Computer Systems and Networks

ECPE 170 – Jeff Shafer – University of the Pacific

C Programming

Lab Schedule

Activities

- **This Week**
  - Intro to C
  - Intro to Build Tools and Makefiles
  - **Lab 3 – Build Tools**
- **Next Week**
  - **Lab 4 – C Programming Project**

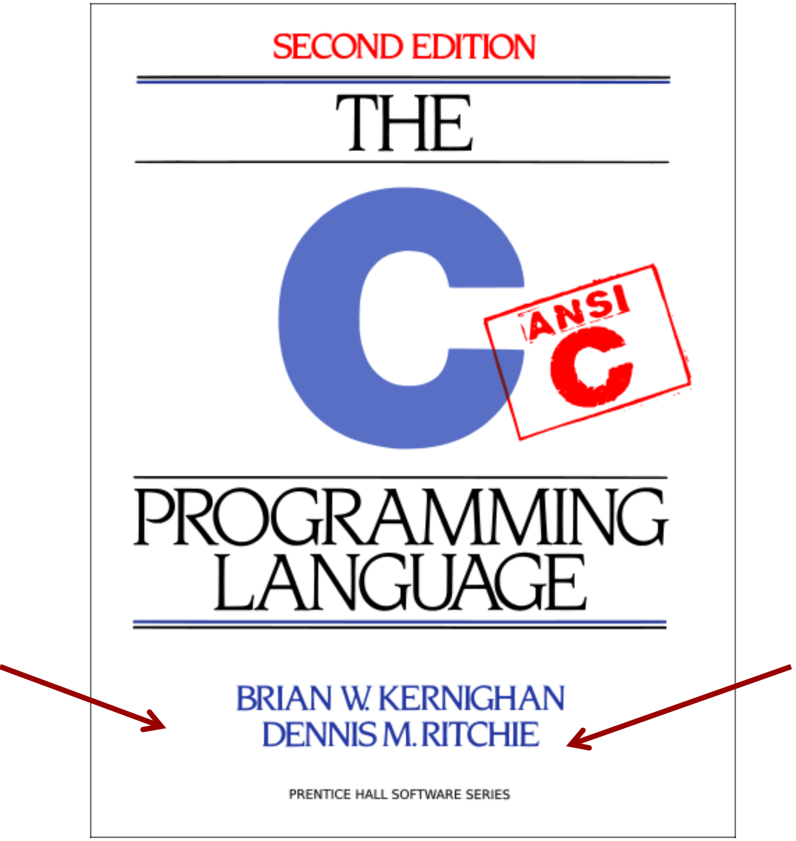
Deadlines

- **Lab 3 – Feb 6th 2017 by 5am**
- **Lab 4 – Feb 20th 2017 by 5am**

Person of the Day: Dennis Ritchie

- Creator of **C programming language**
- Co-creator of **Unix**
(with Ken Thompson, Brian Kernighan, and others at Bell Labs)
- Winner of **ACM Turing Award**
- 9/9/1941—10/12/2011

Person of the Day: Dennis Ritchie



SECOND EDITION

THE C PROGRAMMING LANGUAGE

ANSI C

BRIAN W. KERNIGHAN
DENNIS M. RITCHIE

PRENTICE HALL SOFTWARE SERIES

- *“Pretty much everything on the web uses those two things: C and UNIX. The browsers are written in C. The UNIX kernel — that pretty much the entire Internet runs on — is written in C. Web servers are written in C, and if they’re not, they’re written in Java or C++, which are C derivatives, or Python or Ruby, which are implemented in C. And all of the network hardware running these programs I can almost guarantee were written in C. It’s really hard to overstate how much of the modern information economy is built on the work Dennis did.”*
  - Rob Pike, Bell Labs / Google

Dennis Ritchie and Ken Thompson use a teletypewriter to run a program on a UNIX-based computer system they co-founded at Bell Labs in New Jersey. Their development work more than 40 years ago facilitated the realization of the Internet.

C Programming

C++ Features Not in C

- No **classes** / object-oriented programming
- No **new** / **delete**
- No stream operators (<< and >>), cin, cout, …
- No C++ Standard Libraries (e.g. iostream)
- `bool` keyword
  - Added in C99 standard
- Declare variables anywhere inside function
  - Added in C99 standard

Output with printf()

- `printf("This is a string\n");`
- `printf("The integer is %i\n", num);`
- `printf("The floating-point values are %g and %g\n", num1, num2);`

Output with printf()

Format "Type" Code	Corresponding Variable Type
`d` or `i`	int (interpret as signed 2's comp)
`u`	int (interpret as unsigned)
`x`	int (print as hexadecimal)
`f` or `g`	float/double
`c`	char
`s`	string (null-terminated array of chars)

Prefix with `l` or `ll` (i.e. "long" or "long long" for larger 64-bit data types)

- Lots of formatting options not listed here…
  - # of digits before / after decimal point?
  - Pad with zeros?

Input with scanf()

- Input from console
- `scanf("%d %c", &myint, &mychar)`
- Requires the **address** of the destination variable
  - Use the `&` operator to obtain address
- Caveat: Array names are already the "address of"!

  -
    ```
    char myarray[8];
    scanf("%s", myarray)
    ```

No & needed here!

Documentation

- Man(ual) pages exist for common programming functions too
- `unix>  man printf`
- `unix>  man scanf`

Structures

```
struct database
{
  int id_number;
  int age;
  float salary;
};

int main()
{
  struct database employee;
  employee.age = 22;
  employee.id_number = 1;
  employee.salary = 12000.21;
}
```

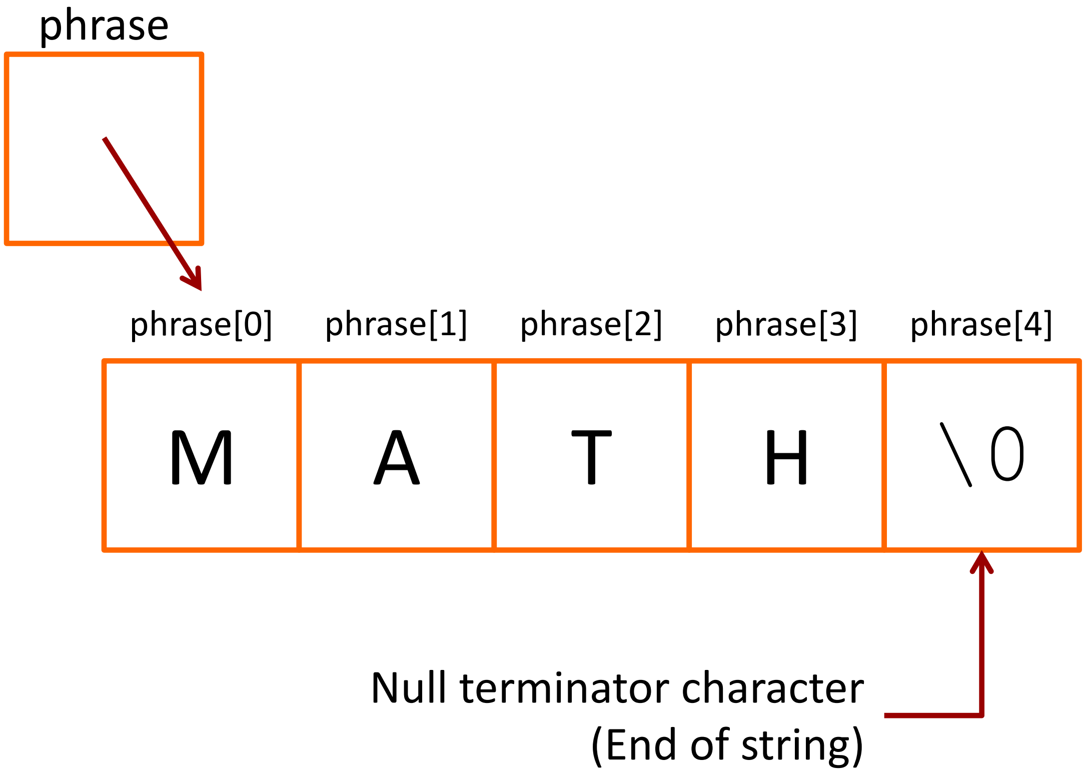
C-Strings (Arrays of Characters)

C Strings

- **There is no such thing as a "string" in C!**
- What do you get? **An array of characters**
  - Terminated by the null character `'\0'`
- Must manipulate element by element…
  - Not enough room in the array? Need a bigger array

Arrays of Characters

- `char phrase[]="Math";`



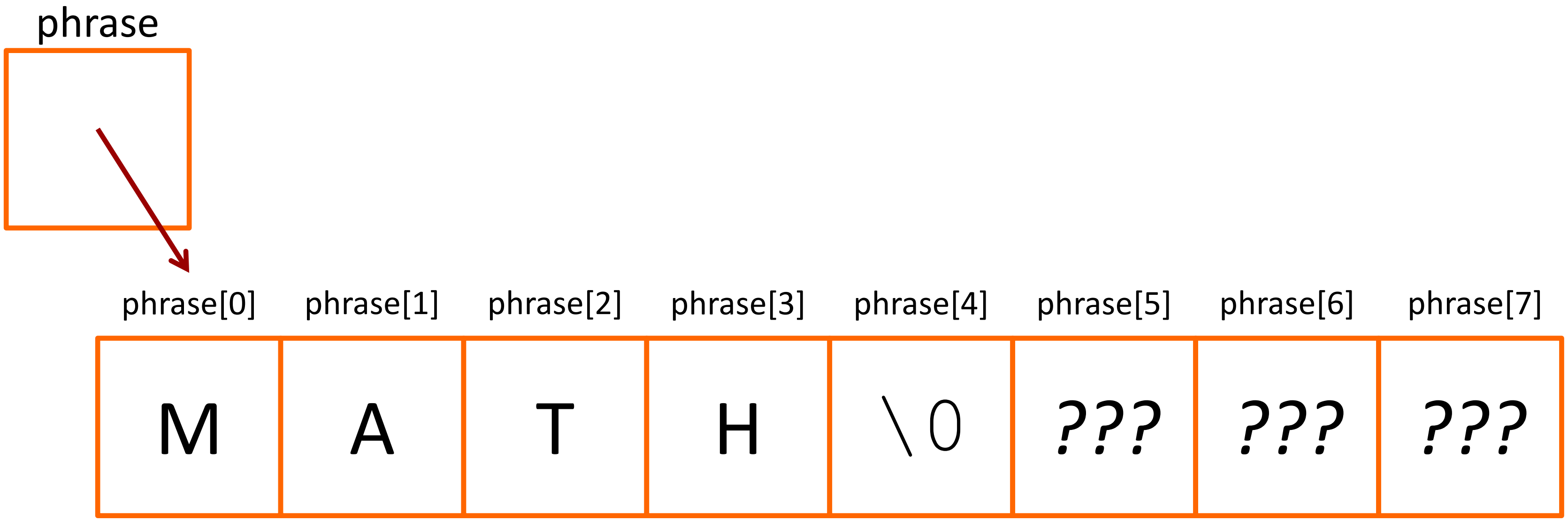
phrase

phrase[0]	phrase[1]	phrase[2]	phrase[3]	phrase[4]
M	A	T	H	\0

Null terminator character
(End of string)

Arrays of Characters

- `char phrase[8]="Math";`



phrase

phrase[0]	phrase[1]	phrase[2]	phrase[3]	phrase[4]	phrase[5]	phrase[6]	phrase[7]
M	A	T	H	\0	???	???	???

```
printf("%s\n", phrase);
```

Prints until it reaches the \0 character!

Helpful Library for Character Arrays

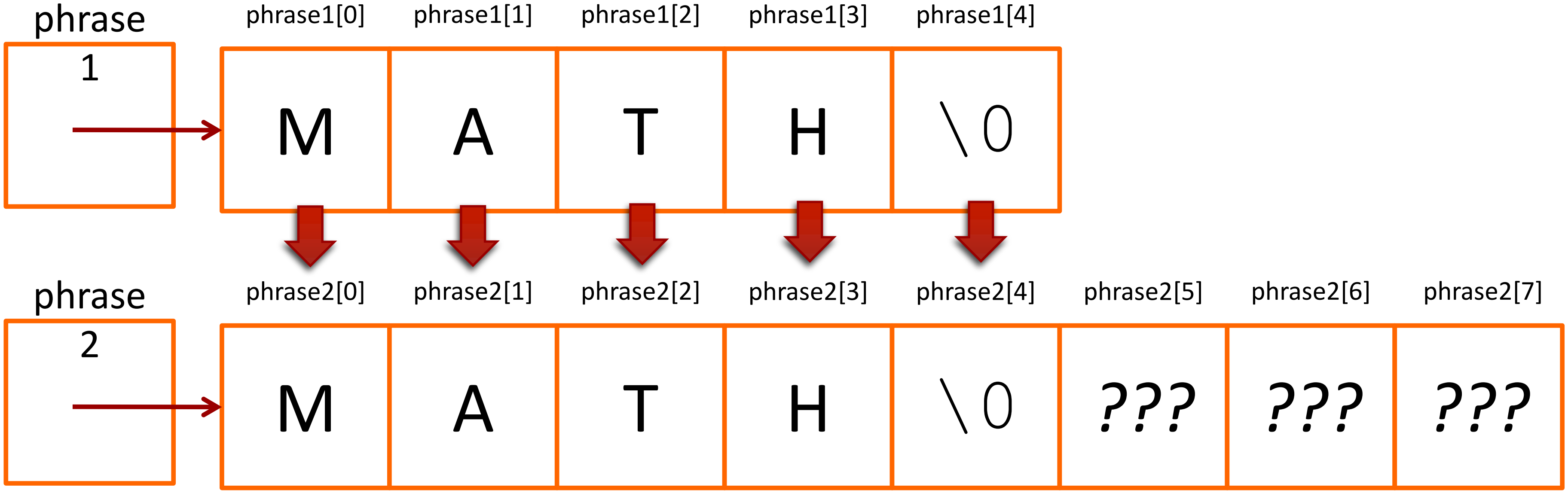
- **`#include <string.h>`**
- Useful functions
  - `strcpy` - String copy
  - `strcmp` - String compare
  - `strlen` - String length
  - `strcat` - String concatenate

String Copy

```
char phrase1[] = "Math";
```

```
char phrase2[8];
```

```
strcpy(phrase2, phrase1);
```



phrase 1

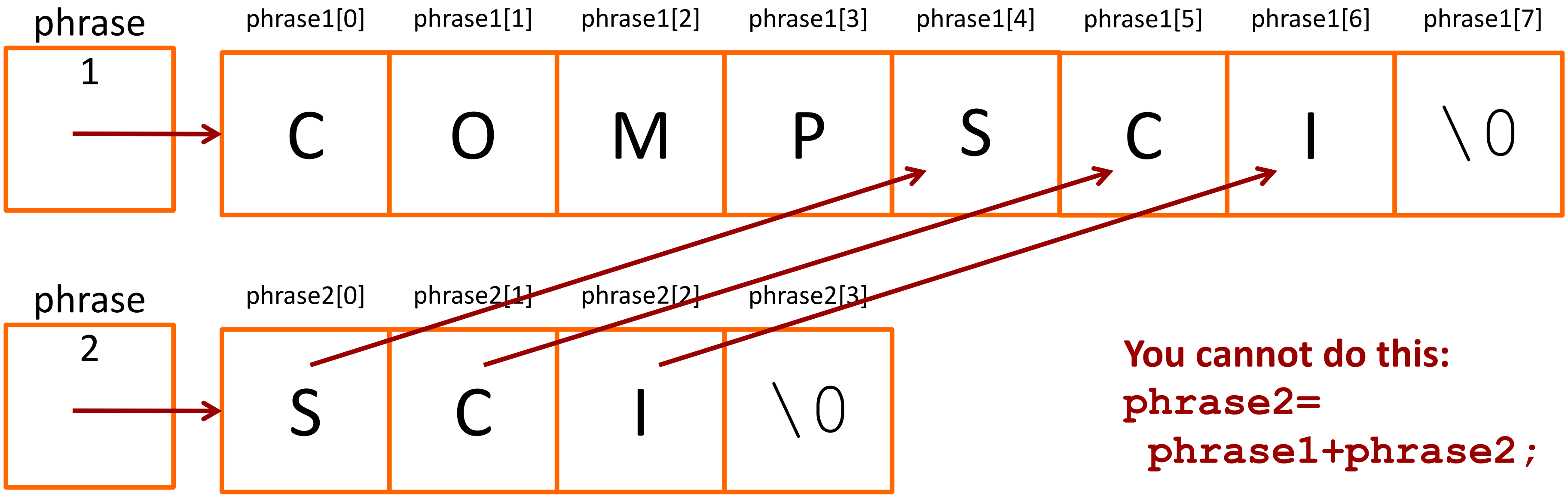
phrase1[0]	phrase1[1]	phrase1[2]	phrase1[3]	phrase1[4]
M	A	T	H	\0

phrase 2

phrase2[0]	phrase2[1]	phrase2[2]	phrase2[3]	phrase2[4]	phrase2[5]	phrase2[6]	phrase2[7]
M	A	T	H	\0	???	???	???

String Concatenation

- `char phrase1[8] = “Comp”;`
- `char phrase2[] = “Sci”;`
- **`strcat(phrase1, phrase2);`**



phrase 1

phrase1[0]	phrase1[1]	phrase1[2]	phrase1[3]	phrase1[4]	phrase1[5]	phrase1[6]	phrase1[7]
C	O	M	P	S	C	I	\0

phrase 2

phrase2[0]	phrase2[1]	phrase2[2]	phrase2[3]
S	C	I	\0

You cannot do this:

```
phrase2=
 phrase1+phrase2;
```

ctype Library

- Useful for character manipulation
- `#include <ctype.h>`
- **`toupper(char)`** / **`tolower(char)`** – Converts character to uppercase or lowercase
  - Example:

```
char c = toupper('a');
printf("%c", c);  // A
```

ctype Library

- **`isalpha(char)`** – Is the character a letter?
- **`isdigit(char)`** – Is the character a number 0-9?
- **`isspace(char)`** – Is the character whitespace? (space or newline character)
- **`ispunct(char)`** – Is the character punctuation? (technically, a visible character that is not whitespace, a letter, or a number)
- … and several other variations

Memory Management

Memory Allocation with malloc()

- `#include <stdlib.h>`
- `void * malloc(int size)`
  - **Allocate** region in memory (aka “new”)
  - Argument: Size of region in bytes to allocate
  - Return value: Pointer to the region
- `void free(void * ptr)`
  - **De-allocate** region in memory (aka “delete”)
  - Argument: Pointer to the region

Memory Allocation with malloc()

- `void * calloc(int count, int size)`
  - Basically the same as malloc!
    - Imagine you want an array of elements…
  - Argument 1: # of elements to allocate
  - Argument 2: Size of each element in bytes
  - Return value: Pointer to the region

Memory Allocation with malloc()

- `void * realloc(void *ptr, int size);`
  - **Resize** a dynamic region of memory
    - Note that it might **move** to a new address!
  - Argument: Pointer to the original region
  - Argument 2: Desired size in bytes of new region
  - Return value: Pointer to the new region
    - It might be at the same address if you made it smaller
    - It might be at a new address if you made it larger

Memory Management

- **Who implemented `malloc()`?**
- **C Standard Library:** `#include <stdlib.h>`
- There are different C Standard Library implementations!
  - Android: Bionic
  - Apple: BSD-based / Proprietary
  - Microsoft: Proprietary C Runtime Library
  - Linux: GNU C Library (glibc) http://www.gnu.org/software/libc/

Memory Management

- **Where does the `malloc()` memory come from?**
- The **Heap**:
  - A region of memory for dynamic memory allocation
  - Per-process – each program gets its own heap
  - Managed by malloc() and related functions
  - Different from the **stack**, which is for static variables (known at compile-time)

Memory Management

- **`malloc()` outline:**

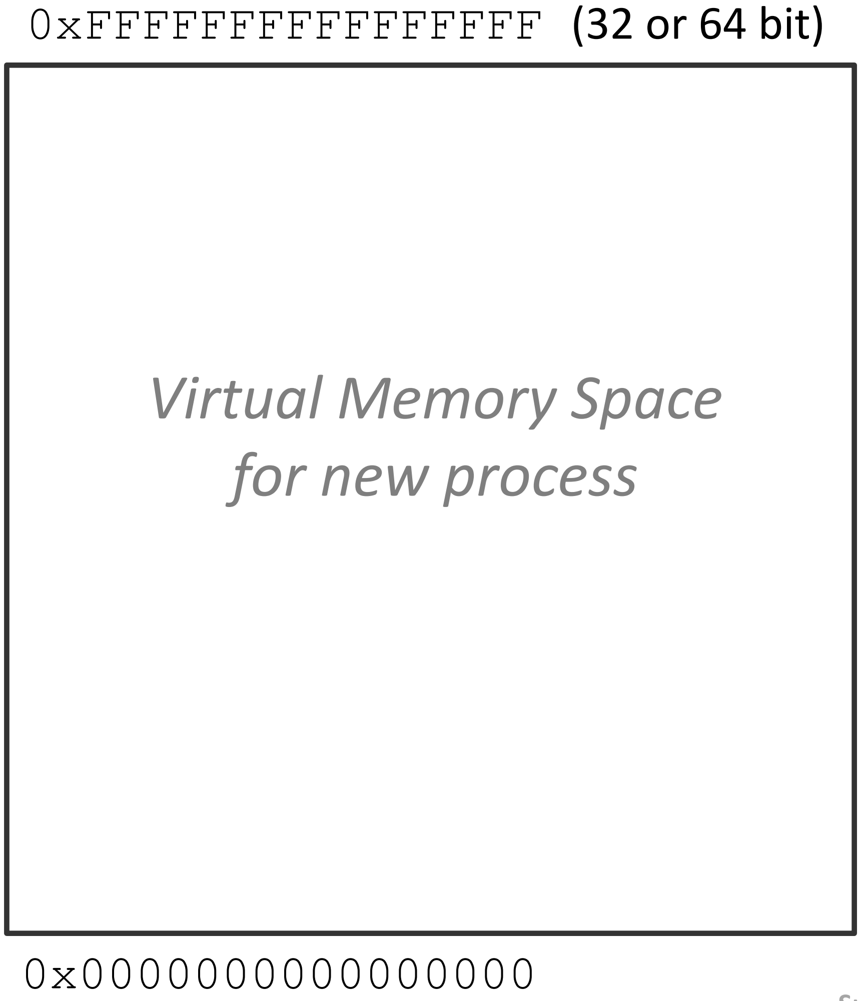
1. Call `malloc()` and request memory
2. `malloc()` checks existing heap size
   - Sufficient? Update bookkeeping to mark space as “used” and return address to your program
   - Insufficient?
     1. **Call operating system** via `brk()/nmap()` to grow the heap (plus a little extra for future requests)
     2. Update bookkeeping and return address to your program

Memory Management

- **Why do we need to call `free()` after calling `malloc()`?**
  - Memory leak
  - `malloc()` cannot re-use that space ever, because its internal bookkeeping still thinks that region is used
  - Will only be recovered upon terminating program
    - Operating system wipes out all the memory allocated to your process (stack, heap, etc…)

Memory Management

- OS creates **virtual memory** space for process when started
- Region is huge (full 32 or 64 bit space)
  - **Not** fully mapped to physical memory
  - Otherwise you could only fit 1 program in memory



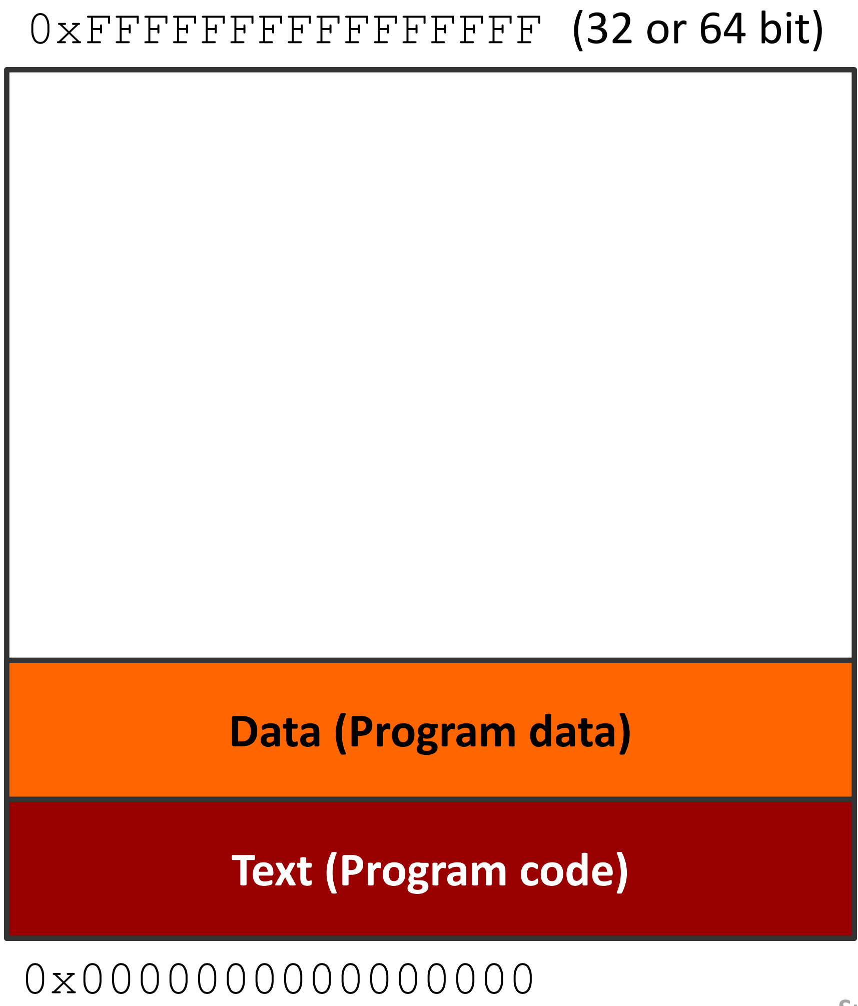
0xFFFFFFFFFFFFFFFF (32 or 64 bit)

Virtual Memory Space for new process

0x0000000000000000

Memory Management

- OS loads in the program from disk
- "Text" region
  - Program **code**
- "Data" region
  - Program fixed **data**


0xFFFFFFFFFFFFFFFF (32 or 64 bit)

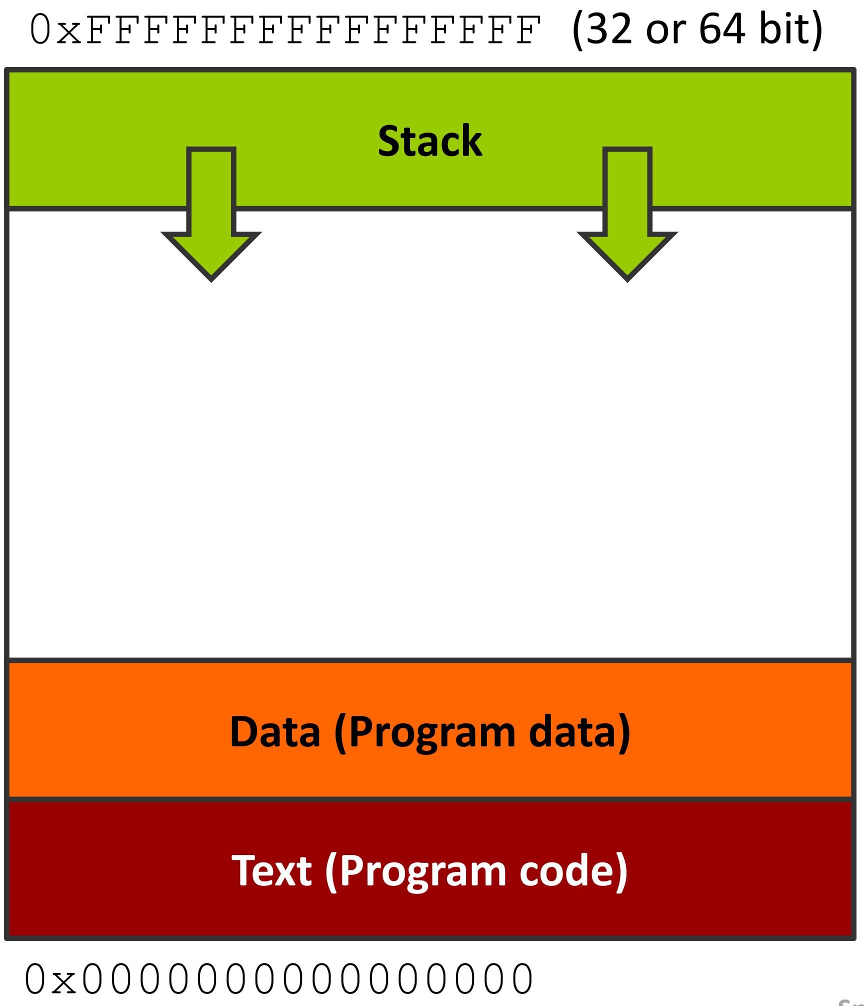
Data (Program data)

Text (Program code)

0x0000000000000000

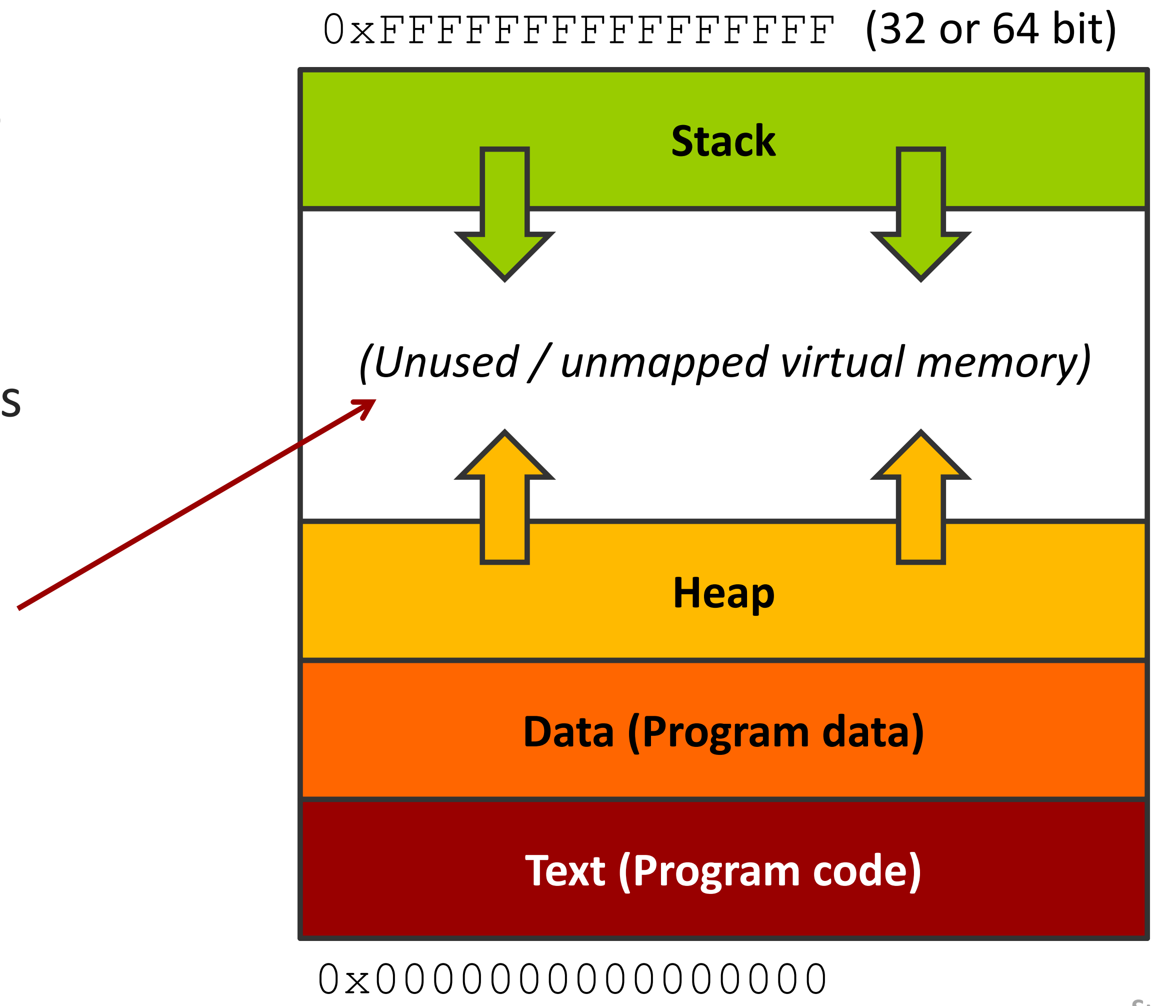
Memory Management

- **Stack** created to track program function calls and local variables



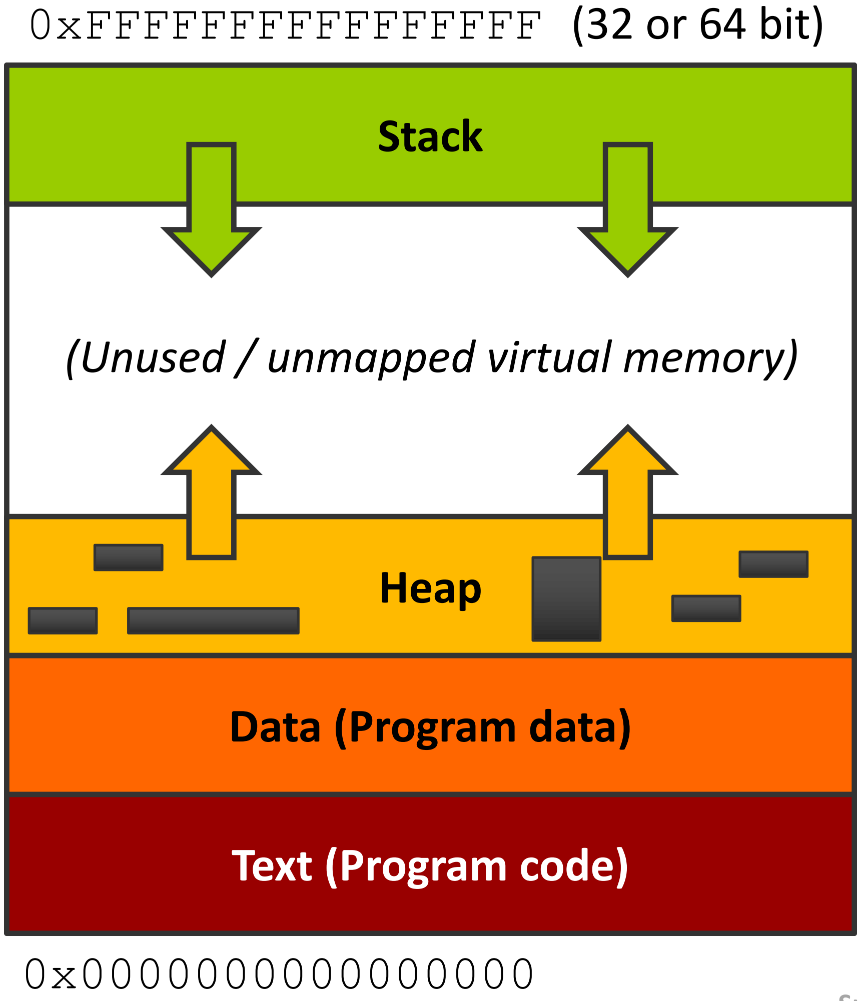
Memory Management

- **Heap** created to store dynamic memory from `malloc()` and related functions
- Not to scale – this unused region is **huge!**


0xFFFFFFFFFFFFFFFF (32 or 64 bit)
Stack
(Unused / unmapped virtual memory)
Heap
Data (Program data)
Text (Program code)
0x0000000000000000

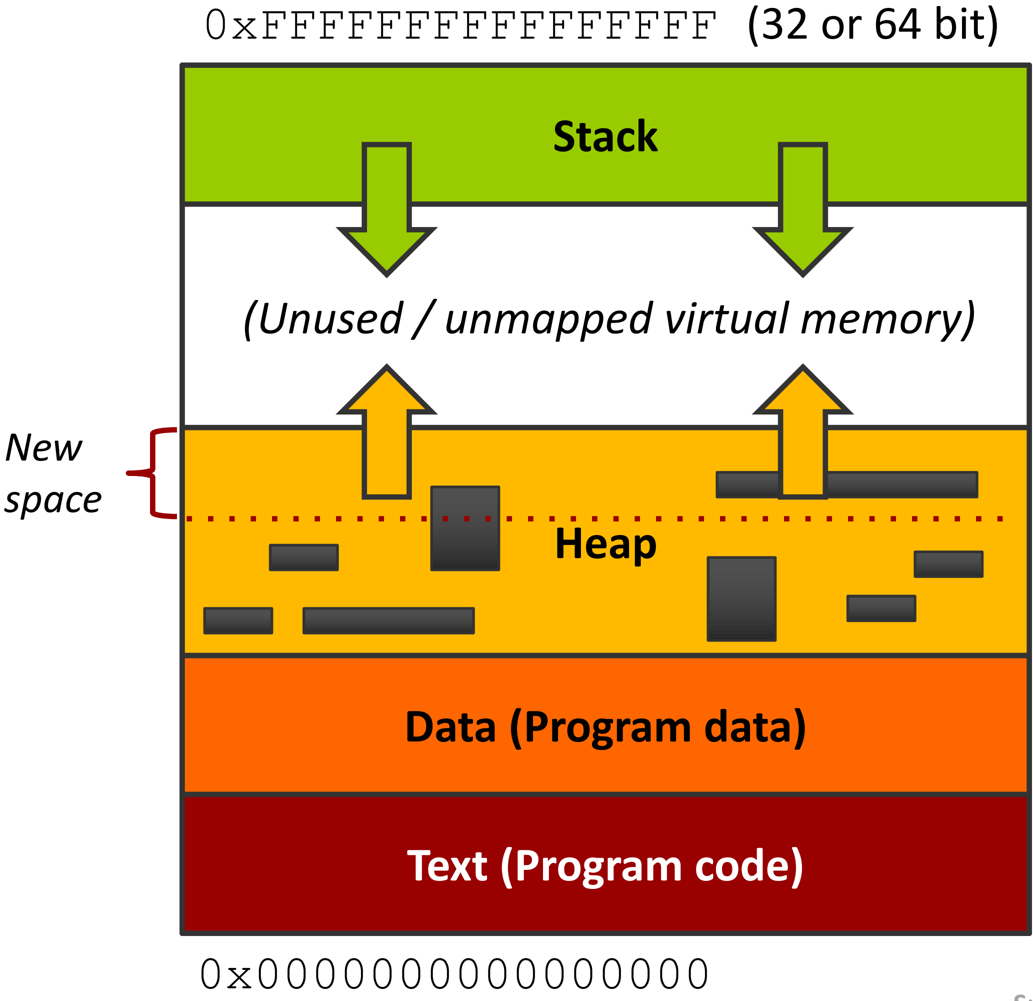
Memory Management

- Program starts running
- `malloc()` allocates some memory


0xFFFFFFFFFFFFFFFF (32 or 64 bit)
Stack
(Unused / unmapped virtual memory)
Heap
Data (Program data)
Text (Program code)
0x0000000000000000

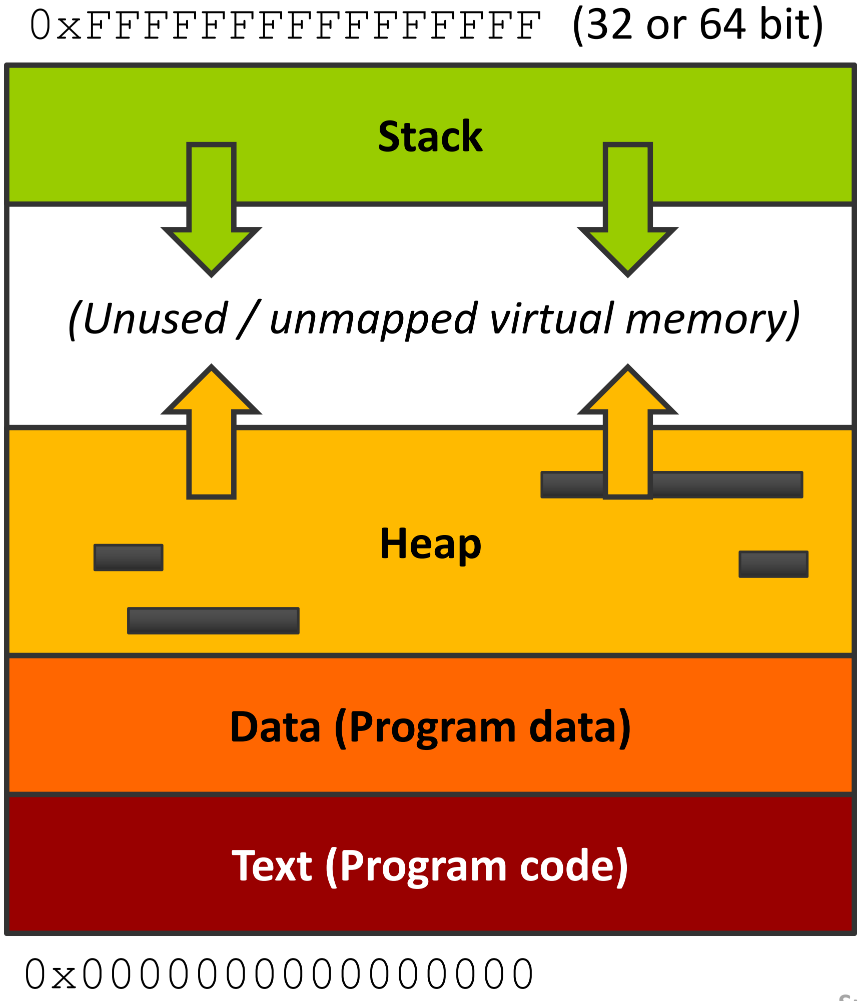
Memory Management

- Original heap space eventually fills up
- `malloc()` *requests* additional space from the kernel by using `brk()` system call



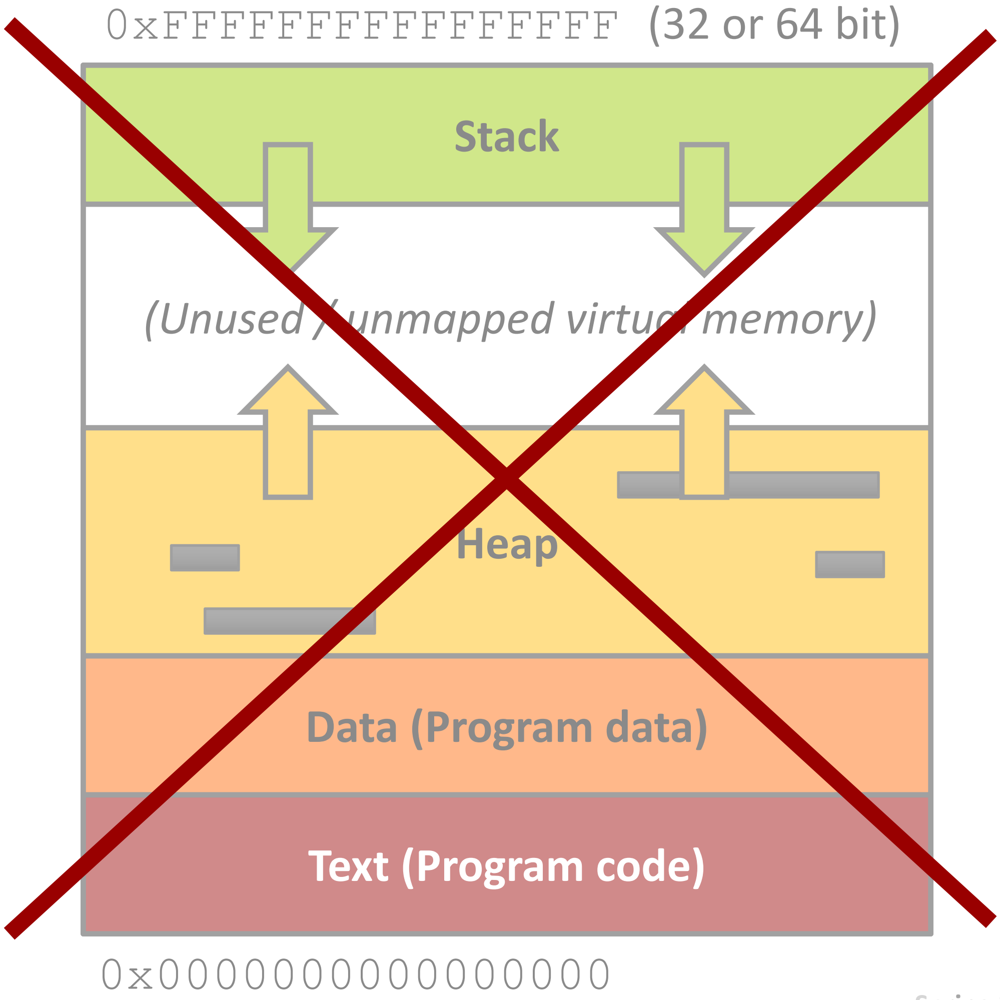
Memory Management

- `free()` deallocates blocks from the heap


0xFFFFFFFFFFFFFFFF (32 or 64 bit)
Stack
(Unused / unmapped virtual memory)
Heap
Data (Program data)
Text (Program code)
0x0000000000000000

Memory Management

- Program terminates
- OS expunges entire virtual address space
  - Everything is deleted


0xFFFFFFFFFFFFFFFF (32 or 64 bit)
Stack
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Data (Program data)
Text (Program code)
0x0000000000000000

Buffer Overflow Vulnerability

- **What is a buffer overflow bug?**

  -
    ```
    char buf1[8]=“”;
    char buf2[8]=“”;
    strcat(buf1, “excessive”);
    ```
- End up overwriting two characters beyond `buf1`!

Buffer Overflow Vulnerability

- **Why is a buffer overflow bug dangerous?**

- What is beyond my buffer in memory?
  - Other variables and data? (probably `buf2`)
  - The stack? (further out)
  - **The return address to jump to after my function finishes?**

- If app is running as administrator, attacker now has full access!

Memory Management

- **Limitless opportunities in C** for errors regarding memory ☹
  - Forgetting to `free()` some dynamic memory
  - Trying to `free()` dynamic memory more than once
  - Losing a pointer to dynamic memory (memory is "lost")
  - Accessing array elements past the end of the array
  - Mis-calculating array pointers that miss their desired target
- **Will learn a tool (*Valgrind*) in Lab 5 to analyze your program and detect / trace errors**

What’s the Error?

```
char *a = malloc(128*sizeof(char));
char *b = malloc(128*sizeof(char));
b = a;
free(a);
free(b);
```

http://www.yolinux.com/TUTORIALS/C++MemoryCorruptionAndMemoryLeaks.html

What’s the (Potential) Error?

```
char *a = malloc(128*sizeof(char));

dataLen = <some value...>

// Copy “dataLen” bytes
// starting at *data to *a
memcpy(a, data, dataLen);
```

http://www.yolinux.com/TUTORIALS/C++MemoryCorruptionAndMemoryLeaks.html

What’s the Error?

```
ptr = (char *) malloc(strlen(string_A));
strcpy(ptr, string_A);
```

http://www.yolinux.com/TUTORIALS/C++MemoryCorruptionAndMemoryLeaks.html

What’s the Error?

```
int *get_ii()
{
   int ii = 2;    // Local stack variable
   return &ii;
}
main()
{
  int *ii;
  ii = get_ii();
  ... Do stuff using ii pointer
}
```

http://www.yolinux.com/TUTORIALS/C++MemoryCorruptionAndMemoryLeaks.html

OKAY, HUMAN.
HUH?
BEFORE YOU HIT 'COMPILE,' LISTEN UP.
YOU KNOW WHEN YOU'RE FALLING ASLEEP, AND YOU IMAGINE YOURSELF WALKING OR SOMETHING,
AND SUDDENLY YOU MISSTEP, STUMBLE, AND JOLT AWAKE?
YEAH!
WELL, THAT'S WHAT A SEGFAULT FEELS LIKE.
DOUBLE-CHECK YOUR DAMN POINTERS, OKAY?

http://xkcd.com/371/

Memory Management

- **What's a NULL pointer?**
  - Pointer value is 0x000000000
  - *Meaning* is that the pointer is not pointing anywhere
- **What happens if you dereference a NULL pointer?**
  - Telling the computer to read from (or write) to the value stored in the pointer, which is 0x000000000
  - Behavior undefined and generally unpleasant on various computer systems

Memory Management

- **"Segfault" = Segmentation Fault**
- Your program tried to read or write a *virtual memory address* that is not allowed
  - Tried to read memory outside of program bounds?
  - Tried to write read-only memory regions? (used for program data)
- "**Segmentation**" was the name of an old system (back before Intel 386 processors) used to divide physical computer memory into many virtual address regions, one per application process
  - The Segfault name stuck even though we now use **paging** to manage virtual memory