CSC2/452 Computer Organization
Introduction

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URCS

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Outline

Introduction

The Long Journey to an Executable

Running a Program

What about Python, Java and JavaScript?

Administrivia

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Behold, a Program

```
 #include <stdio.h>

int main(void) {
  float PI = 3.14159265358979323846264338 32;

  printf("Hello, the value of pi is %f\n", PI);

  return 0;
}
```

Compile and Run It

To compile the code:

```
$ gcc -g hellopi.c
```

(The $ indicates the Unix shell prompt and is not part of the command.)

The output is an *executable binary*. You can run it as:

```
$ ./a.out
Hello, the value of pi is 3.141593
```

Inside a.out

```
$ hexdump -C a.out
 ...
00000690  20 00 55 48 8d 2d 26 07  20 00 53 41 89 fd 49 89  | .UH.-&. .SA..I.|
000006a0  f6 4c 29 e5 48 83 ec 08  48 c1 fd 03 e8 3f fe ff  |.L).H...H....?..|
000006b0  ff 48 85 ed 74 20 31 db  0f 1f 84 00 00 00 00 00  |.H..t 1.........|
000006c0  4c 89 fa 4c 89 f6 44 89  ef 41 ff 14 dc 48 83 c3  |L..L..D..A...H..|
000006d0  01 48 39 dd 75 ea 48 83  c4 08 5b 5d 41 5c 41 5d  |.H9.u.H...[]A\A]|
000006e0  41 5e 41 5f c3 90 66 2e  0f 1f 84 00 00 00 00 00  |A^A_..f.........|
000006f0  f3 c3 00 00 48 83 ec 08  48 83 c4 08 c3 00 00 00  |....H...H.......|
00000700  01 00 02 00 48 65 6c 6c  6f 2c 20 74 68 65 20 76  |....Hello, the v|
00000710  61 6c 75 65 20 6f 66 20  70 69 20 69 73 20 25 66  |alue of pi is %f|
 ...
```

This is a *hexdump*, a convenient way of viewing binary data. Four columns on each line:

- Offset (in file, 0: beginning)
- 8 bytes of data in hexadecimal
- 8 bytes of data in hexadecimal
- 16 bytes of data, printable as-is, while non-printable is '.'

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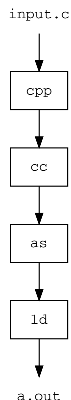
gcc

- gcc is a *compiler driver*
- It orchestrates the execution of many programs:
  - the C preprocessor (cpp)
  - the C compiler proper (cc)
  - the assembler (as)
  - the (static) linker (ld)
- You can invoke these programs individually
  - But it's more convenient to let gcc drive them



The Preprocessor (for C programs)

```
$ cpp hellopi.c > hellopi.i
 ... some 700+ lines not shown ...

int main(void) {
  float PI = 3.1415926535897932384626433832;

  printf("Hello, the value of pi is %f\n", PI);

  return 0;
}
```

- The preprocessor handles lines starting with # (e.g. `#include`).
- Output is a C file without `#include`
  - and other preprocessor *directives*
- The 700 plus lines not shown above come from `#include <stdio.h>`

The Compiler

```
$ cc -S hellopi.c
```

(The -S forces cc to produce assembly code instead of a binary)

```
        .file   "hellopi.c"
        .text
        .section        .rodata
.LC1:
        .string "Hello, the value of pi is %f\n"
        .text
        .globl  main
        .type   main, @function
main:
.LFB0:
        pushq   %rbp
        movq    %rsp, %rbp
        subq    $16, %rsp
        movss   .LC0(%rip), %xmm0
        movss   %xmm0, -4(%rbp)
        cvtss2sd        -4(%rbp), %xmm0
        leaq    .LC1(%rip), %rdi
        movl    $1, %eax
        call    printf@PLT
        movl    $0, %eax
        leave
        ret
        .section        .rodata
        .align 4
.LC0:
        .long   1078530011
```

How to Read Assembly Language Programs

- Assembly language programs are line-based
- Lines beginning with a '.' are assembler *directives*.

```
        .file   "hellopi.c"
        .text
        .section        .rodata
.LC1:
        .string "Hello, the value of pi is %f\n"
```

- Lines ending with a ':' are convenience labels for addresses (e.g. `.LC1:` above)
  - I.e. the assembler converts them to addresses so you don't have to
  - Note that directives DO NOT end with a ':', nor do labels have to start with a '.' (e.g. `main`)
- All other lines specify instructions

Instructions in x86 assembly

- Different assemblers have different syntax for the same CPU instruction
- `as` uses AT&T syntax
  - Source operands are at beginning
  - Destination operands are at end

```
subq $16, %rsp
movss .LC0(%rip), %xmm0
```

- Operands follow
  - Constant operands: `$16`
  - Register operands: `%rsp`, `%xmm0`, `%rip`
  - Address operands: `.LC0(%rip)`
- Different processors will have different instruction sets
  - x86, ARM, PowerPC, RISC-V, etc.
  - Assembly program for one processor *will not* run on another processor

The Assembler

- The assembler converts the output of the compiler to an object file (machine code).
  - Object files are not directly executable
- Not very friendly to view, so let's look at a listing file
  - Obtained using `as -adhln hellopi.s`

An assembly listing for hellopi.c

```
  1                              .file   "hellopi.c"
  2                              .text
  3                              .section        .rodata
  4                      .LC1:
  5 0000 48656C6C                .string "Hello, the value of pi is %f\n"
  5      6F2C2074
  5      68652076
  5      616C7565
  5      206F6620
  6                              .text
  7                              .globl  main
  9                      main:
 10                      .LFB0:
 11 0000 55                      pushq   %rbp
 12 0001 4889E5                  movq    %rsp, %rbp
 13 0004 4883EC10                subq    $16, %rsp
 14 0008 F30F1005                movss   .LC0(%rip), %xmm0
 14      00000000
 15 0010 F30F1145                movss   %xmm0, -4(%rbp)
 15      FC
 16 0015 F30F5A45                cvtss2sd        -4(%rbp), %xmm0
 16      FC
 17 001a 488D3D00                leaq    .LC1(%rip), %rdi
 17      000000
...
```

Object files

- Usually an object file correspond to a single C file
  - Multiple C files lead to multiple object files
- Object files are incomplete
- One: some data addresses are unknown
  - The 000000 indicate space left for an address to be filled in later
  - Final executable binary decides placement of multiple object files

```
14 0008 F30F1005                movss   .LC0(%rip), %xmm0
14      00000000
```

- Two: Some functions may live in different C files and so their addresses are unknown

```
23 0026 E8000000                call    printf@PLT
23      00
```

The (Static) Linker

```
$ ld hellopi.o ...
```

- The static linker combines all the object files to form a single binary
  - static means compile-time
  - there is also a dynamic linker which is used at run-time
- It fills in nearly all addresses
  - the ones it leaves unfilled are filled by the dynamic linker and loader just before the program runs
  - this happens if a function is in a shared object (similar to Windows DLLs)
- Shared objects are objects that are common to all programs on the system
  - you can avoid shared objects (called static linking), but your binary size will increase

Disassembler

```
$ objdump -S a.out

 ...
000000000000064a <main>:
 64a:	55                   	push   %rbp
 64b:	48 89 e5             	mov    %rsp,%rbp
 64e:	48 83 ec 10          	sub    $0x10,%rsp

 652:	f3 0f 10 05 ca 00 00 	movss  0xca(%rip),%xmm0
 659:	00
 65a:	f3 0f 11 45 fc       	movss  %xmm0,-0x4(%rbp)

 65f:	f3 0f 5a 45 fc       	cvtss2sd -0x4(%rbp),%xmm0
 664:	48 8d 3d 99 00 00 00 	lea    0x99(%rip),%rdi
 66b:	b8 01 00 00 00       	mov    $0x1,%eax
 670:	e8 ab fe ff ff       	callq  520 <printf@plt>

 675:	b8 00 00 00 00       	mov    $0x0,%eax
 67a:	c9                   	leaveq

 67b:	c3                   	retq
 ...
```

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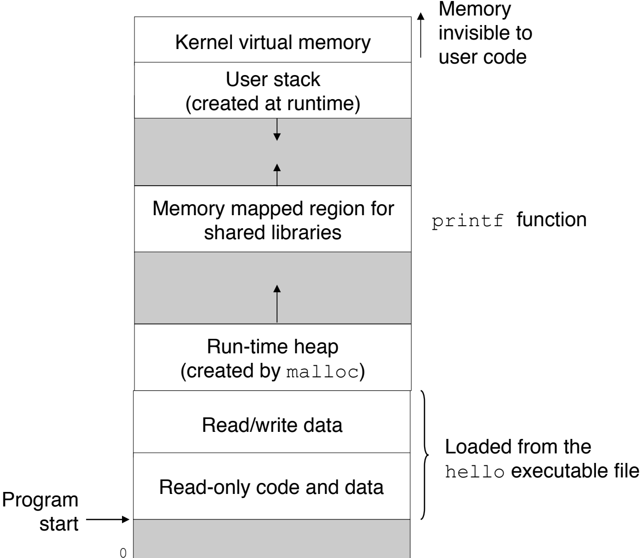
The (Dynamic) Linker and Loader

```
$ ./a.out
```

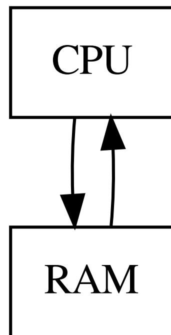
- After you type `./a.out` but before it starts running:
  - it must be loaded into memory
  - all shared objects must be linked in
  - the processor must be instructed where to start executing
- This is the job of the dynamic linker and loader
  - Usually one program on Linux, `ld.so`

Memory Layout of a Program



The Processor

- For now, we'll treat the processor as box
- It reads instructions and data from memory (also a box)
- Performs operations on data specified by the instructions
- Stores the data back into memory
- This is the "von Neumann" model of computation
  - After John Von Neumann who wrote a report about it in 1945
  - We will read this report!



The Operating System

- There are many programs running on your computer
  - Each "believes" it is running alone
  - Illusion of having CPU and RAM to itself
- This illusion is created by the CPU and managed by the *operating system*
  - Loosely speaking, Linux, Windows, macOS X are all operating systems
- The operating system is responsible for:
  - Mediating access to the hardware (through drivers)
  - Protecting programs from each other
  - Protecting users from each other
  - Managing resources such as disks, memory, etc.
  - Lots of other responsibilities (sign up for CSC256)

What did the CPU do?

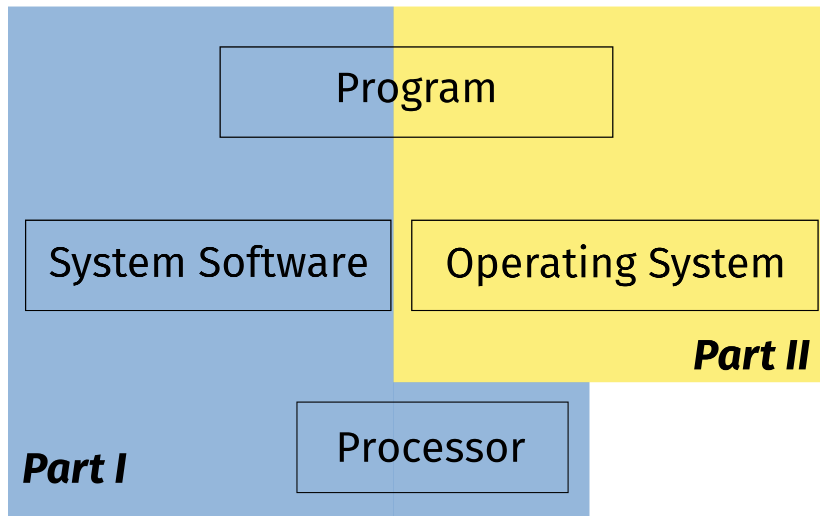
```
$ perf stat -e instructions ./a.out
Hello, the value of pi is 3.141593

 Performance counter stats for './a.out':

           662,172      instructions

       0.001168841 seconds time elapsed
```

- The Linux `perf` command gives you lots of statistics about CPUs and programs (called performance counters)
- `main` was about 10 instructions, where did more than half-a-million instructions come from?
- How fast is this processor (instructions/second)?

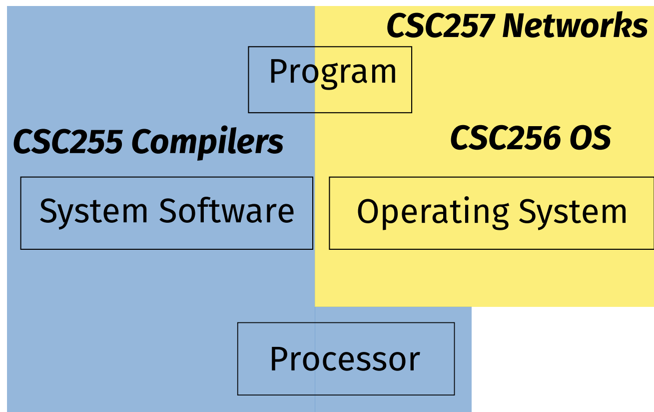
Thinking about System Design

- Why build separate programs (`cc`, `as`, `ld`)?
  - Think about which programs need to change if the processor changes
- Are there other designs other than von Neumann computers?
  - Yes, I research them
- Why do we have different processors?
  - Intel/AMD for desktops/laptops
  - ARM for mobile phones
- Why was Unix such a success?
  - Turing Award in 1983!
  - Still being used nearly 50 years later!

The Big Picture for this Course



What next?



CSC251 Advanced Computer Architecture

ECE112 Logic Design

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Interpreted Languages

- Some languages do not compile to a binary
  - No assembler
  - Language-specific linkers and loader (but these are usually absent)
- Interpreters
  - "CPUs in software" (sometimes called virtual machines)
  - It's very easy to write an interpreter...
- Three notable languages that do this:
  - Python (compiles to a *stack machine* bytecode)
  - Java (also compiles to bytecode)
  - JavaScript (originally not compiled, but nearly all browsers do just-in-time (JIT) compilation)
- Not our focus in this course

Why focus on C?

- Old systems language
  - Invented in 1972 at AT&T Bell Labs
  - Used to write the Unix *kernel* (the core of the operating system)
- Low-level language
  - But not as low-level as assembler
- "Portable" assembler (not specific to a processor)
  - Usually straightforward mapping to assembler
  - (Mostly) easy to understand how the translation from C to assembler is done
- Tremendous impact
  - Both positive and negative
  - Should you write new programs in C?

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People

- Instructor: Dr. Sreepathi Pai
  - E-mail: sree@cs.rochester.edu
  - Office: Wegmans 3409
  - Office Hours: Mondays and Wednesdays 16:40 to 17:45 (i.e. after class)
- TAs:
  - Nisarg Ujjainkar
  - Suumil Roy
  - Yuesong Huang
  - Chengkai Kang
  - Zihao Lin
  - Simon Schiller
  - Phuong Vu

Places

- Class: Wegmans 1400
  - M,W 1525–1640
- Course Website
  - https://cs.rochester.edu/~sree/courses/csc-252-452/fall-2022/
- Blackboard
  - Announcements, Assignments, Discussions, etc.
- Sign up for a CSUG Account if you don't have one:
  - https://accounts.csug.rochester.edu/
  - Required for assignments!

References

- One textbook
  - Computer Systems: A Programmers Perspective, 3/ed, Bryant and O'Hallaron
  - DO NOT LEARN C FROM THIS BOOK
- This course requires a lot of reading!
  - Books have been placed on reserve
  - Online materials will be linked throughout course
- See Blackboard for information on accessing Reserves

Defined Readings

- Required by The College for 2xx courses
- An hour per week of independent reading
- I will assign material that are not textbooks
  - Manuals
  - Papers
  - Articles
- These will make you a better systems programmer and computer scientist
- I will assume you have read these – you will need them for your assignments

Grading

- Homeworks: 10%
- Assignments: 60% (4–6)
- Exam: 15% (midterm) + 15% (final)
- Graduate students should expect to read a lot more, and work on harder problems.

There is no fixed grading curve. Assume absolute grading. Course website has details.
See course website and syllabus for other details.

Academic Honesty

- Unless explicitly allowed (e.g. teams), you may not show your code to other students
- You may discuss, brainstorm, etc. with your fellow students but all submitted work must be your own
- All help received must be acknowledged in writing when submitting your assignments and homeworks
- All external code you use must be clearly marked as such in your submission
  - Use a comment and provide URL if appropriate
- If in doubt, ask the instructor

All violations of academic honesty will be dealt with strictly as per UR's Academic Honesty Policy.

References and Next Week

- Read chapter 1 of the textbook for today's lecture
- Read chapter 2 of the textbook for next week's lecture
- Acknowledgements:
  - Program memory layout figures from the textbook