CSE 351 Section 9

Dynamic Memory Allocation

Dynamic Memory

- Dynamic memory is memory that is “requested” at run-time

- Solves two fundamental dilemmas:
  - How can we control the amount memory used based on run time conditions?
  - How can we control the lifetime of memory?

- Important to understand how dynamic memory works:
  - We want to use allocators efficiently
  - Can result in many errors if used incorrectly

Example Program: why dynamic allocation?

Goal: Dynamically add/remove/sort nodes in a large linked list

Option 1: Without dynamically-allocated memory:

- Use the `mmap()` or equivalent system call to map a virtual address to a page of physical memory
  - This essentially gives you a page of memory to use
- Use pointer addition/subtraction to segment the page into linked list nodes
- Manage which regions of the page have been used
- Request a new page when that one fills up
- MESSY! NOBODY DOES THIS!

Example Program: why dynamic allocation?

<u>Goal:</u> Dynamically add/remove/sort nodes in a large linked list

Option 2: With dynamically-allocated memory:

- Use `malloc()` from the C standard library to request a node-sized chunk of memory for every node in the linked list
- When removing a node, simply carry out the necessary pointer manipulation and use `free()` to allow that space to be used for something else
- You will come to love `malloc()` because it does all the heap management for you…
- …But for the next week it may be more annoying because you are in charge of implementing it

`malloc()`

- Provided to you by the C standard library using `#include <stdlib.h>`
- Programs allocate blocks from the heap by calling the `malloc()` function
- The heap is the memory region dedicated to dynamic storage
- Run `man malloc` in a linux terminal for more information!

- How to use `malloc()`:
  - Takes a `size_t` representing the number of bytes requested
  - Returns a `void*` pointing to the start of the block or `NULL` if there was an error

```
int* array = (int*) malloc(10 * sizeof(int));
```

`free()`

- Also part of the C standard library
- Programmers also need to be able to “free up” dynamically-allocated memory that they no longer need
- Simply pass free() a pointer to a block received from malloc()
- Using free() allows for more efficient heap usage
    - Later calls to malloc() will be able to re-use that block

```
int* array = (int*) malloc(10 * sizeof(int));
...
free(array);
```

`free()`

Double-free

- This occurs when you free the same block twice
- It usually results in a segmentation fault
    - It will become more apparent why when you learn how malloc() is implemented

```
int* array = (int*) malloc(10 * sizeof(int));
...
free(array);
free(array); // Double free...ouch...
```

The Heap

What does the heap look like exactly?

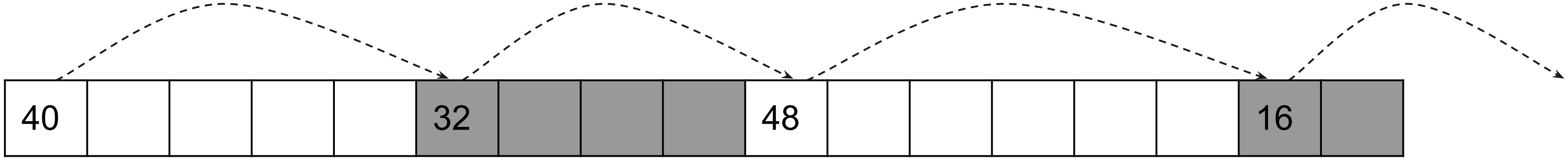
- Imagine a giant contiguous region of memory

- This region is segmented into free blocks and used blocks

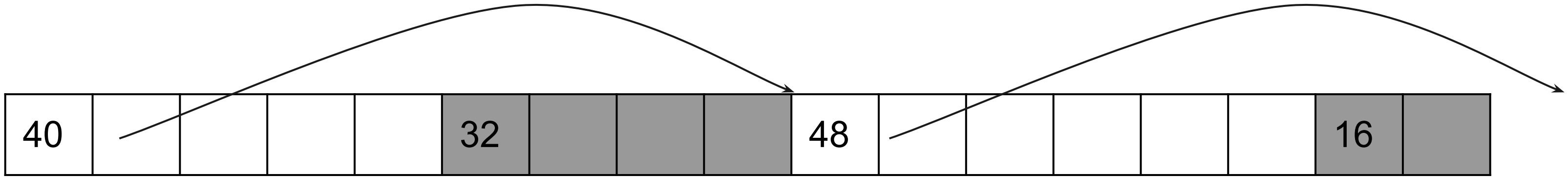
- Consecutive free blocks form what we call a “free list”
- Two types of free lists:
  - Implicit: use block sizes to traverse the heap looking for a free block
  - Explicit: use doubly linked list of free blocks to find a free block

Implicit vs. Explicit Free List

Implicit: Using sizes to traverse blocks, checking to see if each block is allocated



Explicit: Using pointers to create linked list of free blocks



Block Header Format

- Each block needs to indicate its size, if it is used, and if the prev block is used
- Could use two 8-byte fields, but wastes a lot of space
- Standard trick:
    - Since size will always be aligned to a certain multiple of 2, some of the lower order bits will be 0 (for instance if all sizes are multiples of 8, the lowest 3 bits will always be 0)
    - Can store additional tag information in those lowest bits
    - Just need to remember to mask them away when reading the size (see the SIZE macro in the lab5 starter code!)

Block Header Format

- Every block has a 8-byte (64-bit) header
- Three of those bits are used for tags
  - LSB is set if the block is currently used (not in the free list)
  - Next bit (to the left) is set if the block preceding it in memory is used
  - The third bit is not used
- The upper 61 bits store the size of the block
- This 64-bit value is also referred to as the block's "sizeAndTags"

```
+--------------------------------------------+
| 63 | 62 | 61 | 60 |  . . .| 3 | 2 | 1 | 0 |
+--------------------------------------------+
```

Size

X

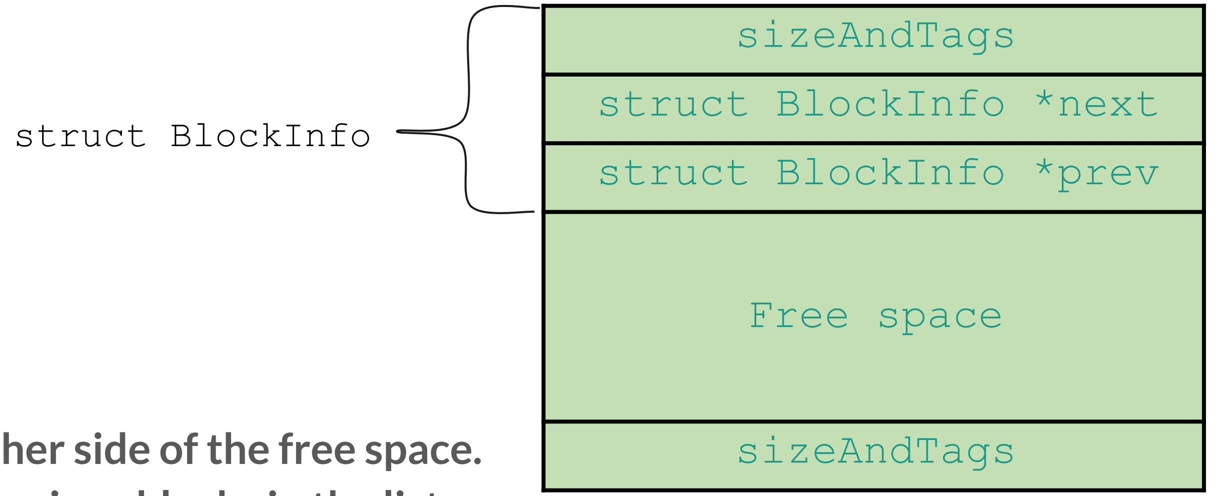
Prev Used?

Used?

Free Blocks

A free block has:

- A sizeAndTags value on either side of the free space.
- Pointers to the next and previous blocks in the list
  Remember, the blocks are not necessarily in address order, so the pointers can point to blocks anywhere in the heap
- Each free block is a BlockInfo struct followed by free space and the boundary tag (footer)



struct BlockInfo

sizeAndTags

struct BlockInfo *next

struct BlockInfo *prev

Free space

sizeAndTags

```
struct BlockInfo {
  size_t sizeAndTags;
  struct BlockInfo *next;
  struct BlockInfo *prev;
};
```

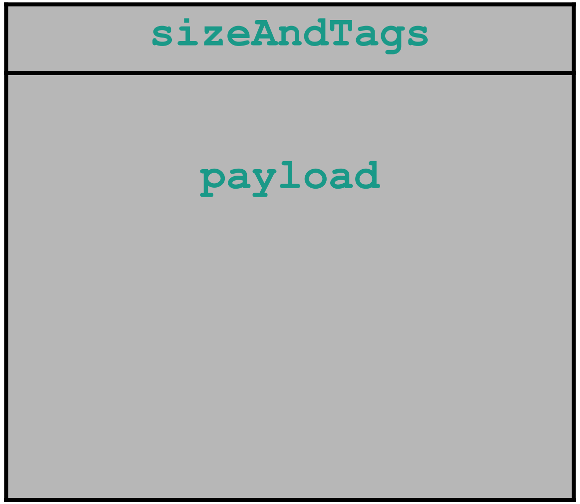
Used Blocks

- Used blocks only have a sizeAndTags, followed by the payload
- The payload is the actual block of memory returned to a user program that invokes malloc()

Example:

```
int* a = (int*) malloc(10 * sizeof(int));
```

`a` points to the payload (not the start of the block!)



Walkthrough of Example Heap

Initial Heap

Note FREE_LIST_HEAD always points to the first block in the free list

Walkthrough of Example Heap

void *ptr1 = malloc(32);

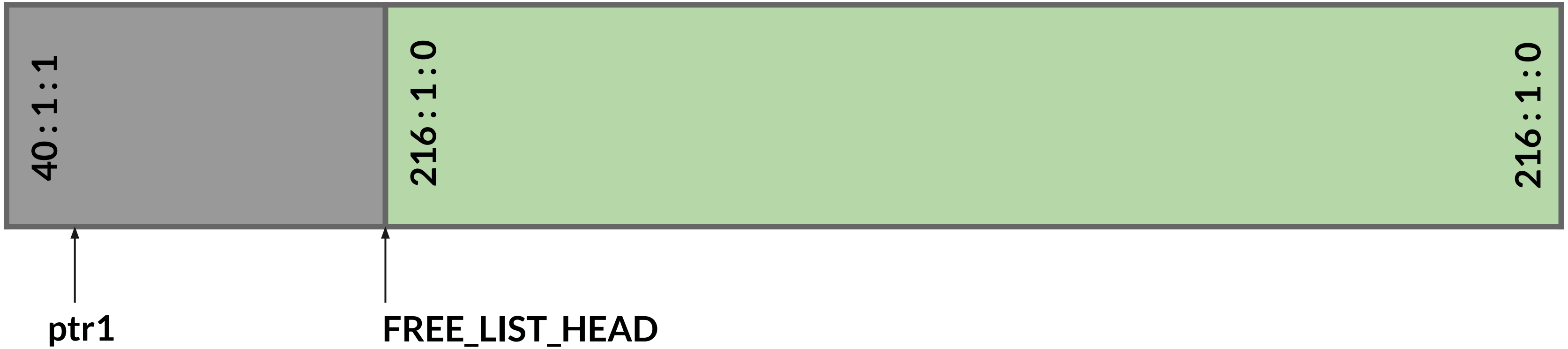
- Need to search free list to find a block big enough for 40 (32 + header) bytes

FREE_LIST_HEAD

Walkthrough of Example Heap

void *ptr1 = malloc(32);

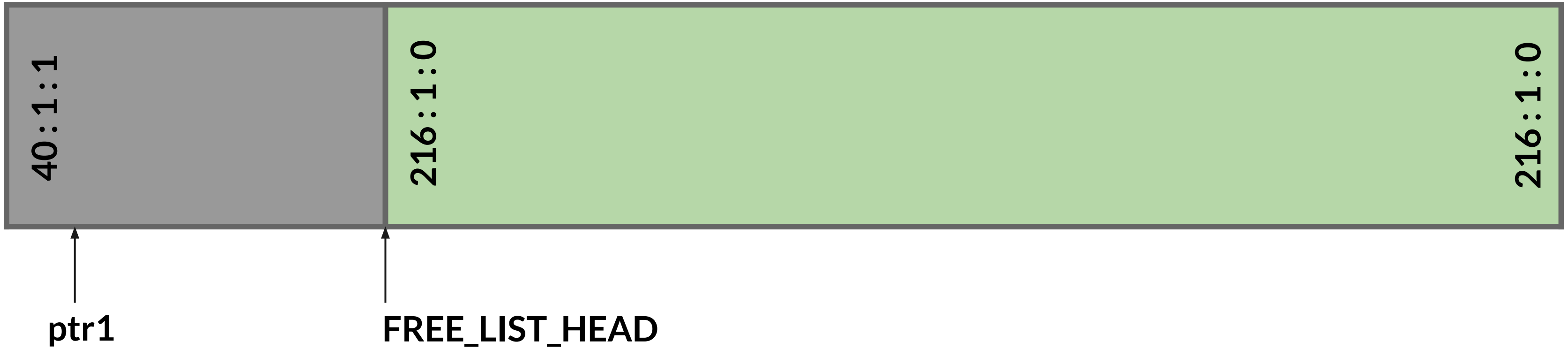
- Note that ptr1 points to the start of the payload, NOT the start of the block
- The initially 256 byte free block is split to maximize memory usage!



Walkthrough of Example Heap

void *ptr2 = malloc(16);

- Only need a block of 24 (16 + header) bytes, but what if we needed to free it later… think about what the minimum block size needs to be



Walkthrough of Example Heap

void *ptr2 = malloc(16);

- Need at least 32 bytes to create a free block, meaning we must allocate at least this much for a used block!

Walkthrough of Example Heap

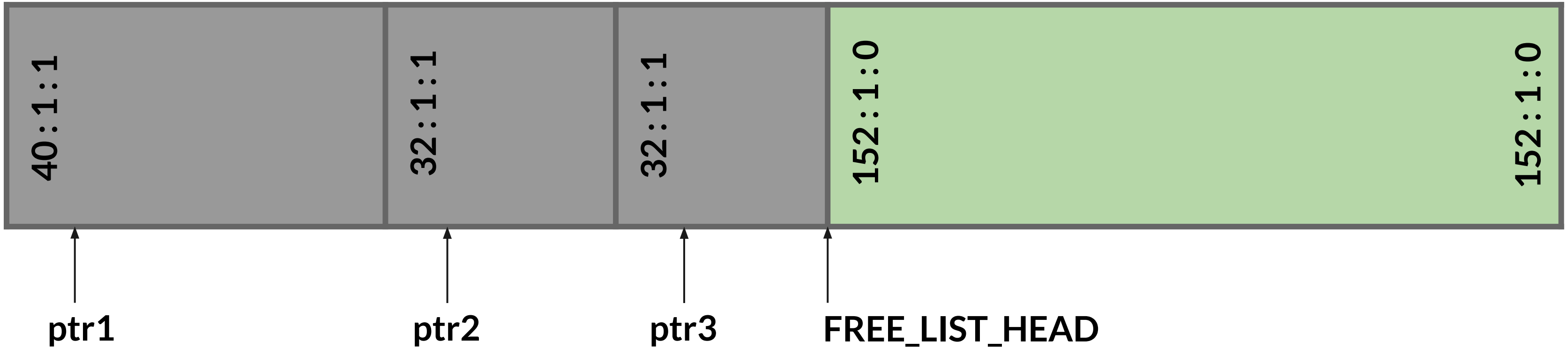
`void *ptr3 = malloc(24);`

- Same procedure as before

Walkthrough of Example Heap

void *ptr3 = malloc(24);

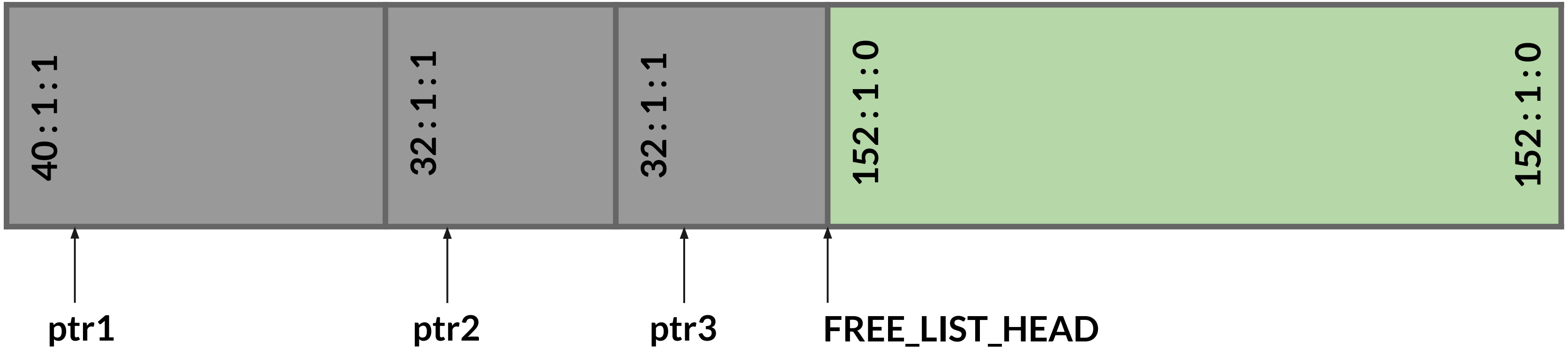
- Same procedure as before



Walkthrough of Example Heap

free(ptr2);

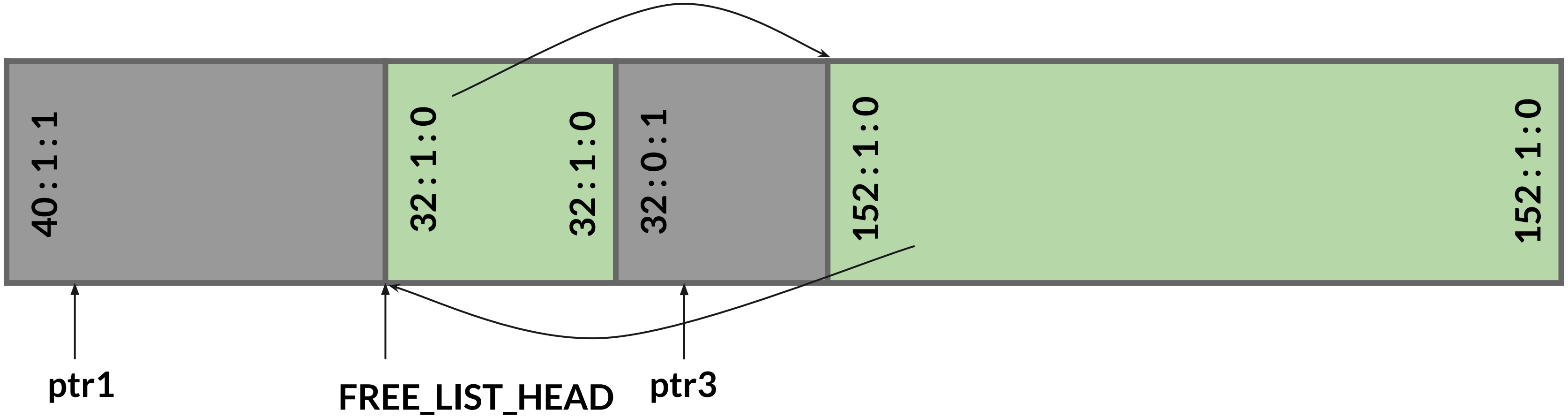
- Now we need to free a block!



Walkthrough of Example Heap

free(ptr2);

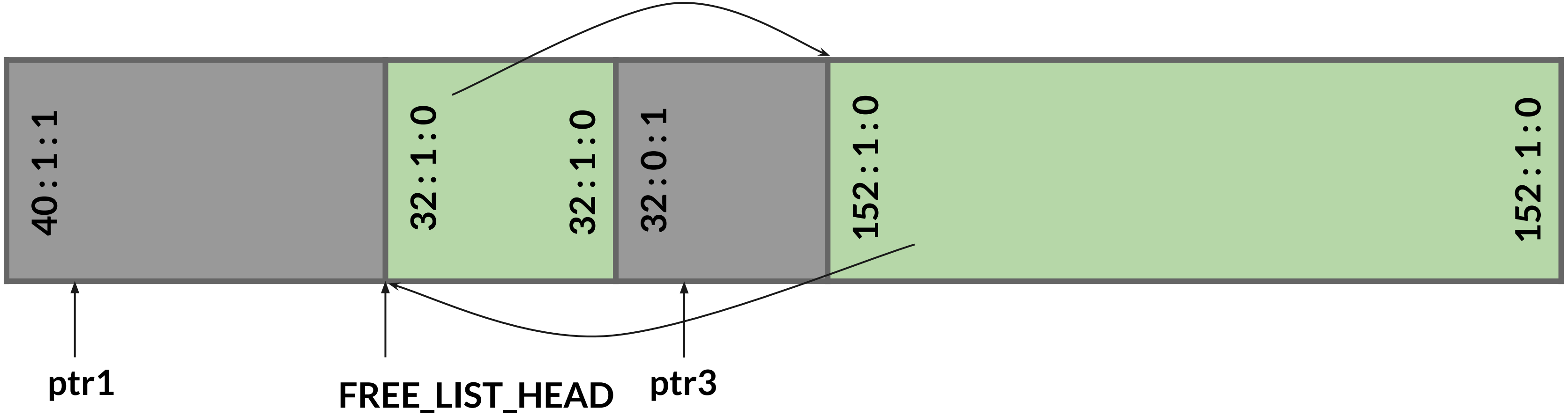
- Need to insert block allocated for ptr2 into the free list (and update tags!)
- Which tags get updated?



Walkthrough of Example Heap

free(ptr3);

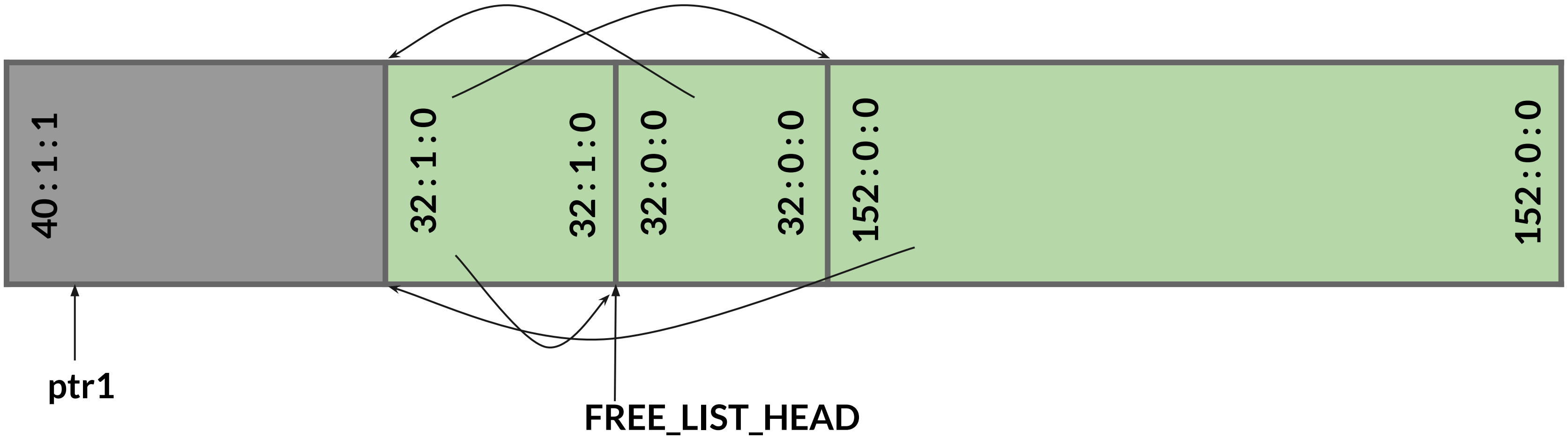
- Same thing as before, except now the pointers get really messy...



Walkthrough of Example Heap

free(ptr3);

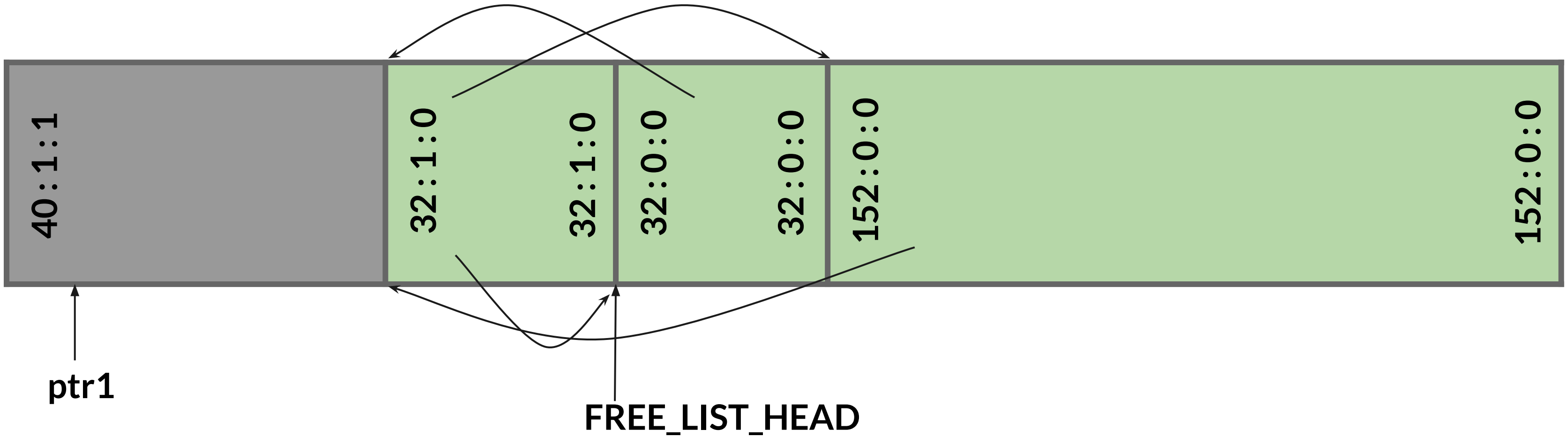
- Same thing as before, except now the pointers get really messy…
  - next pointers are the ones higher up in the diagram, prev lower down...



Walkthrough of Example Heap

free(ptr3);

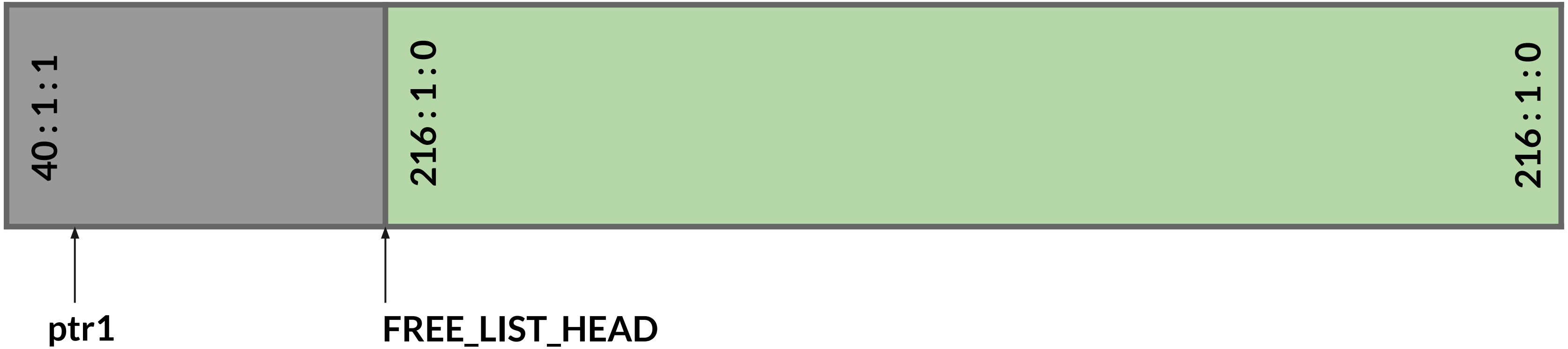
- Good enough? What happens if user calls malloc(200)?



Walkthrough of Example Heap

free(ptr3);

- Coalesce neighboring free blocks into one large free block!
- Allows for larger future mallocs, can still split later for smaller chunks



Lab 5

- You get to implement malloc() and free()!
- Less overwhelming than it may sound, we give you many functions already including:
  - `searchFreeList()`
  - `insertFreeBlock()`
  - `removeFreeBlock()`
  - `coalesceFreeBlock()`
  - `requestMoreSpace()`
  - see spec/starter code for full list!

Some notes about implementing `malloc()`

- Figure out how big a block you need

- Call `searchFreeList()` to get a free block that is large enough
  - NOTE: If you request 16 bytes, it might give you a block that is 500 bytes

- Remove that block from the list
  - Might have to splice into a smaller/bigger chunk (see NOTE above)

- Update size + tags appropriately (do neighbor blocks need updating?)

- Return a pointer to the payload of that block

Some notes about implementing `free()`

- Remember, the pointer you are passed is to the payload!
- Convert the given used block into a free block
- Insert it into the free list
- Update size + tags appropriately (do neighbor blocks need updating?)
- Coalesce if necessary by calling `coalesceFreeBlock()`

C Macros

Pre-compile time “find and replace” your code text

Defining constants:

- `#define NUM_ENTRIES 100`
    - OK

Defining simple operations:

- `#define twice(x) 2*x`
    - Not OK, `twice(x+1)` becomes `2*x+1` because preprocessor uses naive find and replace
- `#define twice(x) (2*(x))`
    - OK, now `twice(x+1)` becomes `2*(x+1)`
    - Always wrap in parentheses!

Why even use Macros?

- Why macros?
    - Create more readable/reusable code for constants
    - “Faster” than function calls
    - In malloc: Quick access to header information (payload size, valid)
- Drawbacks
    - Less expressive than functions
    - Arguments are not typechecked, local variables
    - They can easily lead to errors that are more difficult to find (see prev slide)

Some Lab 5 Provided Macros

- `UNSCALED_POINTER_ADD(p,x)` Add without using "pointer arithmetic"
- `UNSCALED_POINTER_SUB(p,x)` Subtract without using "pointer arithmetic"
- `MIN_BLOCK_SIZE` The size of the smallest block that is safe to allocate
- `SIZE(x)` Gets the size from 'sizeAndTags'
- `TAG_USED` Mask for the used tag
- `TAG_PRECEDING_USED` Mask for the preceding used tag
- ...
- There are lots more, don't forget to use them!
  - They will absolutely make your life easier
  - Part of good C style (which will be part of this assignment's grade)

Getting Started Lab5:

- If you are struggling to understand where to get started, read through coalesceFreeBlock()
  - Understanding the details of this function will provide clarity on the general structure you are manipulating
- Make sure you use the provided macros!
  - They work, so it will help minimize bugs
  - More readable code