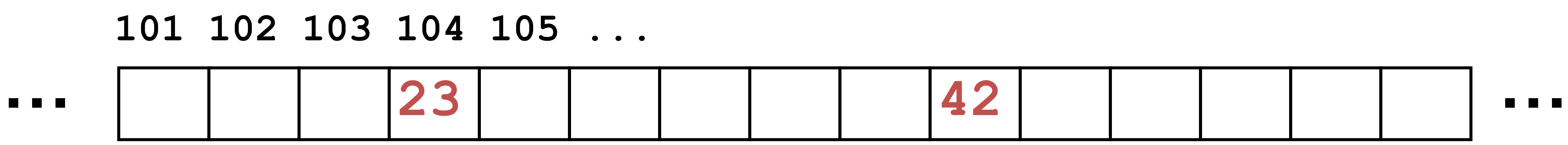
Pointers, Arrays, Memory: AKA the cause of those F@#)(#@*(Segfaults

Agenda

- Pointers Redux
  - This is subtle and important, so going over again
- Arrays in C
- Memory Allocation

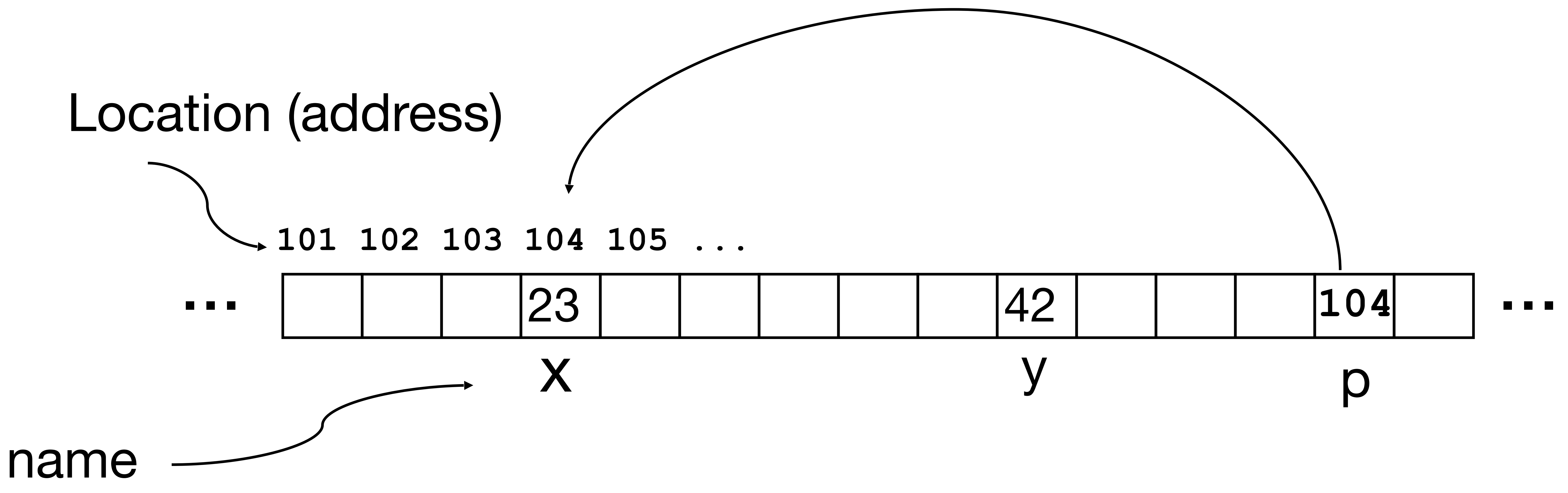
Address vs. Value

- 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



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!
- You can even have pointers to functions…
  - **`int (*fn) (void *, void *) = &foo`**
    - **`fn`** is a function that accepts two **`void *`** pointers and returns an **`int`** and is initially pointing to the function **`foo`**.
    - **`(*fn)(x, y)`** will then call the function

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;
```

Pointers in C

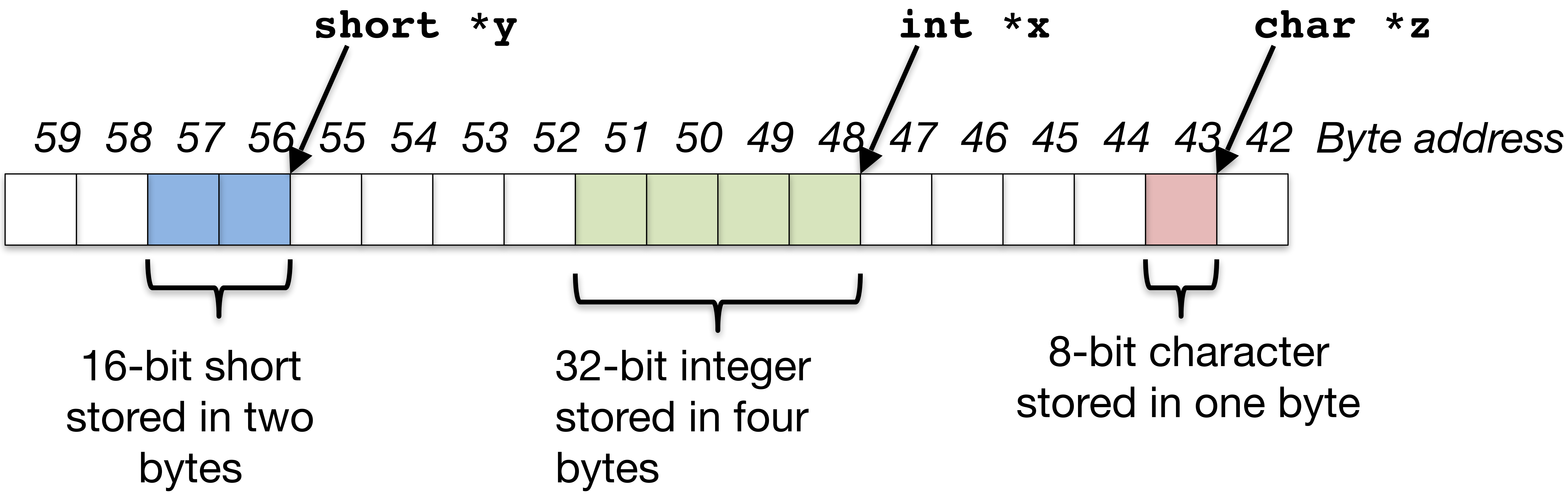
- Why use pointers?
  - If we want to pass a large struct or array, it's easier / faster / etc. to pass a pointer than the whole thing
    - Otherwise we'd need to copy a huge amount of data
  - In general, pointers allow cleaner, more compact code
- So what are the drawbacks?
  - Pointers are probably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

Why Pointers in C?

- At time C was invented (early 1970s), compilers often didn't produce efficient code
  - Computers 100,000x 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

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
- But we actually want “word alignment”
  - Some processors will not allow you to address 32b values without being on 4 byte boundaries
  - Others will just be very slow if you try to access “unaligned” memory.



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
  - Includes any padding needed for alignment
- By Standard C99 definition, **`sizeof(char)==1`**
- Can take **`sizeof(arg)`**, 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>

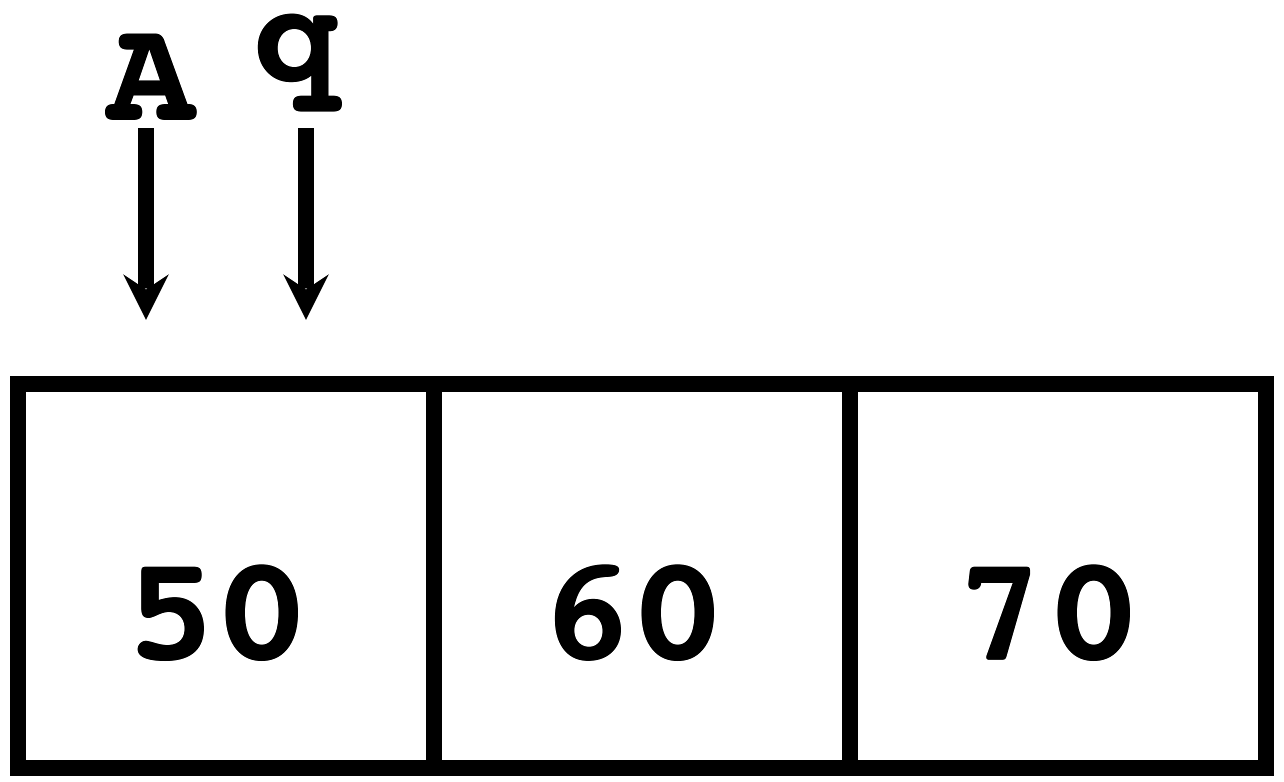
Changing a Pointer Argument?

- 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



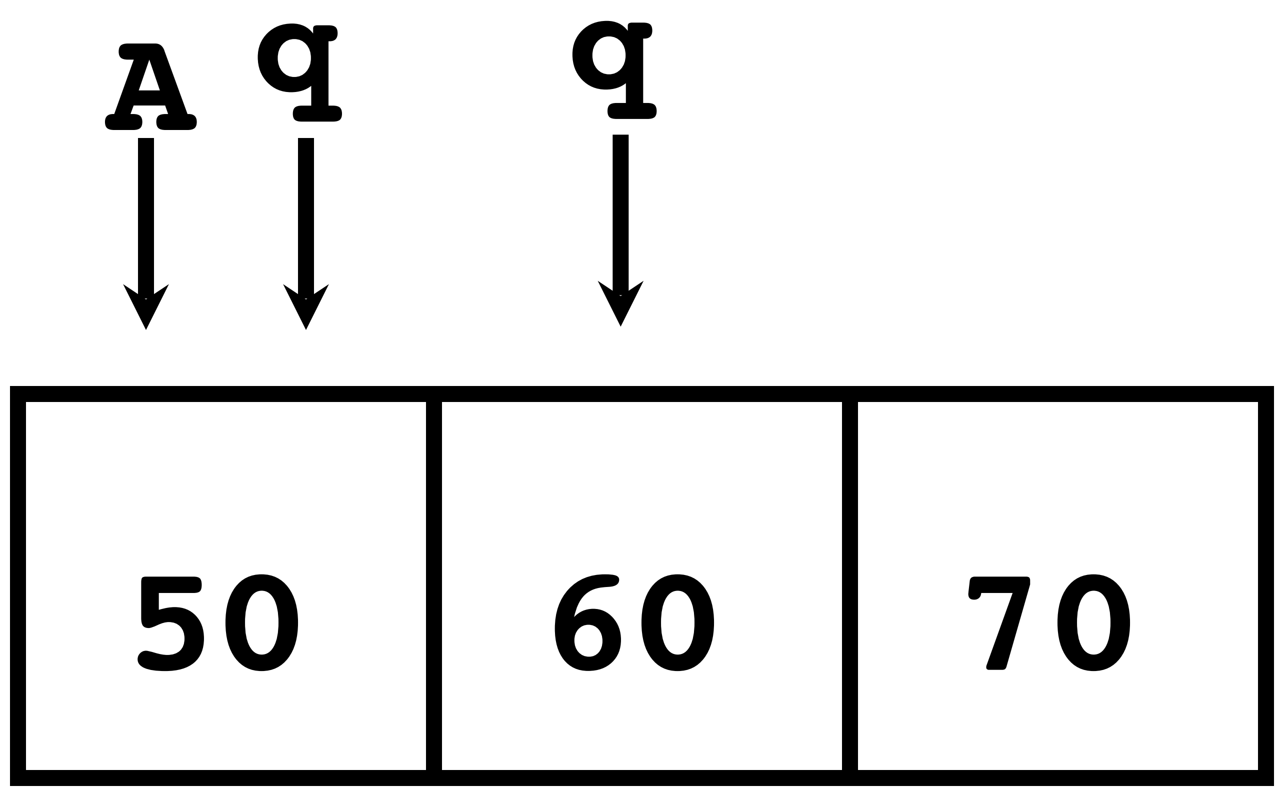
Pointer to a Pointer

- 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);
```

*q = 60



Conclusion on Pointers...

- All data is in memory
  - Each memory location has an address to use to refer to it and a value stored in it
- Pointer is a C version (abstraction) of a data address
  - * "follows" a pointer to its value
  - & gets the address of a value
- C is an efficient language, but leaves safety to the programmer
  - Variables not automatically initialized
  - Use pointers with care: they are a common source of bugs in programs

Administrivia:

- Project 1 is now live...
  - Yes, we are throwing you in the deep end right away
  - Designed to touch on a huge amount of C concepts
- Register your iClicker on Bcourses...

Clickety Click!


```
void foo(int *x, int *y)
{
   int t;
    if ( *x > *y ) { t = *y; *y = *x; *x = t; }
}
int a=3, b=2, c=1;
foo(&a, &b);
foo(&b, &c);
foo(&a, &b);
printf("a=%d b=%d c=%d\n", a, b, c);
```

Result is:

A: **a=3 b=2 c=1**

B: **a=1 b=2 c=3**

C: **a=1 b=3 c=2**

D: **a=3 b=3 c=3**

E: **a=1 b=1 c=1**

C Arrays

- Declaration:

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

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

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

declares and initializes a 2-element integer array

Array Name / Pointer Duality

- *Key Concept*: Array variable is simply a “pointer” to the first (0th) 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
- 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 access arrays

Arrays and Pointers

- Array ≈ pointer to the initial element
  - `a[i] ≡ *(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!
    - Especially avoid things like **`ar++`**;

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) …
}
```

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! (You'll learn how to debug these in lab)
  - But also "fun" to exploit:
    - "Stack overflow exploit", maliciously write off the end of an array on the stack
    - "Heap overflow exploit", maliciously write off the end of an array on the heap

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”): written as 0 (the number) or '\0' as a character
  - Important danger: string length operation does ***not*** include the null terminator when you ask for length of a string!

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

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

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"
  - And don't forget the < rather than <=:
When Nick took 60c, he lost a day to a "segfault in a malloc called by printf on large inputs":
Had a <= rather than a < in a single array initialization!

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? **4**

... because **`array`** is really a pointer (and a pointer is architecture dependent, but likely to be 4 or 8 on modern 32-64 bit machines!)

What does this print? **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!

But the former is ***much more readable***:
Especially don't want to see code like **`ar++`**

When Arrays Go Bad: Heartbleed

- In TLS encryption, messages have a length…
  - And get copied into memory before being processed
- One message was “Echo Me back the following data, its this long...”
  - But the (different) echo length wasn’t checked to make sure it wasn’t too big...

```
M 5 HB L=5000 107:Oul7;GET / HTTP/1.1\r\n
Host: www.mydomain.com\r\nCookie: login=1
17kf9012oeu\r\nUser-Agent: Mozilla….
```

- So you send a small request that says “read back a lot of data”
  - And thus get web requests with auth cookies and other bits of data from random bits of memory…

Clickers!


```
int x[] = { 2, 4, 6, 8, 10 };
int *p = x;
int **pp = &p;
(*pp)++;
(*(*pp))++;
printf("%d\n", *p);
```

Result is:

A: 2

B: 3

C: 4

D: 5

E: None of the above

Clickers/Peer Instruction Time


```
int x[] = { 2, 4, 6, 8, 10 };
int *p = x;
int **pp = &p;
(*pp)++;
(*(*pp))++;
printf("%d\n", *p);
```

P points to the start of X (2)

PP points to P

Increments P point to 2nd element (4)

Increments 2nd element by 1 (5)

Result is:

A: 2

B: 3

C: 4

D: 5

E: None of the above

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?

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
    - Since it is an array of pointers to character arrays
    - Sometimes written as **`char **argv`**

Example

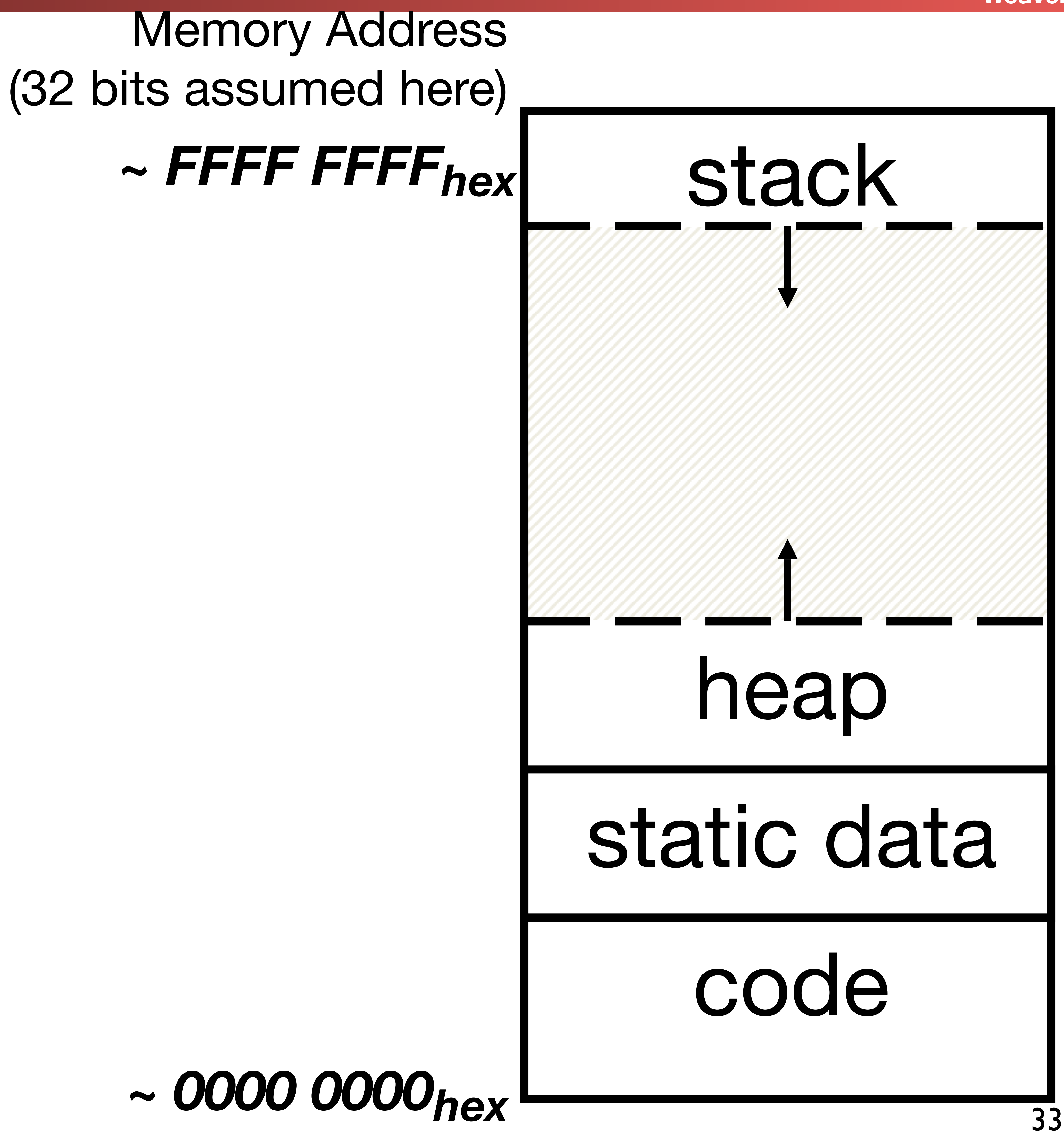
- `foo hello 87 "bar baz"`
- `argc = 4 /* number arguments */`
- ```
  argv[0] = "foo",
  argv[1] = "hello",
  argv[2] = "87",
  argv[3] = "bar baz",
  ```
  - Array of pointers to strings
  ```

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
  - The only real addition is the C runtime has to say "Hey operating system, gimme a big block of memory" when it needs more 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?

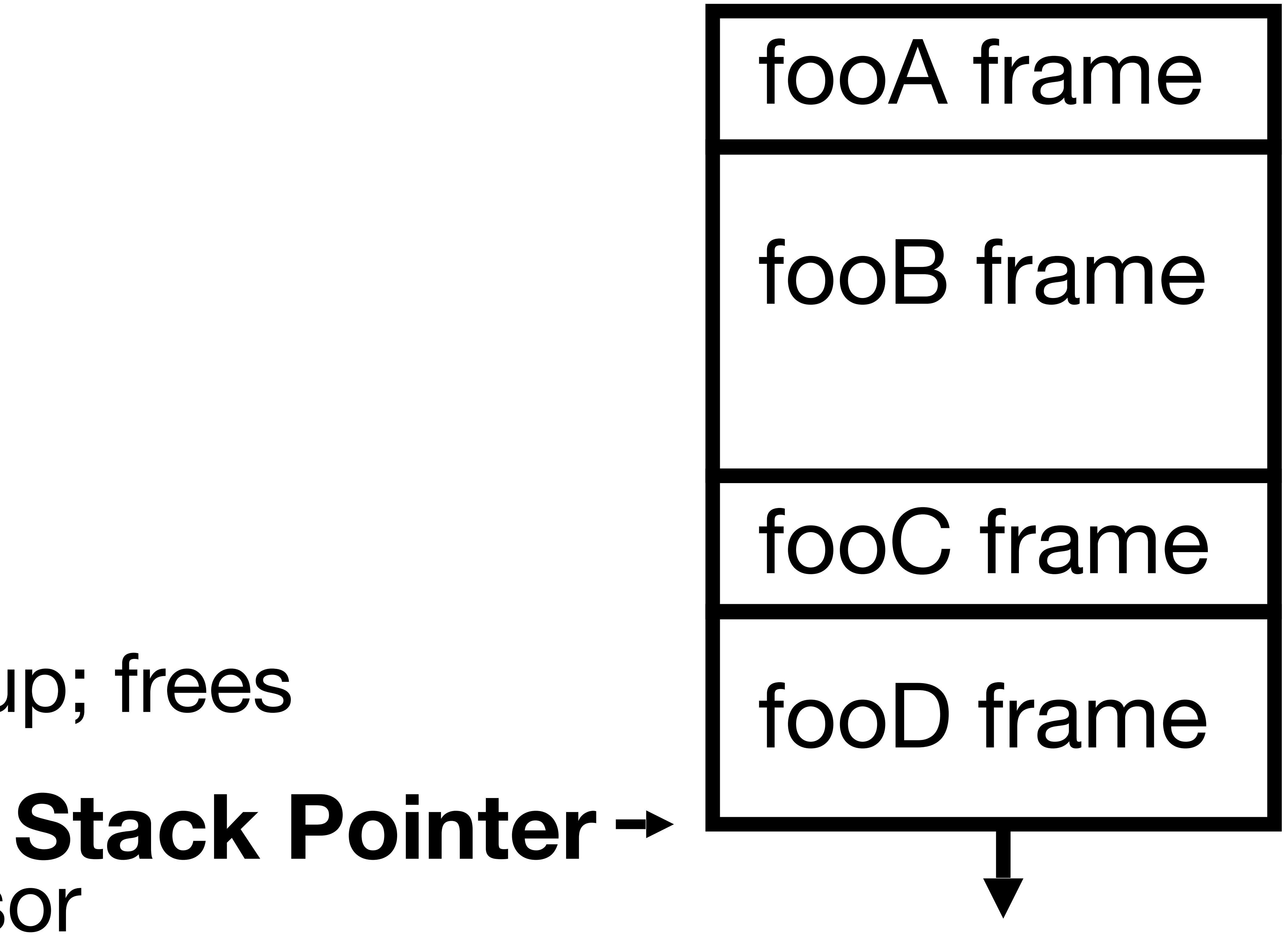
- If declared outside a function, allocated in “static” storage
- If declared inside function, allocated on the “stack” and freed when function returns
  - `main()` is treated like a function
- For both of these types of memory, the management is automatic:
  - You don't need to worry about deallocating when you are no longer using them

```
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 uses contiguous blocks of memory; stack pointer indicates start of stack frame
- When function ends, stack pointer moves up; frees memory for future stack frames
- We'll cover details later for RISC-V processor

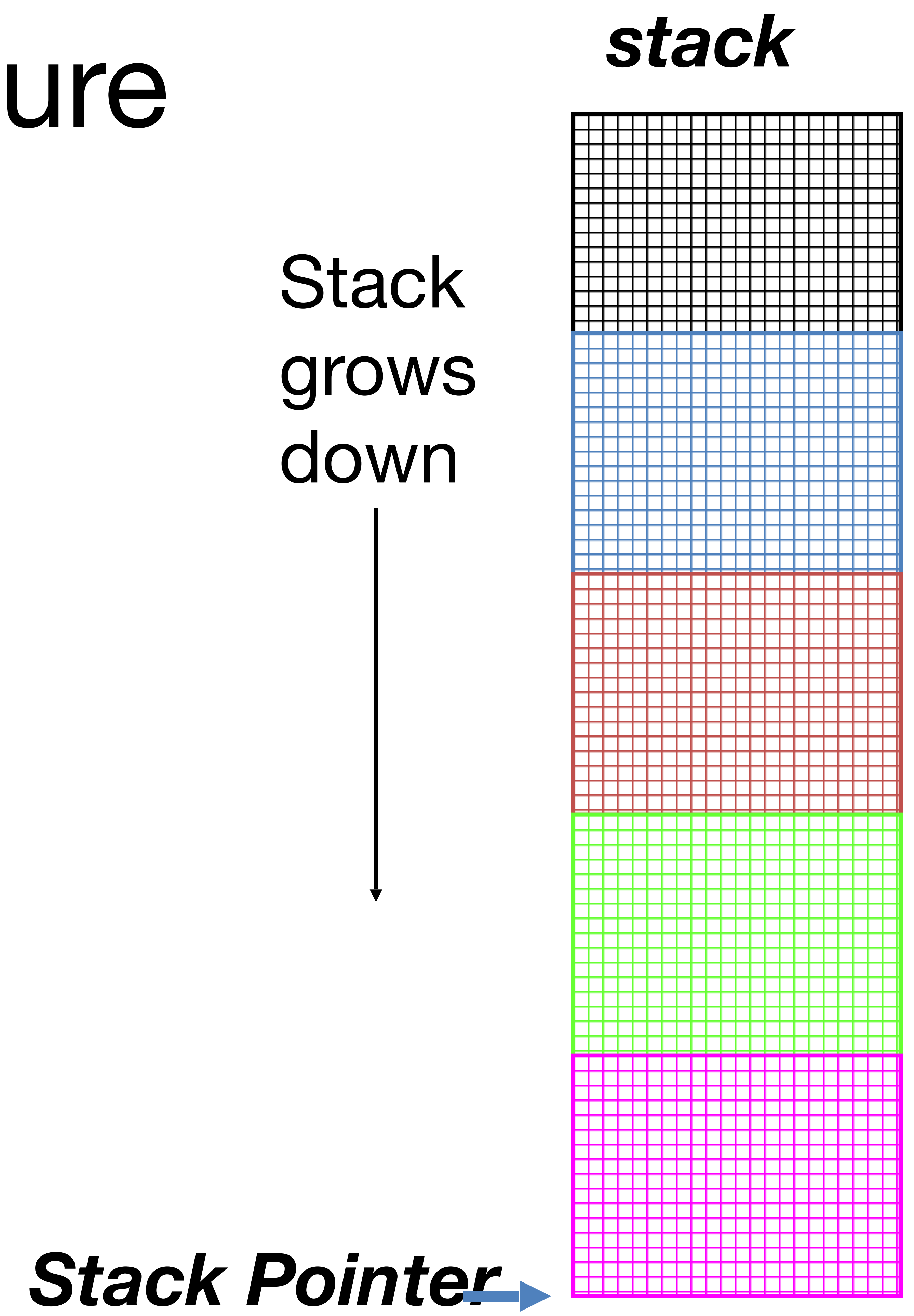
```
fooA() { fooB(); }
fooB() { fooC(); }
fooC() { fooD(); }
```



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 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!
    - And it ***will not update other pointers pointing to the same block of memory***

Malloc()

- **`void *malloc(size_t n)`:**
  - Allocate a block of uninitialized memory
  - NOTE: Subsequent calls probably will not yield adjacent blocks
  - **`n`** is an integer, indicating size of requested memory block in bytes
  - **`size_t`** is an unsigned integer type big enough to "count" memory bytes
  - Returns **`void*`** pointer to block; **`NULL`** return indicates no more memory (check for it!)
  - Additional control information (including size) stored in the heap for each 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));
    ```
- **`sizeof`** returns size of given type in bytes, ***necessary if you want portable code!***

And then free()

- **`void free(void *p):`**
  - **`p`** is a pointer containing the address originally returned by **`malloc()`**
- Examples:
  - ```
    int *ip;
    ip = (int *) malloc(sizeof(int));
    ... .. ..
    free((void*) ip); /* Can you free(ip) after ip++ ? */
    ```
  - ```
    typedef struct {… } TreeNode;
    TreeNode *tp = (TreeNode *) malloc(sizeof(TreeNode));
    ... .. ..
    free((void *) tp);
    ```
- When you free memory, you must be sure that you pass the original address returned from **`malloc()`** to **`free()`**; Otherwise, crash (or worse)!

Using Dynamic Memory

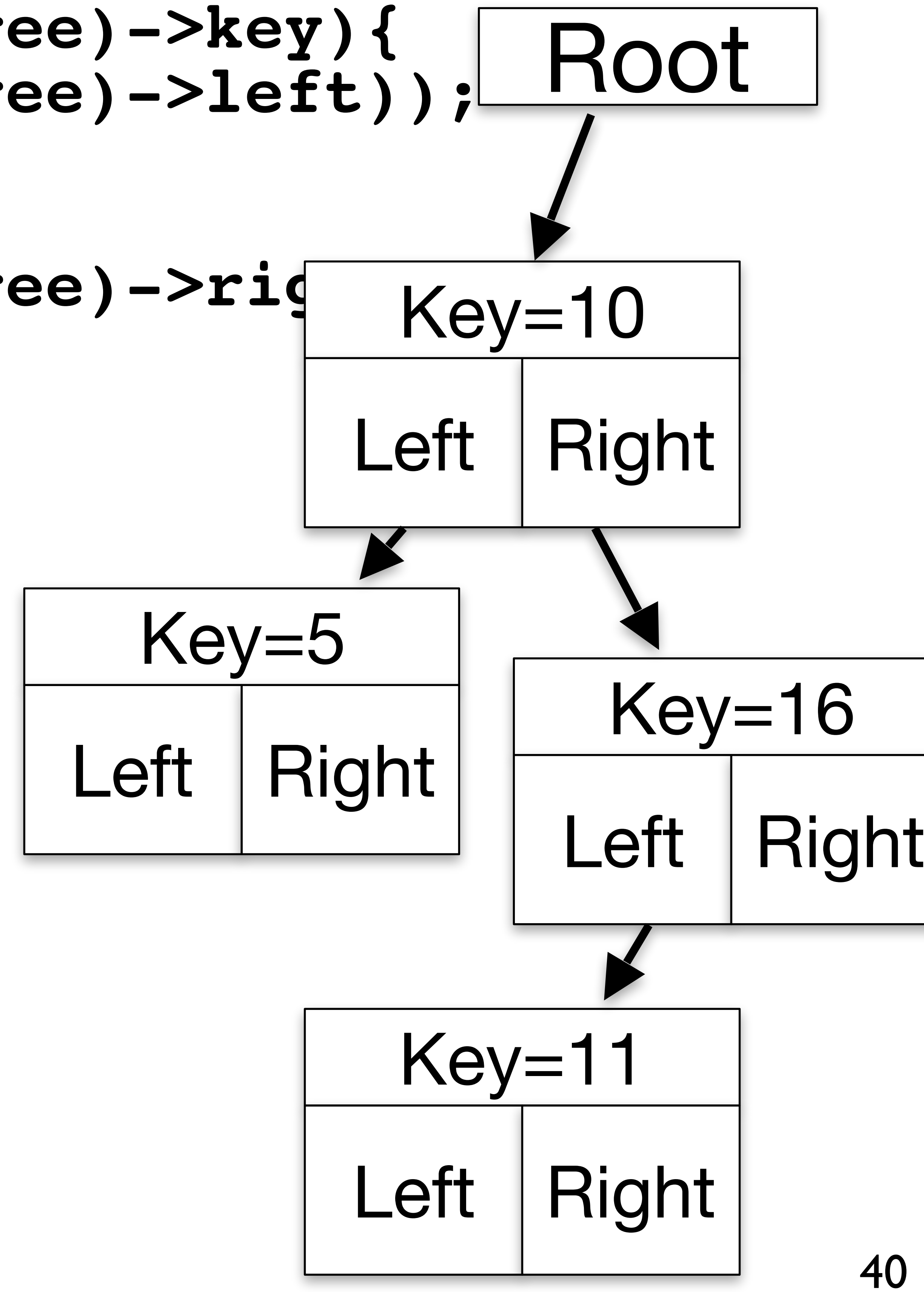

```
typedef struct node {
  int key;
  struct node *left; struct node *right;
} Node;

Node *root = NULL;

Node *create_node(int key, Node *left,
        Node *right){
  Node *np;
  if(!(np =
       (Node*) malloc(sizeof(Node)))){
     printf("Memory exhausted!\n");
     exit(1);}
  else{
     np->key = key;
     np->left = left;
     np->right = right;
     return np;
   }
}
```

```
void insert(int key, Node **tree){
   if ((*tree) == NULL){
     (*tree) = create_node(key, NULL,
           NULL);
   }
   else if (key <= (*tree)->key){
     insert(key, &((*tree)->left));
   }
   else{
     insert(key, &((*tree)->rig
   }
}

int main(){
  insert(10, &root);
  insert(16, &root);
  insert(5, &root);
  insert(11 , &root);
  return 0;
}
```



Observations

- Code, Static storage are easy: they never grow or shrink
- Stack space is relatively easy: stack frames are created and destroyed in last-in, first-out (LIFO) order
- Managing the heap is tricky: memory can be allocated / deallocated at any time
  - If you forget to deallocate memory: “Memory Leak”
    - Your program ***will eventually run out of memory***
  - If you call free twice on the same memory: “Double Free”
    - Possible ***crash or exploitable vulnerability***
  - If you use data after calling free: “Use after free”
    - Possible ***crash or exploitable vulnerability***

When Memory Goes Bad... Failure To Free

- #1: Failure to free allocated memory
  - "memory leak"
- Initial symptoms: nothing
  - Until you hit a critical point, memory leaks aren't actually a problem
- Later symptoms: performance drops off a cliff...
  - Memory hierarchy behavior tends to be good just up until the moment it isn't...
    - There are actually a couple of cliffs that will hit
- And then your program is killed off!
  - Because the OS goes "Nah, not gonna do it" when you ask for more memory

When Memory Goes Bad: Writing off the end of arrays...

- EG...
  -
```
int *foo = (int *) malloc(sizeof(int) * 100);
int i;
....
for(i = 0; i <= 100; ++i){
    foo[i] = 0;
}
```
- Corrupts other parts of the program...
  - Including internal C data
- May cause crashes later

When Memory Goes Bad: Returning Pointers into the Stack

- It is OK to pass a pointer to stack space down
  - EG:
```
char [40]foo;
int bar;
...
strncpy(foo, "102010", strlen(102010)+1);
baz(&bar);
```
- It is catastrophically bad to return a pointer to something in the stack...
  - EG
```
char [50] foo;
....
return foo;
```
- The memory will be overwritten when other functions are called!
  - So your data no longer exists... And writes can overwrite key pointers causing crashes!

When Memory Goes Bad: Use After Free

- When you keep using a pointer..
  -
```
struct foo *f
....
f = malloc(sizeof(struct foo));
....
free(f)
....
bar(f->a);
```
- Reads after the free may be corrupted
  - As something else takes over that memory. Your program will probably get wrong info!
- Writes ***corrupt*** other data!
  - Uh oh... Your program crashes later!

When Memory Goes Bad: Forgetting Realloc Can Move Data...

- When you realloc it can copy data...
  - ```
    struct foo *f = malloc(sizeof(struct foo) * 10);
    ...
    struct foo *g = f;
    ....
    f = realloc(sizeof(struct foo) * 20);
    ```
- Result is g ***may*** now point to invalid memory
  - So reads may be corrupted and writes may corrupt other pieces of memory
    ```

When Memory Goes Bad: Freeing the Wrong Stuff...

- If you free() something never malloc'ed()
  - Including things like

```
struct foo *f = malloc(sizeof(struct foo) * 10)
...
f++;
...
free(f)
```

- Malloc/free may get confused..
  - Corrupt its internal storage or erase other data...

When Memory Goes Bad: Double-Free...

- EG...
  - ```
    struct foo *f = (struct foo *) malloc(sizeof(struct foo) * 10);
    ...
    free(f);
    ...
    free(f);
    ```
- May cause either a use after free (because something else called malloc() and got that data) or corrupt malloc's data (because you are no longer freeing a pointer called by malloc)
    ```

And Valgrind...

- Valgrind slows down your program by an order of magnitude, but...
  - It adds a tons of checks designed to catch most (but not all) memory errors
- Memory leaks
- Misuse of free
- Writing over the end of arrays
- You ***must*** run your program in Valgrind before you ask for debugging help from a TA!
  - Tools like Valgrind are absolutely essential for debugging C code

And In Conclusion, …

- C has three main memory segments in which to allocate data:
  - Static Data: Variables outside functions
  - Stack: Variables local to function
  - Heap: Objects explicitly malloc-ed/free-d.
- Heap data is biggest source of bugs in C code