Malloc Boot Camp

Stan, Nikhil, Kim

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

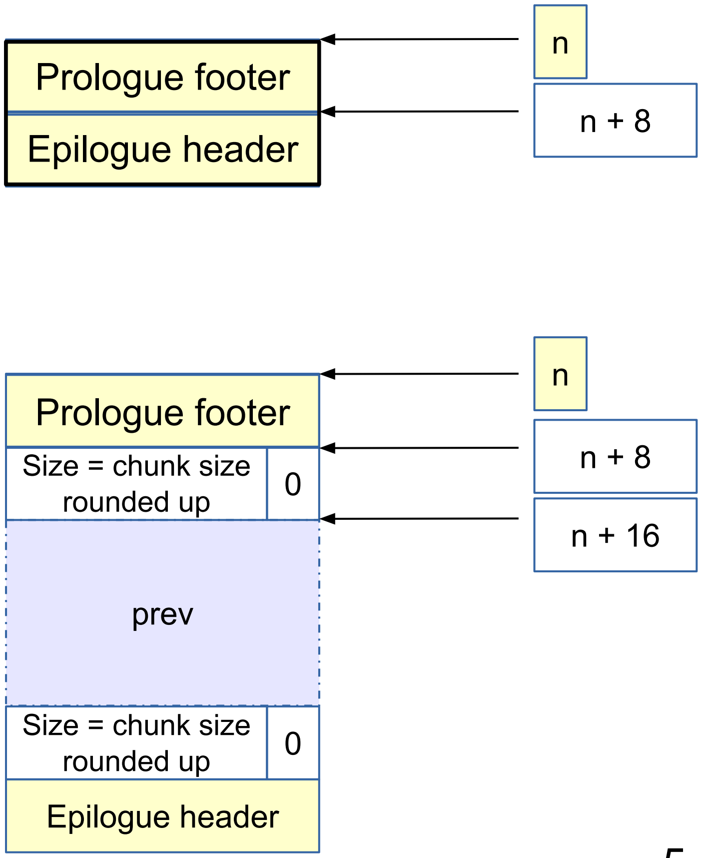
Dynamic Memory Allocation

- 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 re-use that memory for storing other things
- Important terms:
  - malloc/calloc/realloc/free
  - mem_sbrk
  - payload
  - fragmentation (external vs internal)
  - Splitting / coalescing

mm_init

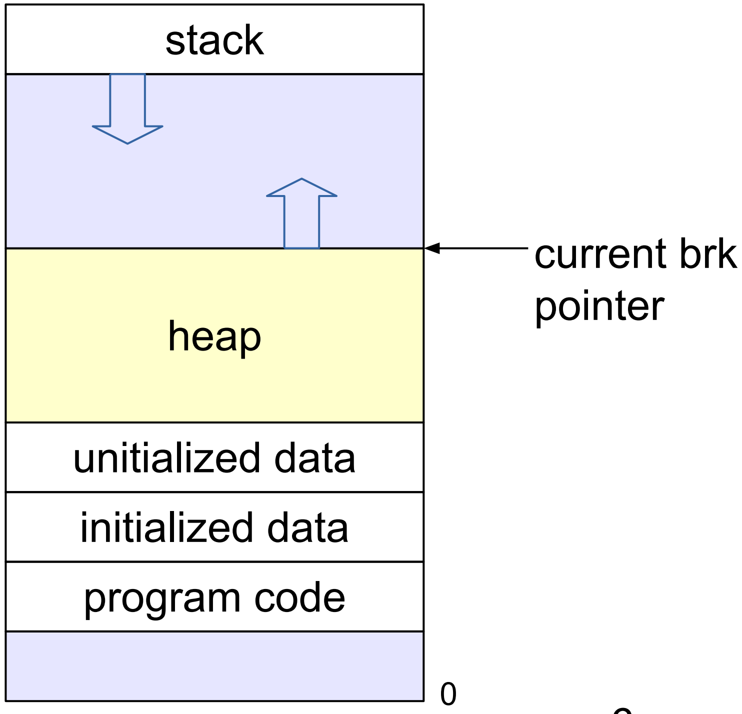
- Why prologue footer and epilogue header?
- Payload must be 16-byte aligned
- But, the size of payload doesn't have to be a multiple of 16!

- Things malloc'd must be within the prologue and epilogue



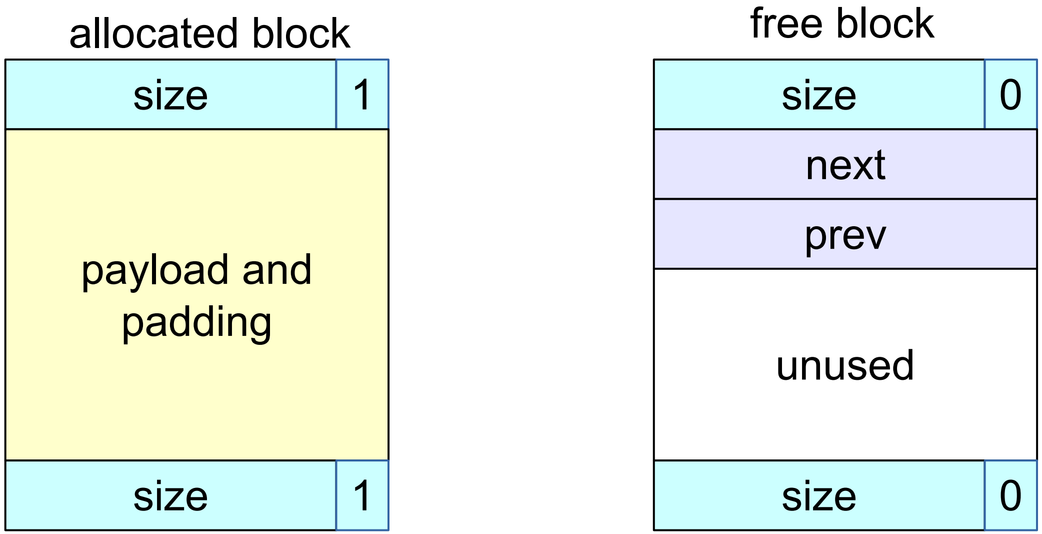
If We Can't Find a Usable Free Block

- Need to extend the heap
  - in Malloclab, use mem_sbrk()
    - sbrk(requested_bytes) allocates requested_bytes of 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 (chunksize)
  - use what you need out of the new space, add the rest as a free block



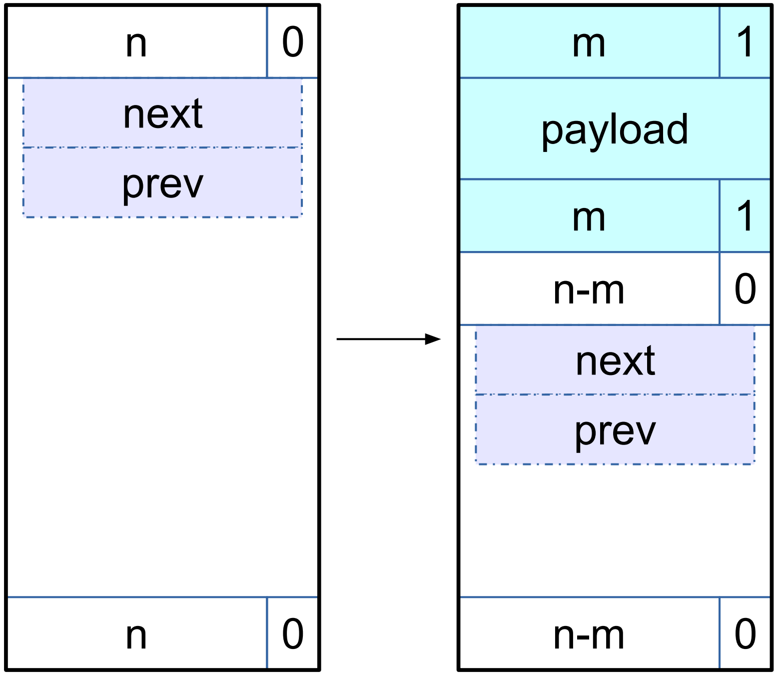
Tracking Blocks: Explicit List

- 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

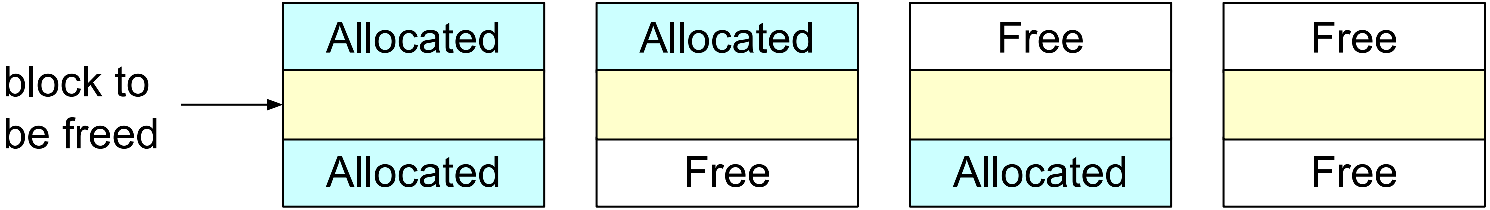
- If the block we find is larger than we need, split it and leave the remainder for a future allocation
  - explicit lists: correct previous and next pointers
  - Segregated lists: same as explicit
- When would we **not** split a block?



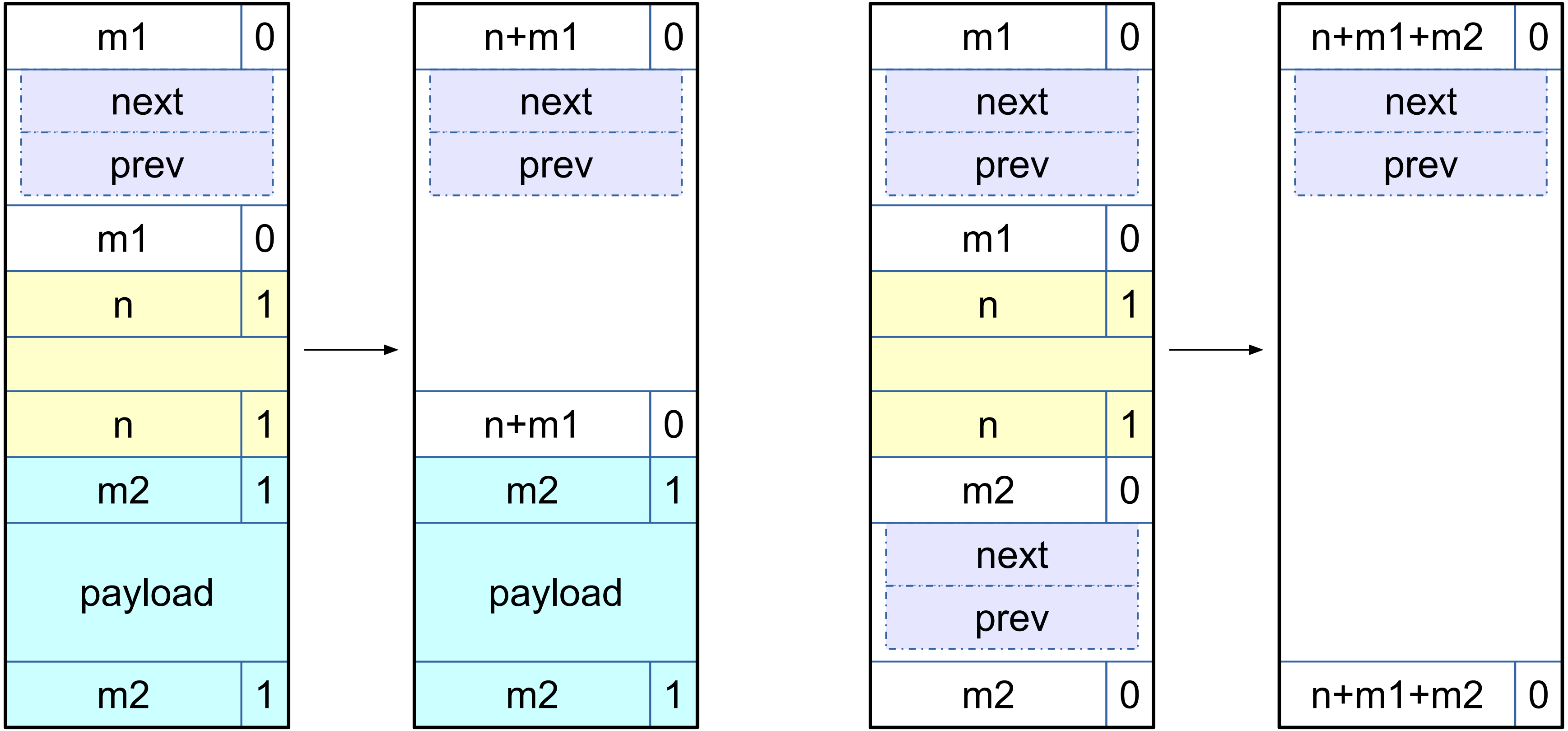
Coalescing Memory

- Combine adjacent blocks if both are free
  - **explicit lists**: look forward and backward using block sizes, **not** next/prev
  - **footerless:** if free, obtain info from footer then use next/prev
  - **segregated lists**: look forward and back using block sizes, then
    - use the size of the coalesced block to determine the proper list
    - insert into list using the insertion policy (LIFO, address-ordered, etc.)

- Four cases:



Coalescing Memory



Design Considerations

- Finding a matching free block
  - First fit vs. next fit vs. best 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 e.g., by using segregated lists.

- Reducing internal fragmentation requires reducing data structure overhead and using the a ‘good’ free block

Segregated Lists

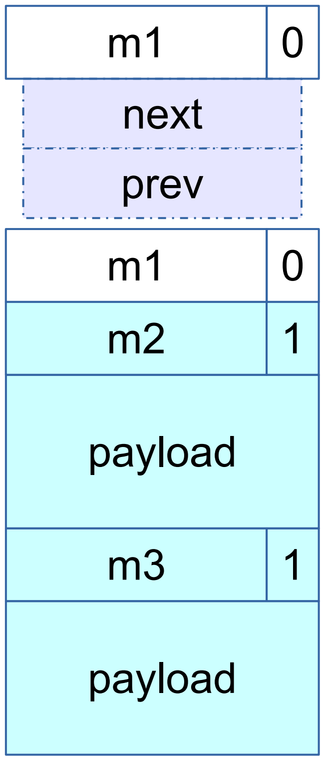
- Just multiple explicit lists where the free blocks are of a certain size range
- Increases throughput and raises probability of choosing a better-sized block

- Need to decide what size classes and you are bounded by 128 byte allowance

- 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 -> ...
- ...

Eliminate footers in allocated blocks

- Reduces internal fragmentation (increase utilization)
- How to coalesce when the allocated block is free?
- Consider how we stored information about whether a block was allocated
- Free blocks still have footers
- Based on that idea, can you design a method that helps you determine when to coalesce?



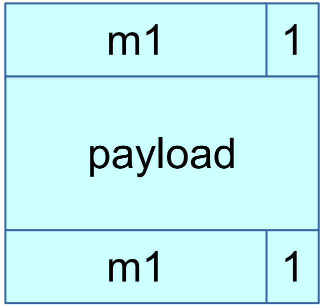
Decrease the minimum block size

- Reduces internal fragmentation (increase utilization)

- Currently, minimum 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

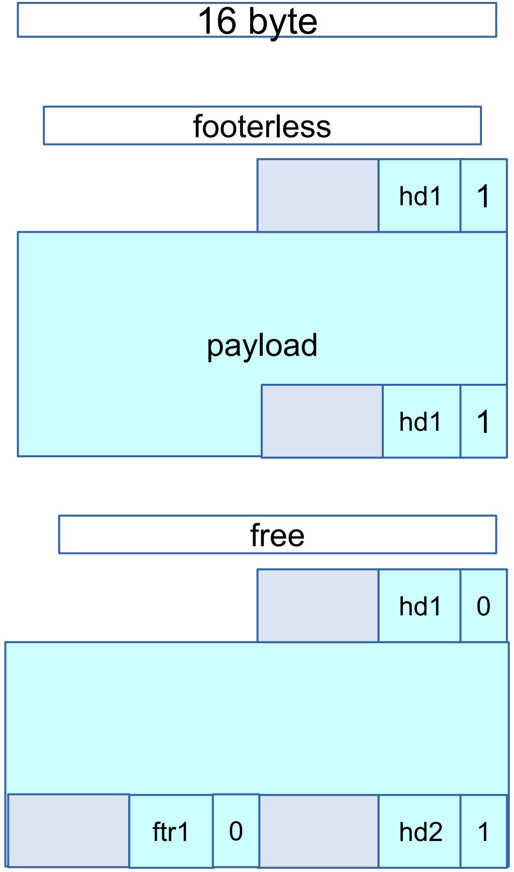


Header Reduction

- 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



Preventing Errors

- Good coding practices can make your code less error-prone
- Plan what each function does before writing it
  - consider edge cases – block at start/end of list, single item on list, etc.
  - draw pictures to help you visualize linked lists, memory layout, etc.
- Document your code as you write it
- Use helper functions!
- Check for common errors:
  - dereferencing invalid pointers / reading uninitialized memory
  - overwriting memory
  - freeing blocks multiple times (or not at all) / referencing freed blocks
  - incorrect pointer arithmetic

Debugging: GDB & The Almighty Heap Checker

Download this handout for fun & profit

- Presentation on course website
  - See “schedule”
- https://cs.cmu.edu/~213/activities/mallocbootcamp.tar

...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!
- layout split - display GDB “text user interface”
  - Way prettier than normal GDB command prompt
  - Can sometimes get messed up by programs that print things
  - refresh - redraws screen
- step - step to the next line of code, stepping into functions if necessary
- next - same as above, but steps *over* functions instead
- finish - continue execution until the end of the current function, then break

Using GDB - Fun with frames

- backtrace - print call stack up until current function
  - backtrace full - print local variables in each stack frame

```
(gdb) backtrace
#0  find_fit (...)
#1  mm_malloc (...)
#2  0x0000000000403352 in eval_mm_valid (...)
#3  run_tests (...)
#4  0x0000000000403c39 in main (...)
```

- frame 1 - switch to mm_malloc's stack frame
  - Good for inspecting local variables of calling functions

Using GDB - Setting breakpoints/watchpoints

- break mm_checkheap - break on function “mm_checkheap”
  - break mm.c:25 - break on line 25 of file “mm.c” - **very useful!**
- break find_fit if size == 24 - break on function “find_fit” if the local variable “size” in the malloc function is equal to 24
  - See mm-baseline.c in malloc handout
- watch heap_listp - break if the value of “heap_listp” changes
- watch block == 0x80000010 - break if “block” is equal to this value
- watch *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

GDB Live Demo

Heap Checker

- int mm_checkheap(int verbose);
- critical for debugging
  - **write this function early!**
  - update it when you change your freelist implementation
  - check all heap invariants (next slide), 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)

Heap Checker Live Demo

How to Ask for Help

- Be specific about what the problem is, and how to cause it
  - **BAD:** “My program segfaults.”
  - **GOOD:** “On the third free() in trace 4, I get an invalid pointer in my free list while coalescing memory.”
  - Try to figure out which part of the trace file triggers the problem
  - 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!
- Practice asking your rubber duck about the problem (see Recitation 9) before asking a TA or instructor

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):

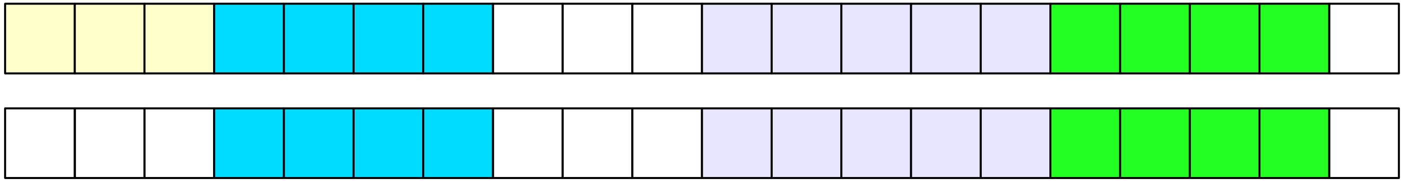
l	e	n	1	p	a	y	l	o	a	d	1	l	e	n	2	p	a	y	l	o	a	d	2

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)

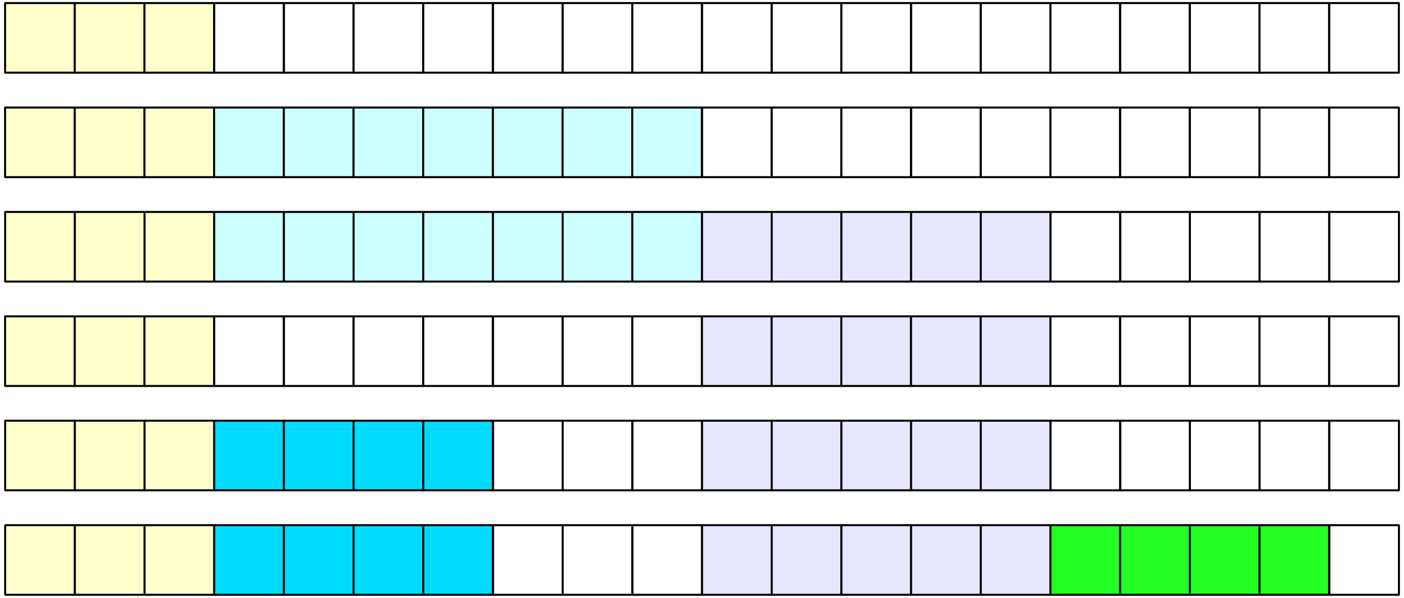
p2 = malloc(7)

p3 = malloc(5)

free(p2)

p4 = malloc(4)

p5 = malloc(4)



The Memory-Block Information Data Structure

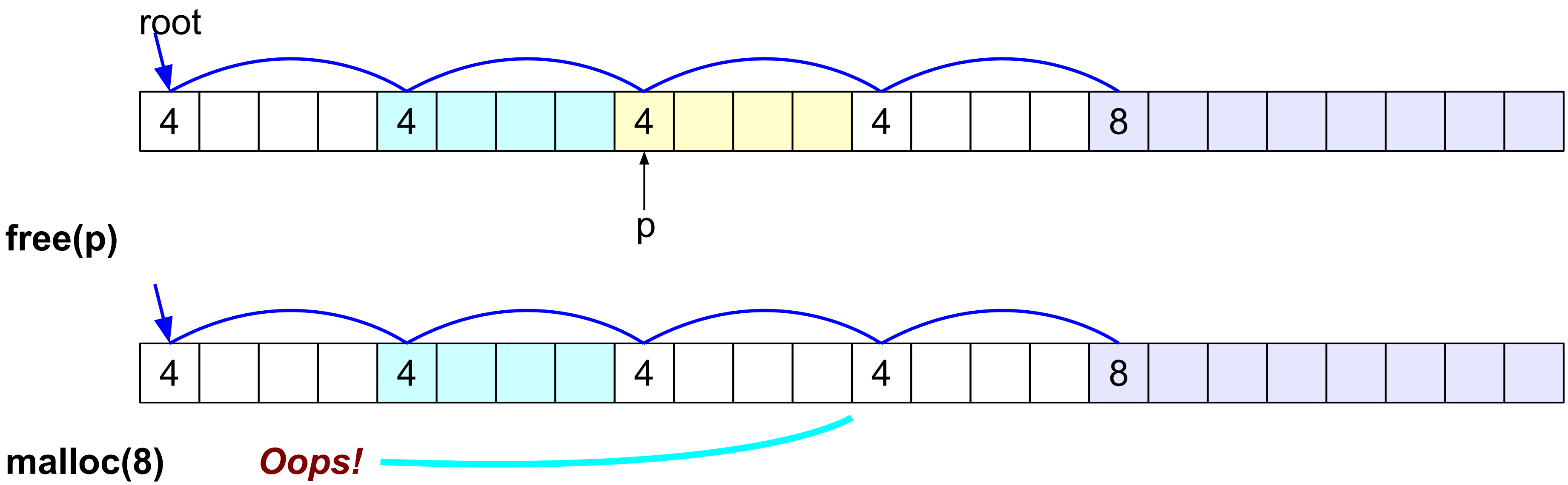
- Requirements:
  - tells us where the blocks are, how big they are, and whether they are free
  - must be able to update the data during calls to malloc and free
  - need to be able to find the **next free block** which is a “good enough fit” for a given payload
  - need to be able to quickly mark a 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



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

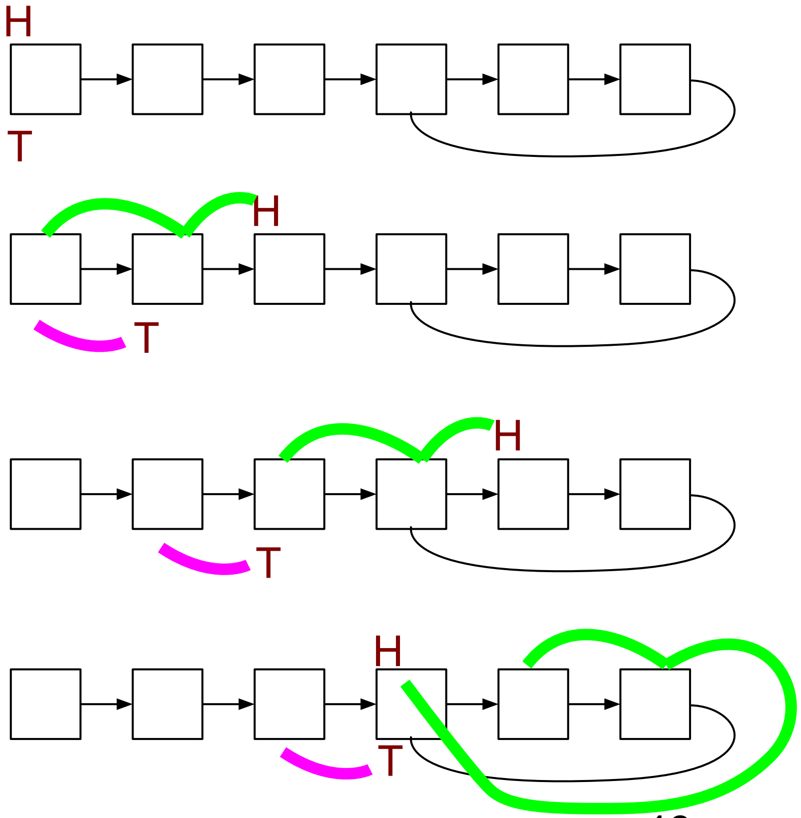
    addr(prev) < addr(curr) < addr(next)
    - pro: lower fragmentation than LIFO
    - con: requires search

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 malloclab
  - but be careful – this can easily lead to hard-to-find errors

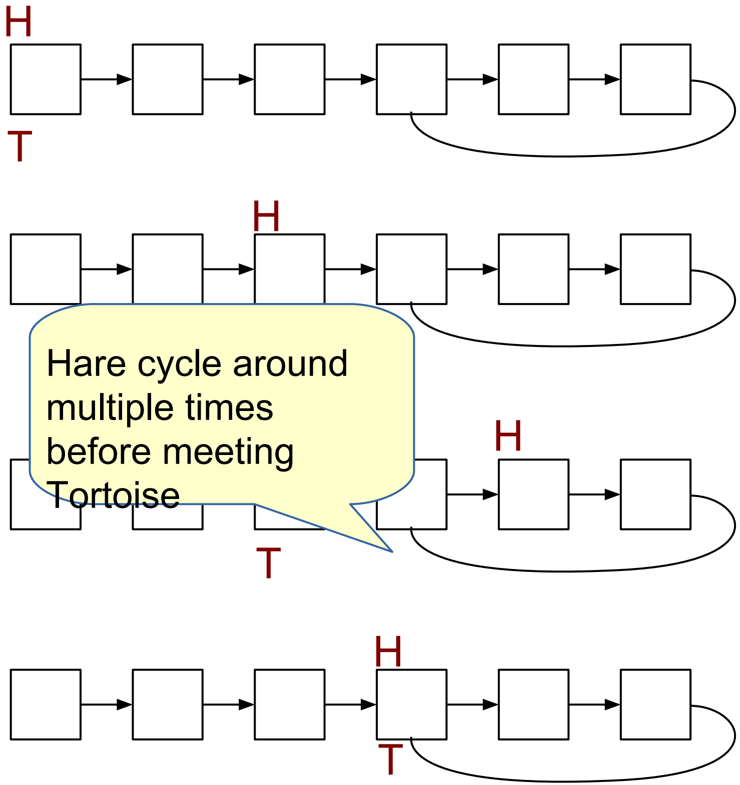
Cycle Checking: Hare and Tortoise Algorithm

- 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



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



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