CS 110
Computer Architecture

Lecture 3: *Introduction to C II*

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Slides based on UC Berkley's CS61C

Agenda

- Pointers
- Pointers & Arrays
- C Memory Management
- C Bugs

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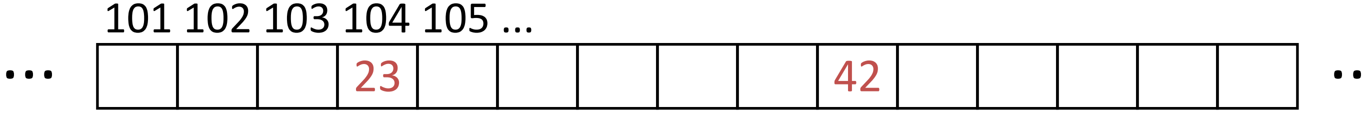
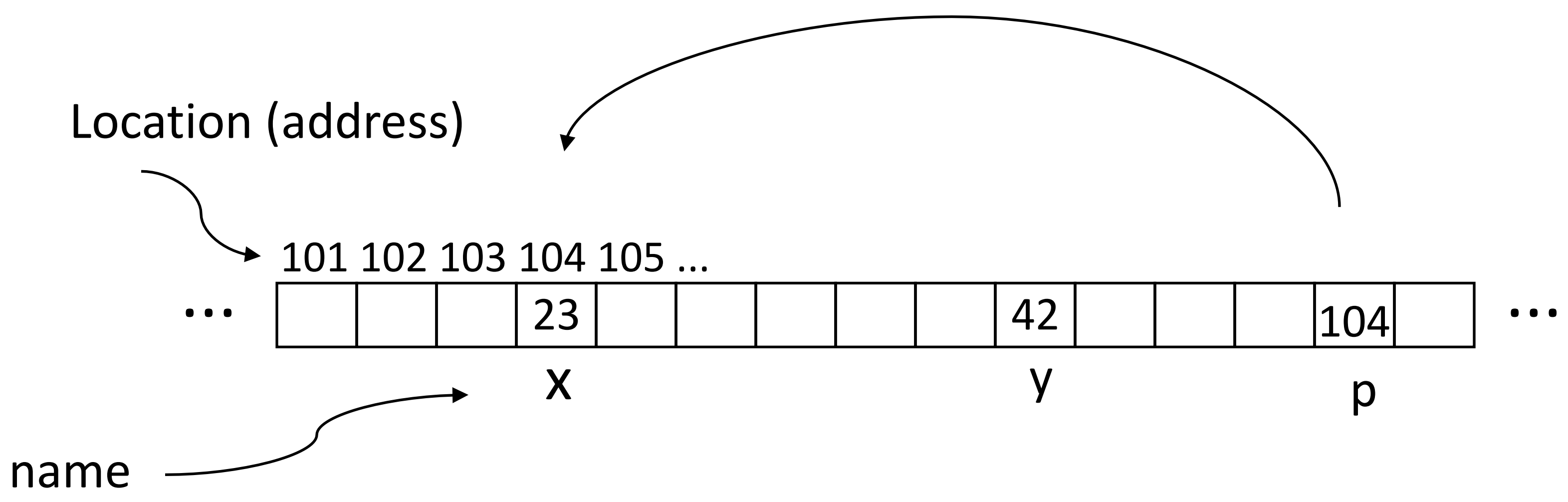
Address vs. Value

- Consider memory to be a single huge array
  - Each cell of the array has an address associated with it
  - Each cell also stores some value
  - For addresses do we use signed or unsigned numbers? Negative address?!
- Don't confuse the address referring to a memory location with the value stored there



Pointers

- An *address* refers to a particular memory location; e.g., it points to a memory location
- *Pointer*: A variable that contains the address of a variable



Pointer Syntax

- `int *x;`
  - Tells compiler that variable x is address of an `int`
- `x = &y;`
  - Tells compiler to assign address of `y` to `x`
  - `&` called the “address operator” in this context
- `z = *x;`
  - Tells compiler to assign value at address in `x` to `z`
  - `*` called the “dereference operator” in this context

Creating and Using Pointers

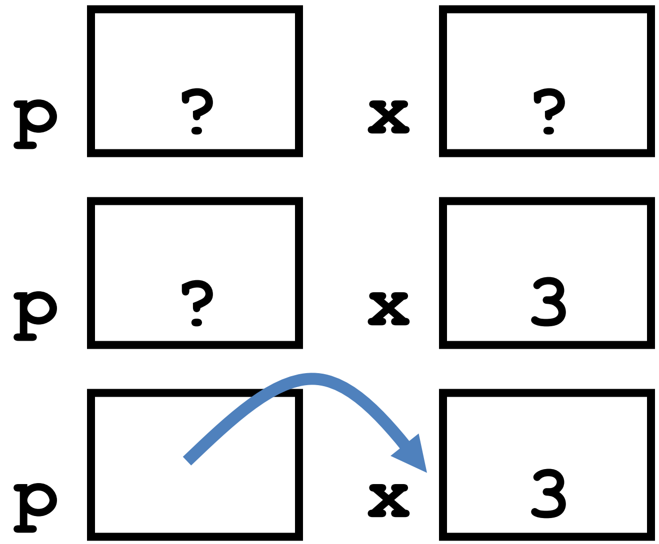
- How to create a pointer:

& operator: get address of a variable

```
int *p, x;

    x = 3;

    p = &x;
```



Note the "*" gets used 2 different ways in this example. In the declaration to indicate that **p** is going to be a pointer, and in the **printf** to get the value pointed to by **p**.

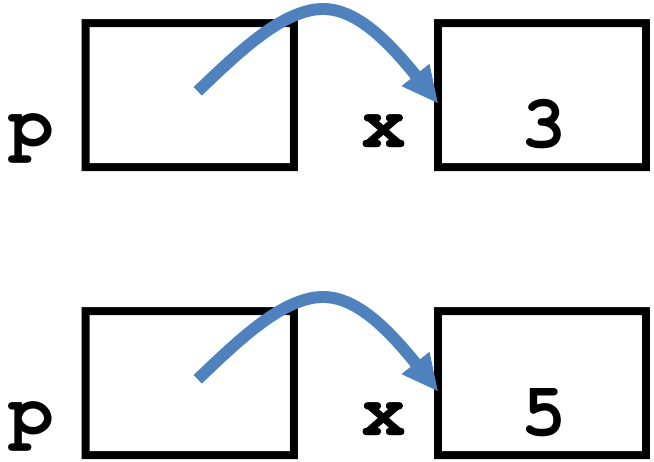
- How get a value pointed to?

"*" (dereference operator): get the value that the pointer points to

```
printf("p points to value %d\n",*p);
```

Using Pointer for Writes

- How to change a variable pointed to?
  - Use the dereference operator ***** on left of assignment operator **=**




```
*p = 5;
```

Pointers and Parameter Passing

- C passes parameters "by value"
  - Procedure/function/method gets a copy of the parameter, *so changing the copy cannot change the original*

```
void add_one (int x) {
    x = x + 1;
  }
int y = 3;
add_one(y);
```

y remains equal to 3

Pointers and Parameter Passing

- How can we get a function to change the value held in a variable?

```
void add_one (int *p) {
   *p = *p + 1;
  }
int y = 3;

add_one(&y);
```

y is now equal to 4

What would you use in C++?

Call by reference:

```
void add_one (int &p) {
   p = p + 1;   // or  p += 1;
}
```

Types of Pointers

- Pointers are used to point to any kind of data (**`int`**, **`char`**, a **`struct`**, etc.)
- Normally a pointer only points to one type (**`int`**, **`char`**, a **`struct`**, etc.).
  - **`void *`** is a type that can point to anything (generic pointer)
  - Use **`void *`** sparingly to help avoid program bugs, and security issues, and other bad things!

More C Pointer Dangers

- *Declaring a pointer just allocates space to hold the pointer – it does not allocate the thing being pointed to!*
- Local variables in C are not initialized, they may contain anything (aka “garbage”)
- What does the following code do?

```
void f()
{
    int *ptr;
    *ptr = 5;
}
```

Pointers and Structures

```
typedef struct {
    int x;
    int y;
} Point;

Point p1;
Point p2;
Point *paddr;
```

```
/* dot notation */
int h = p1.x;
p2.y = p1.y;

/* arrow notation */
int h = paddr->x;
int h = (*paddr).x;

/* This works too */
p1 = p2;
```

Note: C structure assignment is not a ”deep copy”. All members are copied, but not things pointed to by members.

Pointers in C

- Why use pointers?
  - If we want to pass a large struct or array, it's easier / faster / etc. to pass a pointer than the whole thing
  - In general, pointers allow cleaner, more compact code
- So what are the drawbacks?
  - Pointers are probably the single largest source of bugs in C, so be careful anytime you deal with them
    - Most problematic with dynamic memory management
    - *Dangling references* and *memory leaks*

Why Pointers in C?

- At time C was invented (early 1970s), compilers often didn't produce efficient code
  - Computers 100,000 times faster today, compilers better
- C designed to let programmer say what they want code to do without compiler getting in way
  - Even give compilers hints which registers to use!
- Today's compilers produce much better code, so may not need to use pointers in application code
- Low-level system code still needs low-level access via pointers

Agenda

- Pointers
- Pointers & Arrays
- C Memory Management
- C Bugs

C Arrays

- Declaration:

```c
int ar[2];
```

declares a 2-element integer array: just a block of memory

```c
int ar[] = {795, 635};
```

declares and initializes a 2-element integer array

C Strings

- String in C is just an array of characters

```
char string[] = "abc";
```

- How do you tell how long a string is?
  - Last character is followed by a 0 byte (aka “null terminator”)

```
int strlen(char s[])
{
    int n = 0;
    while (s[n] != 0) n++;
    return n;
}
```

Array Name / Pointer Duality

- *Key Concept*: Array variable is a "pointer" to the first (0^{th}) element
- So, array variables almost identical to pointers
  - `char *string` and `char string[]` are nearly identical declarations
  - Differ in subtle ways: incrementing, declaration of filled arrays, sizeof
- Consequences:
  - `ar` is an array variable, but works like a pointer
  - `ar[0]` is the same as `*ar`
  - `ar[2]` is the same as `*(ar+2)`
  - Can use pointer arithmetic to conveniently access arrays

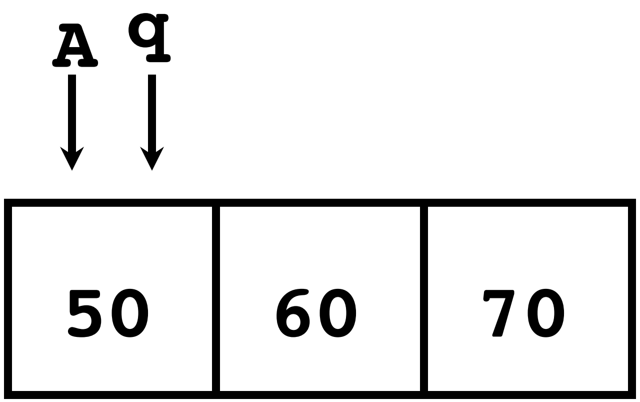
Changing a Pointer Argument?

- What if want function to change a pointer?
- What gets printed?

```
void inc_ptr(int *p)
{     p =  p + 1;    }

int A[3] = {50, 60, 70};
int *q = A;
inc_ptr( q);
printf("*q = %d\n", *q);
```

*q = 50

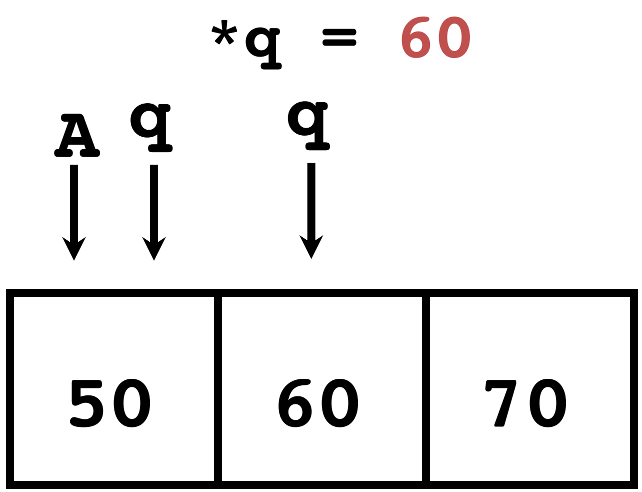


Pointer to a Pointer

- Solution! Pass a pointer to a pointer, declared as `**h`
- Now what gets printed?

```
void inc_ptr(int **h)
{    *h = *h + 1;    }

int A[3] = {50, 60, 70};
int *q = A;
inc_ptr(&q);
printf("*q = %d\n", *q);
```



C Arrays are Very Primitive

- An array in C does not know its own length, and its bounds are not checked!
  - Consequence: We can accidentally access off the end of an array
  - Consequence: We must pass the array *and its size* to any procedure that is going to manipulate it
- Segmentation faults and bus errors:
  - These are VERY difficult to find;
    be careful!

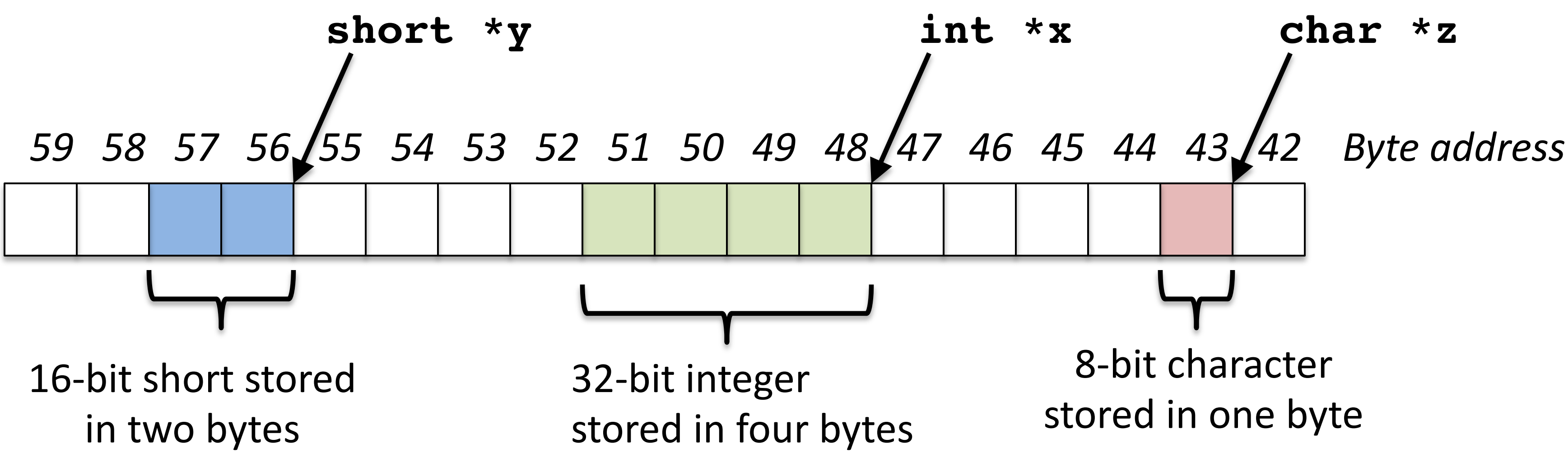
Use Defined Constants

- Array size *n*; want to access from *0* to *n-1*, so you should use counter AND utilize a variable for declaration & incrementation
  - Bad pattern
    ```
    int i, ar[10];
    for(i = 0; i < 10; i++){ ... }
    ```
  - Better pattern
    ```
    const int ARRAY_SIZE = 10;
    int i, a[ARRAY_SIZE];
    for(i = 0; i < ARRAY_SIZE; i++){ ... }
    ```

- SINGLE SOURCE OF TRUTH
  - You’re utilizing indirection and avoiding maintaining two copies of the number 10
  - DRY: “Don’t Repeat Yourself”

Pointing to Different Size Objects

- Modern machines are "byte-addressable"
  - Hardware's memory composed of 8-bit storage cells, each has a unique address
- A C pointer is just abstracted memory address
- Type declaration tells compiler how many bytes to fetch on each access through pointer
  - E.g., 32-bit integer stored in 4 consecutive 8-bit bytes



sizeof() operator

- sizeof(type) returns number of bytes in object
  - But number of bits in a byte is not standardized
    - In olden times, when dragons roamed the earth, bytes could be 5, 6, 7, 9 bits long
- By definition, sizeof(char)==1
- Can take sizeof(arr), or sizeof(structtype)
- We'll see more of sizeof when we look at dynamic memory management

Pointer Arithmetic

pointer + number　　*pointer – number*

e.g., *pointer* **+ 1**　　adds 1 <u>something</u> to a pointer

```
char    *p;
char     a;
char     b;

p = &a;
p += 1;
```

```
int    *p;
int     a;
int     b;

p = &a;
p += 1;
```

In each, p now points to b (Assuming compiler doesn't reorder variables in memory. ***Never code like this!!!!***)

Adds **`1*sizeof(char)`** to the memory address

Adds **`1*sizeof(int)`** to the memory address

Pointer arithmetic should be used <u>cautiously</u>

Arrays and Pointers

- Array ≈ pointer to the initial (0th) array element

$$a[i] \equiv *(a+i)$$

- An array is passed to a function as a pointer
  - The array size is lost!
- Usually bad style to interchange arrays and pointers
  - Avoid pointer arithmetic!

Passing arrays:

Really `int *array`

Must explicitly pass the size

```
int
foo(int array[],
    unsigned int size)
{
   … array[size - 1] …
}

int
main(void)
{
   int a[10], b[5];
   … foo(a, 10)… foo(b, 5)  …
}
```

Arrays and Pointers

```
int
foo(int array[],
    unsigned int size)
{
   …
   printf("%d\n", sizeof(array));
}

int
main(void)
{
   int a[10], b[5];
   … foo(a, 10)… foo(b, 5)  …
   printf("%d\n", sizeof(a));

}
```

What does this print (32bit)? **4**

... because **`array`** is really a pointer (and a pointer is architecture dependent, but likely to be 8 on modern machines!)

What does this print (32bit)? **40**

Arrays and Pointers

```
int  i;
int  array[10];

for (i = 0; i < 10; i++)
{
  array[i] = …;
}
```

```
int *p;
int  array[10];

for (p = array; p < &array[10]; p++)
{
  *p = …;
}
```

These code sequences have the same effect!

C Strings

- String in C is just an array of characters

```
char string[] = "abc";
```

- How do you tell how long a string is?
  - Last character is followed by a 0 byte (aka "null terminator")

```
int strlen(char s[])
{
    int n = 0;
    while (s[n] != 0) n++;
    return n;
}
```

Concise strlen()

```
int strlen(char *s)
{
    char *p = s;
    while (*p++)
        ; /* Null body of while */
    return (p - s - 1);
}
```

What happens if there is no zero character at end of string?

Point past end of array?

- Array size n; want to access from 0 to $n-1$, but test for exit by comparing to address one element past the array

```
int ar[10], *p, *q, sum = 0;
 ...
 p = &ar[0]; q = &ar[10];
 while (p != q)
     /* sum = sum + *p; p = p + 1; */
  sum += *p++;
```

  – Is this legal?

- C defines that one element past end of array must be a valid address, i.e., not cause an error

Valid Pointer Arithmetic

- Add an integer to a pointer.
- Subtract 2 pointers (in the same array)
- Compare pointers (<, <=, ==, !=, >, >=)
- Compare pointer to NULL (indicates that the pointer points to nothing)

Everything else illegal since makes no sense:

- adding two pointers
- multiplying pointers
- subtract pointer from integer

Arguments in `main()`

- To get arguments to the main function, use:
  - `int main(int argc, char *argv[])`
- What does this mean?
  - `argc` contains the number of strings on the command line (the executable counts as one, plus one for each argument). Here `argc` is 2:

    unix% sort myFile
  - `argv` is a *pointer* to an array containing the arguments as strings

Example

- `foo hello 87`
- `argc = 3 /* number arguments */`
- `argv[0] = "foo",`
  `argv[1] = "hello",`
  `argv[2] = "87"`
  - Array of pointers to strings

Summary

- Pointers and arrays are virtually same
- C knows how to increment pointers
- C is an efficient language, with little protection
  - Array bounds not checked
  - Variables not automatically initialized
- (Beware) The cost of efficiency is more overhead for the programmer.
  - "C gives you a lot of extra rope but be careful not to hang yourself with it!"

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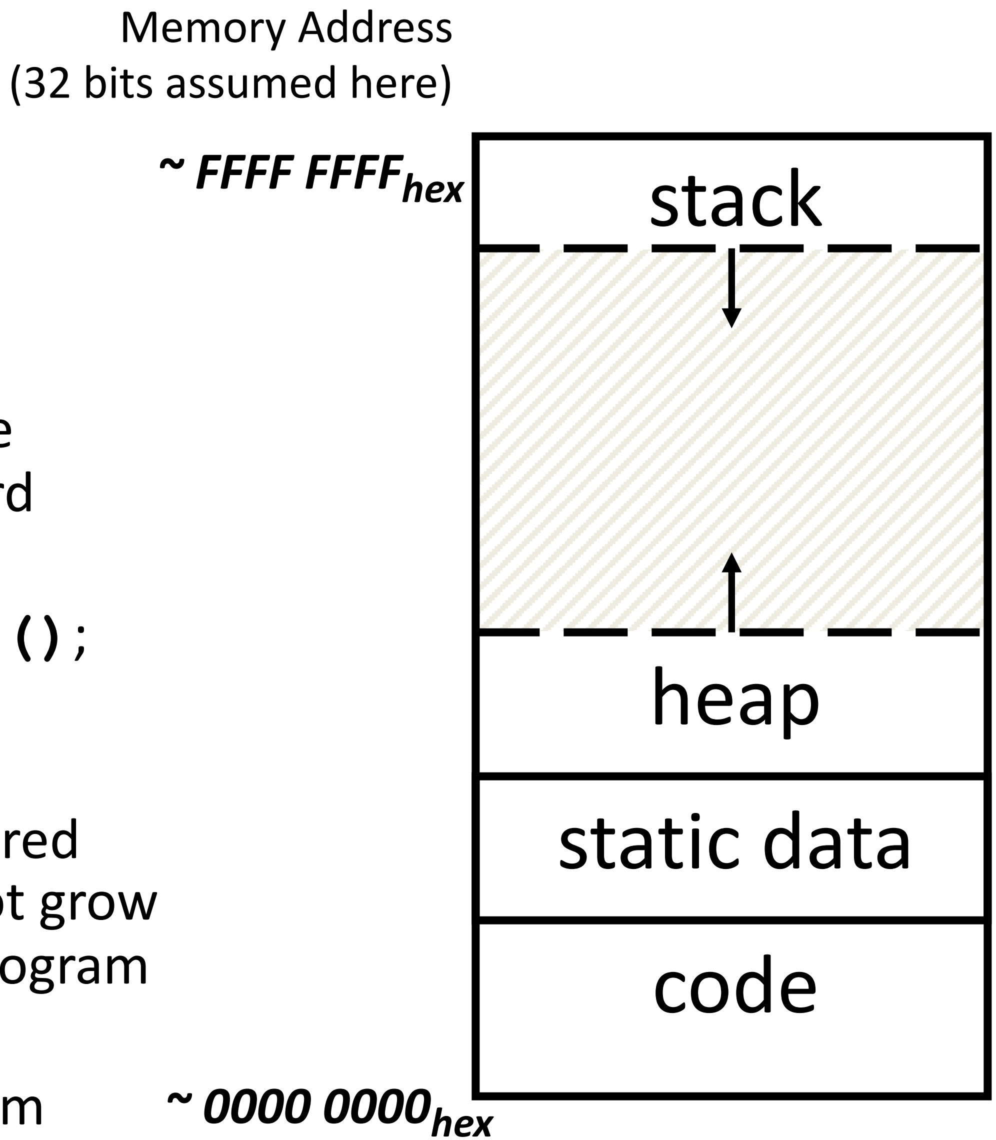
C Memory Management

- How does the C compiler determine where to put all the variables in machine's memory?
- How to create dynamically sized objects?
- To simplify discussion, we assume one program runs at a time, with access to all of memory.
- Later, we'll discuss virtual memory, which lets multiple programs all run at same time, each thinking they own all of memory.

C Memory Management

- Program's *address space* contains 4 regions:
  - stack: local variables inside functions, grows downward
  - heap: space requested for dynamic data via **`malloc()`**; resizes dynamically, grows upward
  - static data: variables declared outside functions, does not grow or shrink. Loaded when program starts, can be modified.
  - code: loaded when program starts, does not change



Where are Variables Allocated?

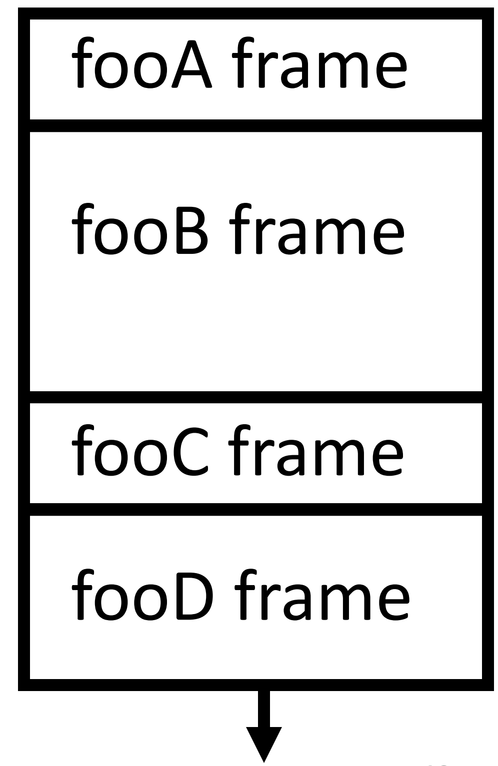
- If declared outside a function, allocated in “static” storage
- If declared inside function, allocated on the “stack” and freed when function returns
  - main() is treated like a function

```
int myGlobal;
main() {
   int myTemp;
}
```

The Stack

- Every time a function is called, a new frame is allocated on the stack
- Stack frame includes:
  - Return address (who called me?)
  - Arguments
  - Space for local variables
- Stack frames contiguous blocks of memory; stack pointer indicates start of stack frame
- When function ends, stack frame is tossed off the stack; frees memory for future stack frames
- We'll cover details later for RISC-V processor

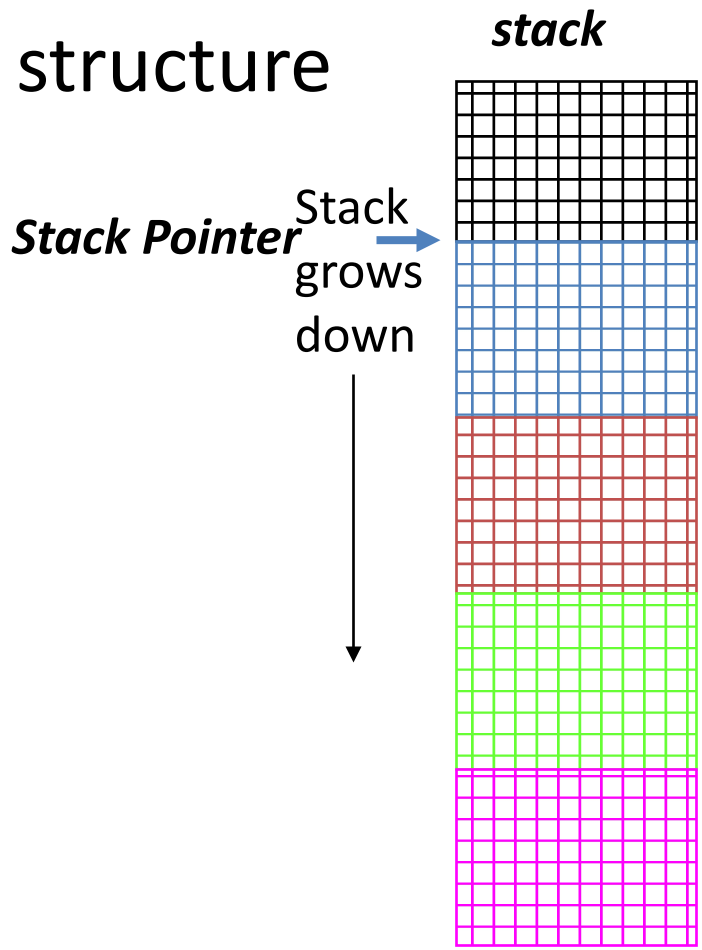
```
fooA() { fooB(); }
fooB() { fooC(); }
fooC() { fooD(); }
```



Stack Animation

- Last In, First Out (LIFO) data structure

```
main ()
{ a(0);
}
  void a (int m)
  { b(1);
  }
    void b (int n)
    { c(2);
    }
      void c (int o)
      { d(3);
      }
       void d (int p)
        {
        }
```



Managing the Heap

C supports five functions for heap management:

- **`malloc()`** allocate a block of uninitialized memory
- **`calloc()`** allocate a block of zeroed memory
- **`free()`** free previously allocated block of memory
- **`realloc()`** change size of previously allocated block
  - careful – it might move!

Malloc()

- **`void *malloc(size_t n)`**:
  - Allocate a block of uninitialized memory
  - NOTE: Subsequent calls might not yield blocks in contiguous addresses
  - **`n`** is an integer, indicating size of allocated memory block in bytes
  - **`size_t`** is an unsigned integer type big enough to "count" memory bytes
  - **`sizeof`** returns size of given type in bytes, produces more portable code
  - Returns **`void*`** pointer to block; **`NULL`** return indicates no more memory
  - Think of pointer as a *handle* that describes the allocated block of memory; Additional control information stored in the heap around the allocated block!

- Examples:

*"Cast" operation, changes type of a variable. Here changes **(void *)** to **(int *)***

```
int *ip;
ip = (int *) malloc(sizeof(int));

typedef struct { … } TreeNode;
TreeNode *tp = (TreeNode *) malloc(sizeof(TreeNode));
```