Dynamic Memory Allocation: Basic Concepts

15-213/15-513: Introduction to Computer Systems
13th Lecture, June 18, 2024

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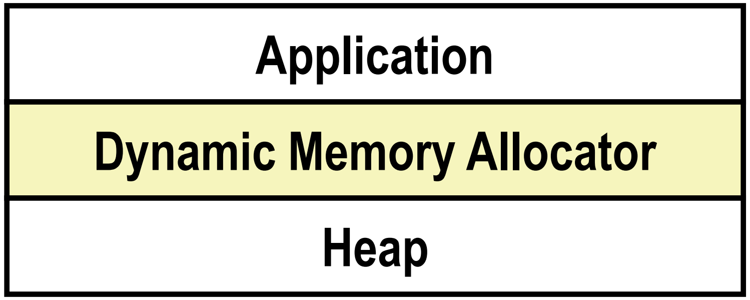
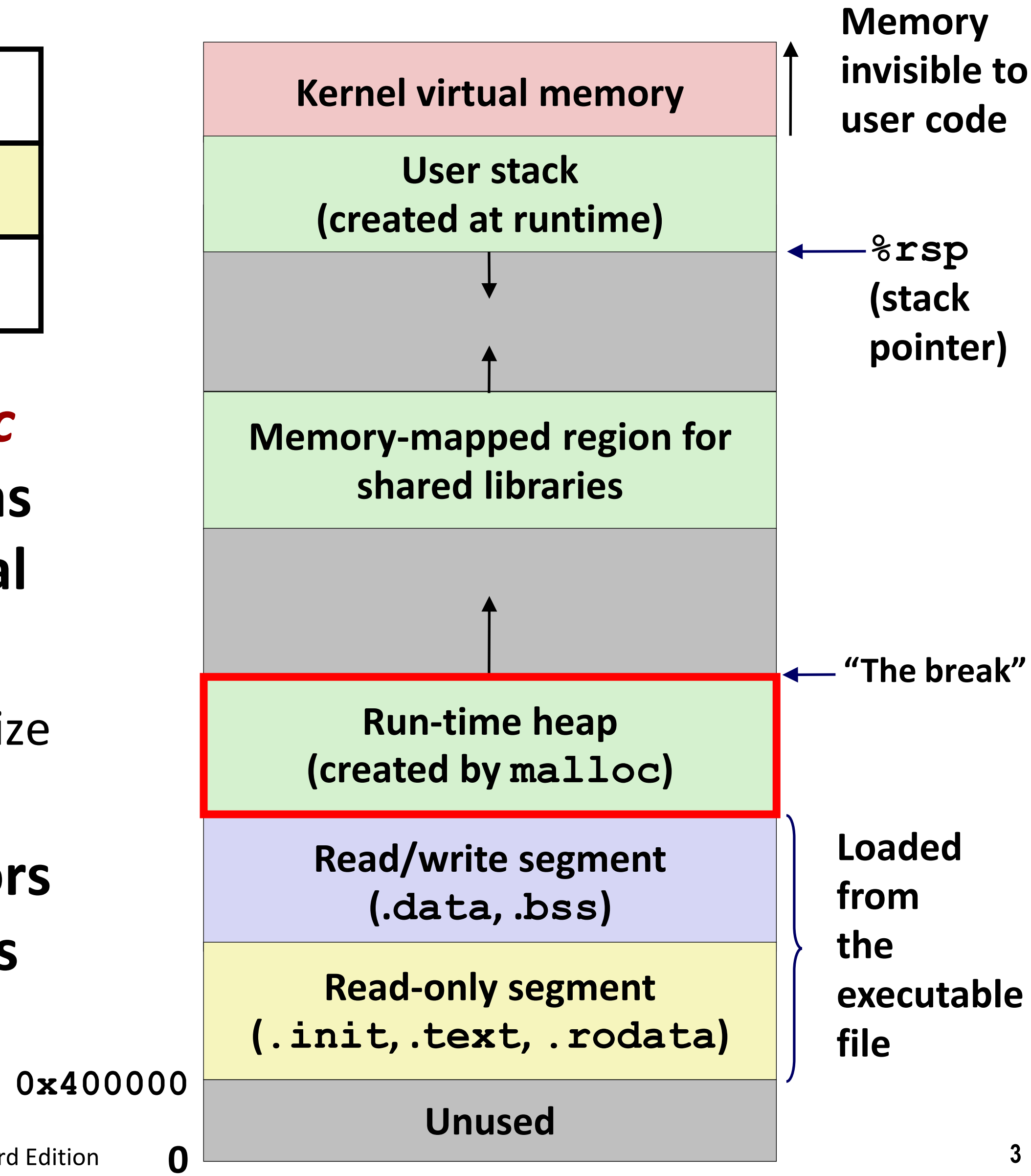
Today

- **Basic concepts**
- Implicit free lists

Dynamic Memory Allocation



- Programmers use ***dynamic memory allocators*** (such as `malloc`) to acquire virtual memory (VM) at runtime
  - For data structures whose size is only known at runtime
- Dynamic memory allocators manage an area of process VM 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., `new` and garbage collection in Java
- **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 a 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`**, **`calloc`**, or **`realloc`**

Other functions

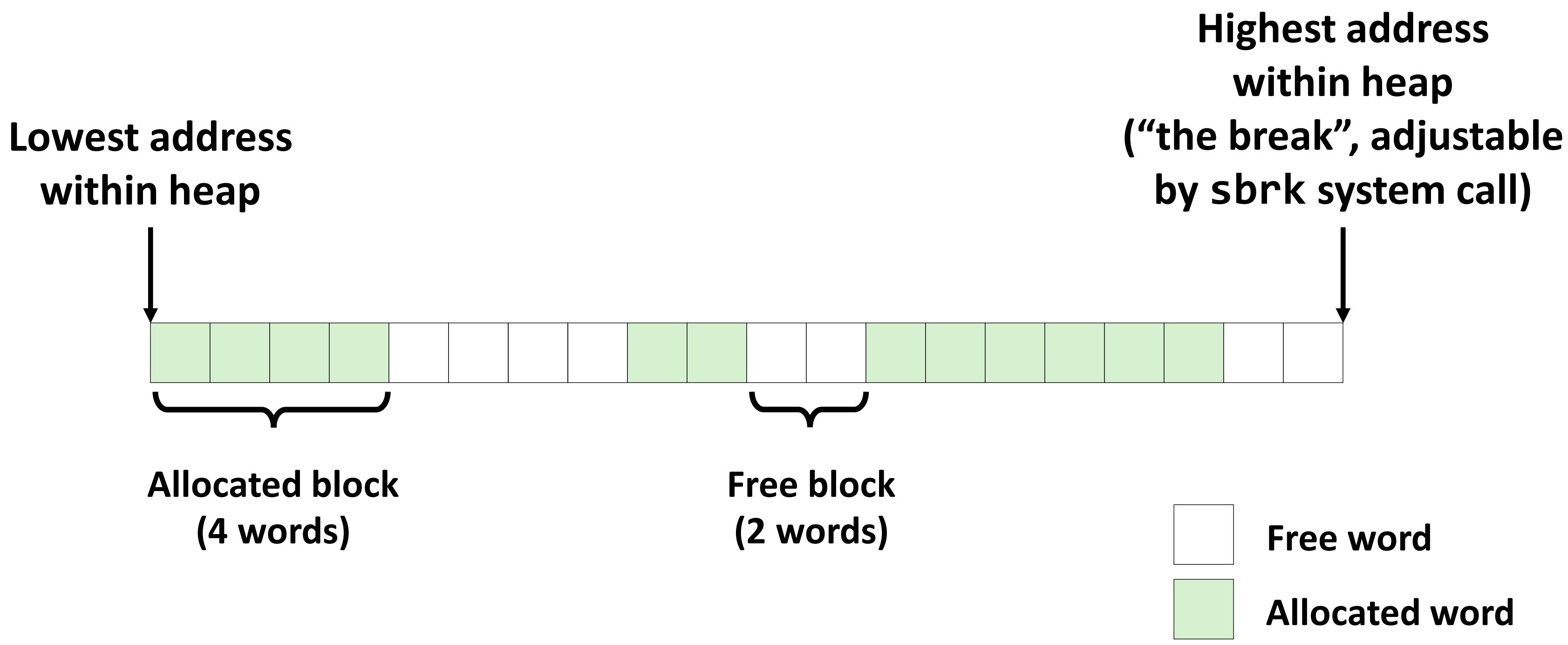
- **`calloc`:** Version of **`malloc`** that initializes allocated block to zero
- **`realloc`:** Changes the size of a previously allocated block
- **`sbrk`:** Used internally by allocators to grow or shrink the heap

malloc Example

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

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

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

    /* Initialize allocated block */
    for (i=0; i<n; i++)
       p[i] = i;
    /* Do something with p */
    . . .
    /* Return allocated block to the heap */
    free(p);
}
```

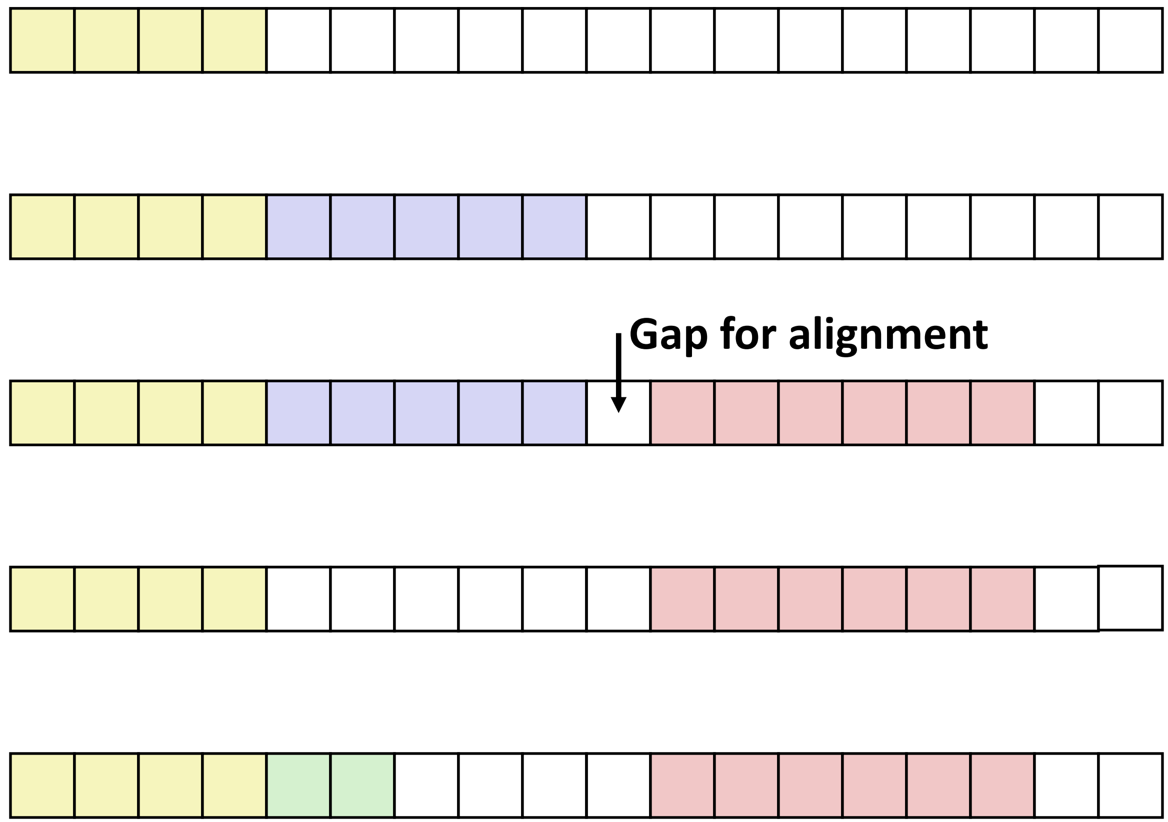
Heap Visualization Convention

- 1 square = 1 “word” = 8 bytes



Allocation Example (Conceptual)

```
p1 = malloc(32)

p2 = malloc(40)

p3 = malloc(48)

free(p2)

p4 = malloc(16)
```



Constraints

- **Applications**
  - Can issue arbitrary sequence of **`malloc`** and **`free`** requests
  - **`free`** request must be to a **`malloc`**'d block

- **Explicit 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 64-bit systems
  - Can manipulate and modify only free memory
  - Can't move the allocated blocks once they are **`malloc`**'d
    - *i.e.*, compaction is not allowed. *Why not?*

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: Minimize Overhead

- **Given some sequence of `malloc` and `free` requests:**
  - $R_0, R_1, \ldots, R_k, \ldots, R_{n-1}$
- ***After k requests we have:***
- ***Def: Aggregate payload P_k***
  - `malloc(p)` results in a block with a ***payload*** of `p` bytes
  - The ***aggregate payload*** P_k is the sum of currently allocated payloads
  - The ***peak aggregate payload*** $\max_{i \le k} P_i$ is the maximum aggregate payload at any point in the sequence up to request
- ***Def: Current heap size H_k***
  - Assume heap only *grows* when allocator uses **`sbrk`**, never shrinks
- ***Def: Overhead, O_k***
  - Fraction of heap space *NOT* used for program data
  - $O_k = (H_k / \max_{i \le k} P_i) - 1.0$

Benchmark Example

- **Benchmark syn-array-short**
  - Trace provided with malloc lab
  - Allocate & free 10 blocks
  - a = allocate
  - f = free
  - Bias toward allocate at beginning & free at end
  - Blocks number 1–10
  - Allocated: Sum of all allocated amounts
  - Peak: Max so far of Allocated

Step	Command	Delta	Allocated	Peak
1	`a 0 9904`	9904	9904	9904
2	`a 1 50084`	50084	59988	59988
3	`a 2 20`	20	60008	60008
4	`a 3 16784`	16784	76792	76792
5	`f 3`	-16784	60008	76792
6	`a 4 840`	840	60848	76792
7	`a 5 3244`	3244	64092	76792
8	`f 0`	-9904	54188	76792
9	`a 6 2012`	2012	56200	76792
10	`f 2`	-20	56180	76792
11	`a 7 33856`	33856	90036	90036
12	`f 1`	-50084	39952	90036
13	`a 8 136`	136	40088	90036
14	`f 7`	-33856	6232	90036
15	`f 6`	-2012	4220	90036
16	`a 9 20`	20	4240	90036
17	`f 4`	-840	3400	90036
18	`f 8`	-136	3264	90036
19	`f 5`	-3244	20	90036
20	`f 9`	-20	0	90036

Benchmark Visualization

Step	Command	Delta	Allocated	Peak
1	`a 0 9904`	9904	9904	9904
2	`a 1 50084`	50084	59988	59988
3	`a 2 20`	20	60008	60008
4	`a 3 16784`	16784	76792	76792
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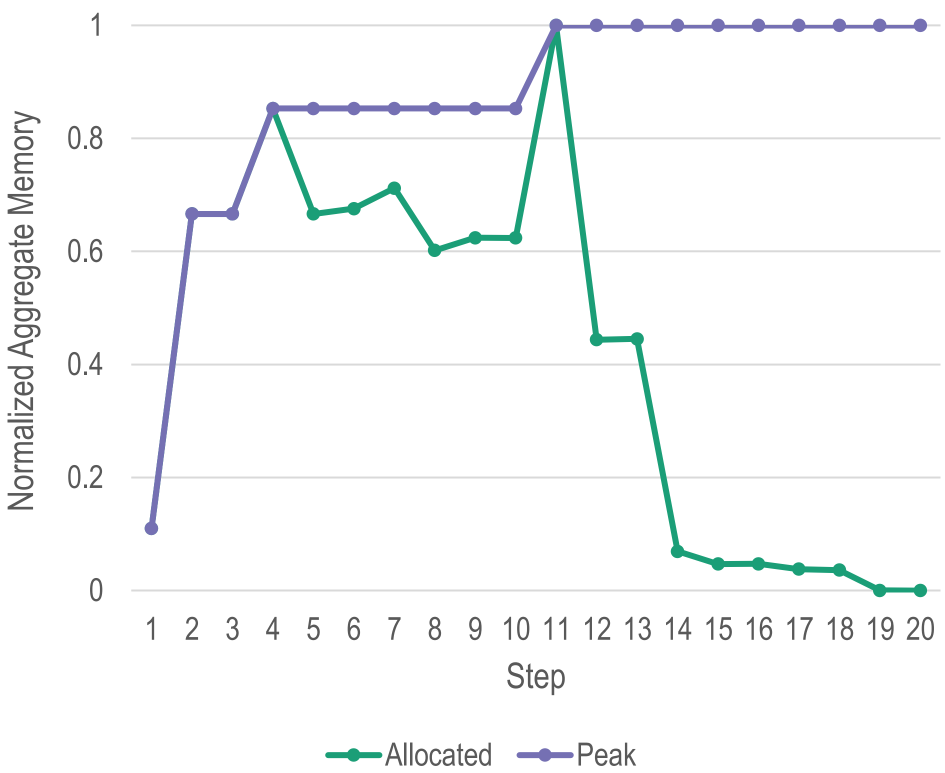
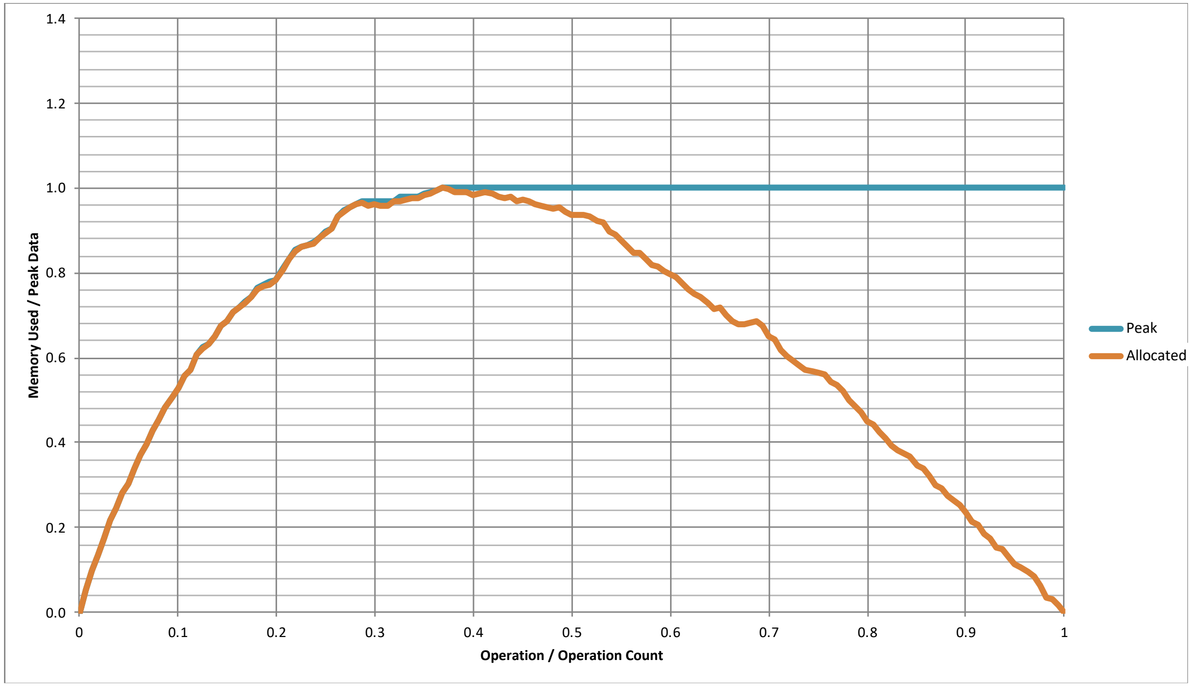


- Plot P_k (allocated) and $\max_{i \le k} P_k$ (peak) as a function of k (step)
- Y-axis normalized — fraction of maximum

Typical Benchmark Behavior



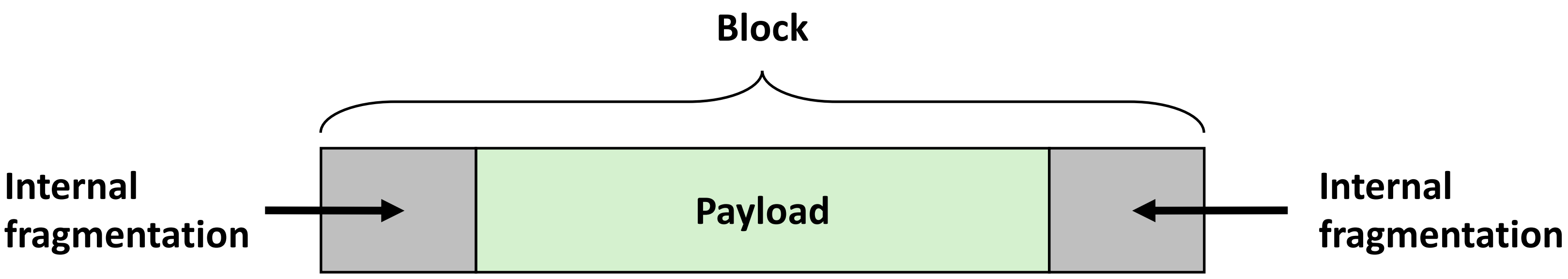
- **Longer sequence of mallocs & frees (40,000 blocks)**
  - Starts with all mallocs, and shifts toward all frees
- **Allocator must manage space efficiently the whole time**
- **Production allocators can shrink the heap**

Fragmentation

- **Poor memory utilization caused by *fragmentation***
  - ***Internal*** fragmentation
  - ***External*** fragmentation

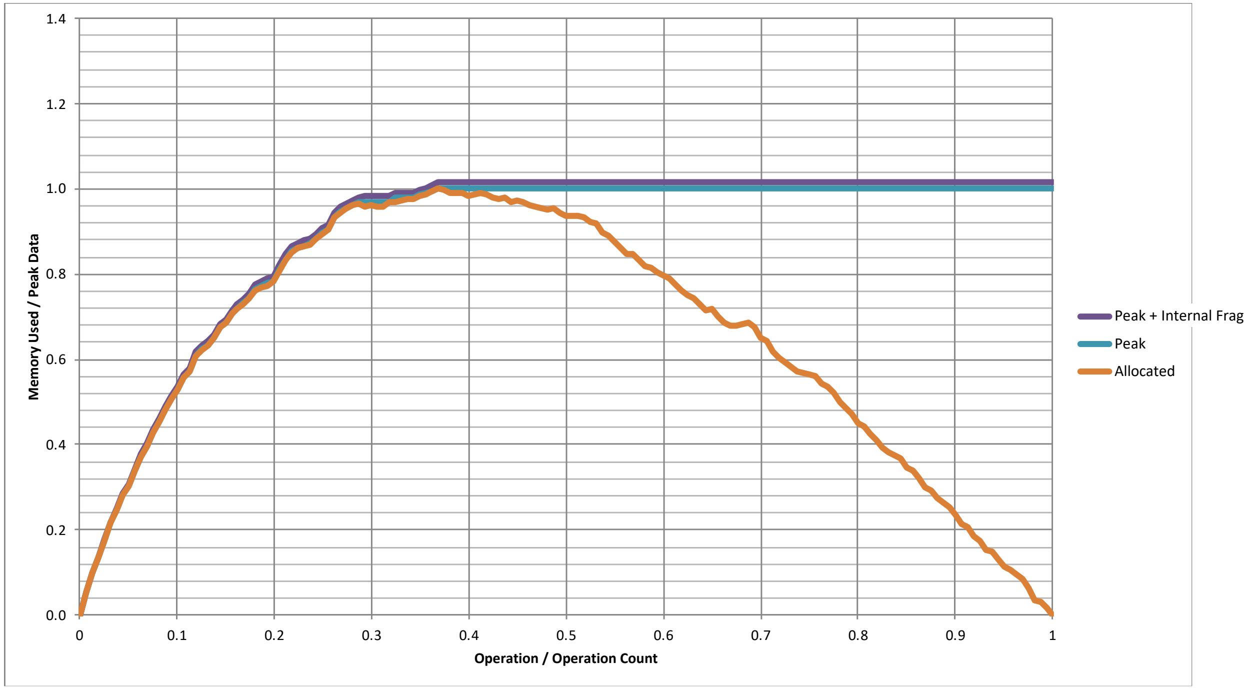
Internal Fragmentation

- **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

Internal Fragmentation Effect

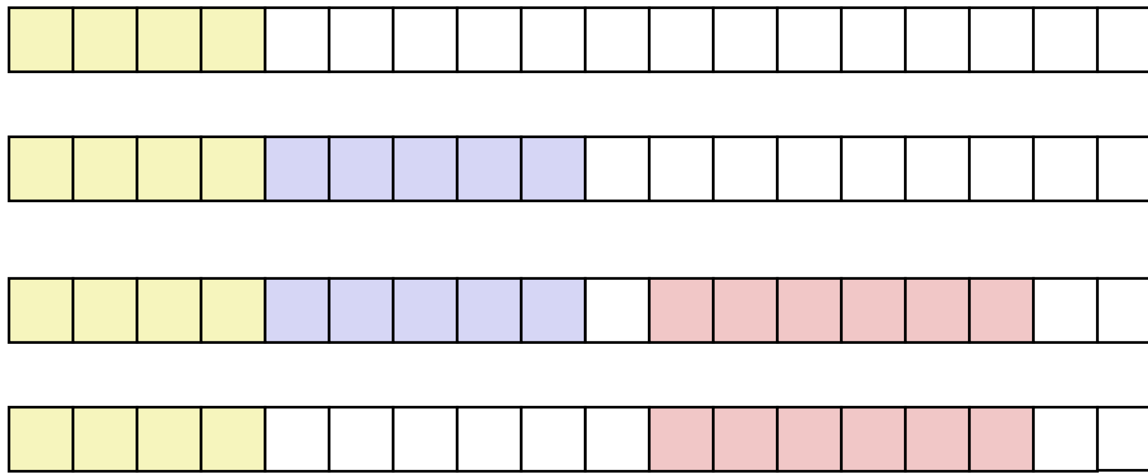


- **Purple line: additional heap size due to allocator's data + padding for alignment**
  - For this benchmark, 1.5% overhead
  - Cannot achieve in practice
  - Especially since cannot move allocated blocks

External Fragmentation

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

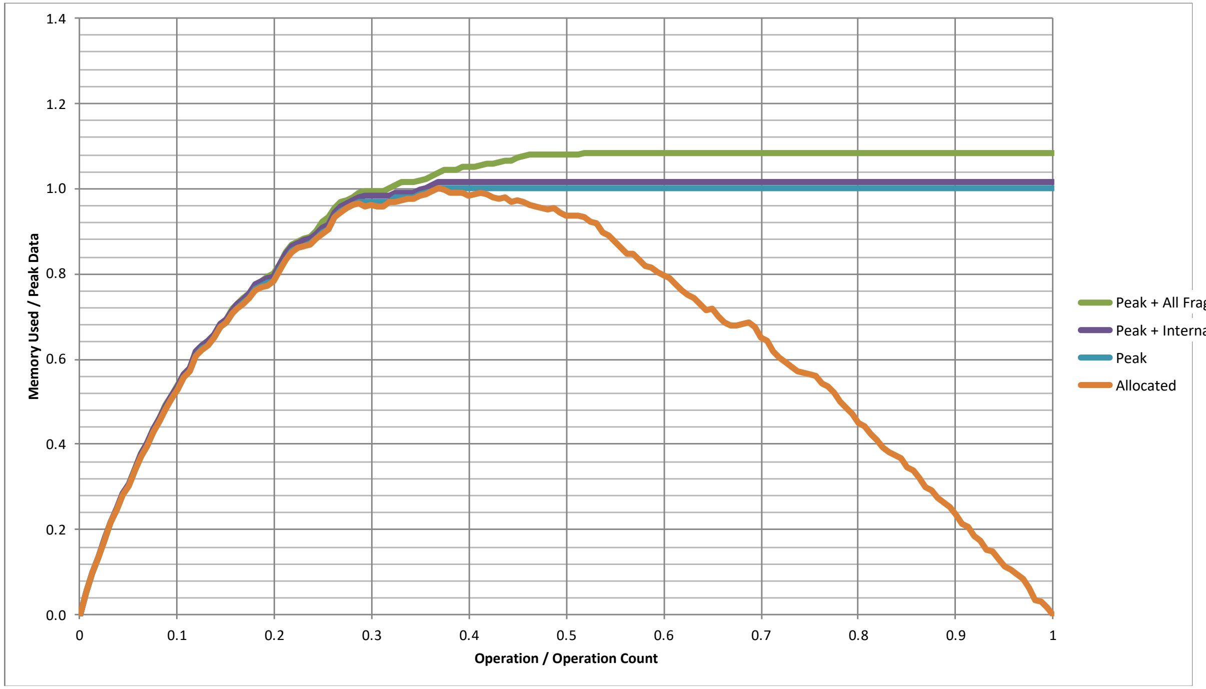
```
p1 = malloc(32)

p2 = malloc(40)

p3 = malloc(48)

free(p2)

p4 = malloc(64)
```



Yikes! (what would happen now?)

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

External Fragmentation Effect



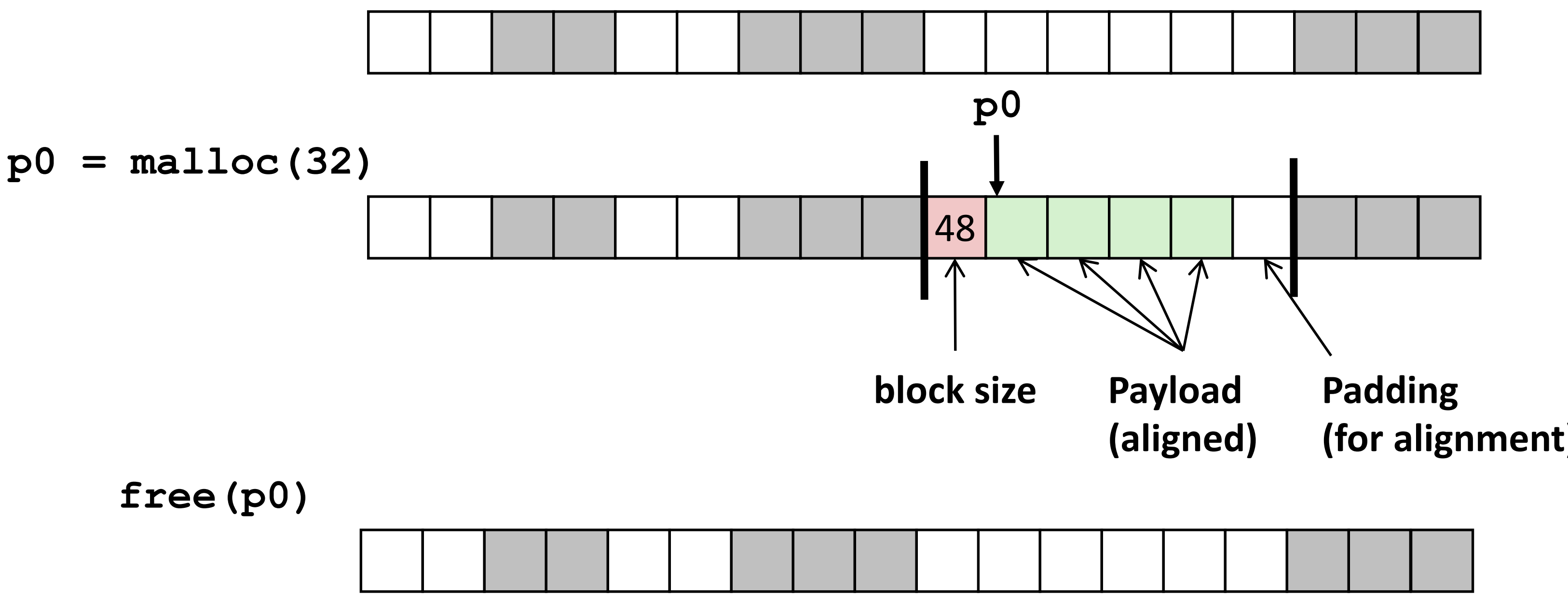
- **Green line: additional heap size due to external fragmentation**
- **Best Fit: One allocation strategy**
  - (To be discussed later)
  - Total overhead = 8.3% on this benchmark

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 reuse a block that has been freed?

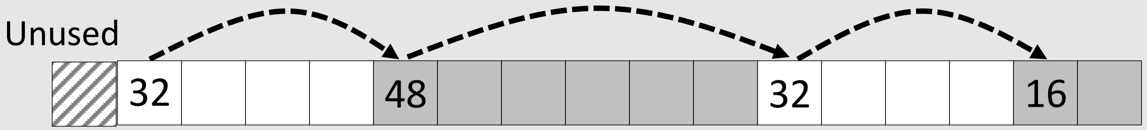
Knowing How Much to Free

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



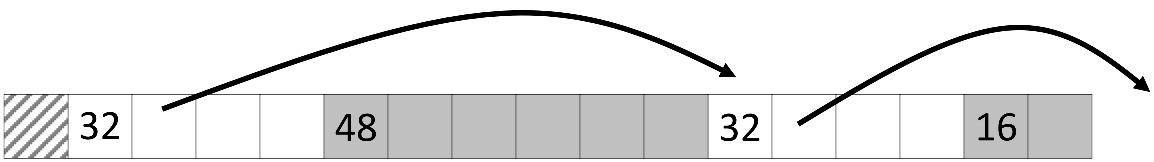
Keeping Track of Free Blocks

- **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

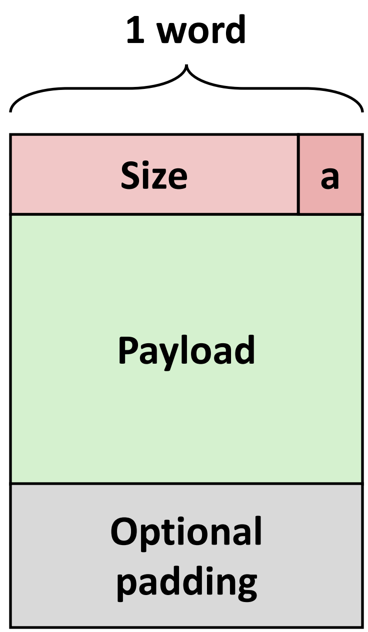
- **Method 4: *Blocks sorted by size***
  - Can use a balanced tree (e.g., Red-Black tree) with pointers within each free block, and the length used as a key

Today

- Basic concepts
- **Implicit free lists**

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



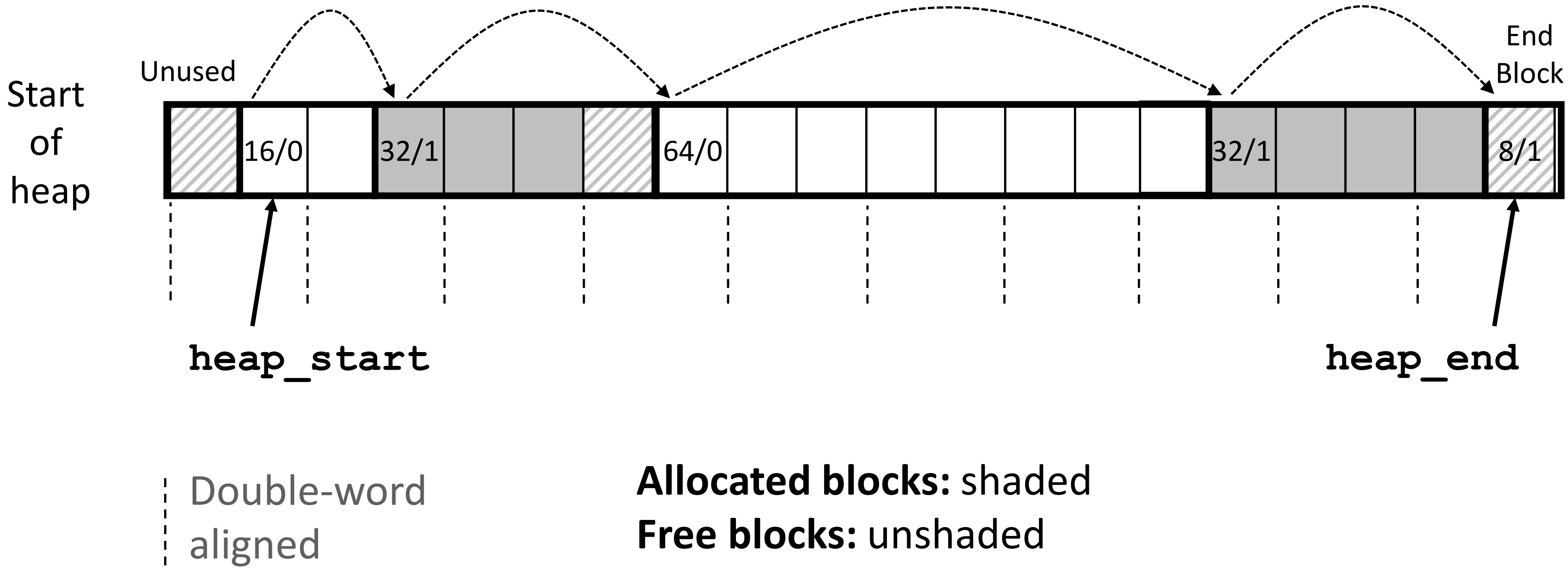
Format of allocated and free blocks

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

Size: total block size

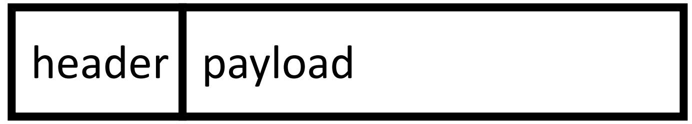
Payload: application data (allocated blocks only)

Detailed Implicit Free List Example



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: Data Structures



- **Block declaration**

```
typedef uint64_t word_t;
```

```
typedef struct block
{
    word_t header;
    unsigned char payload[0];        // Zero length array
} block_t;
```

- **Getting payload from block pointer** // `block_t *block`

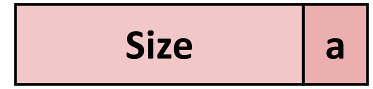
```
return (void *) (block->payload);
```

- **Getting header from payload** // bp points to a payload

```
return (block_t *) ((unsigned char *) bp
                       - offsetof(block_t, payload));
```

C function `offsetof(struct, member)` returns offset of member within struct

Implicit List: Header access



- Getting allocated bit from header

```
return header & 0x1;
```

- Getting size from header

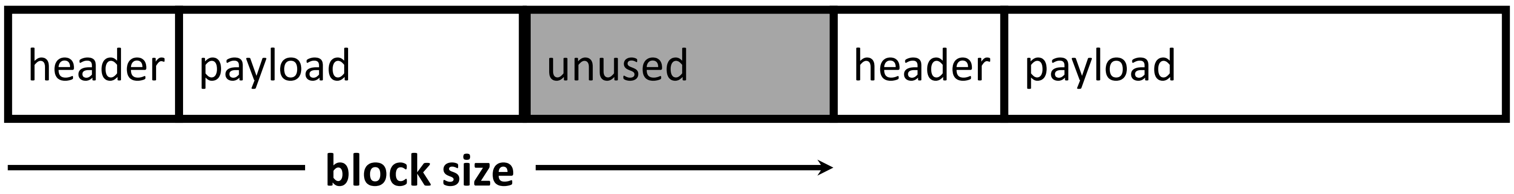
```
return header & ~0xfL;
```

- Initializing header

`// block_t *block`

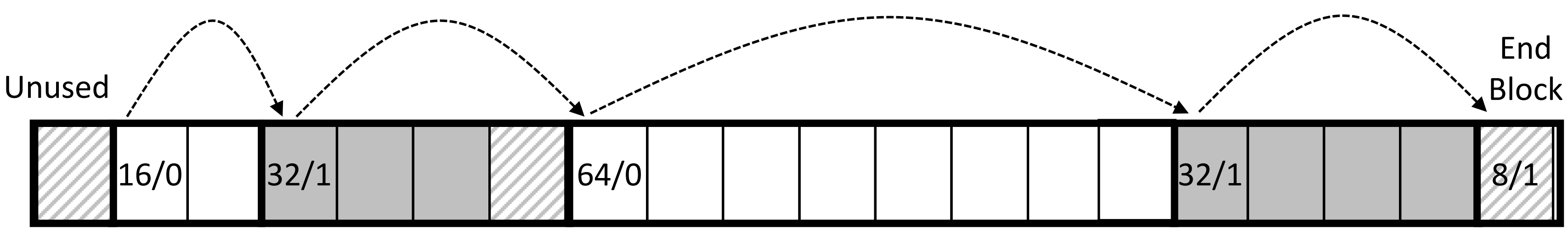
```
block->header = size | alloc;
```

Implicit List: Traversing list



- **Find next block**

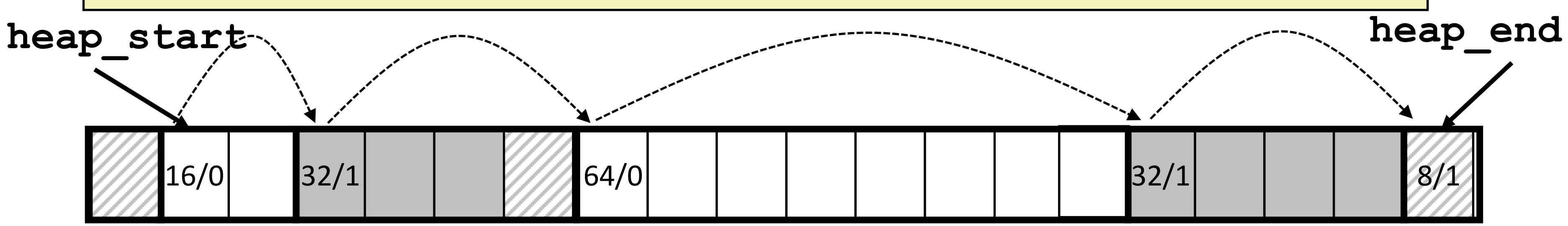
```
static block_t *find_next(block_t *block)
{
    return (block_t *) ((unsigned char *) block
                          + get_size(block));
}
```



Implicit List: Finding a Free Block

- ***First fit:***
  - Search list from beginning, choose ***first*** free block that fits:
  - Finding space for **asize** bytes (including header):

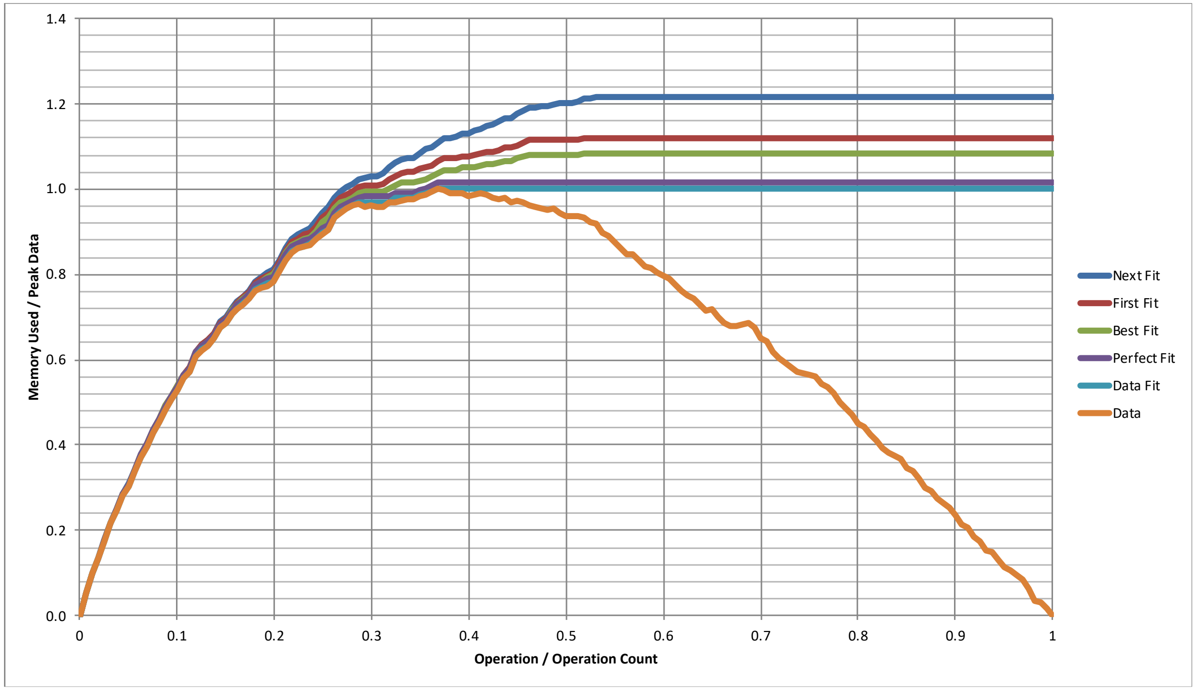
```
static block_t *find_fit(size_t asize)
{
    block_t *block;
    for (block = heap_start; block != heap_end;
         block = find_next(block)) {
    {
      if (!(get_alloc(block))
          && (asize <= get_size(block)))
         return block;
    }
    return NULL; // No fit found
}
```



Implicit List: Finding a Free Block

- ***First fit:***
  - Search list from beginning, choose ***first*** free block that fits:
  - 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
  - Still a greedy algorithm. No guarantee of optimality

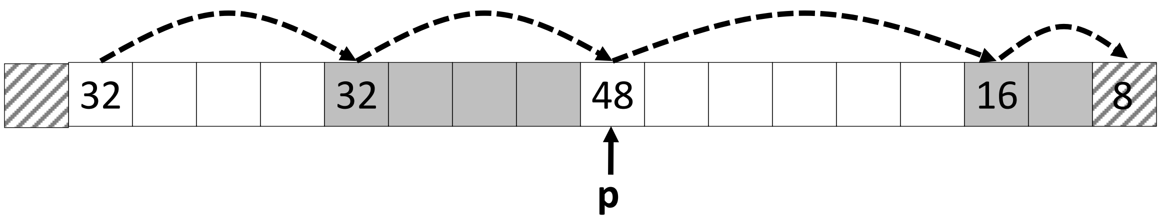
Comparing Strategies



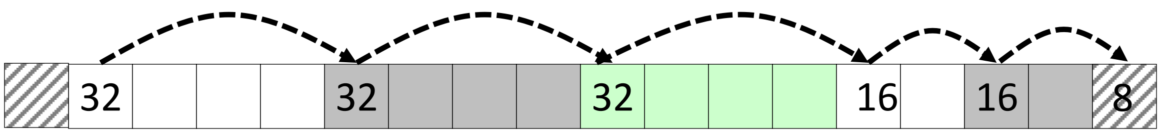
- **Total Overheads (for this benchmark)**
  - Perfect Fit: 1.6%
  - Best Fit: 8.3%
  - First Fit: 11.9%
  - Next Fit: 21.6%

Implicit List: Allocating in Free Block

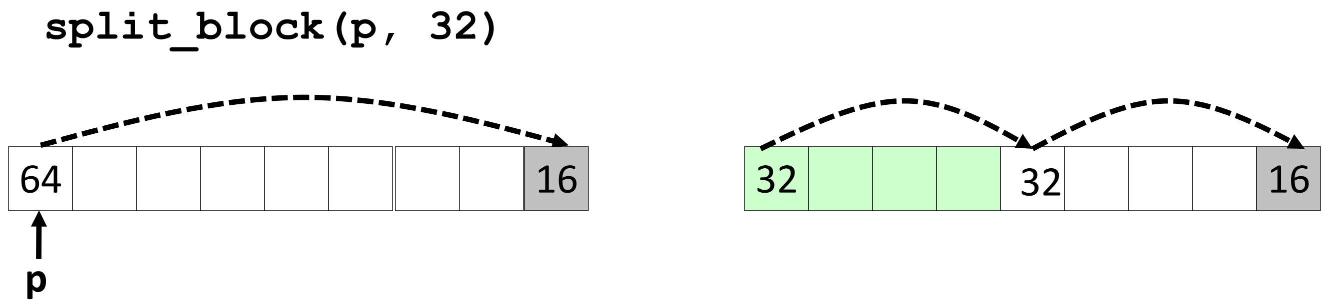
- **Allocating in a free block: *splitting***
  - Since allocated space might be smaller than free space, we might want to split the block



`split_block(p, 32)`



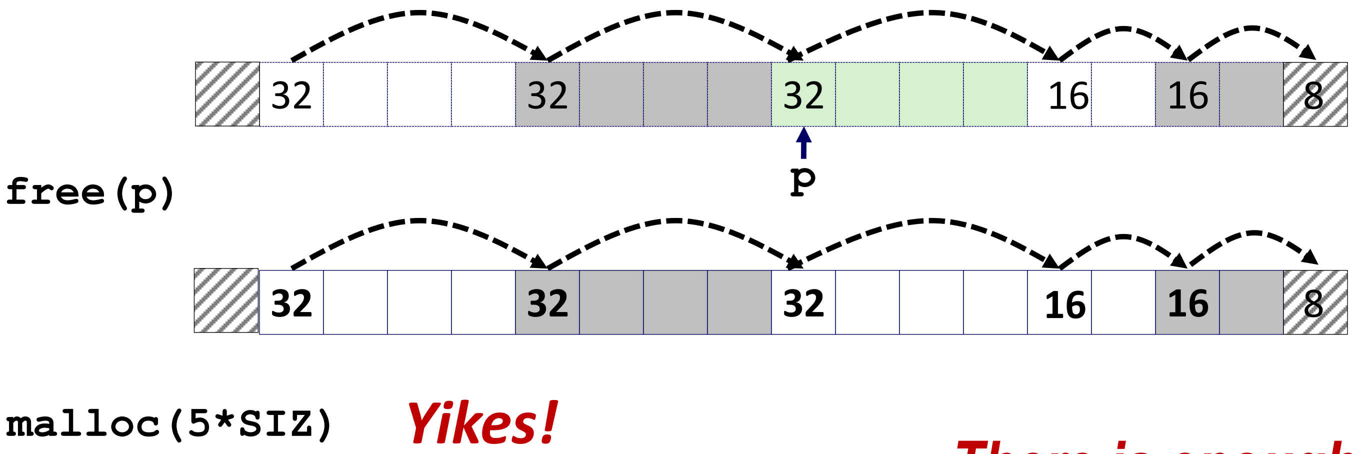
Implicit List: Splitting Free Block




```
// Warning: This code is incomplete

static void split_block(block_t *block, size_t asize){
    size_t block_size = get_size(block);

    if ((block_size - asize) >= min_block_size) {
        write_header(block, asize, true);
        block_t *block_next = find_next(block);
        write_header(block_next, block_size - asize, false);
}
```

Implicit List: Freeing a Block

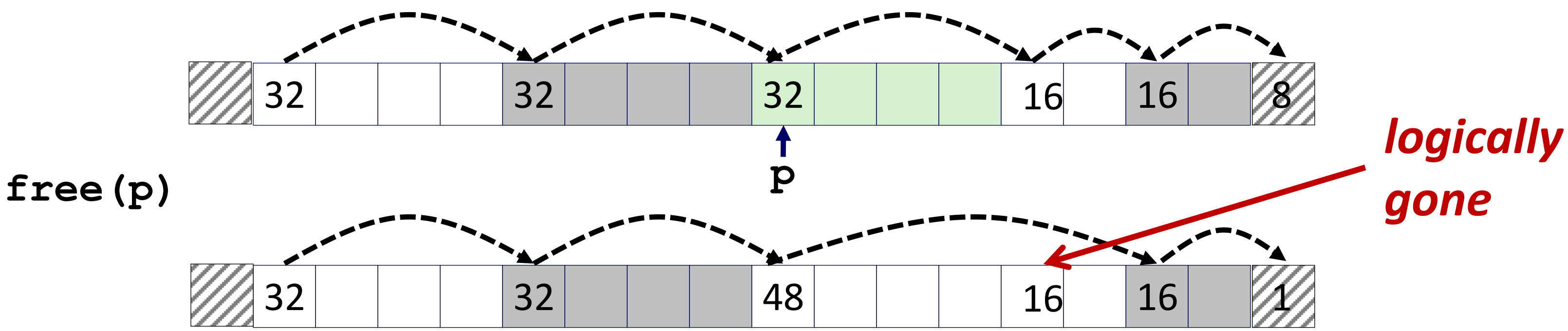
- **Simplest implementation:**
  - Need only clear the "allocated" flag
  - But can lead to "false fragmentation"



There is enough contiguous free space, but the allocator won't be able to find it

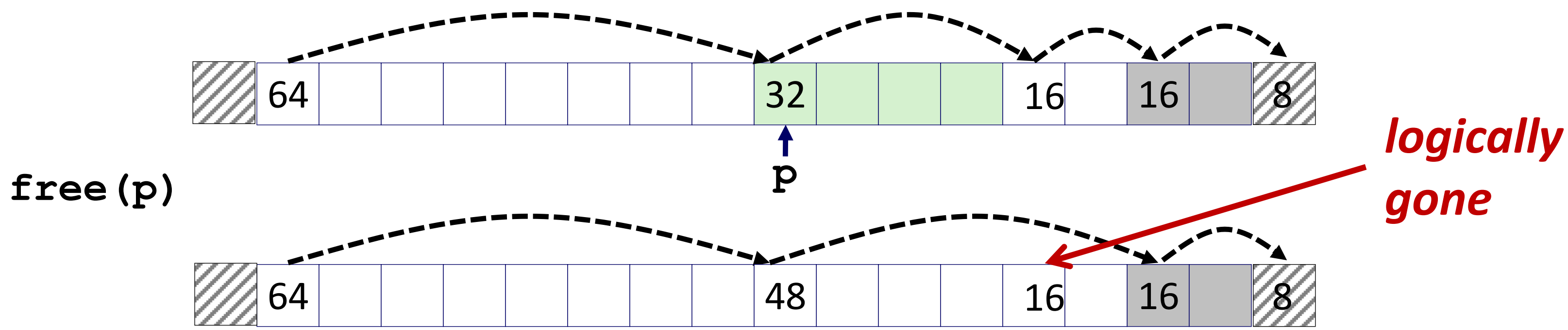
Implicit List: Coalescing

- **Join *(coalesce)* with next/previous blocks, if they are free**
  - Coalescing with next block



Implicit List: Coalescing

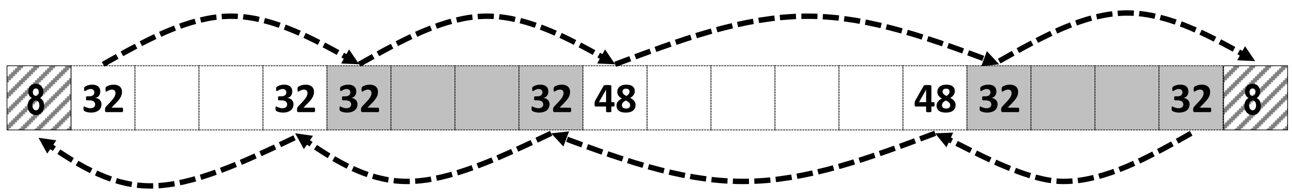
- **Join *(coalesce)* with next block, if it is free**
  - Coalescing with next block



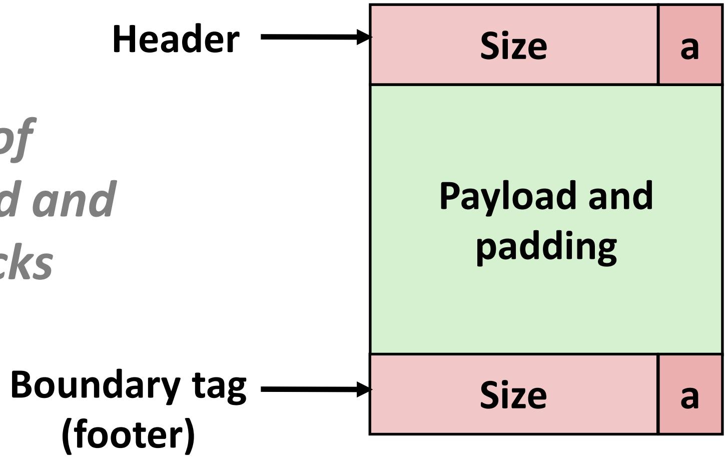
  - How do we coalesce with *previous* block?
    - How do we know where it starts?
    - How can we determine whether its allocated?

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

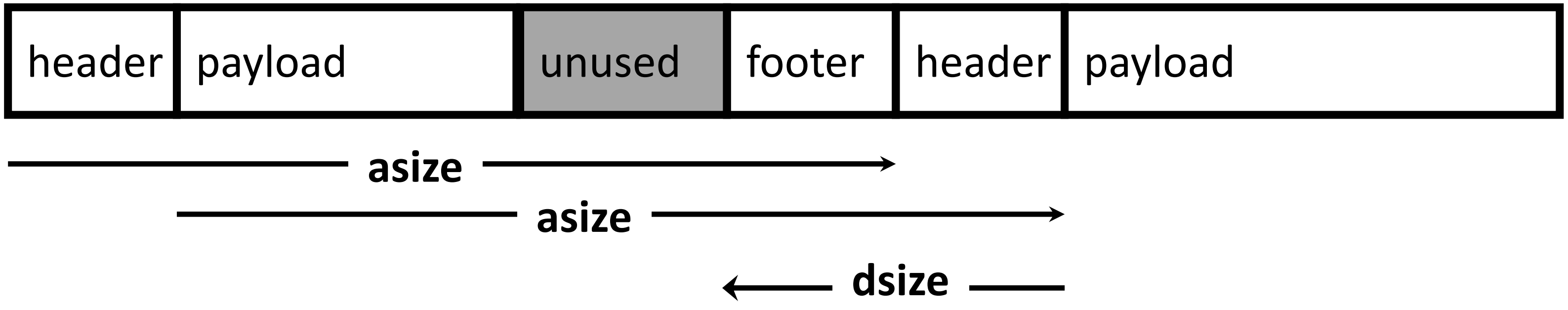
Size: Total block size

Payload: Application data (allocated blocks only)

Quiz

https://canvas.cmu.edu/courses/40739/quizzes/123407

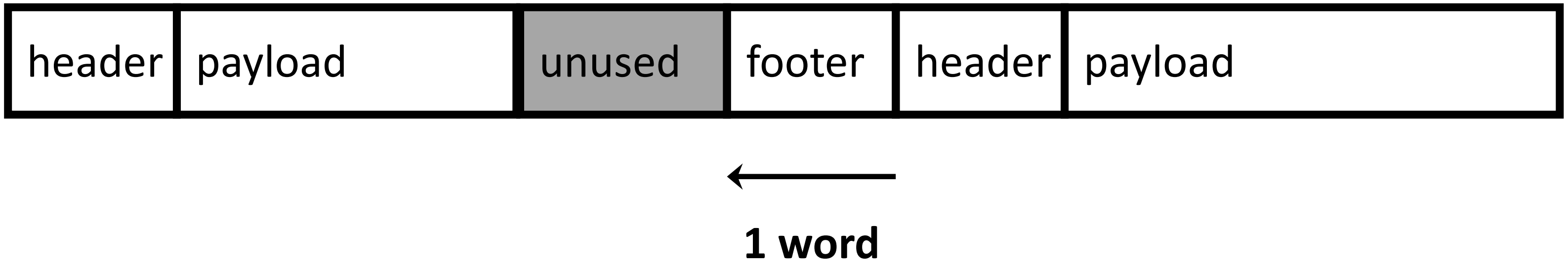
Implementation with Footers



- **Locating footer of current block**

```
const size_t dsize = 2*sizeof(word_t);

static word_t *header_to_footer(block_t *block)
{
    size_t asize = get_size(block);
    return (word_t *) (block->payload + asize - dsize);
}
```

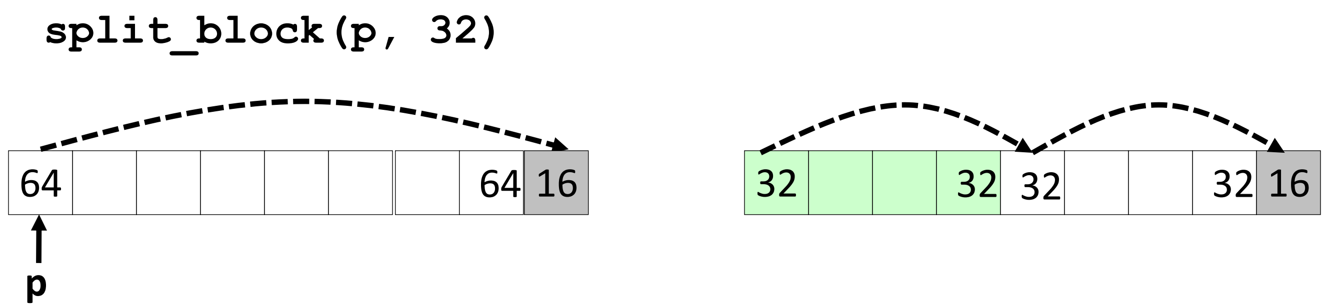
Implementation with Footers



- **Locating footer of previous block**

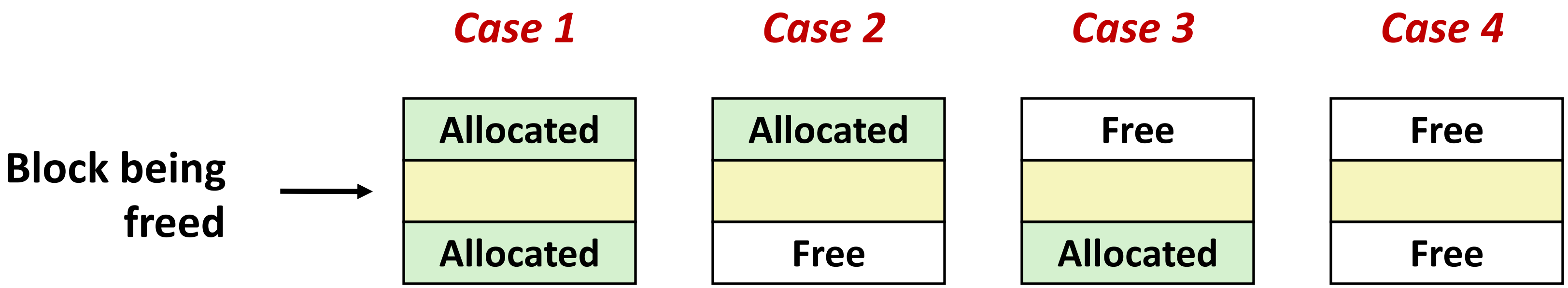
```
static word_t *find_prev_footer(block_t *block)
{
    return &(block->header) - 1;
}
```

Splitting Free Block: Full Version

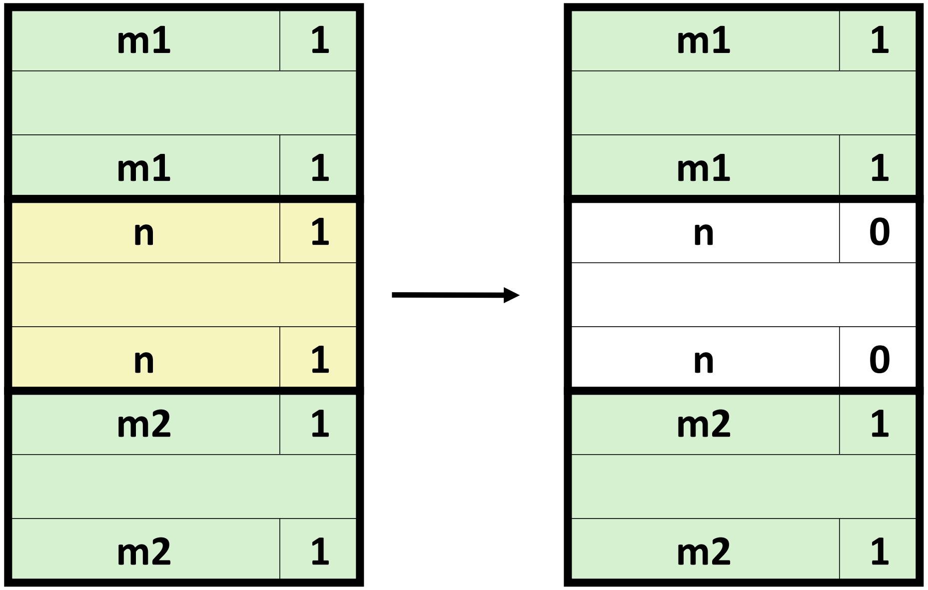



```
static void split_block(block_t *block, size_t asize){
    size_t block_size = get_size(block);

    if ((block_size - asize) >= min_block_size) {
        write_header(block, asize, true);
        write_footer(block, asize, true);
        block_t *block_next = find_next(block);
        write_header(block_next, block_size - asize, false);
        write_footer(block_next, block_size - asize, false);
}
```

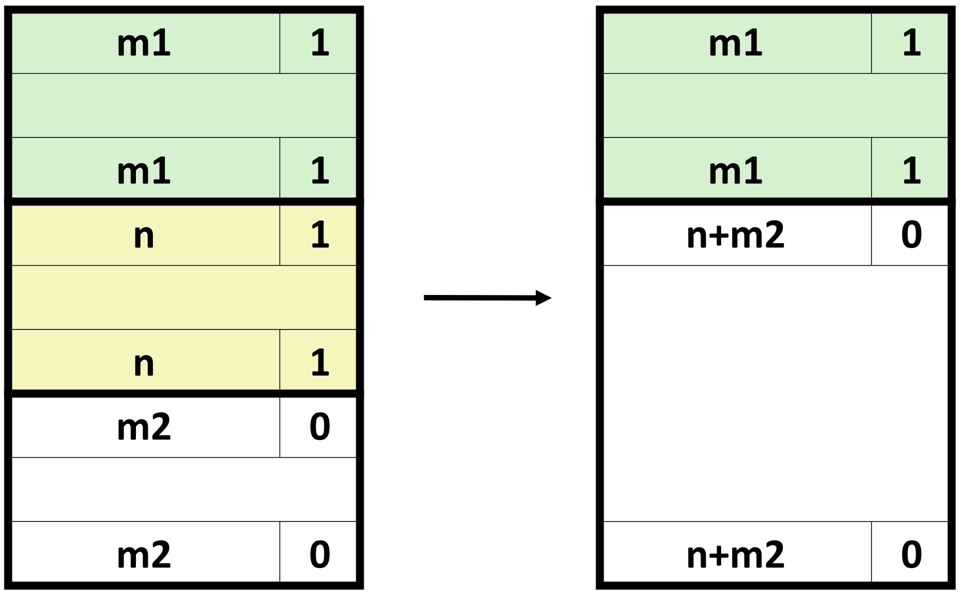
Constant Time Coalescing



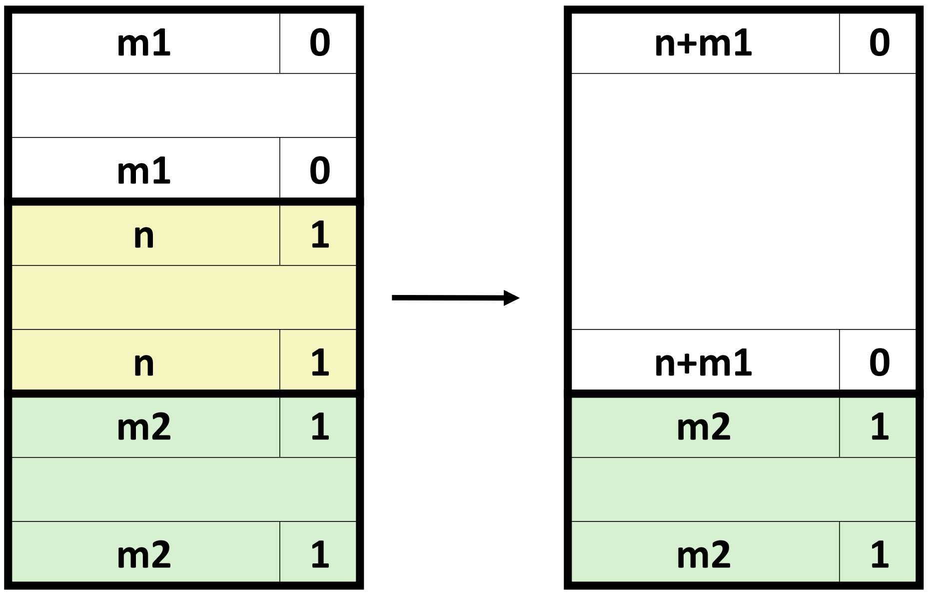
Constant Time Coalescing (Case 1)



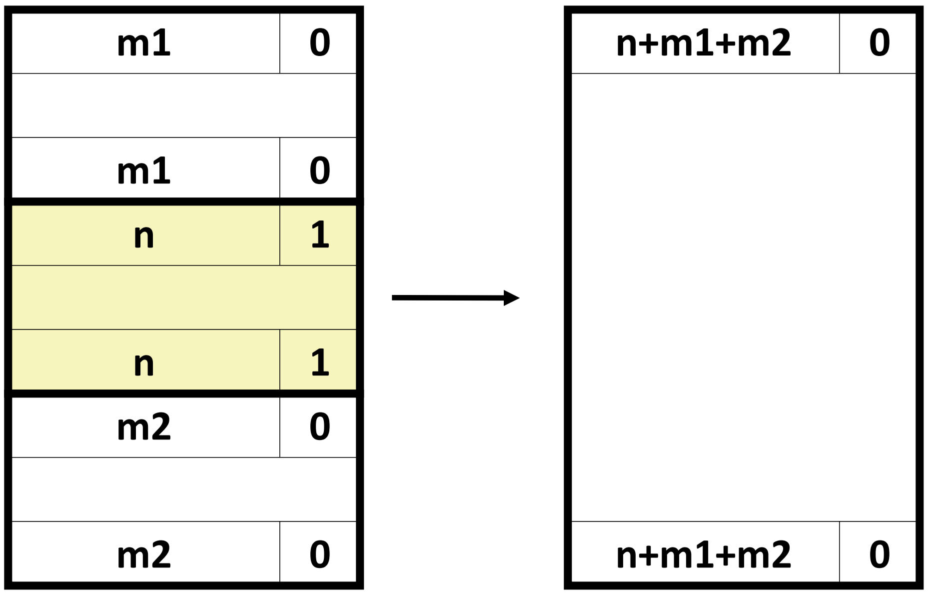
Constant Time Coalescing (Case 2)



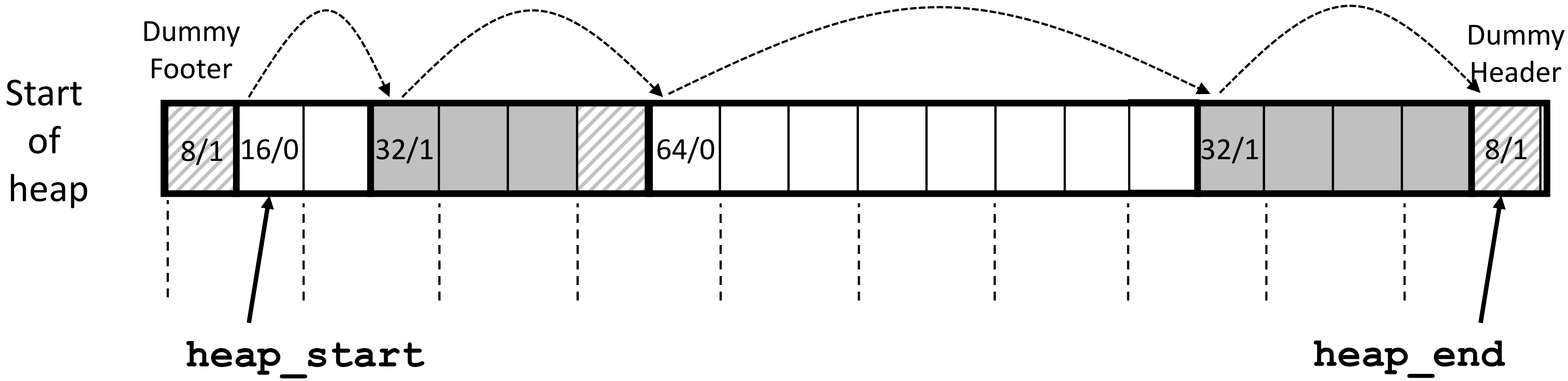
Constant Time Coalescing (Case 3)



Constant Time Coalescing (Case 4)



Heap Structure



- **Dummy footer before first header**
  - Marked as allocated
  - Prevents accidental coalescing when freeing first block
- **Dummy header after last footer**
  - Prevents accidental coalescing when freeing final block

Top-Level Malloc Code

```
const size_t dsize = 2*sizeof(word_t);

void *mm_malloc(size_t size)
{
    size_t asize = round_up(size + dsize, dsize);

    block_t *block = find_fit(asize);

    if (block == NULL)
        return NULL;

    size_t block_size = get_size(block);
    write_header(block, block_size, true);
    write_footer(block, block_size, true);

    split_block(block, asize);

    return header_to_payload(block);
}
```

```
round_up(n, m)
=
m *((n+m-1)/m)
```

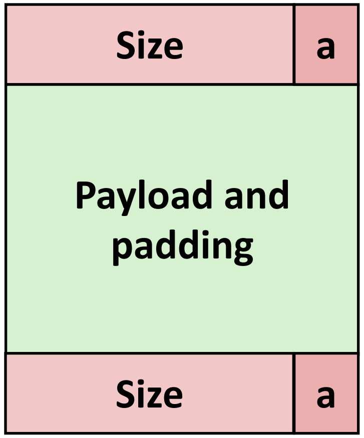
Top-Level Free Code

```
void mm_free(void *bp)
{
    block_t *block = payload_to_header(bp);
    size_t size = get_size(block);

    write_header(block, size, false);
    write_footer(block, size, false);

    coalesce_block(block);
}
```

Disadvantages of Boundary Tags

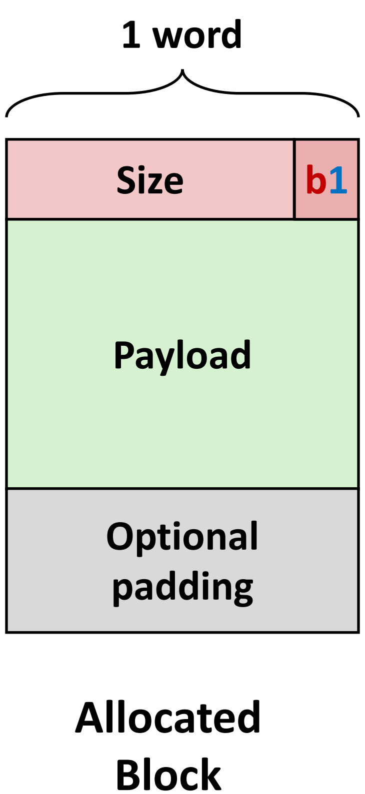
- **Internal fragmentation**

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



No Boundary Tag for Allocated Blocks

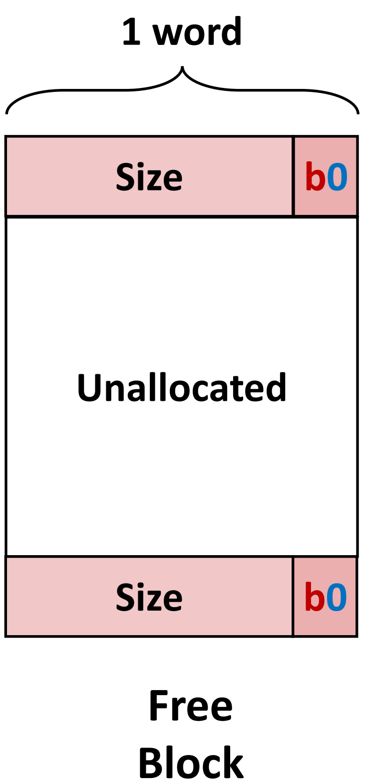
- Boundary tag needed only for free blocks
- When sizes are multiples of 16, have 4 spare bits



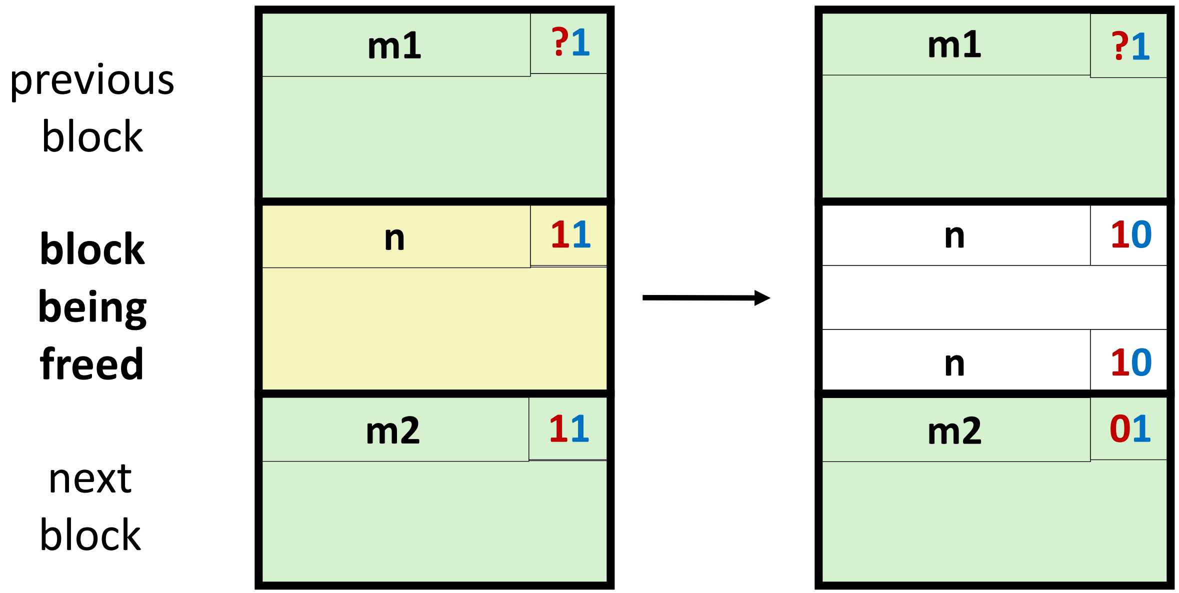
a = 1: Allocated block
a = 0: Free block
b = 1: Previous block is allocated
b = 0: Previous block is free

Size: block size

Payload: application data

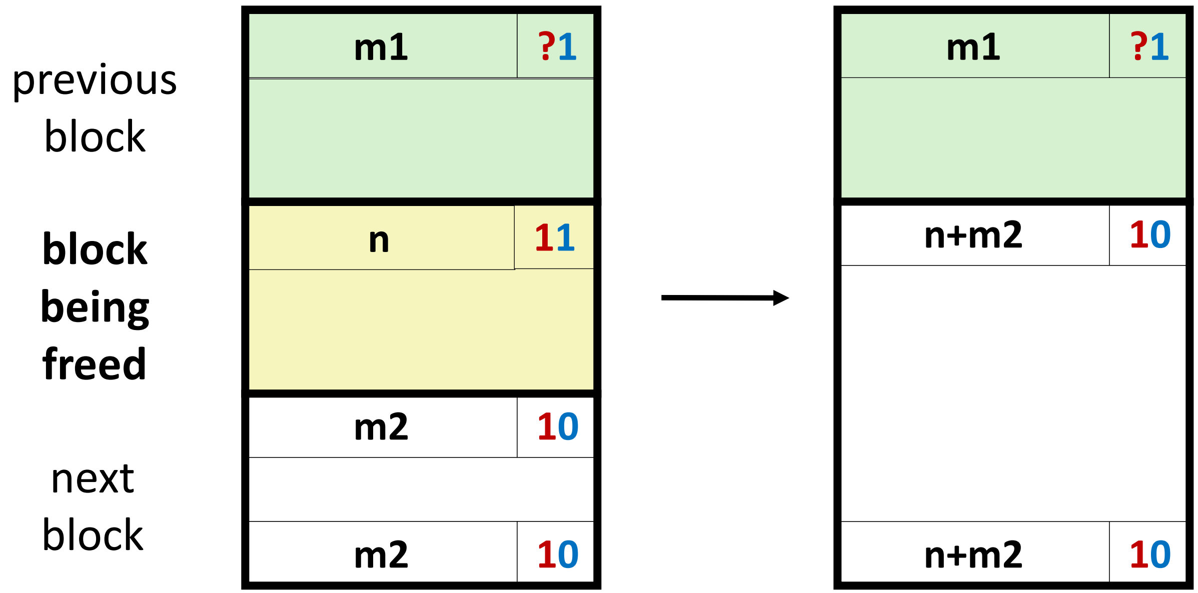


No Boundary Tag for Allocated Blocks (Case 1)



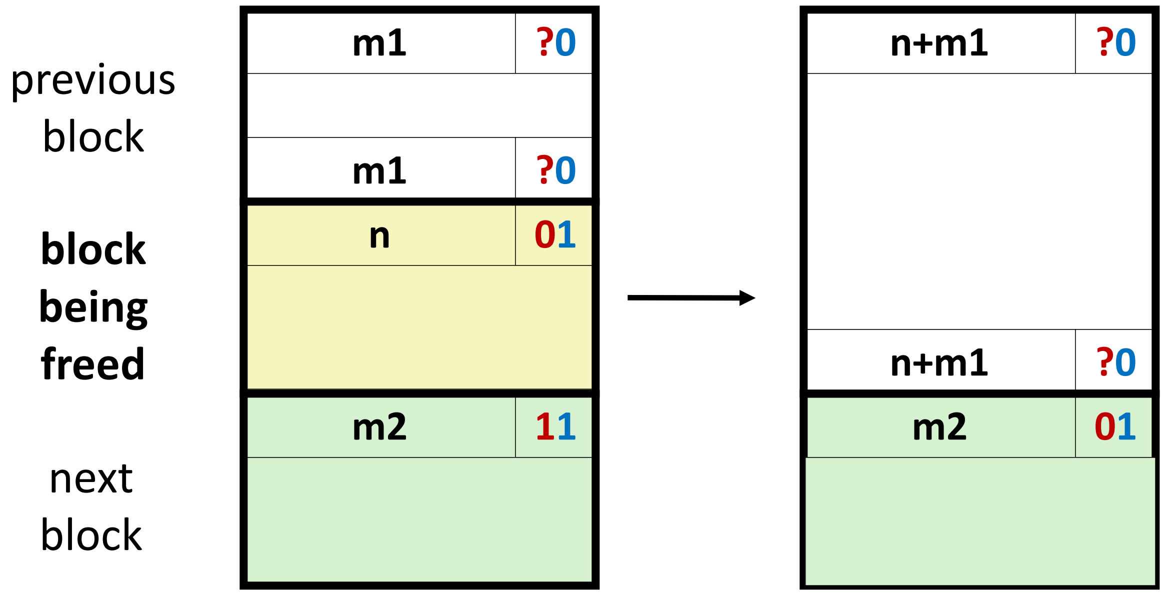
Header: Use 2 bits (address bits always zero due to alignment):
(previous block allocated)<<1 | (current block allocated)

No Boundary Tag for Allocated Blocks (Case 2)



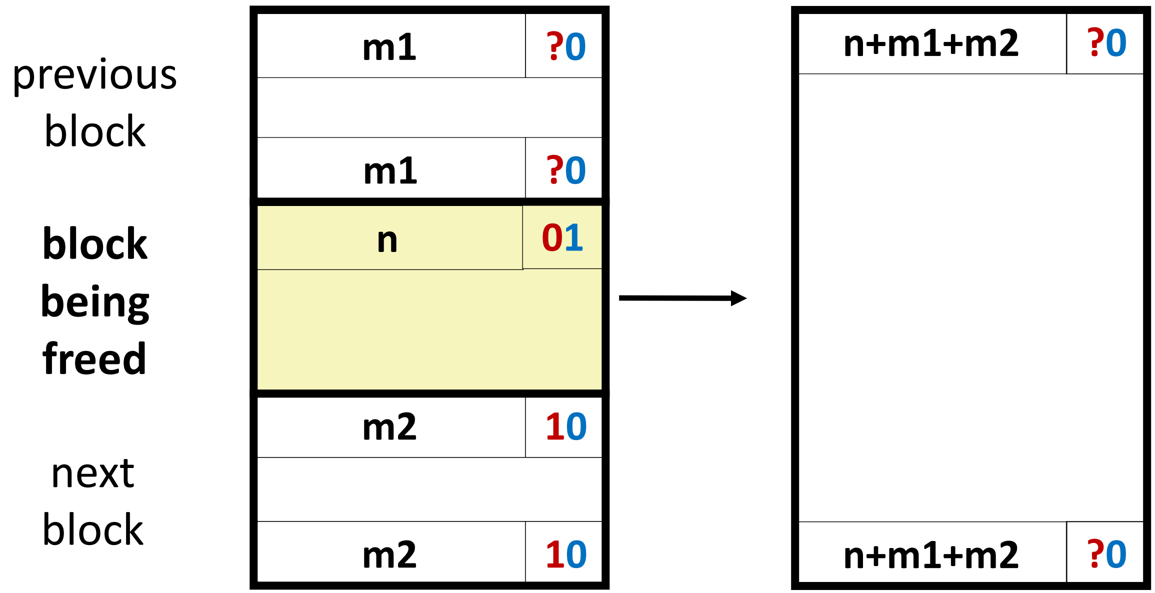
Header: Use 2 bits (address bits always zero due to alignment):
(previous block allocated)<<1 | (current block allocated)

No Boundary Tag for Allocated Blocks (Case 3)



Header: Use 2 bits (address 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 (address 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.

Implicit Lists: Summary

- **Implementation: very simple**
- **Allocate cost:**
  - linear time worst case
- **Free cost:**
  - constant time worst case
  - even with coalescing
- **Memory Overhead**
  - 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**