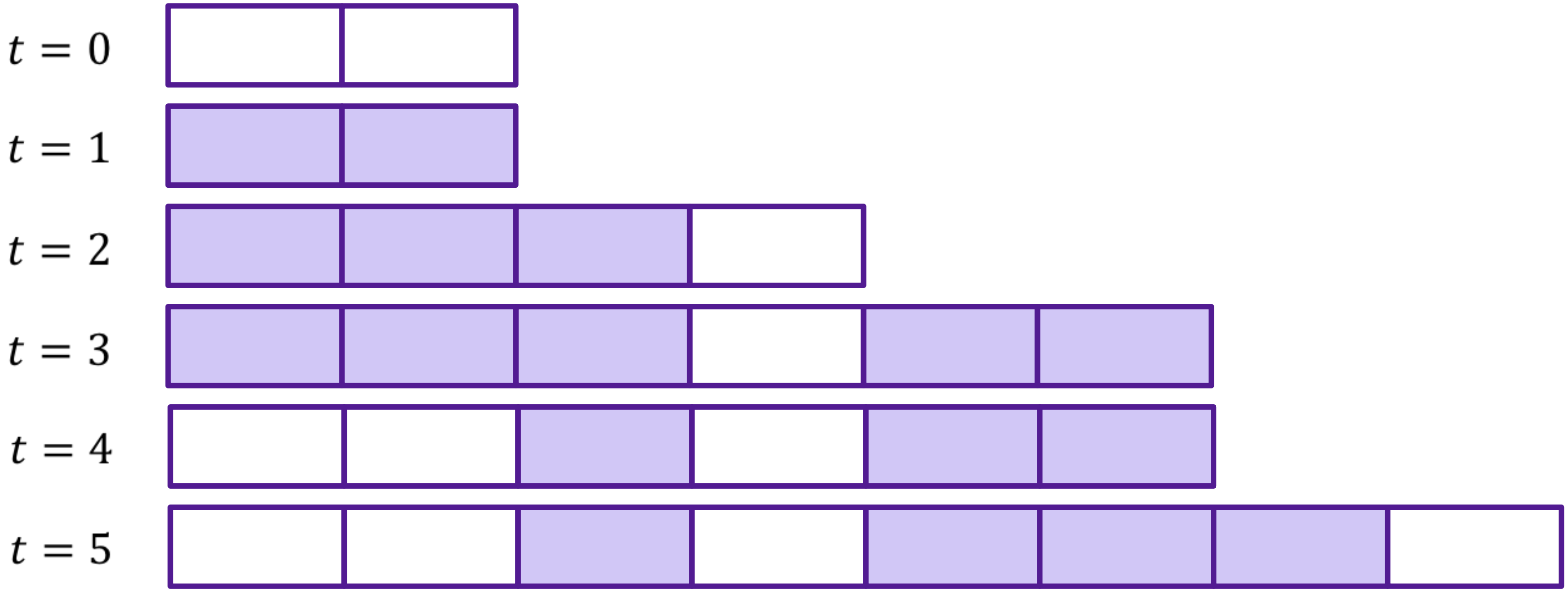

- What is the Peak Memory Utilization at time $t = 2$? **$3/4$**
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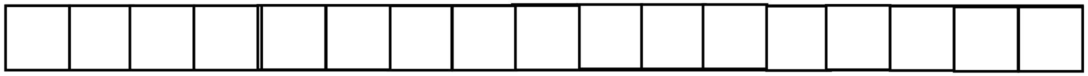
Utilization Blocker: External Fragmentation

- Occurs when there is enough aggregate heap memory, but no single free block is large enough



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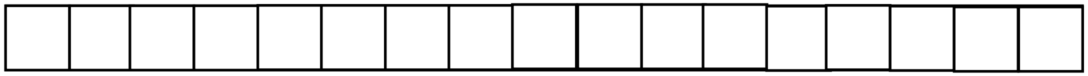

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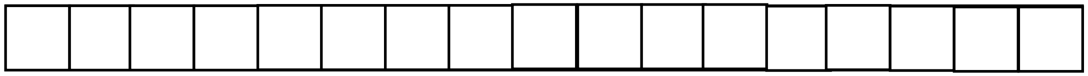

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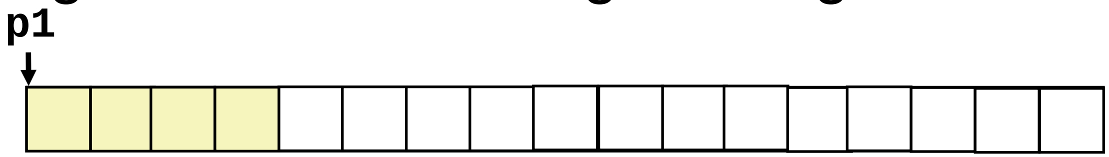

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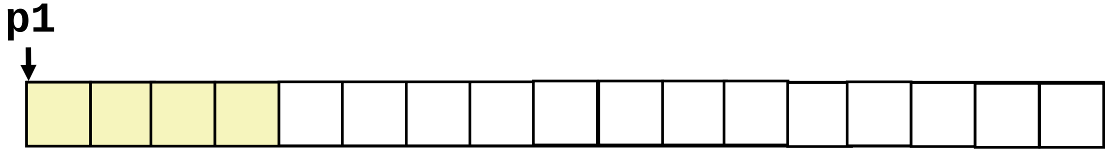

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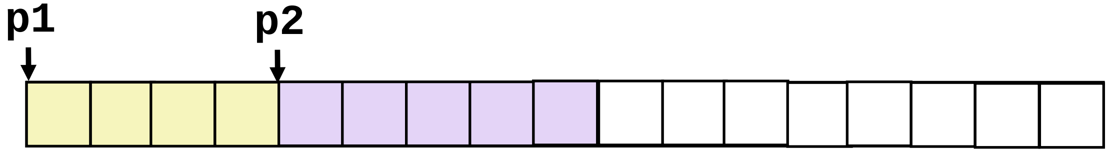

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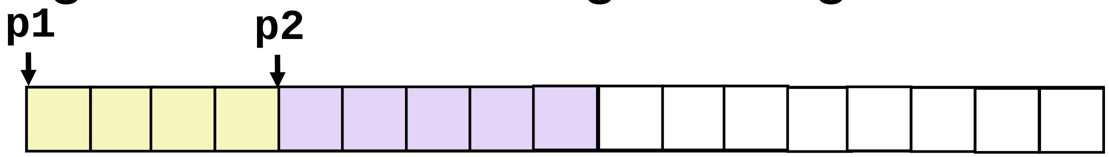

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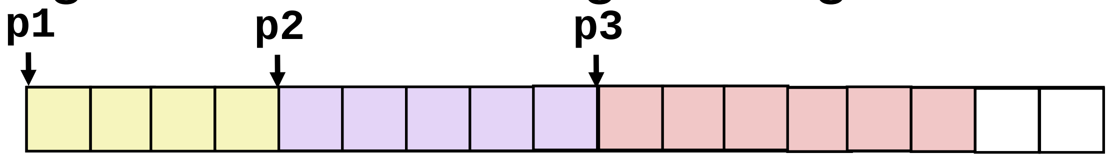

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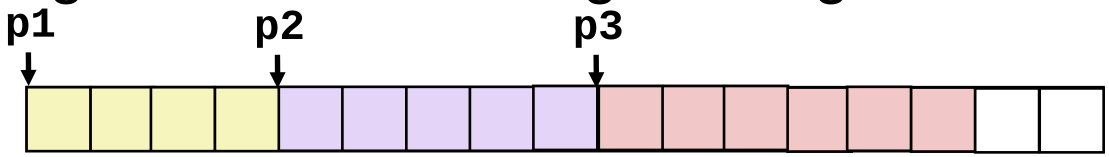

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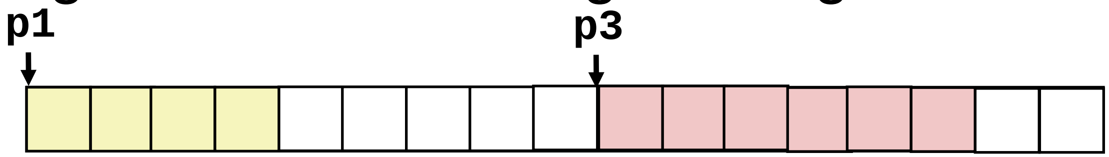

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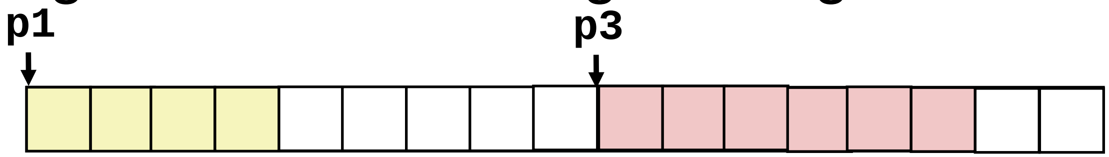

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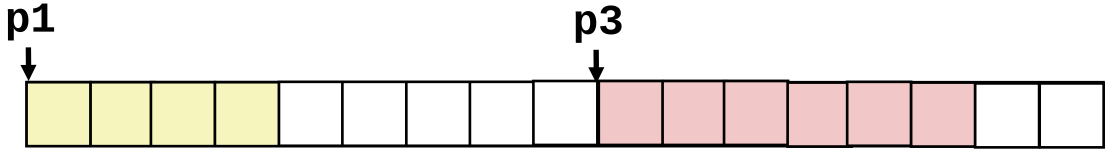

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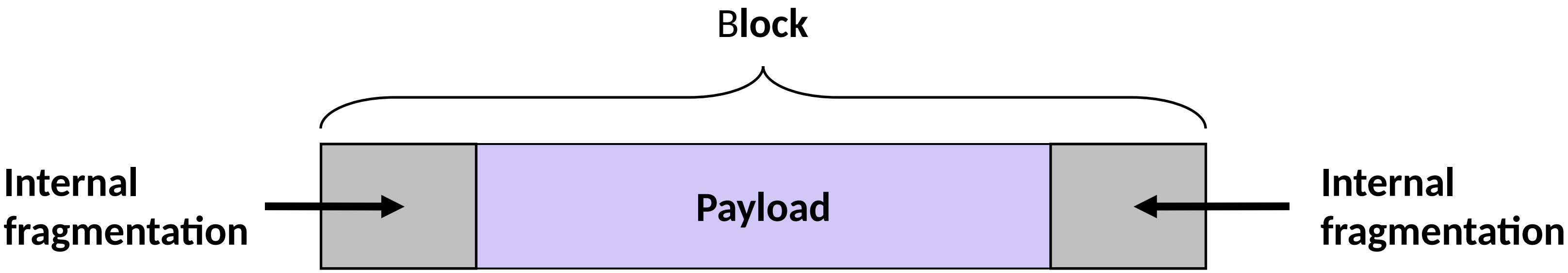
- Depends on the pattern of future requests
  - Thus, difficult to measure

Utilization Blocker: Internal Fragmentation

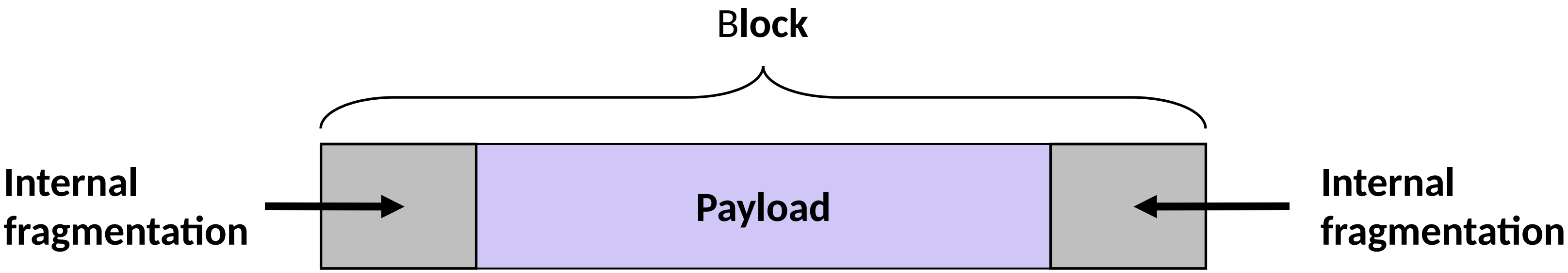
- For a given block, ***internal fragmentation*** occurs if payload is smaller than block size



- Caused by
  - Overhead of maintaining heap data structures
  - Padding for alignment purposes
  - Explicit policy decisions
    (for example, returning a big block to satisfy a small request)

Utilization Blocker: Internal Fragmentation

- For a given block, ***internal fragmentation*** occurs if payload is smaller than block size



- Caused by
  - Overhead of maintaining heap data structures
  - Padding for alignment purposes
  - Explicit policy decisions
    (for example, returning a big block to satisfy a small request)
- Depends only on the pattern of previous requests
  - Thus, easy to measure

Challenges

- Goal: maximize throughput and peak memory utilization

- Implementation challenges:

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Knowing How Much to Free

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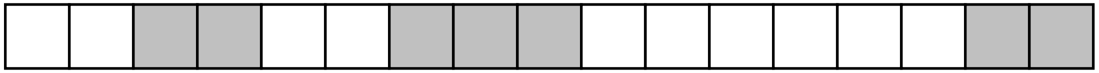
  - Keep the length of a block in the word preceding the block.
    - This word is often called the ***header field*** or ***header***
  - Requires an extra (4 byte) header for every allocated block



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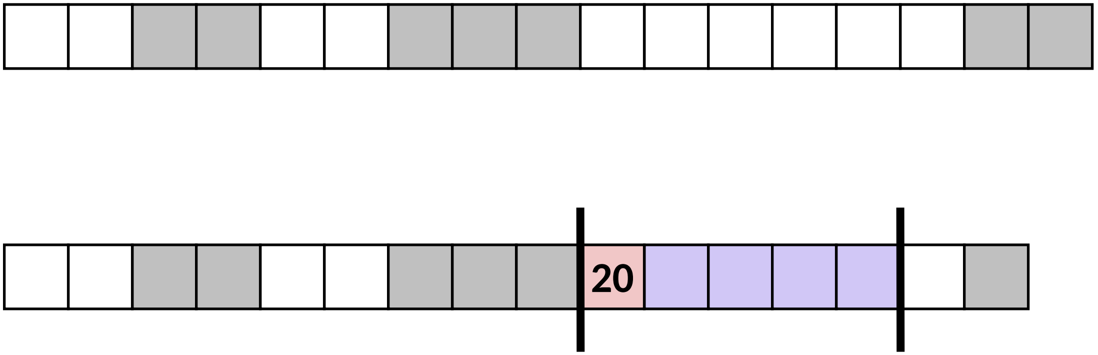

`p0 = malloc(16)`

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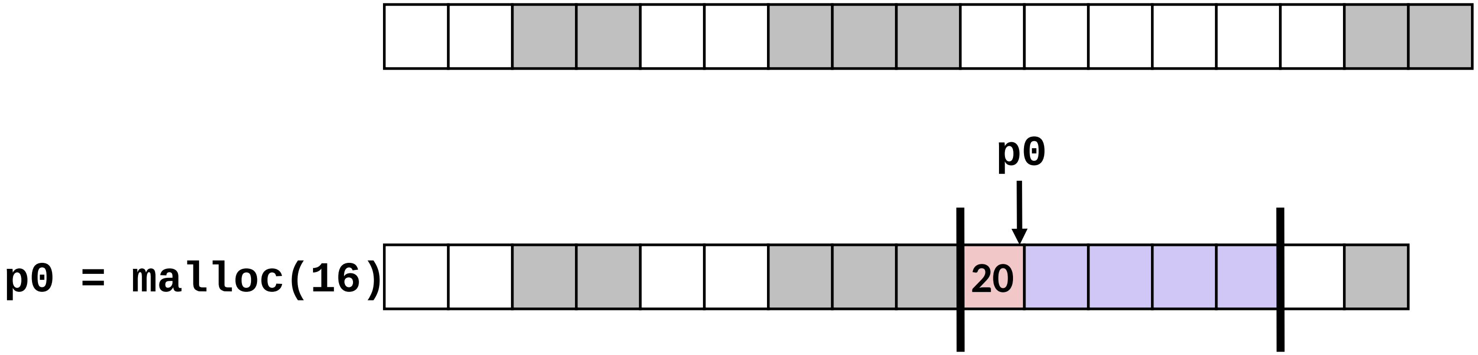

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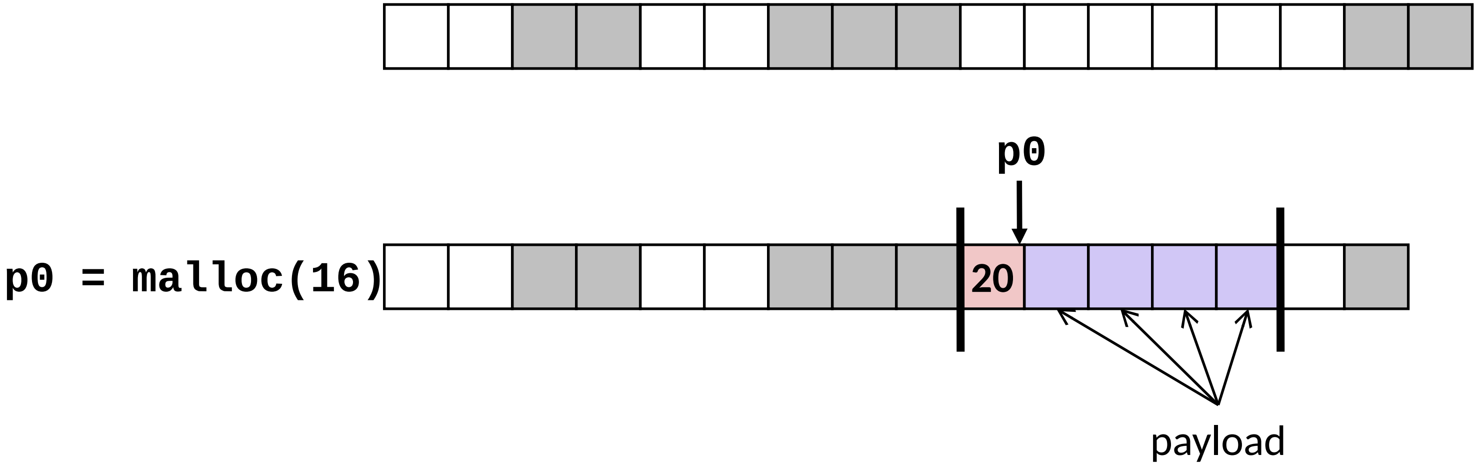

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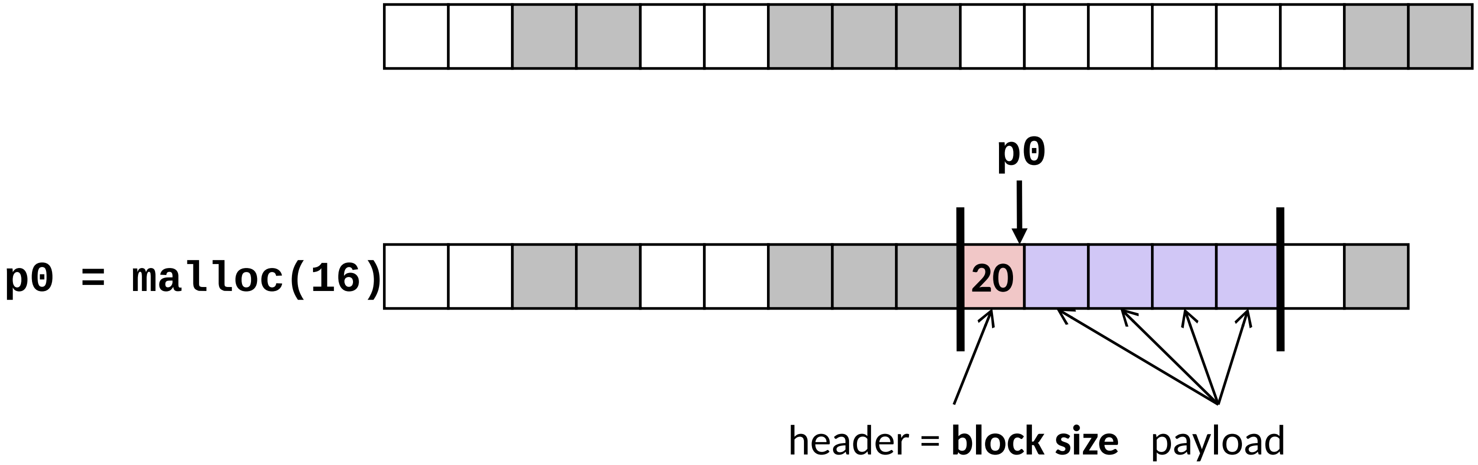

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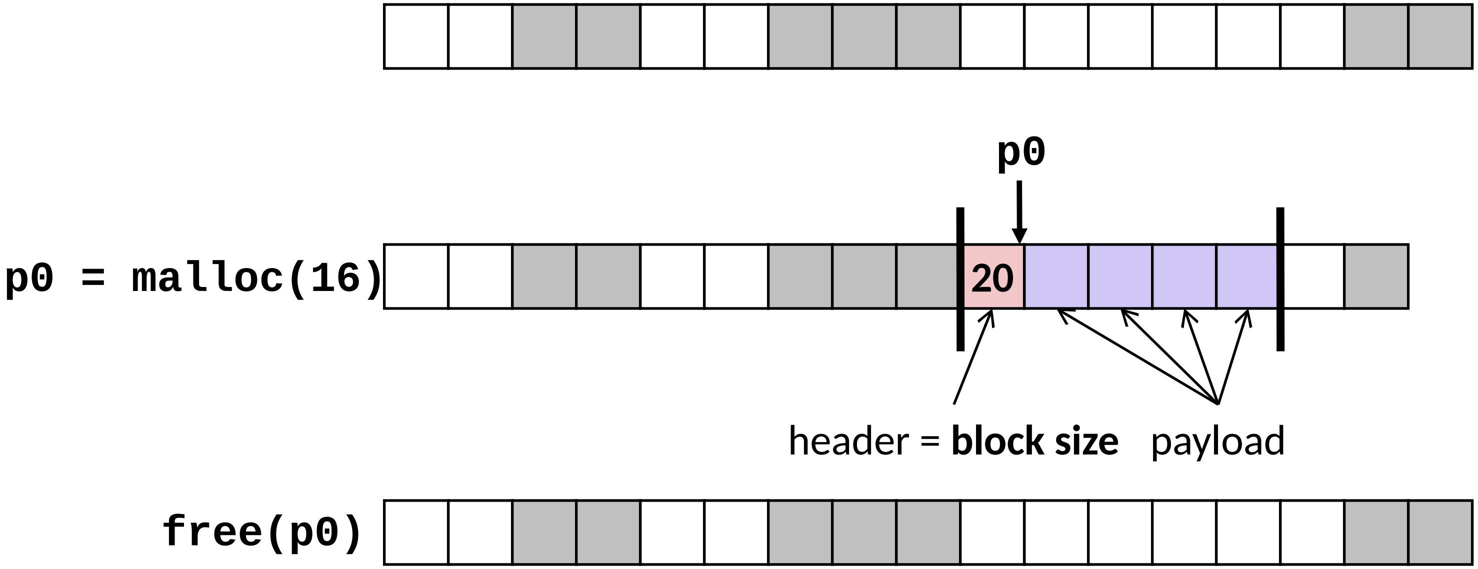

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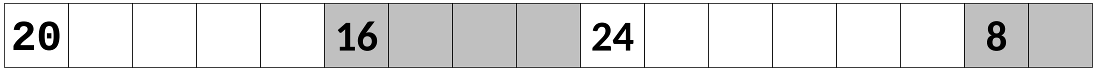
Keeping Track of Free Blocks

- Method 1: ***Implicit list*** using length—links all blocks



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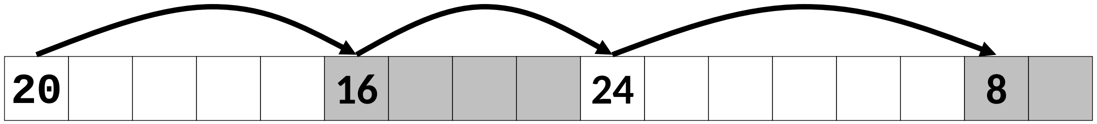

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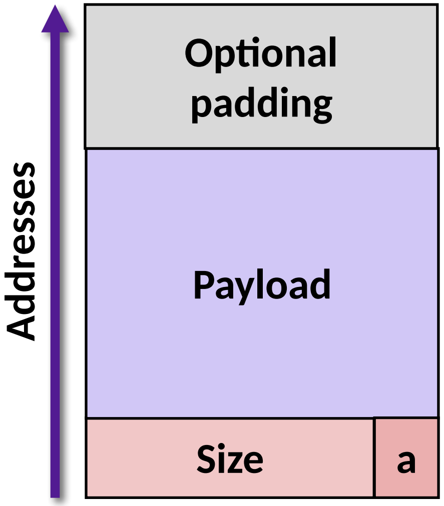
Format of allocated and free blocks



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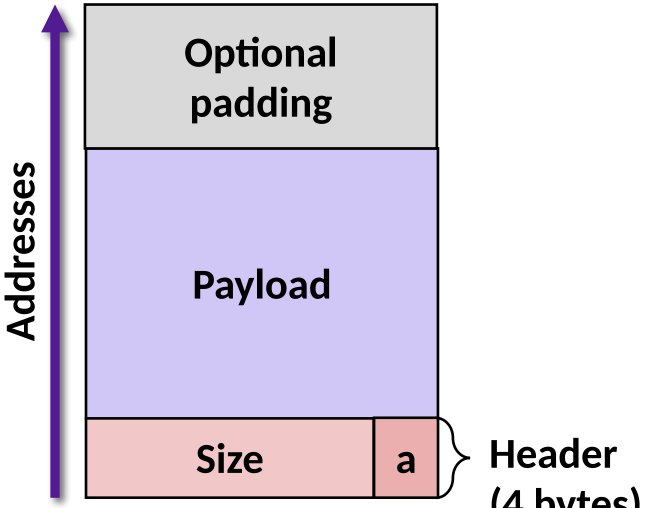

Size: total block size (incl header + padding)

a = 1: Allocated block
a = 0: Free block

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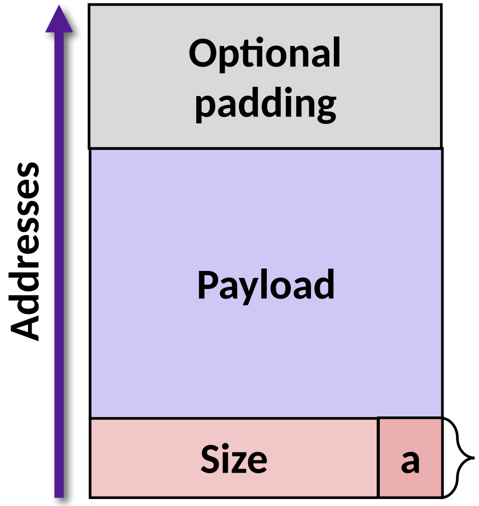

Header (4 bytes)

Payload: application data (allocated blocks only)

Size: total block size (incl header + padding)

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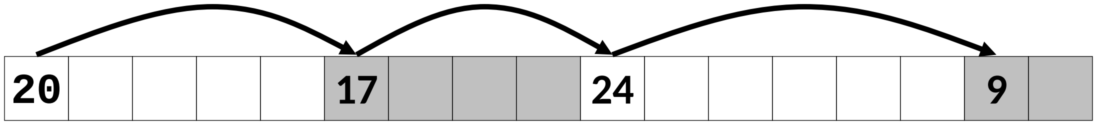

Allocated blocks: shaded
Free blocks: unshaded
Headers: labeled with size in bytes/allocated bit

Exercise: Block Headers

- Determine the block sizes and header values that would result from the following sequence of malloc requests. Assume that the allocator uses an implicit list implementation with the block format just described and maintains 8-byte alignment.

Request	Block size (decimal)	Block header (hex)
malloc(1)		
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malloc(12)		

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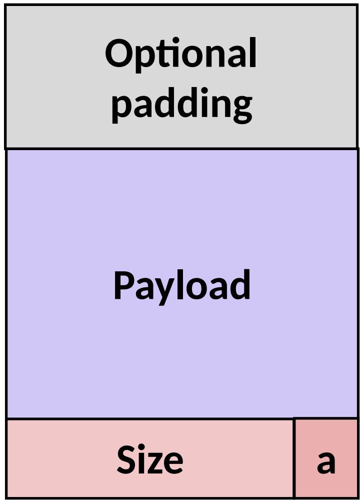

Optional padding

Payload

Size

a

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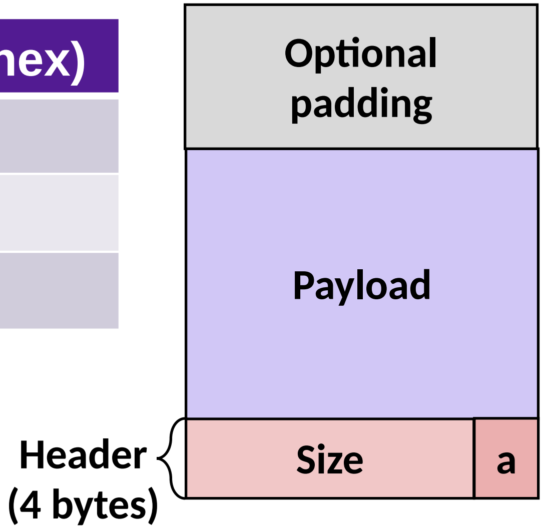

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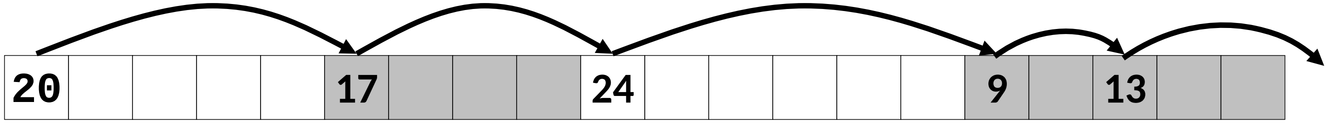

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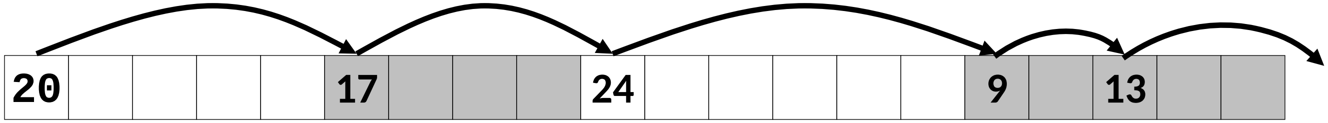

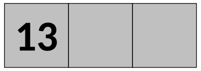

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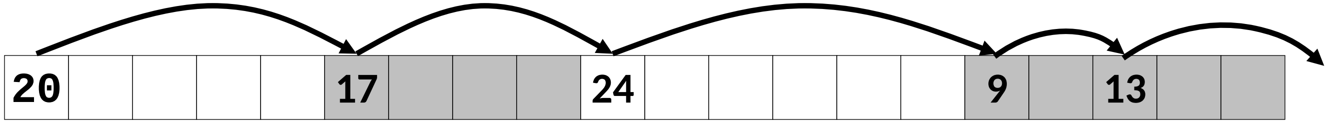

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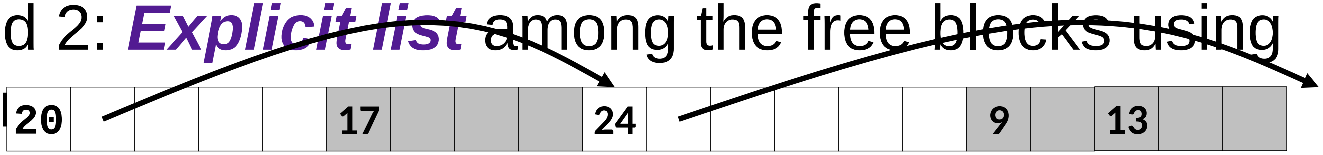

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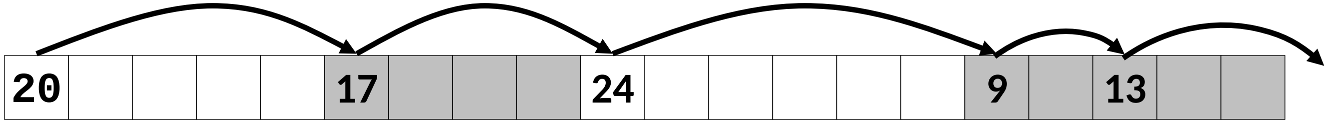

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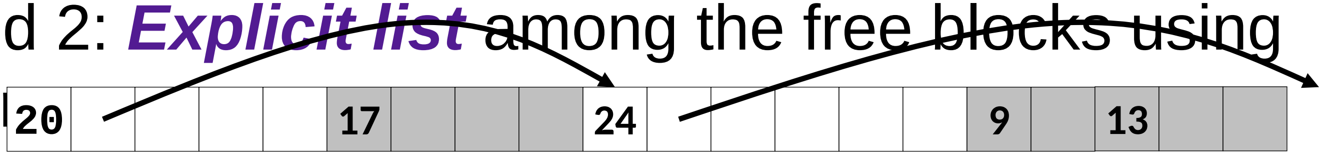

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  - Different free lists for different size classes

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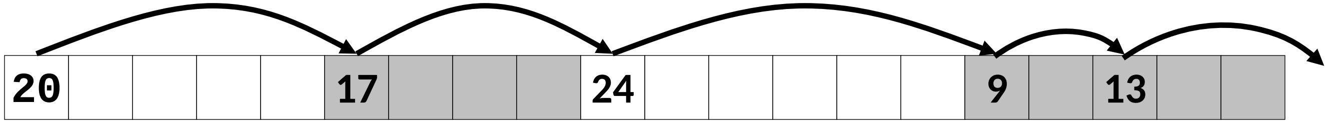
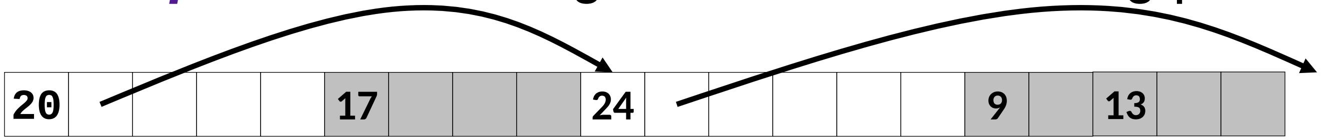


- Method 2: ***Explicit list*** among the free blocks using pointers



- Method 3: ***Segregated free list***
  - Different free lists for different size classes
- Method 4: ***Blocks sorted by size***
  - Can use a balanced tree (e.g. Red-Black tree) with pointers within each free block, and the length used as a key

Challenges

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- Implementation Challenges:
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Implicit List: Finding a Free Block

- ***First fit.*** Search list from beginning, choose first free block that fits:

```
p = start;
while ((p < end) &&     \\ not passed end
       ((*p & 1) ||     \\ already allocated
       (*p  <= len)))   \\ too small
  p = p + (*p & -2);    \\ goto next block (word addressed)
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  - Can take linear time in total number of blocks (allocated and free)
  - In practice it can cause “splinters” at beginning of list

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- ***Best fit.*** Search the list, choose the best free block: fits, with fewest bytes left over:
  - Keeps fragments small—usually improves memory utilization
  - Will typically run slower than first fit

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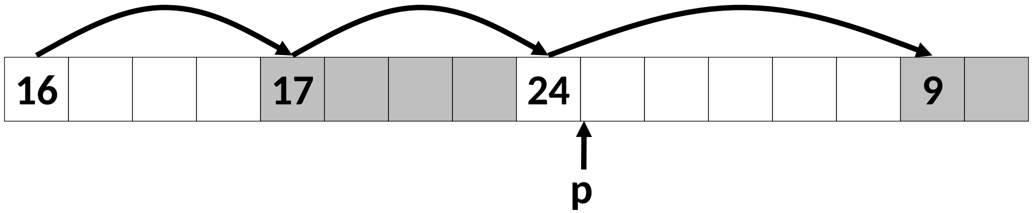
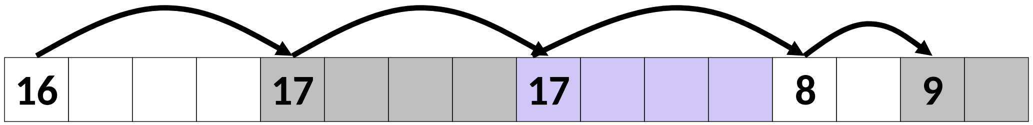
Implicit List: Allocating in Free Block

- Allocating in a free block: ***splitting***
  - Since allocated space might be smaller than free space, we might want to split the block



`addblock(p, 4)`



```
void addblock(ptr p, int len) {
  int newsize = ((len + 1) >> 1) << 1;  // round up to even
  int oldsize = *p & -2;                // mask out low bit
  *p = newsize | 1;                     // set new length
  if (newsize < oldsize)
    *(p+newsize) = oldsize - newsize;   // set length in remaining
}                                       //   part of block
```

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- Simplest implementation:
  - Need only clear the “allocated” flag

```
        void free_block(ptr p) { *p = *p & -2 }
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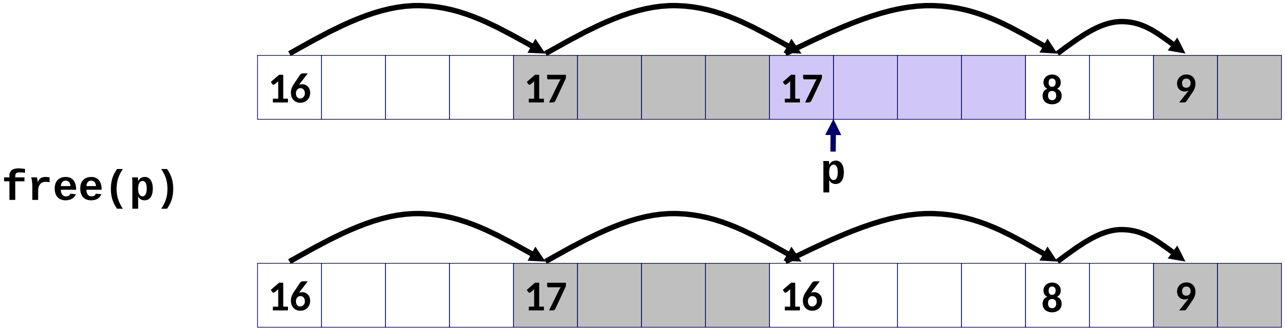

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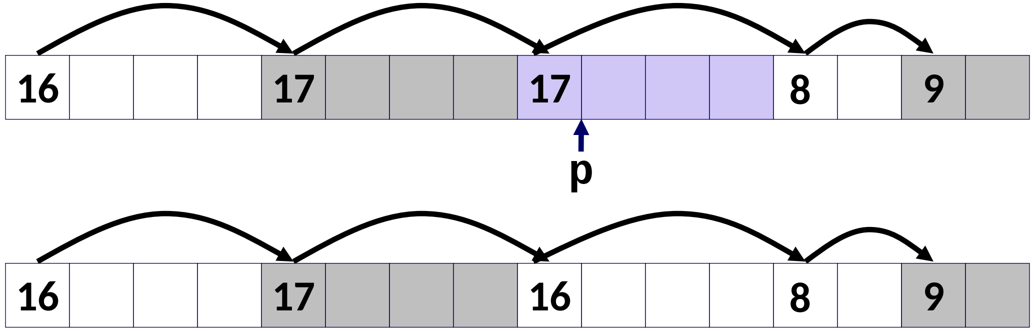

`free(p)`

`malloc(20)` *Oops!*

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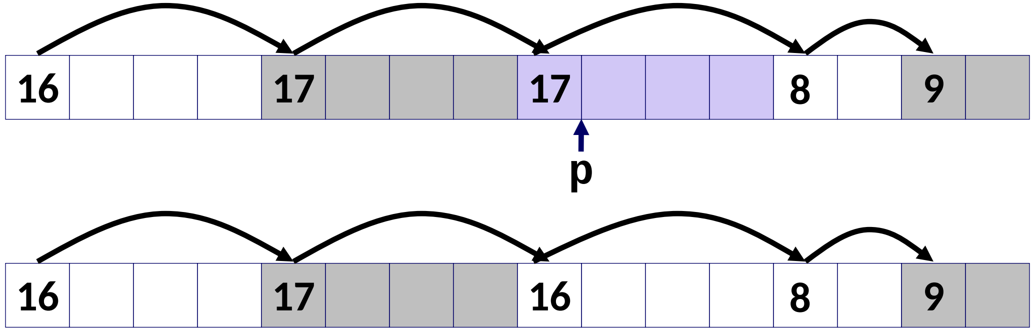


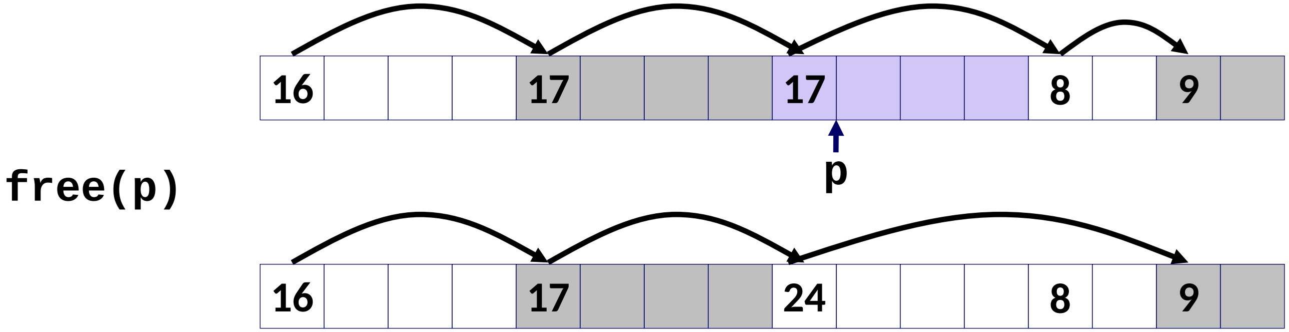
`free(p)`

`malloc(20)` *Oops!*

There is enough free space, but the allocator won’t be able to find it

Implicit List: Coalescing

- Join *(**coalesce**)* with next/previous blocks, if they are free
  - Coalescing with next block



But how do we coalesce with previous block?

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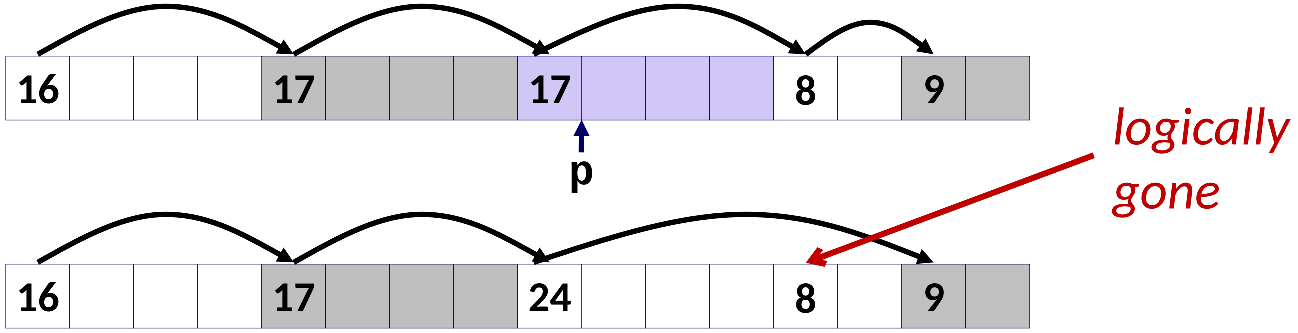
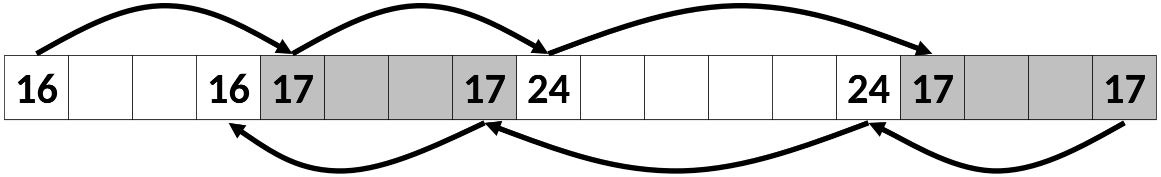


logically gone

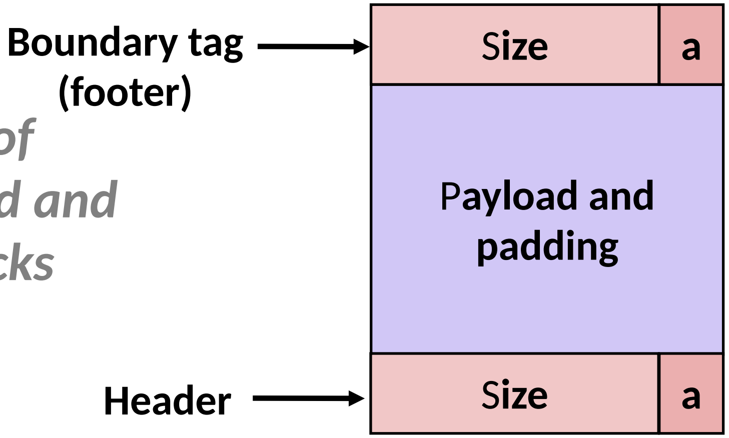
But how do we coalesce with previous block?

Implicit List: Bidirectional Coalescing

- ***Boundary tags*** [Knuth73]
  - Replicate size/allocated word at “bottom” (end) of free blocks
  - Allows us to traverse the “list” backwards, but requires extra space
  - Important and general technique!



Format of allocated and free blocks



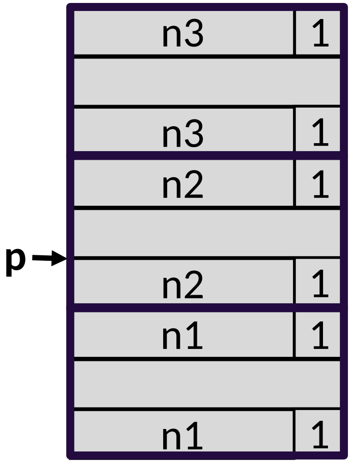
a = 1: Allocated block
a = 0: Free block

Size: Total block size

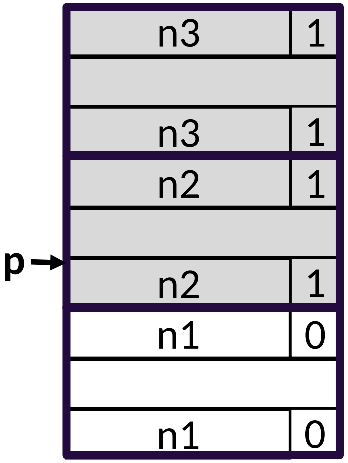
Payload: Application data (allocated blocks only)

Constant-Time Coalescing

Case 1: Prev and next block allocated



Case 2: Prev block free, next block allocated



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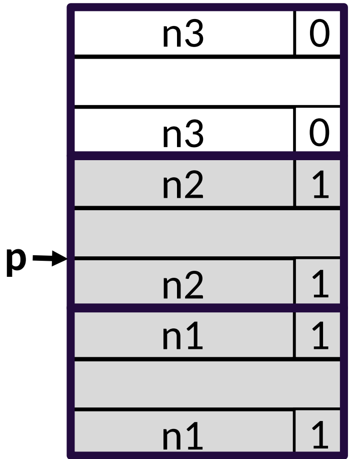
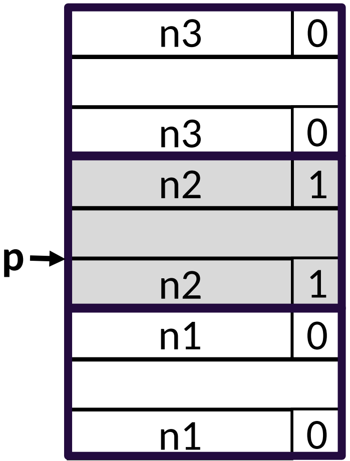
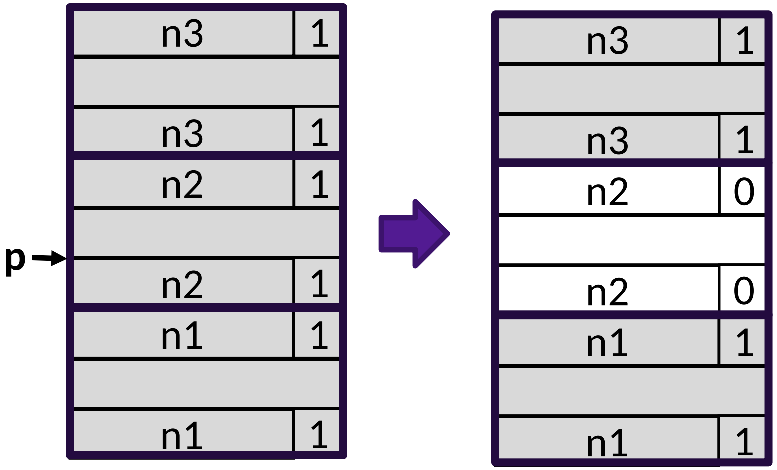


Case 4: Prev and next block free

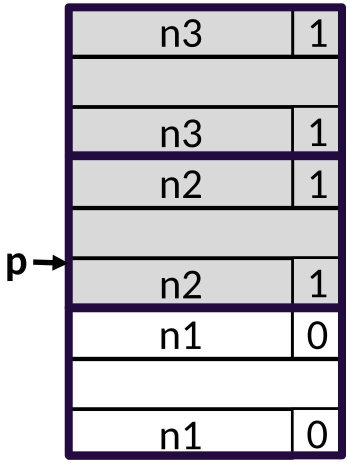


Constant-Time Coalescing

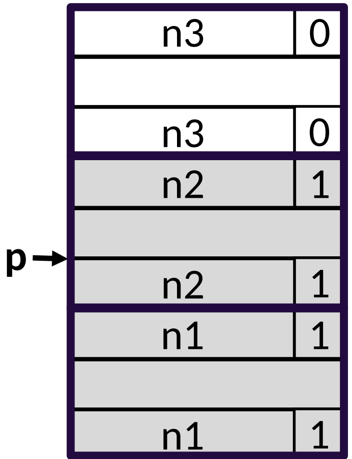
Case 1: Prev and next block allocated



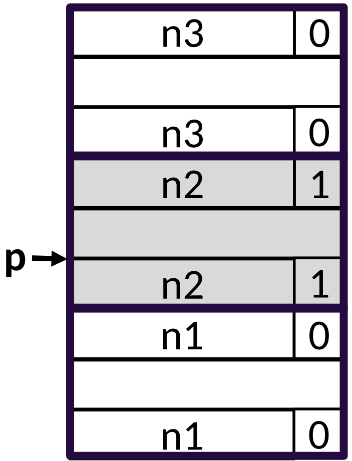
Case 2: Prev block free, next block allocated



Case 2: Prev block allocated, next block free



Case 4: Prev and next block free



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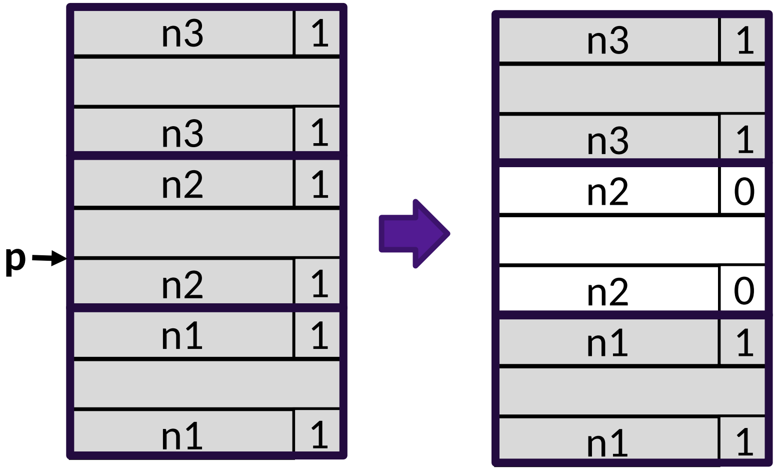

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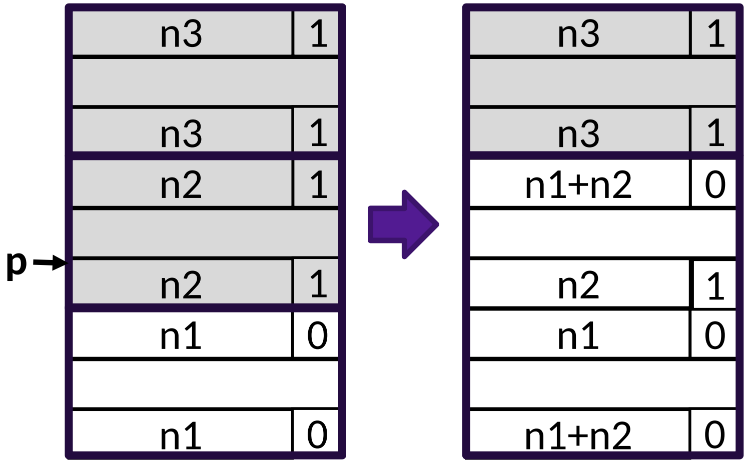

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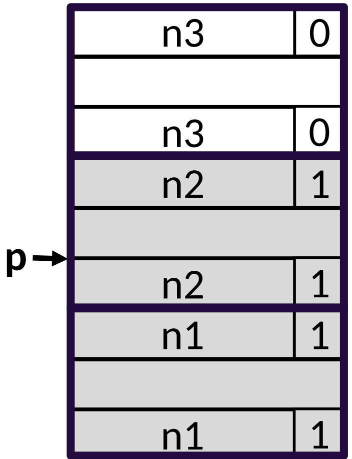

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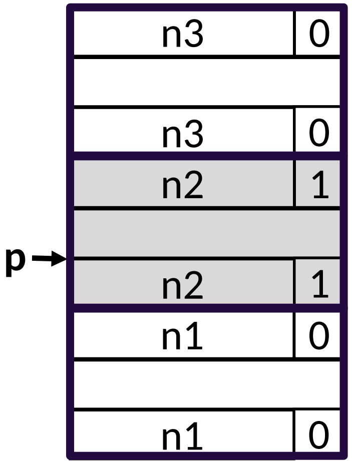

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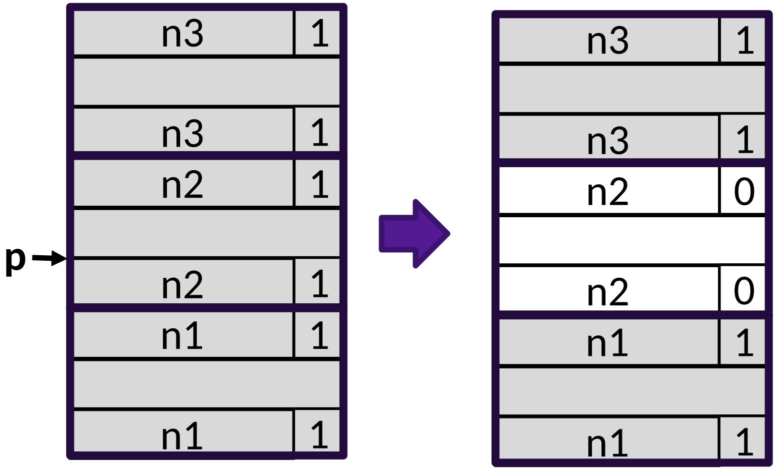

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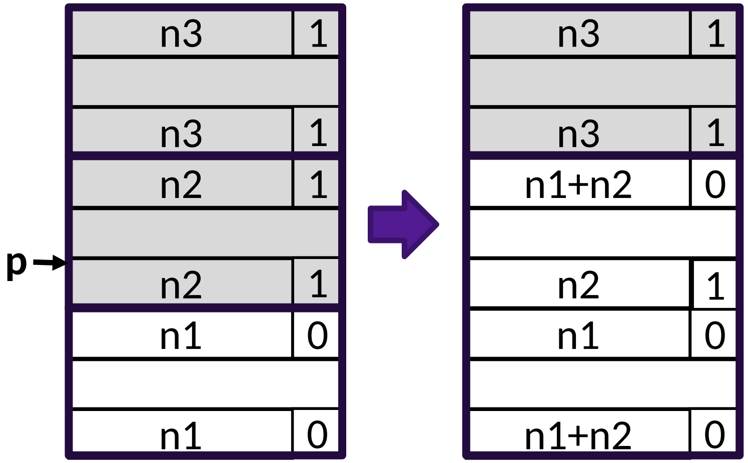

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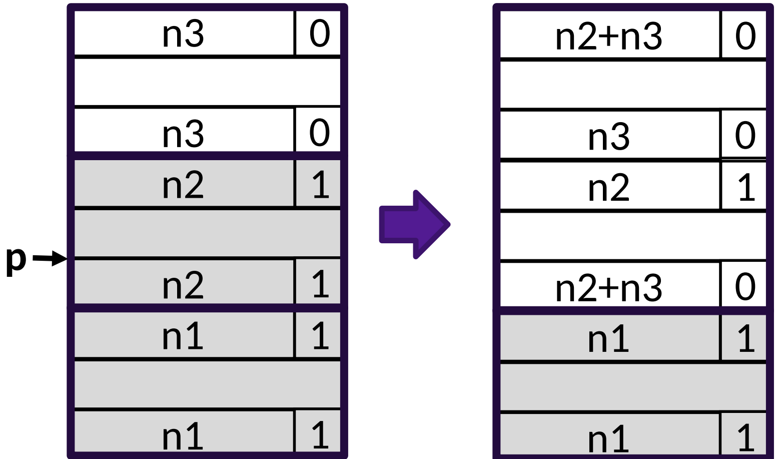

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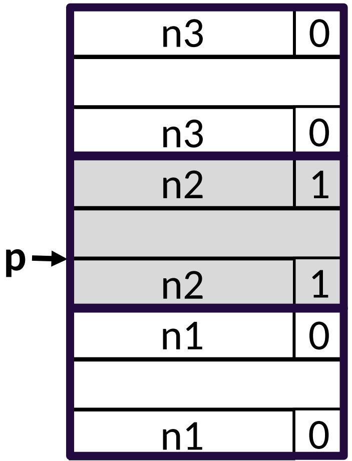

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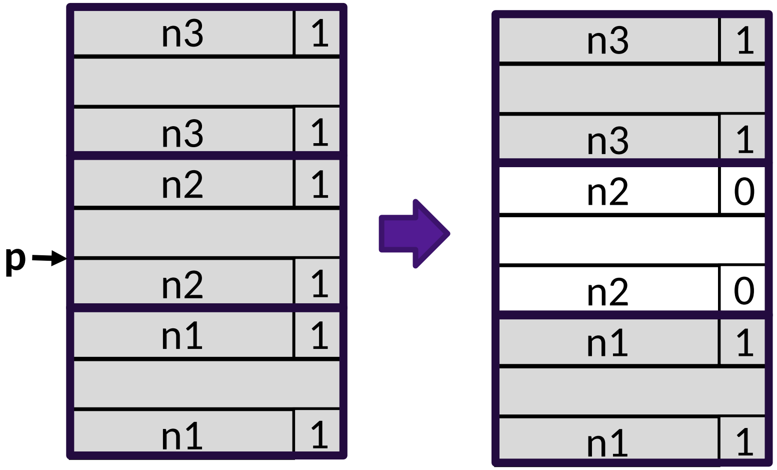

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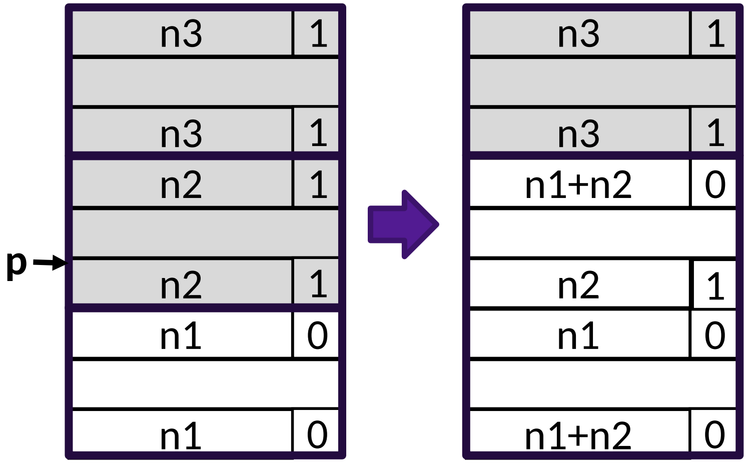

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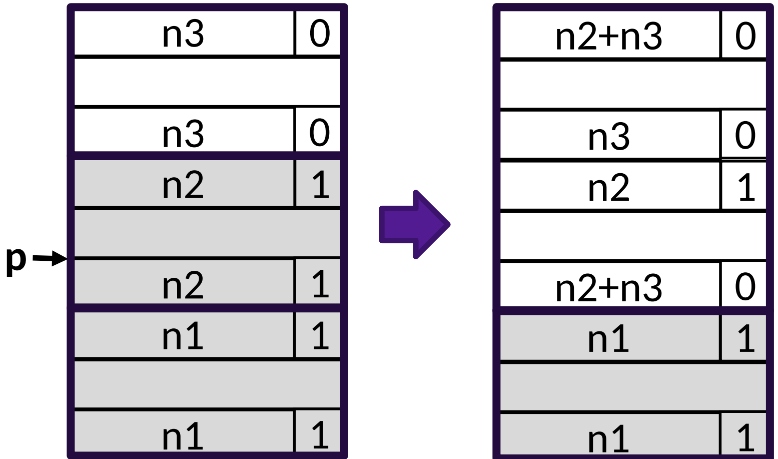

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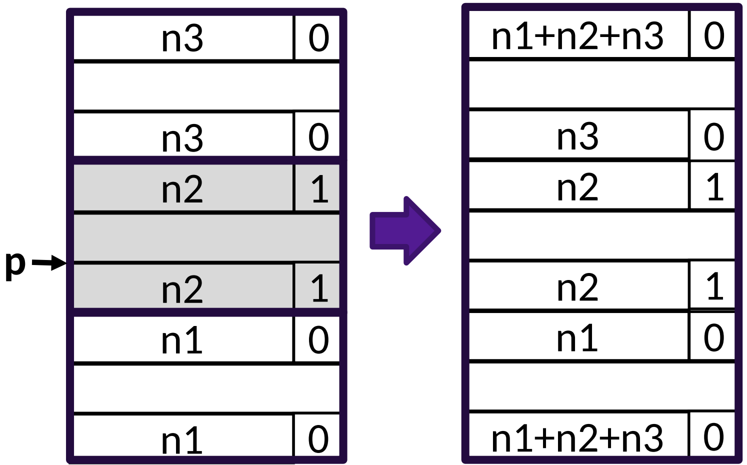
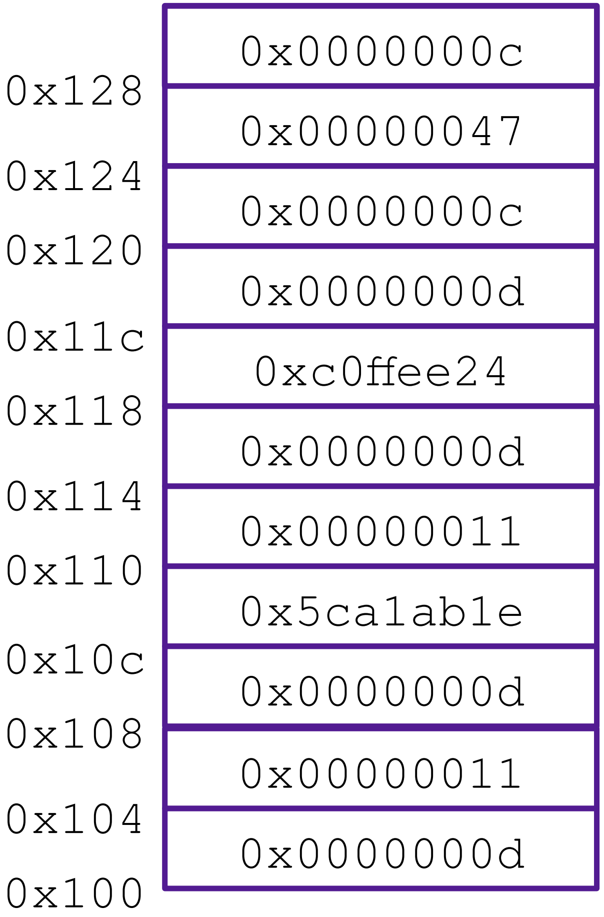


Exercise: Coalescing

- Assume the current heap is shown below. What would be the state of the heap after the function `free(0x118)` is executed?



	0x0000000c
0x128	0x00000047
0x124	0x0000000c
0x120	0x0000000d
0x11c	0xc0ffee24
0x118	0x0000000d
0x114	0x00000011
0x110	0x5ca1ab1e
0x10c	0x0000000d
0x108	0x00000011
0x104	0x0000000d
0x100	

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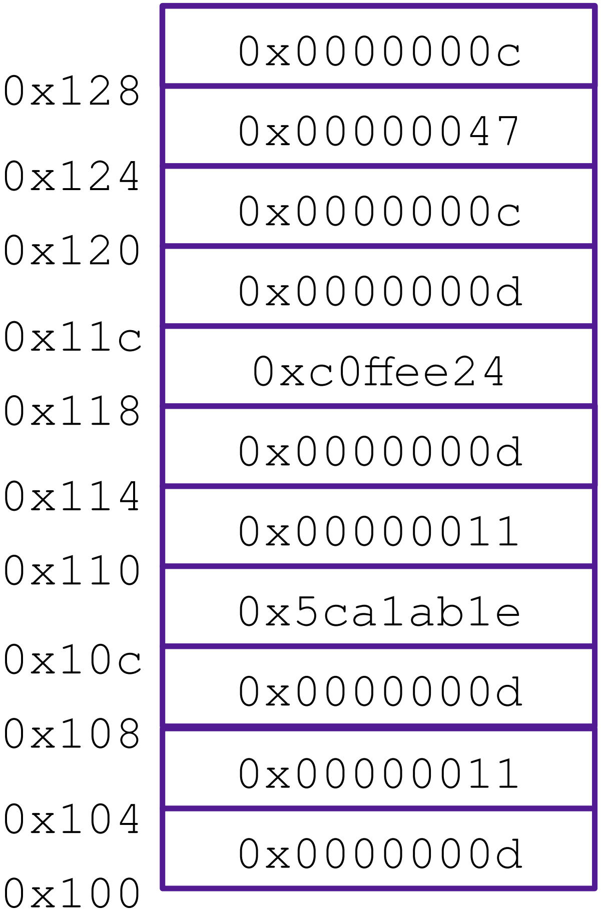

	0x0000000c
0x128	0x00000047
0x124	0x0000000c
0x120	0x0000000d
0x11c	0xc0ffee24
0x118	0x0000000d
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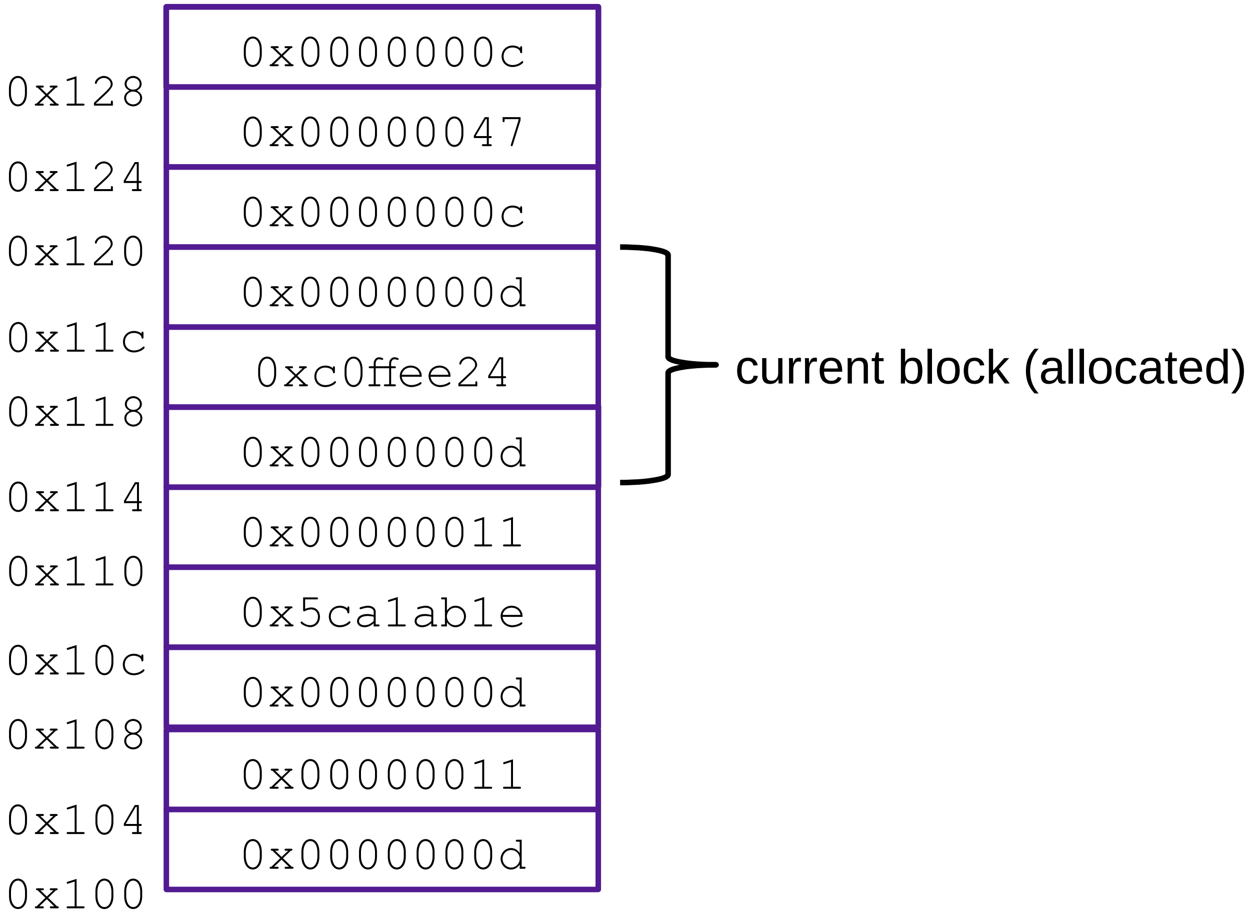

0x128	0x0000000c
0x124	0x00000047
0x120	0x0000000c
0x11c	0x0000000d
0x118	0xc0ffee24
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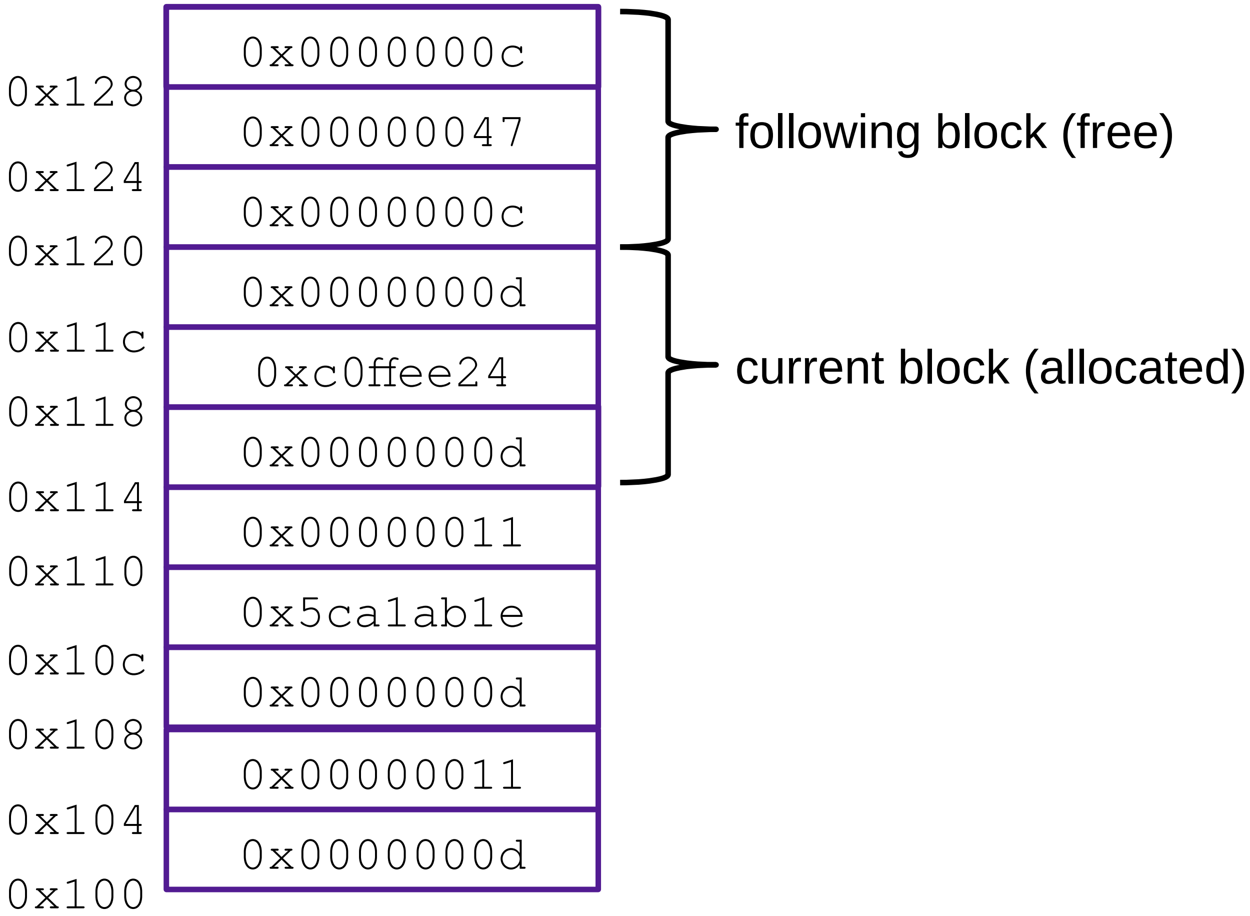

0x0000000c

0x128

0x00000047

0x124

0x0000000c

0x120

0x0000000d

0x11c

0xc0ffee24

0x118

0x0000000d

0x114

0x00000011

0x110

0x5ca1ab1e

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0x00000011

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current block (allocated)

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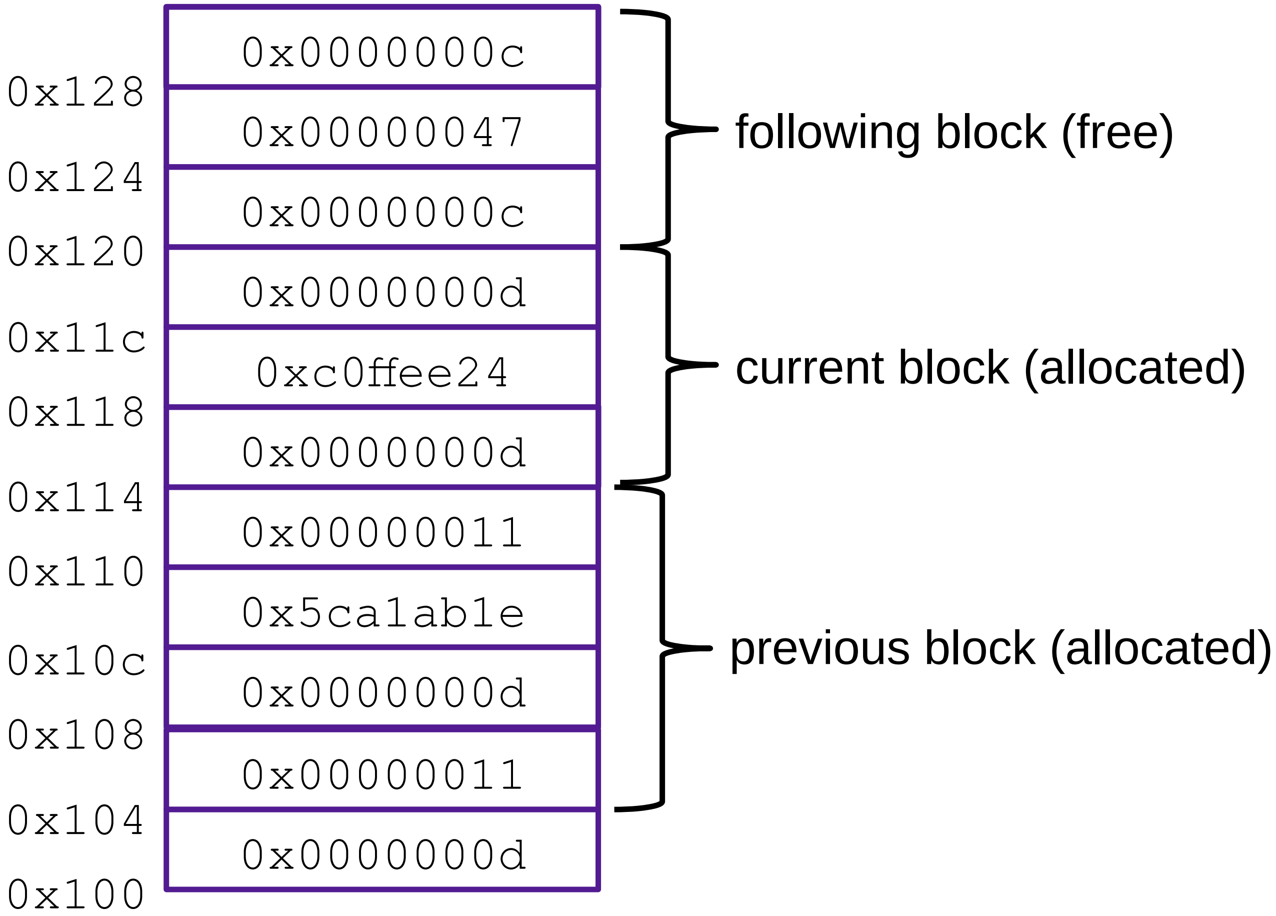

```
         0x0000000c
0x128
         0x00000047
0x124
         0x0000000c
0x120
         0x0000000d
0x11c
         0xc0ffee24
0x118
         0x0000000d
0x114
         0x00000011
0x110
         0x5ca1ab1e
0x10c
         0x0000000d
0x108
         0x00000011
0x104
         0x0000000d
0x100
```

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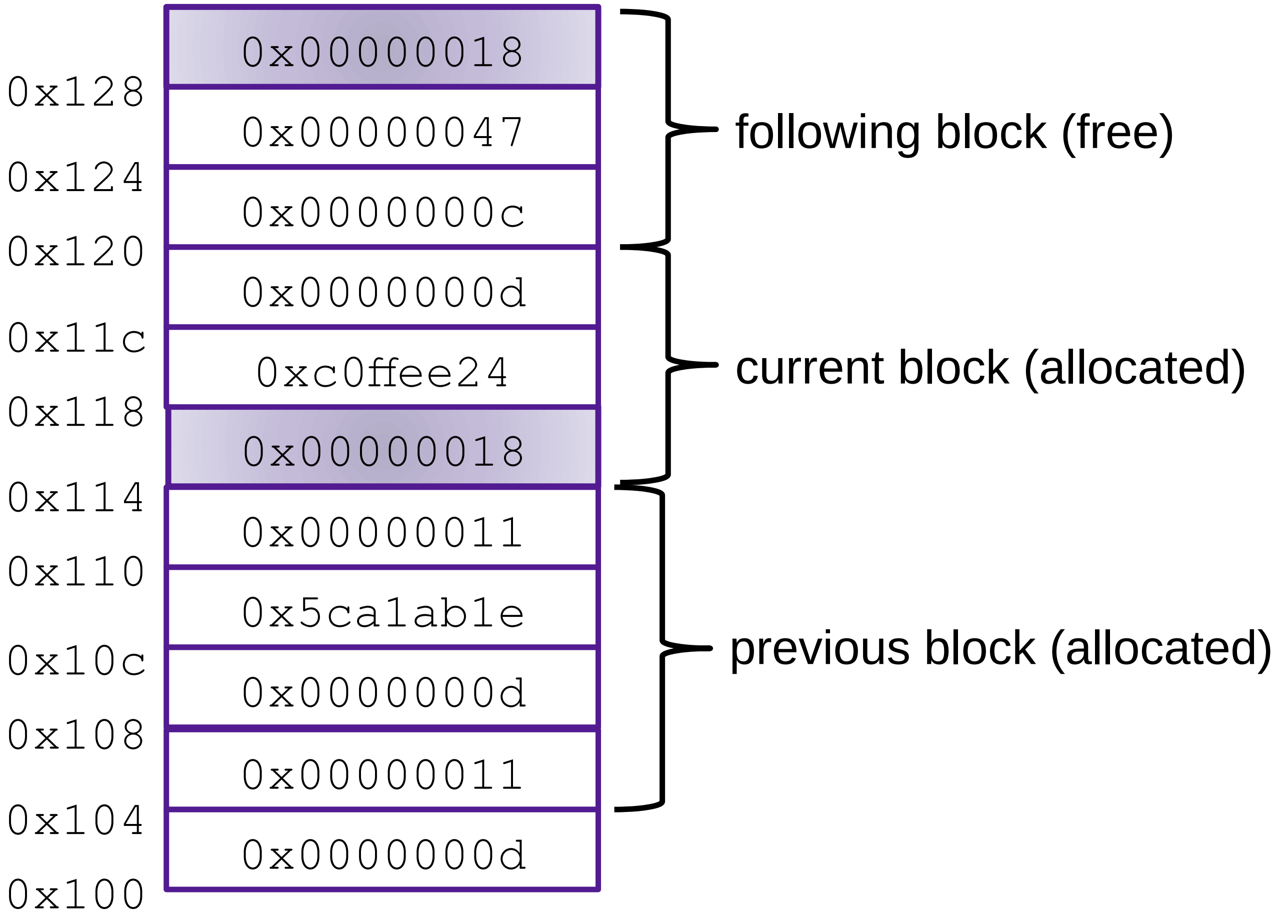

0x00000018
0x00000047
0x0000000c
0x0000000d
0xc0ffee24
0x00000018
0x00000011
0x5ca1ab1e
0x0000000d
0x00000011
0x0000000d

Summary of Key Allocator Policies

- Free-block storage policy:
  - Implicit lists, with boundary tags (nice and simple)
  - Explicit lists, exclude free blocks (faster, but more overhead)
  - Segregated lists (different lists for different sized blocks)
  - Fancy data structures (red-black trees, for example)

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- Coalescing policy:
  - No coalescing (bad choice)
  - ***Immediate coalescing:*** coalesce each time **`free`** is called
  - ***Deferred coalescing:*** coalesce on allocate or after fixed time

Memory-Related Perils and Pitfalls

- Dereferencing bad pointers
- Reading uninitialized memory
- Overreading memory
- Overwriting memory
- Referencing freed blocks
- Freeing blocks multiple times
- Failing to free blocks

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• Failing to free blocks	(Performance)

Memory Bugs Persist…

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