Dynamic Memory Allocation

Introduction to Computer Systems
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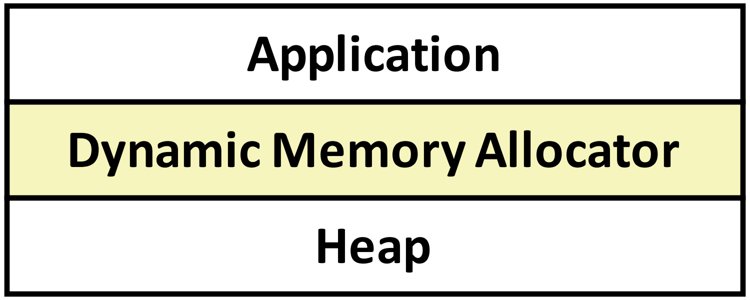
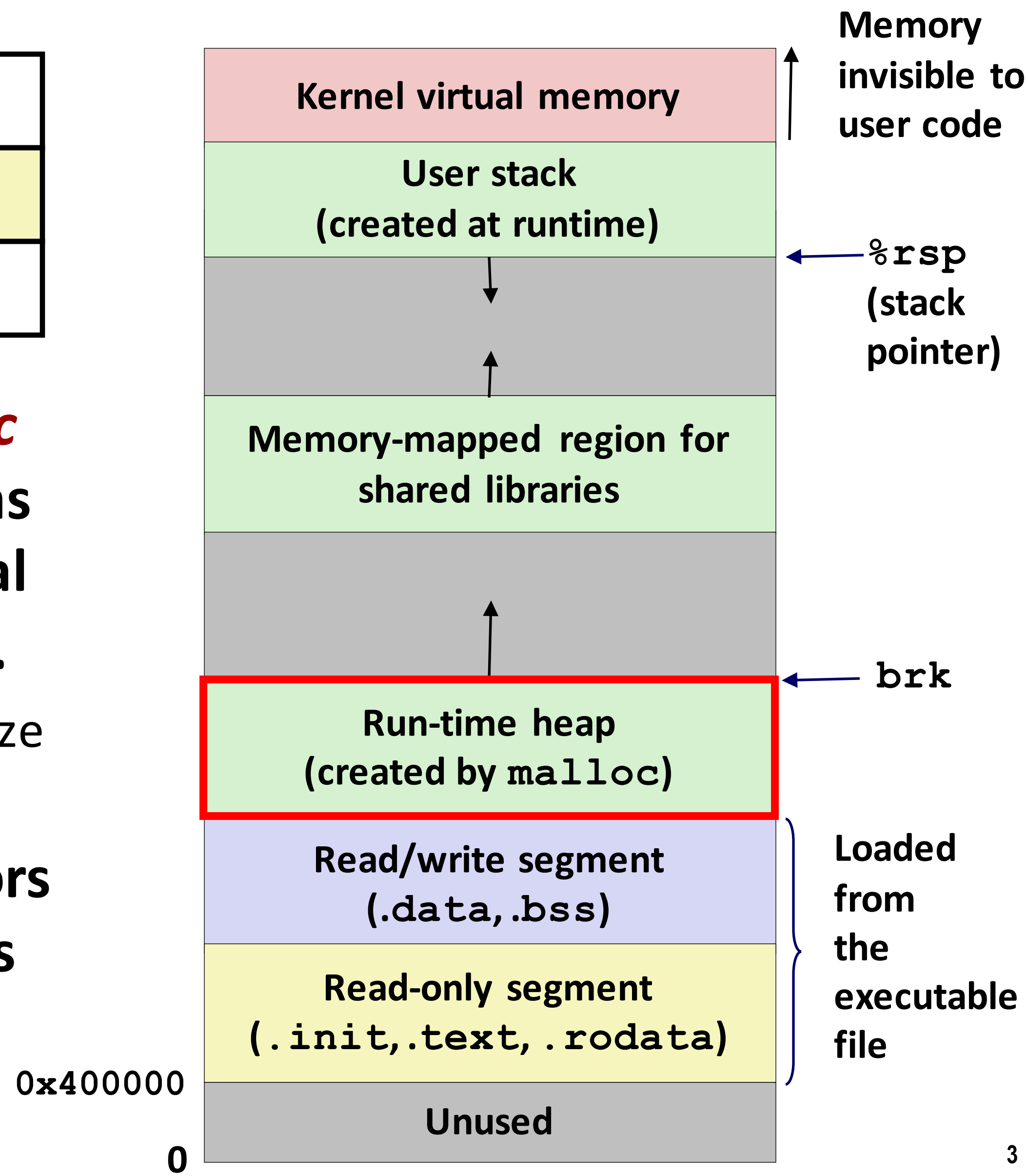
Today

- Basic concepts
- Implicit free lists
- Explicit free lists
- Segregated free lists
- Memory-related perils and pitfalls
- *Garbage collection*

Dynamic Memory Allocation



- Programmers use ***dynamic memory allocators*** (such as `malloc`) to acquire virtual memory (VM) at run time.
  - 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

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

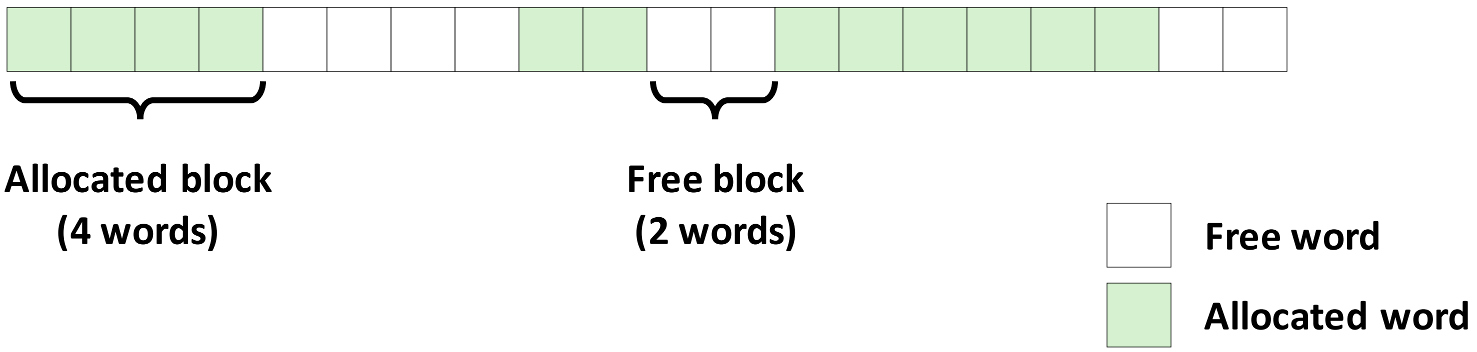
```
#include <stdio.h>
#include <stdlib.h>

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

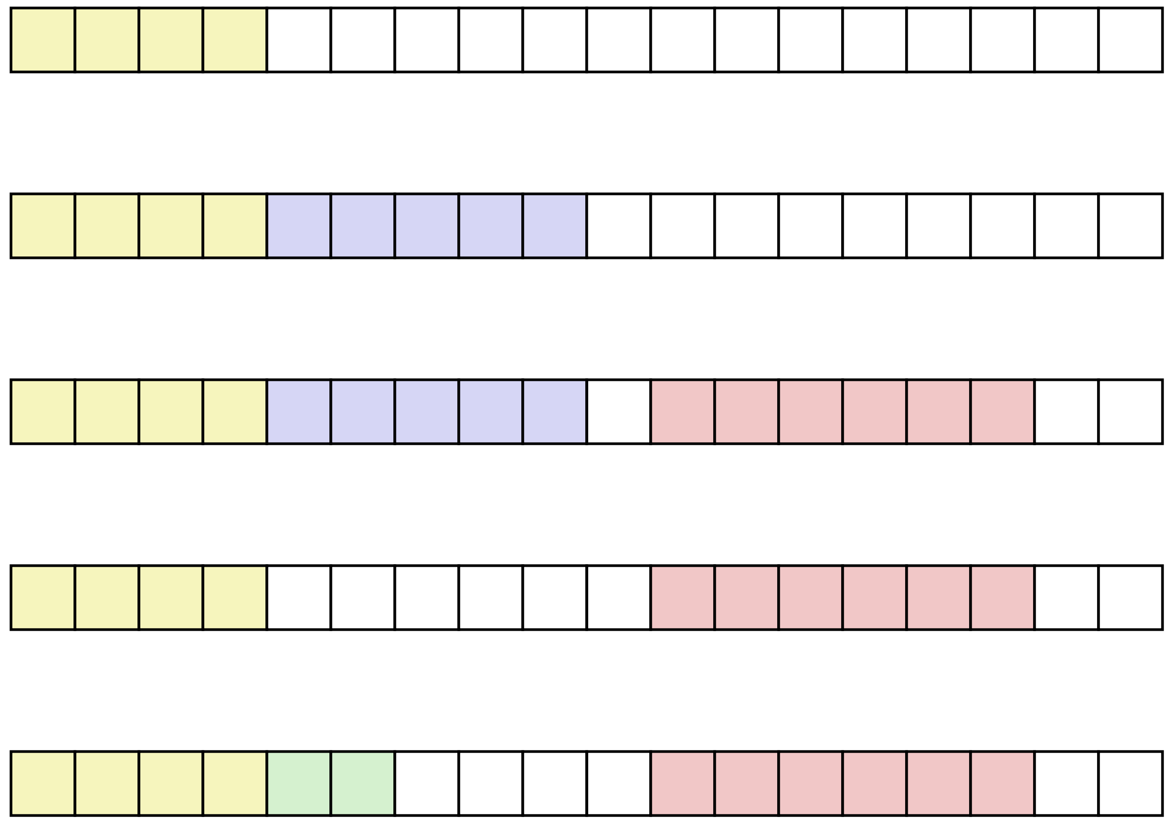
- Show 8-byte words as squares
- Allocations are double-word aligned.



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
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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
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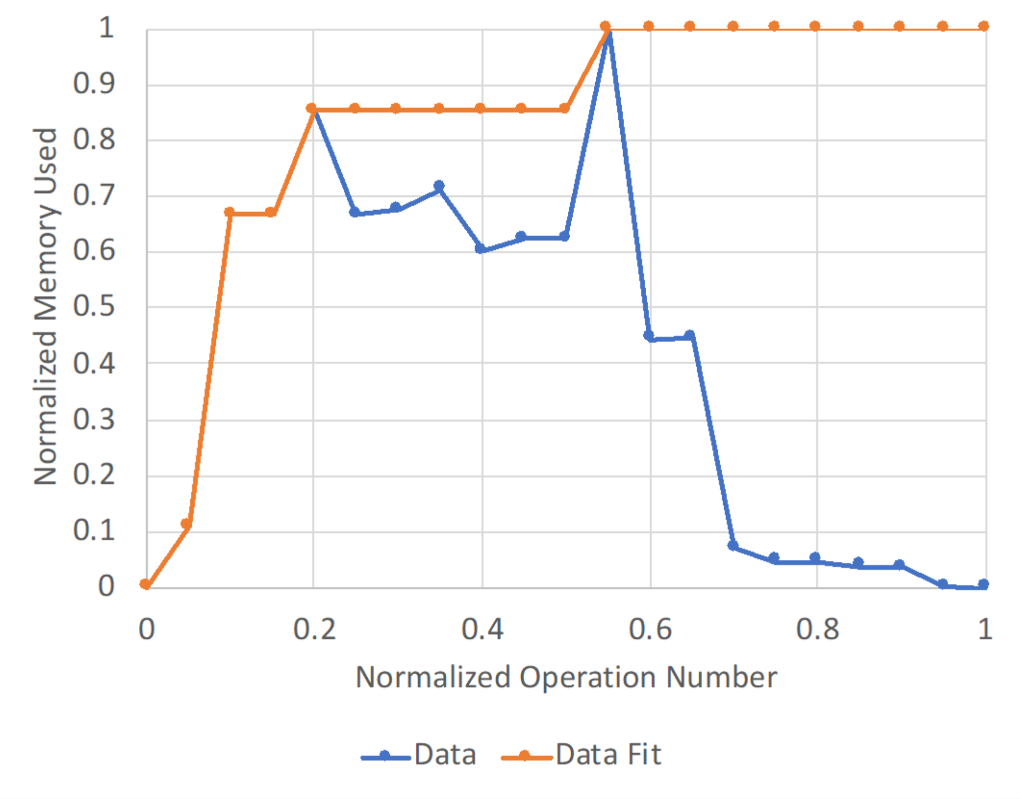
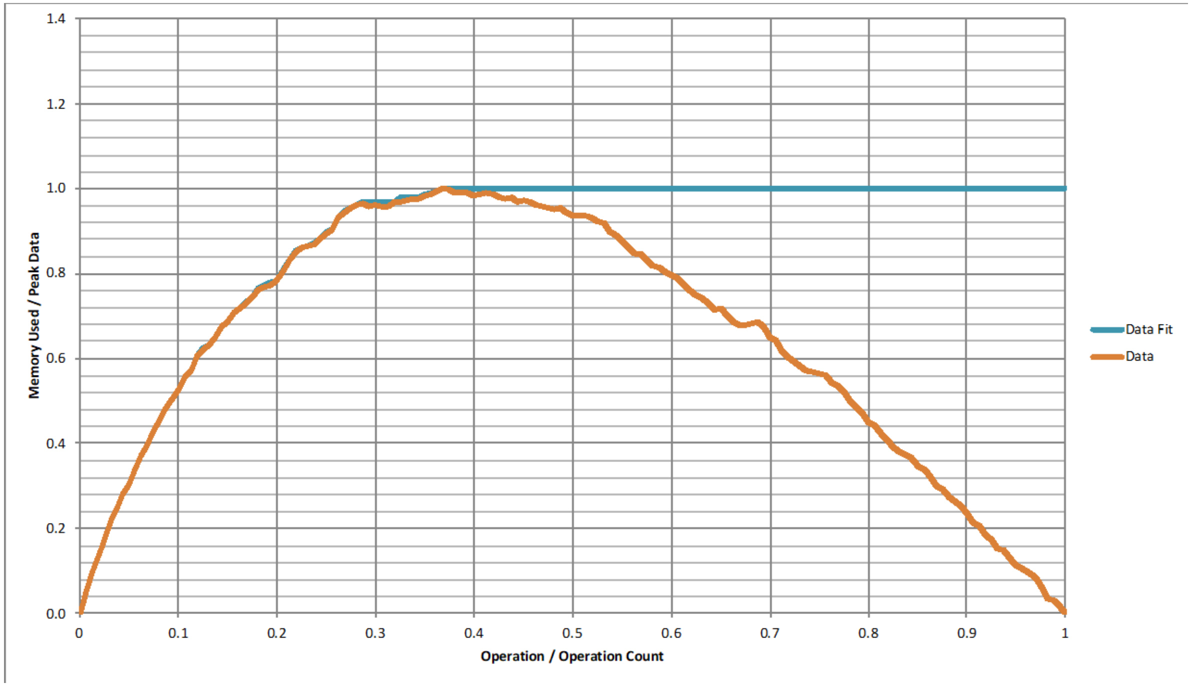


- Data line shows total allocated data (P_i)
- Data Fit line shows peak of total ($\max_{i \le k} P_i$)
- Normalized in X & Y

Full Benchmark Behavior



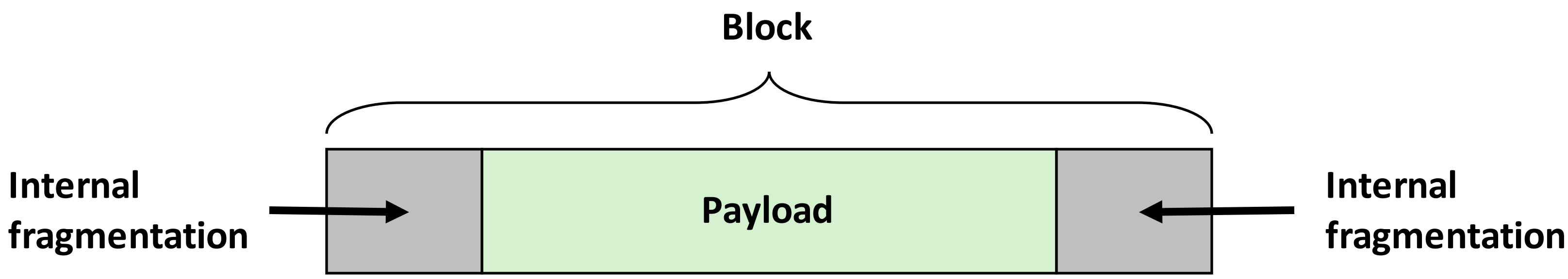
- **Given sequence of mallocs & frees (40,000 blocks)**
  - Starts with all mallocs, and shifts toward all frees
- **Manage space for all allocated blocks**
- **Metrics**
  - Data: P_i
  - Data fit: $\max_{i \le k} P_i$

Fragmentation

- **Poor memory utilization caused by *fragmentation***
  - ***internal*** fragmentation
  - ***external*** fragmentation

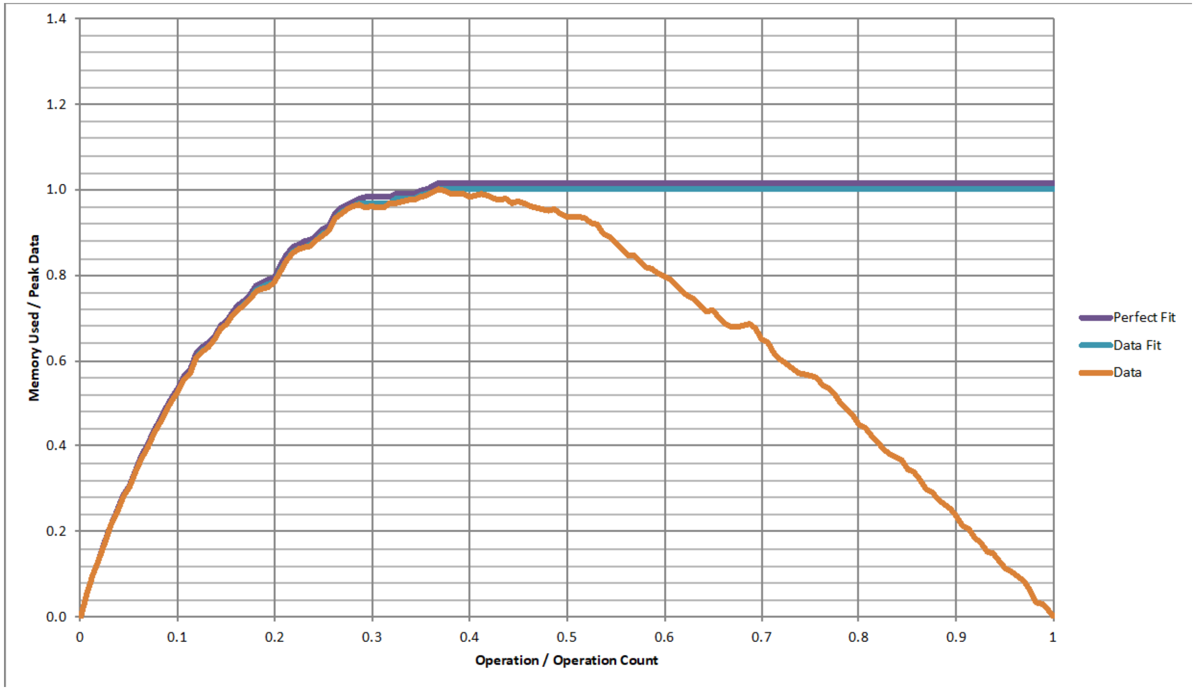
Internal Fragmentation

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



- **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



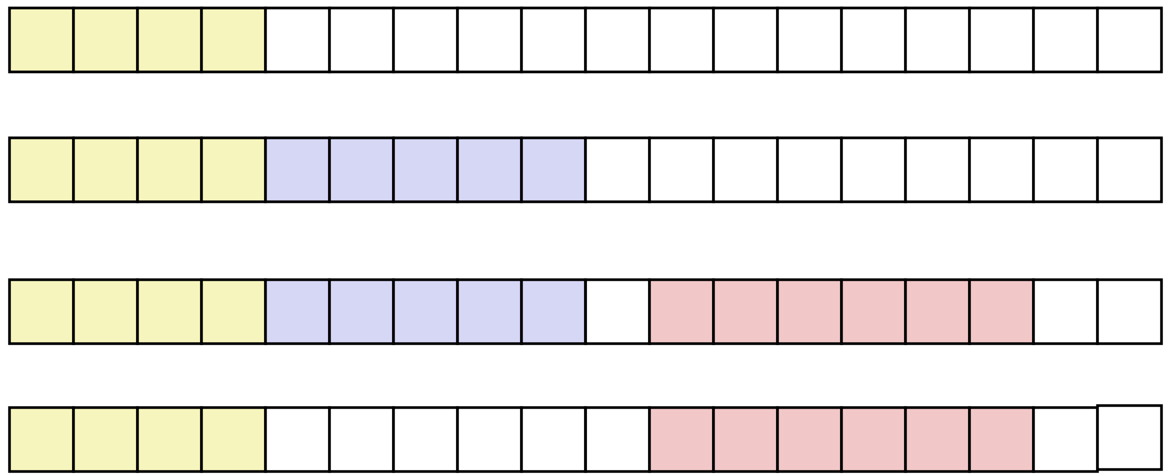
- **Perfect Fit: Only requires space for allocated data, data structures, and unused space due to alignment constraints**
  - For this benchmark, 1.5% overhead
  - Cannot achieve in practice
    - Especially since cannot move allocated blocks

External Fragmentation

```
#define SIZ sizeof(size_t)
```

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

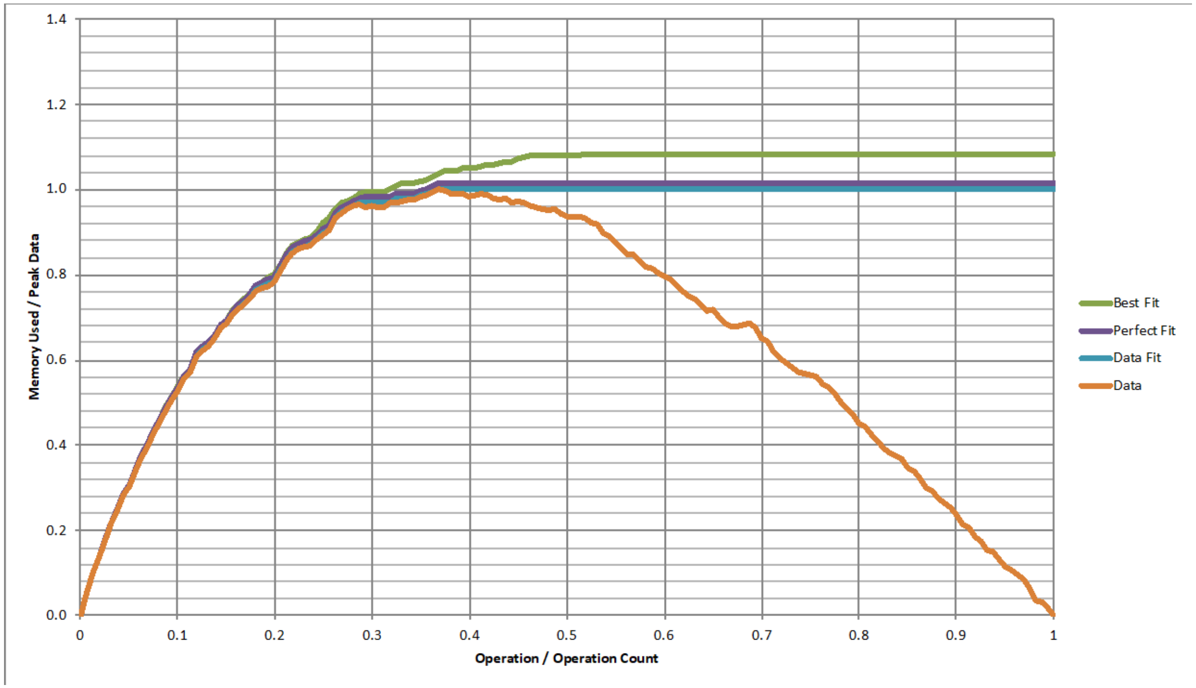
```
p1 = malloc(4*SIZ)
p2 = malloc(5*SIZ)
p3 = malloc(6*SIZ)
free(p2)
p4 = malloc(7*SIZ)
```



Yikes! (what would happen now?)

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

External Fragmentation Effect



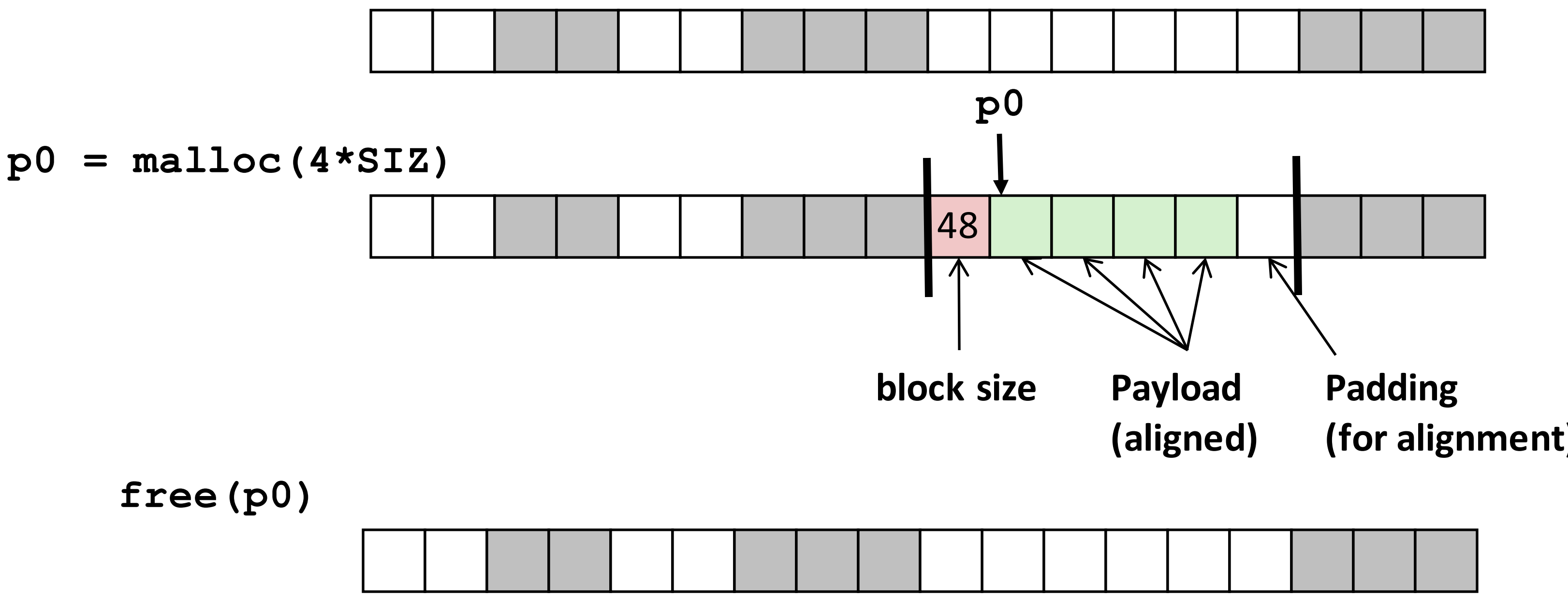
- **Best Fit: One allocation strategy**
  - (To be discussed later)
  - Total overhead = 8.3% on this benchmark

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?

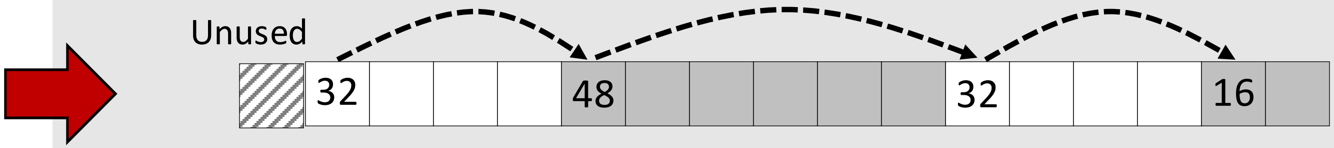
Knowing How Much to Free

- **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



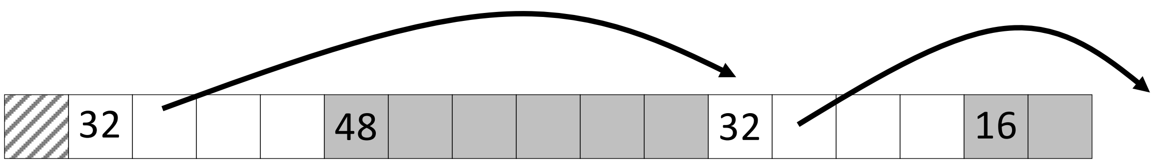
Keeping Track of Free Blocks

- **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

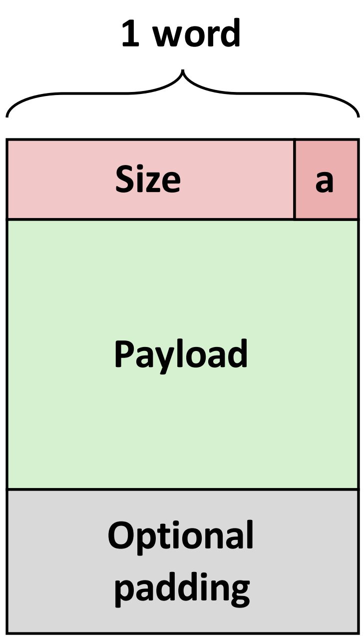
Today

- Basic concepts
- **Implicit free lists**
- Explicit free lists
- Segregated free lists
- Memory-related perils and pitfalls
- *Garbage collection*

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

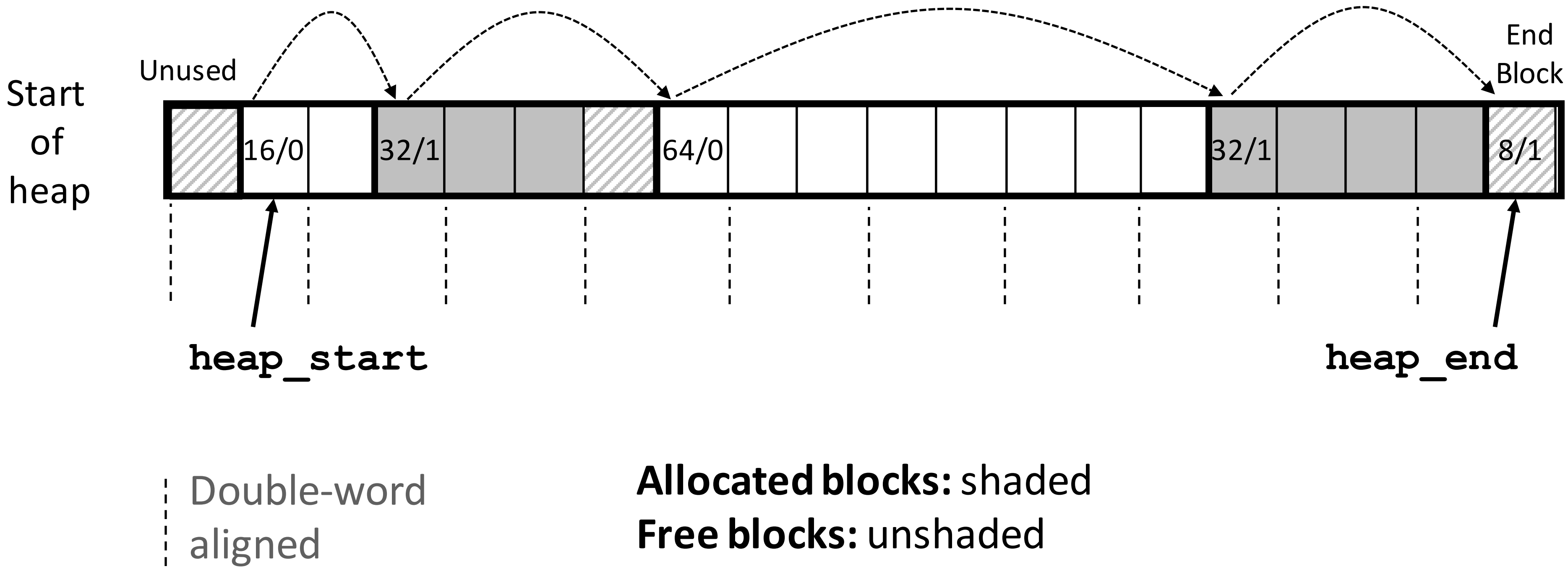


a = 1: Allocated block
a = 0: Free block

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

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

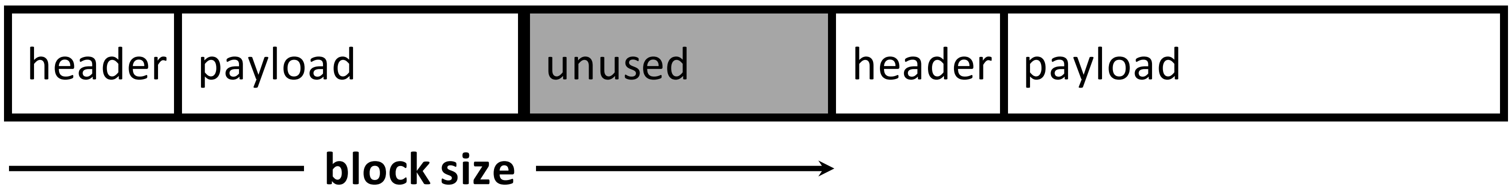
```
return header & ~0xfL;
```

- Initializing header

// block_t *block

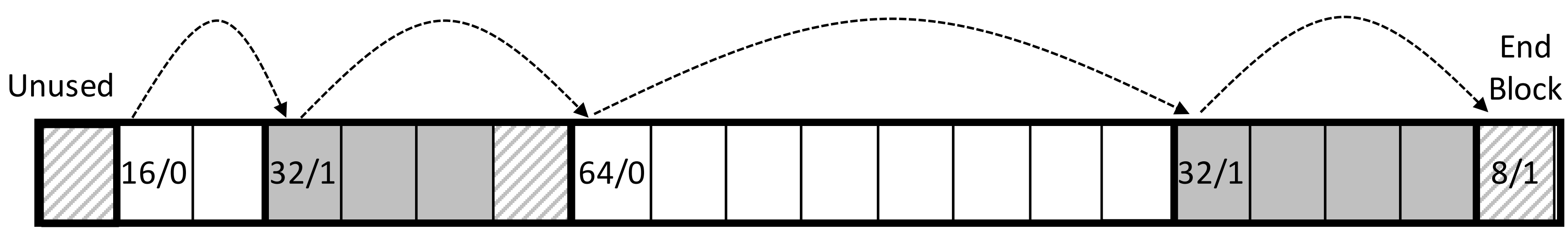
```
block->header = size | alloc;
```

Implicit List: Traversing list



- **Find next block**

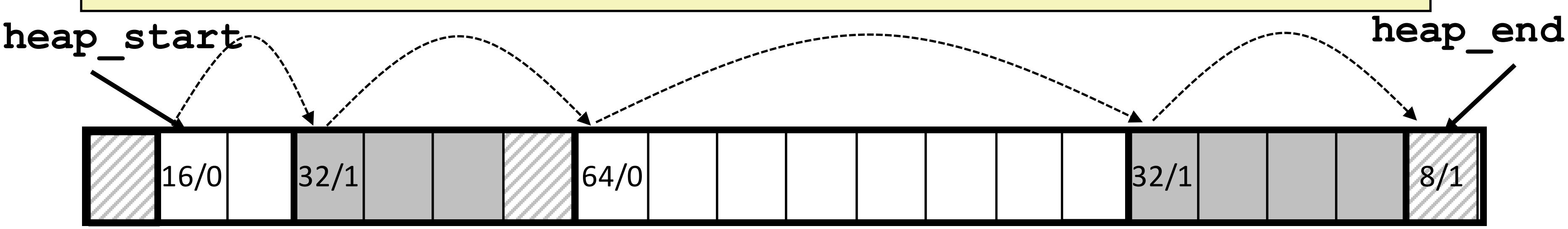
```
static block_t *find_next(block_t *block)
{
    return (block_t *) ((unsigned char *) block
                         + get_size(block));
}
```



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):

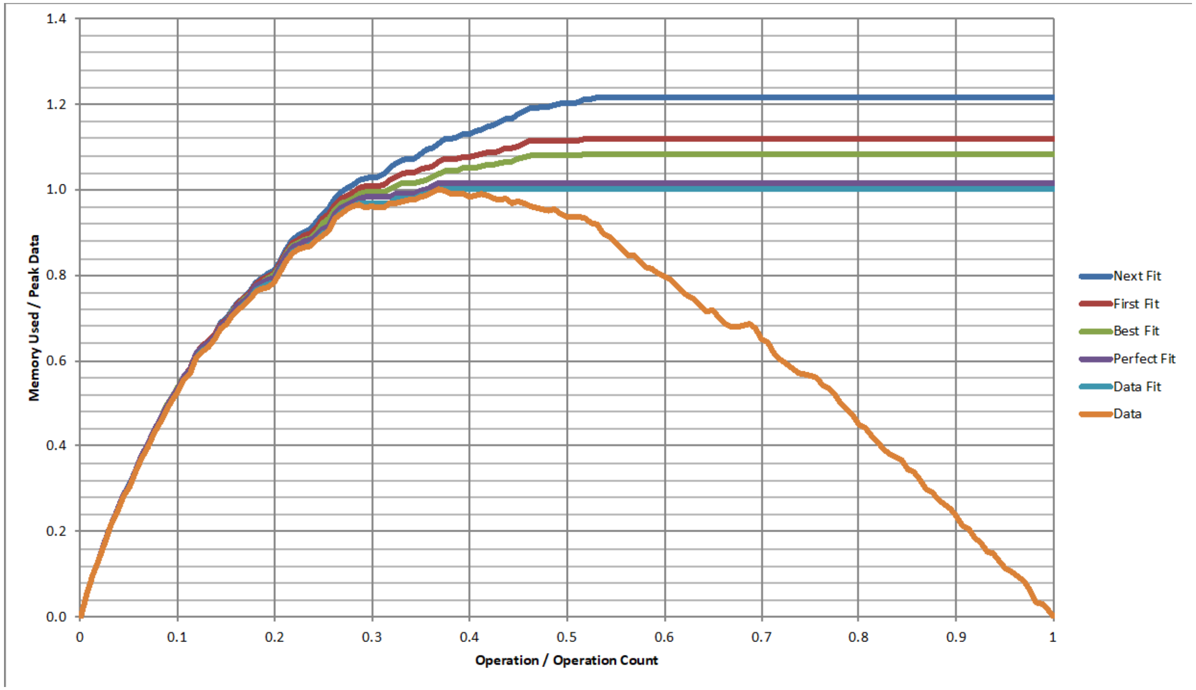
```
static block_t *find_fit(size_t asize)
{
    block_t *block;
    for (block = heap_start; block != heap_end;
         block = find_next(block)) {
    {
      if (!(get_alloc(block))
          && (asize <= get_size(block)))
         return block;
    }
    return NULL; // No fit found
}
```



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

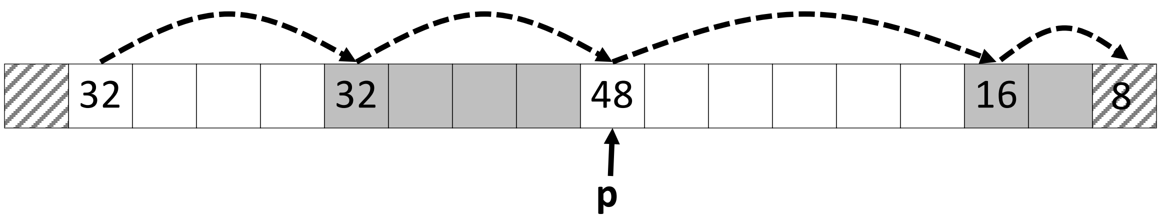
Comparing Strategies



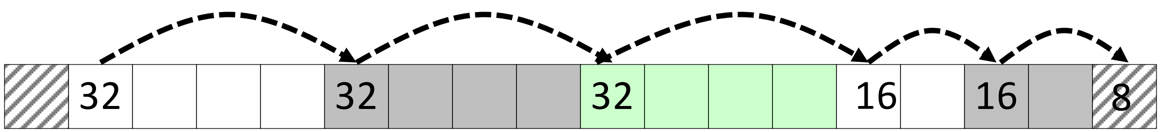
- **Total Overheads (for this benchmark)**
  - Perfect Fit: 1.6%
  - Best Fit: 8.3%
  - First Fit: 11.9%
  - Next Fit: 21.6%

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

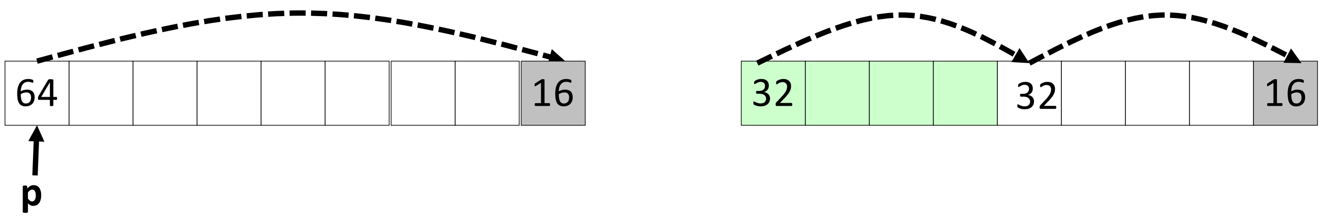


`split_block(p, 32)`



Implicit List: Splitting Free Block

`split_block(p, 32)`

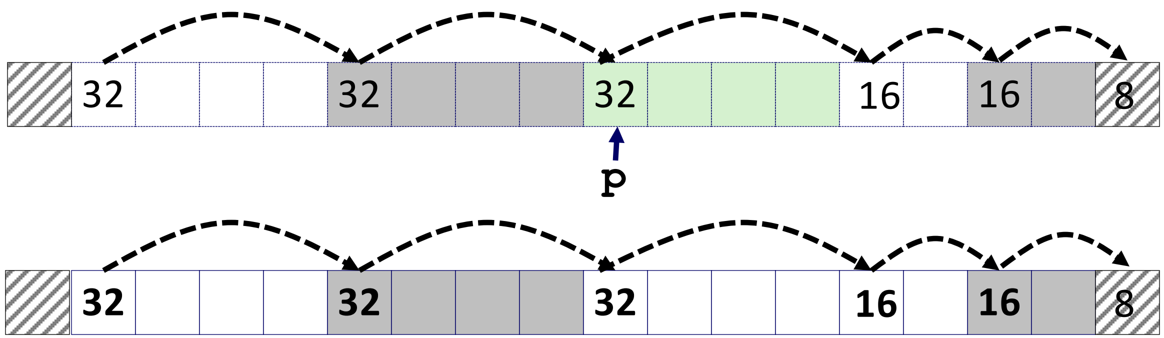



```
// Warning: This code is incomplete

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)`

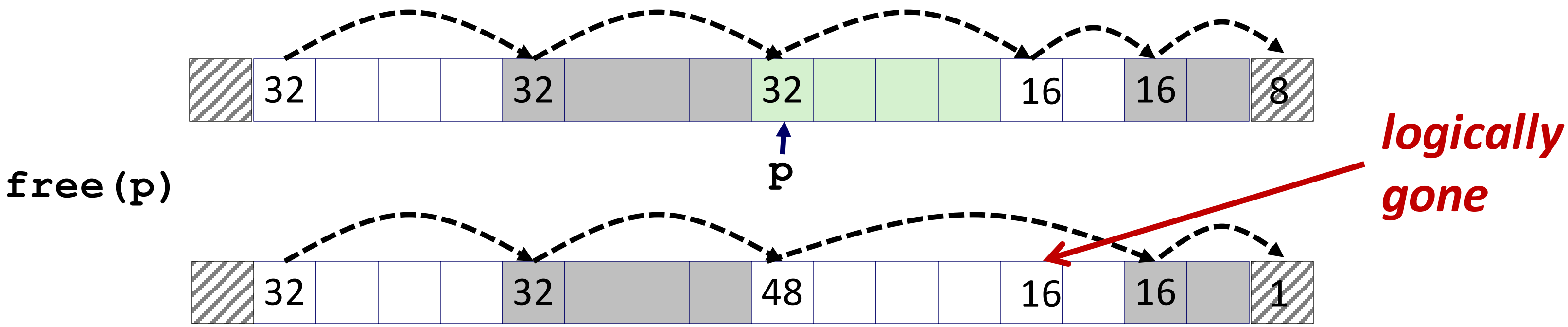


`malloc(5*SIZ)` ***Yikes!***

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

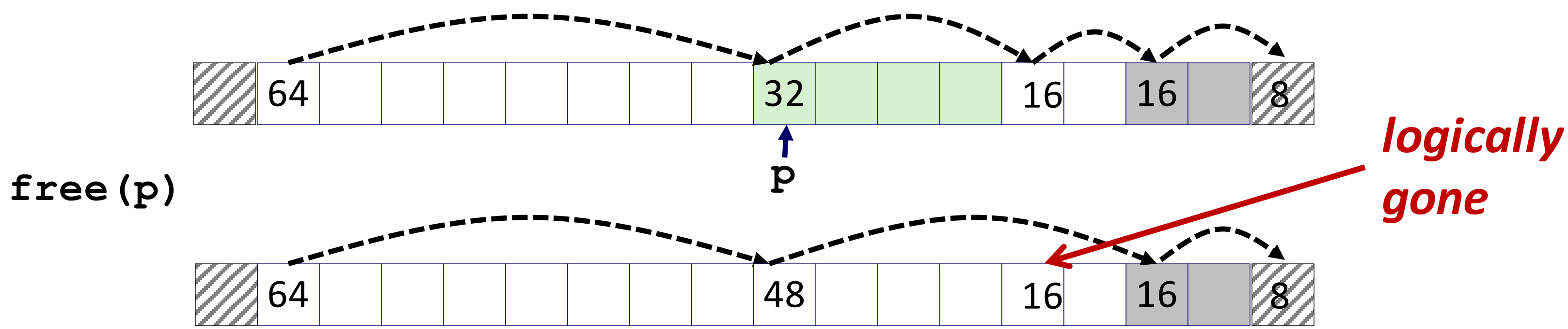
Implicit List: Coalescing

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



Implicit List: Coalescing

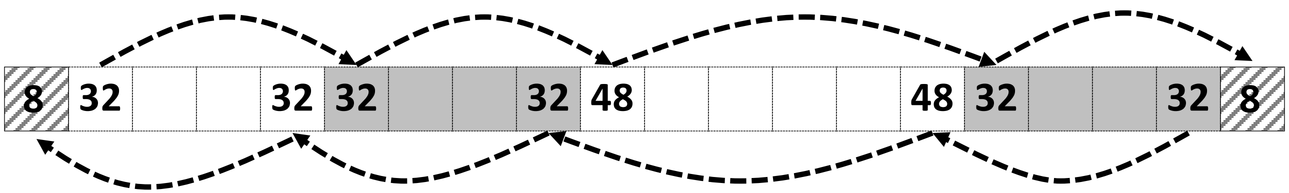
- **Join *(coalesce)* with next block, if it is free**
  - Coalescing with next block

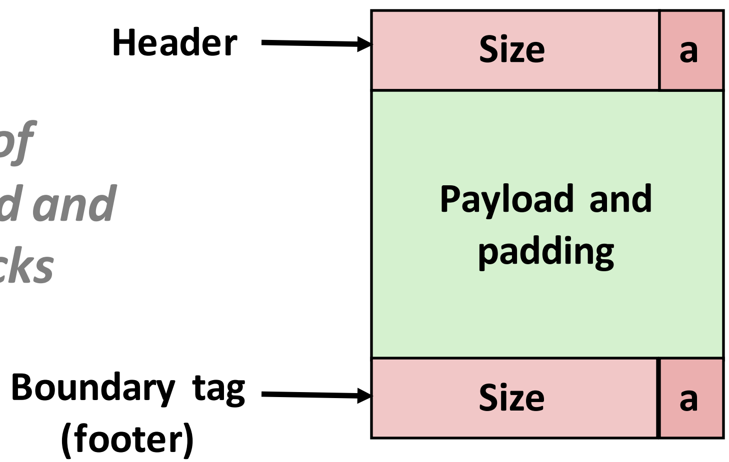


  - How do we coalesce with *previous* block?
    - How do we know where it starts?
    - How can we determine whether its allocated?

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!





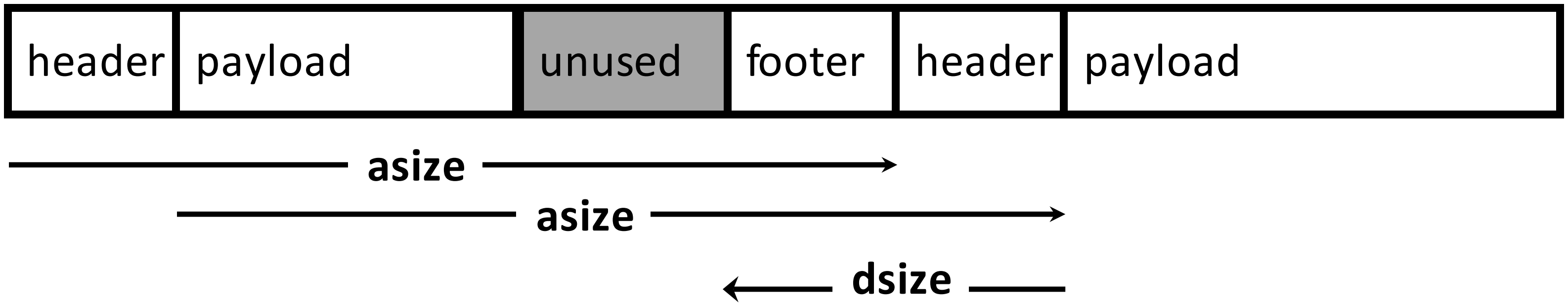
Format of allocated and free blocks

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

Size: Total block size

Payload: Application data (allocated blocks only)

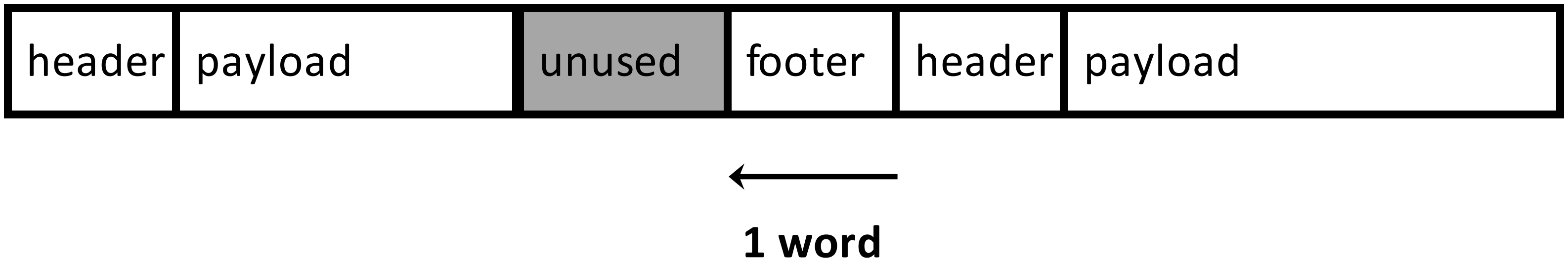
Implementation with Footers



- **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);
}
```

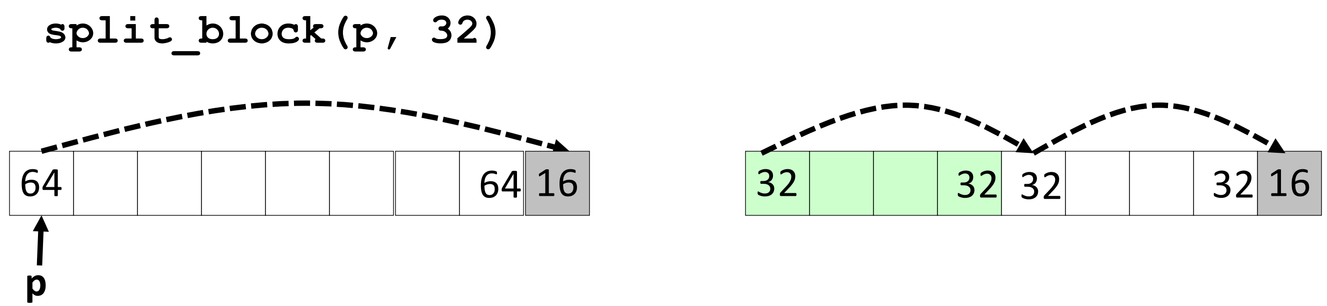
Implementation with Footers



- **Locating footer of previous block**

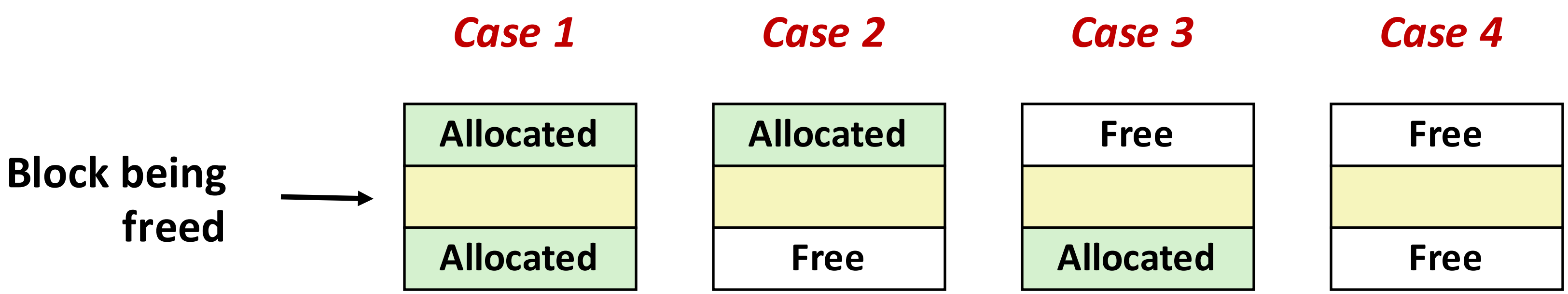
```
static word_t *find_prev_footer(block_t *block)
{
    return &(block->header) - 1;
}
```

Splitting Free Block: Full Version

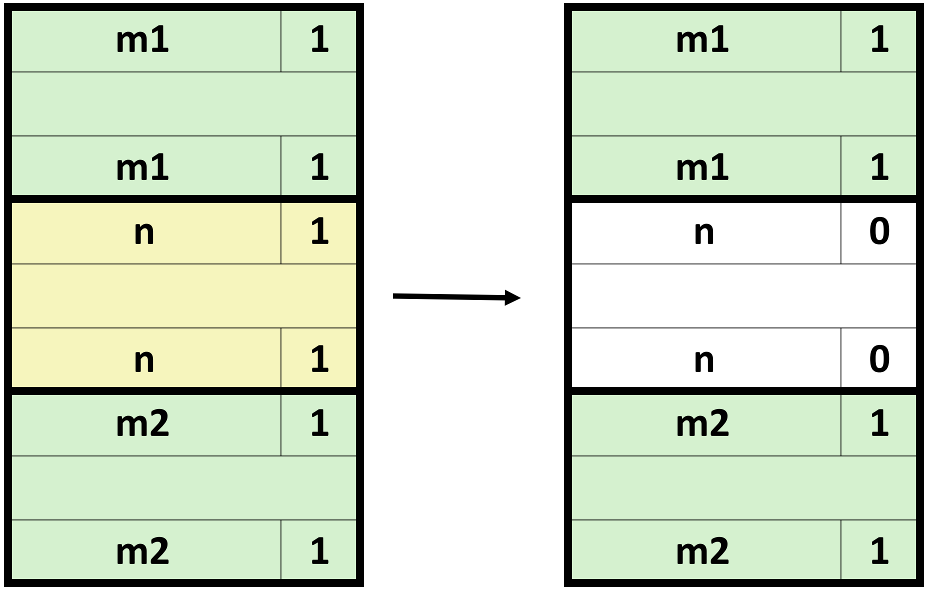



```
static void split_block(block_t *block, size_t asize){
    size_t block_size = get_size(block);

    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);
}
```

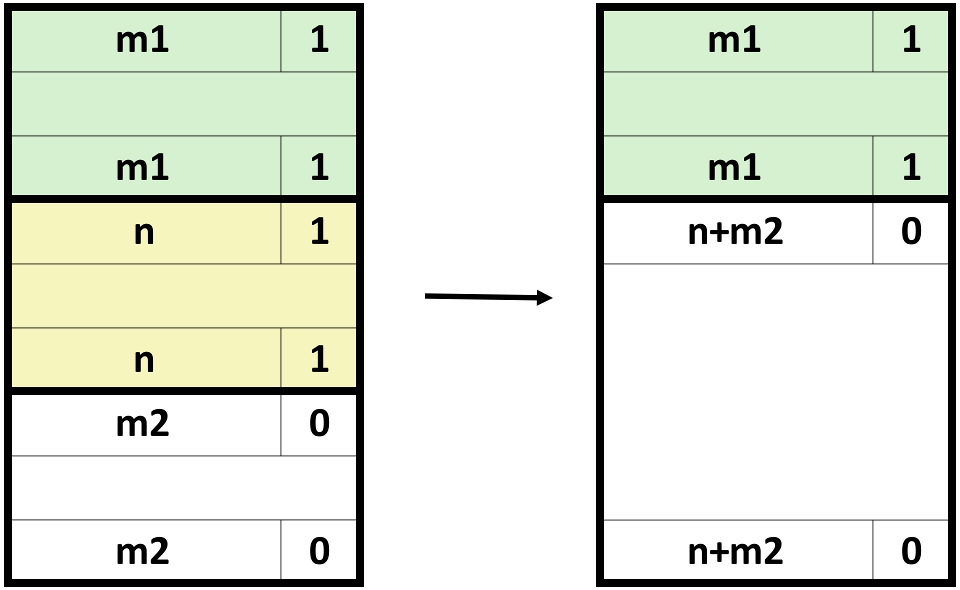
Constant Time Coalescing



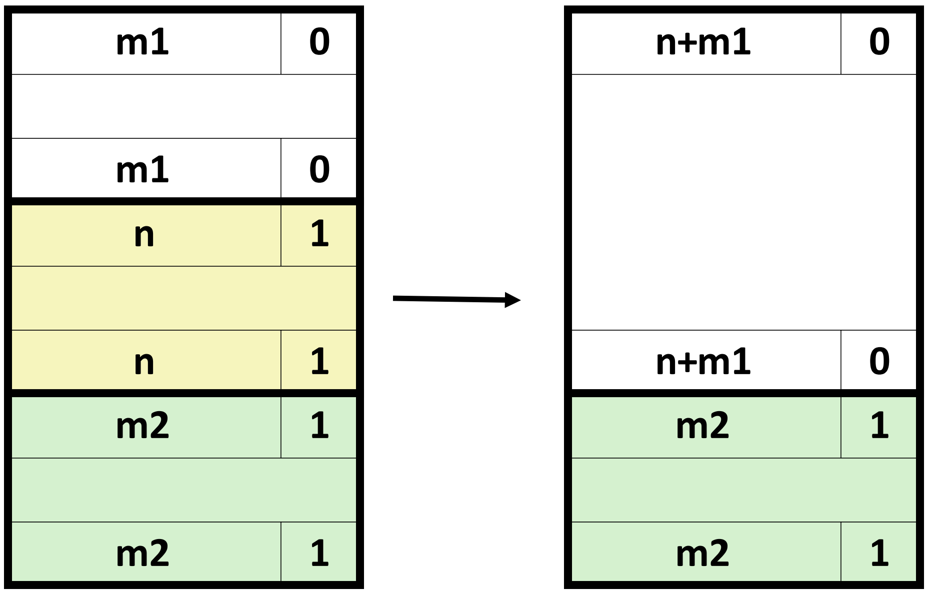
Constant Time Coalescing (Case 1)



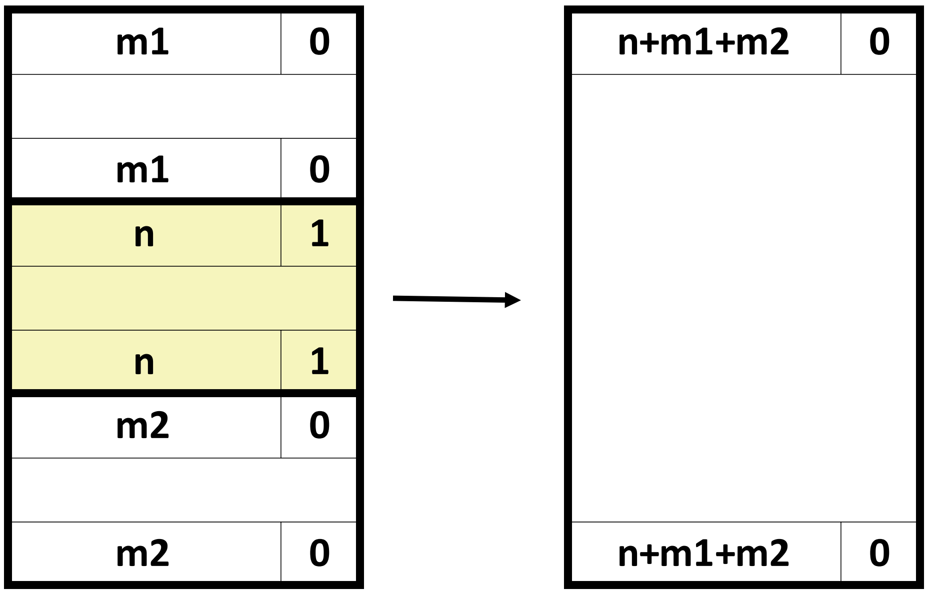
Constant Time Coalescing (Case 2)



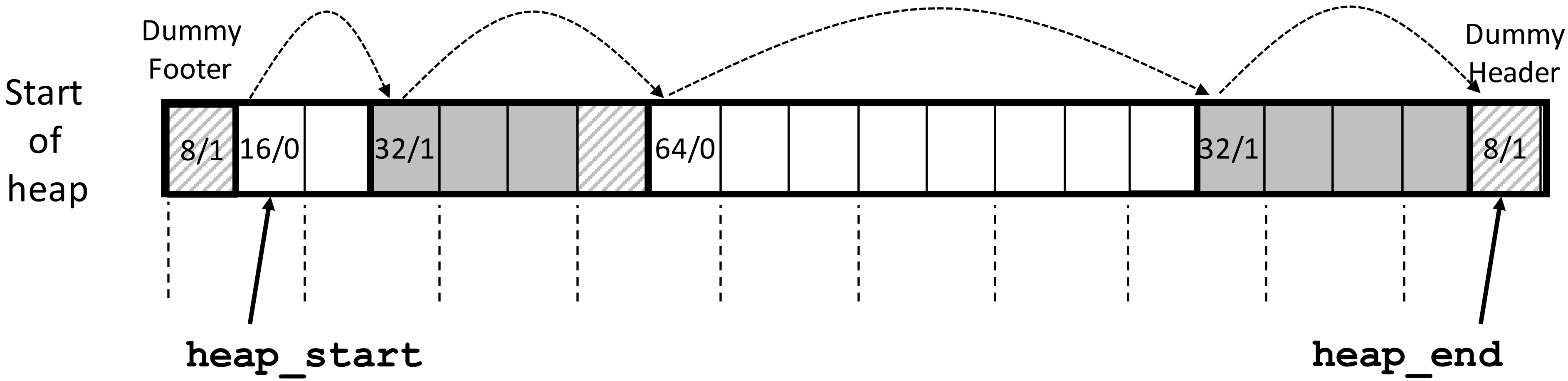
Constant Time Coalescing (Case 3)



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)
```

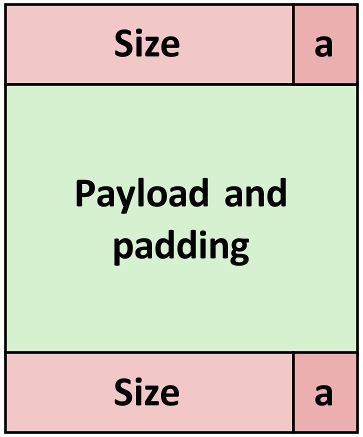
Top-Level Free Code

```
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

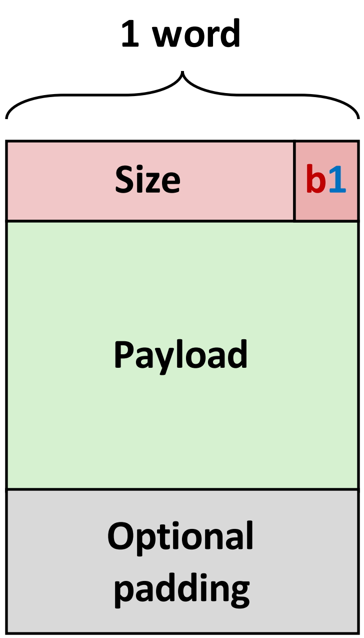
- **Internal fragmentation**

- **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

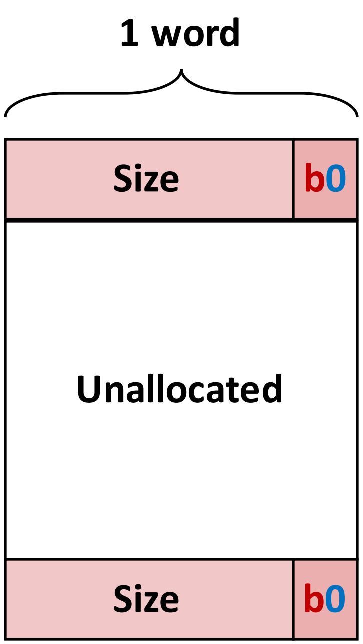


Allocated Block

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

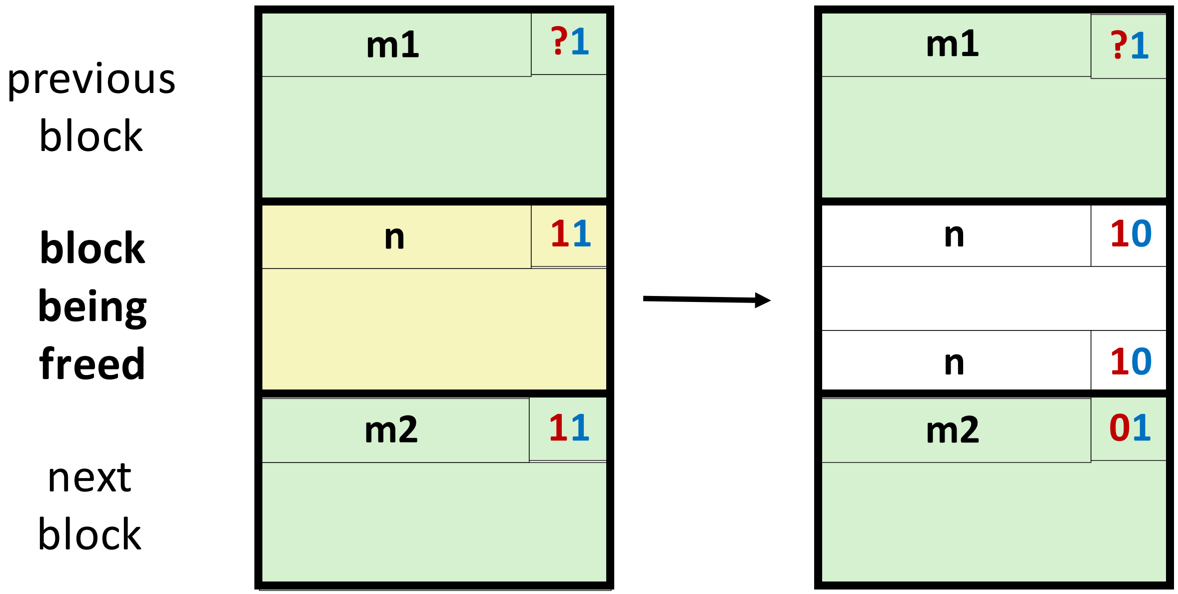
Size: block size

Payload: application data



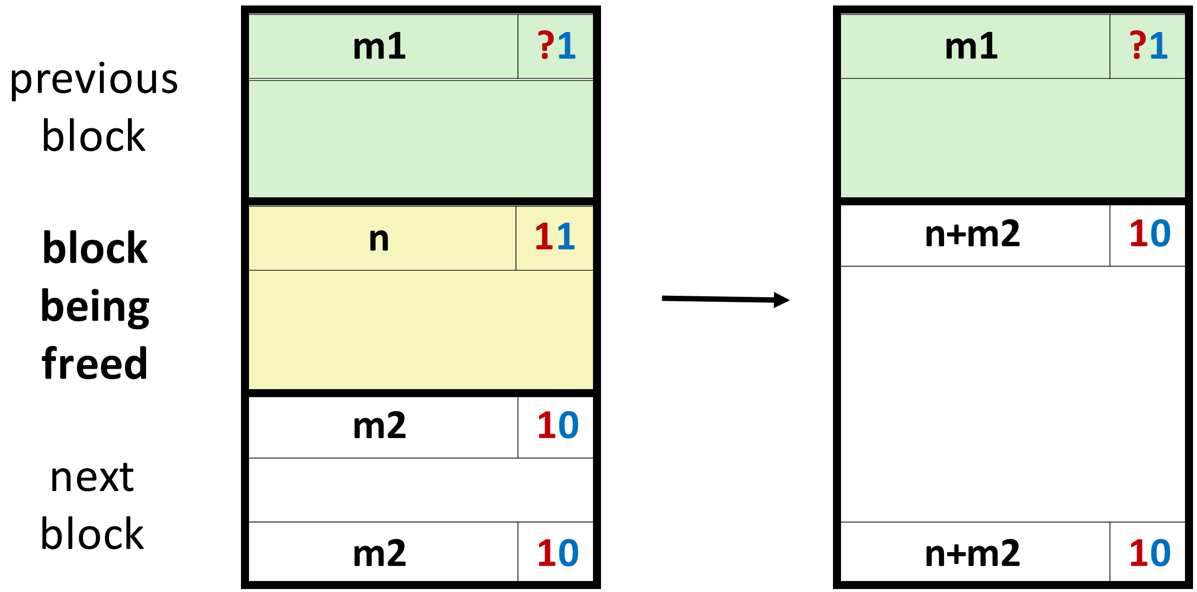
Free Block

No Boundary Tag for Allocated Blocks (Case 1)



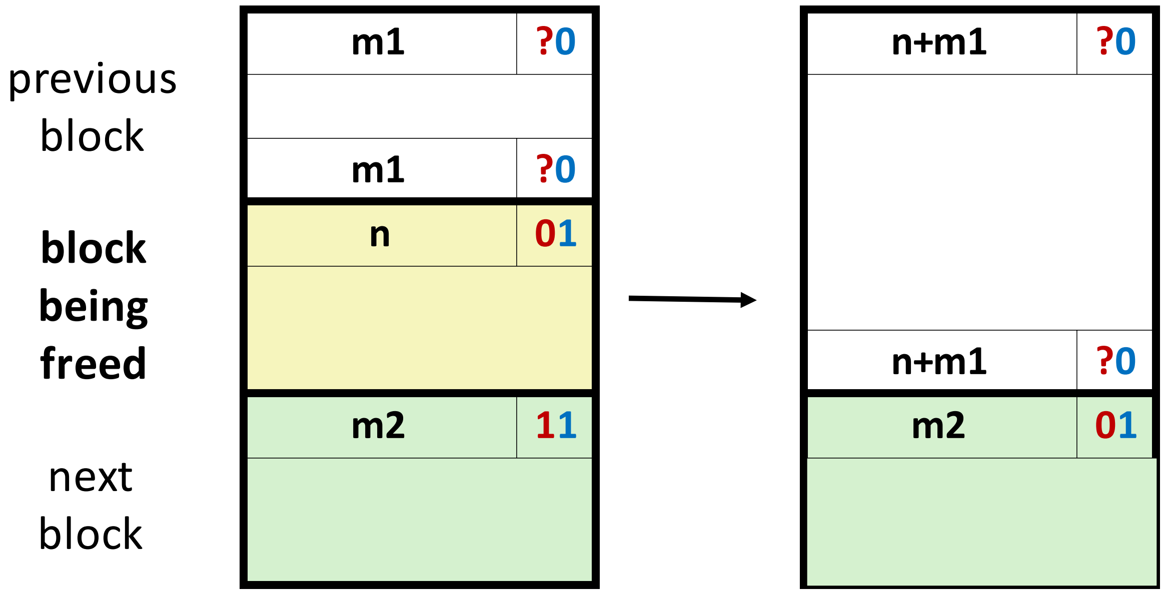
Header: Use 2 bits (address bits always zero due to alignment):
(previous block allocated)<<1 | (current block allocated)

No Boundary Tag for Allocated Blocks (Case 2)



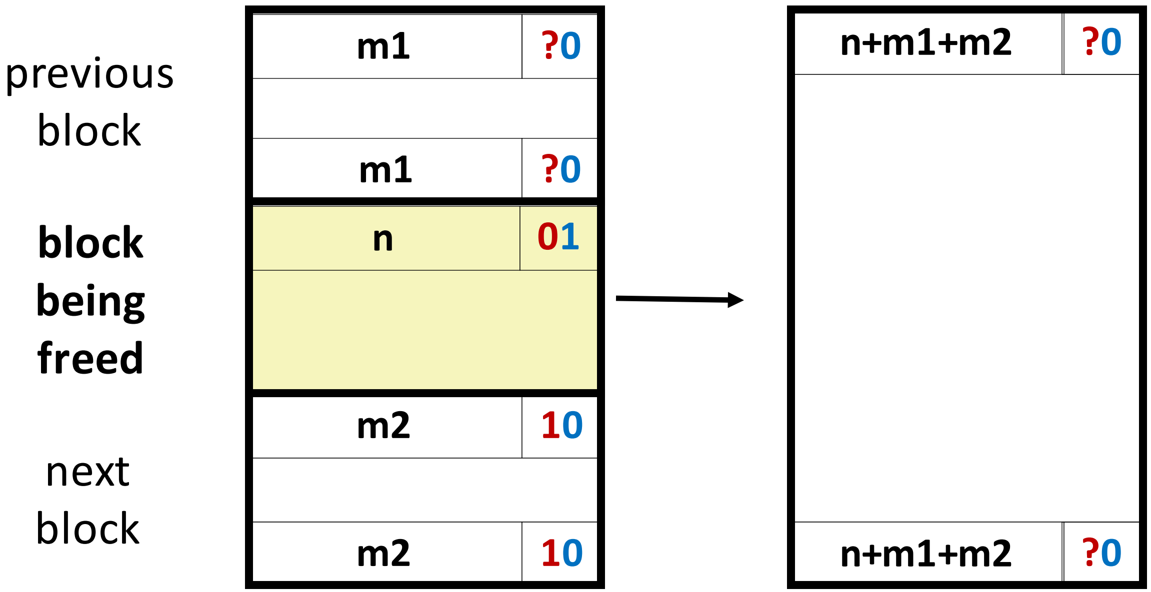
Header: Use 2 bits (address bits always zero due to alignment):
(previous block allocated)<<1 | (current block allocated)

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 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

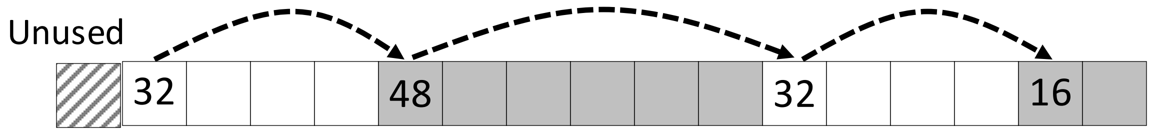
- **Implementation: very simple**
- **Allocate cost:**
  - linear time worst case
- **Free cost:**
  - constant time worst case
  - even with coalescing
- **Memory Overhead**
  - will depend on placement policy
  - First-fit, next-fit or best-fit
- **Not used in practice for `malloc/free` because of linear-time allocation**
  - used in many special purpose applications
- **However, the concepts of splitting and boundary tag coalescing are general to *all* allocators**

Today

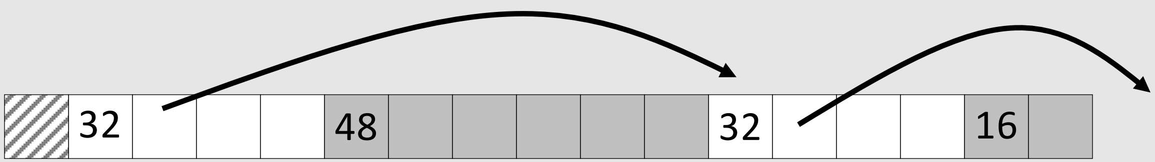
- Basic concepts
- Implicit free lists
- **Explicit free lists**
- Segregated free lists
- Memory-related perils and pitfalls
- *Garbage collection*

Keeping Track of Free Blocks

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



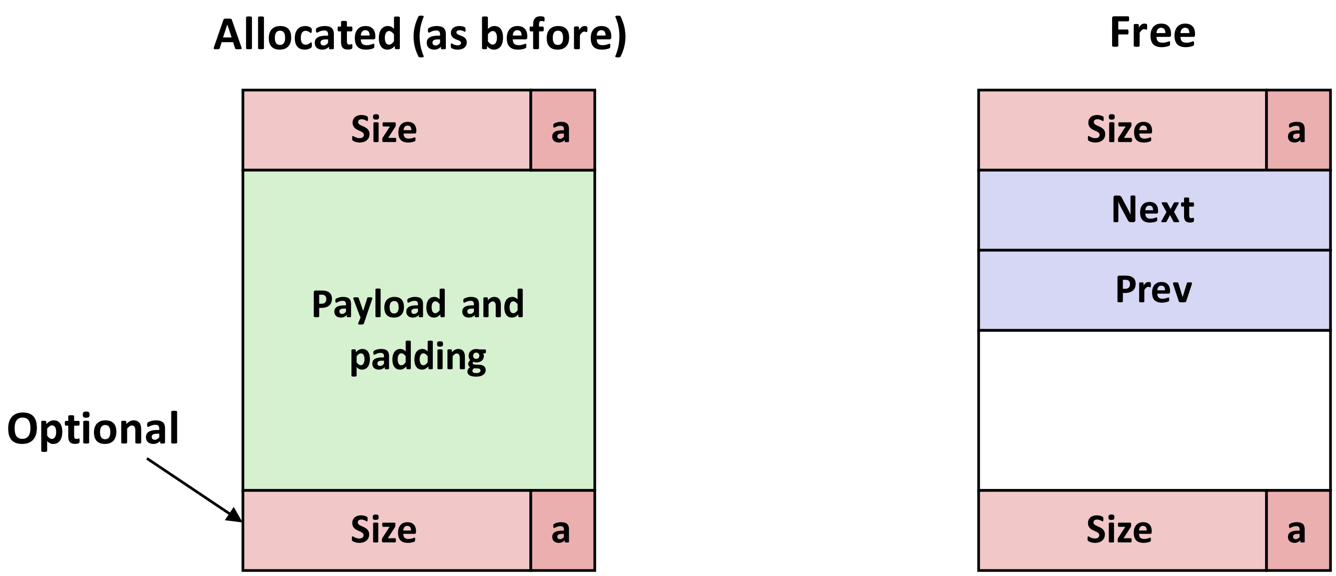
- **Method 2: *Explicit list* among the free blocks using pointers**



- **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

Explicit Free Lists

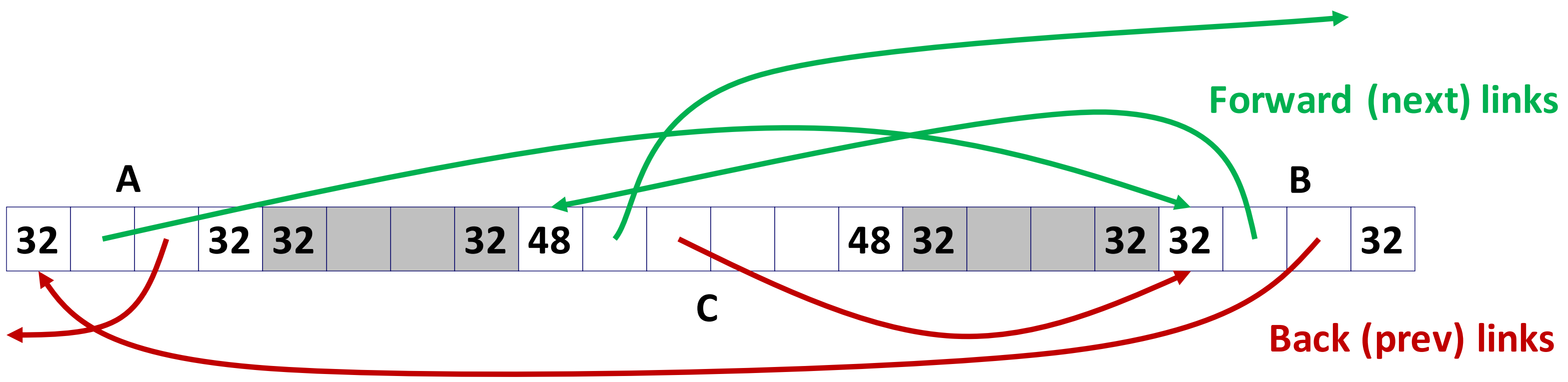


- **Maintain list(s) of *free* blocks, not *all* blocks**
  - Luckily we track only free blocks, so we can use payload area
  - The "next" free block could be anywhere
    - So we need to store forward/back pointers, not just sizes
  - Still need boundary tags for coalescing
    - To find adjacent blocks according to memory order

Explicit Free Lists

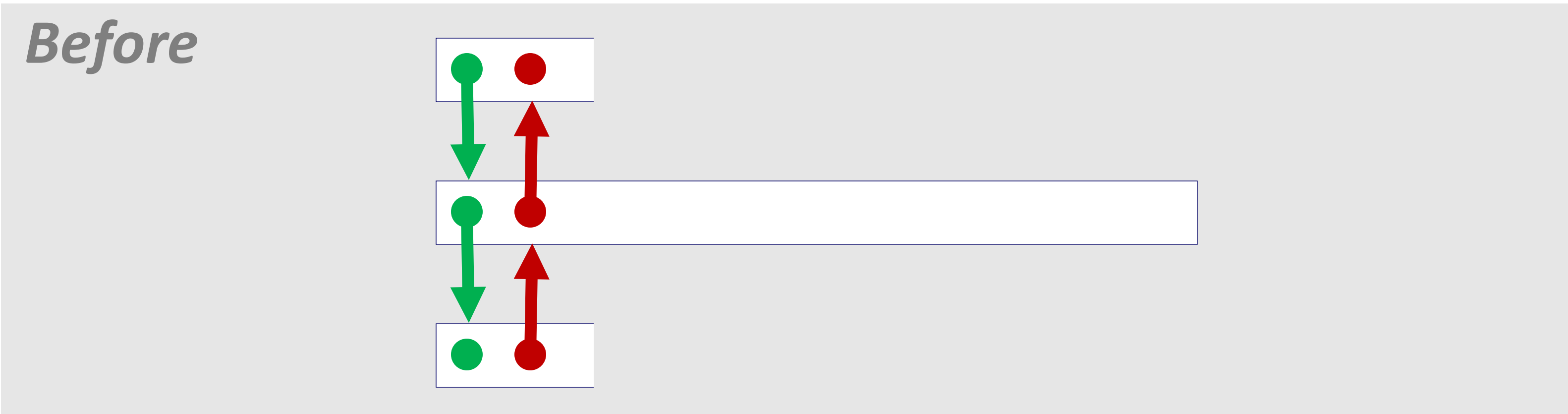
- Logically:

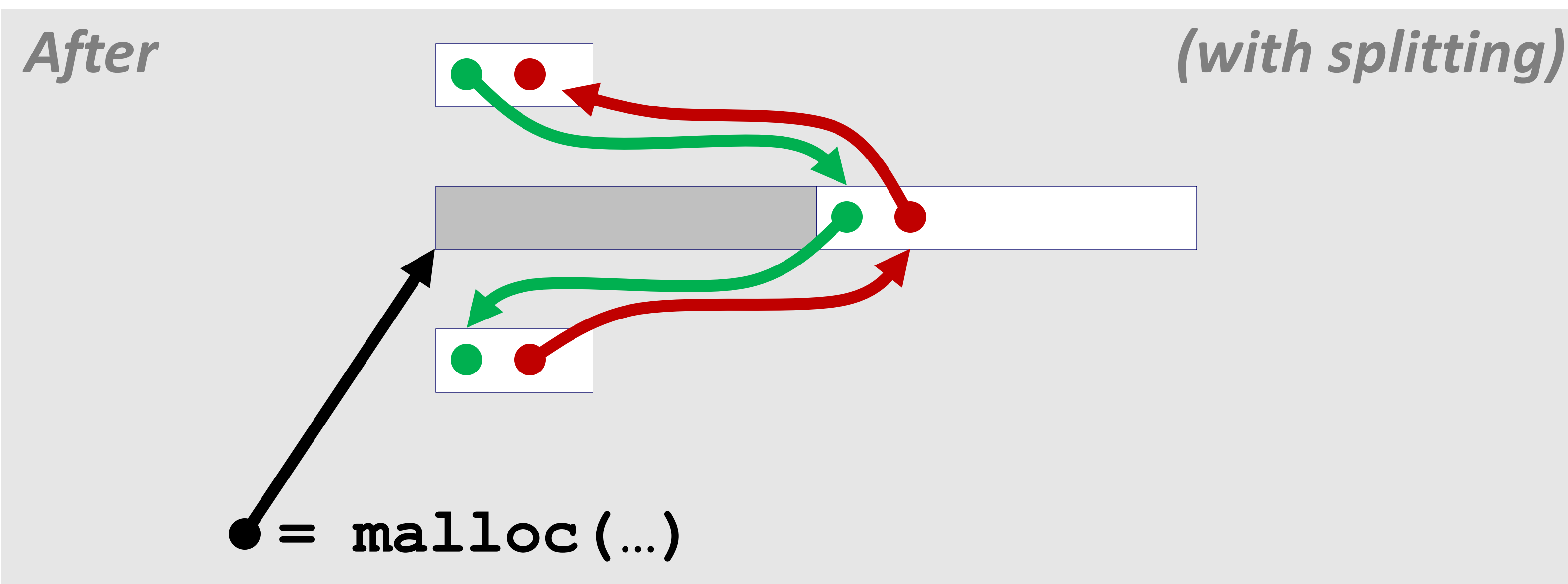
- Physically: blocks can be in any order



Allocating From Explicit Free Lists

conceptual graphic



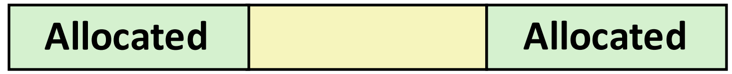


Freeing With Explicit Free Lists

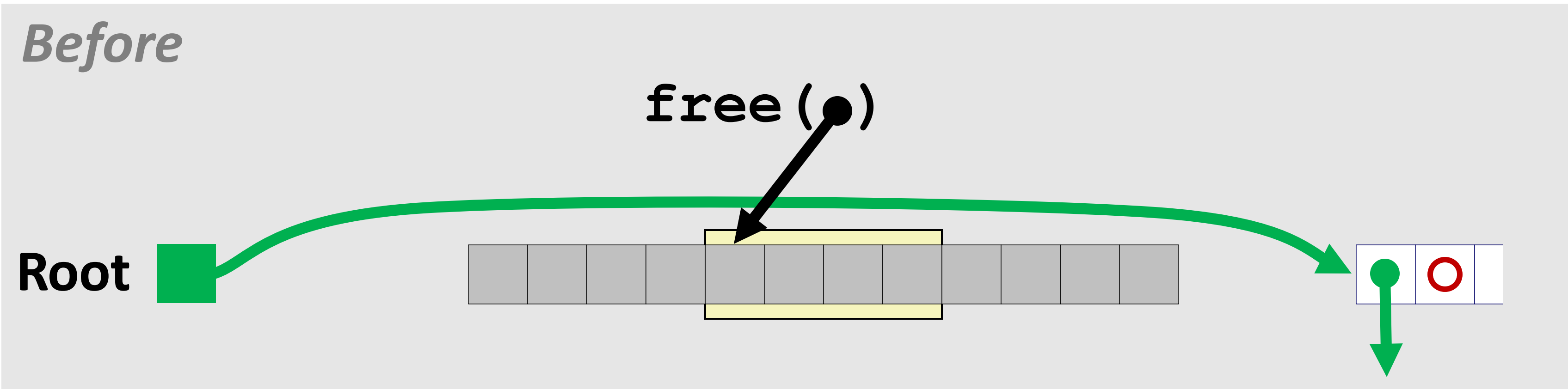
- ***Insertion policy***: **Where in the free list do you put a newly freed block?**
- **Unordered**
  - LIFO (last-in-first-out) policy
    - Insert freed block at the beginning of the free list
  - FIFO (first-in-first-out) policy
    - Insert freed block at the end of the free list
  - ***Pro:*** simple and constant time
  - ***Con:*** studies suggest fragmentation is worse than address ordered
- **Address-ordered policy**
  - Insert freed blocks so that free list blocks are always in address order:

    addr(prev) < addr(curr) < addr(next)
  - ***Con:*** requires search
  - ***Pro:*** studies suggest fragmentation is lower than LIFO/FIFO

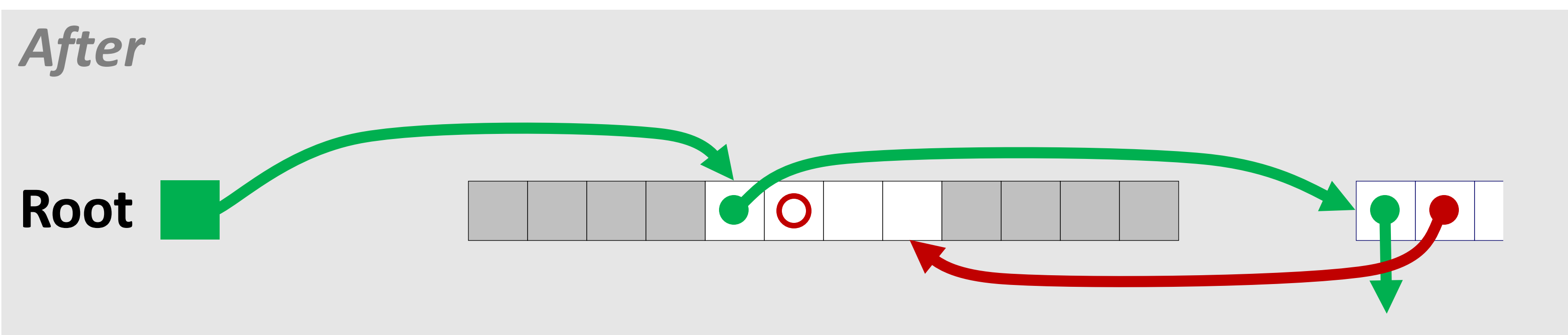
Freeing With a LIFO Policy (Case 1)



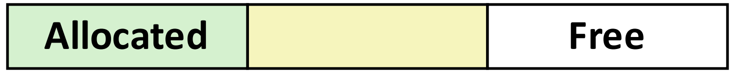
conceptual graphic



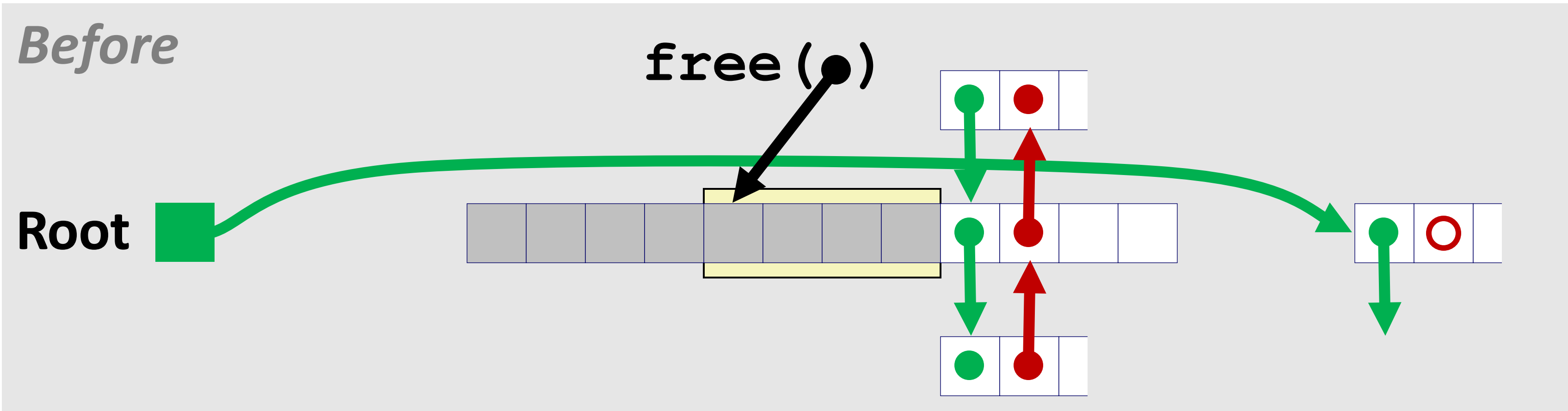
- Insert the freed block at the root of the list



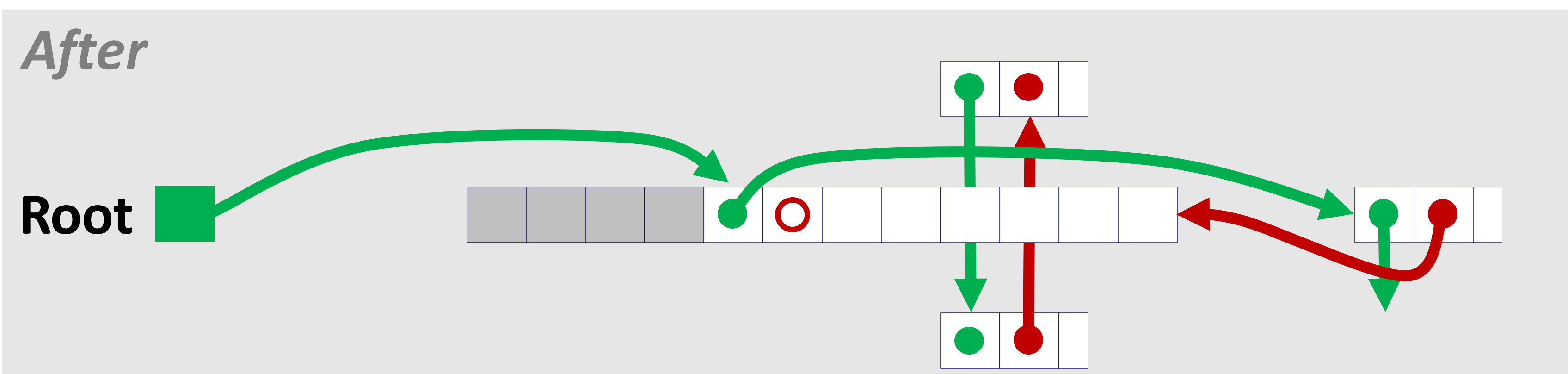
Freeing With a LIFO Policy (Case 2)



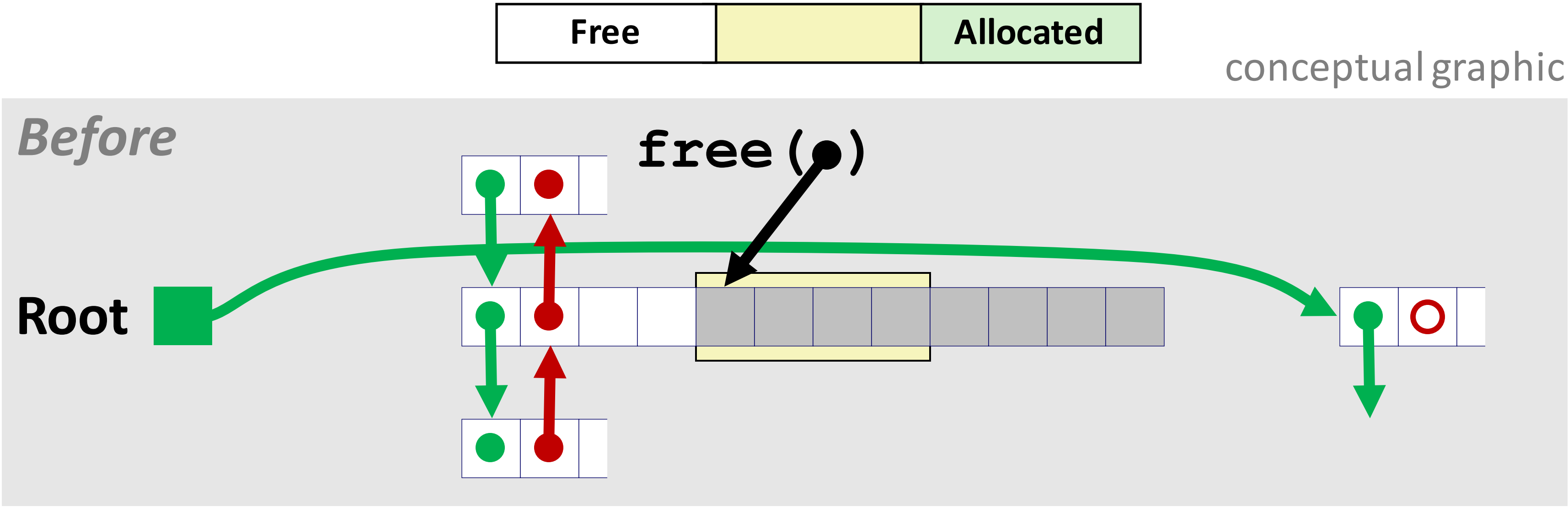
conceptual graphic



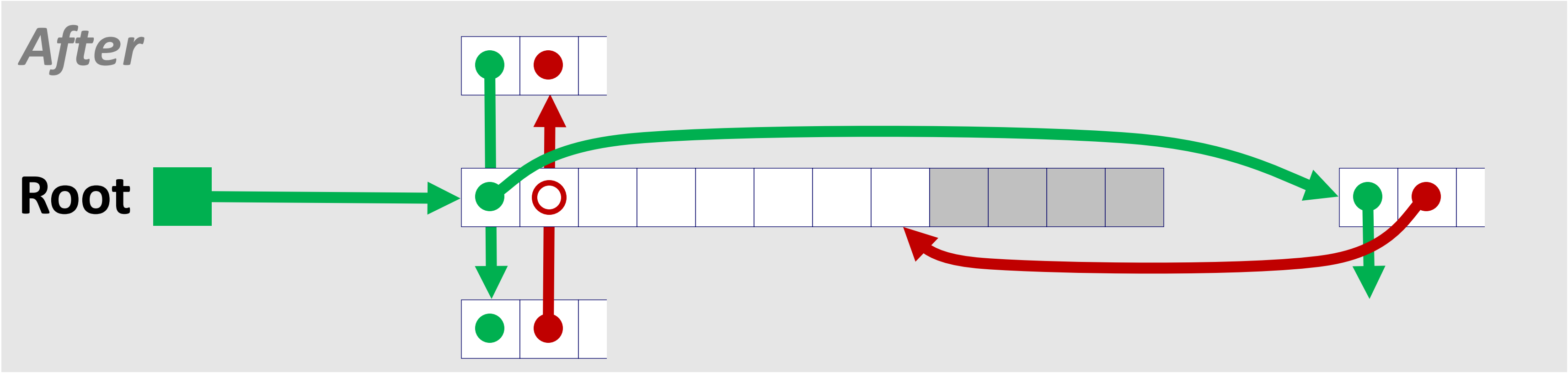
- Splice out adjacent successor block, coalesce both memory blocks, and insert the new block at the root of the list



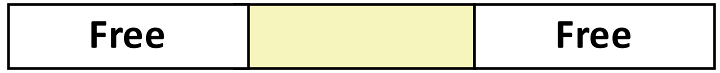
Freeing With a LIFO Policy (Case 3)



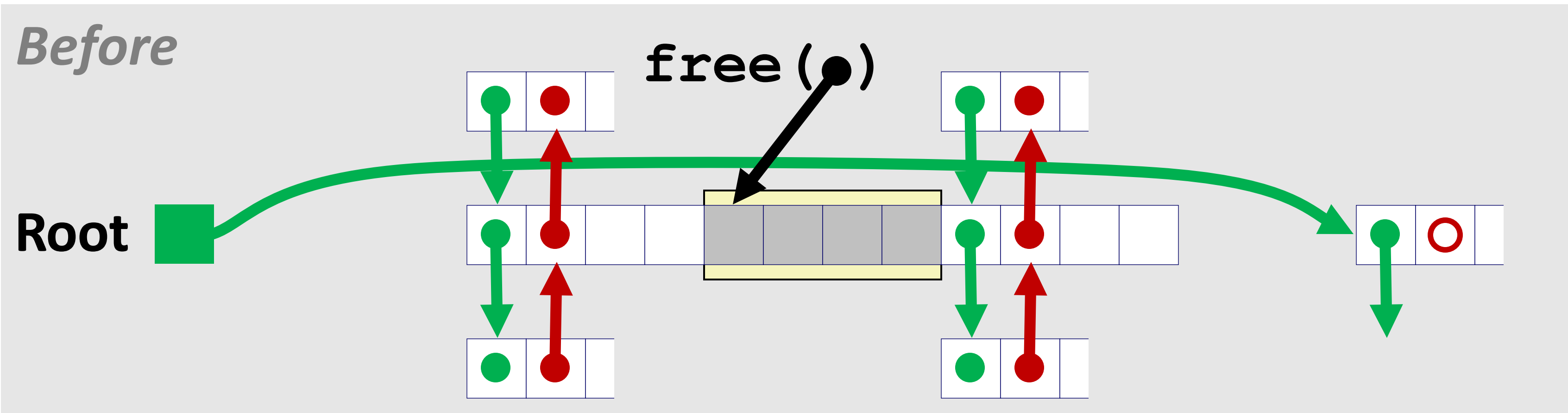
- Splice out adjacent predecessor block, coalesce both memory blocks, and insert the new block at the root of the list



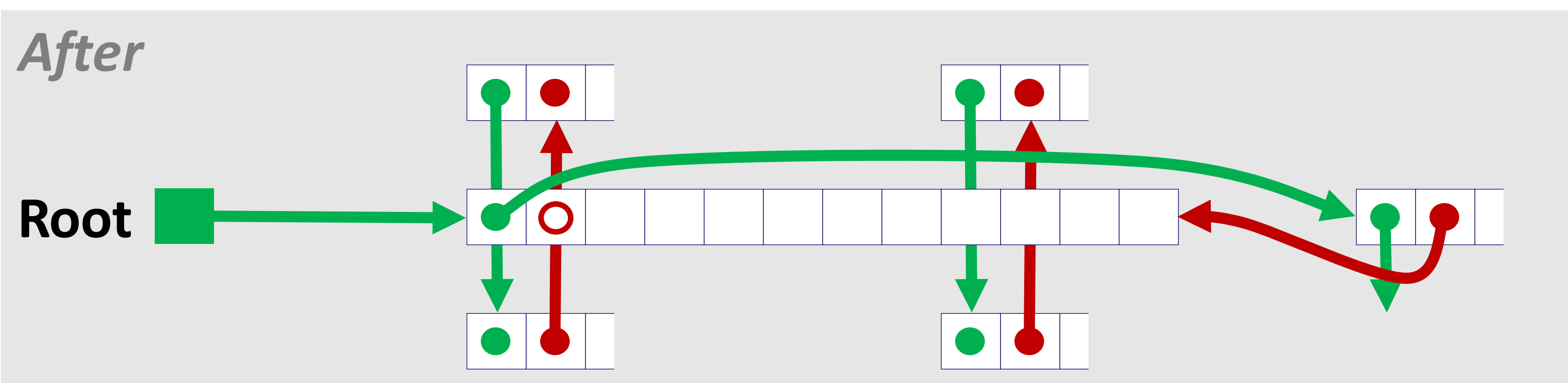
Freeing With a LIFO Policy (Case 4)



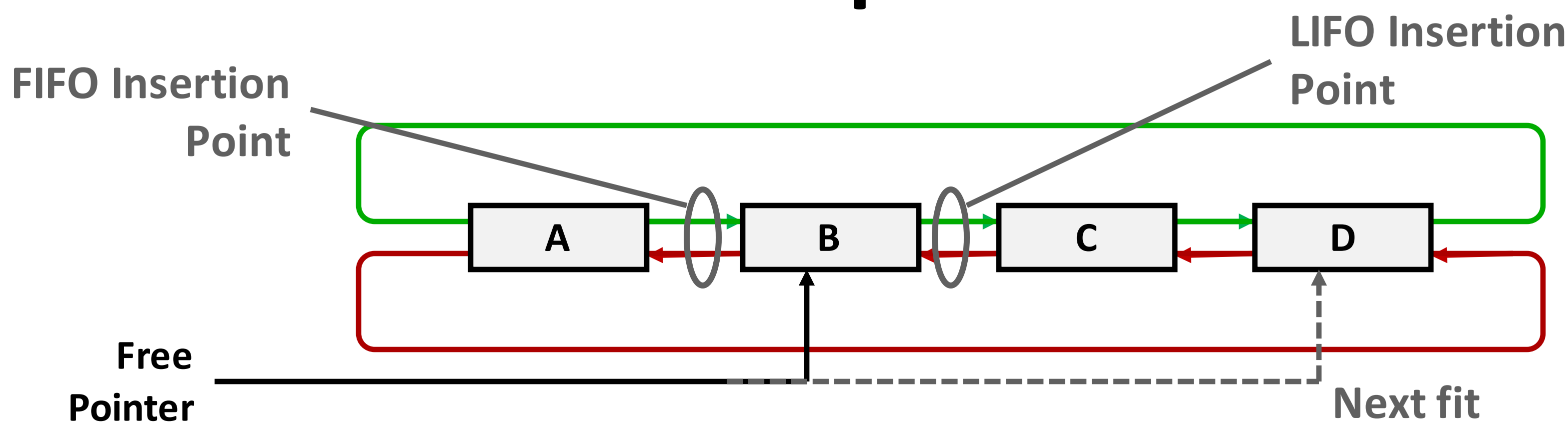
conceptual graphic



- Splice out adjacent predecessor and successor blocks, coalesce all 3 blocks, and insert the new block at the root of the list



Some Advice: An Implementation Trick



- **Use circular, doubly-linked list**
- **Support multiple approaches with single data structure**
- **First-fit vs. next-fit**
  - Either keep free pointer fixed or move as search list
- **LIFO vs. FIFO**
  - Insert as next block (LIFO), or previous block (FIFO)

Explicit List Summary

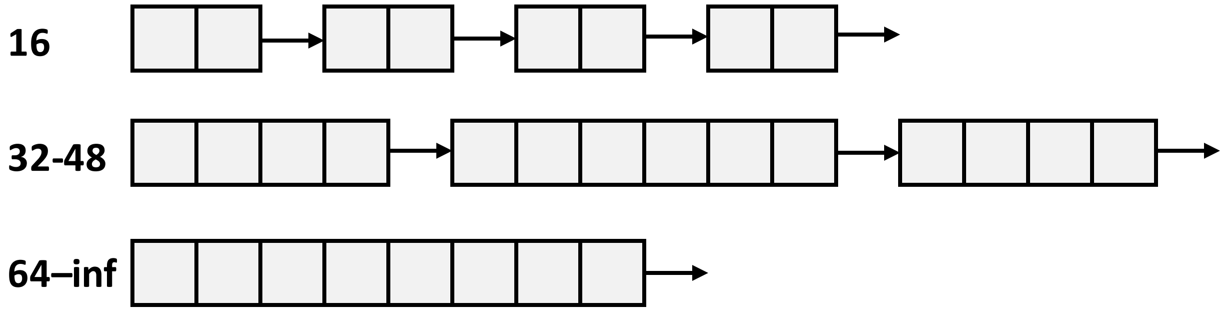
- **Comparison to implicit list:**
  - Allocate is linear time in number of ***free*** blocks instead of ***all*** blocks
    - ***Much faster*** when most of the memory is full
  - Slightly more complicated allocate and free because need to splice blocks in and out of the list
  - Some extra space for the links (2 extra words needed for each block)
    - Does this increase internal fragmentation?

Today

- Basic concepts
- Implicit free lists
- Explicit free lists
- **Segregated free lists**
- Memory-related perils and pitfalls
- *Garbage collection*

Segregated List (Seglist) Allocators

- Each *size class* of blocks has its own free list



- Often have separate classes for each small size
- For larger sizes: One class for each size $[2^i + 1, 2^{i+1}]$

Seglist Allocator

- **Given an array of free lists, each one for some size class**

- **To allocate a block of size *n*:**
  - Search appropriate free list for block of size *m* > *n* (i.e., first fit)
  - If an appropriate block is found:
    - Split block and place fragment on appropriate list
    - If no block is found, try next larger class
  - Repeat until block is found

- **If no block is found:**
  - Request additional heap memory from OS (using **`sbrk()`**)
  - Allocate block of *n* bytes from this new memory
  - Place remainder as a single free block in appropriate size class.

Seglist Allocator (cont.)

- **To free a block:**
  - Coalesce and place on appropriate list

- **Advantages of seglist allocators vs. non-seglist allocators (both with first-fit)**
  - Higher throughput
    - log time for power-of-two size classes vs. linear time
  - Better memory utilization
    - First-fit search of segregated free list approximates a best-fit search of entire heap.
    - Extreme case: Giving each block its own size class is equivalent to best-fit.

More Info on Allocators

- **D. Knuth, *The Art of Computer Programming,* vol 1, 3rd edition, Addison Wesley, 1997**
  - The classic reference on dynamic storage allocation

- **Wilson et al, "*Dynamic Storage Allocation: A Survey and Critical Review*", Proc. 1995 Int'l Workshop on Memory Management, Kinross, Scotland, Sept, 1995.**
  - Comprehensive survey
  - Available from CS:APP student site (csapp.cs.cmu.edu)

Today

- Basic concepts
- Implicit free lists
- Explicit free lists
- Segregated free lists
- **Memory-related perils and pitfalls**
- *Garbage collection*

Memory-Related Perils and Pitfalls

- Dereferencing bad pointers
- Reading uninitialized memory
- Overwriting memory
- Referencing nonexistent variables
- Freeing blocks multiple times
- Referencing freed blocks
- Failing to free blocks

Dereferencing Bad Pointers

- **The classic `scanf` bug**

```
int val;

...

scanf("%d", val);
```

Reading Uninitialized Memory

- Assuming that heap data is initialized to zero

```
/* return y = Ax */
int *matvec(int **A, int *x) {
    int *y = malloc(N*sizeof(int));
    int i, j;

    for (i=0; i<N; i++)
        for (j=0; j<N; j++)
            y[i] += A[i][j]*x[j];
    return y;
}
```

- Can avoid by using `calloc`

Overwriting Memory

- **Allocating the (possibly) wrong sized object**

```
int **p;

p = malloc(N*sizeof(int));

for (i=0; i<N; i++) {
   p[i] = malloc(M*sizeof(int));
}
```

- **Can you spot the bug?**

Overwriting Memory

- Off-by-one errors

```
char **p;

p = malloc(N*sizeof(int *));

for (i=0; i<=N; i++) {
   p[i] = malloc(M*sizeof(int));
}
```

```
char *p;

p = malloc(strlen(s));
strcpy(p,s);
```

Overwriting Memory

- **Not checking the max string size**

```
char s[8];
int i;

gets(s);  /* reads "123456789" from stdin */
```

- **Basis for classic buffer overflow attacks**

Overwriting Memory

- **Misunderstanding pointer arithmetic**

```
int *search(int *p, int val) {

   while (p && *p != val)
      p += sizeof(int);

   return p;
}
```

Overwriting Memory

- **Referencing a pointer instead of the object it points to**

```
int *BinheapDelete(int **binheap, int *size) {
   int *packet;
   packet = binheap[0];
   binheap[0] = binheap[*size - 1];
   *size--;
   Heapify(binheap, *size, 0);
   return(packet);
}
```

- **What gets decremented?**
  - (See next slide)

C operators

<table>
<tr><th>Operators</th><th></th><th>Associativity</th></tr>
<tr><td><code>() [] -> . ++ --</code></td><td>Postfix</td><td>left to right</td></tr>
<tr><td><code>! ~ ++ -- + - * & (type) sizeof</code></td><td>Unary, Unary, Prefix</td><td>right to left</td></tr>
<tr><td><code>* / %</code></td><td></td><td>left to right</td></tr>
<tr><td><code>+ -</code></td><td>Binary</td><td>left to right</td></tr>
<tr><td><code><< >></code></td><td></td><td>left to right</td></tr>
<tr><td><code>< <= > >=</code></td><td></td><td>left to right</td></tr>
<tr><td><code>== !=</code></td><td></td><td>left to right</td></tr>
<tr><td><code>&</code></td><td>Binary</td><td>left to right</td></tr>
<tr><td><code>^</code></td><td></td><td>left to right</td></tr>
<tr><td><code>|</code></td><td></td><td>left to right</td></tr>
<tr><td><code>&&</code></td><td></td><td>left to right</td></tr>
<tr><td><code>||</code></td><td></td><td>left to right</td></tr>
<tr><td><code>?:</code></td><td></td><td>right to left</td></tr>
<tr><td><code>= += -= *= /= %= &= ^= != <<= >>=</code></td><td></td><td>right to left</td></tr>
<tr><td><code>,</code></td><td></td><td>left to right</td></tr>
</table>

- `->`, `()`, and `[]` have high precedence, with `*` and `&` just below
- Unary `+`, `-`, and `*` have higher precedence than binary forms

Source: K&R page 53, updated

Overwriting Memory

- Referencing a pointer instead of the object it points to

```
int *BinheapDelete(int **binheap, int *size) {
   int *packet;
   packet = binheap[0];
   binheap[0] = binheap[*size - 1];
   *size--;
   Heapify(binheap, *size, 0);
   return(packet);
}
```

- Same effect as
  - `size--;`
- Rewrite as
  - `(*size)--;`

Operators	Associativity
() [] -> . ++ --	left to right
! ~ ++ -- + - * & (type) sizeof	right to left
* / %	left to right
+ -	left to right
<< >>	left to right
< <= > >=	left to right
== !=	left to right
&	left to right
^	left to right
|	left to right
&&	left to right
||	left to right
?:	right to left
= += -= *= /= %= &= ^= != <<= >>=	right to left
,	left to right

Referencing Nonexistent Variables

- **Forgetting that local variables disappear when a function returns**

```
int *foo () {
   int val;

   return &val;
}
```

Freeing Blocks Multiple Times

- **Nasty!**

```
x = malloc(N*sizeof(int));
        <manipulate x>
free(x);

y = malloc(M*sizeof(int));
        <manipulate y>
free(x);
```

Referencing Freed Blocks

- Evil!

```
x = malloc(N*sizeof(int));
  <manipulate x>
free(x);
   ...
y = malloc(M*sizeof(int));
for (i=0; i<M; i++)
   y[i] = x[i]++;
```

Failing to Free Blocks (Memory Leaks)

- Slow, long-term killer!

```
foo() {
   int *x = malloc(N*sizeof(int));
   ...
   return;
}
```

Failing to Free Blocks (Memory Leaks)

- Freeing only part of a data structure

```
struct list {
   int val;
   struct list *next;
};

foo() {
   struct list *head = malloc(sizeof(struct list));
   head->val = 0;
   head->next = NULL;
   <create and manipulate the rest of the list>
     ...
   free(head);
   return;
}
```

Dealing With Memory Bugs

- **Debugger: `gdb`**
  - Good for finding bad pointer dereferences
  - Hard to detect the other memory bugs
- **Data structure consistency checker**
  - Runs silently, prints message only on error
  - Use as a probe to zero in on error
- **Binary translator: `valgrind`**
  - Powerful debugging and analysis technique
  - Rewrites text section of executable object file
  - Checks each individual reference at runtime
    - Bad pointers, overwrites, refs outside of allocated block
- **glibc malloc contains checking code**
  - `setenv MALLOC_CHECK_ 3`

Today

- Basic concepts
- Implicit free lists
- Explicit free lists
- Segregated free lists
- Memory-related perils and pitfalls
- ***Garbage collection***

Implicit Memory Management: Garbage Collection

- *Garbage collection:* **automatic reclamation of heap-allocated storage—application never has to explicitly free memory**

```
void foo() {
   int *p = malloc(128);
   return; /* p block is now garbage */
}
```

- **Common in many dynamic languages:**
  - Python, Ruby, Java, Perl, ML, Lisp, Mathematica

- **Variants ("conservative" garbage collectors) exist for C and C++**
  - However, cannot necessarily collect all garbage

Garbage Collection

- **How does the memory manager know when memory can be freed?**
  - In general we cannot know what is going to be used in the future since it depends on conditionals
  - But we can tell that certain blocks cannot be used if there are no pointers to them

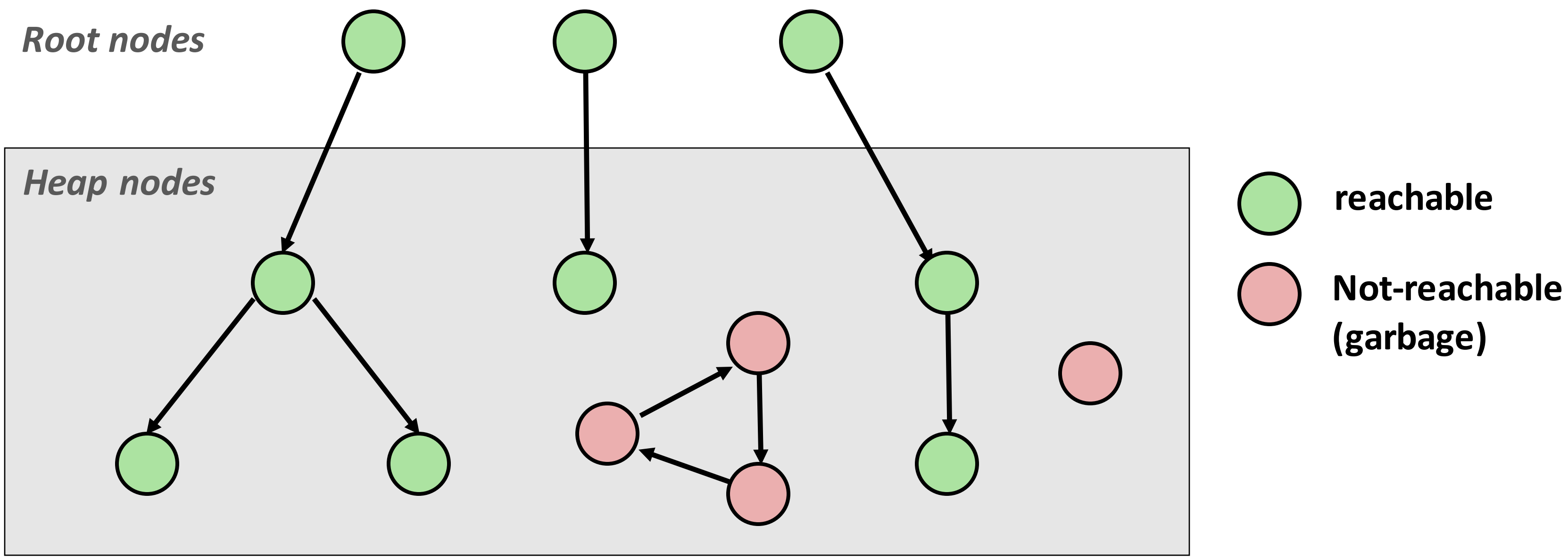
- **Must make certain assumptions about pointers**
  - Memory manager can distinguish pointers from non-pointers
  - All pointers point to the start of a block
  - Cannot hide pointers
    (e.g., by coercing them to an `int`, and then back again)

Classical GC Algorithms

- **Mark-and-sweep collection (McCarthy, 1960)**
  - Does not move blocks (unless you also "compact")
- **Reference counting (Collins, 1960)**
  - Does not move blocks (not discussed)
- **Copying collection (Minsky, 1963)**
  - Moves blocks (not discussed)
- **Generational Collectors (Lieberman and Hewitt, 1983)**
  - Collection based on lifetimes
    - Most allocations become garbage very soon
    - So focus reclamation work on zones of memory recently allocated
- **For more information:**
  Jones and Lin, "*Garbage Collection: Algorithms for Automatic Dynamic Memory*", John Wiley & Sons, 1996.

Memory as a Graph

- **We view memory as a directed graph**
  - Each block is a node in the graph
  - Each pointer is an edge in the graph
  - Locations not in the heap that contain pointers into the heap are called ***root*** nodes (e.g. registers, locations on the stack, global variables)

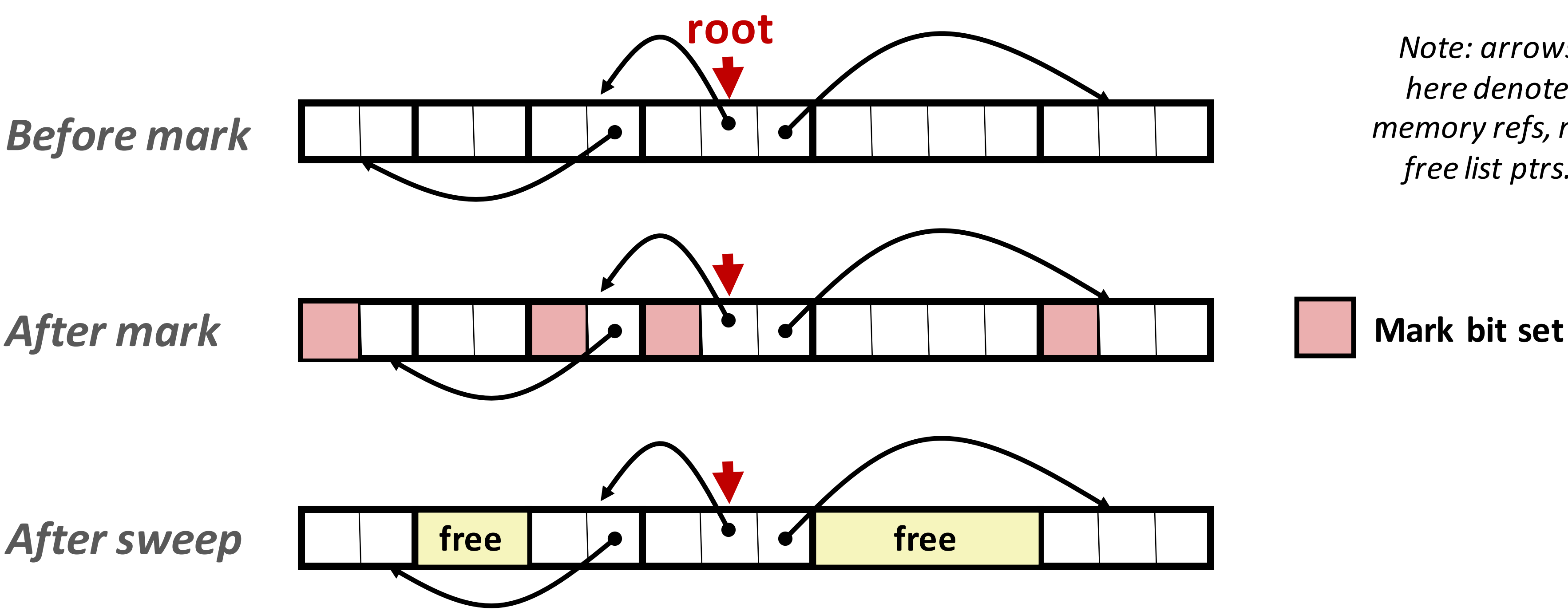


A node (block) is *reachable* if there is a path from any root to that node.

Non-reachable nodes are *garbage* (cannot be needed by the application)

Mark and Sweep Collecting

- **Can build on top of malloc/free package**
  - Allocate using **`malloc`** until you “run out of space”
- **When out of space:**
  - Use extra ***mark bit*** in the head of each block
  - ***Mark:*** Start at roots and set mark bit on each reachable block
  - ***Sweep:*** Scan all blocks and free blocks that are not marked



Note: arrows here denote memory refs, not free list ptrs.

Assumptions For a Simple Implementation

- **Application**
  - `new(n)`: returns pointer to new block with all locations cleared
  - `read(b,i)`: read location `i` of block `b` into register
  - `write(b,i,v)`: write `v` into location `i` of block `b`

- **Each block will have a header word**
  - addressed as `b[-1]`, for a block `b`
  - Used for different purposes in different collectors

- **Instructions used by the Garbage Collector**
  - `is_ptr(p)`: determines whether `p` is a pointer
  - `length(b)`: returns the length of block `b`, not including the header
  - `get_roots()`: returns all the roots

Mark and Sweep Pseudocode

Mark using depth-first traversal of the memory graph

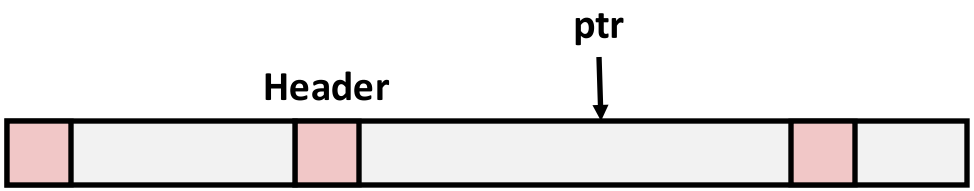
```
ptr mark(ptr p) {
   if (!is_ptr(p)) return;            // if not pointer -> do nothing
   if (markBitSet(p)) return;         // if already marked -> do nothing
   setMarkBit(p);                     // set the mark bit
   for (i=0; i < length(p); i++)      // for each word in p's block
     mark(p[i]);                      //  make recursive call
   return;
}
```

Sweep using lengths to find next block

```
ptr sweep(ptr p, ptr end) {
   while (p < end) {                  // for entire heap
      if markBitSet(p)                // did we reach this block?
         clearMarkBit();              //  yes -> so just clear mark bit
      else if (allocateBitSet(p))     // never reached: is it allocated?
         free(p);                     //  yes -> its garbage, free it
      p += length(p);                 // goto next block
}
```

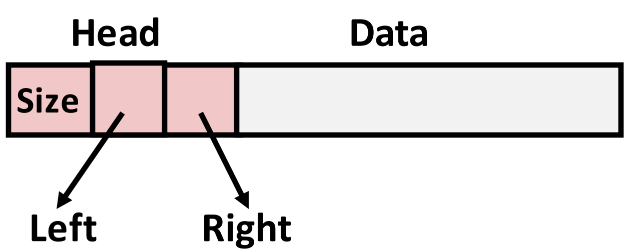
Conservative Mark & Sweep in C

- **A "conservative garbage collector" for C programs**
  - `is_ptr()` determines if a word is a pointer by checking if it points to an allocated block of memory
  - But, in C pointers can point to the middle of a block



Assumes ptr in middle can be used to reach anywhere in the block, but no other block

- **To mark header, need to find the beginning of the block**
  - Can use a balanced binary tree to keep track of all allocated blocks (key is start-of-block)
  - Balanced-tree pointers can be stored in header (use two additional words)



Left: smaller addresses
Right: larger addresses

Supplemental slides

C Pointer Declarations: Test Yourself!

`int *p`	p is a pointer to int
`int *p[13]`	p is an array[13] of pointer to int
`int *(p[13])`	p is an array[13] of pointer to int
`int **p`	p is a pointer to a pointer to an int
`int (*p)[13]`	p is a pointer to an array[13] of int
`int *f()`	f is a function returning a pointer to int
`int (*f)()`	f is a pointer to a function returning int
`int (*(*x[3])())[5]`	x is an array[3] of pointers to functions returning pointers to array[5] of ints

Source: K&R Sec 5.12

Parsing: `int (*(*f())[13])()`

`int (*(*f())[13])()`	`f`
`int (*(*f())[13])()`	`f is a function`
`int (*(*f())[13])()`	`f is a function that returns a ptr`
`int (*(*f())[13])()`	`f is a function that returns a ptr to an array of 13`
`int (*(*f())[13])()`	`f is a function that returns a ptr to an array of 13 ptrs`
`int (*(*f())[13])()`	`f is a function that returns a ptr to an array of 13 ptrs to functions returning an int`