Computer Systems and Networks

ECPE 170 – Jeff Shafer – University of the Pacific

C Programming

Lab Schedule

Activities

- **Today**
  - Intro to C Programming
  - **Lab 3 – C Programming**
- **Next Tuesday**
  - **Lab 3 – C Programming**
- **Next Thursday**
  - **Lab 4 – Performance Measurement**

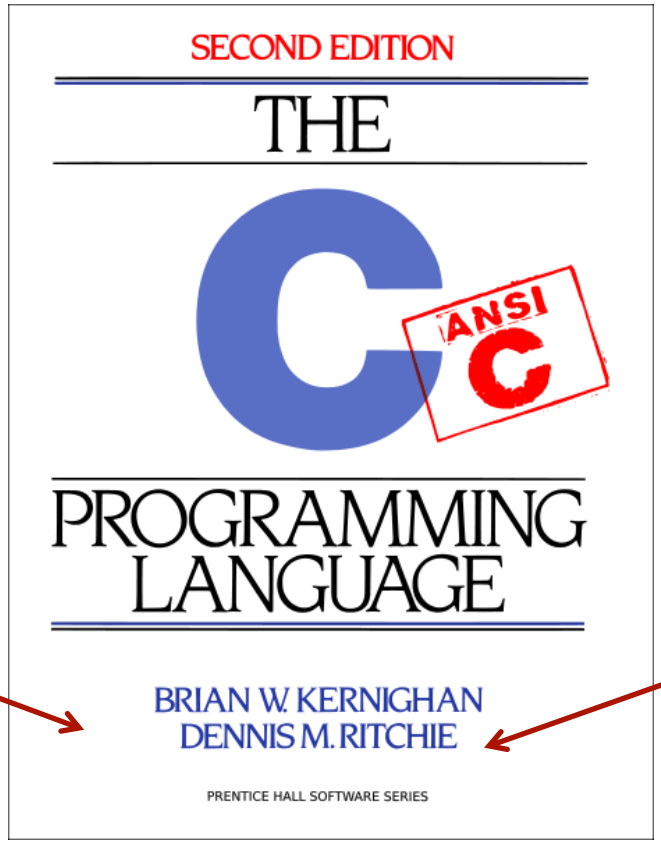
Assignments Due

- **Today**
  - **Lab Report for Lab 2 due by 11:59pm**
    - Submit via Mercurial
- **Next Thursday**
  - **Lab Report for Lab 3 due by 11:59pm**
  - **Prelab for Lab 4 due by start of class**

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



- *"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 back in C99 standard
- Declare variables anywhere inside function
  - Added back 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);`
- Lots of formatting options
  - # of digits before / after decimal point?
  - Pad with zeros?

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)

Input with scanf()

- Input from console
- `scanf("%d %c", &myint, &mychar)`
- Requires the **address** of the destination variable
  - Use the `&` operator to obtain address

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

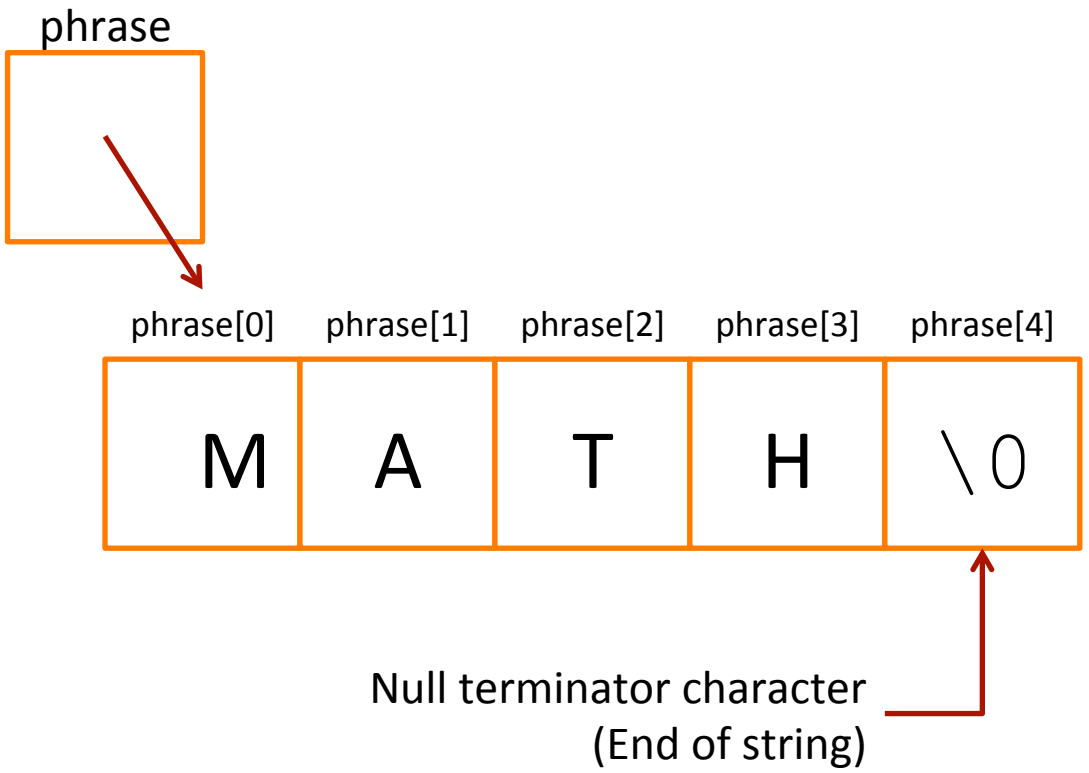
C-Strings (Arrays of Characters)

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

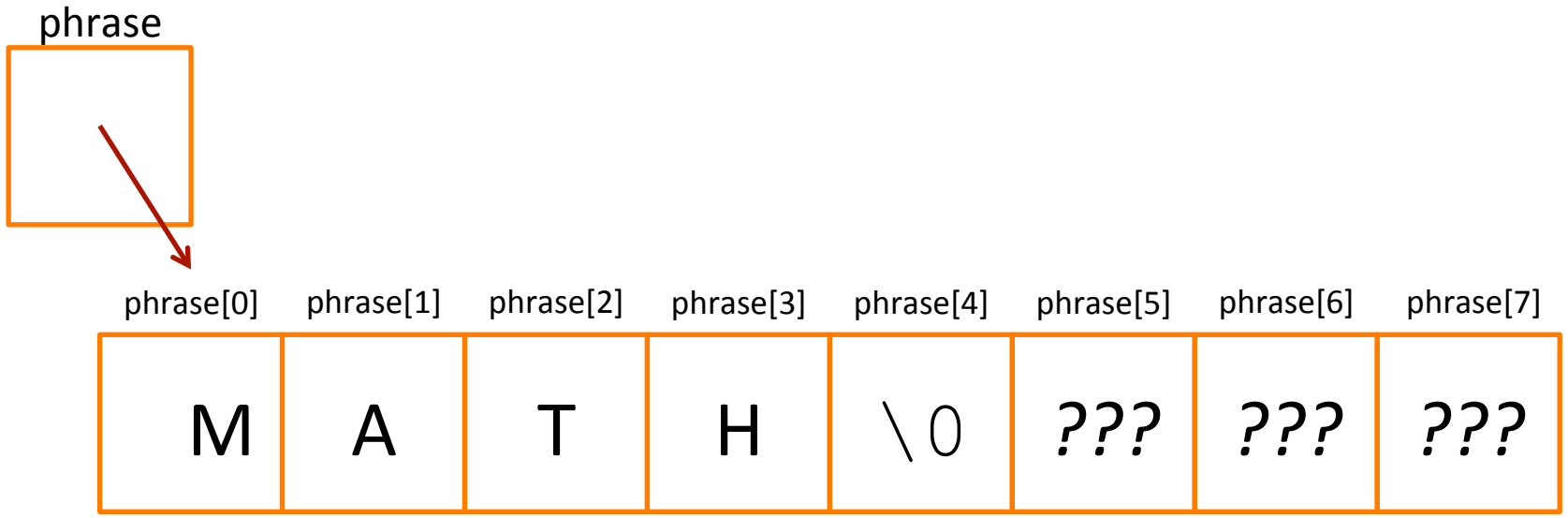
Arrays of Characters

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



Arrays of Characters

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



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

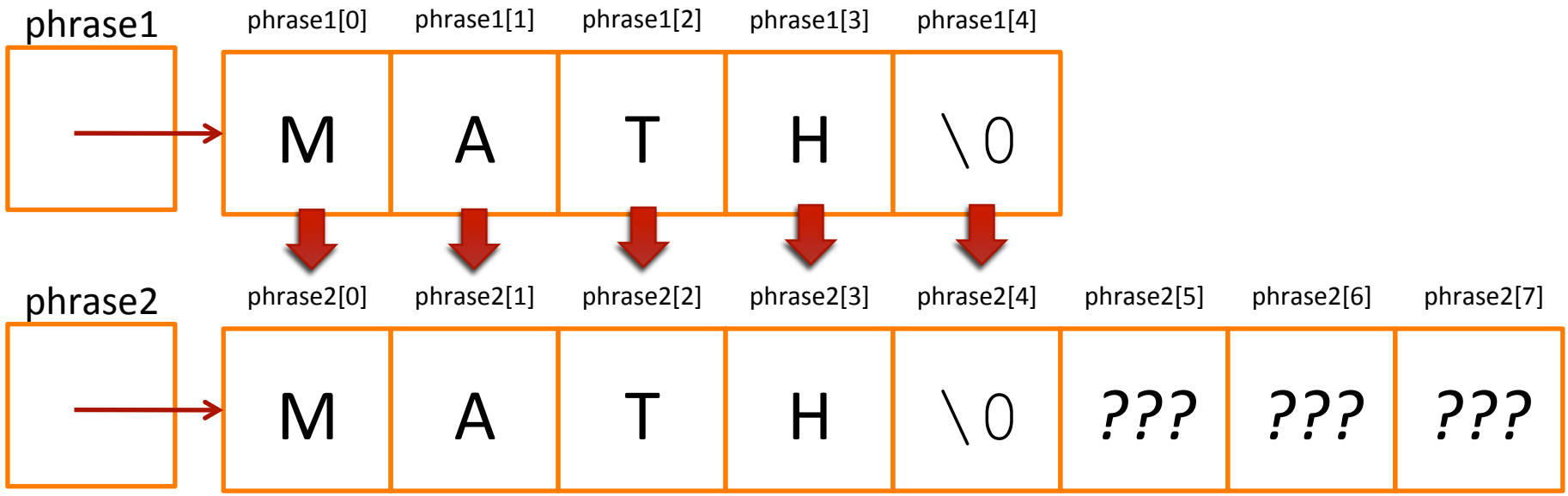
Prints until it reaches the \0 character!

Helpful Library for Character Arrays

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

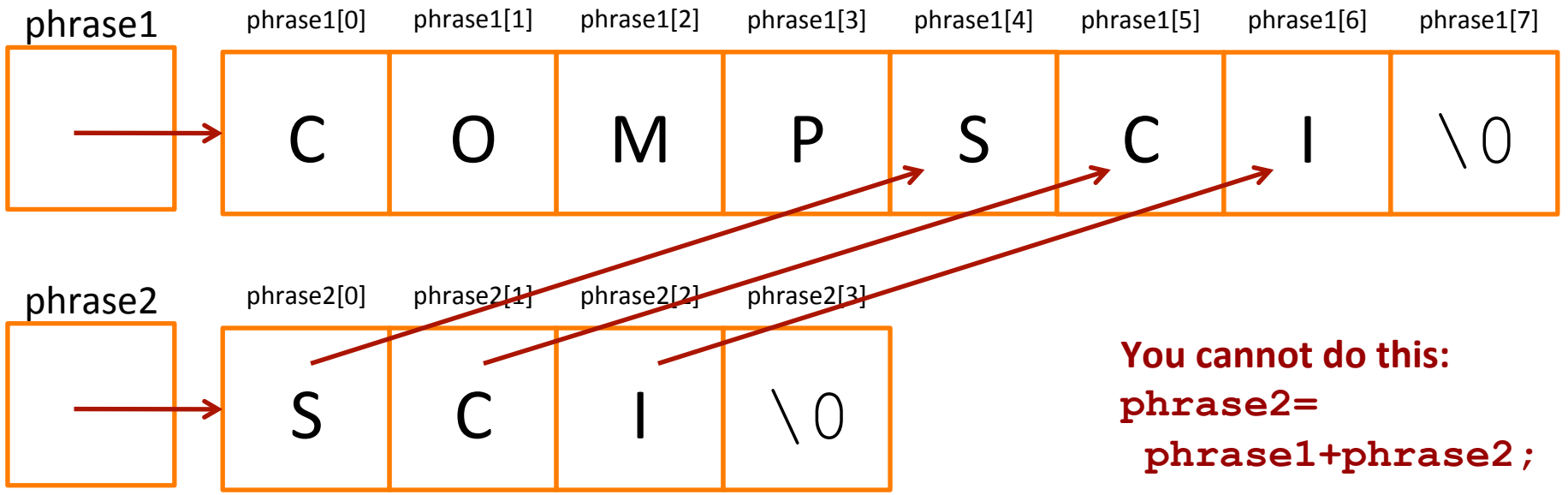
String Copy

- `char phrase1[] = "Math";`
- `char phrase2[8];`
- **`strcpy(phrase2, phrase1);`**



String Concatenation

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



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

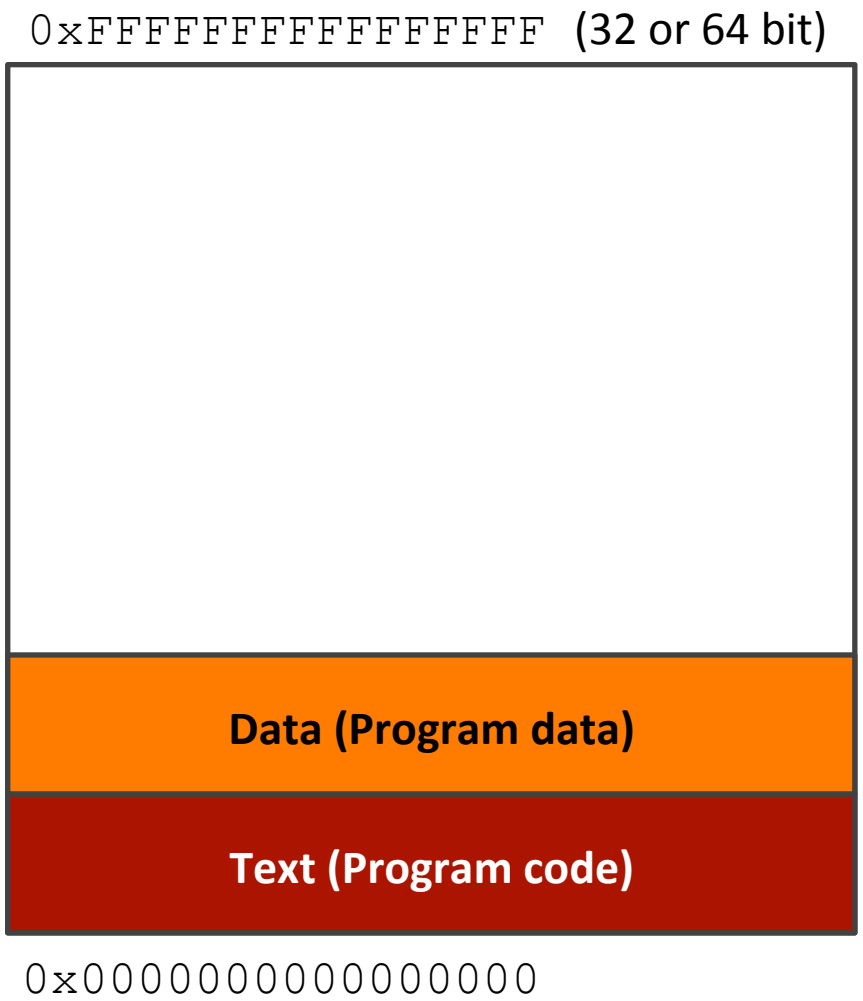
- **Why do we need to call `free()` after calling `malloc()`?**
  - Memory leak
  - `Malloc()` cannot re-use that space ever, because its internal bookkeeping still thinks that region is used
  - Will only be recovered upon terminating program
    - Operating system wipes out all the memory allocated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

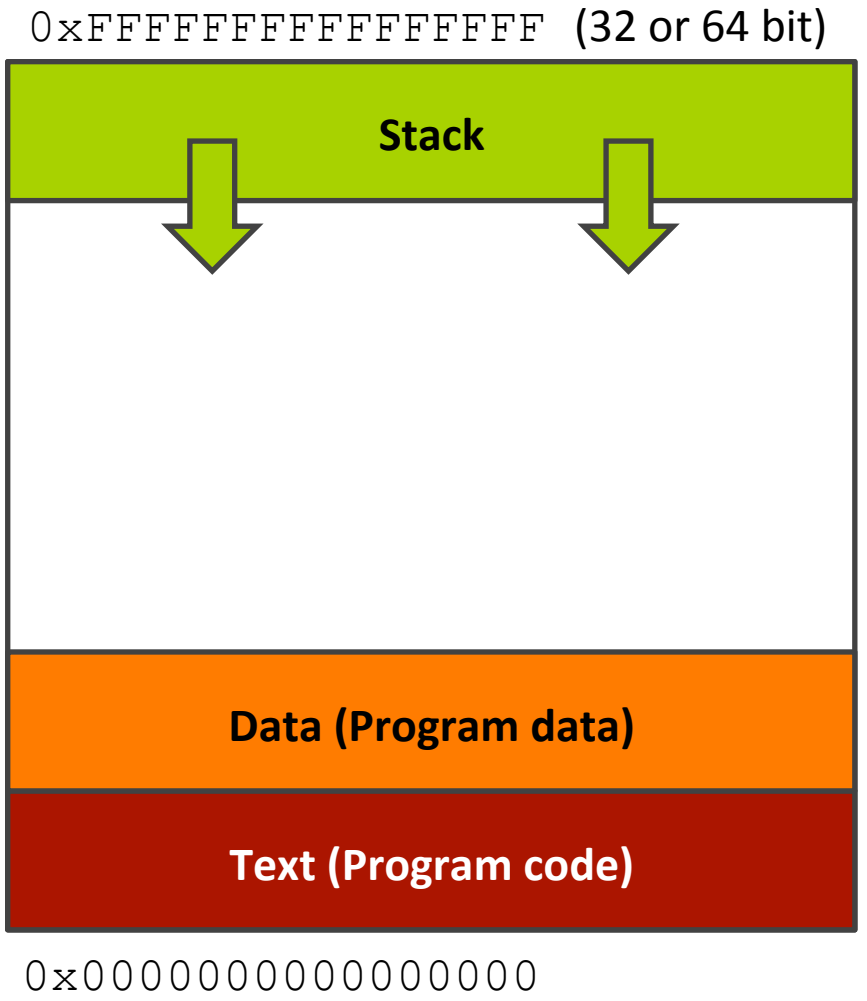
Memory Management

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



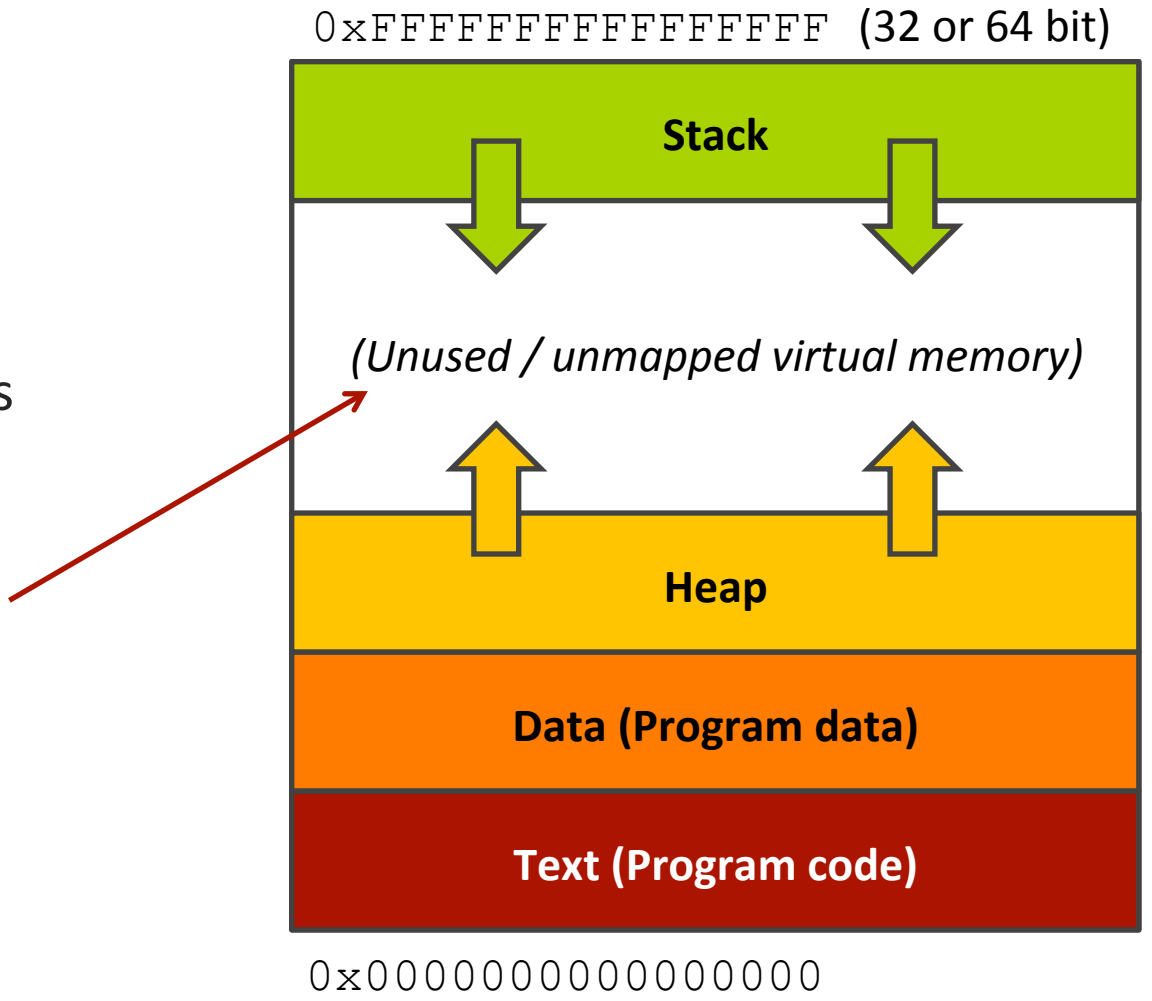
Memory Management

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



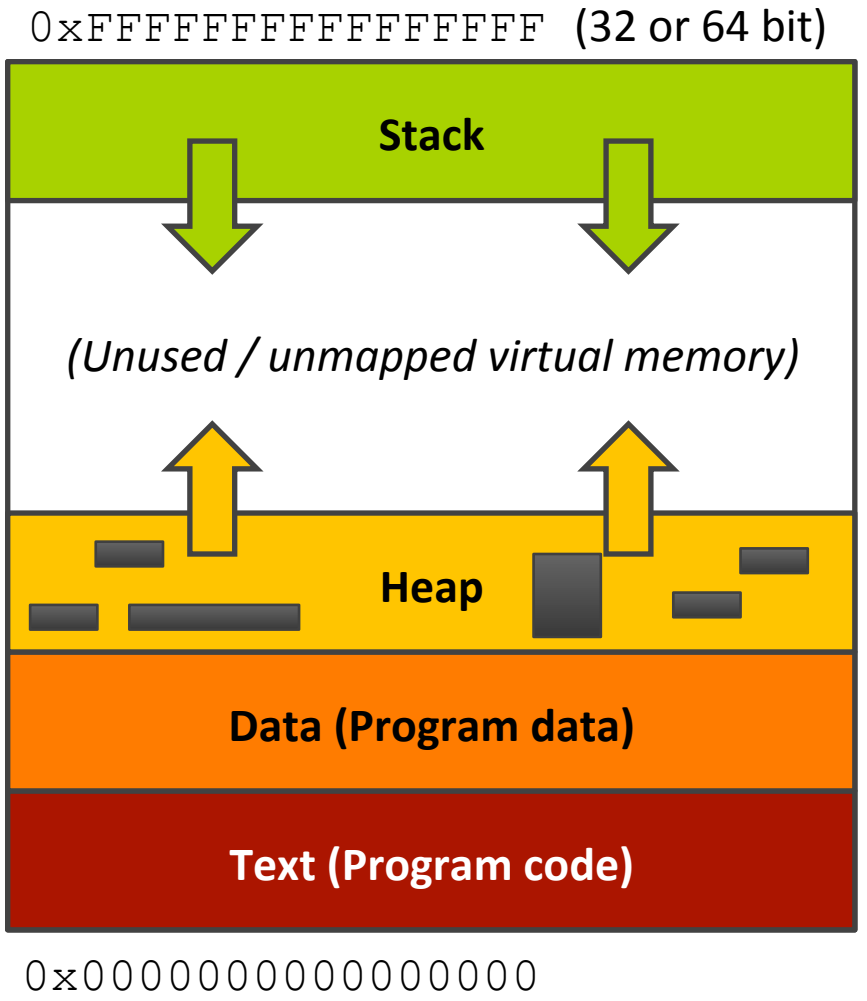
Memory Management

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



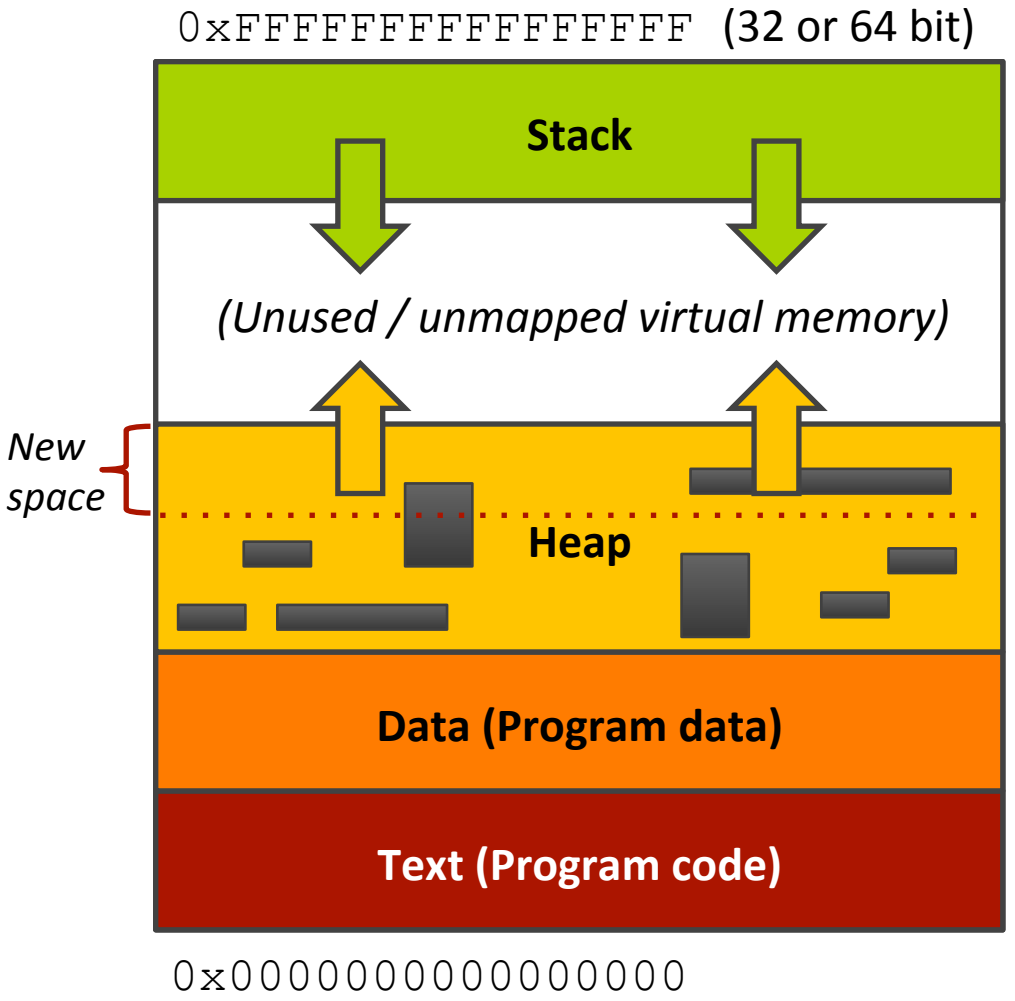
Memory Management

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



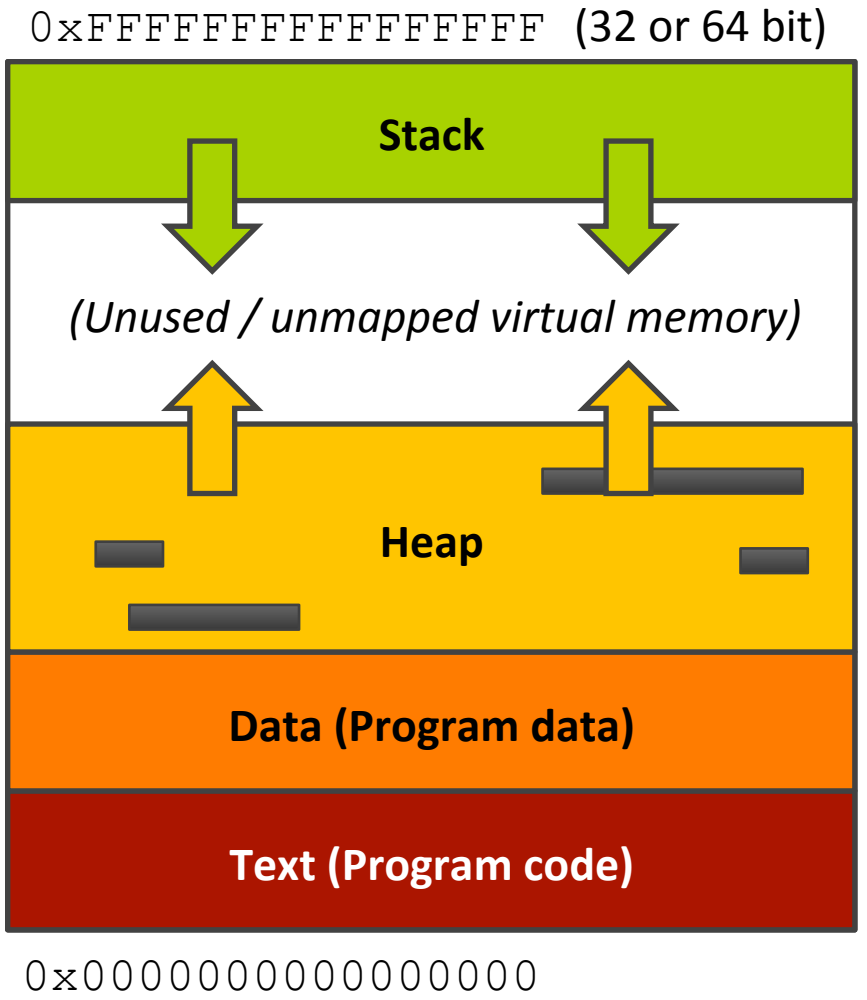
Memory Management

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



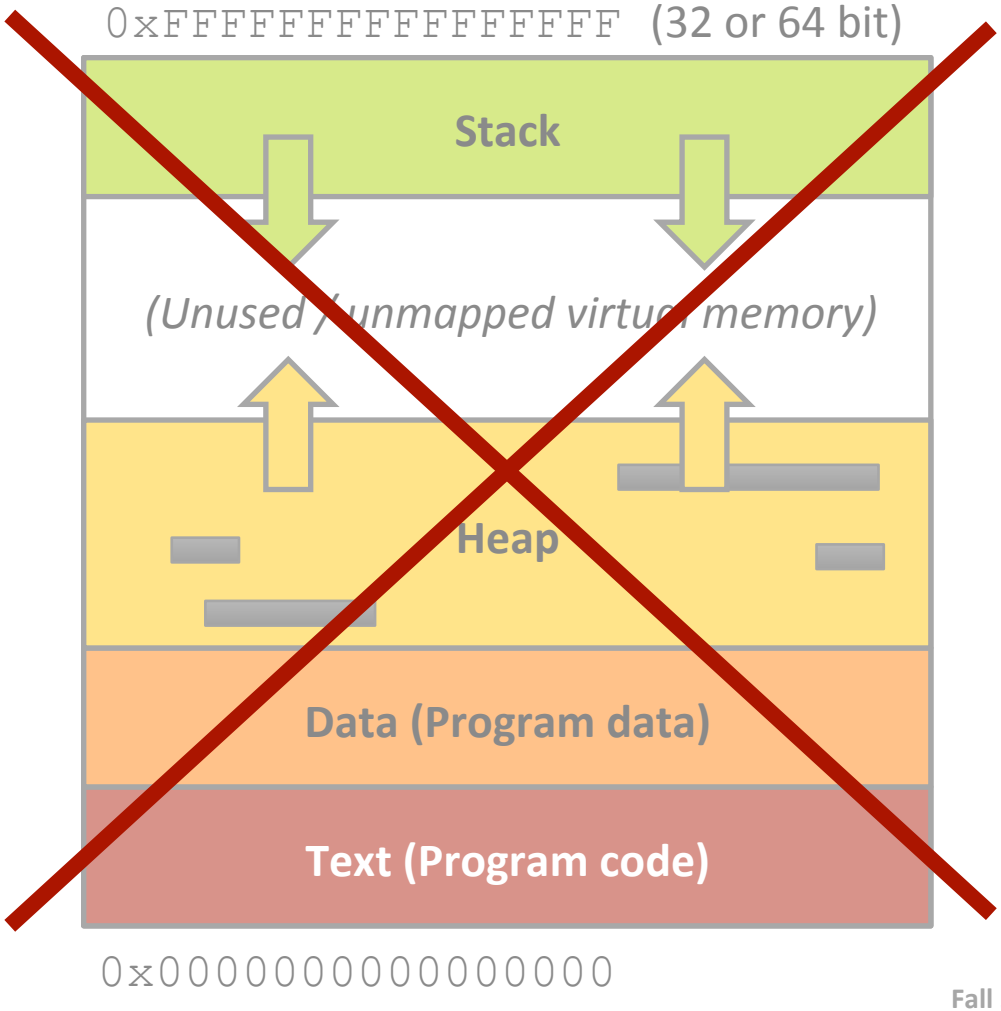
Memory Management

- `free()` deallocates blocks from the heap



Memory Management

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



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 4 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?

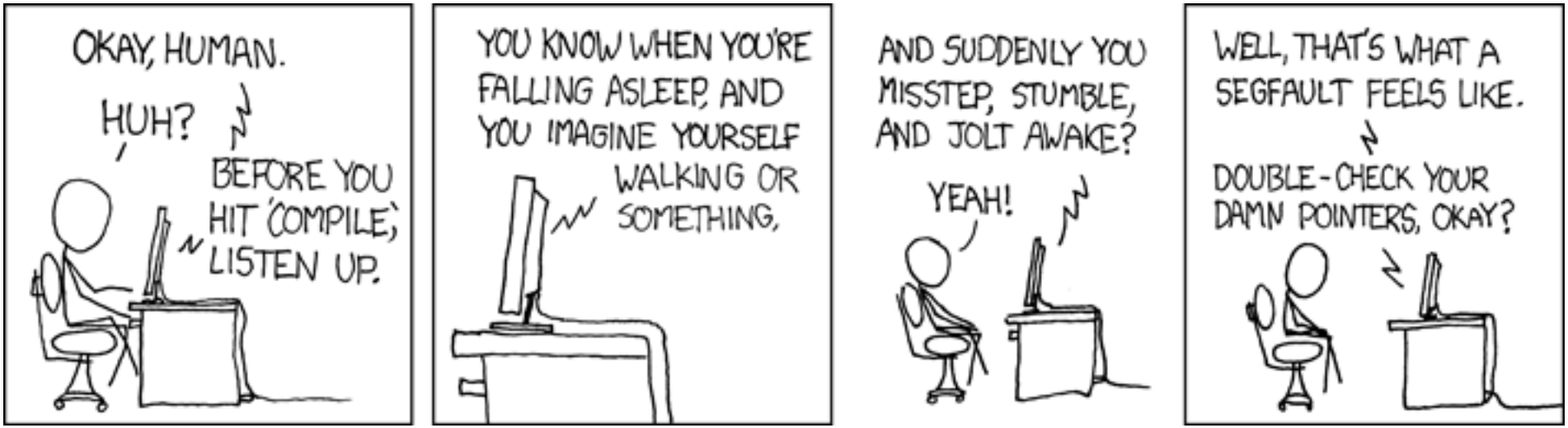
```
ptr = (char *) malloc(strlen(string_A));
strcpy(ptr, string_A);
```

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



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 deference 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