15-213 Recitation
Malloc Lab (Part II)

Your TAs

Friday, October 24th

Agenda

- **Review:**
  - Heap Layout + Quick Roadmap of Malloc Checkpoint
- **Debugging**
  - Finding errors with contracts and `gdb`
  - Instrumentation
- **Malloc Final Overview**
- **Style**

Reminders

- `malloc` Deadlines:
  - *Checkpoint: **October 28th (Tuesday)***
  - *Final: **November 4th (Tuesday)***
  - 7% of final grade (+4% for Checkpoint)
- Written 7 due ***October 29th***
- Watch your email for Checkpoint Code Review sign-ups!

Review: Malloc Checkpoint

Where are we? - Checkpoint

Quick Discussion: What should we implement for checkpoint and how do they aid in performance?

0. Started with a working (but slow) implicit list version
1. Implement `coalesce_block()` *first*.
2. Implement an *explicit free list*.
3. Implement *segregated lists*

This is a good place to currently be!

Debugging

What does "Garbled Bytes" mean?

1. Your **`malloc`** returns a block pointer to satisfy a request.
2. **`mdriver`** writes bytes into payload
3. Later, **`mdriver`** checks that those bytes are intact:
   - If bytes have been overwritten, your **`malloc`** is overwriting data in an allocated block!

Now what?

- Double check your heap invariants. Are they exhaustive?
- If that doesn't help, use **`gdb`** to watch writes to the address getting garbled.

Debugging: Overview

- Refer to last week's recitation for common errors, and what they mean.
- *Use tools*: **gdb** breakpoints and watchpoints.
  - Note: Valgrind will not work!
- *Write a heap checker!* We'll be grading it in the next code review!
  - Add new heap invariants as you add new features.
- ***Today: debugging walkthrough!***
  - Garbled bytes + Using contracts

Debugging Activity

- Log into a Shark machine, then type:

```
$ wget http://www.cs.cmu.edu/~213/activities/rec9.tar
$ tar -xvf rec9.tar
$ cd rec9
```

- **`mm.c`** is a fake implicit list implementation, based on the starter code.
- It is buggy. Let's try and find the bugs!

Debugging Activity

- What happens if we run the program normally?

```
$ ./mdriver -c ./traces/syn-struct-short.rep

ERROR [trace ./traces/syn-struct-short.rep, line 16]: block 1 (at
0x8000000a0) has 8 garbled bytes, starting at byte 16
ERROR [trace ./traces/syn-struct-short.rep, line 21]: block 4 (at
0x800000180) has 8 garbled bytes, starting at byte 16


correctness check finished, by running tracefile
"traces/syn-struct-short.rep".
 => incorrect.

Terminated with 2 errors
```

Not very helpful...

Debugging: Using Watchpoints

- Now let's try again with watchpoints!

```
$ gdb --args ./mdriver-dbg1 -c ./traces/syn-struct-short.rep

(gdb) watch *0x8000000a0
(gdb) run

// Keep continuing through the breaks:
// write_block()
// 4 x memcpy
Hardware watchpoint 1: *0x8000000a0

Old value = 129
New value = 32
write_block() at mm.c:333
```

- Now we know to take a closer look at **`write_block()`**!

Debugging: Using Contracts

- Now let’s run a version of the file that uses *contracts*:

```
$ ./mdriver-dbg2 -c ./traces/syn-struct-short.rep

mdriver-dbg: mm.c:331: void write_block(block_t *, size_t, _Bool):
Assertion `(unsigned long)footerp < ((long)block + size)' failed.
Aborted (core dumped)
```

- This version had a contract in place to check that the footer is where we expect it to be.
- Writing effective contracts can save a lot of debugging time!

Debugging: Miscellaneous Tips

- **`mdriver`**
  - Use **`-D`** option to detect garbled bytes as soon as possible
  - Use **`-V`** for verbose mode to find out which trace caused the error
- If the error happens in the first few allocations, can set breakpoints on **`mm_malloc`** and **`mm_free`** and step through line by line.

Instrumentation

Common Problems

- *Throughput is very low*
  - Which operation is likely the most costly? Where is the program likely to spend most of its time?
- *Utilization is very low / Out of Memory*
  - Which operation can cause you to allocate more memory than you may need?
- We can use *instrumentation* to investigate both problems!

Adding Instrumentation

- Instrumentation: add *temporary* code that collects measurements for metrics you're interested in.
  - **eg.** how often are certain functions called?
  - You can always remove the code afterwards.
  - Can temporarily go over 128 byte writable global limit!
- These measurements can guide your development process:
  - Develop insights into performance before you spend time on implementation.

Instrumentation Example: Low Throughput

- Program is likely to spend most of its time in **`find_fit()`**'s loops.
- How efficient is your fit algorithm? How might you find out?

```
static block_t *find_fit(size_t asize)
{
    block_t *block;  call_count++
    for (block = heap_listp; get_size(block) > 0;
                             block = find_next(block))
    { block_count++
        if (!(get_alloc(block)) && (asize <= get_size(block)))
        {
            return block;
        }
    }
    return NULL; // no fit found
}
```

Instrumentation: Other Metrics

- What are the most common request sizes?
  - How many are 8 bytes or less?
  - How many are 16 bytes or less?
  - How might this inform your design?
- What other things might we want to measure?

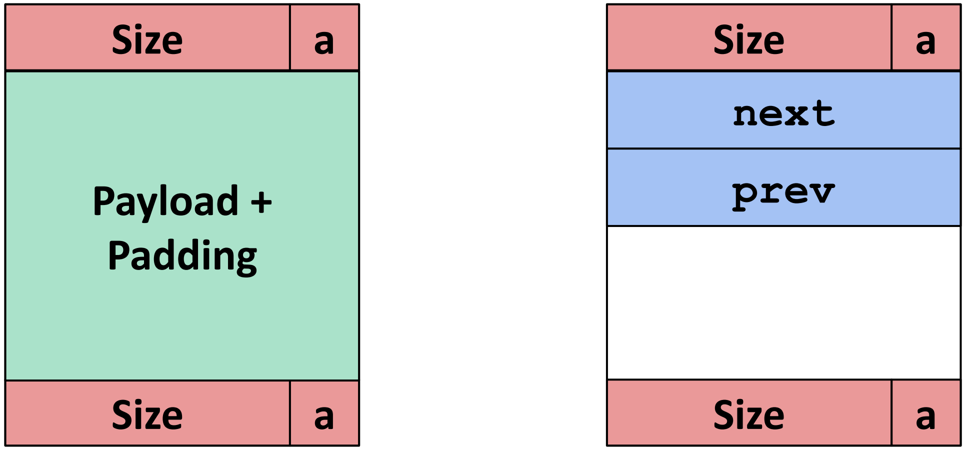
Malloc Final

What are we trying to do?

- In Checkpoint, you dramatically improved the *throughput* of your allocator.
- For Final, you will need to greatly improve *utilization* while maintaining a high throughput.
- We will cover:
  1. Footer Removal in Allocated Blocks
  2. Decreasing Minimum Block Size

Current Block Structure

- Here is the current structure of our block (post-checkpoint)
- When is each component utilized in our implementation?
- Do we **need** each component at all time / in all cases?



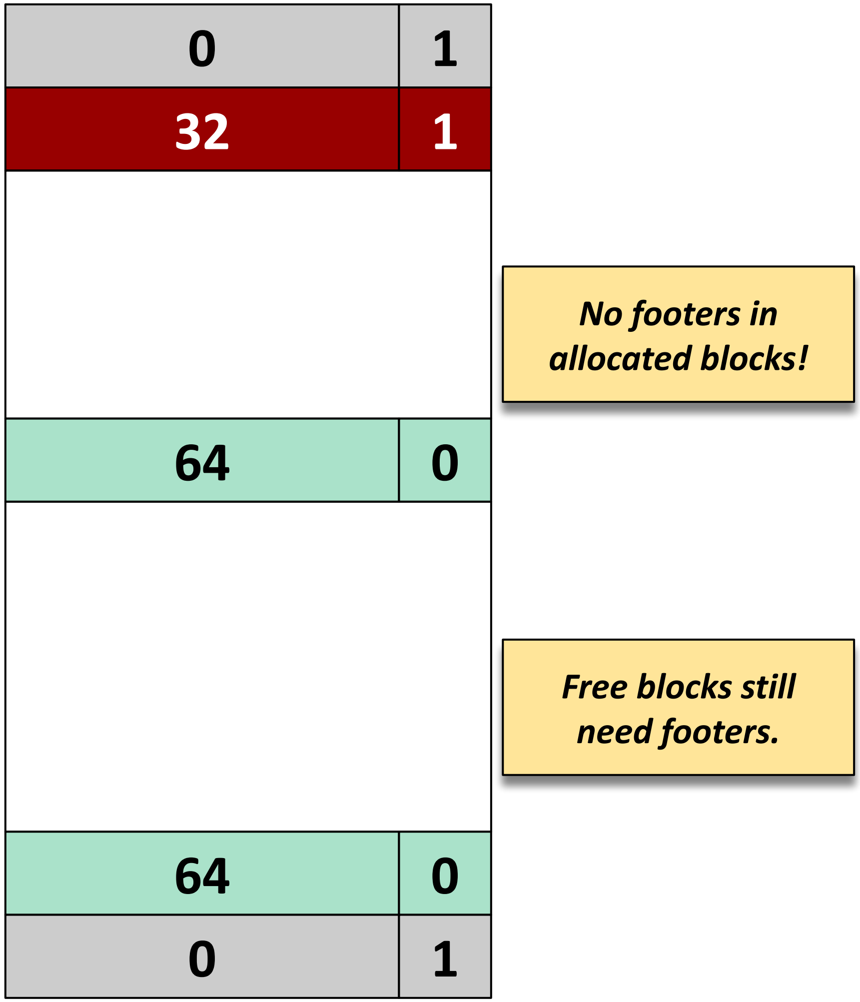
Allocated (as before) *Free*

Zooming In: Footer

- When is the footer used?
  - To access the size/allocation status of previous block during coalescing
- When do we care about the size?
  - When the block is free! If the previous block is allocated, we no longer need to know the size.

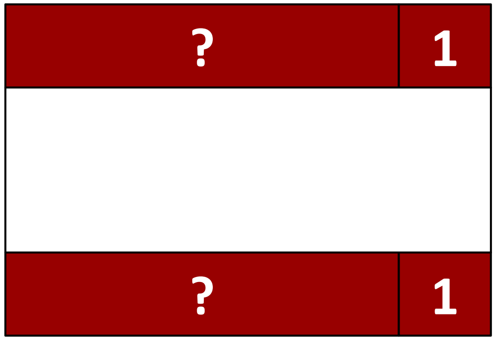
Footer Removal: Implementation

- What do we need footers for?
  - Coalescing
  - ***Key observation:*** do we need to know the size or position of the previous block if we're not going to coalesce with it?
- We just need some way to determine whether the block before us is allocated…



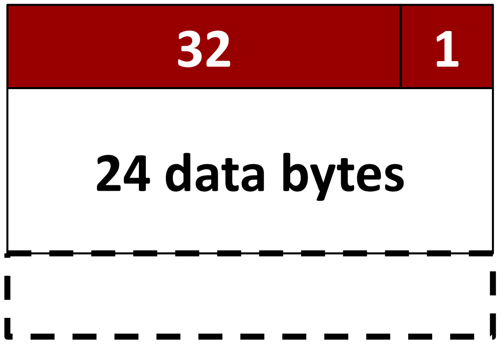
Footer Removal: Example 1

- Let's say we call **`malloc(24)`**. Can our block of size 32 satisfy the request?
- Add on overhead:
  - Header: +8 bytes = 32 bytes
  - Footer: +8 bytes = 40 bytes
- Round to multiple of 16 => 48 bytes
- Doesn't fit!



Footer Removal: Example 1

- What if we had no footer?
- Add on overhead:
  - Header: +8 bytes = 32 bytes
  - ~~Footer: +8 bytes = 40 bytes~~
- Round to multiple of 16 => 32 bytes
- Now it fits!
  - We have reduced *internal fragmentation*.



Footer Removal: Example 2

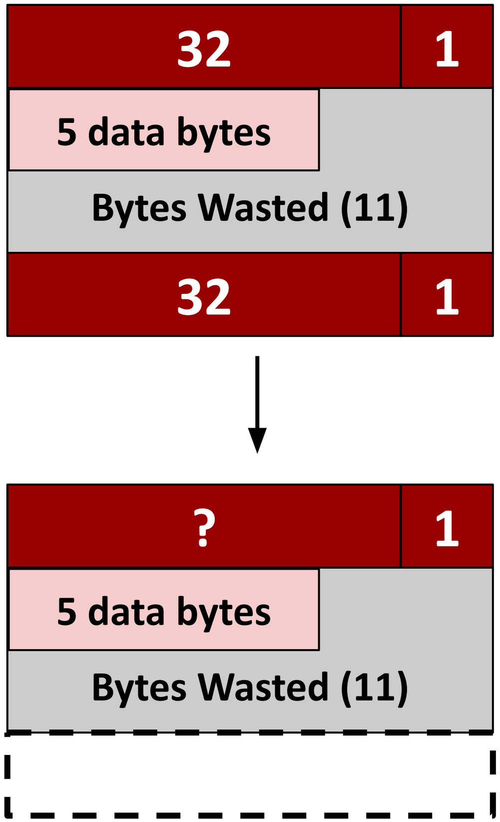
- Now suppose we call `malloc(5)`.

  Does removing footers help?

- What is our minimum block size?
  - Still 32 bytes! (header, next, prev, footer for free blocks)

- Header + 16 byte minimum payload uses 24 bytes => round up to minimum block size

- **No benefits in this case!**



Recap: Removing Footers

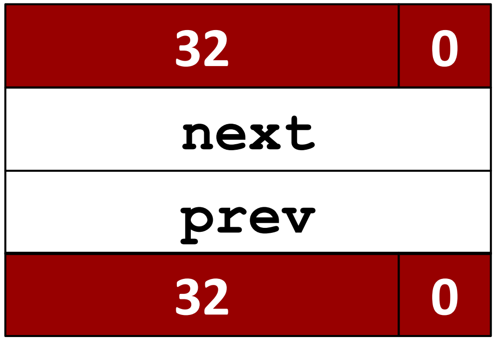
- For a large enough allocation request we can:
  - Include all the information we need for free blocks
  - Also reduce the total block size by cutting the overhead from footers!
- Remember, this does **not** reduce the minimum block size!
  - Though it can help us build towards it…

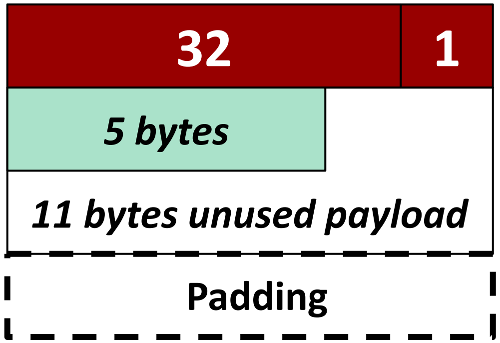
Why Mini Blocks?

- Let's go back to the example where we called **`malloc(5)`**
- What was the reason that removing footers yielded no benefits?
- How can we circumvent this barrier to reduce internal fragmentation?

Decreasing Minimum Block Size

- Currently, minimum block size is 32:
  - 8 byte header
  - 16 byte payload (min.)
  - 8 byte footer (for free blocks)
- If we do **`malloc(5)`**, there's a lot of wasted space due to the min size constraint
- Can we create a design with a smaller minimum block size?





Final Tips

- The shift from checkpoint to final requires us to think more about utilization rather than throughput!
- We talked about several features we can add to improve utilization in certain cases
- What are other features of malloc we can modify to further improve utilization? How do they help?

Warning!

- Note that there are implementations that may achieve better performance vs be less complex to design!
- Compressed headers is a technique that reduces the size of the header, reducing internal fragmentation
- Another possible design is to represent your explicit list as a tree!
- Proceed with caution in implementing these two features as they have a higher complexity!

Style

Style

- Checkpoint Code Review: Heap Checker Quality
- Final Code Review: Code Style
- Remember the style guidelines!
  - Modularity: use helper functions (e.g., for linked lists)!
  - Documentation
    - *File header:* have you described all your design decisions (block structure, fit algorithm, etc.)?

Wrapping Up

- `malloc` Deadlines:
  - *Checkpoint: **October 28th (Tuesday)***
  - *Final: **November 4th (Tuesday)***
- Written 7 due ***October 29th***

The End