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

- Dynamically adds/removes/sorts nodes in a large linked list
- 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
    - Get fired from your job
    - MESSY! NOBODY DOES THIS!

Example Program

- 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
  - Keep your job!
- You will come to love `malloc()` because it does all the heap management for you…
- …But for the next week you will hate it, 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
- 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
  - Subsequent calls to `malloc()` will be able to re-use that block
- Double-free
  - This occurs when you free the same block twice
  - It usually results in a segmentation fault
  - We will see why that might occur when we look at how `malloc()` is implemented

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
  - The free blocks form an explicit, doubly-linked list
  - To allocate a block, we remove it from the list and return a pointer to it
  - To free a block, we insert it back into the list

Block Header

- Every block has a 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"

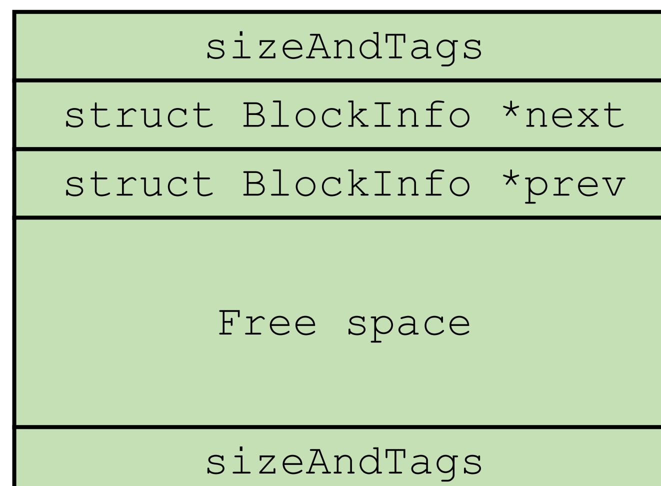
```
+--------------------------------------------+
| 63 | 62 | 61 | 60 |  . . . .  | 2 | 1 | 0 |
+--------------------------------------------+
  ^                                       ^
high bit                              low bit
```

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

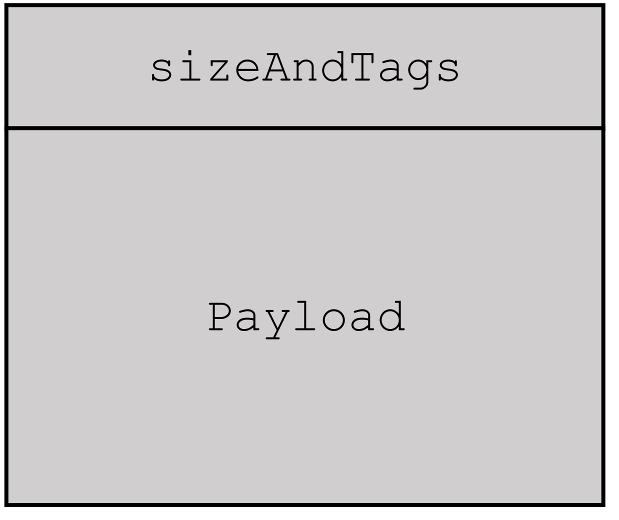


Used Blocks

- 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()`

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

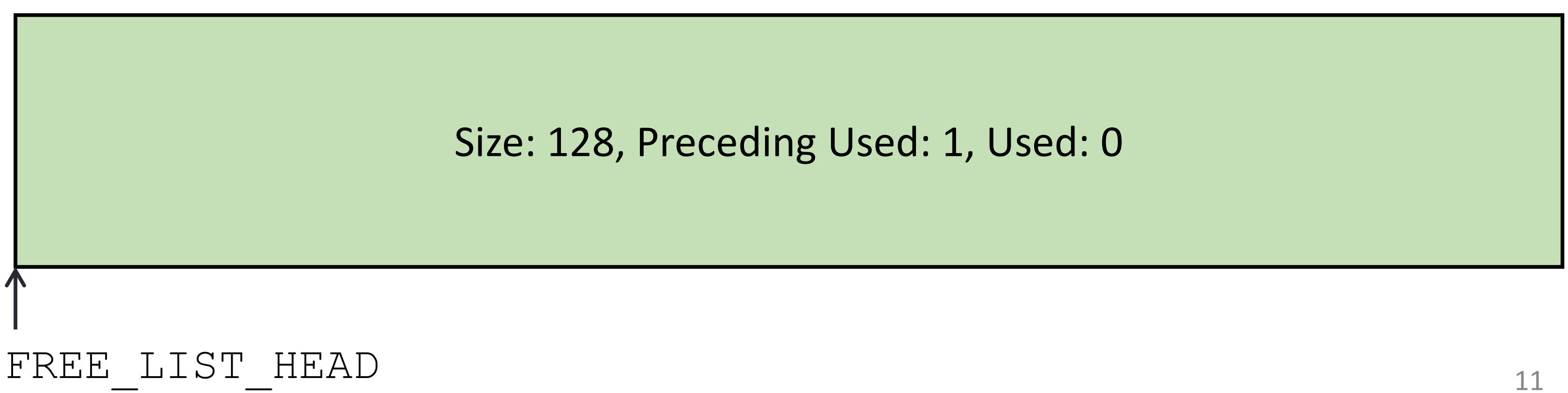
- This means `a` points to the payload



Putting it All Together

Initial 128-byte heap layout:

- `BlockInfo* FREE_LIST_HEAD` always points to the first block in the free list
- The `BlockInfo` for this free block would look like this:
  - sizeAndTags: 130 (128 + 0x2)
  - next: null
  - prev: null
- The PrecedingUsed tag is set because the previous block is not free (comes into play when we look at coalescing later)

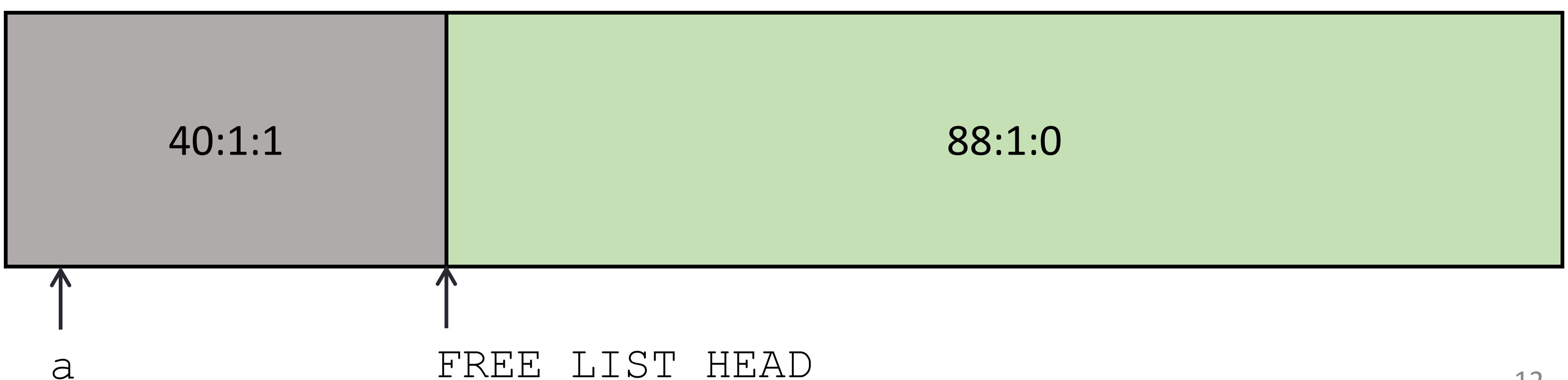


Allocating Blocks

Note: "a" does not point to sizeAndTags! Points to payload, or where the "next" pointer would be stored in the BlockInfo

`void* a = malloc(32)`

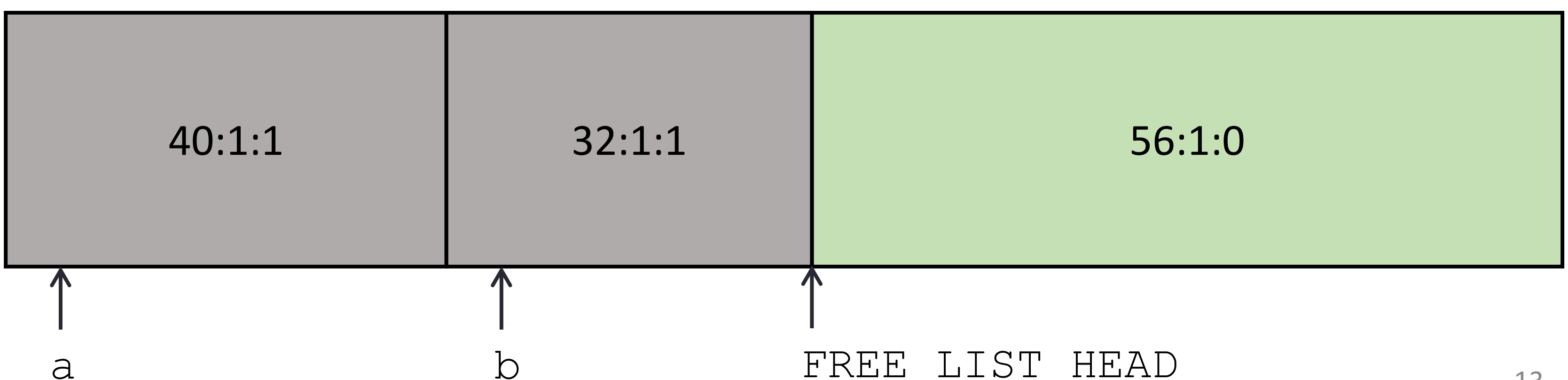
- Searches the free list for a block big enough
- The first (and only) block is 128 bytes, which will work
- Bad implementation: return a 120-byte payload (8-byte header)
- Good implementation: split off 40 bytes, return a 32-byte payload



Allocating Blocks

```
void* b = malloc(16)
```

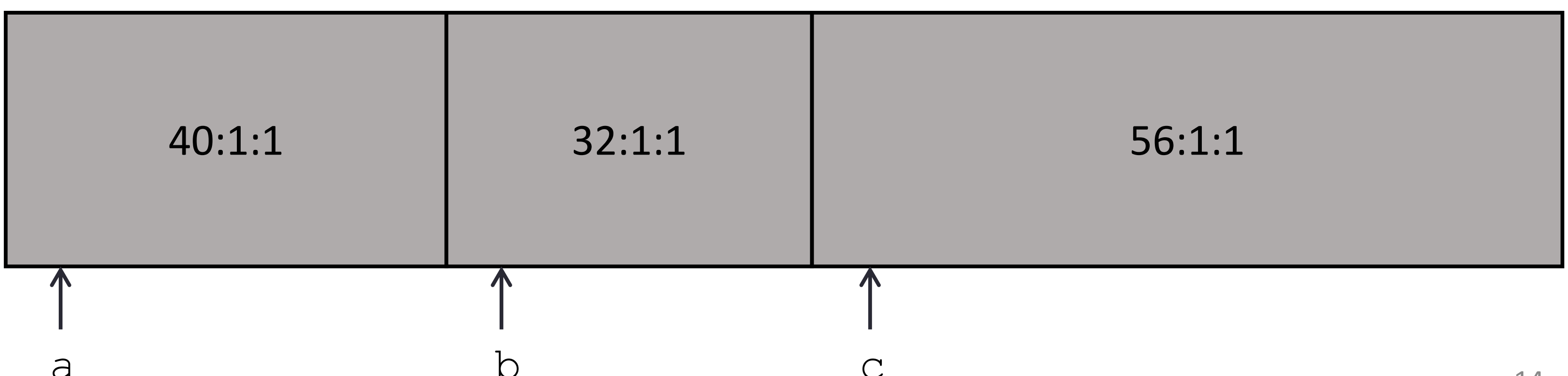
- Only needs a block of 16 + 8 = 24 bytes, but if we were to free this block in the future, we would need at least 32 bytes to create a free block.
- The minimum block size is 32 bytes



Allocating Blocks

```
void* c = malloc(48)
```

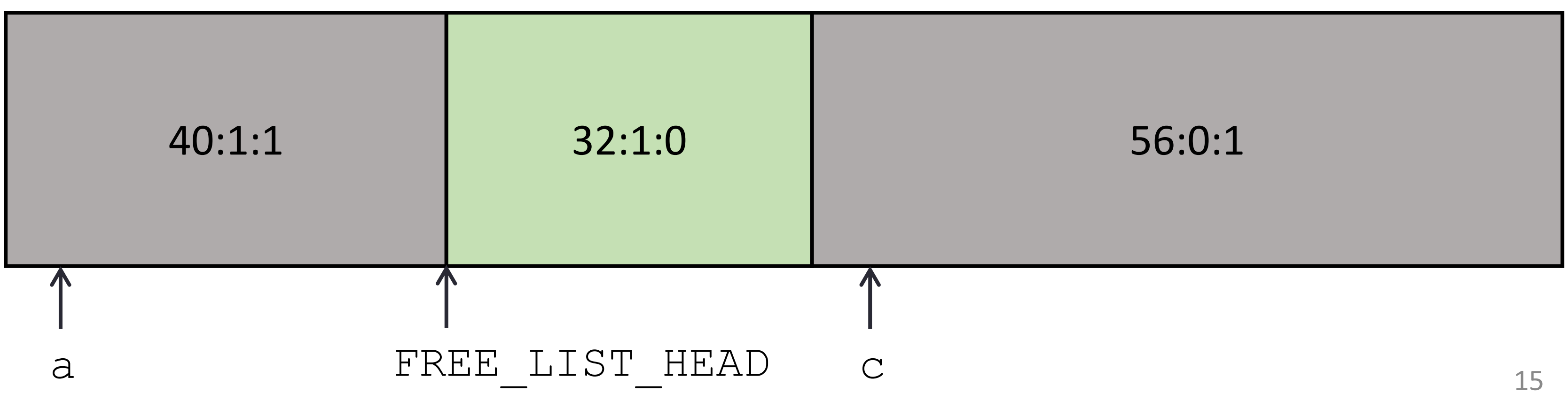
- FREE_LIST_HEAD = null



Freeing Blocks

`free(b)`

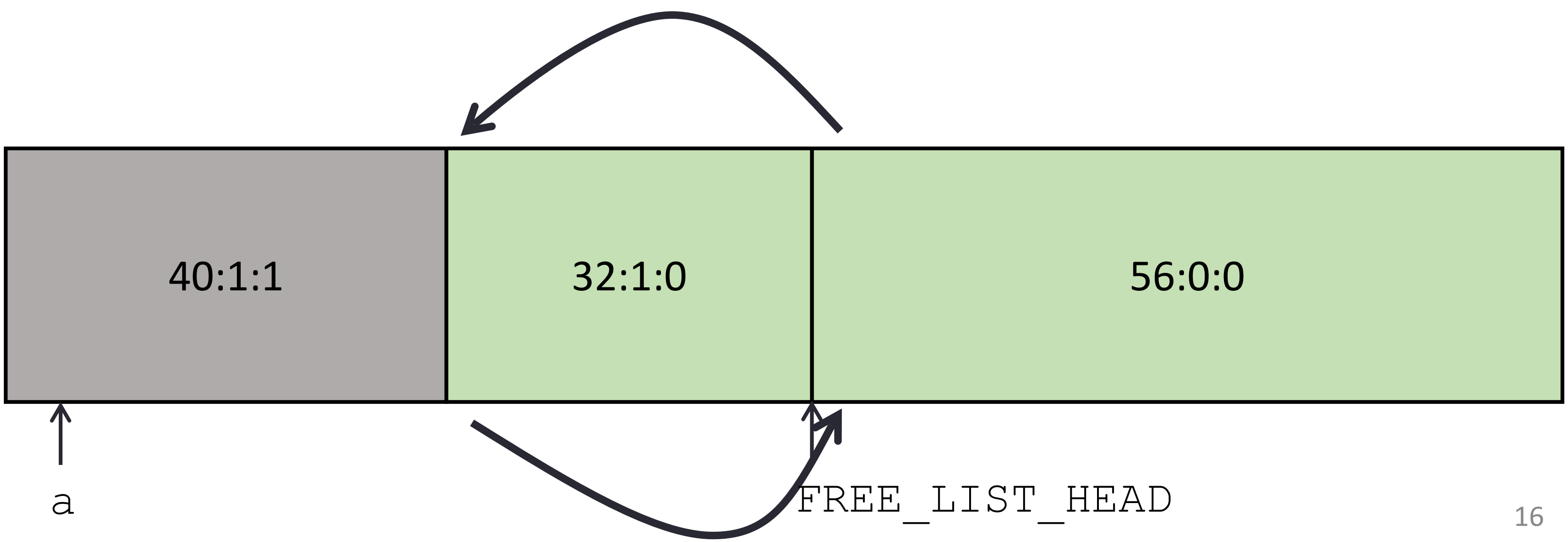
- Inserts block b into the beginning of the free list
- Notice how the tags in the block after needed to be updated



Freeing Blocks

`free(c)`

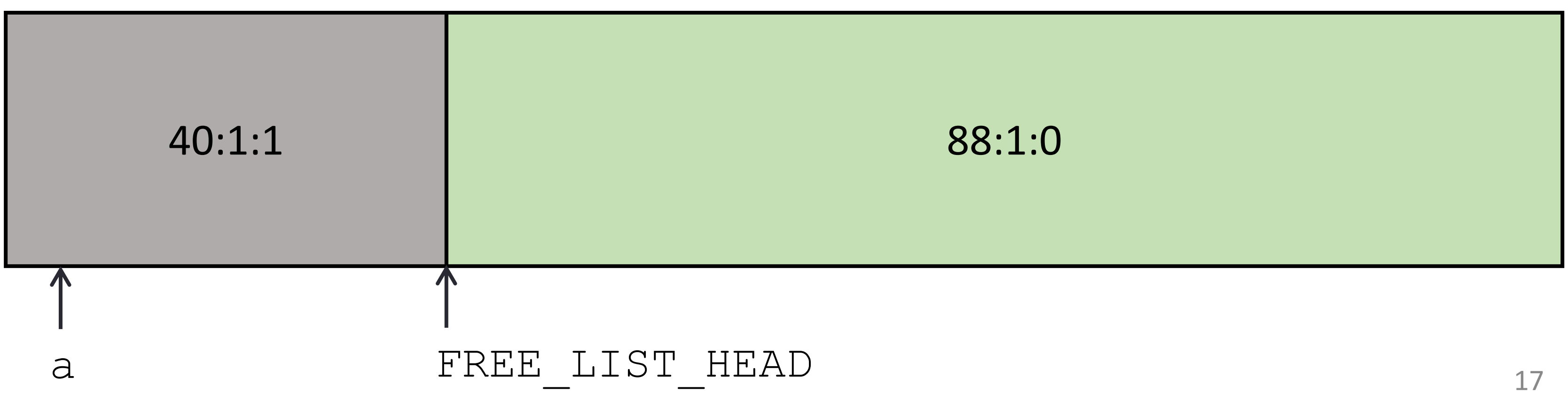
- Is this what the heap should look like at the end of `free(c)`?



Coalesce Free Blocks

When we have multiple free blocks adjacent to each other in memory, we should coalesce them.

- Coalescing basically combines free blocks together
- Bigger blocks are always better; a large block can satisfy both large and small `malloc()` requests



Lab 5

Implement `malloc()` and `free()`

- Before you start to feel overwhelmed…
- We give you many functions already including:
  - `searchFreeList()`
  - `insertFreeBlock()`
  - `removeFreeBlock()`
  - `coalesceFreeBlock()`
  - `requestMoreSpace()`

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
- Update size + tags appropriately
- Return a pointer to the payload of that block

Implementing `free()`

- **Remember, the pointer you are passed is to the <u>payload</u>**
- Convert the given used block into a free block
- Insert it into the free list
- Update size + tags appropriately
- Coalesce if necessary by calling `coalesceFreeBlock()`

Macros

- Pre-compile time "find and replace"
- Define constants:
  - #define NUM_ENTRIES 100
    - OK
- Define simple operations:
  - #define twice(x) 2*x
    - Not OK
    - twice(x+1) becomes 2*x+1
  - #define twice(x) (2*(x))
    - OK
  - Always wrap in parentheses; it's a naive search-and-replace!

Macros

- Why macros?
  - “Faster” than function calls
    - Why?
  - For malloc
    - Quick access to header information (payload size, valid)
- Drawbacks
  - Less expressive than functions
  - Arguments are *not* typechecked, local variables
    - This can easily lead to errors that are more difficult to find

Some 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
  Mast for the preceding used tag
- There are more. Don’t forget to use them!

Running the PreProcessor

- Run gcc with the -E switch
- Executes all preprocessor instructions
  - Lines that start with `#`
  - `#include`
  - `#define`
  - `#ifdef`
  - etc
- Outputs as a c file
  gcc -E -P foo.c > bar.c

Starter code

- We'll now go through some of the starter code included in the assignment
- If you are struggling to understand where to get started, read through `coalesceFreeBlock()`
  - If you can understand this function, you will understand everything
- Make sure you use the provided macros
  - They work, so it will help minimize bugs
  - More readable code