Lecture Participation Poll #25

Log onto pollev.com/cse374
Or
Text CSE374 to 22333

Lecture 25: Assembly

CSE 374: Intermediate Programming Concepts and Tools

Administrivia

Decriminalizing Our College Campuses
Date: **Thursday, December 3, 2020**

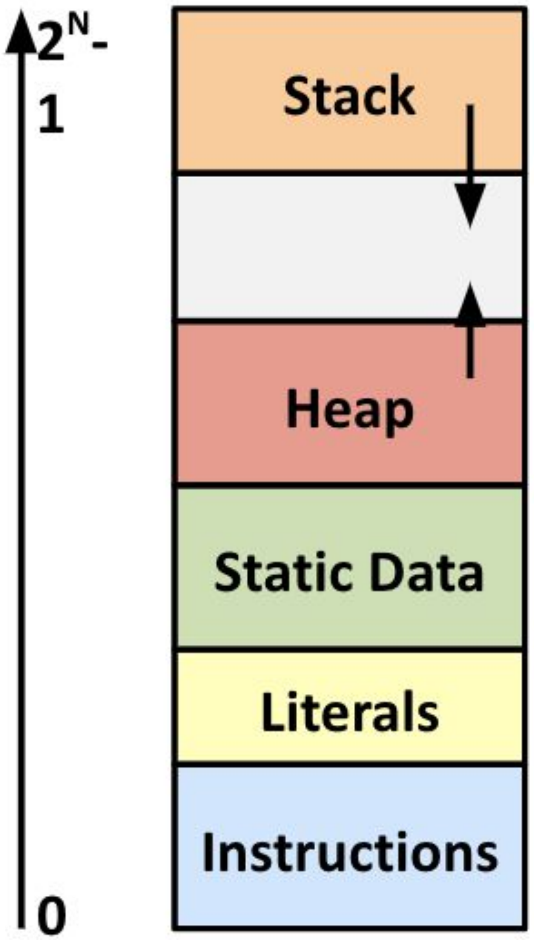
Time: **6-8 pm**
Location: **Zoom link will be emailed to everyone who RSVPs**
RSVP link: https://forms.gle/5FSZQsFTgAaYKUh56

- HW 4 posted -> Extra credit due date Thursday Dec 3rd
- HW 5 (final HW) coming later today
- HW 6 extra credit releasing next week
- 2 more exercises coming – 1 later today, 1 next week
- Final review assignment will release last week of quarter
- **End of quarter due date Wednesday December 16th @ 9pm**

THANK YOU FOR YOUR PATIENCE

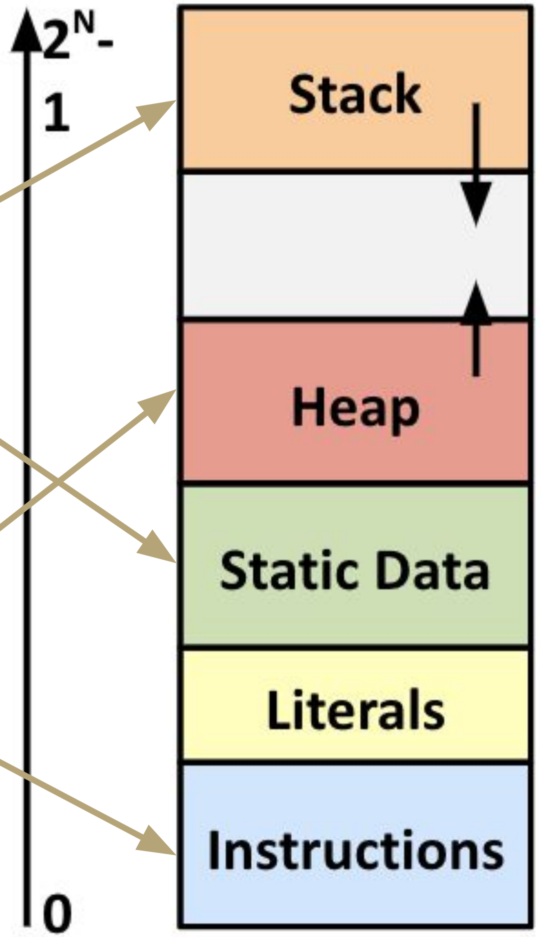
Review: General Memory Layout

- Stack
  - Local variables (procedure context)
- Heap
  - Dynamically allocated as needed
  - malloc(), calloc(), new, …
- Statically allocated Data
  - Read/write: global variables (Static Data)
  - Read-only: string literals (Literals)
- Code/Instructions
  - Executable machine instructions
  - Read-only

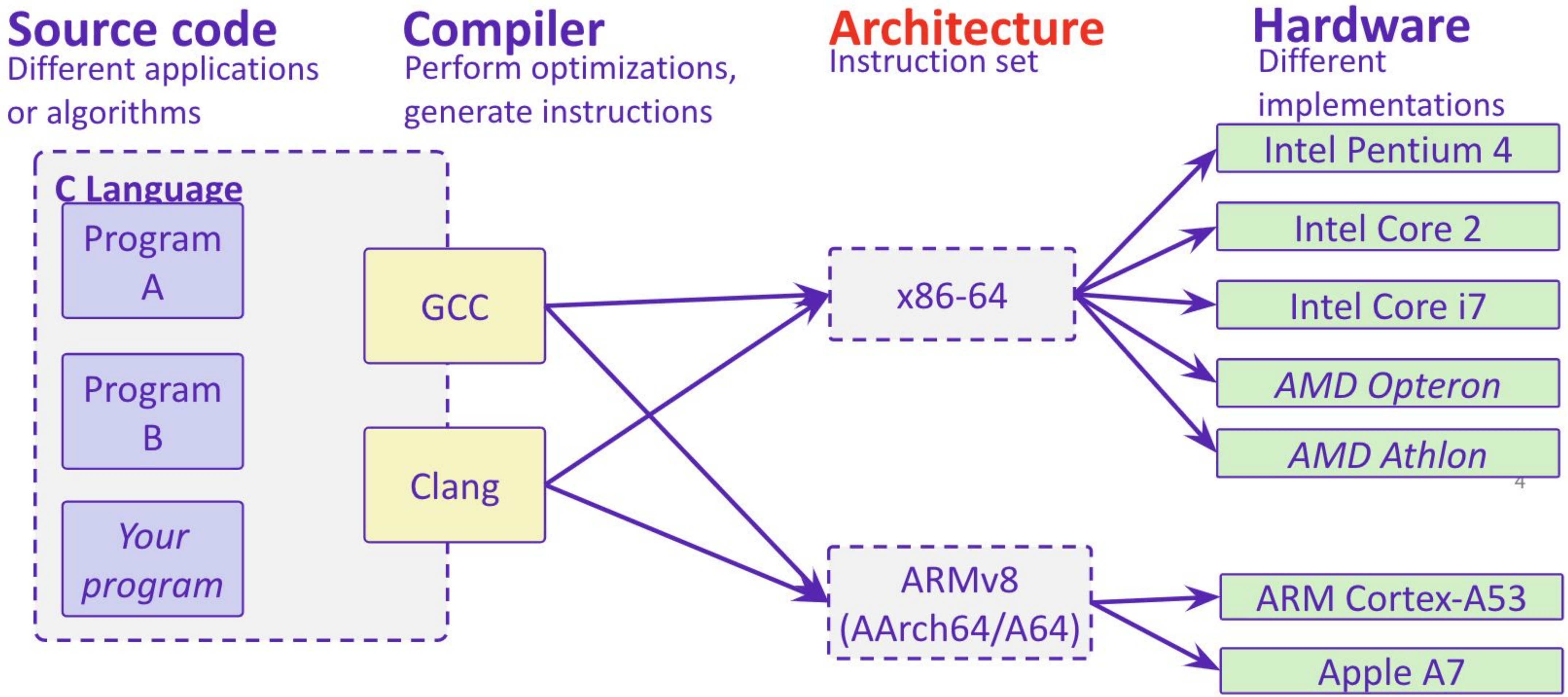


Where does everything go?

```
char big_array[1L<<24];   /* 16 MB */
char huge_array[1L<<31]; /*  2 GB */

int global = 0;

int useless() { return 0; }

int main()
{
    void *p1, *p2, *p3, *p4;
    int local = 0;
    p1 = malloc(1L << 28); /* 256 MB */
    p2 = malloc(1L << 8);  /* 256  B */
    p3 = malloc(1L << 32); /*   4 GB */
    p4 = malloc(1L << 8);  /* 256  B */
    /* Some print statements ... */
}
```



Hardware Software Interface



From Human to Computer

- C /C++ is translated directly into assembly by compiler
  - Other languages may be translated into another form
    - Java is translated into an assembly-like form, which is then run by the Java interpreter/runtime
    - The Java runtime is executing assembly instructions!
  - Some languages are directly interpreted without being translated into another form
    - Most Bash implementations will directly interpret the commands without compiling
    - Python can do either. It can be used as an interpreter or compile scripts
- Assembler translates assembly into machine code

C

```
#include <stdio.h>

int main()
{
   char name[20];
   …
   return 0;
}
```

Compiler

Assembly

```
push ebp
mov  ebp, esp
sub  esp,
0C0h
```

Assembler

Machine Code

```
83 ec 08
83 e4 f0
b8 00 00 00 00
83 c0 0f
```

Computer Architecture

- **Instruction Set Architecture (ISA):** The "programming language" of the processor, the syntax and language of how to give commands to the processor.
  - There are a set of ISAs that are supported by a larger collection of microarchitectures
  - Ex: x86, ARM ISA, TI DSPs ISA

  The ISA defines:
  - The system's state (*e.g.* registers, memory, program counter)
  - The instructions the CPU can execute
  - The effect that each of these instructions will have on the system state

- **Microarchitecture:** The way a specific processor executes a given ISA based on the processor's design.
  - The Microarchitecture defines how the data (data path) moves through the parts of the processor (control path), often represented as a data flow diagram.
  - microarchitecture dictates the flow of instructions through items within the processor such as logic gates, registers, Arithmetic Logic Units (ALUs)

Mainstream ISAs

x86

Designer	Intel, AMD
Bits	16-bit, 32-bit and 64-bit
Introduced	1978 (16-bit), 1985 (32-bit), 2003 (64-bit)
Design	CISC
Type	Register-memory
Encoding	Variable (1 to 15 bytes)
Endianness	Little

Macbooks & PCs
(Core i3, i5, i7, M)
x86-64 instruction set

ARM architectures

Designer	ARM Holdings
Bits	32-bit, 64-bit
Introduced	1985; 31 years ago
Design	RISC
Type	Register-Register
Encoding	AArch64/A64 and AArch32/A32 use 32-bit instructions, T32 (Thumb-2) uses mixed 16- and 32-bit instructions. ARMv7 user-space compatibility[1]
Endianness	Bi (little as default)

Smartphone (and similar) devices
(iPhone, iPad, Raspberry Pi)
ARM instruction set

MIPS

Designer	MIPS Technologies, Inc.
Bits	64-bit (32→64)
Introduced	1981; 35 years ago
Design	RISC
Type	Register-Register
Encoding	Fixed
Endianness	Bi

Digital home & networking
(Blu-ray, Playstation 2)
MIPS instruction set

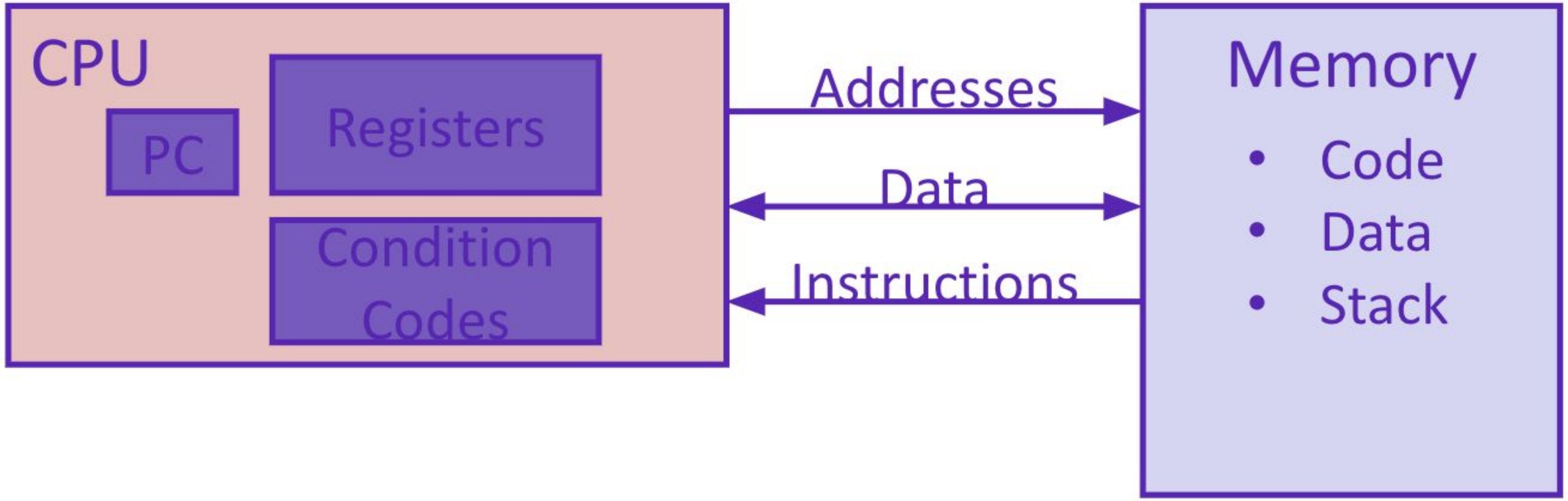
So… who writes assembly?

- Chances are, you'll never write a program in assembly!
  - BUT understanding assembly is the key to the machine-level execution model.

- Some use cases for assembly:
  - When working in embedded where you can't trust the compiler to reduce program size as efficiently as possible
  - When special purpose subroutines are required that are not possible in higher level languages
  - Behavior of programs in the presence of bugs
    - When high-level language model breaks down
  - Tuning program performance
  - Implementing systems software
  - Fighting malicious software
    - Distributed software is in binary form

Assembly Programmer's View

- Programmer-visible state
  - PC: the Program Counter (%rip in x86-64)
    - Address of next instruction
  - Named registers
    - Heavily used program data
  - Condition codes
    - Store status information about most recent arithmetic operation
    - Used for conditional branching



Registers

- A location in the CPU that stores a small amount of data, which can be accessed very quickly (once every clock cycle)
- Registers have *names*, not *addresses*
  - In assembly, they start with % (*e.g.* %rsi)
- Registers are at the heart of assembly programming
  - They are a precious commodity in all architectures, but *especially* x86

Memory

- Addresses (EX: 0x7FFFD024C3DC)
- Big ~ 8 GiB
- Slow ~50-100 ns
- Dynamic – Can "grow" as needed while program runs

Registers

- Names (EX: %rdi)
- Small – (16 x 8 B) = 128 B
- Fast – sub-nanosecond timescale
- Static – fixed number in hardware

Assembly Instruction Basics

Assembly instructions fall into one of 3 categories:

- **Transfer data** between memory and register
  - Load data from memory into register
    - %reg = Mem[address]
  - Store register data into memory
    - Mem[address] = %reg
- **Perform arithmetic** operation on register or memory data
  - c = a + b;   z = x << y;   i = h & g;
- **Control flow**: what instruction to execute next
  - Unconditional jumps to/from procedures
  - Conditional branches

Items in Assembly fall into one of 3 operand categories:

- **Immediate**: Constant integer data
  - Examples: $0x400, $-533
  - Like C literal, but prefixed with '$'
  - Encoded with 1, 2, 4, or 8 bytes
- **Register**: 1 of 16 integer registers
  - Examples: %rax, %r13
- **Memory**: Consecutive bytes of memory at a computed address
  - Simplest example: (%rax)

Example: Moving Data

Assume we have two variables called rax and rdx.

Which assembly instruction does `*rdx = rax`?

1. `movq %rdx, %rax`
2. `movq (%rdx), %rax`
3. `movq %rax, (%rdx)`
4. `movq (%rax), %rdx`

- General form: `mov_ source, destination`
  - Missing letter (_) specifies size of operands
  - Lots of these in typical code

Examples:

- `movb src, dst`
  - Move 1-byte "byte"
- `movw src, dst`
  - Move 2-byte "word"
- `movl src, dst`
  - Move 4-byte "long word"
- `movq src, dst`
  - Move 8-byte "quad word"

	Source	Dest	Src, Dest	C Analog
movq	Imm	Reg	`movq $0x4, %rax`	`rax = 4;`
		Mem	`movq $-147, (%rax)`	`*rax = -147;`
	Reg	Reg	`movq %rax, %rdx`	`rdx = rax;`
		Mem	`movq %rax, (%rdx)`	`*rdx = rax;`
	Mem	Reg	`movq (%rax), %rdx`	`rdx = *rax;`

Arithmetic Operation Instructions

- Binary (two-operand) Instructions:
  - Beware argument order!
  - How do you implement
- "r3 = r1 + r2"?

Format	Computation	
addq *src*, *dst*	*dst = dst + src*	(*dst += src*)
subq *src*, *dst*	*dst = dst – src*	
imulq *src*, *dst*	*dst = dst * src*	signed mult
shrq *src*, *dst*	*dst = dst >> src*	
shlq *src*, *dst*	*dst = dst << src*	(same as `salq`)
xorq *src*, *dst*	*dst = dst ^ src*	
andq *src*, *dst*	*dst = dst & src*	
orq *src*, *dst*	*dst = dst | src*	

q = operand size specifier
(e.g. b, w, l, q = 1, 2, 4, 8)

Example: Arithmetic Operations

```
long simple_arith(long x, long y)
{
  long t1 = x + y;
  long t2 = t1 * 3;
  return t2;
}
```

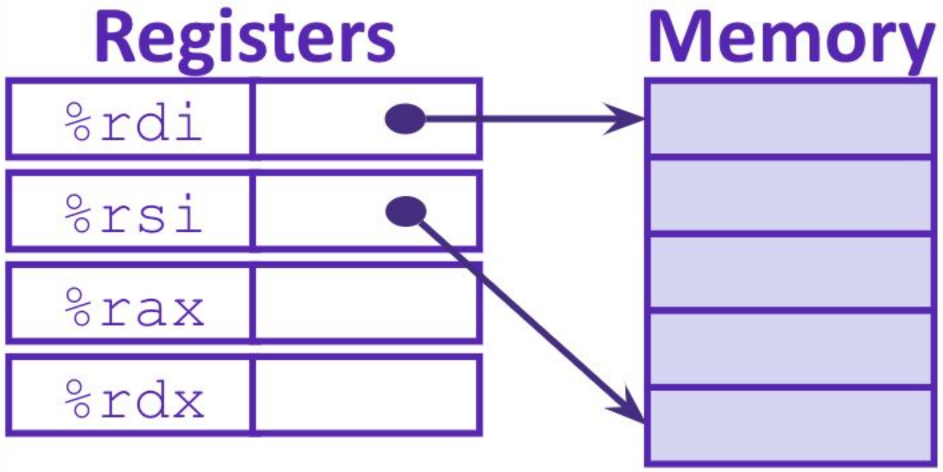
Register	Use(s)
`%rdi`	1st argument (`x`)
`%rsi`	2nd argument (`y`)
`%rax`	return value

```
y += x;
y *= 3;
long r = y;
return r;
```

```
simple_arith:
  addq    %rdi, %rsi
  imulq     $3, %rsi
  movq    %rsi, %rax
  ret
```

Example: swap()

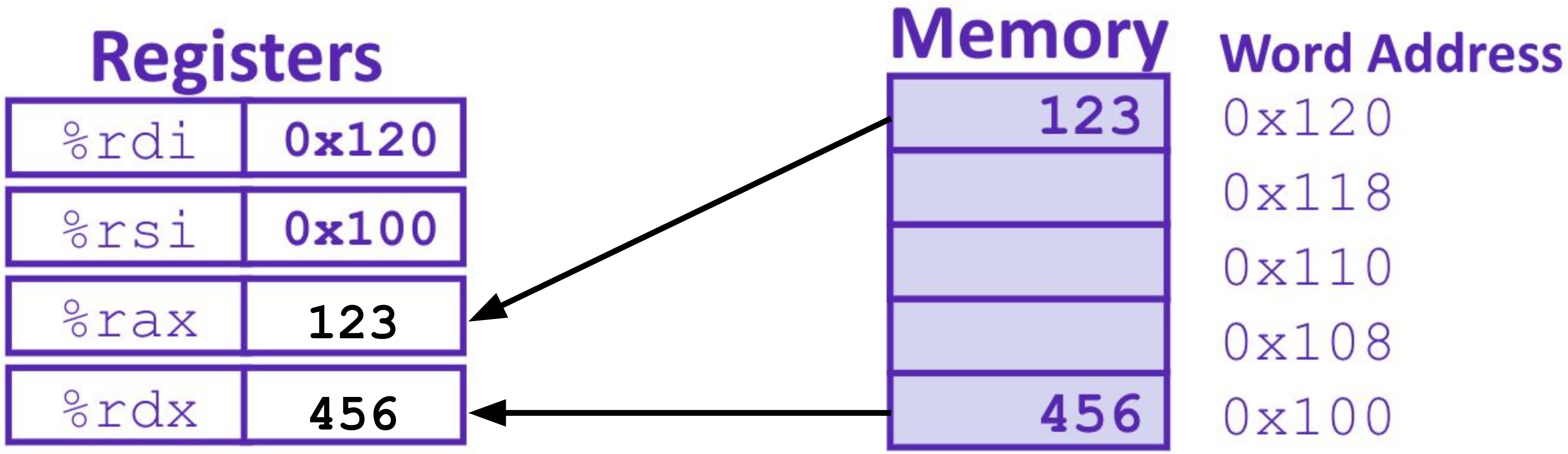
```c
void swap(long *xp, long *yp){
  long t0 = *xp;
  long t1 = *yp;
  *xp = t1;
  *yp = t0;
}
```




```
swap:
   movq   (%rdi), %rax
   movq   (%rsi), %rdx
   movq   %rdx, (%rdi)
   movq   %rax, (%rsi)
   ret
```

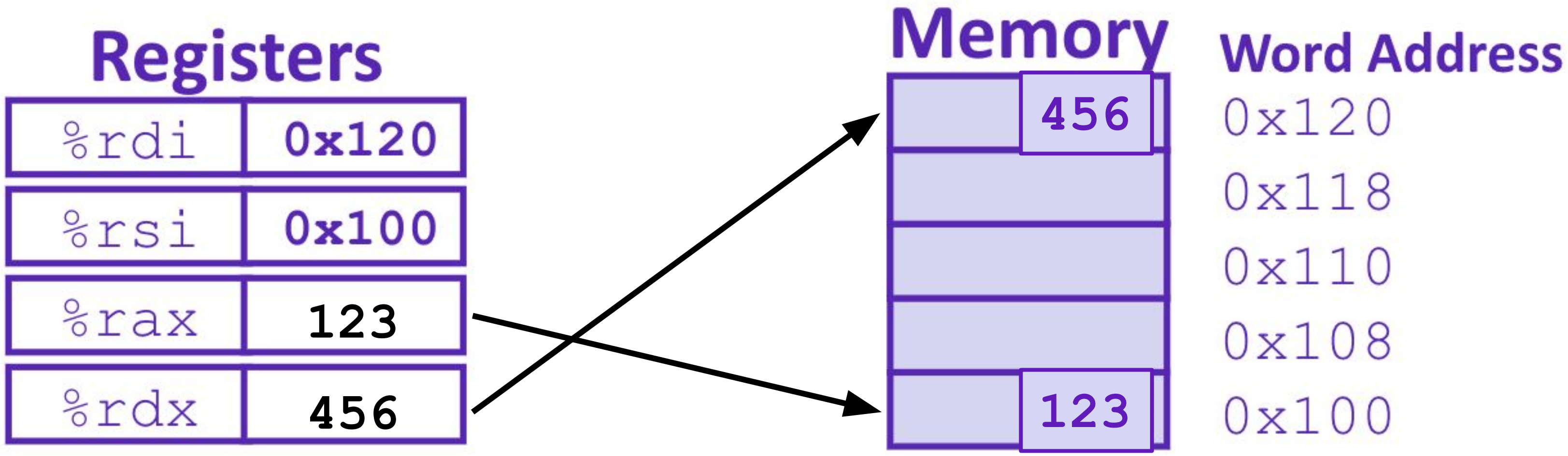
Register		Variable
%rdi	⇔	xp
%rsi	⇔	yp
%rax	⇔	t0
%rdx	⇔	t1

Example: swap()




```
swap:
   movq   (%rdi), %rax   #  t0 = *xp
   movq   (%rsi), %rdx   #  t1 = *yp
   movq   %rdx, (%rdi)   # *xp =  t1
   movq   %rax, (%rsi)   # *yp =  t0
   ret
```

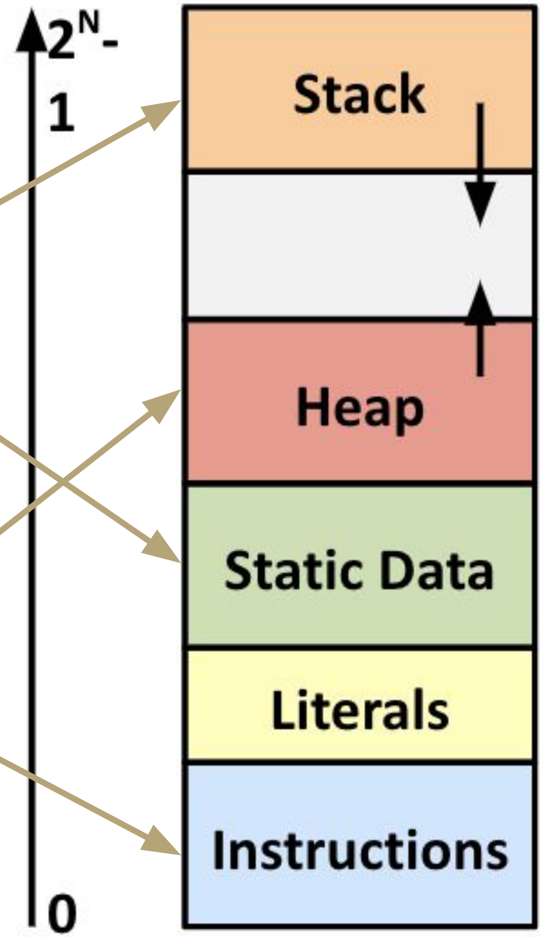
Example: swap()




```
swap:
    movq   (%rdi), %rax   #  t0 = *xp
    movq   (%rsi), %rdx   #  t1 = *yp
    movq   %rdx, (%rdi)   # *xp =  t1
    movq   %rax, (%rsi)   # *yp =  t0
    ret
```

Where does everything go?

```c
char big_array[1L<<24];   /* 16 MB */
char huge_array[1L<<31];  /*  2 GB */

int global = 0;

int useless() { return 0; }

int main()
{
    void *p1, *p2, *p3, *p4;
    int local = 0;
    p1 = malloc(1L << 28); /* 256 MB */
    p2 = malloc(1L << 8);  /* 256  B */
    p3 = malloc(1L << 32); /*   4 GB */
    p4 = malloc(1L << 8);  /* 256  B */
    /* Some print statements ... */
}
```

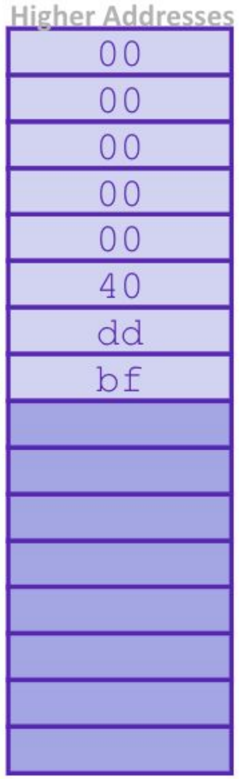


Buffer Overflow

- A buffer is an array used to temporarily store data
  - You've probably seen "video buffering…"
  - The video is being written into a buffer before being played
  - Buffers can also store user input
- C does not check array bounds
  - Many Unix/Linux/C functions don't check argument sizes
  - Allows overflowing (writing past the end) of buffers (arrays)
- "Buffer Overflow" = Writing past the end of an array
- Characteristics of the traditional Linux memory layout provide opportunities for malicious programs
  - Stack grows "backwards" in memory
  - Data and instructions both stored in the same memory

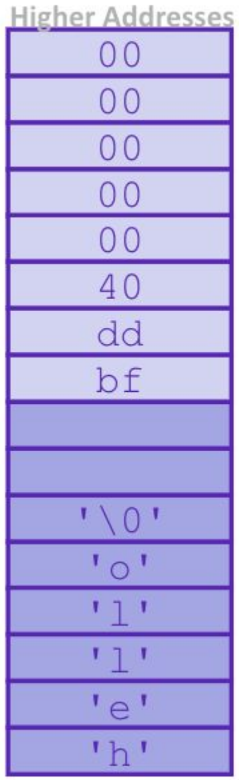
Buffer Overflow

- Stack grows *down* towards lower addresses
- Buffer grows *up* towards higher addresses
- If we write past the end of the array, we overwrite data on the stack!



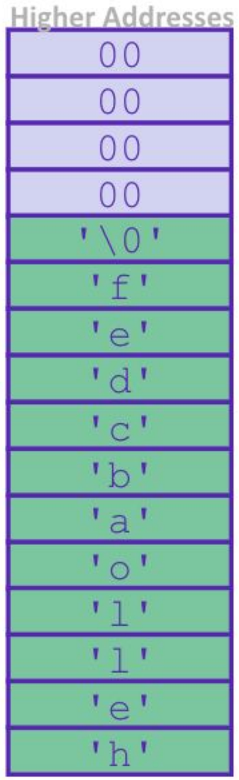
`Enter input: hello`

-> no overflow



`Enter input: helloabcdef`

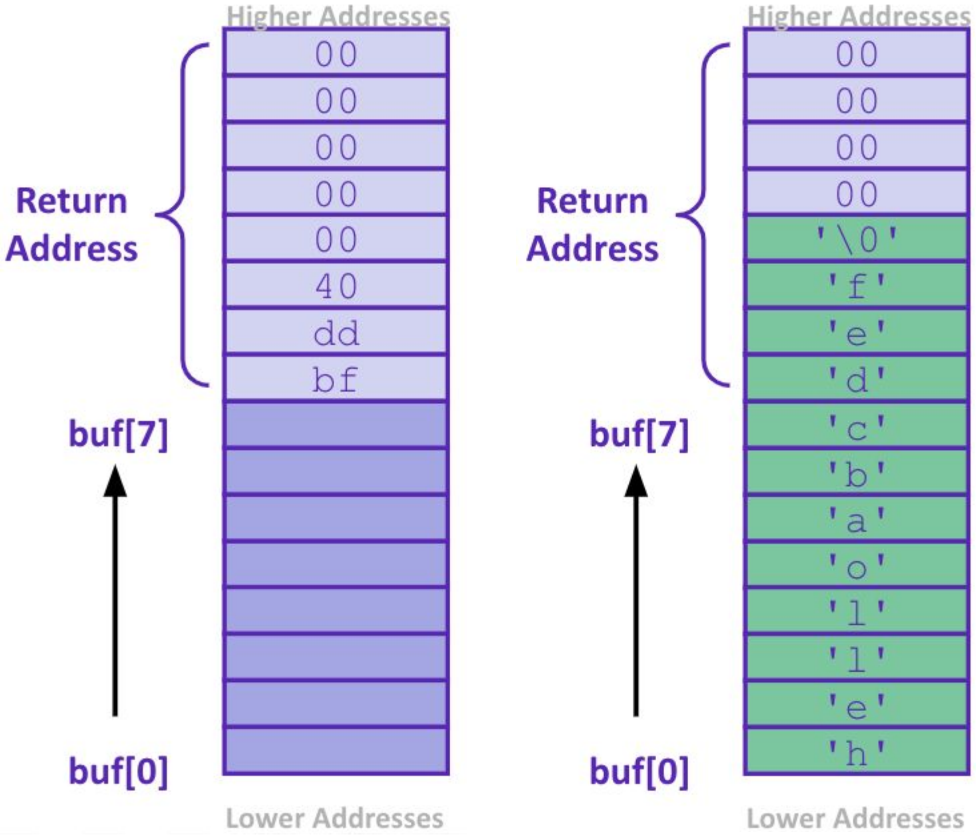
-> overflow!



What happens when there is an overflow?

- Buffer overflows on the stack can overwrite "interesting" data
  - Attackers just choose the right inputs
- Simplest form (sometimes called "stack smashing")
  - Unchecked length on string input into bounded array causes overwriting of stack data
  - Try to change the return address of the current procedure
- Why is this a big deal?
  - It was the #1 *technical* cause of security vulnerabilities
    - #1 *overall* cause is social engineering / user ignorance

`Enter input: helloabcdef`



`We've lost our way!`
Lost address of function pointer telling us which instruction to return to

Malicious Buffer Overflow – Code Injection

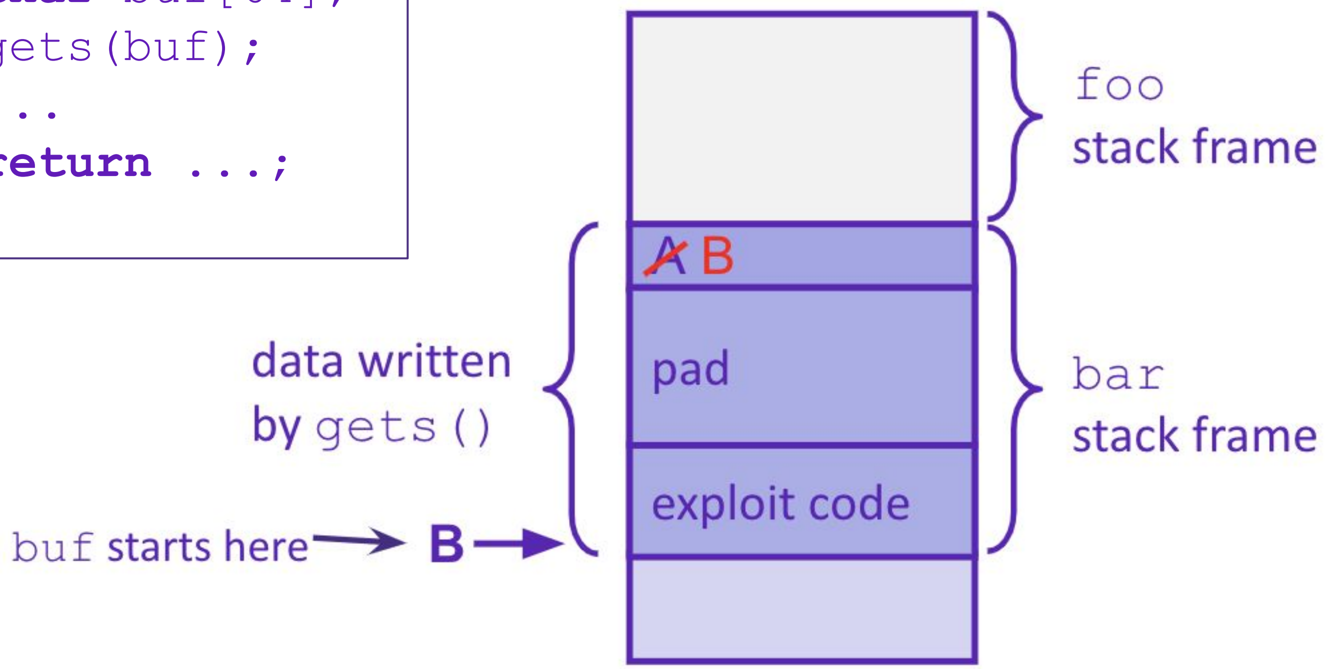
- Buffer overflow bugs can allow attackers to execute arbitrary code on victim machines
  - Distressingly common in real programs
- Input string contains byte representation of executable code
- Overwrite return address A with address of buffer B
- When bar() executes ret, will jump to exploit code

```
void foo(){
  bar();
A:...
}
```

return address A

```
int bar() {
  char buf[64];
  gets(buf);
  ...
  return ...;
}
```

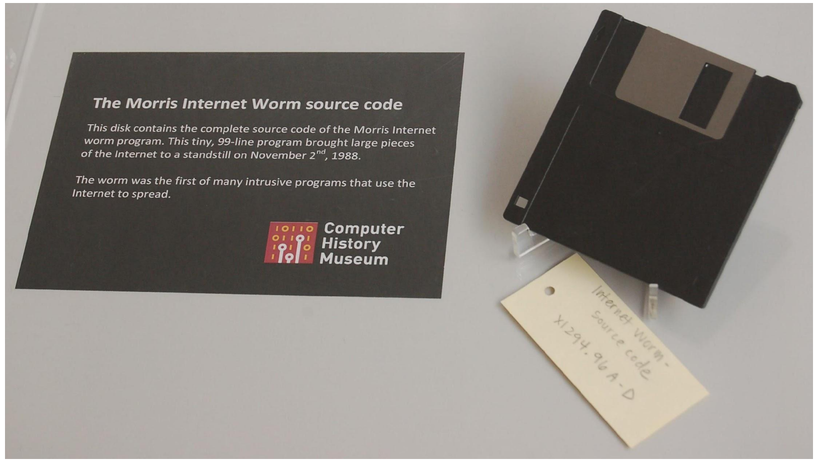
Stack after call to gets()



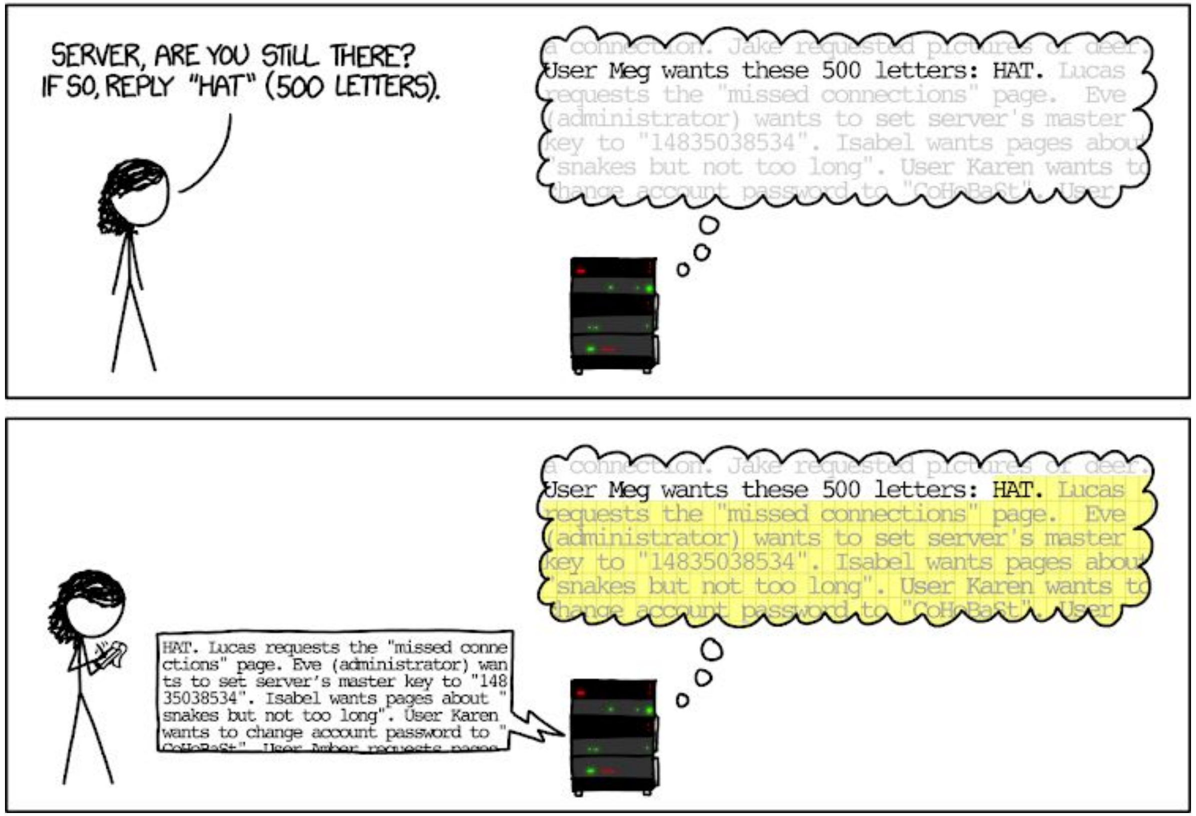
https://www.gao.gov/assets/700/694913.pdf

Examples

- Original "Internet worm" (1988)
  - Early versions of the finger server (fingerd) used gets() to read the argument sent by the client: finger droh@cs.cmu.edu
  - Worm attacked fingerd server with phony argument:
    - finger *"exploit-code padding new-return-addr"*
    - Exploit code: executed a root shell on the victim machine with a direct connection to the attacker
  - Robert Morris is now a professor at MIT, first person convicted under the '86 Computer Fraud and Abuse Act



- Heartbleed (2014, affected 17% of servers)
  - Buffer over-read in OpenSSL
  - "Heartbeat" packet
    - Specifies length of message and server echoes it back
    - Library just "trusted" this length
    - Allowed attackers to read contents of memory anywhere they wanted
  - Est. 17% of Internet affected
  - Similar issue in Cloudbleed (2017)



Protect Your Code!

- Employ system-level protections
  - Code on the Stack is not executable
  - Randomized Stack offsets
- Avoid overflow vulnerabilities
  - Use library routines that limit string lengths
  - Use a language that makes them impossible
- Have compiler use “stack canaries”
  - place special value (“canary”) on stack just beyond buffer

System Level Protections

- **Non-executable code segments**
- In traditional x86, can mark region of memory as either "read-only" or "writeable"
  - Can execute anything readable
- x86-64 added explicit "execute" permission
- Stack marked as non-executable
  - Do *NOT* execute code in Stack, Static Data, or Heap regions
  - Hardware support needed
- Works well, but can't always use it
- Many embedded devices *do not* have this protection
  - Cars
  - Smart homes
  - Pacemakers
- Some exploits still work!

- **Randomized stack offsets**
  - At start of program, allocate random amount of space on stack
  - Shifts stack addresses for entire program
    - Addresses will vary from one run to another
  - Makes it difficult for hacker to predict beginning of inserted code

Avoid Overflow Vulnerabilities

- Use library routines that limit string lengths
  - fgets instead of gets (2nd argument to fgets sets limit)
  - strncpy instead of strcpy
  - Don't use scanf with %s conversion specification
    - Use fgets to read the string
    - Or use %ns where n is a suitable integer

```
/* Echo Line */
void echo()
{
    char buf[8];  /* Way too small! */
    fgets(buf, 8, stdin);
    puts(buf);
}
```

- Alternatively, don't use C – use a language that does array index bounds check
  - Buffer overflow is impossible in Java
    - ArrayIndexOutOfBoundsException
  - Rust language was designed with security in mind
    - Panics on index out of bounds, plus more protections

Stack Canaries

- Basic Idea: place special value ("canary") on stack just beyond buffer
  - *Secret* value that is randomized before main()
  - Placed between buffer and return address
  - Check for corruption before exiting function
- GCC implementation
  - -fstack-protector

```
unix>./buf
Enter string: 12345678
12345678
```

```
unix> ./buf
Enter string: 123456789
*** stack smashing detected ***
```

Questions