Dynamic Memory Allocation: Basic Concepts

Dynamic Memory Allocation – Basic Concepts

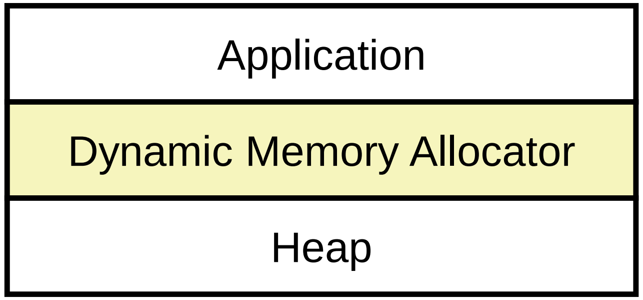
- **How do malloc/free work?**
- **Design Principles**
- Implementation 1: Implicit free lists

Acknowledgement: slides based on the cs:app2e material

Dynamic Memory Allocation?

- Why not use globals?
  - The size of certain data structures may only be known at runtime

- Memory Allocators
  - VM hardware and kernel allocate pages
  - application objects are typically smaller
  - allocator manages objects within pages



- 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

- We first discuss simple explicit memory allocation

The 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`

- 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

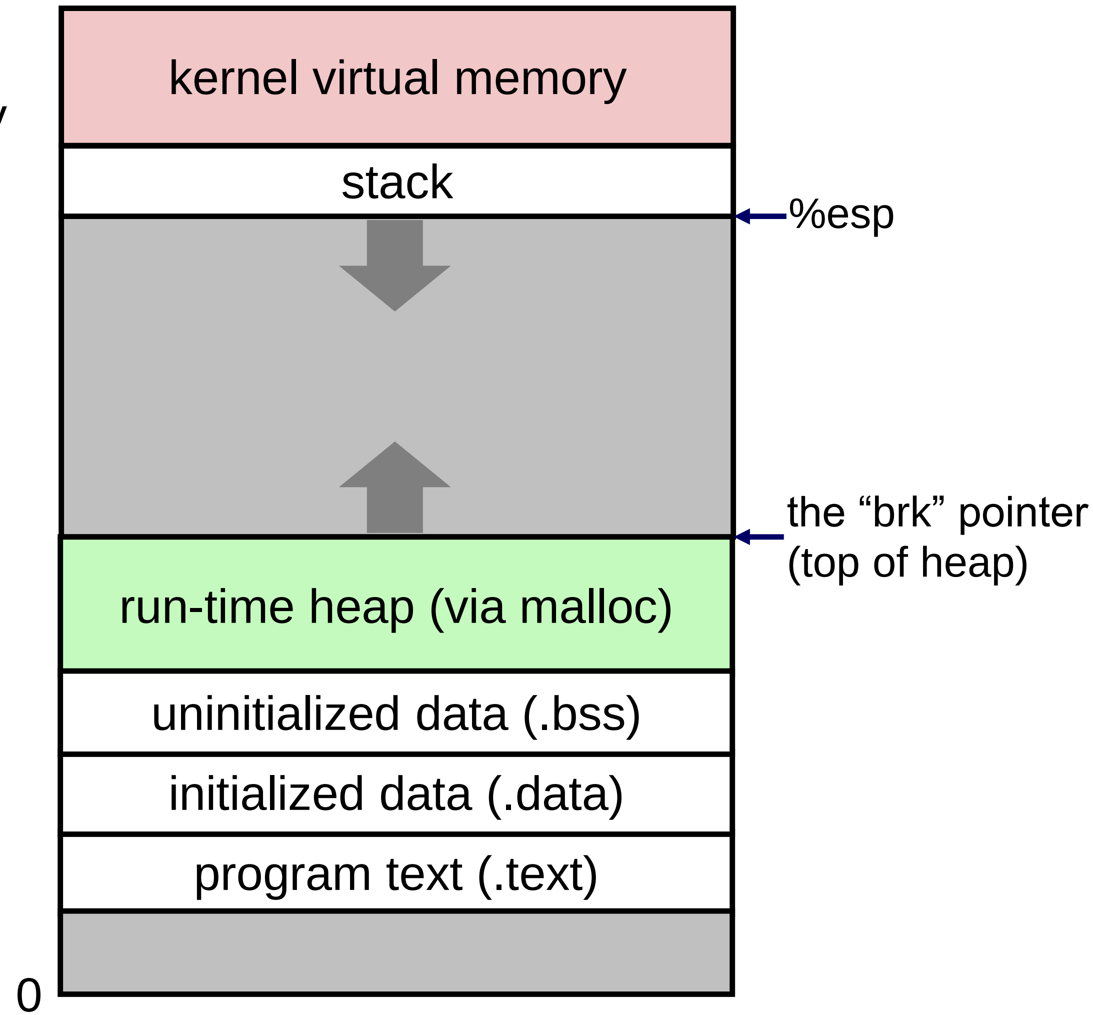
malloc Example

```
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);
    }
    for (i=0; i<n; i++) p[i] = i;

    /* add m bytes to end of p block */
    p = (int *) realloc(p, (n+m) * sizeof(int));
    if (p == 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", [i]);

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

Process Memory Image and Dynamic Memory Allocation

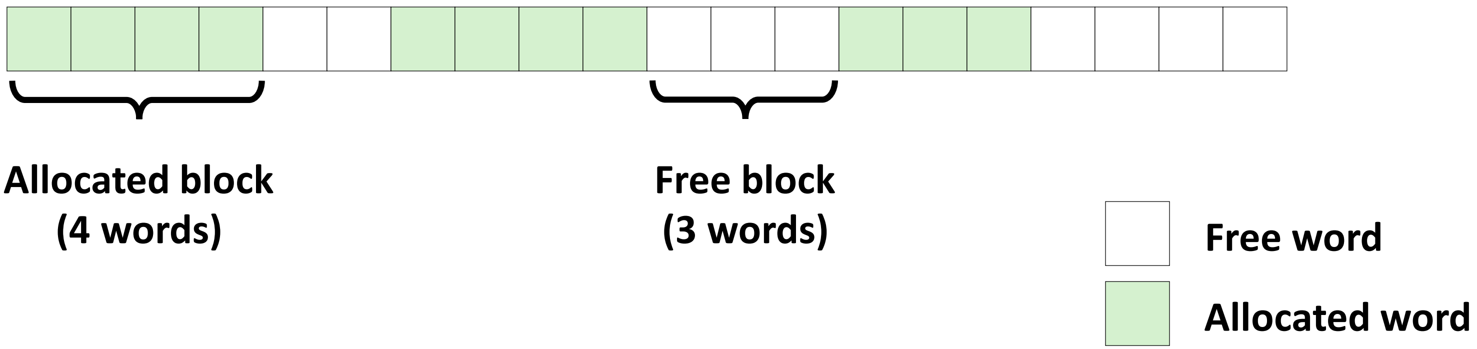
- If the dynamic memory allocator runs out of free memory, it can request additional heap memory from the kernel using the `sbrk()` function

```
err = sbrk(amount_more);
```



Assumptions Made in This Lecture

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



Allocation Example

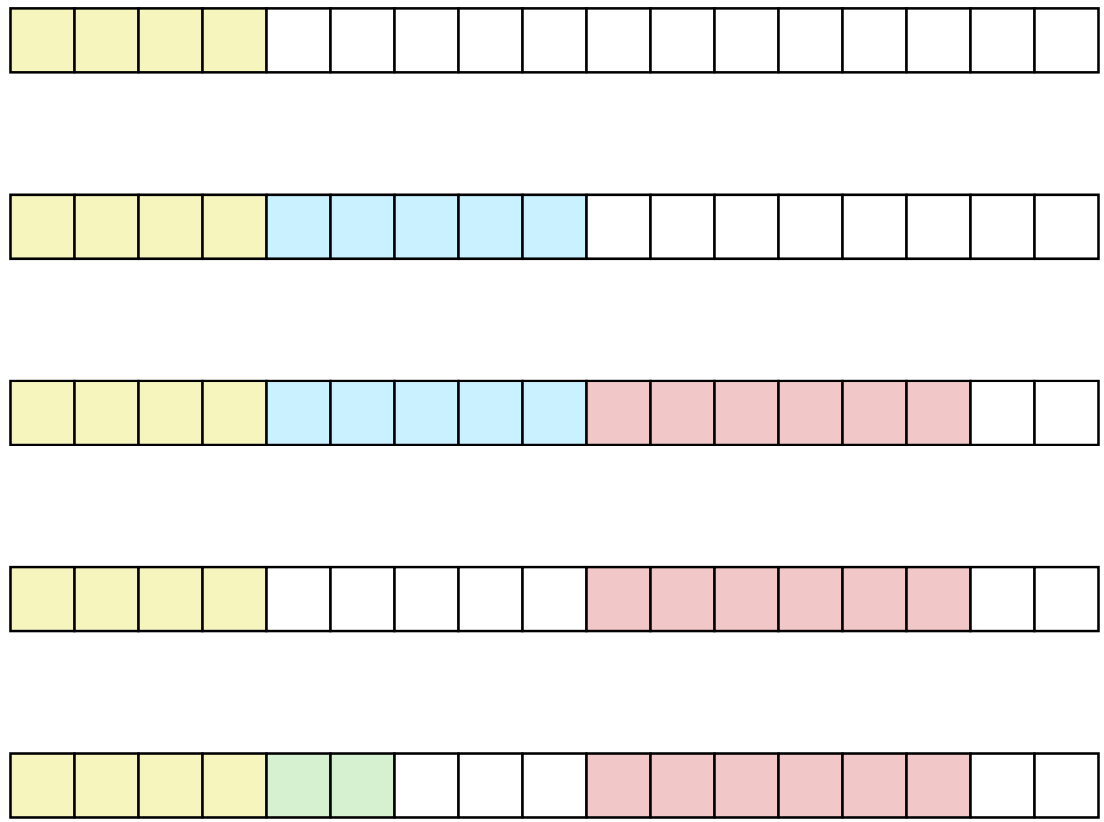
`p1 = malloc(4)`

`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 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:
  - R0, R1, ..., Rk, ... , Rn-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)?

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`

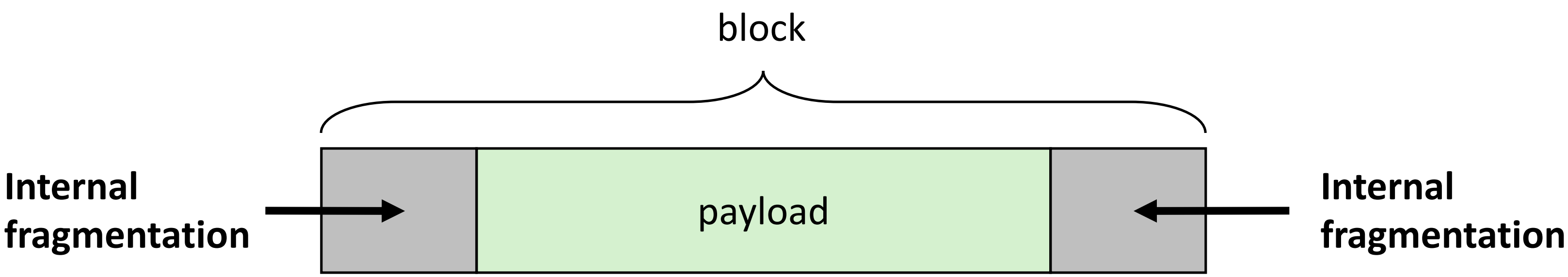
- Def: Peak memory utilization after k requests
  - $U_k = (\max_{i<k} P_i) \; / \; H_k$

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

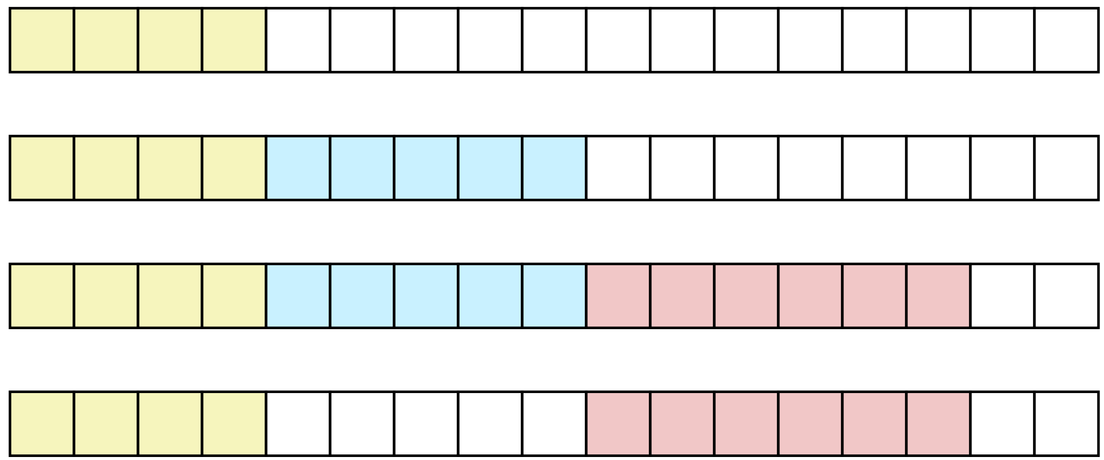


- Caused by
  - Overhead of maintaining heap data structures
  - Padding for alignment purposes
  - Explicit policy decisions
    (e.g., to return a big block to satisfy a small request)
- Depends only on the pattern of previous requests
  - Thus, easy to measure

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?)

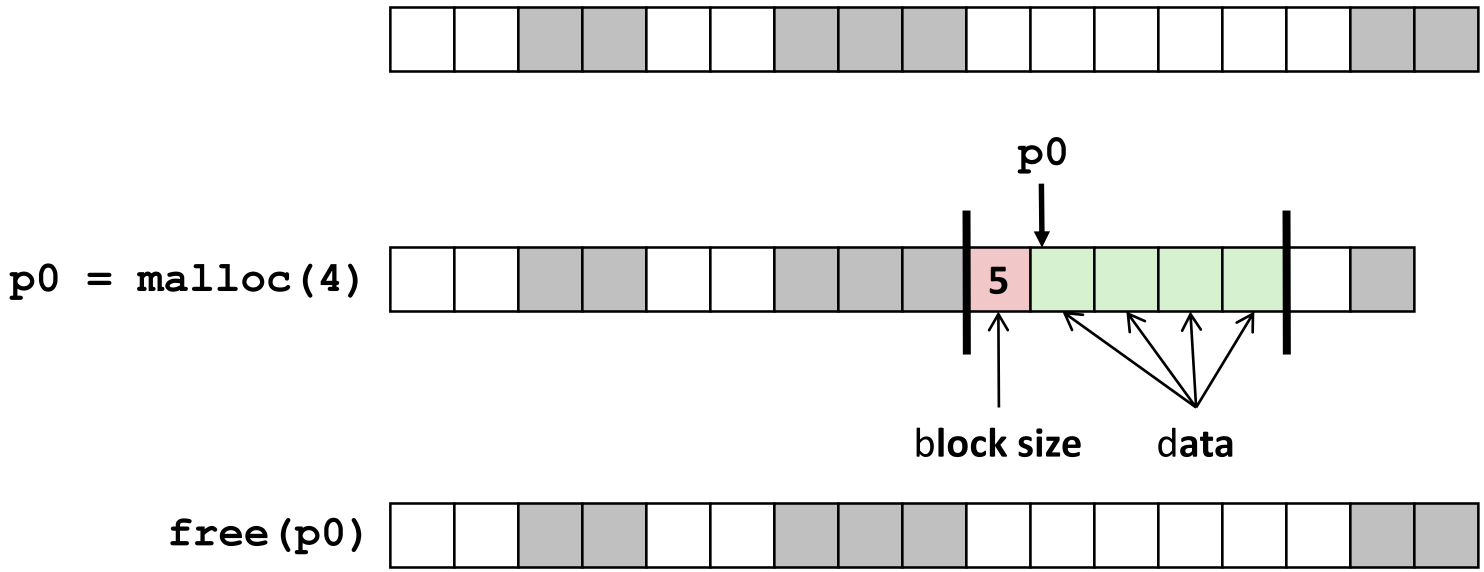
- Depends on the pattern of future requests
  - Thus, difficult to measure

Implementation Issues

- How do we know how much memory is being `free()`'d when it is given only a pointer (and no length)?
- 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 a freed block into the heap?

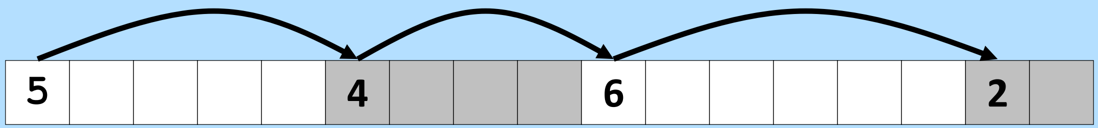
Knowing How Much to Free

- 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

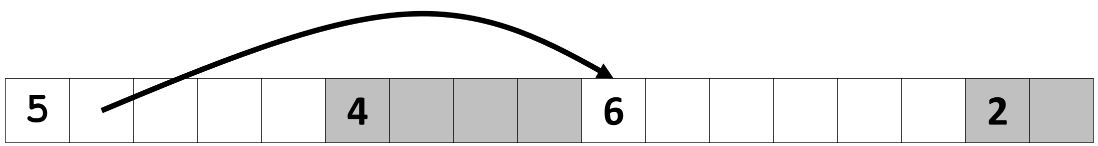


Keeping Track of Free Blocks

- 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

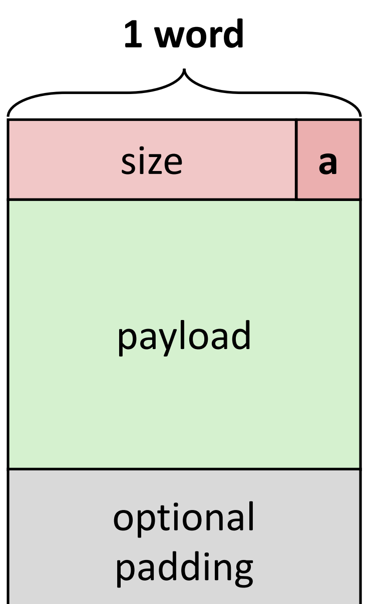
Dynamic Memory Allocation – Basic Concepts

- How does malloc/free work?
- Design Principles
- **Implementation 1: 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



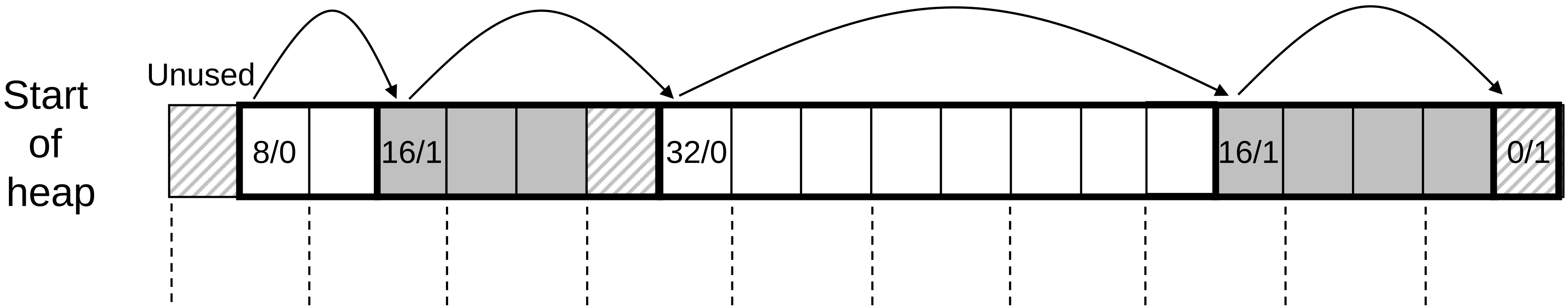
a = 1: allocated block
a = 0: free block

size: block size

payload: application data
(allocated blocks only)

Format of allocated and free blocks

Free List Example



Double-word aligned

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)
```

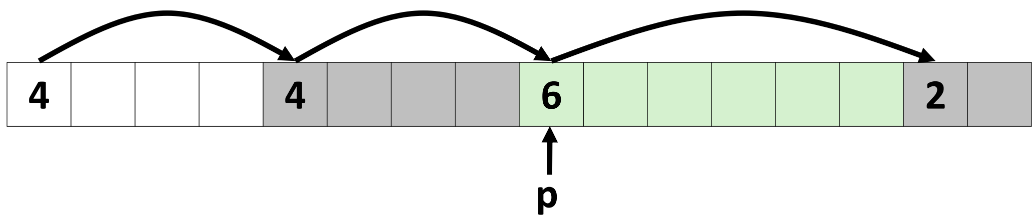
  - Can take linear time in total number of blocks (allocated and free)
  - In practice it can cause “splinters” at beginning of list

- 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

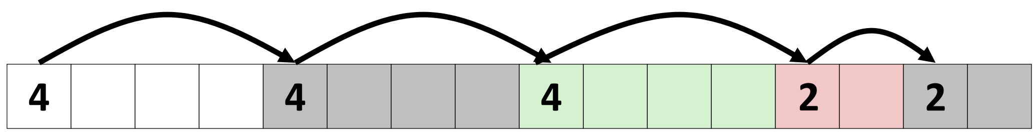
- Best fit:
  - Search the list, choose the best free block: fits, with fewest bytes left over
  - Keeps fragments small—usually helps fragmentation
  - Will typically run slower than first fit

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



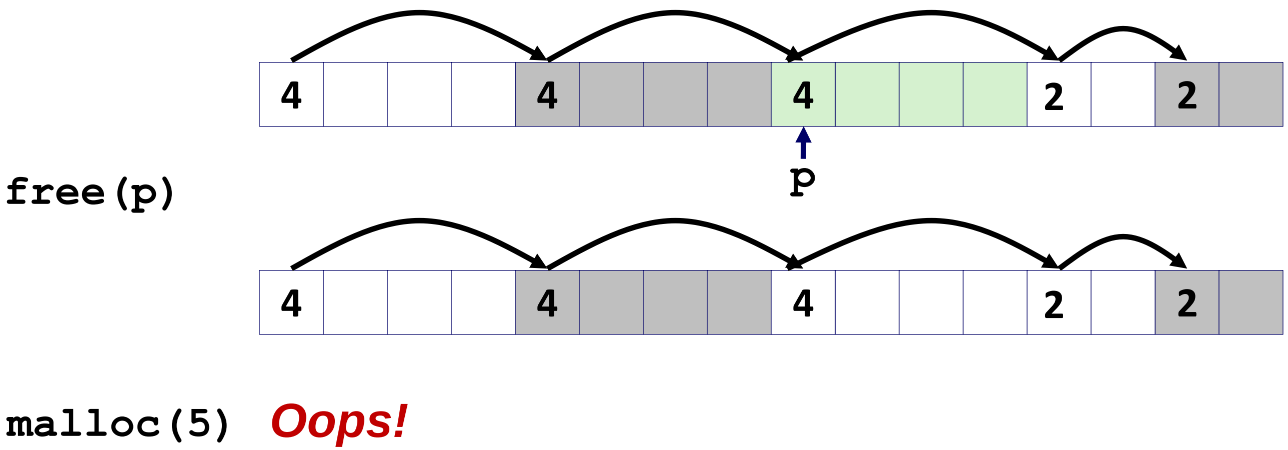
`addblock(p, 4)`




```
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

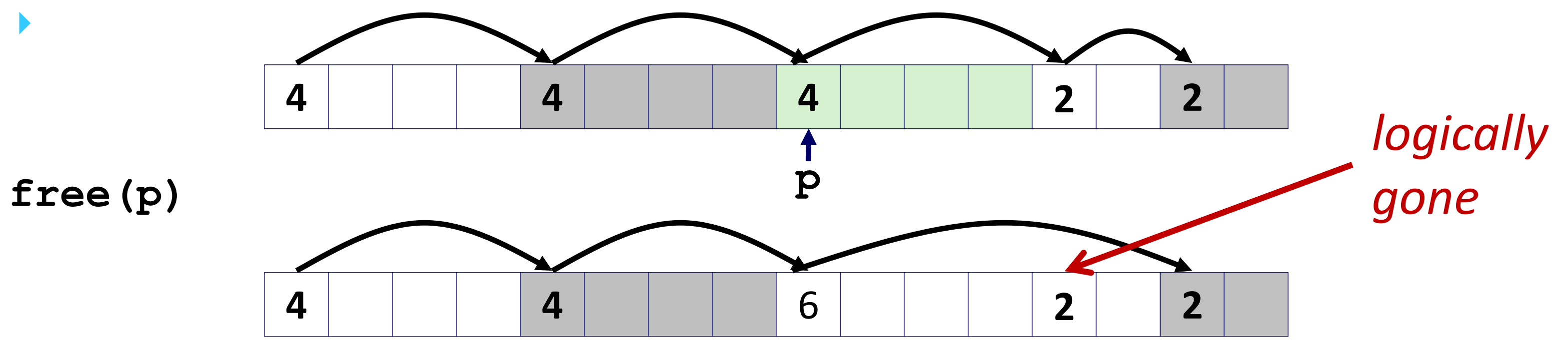
- Simplest implementation:
  - Need only clear the "allocated" flag
    - void free_block(ptr p) { *p = *p & -2 }
  - But can lead to "false fragmentation"



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?

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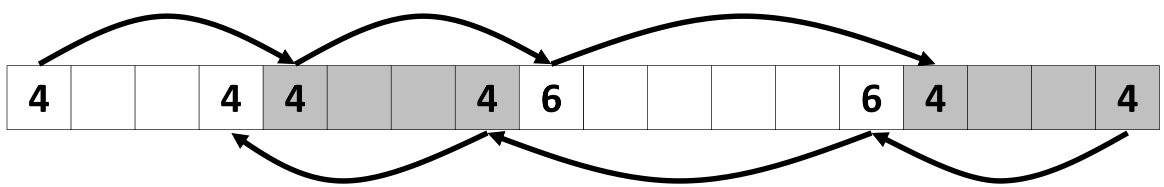
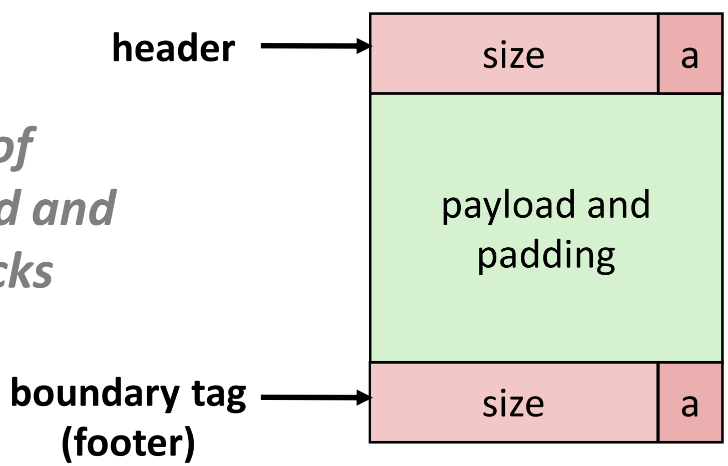
Implicit List: Bidirectional Coalescing

- 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

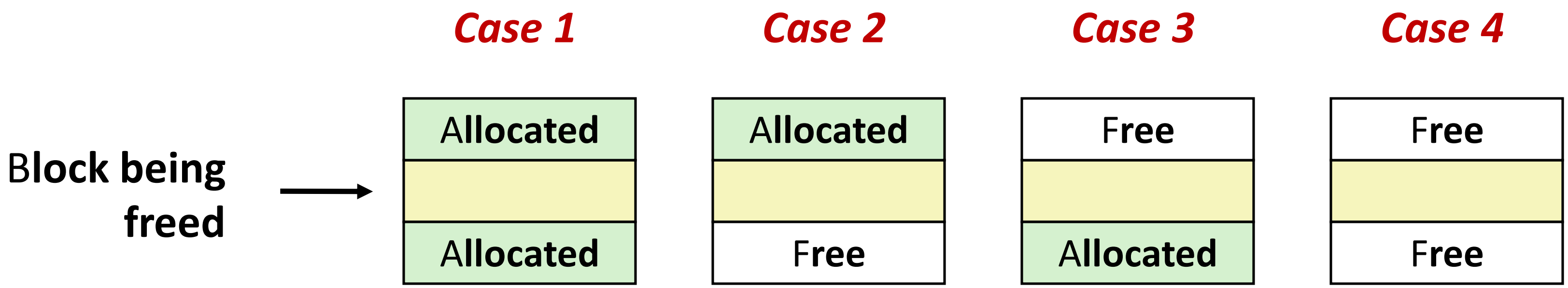


a = 1: allocated block
a = 0: free block

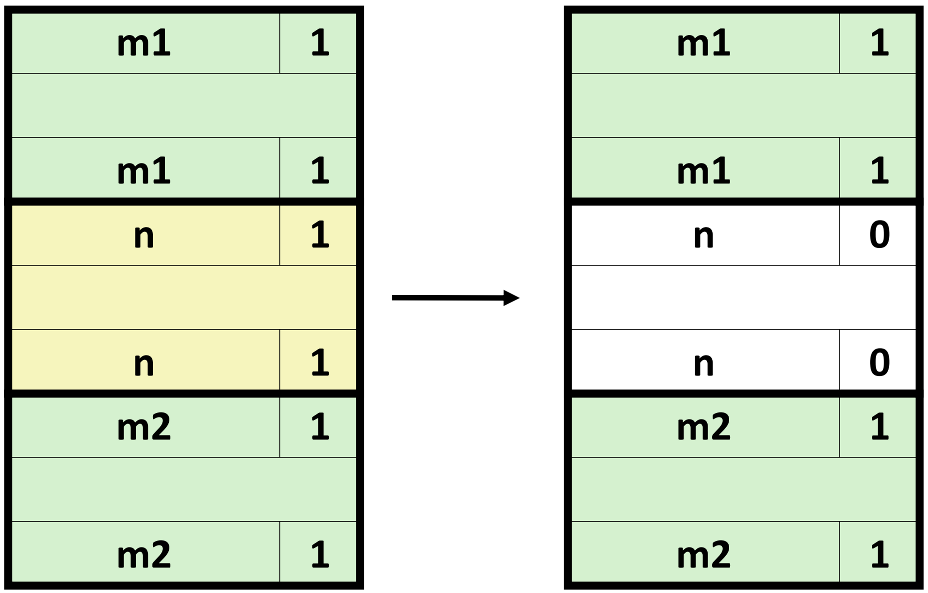
size: total block size

payload: application data (allocated blocks only)

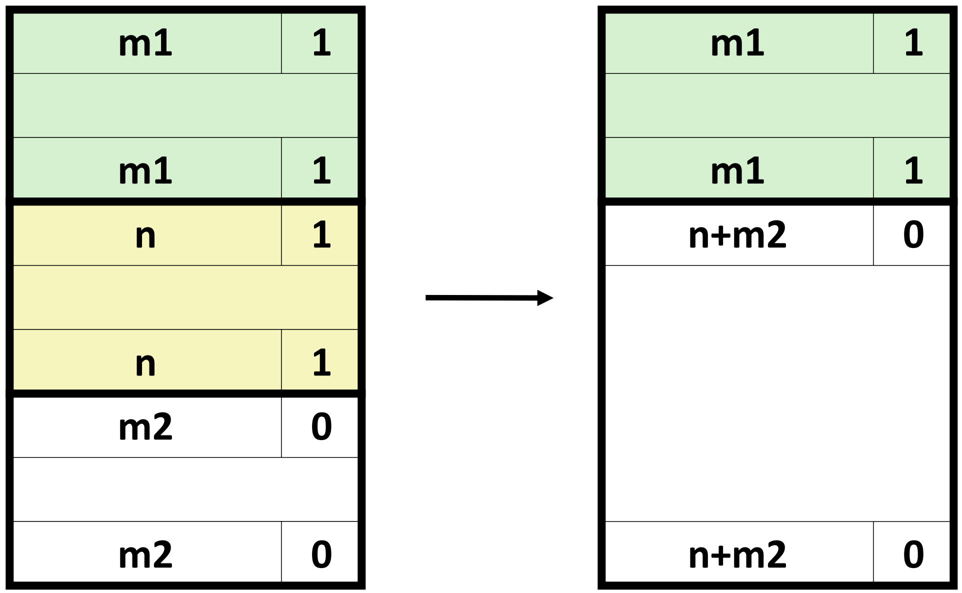
Constant Time Coalescing



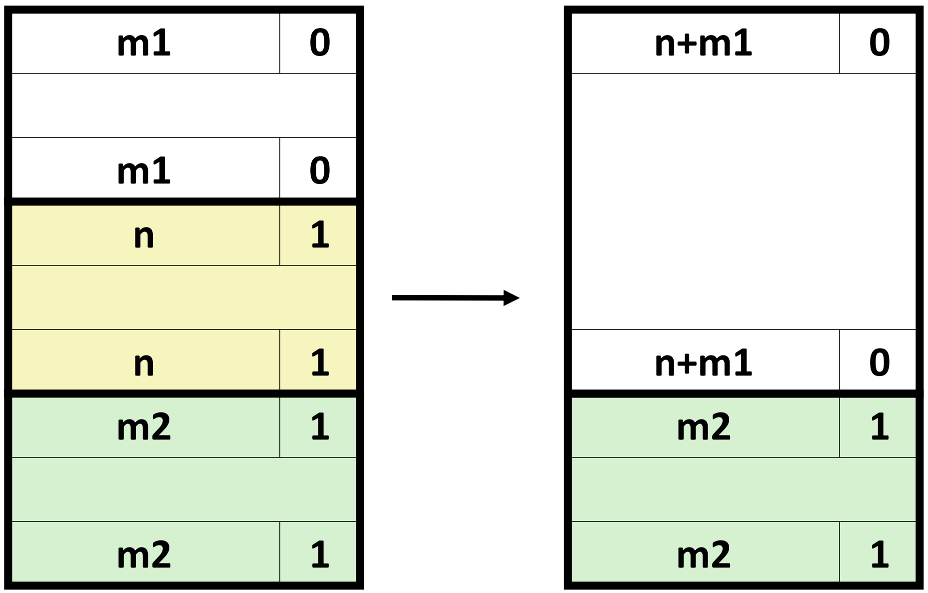
Constant Time Coalescing (Case 1)



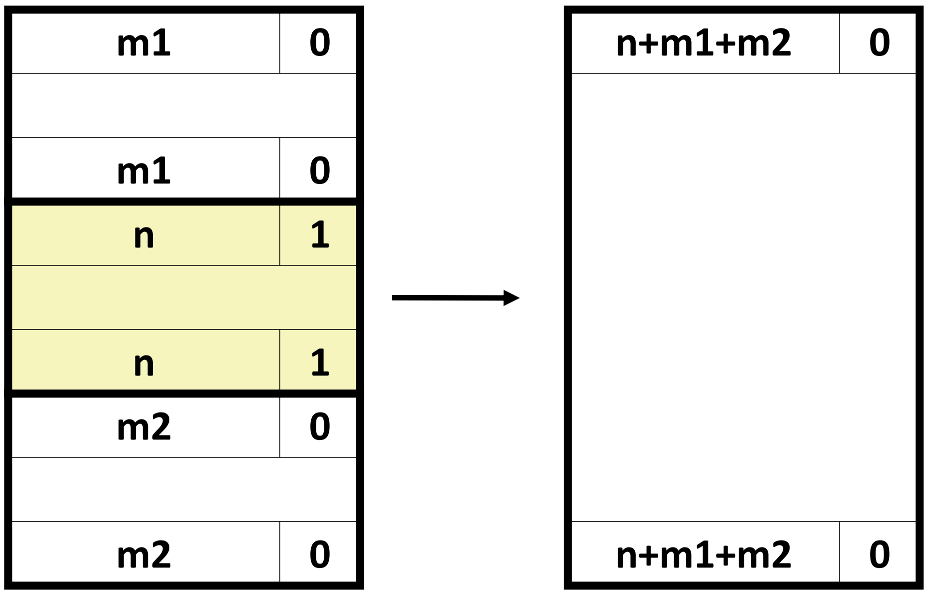
Constant Time Coalescing (Case 2)



Constant Time Coalescing (Case 3)



Constant Time Coalescing (Case 4)



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Disadvantages of Boundary Tags

- Internal fragmentation

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

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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