Dynamic Memory Allocation: Basic Concepts

15-213 / 18-213: Introduction to Computer Systems
18th Lecture, March 24, 2015

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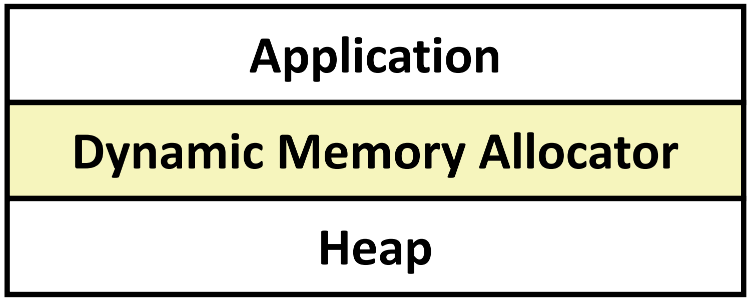
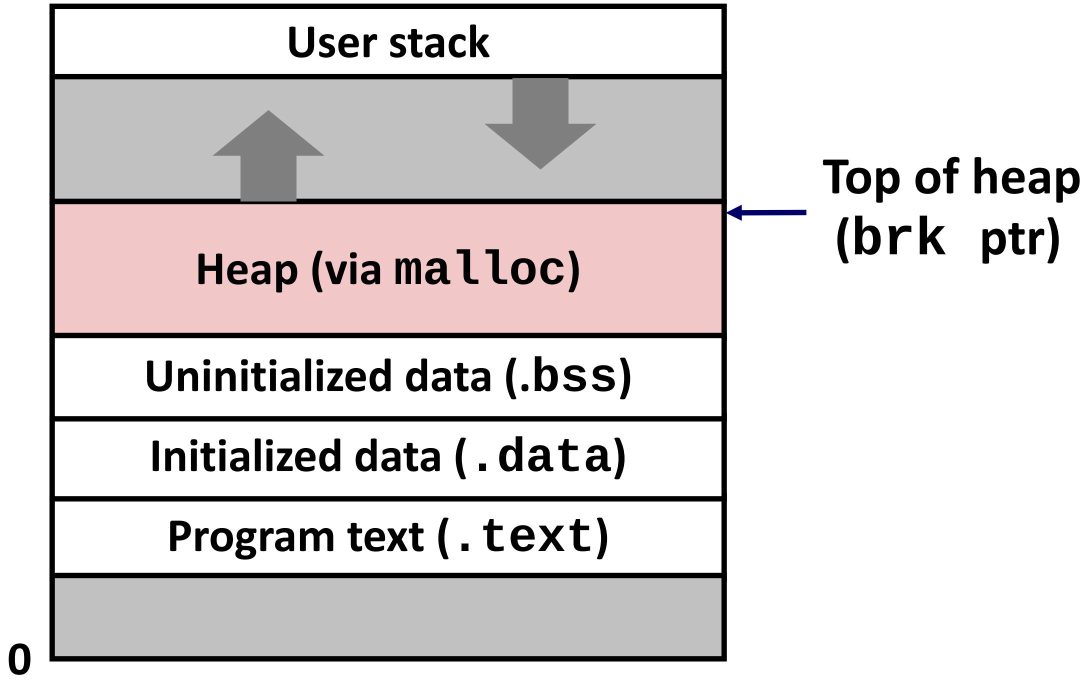
Today

- **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*.**





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 8-byte (x86) or 16-byte (x86-64) 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`**

Other functions

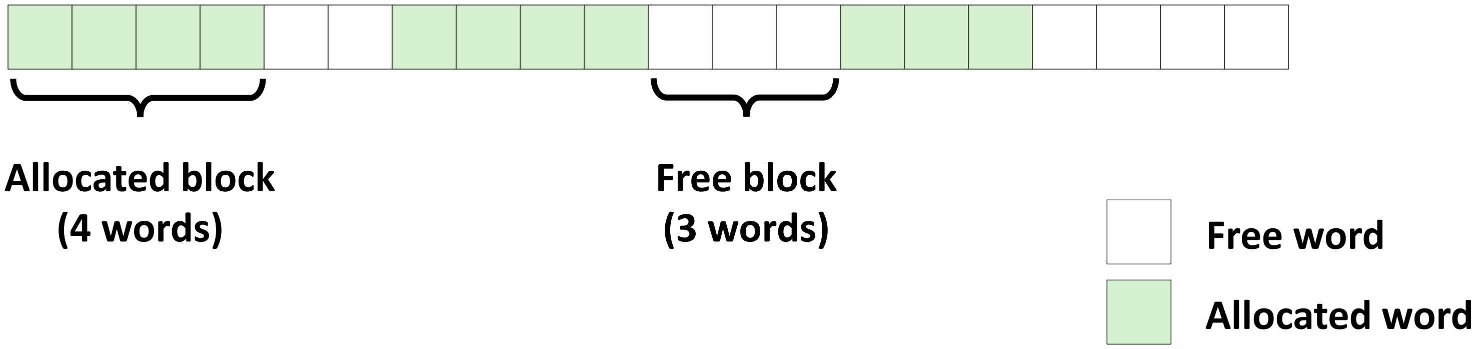
- **`calloc`**: Version of **`malloc`** that initializes allocated block to zero.
- **`realloc`:** Changes the size of a previously allocated block.
- **`sbrk`**: Used internally by allocators to grow or shrink the heap

`malloc` Example

```
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);
    }

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


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

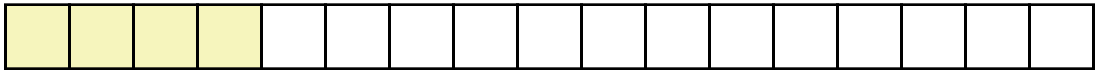
Assumptions Made in This Lecture

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

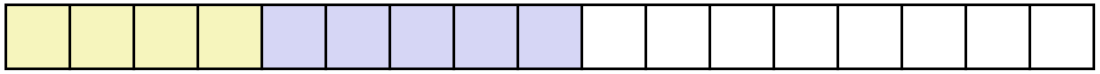


Allocation Example

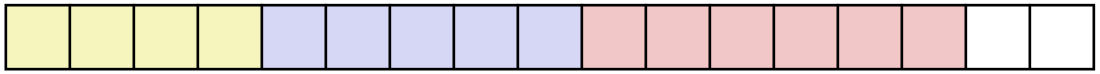
`p1 = malloc(4)`



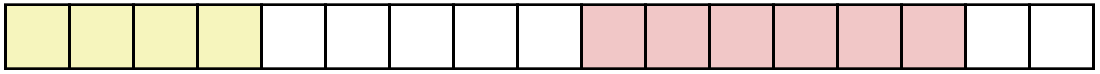
`p2 = malloc(5)`



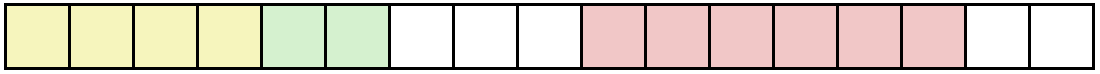
`p3 = malloc(6)`



`free(p2)`



`p4 = malloc(2)`



Constraints

- **Applications**
  - Can issue arbitrary sequence of **`malloc`** and **`free`** requests
  - **`free`** 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
    - 8-byte (x86) or 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:**
  - $R_0, R_1, \ldots, R_k, \ldots, R_{n-1}$

- **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

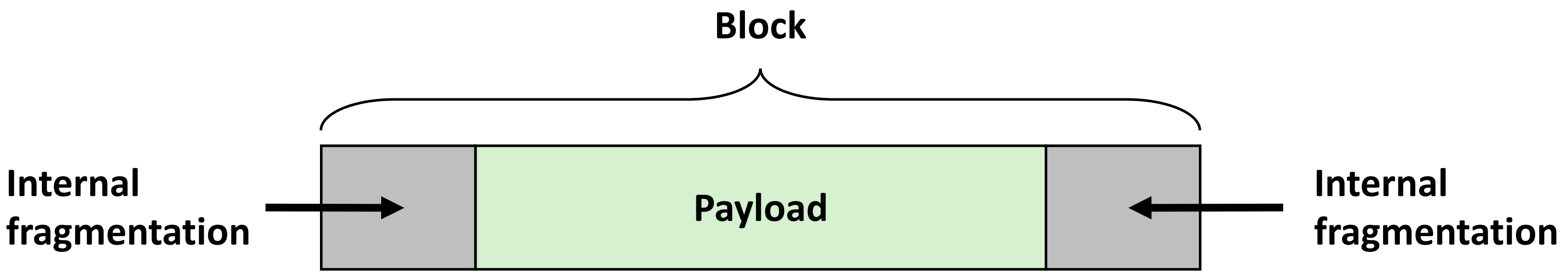
- **Given some sequence of `malloc` and `free` requests:**
  - $R_0, R_1, \ldots, R_k, \ldots, R_{n-1}$
- ***Def:* Aggregate payload P_k**
  - **`malloc(p)`** results in a block with a ***payload*** of **`p`** bytes
  - After request R_k has completed, the ***aggregate payload*** P_k is the sum of currently 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**
  - $U_k = (\max_{i<=k} P_i) \;/\; H_k$

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**

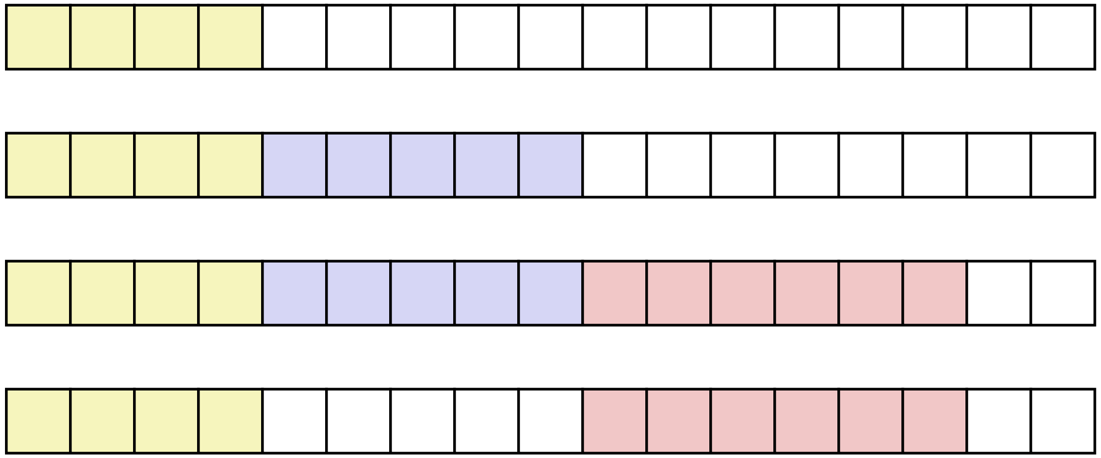
`p1 = malloc(4)`

`p2 = malloc(5)`

`p3 = malloc(6)`

`free(p2)`

`p4 = malloc(6)`



Oops! (what would happen now?)

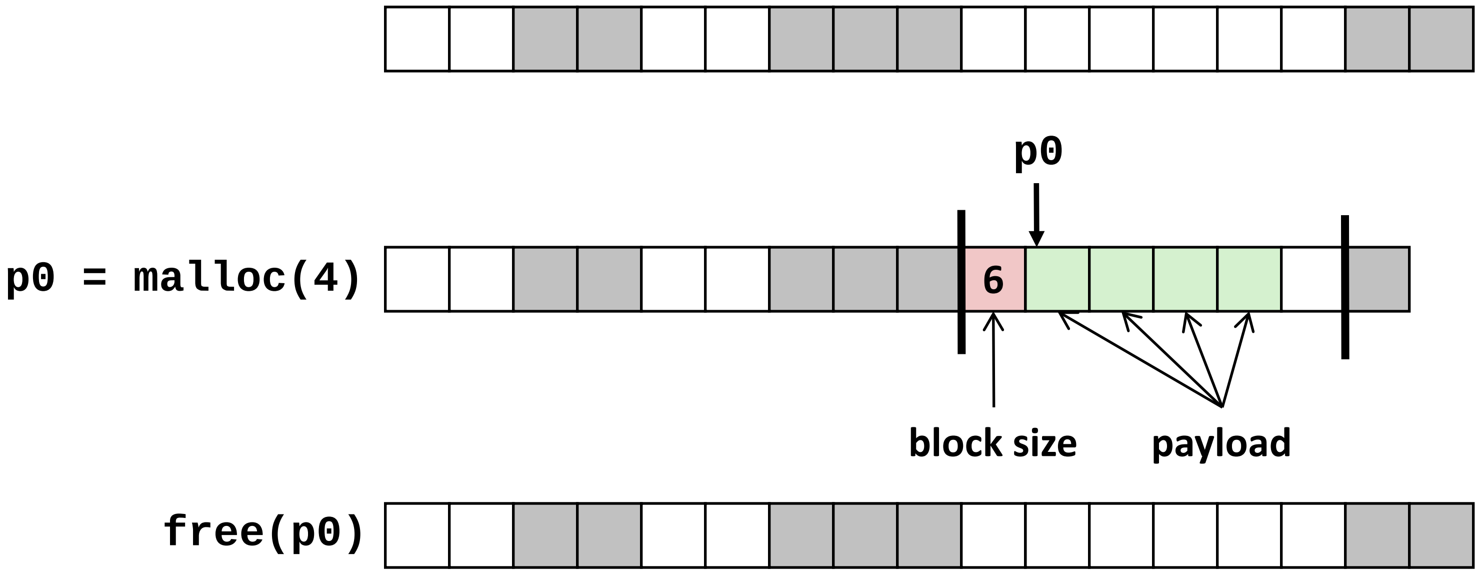
- **Depends on the pattern of future requests**
  - Thus, difficult to measure

Implementation Issues

- How 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?

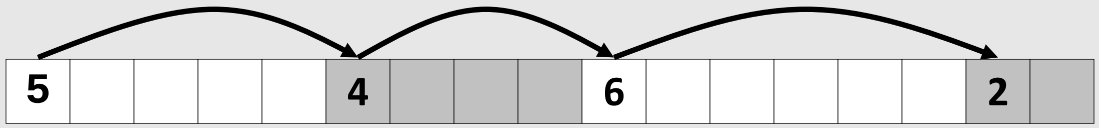
Knowing How Much to Free

- **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

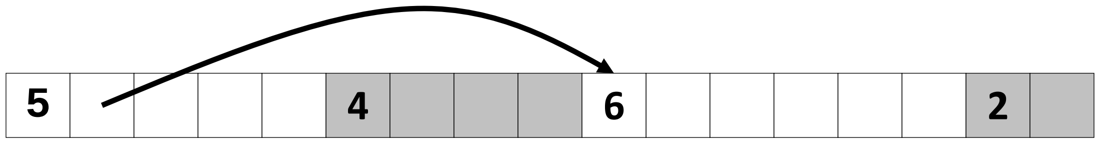


Keeping Track of Free Blocks

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



- **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

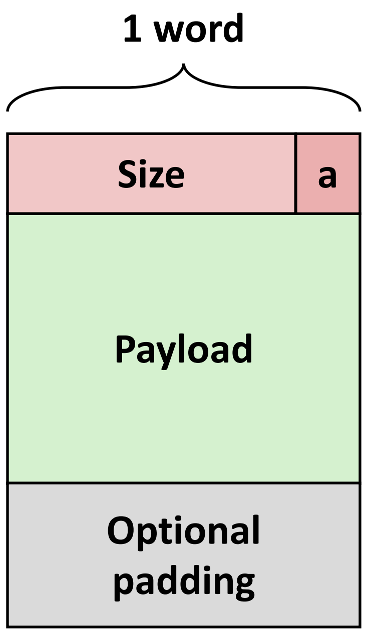
Today

- Basic concepts
- **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 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

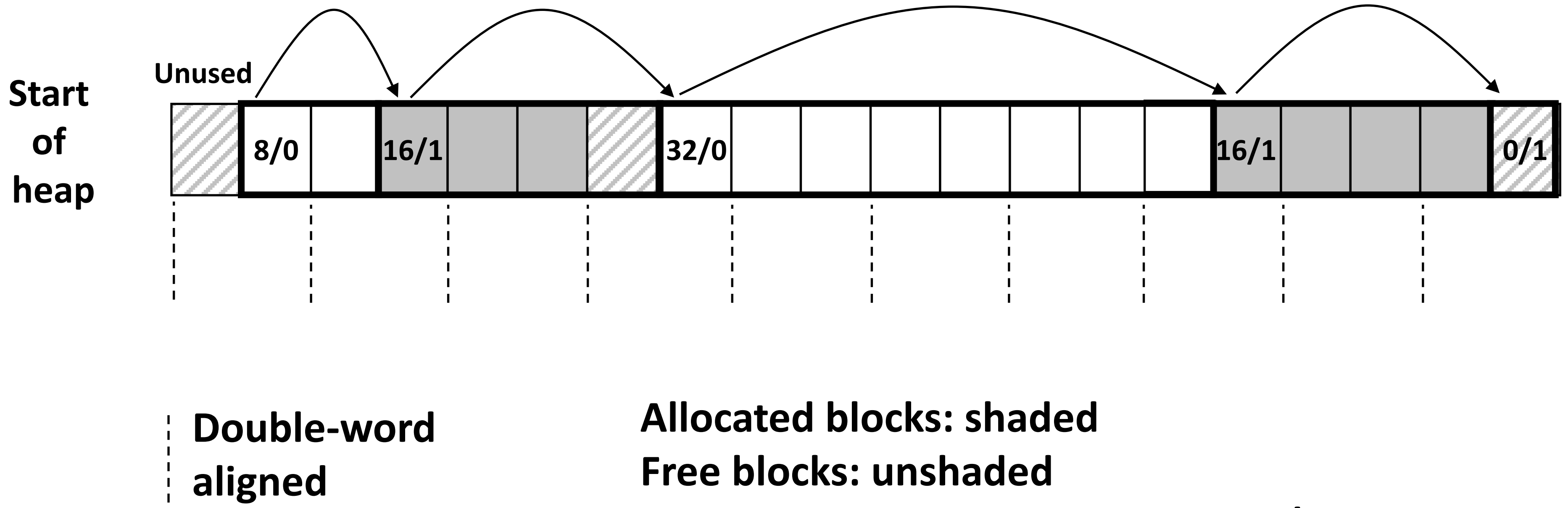


a = 1: Allocated block
a = 0: Free block

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

First Fit code, Style (1)

```
typedef uint32_t word;
typedef int bool;
```

// Return true if the block is not after end. Assume block > start

```
static inline bool isBeforeEnd(const word* block) {
  REQUIRES(block != NULL);
  REQUIRES(block >= mem_heap);
  return (block < mem_brk);
}
```

// Return true if the block pts to a valid address in the heap

```
static inline bool isInHeap(const word* block) {
  return ((block >= mem_heap)&&(block < mem_brk));
}
```

First Fit code, Style (1)

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static inline bool isInHeap(const word* block) {
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}
```

REQUIRES is a macro which states a pre-condition.

I highly recommend using it!

`contracts.h`

- REQUIRES(condition) a precondition
- ENSURES(condition) a postcondition
- ASSERT(condition) an assertion

- Using these will improve readability
- Using these will reduce debugging time
- Used properly they will NOT decrease performance

First Fit code, Style (1)

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  return (block < mem_brk);
}
```

// Return true if the block pts to a valid address in the heap

```
static inline bool isInHeap(const word* block) {
  return ((block >= mem_heap)&&(block < mem_brk));
}
```

First Fit code, Style (2)

// Return true if the block is allocated, false otherwise

```
static inline bool isAllocated(const word* block) {
  REQUIRES(block != NULL);
  REQUIRES(isInHeap(block));

  return *block&0x01;
}
```

// return length of this UNallocated block in words

```
static inline int getLengthOfFreeBlock(const word* block) {
  REQUIRES(!isAllocated(block));
  return *block;
}
```

First Fit code, Style (3)

```
// return length of this block in words
static inline int getLengthOfBlock(const word* block) {
  REQUIRES(block != NULL);
  REQUIRES(isInHeap(block));
  return (*block & -2);
}

// get ptr to next block
static inline word* nextBlock(const word* block) {
  REQUIRES(block != NULL);
  REQUIRES(isInHeap(block));
  return block+getLengthOfBlock(block);
}
```

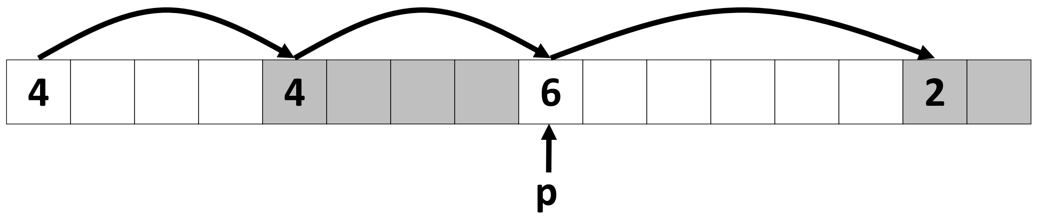
First Fit code, Style (4)

```
p = start;
while (isBeforeEnd(p) &&                      // not past end AND
       (isAllocated(p) ||                     // (Already allocated OR
        getLengthOfFreeBlock(p) <= len))      // too small)
  p = nextBlock(p);                           // goto next block
```

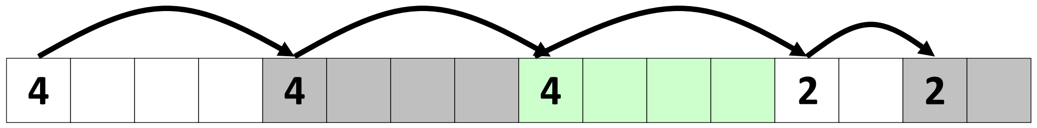
```
p = start;
while ((p < end) &&      \\ not passed end
       ((*p & 1) ||      \\ already allocated
       (*p  <= len)))    \\ too small
  p = p + (*p & -2);     \\ goto next block (word addressed)
```

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



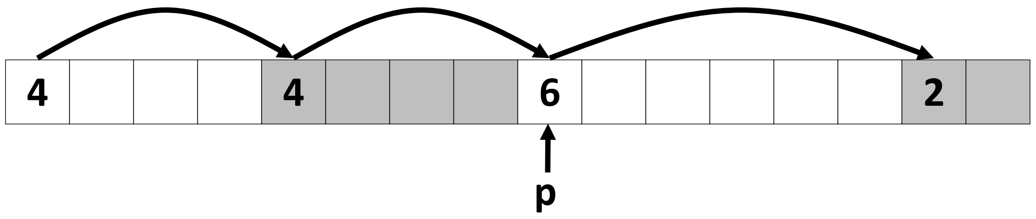
```
addblock(p, 4)
```



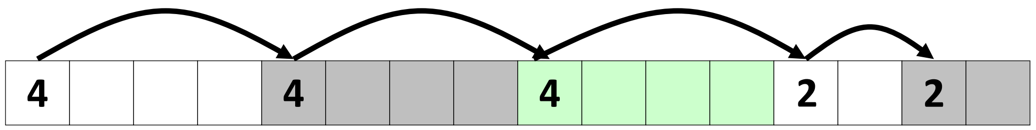
```
void addblock(ptr p, int len) {
  int newsize = ((len + 1) >> 1) << 1;  // round up to even
  int oldsize = *p & -2;                // mask out low bit
  *p = newsize | 1;                     // set new length
  if (newsize < oldsize)
    *(p+newsize) = oldsize - newsize;   // set length in remaining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

Implicit List: 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)`

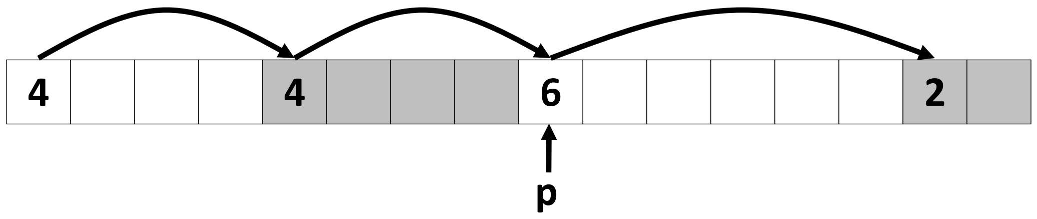


Better Style

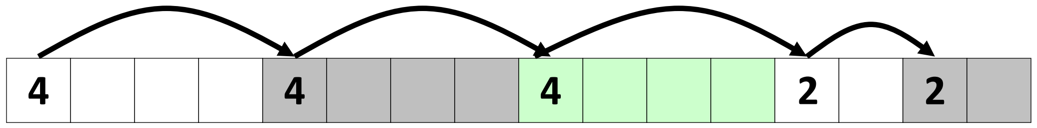
```
void addblock(ptr p, int len) {
  int newsize = ((len + 1) >> 1) << 1;  // round up to even
  int oldsize = getLengthOfBlock(p);    // get current size
  *p = newsize | 1;                     // set new length
  if (newsize < oldsize)
    *(p+newsize) = oldsize - newsize;   // set length in remaining
}                                       //   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)`



Should Also

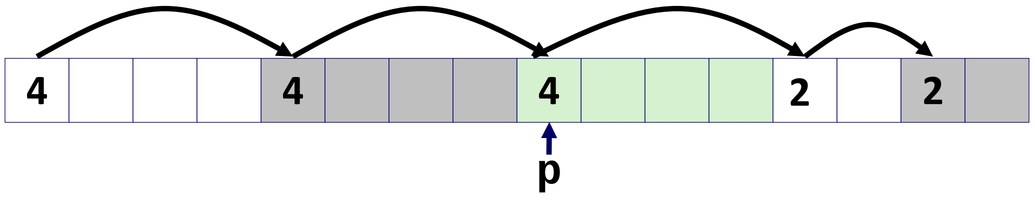
```
void addblock(ptr p, int len) {
  int newsize = ((len + 1) >> 1) << 1;  // round up to even
  int oldsize = getLengthOfBlock(p);    // get current size
  *p = newsize | 1;                     // set new length
  if (newsize < oldsize)
    *(p+newsize) = oldsize - newsize;   // set length in remaining
}                                       //   part of block
```

Implicit List: Freeing a Block

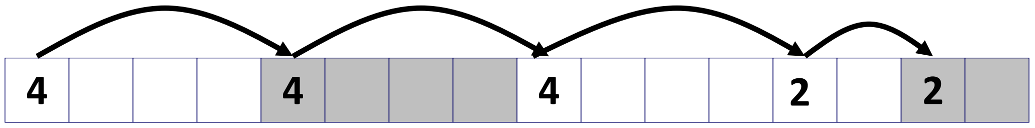
- **Simplest implementation:**
  - Need only clear the "allocated" flag

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

  - But can lead to "false fragmentation"



`free(p)`

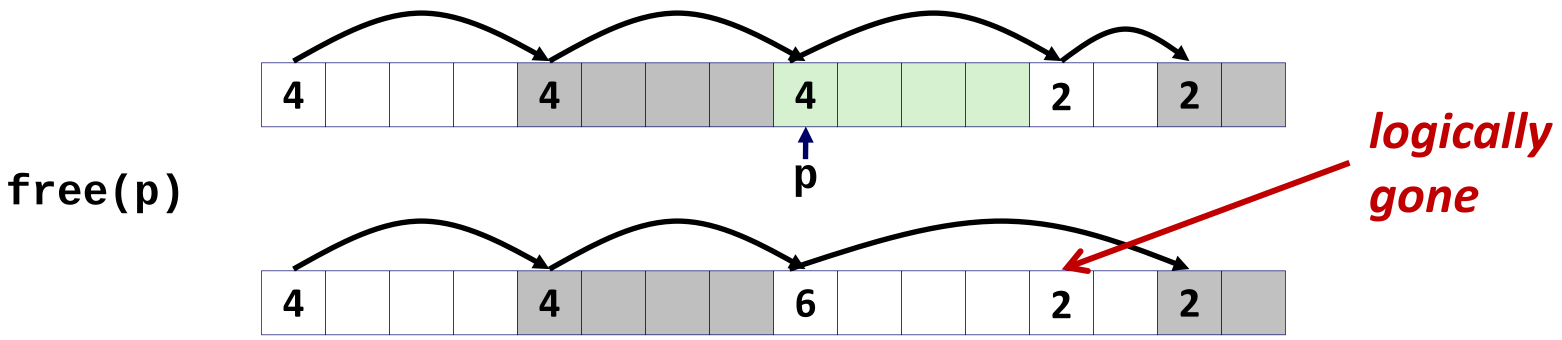


`malloc(5)` ***Oops!***

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

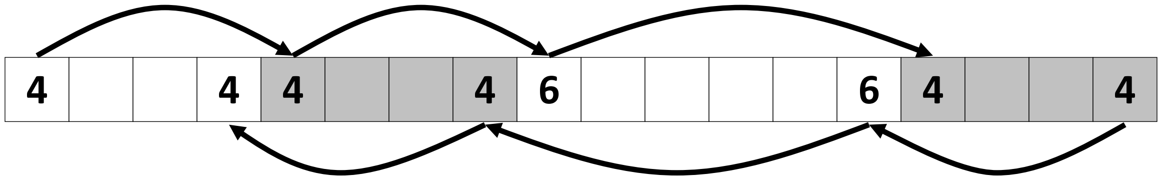


```
void free_block(ptr p) {
    *p = *p & -2;              // clear allocated flag
    next = p + *p;             // find next block
    if ((*next & 1) == 0)
      *p = *p + *next;         // add to this block if
}                              //    not allocated
```

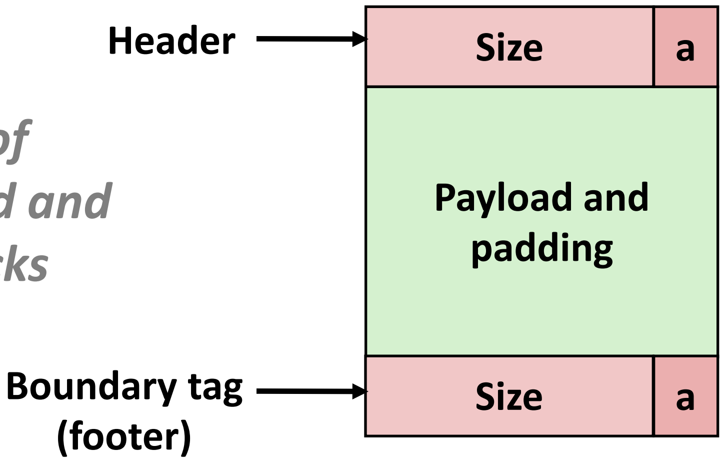
  - But how do we coalesce with *previous* block?

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

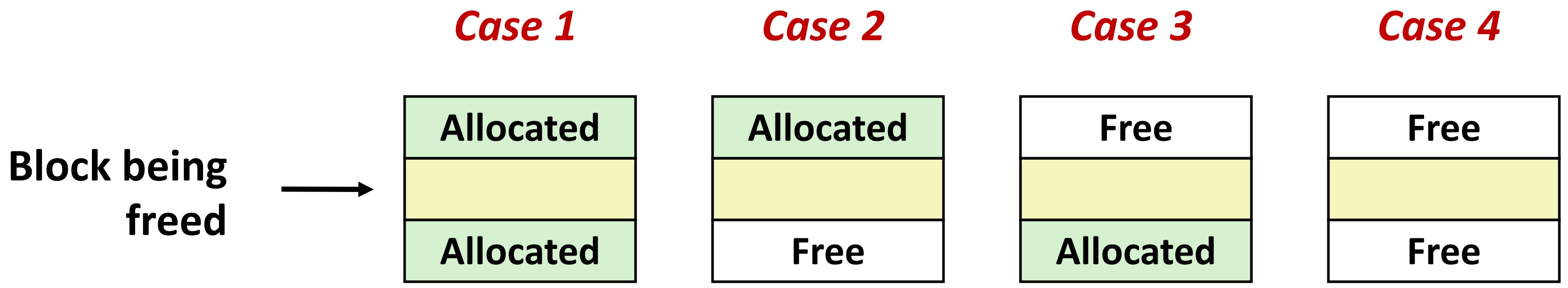


a = 1: Allocated block
a = 0: Free block

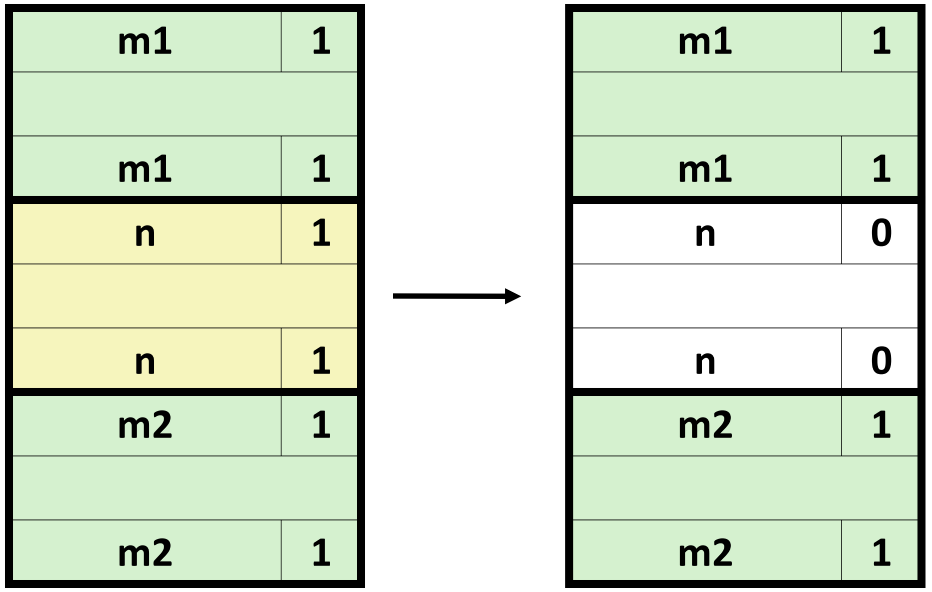
Size: Total block size

Payload: Application data (allocated blocks only)

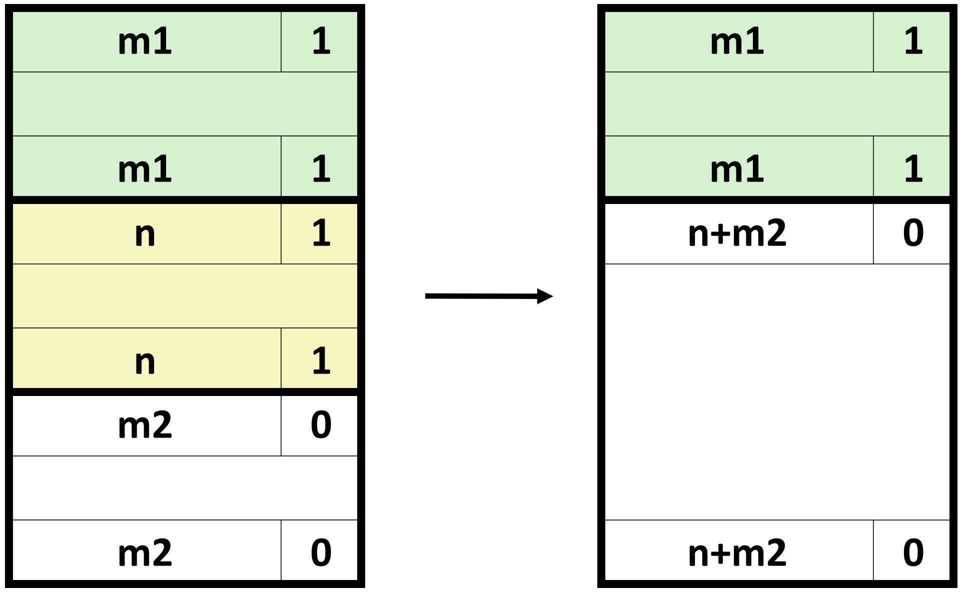
Constant Time Coalescing



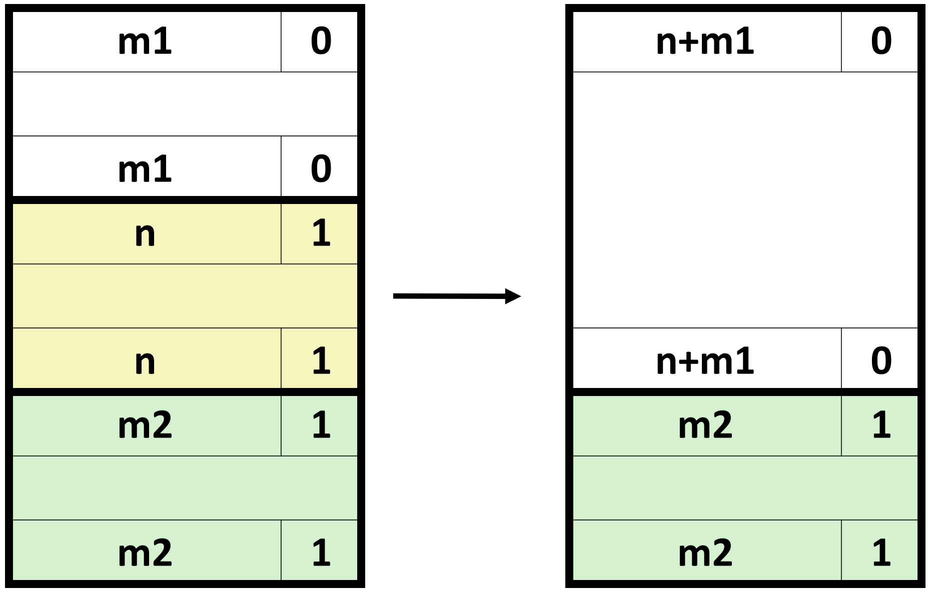
Constant Time Coalescing (Case 1)



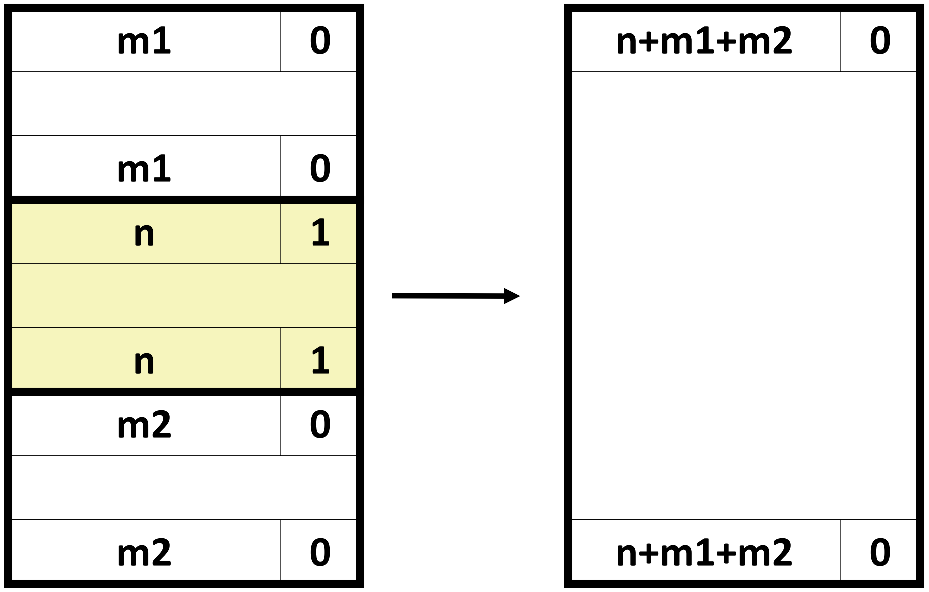
Constant Time Coalescing (Case 2)



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**