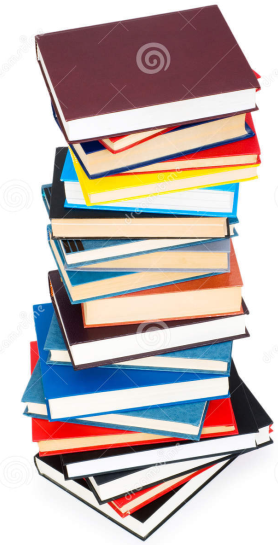
Goals for today



Leftover from previous

Stack, APCS full frame

Thanks for the memory!

Linker memory map

Address space layout

Loading

How an executable file becomes a running program

Heap allocation

Malloc, realloc, and free

This week:

printf perseverance and pride!!

```
// start.s
mov sp, #0x8000000
bl main
```

```
void main(void)
{
    delta(10,7);
}


int delta(int x, y)
{
   return abs(x - y);
}


int abs(int v)
{
   return v < 0 : -v : v;
}
```

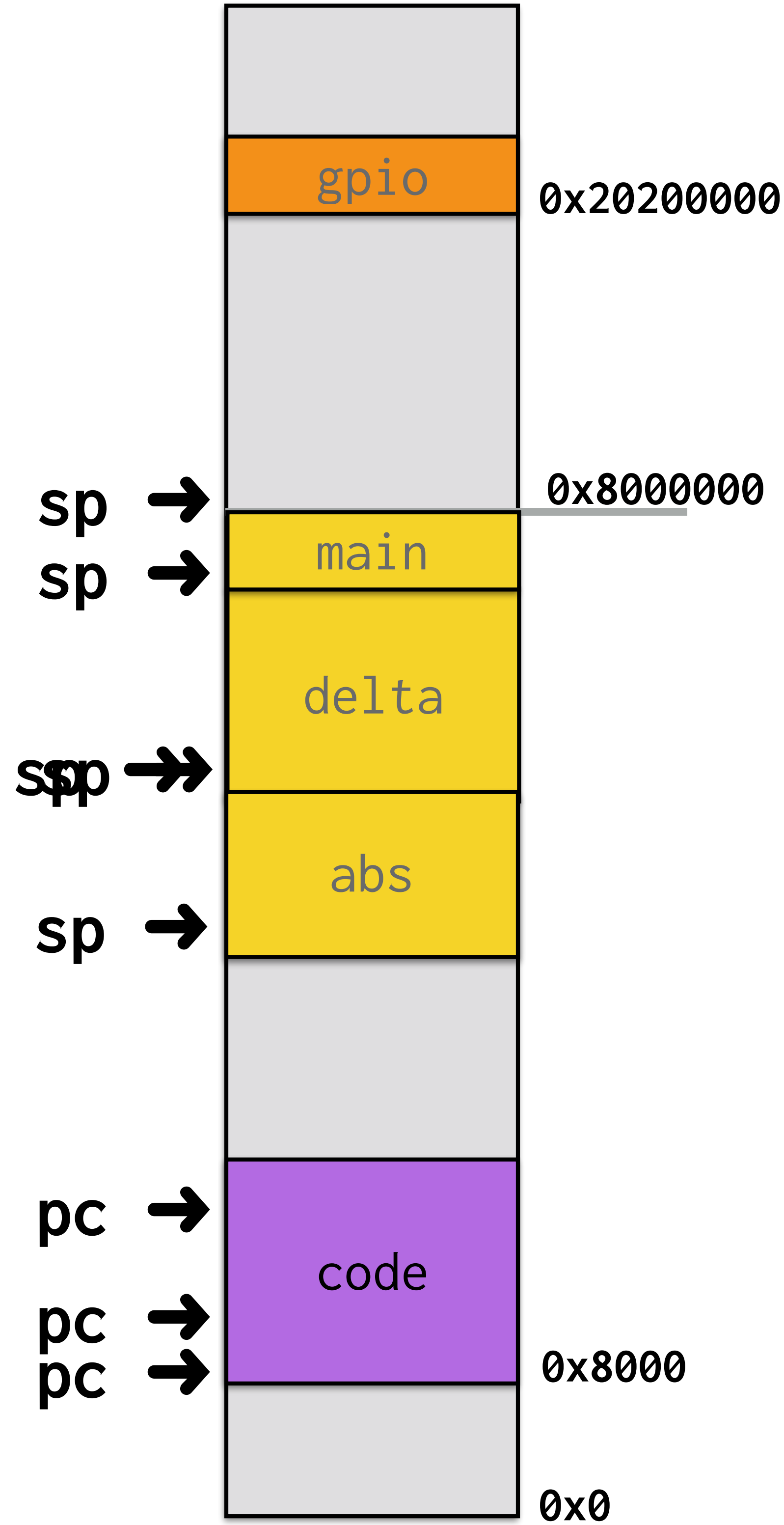


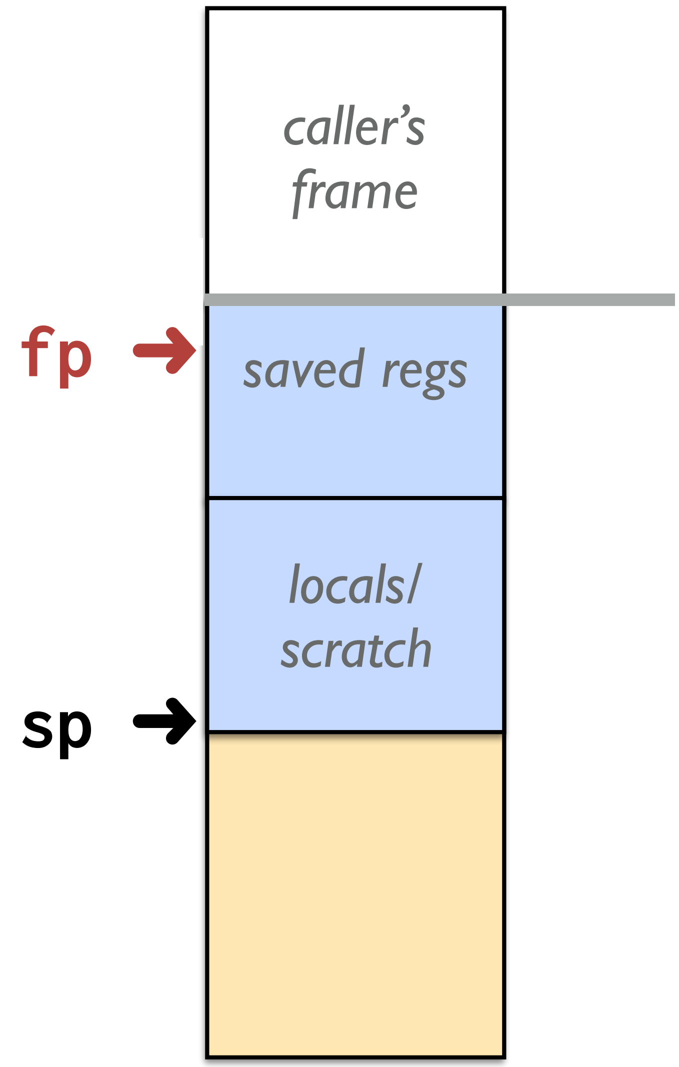
Diagram not to scale

Add frame pointer

Dedicate `fp` register to be used as fixed anchor

Assign on entry to new function to point to top of stack frame

`fp` doesn't change, can access data at fixed offset relative to `fp`



APCS “full frame”

APCS = ARM Procedure Call Standard

Conventions for frame pointer and frame layout

Enable reliable stack introspection

CFLAGS to enable: `-mapcs-frame`

`r11` used as `fp`

Adds a prolog/epilog to each function that sets up/tears down the standard frame and manages `fp`

Trace APCS full frame

Prolog

`push fp, sp*, lr, pc`

set `fp` to first word pushed

Body

`fp` stays anchored

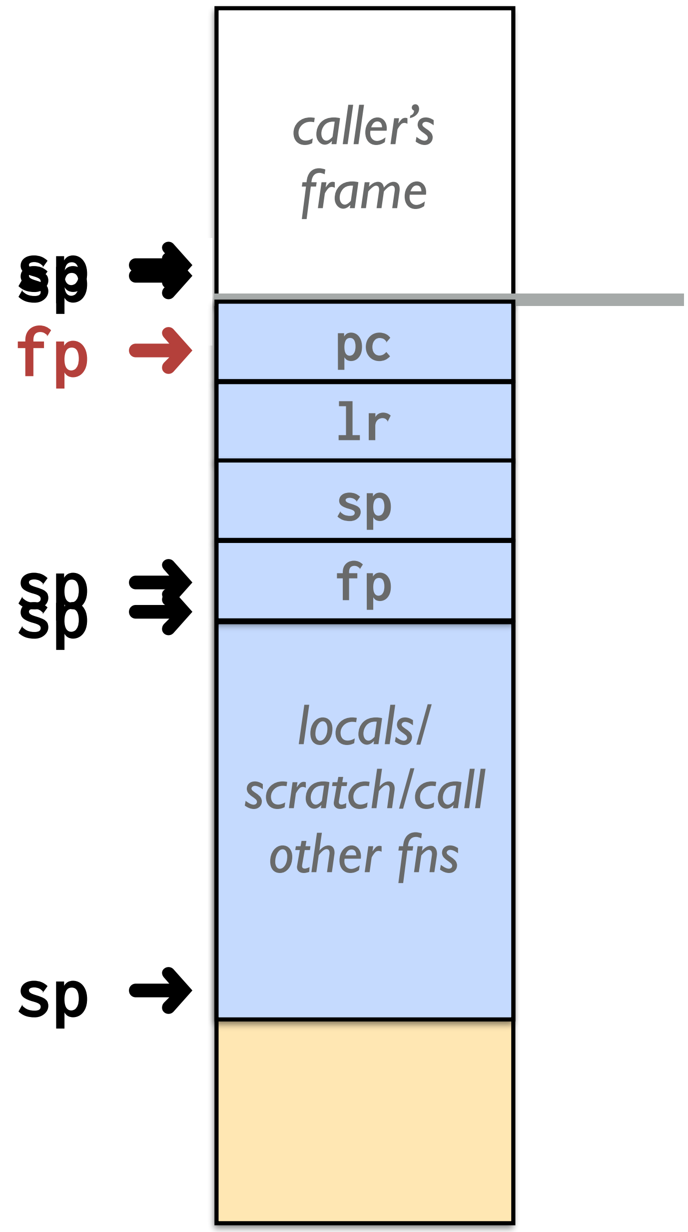
access data on stack `fp`-relative

offsets don't vary even if **sp** changing

Epilog

`pop fp, sp*, lr, pc*`

* I am fudging a bit about direct use of push and pop
sp cannot be directly pushed/popped, instead moved through r12
pc not popped, instead removed from stack, no restore orig value

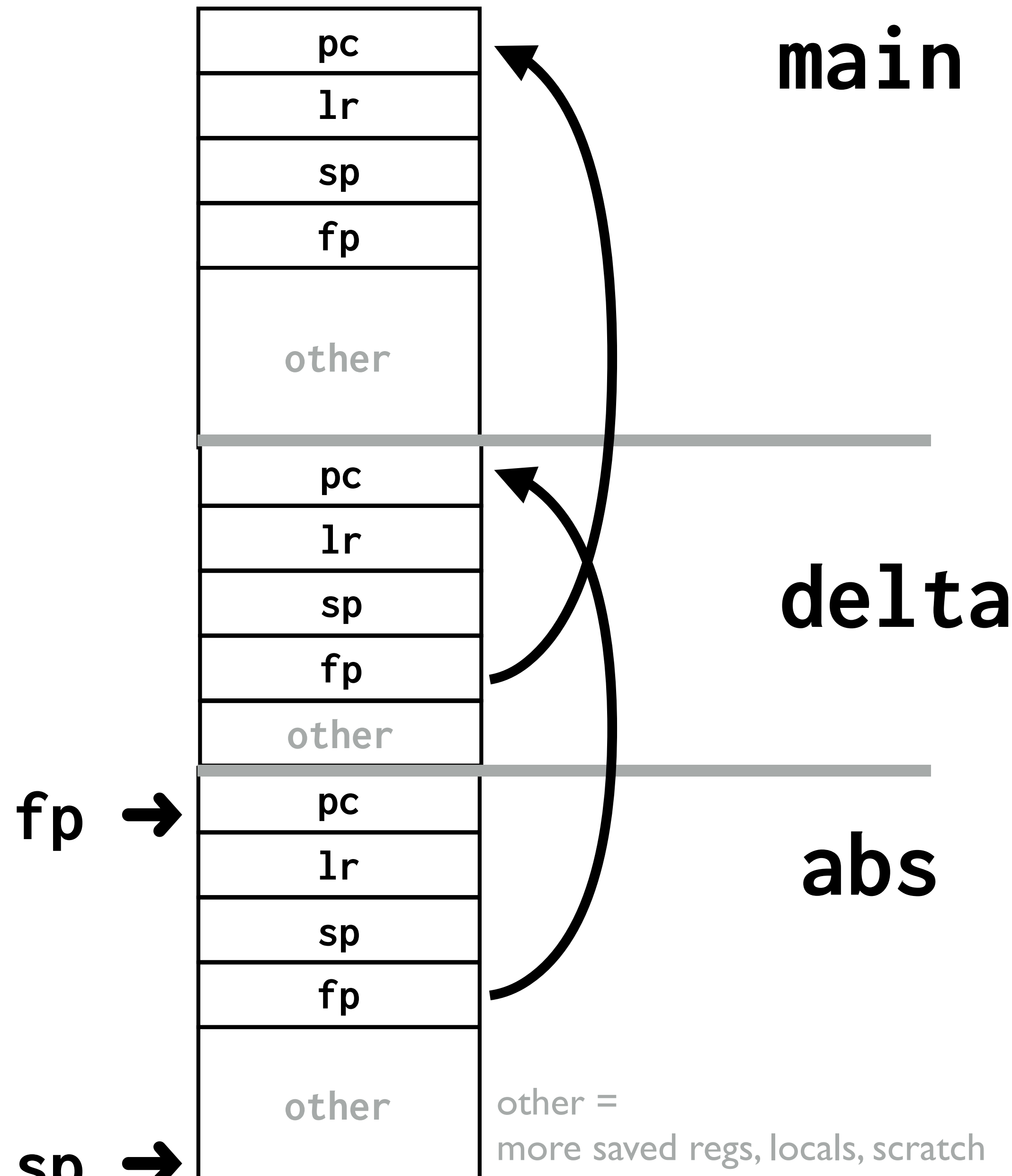


Frame pointers form linked chain

Can start at currently executing call (**abs**) and back up to caller (**delta**), from there to its caller (**main**).

Where does chain end?

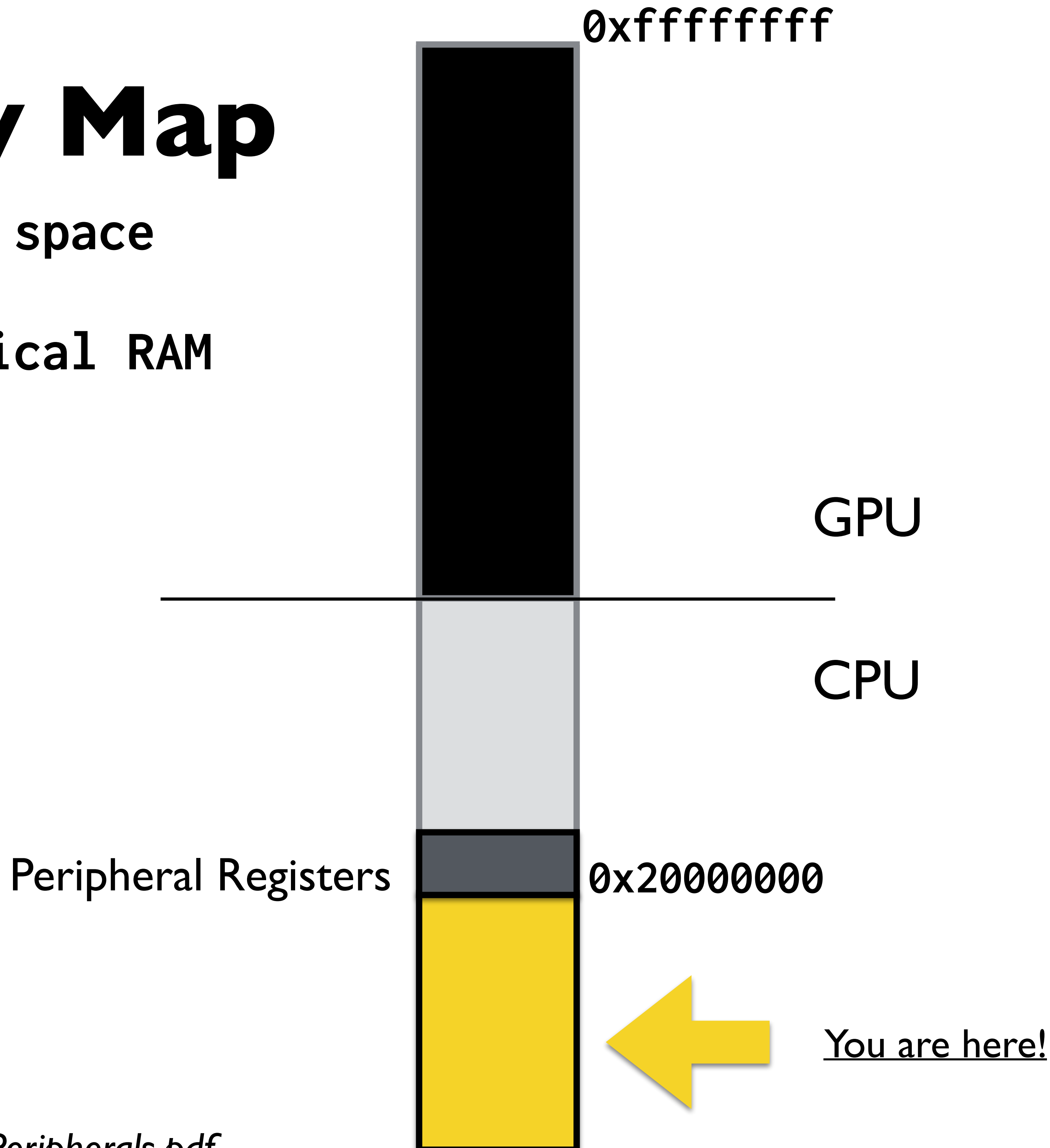
```
// start.s

// init fp = NULL
mov sp, #0x8000000
mov fp, #0
bl main
```



Memory Map

32-bit address space

512 MB of physical RAM



Ref: BCM2835-ARM-Peripherals.pdf

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

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

0x8000000


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

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

Use this memory for heap ☞

__bss_end__

(zeroed data) .bss

__bss_start__

(read-only data) .rodata

(initialized data) .data

blink.bin

.text

0x8000

Global allocation

+ **Convenient**
    Fixed location, shared across entire program
+ **Fairly efficient, plentiful**
    No explicit allocation/deallocation
    Oversize pays bootloader cost
+ **Reasonable type safety**

- **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
    Frowned upon stylistically

Stack allocation

+ **Convenient, plentiful**
  Automatic alloc/dealloc on function entry/exit
+ **Efficient, fairly plentiful**
  Fast to allocate/deallocate, ok to oversize
+ **Reasonable type safety**
- **Size fixed at declaration, no option to resize**

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

  Private to stack frame

  Does not persist after call exits

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**
  Interface is raw void *, number of bytes
- **Lots of opportunity for error**
  (allocate wrong size, use after free, double free)
- **Leaks** (less critical, but annoying nonetheless)

Heap interface

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

void* pointer

Variable of type address with unspecified/unknown pointee type

What you can do with a void *

Pass to/from function, pointer assignment

What you cannot

Cannot dereference (must cast first)

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

Cannot use array indexing

Why do we need a heap?

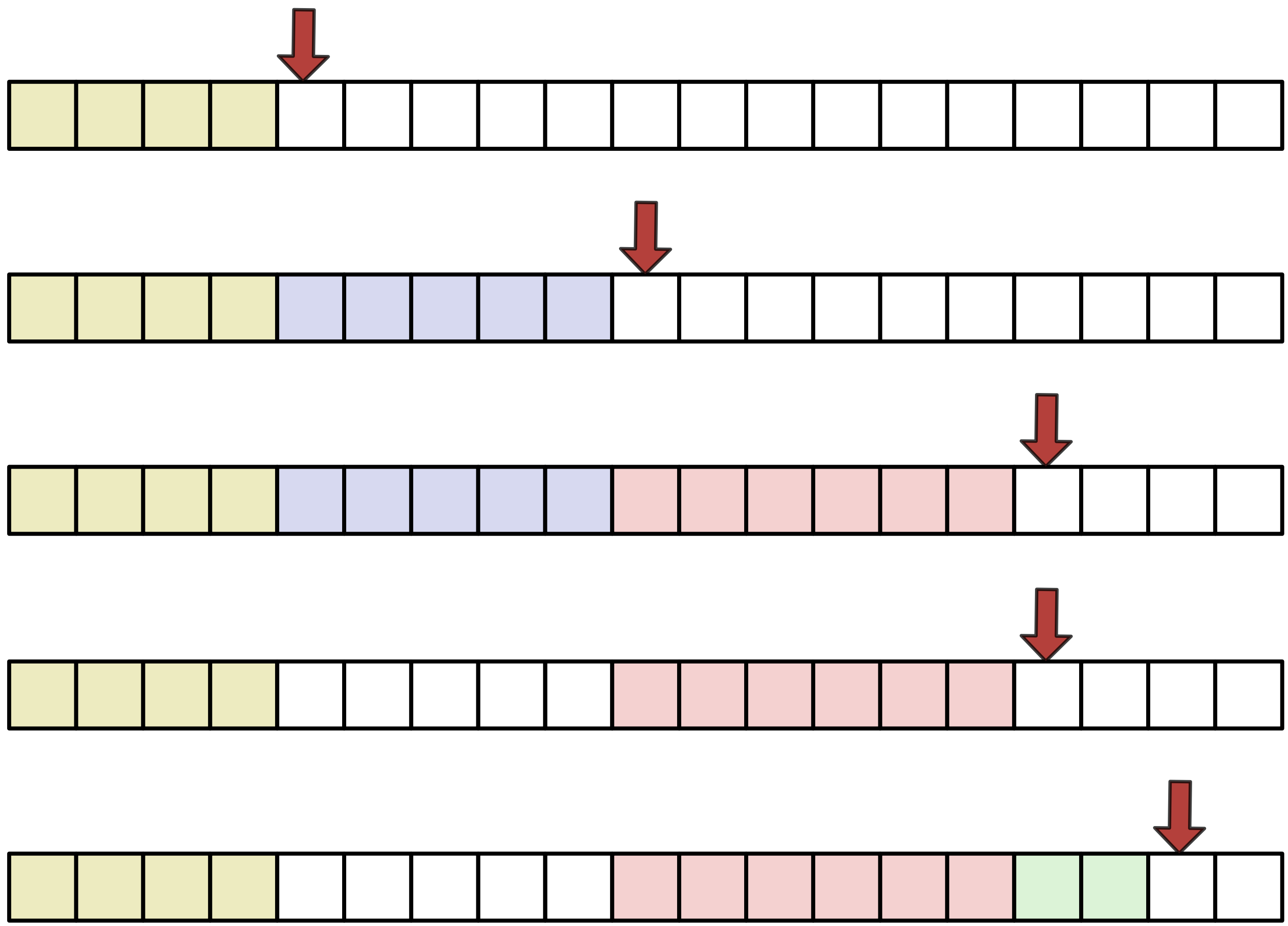
Let's see an example!

`code/heap.c`

How is a heap implemented?

Tracing the bump allocator

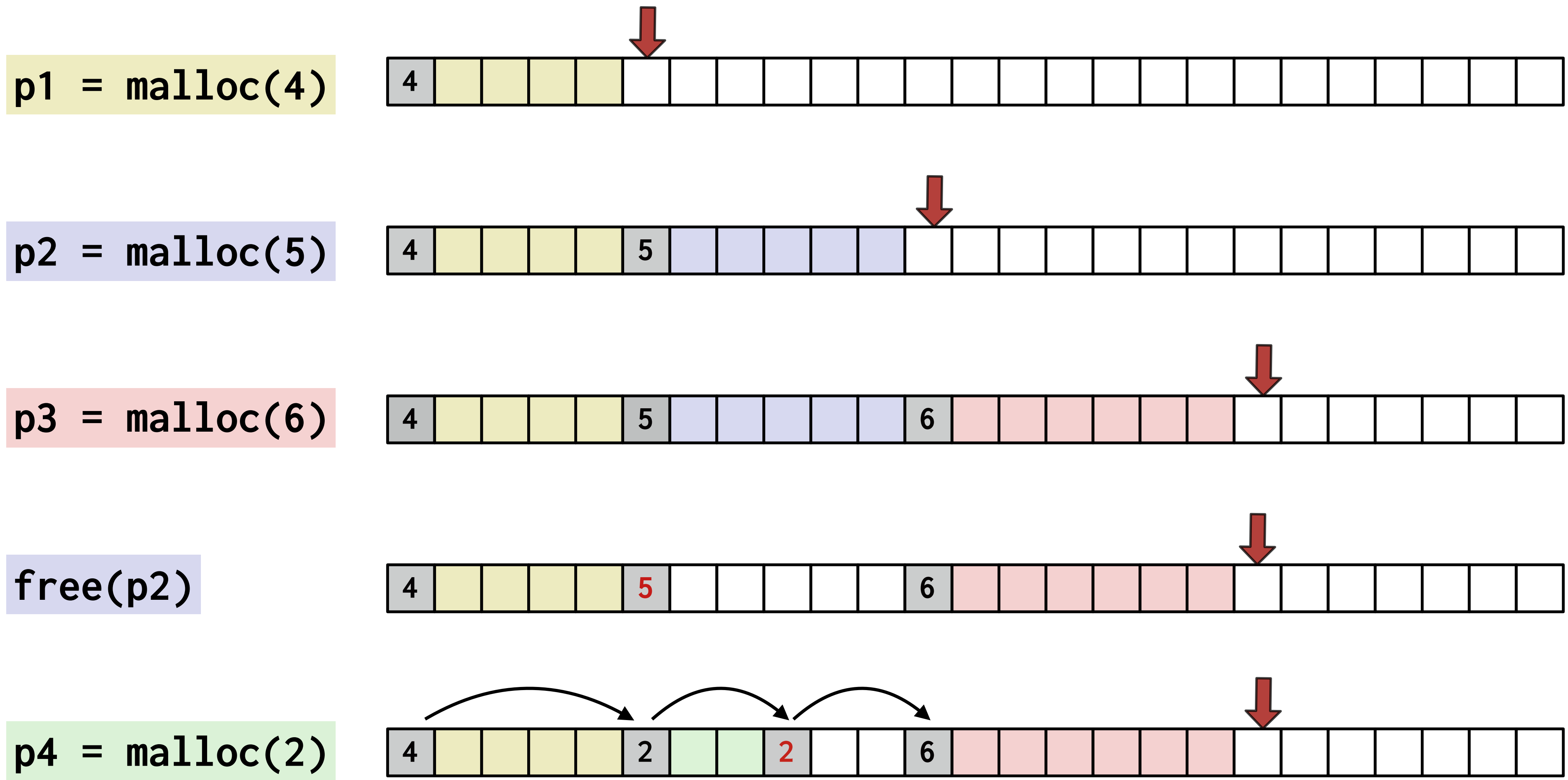
```
p1 = malloc(4)
p2 = malloc(5)
p3 = malloc(6)
free(p2)
p4 = malloc(2)
```



Bump Memory Allocator

`malloc.c`

Pre-block header, implicit list



Header struct (with bitfield)

```
struct header {
    unsigned int size : 31;
    unsigned int status : 1;
};

enum { IN_USE = 0, FREE = 1};

void *malloc(size_t nbytes)
{
    nbytes = roundup(nbytes, 8);

    struct header *hdr = heap_end;
    heap_end  = (char *)heap_end + nbytes + sizeof(struct header);
    hdr->size = nbytes;
    hdr->status = IN_USE;
    return (char *)hdr + sizeof(struct header);
}
```

Challenges for malloc client

- **Correct allocation (size)**
- **Correct access to block (within bounds, not freed)**
- **Correct free at correct time**

What happens if you…

— forget to free a pointer after you are done using it?
— access a memory block after it has been freed?
— free a block twice?
— free a pointer you didn't malloc?
— access past the bounds of a heap block?

Challenges for malloc implementor

just `malloc` is easy 😎

`malloc` with `free` is hard 🤔

Efficient `malloc` with `free` ….Yikes! 🥵

Tricky code (pointer math, typecasts)

Testing is difficult (even more than usual)

Critical system component

correctness is non-negotiable, ideally also fast and compact

Survival strategies:

draw pictures

printf (you've earned it!!)

Early tests on examples small enough to trace by hand if need be