

# Dynamic Memory Allocation: Basic Concepts

15-213: Introduction to Computer Systems  
19<sup>th</sup> Lecture, March 29, 2018

## **Instructor:**

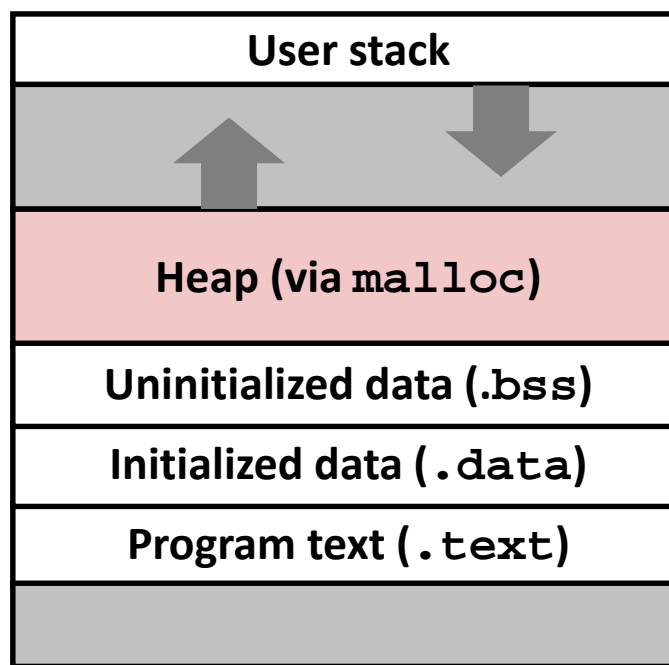
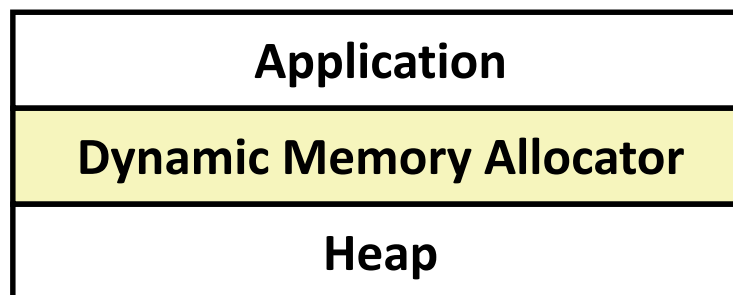
Franz Franchetti, Seth Copen Goldstein, and Brian Railing

# Today

- **Basic concepts**
- **Implicit free lists**

# 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*.



Top of heap  
(brk ptr)

# 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

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

```
void *malloc(size_t size)
```

- Successful:
  - Returns a pointer to a memory block of at least **size** bytes aligned to an 16-byte boundary (on x86-64)
  - If **size == 0**, returns NULL
- Unsuccessful: returns NULL (0) and sets **errno**

```
void free(void *p)
```

- Returns the block pointed at by **p** to pool of available memory
- **p** must come from a previous call to **malloc** or **realloc**

## 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

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

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

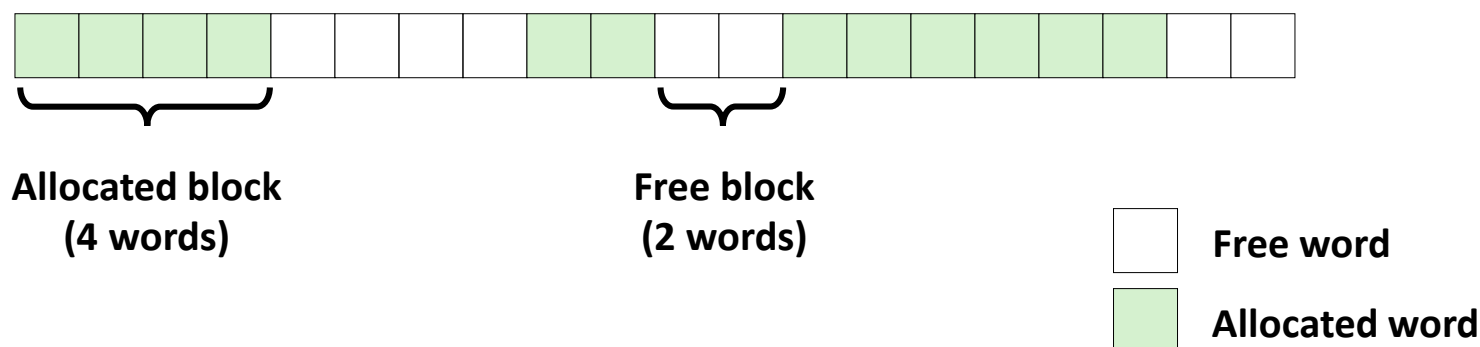
    /* Allocate a block of n ints */
    p = (int *) malloc(n * sizeof(int));
    if (p == NULL) {
        perror("malloc");
        exit(0);
    }

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

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

# Simplifying Assumptions Made in This Lecture

- Memory is word addressed.
- Words are int-sized.
- Allocations are double-word aligned.



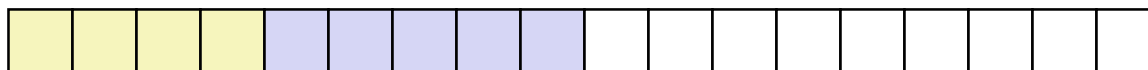
# Allocation Example

```
#define SIZ sizeof(int)
```

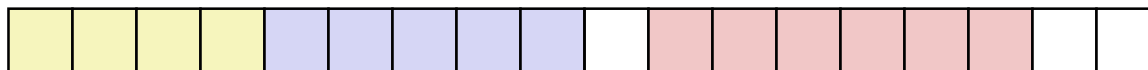
```
p1 = malloc(4*SIZ)
```



```
p2 = malloc(5*SIZ)
```



```
p3 = malloc(6*SIZ)
```



```
free(p2)
```



```
p4 = malloc(2*SIZ)
```





# 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
  - *i.e.*, can't reorder or buffer requests
- Must allocate blocks from free memory
  - *i.e.*, can only place allocated blocks in free memory
- Must align blocks so they satisfy all alignment requirements
  - 16-byte (x86-64) alignment on Linux boxes
- Can manipulate and modify only free memory
- Can't move the allocated blocks once they are **malloc**'d
  - *i.e.*, compaction is not allowed

# Performance Goal: Throughput

- Given some sequence of `malloc` and `free` requests:
  - $R_0, R_1, \dots, R_k, \dots, R_{n-1}$
- 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

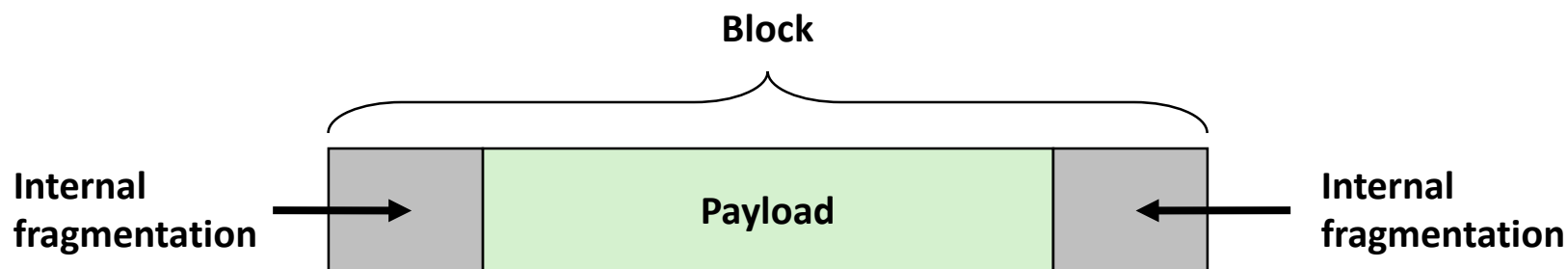
- Given some sequence of `malloc` and `free` requests:
  - $R_0, R_1, \dots, R_k, \dots, R_{n-1}$
- **Def: Aggregate payload  $P_k$** 
  - `malloc(p)` results in a block with a **payload** of `p` bytes
  - After request  $R_k$  has completed, the **aggregate payload**  $P_k$  is the sum of currently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

# 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

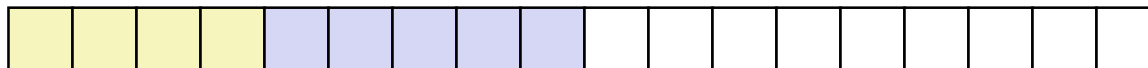
```
#define SIZ sizeof(int)
```

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

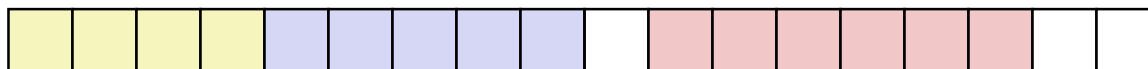
```
p1 = malloc(4*SIZ)
```



```
p2 = malloc(5*SIZ)
```



```
p3 = malloc(6*SIZ)
```



```
free(p2)
```



```
p4 = malloc(7*SIZ)
```

*Oops! (what would happen now?)*

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

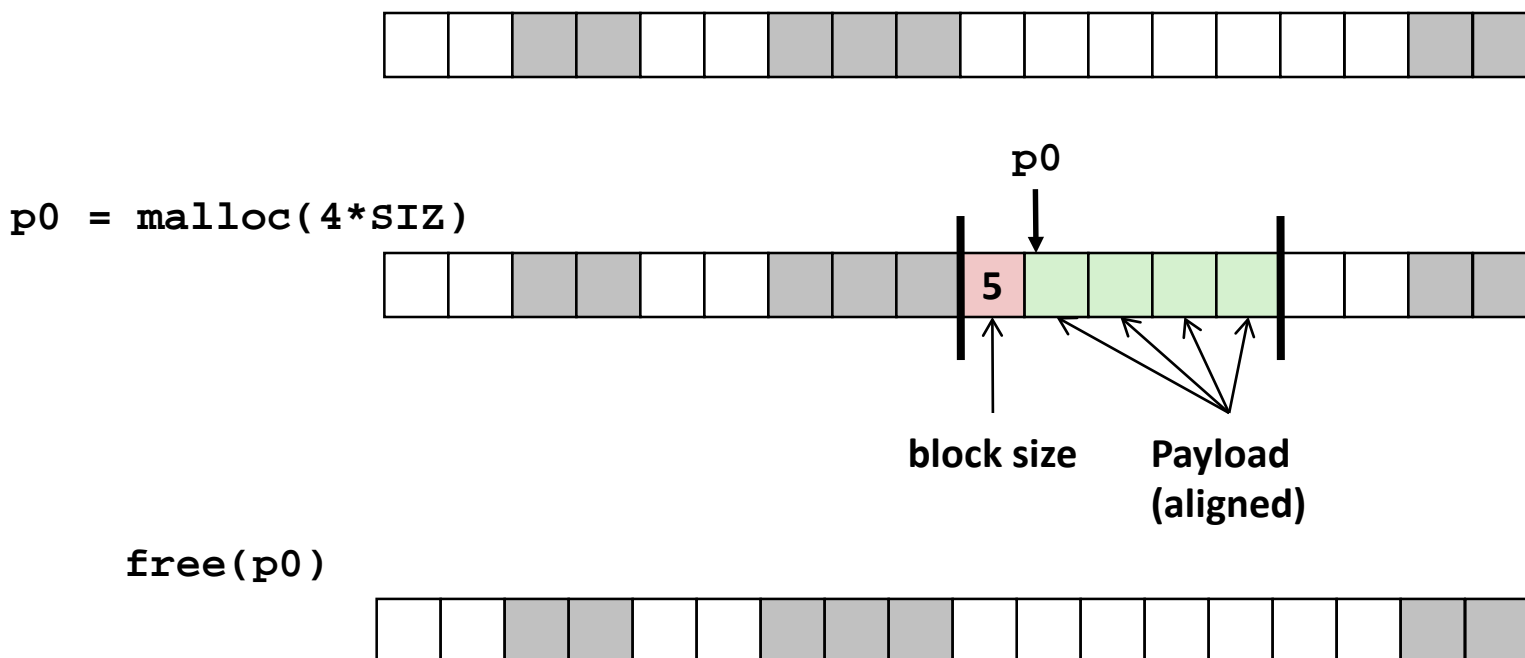
# Implementation Issues

- **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?**
- **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

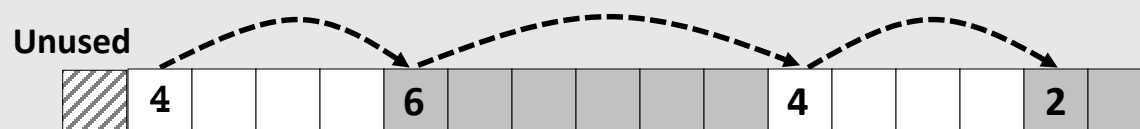
- Keep the length of a block in the word preceding the block.
  - This word is often called the *header field* or *header*
- Requires an extra word for every allocated block





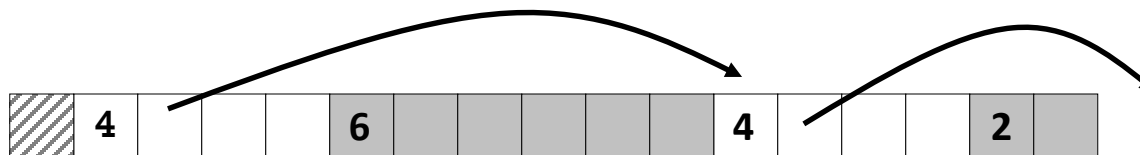
# Keeping Track of Free Blocks

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



Need to tag each block as allocated/free

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



Need space for 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

# Today

- Basic concepts
- **Implicit free lists**

# Quiz Time!

*Ytse Jam*: Song by Dream Theater

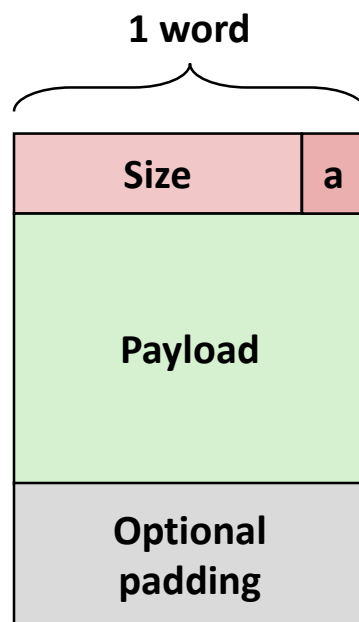
Check out: quiz: day 19: Malloc Basics

<https://canvas.cmu.edu/courses/3822>

# Method 1: Implicit Free List

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

*Format of  
allocated and  
free blocks*



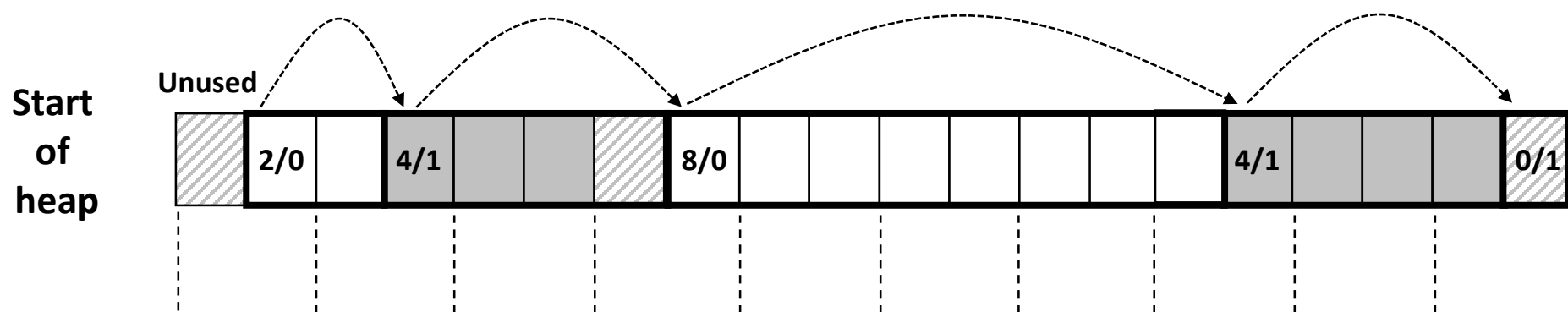
**a = 1: Allocated block**

**a = 0: Free block**

**Size: block size**

**Payload: application data  
(allocated blocks only)**

# Detailed Implicit Free List Example



Double-word  
aligned

**Allocated blocks:** shaded

**Free blocks:** unshaded

**Headers:** labeled with “size in words/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

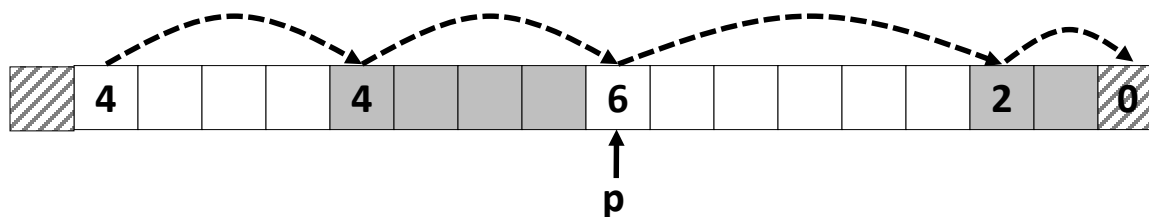
## ■ *Best fit:*

- 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

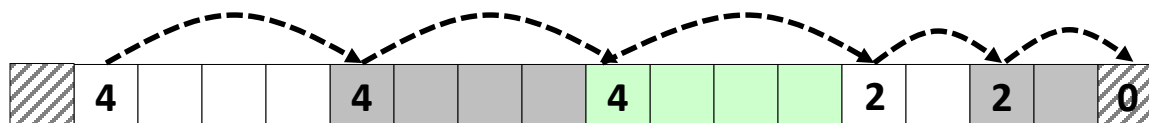
# Implicit List: Allocating in Free Block

## ■ Allocating in a free block: *splitting*

- Since allocated space might be smaller than free space, we might want to split the block



addblock(p, 4)

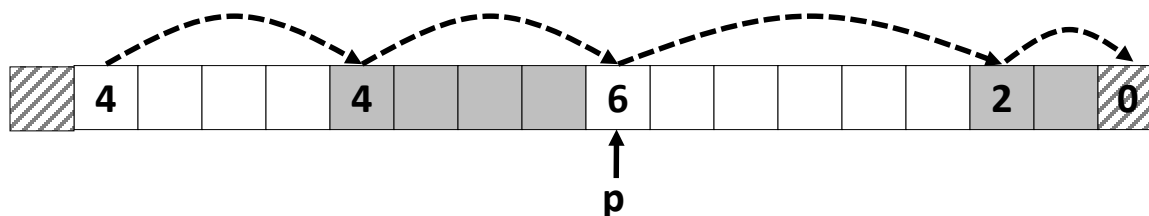


```
void addblock(ptr p, int len) {
    int newsize = ((len + 1) >> 1) << 1; // round up to even
    int oldsize = *p & -2;                 // mask out low bit
    *p = newsize | 1;                       // set new length
    if (newsize < oldsize)
        *(p+newsize) = oldsize - newsize; // set length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

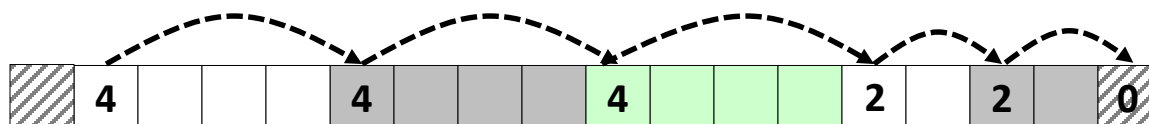
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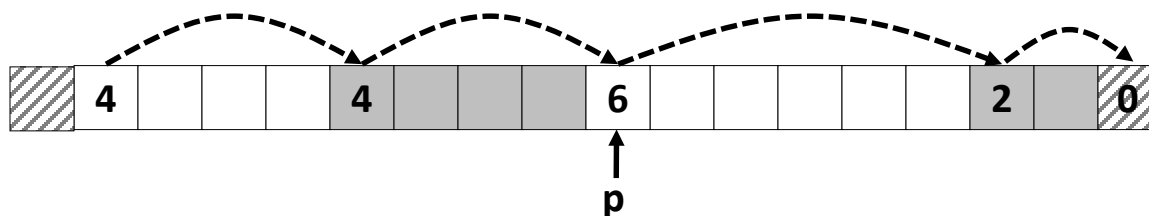
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    int oldsize = *p & -2;                    // mask out low bit
    *p = newsize | 1;                         // set new length
    if (newsize < oldsize)
        *(p+newsize) = oldsize - newsize;    // set length in remaining
                                                // part of block
}
```



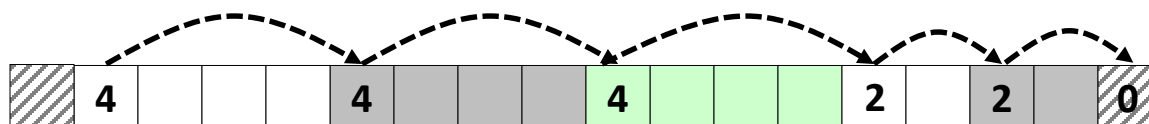
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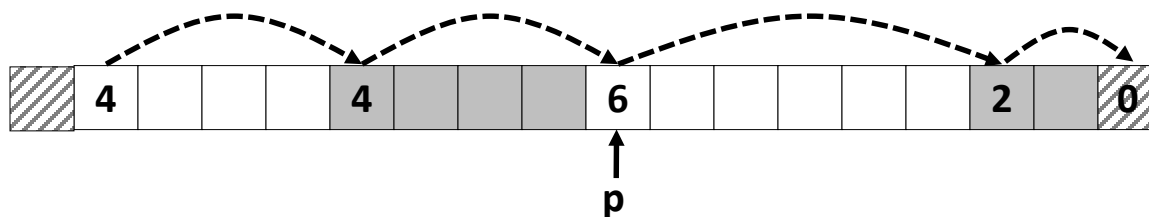


```
void addblock(ptr p, int len) {
    int newsize = ((len + 1) >> 1) << 1;    // round up to even
    int oldsize = *p & -2;                    // mask out low bit
    *p = newsize | 1;                         // set new length
    if (newsize < oldsize)
        *(p+newsize) = oldsize - newsize;  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

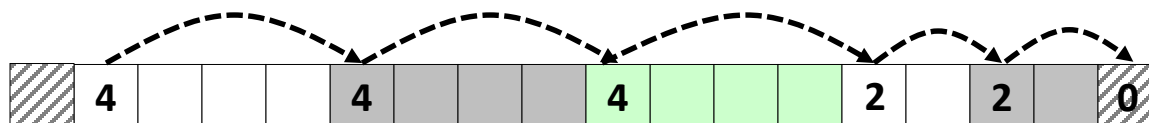
# Implicit List: Allocating in Free Block

## ■ 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)



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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
}
```

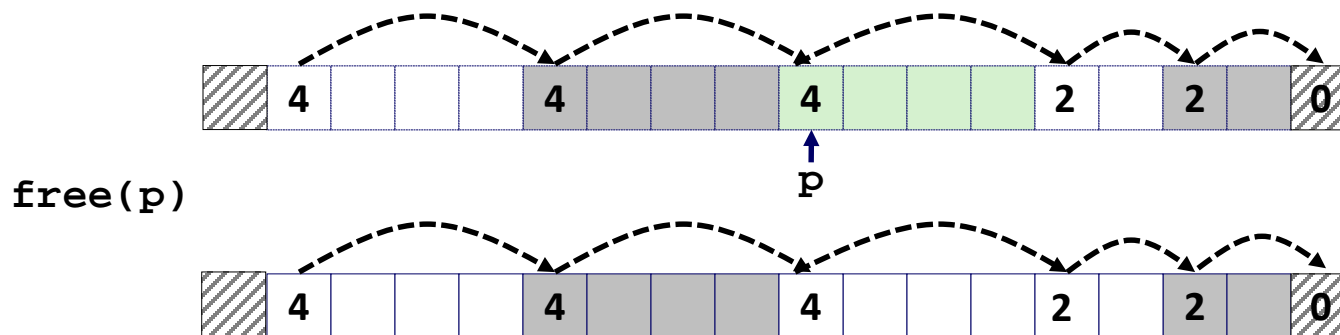
# Implicit List: Freeing a Block

## ■ Simplest implementation:

- Need only clear the “allocated” flag

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

- But can lead to “false fragmentation”



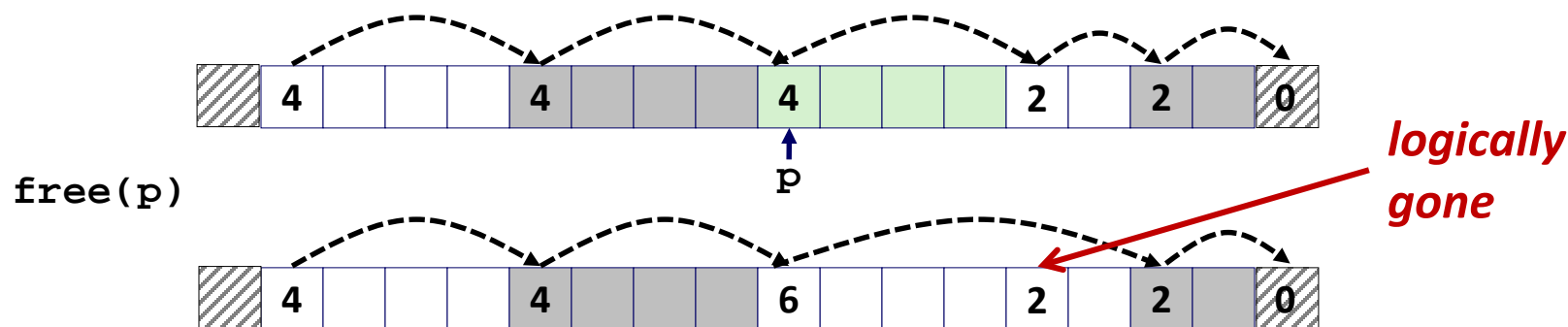
`malloc(5*SIZ)`    ***Oops!***

***There is enough contiguous 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



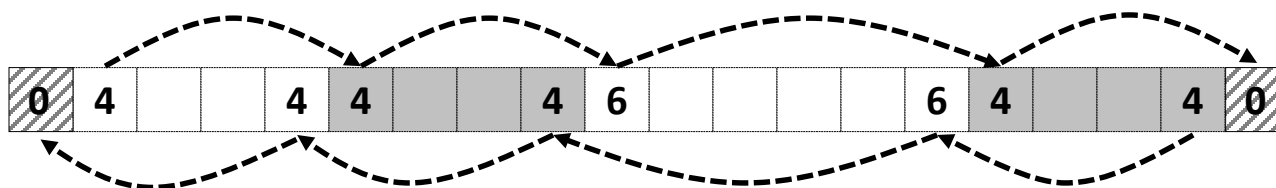
```
void free_block(ptr p) {
    *p = *p & -2;           // clear allocated flag
    next = p + *p;          // find next block
    if ((*next & 1) == 0)
        *p = *p + *next;    // add to this block if
                             // not allocated
}
```

### ■ But how do we coalesce with *previous* block?

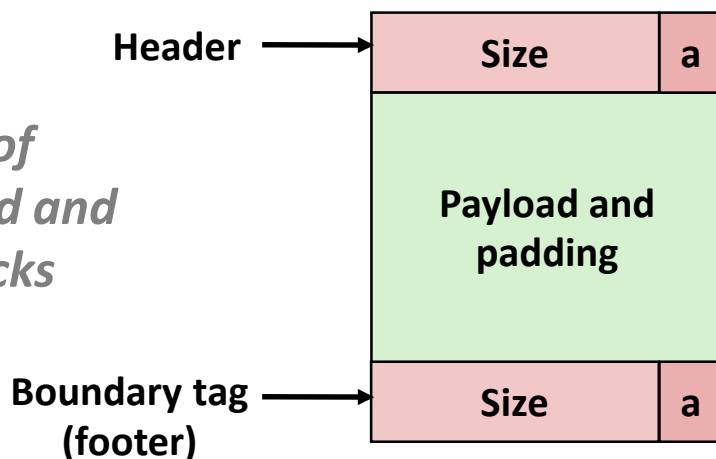
# Implicit List: Bidirectional Coalescing

## ■ *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*

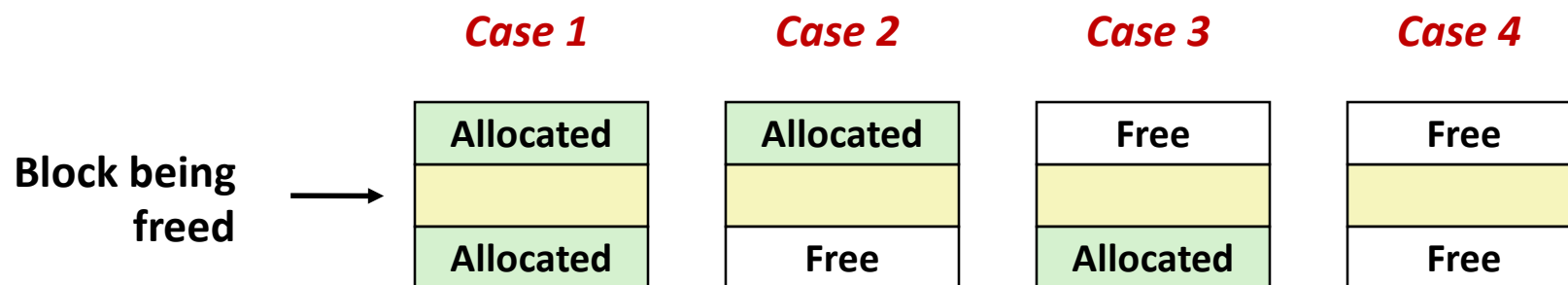


a = 1: Allocated block  
a = 0: Free block

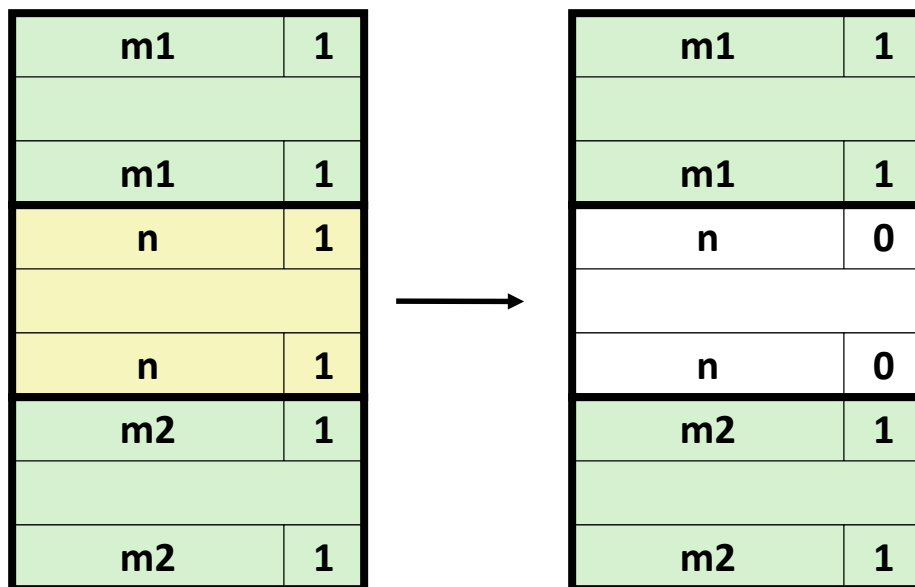
Size: Total block size

Payload: Application data  
(allocated blocks only)

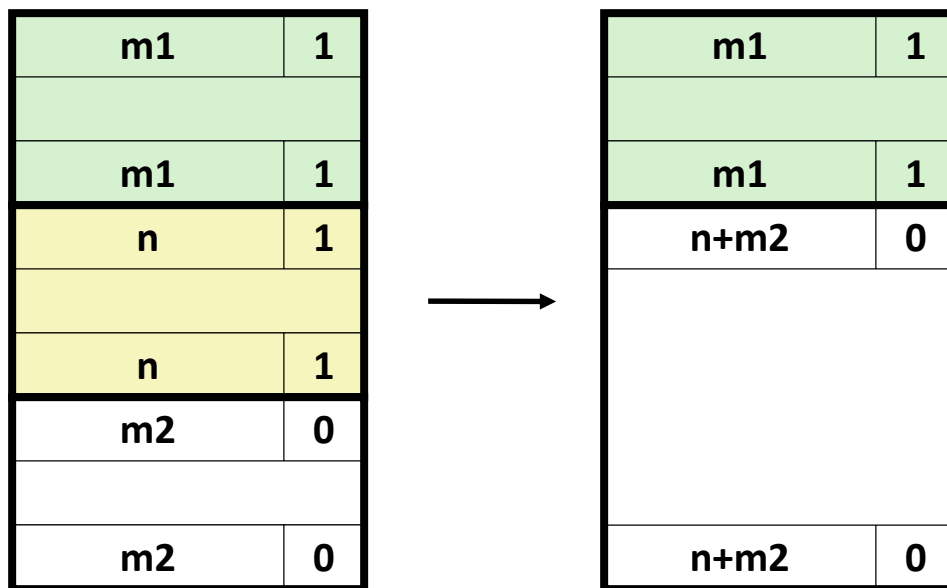
# Constant Time Coalescing



# Constant Time Coalescing (Case 1)

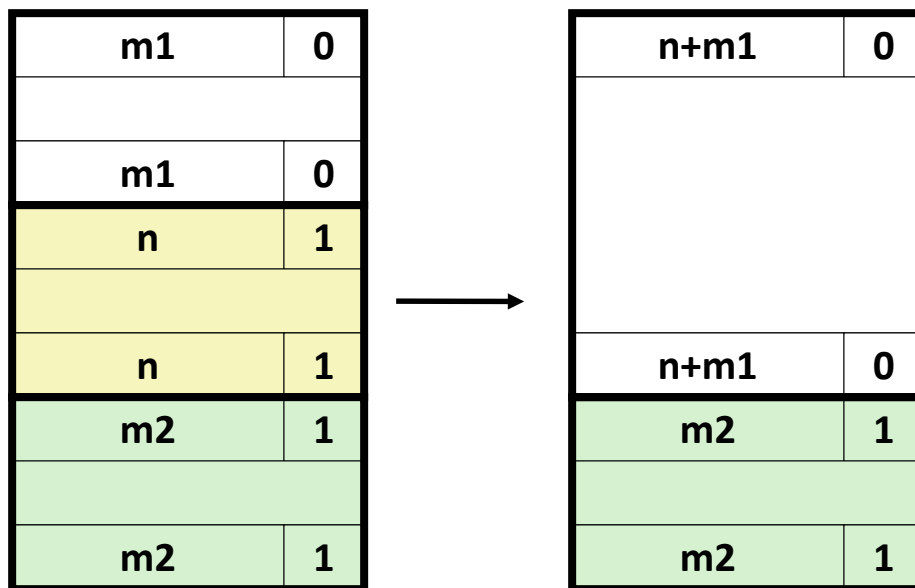


# Constant Time Coalescing (Case 2)

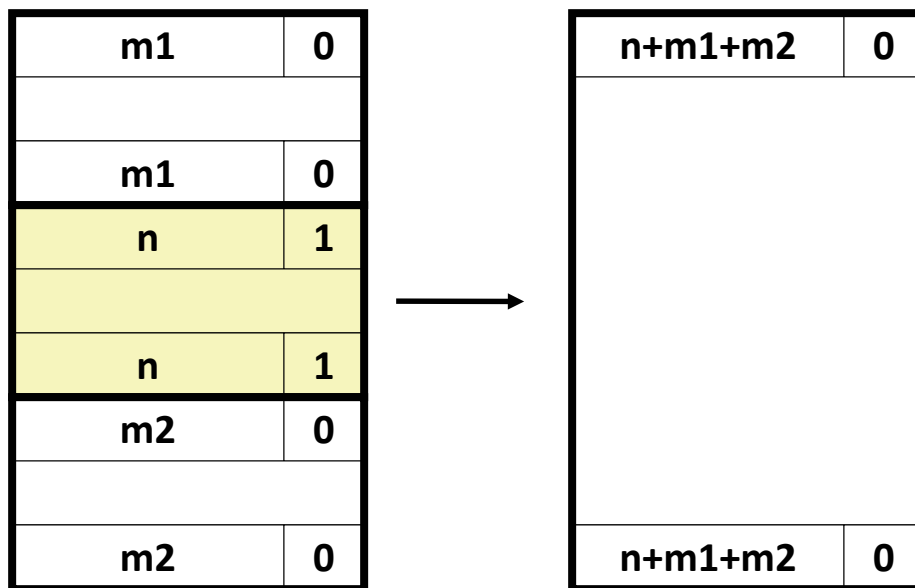




# Constant Time Coalescing (Case 3)



# Constant Time Coalescing (Case 4)

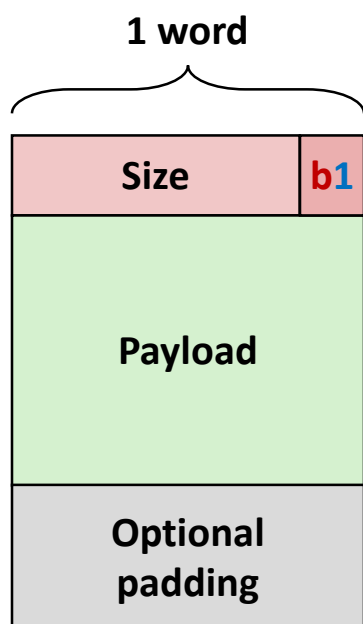


# Disadvantages of Boundary Tags

- Internal fragmentation
- Can it be optimized?
  - Which blocks need the footer tag?
  - What does that mean?

# No Boundary Tag for Allocated Blocks

- Boundary tag needed only for free blocks
- When sizes are multiples of 4 or more, have 2+ spare bits

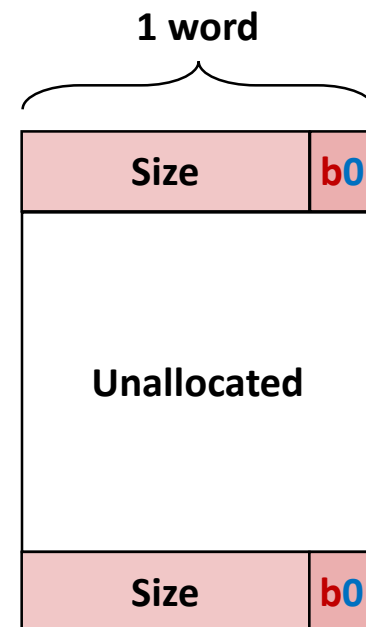


**Allocated  
Block**

**a = 1: Allocated block**  
**a = 0: Free block**  
**b = 1: Previous block is allocated**  
**b = 0: Previous block is free**

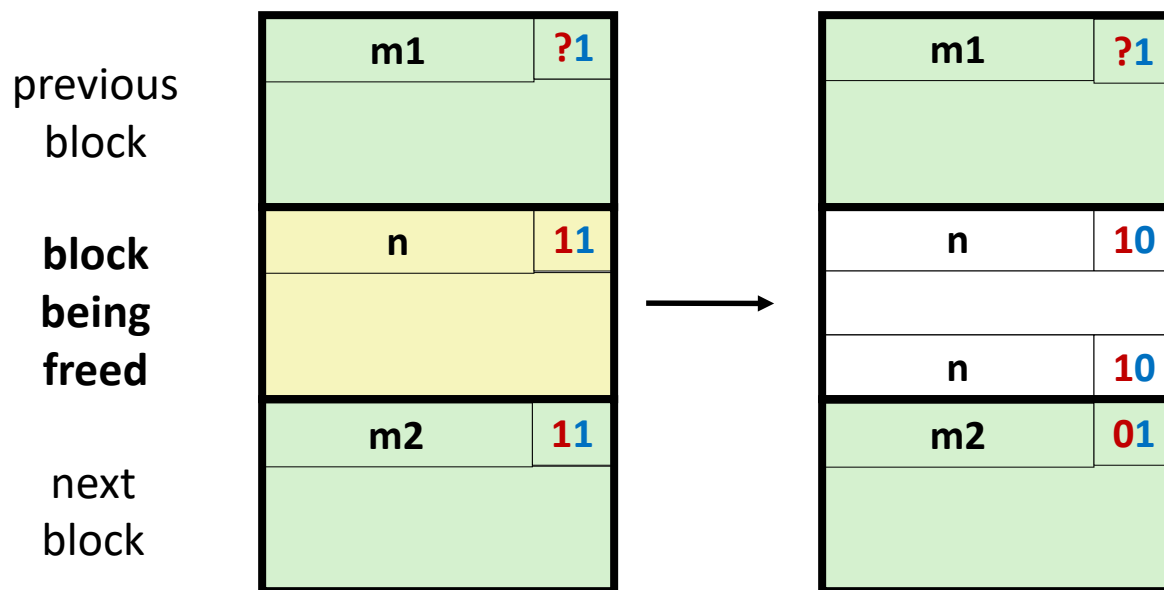
**Size: block size**

**Payload: application data**



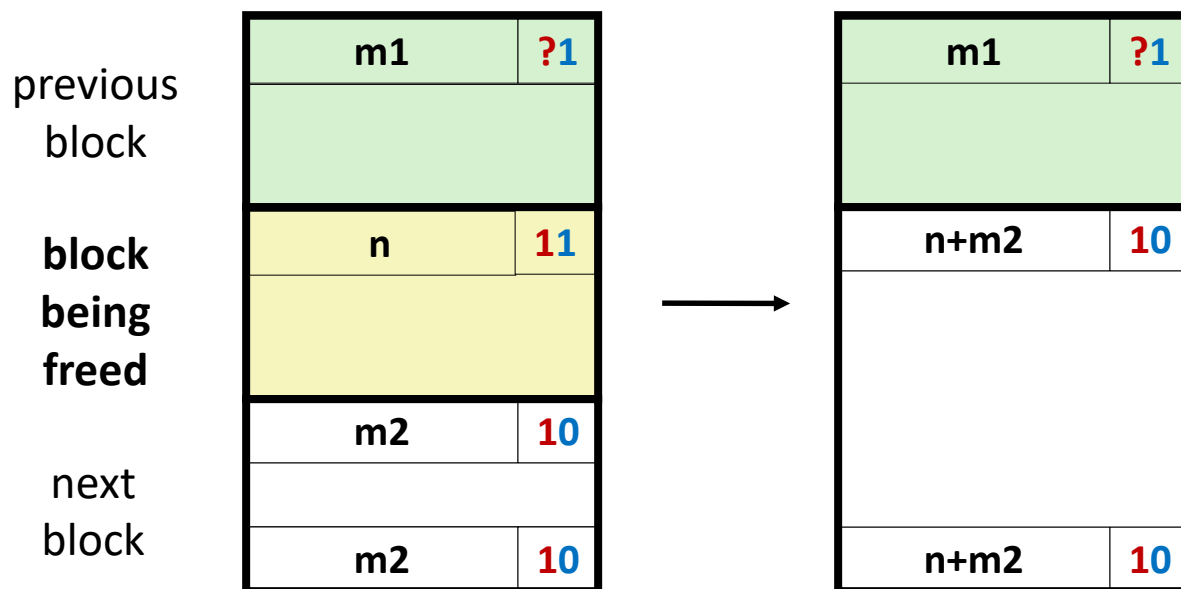
**Free  
Block**

# No Boundary Tag for Allocated Blocks (Case 1)



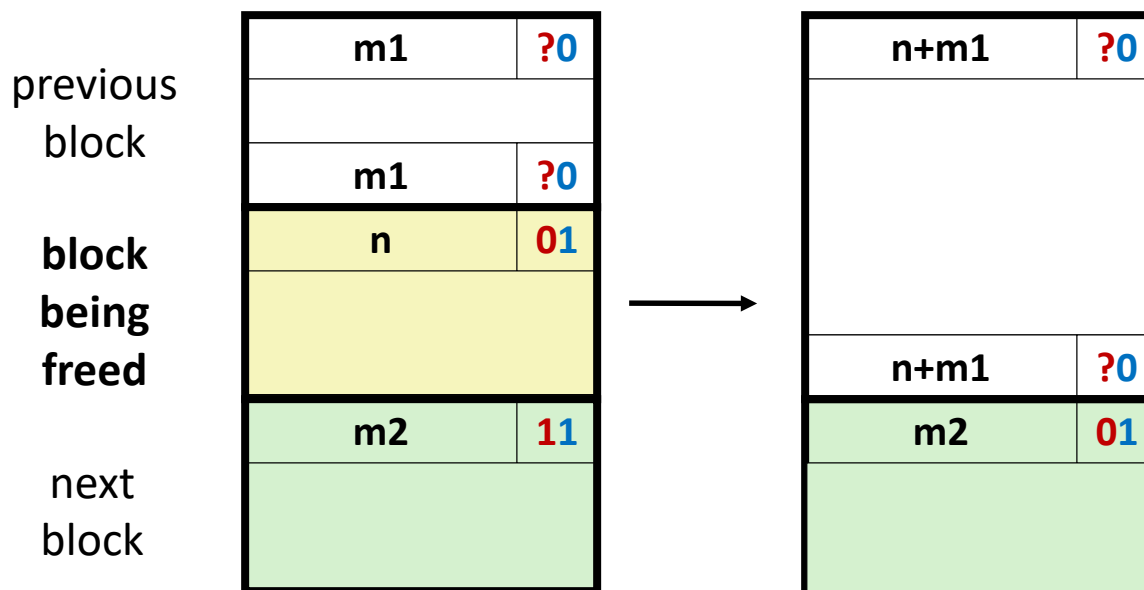
**Header:** Use 2 bits (always zero due to alignment):  
 $(\text{previous block allocated}) \ll 1 \mid (\text{current block allocated})$

# No Boundary Tag for Allocated Blocks (Case 2)



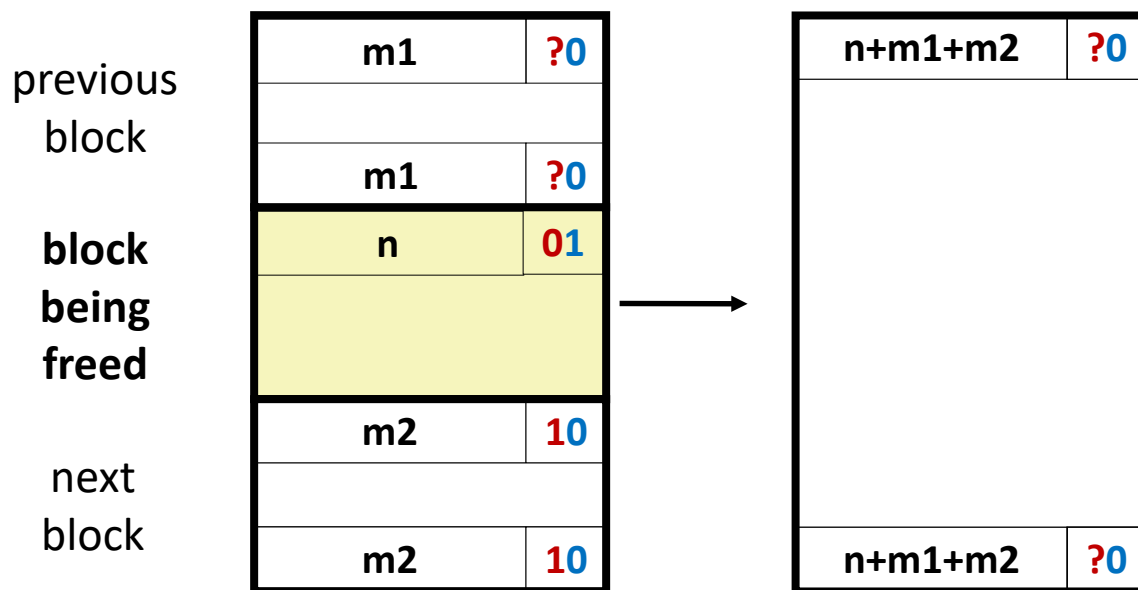
Header: Use 2 bits (always zero due to alignment):  
 (previous block allocated)<<1 | (current block allocated)

# No Boundary Tag for Allocated Blocks (Case 3)



Header: Use 2 bits (always zero due to alignment):  
 (previous block allocated) << 1 | (current block allocated)

# No Boundary Tag for Allocated Blocks (Case 4)



Header: Use 2 bits (always zero due to alignment):  
 (previous block allocated)<<1 | (current block allocated)



# Summary of Key Allocator Policies

## ■ Placement policy:

- First-fit, next-fit, best-fit, etc.
- Trades off lower throughput for less fragmentation
- **Interesting observation:** segregated free lists (next lecture)  
approximate a best fit placement policy without having to search entire free list

## ■ 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:** try to improve performance of **free** by deferring coalescing until needed. Examples:
  - Coalesce as you scan the free list for **malloc**
  - 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**
  - used in many special purpose applications
- **However, the concepts of splitting and boundary tag coalescing are general to *all* allocators**