Agenda

- Macros / Inline functions
- Quick pointer review
- Malloc

Malloc Lab Preview

- **You will write your own dynamic storage allocator – i.e., your own `malloc`, `free`, `realloc`, `calloc`.**
- **This week in class, you will learn about different ways to keep track of free and allocated blocks of memory.**
  - Implicit linked list of blocks.
  - Explicit linked list of *free* blocks.
  - Segregated lists of different *size* free blocks.
- **Other design decisions:**
  - How will you look for free blocks? (First fit, next fit, best fit…)
  - Should the linked lists be doubly linked?
  - When do you coalesce blocks?
- **This is exactly what you'll do in this lab, so pay lots of attention in class. ☺**

Malloc Lab Preview

- **If you haven't been using version control so far, this is a good time to start.**
- **Workflow:**
  - Implement indirect linked lists. Make sure it works.
  - Implement explicit linked lists. Make sure it still works.
  - Implement segregated lists. Make sure it still works.
  - You WILL break things and need to revert.
- **Barebones guide to using git:**
  - `git init` starts a local repository.
  - `git add foo.c` adds foo.c to that repository.
  - `git commit -a –m 'Describe changes here'` updates your repository with the current state of all files you've added.

Macros / Inline Functions

Macros

- **Pre-compile time**
- **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

Inline Functions

- **What's the keyword `inline` do?**
  - At **compile-time** replaces "function calls" with code
- **More efficient than a normal function call**
  - Less overhead – no need to set up stack/function call
  - Useful for functions that are
    - Called frequently
    - Small, e.g., int add(int x, int y);

Differences

- **Macros done at pre-compile time**
- **Inline functions done at compile time**
  - Stronger type checking / Argument consistency
- **Macros cannot return anything (why not?)**
- **Macros can have unintended side effects**
  - #define xsquared(x) (x*x)
  - What happens when xsquared(x++) is called?
- **Hard to debug macros – errors generated on expanded code, not code that you typed**

Macros / Inline Functions

- **You will likely use both in malloc lab**
- **Macros are good for small tasks**
  - Saves work in retyping tedious calculations
  - Can make code easier to understand
    - HEADER(ptr) versus doing the pointer arithmetic
- **Some things are hard to code in macros, so this is where inline functions come into play**
  - More efficient than normal function call
  - More expressive than macros

Pointers: casting, arithmetic, and dereferencing

Pointer casting

- **Cast from**
  - <type_a>* to <type_b>*
    - Gives back the same value
    - Changes the behavior that will happen when dereferenced
  - <type_a>* to integer/ unsigned int
    - Pointers are really just 8-byte numbers
    - Taking advantage of this is an important part of malloc lab
    - Be careful, though, as this can easily lead to errors
  - integer/ unsigned int to <type_a>*

Pointer arithmetic

- The expression `ptr + a` doesn't mean the same thing as it would if `ptr` were an integer.
- Example:
  ```
  type_a* pointer = …;
  (void *) pointer2 = (void *) (pointer + a);
  ```
- This is really computing:
  - `pointer2 = pointer + (a * sizeof(type_a))`
  - `lea (pointer, a, sizeof(type_a)), pointer2;`
- Pointer arithmetic on `void*` is undefined

Pointer arithmetic

- ```
  int * ptr = (int *)0x12341230;
  int * ptr2 = ptr + 1;
  ```

- ```
  char * ptr = (char *)0x12341230;
  char * ptr2 = ptr + 1;
  ```

Pointer arithmetic

- `int * ptr = (int *)0x12341230;`
  `int * ptr2 = ptr + 1; //ptr2 is 0x12341234`

- `char * ptr = (char *)0x12341230;`
  `char * ptr2 = ptr + 1; //ptr2 is 0x12341231`

Pointer dereferencing

- **Basics**
  - It must be a POINTER type (or cast to one) at the time of dereference
  - Cannot dereference expressions with type `void*`
  - Dereferencing a `t*` evaluates to a value with type `t`

Pointer dereferencing

- What gets "returned?"

```
int * ptr1 = malloc(sizeof(int));
*ptr1 = 0xdeadbeef;

int val1 = *ptr1;
int val2 = (int) *((char *) ptr1);
```

What are val1 and val2?

Pointer dereferencing

- **What gets "returned?"**

```
int * ptr1 = malloc(sizeof(int));
*ptr1 = 0xdeadbeef;


int val1 = *ptr1;
int val2 = (int) *((char *) ptr1);
```

```
//   val1 = 0xdeadbeef;
//   val2 = 0xffffffef;
```

Malloc

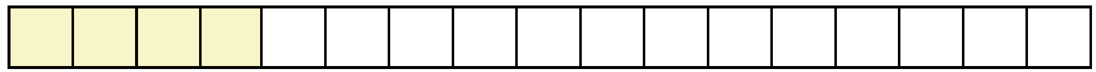
Malloc basics

- **What is dynamic memory allocation?**

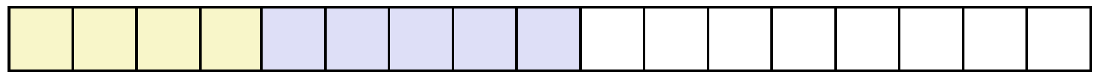
- **Terms you will need to know**
  - malloc/ calloc / realloc
  - free
  - sbrk
  - payload
  - fragmentation (internal vs. external)
  - coalescing
    - Bi-directional
    - Immediate vs. Deferred

Allocation Example

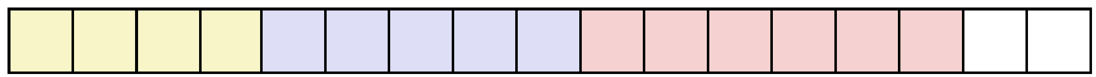
`p1 = malloc(4)`



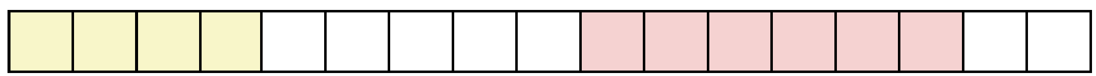
`p2 = malloc(5)`



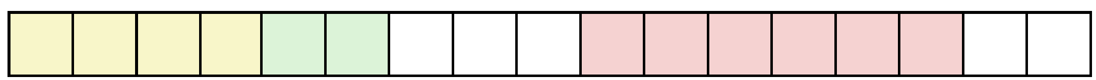
`p3 = malloc(6)`



`free(p2)`



`p4 = malloc(2)`



Fragmentation

- **Internal fragmentation**
  - Result of **payload** being smaller than block size.
  - `void * m1 = malloc(3); void * m1 = malloc(3);`
  - `m1,m2` both have to be aligned to 8 bytes…

- **External fragmentation**

External Fragmentation

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

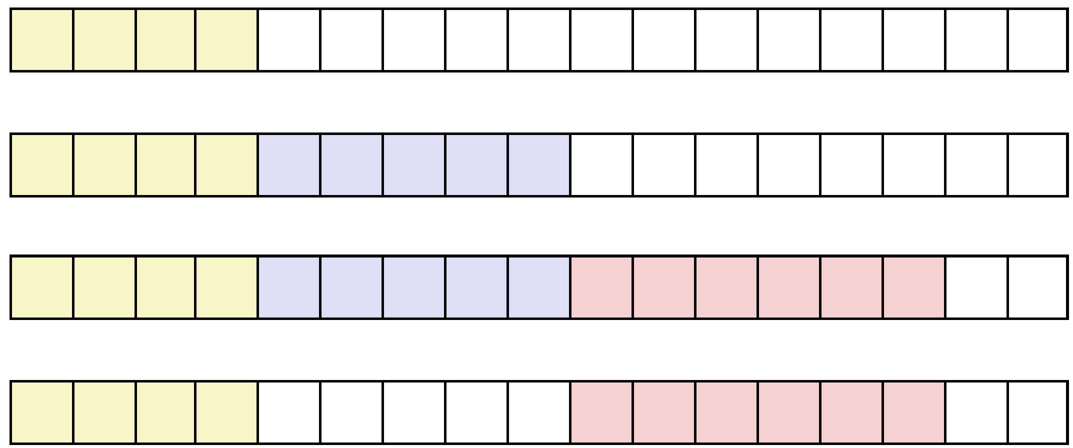
```
p1 = malloc(4)

p2 = malloc(5)

p3 = malloc(6)

free(p2)

p4 = malloc(6)
```



Oops! (what would happen now?)

- Depends on the pattern of future requests
  - Thus, difficult to measure

Implementation Hurdles

- **How do we know where the blocks are?**
- **How do we know how big the blocks are?**
- **How do we know which blocks are free?**
- **Remember: can’t buffer calls to malloc and free… must deal with them real-time.**
- **Remember: calls to `free` only takes a pointer, not a pointer and a size.**
- **Solution: <u>Need a data structure to store information on the “blocks”</u>**
  - Where do I keep this data structure?
  - We can’t allocate a space for it, that’s what we are writing!

The data structure

- **Requirements:**
  - The data structure needs to tell us where the blocks are, how big they are, and whether they're free
  - We need to be able to CHANGE the data structure during calls to malloc and free
  - We need to be able to find the **next free block** that is "a good fit for" a given payload
  - We need to be able to quickly mark a block as free/allocated
  - We need to be able to detect when we're out of blocks.
    - What do we do when we're out of blocks?

The data structure

- **The data structure IS your memory!**
- **A start:**
  - <h1> <pl1> <h2> <pl2> <h3> <pl3>
  - What goes in the header?
    - That's your job!
  - Lets say somebody calls free(p2), how can I coalesce?
    - Maybe you need a **footer**? Maybe not?

The data structure

- **Common types**
  - Implicit List
    - Root -> block1 -> block2 -> block3 -> …
  - Explicit List
    - Root -> free block 1 -> free block 2 -> free block 3 -> …
  - Segregated List
    - Small-malloc root -> free small block 1 -> free small block 2 -> …
    - Medium-malloc root -> free medium block 1 -> …
    - Large-malloc root -> free block chunk1 -> …

Implicit List

- **From the root, can traverse across blocks using headers**
- **Can find a free block this way**
- **Can take a while to find a free block**
  - How would you know when you have to call sbrk?

Explicit List

- **Improvement over implicit list**
- **From a root, keep track of all free blocks in a (doubly) linked list**
  - Remember a doubly linked list has pointers to next and previous
- **When malloc is called, can now find a free block quickly**
  - What happens if the list is a bunch of small free blocks but we want a really big one?
  - How can we speed this up?

Segregated List

- **An optimization for explicit lists**
- **Can be thought of as multiple explicit lists**
  - What should we group by?
- **Grouped by size – let’s us quickly find a block of the size we want**
- **What size/number of buckets should we use?**
  - This is up to you to decide

Design Considerations

- I found a chunk that fits the necessary payload… should I look for a better fit or not? (First fit vs. Best fit)
- Splitting a free block:

```
void* ptr = malloc(200);
free(ptr);
ptr = malloc(50); //use same space, then "mark" remaining
bytes                           as free

void* ptr = malloc(200);
free(ptr);
ptr = malloc(192);//use same space, then "mark" remaining
bytes                           as free??
```

Design Considerations

- **Free blocks: address-ordered or LIFO**
  - What’s the difference?
  - Pros and cons?
- **Coalescing**
  - When do you coalesce?
- **You will need to be using an explicit list at minimum score points**
  - But don’t try to go straight to your final design, build it up iteratively.

Heap Checker

- **Part of the assignment is writing a heap checker**
  - This is here to help you.
  - Write the heap checker as you go, don't think of it as something to do at the end
  - A good heap checker will make debugging much, much easier
- **Heap checker tips**
  - Heap checker should run silently until it finds an error
    - Otherwise you will get more output than is useful
    - You might find it useful to add a "verbose" flag, however
  - Consider using a macro to turn the heap checker on and off
    - This way you don't have to edit all of the places you call it
  - There is a built-in macro called `__LINE__` that gets replaced with the line number it's on
    - You can use this to make the heap checker tell you where it failed

Demo

- Running Traces
- Heap checker
- Using `gprof` to profile