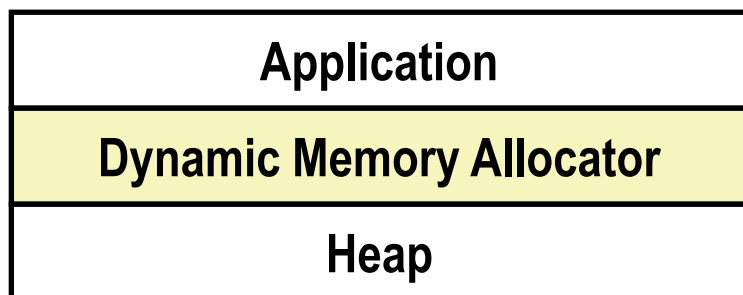# Dynamic Memory Allocation: Basic Concepts

15-213/18-213/15-513:
Introduction to Computer Systems
15th Lecture, June 19, 2020
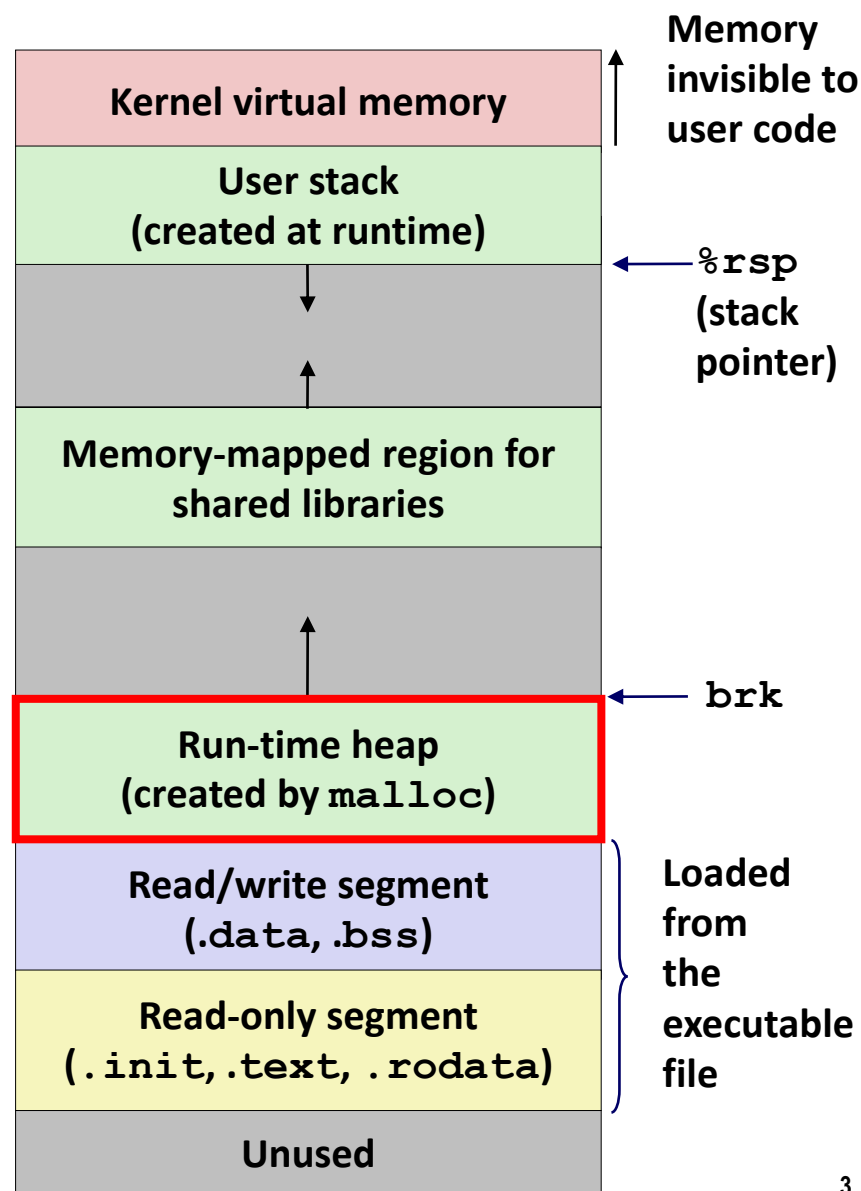
Today

- **Basic concepts**
- **Implicit free lists**

Dynamic Memory Allocation

Application
Dynamic Memory Allocator
Heap

- **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***

Kernel virtual memory
User stack (created at runtime)
Memory-mapped region for shared libraries
Run-time heap (created by `malloc`)
Read/write segment (`.data`, `.bss`)
Read-only segment (`.init`, `.text`, `.rodata`)
Unused

Memory invisible to user code

`%rsp` (stack pointer)

`brk`

Loaded from the executable file

`0x400000`

0

3

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` to ENOMEM

`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

```c
#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);
}
```

# Sample Implementation

- **Code**
  - File `mm-reference.c`
  - Manages fixed size heap
  - Functions `mm_malloc`, `mm_free`
- **Features**
  - Based on *words* of 8-bytes each
  - Pointers returned by malloc are double-word aligned
    - Double word = 2 words
  - Compile and run tests with command interpreter
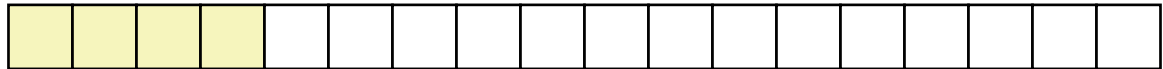
Visualization Conventions

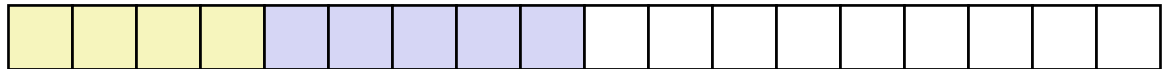- **Show 8-byte words as squares**
- **Allocations are double-word aligned**

Allocated block
(4 words)

Free block
(2 words)

☐ **Free word**

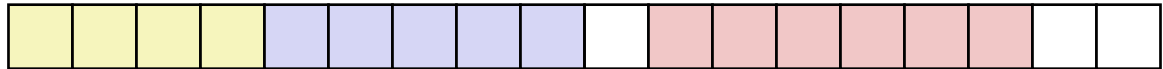🟩 **Allocated word**
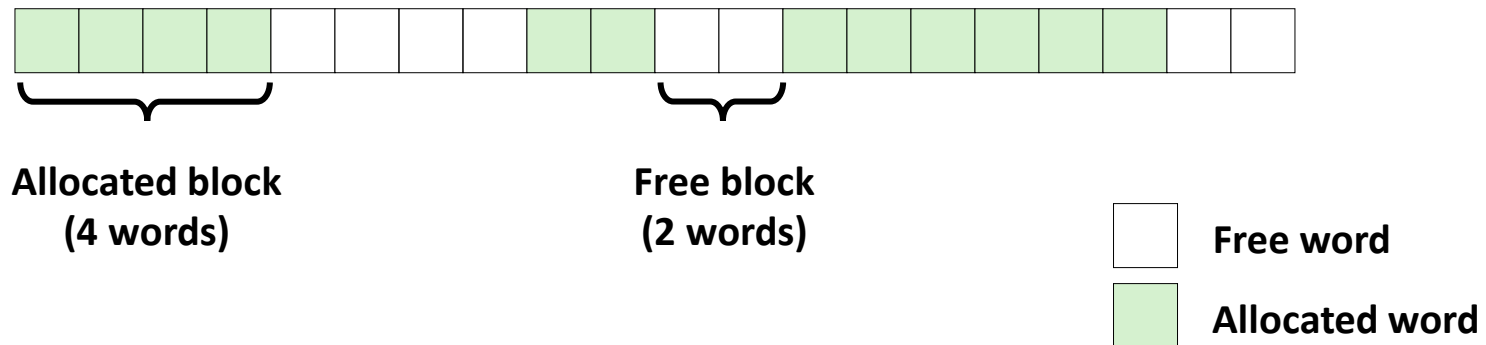
Allocation Example (Conceptual)

`#define SIZ sizeof(size_t)`

`p1 = malloc(4*SIZ)`

`p2 = malloc(5*SIZ)`

`p3 = malloc(6*SIZ)`

`free(p2)`

`p4 = malloc(2*SIZ)`

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:**
  - $R_0, R_1, ..., R_k, ... , R_{n-1}$

- **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

Performance Goal: Minimize Overhead

- **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: Overhead after k+1 requests*

  - Fraction of heap space *NOT* used for program data
  - $O_k = H_k / (\max_{i \le k} P_i) - 1.0$
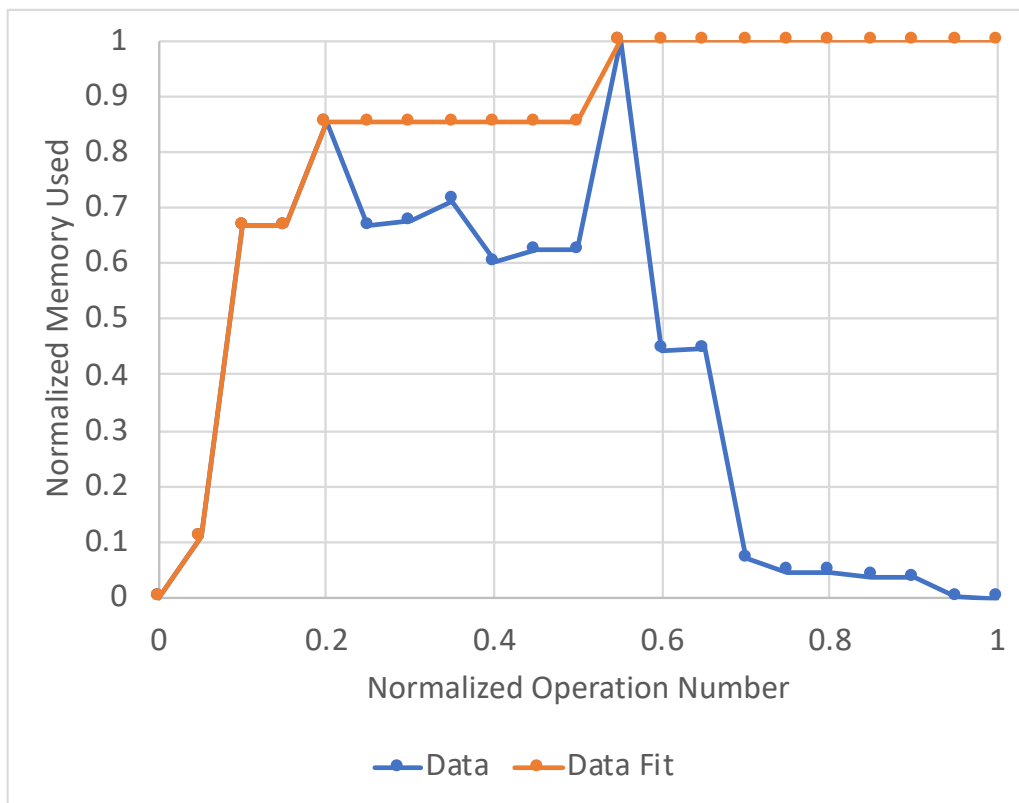
Benchmark Example

- **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
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

- Data line shows total allocated data (P_i)
- Data Fit line shows peak of total ($\max_{i \le k} P_i$)
- Normalized in X & Y

Full Benchmark Behavior
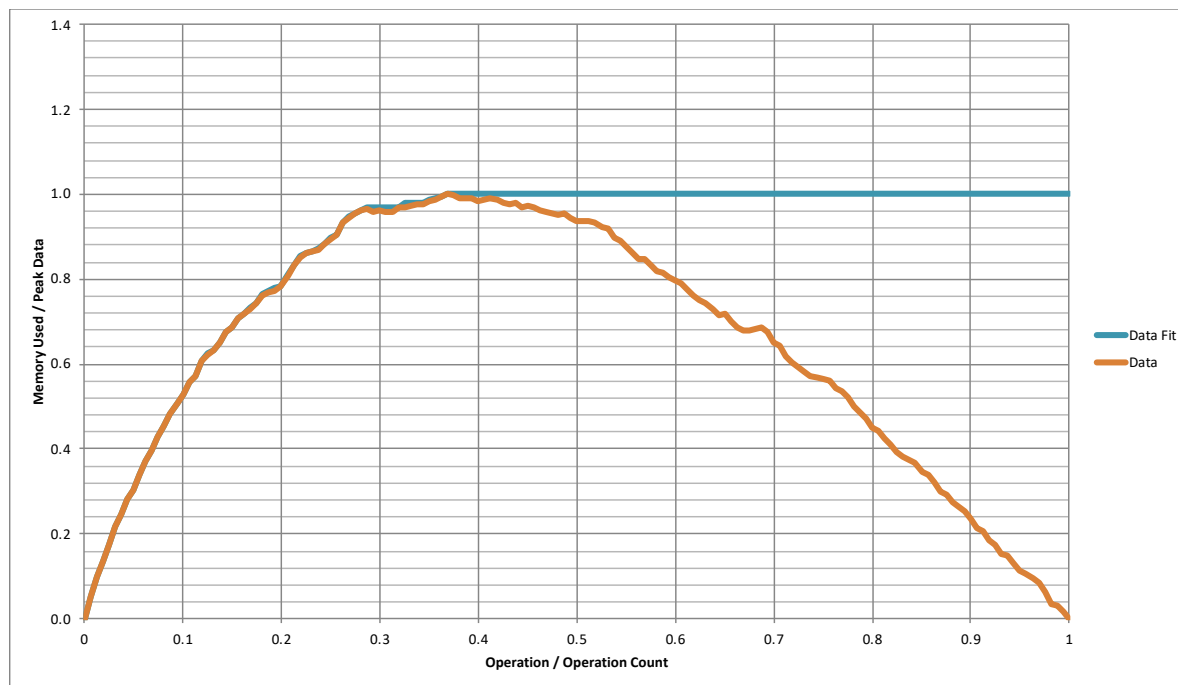
- **Given sequence of mallocs & frees (40,000 blocks)**
  - Starts with all mallocs, and shifts toward all frees

- **Manage space for all allocated blocks**

- **Metrics**
  - Data: P_i
  - Data fit: $\max_{i \leq k} P_i$

Fragmentation

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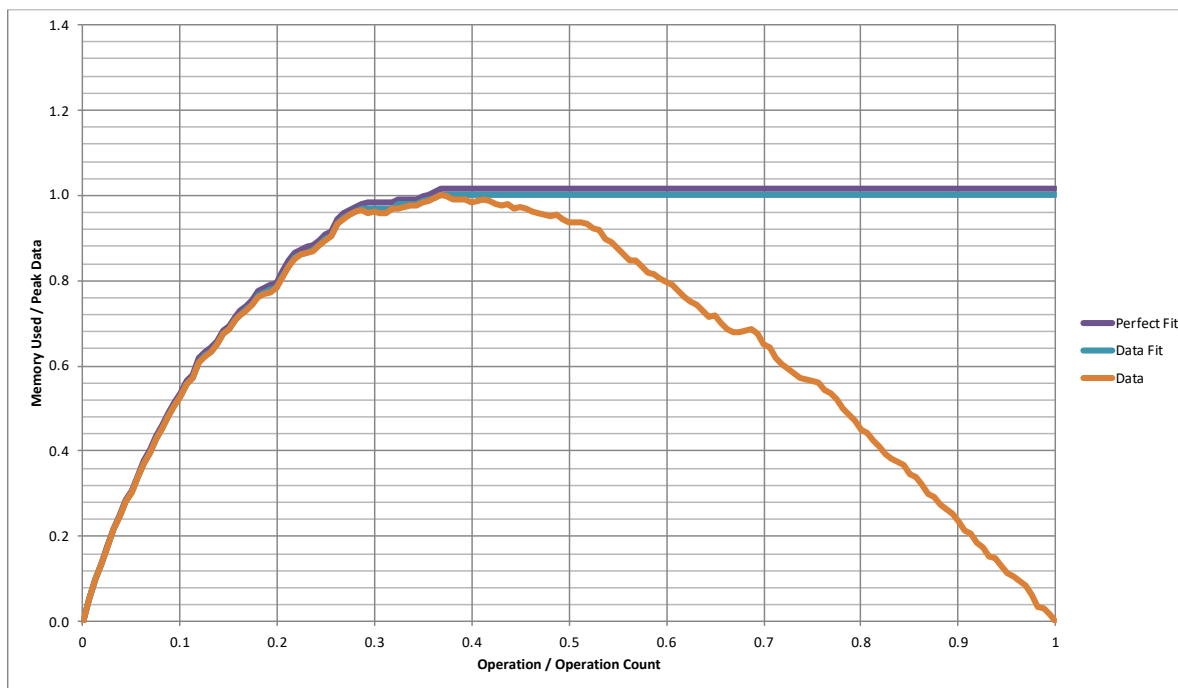 - *Internal* fragmentation
  - *External* fragmentation

Internal Fragmentation

- **For a given block,** *internal fragmentation* **occurs if payload is smaller than block size**

Block

| Internal fragmentation → | | Payload | | ← Internal fragmentation |
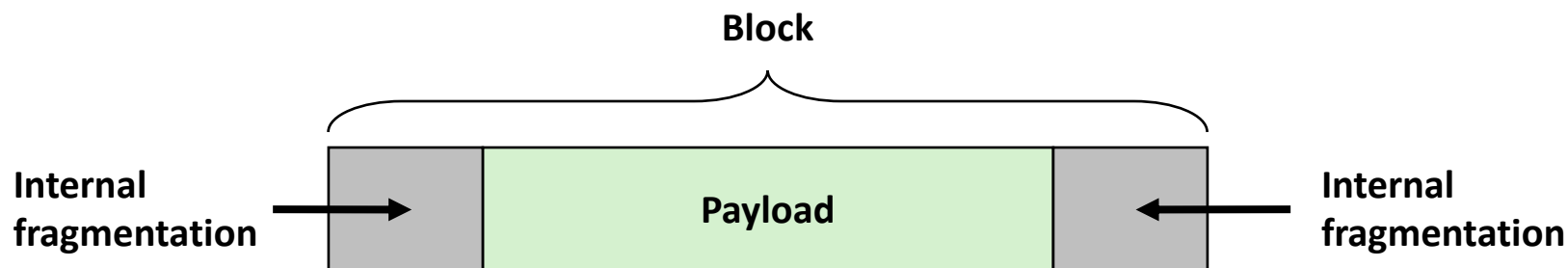
- **Caused by**
  - Overhead of maintaining heap data structures
  - Padding for alignment purposes
  - Explicit policy decisions
    (e.g., to return a big block to satisfy a small request)

- **Depends only on the pattern of *previous* requests**
  - Thus, easy to measure

Internal Fragmentation Effect

- **Perfect Fit: Only requires space for allocated data, data structures, and unused space due to alignment constraints**

  - For this benchmark, 1.5% overhead

  - Cannot achieve in practice

    - Especially since cannot move allocated blocks
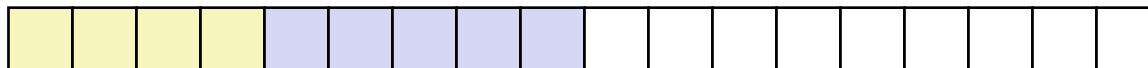
External Fragmentation

`#define SIZ sizeof(size_t)`

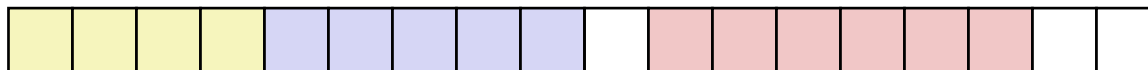- **Occurs when there is enough aggregate heap memory, but no single free block is large enough**

`p1 = malloc(4*SIZ)`

`p2 = malloc(5*SIZ)`
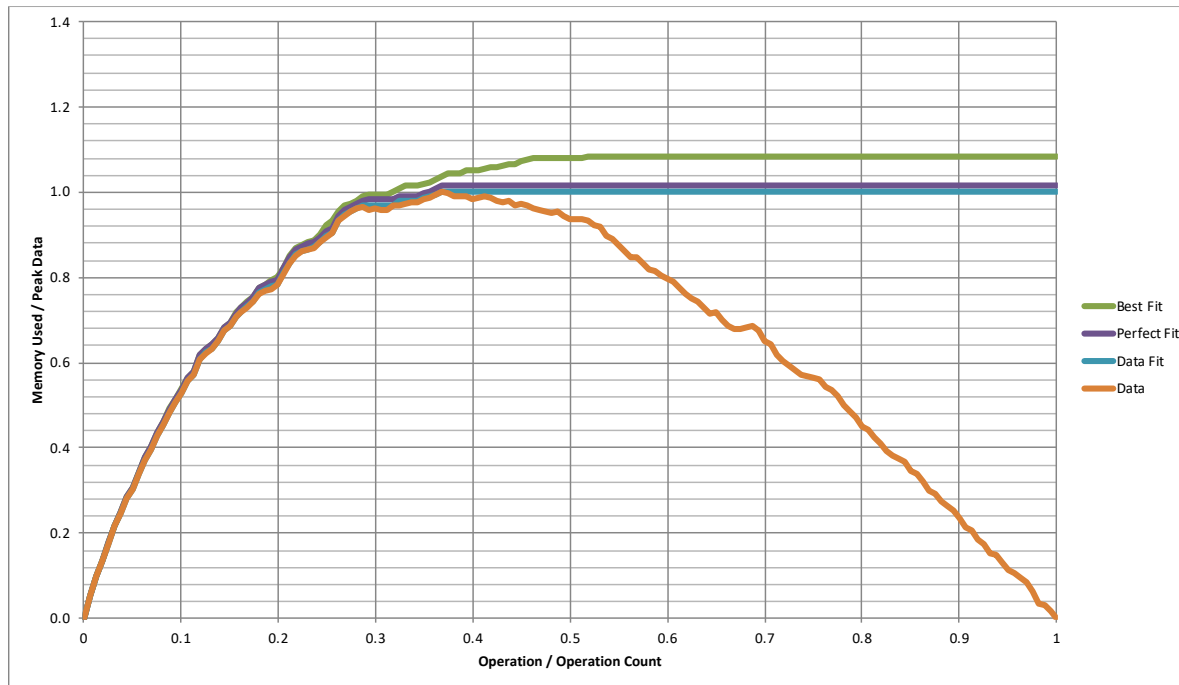
`p3 = malloc(6*SIZ)`

`free(p2)`

`p4 = malloc(7*SIZ)`   *Yikes! (what would happen now?)*

- **Amount of external fragmentation depends on the pattern of future requests**
  - Thus, difficult to measure

External Fragmentation Effect

- **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*
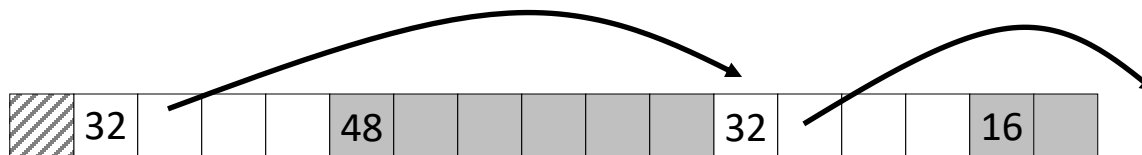 - Requires an extra word for every allocated block

p0 = malloc(4*SIZ)

p0

48

block size **Payload (aligned)** **Padding (for alignment)**

free(p0)
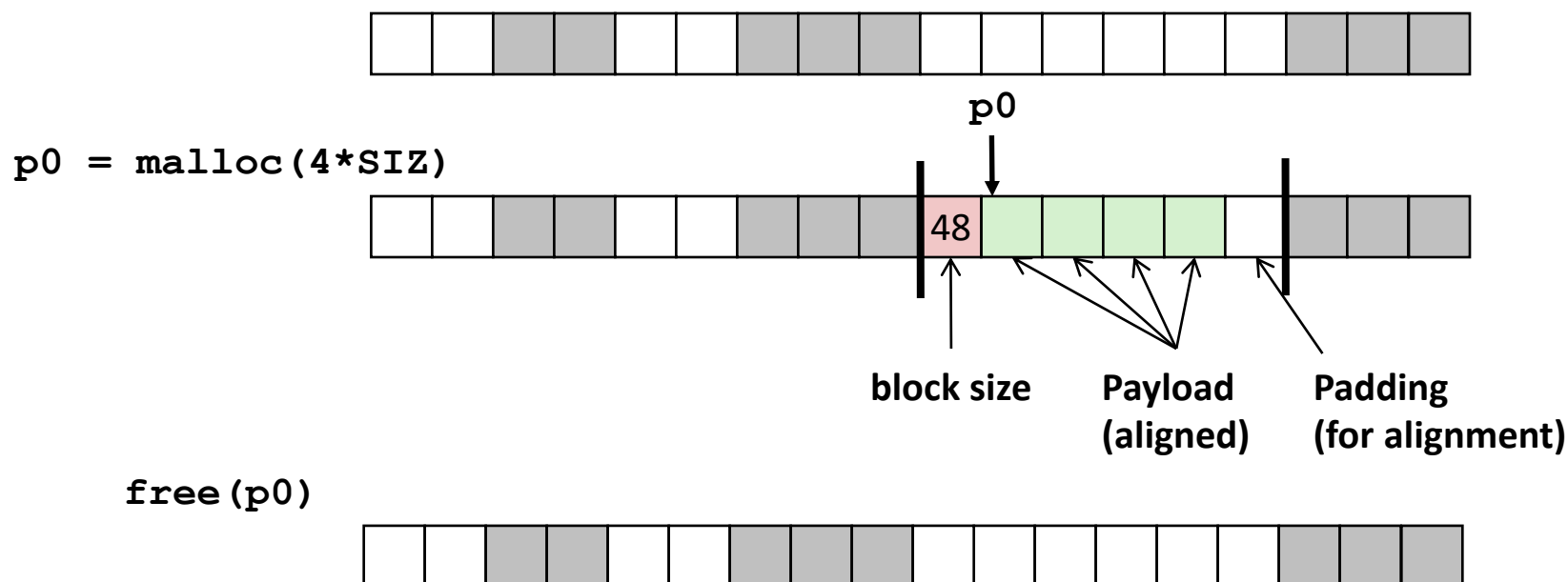
Keeping Track of Free Blocks

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

Unused

| 32 | | | | 48 | | | | | 32 | | | 16 | |
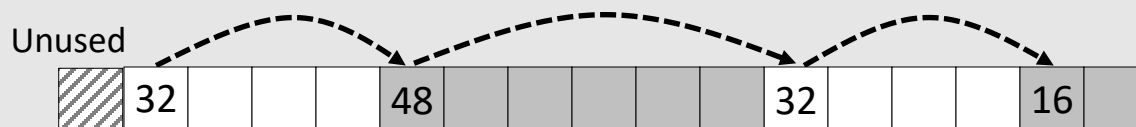
Need to tag each block as allocated/free

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

| 32 | | | 48 | | | | 32 | | 16 | |

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
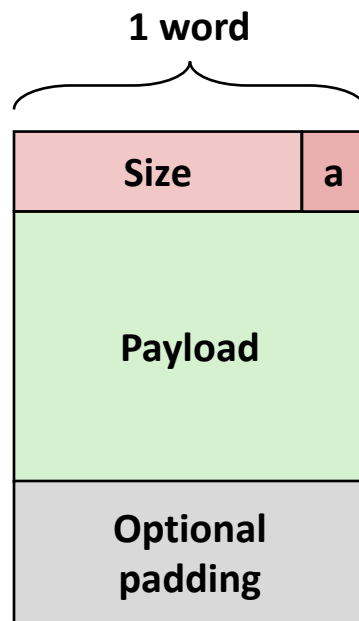
1 word

Format of allocated and free blocks

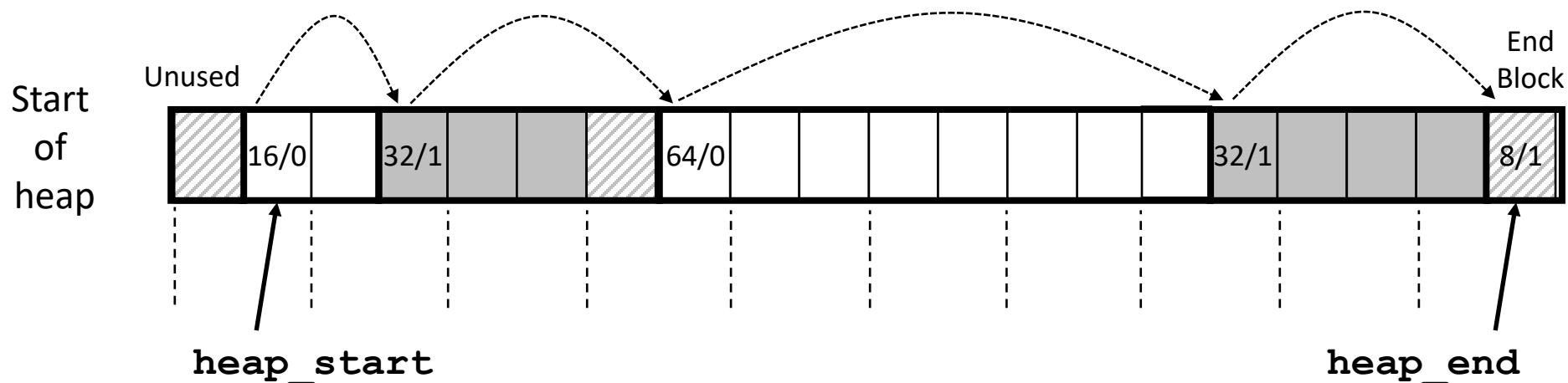| Size	a
Payload	
Optional padding	

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

Size: total block size

Payload: application data
(allocated blocks only)

Detailed Implicit Free List Example

Start of heap

Unused

End Block

16/0 32/1 64/0 32/1 8/1

heap_start

heap_end

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: Data Structures

header	payload

- **Block declaration**

```
typedef uint64_t word_t;
```

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

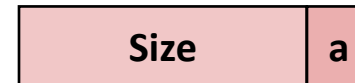- **Getting payload from block pointer**   `// block_t *block`

```
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

Size	a

- **Getting allocated bit from header**

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

- **Getting size from header**
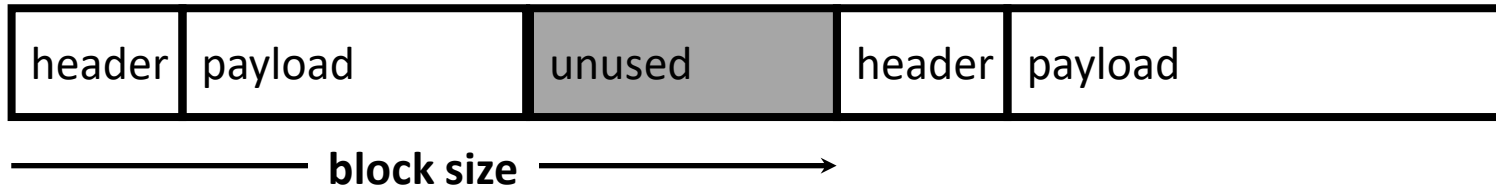
```
return header & ~0xfL;
```

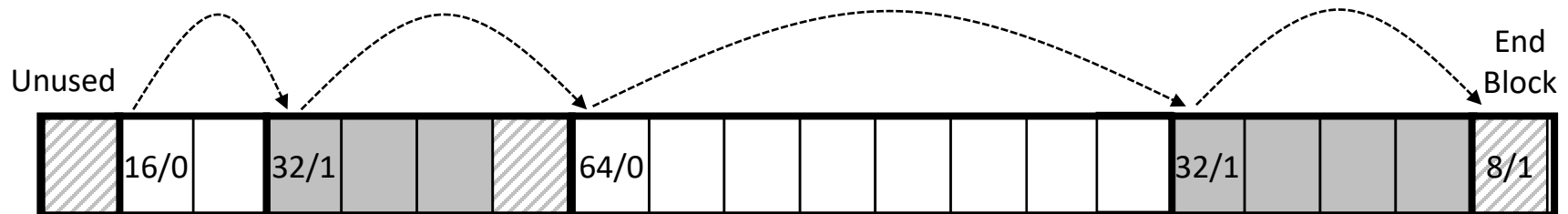- **Initializing header**   `//block_t *block`

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

Implicit List: Traversing list

header	payload	unused	header	payload

$\xleftarrow{\hspace{1cm}}$ **block size** $\xrightarrow{\hspace{1cm}}$

- **Find next block**

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

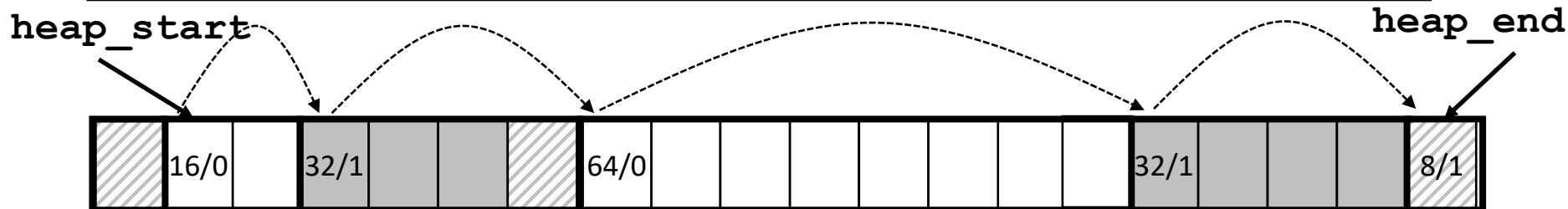Unused   16/0   32/1   64/0   32/1   End Block   8/1

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
}
```


heap_start   **heap_end**

| | 16/0 | | 32/1 | | | | 64/0 | | | | | | | | 32/1 | | | | 8/1 | |

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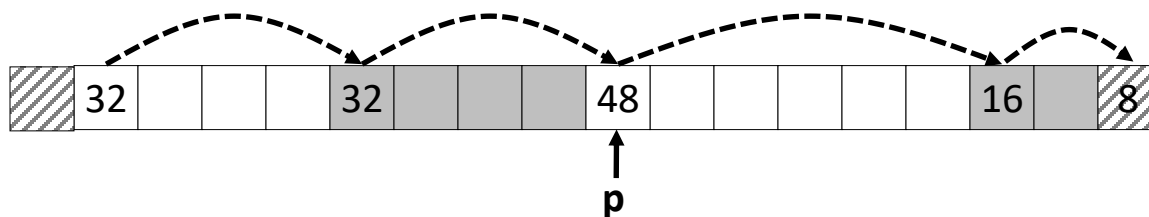
Comparing Strategies
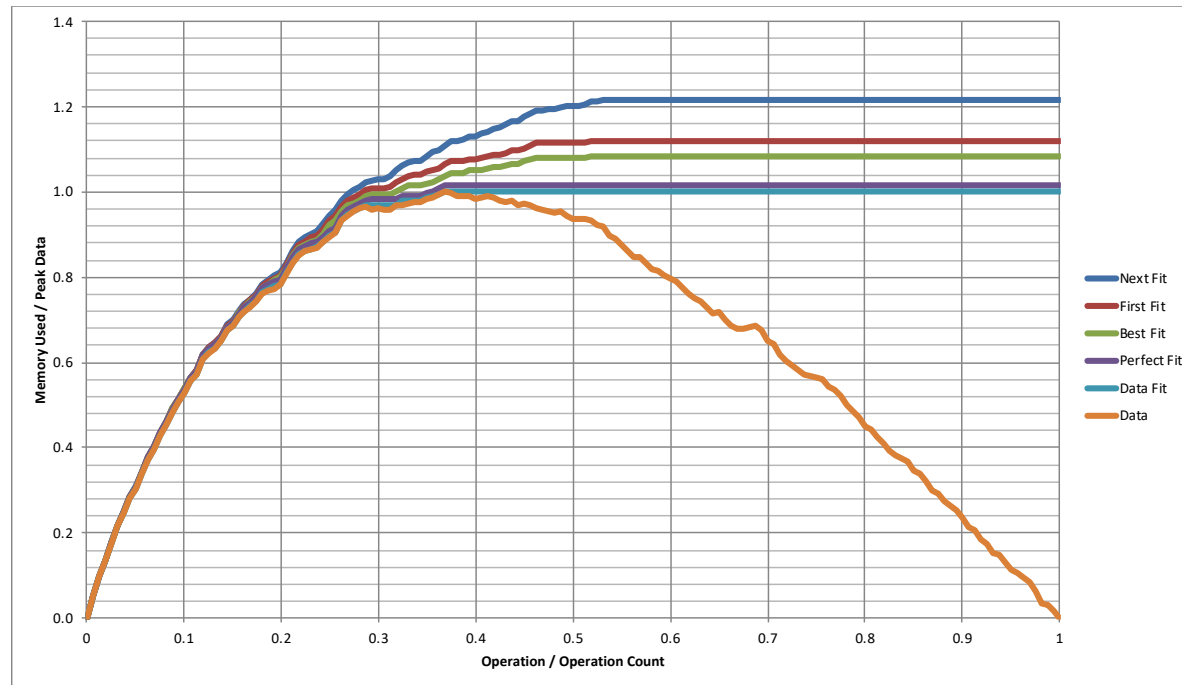
- **Total Overheads (for this benchmark)**
  - Perfect Fit: 1.6%
  - Best Fit: 8.3%
  - First Fit: 11.9%
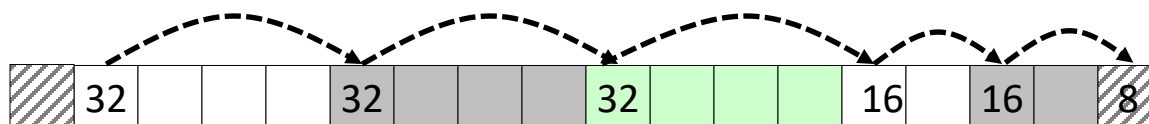 - Next Fit: 21.6%

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
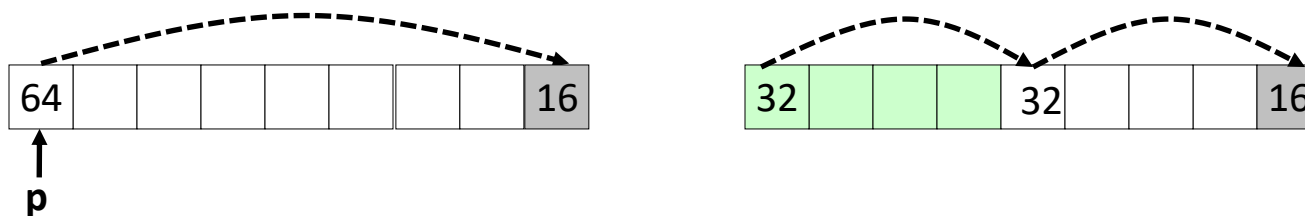

`split_block(p, 32)`

Implicit List: Splitting Free Block

`split_block(p, 32)`



```
// 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
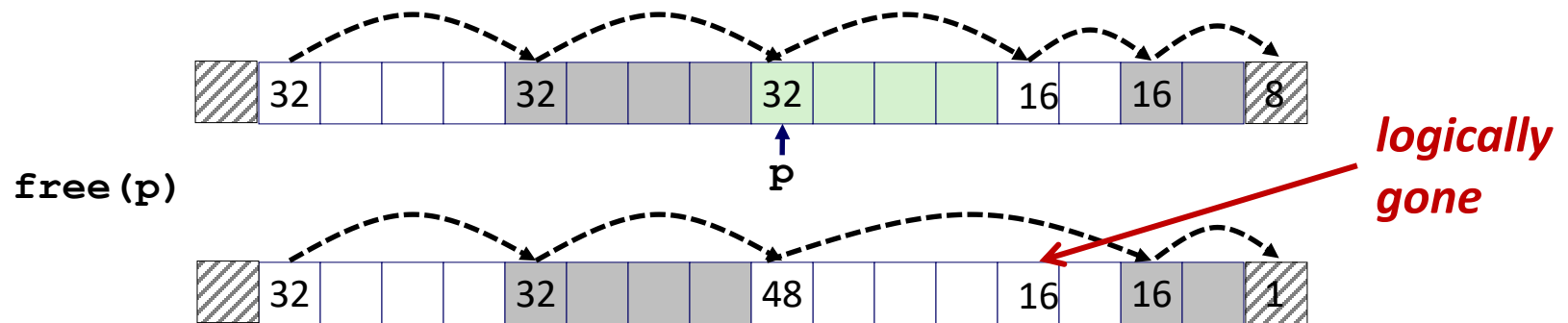 - But can lead to "false fragmentation"

free(p)
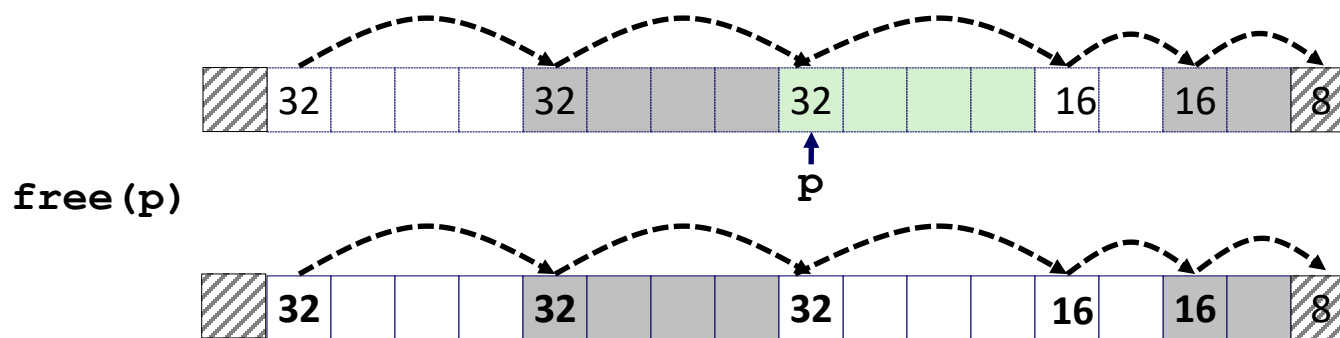
malloc(5*SIZ)   *Yikes!*

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

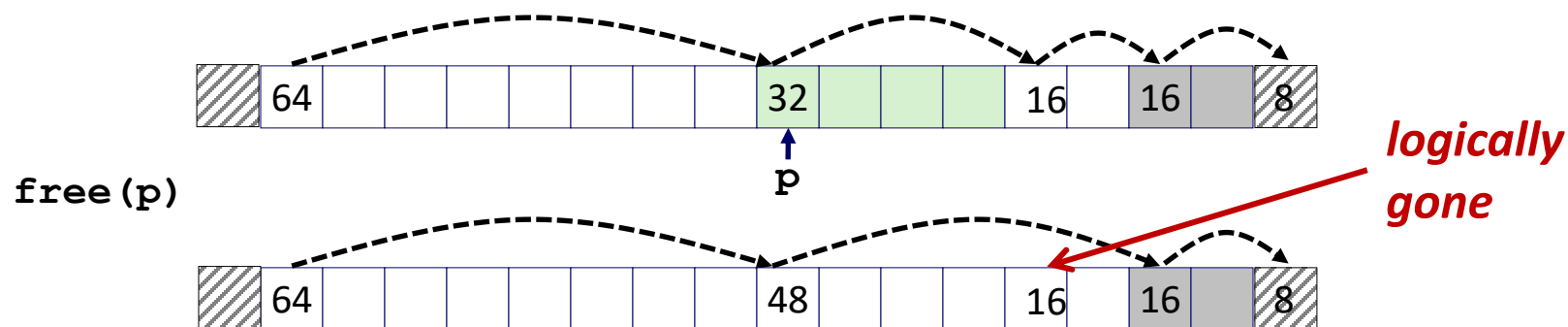# Implicit List: Coalescing

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

logically gone

`free(p)`

Implicit List: Coalescing

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

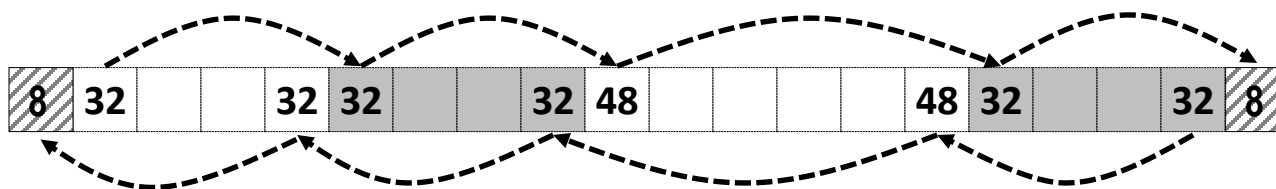free(p)

logically gone

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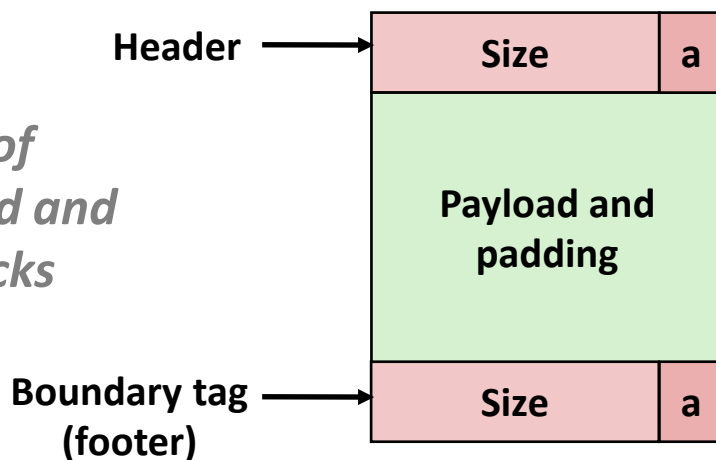   - How can we determine whether its allocated?

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!

| 8 | 32 | | | 32 | 32 | | | 32 | 48 | | | | 48 | 32 | | | 32 | 8 |

Format of allocated and free blocks

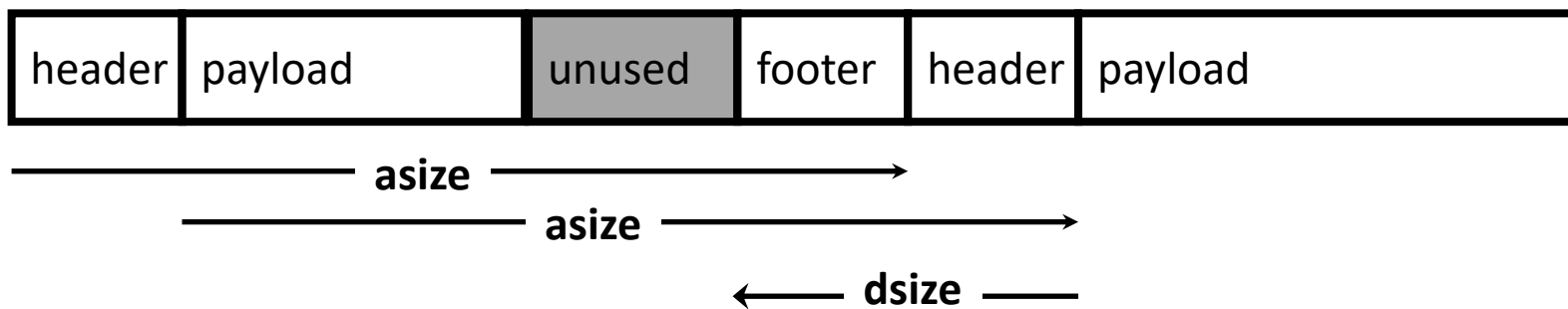| Header →	Size	a
	Payload and padding	
Boundary tag (footer) →	Size	a

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

Size: Total block size

Payload: Application data (allocated blocks only)

Implementation with Footers

header	payload	unused	footer	header	payload

asize →

asize →

← dsize →

- **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

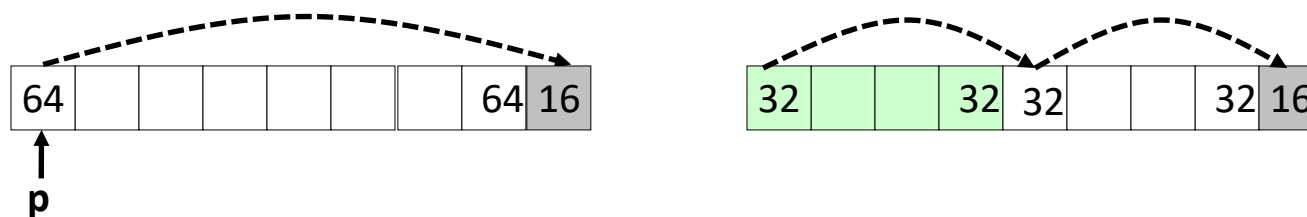| header	payload	unused	footer	header	payload

⟵

1 word

- **Locating footer of previous block**

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

Splitting Free Block: Full Version

`split_block(p, 32)`


```
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
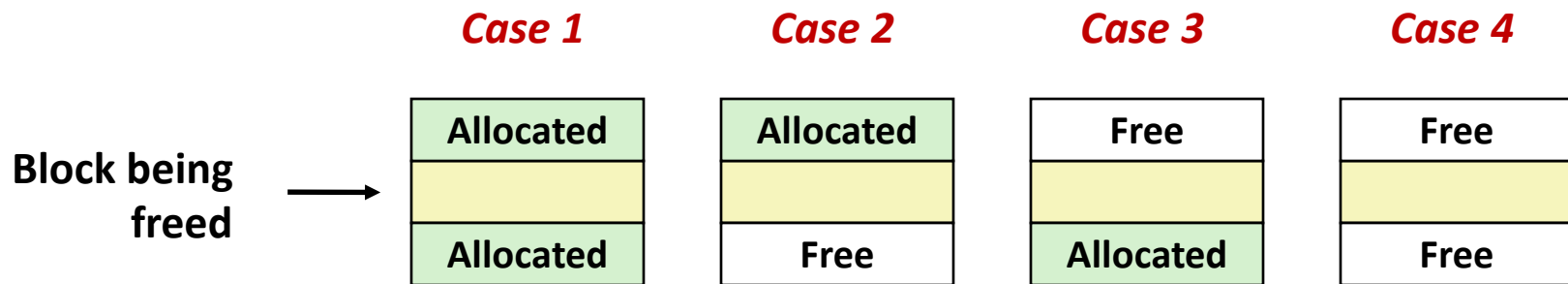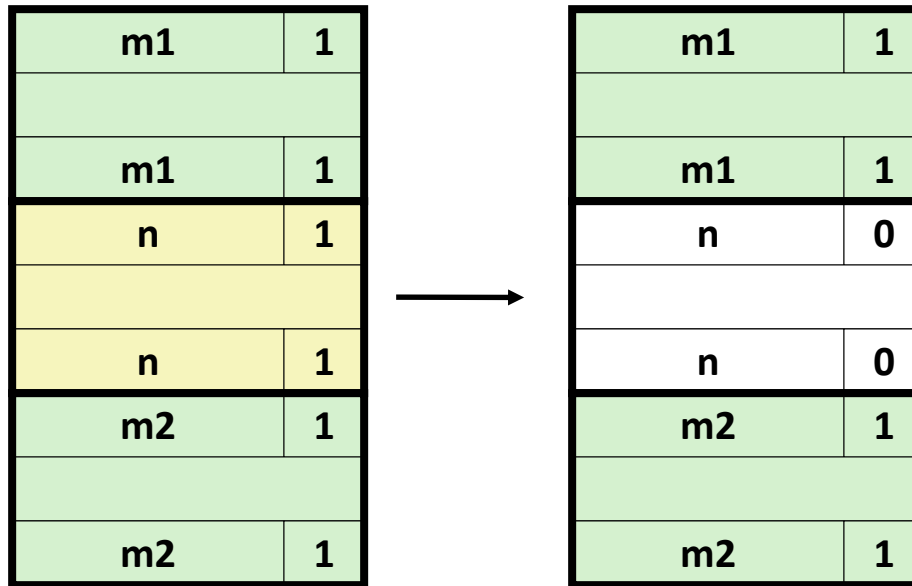
Block being freed →

Case 1	Case 2	Case 3	Case 4
Allocated	Allocated	Free	Free
Allocated	Free	Allocated	Free

Constant Time Coalescing (Case 1)

m1	1
m1	1
n	1
n	1
m2	1
m2	1

→

m1	1
m1	1
n	0
n	0
m2	1
m2	1

Constant Time Coalescing (Case 2)

m1	1
m1	1
n	1
n	1
m2	0
m2	0

→

m1	1
m1	1
n+m2	0
n+m2	0

Constant Time Coalescing (Case 3)

m1	0
m1	0
n	1
n	1
m2	1
m2	1

→

n+m1	0
n+m1	0
m2	1
m2	1

Constant Time Coalescing (Case 4)

m1	0
m1	0
n	1
n	1
m2	0
m2	0

→

n+m1+m2	0
n+m1+m2	0
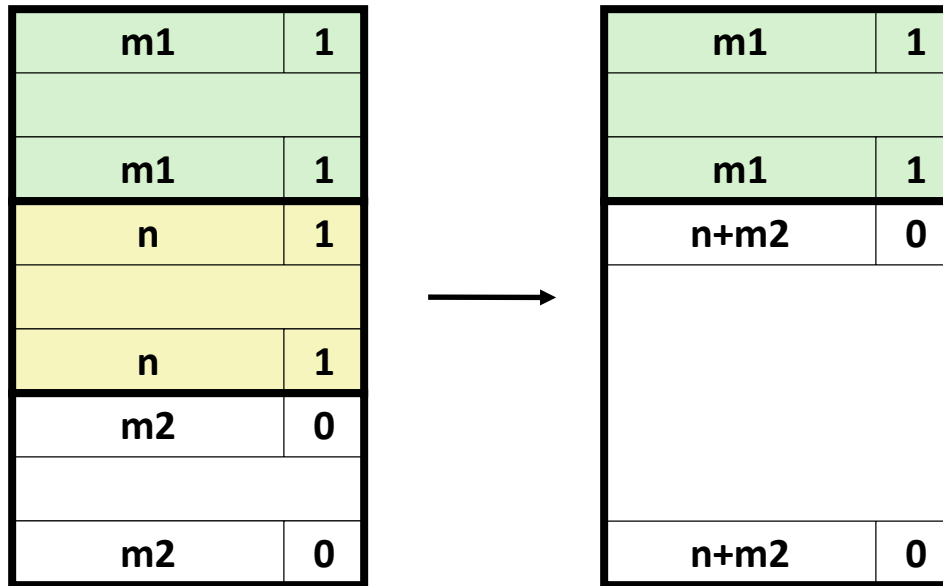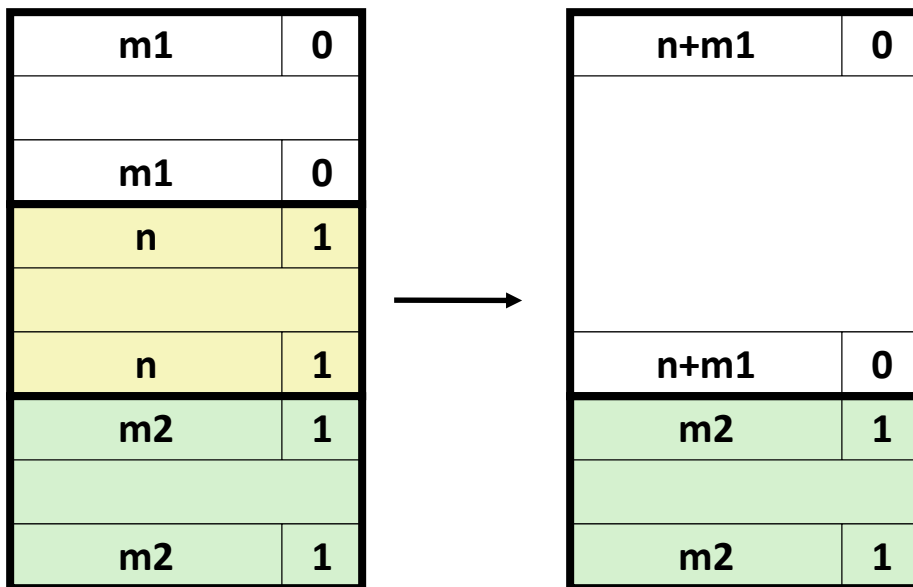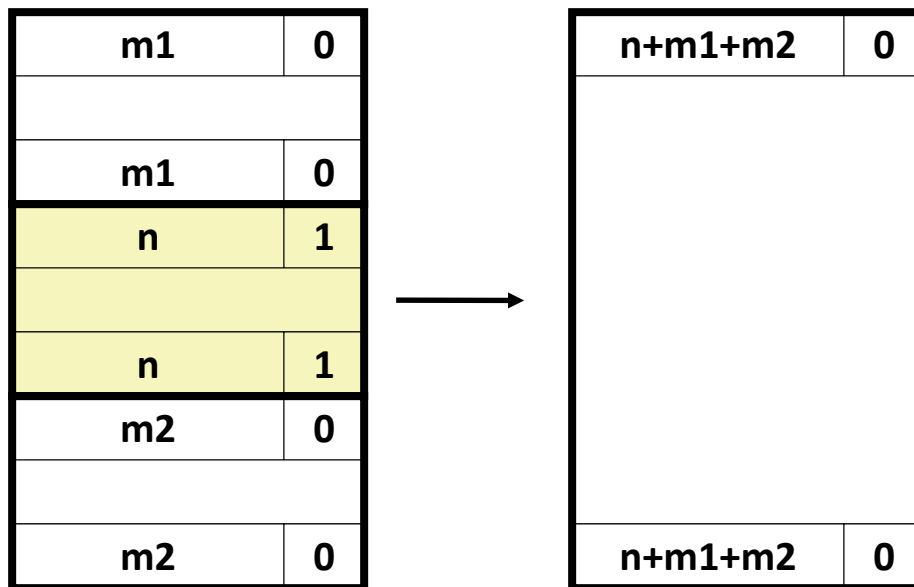
Heap Structure
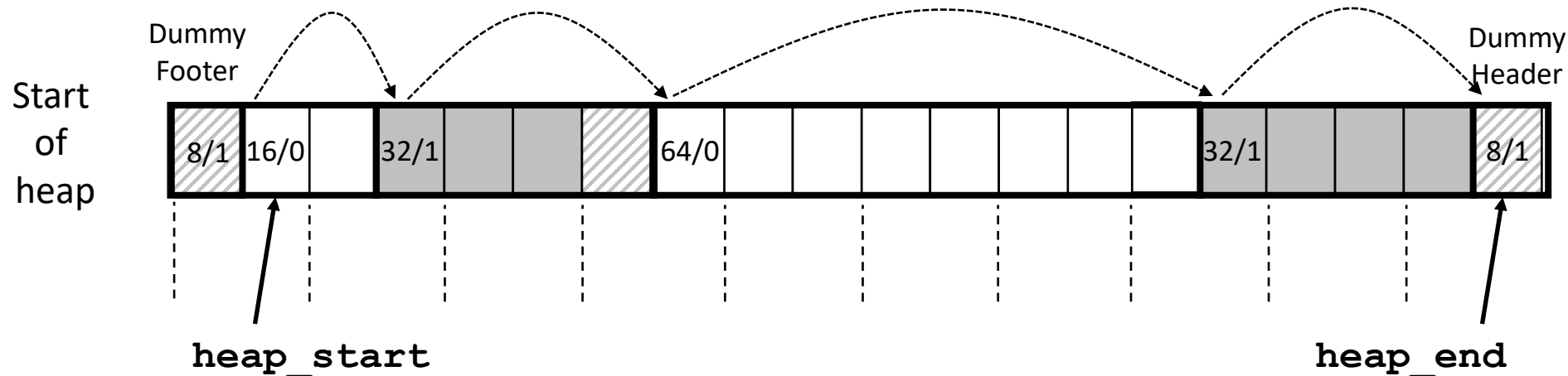
- **Dummy footer before first header**
  - Marked as allocated
  - Prevents accidental coalescing when freeing first block
- **Dummy header after last footer**
  - Prevents accidental coalescing when freeing final block

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)
```
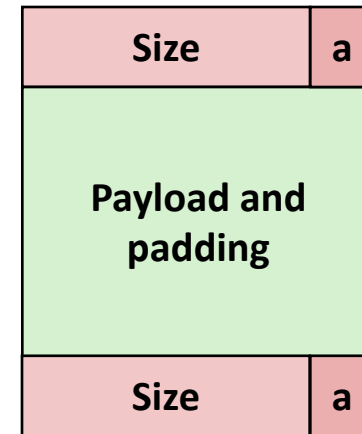
Top-Level Free Code

```c
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);
}
```
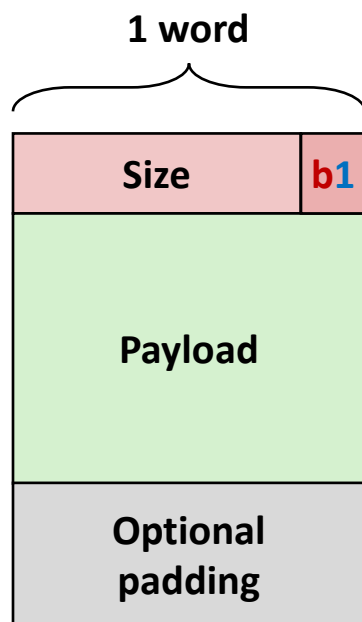
Disadvantages of Boundary Tags

- **Internal fragmentation**

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

Size	a
Payload and padding	
Size	a

No Boundary Tag for Allocated Blocks

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

1 word

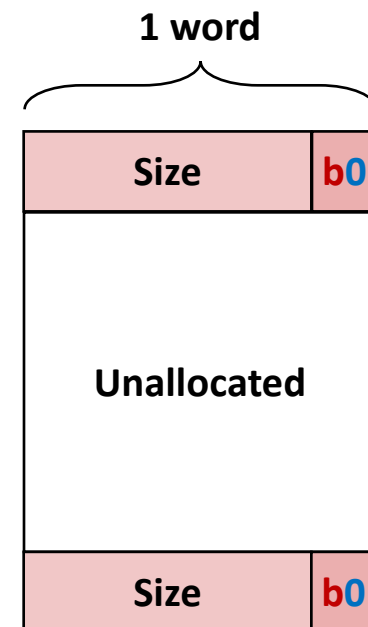| Size	**b1**
Payload	
Optional padding	

Allocated Block

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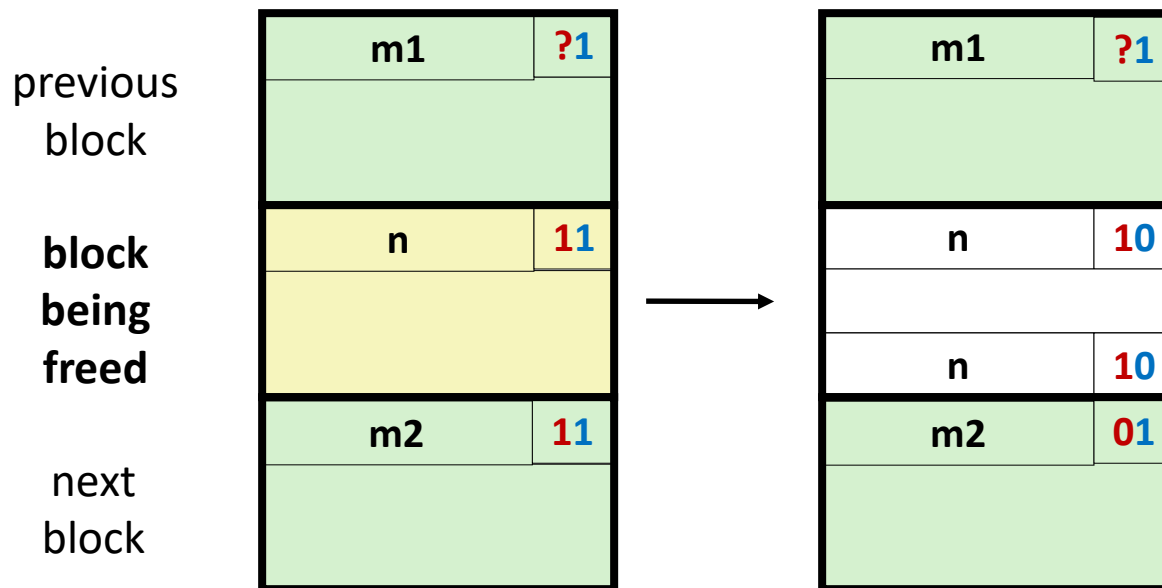**b = 1: Previous block is allocated**
b = 0: Previous block is free

Size: block size

Payload: application data

1 word

Size	**b0**
Unallocated	
Size	**b0**

Free Block

No Boundary Tag for Allocated Blocks (Case 1)

previous block

block being freed

next block

m1	?1

n	11

m2	11

→

m1	?1

n	10
n	10

m2	01

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)

previous block	m1	?1
block being freed	n	11
next block	m2	10
	m2	10

→

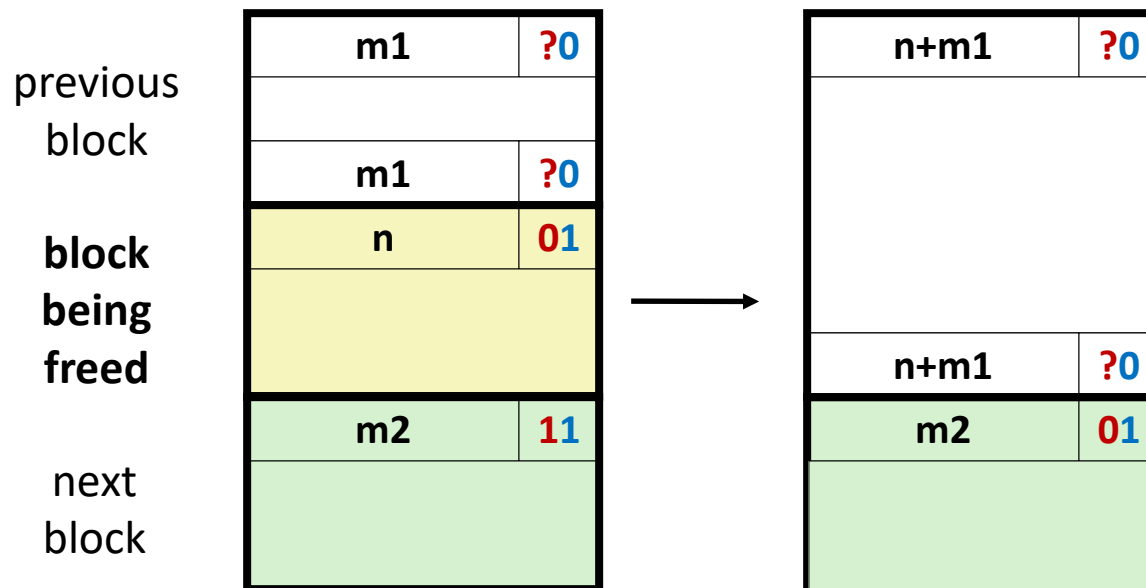|	m1	?1
	n+m2	10
	n+m2	10

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)

previous block	m1	?0
	m1	?0
block being freed	n	01
next block	m2	11

→

	n+m1	?0
	n+m1	?0
	m2	01
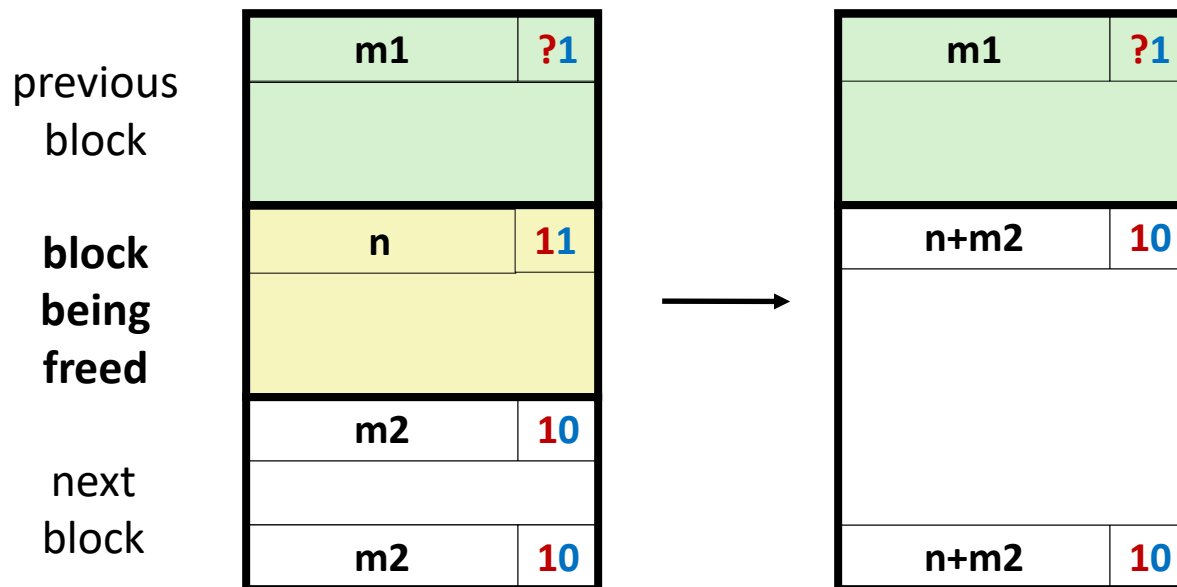
Header: Use 2 bits (address bits always zero due to alignment):
(previous block allocated)<<1 | (current block allocated)
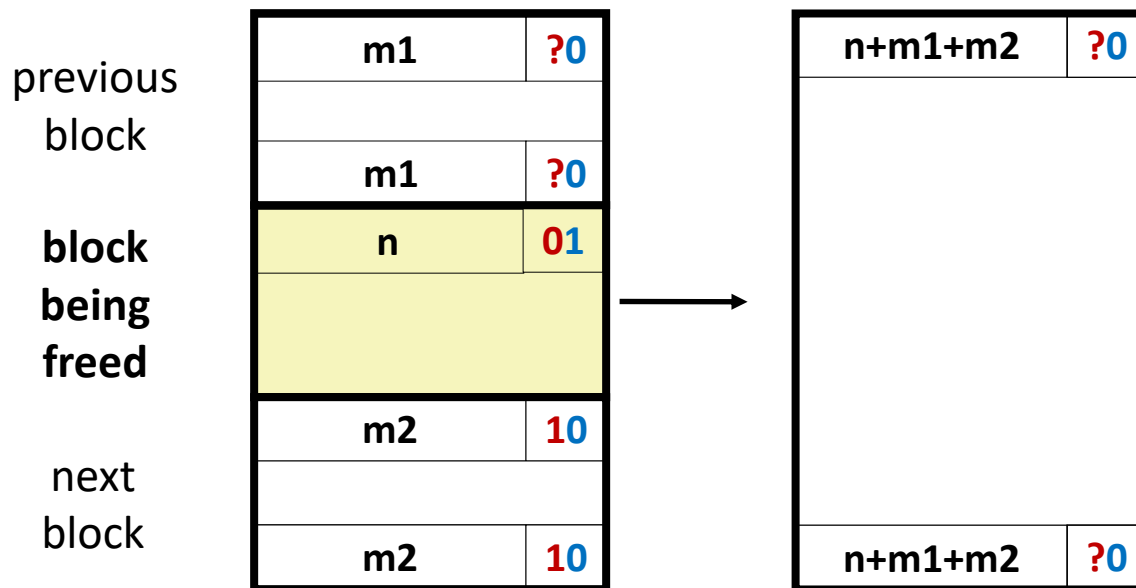
No Boundary Tag for Allocated Blocks (Case 4)

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**