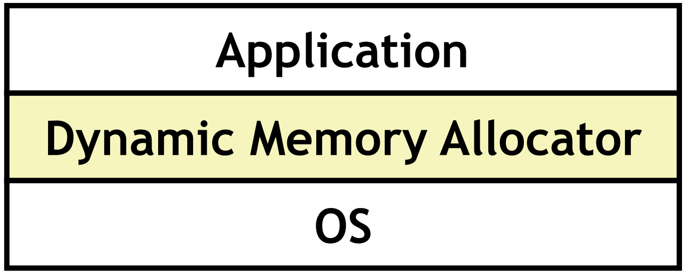
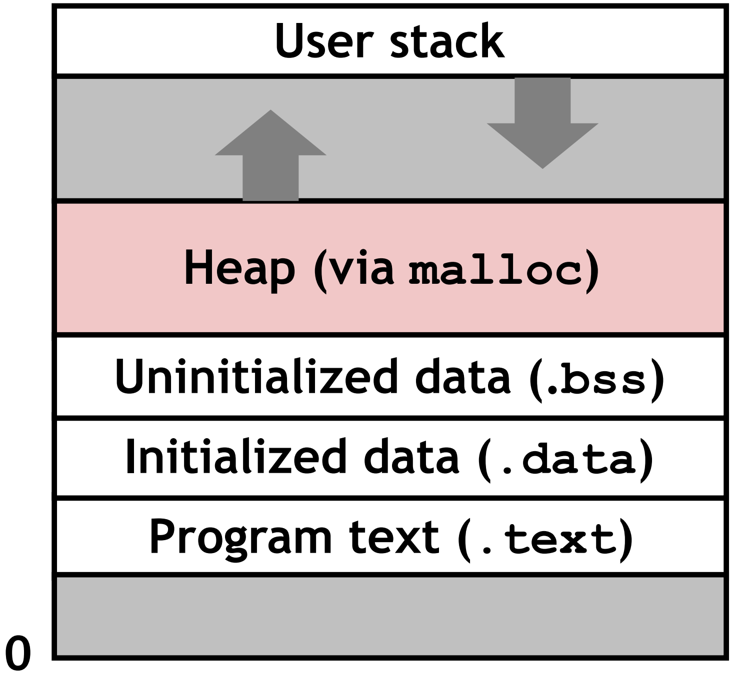
Dynamic Memory Allocation

Dynamic Memory Allocators

- **Programmers use dynamic memory allocators to acquire virtual memory at run time.**
  - For data structures whose size is only known at runtime.

- **Dynamic memory allocators manage an area of process virtual memory known as the heap.**





+ Types of Dynamic Memory Allocators

- **Allocator maintains heap as collection of variable sized *blocks*, which are either *allocated* or *free***

- **Types of allocators**
  - *Explicit* allocator: application allocates and frees space
    - E.g., `malloc` and `free` in C
  - *Implicit* allocator: application allocates, but does not free space
    - E.g. garbage collection in Java, ML, and Lisp

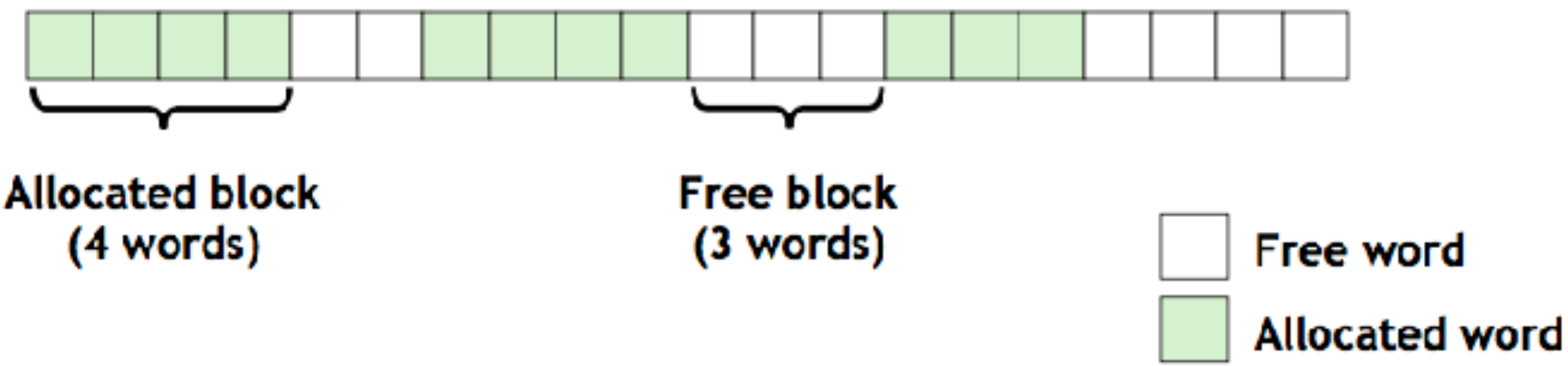
- **Will discuss simple explicit memory allocation today**

+ The `malloc` Package *(review)*

- **`#include <stdlib.h>`**
- **`void* malloc(int size)`**
  - Successful:
    - Returns a pointer to a memory block of at least size bytes
    - If size == 0, returns `NULL`
  - Unsuccessful: returns `NULL` (0)
- **`void free(void* p)`**
  - Releases the block pointed at by `p` to pool of available memory
  - `p` must come from a previous call to `malloc` or `calloc`
- **Other functions**
  - `calloc`: Version of `malloc` that initializes allocated block to zero.
  - `realloc`: Changes the size of a previously allocated block.
  - `sbrk`: Used internally by allocators to grow or shrink the heap

Assumptions Made in This Lecture

- **Memory is word addressed.**
- **Words are int-sized.**



+ Allocation Example

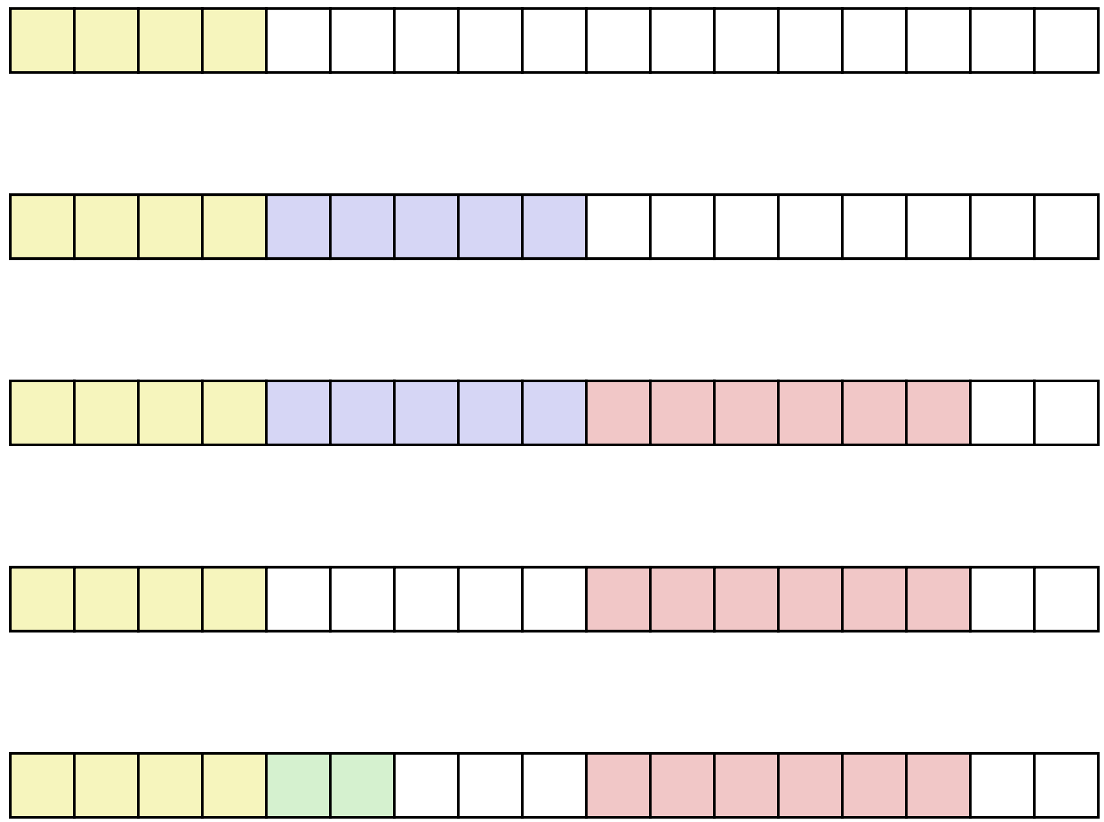
`p1 = malloc(4)`

`p2 = malloc(5)`

`p3 = malloc(6)`

`free(p2)`

`p4 = malloc(2)`



(Arguments to malloc are in words for simplification, i.e. malloc(4) allocates 4 words.)

Constraints

- **Applications**
  - Can issue arbitrary sequence of `malloc` and `free` requests
  - `free` request must be to a `malloc`'d block
- **Allocators**
  - Can't control number or size of allocated blocks
  - Must respond immediately to `malloc` requests (can't reorder or buffer requests)
  - Must allocate blocks from *free* memory
  - Can manipulate and modify only *free* memory
  - Can't move the allocated blocks once they are `malloc'd`

+ Performance Goal: Throughput

- **Given some sequence of `malloc` and `free` requests:**
  - R_0, R_1, ..., R_k, ... , R_{n-1}
- **Goals: maximize throughput and peak memory utilization**
  - These goals are often conflicting
- **Throughput:**
  - Number of completed requests per unit time
  - Example:
    - 5,000 `malloc` calls and 5,000 `free` calls in 10 seconds
    - Throughput is 1,000 operations/second

+ Performance Goal: Peak Memory Utilization

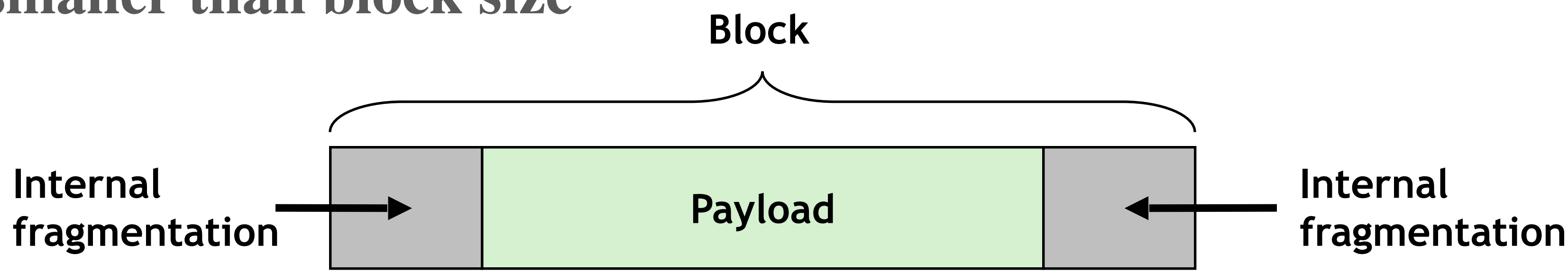
- **Given some sequence of `malloc` and `free` requests:**
  - R_0, R_1, ..., R_k, ... , R_{n-1}
- **Definition:** ***Aggregate payload*** **P_k**
  - `malloc(p)` results in a block with a payload of `p` bytes
  - After request R_k has completed, the aggregate payload P_k is the sum of currently allocated payloads
- **Definition:** ***Current heap size*** **H_k**
  - Assume H_k is monotonically nondecreasing
    - i.e., heap grows when allocator uses `sbrk`
- **Definition:** ***Peak memory utilization*** **(after `k` requests)**
  - $U_k = P_k / H_k$

+ Fragmentation

- **Poor memory utilization caused by fragmentation**
  - internal fragmentation
  - external fragmentation

Internal Fragmentation

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



- **Caused by**
  - Metadata for maintaining heap data structure
  - Padding for alignment purposes
  - Explicit policy decisions
    (e.g., to return a big block to satisfy a small request)

External Fragmentation

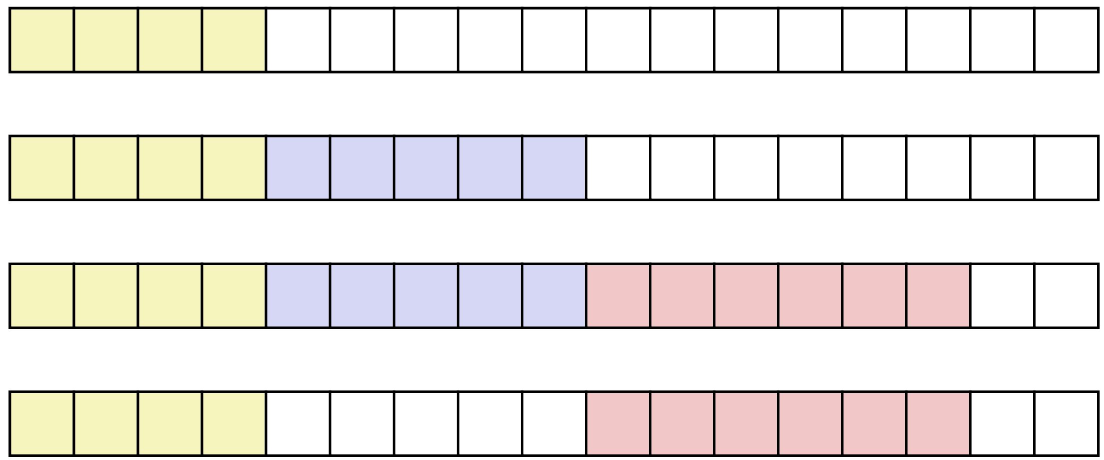
- **Occurs when there is enough aggregate heap memory, but no single free block is large enough**

`p1 = malloc(4)`

`p2 = malloc(5)`

`p3 = malloc(6)`

`free(p2)`



`p4 = malloc(6)`

Oops! (what would happen now?)

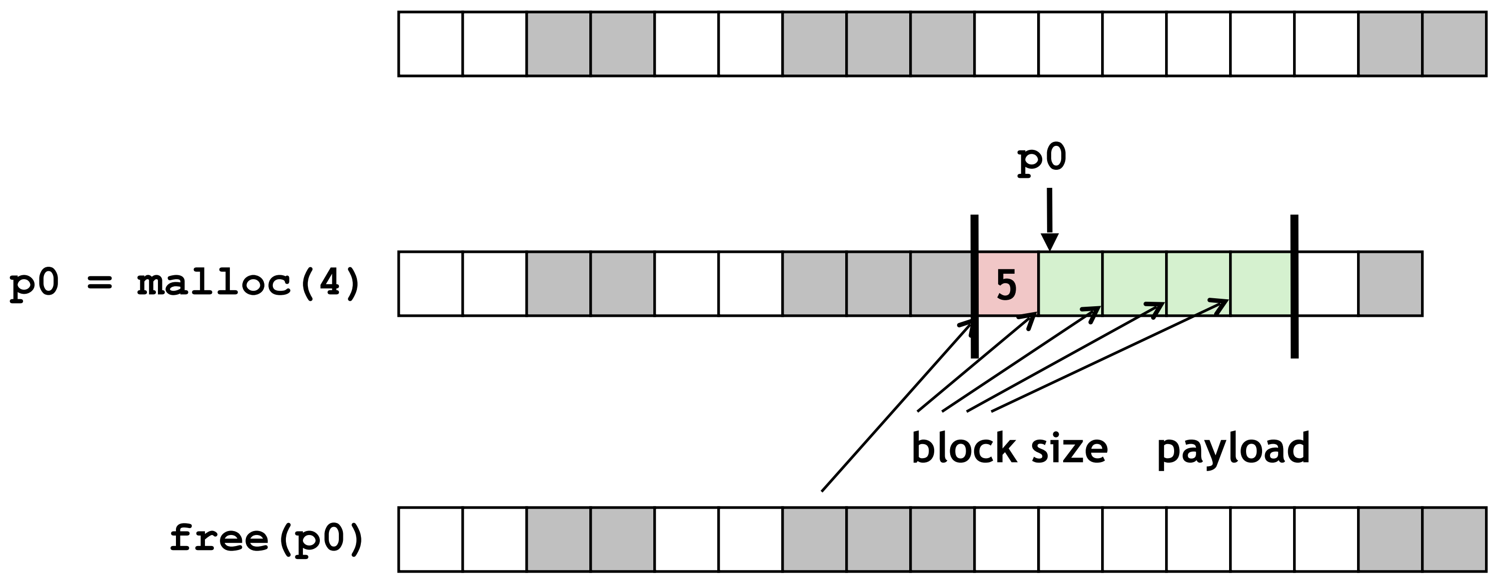
- **Depends on the pattern of future requests**
  - Thus, harder to counteract or measure

+ Implementation Issues

- Open Questions
  - How do we know how much memory to free given just a pointer?
  - How do we keep track of the free blocks?
  - What do we do with the extra space when allocating a structure that is smaller than the free block it is placed in?
  - How do we pick a block to use for allocation -- many might fit?
  - How do we deallocate a freed block?
- Answers to some of these depend on allocator implementation.

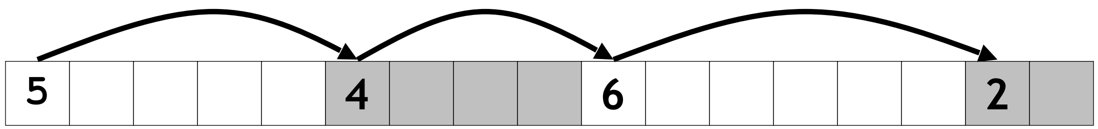
+ Knowing How Much to Free

- **Standard method**
  - 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 word for every allocated block

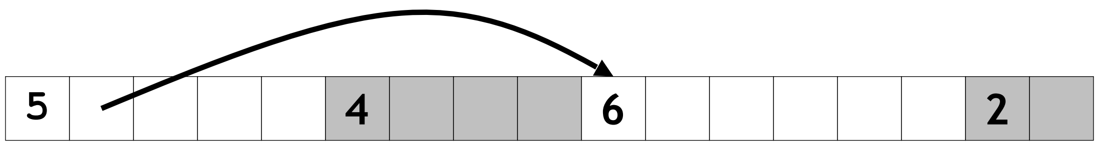


Keeping Track of Free Blocks

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



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



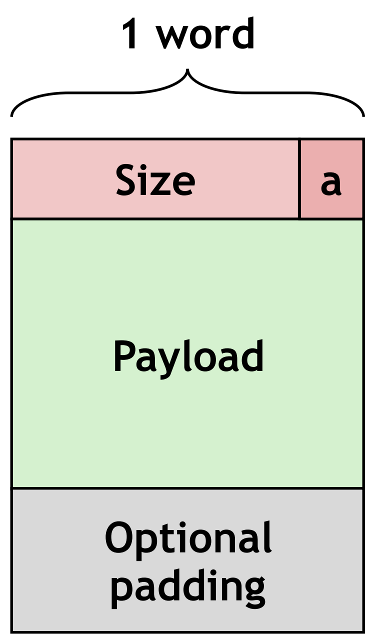
- **Method 3: Segregated free list**
  - Different free lists for different size classes

Implicit Free Lists

+ Method 1: Implicit List

- **For each block we need both size and allocation status**
  - Could store this information in two words: wasteful!
- **Standard trick**
  - If blocks are word-aligned, some low-order address bits are always 0
  - Instead of storing an always-0 bit, use it as a allocated/free flag
  - When reading size word, must mask out this bit

Format of allocated and free blocks

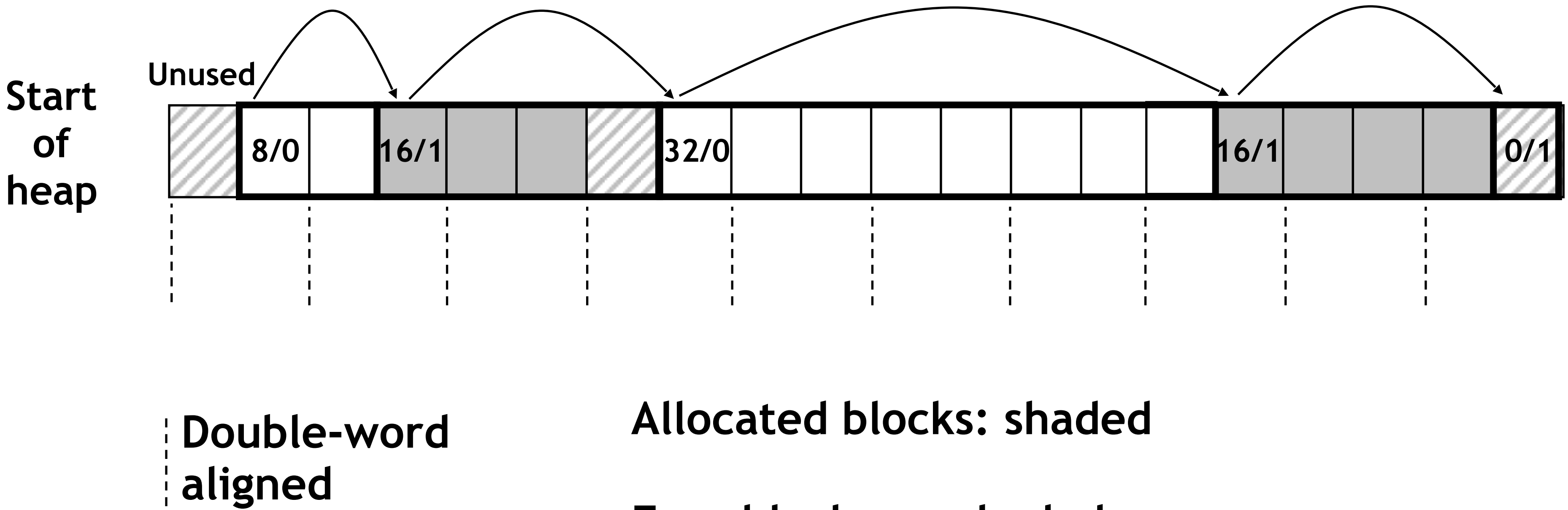


a = 1: Allocated block
a = 0: Free block

Size: block size

Payload: application data
(allocated blocks only)

Detailed Implicit Free List Example



Allocated blocks: shaded

Free blocks: unshaded

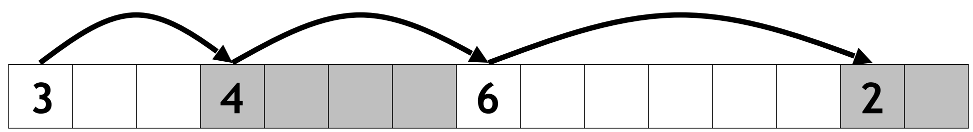
Headers: labeled with size in bytes/allocated bit

+ Implicit List: Finding a Free Block

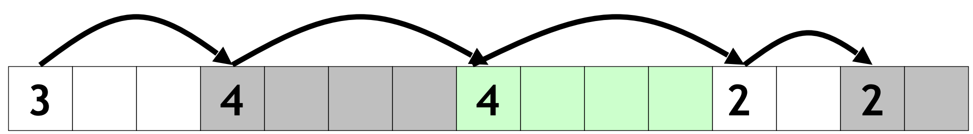
- **First fit:**
  - Search list from beginning, choose first free block that fits
  - Can take linear time in total number of blocks (allocated and free)
  - In practice it can cause "splinters" at beginning of list
- **Next fit:**
  - Like first fit, but search list starting where previous search finished
  - Should often be faster than first fit: avoids re-scanning unhelpful blocks
  - Some research suggests that fragmentation is worse
- **Best fit:**
  - Search the list, choose the best free block: i.e. fewest bytes left over
  - Keeps fragments small—usually improves memory utilization
  - Will typically run slower than first fit

Implicit List: Allocating in Free Block

- **Allocating in a free block: splitting**
  - Allocated space might be smaller than free space….



  - Perhaps split block

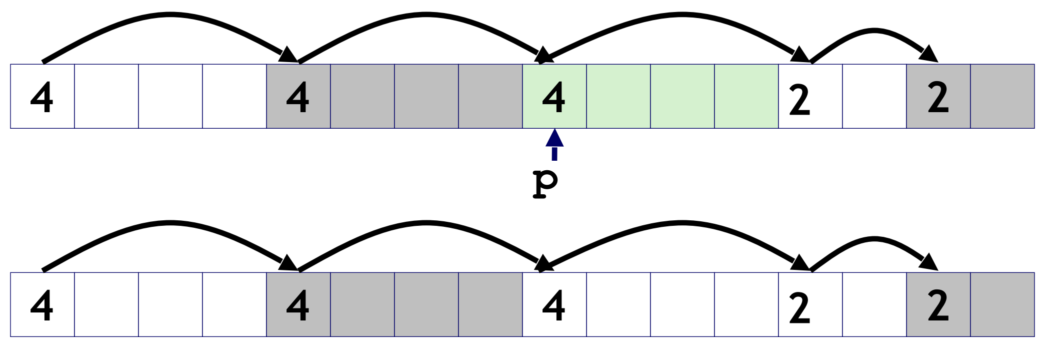


  - Reduces internal fragmentation

+ Implicit List: Freeing a Block

- **Simplest implementation:**
  - Need only clear the "allocated" flag
  - But can lead to "false fragmentation"

`free(p)`

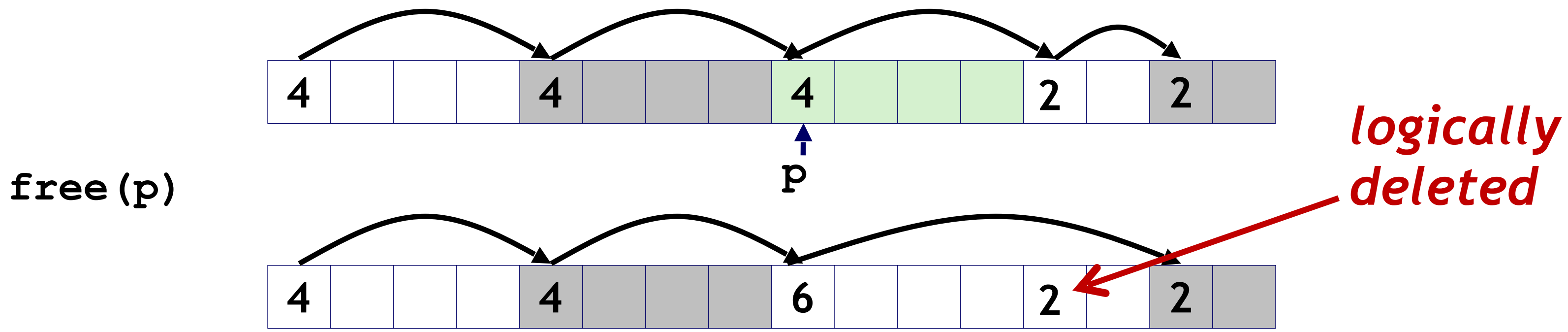


`malloc(5)`

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

+ Implicit List: Coalescing

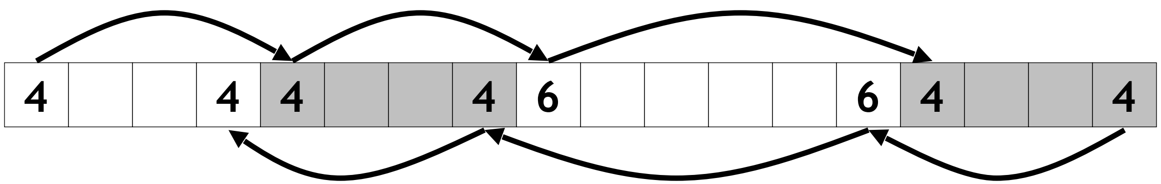
- **Join (coalesce) with next/previous blocks, if they are free**
  - Coalescing with next block



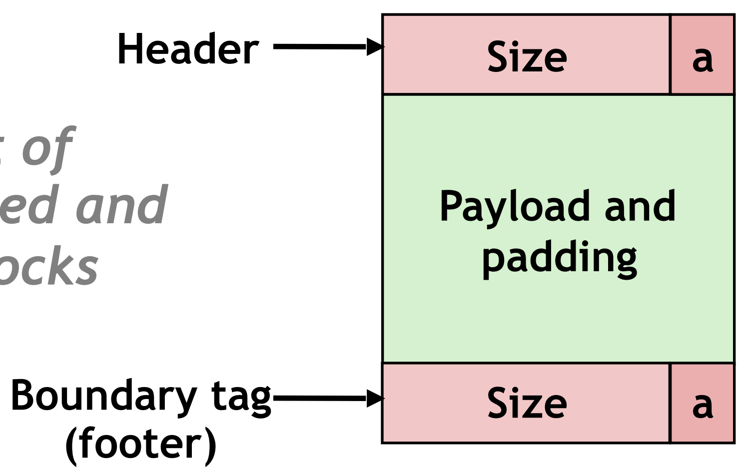
  - But how do we coalesce with previous block?

Implicit List: Boundary Tags (footers)

- **Boundary tags [Knuth '73]** **https://en.wikipedia.org/wiki/Donald_Knuth**
  - Replicate size/allocated word at "bottom" (end) of free blocks
  - Allows us to traverse the "list" backwards, but requires extra space



Format of allocated and free blocks

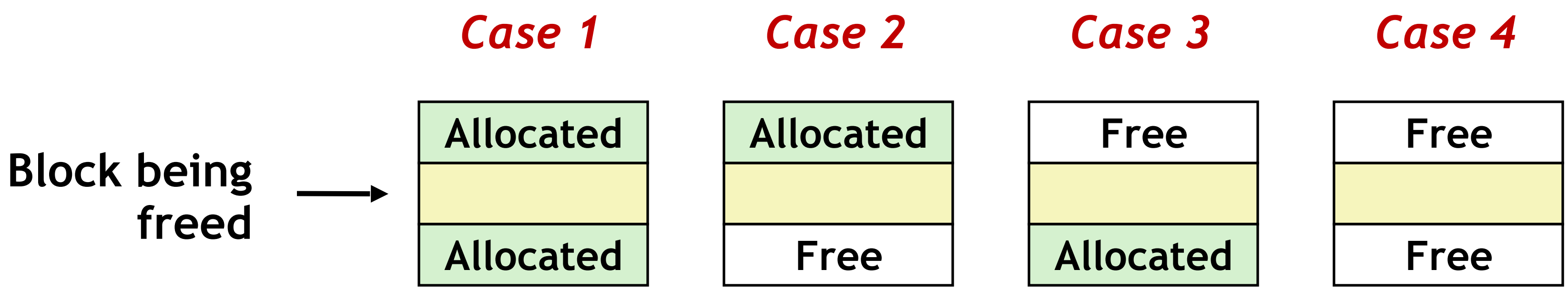


a = 1: Allocated block
a = 0: Free block

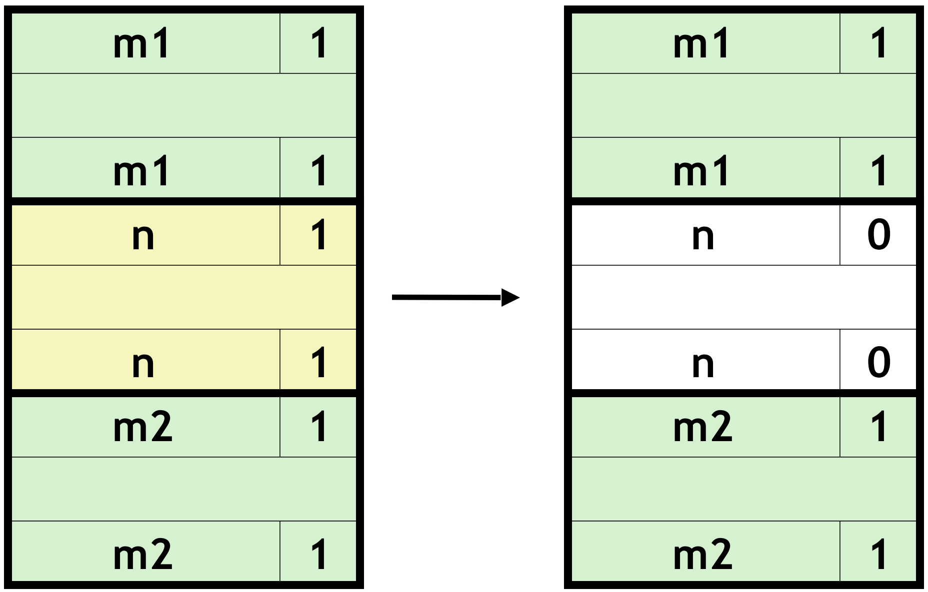
Size: Total block size

Payload: Application data (allocated blocks only)

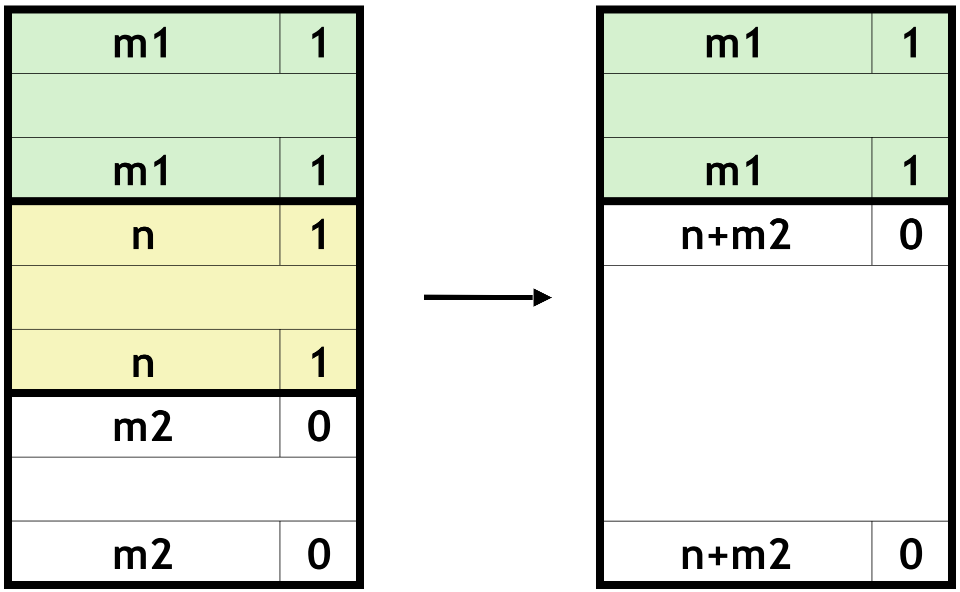
+ Constant Time Coalescing



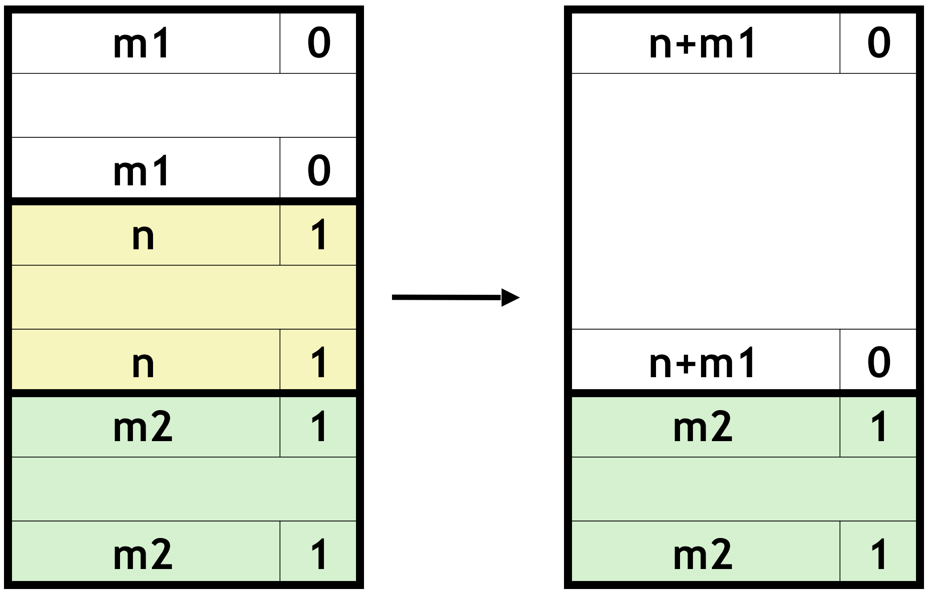
Constant Time Coalescing (Case 1)



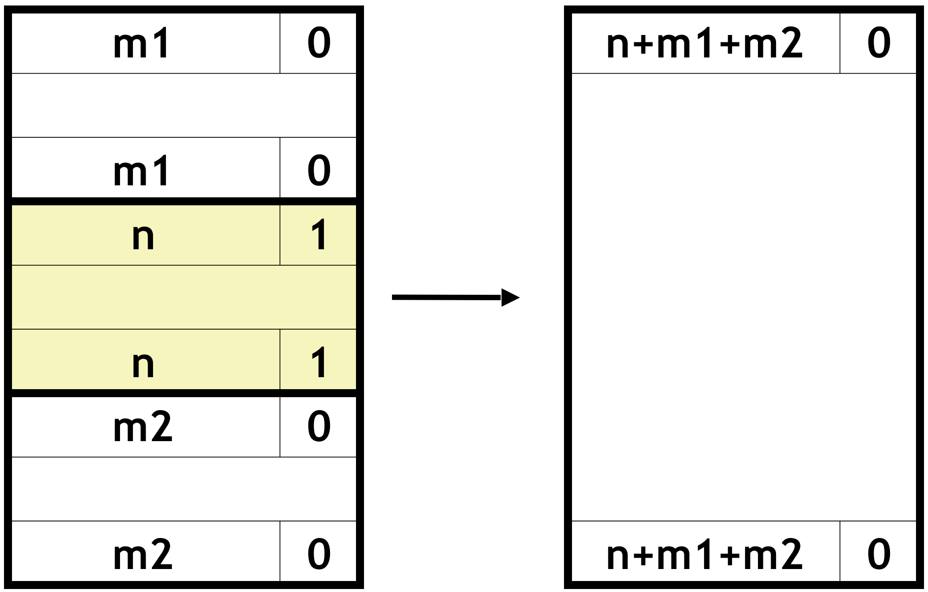
+ Constant Time Coalescing (Case 2)



Constant Time Coalescing (Case 3)



Constant Time Coalescing (Case 4)



Disadvantages of Boundary Tags

- **Internal fragmentation**
  - Again we are trading space for time, utilization for throughput
- **Can it be optimized?**
  - Which blocks need the footer tag?
  - Only free blocks!
- **So how do we know if the last word in the previous block is a boundary tag or not, after all its just bits back there!**
  - We can use one of those low order bits in the header to indicate the allocation status of the previous block.

+ Implicit Lists: Summary

- **Implementation: very simple**
- **Allocate cost:**
  - linear time
- **Free cost:**
  - constant time (even with coalescing)
- **Memory usage:**
  - Will depend on placement policy
    - First-fit, next-fit or best-fit
- **Not used in practice for malloc/free because of linear-time allocation**
- **Concepts of splitting and boundary tag coalescing are general to all allocators**