Admin

- Assign 2

  Demo your clock extension to me! See my Ed post

  Functionality test results out soon, revise and resubmit on open issues will be avail
- Assign 3

  printf perseverance and pride!
- Lab4

  stack, heap, build process

Today: Thanks for the memory!

Runtime stack, stack frame layout

Linker memory map, address space layout

Loading, how an executable file becomes a running program

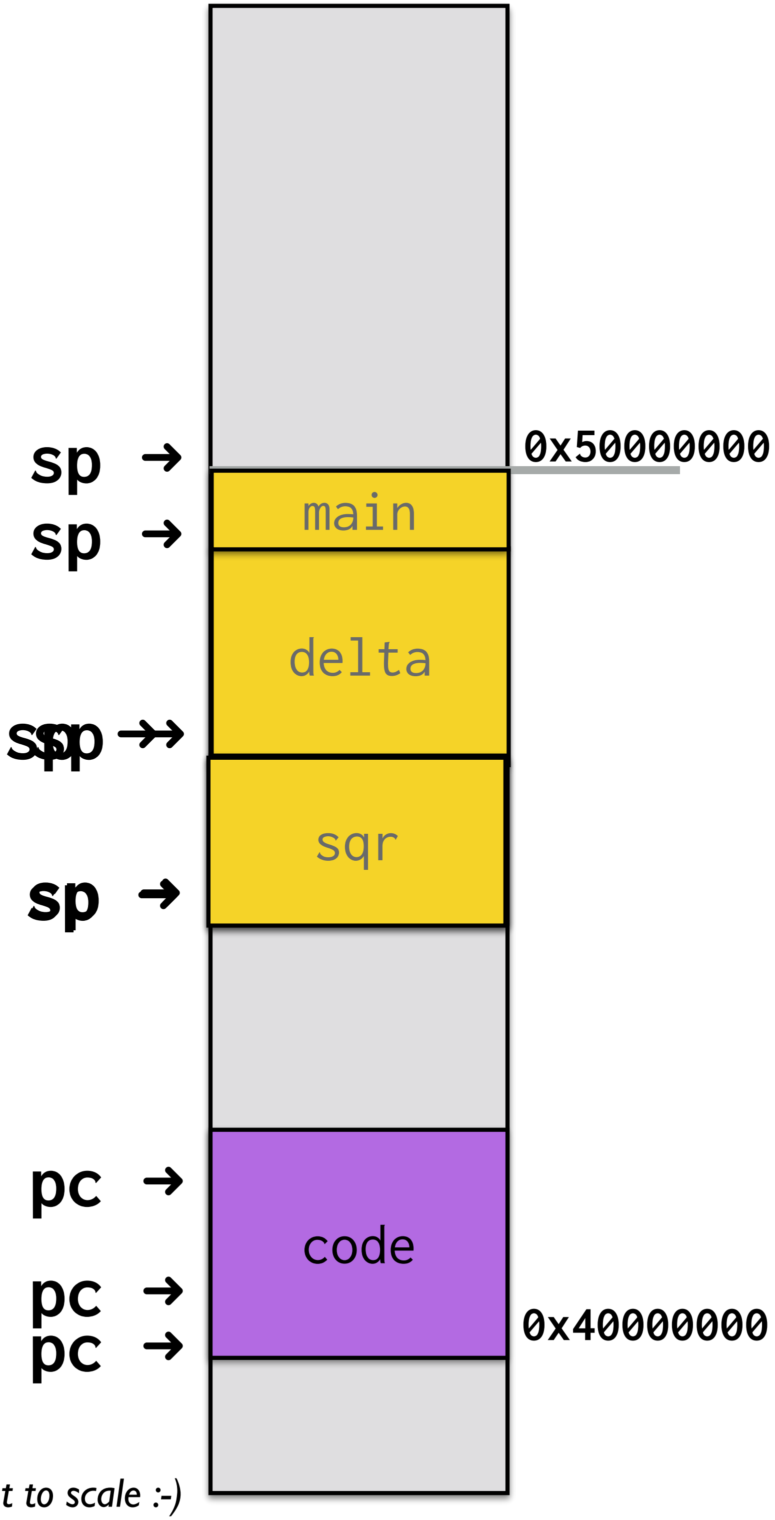
Heap allocation, malloc and free

```
// start.s
lui    sp,0x5000
jal    ra,main
```

```
void main(void)
{
    delta(3, 7);
}


int delta(int a, int b)
{
   int diff = sqr(a) - sqr(b);
   return diff;
}


int sqr(int v)
{
   return v * v;
}
```



sp →
sp →
sp →
sp →
sp →
0x50000000
main
delta
sqr
pc →
pc →
pc →
code
0x40000000

Memory diagram not to scale :-)

Frame pointer

Designate register `s0` for use as **frame pointer** `fp`

Stack pointer **`sp`** is top of stack, additional register **`fp`** marks boundary of current stack frame

Each frame saves previous **`fp`** — this gives reliable way to backtrace entire stack

CFLAGS to enable: **`-f-no-omit-frame-pointer`**

Add instructions to prolog/epilog that set up **`fp`** on entry and restore saved on exit

Tracing stack frames

Prolog

Adjust stack pointer to make space (16 + `rest)`

Store ra and fp to stack

Set `fp` to where sp was (end of prev stack frame)

Body

`fp` stays anchored

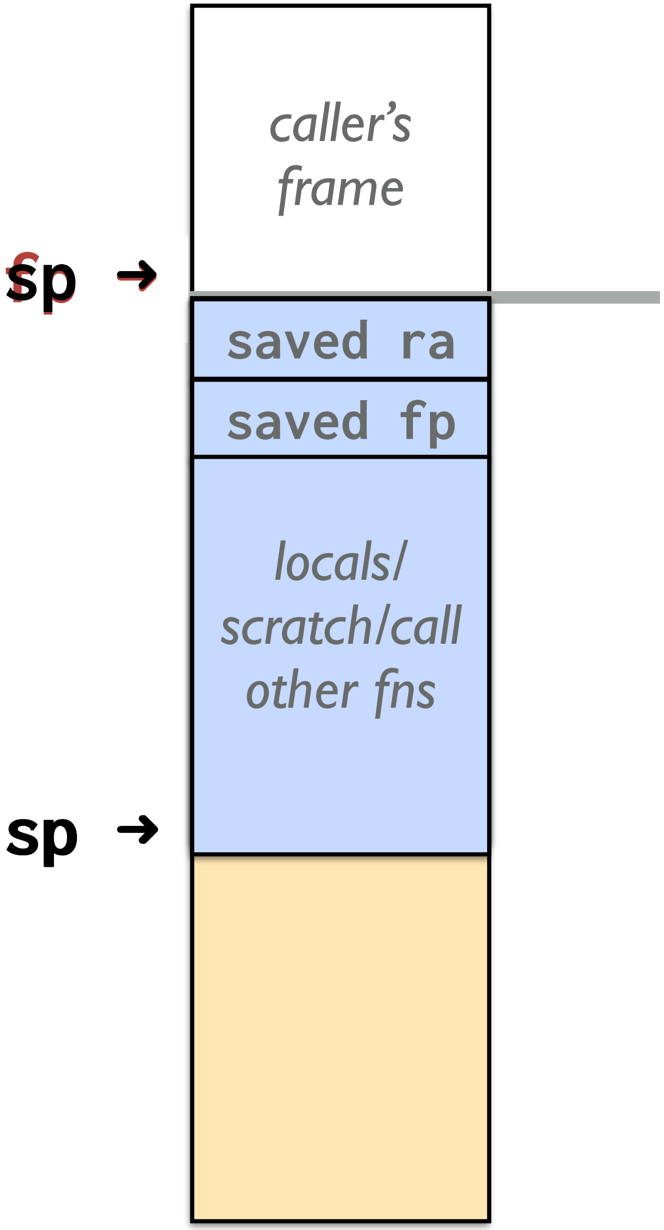
access data on stack `fp`-relative

fp offsets remain stable (even if **sp** changes)

Epilog

Restore ra, fp to saved values

Adjust sp to remove frame



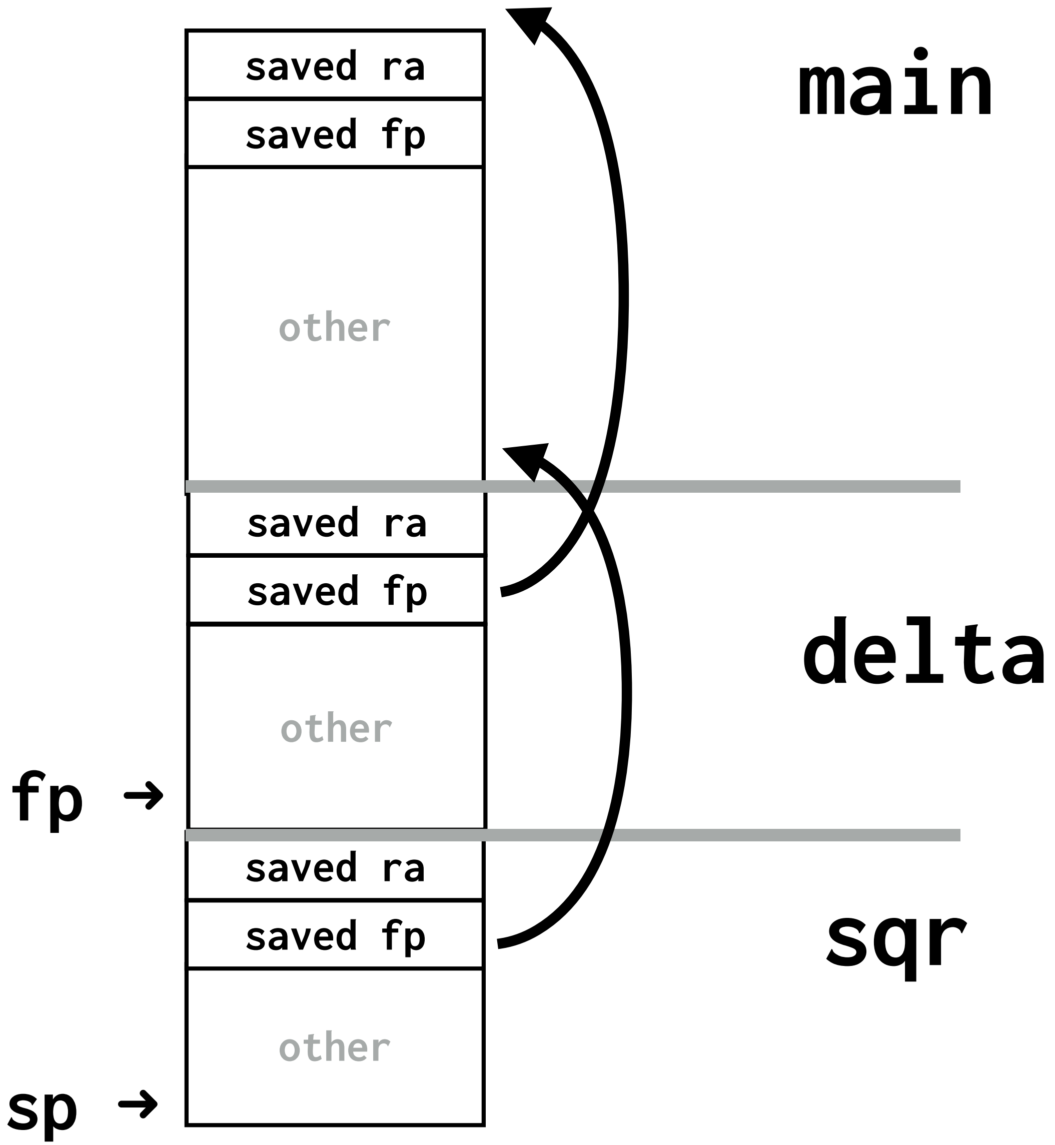
Linked chain of frame pointers

Can traverse from innermost frame (**sqr**) to frame of its caller (**delta**), from there to its caller (**main**) …

```
// start.s

// init fp = 0 as termination
li fp,0
lui sp,0x50000
jal _cstart
```

Deep dive into full frame coming up in this week's lab!



main

saved ra

saved fp

other

delta

saved ra

saved fp

other

fp →

sqr

saved ra

saved fp

other

sp →

other =
more saved regs, locals, scratch

Frame pointer tradeoffs

+ Anchored `fp`, offsets are constant

+ Standard frame layout enables runtime introspection

+ Backtrace for debugging, instrumentation

- `fp` register removed from general pool

- Add'l 3 instructions in prolog,epilog to manage `fp`

- Adds 8 bytes to frame size, another saved register

Aside: "Fedora's tempest in a stack frame"

https://developers.redhat.com/articles/2023/07/31/frame-pointers-untangling-unwinding

https://fedoraproject.org/wiki/Changes/fno-omit-frame-pointer https://lwn.net/Articles/919940/

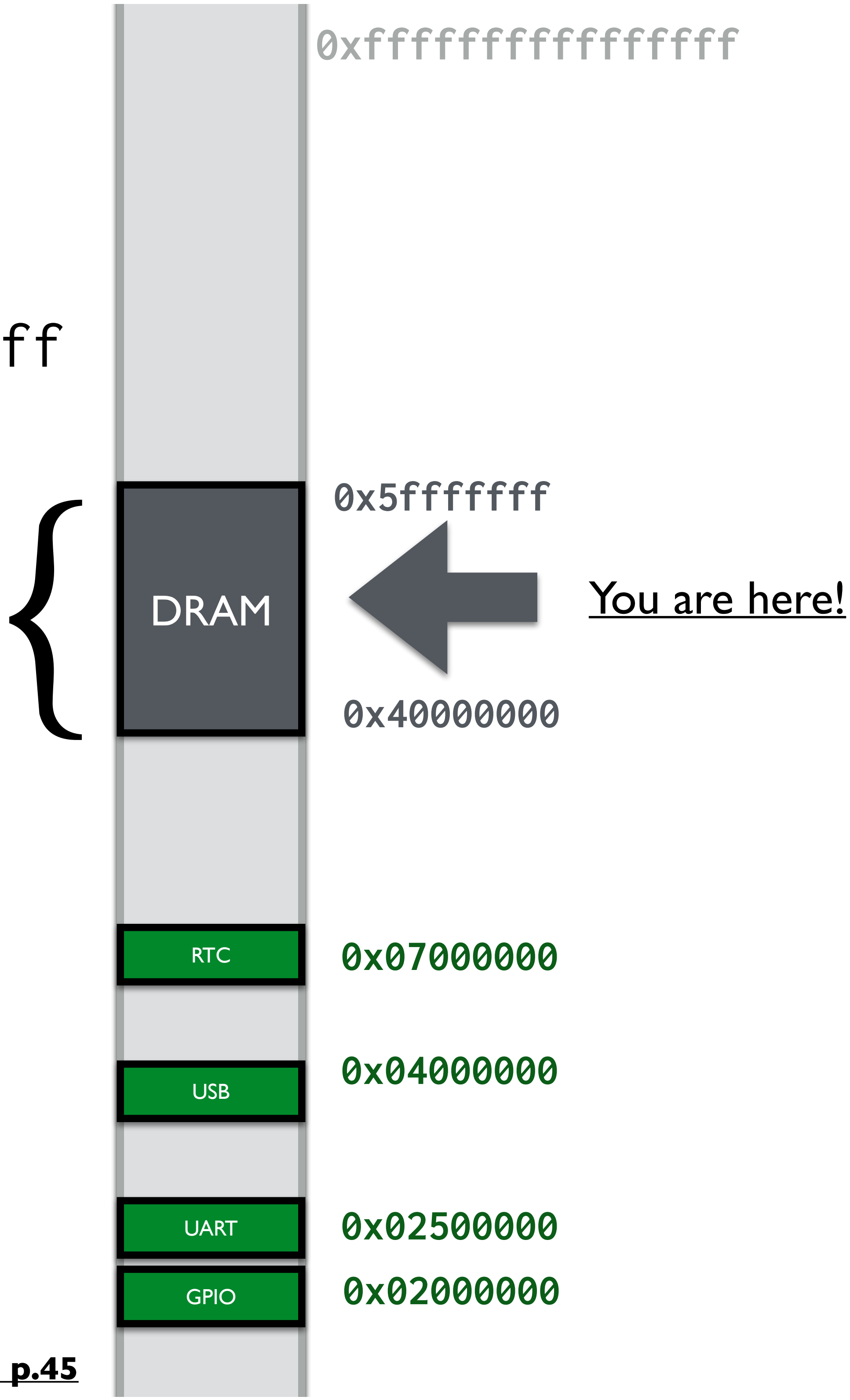
Memory map

64-bit address space

`0x0 - 0xffffffffffffffff`

512MB physical RAM at

`0x40000000-0x5fffffff`

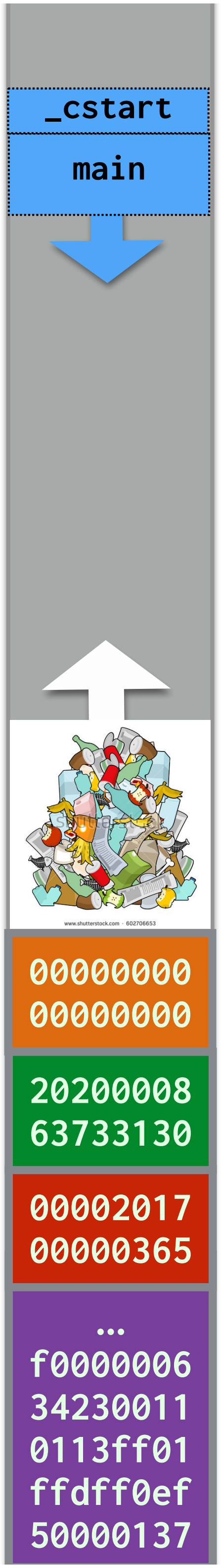


Ref: D1-H User Manual p.45

```
SECTIONS
{
  .text 0x40000000 :{ *(.text.start)
                      *(.text*)}
  .rodata :          { *(.rodata*) }
  .data :            { *(.data*) }
  __bss_start        = .;
  .bss :             { *(.bss*) }
  __bss_end          = . ;
}
```

```
_start:
   lui    sp,0x50000
   jal    _cstart
```

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



Use this memory for heap☞

(zeroed data) .bss

```
00000000
00000000
```

(initialized data) .data

```
20200008
63733130
```

(read-only data) .rodata

```
00002017
00000365
```

.text

```
…
f0000006
34230011
0113ff01
ffdff0ef
50000137
```

```
$ xfel write 0x40000000 program.bin
$ xfel exec  0x40000000
```

We have global storage ...

+ **Convenient**

  Fixed location, shared across entire program

  No explicit allocate/deallocate

+ **Fairly efficient, plentiful**

  (But cost to send over serial line to bootloader)

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

  No encapsulation, hard to track use/dependencies

  One shared namespace, possibility of conflicts

  Frowned upon stylistically

... and we have stack storage ...

+ **Convenient**

Automatic alloc/dealloc on function entry/exit

+ **Efficient, fairly plentiful**

(But finite size limit on total stack usage)

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

Private to stack frame

Does not persist after function exits

Why do we also need a heap?

An example:

`code/heap/names.c`

Dynamic storage

+ Programmer controls scope/lifetime

Versatile, precise

Works for situations where global/stack do not

- Needs software runtime support

Library module to manage heap memory

Functions to allocate/deallocate memory (explicit calls by client)

- C version is low on safety

No type safety (raw `void*`, size in number of bytes)

Much opportunity for error

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

Heap module interface

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

What is a `void*` pointer?

"Generic" pointer, holds a memory address

Type of pointee is not specified, could be any type of data

What you can do with a `void*`

Pass to/from function, assignment

What you cannot do with a `void*`

No dereference without cast

No pointer arithmetic without cast (scaling unknown!)

No array indexing (size of pointee unknown!)

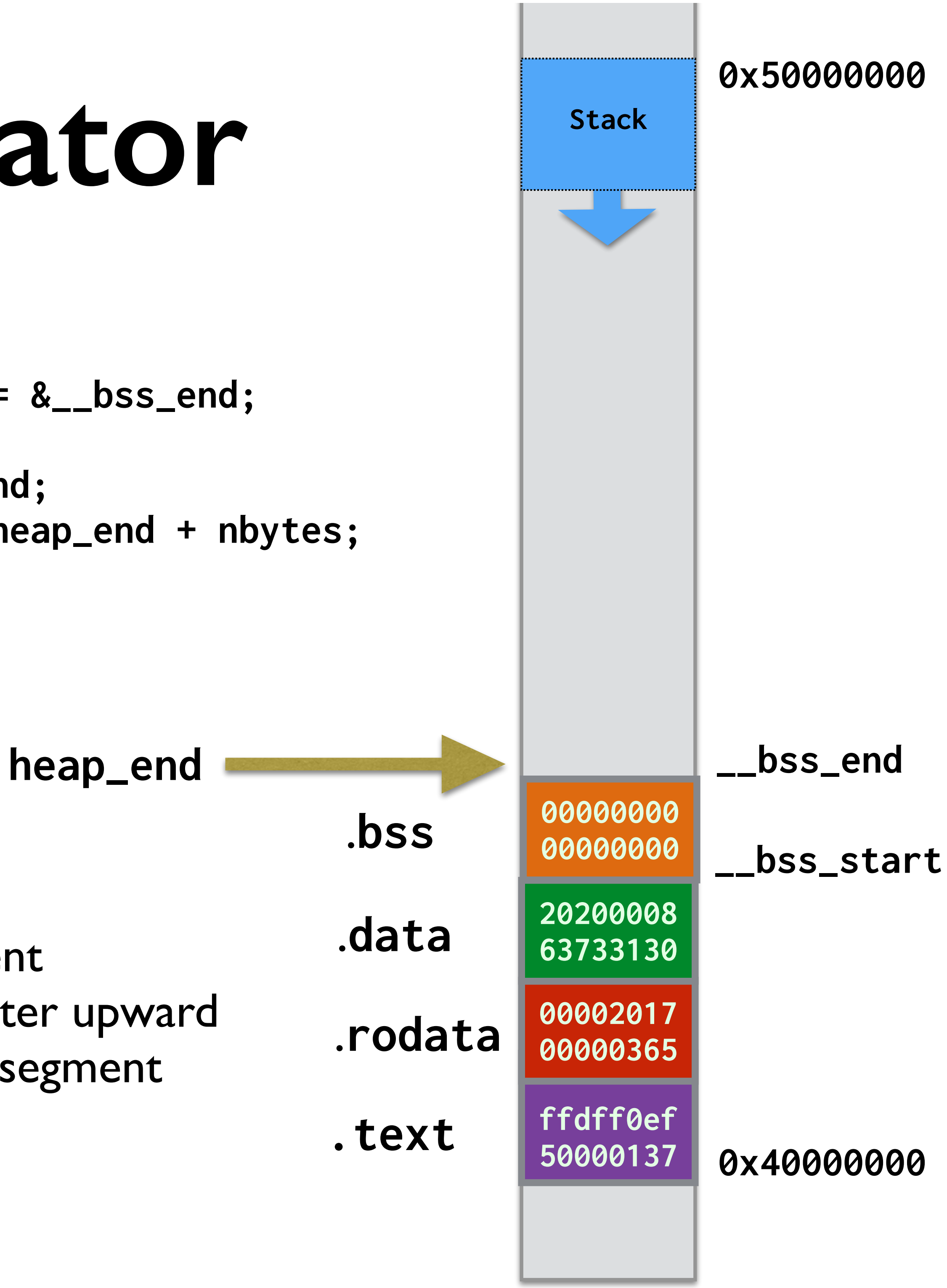
How to implement a heap

Drawing by Jane Lange

Bump allocator

```
void *sbrk(int nbytes)
{
    static void *_cur_heap_end = &__bss_end;

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



- Keep pointer to end of heap segment
- Service malloc request adjusts pointer upward
- Every request extends/grows heap segment
- No reuse/recycle

Tracing the bump allocator

Each square represents 8 bytes of space

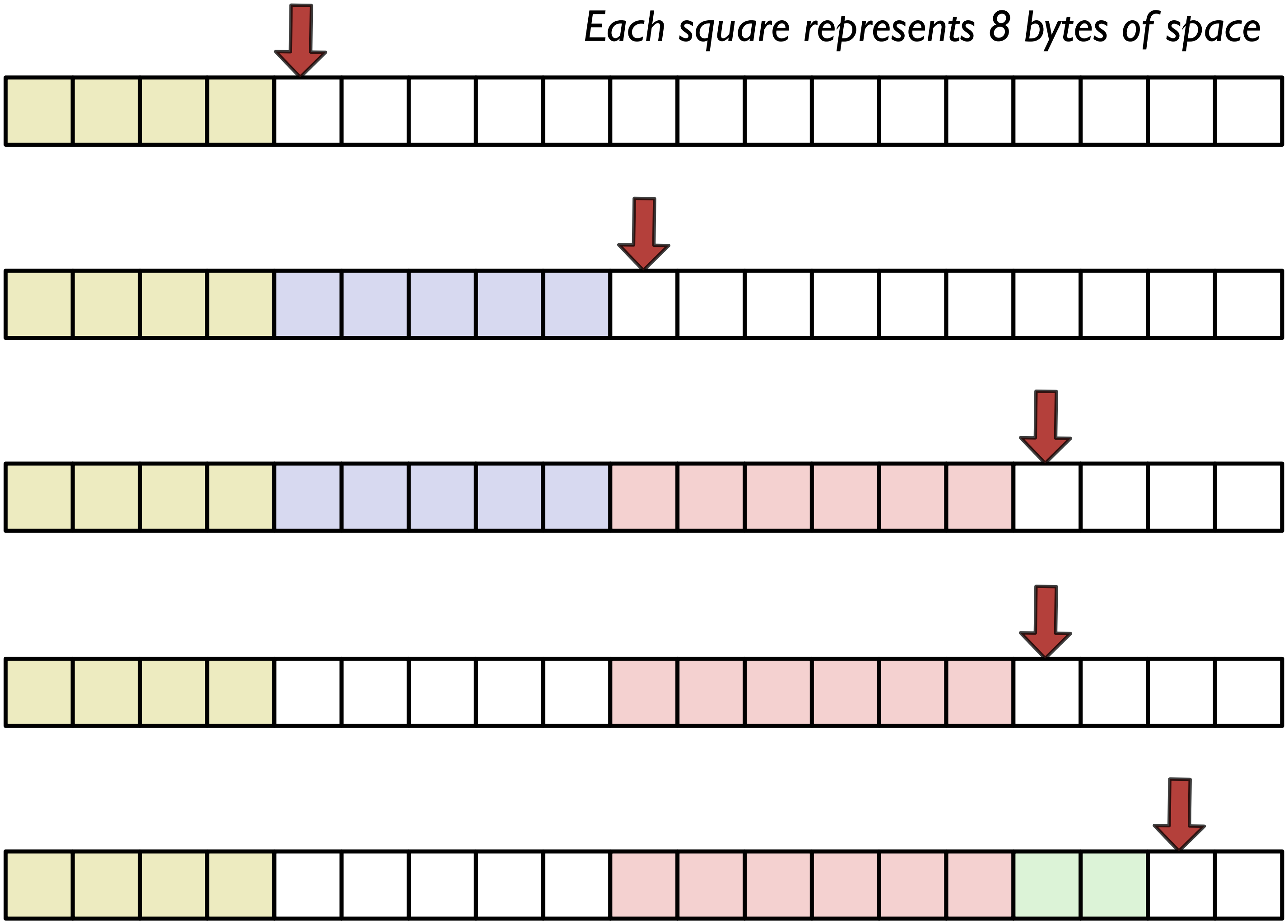
```
p1 = malloc(32)

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?)

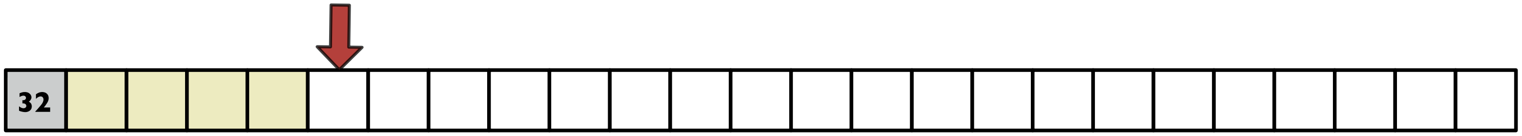
- Sad consequences if `sbrk()` advances into stack

  (what can we do about that?)

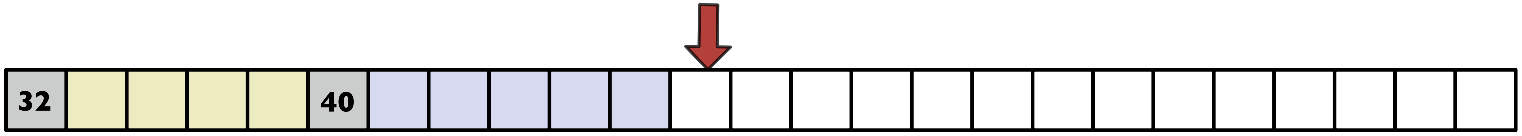
Pre-block header, implicit list

Each square represents 8 bytes, header records size of payload in bytes

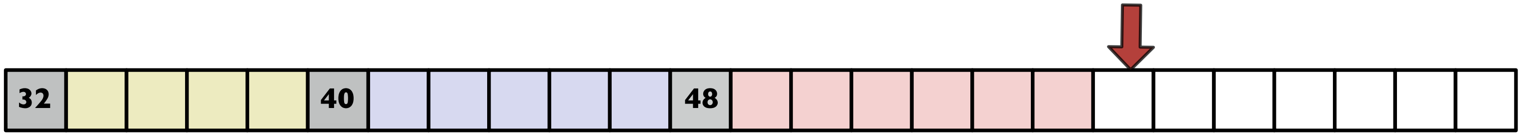
`p1 = malloc(32)`



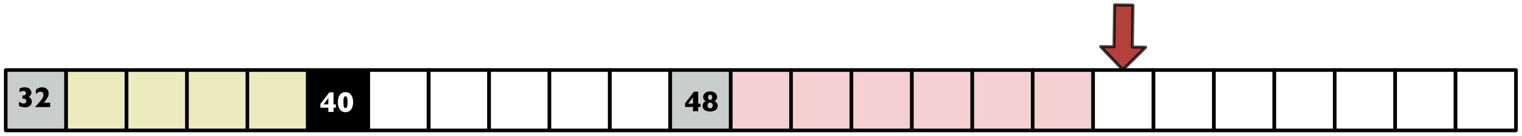
`p2 = malloc(40)`



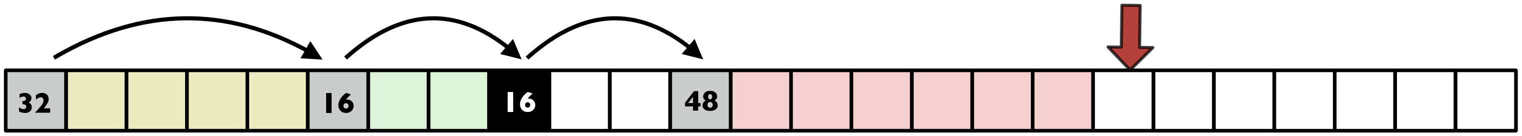
`p3 = malloc(48)`



`free(p2)`



`p4 = malloc(16)`



Header struct on each block

```
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); // extend end of heap
    hdr->size = nbytes;
    hdr->status = IN_USE;
    return hdr + 1;     // return address at start of payload
}
```

Challenge 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?

Challenge for malloc implementor

just `malloc` is easy 😎
`malloc` with `free` is hard 🤔
Efficient `malloc` with `free` ….Yikes! 🥵

Complex code (pointer math, typecasts)
Critical system component
- correctness is non-negotiable!

Thorough testing is essential

Survival strategies:
- draw lots of pictures
- printf (you've earned it!!)
- early tests on inputs small enough to trace by hand if need be
- build up to more complex tests