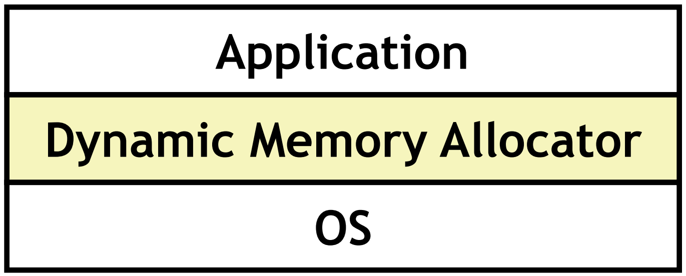
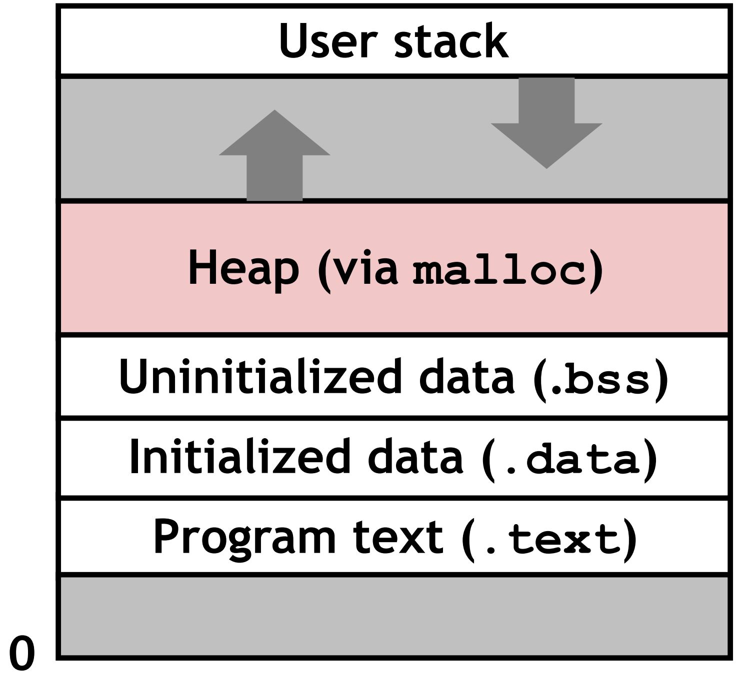
Dynamic Allocation

+ Dynamic Memory Allocation

- **Programmers use dynamic memory allocators (such as malloc) to acquire VM 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.**





+ Dynamic Memory Allocation

- **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)*

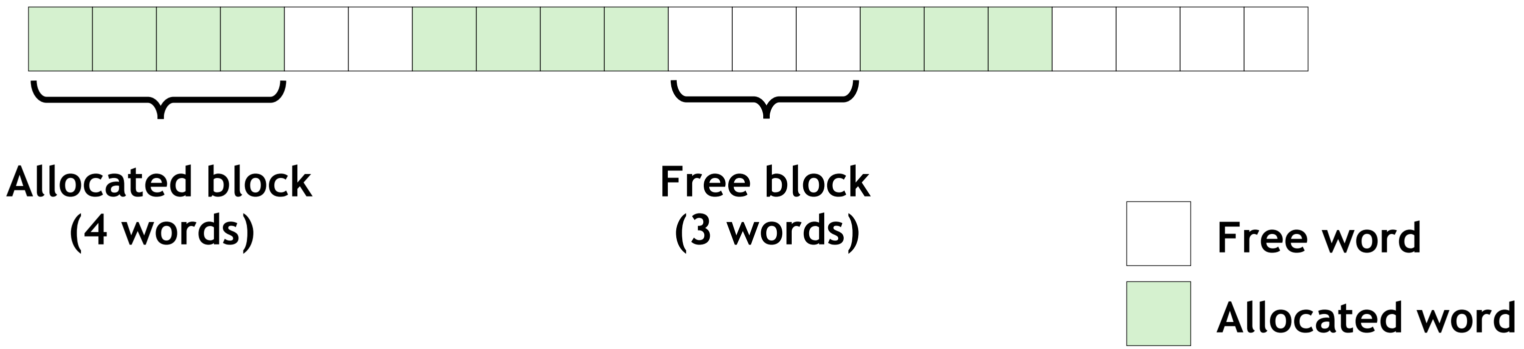
- **`#include <stdlib.h>`**
- **`void *malloc(size_t size)`**
  - Successful:
    - Returns a pointer to a memory block of at least size bytes aligned to a 16-byte boundary
    - If size == 0, returns `NULL`
  - Unsuccessful: returns `NULL` (0) and sets errno
- **`void free(void *p)`**
  - Releases the 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

+ malloc Example *(review)*

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

void foo(int n) {
    int i, *p;

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

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


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

Assumptions Made in This Lecture

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



+ Allocation Example

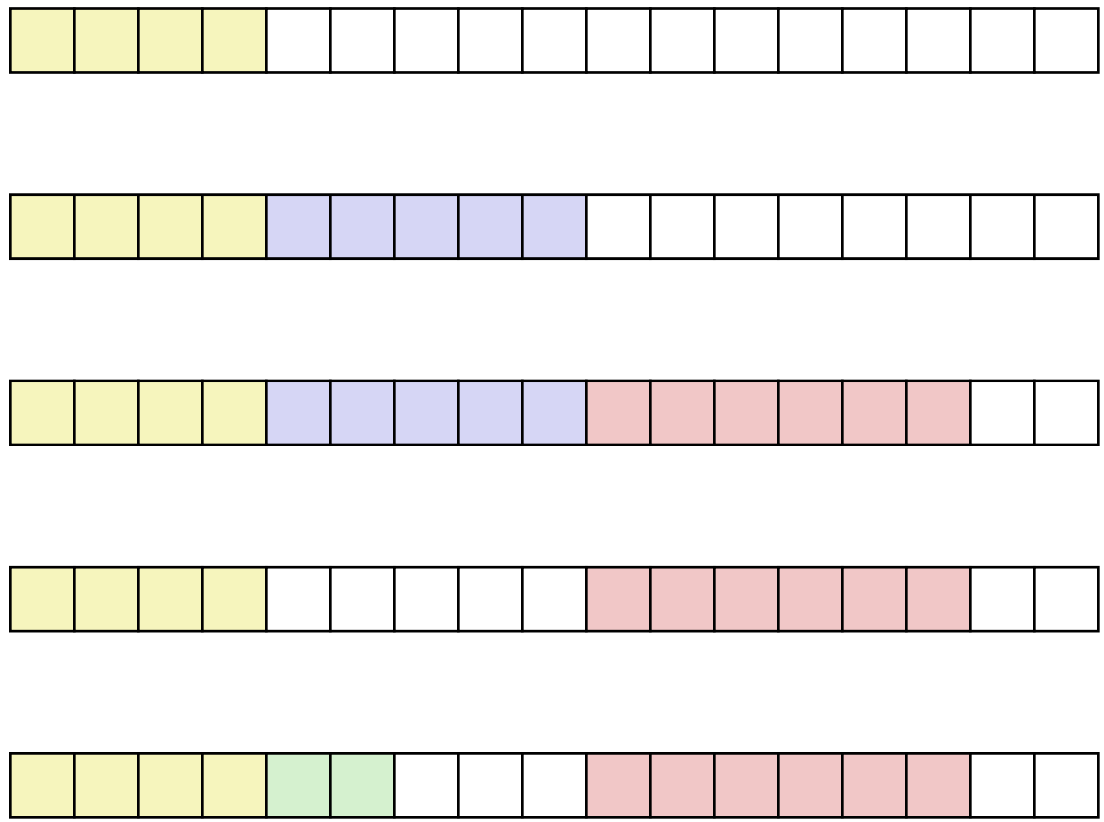
`p1 = malloc(4)`

`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`
  - Must align blocks so they satisfy all alignment requirements
    - 16-byte alignment on Linux boxes

+ 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

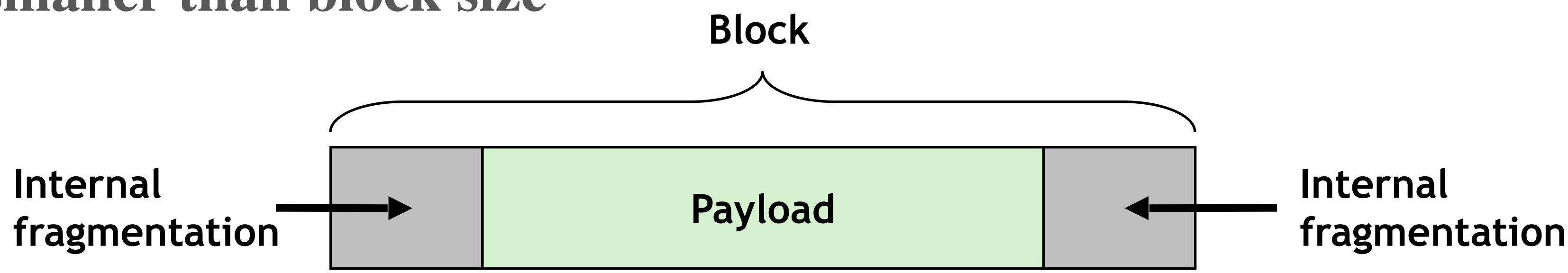
- **Given some sequence of `malloc` and `free` requests:**
  - R_0, R_1, ..., R_k, ... , R_{n-1}
- **Definition: *Aggregate payload* P_k**
  - `malloc(p)` results in a block with a payload of `p` bytes
  - After request R_k has completed, the aggregate payload P_k is the sum of currently allocated payloads
- **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**
  - Overhead of maintaining heap data structures
  - Padding for alignment purposes
  - Explicit policy decisions
    (e.g., to return a big block to satisfy a small request)

- **Depends only on the pattern of previous requests**
  - Thus, easy to measure

External Fragmentation

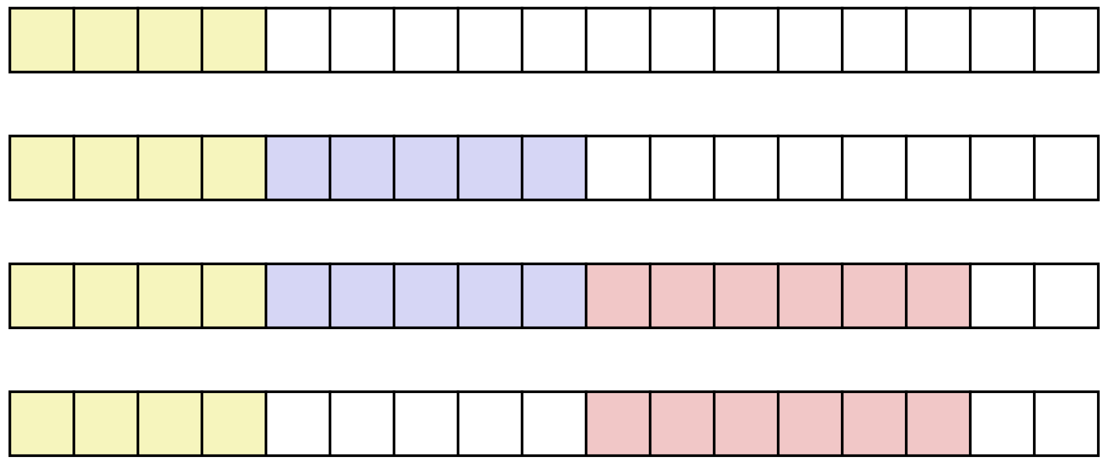
- **Occurs when there is enough aggregate heap memory, but no single free block is large enough**

`p1 = malloc(4)`

`p2 = malloc(5)`

`p3 = malloc(6)`

`free(p2)`



`p4 = malloc(6)`

Oops! (what would happen now?)

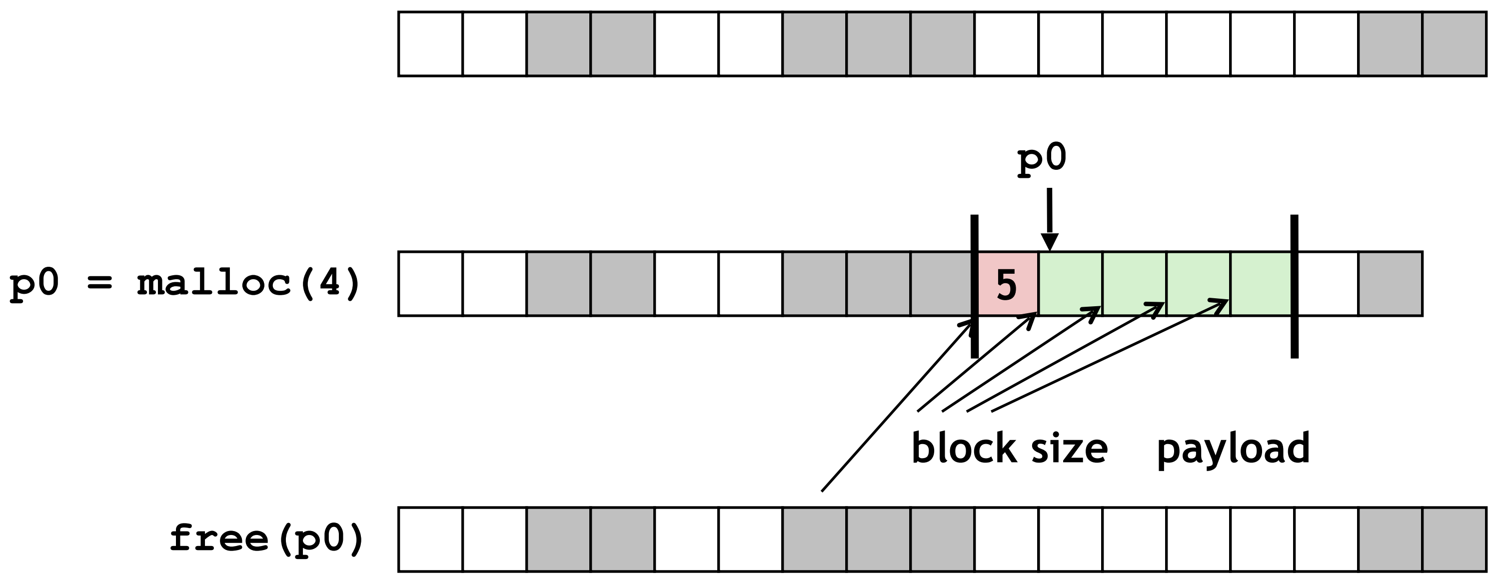
- **Depends on the pattern of future requests**
  - Thus, difficult to measure

+ Implementation Issues

- 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? Do we split blocks?
- How do we pick a block to use for allocation -- many might fit?
- How do we reinsert freed block?

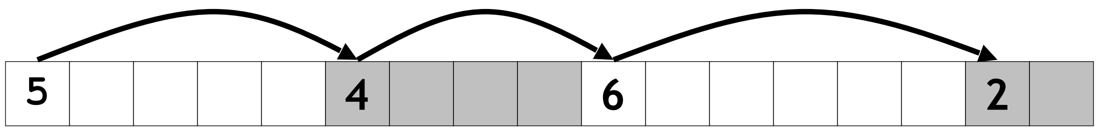
+ Knowing How Much to Free

- **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

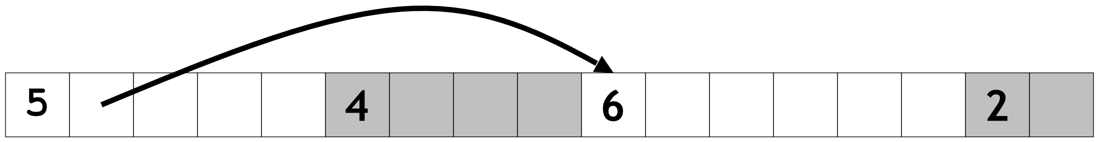


Keeping Track of Free Blocks

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



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

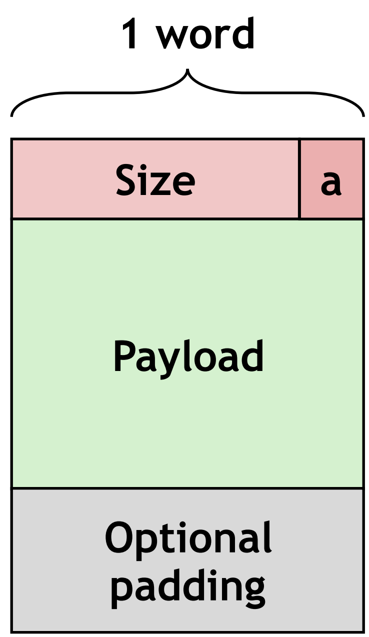


- **Method 3: Segregated free list**
  - Different free lists for different size classes

+ 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 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

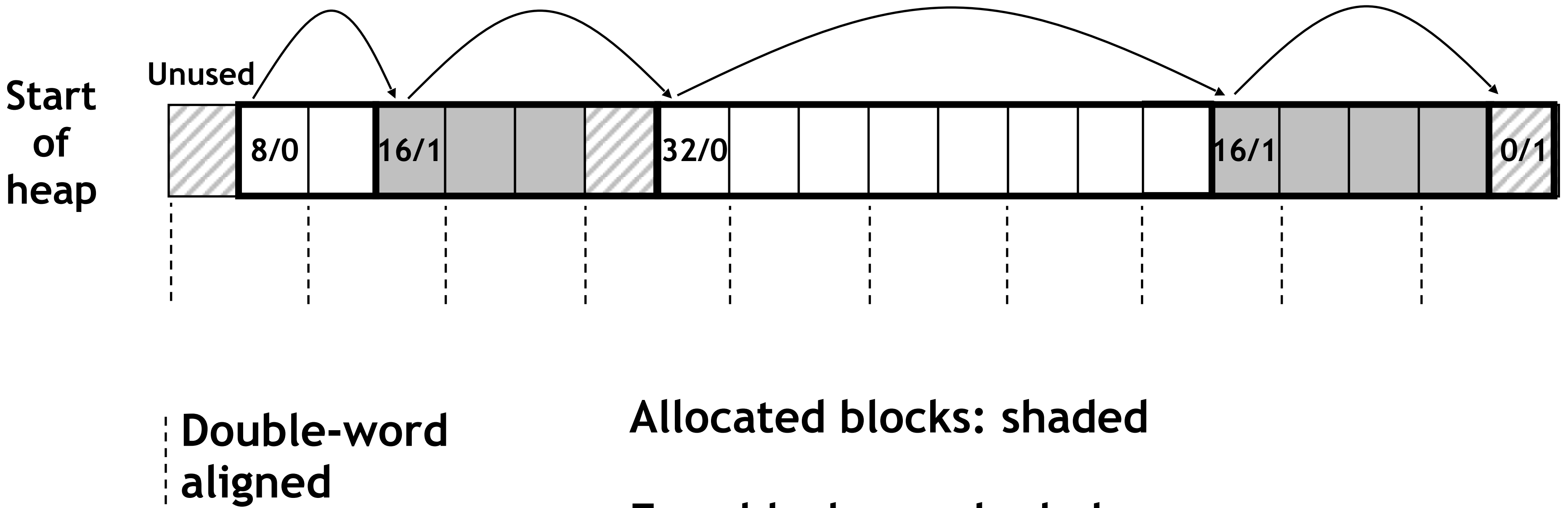


a = 1: Allocated block
a = 0: Free block

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:

```
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)
```

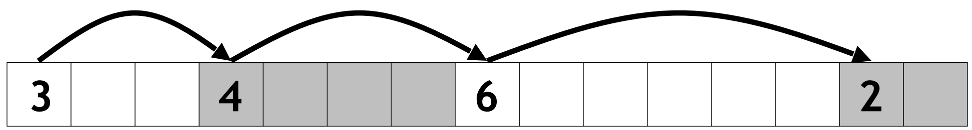
  - Can take linear time in total number of blocks (allocated and free)
  - In practice it can cause “splinters” at beginning of list

- **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

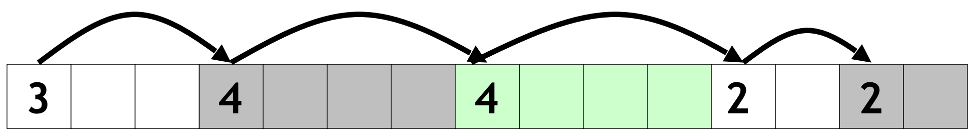
- **Best fit:**
  - Search the list, choose the best free block: fits, with fewest bytes left over
  - Keeps fragments small—usually improves memory utilization
  - Will typically run slower than first fit

+ Implicit List: Allocating in Free Block

- **Allocating in a free block: splitting**
  - Allocated space might be smaller than free space, maybe split block



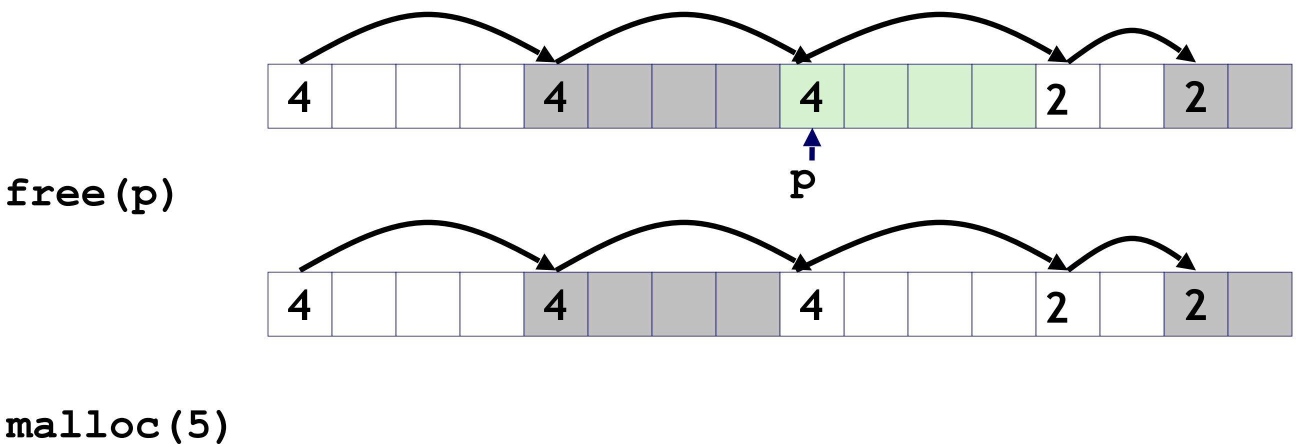
`addblock(p, 4)`




```
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
```

+ Implicit List: Freeing a Block

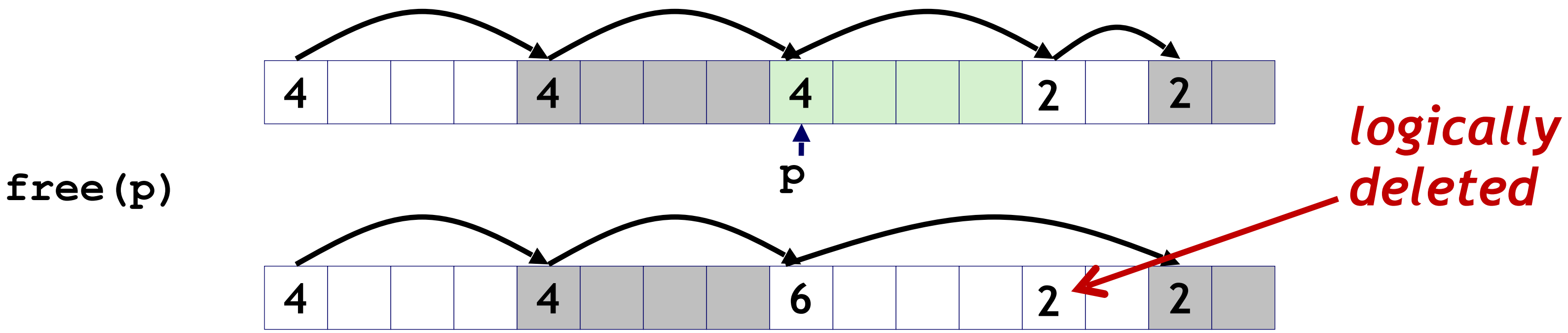
- **Simplest implementation:**
  - Need only clear the "allocated" flag
    - `void free_block(ptr p) { *p = *p & -2 }`
  - But can lead to "false fragmentation"



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

Implicit List: Coalescing

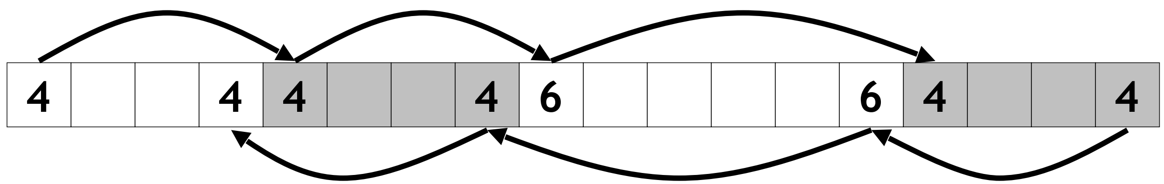
- **Join (coalesce) with next/previous blocks, if they are free**
  - Coalescing with next block



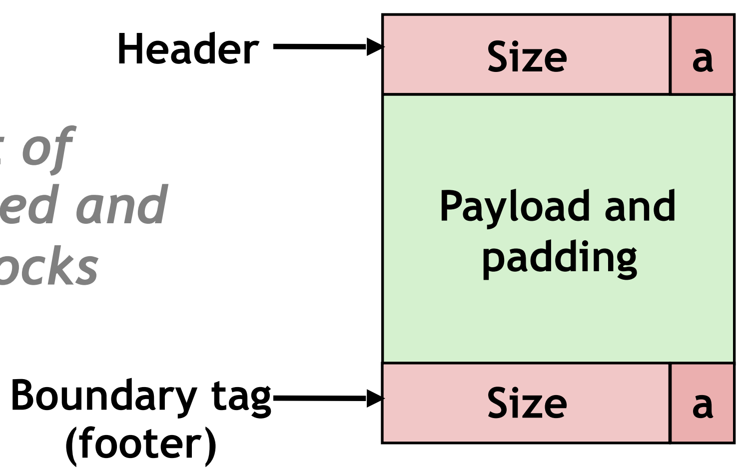
  - But how do we coalesce with previous block?

+ Implicit List: Bidirectional Coalescing

- **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
  - Important and general technique!



Format of allocated and free blocks

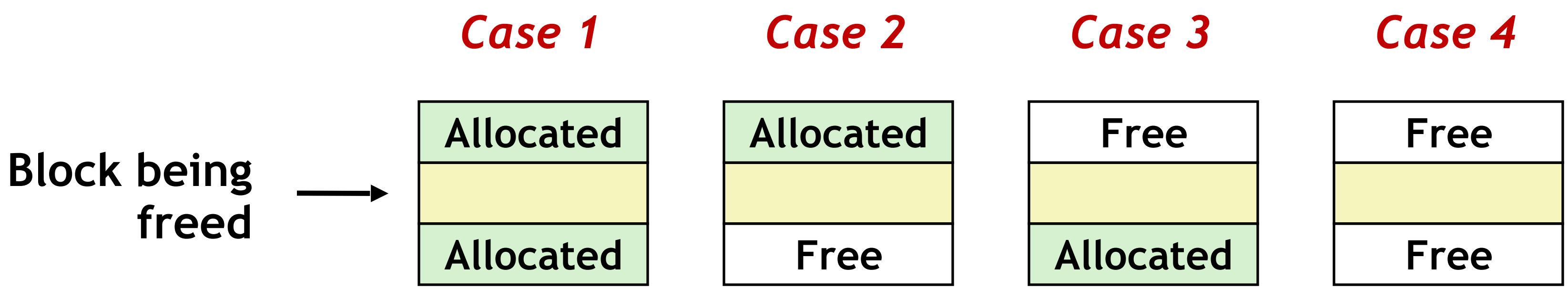


a = 1: Allocated block
a = 0: Free block

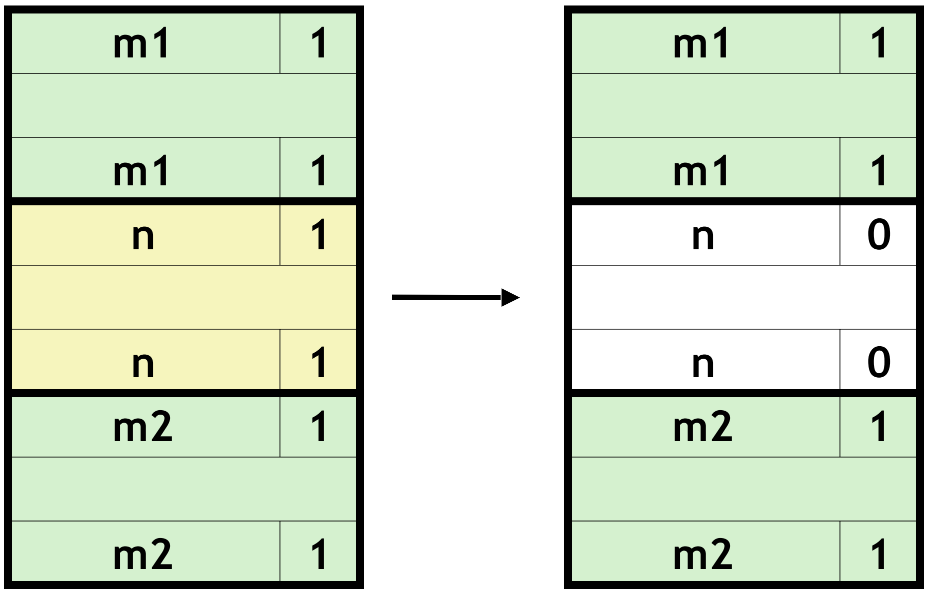
Size: Total block size

Payload: Application data (allocated blocks only)

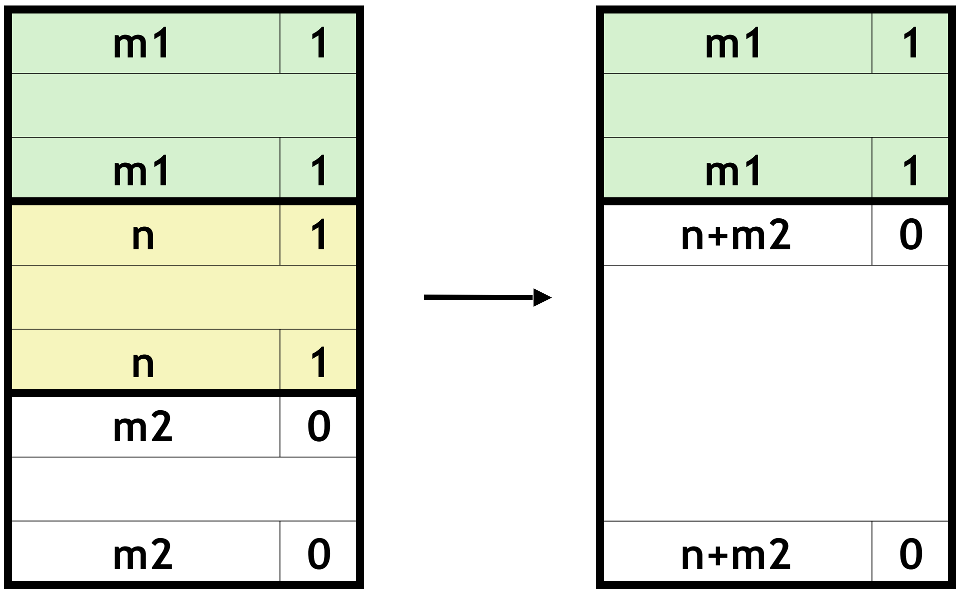
+ Constant Time Coalescing



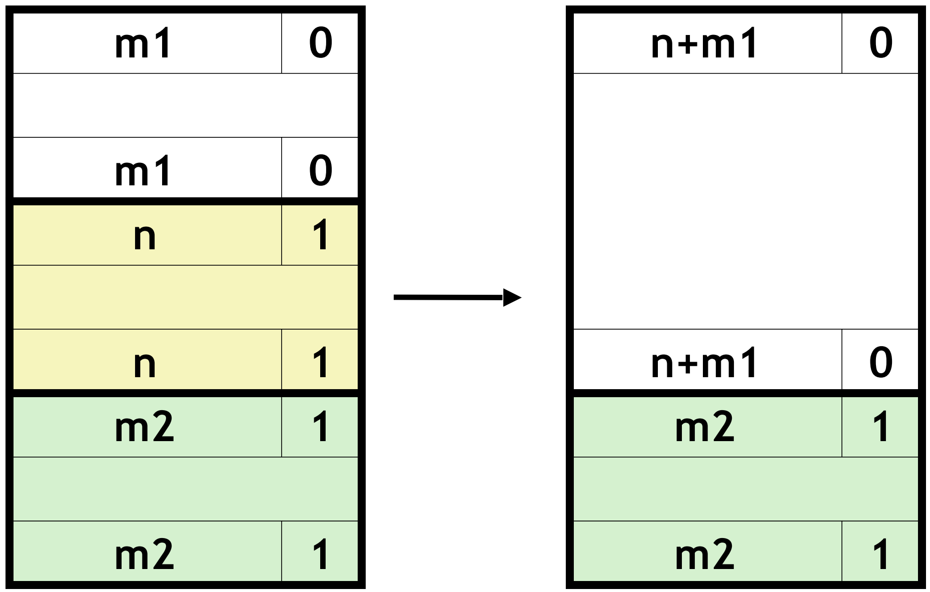
+ Constant Time Coalescing (Case 1)



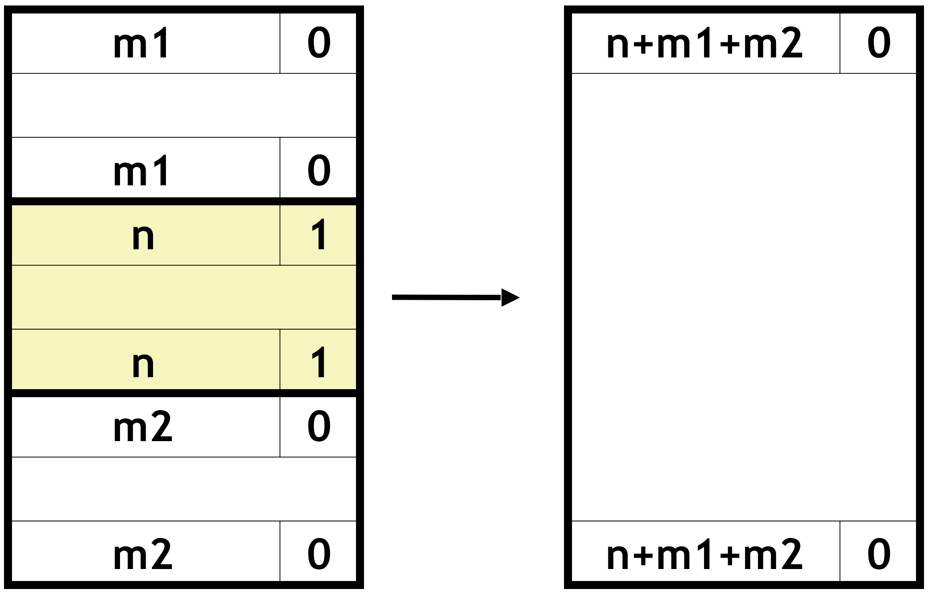
Constant Time Coalescing (Case 2)



+ Constant Time Coalescing (Case 3)



Constant Time Coalescing (Case 4)



+ Disadvantages of Boundary Tags

- **Internal fragmentation**
- **Can it be optimized?**
  - Which blocks need the footer tag?

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- **Internal fragmentation**
- **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!**

+ Disadvantages of Boundary Tags

- **Internal fragmentation**
- **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.

+ Summary of Key Allocator Policies

- **Placement policy:**
  - *First-fit, next-fit, best-fit, etc.*
  - Trades off lower throughput for less fragmentation
- **Splitting policy:**
  - When do we go ahead and split free blocks?
  - How much internal fragmentation are we willing to tolerate?
- **Coalescing policy:**
  - *Immediate coalescing*: coalesce each time free is called
  - *Deferred coalescing*: improve performance of `free` by deferring coalescing.
    - Ex. Coalesce as you scan the free list for `malloc`
    - Ex. Coalesce when the amount of external fragmentation reaches some threshold

+ Implicit Lists: Summary

- **Implementation: very simple**
- **Allocate cost:**
  - linear time worst case
- **Free cost:**
  - constant time worst case
    - 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**