Malloc Lab

15-213: Introduction to Computer Systems
Recitation 11: Nov. 4, 2013

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Recitation A

Weekly Update

- **Malloc lab is out**
  - Due Thursday, Nov. 14
  - Start early
  - Seriously... start early.

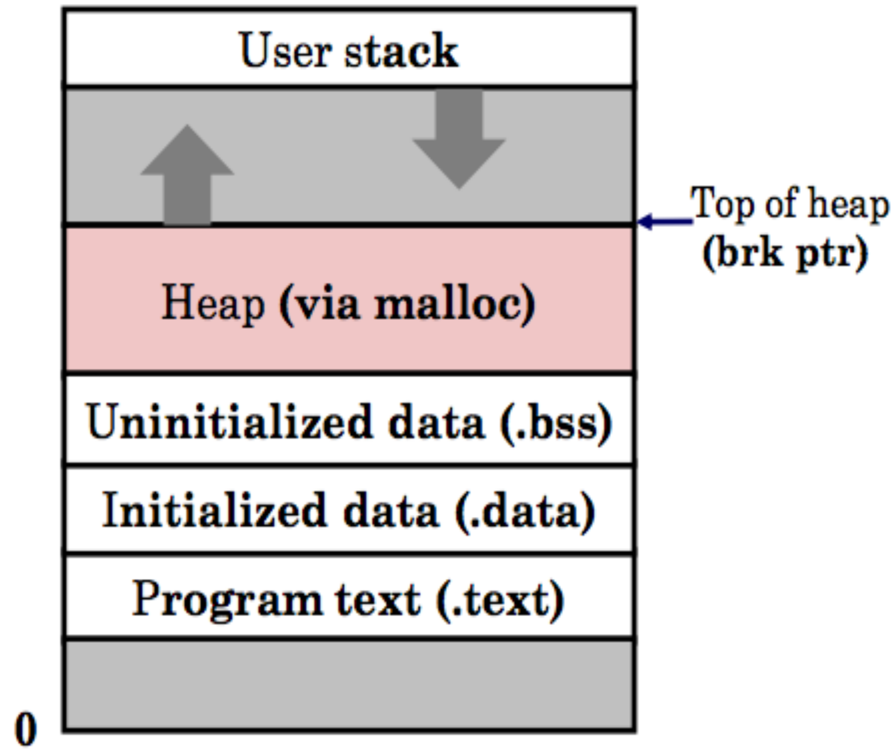
  - “It is possible to write an efficient malloc package with a few pages of code. However, we can guarantee that it will be some of the most difficult and sophisticated code you have written so far in your career.”

Agenda

- **Malloc Overview**
- Casting & Pointer Review
- Macros & Inline Functions
- Malloc Design
- Debugging & an Action Plan

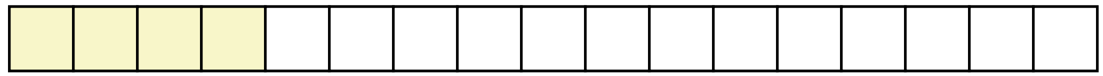
Dynamic Memory Allocators

- Are used to acquire memory for data structures whose size is known only at run time.
- Manage area in a part of memory known as the heap.

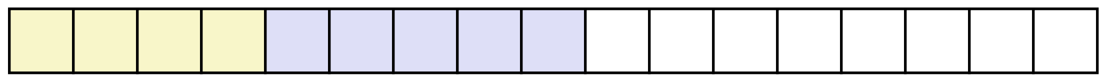


Allocation Example

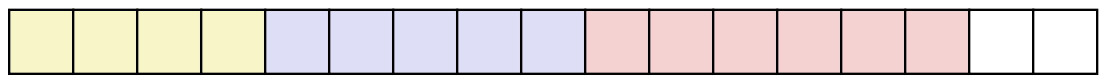
`p1 = malloc(4)`



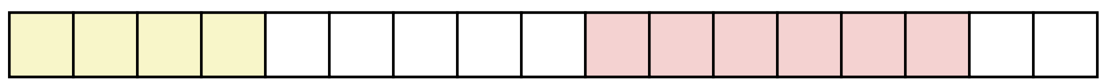
`p2 = malloc(5)`



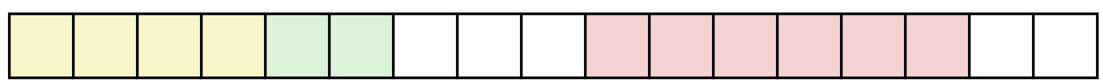
`p3 = malloc(6)`



`free(p2)`



`p4 = malloc(2)`



Malloc Lab

- **Create a *general-purpose* allocator that dynamically modifies the size of the heap as required.**
- **The driver calls your functions on various trace files to simulate placing data in memory.**
- **Grade is based on:**
  - Space utilization (minimizing fragmentation)
  - Throughput (processing requests quickly)
  - Your heap checker
  - Style & correctness, hand-graded as always

Functions You Will Implement

- **`mm_init`** initializes the heap before malloc is called.
- **`malloc`** returns a pointer to a free block (>= req. size).
- **`calloc`** same, but zeros the memory first.
- **`realloc`** changes the size of a previously allocated block. (May move it to another location.)
- **`free`** marks allocated memory available again.
- **`mm_checkheap`** debugging function (more on this later)

Functions You May Use

- **mem_sbrk**
  - Used for expanding the size of the heap.
  - Allows you to dynamically increase your heap size as required.
  - Helpful to initialize your heap.
  - Returns a pointer to first byte in newly allocated heap area.
- **mem_heap_lo**
  - Pointer to first byte of heap
- **mem_heap_hi**
  - Pointer to last byte of heap
- **mem_heapsize**
- **mem_pagesize**

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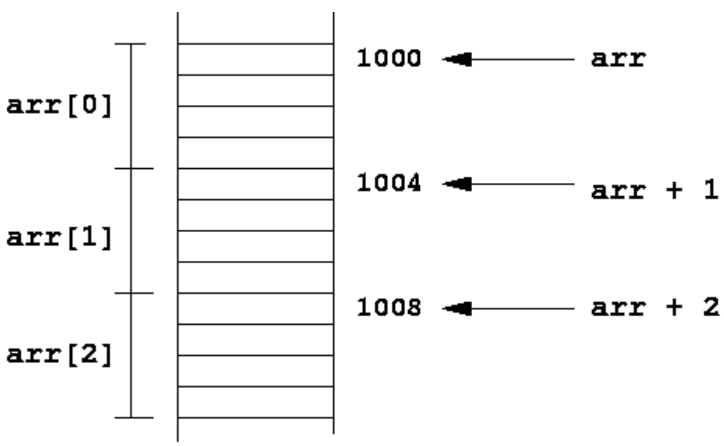
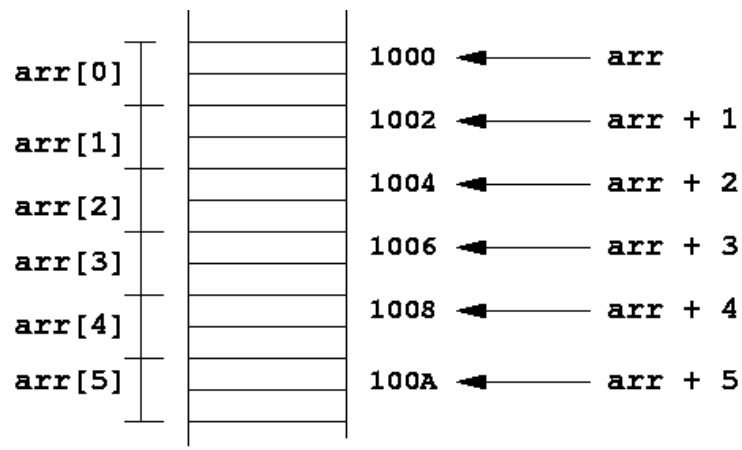
Pointer Arithmetic

- `*(arr + i)` is equivalent to `arr[i]`
- Thus the result of arithmetic involving pointers depends on the type of the data the pointer points at.

```
int *arr     = 0x1000          short *arr   = 0x1000
arr + 1      = 0x1004          arr + 1      = 0x1002
```





- So `ptr + i` is really `ptr + (i * sizeof(ptr-type))`

example and pictures from http://www.cs.umd.edu/class/spring2003/cmsc311/Notes/BitOp/pointer.html

Pointer Casting

- **Pointer casting can thus be used to make sure the pointer arithmetic comes out right.**
- **Since chars are 1 byte, casting a pointer as a char pointer then makes arithmetic on it work "normally."**

```
int  *ptr  = 0x10203040

char *ptr2 = (char *)ptr + 2    = 0x10203042

char *ptr3 = (char *) (ptr + 2) = 0x10203048
```

Examples

1.
```
int *ptr  = (int *) 0x12341234;
int *ptr2 = ptr + 1;                     = 0x12341238
```

2.
```
char *ptr  = (char *) 0x12341234;
char *ptr2 = ptr + 1;                    = 0x12341235
```

3.
```
void *ptr  = (int *) 0x12341234;
void *ptr2 = ptr + 1;                    = 0x12341235
```

4.
```
int *ptr  = (int *) 0x12341234;
int *ptr2 = ((int *) (((char *) ptr) + 1)));
                                         = 0x12341235 ☹
```

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- **Macros & Inline Functions**
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Macros

```
#define   NAME   replacement-text
```

- Maps “name” to a definition or instruction.
- Macros are expanded by the preprocessor, i.e., before compile time.
- They’re faster than function calls.
- For malloc lab: use macros to give you quick (and reliable) access to header information — payload size, valid bit, pointers, etc.

Macros

- **Useful for "magic number" constants – acts like a naïve search-and-replace**
  - `#define ALIGNMENT 8`
- **Useful for simple accesses and computations**
  - **Use parentheses** for computations.

```
#define     multByTwoA(x)     2*x
#define     multByTwoB(x)     2*(x)
```

  - `multByTwoA(5+1)` **= 2*5+1** **= 11**
  - `multByTwoB(5+1)` **= 2*(5+1)** **= 12**

Macros

- **Useful for debugging**
  - `__FILE__` is the file name (%s)
  - `__LINE__` is the line number (%d)
  - `__func__` is the function it's in (%s)

```
#include <stdio.h>

int hello(){
        printf("hello from function %s\n", __func__);
}

int main(){
        hello();
        printf("This is line %d.\n", __LINE__);
        printf("Belongs to function: %s\n", __func__);
        printf("In filename: %s\n", __FILE__);
}
```

Output:

hello from function hello
This is line 9.
Belongs to function: main
In filename: macros.c

Macros

- **Useful for debugging: conditional printfs**

```
// #define DEBUG

# ifdef DEBUG
#define dbg_printf(...) printf(__VA_ARGS__)
#else
#define dbg_printf(...)
#endif
```

Inline Functions

- **Alternative to macros: still more efficient than a function call, and easier to get right!**

```
#define  max(A,B)  ((A) > (B) ? (A) : (B))
```

vs.

```
inline int max(int a, int b) {
  return a > b ? a : b?
}
```

- **The compiler replaces each *call* to the function with the code for the function itself.**
  (So, no stack setup, no call/ret.)
- **Useful for small, frequently called functions.**

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Malloc Design

- You have a ton of design decisions to make! ☺
- Thinking about fragmentation
- Method of managing free blocks
  - Implicit List
  - Explicit List
  - Segregated Free List
- Policy for finding free blocks
  - First fit
  - Next fit
  - Best fit
- Free-block insertion policy
- Coalescing (or not)

Fragmentation

- **Internal fragmentation**
  - Result of payload being smaller than block size.
    - Header & footer
    - Padding for alignment
  - Mostly unavoidable.

Fragmentation

- **External fragmentation**
  - Occurs when there is enough aggregate heap memory, but no single free block is large enough

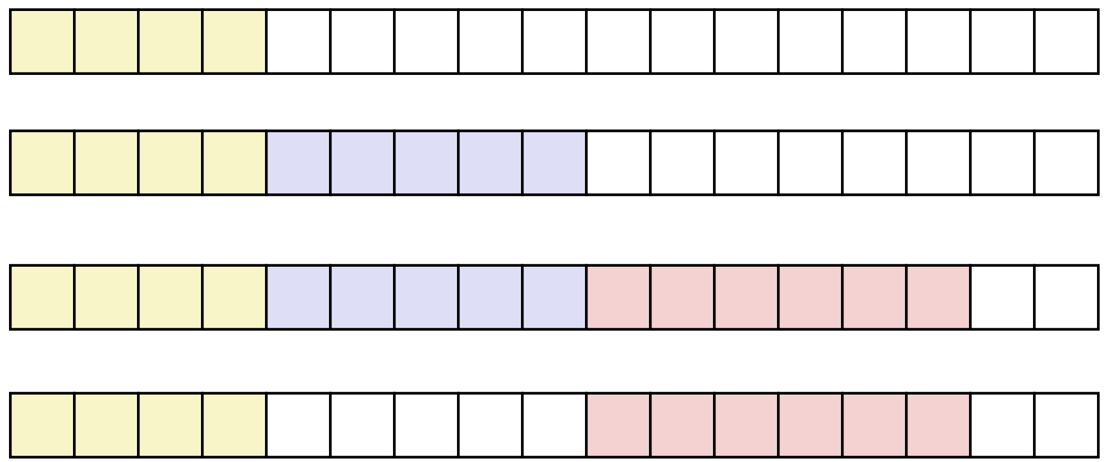
```
p1 = malloc(4)

p2 = malloc(5)

p3 = malloc(6)

free(p2)

p4 = malloc(6)
```

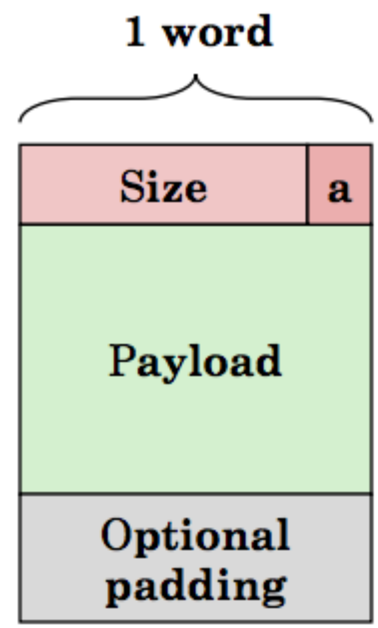


Oops! (what would happen now?)

  - Some policies are better than others at minimizing external fragmentation.

Managing free blocks

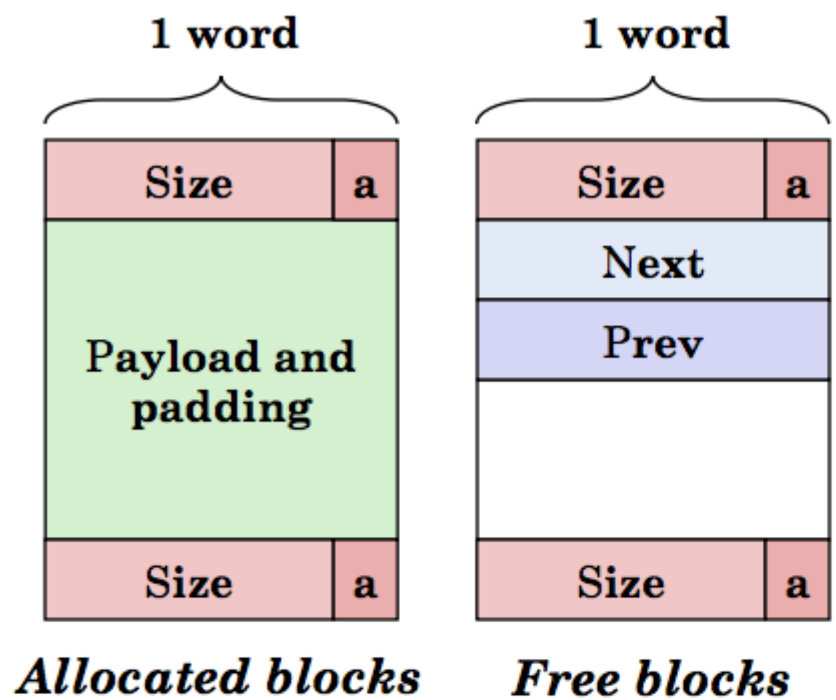
- **Implicit list**
  - Uses block length to find the next block.
  - Connects *all* blocks (free and allocated).
  - All blocks have a 1-word header before the payload that tells you:
    - its size (so you know where to look for the next header) and
    - whether or not it's allocated
  - You may also want a 1-word footer so that you can crawl the list in both directions to coalesce.

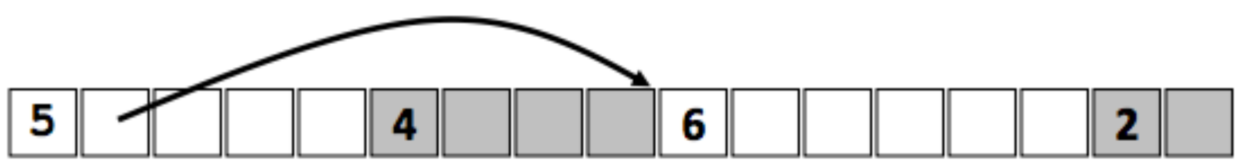


Format of allocated and free blocks

Managing free blocks

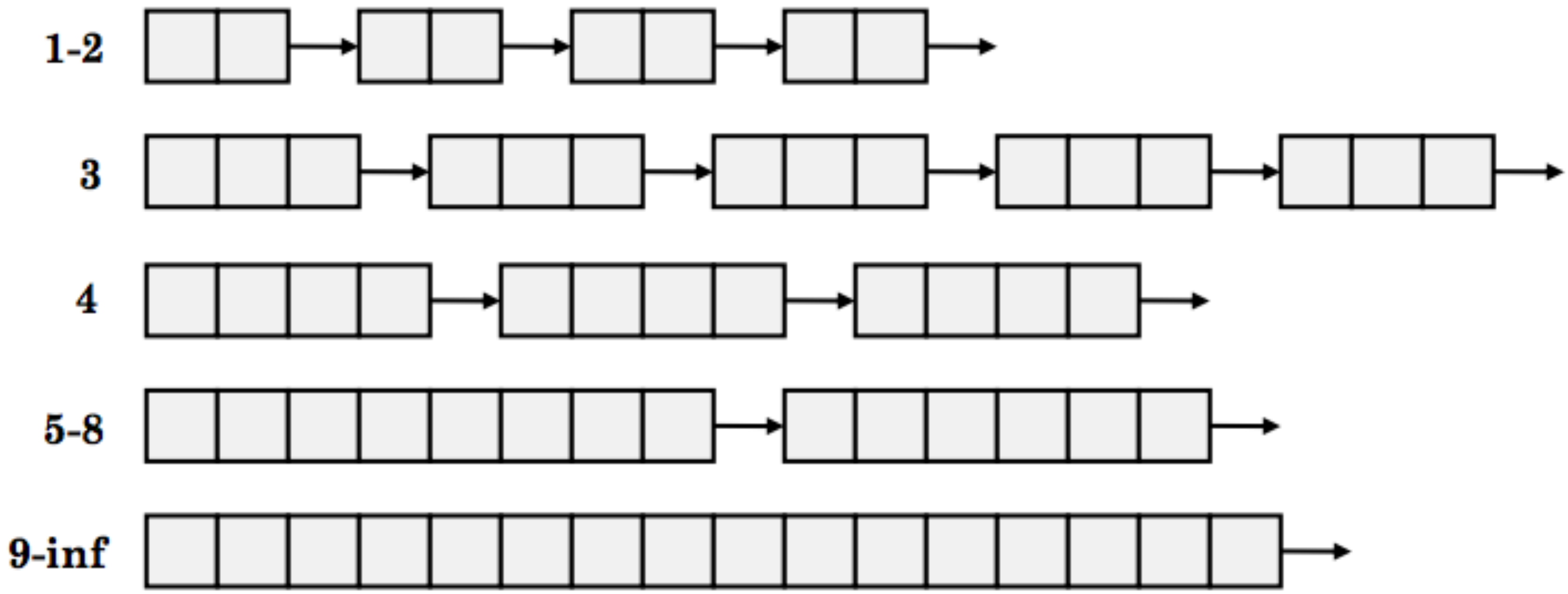
- **Explicit list**
  - A list of *free* blocks, each of which stores a pointer to the next free block.
  - Since only free blocks store this info, the pointers can be stored where the payload would be.
  - This allows you to search the free blocks much more quickly.
  - Requires an insertion policy.





Managing free blocks

- **Segregated free list**
  - Each size class has its own free list.
  - Finding an appropriate block is much faster (so next fit may become good enough); coalescing and reinsertion are harder.



Finding free blocks

- **First fit**
  - Start from the beginning.
  - Find the first free block.
  - Linear time.
- **Next fit**
  - Search starting from where previous search finished.
  - Often faster than first fit.
- **Best fit**
  - Choose the free block closet in size to what you need.
  - Better memory utilization (less fragmentation), *but* it's very slow to traverse the full list.
- **What if no blocks are large enough?**
  - Extend the heap

Insertion policy

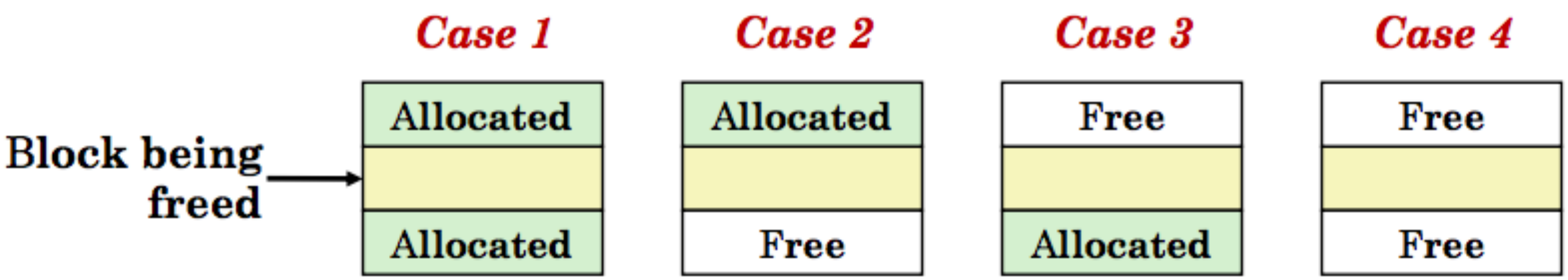
- **Where should free blocks go?**
  - Blocks that have just been `free()`d.
  - "Leftovers" when allocating *part* of a block.

- **LIFO (Last In First Out)**
  - Insert the free block at the beginning of the list.
  - Simple and constant time.
  - Studies suggest potentially worse fragmentation.

- **Address-Ordered**
  - Keep free blocks list sorted in address order.
  - Studies suggest better fragmentation.
  - Slower since you have to find where it belongs.

Coalescing policy

- **Use the block size in the header to look left & right.**



- **Implicit list:**
  - Write new size in the header of first block & footer of last block.
- **Explicit list:**
  - Must also relink the new block according to your insertion policy.
- **Segregated list:**
  - Must also use the new block size to figure out which bucket to put the new block in.

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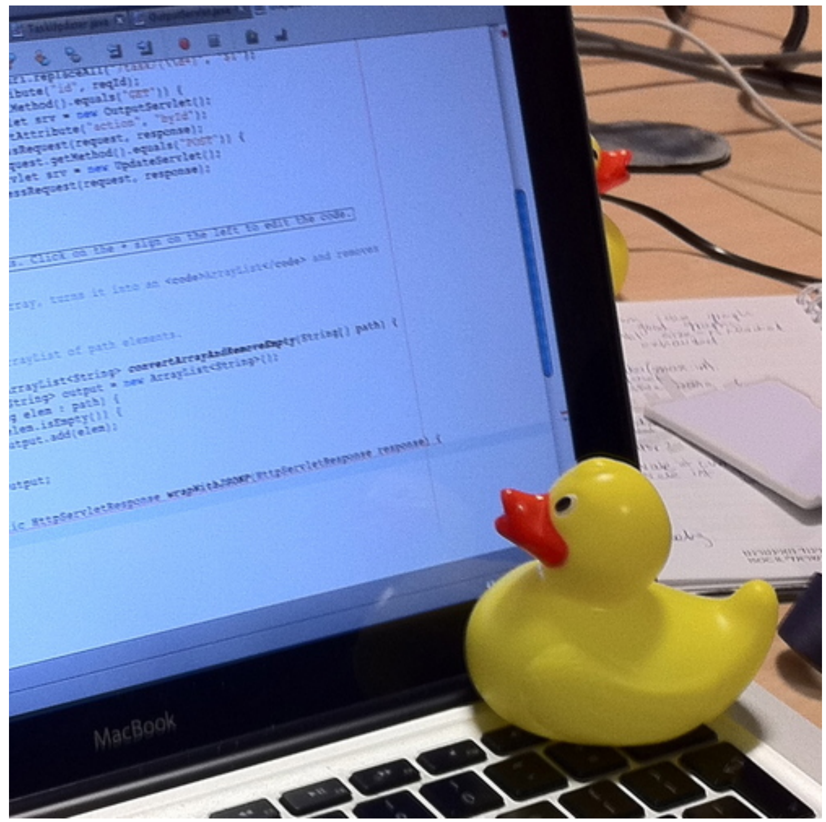
Debugging

- **Debugging malloc lab is hard!**
  - rubber duck debugging
  - GDB
  - valgrind
  - mm_checkheap



mm_checkheap

- **mm_checkheap**
  - A consistency checker to check the correctness of your heap.
  - **Write it early** and update as needed.
  - What to check for? Anything that could go wrong!
    - address alignment
    - consistency of header & footer
    - whether free blocks are coalescing
    - consistency of linked list pointers
    - whether blocks are being placed in the right segregated list
    - …
  - Focus on correctness, not efficiency.
  - Once you get it working, it should be *silent* and only output when your heap has messed up.
  - You can insert a call to it before & after functions to pin down exactly where things are going wrong.
  - **Do not request debugging help from a TA without a working checkheap.**

Suggested action plan

1. Start early — make the most use of empty office hours.
2. Keep consulting the handout (e.g. the "rules") throughout your coding process.
3. Understand and implement a basic implicit list design.
4. Write your heap checker.
5. Come up with something faster/more memory efficient.
6. Implement it.
7. Debug it.
8. Git commit and/or submit.
9. Goto 5.

Questions?

- GOOD LUCK!!