Dynamic Memory Allocation: Basic Concepts

CSCI 237: Computer Organization
28th Lecture, Apr 28, 2025

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Administrative Details

- Lab 5 – Cache lab
  - Due Tue/Wed
- Glow HW due Fri
  - Covers virtual memory
- Lab 6 – Malloc lab
  - Partners allowed again – submit form
  - Tricky lab! Please take a moment to read the webpage and look at the starter code before your lab session
- Final exam options
  - Thur May 22 in the morning (time/location TBD)
  - Sat May 24 in the afternoon (registrar scheduled time and place)

Last time

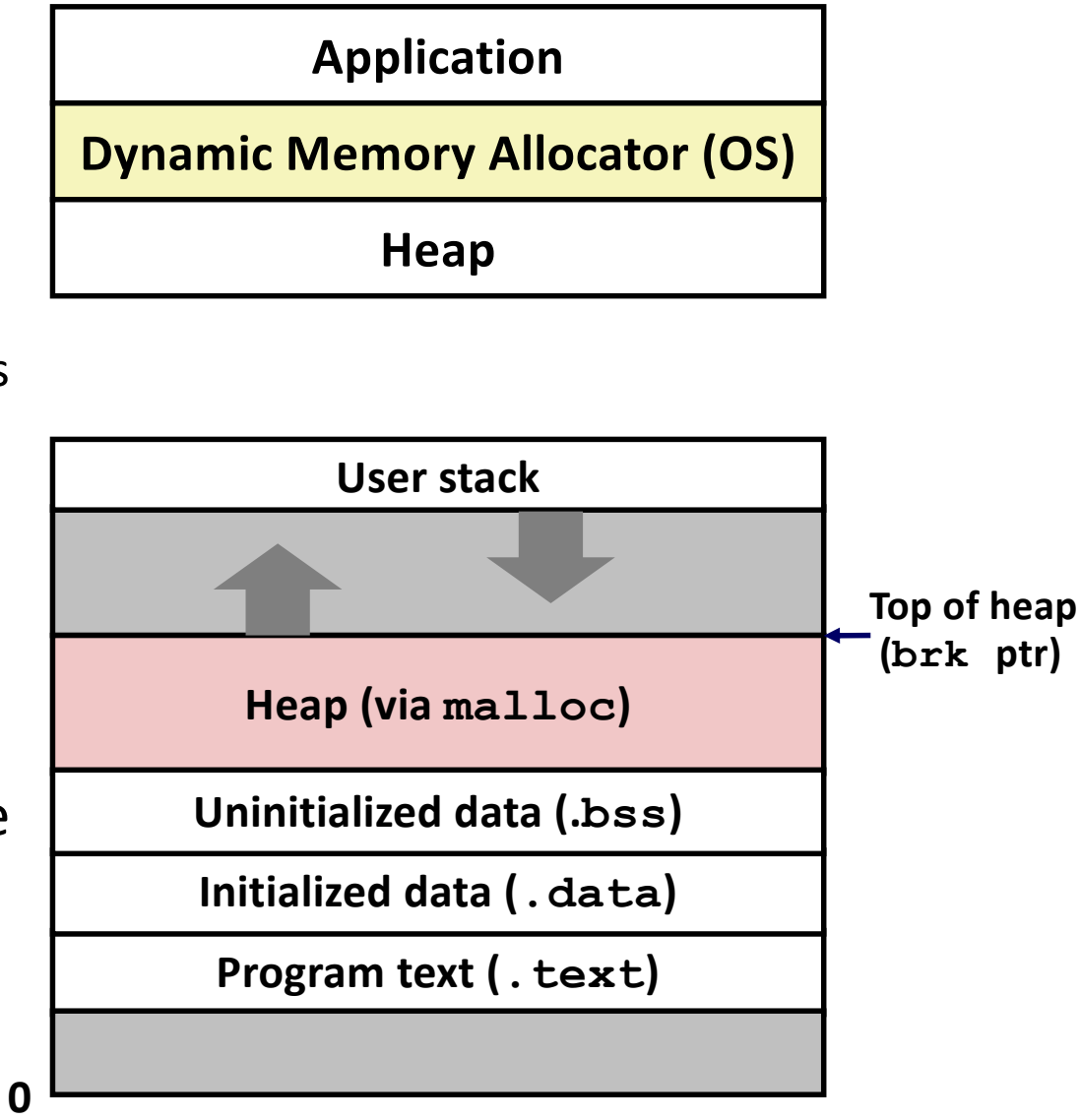
- Simple memory system example wrapup (Ch 9.6)
- Case study: Core i7/Linux memory system (Ch 9.7)

Today

- Dynamic Memory Allocation (Ch 9.9)
  - Basic concepts
  - Implicit free lists

Dynamic Memory Allocation

- Programmers use *dynamic memory allocators* (such as `malloc`) to acquire virtual memory at run time.
  - For data structures whose size is only known at runtime (rather than compile time).
- 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 and Python

- 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

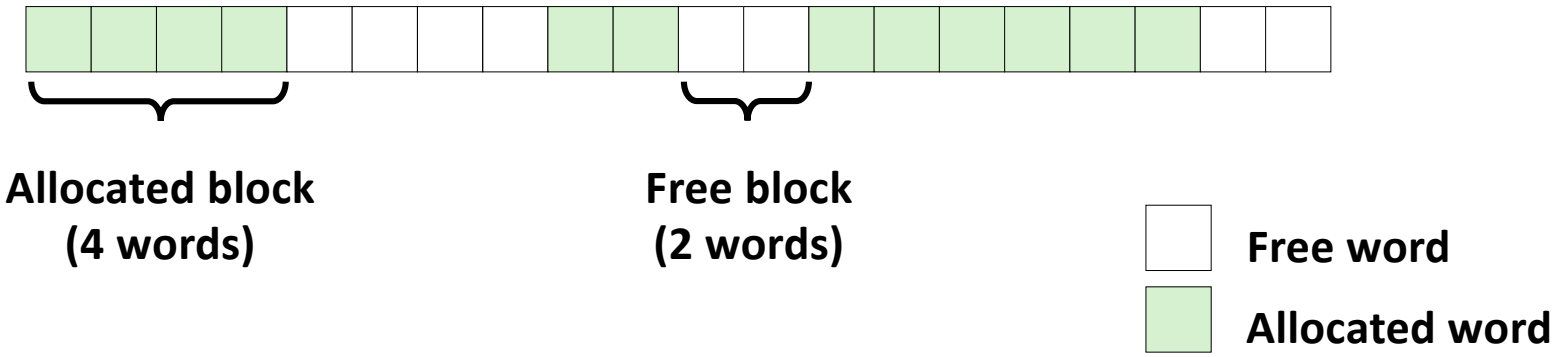
- **`calloc`**: Version of **`malloc`** that initializes allocated block to zero.
- **`realloc`**: Changes the size of a previously allocated block.
- **`sbrk`**: Used internally by allocators to grow or shrink the heap

`malloc` Example

```c
#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

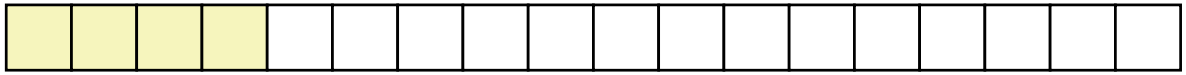
- Memory is word addressed
- Words are int-sized (4 bytes)
  - Each box below contains 4 bytes
- Allocations are double-word (8 byte) aligned



Allocation Example

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

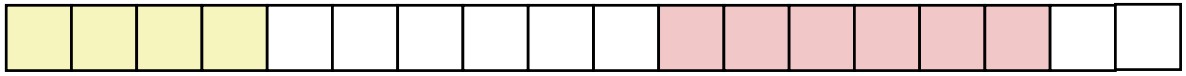
```
p1 = malloc(4*SIZ)
```



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

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

```
free(p2)
```



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

Constraints

- Applications ((i.e., programs)
  - 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 machines
  - 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 Goals: Throughput

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

- 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:
  - $R_0, R_1, ..., R_k, ..., R_{n-1}$
- *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*
  - $U_k = (max_{i \le k} P_i) \ / \ H_k$

Performance Goal: Peak Memory Utilization

- Given some sequence of `malloc` and `free` requests:
  - $R_0, R_1, ..., R_k, ..., R_{n-1}$
- *Def: Aggregate payload P_k*

- **Performance Goals:**
  - **1) Maximize throughput**
  - **2) Maximize peak memory utilization**
- **These goals are often conflicting!**

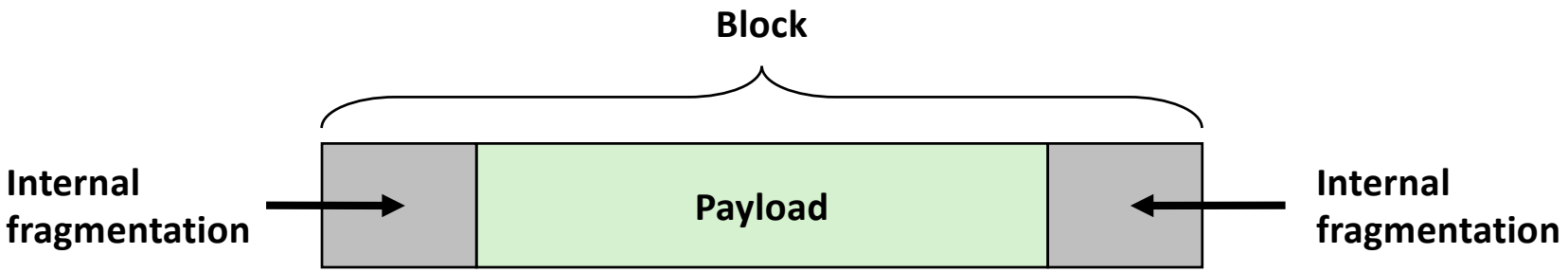
  - i.e., heap only grows when allocator uses **`sbrk`**
- *Def: Peak memory utilization after k+1 requests*
  - $U_k = (max_{i \le k} P_i) \ / \ H_k$

Fragmentation

- Poor memory utilization often 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)
```

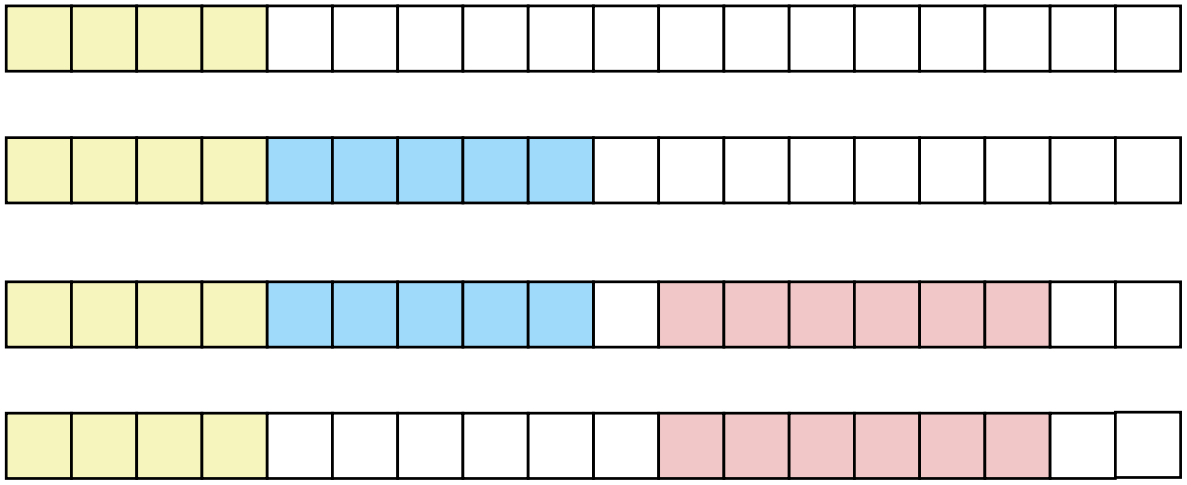
- Occurs when there is enough aggregate heap memory, but no single free block is large enough

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

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

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

```
free(p2)
```



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

Oops! (what would happen now?)

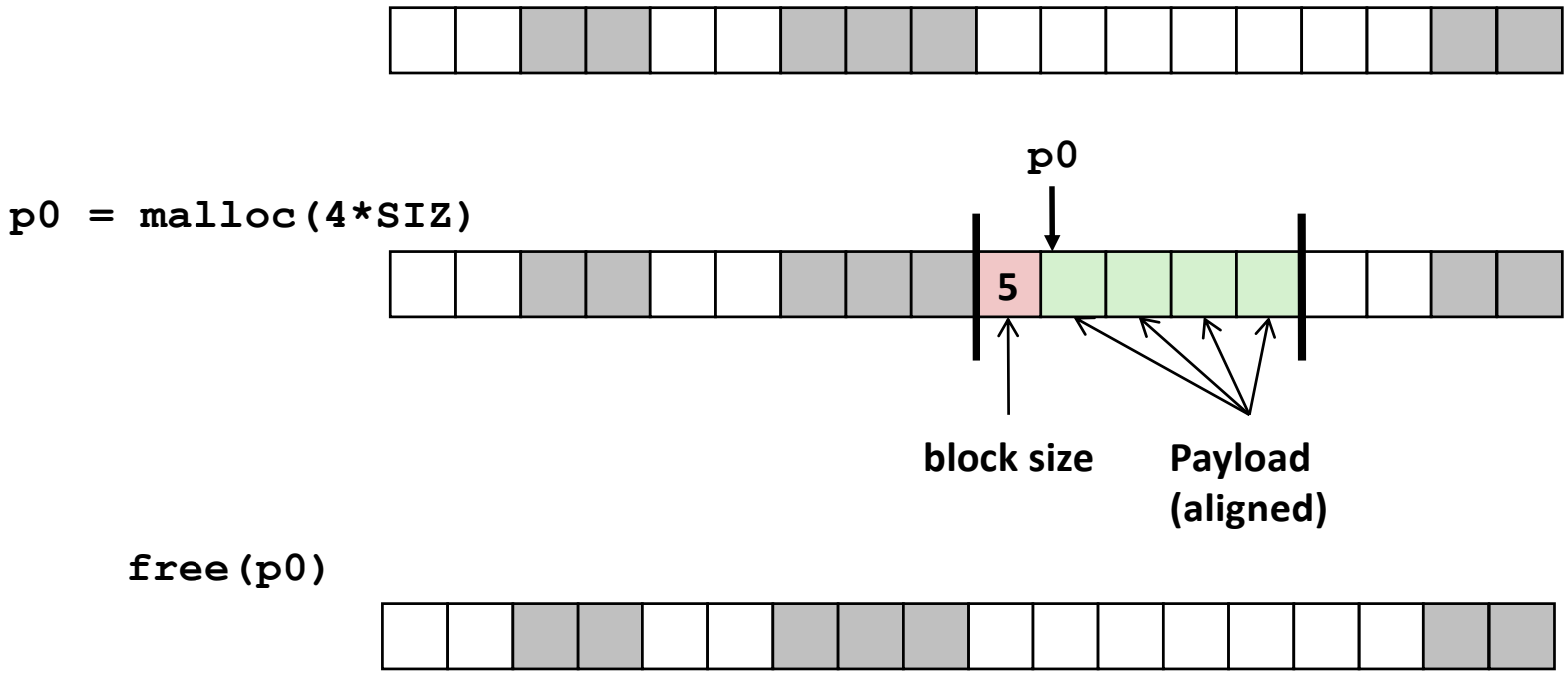
- Depends on the pattern of future requests
  - Thus, difficult to measure

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?

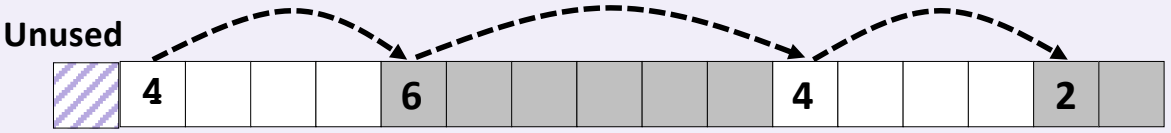
Knowing How Much to Free

- 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

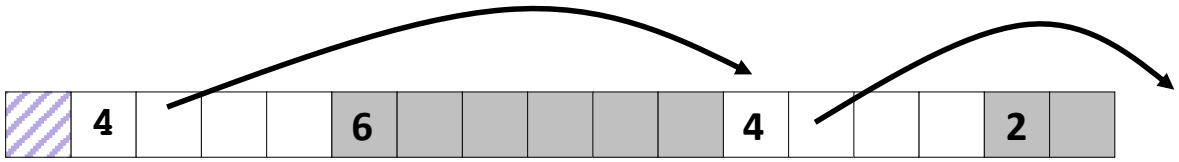
- Method 1: *Implicit list* using length—links all blocks



Need to tag each block as allocated/free

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

Lab 6!



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

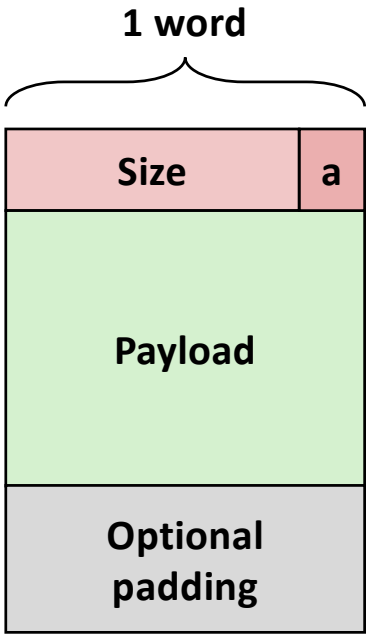
Today

- Dynamic Memory Allocation (Ch 9.9)
  - Basic concepts
  - Implicit free lists

Method 1: Implicit Free List (Ch 9.9.6)

- 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 (3) 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

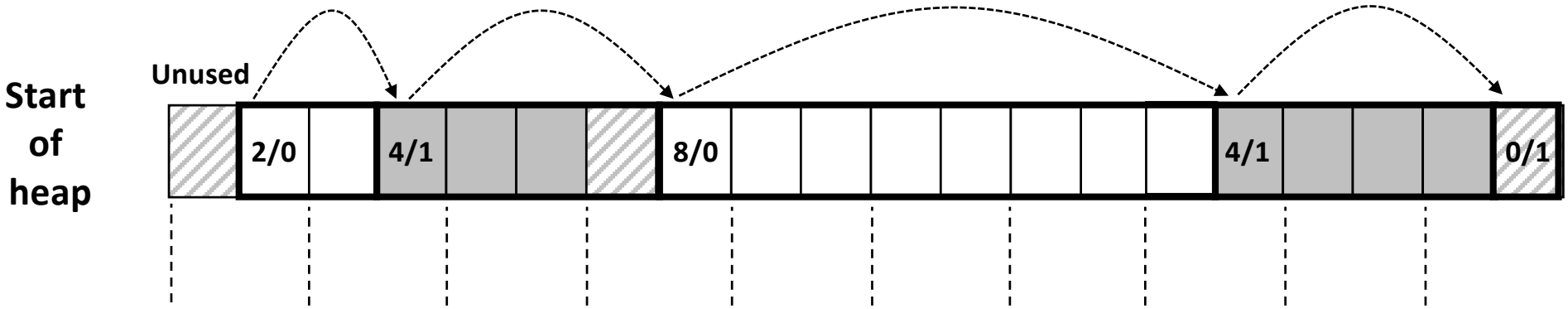


a = 1: Allocated block
a = 0: Free block

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"

Headers are at non-aligned positions
Payloads are aligned

Implicit List: Finding a Free Block (9.9.7)

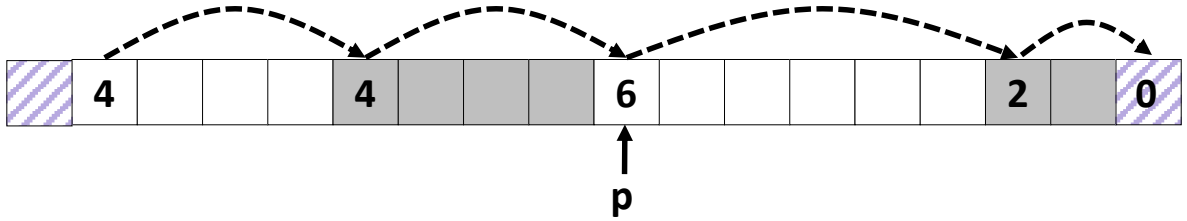
- *First fit:*
  - Search list from beginning, choose ***first*** free block that fits:

```
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)
```

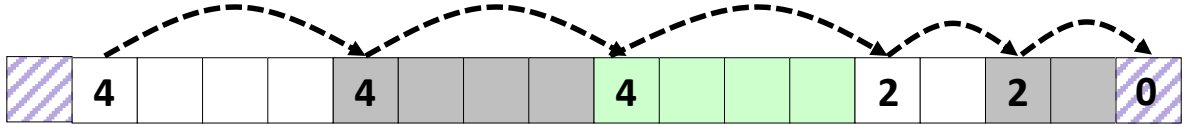
  - Can take linear time in total number of blocks (allocated and free)
  - In practice it can cause "splinters" at beginning of list
- *Next fit:*
  - Like first fit, but search list starting where previous search finished
  - Should often be faster than first fit: avoids re-scanning unhelpful blocks
  - 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)`



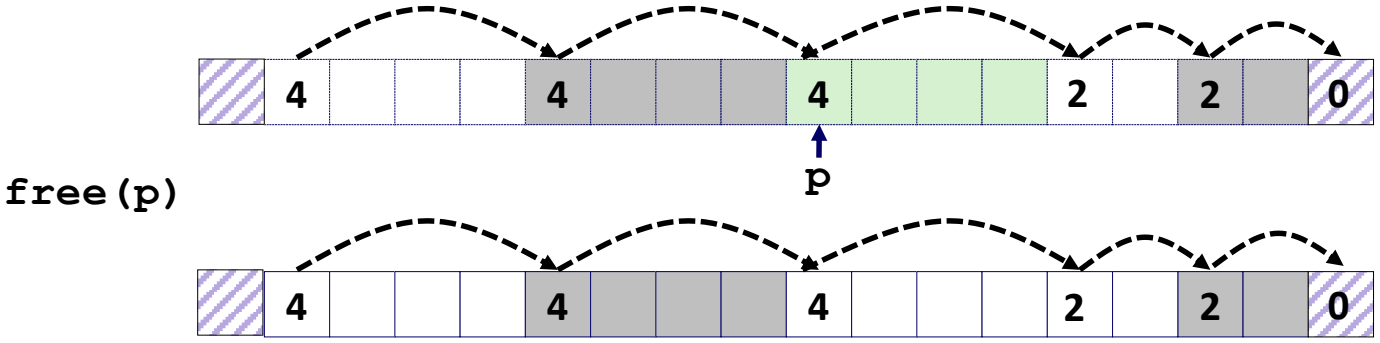

```
void addblock(ptr p, int len) {
  int newsize = ((len + 1) >> 1) << 1;  // round up to even
  int oldsize = *p & -2;                // mask out low bit
  *p = newsize | 1;                     // set new length
  if (newsize < oldsize)
    *(p+newsize) = oldsize - newsize;   // set length in remaining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

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"



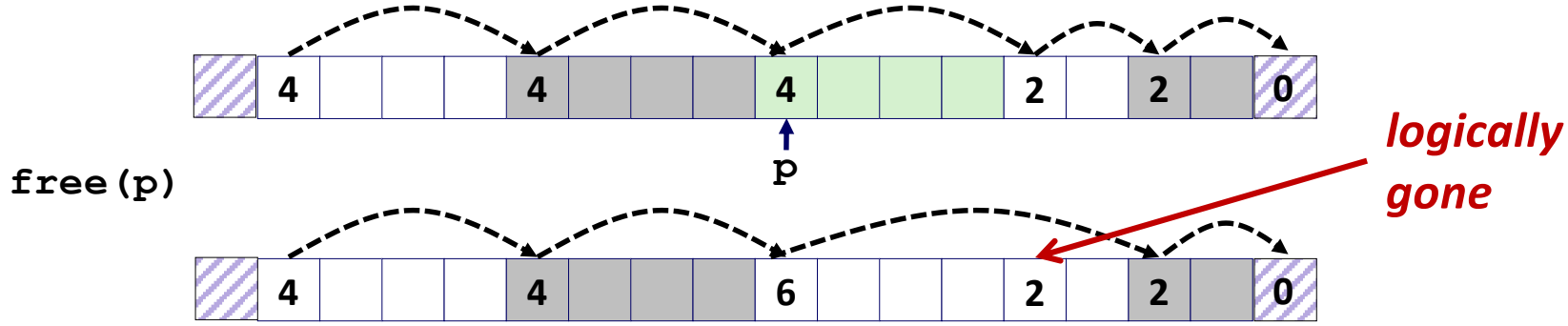

```
malloc(5*SIZ)
```

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

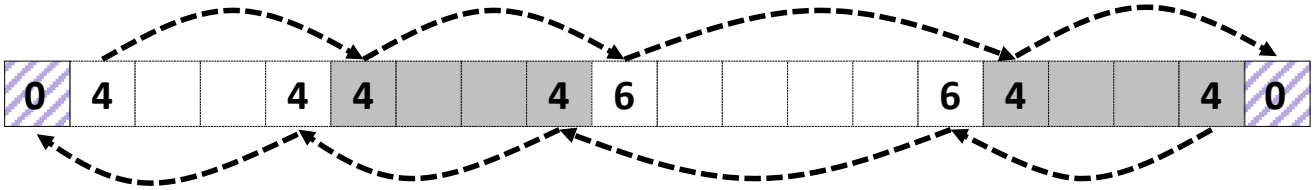



```
void free_block(ptr p) {
    *p = *p & -2;           // clear allocated flag
    next = p + *p;          // find next block
    if ((*next & 1) == 0)
      *p = *p + *next;      // add to this block if
}                           //    not allocated
```

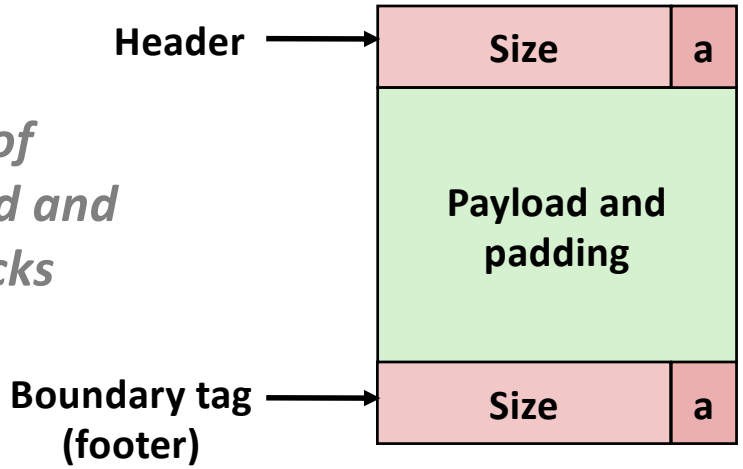
  - But how do we coalesce with *previous* block?

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

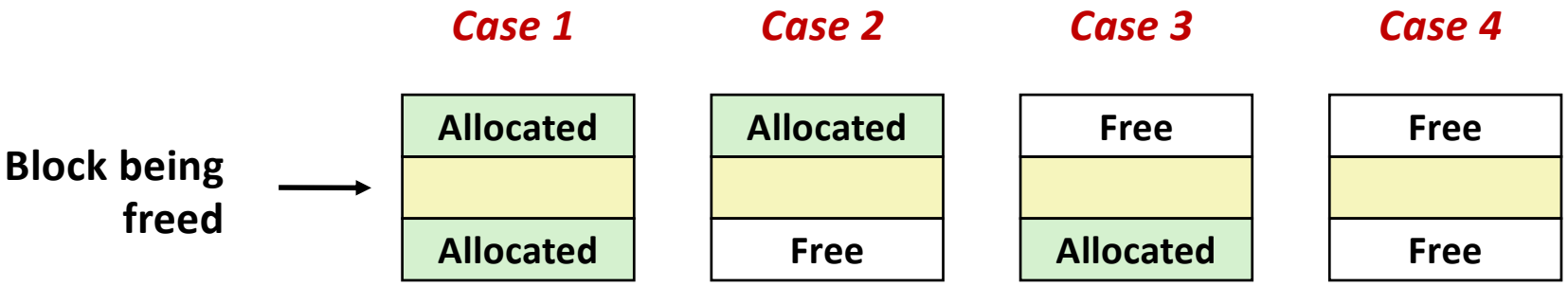


a = 1: Allocated block
a = 0: Free block

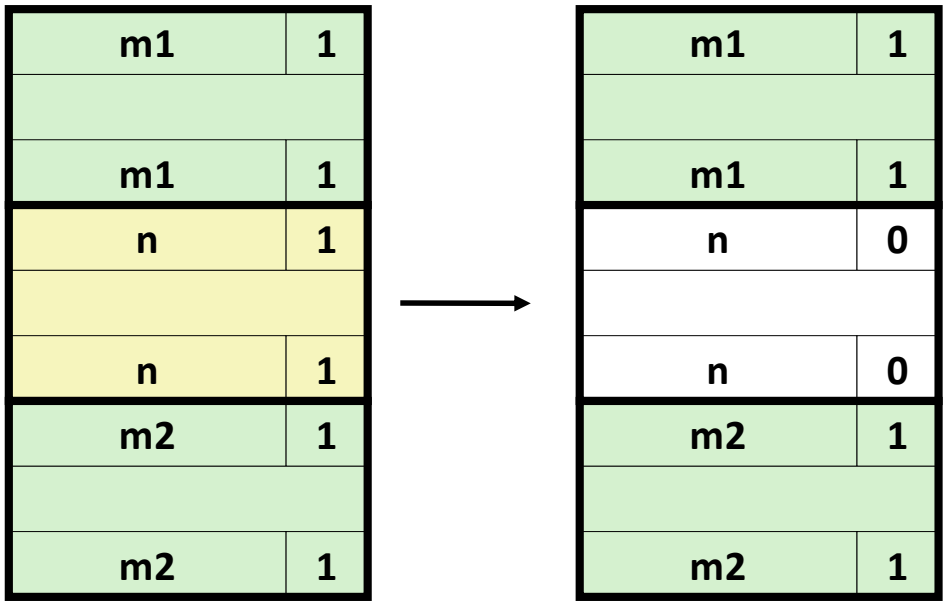
Size: Total block size

Payload: Application data (allocated blocks only)

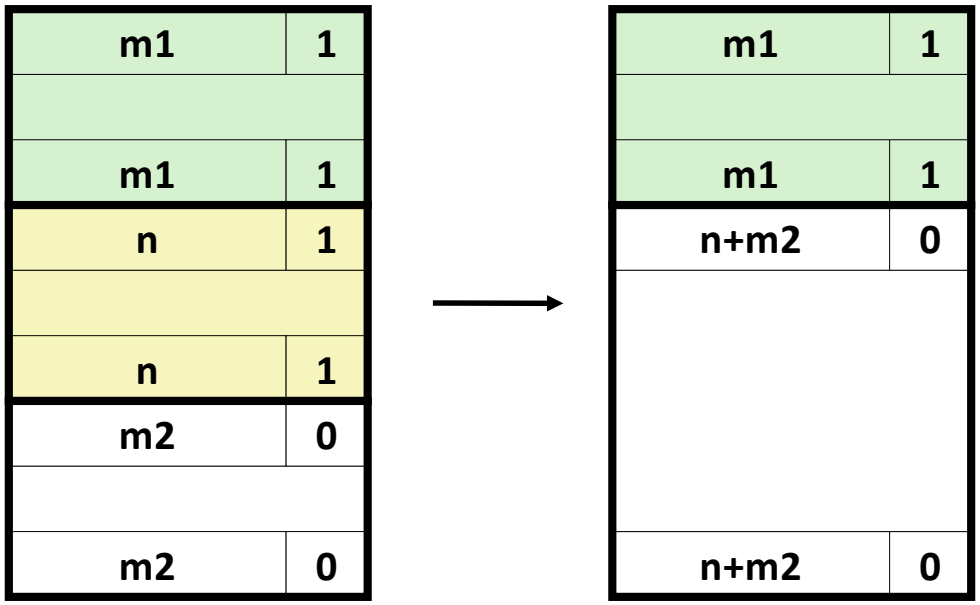
Constant Time Coalescing



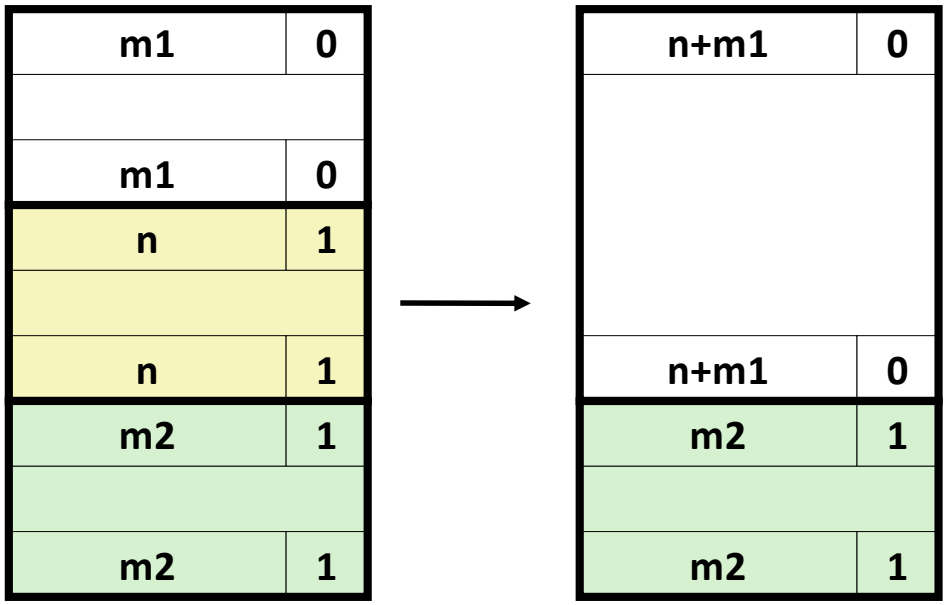
Constant Time Coalescing (Case 1)



Constant Time Coalescing (Case 2)



Constant Time Coalescing (Case 3)



Constant Time Coalescing (Case 4)