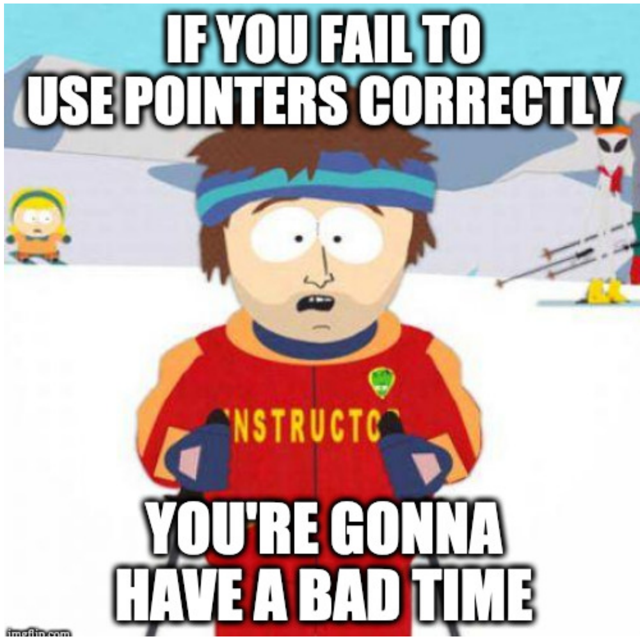
Pointers, Arrays, Memory: AKA the cause of those F@#)(#@*(Segfaults



Berkeley EECS
ELECTRICAL ENGINEERING & COMPUTER SCIENCES

Announcements!

- Lab 0 due date extended until next Friday
  - But do it this week if you can...
- Next week lecture will still be fully remote
  - As much as we love in-person teaching...
    the ZoomCave is a better recording studio than 310 Soda
- Project 1 will be released Real Soon Now (RSN)
  - Start it early:
    It covers a lot of tricky language issues
- No lecture & discussion on Monday
  - It is a holiday!

C Syntax: Variable Declarations

- Similar to Java, but with a few minor but important differences
  - All variable declarations must appear before they are used
  - All must be at the beginning of a block.
  - A variable may be initialized in its declaration;
    if not, it holds garbage! (the contents are undefined)
- Examples of declarations:
  - Correct: `{ int a = 0, b = 10; ...`
  - Incorrect: `for (int i = 0; i < 10; i++) { ...`

Newer C standards are more flexible about this

An Important Note: Undefined Behavior…

- A lot of C has "Undefined Behavior"
  - This means it is often un***predictable*** behavior
    - It will run one way on one compiler and computer…
    - But some other way on another
    - Or even just be different each time the program is executed!
- Often contributes to ***Heisenbugs***
  - Bugs that seem random/hard to reproduce
  - (In contrast to ***Bohrbugs*** which are deterministic and therefore reproducible)

C Syntax : Control Flow (1/2)

- Within a function, remarkably close to Java constructs (shows Java's legacy) in terms of control flow
  - A statement can be a `{}` of code or just a standalone statement
- if-else
  - `if (expression) statement`
    - `if (x == 0) y++;`
    - `if (x == 0) {y++;}`
    - `if (x == 0) {y++; j = j + y;}`
  - `if (expression) statement1 else statement2`
    - There is an ambiguity in a series of if/else if/else if you don't use `{}`s, so ***always*** use `{}`s to block the code
    - In fact, it is a bad C habit to not always have the statement in `{}`s, it has resulted in some amusing errors...
- while
  - `while (expression) statement`
  - `do statement while (expression);`

C Syntax : Control Flow (2/2)

- for
  - `for (initialize; check; update) statement`
- switch
  - ```
    switch (expression){
      case const1:    statements
      case const2:    statements
      default:        statements
    }
    ```
  - `break; /* need to break out of case */`
 - Note: until you do a break statement things keep executing in the switch statement
- C also has `goto`
  - But it can result in spectacularly bad code if you use it, so don't! Makes your code hard to understand, debug, and modify.
    ```

C Syntax: True or False

- What evaluates to *FALSE* in C?
  - 0 (integer)
  - NULL (a special kind of pointer that is also 0: more on this later)
  - ***No explicit Boolean type in old-school C***
    - Often you see `#define bool (int)`
    - Then `#define false 0`
  - Basically anything where all the bits are 0 is false
- What evaluates to *TRUE* in C?
  - ***Anything*** that isn't false is true
  - Same idea as in Python: only 0s or empty sequences are false, anything else is true!

C and Java operators nearly identical

- arithmetic: `+, -, *, /, %`
- assignment: `=`
- augmented assignment: `+=, -=, *=, /=, %=, &=, |=, ^=, <<=, >>=`
- bitwise logic: `~, &, |, ^`
- bitwise shifts: `<<, >>`
- boolean logic: `!, &&, ||`
- equality testing: `==, !=`
- subexpression grouping: `()`
- order relations: `<, <=, >, >=`
- increment and decrement: `++` and `--`
- member selection: `., ->`
  - This is slightly different than Java because there are both structures and pointers to structures, more later
- conditional evaluation: `? :`

Our Tip of the Day… Valgrind

- Valgrind turns most unsafe "heisenbugs" into "bohrbugs"
  - It adds almost all the checks that Java does but C does not
  - The result is your program ***immediately*** crashes where you make a mistake
  - It is installed on the lab machines
    - You can install it on some home machines, but not currently supported on MacOS-11
- Nick's scars from his 60C experience:
  - First C project, spent an entire day tracing down a fault...
    - Program would crash ***in a print statement*** only when there was a lot of input
  - That turned out to be a <= instead of a < in initializing an array!

Remember What We Said Earlier About Buckets of Bits?

- C's memory model is that conceptually there is simply one ***huge*** bucket of bits
  - Arranged in bytes
- Each byte has an ***address***
  - Starting at 0 and going up to the maximum value (0xFFFFFFFF on a 32b architecture)
    - 32b architecture means the # of bits in the address
- We commonly think in terms of "words"
  - Least significant bits of the address are the offset within the word
  - Word size is 32b for a 32b architecture, 64b for a 64b architecture:
    A word is big enough to hold an ***address***

0xFFFFFFFC	xxxx	xxxx	xxxx	xxxx
0xFFFFFFF8	xxxx	xxxx	xxxx	xxxx
0xFFFFFFF4	xxxx	xxxx	xxxx	xxxx
0xFFFFFFF0	xxxx	xxxx	xxxx	xxxx
0xFFFFFFEC	xxxx	xxxx	xxxx	xxxx
. . .	. . .	. . .	. . .	. . .
0x14	xxxx	xxxx	xxxx	xxxx
0x10	xxxx	xxxx	xxxx	xxxx
0x0C	xxxx	xxxx	xxxx	xxxx
0x08	xxxx	xxxx	xxxx	xxxx
0x04	xxxx	xxxx	xxxx	xxxx
0x00	xxxx	xxxx	xxxx	xxxx

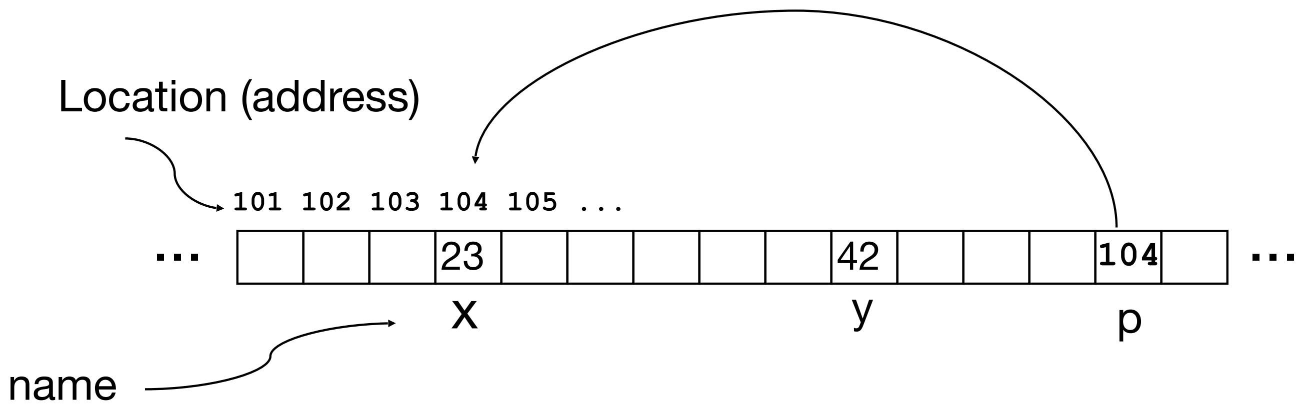
Address vs. Value

- 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

	101	102	103	104	105	...										
...				23						42						...

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

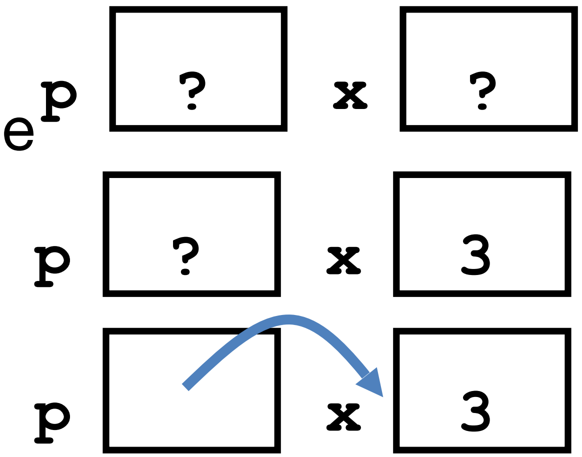
Creating and Using Pointers

- How to create a pointer:

`&` operator: get address of a variable

```
int *p, x;        x = 3;

                  p = &x;
```



Note the "`*`" gets used two 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`**.

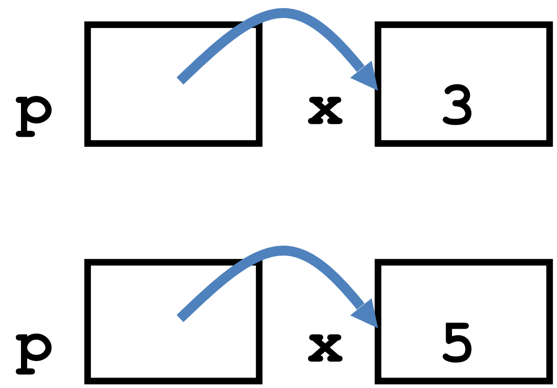
- How get a value pointed to?

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

```
printf("p points to %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

- Java and C pass basic 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

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

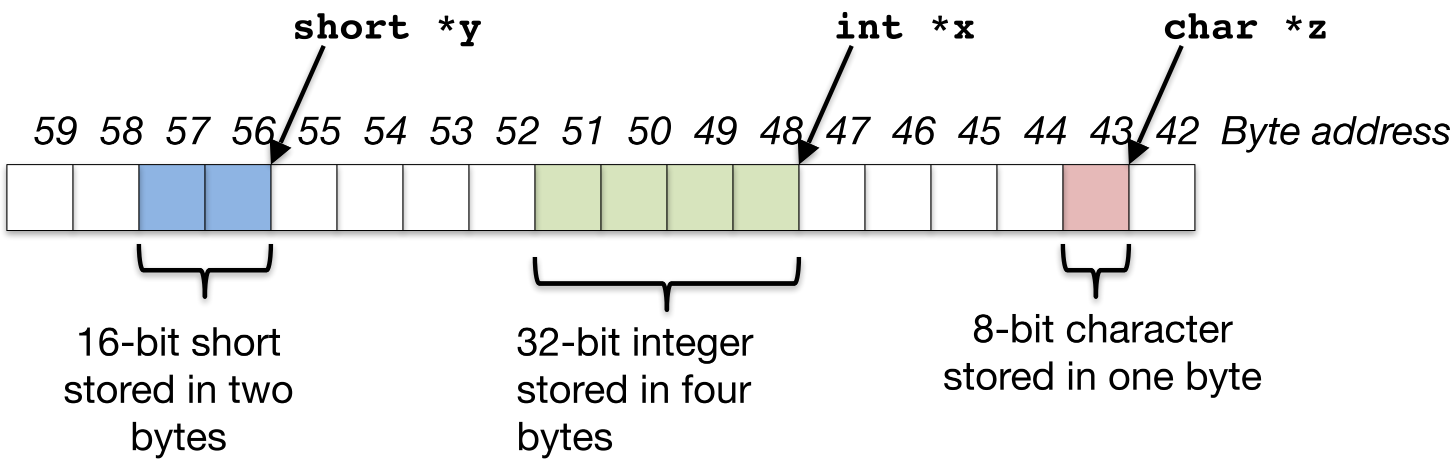
- Why use pointers?
  - If we want to pass a large struct or array, it's easier / faster / etc. to pass a pointer than the whole thing
    - Otherwise we'd need to copy a huge amount of data
    - You notice in Java that more complex objects are passed by reference.... Under the hood this is a pointer
  - 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

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 are ***massively*** 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 don't need to use raw pointers in application code
  - Most other languages use "pass by reference" for objects, which is semantically similar but with checks for misuse
- Low-level system code still needs low-level access via pointers
  - And compilers basically convert "pass by reference" into pointer-based code

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;
```

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

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

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

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

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

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

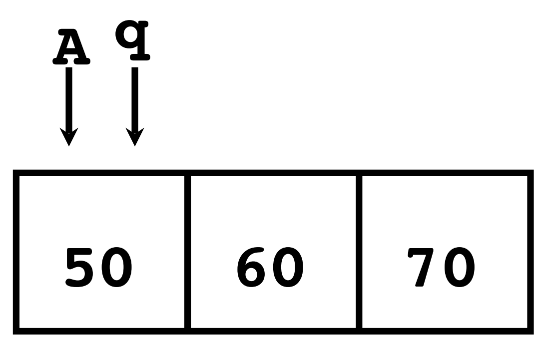
Changing a Pointer Argument?

- 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

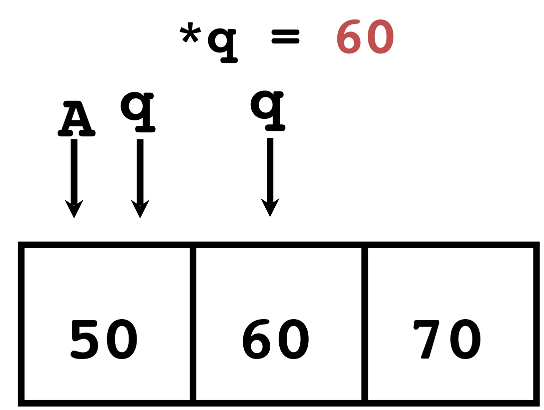


Pointer to a Pointer

- 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);
```



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...

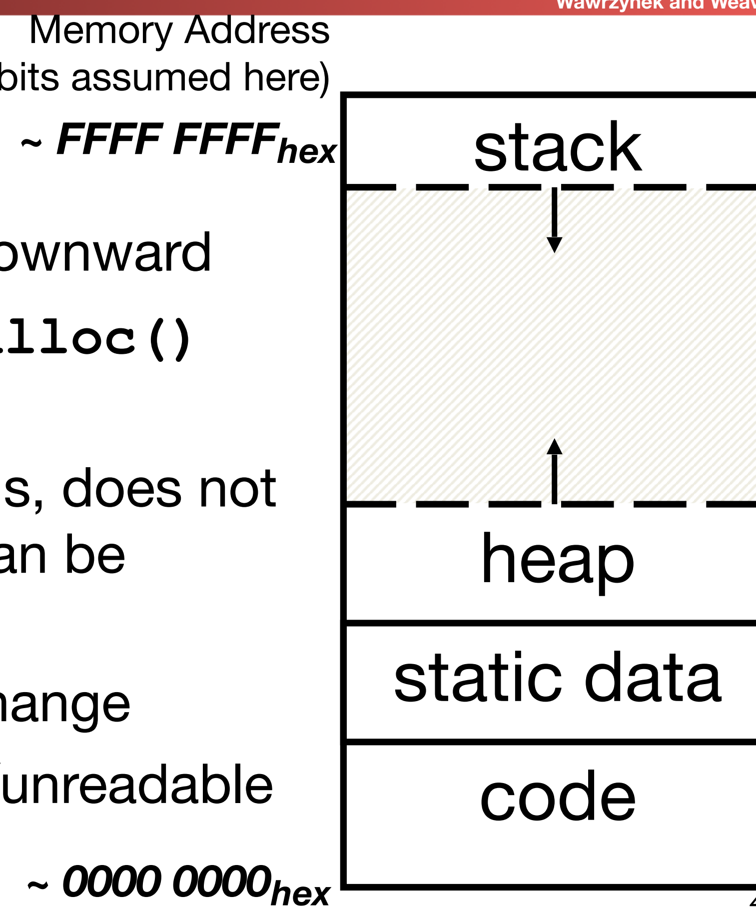
- It generally doesn't matter if you write portable C code running on one computer...
  - After all, you shouldn't be treating an integer as a series of raw bytes
  - Well, it matters when you take CS161:
    x86 is little endian and you may write an address as a string
- It does matter when you want to communicate across computers...
  - The "network byte order" is big-endian, but your computer may be 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

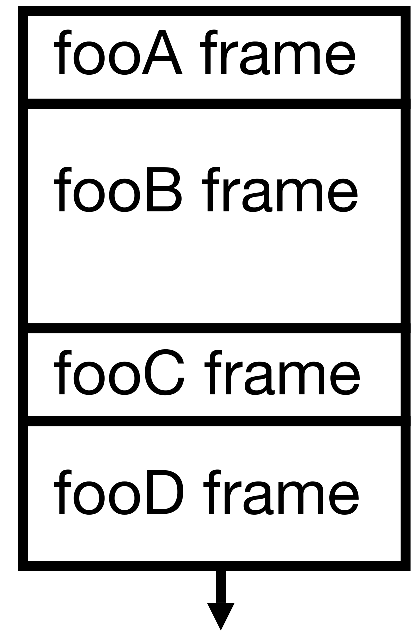
```
int myGlobal;
main() {
  int myTemp;
}
```

- 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

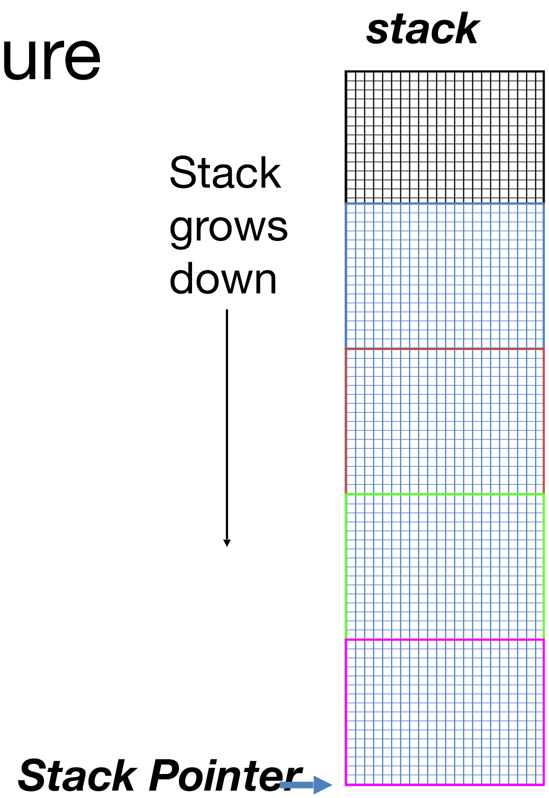
```
fooA() { fooB(); }
fooB() { fooC(); }
fooC() { fooD(); }
```



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

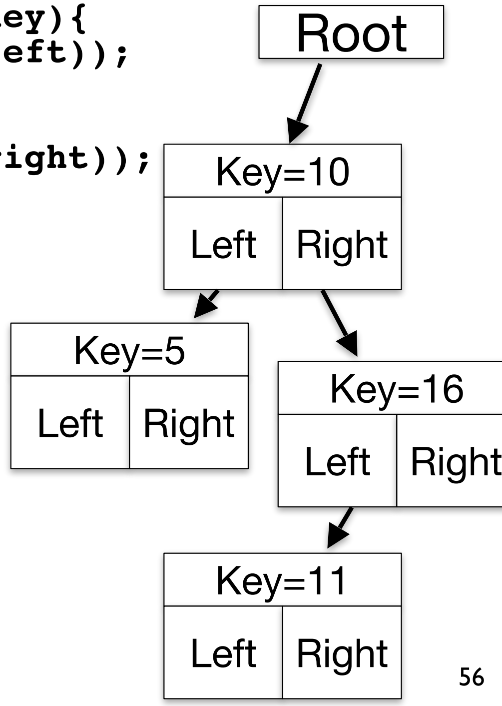

```
typedef struct node {
  int key;
  struct node *left; struct node
*right;
} Node;

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