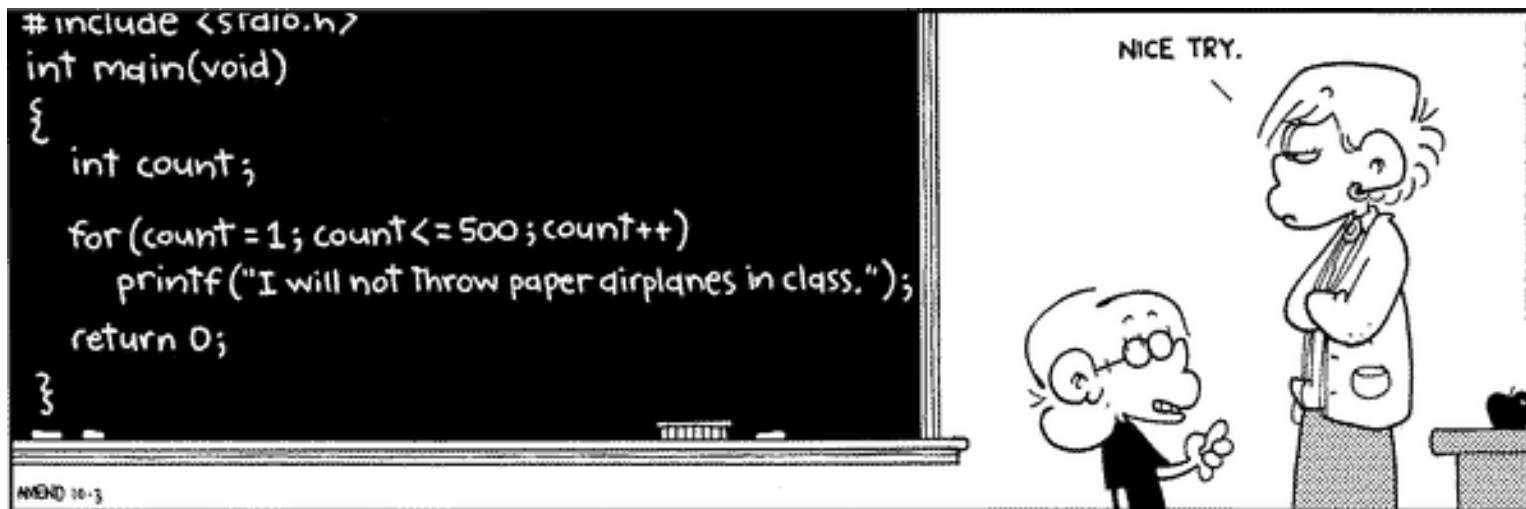


Admin

- Halfway there!
- A deep appreciation for printf -- and you'll appreciate having it!
- Project proposals due tomorrow (Saturday)



Today: Thanks for the memory!

Linker memory map, address space layout

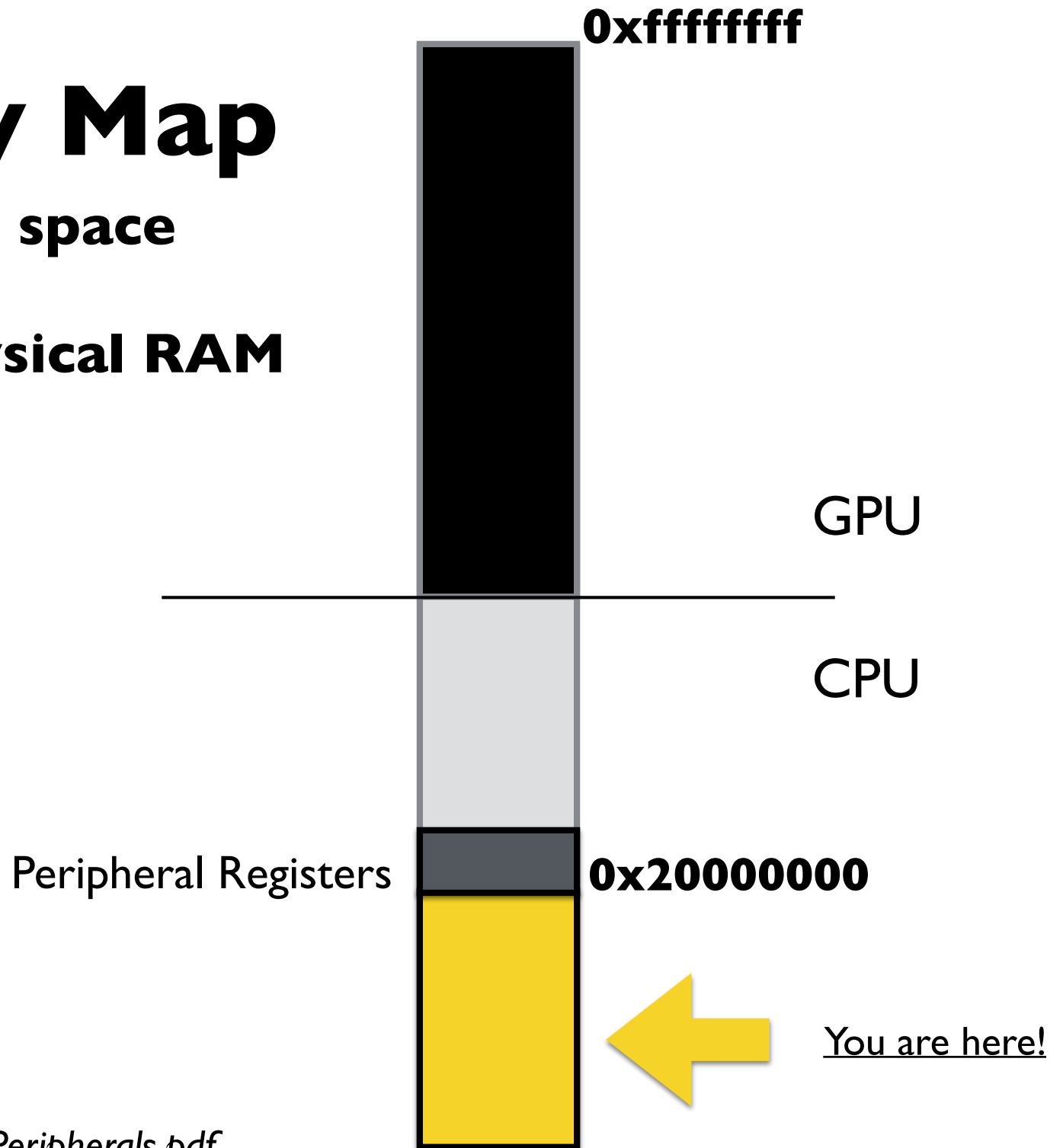
Loading, how an executable file becomes a running program

Heap allocation, malloc and free

Memory Map

32-bit address space

512 MB of physical RAM



SECTIONS

```
{
    .text 0x8000 : { start.o(.text*)
                    *(.text*)}

    .data :        { *(.data*) }
    .rodata :      { *(.rodata*) }

    __bss_start__ = .;
    .bss :         { *(.bss*)
                    *(COMMON) }
    __bss_end__ = ALIGN(8);
}
```

Use this memory for heap 

(zeroed data) **.bss**

(read-only data) **.rodata**

(initialized data) **.data**

.text



0x8000000

```
_start:
    mov sp, #0x8000000
    mov fp, #0
    bl _cstart
```

```
void _cstart(void) {
    int *bss = &__bss_start__;
    while (bss < &__bss_end__)
        *bss++ = 0;
}

main();
}
```

__bss_end__

__bss_start__

blink.bin

0x8000

Global allocation

- + **Convenient**

- Fixed location, shared across entire program

- + **Fast, plentiful**

- No explicit allocation/deallocation

- But have to send over serial to bootloader (can be slow)

- **Size fixed at declaration, no option to resize**

- +/- **Scope and lifetime is global**

- No encapsulation, hard to track use/dependencies

- One shared namespace, have to manually manage conflicts

- Static variables can address some issues

- Frowned upon stylistically (advanced systems reasons)

Stack allocation

- + **Convenient**

 - Automatic alloc/dealloc on function entry/exit

- + **Fast**

 - Fast to allocate/deallocate, good locality

- **Usually don't allocate large chunks (megabytes)**

- **Size fixed at declaration, no option to resize**

- +/- **Scope/lifetime dictated by control flow**

 - Private to stack frame

 - Does not persist after function exits

- **Memory bug can corrupt execution**

Heap allocation

- + **Moderately efficient**

 - Have to search for available space, update record-keeping

- + **Very plentiful**

 - Heap enlarges on demand to limits of address space

- + **Versatile, under programmer control**

 - Can precisely determine scope, lifetime

 - Can be resized

- **Low type safety (can't access by value)**

 - Interface is raw void *, number of bytes

- **Lots of opportunity for error**

 - (allocate wrong size, use after free, double free)

- **Leaks**

- **Hard to track down sources of corruption**

Heap interface

```
void *malloc (size_t nbytes);  
void free (void *ptr);  
void *realloc (void *ptr, size_t nbytes);
```

void* pointer

"Generic" pointer, a memory address

Type of pointee is not specified, unknown

What you can do with a void*

Pass to/from function, pointer assignment

What you cannot do with a void*

Cannot dereference (must cast first)

Cannot do pointer arithmetic (cast to char * to manually control scaling)

Why do we need a heap?

Let's see an example!

code/heap/names.c

How to implement a heap

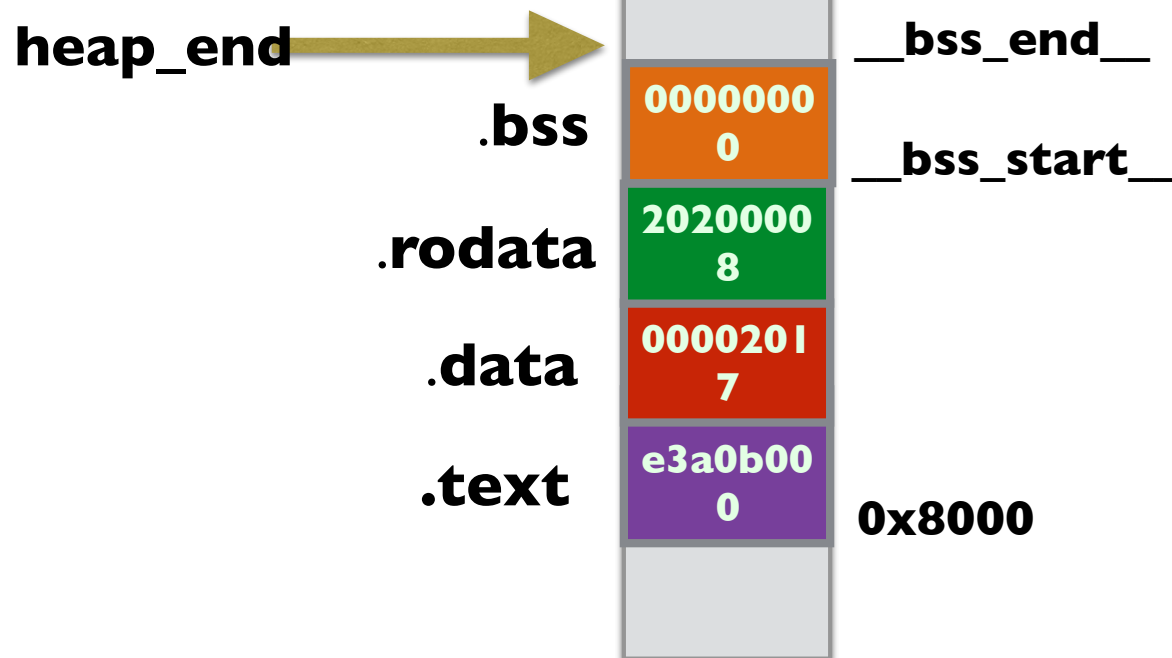


```

void *sbrk(int nbytes)
{
    static void *heap_end = &__bss_end__;

    void *prev_end = heap_end;
    heap_end = (char *)heap_end + nbytes;
    return prev_end;
}

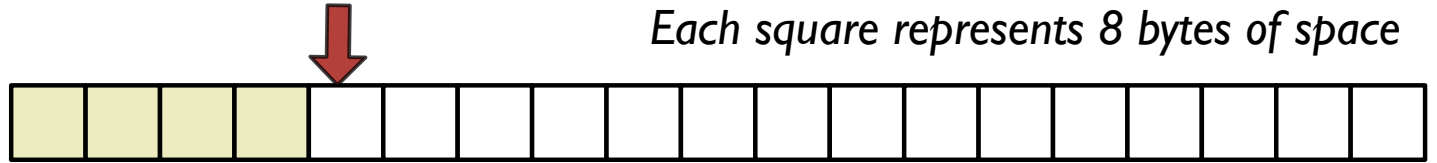
```



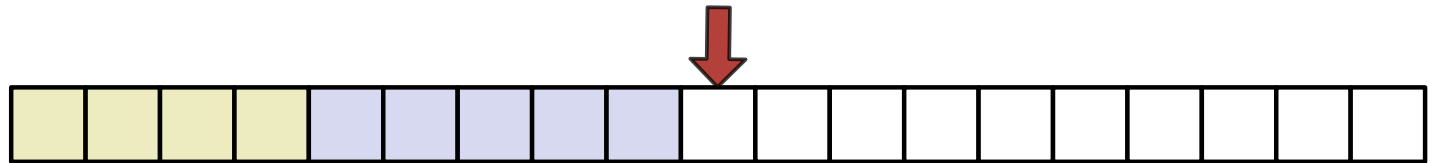
Tracing the bump allocator

Each square represents 8 bytes of space

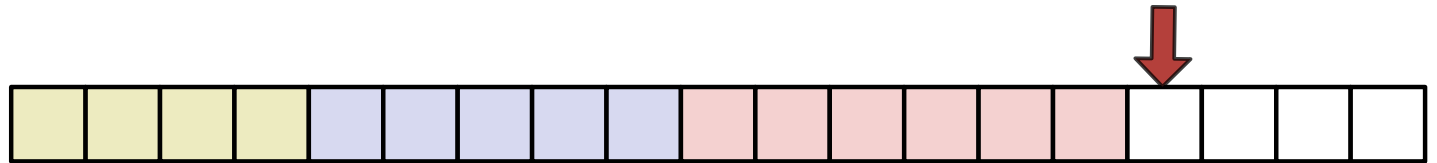
p1 = malloc(32)



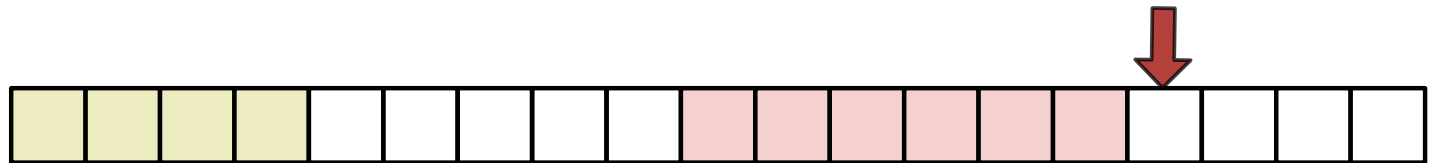
p2 = malloc(40)



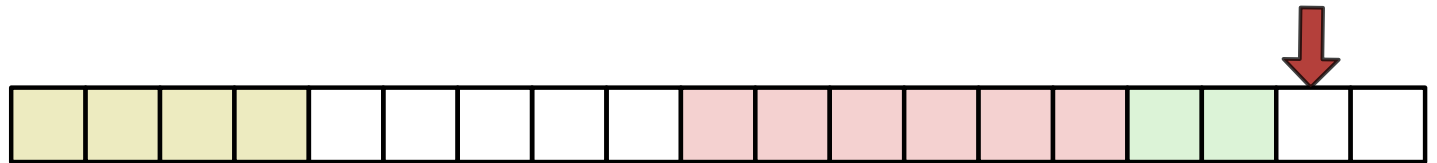
p3 = malloc(48)



free(p2)



p4 = malloc(16)



Bump Memory Allocator

`code/heap/malloc.c`

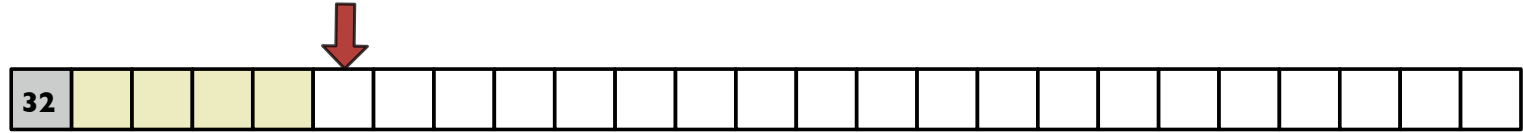
Evaluate bump allocator

- + Operations super-fast
- + Very simple code, easy to verify, test, debug
- No recycling/re-use
 - (in what situations will this be problematic?)
- Sad consequences when `sbrk()` advances into stack
 - (what can we do about that?)

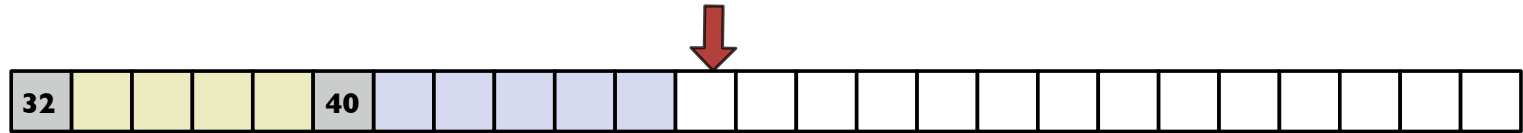
Pre-block header, implicit list

Each square represents 8 bytes of space, size recorded as total byte count

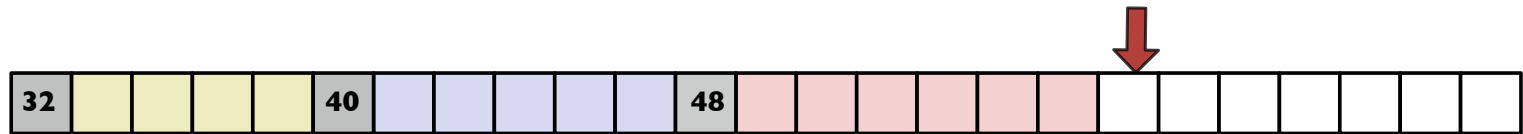
p1 = malloc(32)



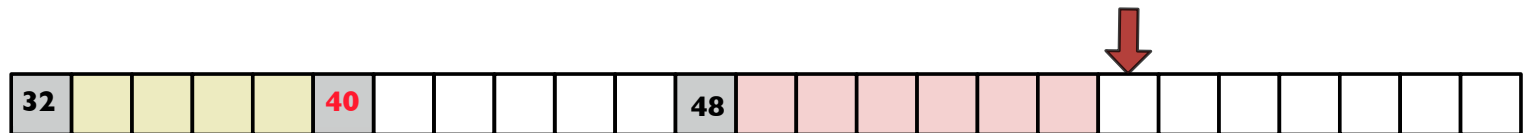
p2 = malloc(40)



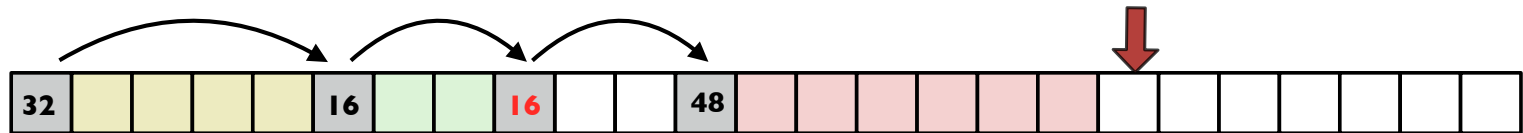
p3 = malloc(48)



free(p2)



p4 = malloc(16)



Header struct

```
struct header {
    unsigned int size;
    unsigned int status;
};                                     // sizeof(struct header) = 8 bytes

enum { IN_USE = 0, FREE = 1};

void *malloc(size_t nbytes)
{
    nbytes = roundup(nbytes, 8);
    size_t total_bytes = nbytes + sizeof(struct header);

    struct header *hdr = sbrk(total_bytes);
    hdr->size = nbytes;
    hdr->status = IN_USE;
    return hdr + 1;    // return address at start of payload
}
```

Challenges for malloc client

- **Correct allocation (size in bytes)**
- **Correct access to block (within bounds, not freed)**
- **Correct free (once and only once, at correct time)**

What happens if you...

- forget to free a block after you are done using it?
- access a memory block after you freed it?
- free a block twice?
- free a pointer you didn't malloc?
- access outside the bounds of a heap-allocated block?

Challenges for malloc implementor

just **malloc** is easy 😎

malloc with **free** is hard 🤔

Efficient **malloc** with **free**Yikes! ❓

Complex code (pointer math, typecasts)

Thorough testing is challenge (more so than usual)

Critical system component

correctness is non-negotiable, ideally fast and compact

Survival strategies:

draw pictures

printf (you've earned it!!)

early tests use examples small enough to trace by hand if need be
build up to bigger, more complex tests