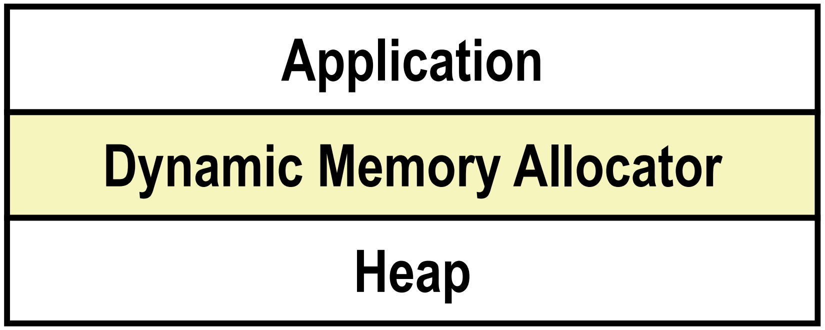
Dynamic Memory Allocation: Basic Concepts

CS2011: Introduction to Computer Systems
Lecture 13 (**9.9**)

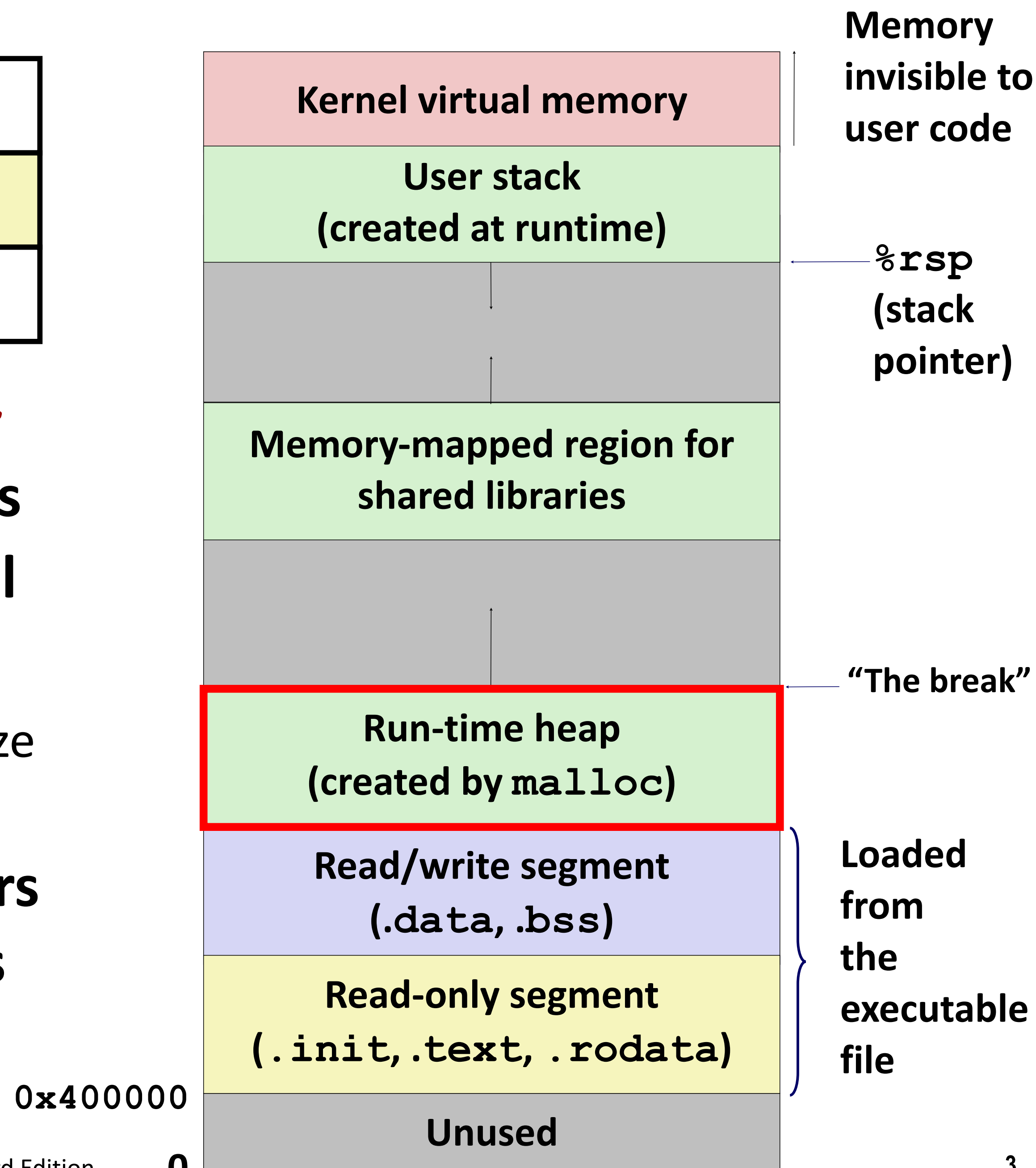
Dynamic Memory Allocation: Basic Concepts

- **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**
  - ***1) Explicit allocator*:** application allocates and frees space
    - e.g., `malloc` and `free` in **C**
  - ***2) Implicit allocator:*** application allocates, but does not free space
    - e.g., `new` and garbage collection in **Java**
- **Will discuss simple explicit memory allocation in this lecture**

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

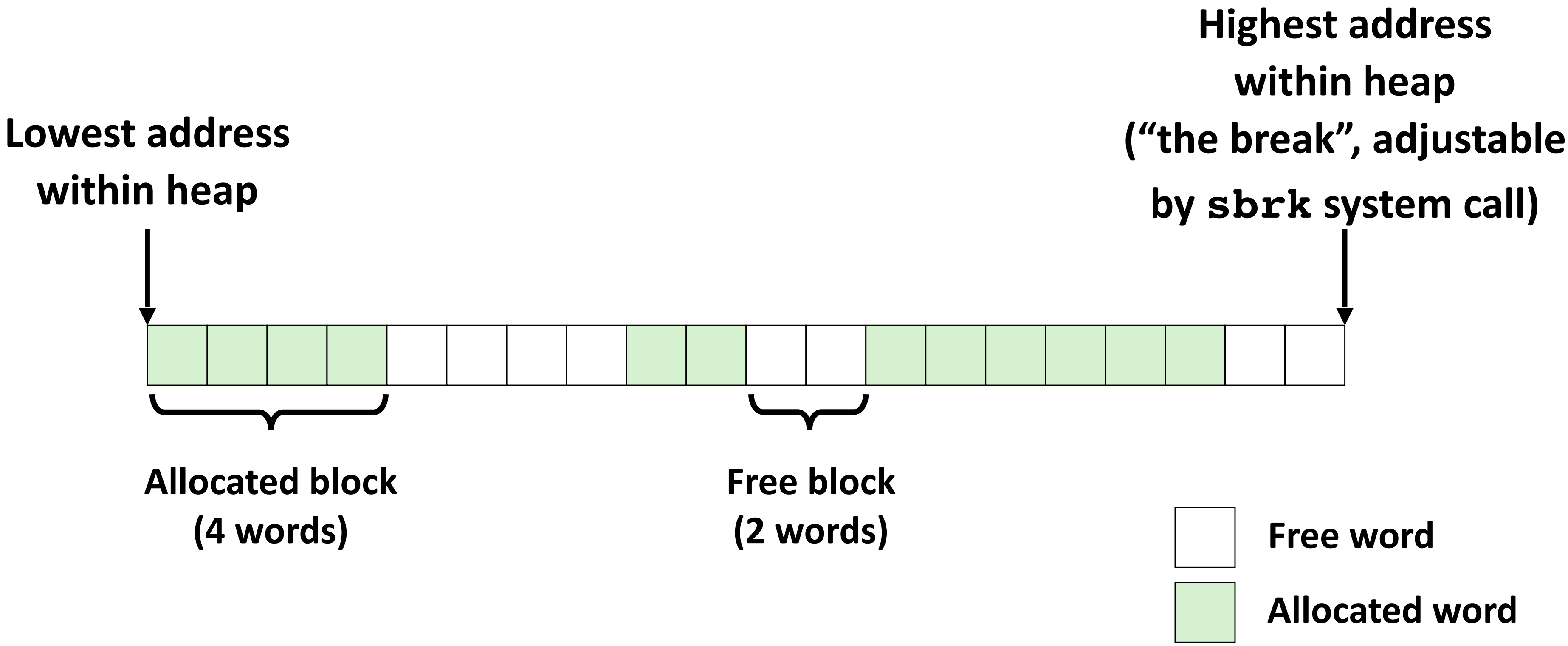
- `calloc`: Version of `malloc` that initializes allocated block to zero
- `realloc`: Changes the size of a previously allocated block
- `sbrk`: Used internally by allocators to grow or shrink the heap

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);
}
```

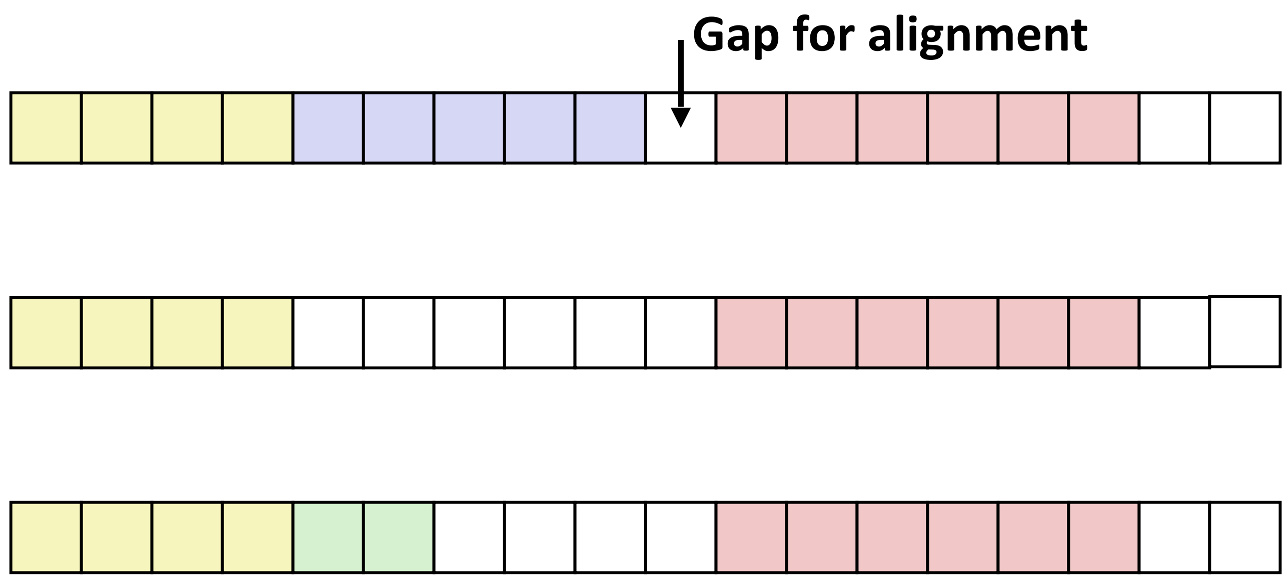
Heap Visualization Convention / Assumption

- 1 square = 1 "word" = 8 bytes
- Allocations are double-word (2-word) aligned



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 (no special ordering)
  - `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 blocks
  - **Can't move** the allocated blocks once they are `malloc`'d
    - *i.e.*, compaction is not allowed. (Program wouldn't know how to free pointer if moved)

Performance Goal 1: Maximize 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:
    - 500 **`malloc`** calls and 500 **`free`** calls in 1 seconds
    - Throughput is 1,000 operations/second

Performance Goal 2: Maximize Memory Utilization

- **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: Peak memory utilization after k+1 requests***
  - $U_k = (\max_{i \le k} P_i) \ / \ H_k$
- ***Def: Overhead, O_k***
  - **Fraction** of heap space *NOT* used for program data
  - $O_k = (H_k / \max_{i \le k} P_i) - 1.0$
  - Goal: minimize overhead

Benchmark Example

- **Benchmark syn-array-short**
  - Example Trace
  - 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 (i.e. ***aggregate payload***)
  - **Peak**: **Max** so far of Allocated (**peak aggregate payload**)

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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14	`f 7`	-33856	6232	90036
15	`f 6`	-2012	4220	90036
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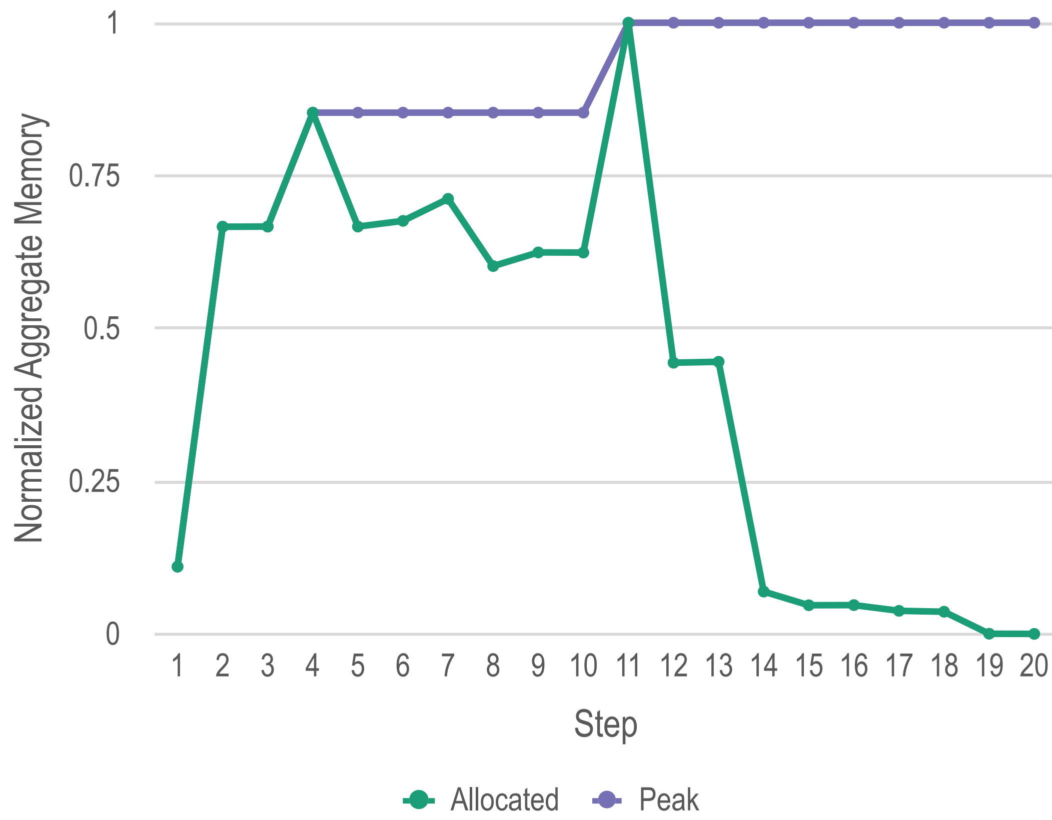
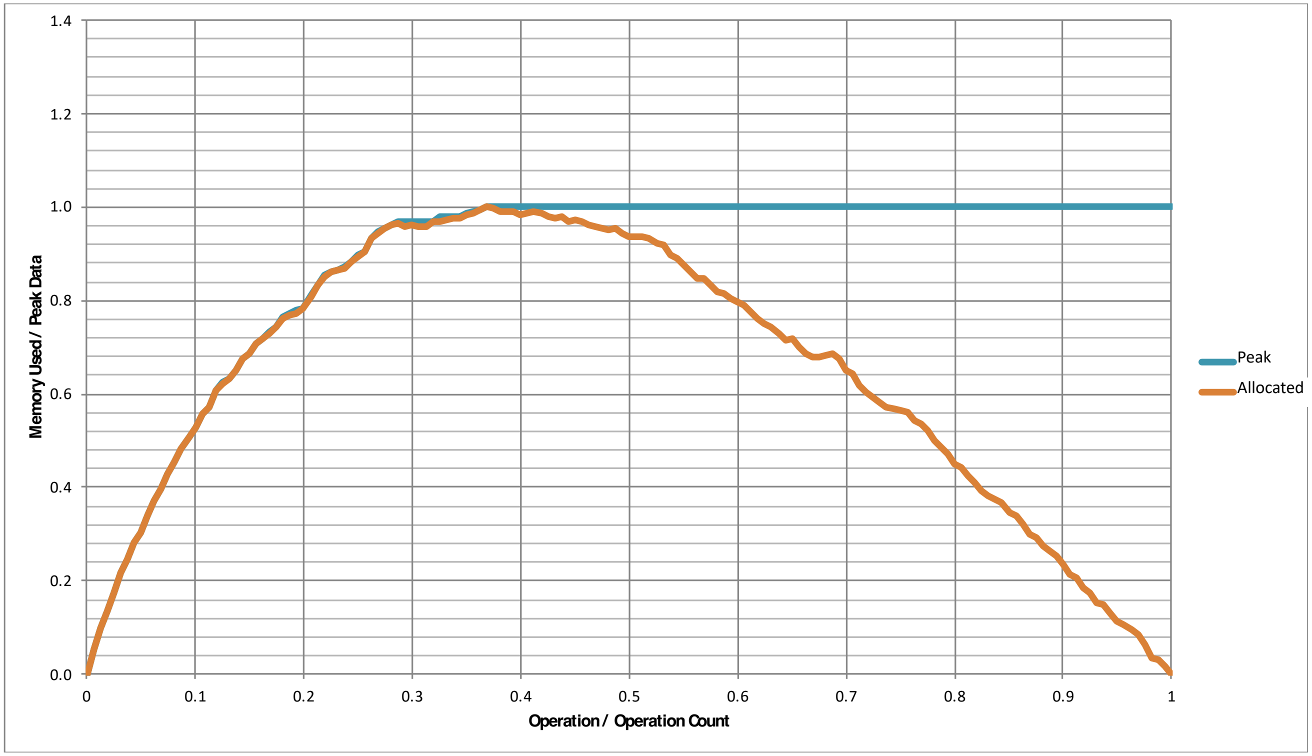


- Plot P_k (**allocated**) and $\max_{i \le k} P_k$ (**peak**) as a function of k (step)
- Y-axis normalized — fraction of maximum

Typical Benchmark Behavior



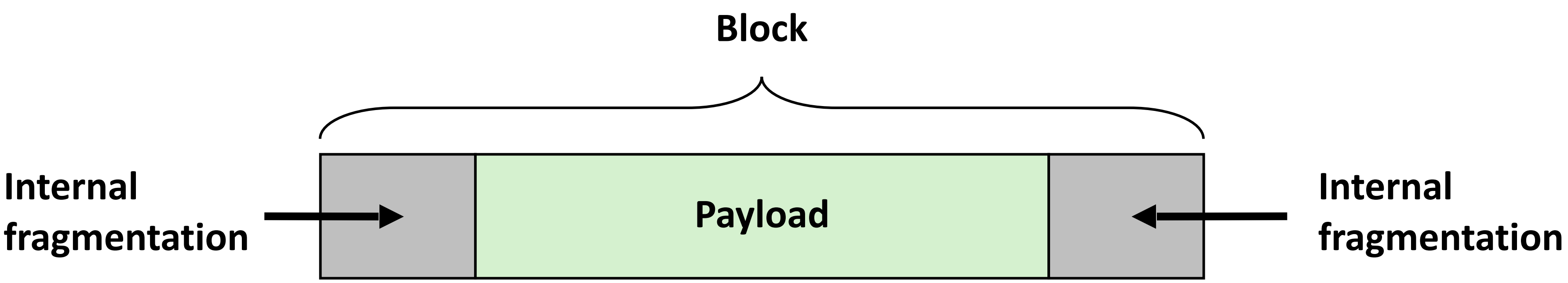
- **Longer sequence of mallocs & frees (40,000 blocks)**
  - *Starts with all mallocs, and shifts toward all frees*
- **Allocator must manage space efficiently the whole time (i.e. maximize Utilization)**
- **Production allocators can shrink the heap**

Fragmentation

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

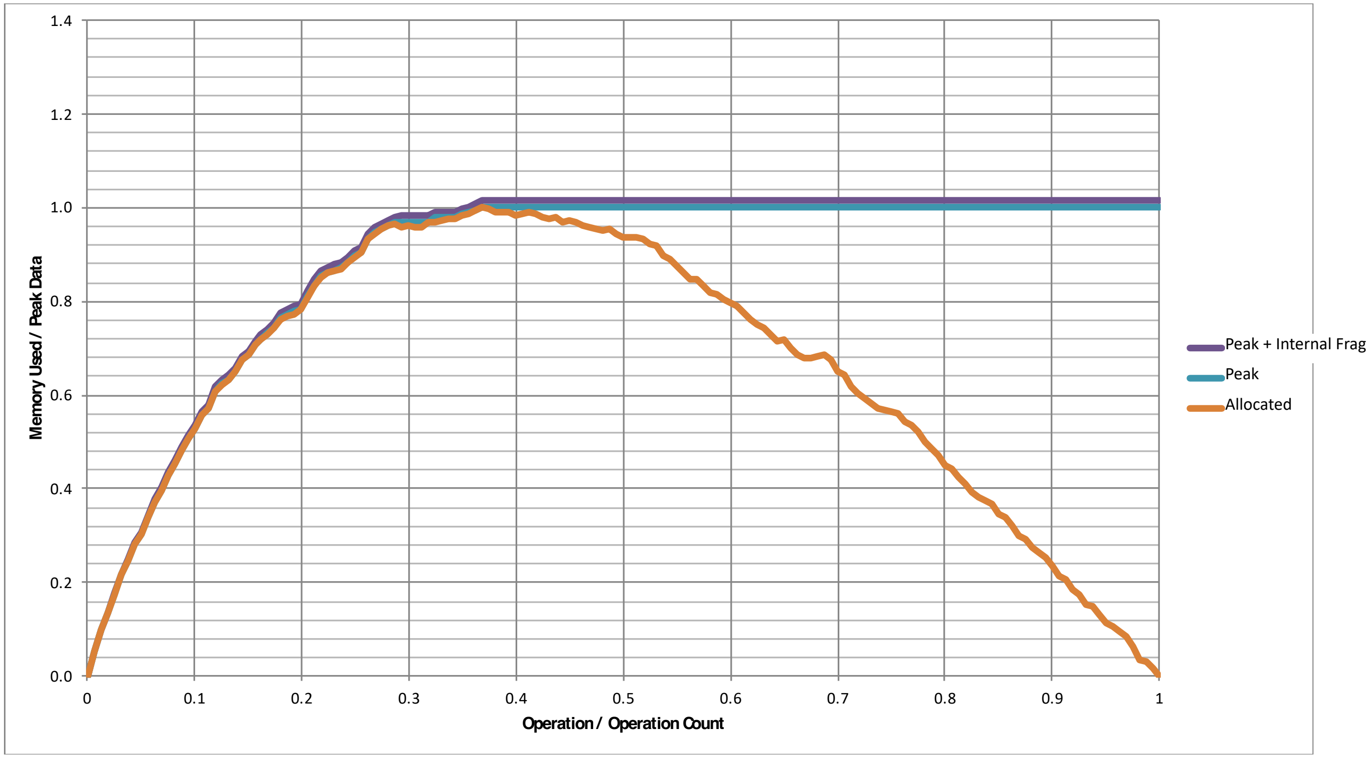
Internal Fragmentation

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



- **Caused by**
  - Overhead of maintaining heap data structures
  - Allocator implementation forces a minimum size of allocated blocks
  - 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
    ("size of all allocated blocks" - "size of all payloads")

Internal Fragmentation Effect

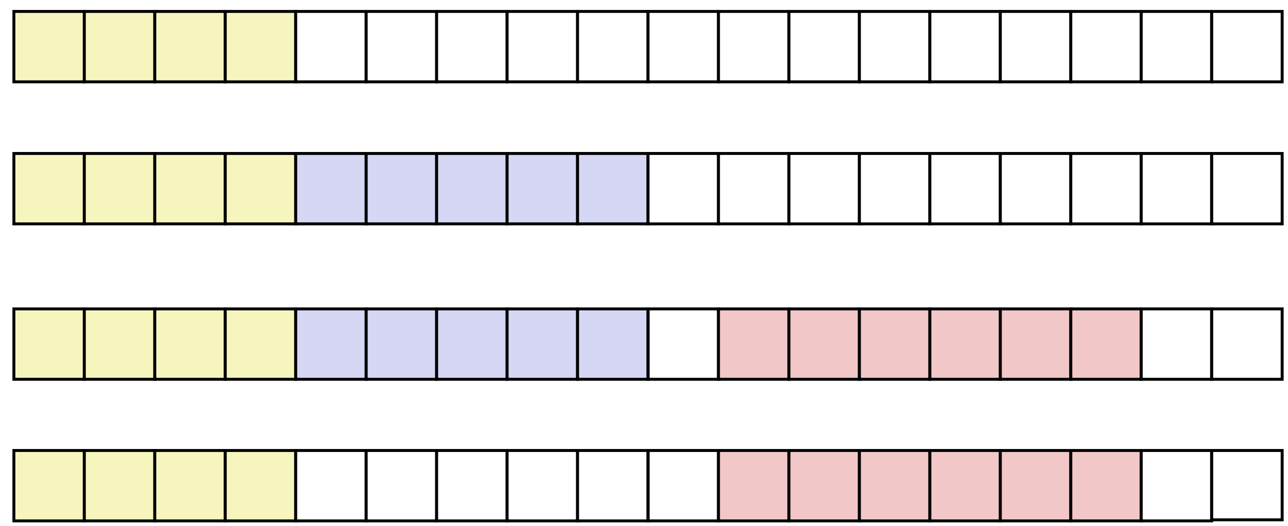


- **Purple line: additional heap size due to allocator's data + padding for alignment**
  - For this benchmark, 1.5% overhead
  - Cannot achieve in practice
  - Especially since cannot move allocated blocks

External Fragmentation

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

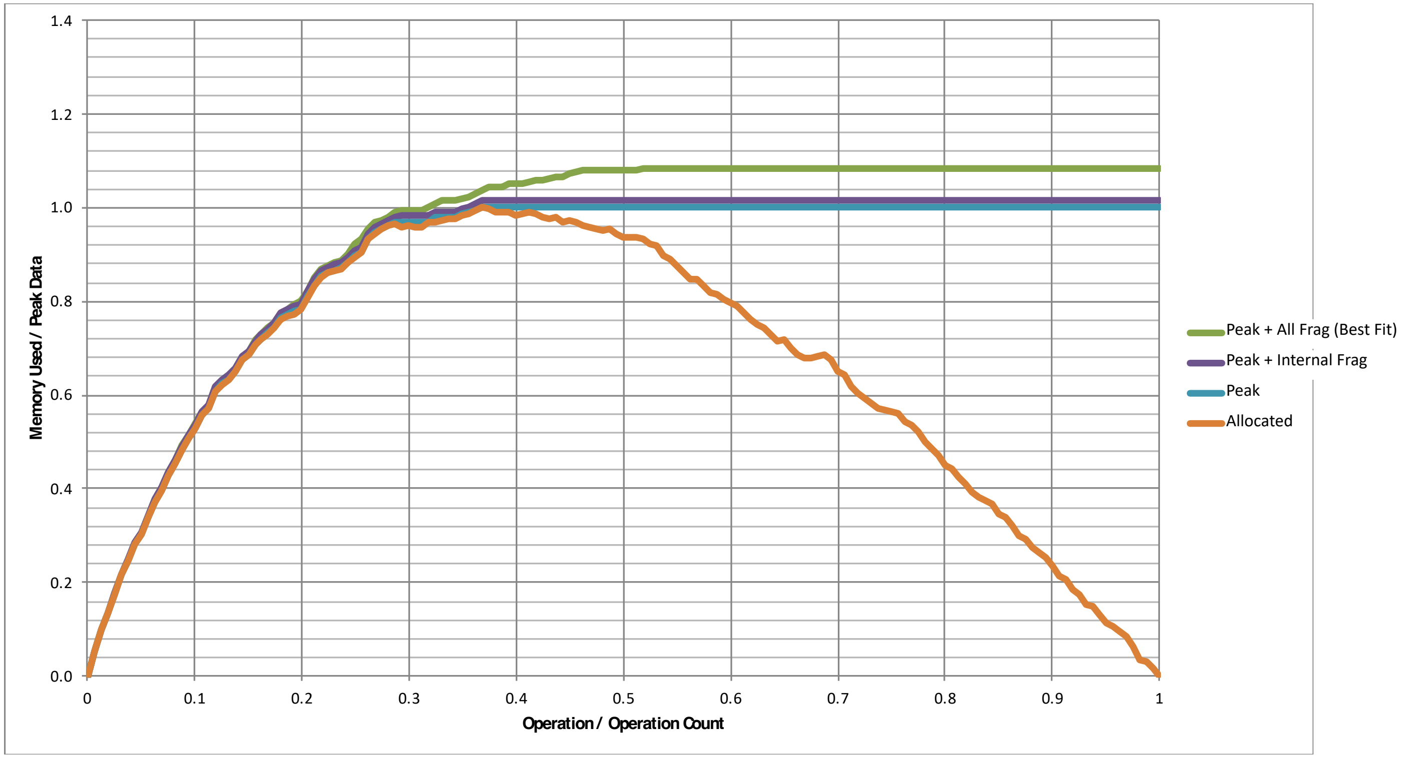
```
p1 = malloc(32)
p2 = malloc(40)
p3 = malloc(48)
free(p2)
p4 = malloc(64)
```



Yikes! (what would happen now?)

- **Depends on the pattern of future requests**
  - Thus, difficult to measure (*e.g., if next request fits then no fragmentation*)

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?**

- **Free Block Organization**
  - How do we **keep track of the free blocks**?

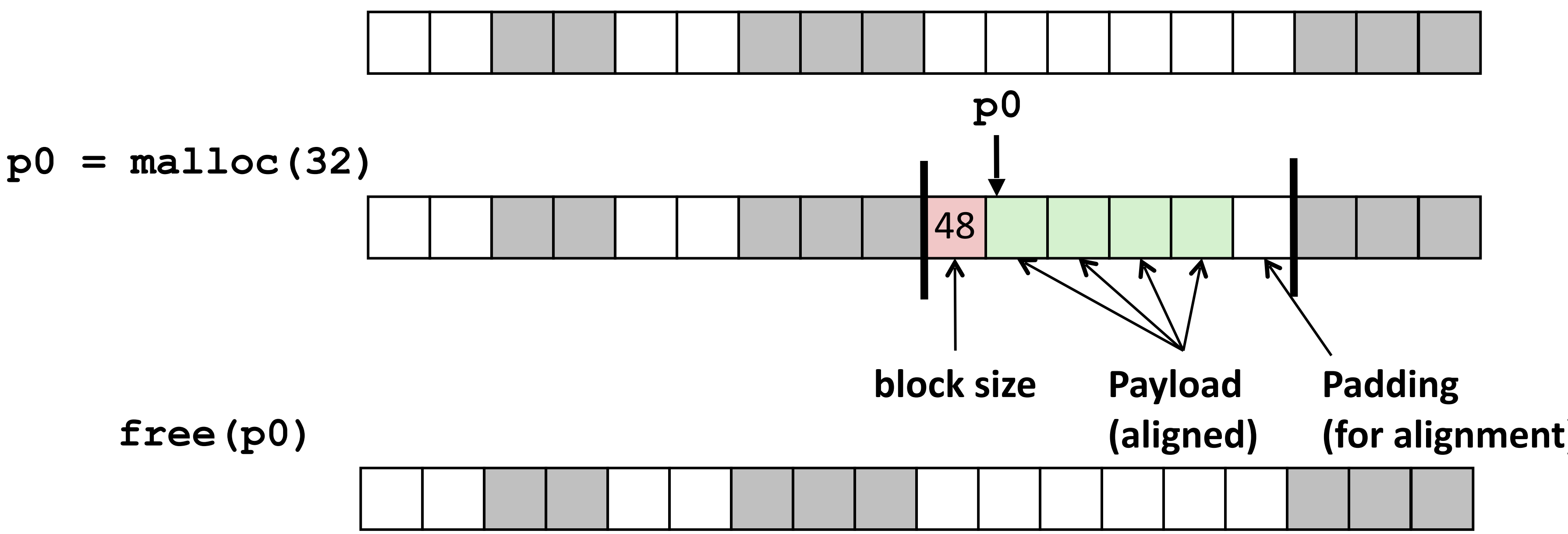
- **Placement**
  - How do we **pick a block to use** for allocation -- many might fit?

- **Splitting**
  - What do we do with the **extra space when allocating** a structure that is smaller than the free block it is placed in?

- **Coalescing**
  - How do we **reuse a block** that has been freed?

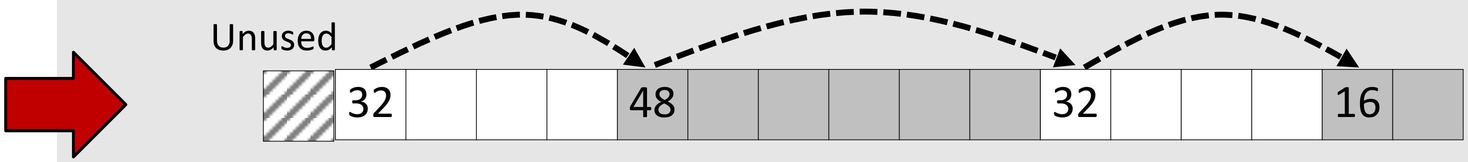
Knowing How Much to Free

- **Standard method**
  - Keep the **length (in bytes)** of a block in the word *preceding* the block.
    - This word is often called the ***header field*** or ***header***
    - ***Length/Size*** includes the header and any possible padding
      - Remember: Only payload needs to be aligned NOT the header
  - Requires an extra word for every allocated block



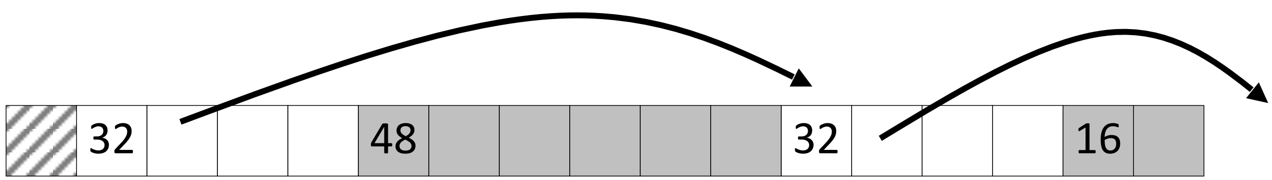
Keeping Track of Free Blocks

- **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 combinations of free lists (e.g., implicit, explicit, etc) for different size classes (e.g., 4 bytes, 8 bytes, etc.)

- **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

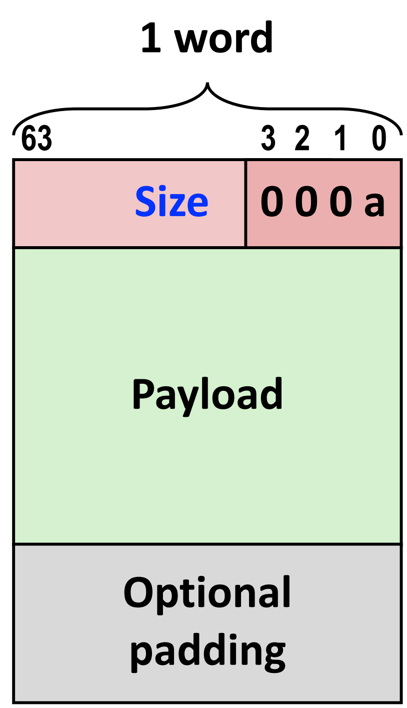
Dynamic Memory Allocation: Basic Concepts

- Basic concepts
- **Implicit free lists**

Method 1: Implicit Free List

- Called **implicit** because free blocks are linked implicitly by the size fields in the header
- **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
    - If we impose that blocks are always **2-word aligned**, the lowest-order 4 bits of address are always 0
      size is always a multiple of 16 **(Remember we are assuming a word is 8 bytes)**
  - Instead of storing an always-0 lowest-order bit, use it as an allocated/free flag
  - **When reading** the **Size** word, **must mask out this bit**
    (E.g., 0x0000000000000033 & ~0xF = 0x0000000000000033 & 0xFFFFFFFFFFFFFFF0 = 0x0000000000000032)

Format of allocated and free blocks

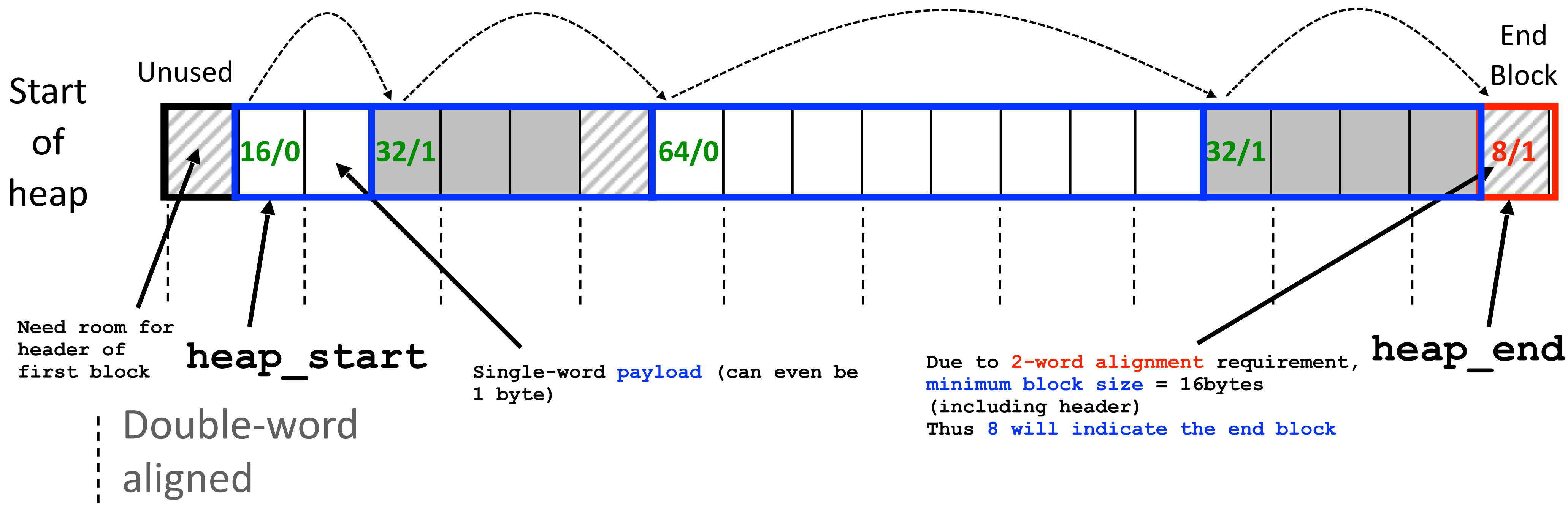


a = 1: Allocated block
a = 0: Free block

Size: total block size including header, payload, and any padding

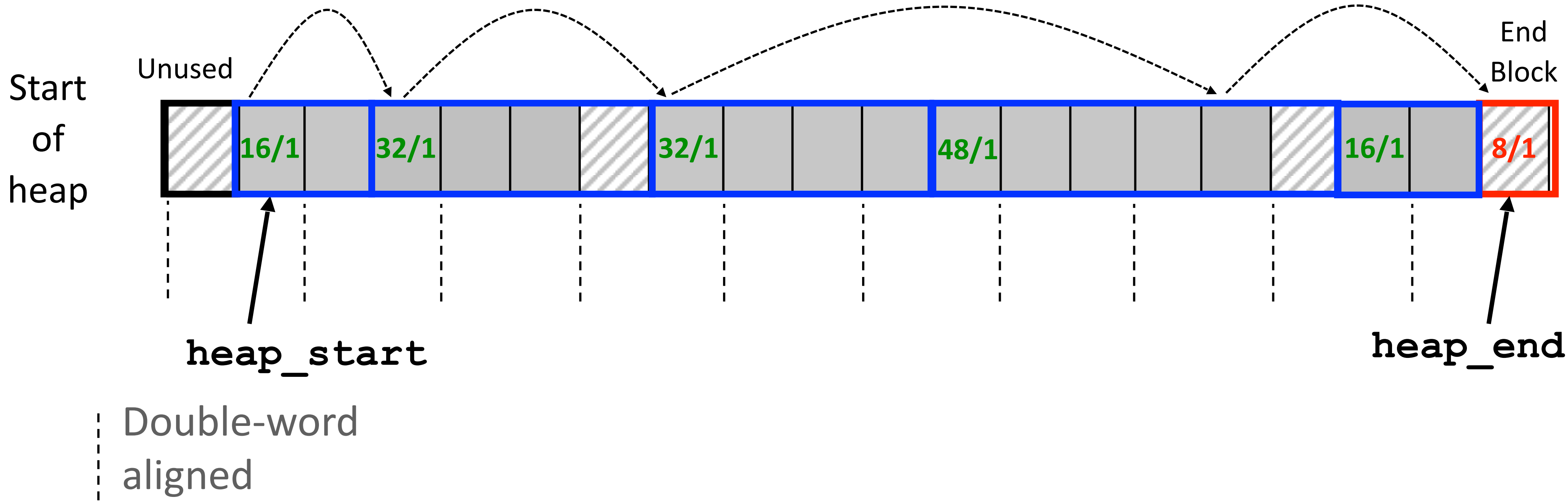
Payload: application data (allocated blocks only)

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 Free List Example Sequence



Example Sequence:	Header Value:
Malloc (1)	0x11
Malloc (9)	0x21
Malloc (24)	0x21
Malloc (26)	0x31
Malloc (5)	0x11

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 (get_alloc)

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

- Getting size from header (get_size)

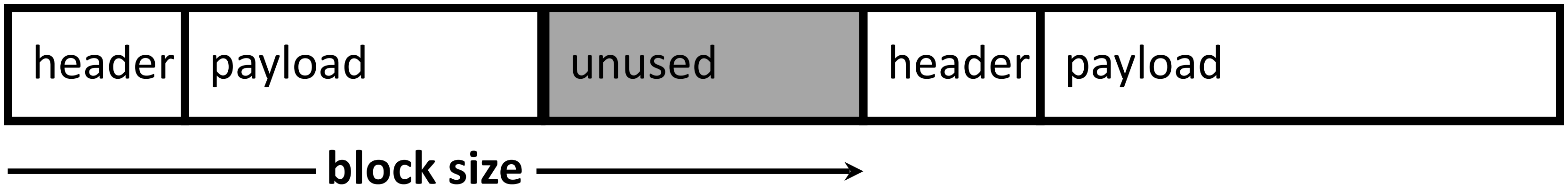
```
return header & ~0xFL; // L indicates Long
```

- Initializing header

```
//block_t *block
```

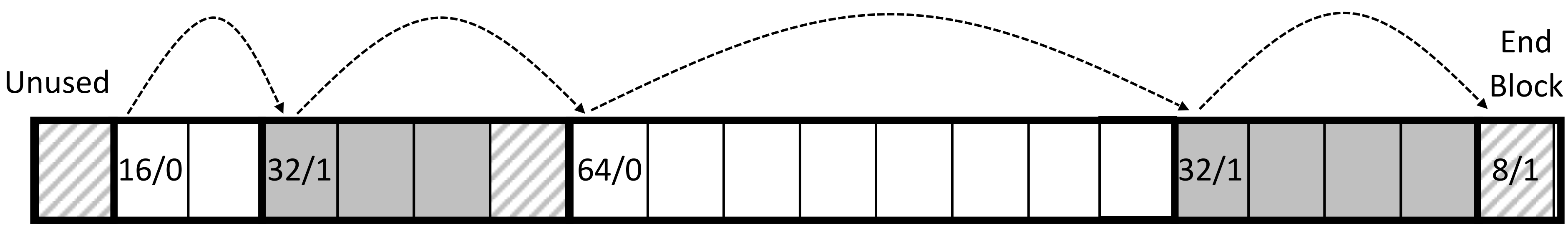
```
block->header = size | alloc;
```

Implicit List: Traversing list



- **Find next block**

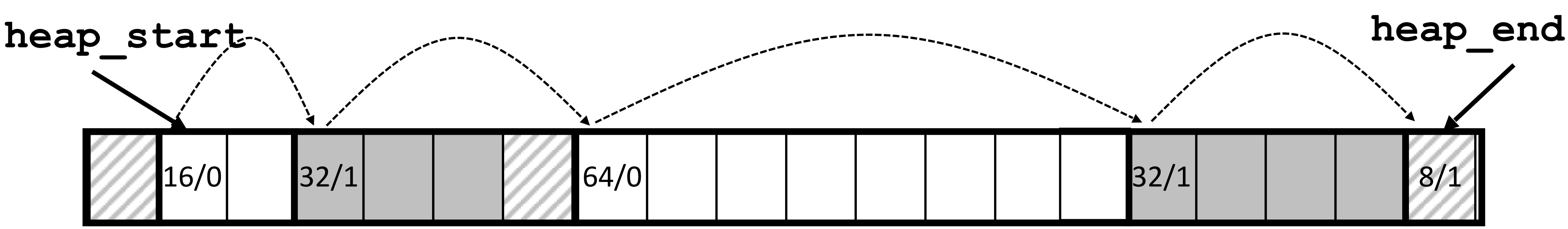
```
static block_t *find_next(block_t *block)
{
    return (block_t *) ((unsigned char *) block
                          + get_size(block));
}
```



Implicit List: Finding a Free Block (Placement)

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

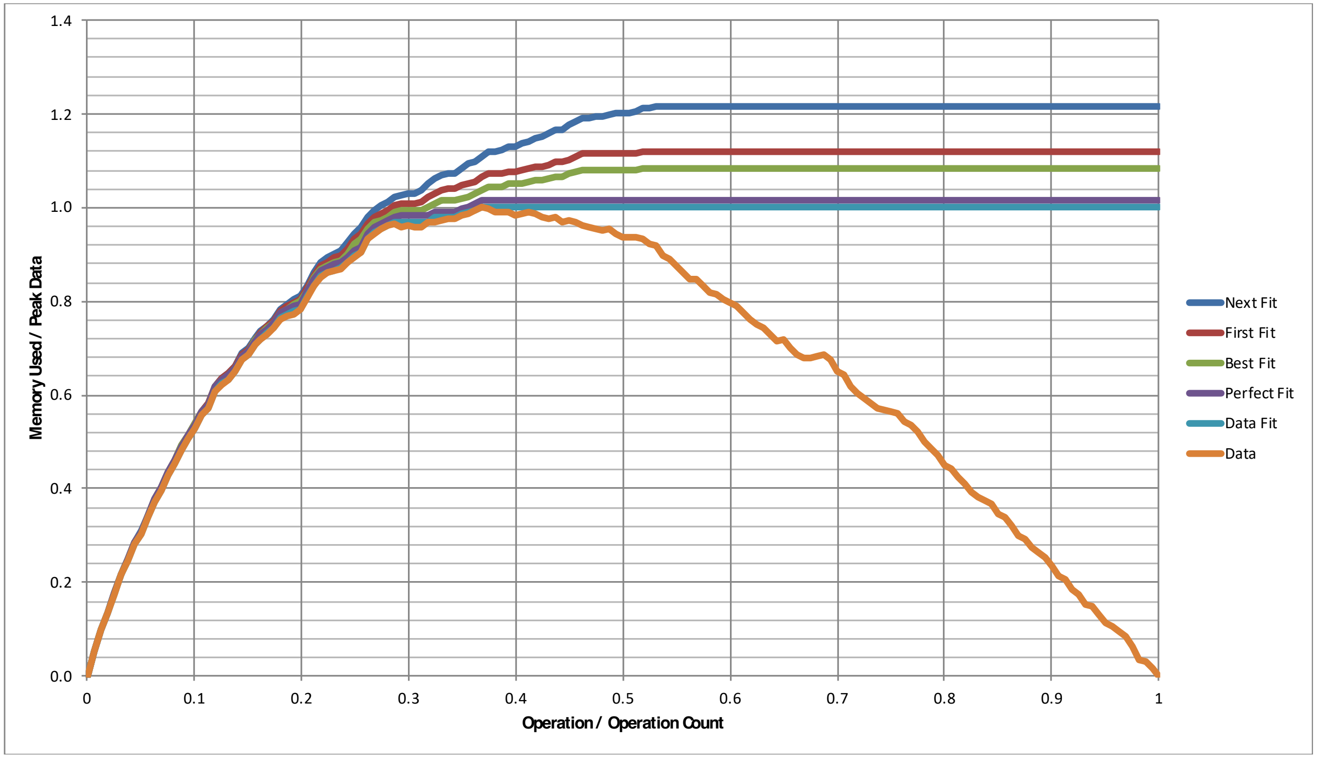
```
static block_t *find_fit(size_t asize)
{
    block_t *block;
    for (block = heap_start; block != heap_end; block = find_next(block)) {
      if (!(get_alloc(block)) && (asize <= get_size(block)))
         return block;
    }
    return NULL; // No fit found
}
```



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)
  - **Disadvantage**: In practice it can cause **"splinters/clutter" of small free blocks at beginning of list (due to splitting)**
    - **Increases the search time for larger blocks**
- ***Next fit:***
  - Like first fit, but search list **starting where previous search finished or left off**
  - Should often be **faster** than first fit: **avoids re-scanning unhelpful blocks**
    - **e.g., if size of next block is same as previously allocated block**
  - **Disadvantage**: Some research suggests that **fragmentation is worse**
- ***Best fit:***
  - Search the list, choose the ***best*** free block: fits, with fewest bytes left over
    - Examine **every free block** and choose the one with **smallest size** that fits
    - If you find a perfect match, you can stop the search there
  - **Keeps fragments small**—usually **improves memory utilization**
  - **Disadvantage**: Will typically run **slower** than first fit
  - Still a greedy algorithm. No guarantee of optimality (Exhaustive search)

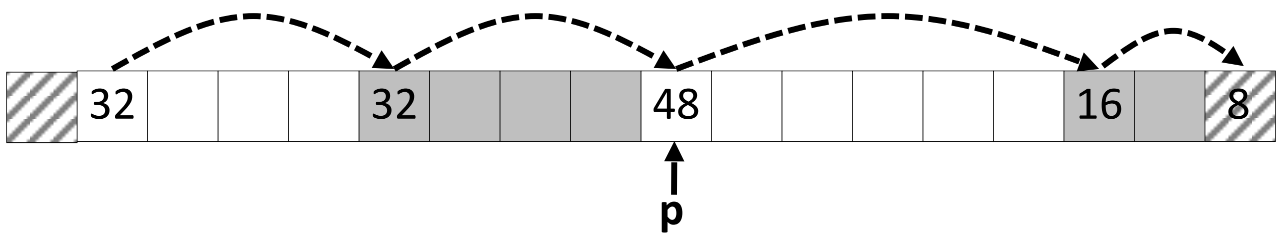
Comparing Strategies



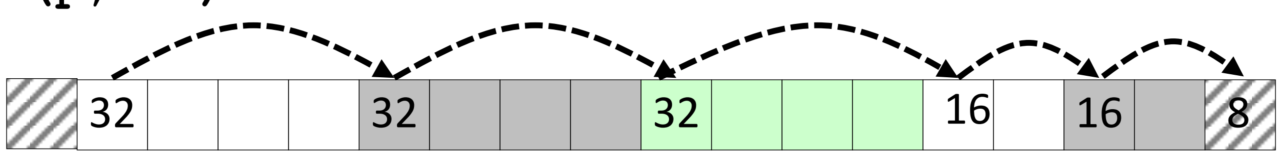
- **Total Overheads (for this benchmark)**
  - Perfect Fit: 1.6%
  - Best Fit: 8.3%
  - First Fit: 11.9%
  - Next Fit: 21.6%

Implicit List: Splitting Free Block on Allocation

- **Allocating in a free block: *splitting***
  - Since allocated space might be smaller than free space, we **might** want to split the block
    - If placement policy produces good fits, some additional internal fragmentation is acceptable and no need for splitting

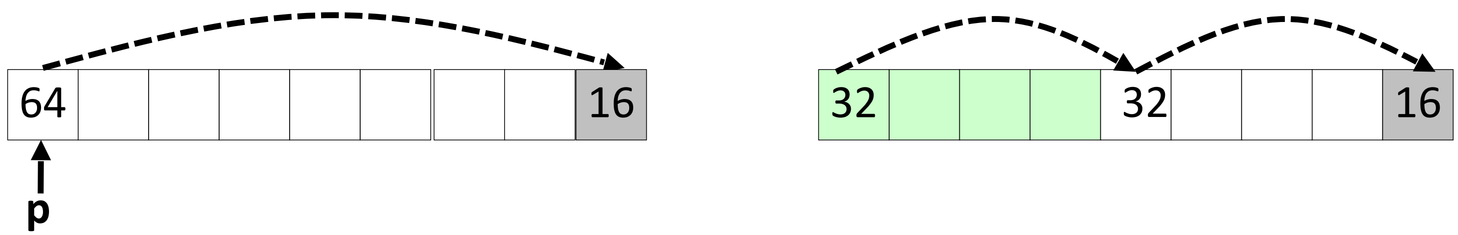


`split_block(p, 32)`



Implicit List: Splitting Free Block

`split_block(p, 32)`



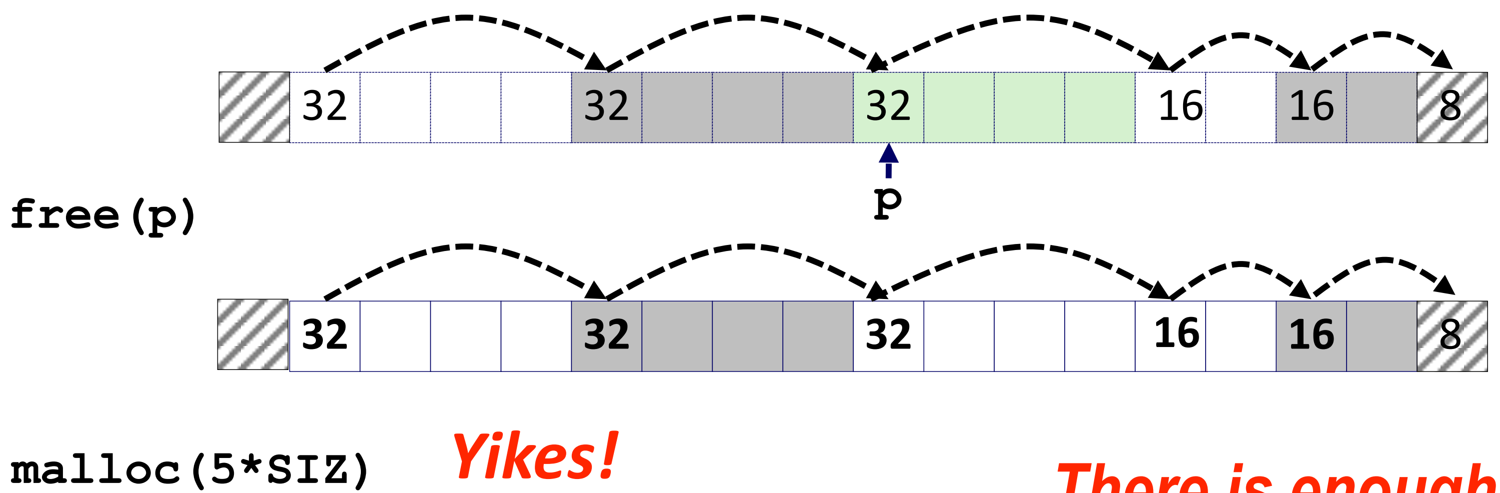

```
// Warning: This code is incomplete

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

    // Split only if remainder of block is enough to fit
    // the smallest possible data
    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

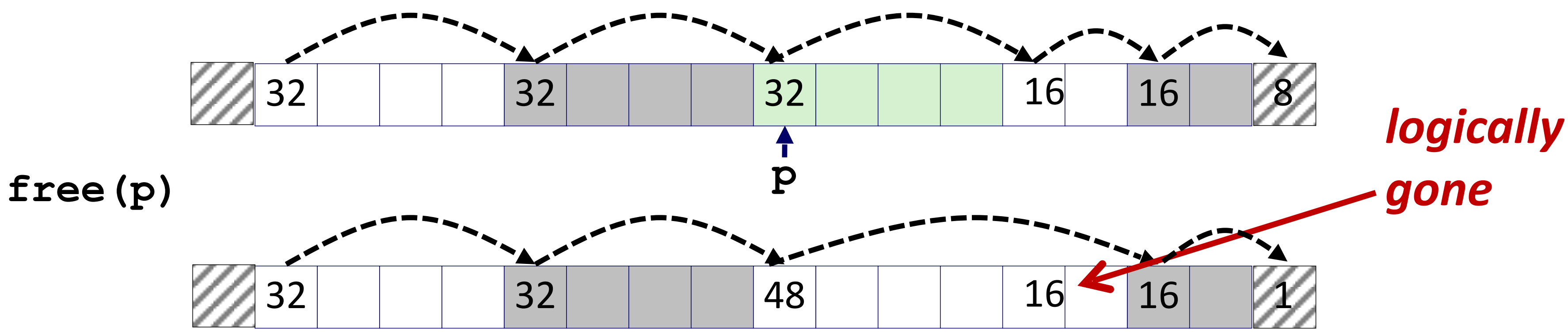
- **Simplest implementation:**
  - Need only **clear the "allocated" flag (bit 1 becomes 0)**
  - But can lead to "**false fragmentation**" phenomena



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

Implicit List: Coalescing Free Blocks

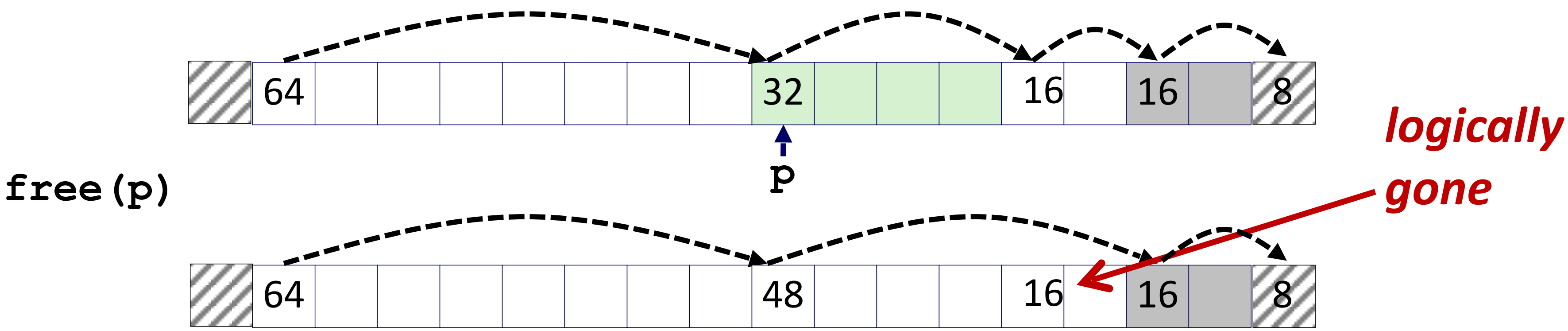
- **Join/merge *(coalesce)* with next/previous blocks, if they are free**
  - Coalescing with **next block**



  - **When to merge?**
    - Allocator may go for **immediate coalescing** (discussed here)
    - Allocator may go for deferred coalescing (wait until later time)
      - To reduce the amount of possible repeated splitting and coalescing

Implicit List: Coalescing

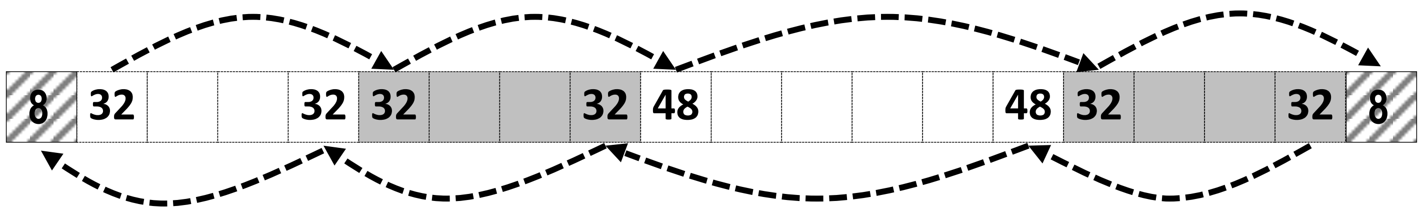
- **Join *(coalesce)* with next block, if it is free**
  - Coalescing with **next block** is **simple** and takes **constant time**
    - We simply check the next block if free or allocated. If free, its size will be added to the size of the current block



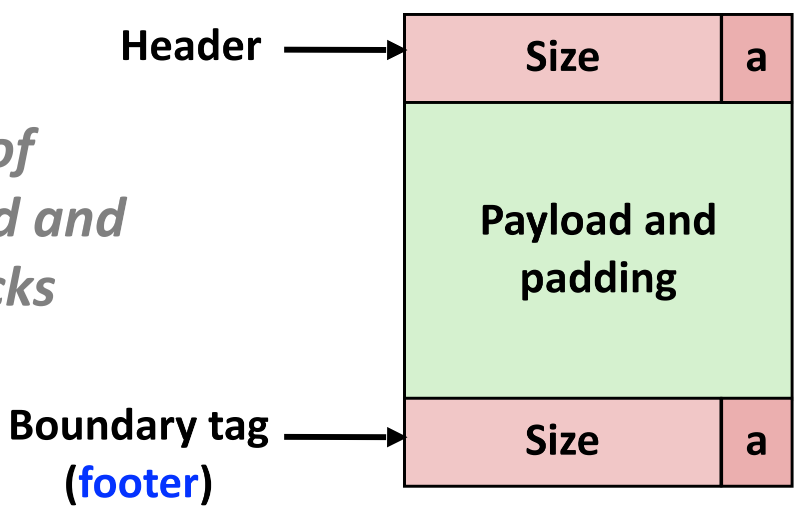
- But, how do we coalesce with ***previous* block**?
  - How do we know where it starts?
  - How can we determine whether it's allocated?
  - Solution: **Boundary Tags**

Implicit List: Bidirectional Coalescing

- ***Boundary tags*** [Knuth73]
  - **Replicate** size/allocated word (i.e. **header**) 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

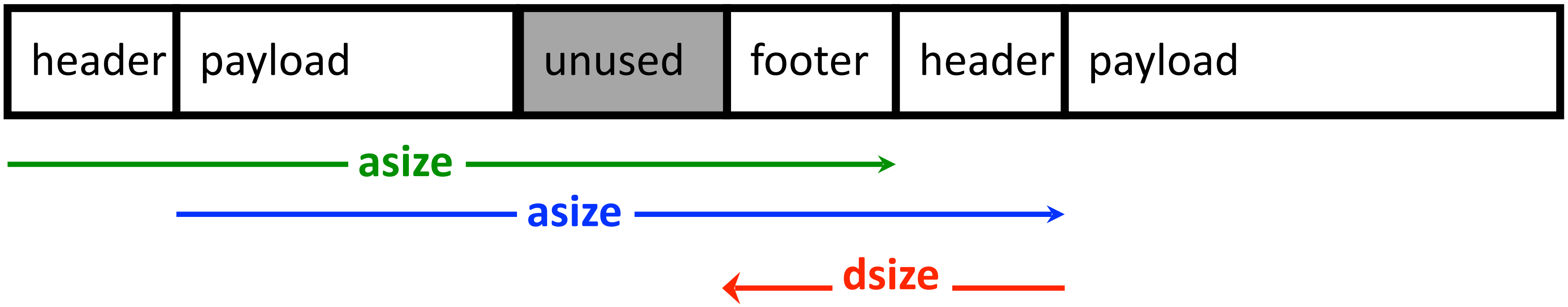


a = 1: Allocated block
a = 0: Free block

Size: Total block size

Payload: Application data (allocated blocks only)

Implementation with Footers

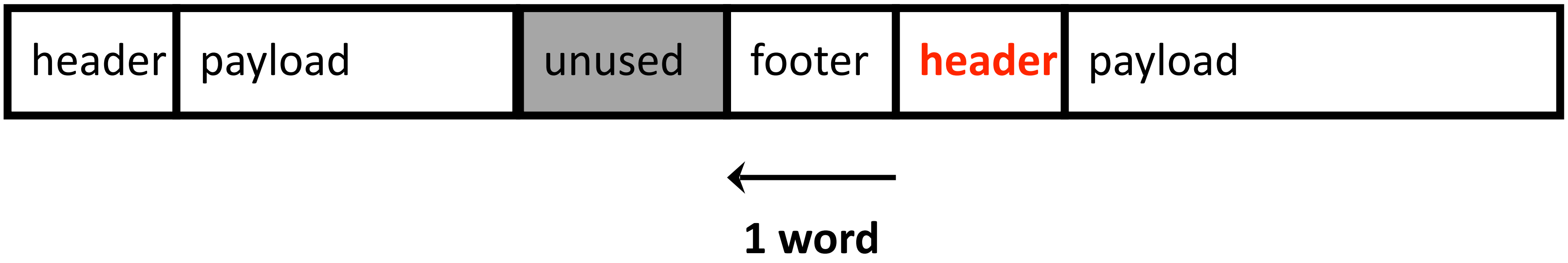


Locating footer of current block

```
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);
}
```

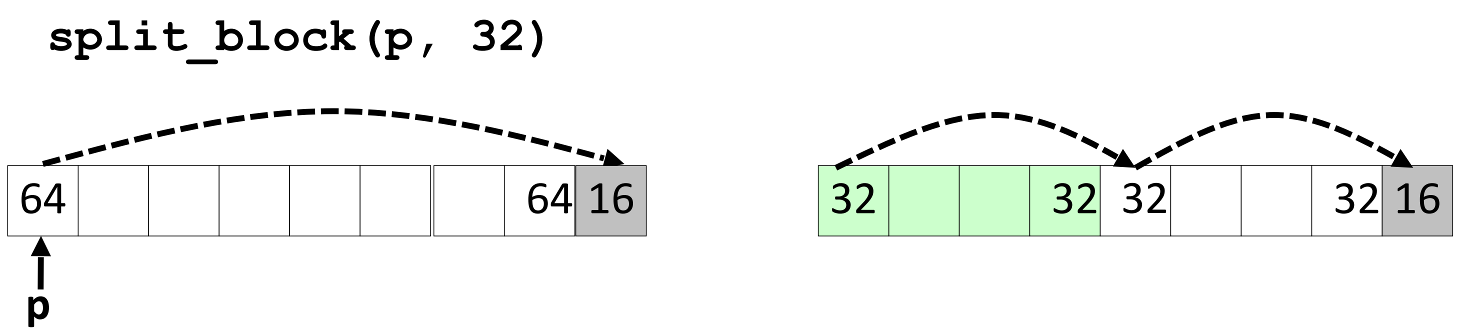
Implementation with Footers



- **Locating footer of previous block**

```
static word_t *find_prev_footer(block_t *block)
{
    return &(block->header) - 1; // 1 word = 8 bytes
}
```

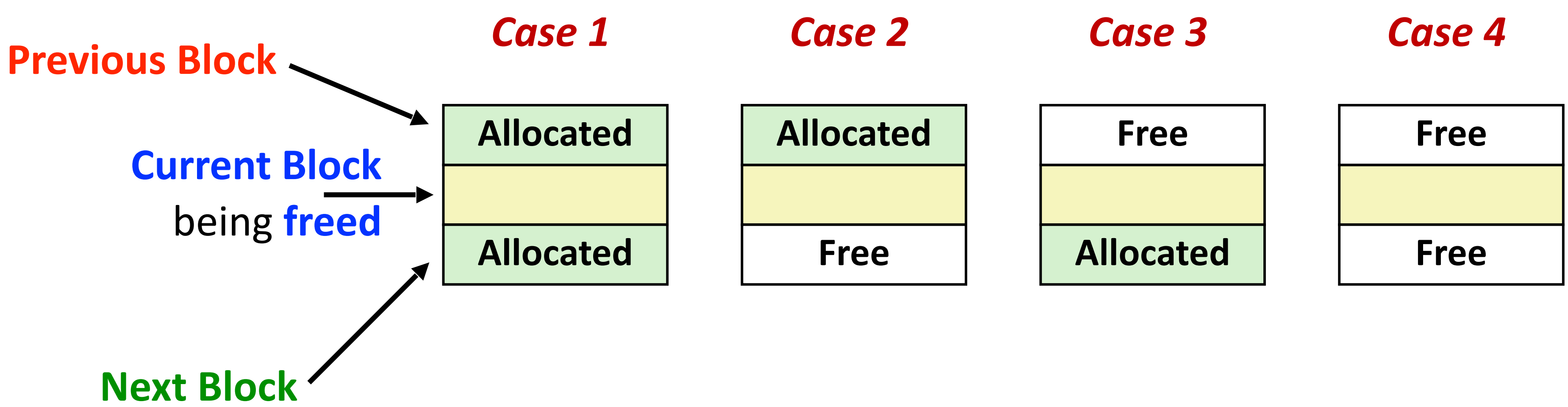
Splitting Free Block: Full Version



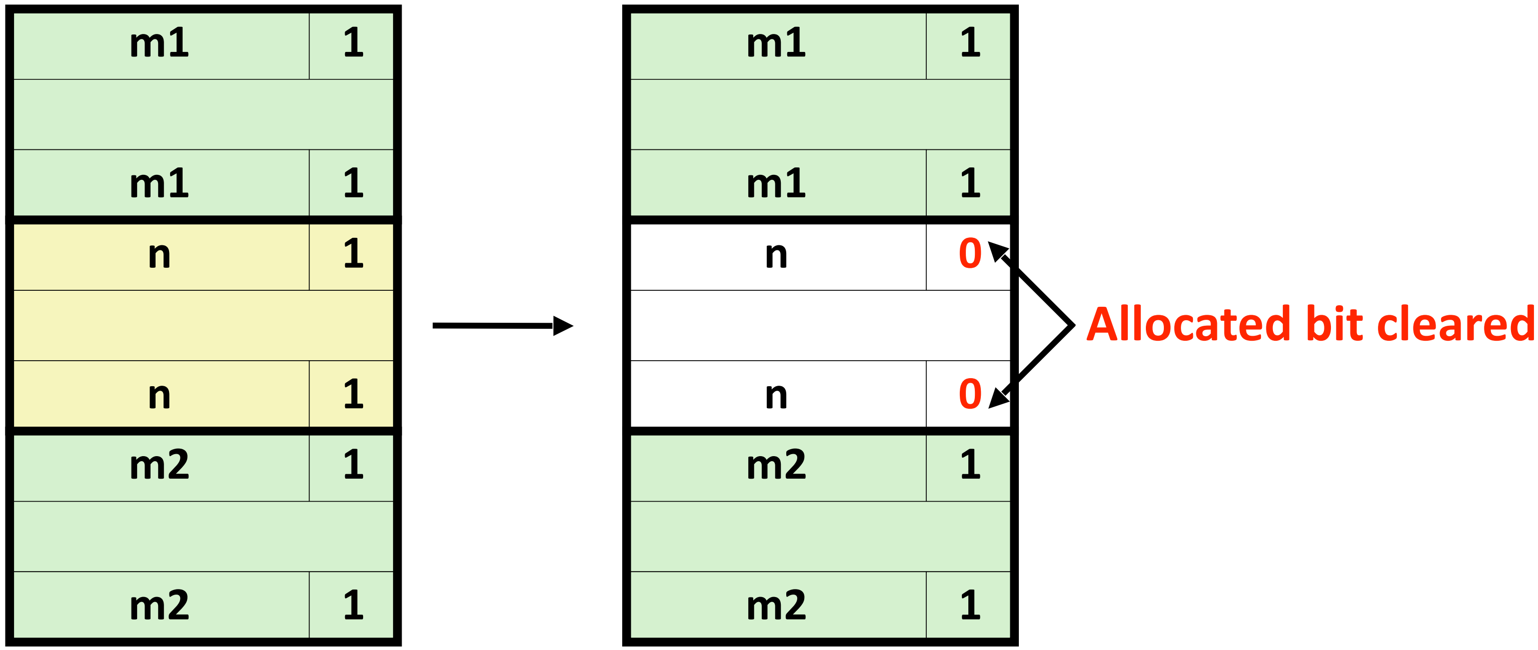

```
static void split_block(block_t *block, size_t asize){
    size_t block_size = get_size(block);

    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);
}
```

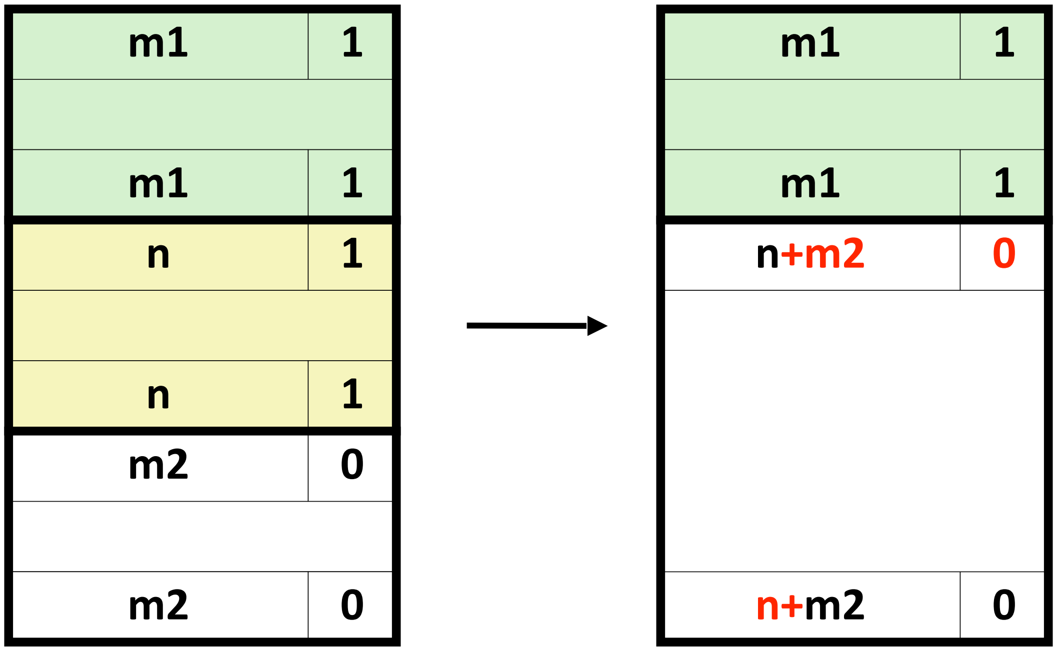
Constant Time Coalescing



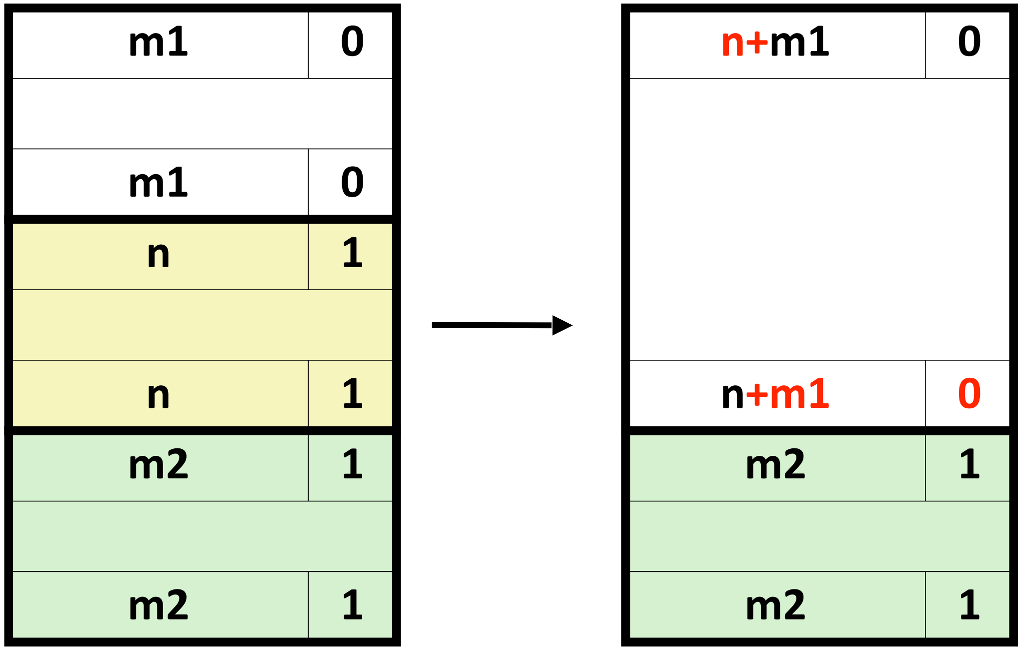
Constant Time Coalescing (Case 1)



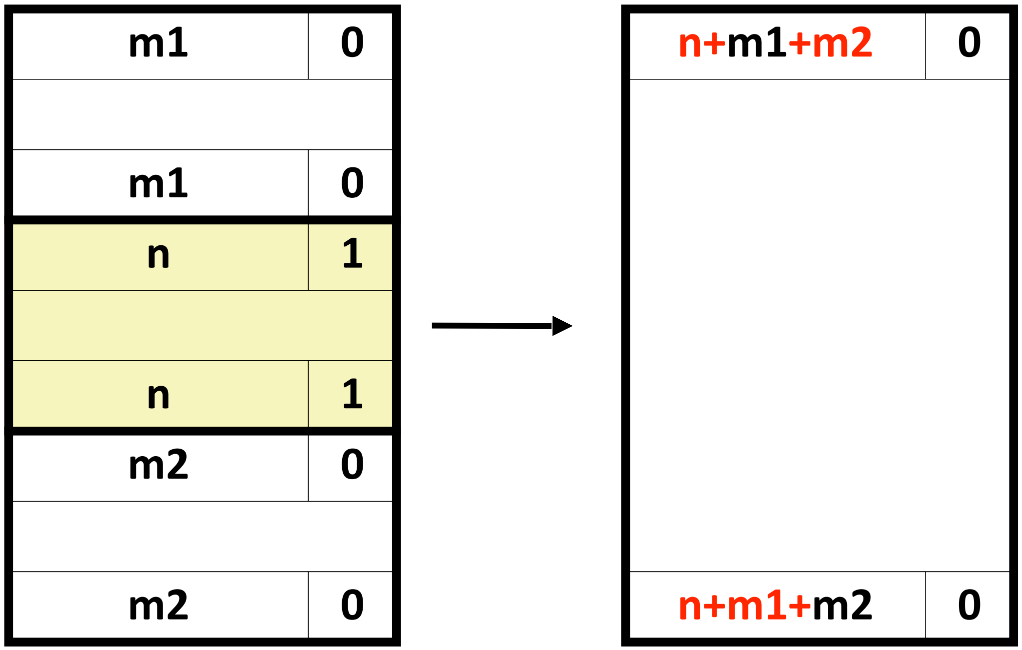
Constant Time Coalescing (Case 2)



Constant Time Coalescing (Case 3)



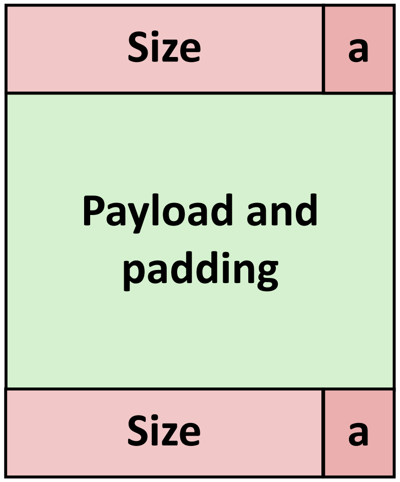
Constant Time Coalescing (Case 4)



Disadvantages of Boundary Tags

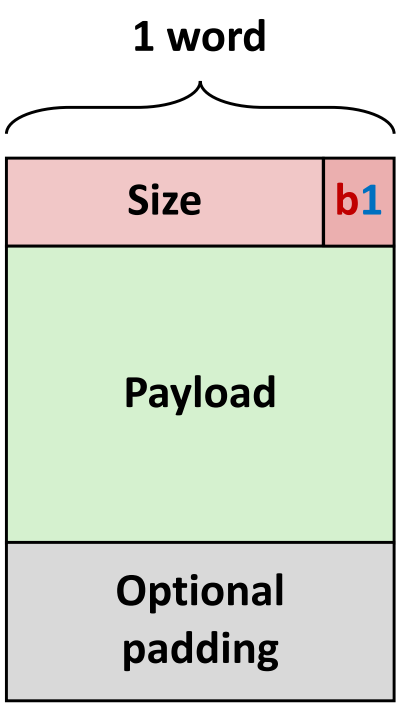
- **Significant memory overhead** due to both header and footer **if** application uses **many small blocks** (e.g., graph with nodes each requiring one 1 word of payload)

- **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

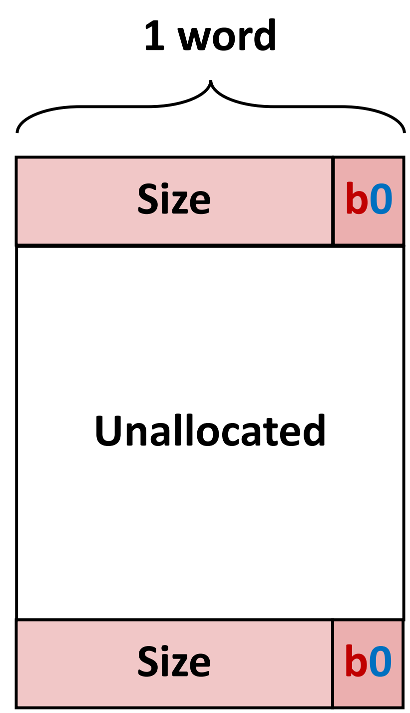


Allocated
Block

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

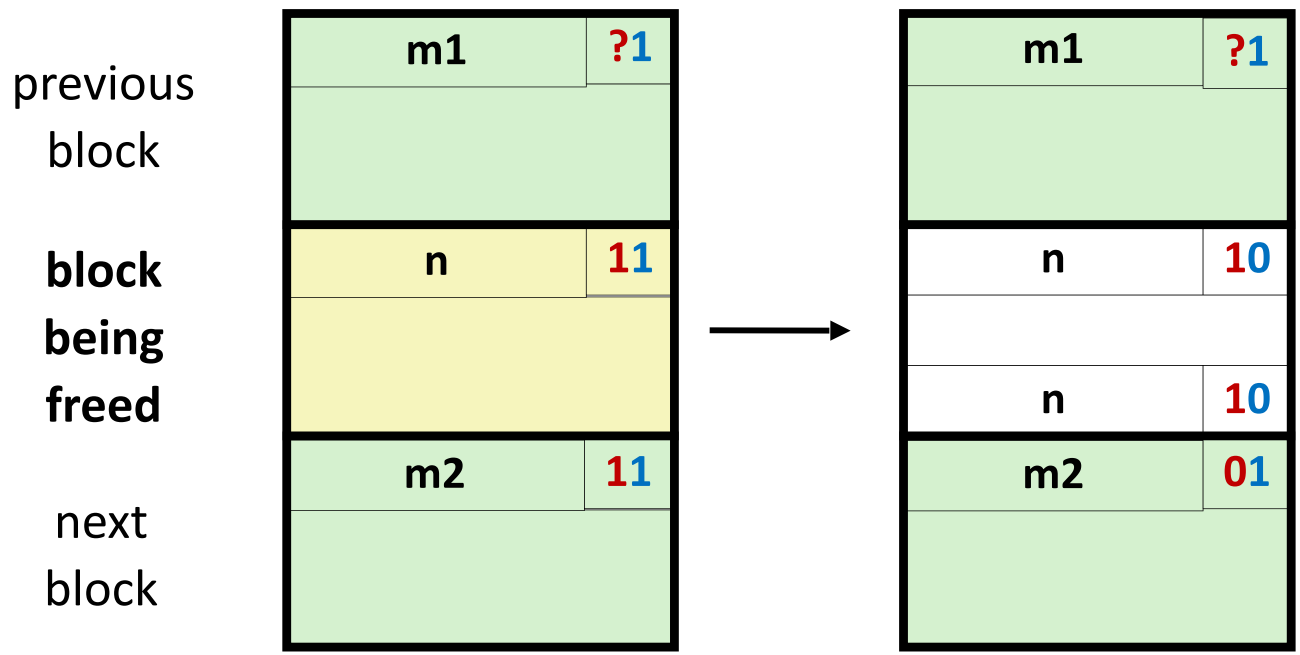
Size: block size

Payload: application data



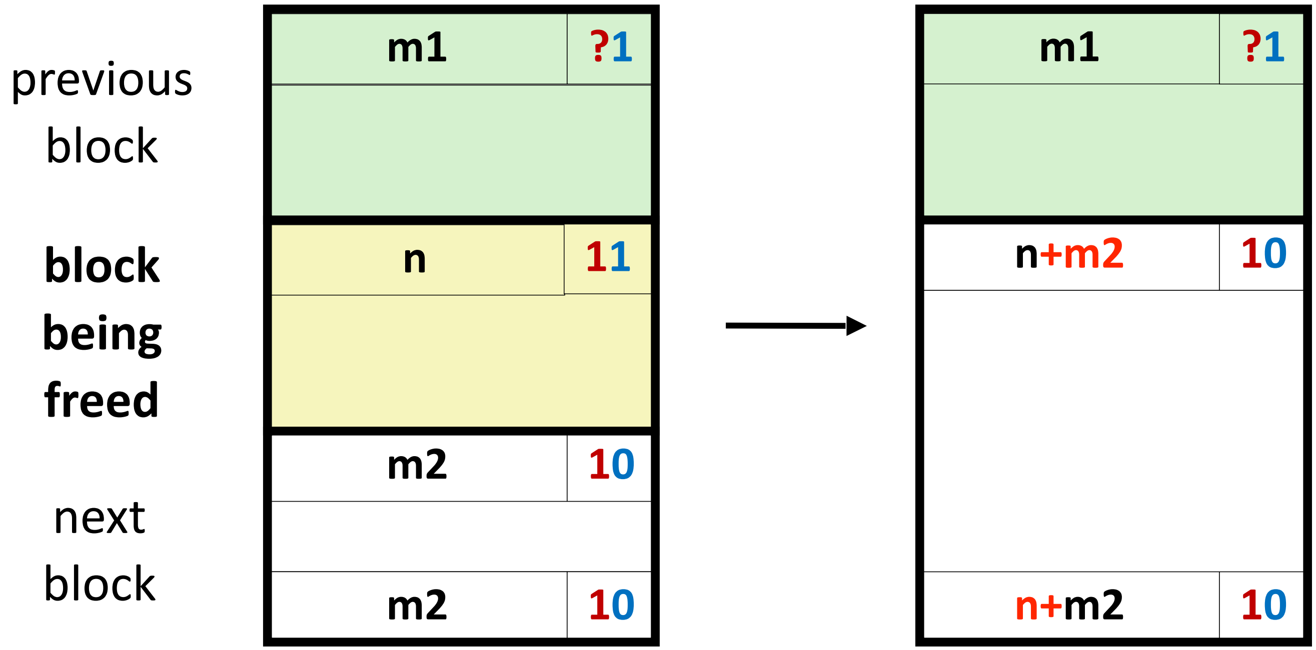
Free
Block

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)

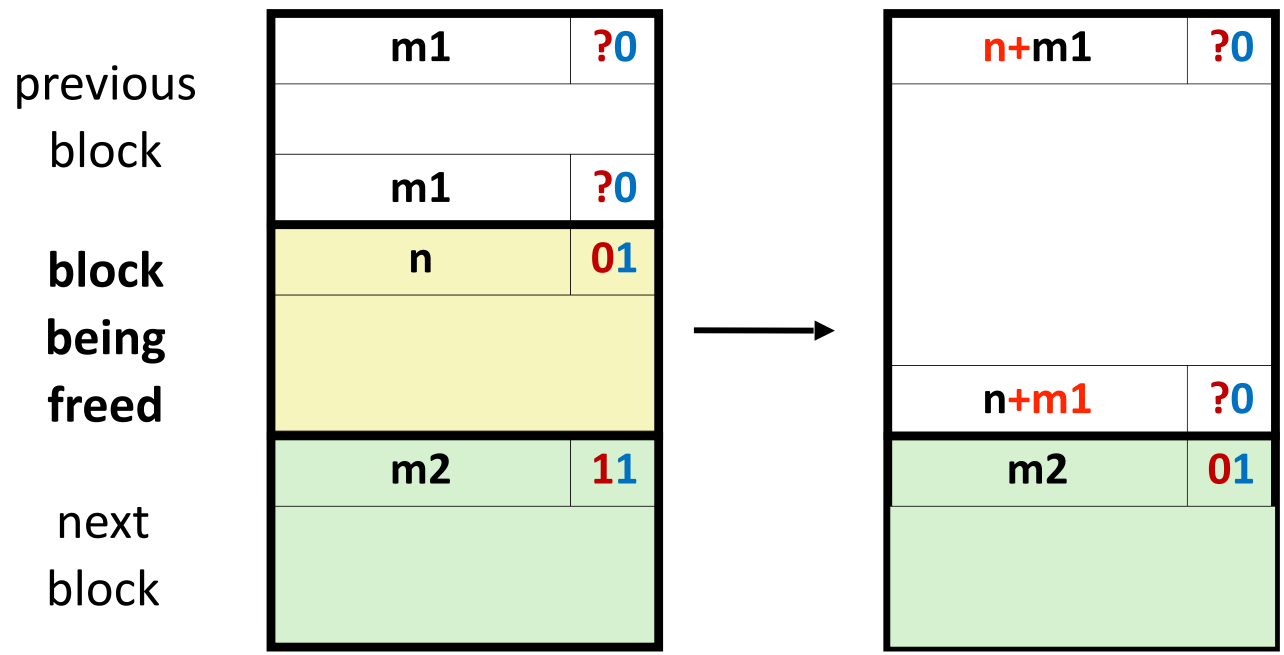
No Boundary Tag for Allocated Blocks (Case 2)



We do not need m1, so previous block does not require a footer

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

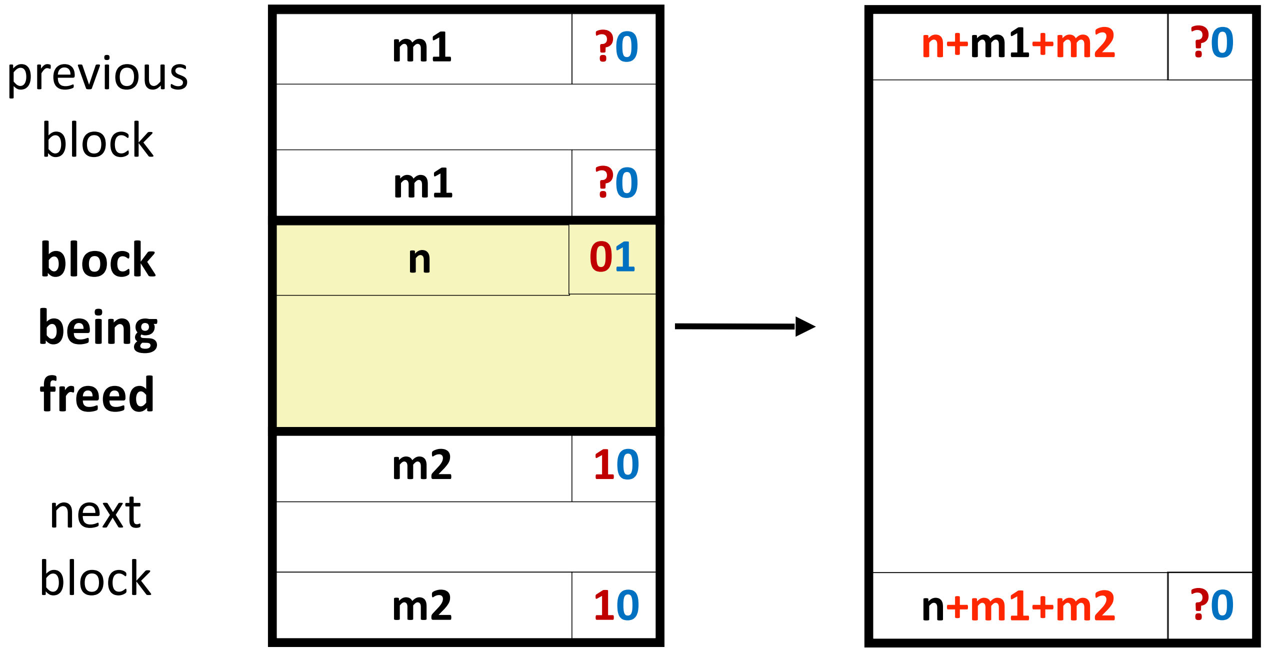
No Boundary Tag for Allocated Blocks (Case 3)



We need **m1**, so previous block must have a footer

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

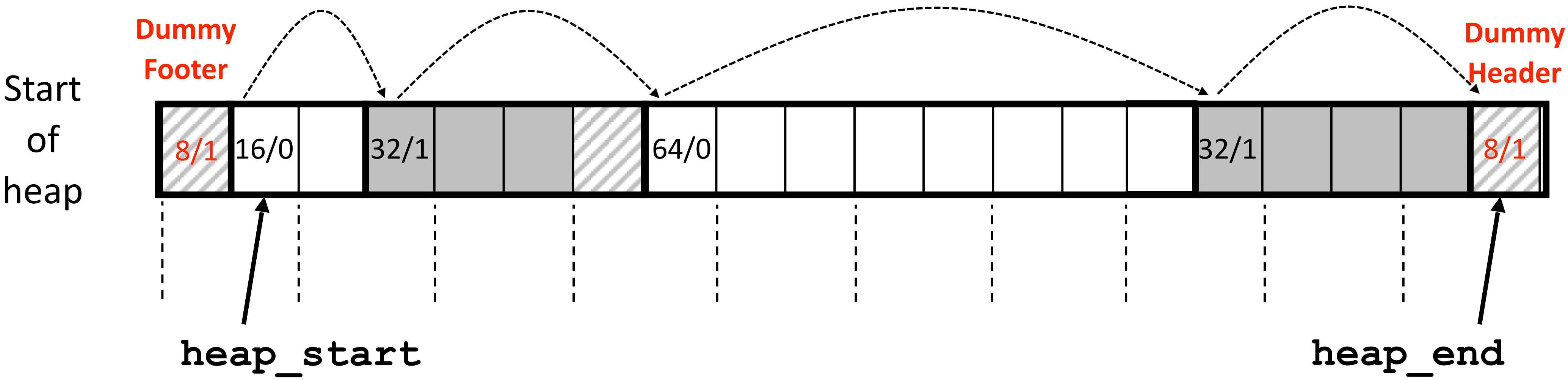
No Boundary Tag for Allocated Blocks (Case 4)



We need **m1/m2**, so **previous** and **next** blocks must have a footer

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

New Heap Structure After Adding Tags



- **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)
{
    // asize includes header and footer
    size_t asize = round_up(size + dsize, dsize);

    block_t *block = find_fit(asize);

    if (block == NULL)
        return NULL;

    // first utilize entire free area
    size_t block_size = get_size(block);
    write_header(block, block_size, true);
    write_footer(block, block_size, true);

    split_block(block, asize);

    // always return pointer to payload not block
    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); // bp is pointer to payload
    size_t size = get_size(block);

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

    coalesce_block(block);
}
```

Getting Additional Heap Memory

- **No fit found even after coalescing free blocks?**
  - 1) Ask the kernel for additional heap memory
    - Allocator calls **sbrk** function
  - 2) Additional memory given by kernel is **transformed** into **a single large free block** and **attached** to the end of the heap
  - 3) **Place requested block** in the new free block
    - Perform splitting if necessary

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 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**