Computer Systems and Networks

ECPE 170 – University of the Pacific

C Programming

Lab Schedule

Activities

- **Today**
  - Intro to C Programming
  - Intro to Build Tools and Makefiles
- **Thurs**
  - **Lab 3 – C Programming**

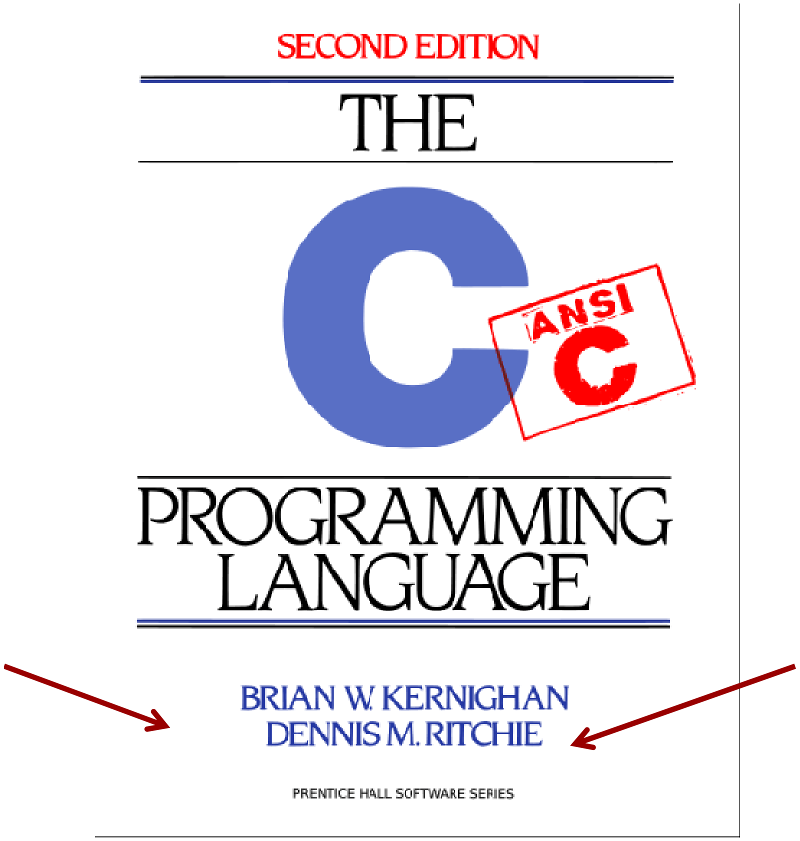
Assignments Due

- **Today**
  - **Lab Report for Lab 1 due by 11:59pm**
    - Submit via Sakai
- **Thurs**
  - **Lab Report for Lab 2 due by 11:59pm**
    - Submit via Mercurial

The First Person of the Day: Dennis Ritchie

- Creator of **C programming language**
- Co-creator of **Unix** (with Ken Thompson, Brian Kernighan, and others at AT&T 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

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;
}
```

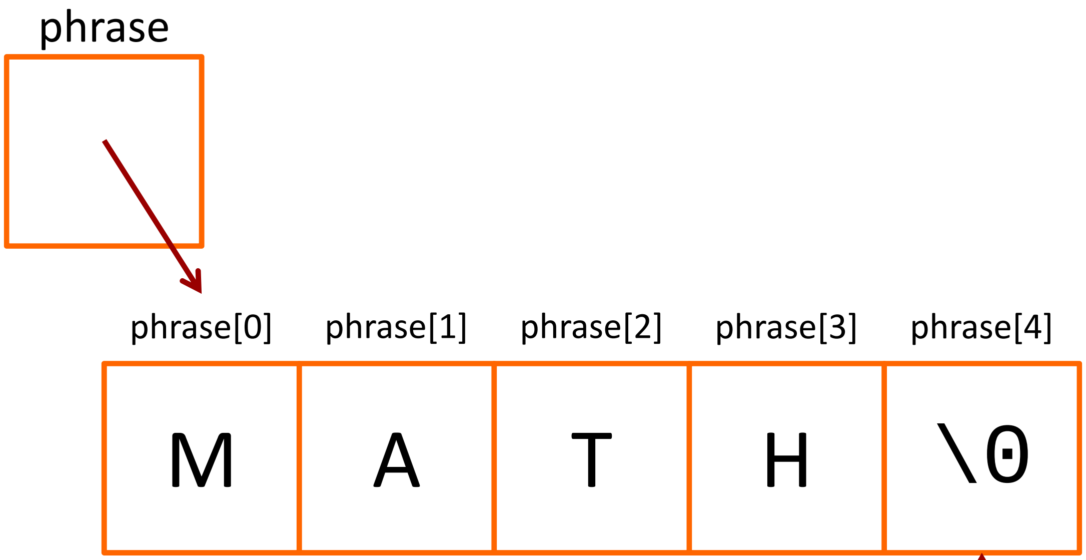
C-Strings (Arrays of Characters)

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

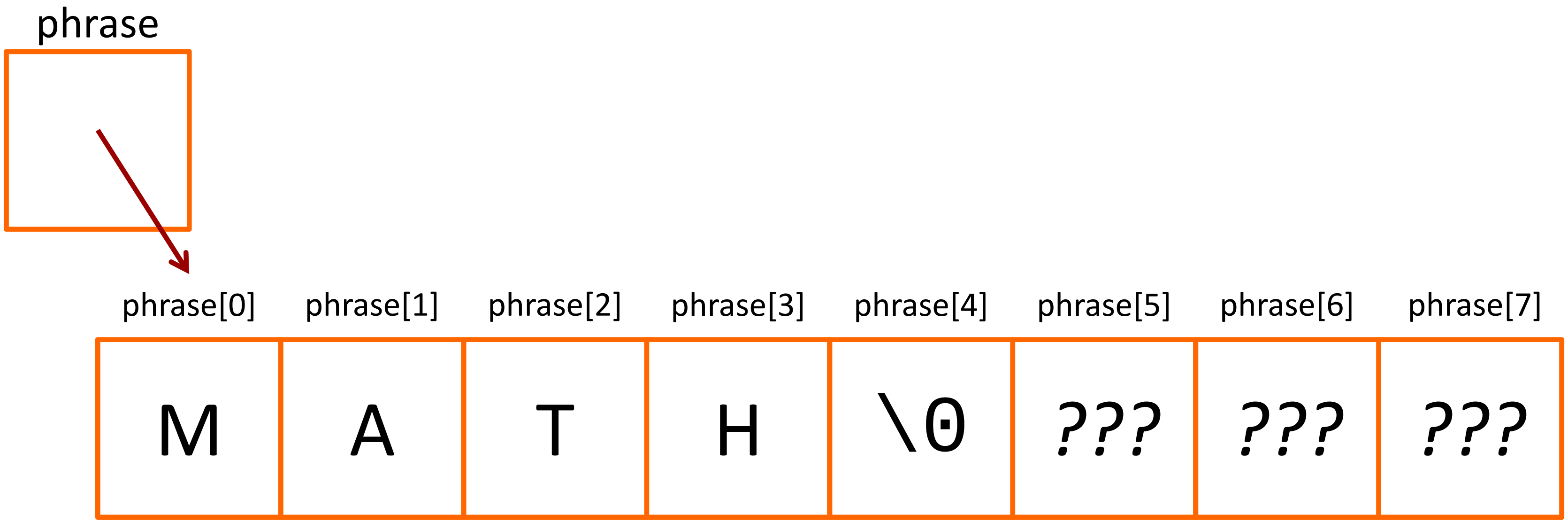
- `char phrase[]="Math";`



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);
```

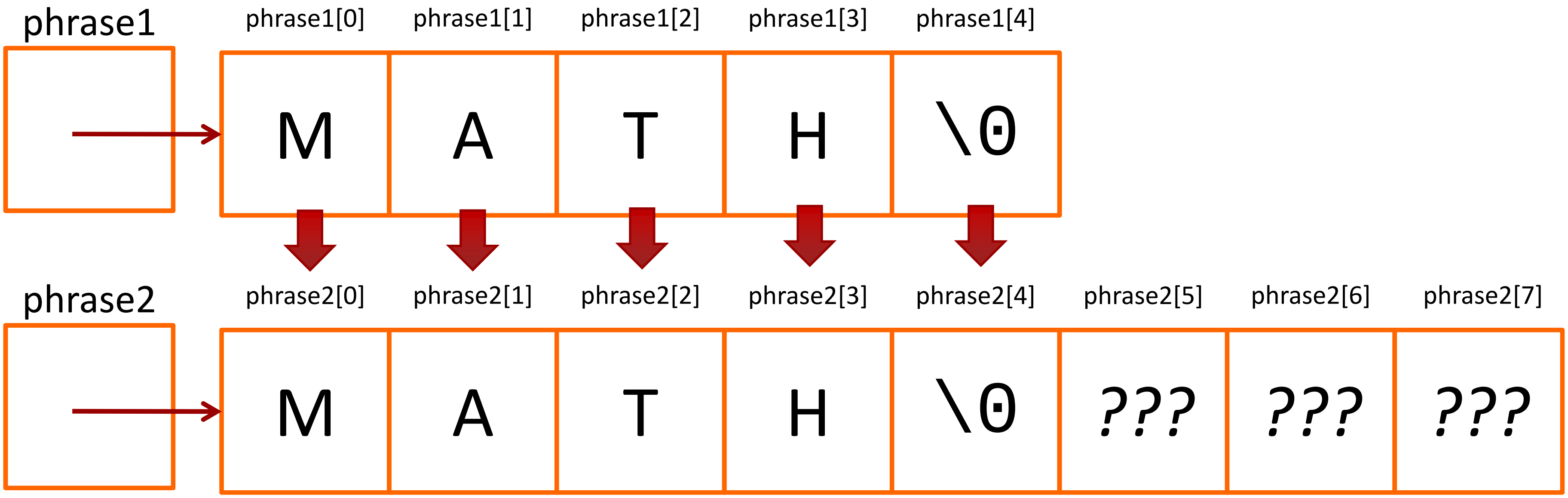
Prints until it reaches the `\0` character!

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);`**



phrase1

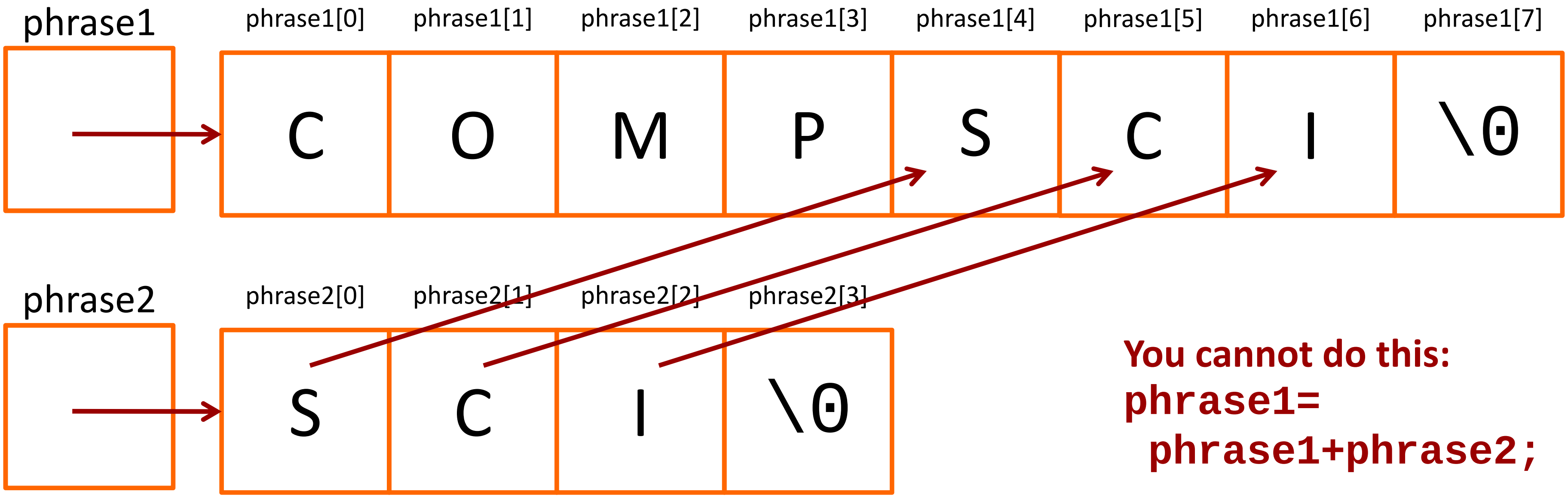
phrase1[0]	phrase1[1]	phrase1[2]	phrase1[3]	phrase1[4]
M	A	T	H	\0

phrase2

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);`**



You cannot do this:

```
phrase1=
  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:**

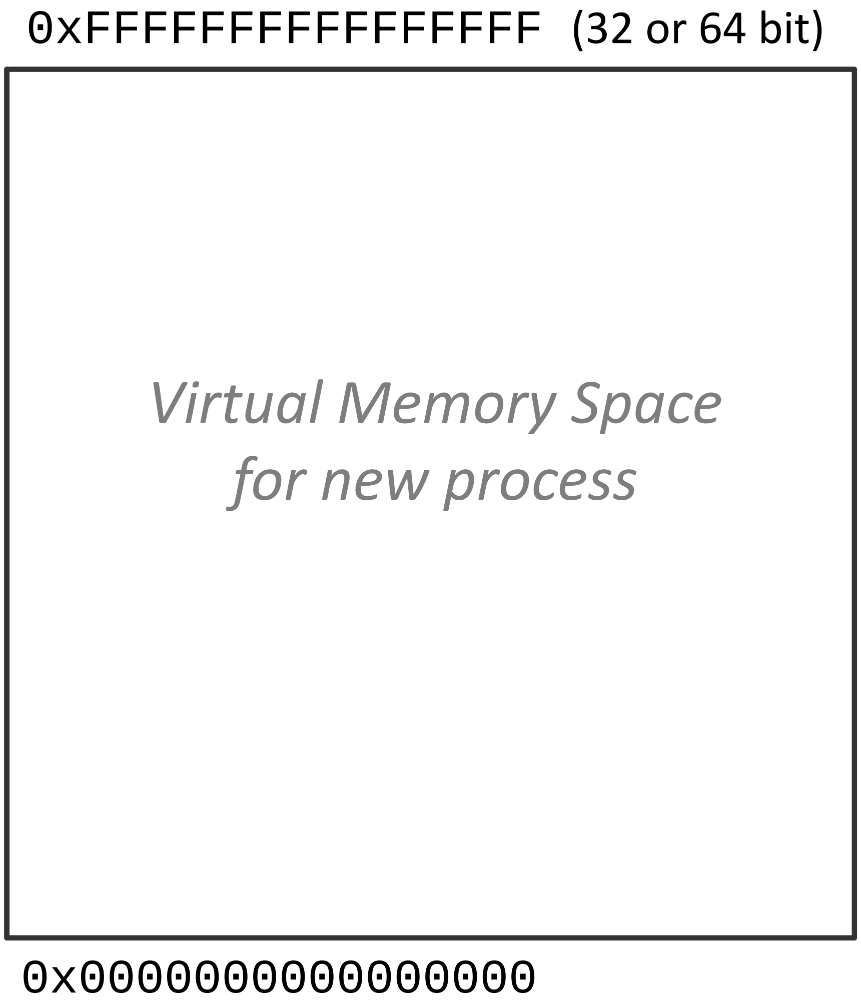
1. Call `malloc()` and request memory
2. `malloc()` checks existing heap size
   - Sufficient? Update bookkeeping to mark space as “used” and return address to your program
   - Insufficient?
     1. **Call operating system** via `brk()`/`mmap()` to grow the heap (plus a little extra for future requests)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



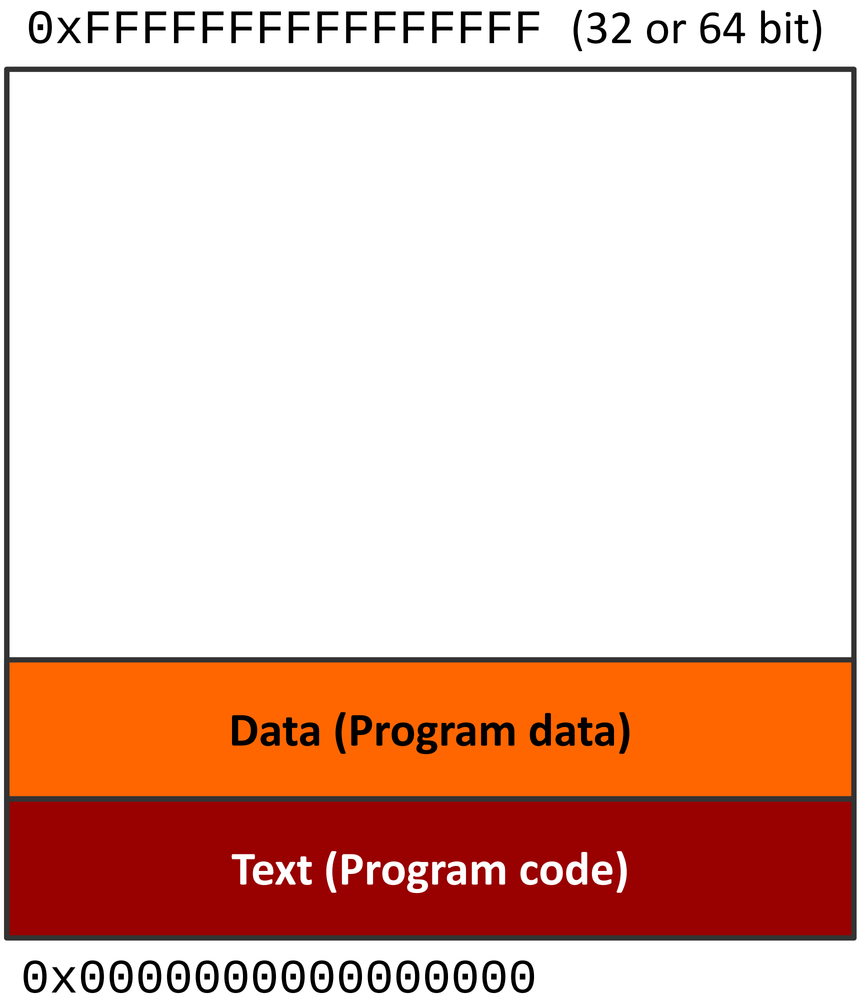
0xFFFFFFFFFFFFFFFF (32 or 64 bit)

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)

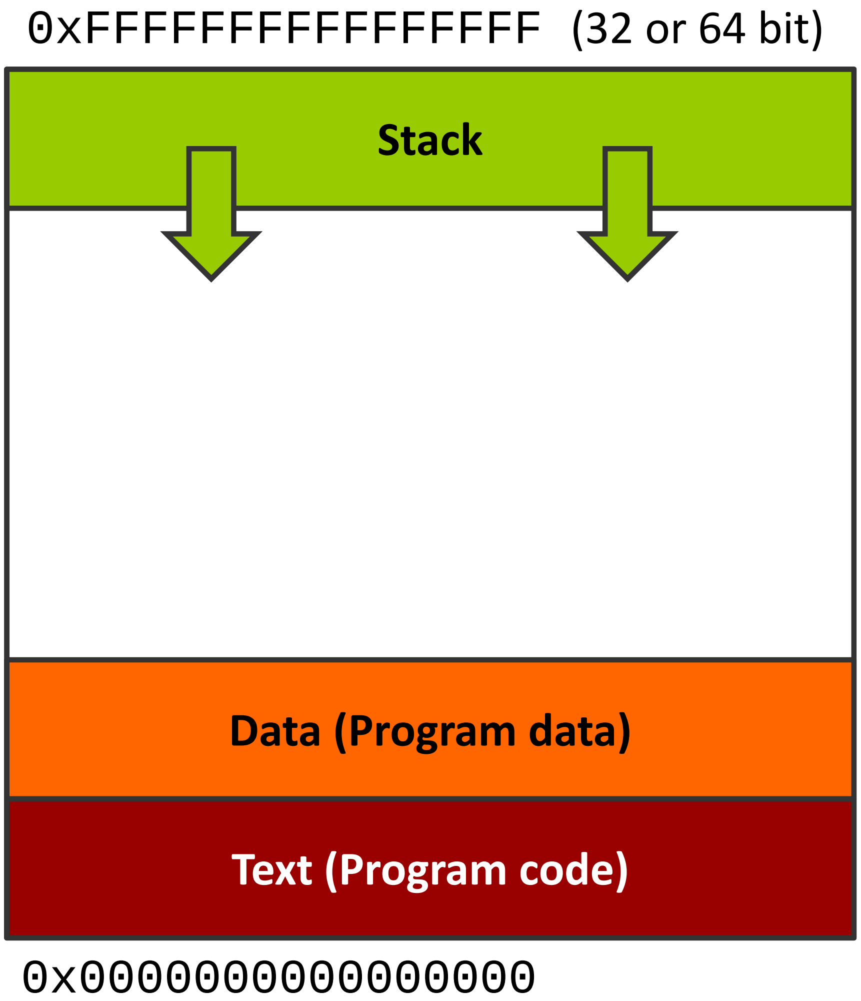
Data (Program data)

Text (Program code)

0x0000000000000000

Memory Management

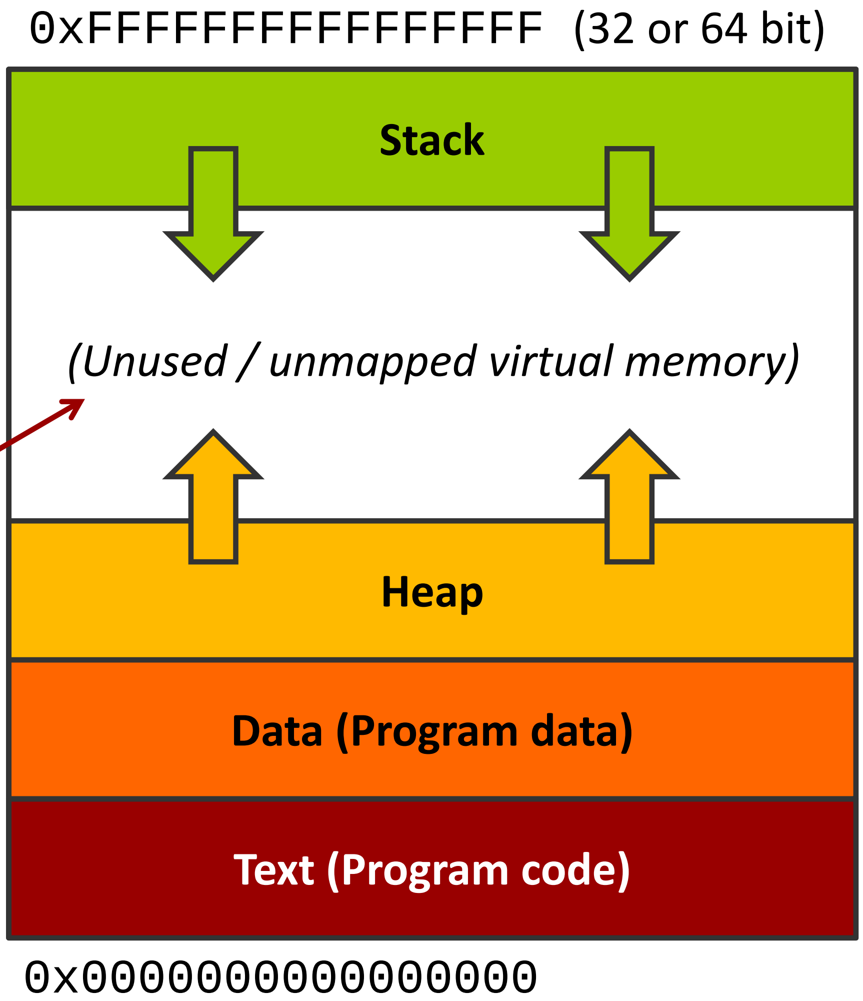
- **Stack** created to track program function calls and local variables



Memory Management

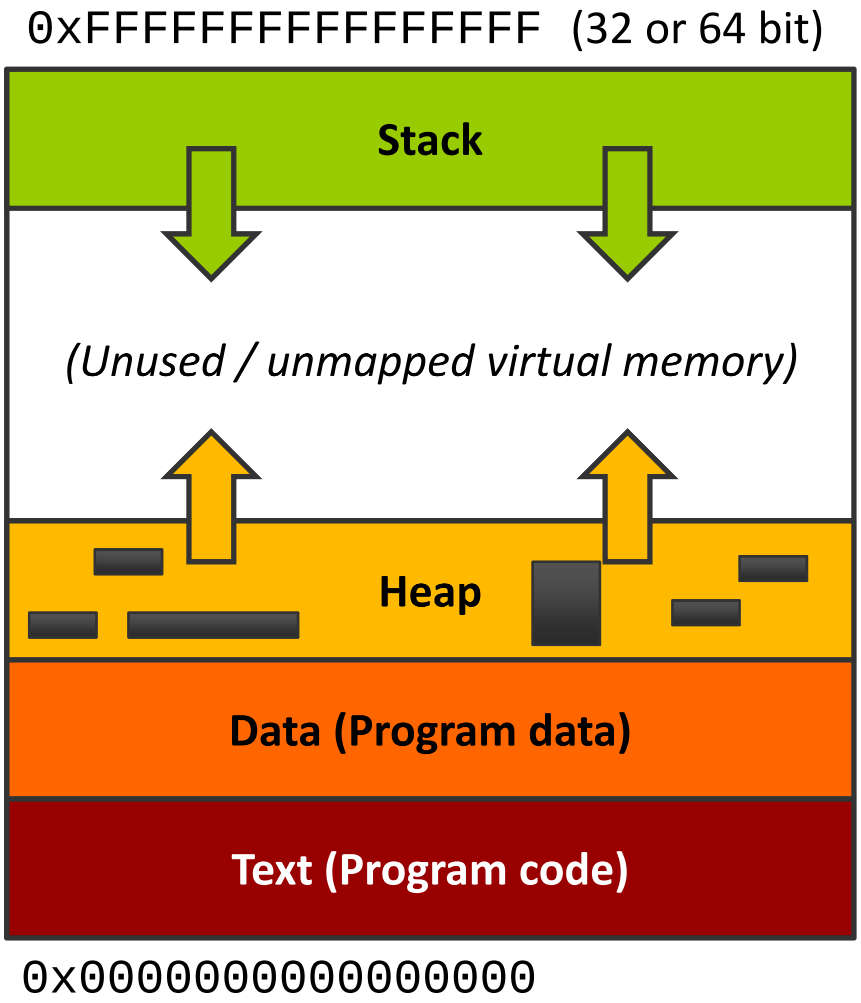
- **Heap** created to store dynamic memory from `malloc()`and related functions

- 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

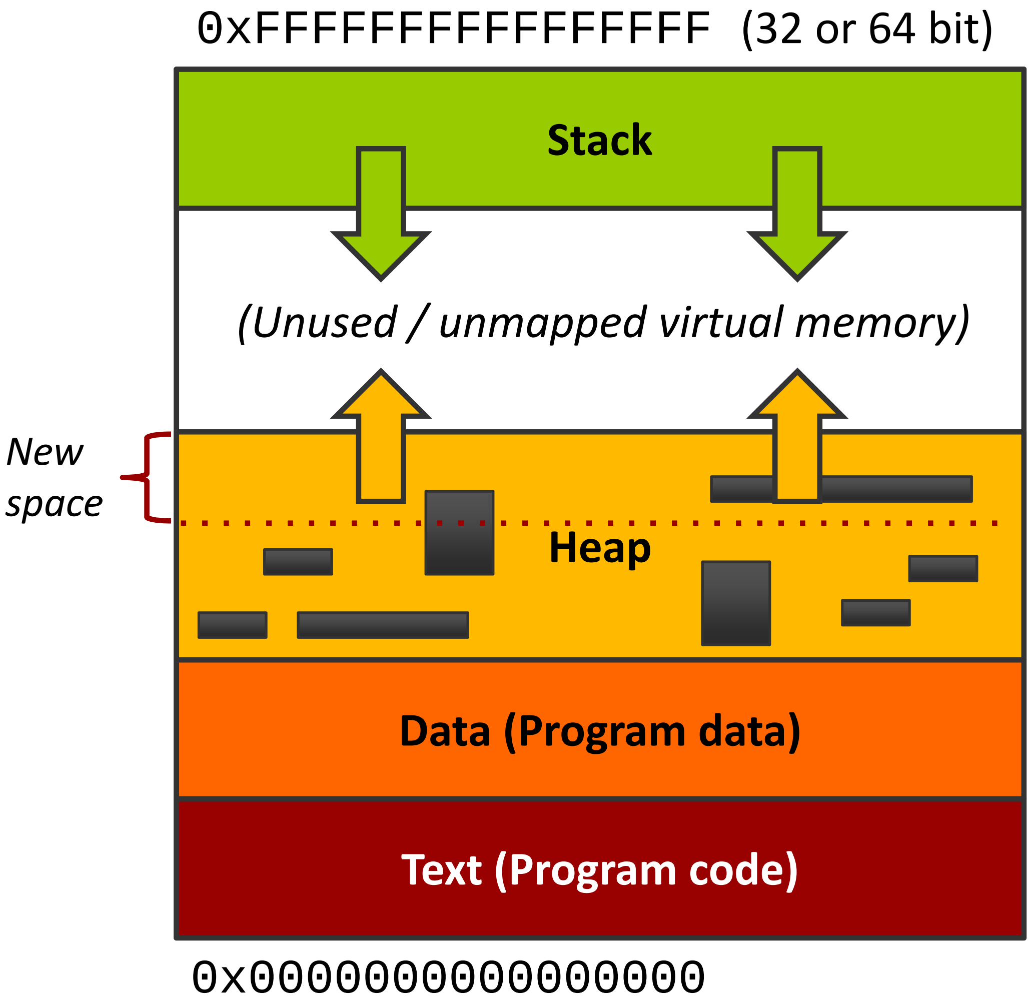
Memory Management

- 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

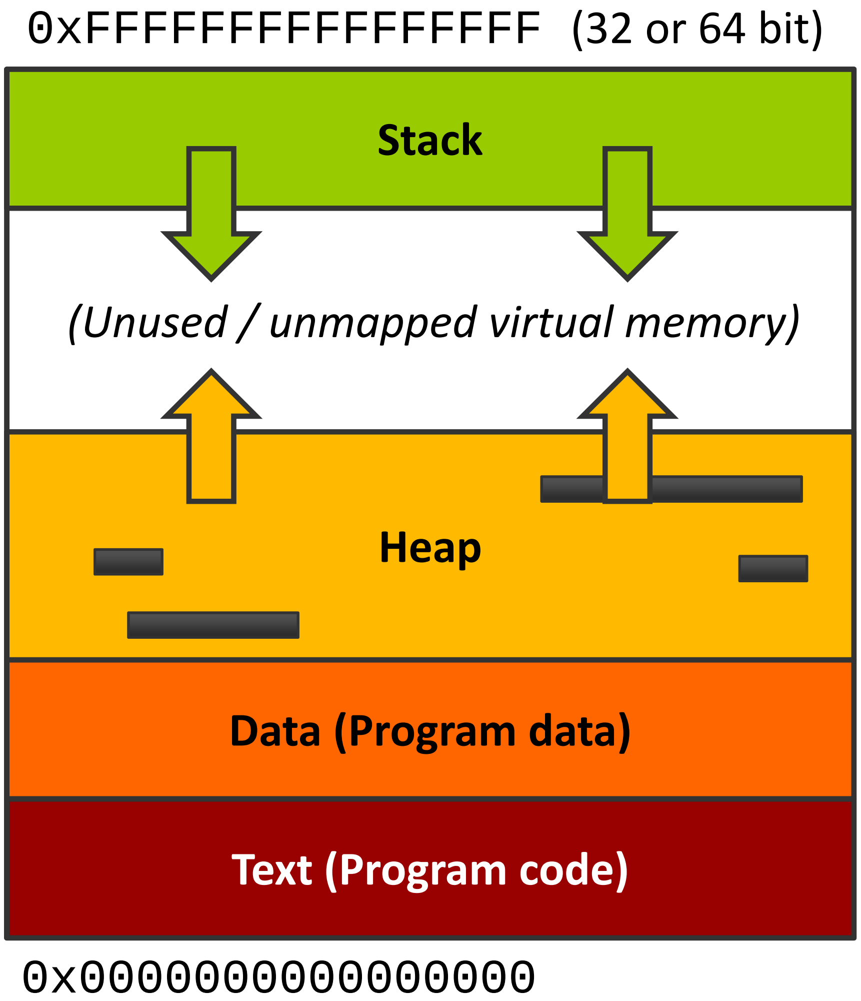
Memory Management

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



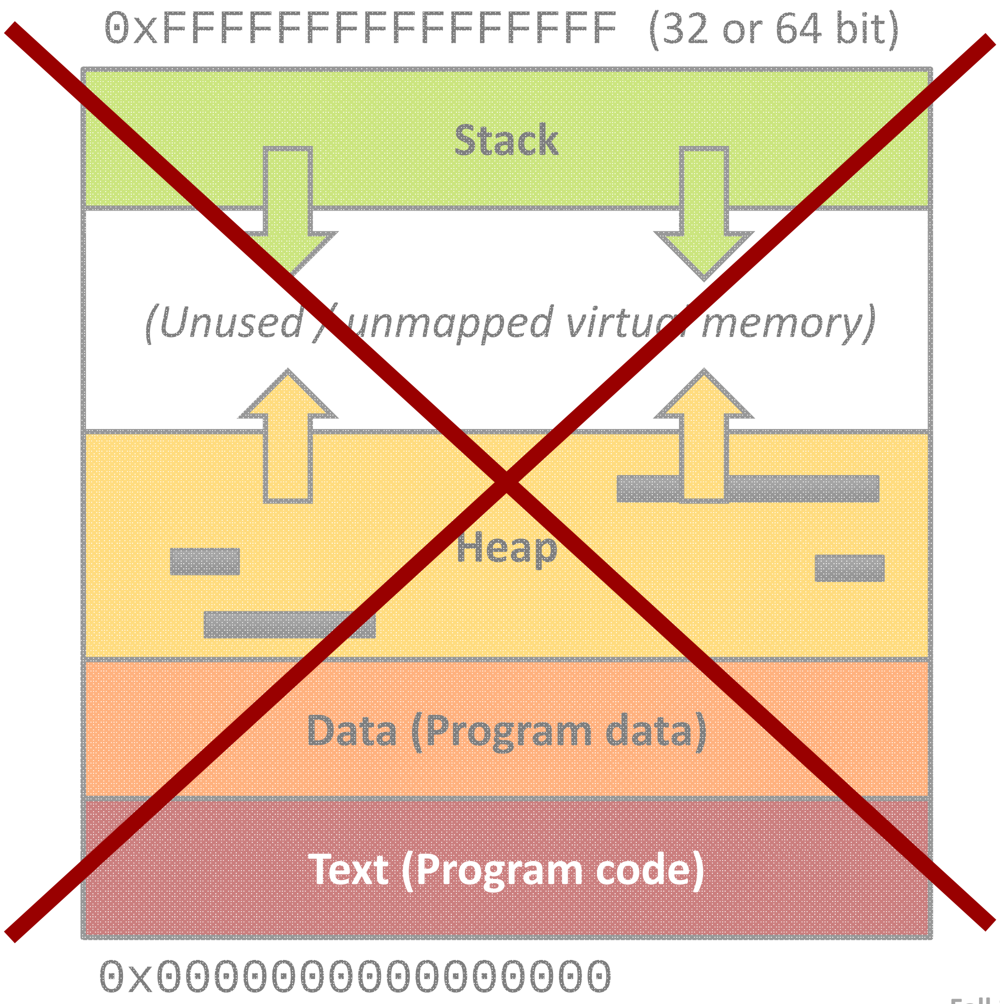
Memory Management

- `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?

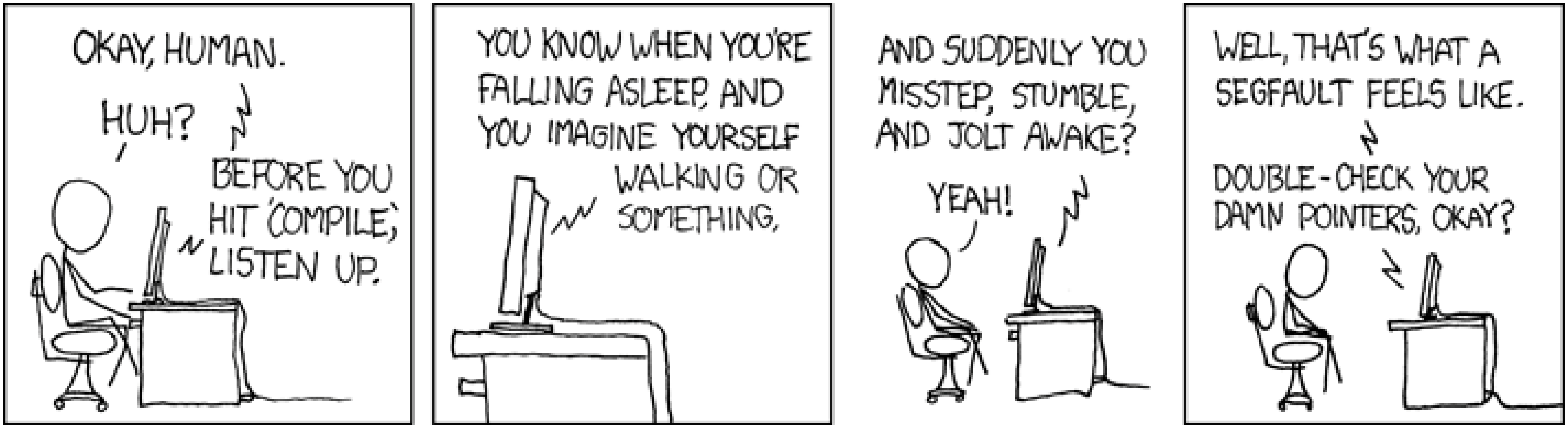
```
ptr = (char *) malloc(strlen(string_A));
strcpy(ptr, string_A);
```

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

Build Tools + Makefiles

The Other Person of the Day: Richard Stallman

- Founder of
  - GNU project – "GNU's not Unix"
  - Free Software Foundation
- Author
  - GNU C Compiler (GCC)
  - Emacs text editor
- GNU Manifesto
  1. Freedom to run a program for any purpose
  2. Freedom to study the mechanics of the program and modify it
  3. Freedom to redistribute copies
  4. Freedom to improve and change modified versions for public use

The Other Person of the Day: Richard Stallman

- "Steve Jobs, the pioneer of the computer as a jail made cool, designed to sever fools from their freedom, has died.

  As Chicago Mayor Harold Washington said of the corrupt former Mayor Daley, "I'm not glad he's dead, but I'm glad he's gone." Nobody deserves to have to die — not Jobs, not Mr. Bill, not even people guilty of bigger evils than theirs. But we all deserve the end of Jobs' malign influence on people's computing.

  Unfortunately, that influence continues despite his absence. We can only hope his successors, as they attempt to carry on his legacy, will be less effective."
  - Richard Stallman, 10/6/2011

Toolchain

```c
#include <stdio.h>

int main(void)
{
    printf("hello, world\n");
    return 0;
}
```

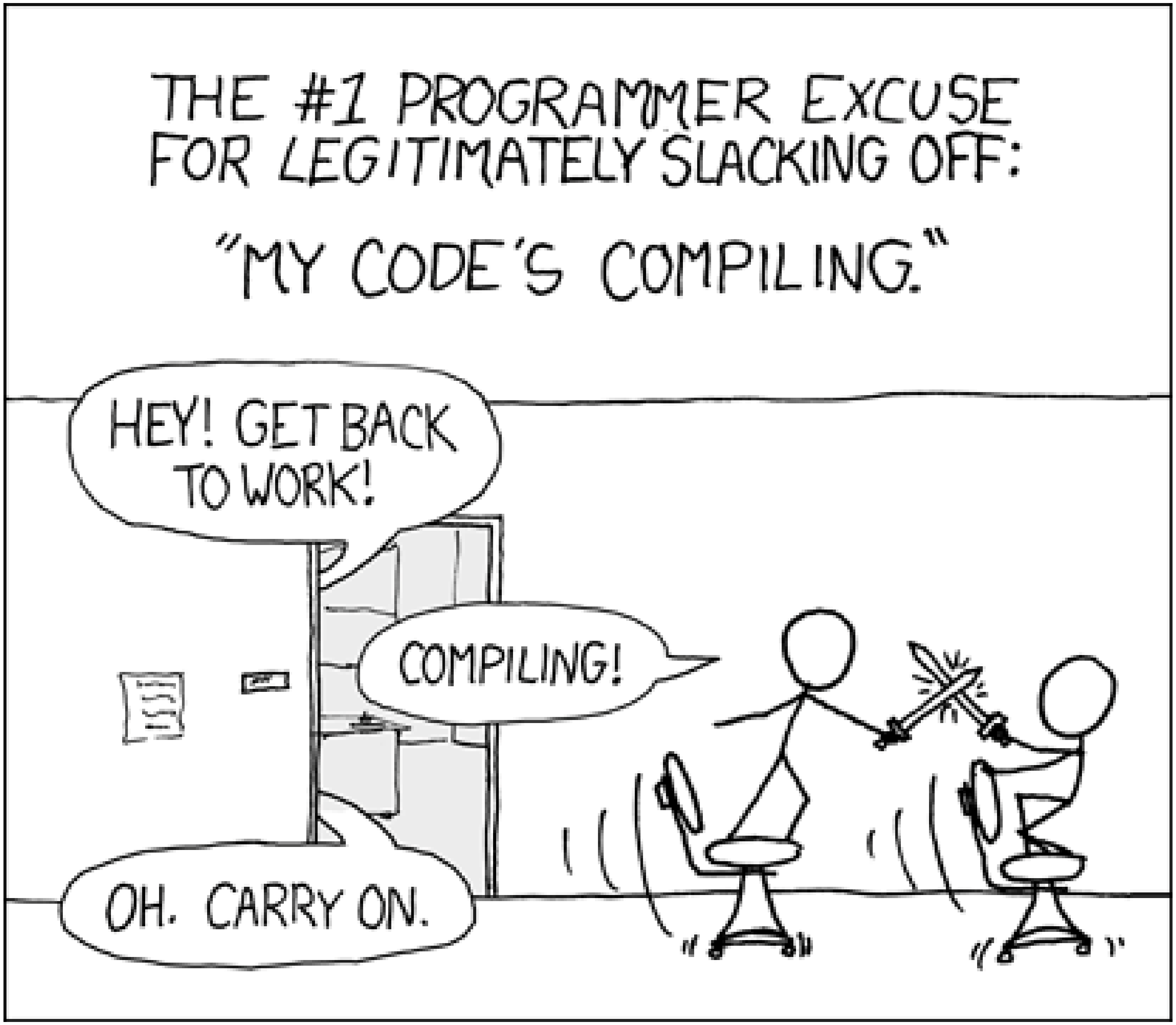
```
unix>  ./program
hello, world
```

Behind the Scenes

- **Motivating Question**
  - **What really happens between typing in the “Hello Word” program, and seeing the output on the console?**

Pre-Processor

- **Think of this as a "find and replace" wizard for your source code**
- **Include header files**
  - Literally insert .h file lines into .c file
- **Macro expansion**
  - Macro = fragment of C code
    - `#define IS_POSITIVE( _x ) ( _x > 0 )`
  - Preprocessor replaces macro with original definition in source code
- **Conditional compilation**
  - Include or exclude parts of the program
  - `#ifdef CONTROL`


THE #1 PROGRAMMER EXCUSE FOR LEGITIMATELY SLACKING OFF:
"MY CODE'S COMPILING."
HEY! GET BACK TO WORK!
COMPILING!
OH. CARRY ON.

Compiler

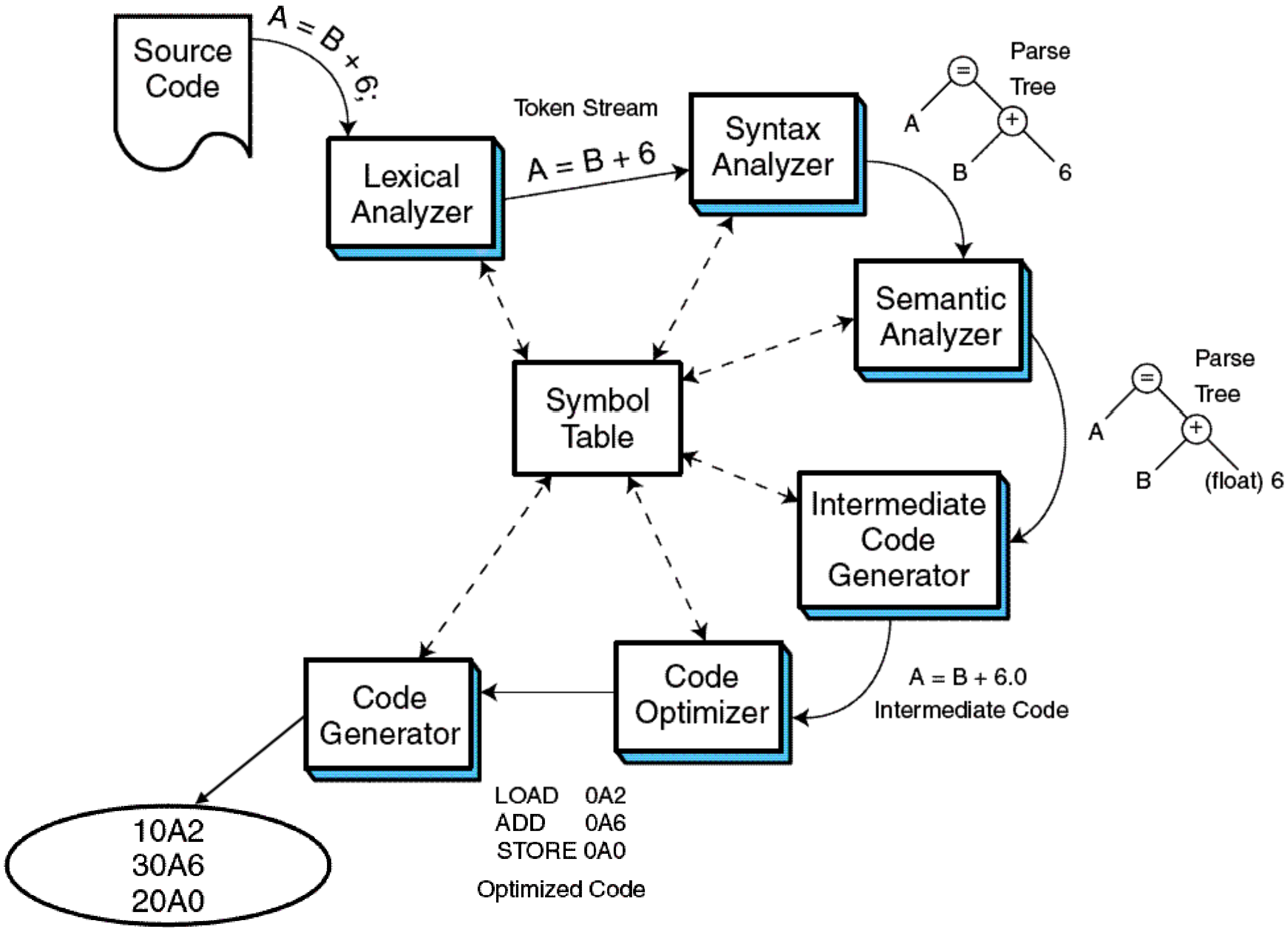
- Basic goal
  - Input: **High-level language source code**
  - Output: **Machine code** for processor family
- 6 steps to accomplish transformation
- Steps 1-3 – source code analysis:
  1. **Lexical analysis** extracts tokens, e.g., reserved words and variables
  2. **Syntax analysis** (parsing) checks statement construction
  3. **Semantic analysis** checks data types and the validity of operators

Compiler Operation

- Steps 4-6 – **Synthesis** phases:
  4. **Intermediate code generation** creates three address code ("fake assembly code") to facilitate optimization and translation
  5. **Optimization** creates (real) assembly code while taking into account architectural features that can make the code efficient
  6. **Code generation** creates binary code from the optimized assembly code

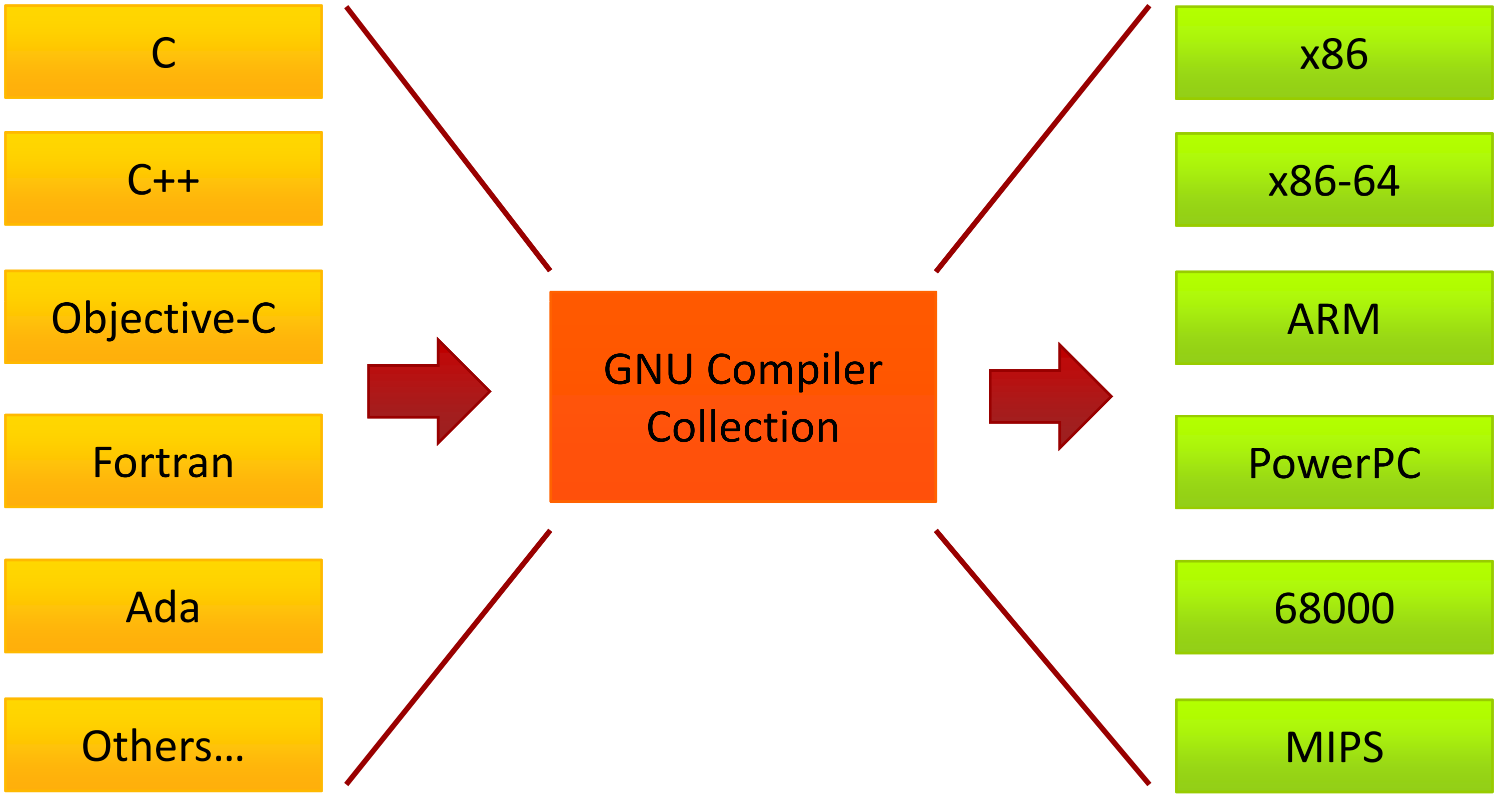
- We write these steps as separate modules
  - Benefit: Compilers can be written for various CPU architectures by rewriting only the last two modules

Compiler Operation



Why So Many Compilation Steps?

We don't *just* care about 1 language or 1 processor family!



C

C++

Objective-C

Fortran

Ada

Others…

GNU Compiler Collection

x86

x86-64

ARM

PowerPC

68000

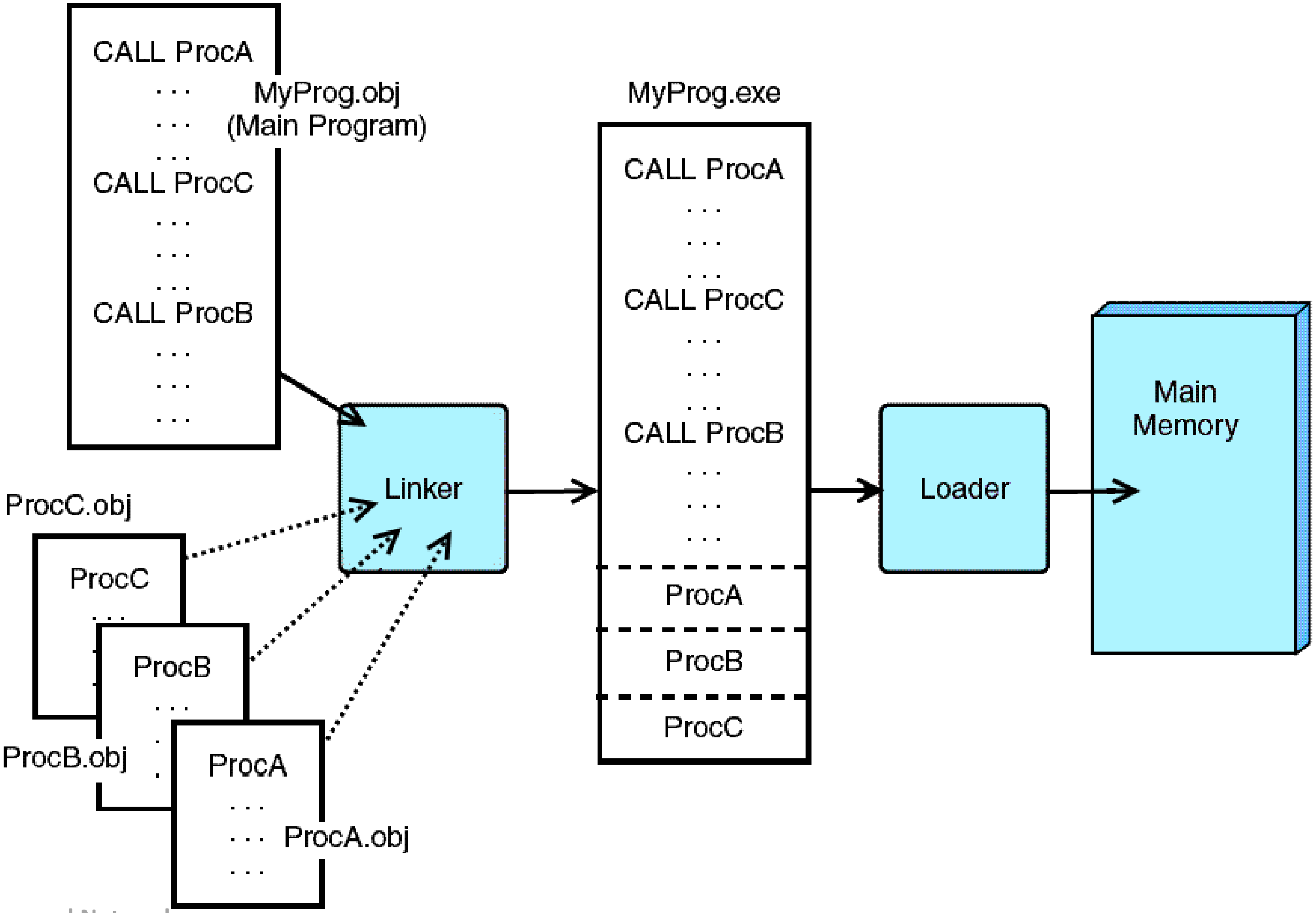
MIPS

(and many more!)

Linker

- Real programs are typically written with **multiple source files** and many subroutines
  - Each file is compiled separately
  - But we need some way to join everything together into a single executable file
- This is the job of the **linker** (aka "link editor")
  - Input – many files with binary machine code
  - Output – single file with all of the necessary binary machine code

Linker + Loader



Result: Program binary (saved on disk)

```
11011101010000001010000001101110101000
00010100000011011101010000001010000001
10111010100000010100000011011101010000
00101000000110111010100000010100000011
01110101000000101000000110111010100000
01010000001101110101000000101000000110
11101010000001010000001101110101000000
10100000011011101010000001010000001101
11010100000010100000011011101010000001
```

Shell / GUI

- User instructs computer to run program
  - Shell command?
  - Mouse / keyboard action in GUI?

Operating System

- Security: OK to run file?
- Memory management: Find space and create new virtual memory region for this program
- Filesystem: Retrieve program binary code from disk
- Loader: Place program binary code into memory
- Scheduler: Find CPU time for program to run
- Context switch – Program starts running

Makefiles – Lab 3

Makefile

- Goal: Build our program with one command:

```
unix>  make
```

- Challenge
  - Every program is different!
  - Different source files, different compilers / settings, different external libraries, etc…
- A **Makefile** is a **text file** that specifies how to build your program
  - The `make` utility reads the Makefile
  - You'll learn how this file works in Lab 3