# Introduction to Computer Systems

15-213/18-243, fall 2009

16th Lecture, Oct. 22th

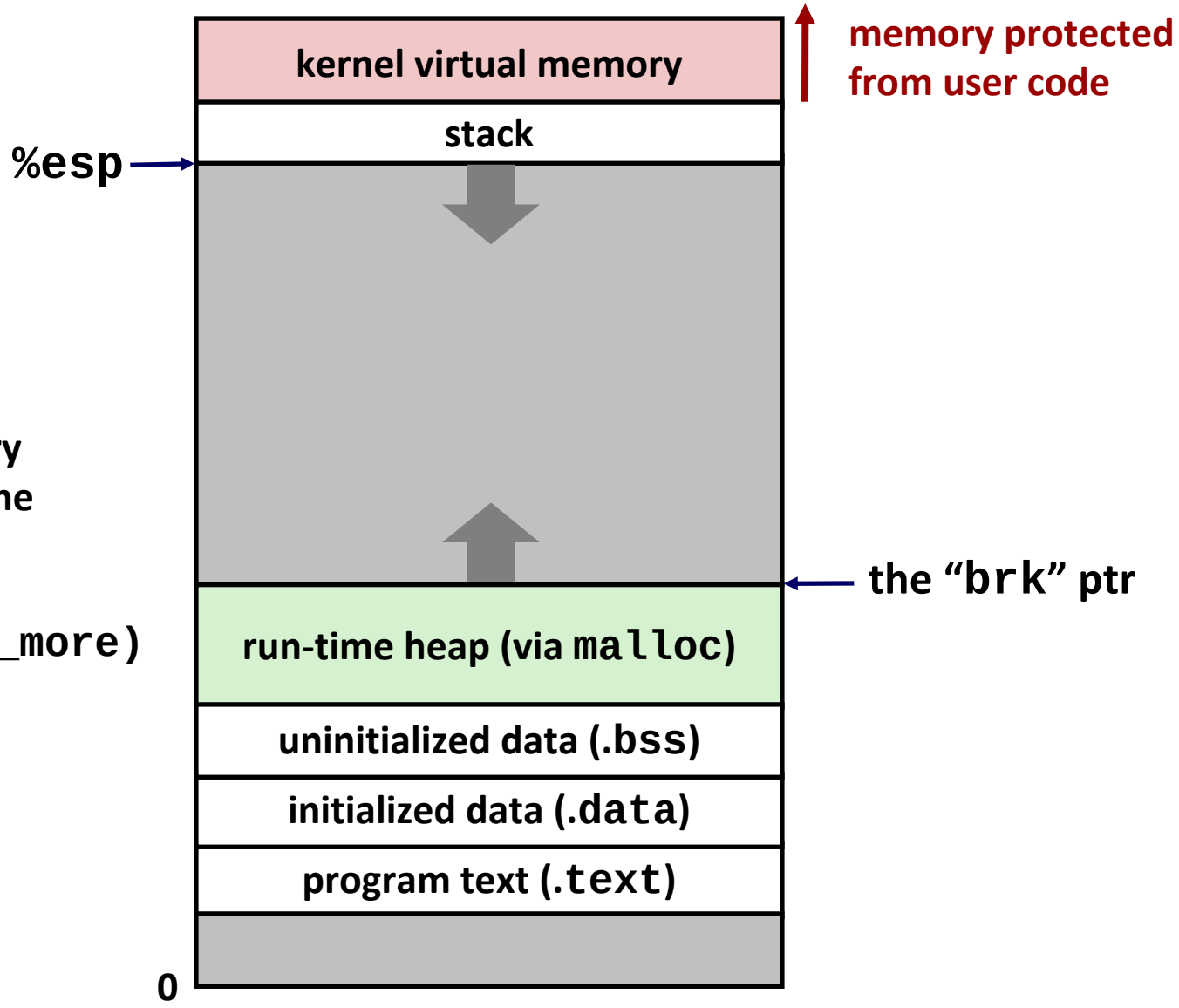
**Instructors:**

Gregory Kesden and Markus Püschel

# Today

- **Dynamic memory allocation**

# Process Memory Image




Allocators request additional heap memory from the kernel using the `sbrk()` function:

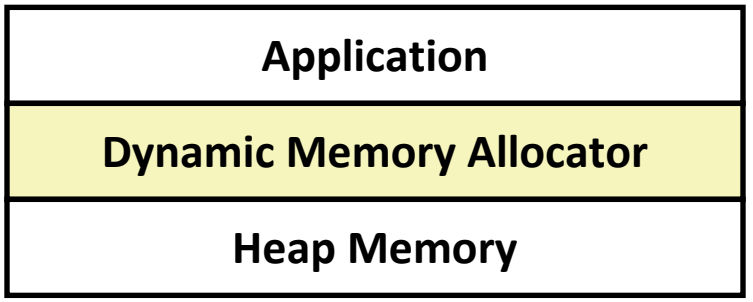
```
error = sbrk(amt_more)
```

# Why Dynamic Memory Allocation?

- Sizes of needed data structures may only be known at runtime

# Dynamic Memory Allocation

- **Memory allocator?**
  - VM hardware and kernel allocate pages
  - Application objects are typically smaller
  - Allocator manages objects within pages




- **Explicit vs. Implicit Memory Allocator**
  - ***Explicit:*** application allocates and frees space
    - In C: **`malloc()`** and **`free()`**
  - ***Implicit:*** application allocates, but does not free space
    - In Java, ML, Lisp: garbage collection
- **Allocation**
  - A memory allocator doles out memory blocks to application
  - A "block" is a contiguous range of bytes
    - of any size, in this context
- ***Today:*** **simple explicit memory allocation**

# Malloc Package

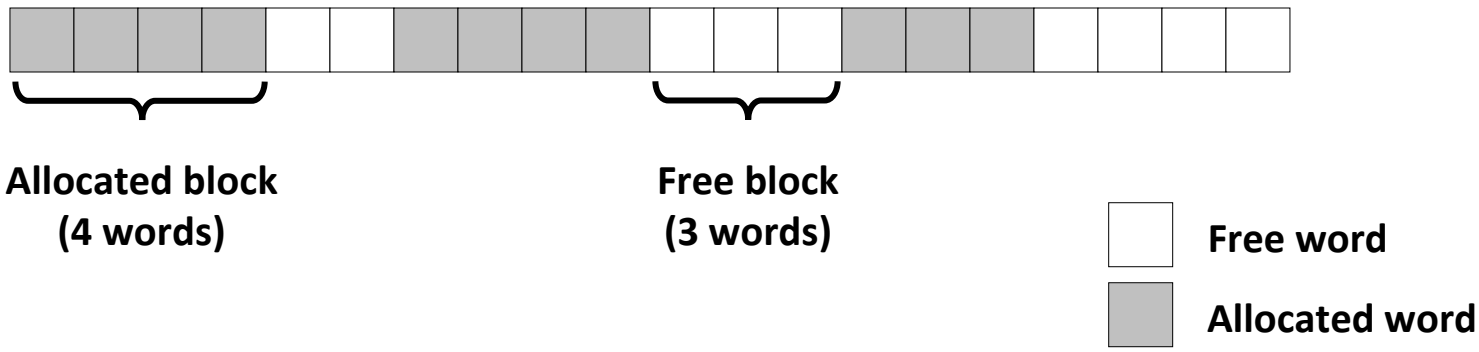
- `#include <stdlib.h>`
- `void *malloc(size_t size)`
  - Successful:
    - Returns a pointer to a memory block of at least `size` bytes (typically) aligned to 8-byte boundary
    - If `size == 0`, returns NULL
  - Unsuccessful: returns NULL (0) and sets errno
- `void free(void *p)`
  - Returns the block pointed at by `p` to pool of available memory
  - `p` must come from a previous call to `malloc()` or `realloc()`
- `void *realloc(void *p, size_t size)`
  - Changes size of block `p` and returns pointer to new block
  - Contents of new block unchanged up to min of old and new size
  - Old block has been `free()`'d (logically, if new != old)

# Malloc Example

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

  /* allocate a block of n ints */
  p = (int *)malloc(n * sizeof(int));
  if (p == NULL) {
    perror("malloc");
    exit(0);
  }
  for (i=0; i<n; i++) p[i] = i;

  /* add m bytes to end of p block */
  if ((p = (int *)realloc(p, (n+m) * sizeof(int))) == NULL) {
    perror("realloc");
    exit(0);
  }
  for (i=n; i < n+m; i++) p[i] = i;

  /* print new array */
  for (i=0; i<n+m; i++)
    printf("%d\n", p[i]);

  free(p); /* return p to available memory pool */
}
```

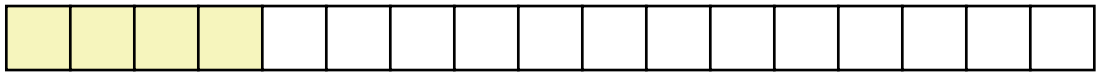
# Assumptions Made in This Lecture

- Memory is word addressed (each word can hold a pointer)

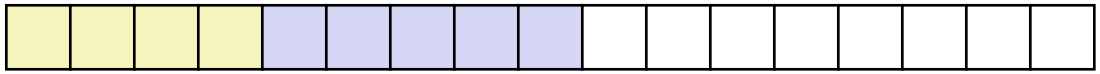


# Allocation Example

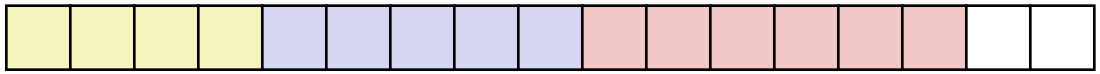
```
p1 = malloc(4)
```



```
p2 = malloc(5)
```



```
p3 = malloc(6)
```



```
free(p2)
```

```
p4 = malloc(2)
```

# Constraints

- **Applications**
  - Can issue arbitrary sequence of malloc() and free() requests
  - free() requests 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
    - 8 byte alignment for GNU malloc (**`libc`** malloc) 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:**
  - $R_0, R_1, ..., R_k, ..., R_{n-1}$
- **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
  - ***How to do `malloc()` and `free()` in O(1)? What's the problem?***

# Performance Goal: Peak Memory Utilization

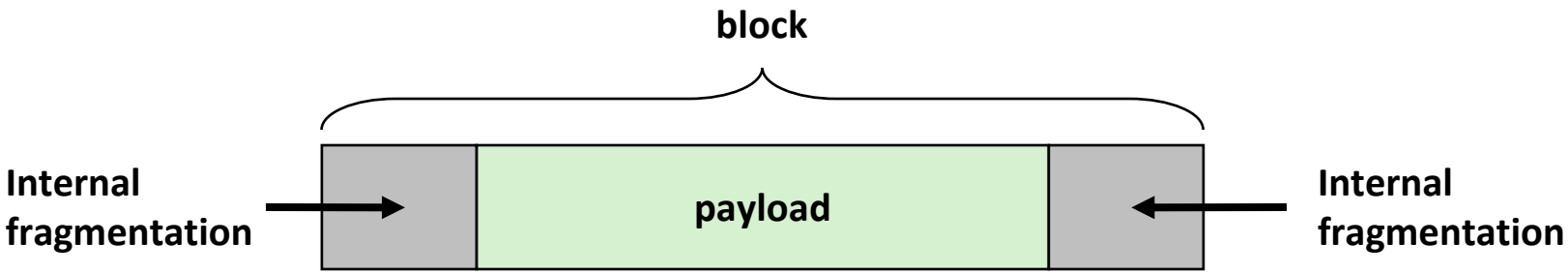
- **Given some sequence of `malloc` and `free` requests:**
  - $R_0, R_1, ..., R_k, ..., R_{n-1}$
- ***Def:* Aggregate payload $P_k$**
  - **`malloc(p)`** results in a block with a ***payload*** of **`p`** bytes
  - After request $R_k$ has completed, the ***aggregate payload*** $P_k$ is the sum of currently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

# 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

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

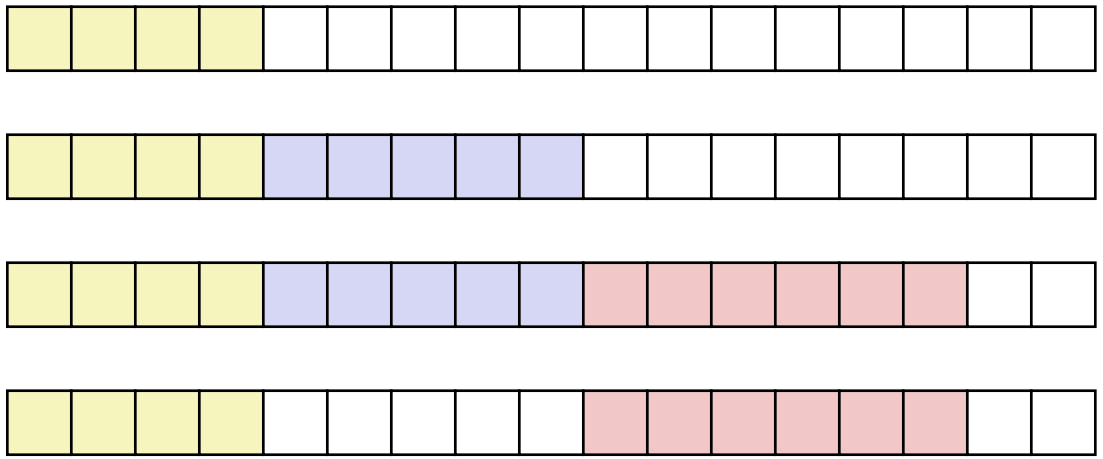
```
p1 = malloc(4)
```

```
p2 = malloc(5)
```

```
p3 = malloc(6)
```

```
free(p2)
```

```
p4 = malloc(6)
```



*Oops! (what would happen now?)*

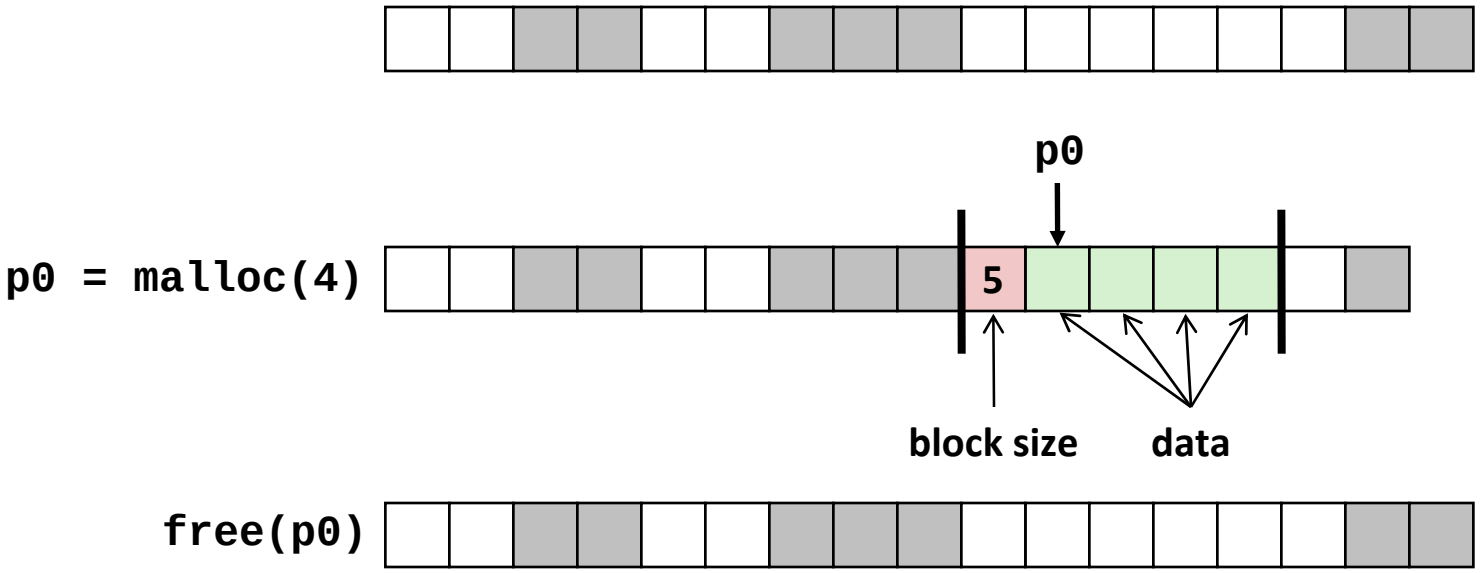
- Depends on the pattern of future requests
  - Thus, difficult to measure

# Implementation Issues

- How to know how much memory is being `free( )`'d when it is given only a pointer (and no length)?
- How to keep track of the free blocks?
- What to do with extra space when allocating a block that is smaller than the free block it is placed in?
- How to pick a block to use for allocation—many might fit?
- How to reinsert a freed block into the heap?

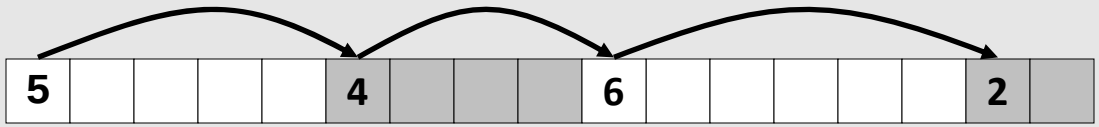
# Knowing How Much to Free

- **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

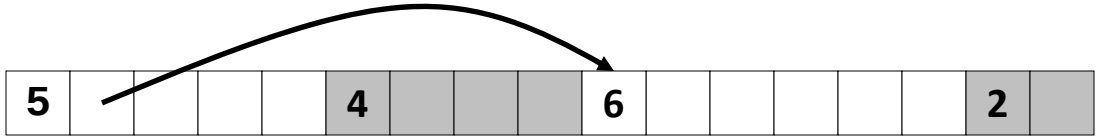


# Keeping Track of Free Blocks

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




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



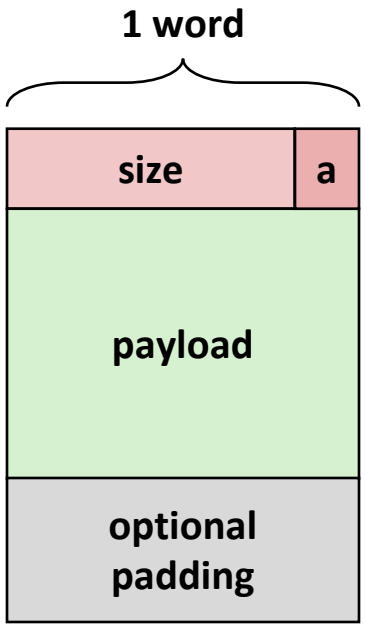

- Method 3: *Segregated free list*
  - Different free lists for different size classes

- Method 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

# Method 1: Implicit List

- **For each block we need: length, is-allocated?**
  - 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)**

# Implicit List: Finding a Free Block

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

```
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 helps fragmentation
  - Will typically run slower than first-fit

# Bit Fields

- How to represent the Header: Masks and bitwise operators

```
#define SIZEMASK            (~0x7)
#define PACK(size, alloc)   ((size) | (alloc))
#define GET_SIZE(p)         ((p)->size & SIZEMASK)
```

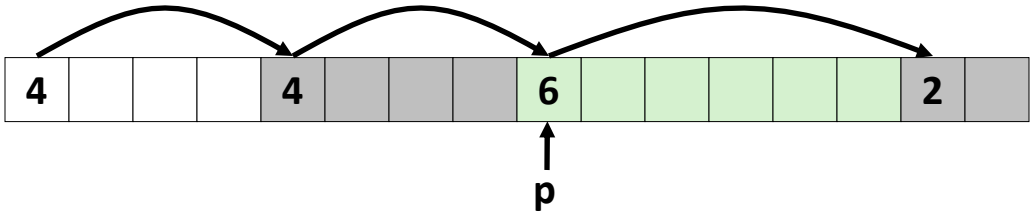
- Bit Fields

```
 struct {
     unsigned allocated:1;
     unsigned size:31;
} Header;
```

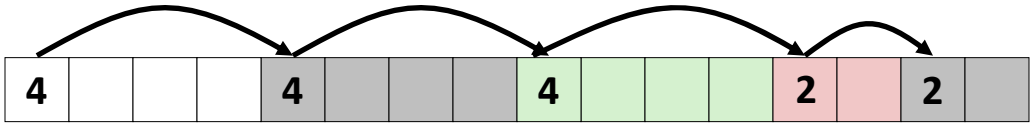
Check your K&R: structures are not necessarily packed

# 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)`



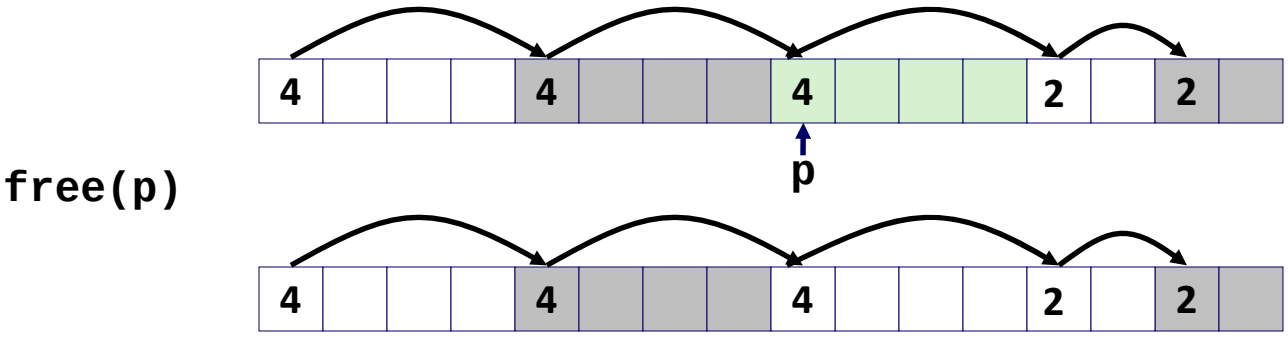

```
void addblock(ptr p, int len) {
  int newsize = ((len + 1) >> 1) << 1;  // round up to even
  int oldsize = *p & -2;                // mask out low bit
  *p = newsize | 1;                     // set new length
  if (newsize < oldsize)
    *(p+newsize) = oldsize - newsize;   // set length in remaining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

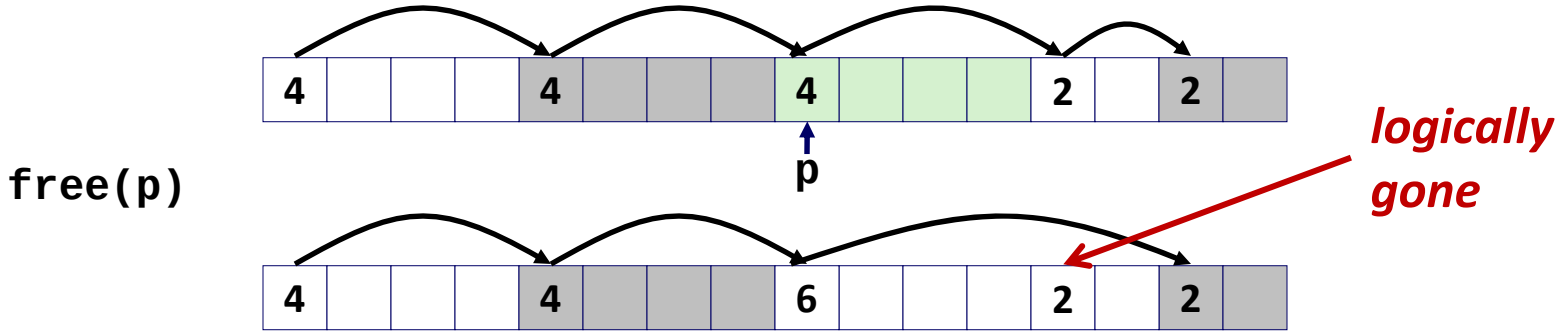



`malloc(5)` ***Oops!***

***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

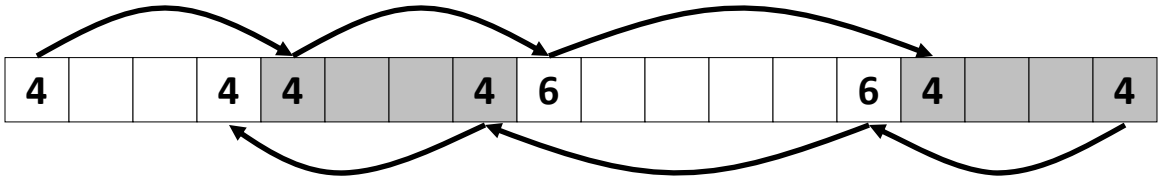



```
void free_block(ptr p) {
    *p = *p & -2;          // clear allocated flag
    next = p + *p;         // find next block
    if ((*next & 1) == 0)
      *p = *p + *next;     // add to this block if
}                          //    not allocated
```

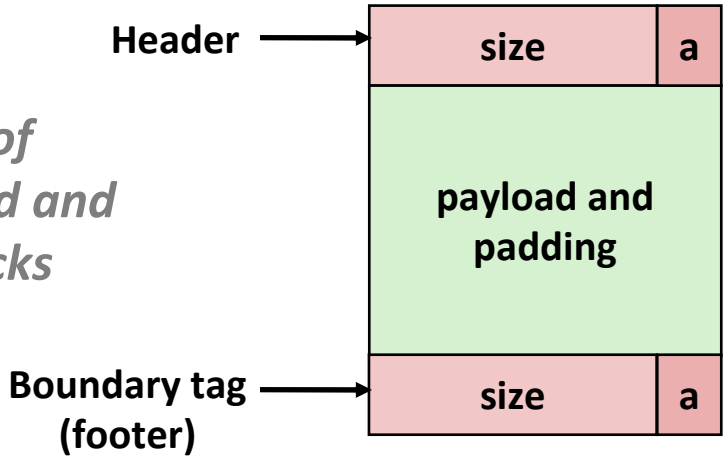
  - But how do we coalesce with *previous* block?

# 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*

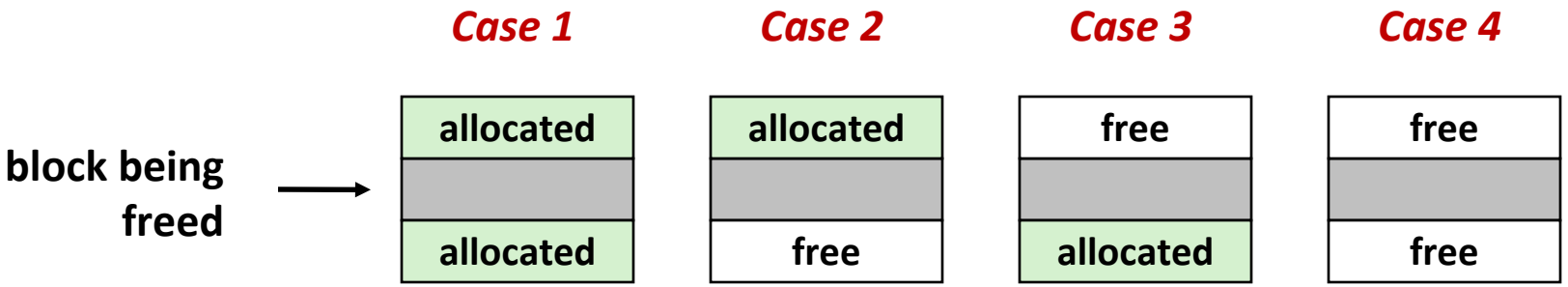



**a = 1: allocated block**
**a = 0: free block**

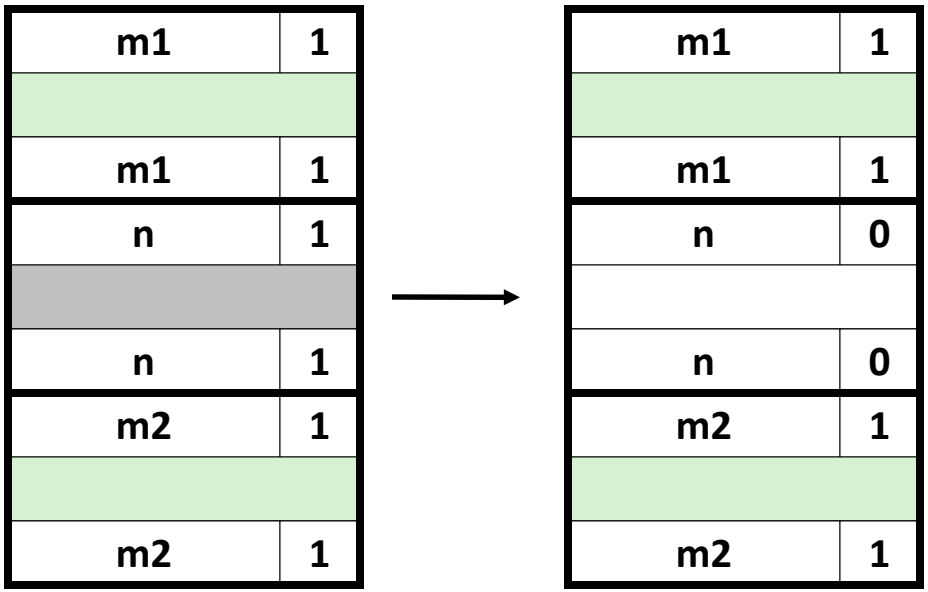
**size: total block size**

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

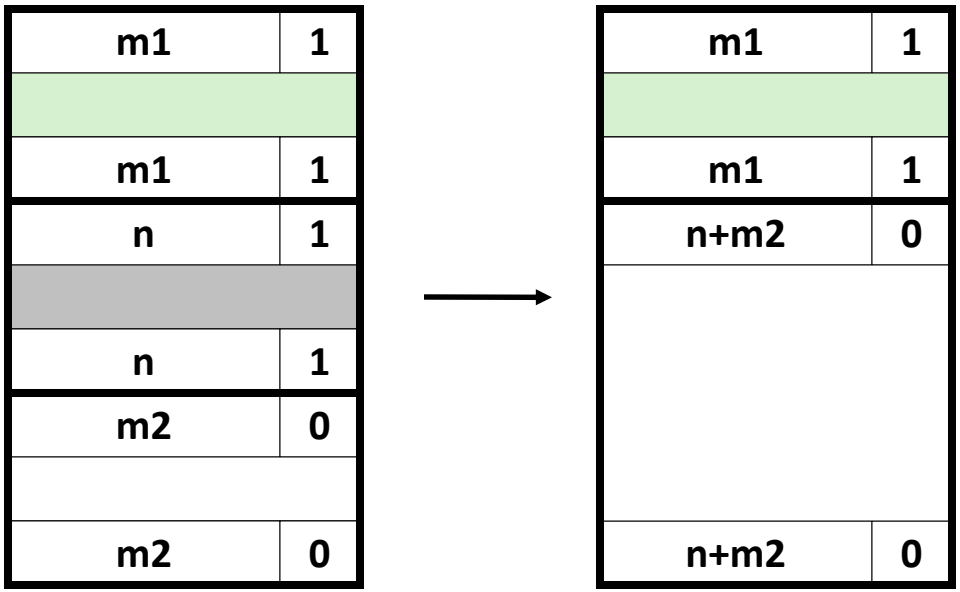
# Constant Time Coalescing



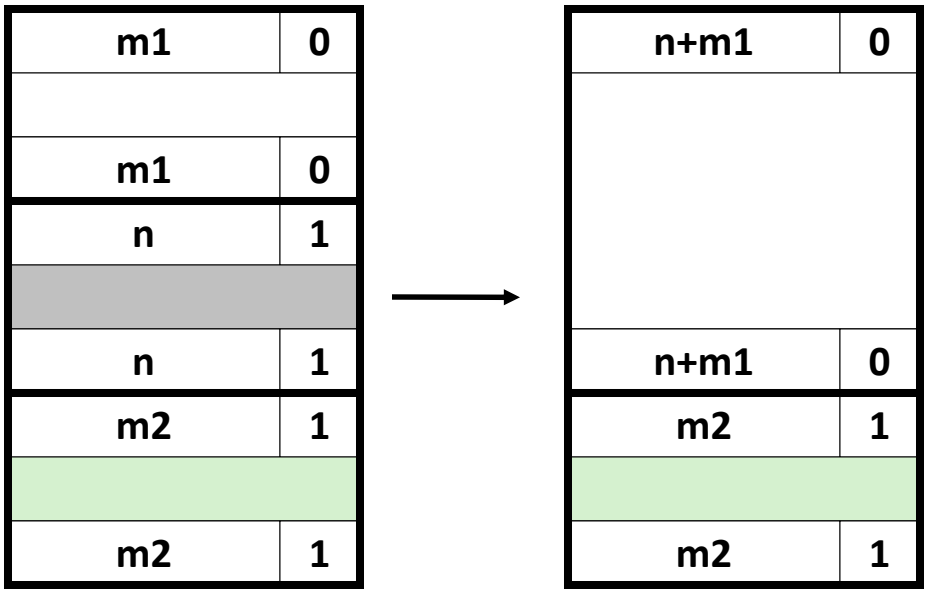
# Constant Time Coalescing (Case 1)



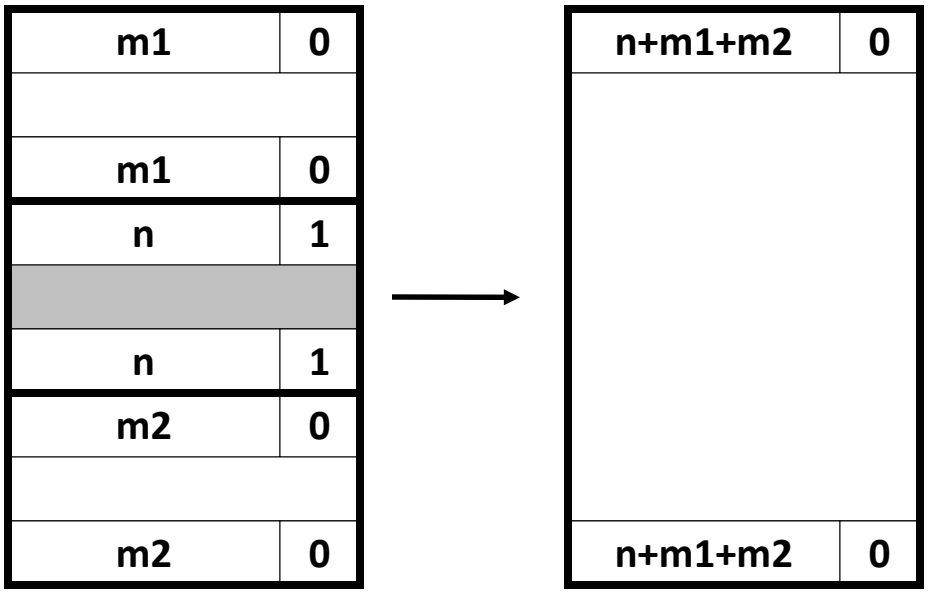
# Constant Time Coalescing (Case 2)



# 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?

# 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**