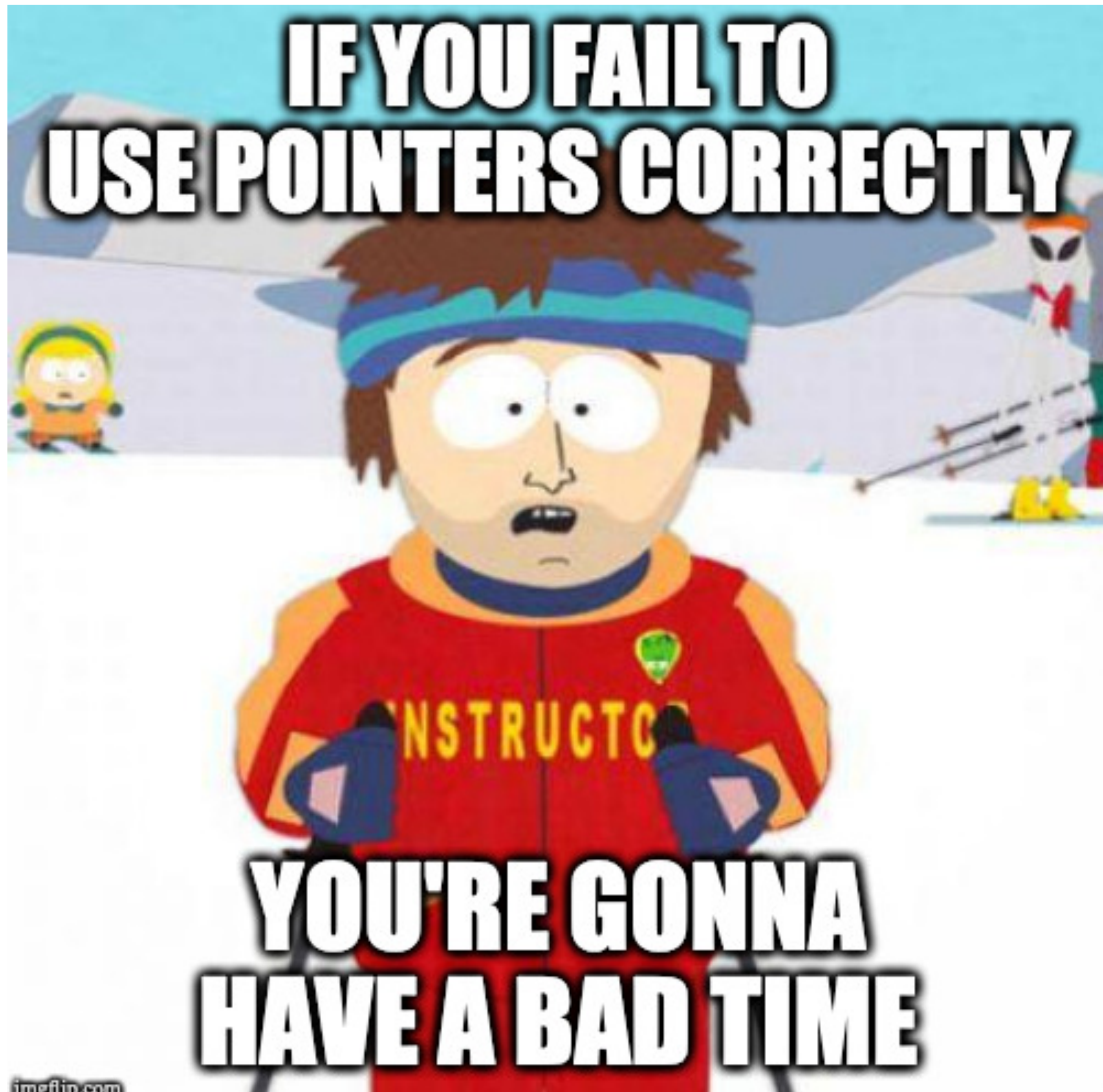
Pointers, Arrays, Memory: AKA the cause of those F@#)(#@*(Segfaults


IF YOU FAIL TO USE POINTERS CORRECTLY
YOU'RE GONNA HAVE A BAD TIME
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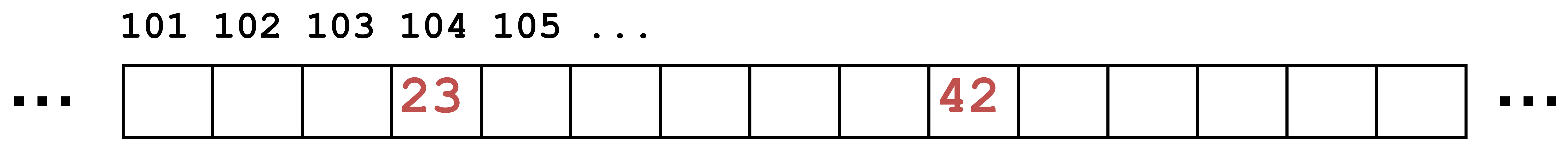
ELECTRICAL ENGINEERING & COMPUTER SCIENCES

Announcements!

- HW1 is due Friday, January 28
- Lab 1 is due Monday, January 31
- Discussion and lab schedule has been uploaded to the website
- Office hours schedule coming soon
- Project 1 estimated release... Wednesday
  - Trying for maximum debugging ***and debuggability*** for **`snek`**!

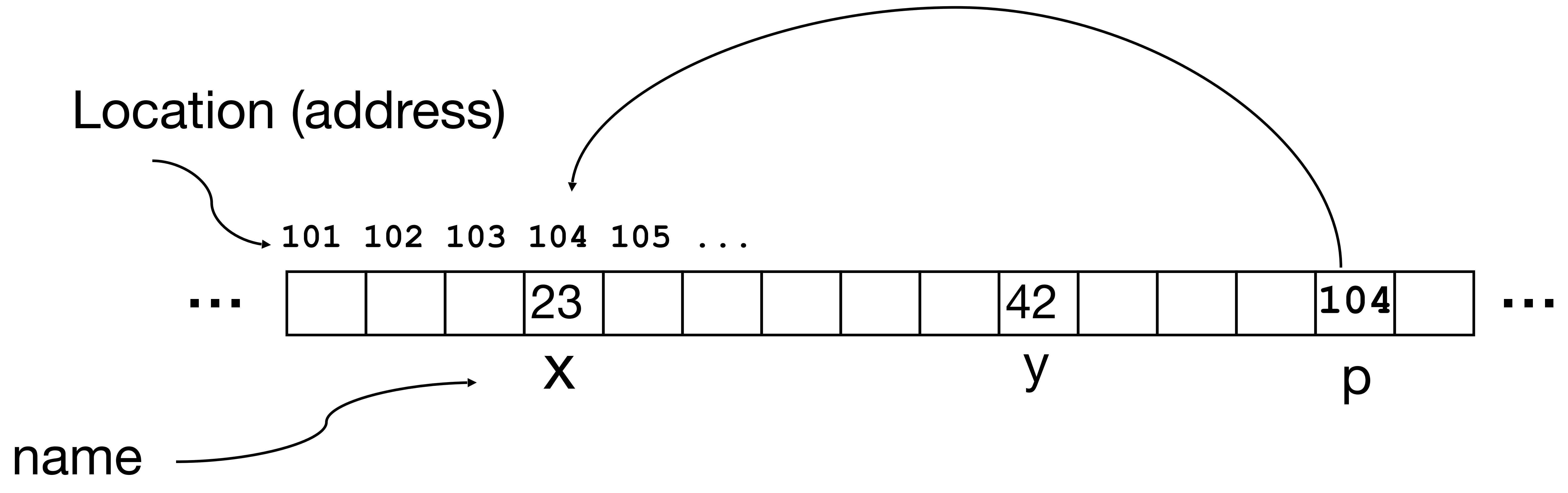
Address vs. Value

- 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?!
    - Answer: Addresses are ***unsigned***
- 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`**, a pointer to a pointer to a pointer to a **`char`**, 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!
    - Can convert types (BUT BE CAREFUL):

```
void *a = ....
int *p = (int *) a;   /* p now points to the same place as a,
                         but is treated as a pointer to an int */
int **q = (int **) a; /* q now points to the same place as a,
                         but is treated as a pointer to a pointer to an int */
```

- 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

NULL pointers...

- The pointer of all 0s is special
  - The "NULL" pointer, like in Java, python, etc...
- If you write to or read a null pointer, your program should crash immediately
  - The memory is set up so that this should never be valid
- Since "0 is false", its very easy to do tests for null:
- `if(!p) { /* p is a null pointer */ }`
- `if(q) { /* q is not a null pointer */}`

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;
paddr = &p2;
```

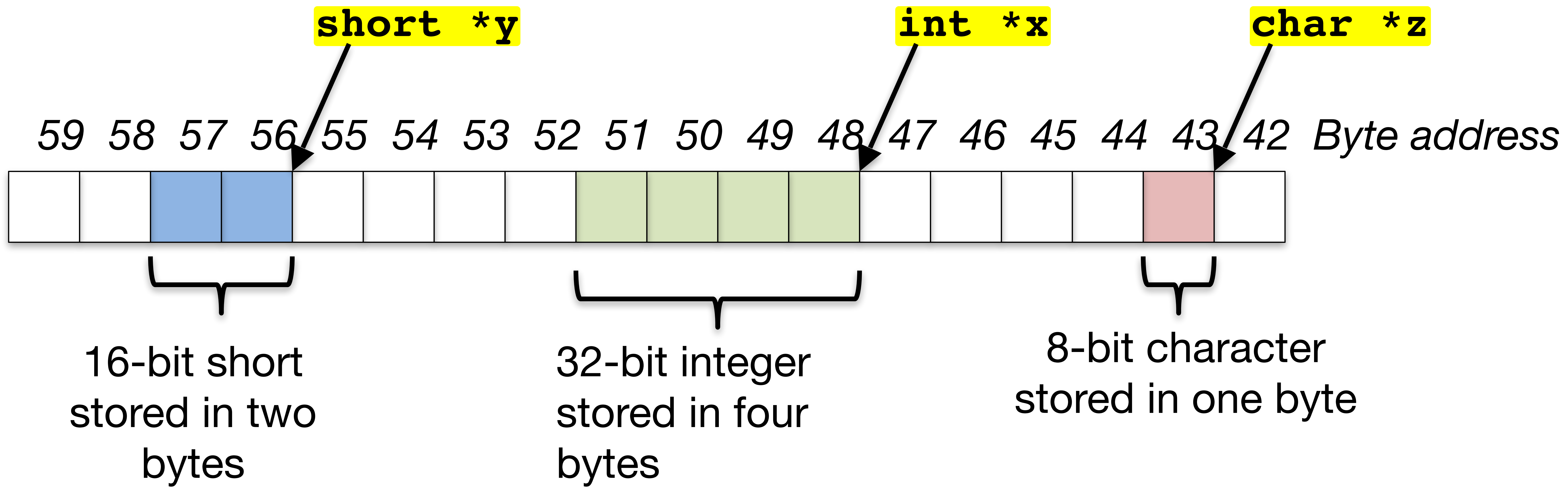
```
/* dot notation */
int h = p1.x;
p2.y = p1.y;

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

/* This works too:
   copies all of p2 */
p1 = p2;
p1 = *paddr;
```

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
    - You notice in Java that more complex objects are passed by reference.... Under the hood this is a pointer
  - 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 time
    - Dangling references and memory leaks

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.


short *y
int *x
char *z
59 58 57 56 55 54 53 52 51 50 49 48 47 46 45 44 43 42 Byte address
16-bit short stored in two bytes
32-bit integer stored in four bytes
8-bit character stored in one byte

sizeof() operator

- **`sizeof(type)`** returns number of bytes in object
  - But number of bits in a byte is not standardized technically
    - In olden times, when dragons roamed the earth, bytes could be 5, 6, 7, 9 bits long
  - Includes any padding needed for alignment
    - So that every **`int`** will start at a boundary divisible by 4...
- 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
- **`sizeof`** is ***not a function!*** It is a compile-time operation

Pointer Arithmetic

pointer + number *pointer – number*

e.g., *pointer* + `1` adds 1 something 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 cautiously

Basic rule for pointer arithmetic

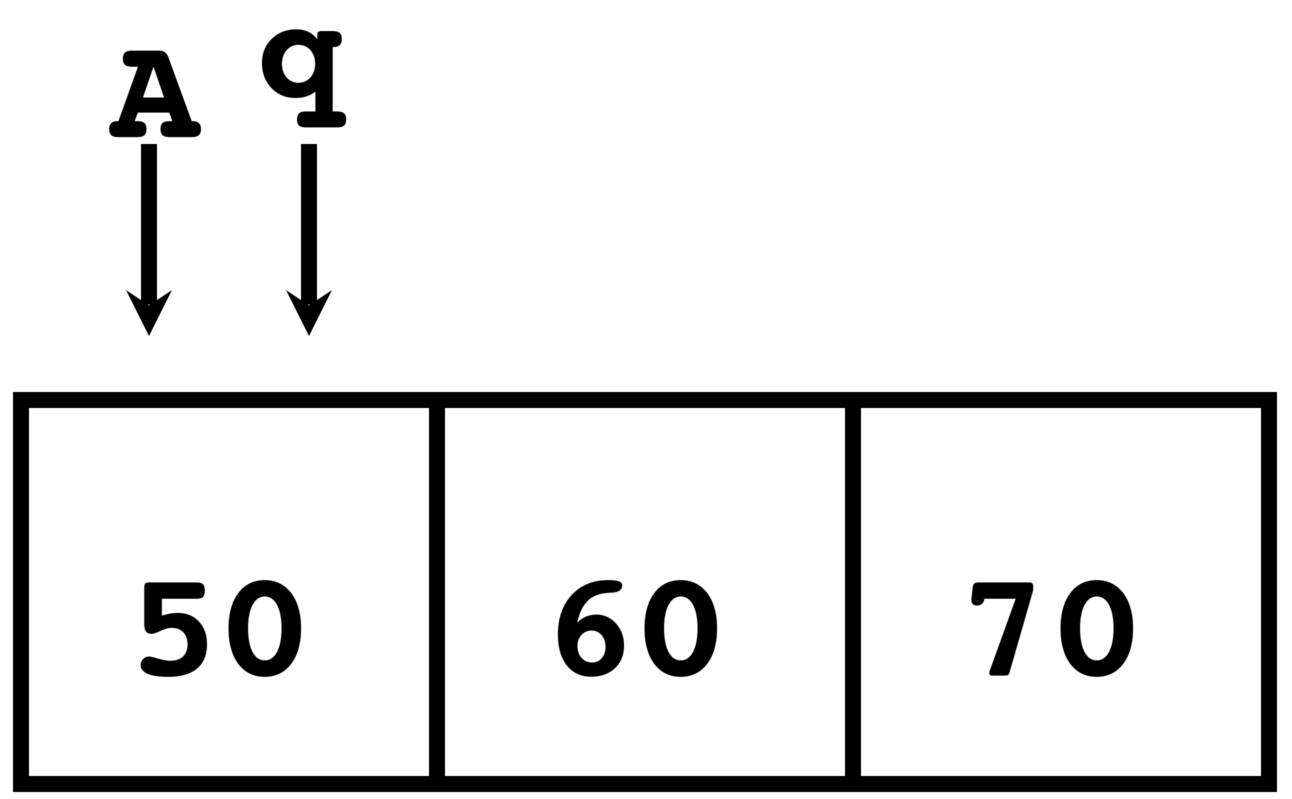
- We cover it for two reasons
  - You may encounter code using this in the future...
  - You need to understand this to understand how this code gets converted to assembly
- Look at the type the pointer points ***to***
  - So a (char *) points to a (char), while a (char **) points to a (char *)
  - The ***actual value used by the compiler (NOT THE VALUE YOU USE)*** is the size of what you are pointing to time the amount to increment
- So ***under the hood***: `char *c; char **d;`
- `(c + 5)` -> `c + sizeof(char) * 5` -> `c + 5`
- `(d + 7)` -> `d + sizeof(char *) * 5` -> `d + 20`

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

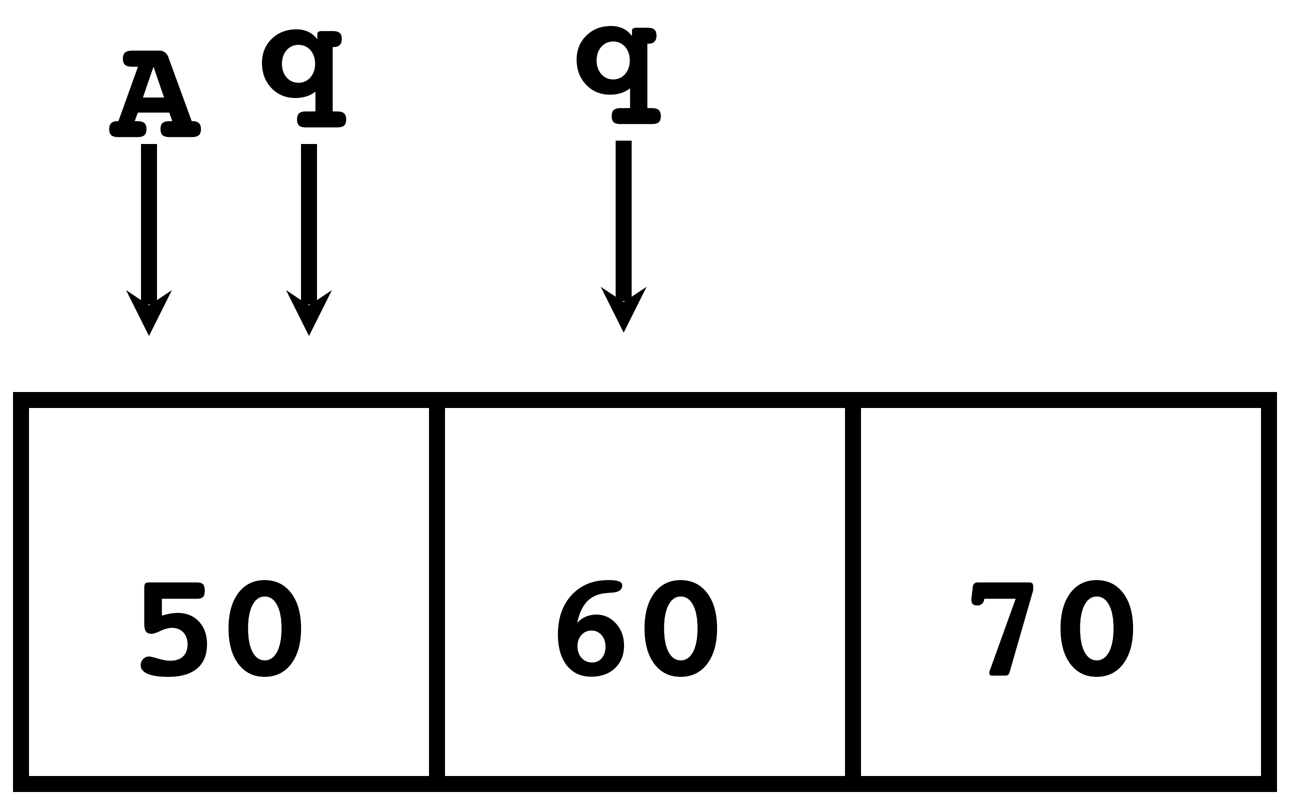


Pointer to a Pointer

- 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`



It can never end...

- You can have something like this:
  ```
  int **********x;
  ```
- x is a pointer to a pointer to a pointer to a pointer to a pointer to a pointer to a pointer to a pointer to a pointer to a pointer to an integer!

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

Structures Revisited

- A "struct" is really just an instruction to C on how to arrange a bunch of bytes in a bucket...

-
  ```
  struct foo {
      int a;
      char b;
      struct foo *c;
  }
  ```
- Provides enough space and ***aligns*** the data with padding
  So actual layout on a 32b architecture will be:
  - 4-bytes for A
  - 1 byte for b
  - 3 unused bytes
  - 4 bytes for C
  - `sizeof(struct foo) == 12`

Plus also Unions

- A "union" is also instruction to C on how to arrange a bunch of bytes

-
  ```
  union foo {
      int a;
      char b;
      union foo *c;
  }
  ```
- Provides enough space for the ***largest element***

-
  ```
  union foo f;
  f.a = 0xDEADB33F; /* treat f as an integer and store
                       that value */
  f.c = &f; /* treat f as a pointer of type
               "union foo *" and store the
               address of f in itself */
  ```

C Arrays

- Declaration:

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

declares a 2-element integer array: just a block of memory which is uninitialized. The number of elements is static in the declaration, you can't do "`int ar[x]`" where x is a variable

```
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 are ***almost*** identical to pointers
  - **`char *string`** and **`char string[]`** are nearly identical declarations
    - Differ in subtle ways: incrementing & declaration of filled arrays
- Consequences:
  - **`ar[32]`** is an array variable with 32 elements, 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++`**

Arrays And Structures And Pointers

-
  ```
  typedef struct bar {
      char *a;     /* A pointer to a character */
      char b[18]; /* A statically sized array
                     of characters */
  } Bar;
  ...
  Bar *b = (Bar*) malloc(sizeof(struct bar));
  b->a = malloc(sizeof(char) * 24);
  ```
- Will require 24 bytes on a 32b architecture for the structure:
  - 4 bytes for a (its a pointer)
  - 18 bytes for b (it is 18 characters)
  - 2 bytes padding (needed to align things)

Some Code Examples

- `b->b[5] = 'd'`
  - Location written to is 10th byte pointed to by b...
    `*((char *) b + 4 + 5) = 'd'`
- `b->a[5] = 'c'`
  - location written to is the first word pointed to by b, treat that as a pointer, add 5, and write 'c' there...
    aka `*(*((char **) b) + 5) = 'c'`
- `b->a = b->b`
  - Location written to is the first word pointed to by b
  - Value it is set to is b's address + 4)...
    aka `*((char **)b) = ((char *) b) + 4`

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…

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

Endianness...

- Consider the following

-
  ```
  union confuzzle { int a; char b[4]; };
  union confuzzle foo;
  foo.a = 0x12345678;
  ```
- In a 32b architecture, what would foo.b[0] be?
  0x12? 0x78?
- Its actually dependent on the architecture's "endianness"
  - Big endian: The first character is the most significant byte: **`0x12`**
  - Little endian: The first character is the least significant byte: **`0x78`**

Endianness and You...

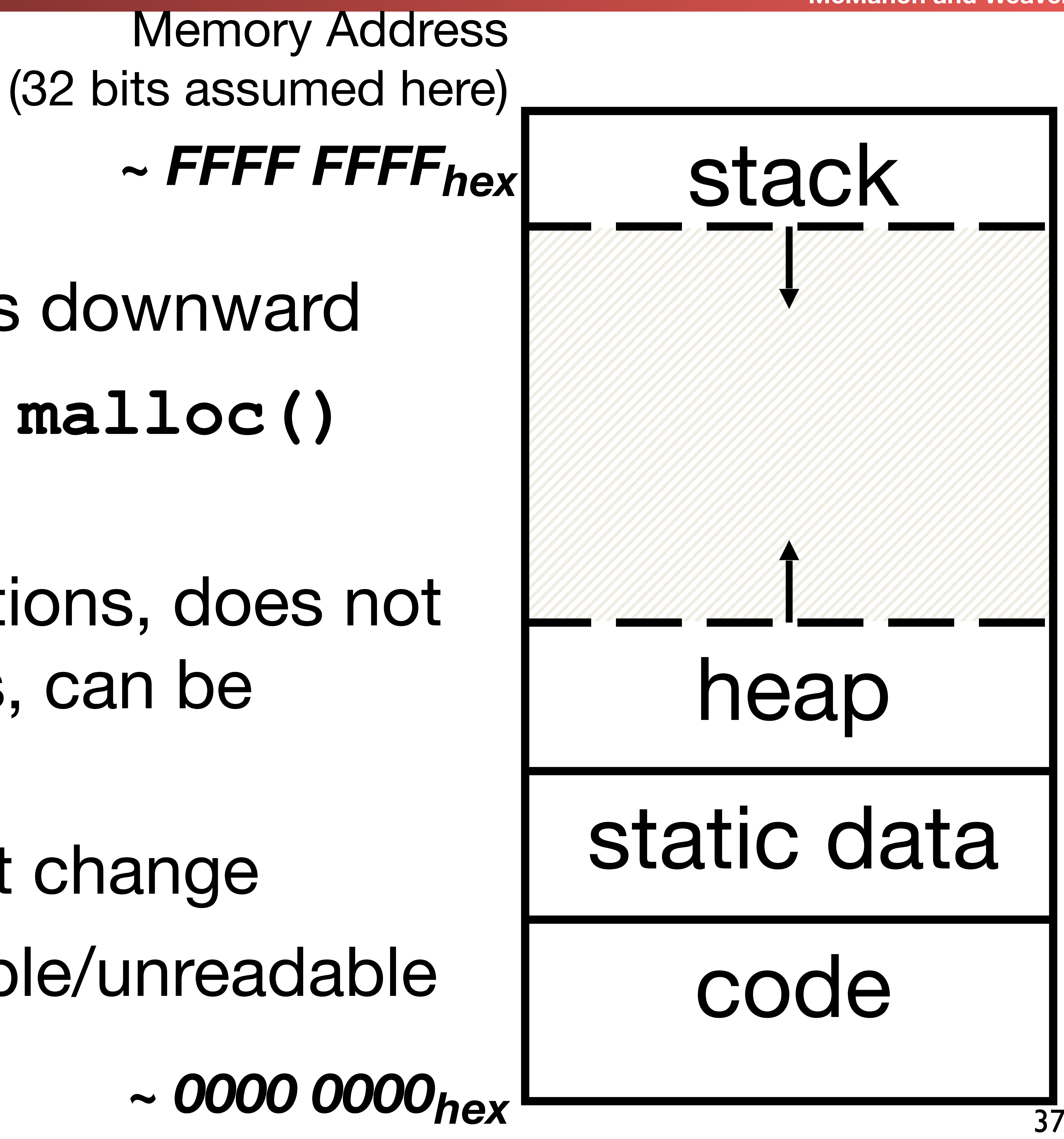
- It generally doesn't matter if you write portable C code running on one computer...
  - After all, you shouldn't be treating an integer as a series of raw bytes
  - Well, it matters when you take CS161:
    x86 is little endian and you may write an address as a string
- It does matter when you want to communicate across computers...
  - The "network byte order" is big-endian, but your computer is likely to be little-endian
    - x86, RISC-V, Apple M1 in practice are all little-endian
- Endian conversion functions:
  - **`ntohs()`**, **`htons()`**: Convert 16 bit values from your native architecture to network byte order and vice versa
  - **`ntohl()`**, **`htonl()`**: Convert 32 bit values from your native architecture to network byte order and vice versa

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
  - 0x0000 0000 hunk is reserved and unwriteable/unreadable so you crash on null pointer access



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

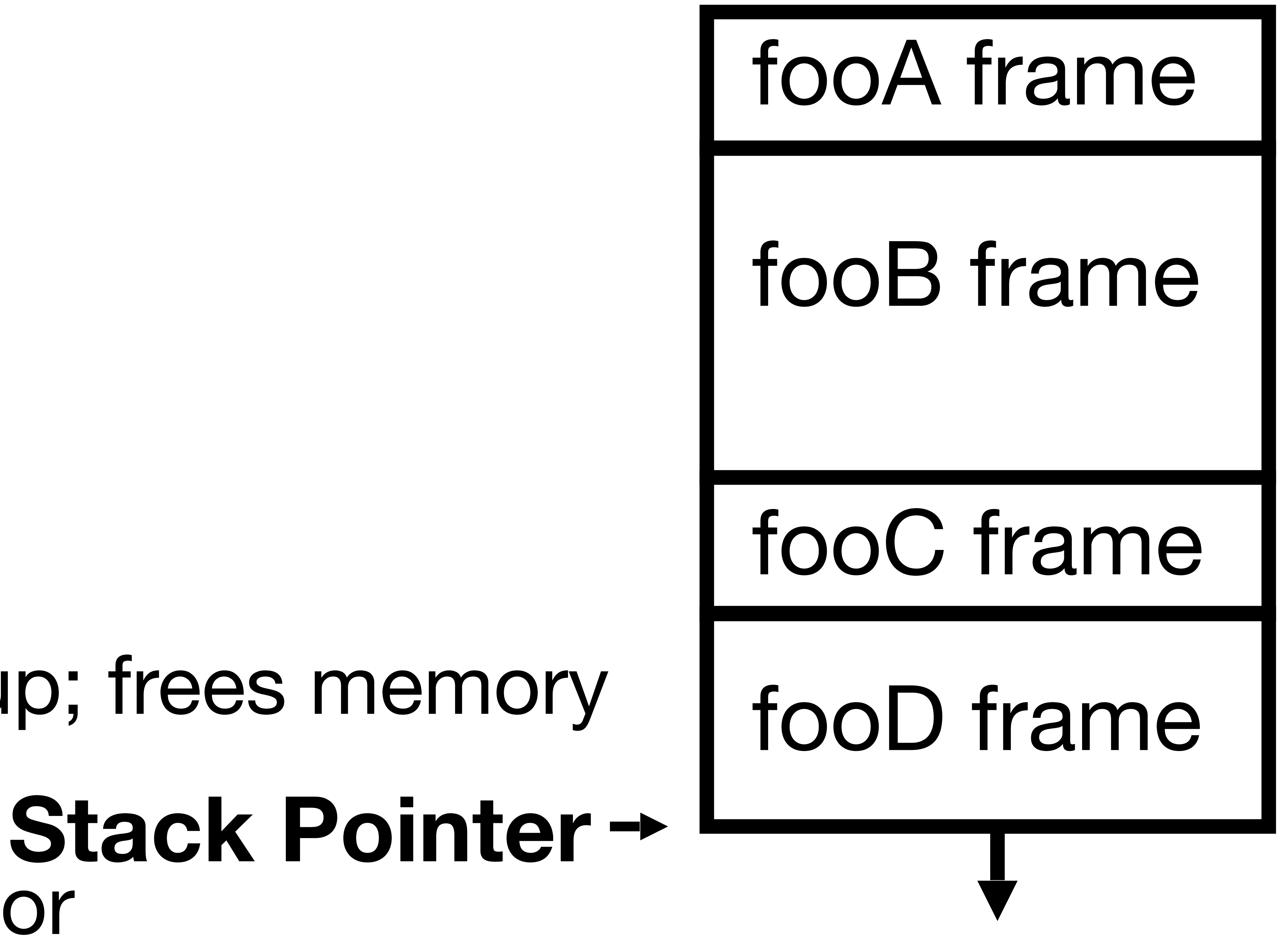
```
int myGlobal;
main() {
   int myTemp;
}
```

- 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
  - But a variable ***does not exist anymore*** once a function ends! Big difference from Java

The Stack

- Every time a function is called, a new "stack 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

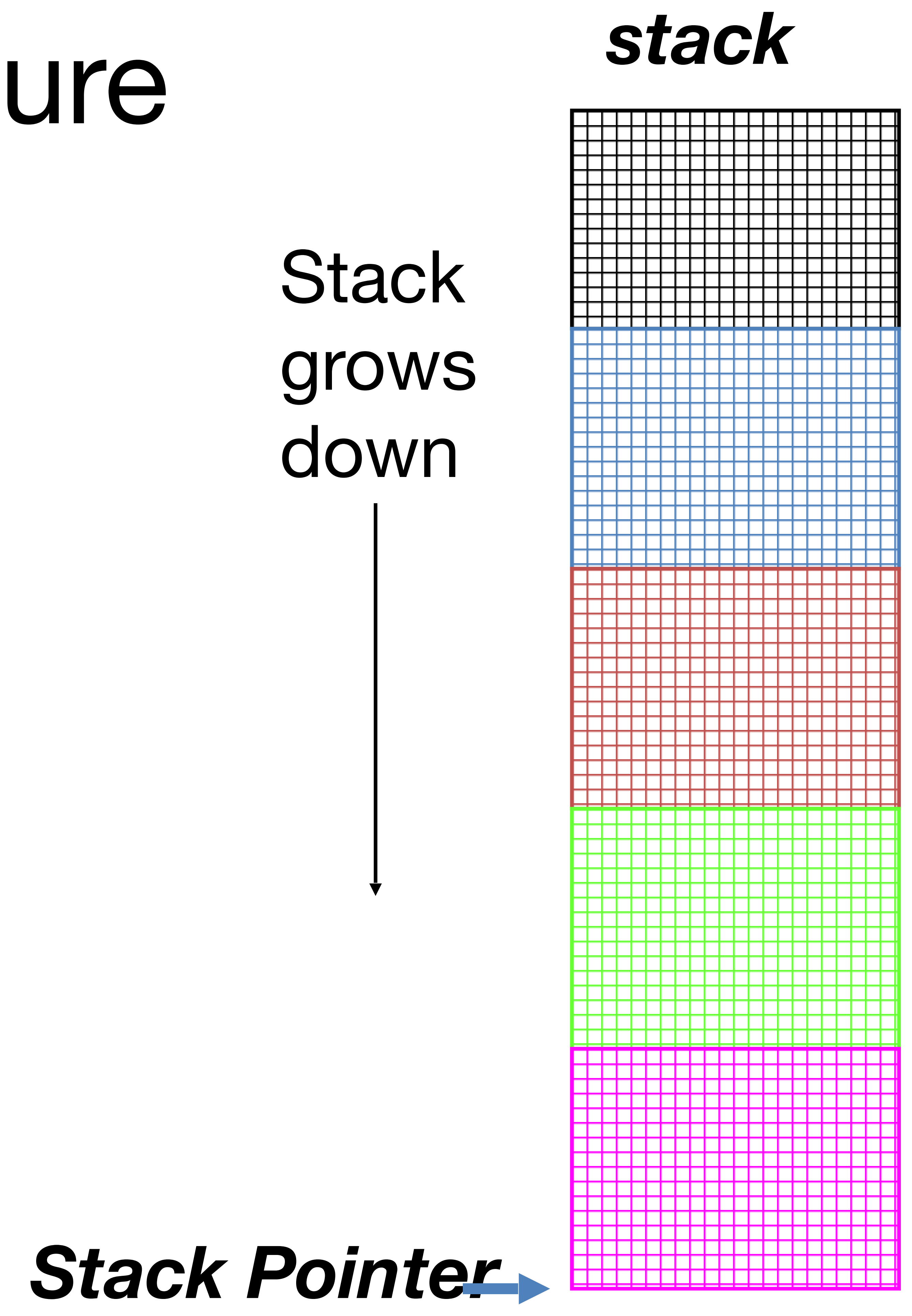
```
fooA() { fooB(); }
fooB() { fooC(); }
fooC() { fooD(); }
```



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:

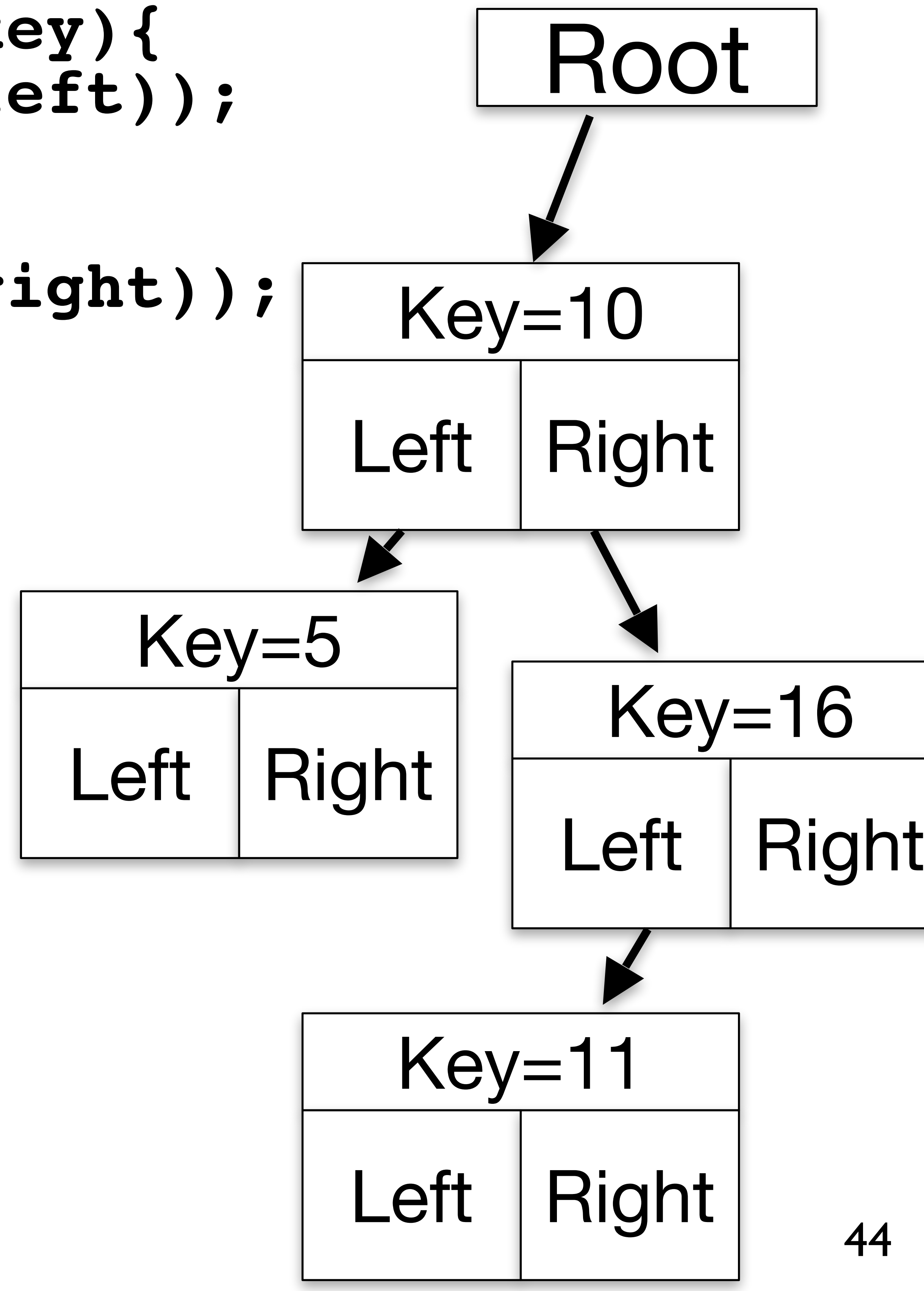
  -
    ```
    int *ip;
    ip = (int *) malloc(sizeof(int));
    ... .. ..
    free((void*) ip); /* Can you free(ip) after ip++ ? */
    ```

  -
    ```
    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)->right));
    }
}


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 used by **`malloc()`**
- 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 address) 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