CS 211: Intro to Computer Architecture

7.1: Dynamic Memory Management

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Spring 2025 – Tuesday 4 March

Announcements

- PA2 survey announced via Canvas

- This week:
  - **WA4 + WA5**: assigned through Canvas; due **next Tuesday @ 23:59**
    - Short and simple: combined difficulty == WA1/2/3
  - **PA3**: TBA tomorrow or Thursday, due after spring break
    - Encompasses pointers, arrays, and memory management
    - Please skim the doc and code immediately so you know what you're getting into

- Next week:
  - No recitations, but extra office hours instead
  - Tuesday's lecture will be partially exam review

Midterm Preparation

- The WAs will be representative for questions
- We will draw on material from lectures, WAs, and PAs

- We are working on:
  - Some sort of “practice sheet” for later this week
  - A list of topics that will be covered

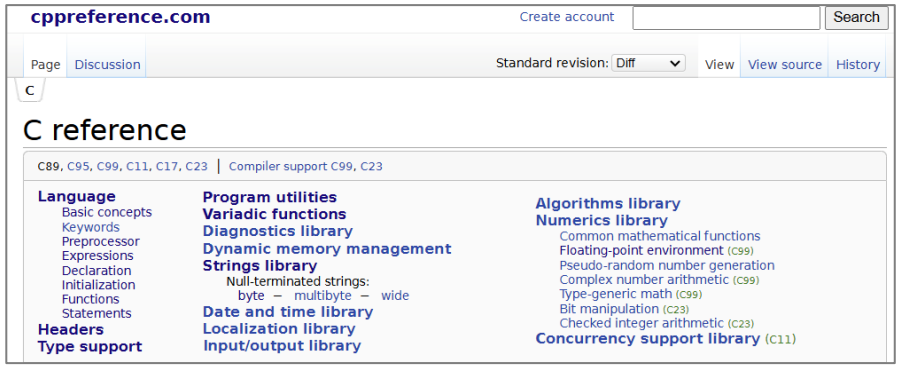
The CSL and RUCATS are Both Hiring

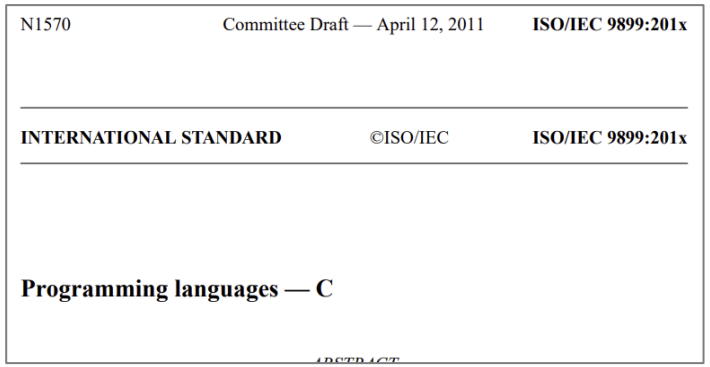
- RUCATS hiring form
- CSL hiring form

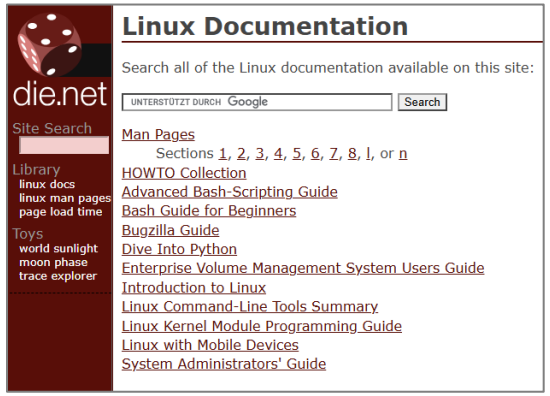
Reference Material

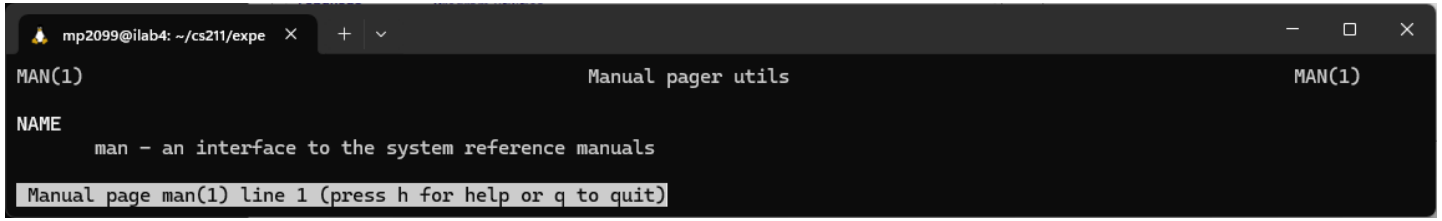
- Today's lecture draws heavily from:
  - CS 61C @ UC Berkeley (Prof. Dan Garcia)

And Various C and Linux Reference Materials

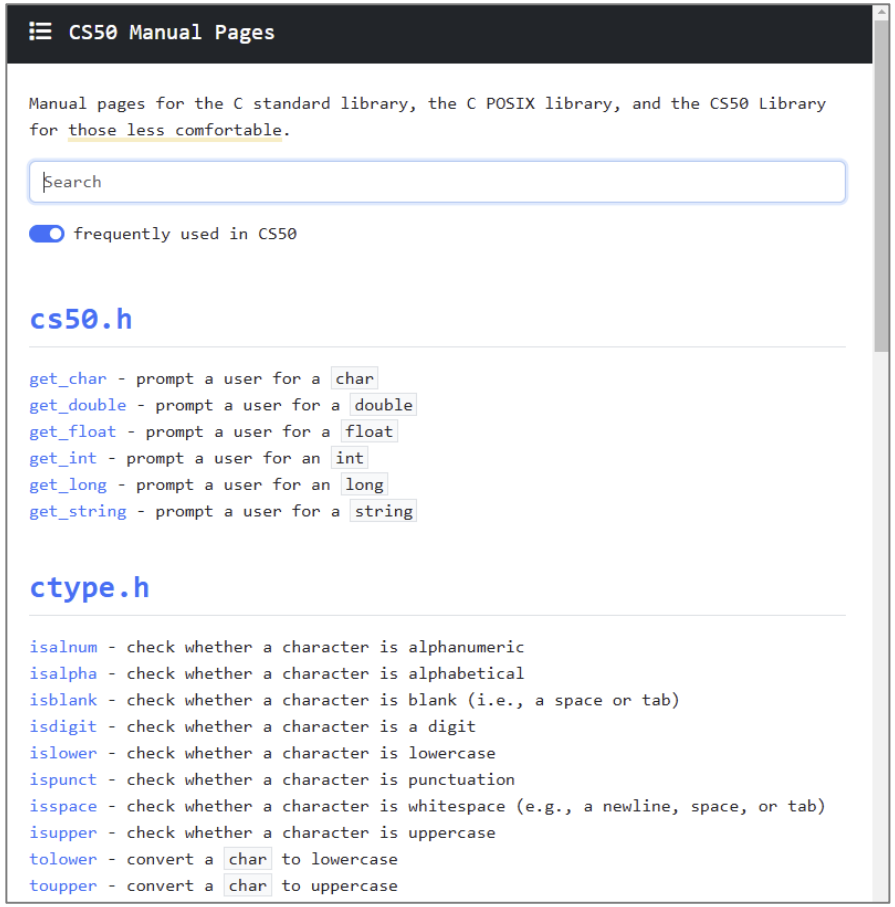


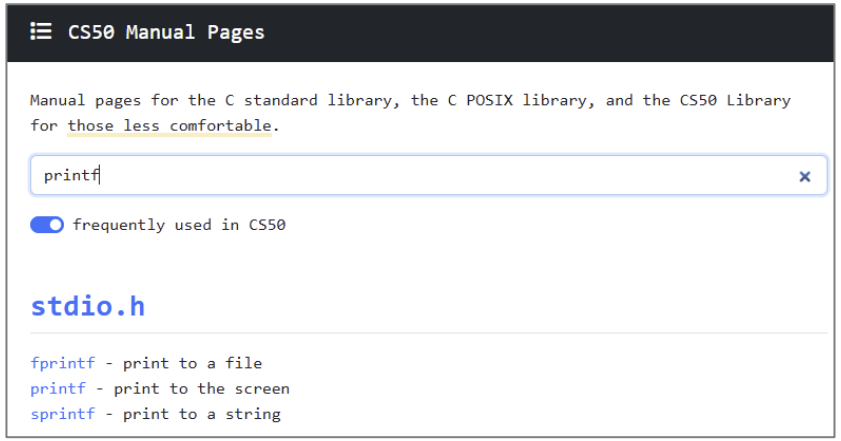


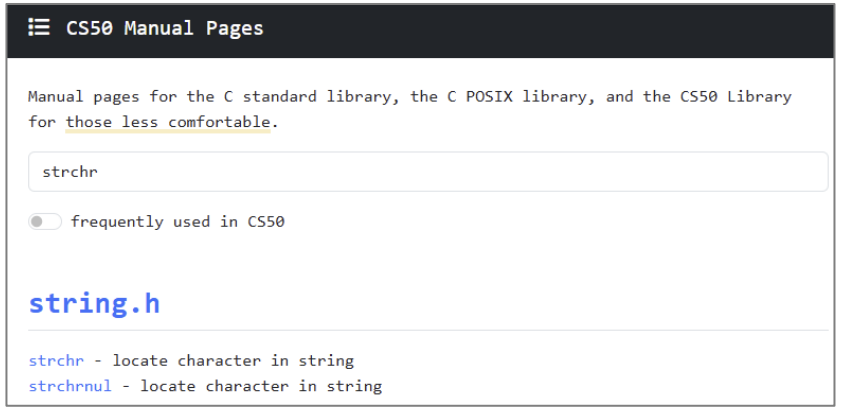


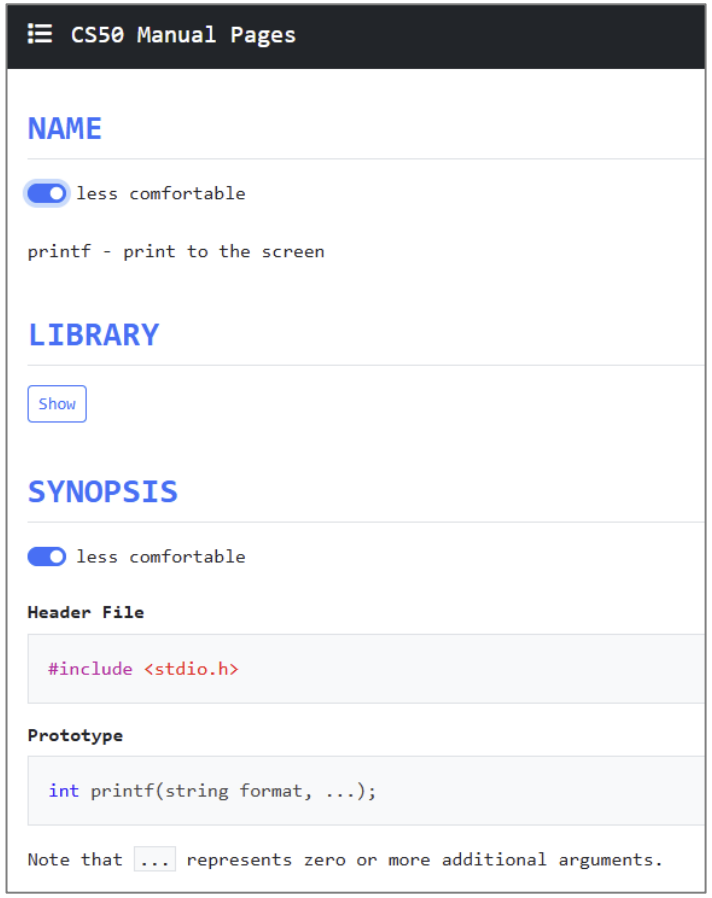


A Simplified C Library Reference: manual.cs50.io









Agenda

- **Functions**

- Loaders and the C Memory Layout

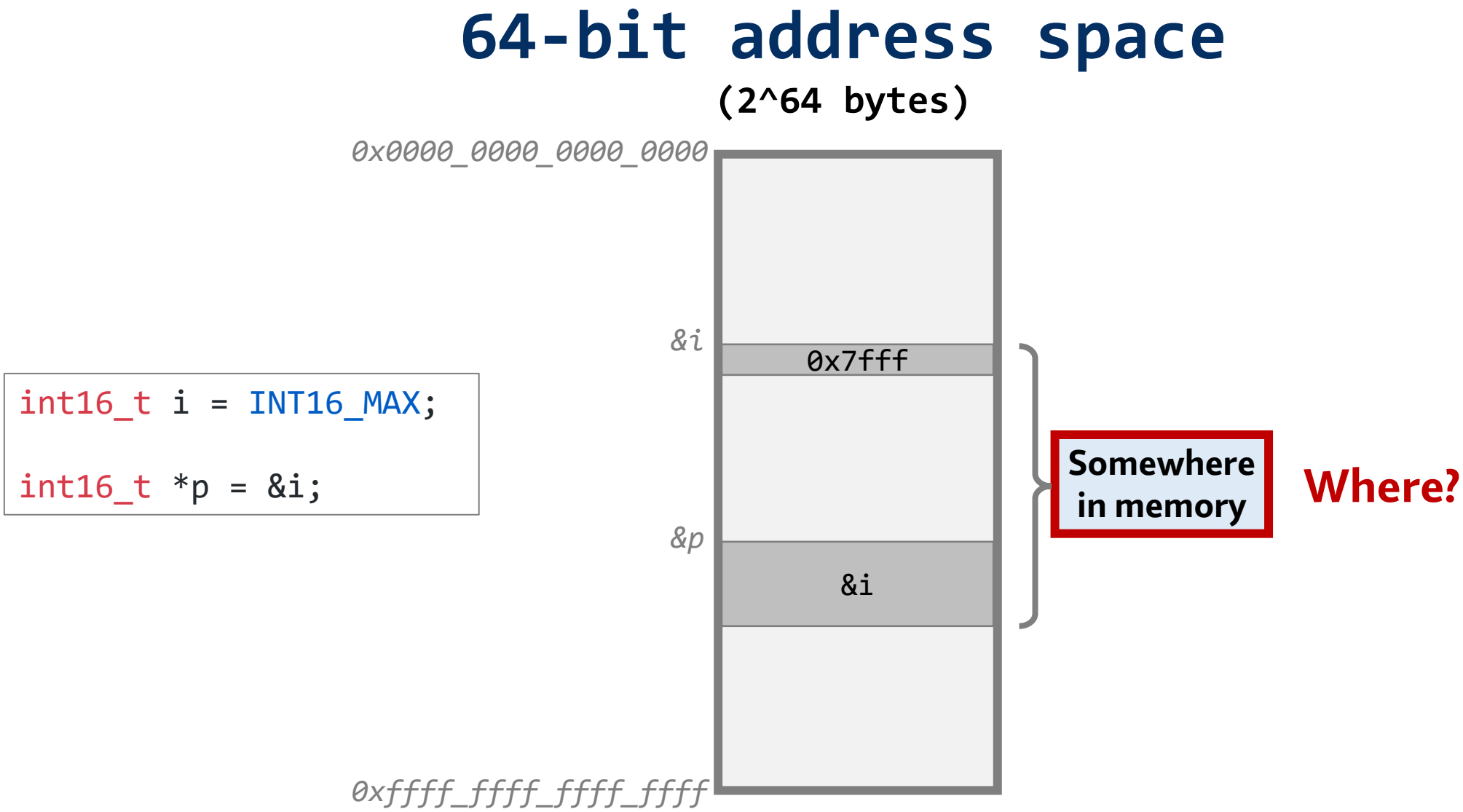
- Dynamic Memory Allocation

- C Generics
  - C Library Functions

Recap: C's Type System

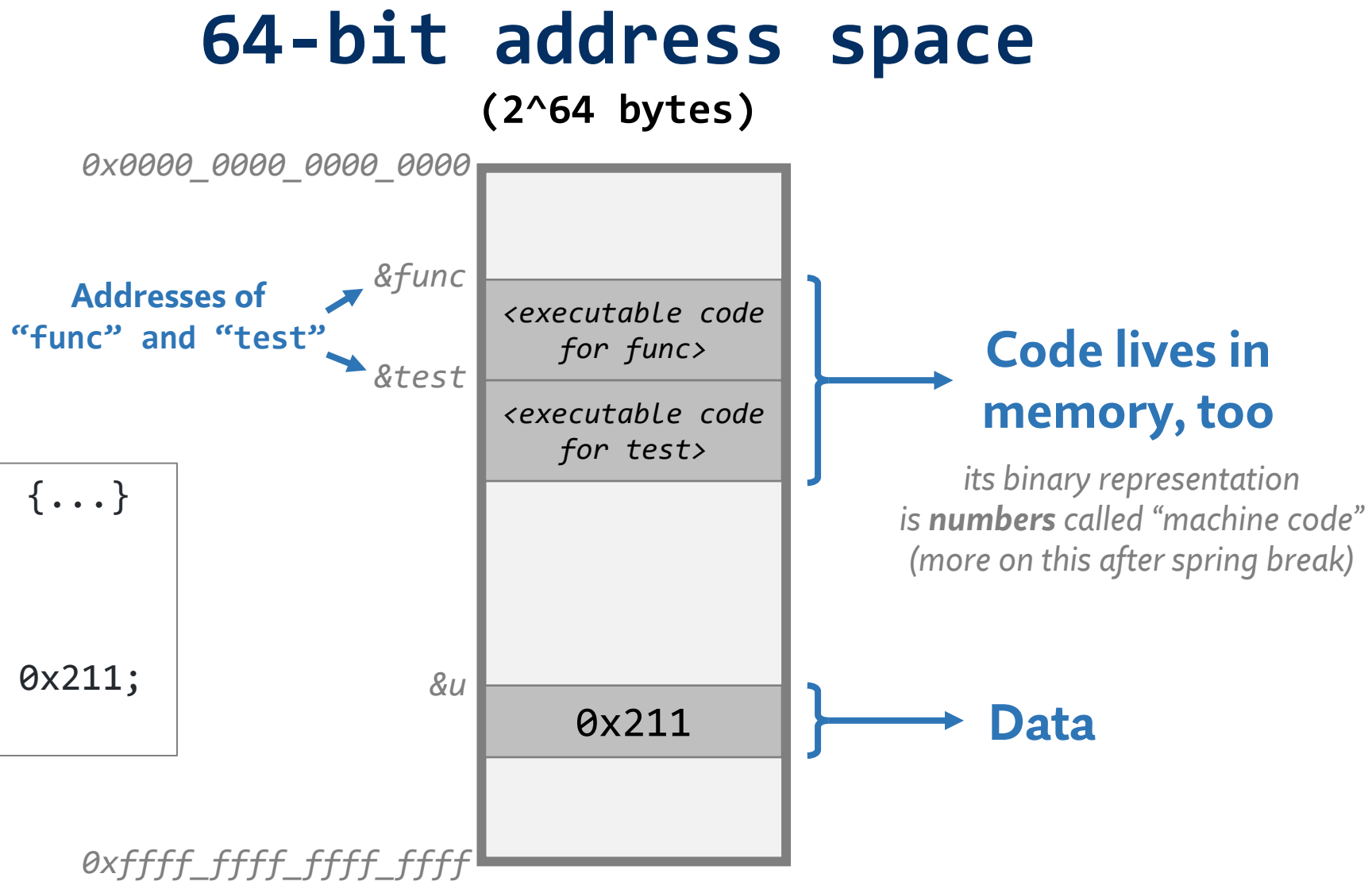
- void
- basic types
  - char
  - signed integers
  - unsigned integers
  - floating-point
- enumerated types
- **derived types**
  - structures
  - pointers
  - arrays
  - unions
  - **functions** ← Almost done!

Recap: A 64-bit Address Space




```
int16_t i = INT16_MAX;

int16_t *p = &i;
```

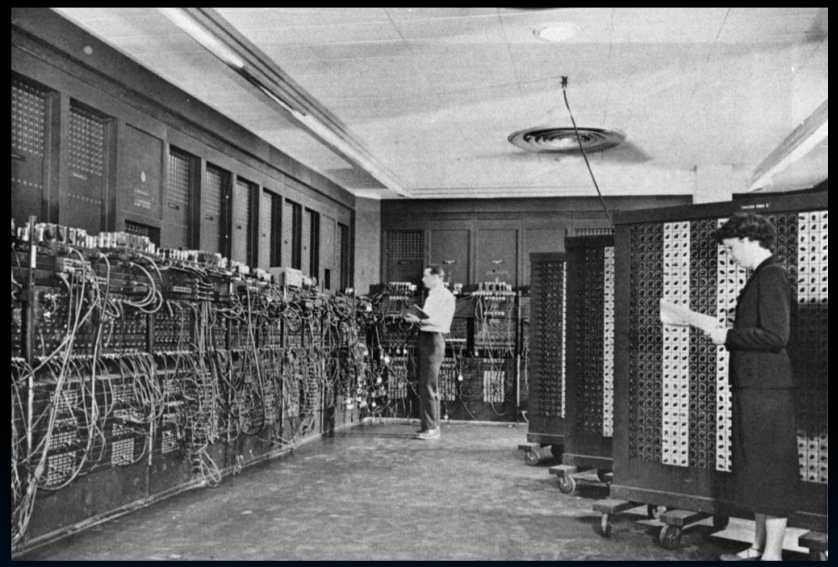
Functions in Memory



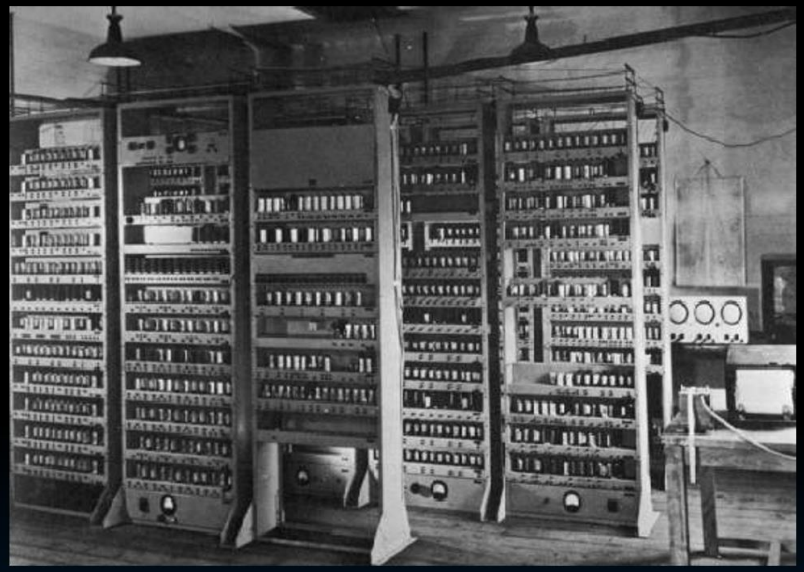

```
void func(int a) {...}

void test(void)
{
    uint64_t u = 0x211;
}
```

Code Lives in Memory, Too

From ENIAC (1946) to EDSAC (1949)



- ENIAC: First Electronic General-Purpose Computer
- Needed 2-3 days to setup new program
- Programmed with patch cords and switches
  - At that time & before, "computer" mostly referred to people who did calculations
  - Mostly women! (See *Hidden Figures*, 2016)

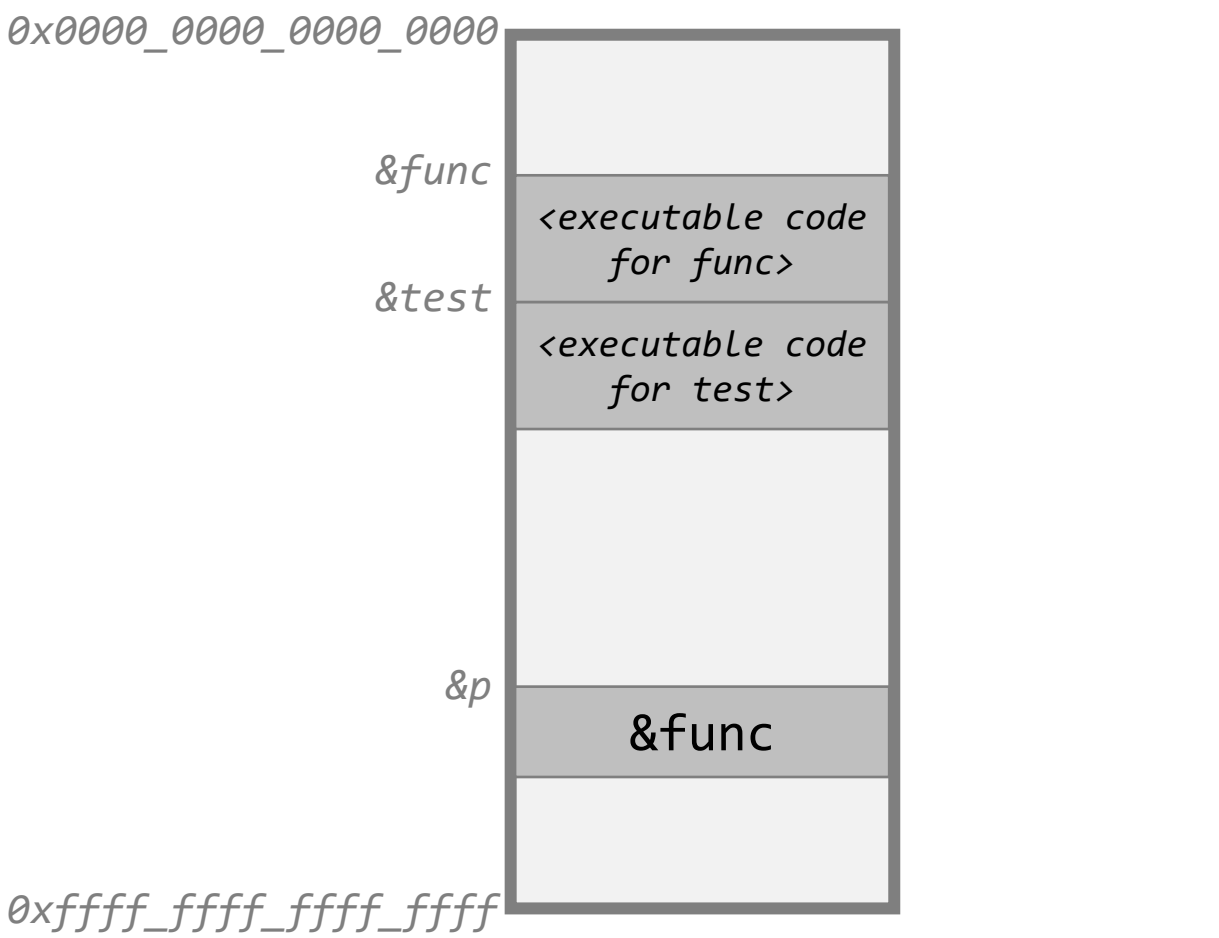


- EDSAC: First General Stored-Program Computer
- Programs held as **numbers in memory**
  - Revolution! Program is also data!
- 35-bit binary **two's complement** words

Function Pointers

```
void func(int a) {...}

void test(void)
{
    void (*p)(int a) = &func;
    (*p)(1);
}
```

Identifier ‘p’ points to ‘func’



Function Pointer Syntax: Best Practice

Function identifier

```
void test(int a)
{
    void (*fn)(int a) = &test;
    (*fn)(1);
}
```

Equivalent Code

```
void test(int a)
{
    void (*fn)(int a) = test;
    fn(1);
}
```

- The compiler **implicitly converts** function identifiers to pointers
- Best practice: prefer **explicitness**

We will come back to function pointers on Thursday

Agenda

- Functions
- **Loaders and the C Memory Layout**
- Dynamic Memory Allocation
- C Generics
  - C Library Functions

Loading a Program into Memory

- **Q:** How does your program (all the code, C objects, etc.) get into memory?

```
netid@ilab:~$ gcc -o hello hello.c
netid@ilab:~$ ./hello world
Hello, World
netid@ilab:~$
```

- A special program called the "loader" parses the **executable file** generated by GCC and loads it bit-by-bit into memory

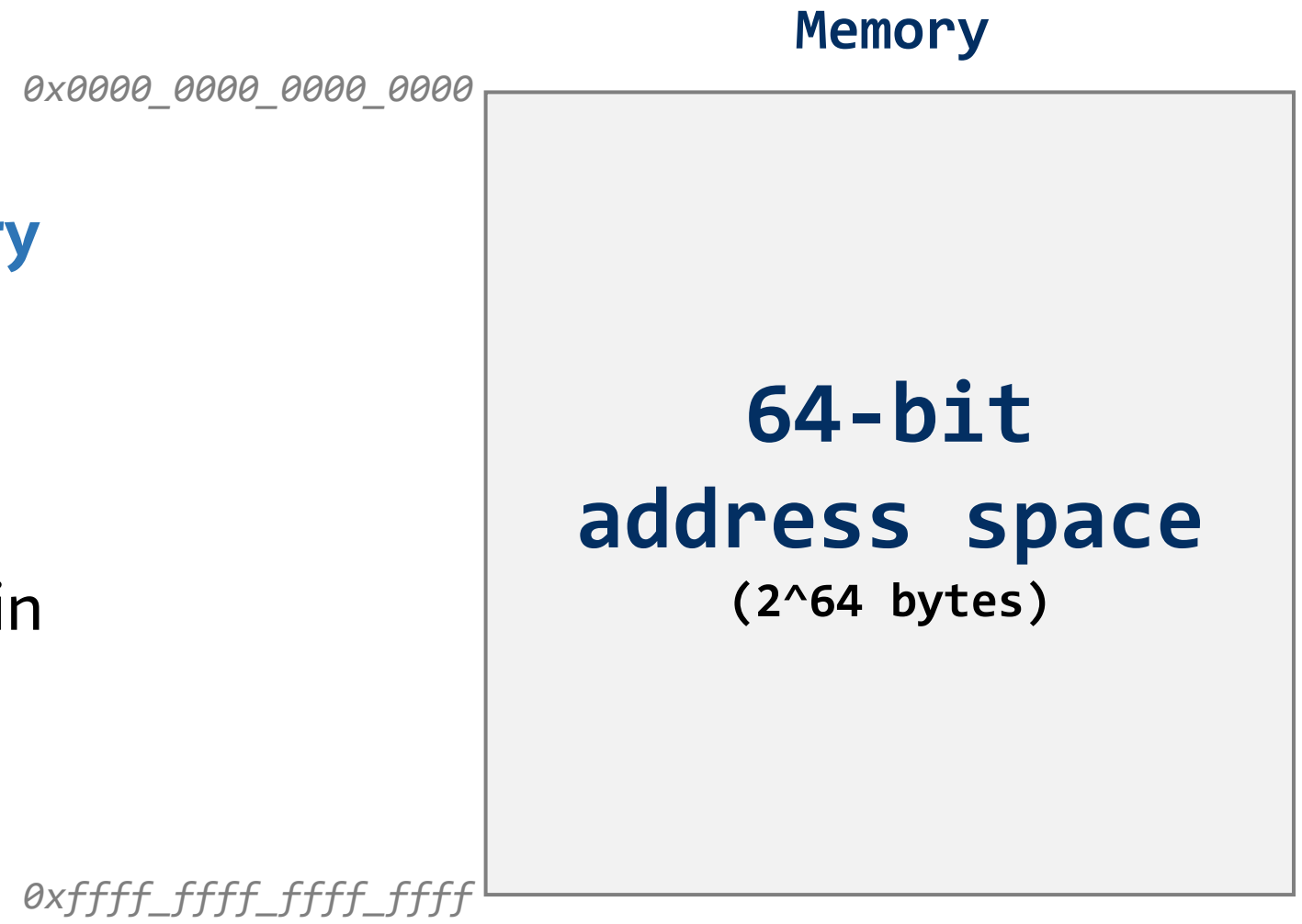
```
mp2099@ilab1:~/cs211/experiment$ /common/users/shared/cs211_s25_5678/toolchain_glibc2/sysroot/lib/ld-linux-riscv64-lp64.so.1
/common/users/shared/cs211_s25_5678/toolchain_glibc2/sysroot/lib/ld-linux-riscv64-lp64.so.1: missing program name
Try '/common/users/shared/cs211_s25_5678/toolchain_glibc2/sysroot/lib/ld-linux-riscv64-lp64.so.1 --help' for more information.
```

```
mp2099@ilab1:~/cs211/experiment$ /common/users/shared/cs211_s25_5678/toolchain_glibc2/sysroot/lib/ld-linux-riscv64-lp64.so.1 --help
Usage: /common/users/shared/cs211_s25_5678/toolchain_glibc2/sysroot/lib/ld-linux-riscv64-lp64.so.1 [OPTION]... EXECUTABLE-FILE [ARGS-FOR-PROGRAM...]
You have invoked 'ld.so', the program interpreter for dynamically-linked
ELF programs.  Usually, the program interpreter is invoked automatically
when a dynamically-linked executable is started.

You may invoke the program interpreter program directly from the command
line to load and run an ELF executable file; this is like executing that
file itself, but always uses the program interpreter you invoked,
instead of the program interpreter specified in the executable file you
run.  Invoking the program interpreter directly provides access to
additional diagnostics, and changing the dynamic linker behavior without
setting environment variables (which would be inherited by subprocesses).
```

A C Program's Address Space

- The loader's job: **fill in memory**

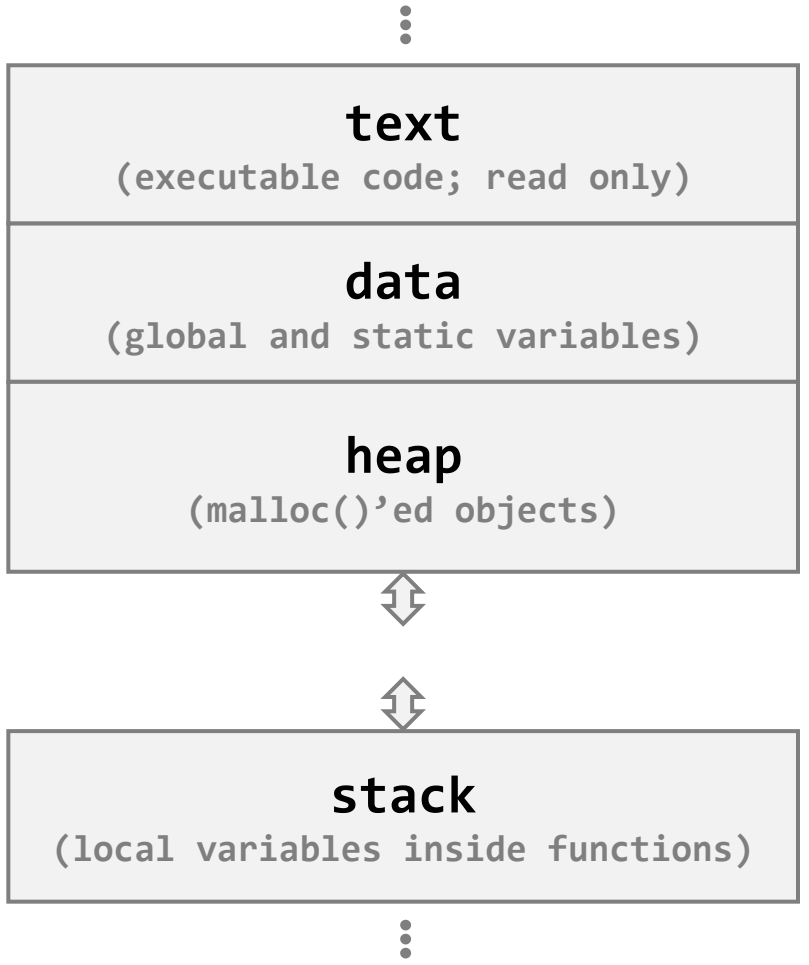
- So far, we've treated all bytes in memory as equal
  - Surprise: **they're not equal**



Sections of the Address Space

```
netid@ilab:~$ gcc -o hello hello.c
netid@ilab:~$ ./hello world
Hello, World
netid@ilab:~$
```

Loader

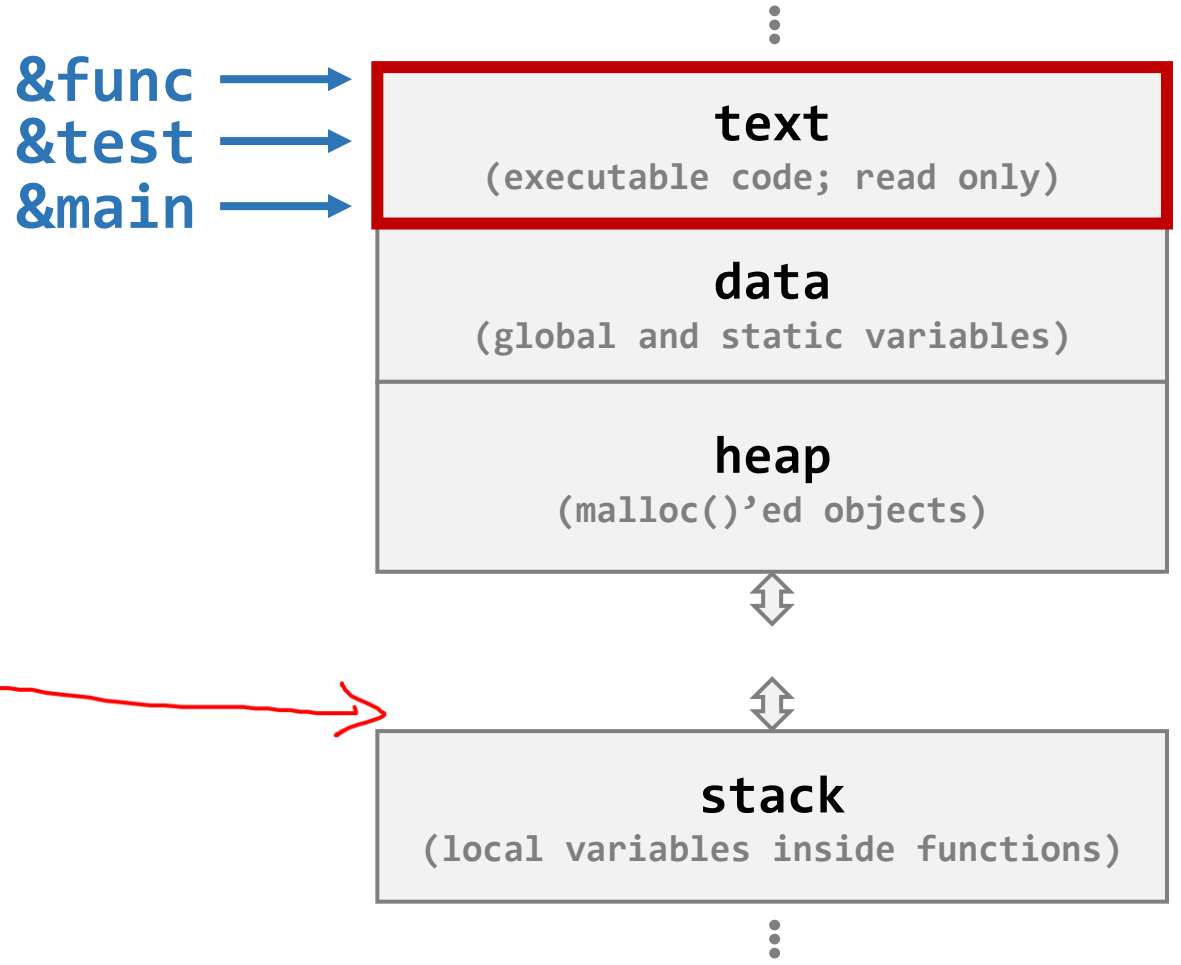


- Many parts of a C program
  - **Executable code** (i.e., your functions)
  - **Data** (i.e., your C objects)
    - Initialized and uninitialized data
    - Compiler-allocated and dynamically-allocated
  - **Debugging information**
  - …

Sections of the Address Space: text

- Read-only section for executable code

```
void func(int a) {...}

void test(void)
{
    uint64_t u = 0x211;
}
```

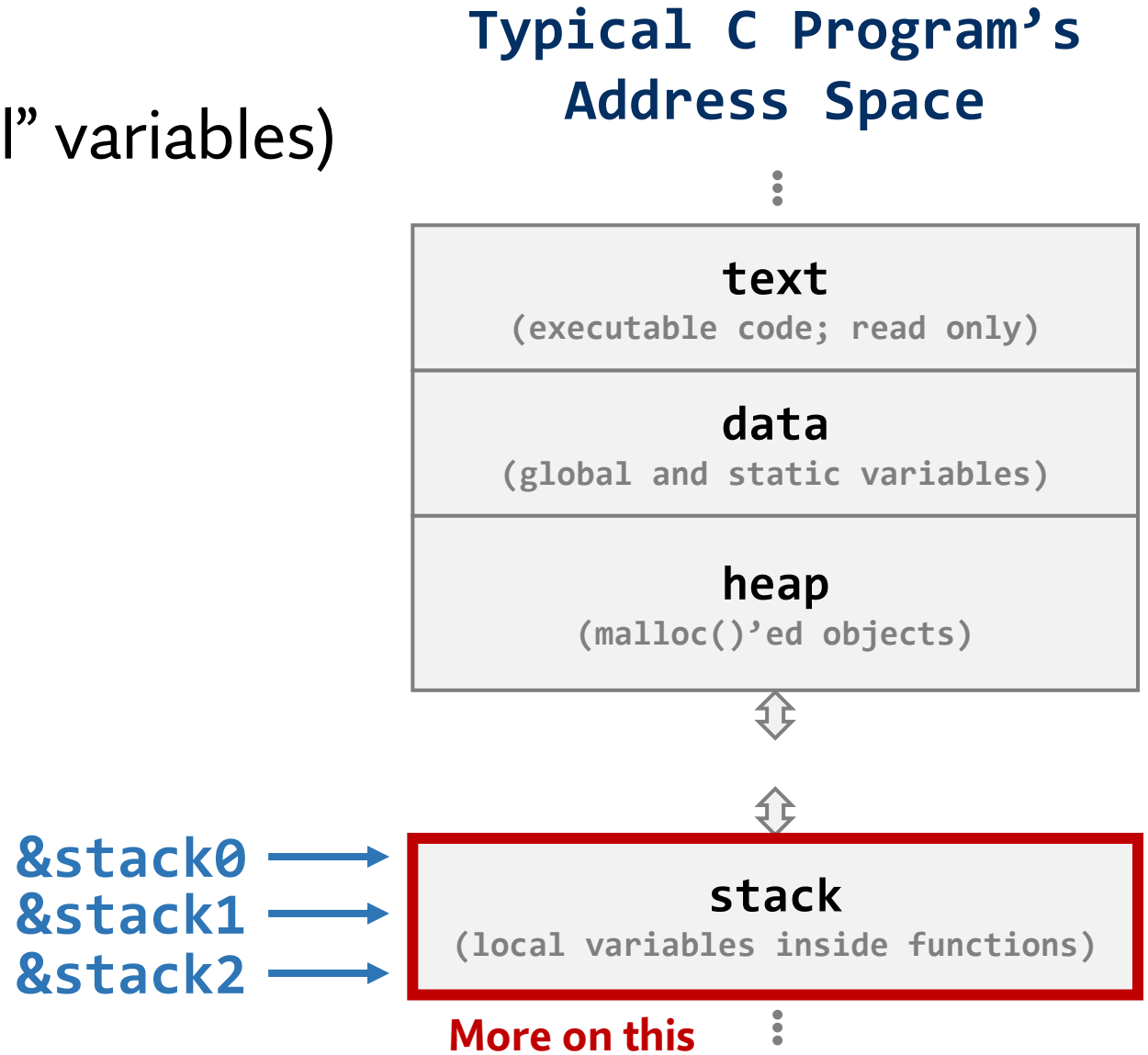


- Just a bunch of numbers
  - Representation = "machine code"
  - More on this after Spring Break

Sections of the Address Space: stack

- Any variable inside a function ("local" variables)
- Lives **only** within the function

```
int main(int argc, char **argv)
{
    uint64_t stack0[100] = {0x211};
    uint64_t *stack1 = stack0;

    ...
}

void func(void)
{
    struct test stack2;

    ...
}
```



Aside: Variable Scope in C

- C objects exist only within their "scope"

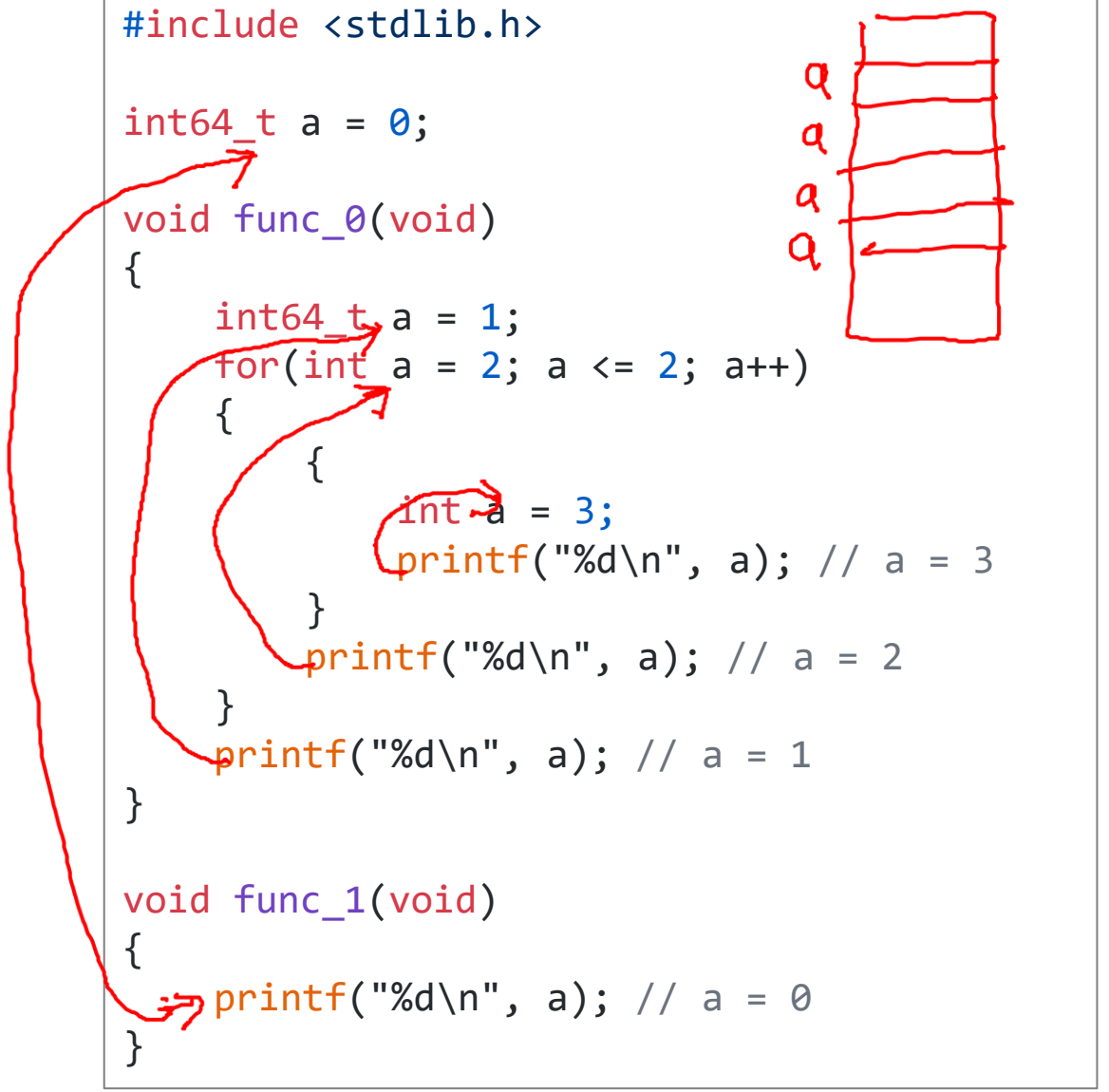
"Local": Block Scope

- The innermost block { ... } is in scope
- Live as long as the scope

"Global": File Scope

- In scope for everything in the file
- Live as long as the program

```c
#include <stdlib.h>

int64_t a = 0;

void func_0(void)
{
    int64_t a = 1;
    for(int a = 2; a <= 2; a++)
    {
        {
            int a = 3;
            printf("%d\n", a); // a = 3
        }
        printf("%d\n", a); // a = 2
    }
    printf("%d\n", a); // a = 1
}

void func_1(void)
{
    printf("%d\n", a); // a = 0
}
```



Aside: Two Types of Global Variables

Global

visible to all functions in the file

```c
#include <stdlib.h>

int64_t a = 0;

void func_0(void)
{
    a++;
    printf("%d\n", a); // prints 2, then 4
}

int main(int argc, int *argv[])
{
    a++;
    func_0();
    a++;
    func_0();
}
```

Static

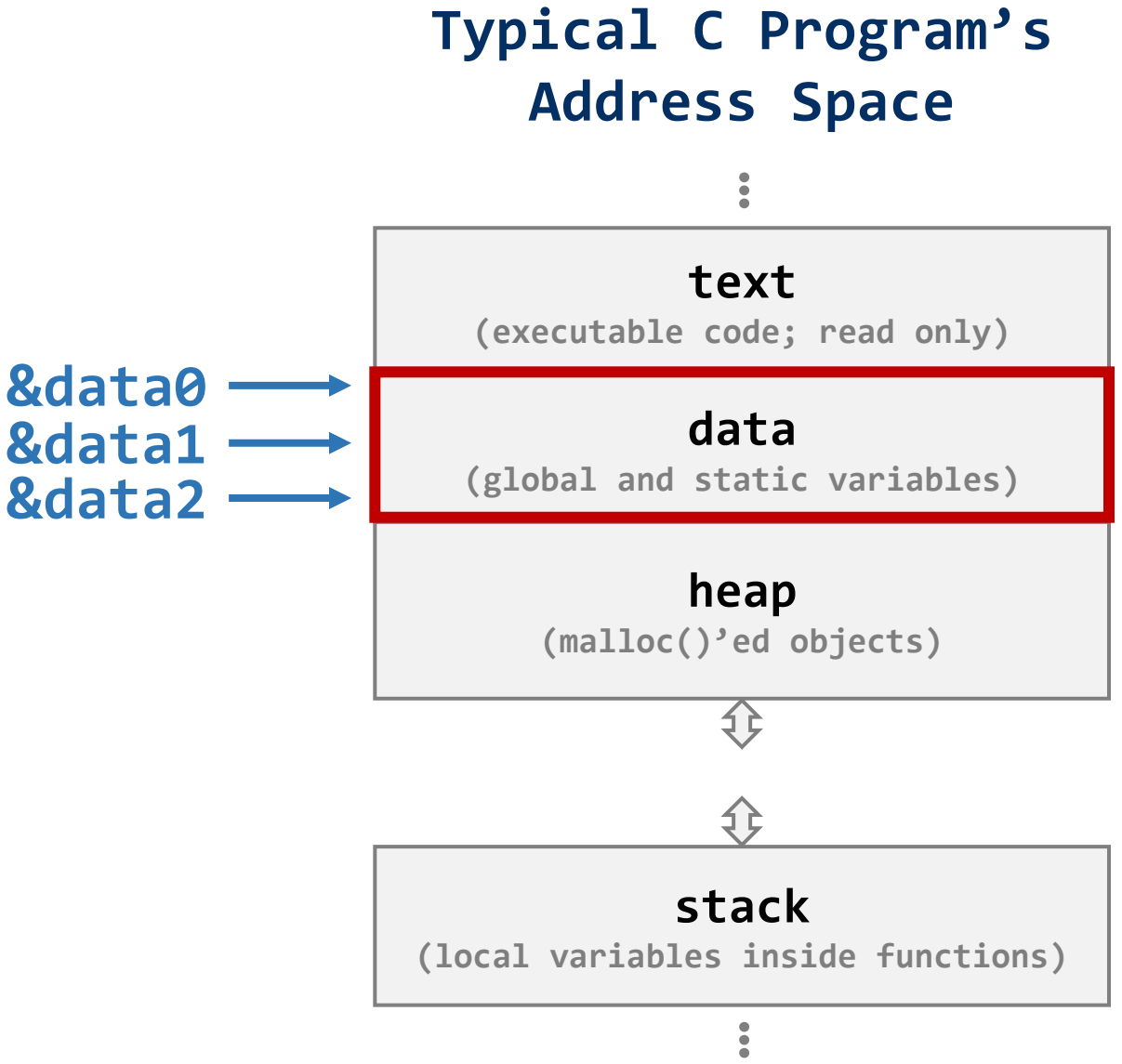
persists between function calls

```c
#include <stdlib.h>

void func_0(void)
{
    static int64_t a = 1;
    a++;
    printf("%d\n", a); // prints 2, then 3
}

int main(int argc, int *argv[])
{
    static int64_t a = 2; // different ‘a’
    func_0();
    func_0();
}
```

Sections of the Address Space: data

- Static and global variables
- Live **as long as** the entire program

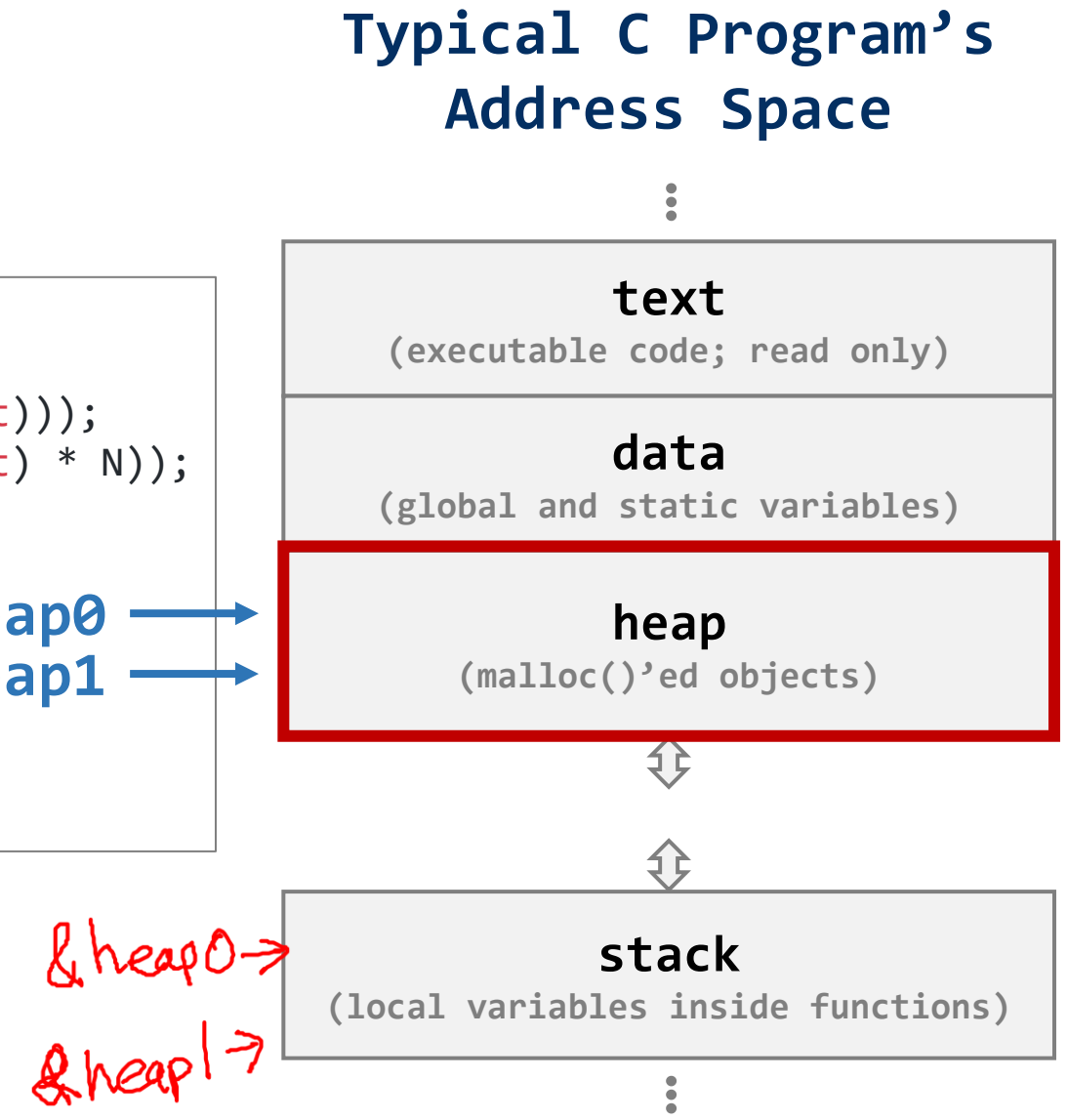
```
uint64_t data2[100];

int main(int argc, char **argv)
{
    static uint64_t *data0 = NULL;
    ...
}

void func(void)
{
    static uint64_t *data1;
    ...
}
```



Sections of the Address Space: heap

- Any object created with malloc()
  - Lives **until it is free()'d**

```
int main(int argc, char **argv)
{
    uint64_t *heap0 = (uint64_t *)malloc(sizeof(uint64_t));
    uint64_t *heap1 = (uint64_t *)malloc(sizeof(uint64_t) * N));

    *heap0 = 1;
    heap1[N - 1] = 0x211;

    free(heap0);
    free(heap1);
}
```

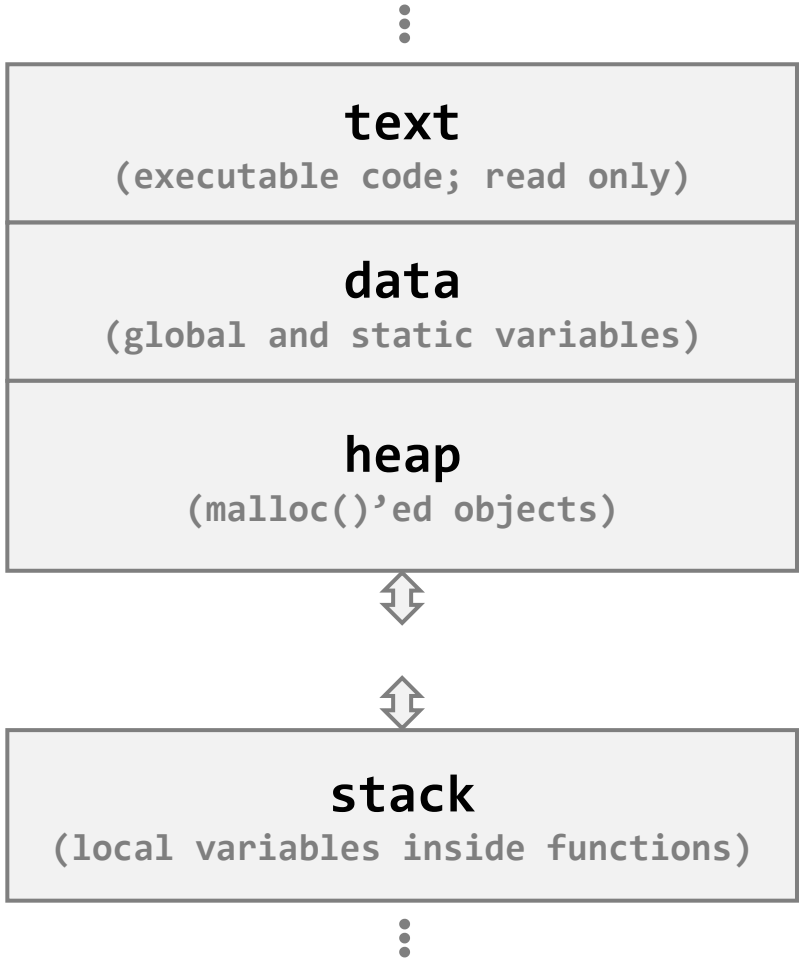


Inspecting Sections of an Executable File

```
mp2099@ilab1:~/cs211/experiment$ /common/users/shared/cs211_s25_5678/to
olchain_glibc2/bin/riscv64-unknown-linux-gnu-gcc -o hello hello.c
mp2099@ilab1:~/cs211/experiment$ readelf -S hello
There are 28 section headers, starting at offset 0x1a88:

Section Headers:
  [Nr] Name              Type            Address          Offset
       Size              EntSize         Flags  Link  Info  Align
  [ 0]                   NULL            0000000000000000  00000000
       0000000000000000  0000000000000000           0     0     0
  [ 1] .interp           PROGBITS        0000000000010270  00000270
       0000000000000020  0000000000000000   A       0     0     1
  [ 2] .note.ABI-tag     NOTE            0000000000010290  00000290
       0000000000000020  0000000000000000   A       0     0     4
  [ 3] .hash             HASH            00000000000102b0  000002b0
       0000000000000024  0000000000000004   A       5     0     8
  [ 4] .gnu.hash         GNU_HASH        00000000000102d8  000002d8
       0000000000000030  0000000000000000   A       5     0     8
  [ 5] .dynsym           DYNSYM          0000000000010308  00000308
       0000000000000060  0000000000000018   A       6     1     8
  [ 6] .dynstr           STRTAB          0000000000010368  00000368
       000000000000004a  0000000000000000   A       0     0     1
  [ 7] .gnu.version      VERSYM          00000000000103b2  000003b2
       0000000000000008  0000000000000002   A       5     0     2
  [ 8] .gnu.version_r    VERNEED         00000000000103c0  000003c0
       0000000000000030  0000000000000000   A       6     1     8
  [ 9] .rela.plt         RELA            00000000000103f0  000003f0
       0000000000000030  0000000000000018  AI       5    20     8
  [10] .plt              PROGBITS        0000000000010420  00000420
       0000000000000040  0000000000000010  AX       0     0    16
  [11] .text             PROGBITS        0000000000010460  00000460
       00000000000000c2  0000000000000000  AX       0     0     4
  [12] .rodata           PROGBITS        0000000000010528  00000528
       0000000000000015  0000000000000000   A       0     0     8
  [13] .eh_frame_hdr     PROGBITS        0000000000010540  00000540
       0000000000000024  0000000000000000   A       0     0     4
  [14] .eh_frame         PROGBITS        0000000000010568  00000568
       000000000000006c  0000000000000000   A       0     0     8
  [15] .preinit_array    PREINIT_ARRAY   0000000000011df0  00000df0
       0000000000000008  0000000000000008  WA       0     0     1
  [16] .init_array       INIT_ARRAY      0000000000011df8  00000df8
       0000000000000008  0000000000000008  WA       0     0     8
  [17] .fini_array       FINI_ARRAY      0000000000011e00  00000e00
       0000000000000008  0000000000000008  WA       0     0     8
  [18] .dynamic          DYNAMIC         0000000000011e08  00000e08
       00000000000001e0  0000000000000010  WA       6     0     8
  [19] .got              PROGBITS        0000000000011fe8  00000fe8
       0000000000000008  0000000000000008  WA       0     0     8
  [20] .got.plt          PROGBITS        0000000000011ff0  00000ff0
       0000000000000020  0000000000000008  WA       0     0     8
  [21] .sdata            PROGBITS        0000000000012010  00001010
       0000000000000008  0000000000000000  WA       0     0     8
  [22] .bss              NOBITS          0000000000012018  00001018
       0000000000000008  0000000000000000  WA       0     0     1
  [23] .comment          PROGBITS        0000000000000000  00001018
       000000000000002b  0000000000000001  MS       0     0     1
  [24] .riscv.attributes RISCV_ATTRIBUTE  0000000000000000  00001043
       0000000000000066  0000000000000000           0     0     1
  [25] .symtab           SYMTAB          0000000000000000  000010b0
       0000000000000678  0000000000000018          26    52     8
  [26] .strtab           STRTAB          0000000000000000  00001728
       0000000000000262  0000000000000000           0     0     1
  [27] .shstrtab         STRTAB          0000000000000000  0000198a
       00000000000000fc  0000000000000000           0     0     1
Key to Flags:
  W (write), A (alloc), X (execute), M (merge), S (strings), I (info),
  L (link order), O (extra OS processing required), G (group), T (TLS),
  C (compressed), x (unknown), o (OS specific), E (exclude),
  D (mbind), p (processor specific)
mp2099@ilab1:~/cs211/experiment$
```

- Clearly, there's more
- Extra sections for
  - Initialization
  - Debugging (e.g., GDB)
  - Metadata (e.g., supported platforms)
- Sub-sections of data
  - e.g., read-only
  - Uninitialized

Typical C Program's Address Space



Agenda

- Functions
- Loaders and the C Memory Layout
- **Dynamic Memory Allocation**
- C Generics
  - C Library Functions

Malloc

An **unsigned integer** type: wide enough to count the entire memory's worth of bytes

7.22.3.4 The `malloc` function

Synopsis

```
#include <stdlib.h>
void *malloc(size_t size);
```

Description

The **`malloc`** function allocates space for an object whose size is specified by **`size`** and whose value is indeterminate.

7.22.3.3 The `free` function

Synopsis

```
#include <stdlib.h>
void free(void *ptr);
```

Description

The **`free`** function causes the space pointed to by **`ptr`** to be deallocated, that is, made available for further allocation. If **`ptr`** is a null pointer, no action occurs.

ISO Standard 9899:2011

- Allocates the requested number of **uninitialized bytes**
  - Malloc **does not care** how you will use the allocated memory
  - Assuming '`size`' is very error-prone: use "`sizeof(type) * N`"
- Returns NULL on failure (e.g., run out of memory): **always check**!

Dynamic Memory Allocation

- You can dynamically allocate anything that you can statically allocate

Basic Objects

```
uint64_t *u = (uint64_t *)malloc(sizeof(uint64_t));
if(u != NULL)
{
    *u = 1;
    u[0]++;
    free(u);
}
```

Array Objects

```
#define N (2 * 1024 * 1024)
uint64_t *arr = (uint64_t *)malloc(sizeof(uint64_t) * N));
if(arr != NULL)
{
    *arr = 0;
    arr[N - 1] = N - 1;
    free(u);
}
```

Malloc'ing Pointers

- Dynamically allocating **a pointer** requires a pointer-to-pointer

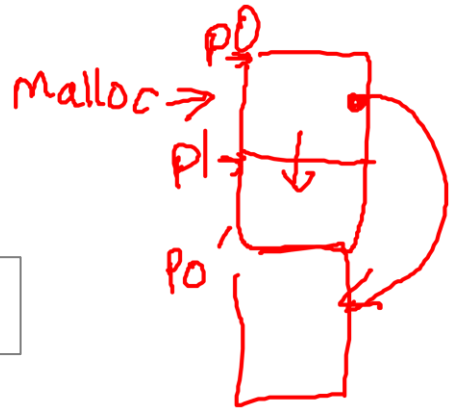
```
struct my_struct
{
    uint8_t u;
    ...
}

// pointer to a pointer-to-struct
struct my_struct **pps = (struct my_struct **)malloc(sizeof(struct my_struct*)));
if(pps != NULL)
{
    // pointer-to-struct
    *pps = (struct my_struct *)malloc(sizeof(struct my_struct)));
    if(*pps != NULL)
    {   (**pps).u=0
        (*pps)->u = 0;
        free(*pps);
    }
    free(pps); // one free() for every successful malloc()
}
```

Friends of malloc()

```
malloc(3)                Library Functions Manual                malloc(3)

NAME
       malloc, free, calloc, realloc, reallocarray - allocate and free
       dynamic memory

LIBRARY
       Standard C library (libc, -lc)

SYNOPSIS
       #include <stdlib.h>

       void *malloc(size_t size);
       void free(void *ptr);
       void *calloc(size_t nmemb, size_t size);
       void *realloc(void *ptr, size_t size);
       void *reallocarray(void *ptr, size_t nmemb, size_t size);
```

- Helper functions:
  - **`calloc()`**: also initialize the allocated bytes to '0'
  - **`realloc()`**: change the size of a previously-malloc'd region

Realloc for Resizing




```
void *realloc(void *ptr, size_t size);
```

- Resizes a previously-allocated block at **`ptr`** to a new **`size`**
  - Might require moving the block to a new location!
  - Automatically copies the data and free's the old block, if necessary

- On success:
  - New pointer is **valid**
  - Old pointer is **invalid** – do not try to use or free() it

- On failure:
  - New pointer is **NULL**
  - Old pointer is unchanged

```
void func(void)
{
    uint64_t *u = (uint64_t *)malloc(sizeof(uint64_t));
    ...
    uint64_t *v = realloc(u, sizeof(uint64_t) * 2);
}
```

Four Common Bugs with Malloc

All can cause a **program crash or security vulnerability**

Memory Leak

```
void func(void)
{
    uint64_t *u = (uint64_t *)
        malloc(sizeof(uint64_t));
    ...
    return;
}
```

Use After Free

```
void func(void)
{
    uint64_t *u = (uint64_t *)
        malloc(sizeof(uint64_t));
    free(u);
    u[0] = 1;
}
```

Double Free

```
void func(void)
{
    uint64_t *u = (uint64_t *)
        malloc(sizeof(uint64_t));
    free(u);
    free(u);
}
```

Incorrect Allocation Size

```
void func(void)
{
    uint64_t *u = (uint64_t *)
        malloc(1);
    u[0] = 0xffffffffffffffff;
}
```

Example: Use After Free

- Your code will usually crash **some time later** than the actual bug

```
void func(void)
{
    uint64_t *u = (uint64_t *)malloc(sizeof(uint64_t));
    if(u != NULL)
        free(u);

    ... // meanwhile, ‘u’ was reallocated to a different object

    printf(“%lx”, u);  // prints data from somewhere else in the program
}
```

```
void func(void)
{
    uint64_t *u = (uint64_t *)malloc(sizeof(uint64_t));
    if(u != NULL)
        free(u);

    ... // meanwhile, ‘u’ was NOT reallocated

    printf(“%lx”, u);  // crash trying to access memory at ‘u’
}
```

Example: Double-Free

- Your code will usually crash **some time later** than the actual bug

```
void func(void)
{
    uint64_t *u = (uint64_t *)malloc(sizeof(uint64_t));
    if(u != NULL)
        free(u);

    ... // meanwhile, ‘u’ was reallocated to a different object

    if(u != NULL)
        free(u);  // free’s somebody else’s memory

    ... // bad things happen: the other object will experience a use-after-free
}
```

Example: `realloc()` misuse

- Your code will usually crash **some time later** than the actual bug

```
void func(void)
{
    uint64_t *u = (uint64_t *)malloc(sizeof(uint64_t));
    ...
    uint64_t *v = (uint64_t *)realloc(u, sizeof(uint64_t) * 2);
    // IF realloc failed, v == NULL; u == still valid
    // IF realloc passeed, v == new memory; u == invalid

    ... // need to be careful to use the right pointer!
}
```

Avoiding Memory Bugs

Proactive measures:

1. Always initialize pointers to NULL
2. Always set pointers to NULL after free() or successful realloc()
3. Always check the results of malloc() and friends
4. Avoid magic numbers in the code for allocation/array sizes

Debugging tools:

1. **GDB:** line-by-line debugging
2. **Valgrind:** slows down your code, but checks for memory misuse
   - Memory leaks
   - Use-after-free
   - Out of bounds accesses

CS 211: Intro to Computer Architecture

7.1: Dynamic Memory Management

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