

# Malloc Boot Camp

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# Agenda

- Conceptual Overview
  - Explicit List
  - Segregated list
  - Splitting, coalescing
  - Hints on hints
- Advanced debugging with GDB
  - Fun GDB tricks
- Writing a good heap checker
- Appendix

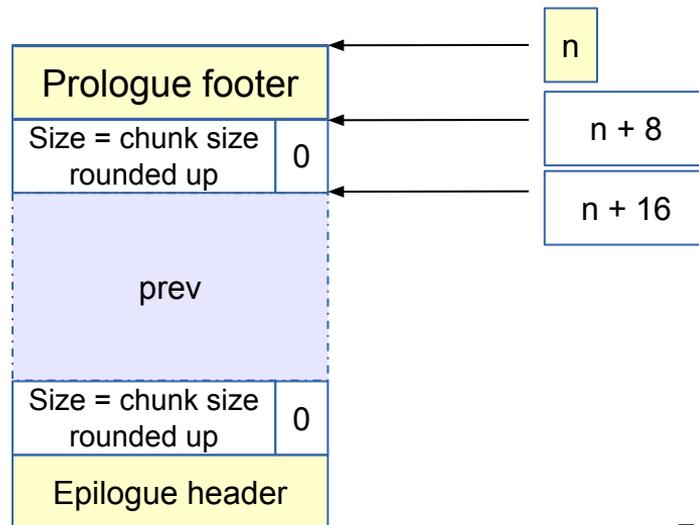
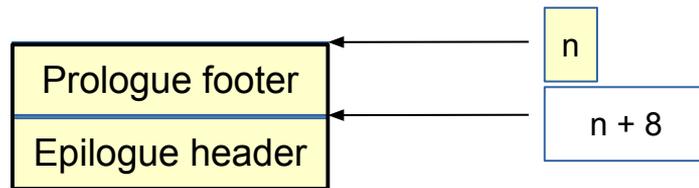
# Conceptual Outline

# Dynamic Memory Allocation

- Used when
  - we don't know at compile-time how much memory we will need
  - when a particular chunk of memory is not needed for the entire run
    - lets us reuse that memory for storing other things
- Important terms:
  - malloc/calloc/realloc/free
  - mem\_sbrk
  - payload
  - fragmentation (external vs internal)
  - Splitting / coalescing

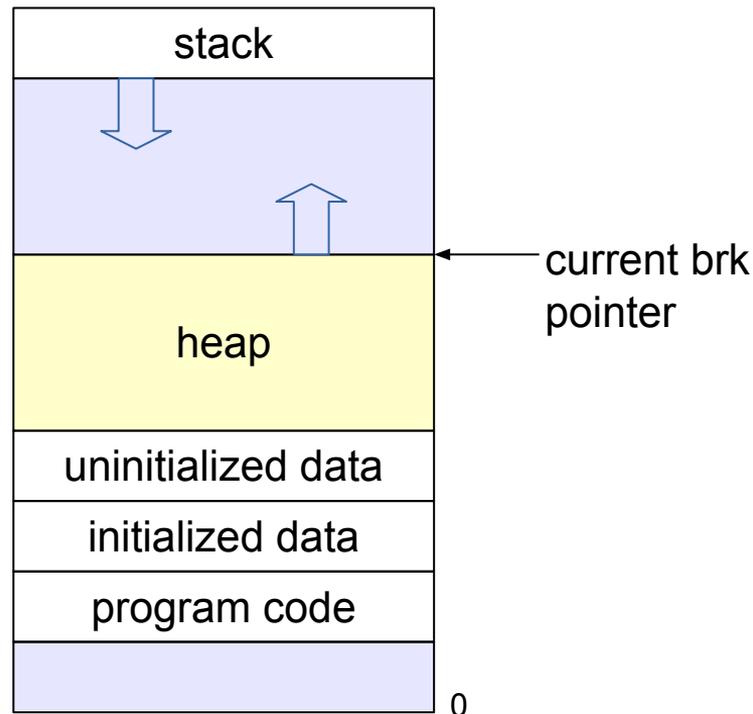
# mm\_init

- Why prologue footer and epilogue header?
- Payload must be 16-byte aligned
- But, the size of payload doesn't have to be a multiple of 16 - just the block does!
- Things malloc'd must be within the prologue and epilogue



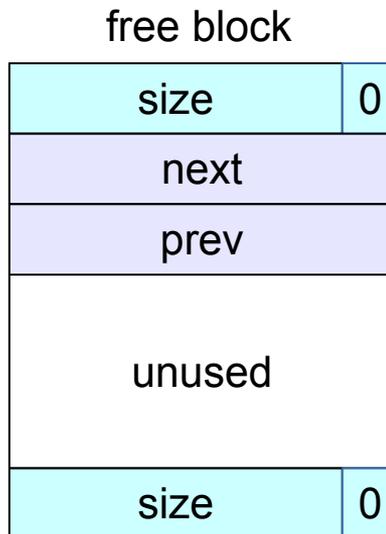
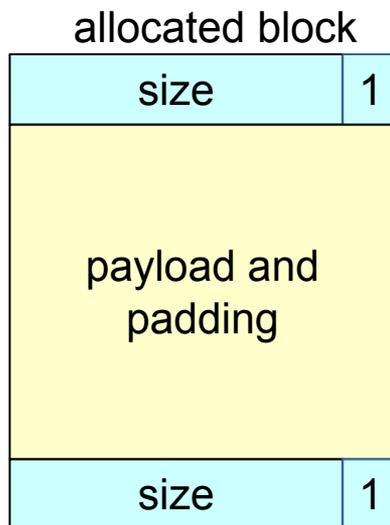
# If We Can't Find a Usable Free Block

- Assume an implicit list implementation
- Need to extend the heap
  - `mem_sbrk()`
    - `sbrk(num_bytes)` allocates space and returns pointer to start
    - `sbrk(0)` returns a pointer to the end of the current heap
  - For speed, extend the heap by a little more than you need immediately
    - use what you need out of the new space, add the rest as a free block
    - What are some tradeoffs you can make?



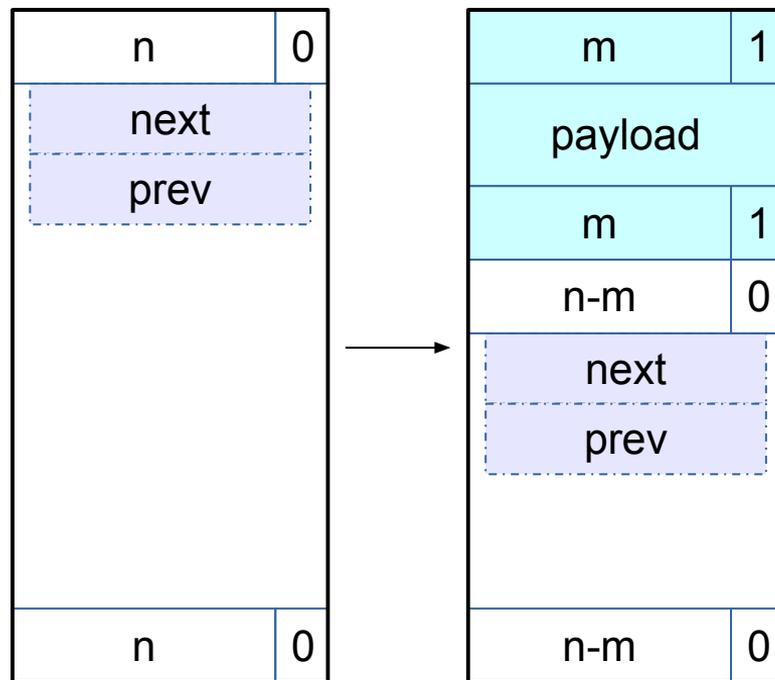
# Tracking Blocks: Explicit List

- Maintain a list of *free* blocks instead of *all* blocks
  - means we need to store forward/backward pointers, not just sizes
  - we only track free blocks, so we can store the pointers in the payload area!
  - need to store size at end of block too, for coalescing



# Splitting a Block

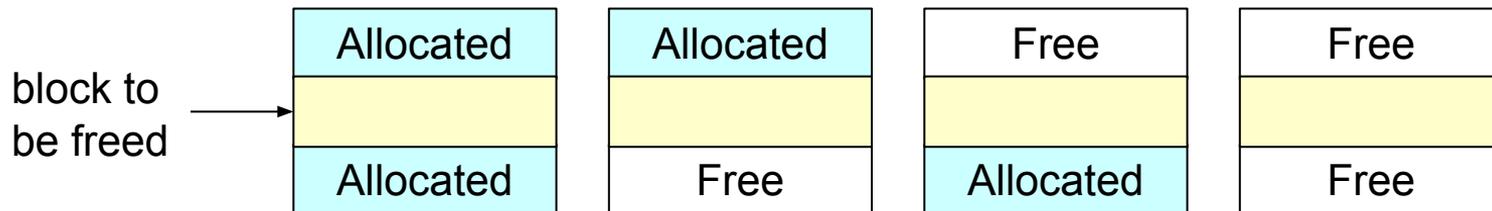
- If the block we find is larger than we need, split it and leave the remainder for a future allocation
  - explicit lists: correct previous and next pointers
  - Segregated lists: same as explicit
- When would we **not** split a block?



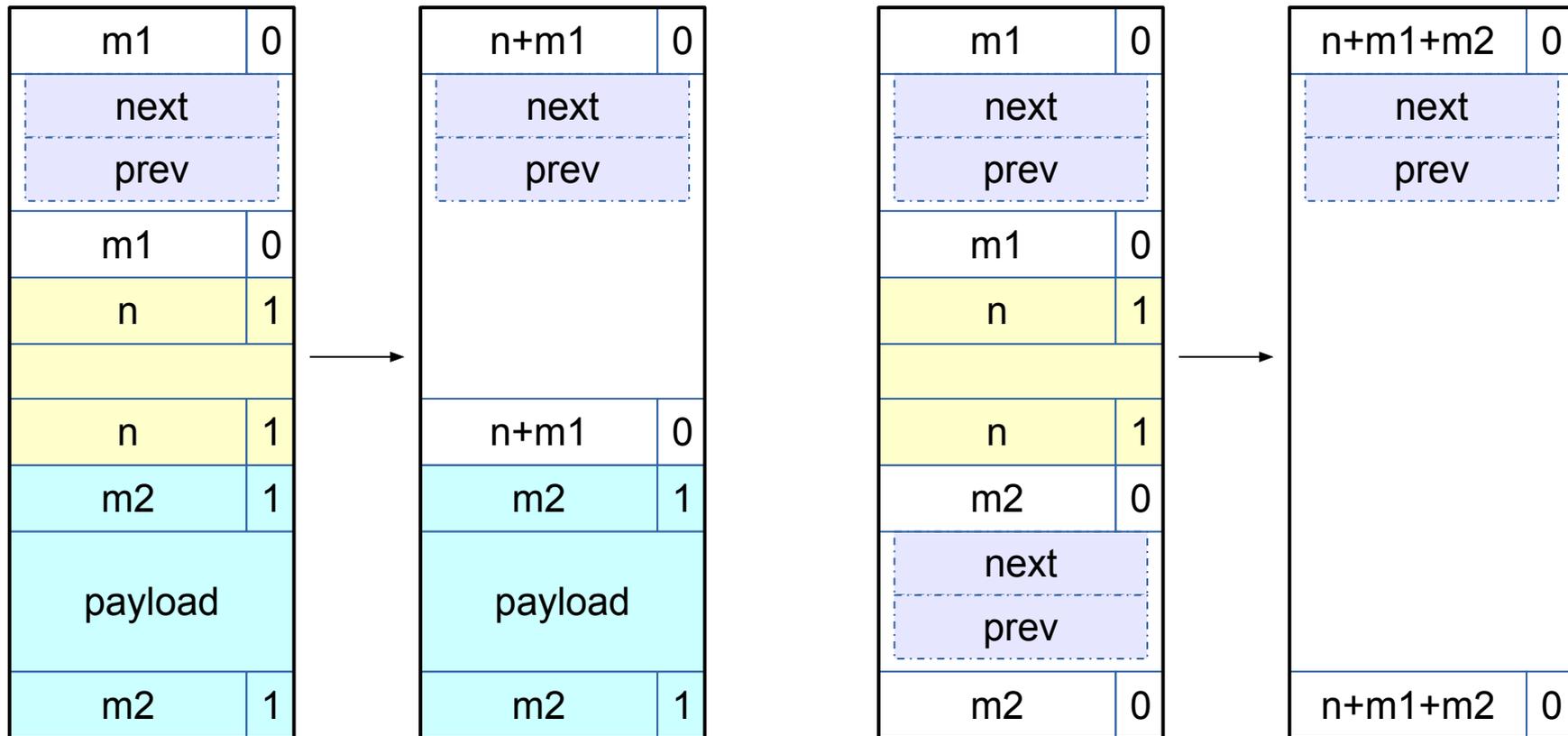
# Coalescing Memory

- Combine adjacent blocks if both are free
  - **explicit lists**: look forward and backward **in the heap**, using block sizes, **not** next/prev

- Four cases:



# Coalescing Memory



# Design Considerations

- Finding a matching free block
  - First fit vs. next fit vs. best fit vs. “good enough” fit
  - continue searching for a closer fit after finding a big-enough free block?
- Free block ordering
  - LIFO, FIFO, or address-ordered?
- When to coalesce
  - while freeing a block or while searching for free memory?
- How much memory to request with `sbrk()`
  - larger requests save time in system calls but increase maximum memory use

# Hints on hints

For the final, you must greatly increase the utilization and keep a high throughput.

- Reducing external fragmentation requires achieving something closer to best-fit allocated
  - Using a better fit algorithm
  - Combine with a better data structure that lets you run more complex algorithms
- Reducing internal fragmentation requires reducing data structure overhead and using the a 'good' free block

# Segregated Lists

- Multiple explicit lists where the free blocks are of a certain size range
- Increases throughput and raises probability of choosing a better-sized block
- Need to decide what size classes (only 128 bytes of stack space)
  - Diminishing returns
  - What do you do if you can't find something in the current size class?
- RootSizeClass1 -> free-block 1 -> free-block 2 -> free-block 3 ->
- RootSizeClass2 -> free-block 1 -> free-block 2 -> free-block 3 -> ...
- RootSizeClass3 -> free-block 1 -> free-block 2 -> free-block 3 -> ...
- ...

# Modularity and Design

- Now you need to have more than one list
  - List operations are the same for all lists
    - Insert
    - Remove
  - Deciding which size class a block should go into
    - 14 if statements :(
    - A small **const** array of sizes + a loop :)
- It would be quite painful to maintain copy-pasted code
  - Abstractions are nice - it's what CS is all about!

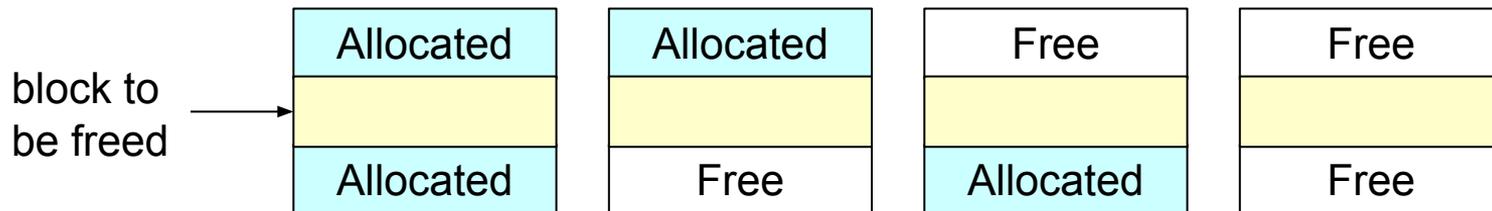
# Modularity and Design

- Make sure you have modular, extensible code
  - It will save you a lot of time spent debugging and style points
  - It will make you happy when you come back to your code
    - In 6 days when you start the final submission
    - Or in 6 hours if you're missing sleep - please get some rest!
  - It will make it easier to explain to students when you become a TA later :)
- Labs in this course are NOT meant to be done in one sitting
- Labs in this course are NOT meant to be done in 2-3 nights
- Plan ahead, leave plenty of time for **design**
  - Measure twice, cut once
- Take a break between sittings
  - Your brain can keep working subconsciously
  - Leave time for “aha!” moments

# Coalescing Memory

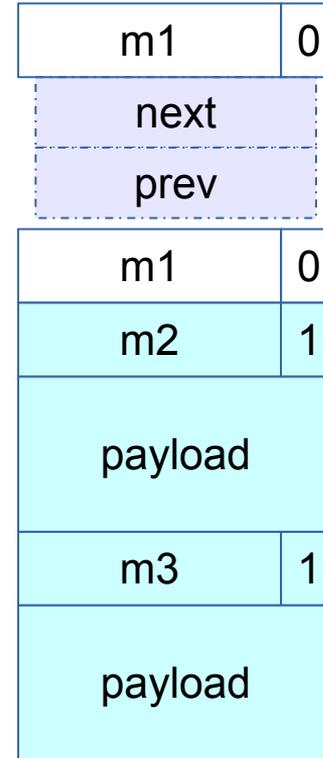
- Combine adjacent blocks if both are free
  - **segregated lists**: look forward and back using block sizes, then
    - Use the **size** of the **coalesced** block to determine the proper list
      - What else might you need to do to maintain your seglists?
    - Insert into list using the insertion policy (LIFO, address-ordered, etc.)

- Four cases:



# Eliminate footers in allocated blocks

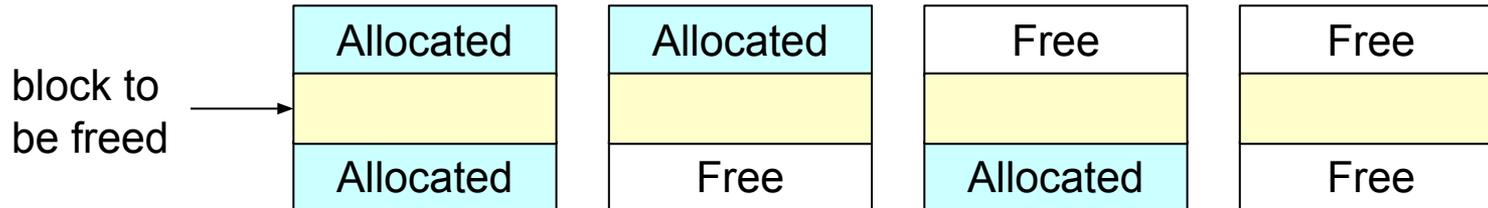
- Reduces internal fragmentation (increase utilization)
- Why do we need footers?
  - Coalescing blocks
  - What kind of blocks do we coalesce?
- Do we need to know the size of a block if we're not going to coalesce it?
- Based on that idea, can you design a method that helps you determine when to coalesce?
  - Hint: where could you store a little **bit** of extra information for each block?



# Coalescing Memory

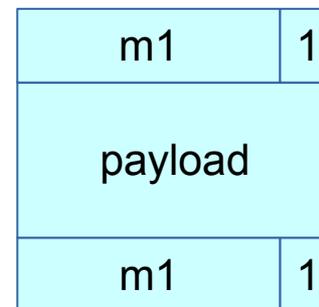
- Combine adjacent blocks if both are free
  - **footerless**: if free, obtain info from footer then use next/prev

- Four cases:



# Decrease the minimum block size

- Reduces internal fragmentation (increase utilization)
- Currently, min block size is 32.
  - 8 byte header
  - 16 byte payload (or 2 8 byte pointers for free)
  - 8 byte footer
- If you just need to malloc(5), and the payload size is 16, you waste 9.
- Must manage free blocks that are too small to hold the pointers for a **doubly** linked free list



# Debugging: GDB & The Almighty Heap Checker



...except it's not.

# Better than printf: using GDB

- Use GDB to determine where segfaults happen!
- **gdb mdriver** will open the malloc driver in gdb
  - Type run and your program will run until it hits the segfault!
- **step/next** - (abbrev. **s/n**) step to the next line of code
  - **next** steps over function calls
- **finish** - continue execution until end of current function, then break
- **print <expr>** - (abbrev. **p**) Prints **any C-like expression** (including results of function calls!)
  - Consider writing a heap printing function to use in GDB!
- **x <expr>** - Evaluate <expr> to obtain address, then examine memory at that address
  - **x /a <expr>** - formats as address
  - See **help p** and **help x** for information about more formats

# Using GDB - Fun with frames

- **backtrace** - (abbrev. **bt**) print call stack up until current function
  - **backtrace full** - (abbrev. **bt full**) print local variables in each frame

```
(gdb) backtrace
```

```
#0 find_fit (...)
```

```
#1 mm_malloc (...)
```

```
#2 0x0000000000403352 in eval_mm_valid (...)
```

```
#3 run_tests (...)
```

```
#4 0x0000000000403c39 in main (...)
```

- **frame 1** - (abbrev. **f 1**) switch to mm\_malloc's stack frame
  - Good for inspecting local variables of calling functions

# Using GDB - Setting breakpoints/watchpoints

- **break mm\_checkheap** - (abbrev. **b**) break on “mm\_checkheap()”
  - **b mm.c:25** - break on line 25 of file “mm.c” - **very useful!**
- **b find\_fit if size == 24** - break on function “find\_fit()” if the local variable “size” is equal to 24 - “**conditional breakpoint**”
- **watch heap\_listp** - (abbrev. **w**) break if value of “heap\_listp” changes - “**watchpoint**”
- **w block == 0x80000010** - break if “block” is equal to this value
- **w \*0x15213** - watch for changes at memory location 0x15213
  - Can be *very* slow
- **rwatch <thing>** - stop on reading a memory location
- **awatch <thing>** - stop on *any* memory access

# Heap Checker

- `int mm_checkheap(int verbose);`
- critical for debugging
  - **write this function early!**
  - update it when you change your implementation
  - check all heap invariants, make sure you haven't lost track of any part of your heap
    - check should pass if and only if the heap is truly well-formed
    - should only generate output if a problem is found, to avoid cluttering up your program's output
- meant to be correct, **not** efficient
- call before/after major operations **when the heap should be well-formed**

# Heap Invariants (**Non-Exhaustive**)

- Block level
  - What are some things which should always be true of every block in the heap?

# Heap Invariants (**Non-Exhaustive**)

- Block level
  - header and footer match
  - payload area is aligned, size is valid
  - no contiguous free blocks unless you defer coalescing
- List level
  - What are some things which should always be true of every element of a free list?

# Heap Invariants (**Non-Exhaustive**)

- Block level
  - header and footer match
  - payload area is aligned, size is valid
  - no contiguous free blocks unless you defer coalescing
- List level
  - next/prev pointers in consecutive free blocks are consistent
  - no allocated blocks in free list, all free blocks are in the free list
  - no cycles in free list unless you use a circular list
  - each segregated list contains only blocks in the appropriate size class
- Heap level
  - What are some things that should be true of the heap as a whole?

# Heap Invariants (**Non-Exhaustive**)

- Block level
  - header and footer match
  - payload area is aligned, size is valid
  - no contiguous free blocks unless you defer coalescing
- List level
  - next/prev pointers in consecutive free blocks are consistent
  - no allocated blocks in free list, all free blocks are in the free list
  - no cycles in free list unless you use a circular list
  - each segregated list contains only blocks in the appropriate size class
- Heap level
  - all blocks between heap boundaries, correct sentinel blocks (if used)

# How to Ask for Help

- Be specific about what the problem is, and how to cause it
  - **BAD:** “My program segfaults.”
  - **GOOD:** “I ran mdriver in gdb and it says that a segfault occurred due to an invalid next pointer, so I set a watchpoint on the segfaulting next pointer. How can I figure out what happened?”
  - **GOOD:** “My heap checker indicates that my segregated list has a block of the wrong size in it after performing a coalesce(). Why might that be the case?”
  - What sequence of events do you expect around the time of the error? What part of the sequence has already happened?
- Have you written your mm\_checkheap function, and is it working?
  - We **WILL** ask to see it!
- Use a rubber duck!

# If You Get Stuck

## ■ *Please read the writeup!*

- CS:APP Chapter 9
- View lecture notes and course FAQ at <http://www.cs.cmu.edu/~213>
- Office hours Sunday through Thursday 5:00-9:00pm in WeH 5207
- Post a **private** question on Piazza
- Obtain a rubber duck....

# APPENDIX

# Internal Fragmentation

- Occurs when the *payload* is smaller than the block size
  - due to alignment requirements
  - due to management overhead
  - as the result of a decision to use a larger-than-necessary block
- Depends on the current allocations, i.e. the pattern of *previous* requests

# Internal Fragmentation

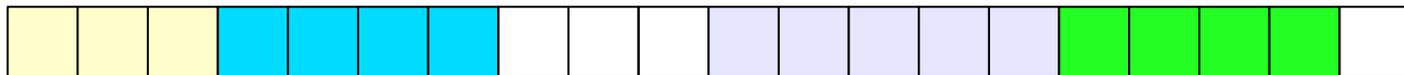
- Due to alignment requirements – the allocator doesn't know how you'll be using the memory, so it has to use the strictest alignment:
  - `void *m1 = malloc(13); void *m2 = malloc(11);`
  - `m1` and `m2` both have to be aligned on 8-byte boundaries
- Due to management overhead (each cell is 2 bytes):



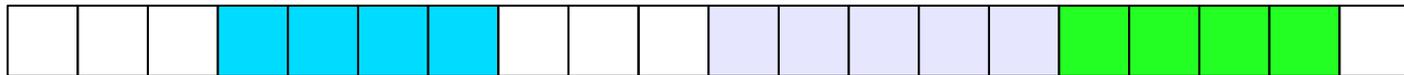
# External Fragmentation

- Occurs when the total free space is sufficient, but no single free block is large enough to satisfy the request
- Depends on the pattern of *future* requests
  - thus difficult to predict, and any measurement is at best an estimate
- Less critical to malloc traces than internal fragmentation

p5 = malloc(4)



free(p1)



p6 = malloc(5)

**Oops! Seven bytes available, but not in one chunk....**

# C: Pointer Arithmetic

- Adding an integer to a pointer is different from adding two integers
- The value of the integer is always multiplied by the size of the type that the pointer points at
- Example:
  - `type_a *ptr = ...;`
  - `type_a *ptr2 = ptr + a;`
- is really computing
  - `ptr2 = ptr + (a * sizeof(type_a));`
  - i.e. `lea (ptr, a, sizeof(type_a)), ptr2`
- Pointer arithmetic on `void*` is undefined (what's the size of a void?)

# C: Pointer Arithmetic

- `int *ptr = (int*)0x152130;`  
`int *ptr2 = ptr + 1;`
- `char *ptr = (char*)0x152130;`  
`char *ptr2 = ptr + 1;`
- `char *ptr = (char*)0x152130;`  
`void *ptr2 = ptr + 1;`
- `char *ptr = (char*)0x152130;`  
`char *p2 = ((char*)((int*)ptr)+1);`

# C: Pointer Arithmetic

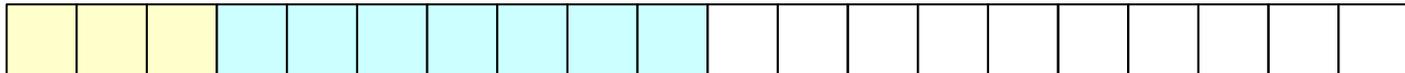
- `int *ptr = (int*)0x152130;`  
`int *ptr2 = ptr + 1; // ptr2 is 0x152134`
- `char *ptr = (char*)0x152130;`  
`char *ptr2 = ptr + 1; // ptr2 is 0x152131`
- `char *ptr = (char*)0x152130;`  
`void *ptr2 = ptr + 1; // ptr2 is still 0x152131`
- `char *ptr = (char*)0x152130;`  
`char *p2 = ((char*)((int*)ptr)+1); // p2 is 0x152134`

# Dynamic Memory Allocation: Example

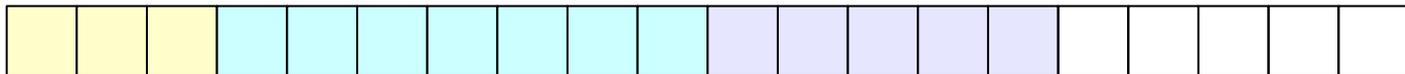
p1 = malloc(3)



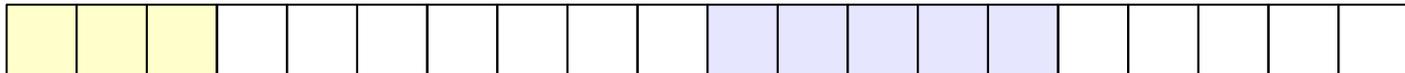
p2 = malloc(7)



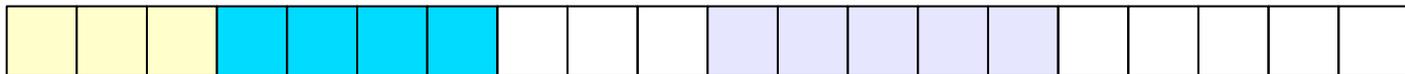
p3 = malloc(5)



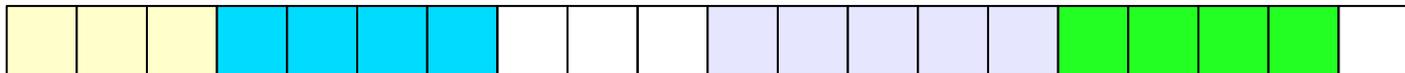
free(p2)



p4 = malloc(4)



p5 = malloc(4)



# The Memory-Block Information Data Structure

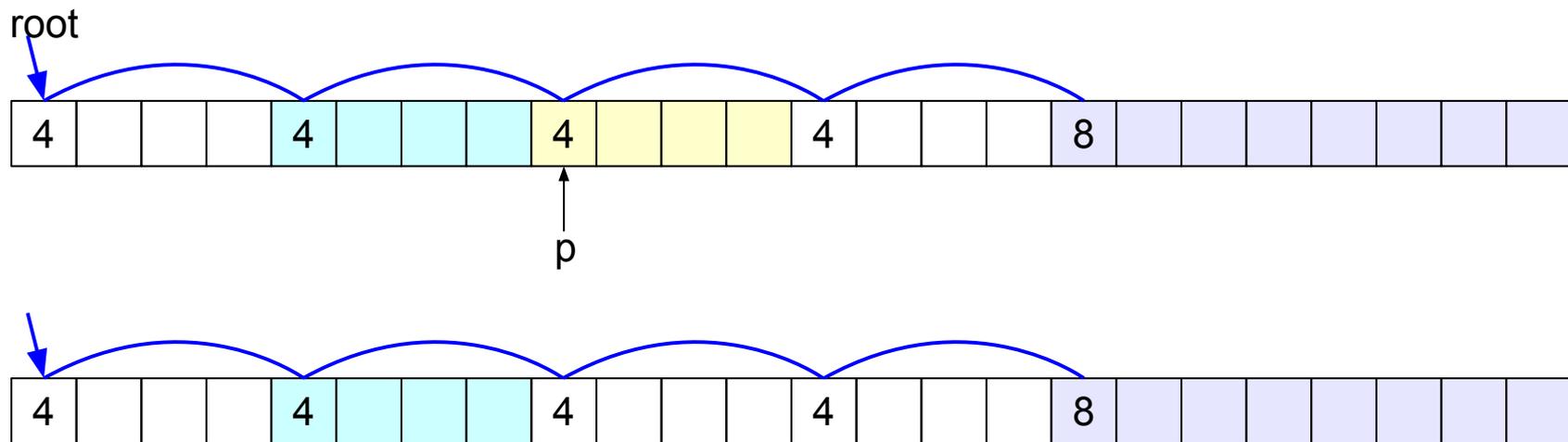
- Requirements:
  - tells us where the blocks are, how big they are, and whether they are free
  - must be able to update the data during calls to malloc and free
  - need to be able to find the **next free block** which is a “good enough fit” for a given payload
  - need to be able to quickly mark a block as free or allocated
  - need to be able to detect when we run out of blocks
    - what do we do in that case?
- The only memory we have is what we're handing out
  - ...but not all of it needs to be payload! We can use part of it to store the block information.

# Finding a Free Block

- First Fit
  - search from beginning, use first block that's big enough
  - linear time in total number of blocks
  - can cause small “splinters” at beginning of list
- Next Fit
  - start search from where previous search finished
  - often faster than first fit, but some research suggests worse fragmentation
- Best Fit
  - search entire list, use smallest block that's big enough
  - keeps fragments small (less wasted memory), but slower than first fit

# Freeing Blocks

- Simplest implementation is just clearing the “allocated” flag
  - but leads to external fragmentation



malloc(8)

*Oops!*

# Insertion Policy

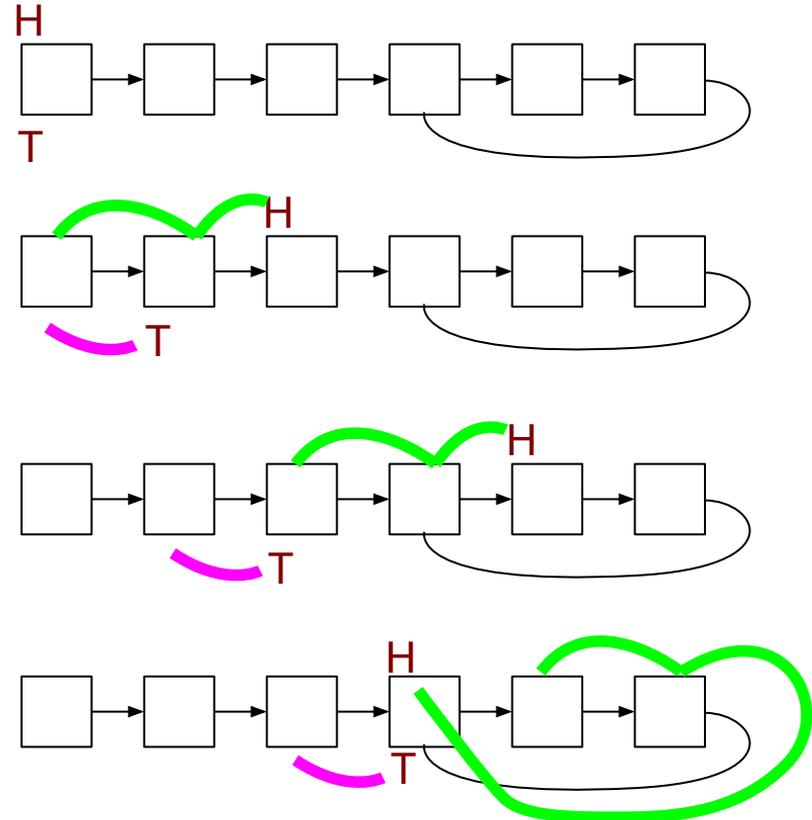
- Where do you put a newly-freed block in the free list?
  - LIFO (last-in-first-out) policy
    - add to the beginning of the free list
    - pro: simple and constant time (very fast)  
*block->next = freelist; freelist = block;*
    - con: studies suggest fragmentation is worse
  - Address-ordered policy
    - insert blocks so that free list blocks are always sorted by address  
 $\text{addr}(\text{prev}) < \text{addr}(\text{curr}) < \text{addr}(\text{next})$
    - pro: lower fragmentation than LIFO
    - con: requires search

# C: Pointer Casting

- Notation:  $(b^*)$  a “casts” a to be of type  $b^*$
- Casting a pointer doesn't change the bits!
  - `type_a *ptr_a=...; type_b *ptr_b=(type_b*)ptr_a;`  
makes `ptr_a` and `ptr_b` contain identical bits
- But it does change the behavior when dereferencing
  - because we *interpret* the bits differently
- Can cast `type_a*` to long/unsigned long and back
  - pointers are really just 64-bit numbers
  - such casts are important for mallocclab
  - but be careful – **this can easily lead to hard-to-find errors**

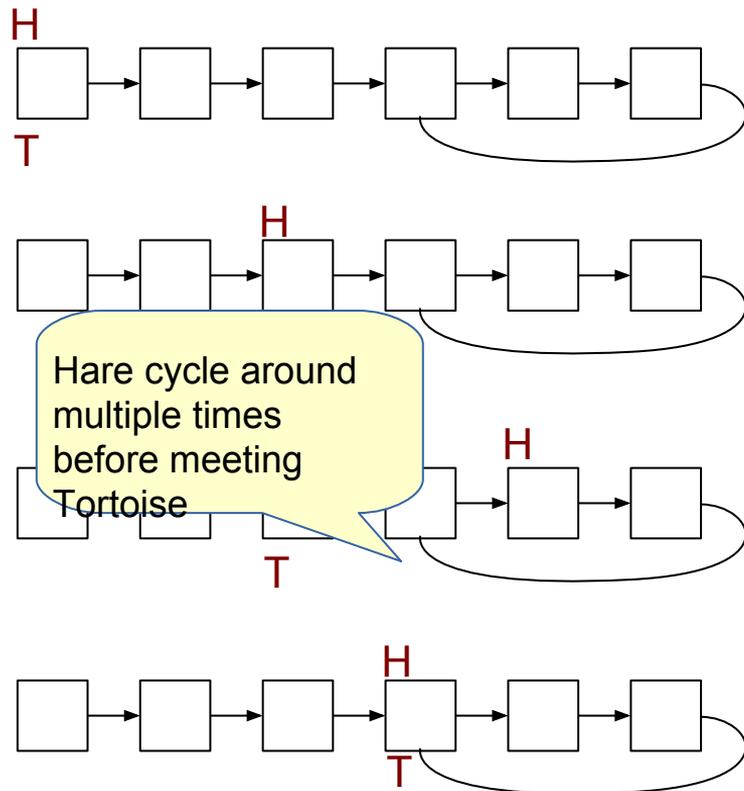
# Cycle Checking: Hare and Tortoise Algorithm

- This algorithm detects cycles in linked lists
- Set two pointers, called “hare” and “tortoise”, to the beginning of the list
- During each iteration, move “hare” forward by two nodes, “tortoise” by one node
  - if “tortoise” reaches the end of the list, there is no cycle
  - if “tortoise” equals “hare”, the list has a cycle



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# Debugging Tip: Using the Preprocessor

- Use conditional compilation with `#if` or `#ifdef` to easily turn debugging code on or off

```
#ifdef DEBUG
# define DBG_PRINTF(...) fprintf(stderr, __VA_ARGS__)
# define CHECKHEAP(verbose) mm_checkheap(verbose)
#else
# define DBG_PRINTF(...)
# define CHECKHEAP(verbose)
#endif /* DEBUG */
```

```
void free(void *p)
{
    DBG_PRINTF("freeing %lx\n", (long)p);
    CHECKHEAP(1);
    ...
}
```

# Debugging Tip: GDB

- Use breakpoints / conditional breakpoints
  - `break {address} if {condition}`
- Use watchpoints
  - like breakpoints, but stop the program when the watched expression changes or location is written
  - `watch {expression}`      `watch block->next`
    - break any time the expression changes value; can be extremely slow!
  - `watch -l {expression}`      `watch -l *0x15213`
    - evaluate the expression and watch the memory location at that address
    - program runs at full speed if GDB can set a hardware watchpoint
  - `rwatch` to stop on *reading* a location, `awatch` to stop on **any** access

# Header Reduction

- **Note:** this is completely optional and generally **discouraged** due to its relative difficulty
  - Do **NOT** attempt unless you are satisfied with your implementation as-is
- When to use 8 or 4 byte header? (must support all possible block sizes)
- If 4 byte, how to ensure that payload is aligned?
- Arrange accordingly
- How to coalesce if 4 byte header block is followed by 8 byte header block?
- Store extra information in headers

