Lecture Participation Poll #25

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Lecture 25:Assembly Contd…

CSE 374: Intermediate Programming Concepts and Tools

Administrivia

- Reminder: HW1 turnin closes on Friday
- HW5 due today
  - rubric to be posted
- HW6 posted
  - due Monday of finals week
- Thanks for your feedback!
  - HW4 individual assignment coming with example exam questions
  - HW5 & 6 individual assignments will have example exam questions
  - converting these to multiple choice so you can have practice without worrying as much about points

Human to Computer Roadmap

C:

```
car *c = malloc(sizeof(car));
c->miles = 100;
c->gals = 17;
float mpg = get_mpg(c);
free(c);
```

Java:

```
Car c = new Car();
c.setMiles(100);
c.setGals(17);
float mpg =
    c.getMPG();
```

Assembly language:

```
get_mpg:
    pushq   %rbp
    movq    %rsp, %rbp
    ...
    popq    %rbp
    ret
```

Machine code:

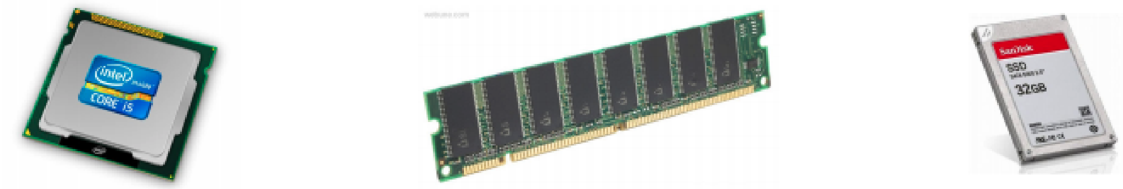
```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

OS:

Windows 10

OS X Yosemite

Computer system:



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

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

- **Memory**: Consecutive bytes of memory at a computed address
  - Simplest example: (%rax)

Example: Moving Data

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

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`

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;`

Example: Arithmetic Operations

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

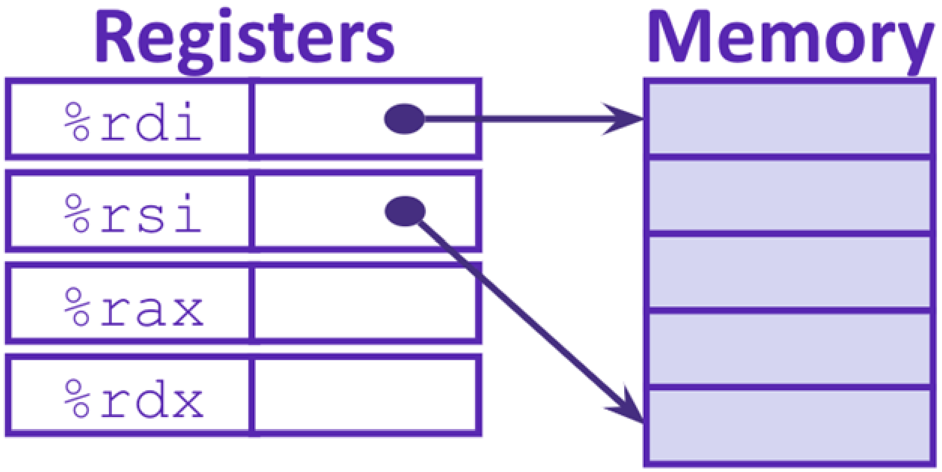
Register	Use(s)
%rdi	1st argument (x)
%rsi	2nd argument (y)
%rax	return value

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

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

Example: swap()

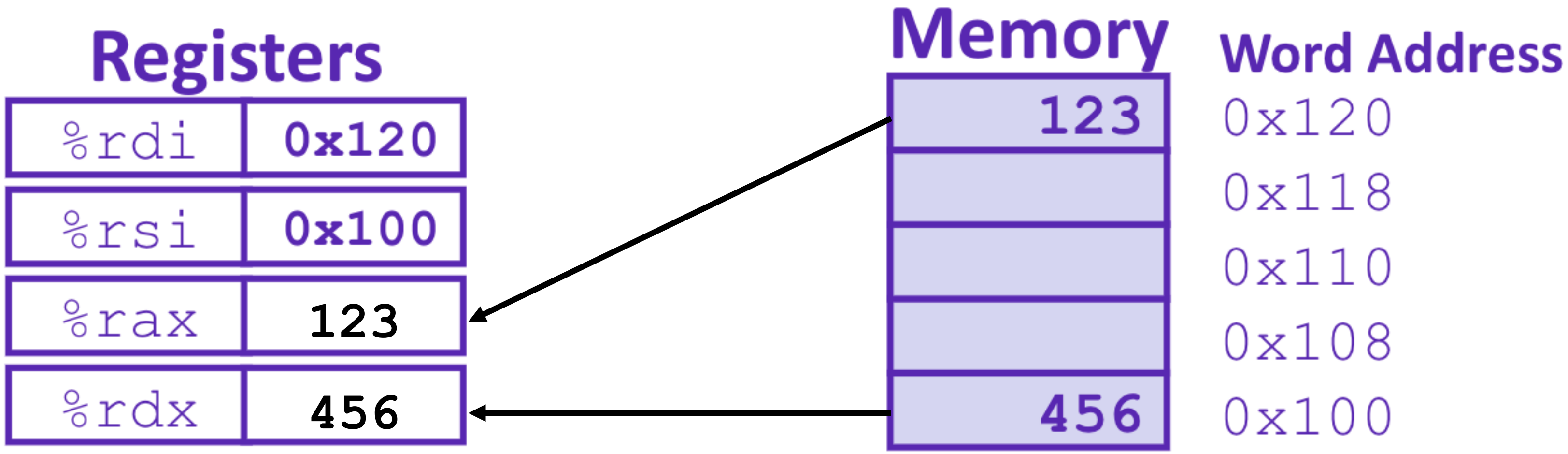
```
void swap(long *xp, long *yp){
   long t0 = *xp;
   long t1 = *yp;
   *xp = t1;
   *yp = t0;
}
```




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

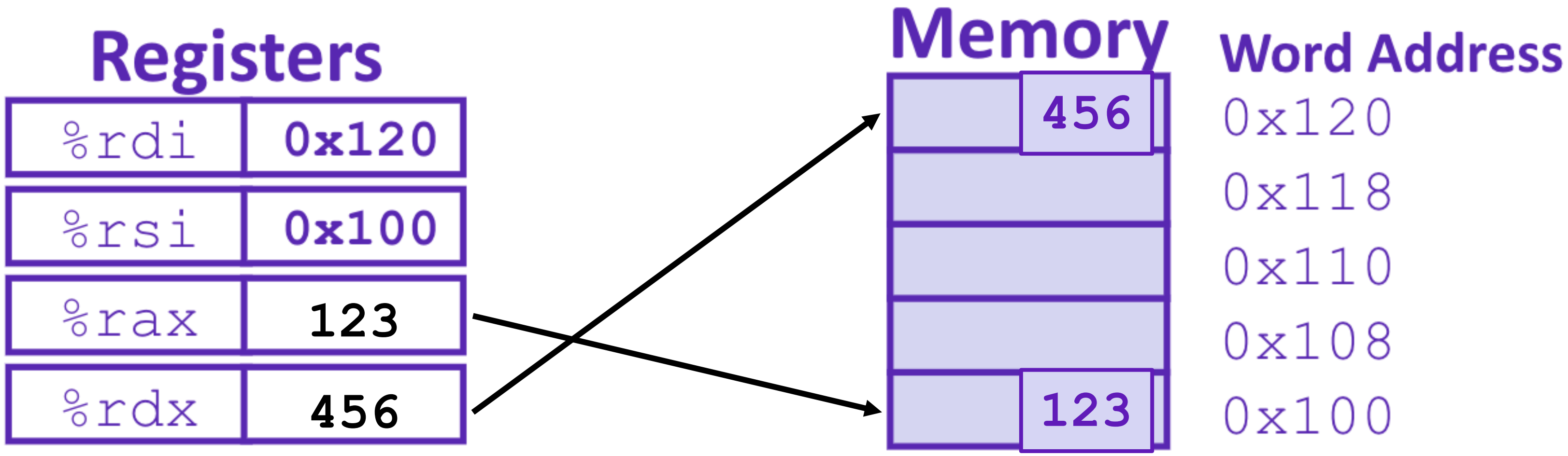
Register		Variable
%rdi	⇔	xp
%rsi	⇔	yp
%rax	⇔	t0
%rdx	⇔	t1

Example: swap()




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

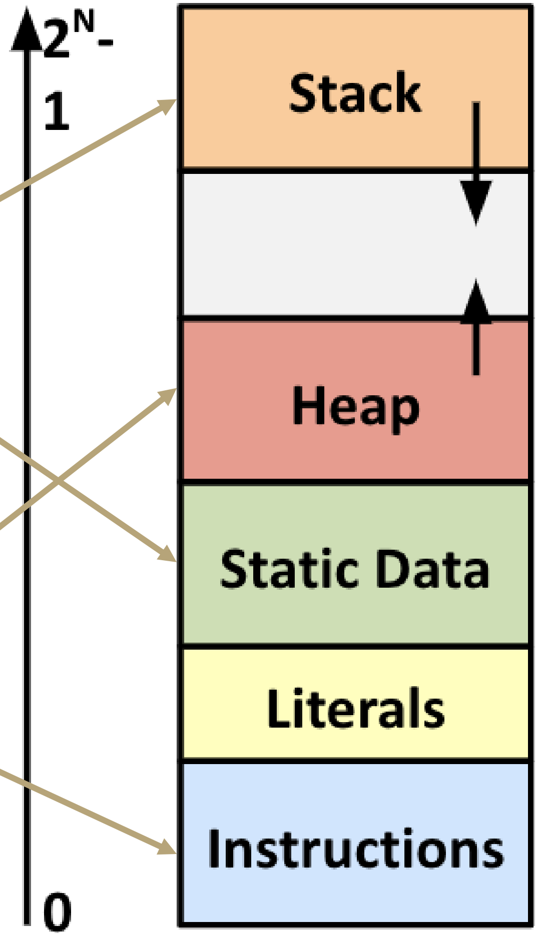
Example: swap()



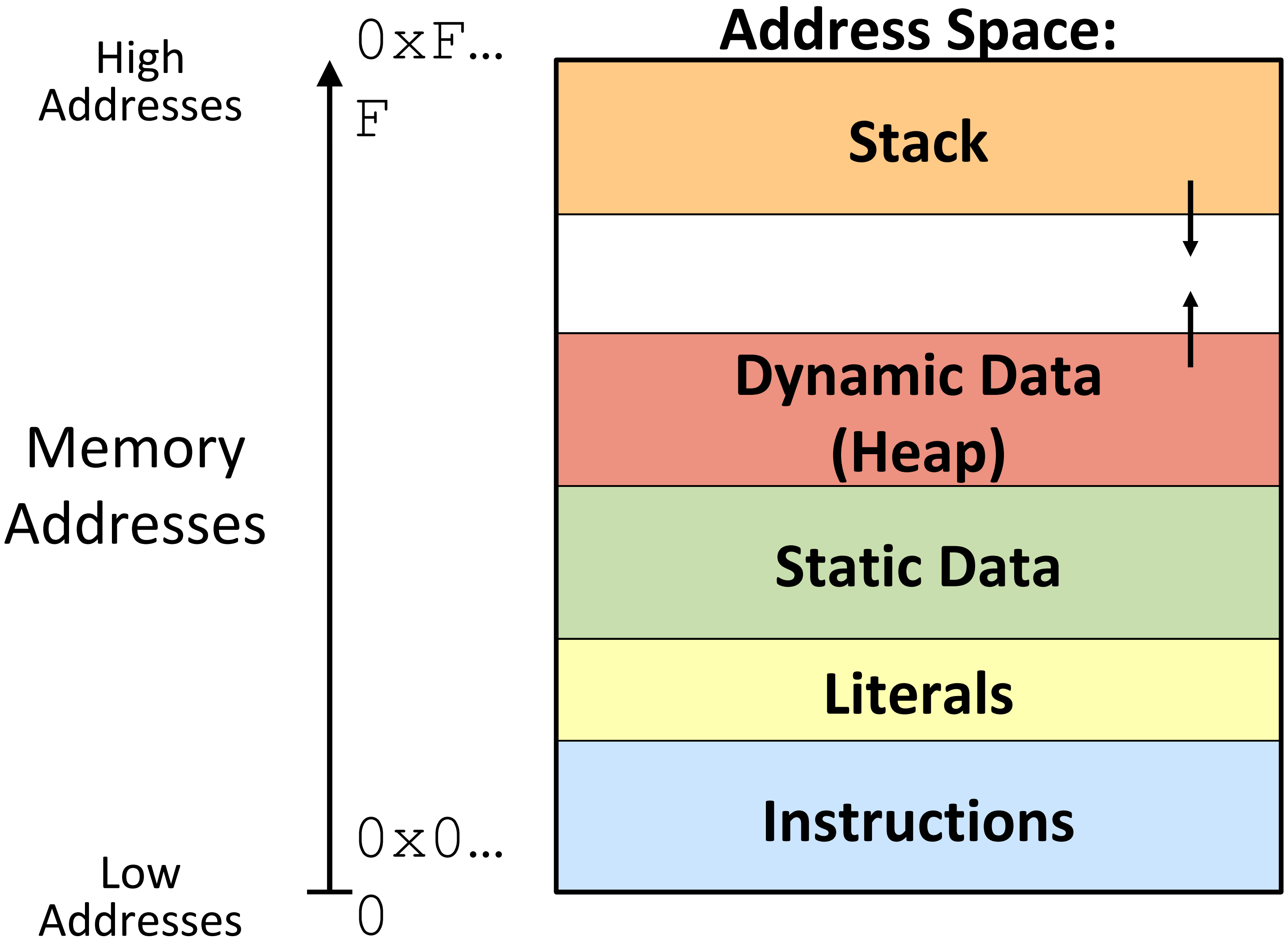

```
swap:
    movq    (%rdi), %rax    #  t0 = *xp
    movq    (%rsi), %rdx    #  t1 = *yp
    movq    %rdx, (%rdi)    # *xp =  t1
    movq    %rax, (%rsi)    # *yp =  t0
    ret
```

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 ... */
}
```



Simplified Memory Layout



What Goes Here:

local variables and procedure context

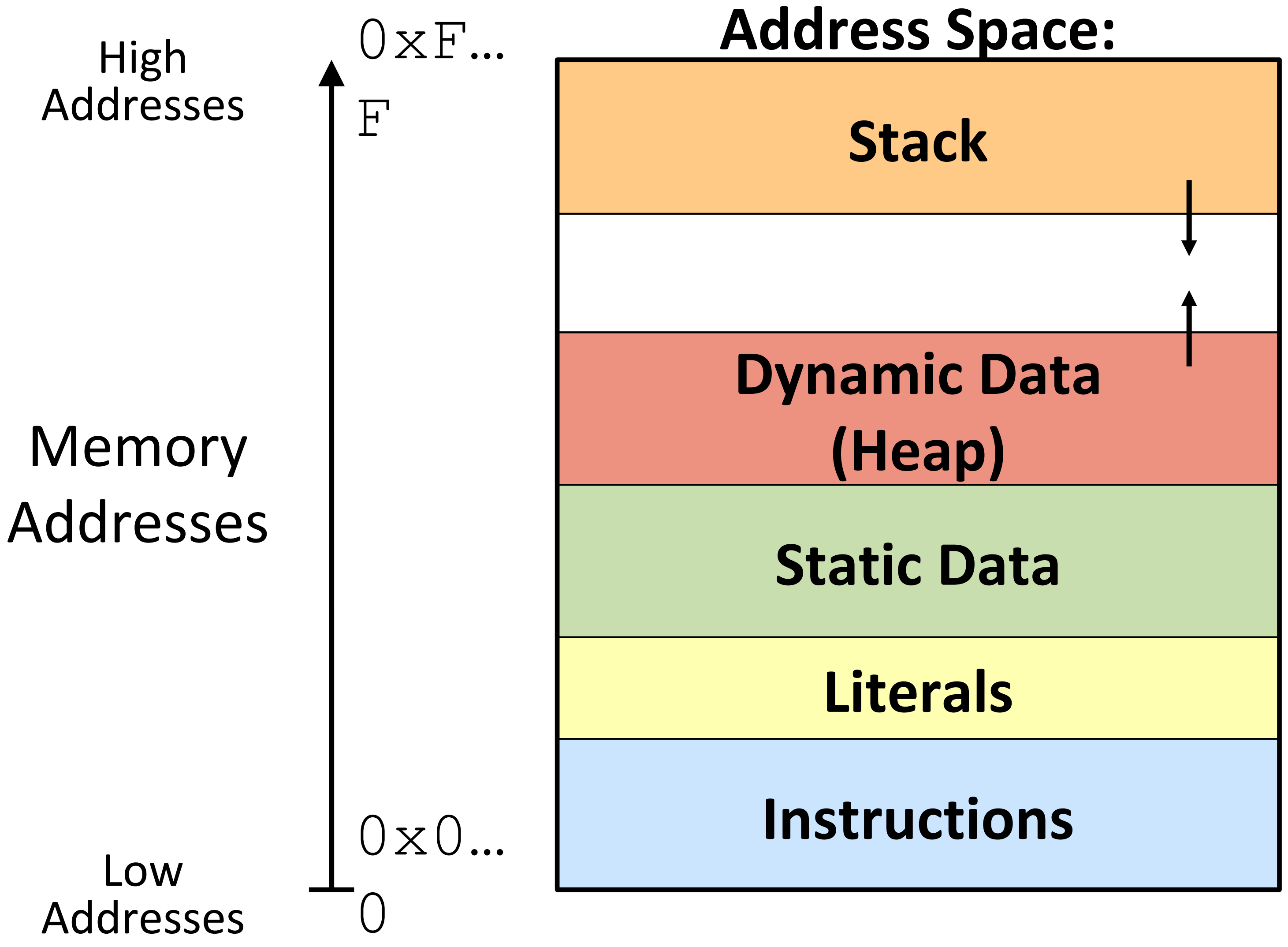
variables allocated with `new` or `malloc`

static variables (including global variables)

large literals/constants (*e.g.* "example")

program code

Memory Management



Who's Responsible:

Managed "automatically" (by compiler/assembly)

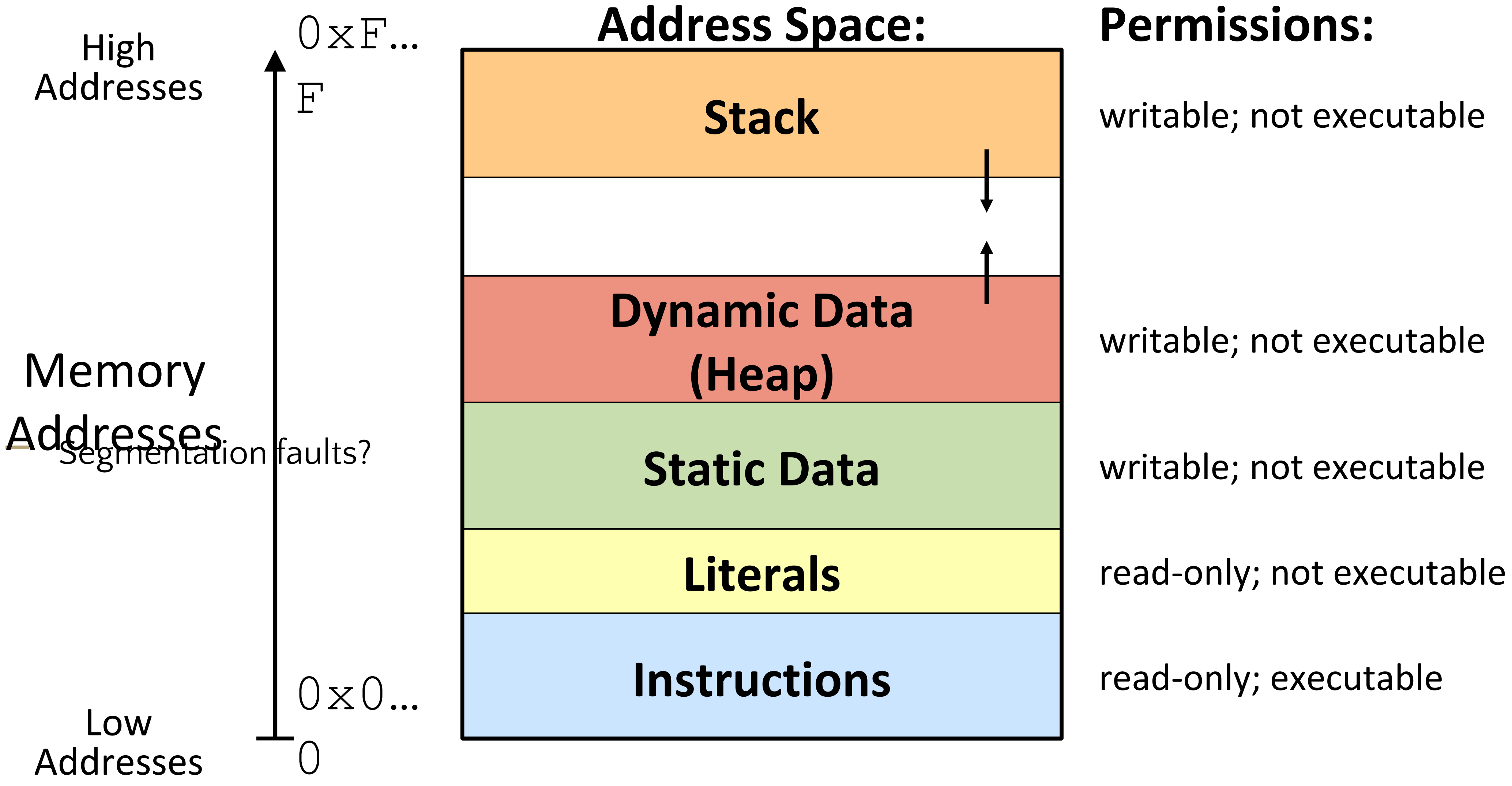
Managed "dynamically" (by programmer)

Managed "statically" (initialized when process starts)

Managed "statically" (initialized when process starts)

Managed "statically" (initialized when process starts)

Memory Permissions



- Segmentation faults?

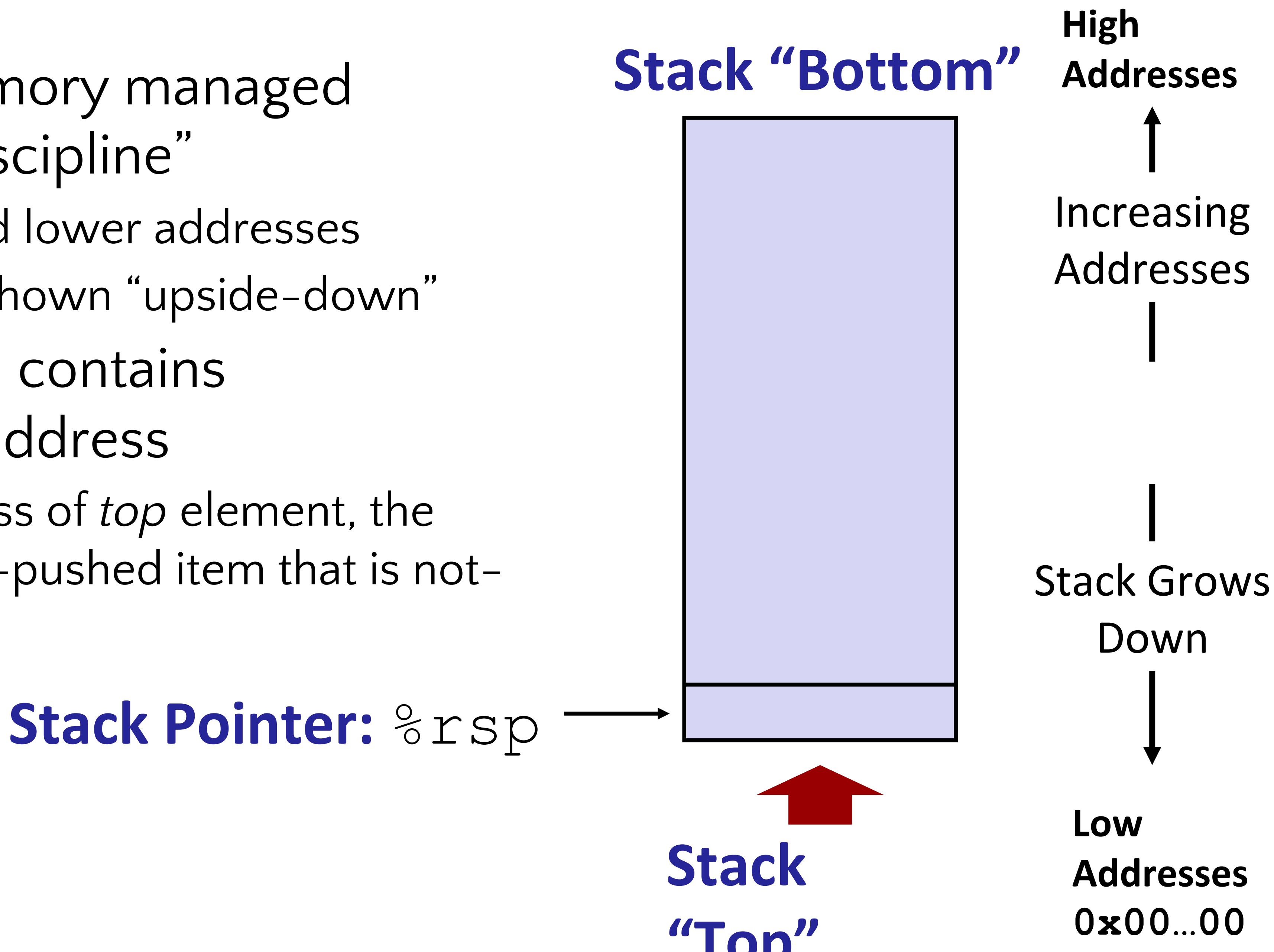
The Stack

- top most byte of stack pointed to by %rsp
- call pushes "return address" on stack, then jumps
- ret pops return address and jumps to there
- pushq/popq allows you to place other data on the stack
  - commonly used to save registers
- often useful to have a pointer to the bottom of the current stack frame
  - called the "base pointer"
  - stored in %rbp
- copy current stack pointer to %rbp at beginning of function
- Beware: both %rsp and %rbp are callee saved
  - must restore thief values before returning
- common pattern: save old %rbp on stack and restore before returning

```
pushq %rbp
movq %rsp, %rbp
# other stack setup
… # rest of function
movq %rbp, %rsp
popq %rbp
ret
```

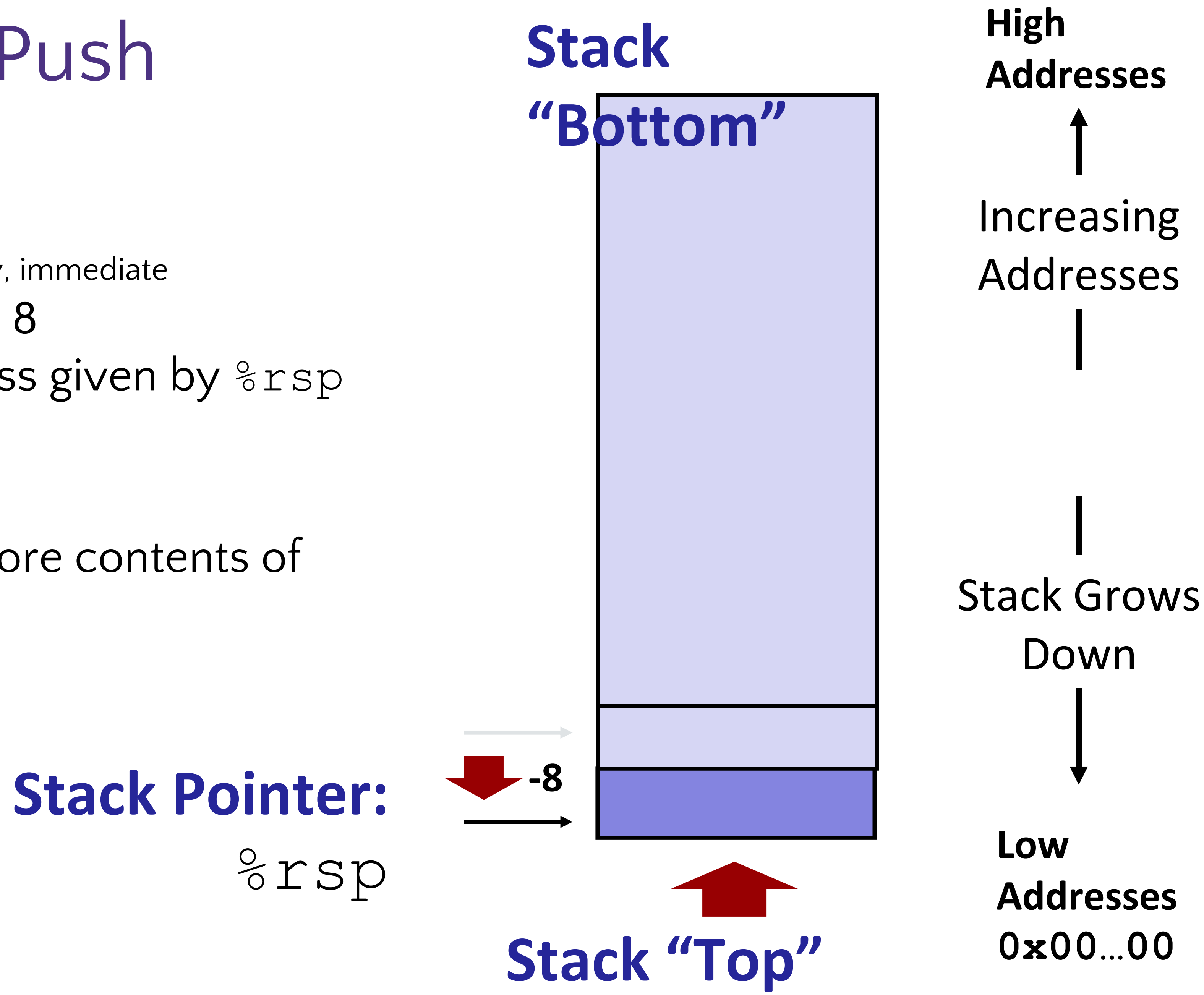
x86-64 Stack

- Region of memory managed with stack "discipline"
  - Grows toward lower addresses
  - Customarily shown "upside-down"
- Register `%rsp` contains *lowest* stack address
  - `%rsp` = address of *top* element, the most-recently-pushed item that is not-yet-popped



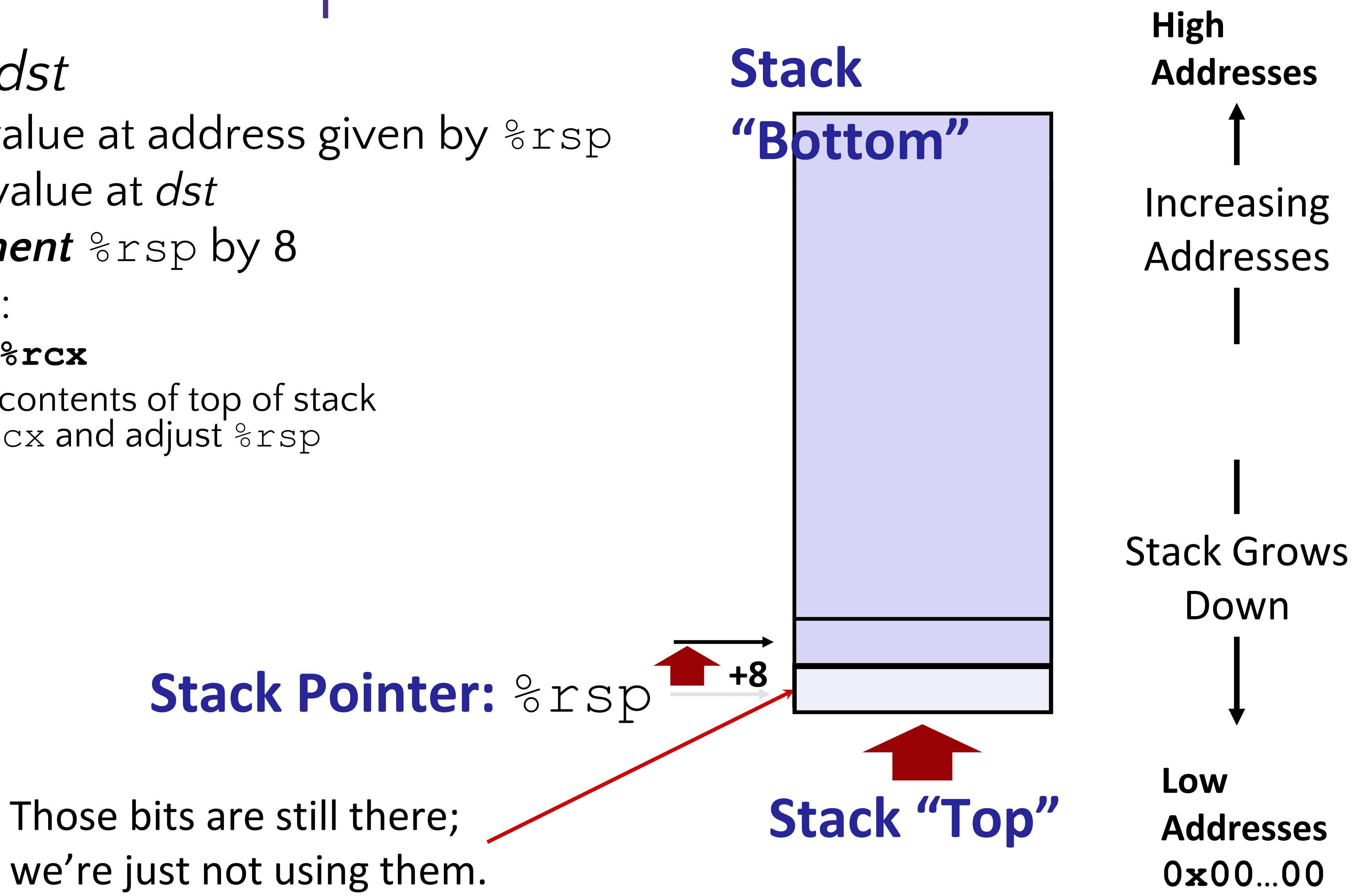
x86-64 Stack: Push

- `pushq` *src*
  - Fetch operand at *src*
    - *Src* can be reg, memory, immediate
  - ***Decrement*** `%rsp` by 8
  - Store value at address given by `%rsp`
- Example:
  - **`pushq %rcx`**
  - Adjust `%rsp` and store contents of `%rcx` on the stack



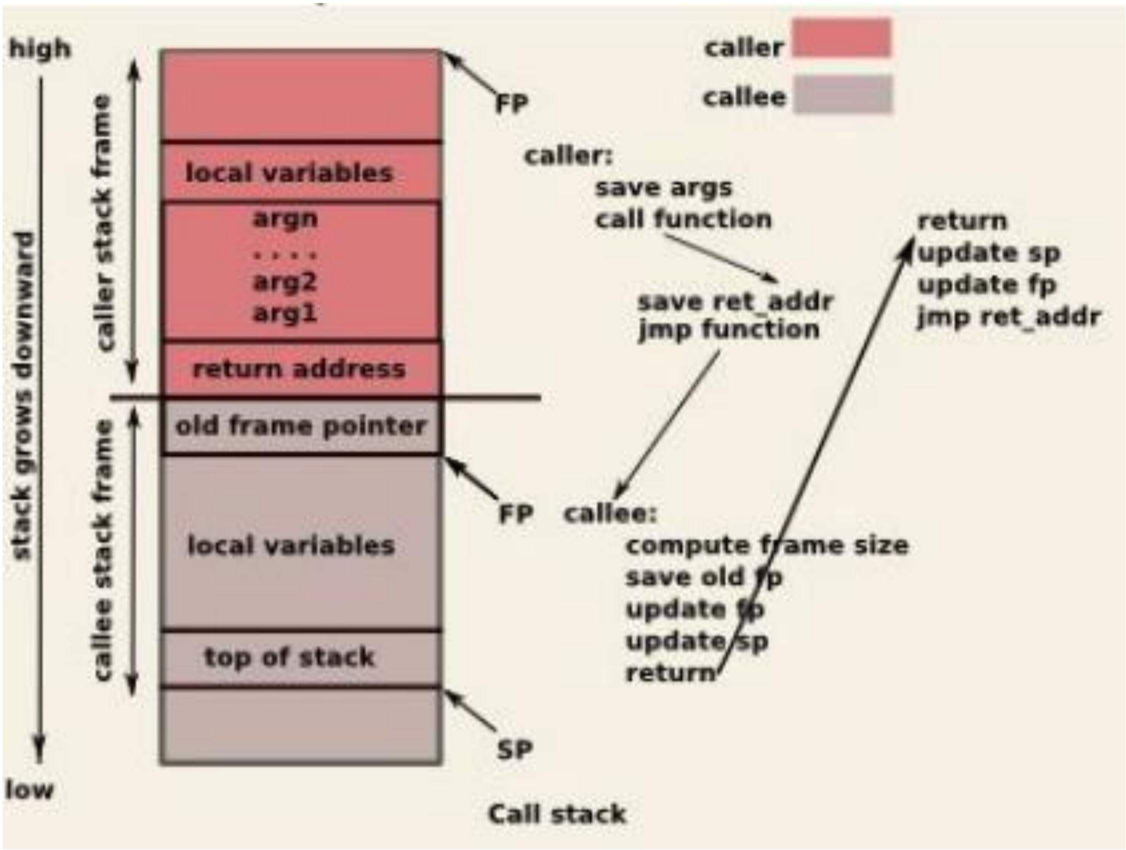
x86-64 Stack: Pop

- `popq` *dst*
  - Load value at address given by `%rsp`
  - Store value at *dst*
  - ***Increment*** `%rsp` by 8
- Example:
  - **`popq %rcx`**
  - Stores contents of top of stack into `%rcx` and adjust `%rsp`



Function Pointers & Frames

- Coded instructions are translated into numerical values stored in memory and fed into the processor for execution
- **function pointer** – address of a function stored in memory, pointing to the start of the block of memory storing the set of instructions expressed by the function.
- **stack frames** – section of the stack that is set aside for each function call
  - frame pushed onto the stack when the function is called and popped off when the function returns.
  - each frame contains: arguments, return address, pointer to last frame, local variables



Calling functions “the calling convention”

```
call label # jump to label, but “remember” next location
ret        # return to after most recent call
```

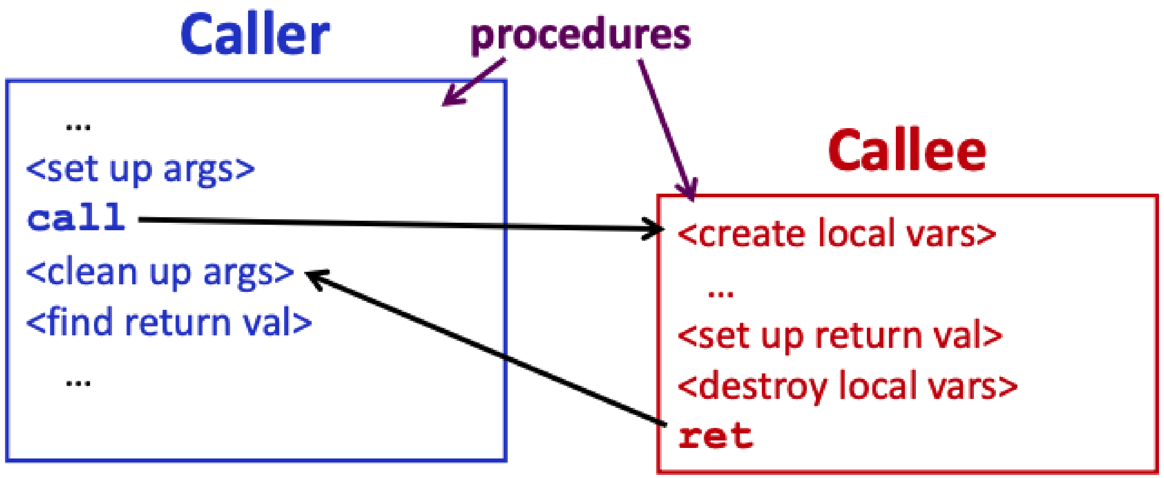
Example:

```
    call helper
    “print” %rax
    helper:
       movq $7, %rax
       ret
```

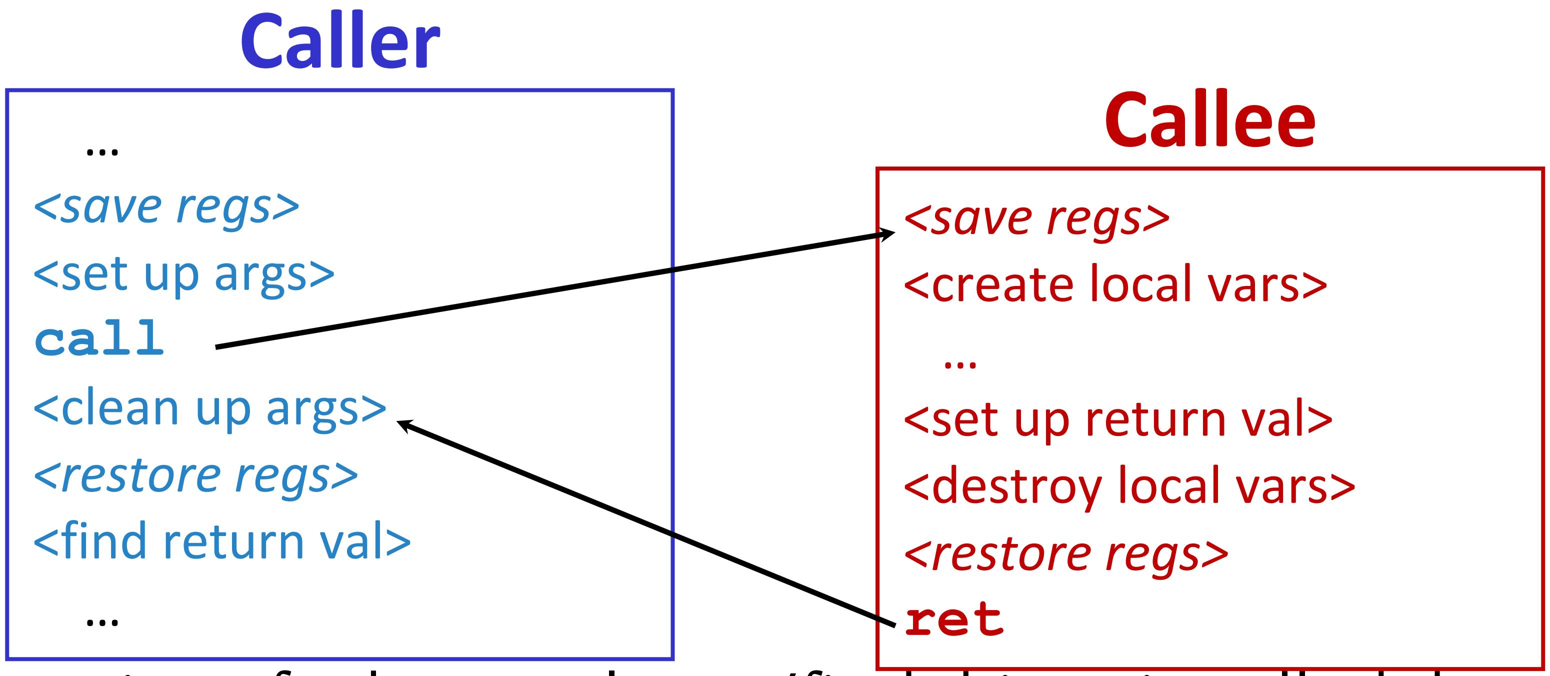
- no such thing as arguments/return value
- instead a convention is used for registers
  - return value (if any) passed into %rax
  - first arg (if any) passed into %rdi
  - second arg (if any) passed into %rsi
- important distinction between caller saved and callee saved registers
  - any function may use a caller saved register however they want
  - functions must restore values if using a callee saved register
- when you call a function you must assume it trashes the caller saved registers
- arguments and return values are caller saved

Procedure Call Overview

- Coordinating between function memory frames
  - Callee must know where to find arguments
  - Callee must know where to find return address
  - Caller must know where to find return value
- Caller and Callee run on the same CPU, so they use the same registers
- calling convention – convention of where to leave/find things
  - caller saves contents of %rax before triggering callee that returns value (to prevent lose due to overwrite)
  - callee places return value into %rax
  - for values greater than 8 bytes, return pointer



Procedure Call Overview

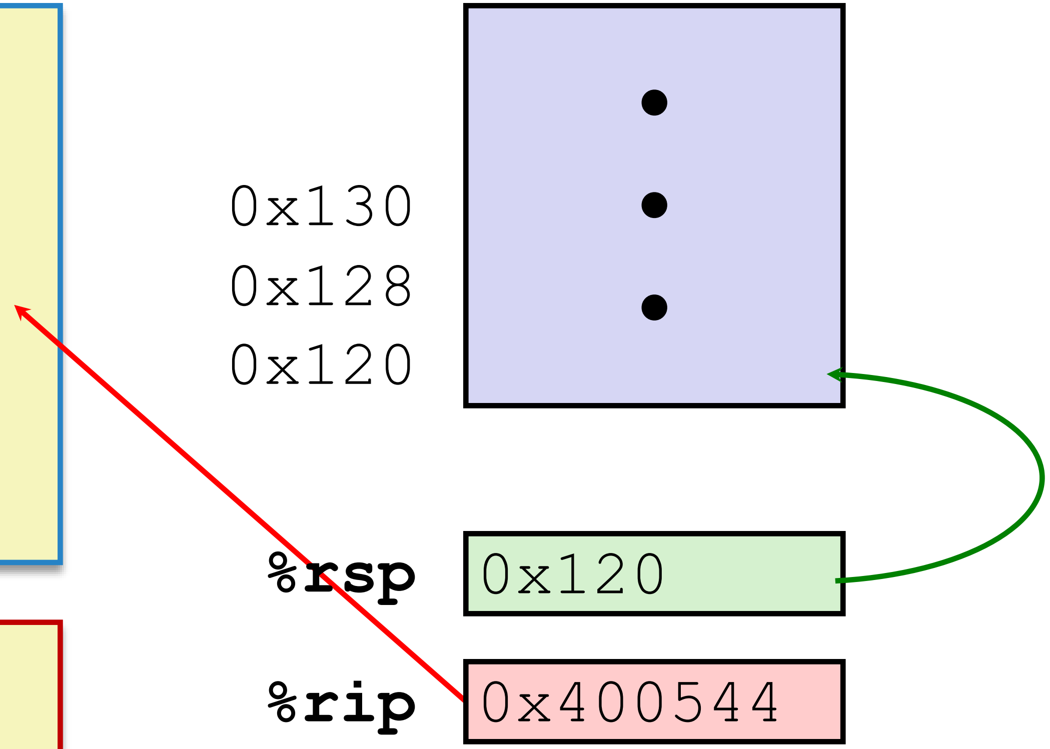


- The *convention* of where to leave/find things is called the calling convention (or procedure call linkage)
  - Details vary between systems
  - We will see the convention for x86-64/Linux in detail
  - What could happen if our program didn't follow these conventions?

Procedure Call Example (step 1)

```
0000000000400540 <multstore>:
  •
  •
  400544: call    400550 <mult2>
  400549: movq    %rax,(%rbx)
  •
  •
```

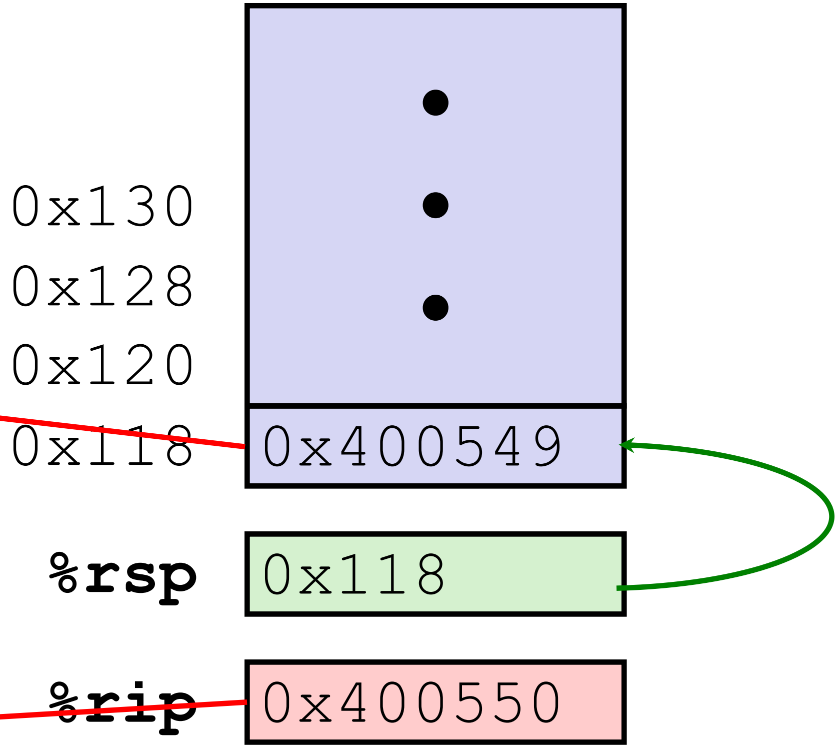
```
0000000000400550 <mult2>:
  400550:  movq    %rdi,%rax
  •
  •
  400557:  ret
```



Procedure Call Example (step 2)

```
0000000000400540 <multstore>:
  •
  •
  400544: call   400550 <mult2>
  400549: movq   %rax,(%rbx)
  •
  •
```

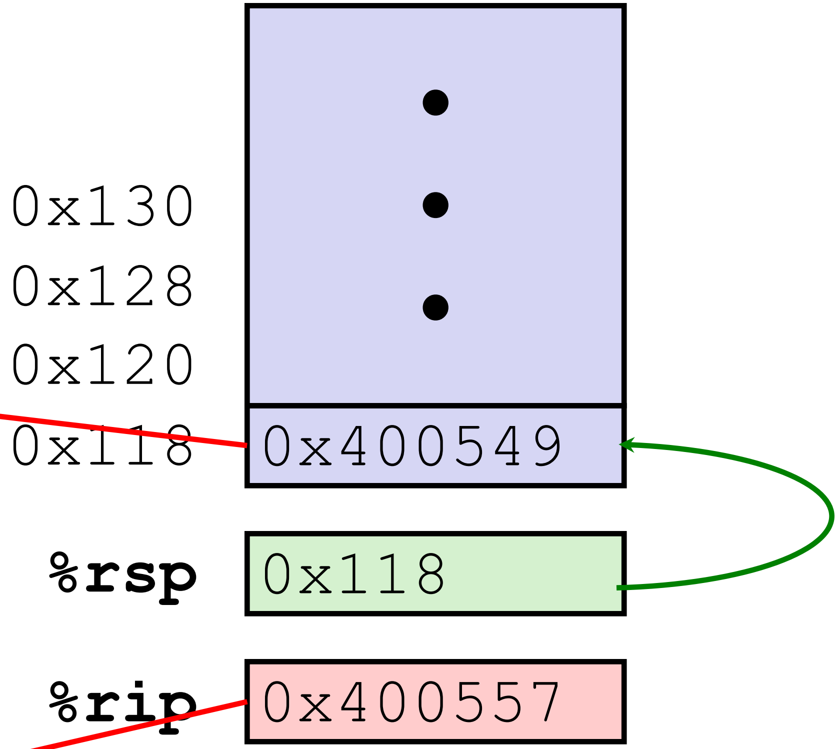
```
0000000000400550 <mult2>:
  400550:  movq   %rdi,%rax
  •
  •
  400557:  ret
```



Procedure Return Example (step 1)

```
0000000000400540 <multstore>:
  •
  •
  400544: call   400550 <mult2>
  400549: movq   %rax,(%rbx)
  •
  •
```

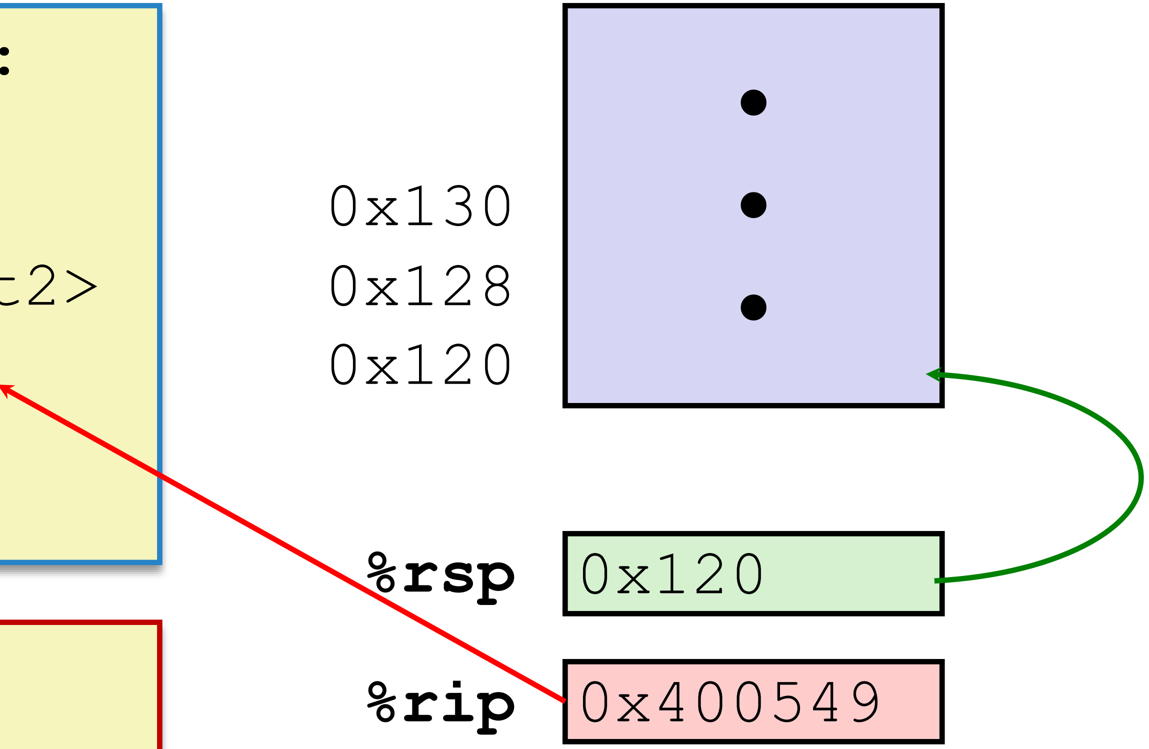
```
0000000000400550 <mult2>:
  400550:  movq   %rdi,%rax
  •
  •
  400557:  ret
```



Procedure Return Example (step 2)

```
0000000000400540 <multstore>:
  •
  •
  400544: call    400550 <mult2>
  400549: movq    %rax,(%rbx)
  •
  •
```

```
0000000000400550 <mult2>:
  400550:  movq    %rdi,%rax
  •
  •
  400557:  ret
```



Jumps

```
jmp label # continue execution at label
```

- most arithmetic instructions set the conditional codes (CCs, aka “flags)
- special cmp instruction to compare
  - `cmpq a,b # sets CCs based on b-a`
- can jump conditionally based on CCs
  - `je label   # jump to label if condition is true`
  - `jne label  # else, continue to next instruction`
  - `jl label`

Memory in Assembly

- many instructions can refer to memory instead of registers
  - use an “addressing mode” to specify what memory
- “register indirect mode” refers to memory through address stored in a register
  - written with parentheses around the register
  - example:
    - `movb (%rdi), %al`
    - reads 1 byte of memory pointed to by %rdi into %al like “`*%rdi`”
- “general indirect” mode allows indexing
  - written as two registers in parans with comma
  - example:
    - `movb (%rdi, %rsi), %al`
    - reads one byte from the address %rdi + %rsi like “`%rdi[%rsi]`”
- general form also allows a size to be given
  - example:
    - movl (%rdi, %rsi, 4), %eax
    - reads 4 bytes (l) from address %rdi + 4*%rsi
    - like %rdi[%rsi] if we think of %rdi as int*
  - only sizes 1,2,4 and 8 are allowed

What is a Buffer?

- A buffer is an array used to temporarily store data
  - You've probably seen "video buffering…"
  - Functions that accept user input set aside memory for incoming data
    - Specify size of buffer before you know size of user input

```
void echo() {
   char buf[8];
   gets(buf);
   puts(buf);
}
```

Unix buffer overflow vulnerability

- C does not check array bounds, no way to specify limit on number of characters to read into a function
  - arrays in C/C++ don't store their length
  - Many Unix/Linux/C functions don't check argument sizes
    - strcpy: copies string of arbitrary length to a destination
    - scanf, fscanf, sscanf,
- Allows overflowing (writing past the end) of buffers (arrays)
  - Buffer Overflow – Writing past the end of an array
- Provides opportunities for malicious programs
  - Stack grows "backwards" in memory
  - Data and instructions both stored in the same memory
  - surprisingly easy to exploit, programmers often leave code open to attacks

Implementation of Unix gets()

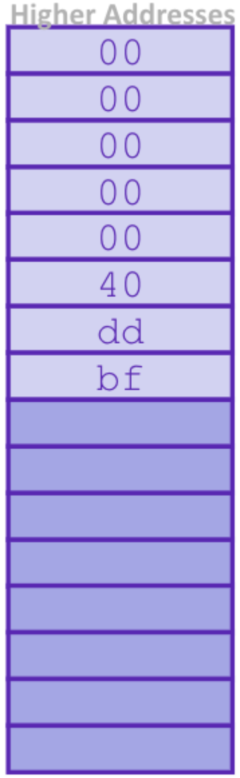
```
/* Get string from stdin */
char* gets(char* dest) {
    int c = getchar();
    char* p = dest;
    while (c != EOF && c != '\n') {
        *p++ = c;
        c = getchar();
    }
    *p = '\0';
    return dest;
}
```

pointer to start of an array

Same as:
```
*p = c;
p++;
```

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!

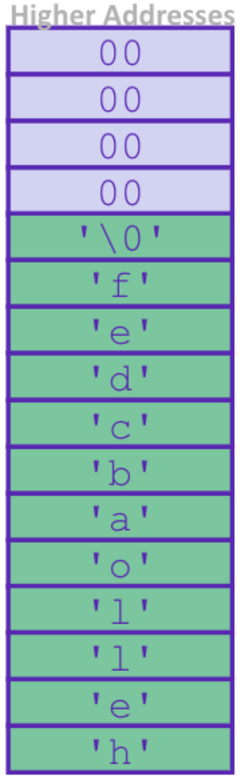


Enter input: hello

-> no overflow

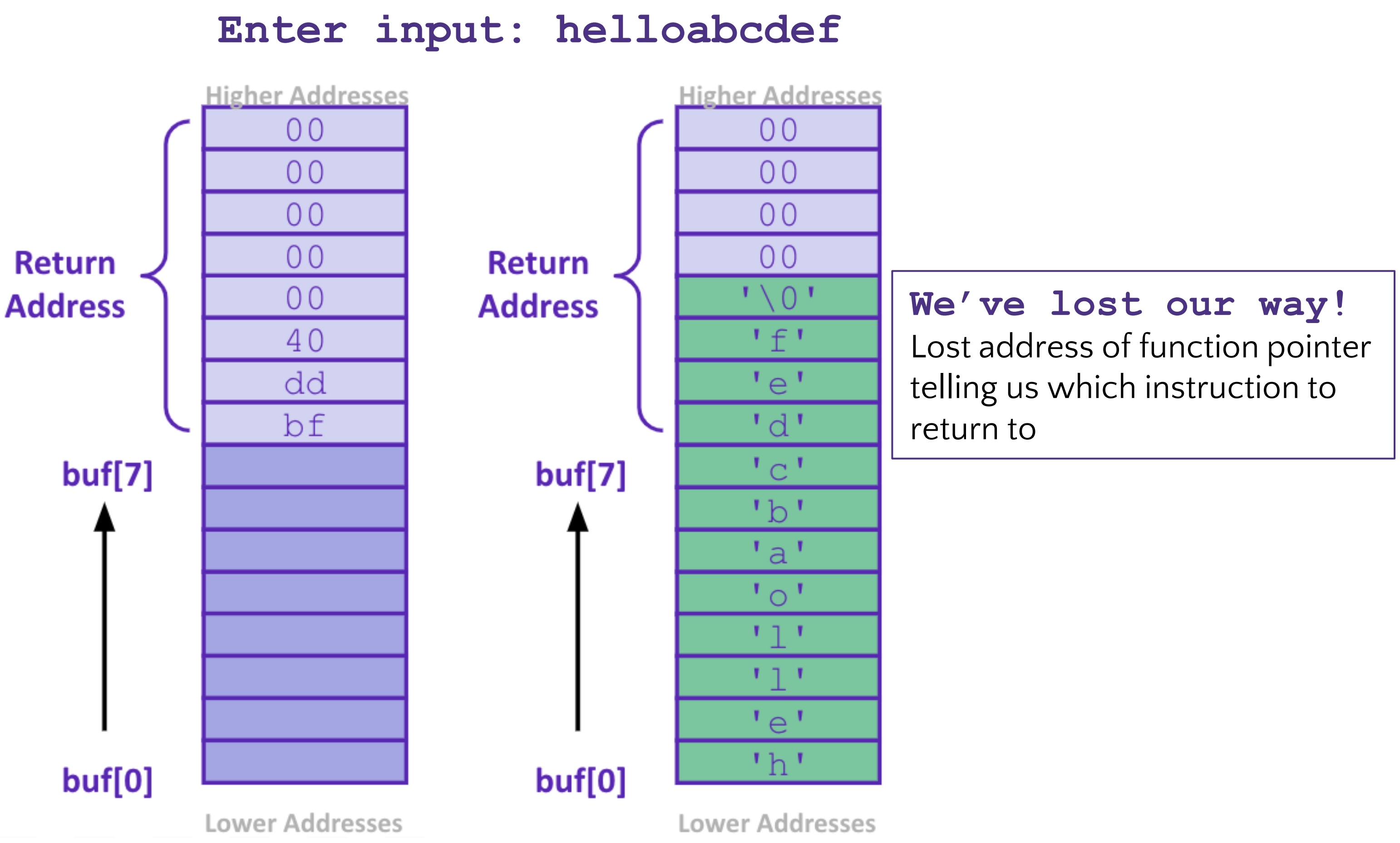
Enter input: helloabcdef

-> 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

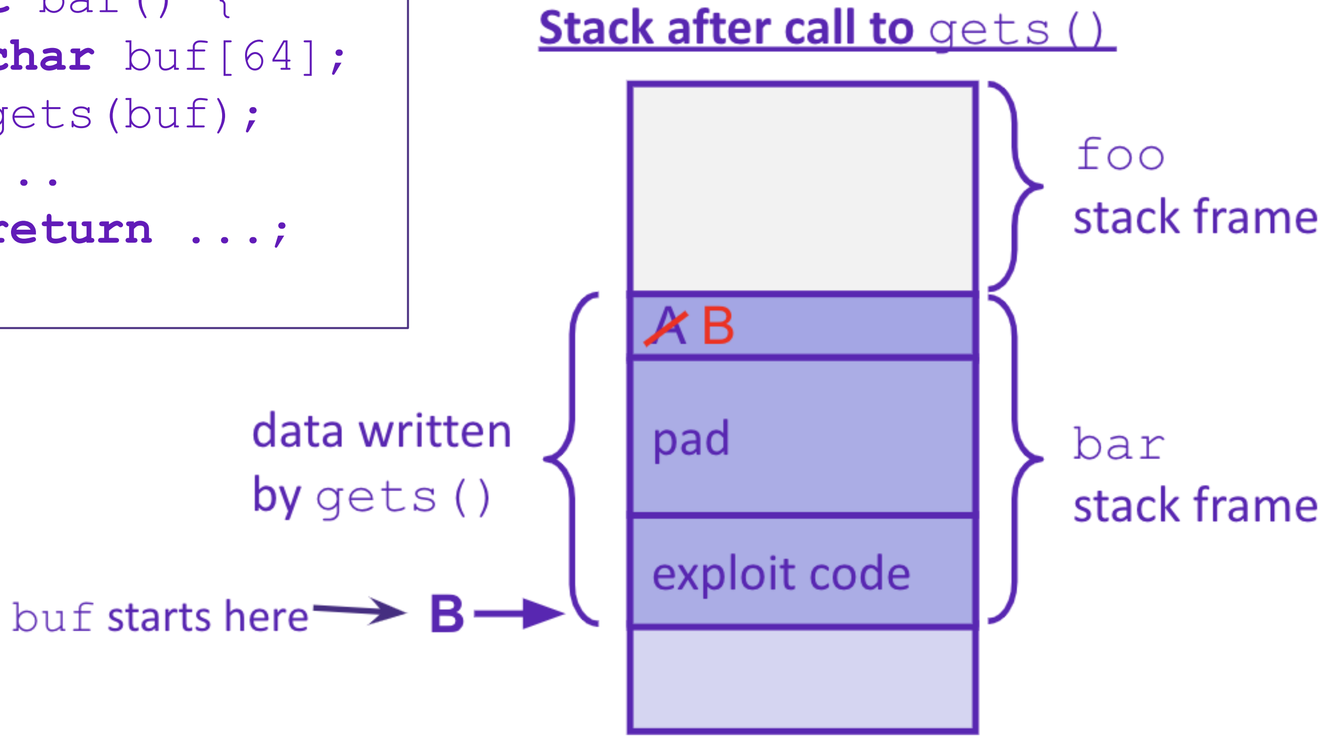


Malicious Buffer Overflow – Code Injection

- 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 ...;
}
```



https://arstechnica.com/gadgets/2020/12/iphone-zero-click-wi-fi-exploit-is-one-of-the-most-breathtaking-hacks-ever/

Change return to last frame

- Skip the line "x = 1;" in the main function by modifying function's return address.
  - Identify where the return address is in relation to the local variable buffer1
  - Figure out how many bytes the actual compiled C instruction "x=1;" takes, so that we can increment by that many bytes
- Use GDB
  - `break function`
    - break right at beginning of function execution
  - `x buffer1`
    - prints the location of buffer1
  - `info frame`
    - "rip" will hold the location of the return address
  - `print <rip-location> - <buffer1-location>`
    - prints the number of bytes between buffer1 and rip
  - `disassemble main`
    - shows the machine code and how many bytes each instruction takes up.
    - We identify the line that calls function, then see that the next // instruction moves 1 into x. That instruction takes 7 bytes, so we
    - have now found the second number!

```
void bufferplay (int a, int b, int c) {
  char buffer1[5];
  uintptr_t ret; //holds an address

  //calculate the address of the return pointer
  ret = (uintptr_t) buffer1 + 0; //change to be address of return

  //treat that number like a pointer,
  //and change the value in it
  *((uintptr_t*)ret) += 0; //change to add how much to advance
}

int main(int argc, char** argv) {
  int x;
  x = 0;
  printf("before: %d\n",x);
  bufferplay (1,2,3);
  x = 1; // want to skip this line
  printf("after: %d\n",x);
  return 0;
}
```

Trigger malicious program

```
int bar(char *arg, char *out) {
  strcpy(out, arg);
  return 0;
}
void foo(char *argv[]) {
  char buf[256];
  bar(argv[1], buf);
}
int main(int argc, char *argv[]) {
  if (argc != 2) {
    fprintf(stderr, "target1: argc != 2\n");
    exit(1);
  }
  foo(argv);
  return 0;
}
```

Victim Program

Attacker Program

```
int main(void) {
char *args[3];
char *env[1];
args[0] = "/tmp/target";
args[2] = NULL;
env[0] = NULL;

args[1] = (char*) malloc(sizeof(char)*265);

memset(args[1], 0x90, 264);

// Null-terminate the string.
args[1][264] = '\0';

// Add in the attack code to the front of the
argument. memcpy(args[1], shellcode,
strlen(shellcode));

*(uintptr_t*)(args[1] + 264) = 0x7fffffffdb90;
// call the victim program.
execve("/tmp/target", args, env); }
```

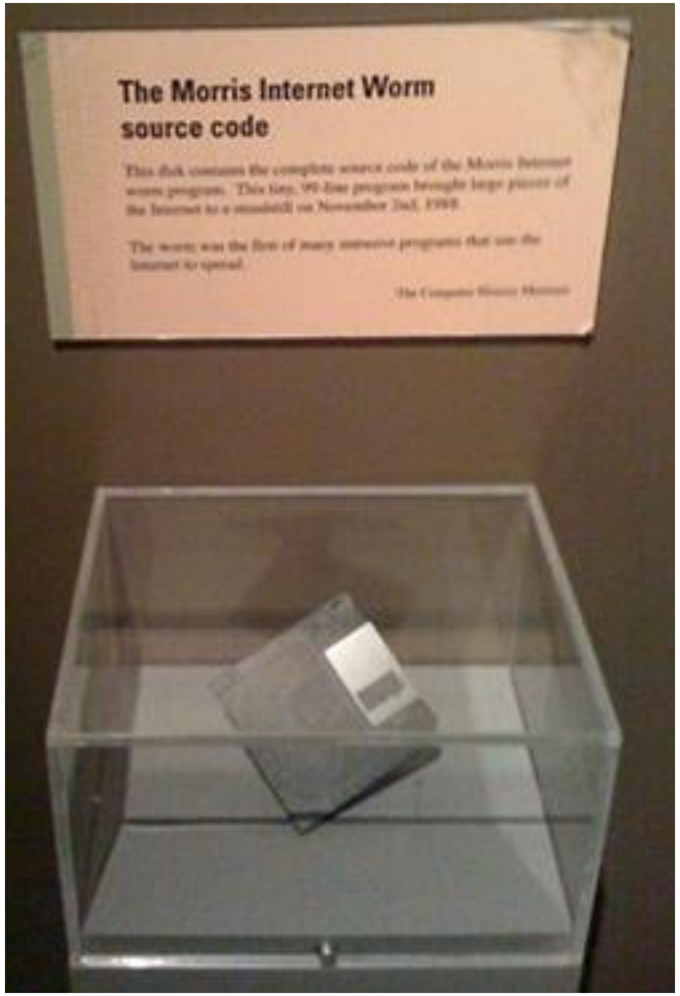
used gdb – there are 264 bytes between buf and return address, so we malloc space for 264, characters plus one for the null terminator.

set the memory to a value to ensure no null-termination in string before final character.
0x90 is also a byte that means "no-op" in terms of byte instructions.

Store address of buf at appropriate location in string

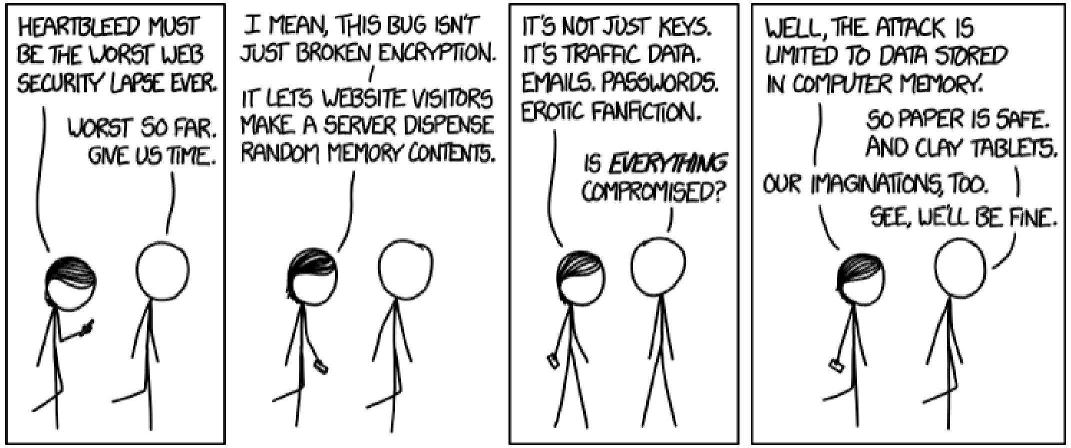
Hack – Internet Worm

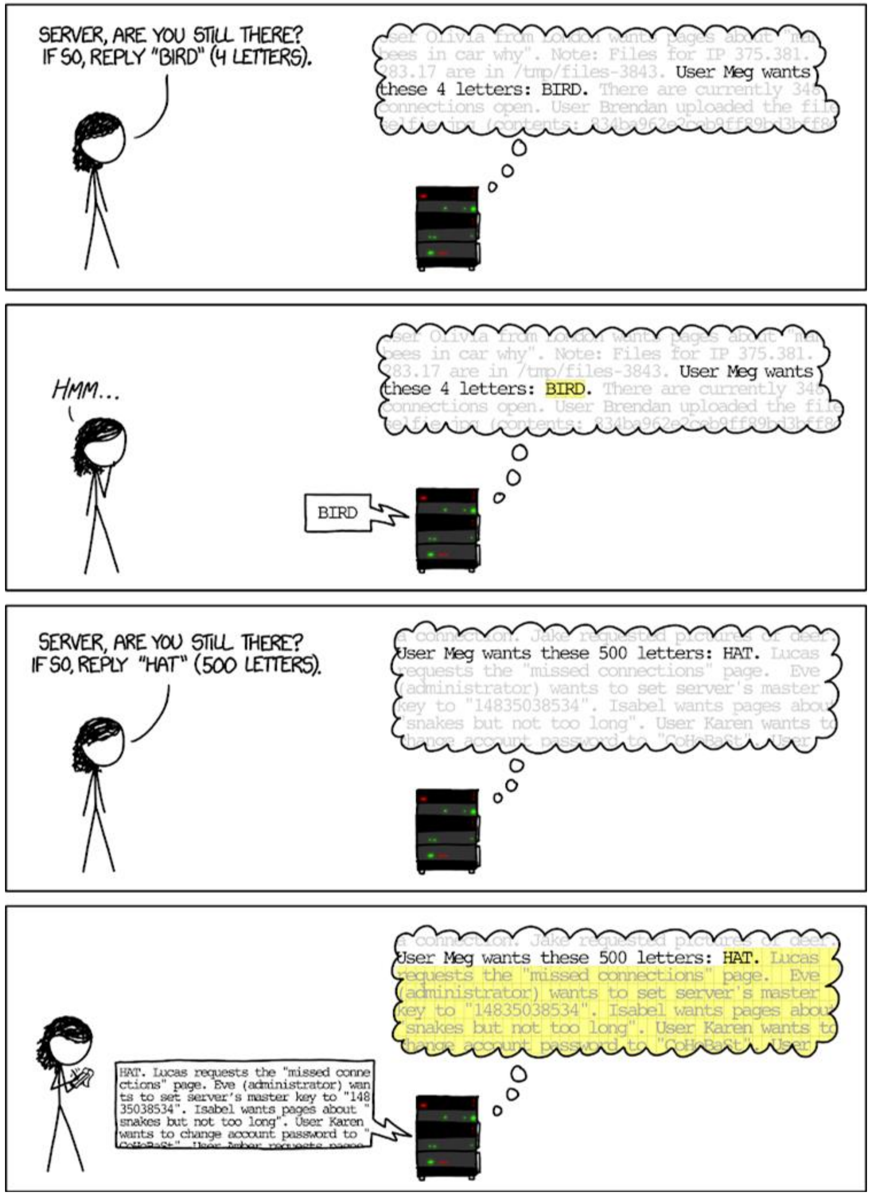
- Original "Internet worm" (1988)
- Exploited vulnerability in gets() method used in Finger protocol
  - Worm attacked fingerd server with phony argument
    - `finger "exploit-code padding new-return-addr"`
    - Exploit code: executed a root shell on the victim machine with a direct connection to the attacker
- Worm spread from machine to machine automatically
  - denial of service attack – flood machine with so many requests it is overloaded and unavailable to its intended users
  - took down 6000 machines, took days to get machine back online
  - government estimated damage $100,000 to $10,000,000
- Written by Robert Morris while a grad student at Cornell, but launched it from the MIT computer system
  - meant to be an intellectual experiment, but made it too damaging by accident
  - Now a professor at MIT, first person convicted under the '86 Computer Fraud and Abuse Act



Hack – Heartbleed

- Buffer over-read in Open-Source Security Library
  - when program reads beyond end of intended data from a buffer and reads
- maliciously designed input – "Heartbeat" packet sent out
  - 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



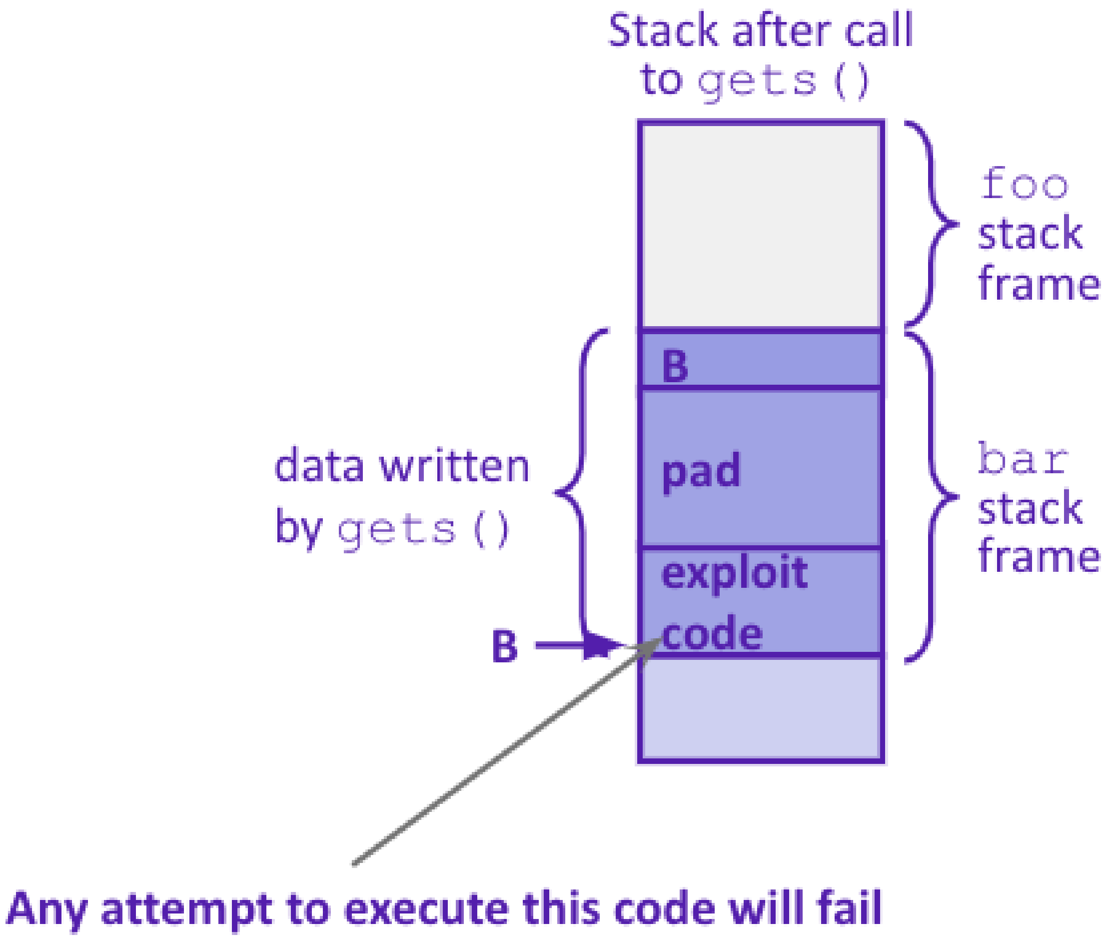


Protect Your Code!

- 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

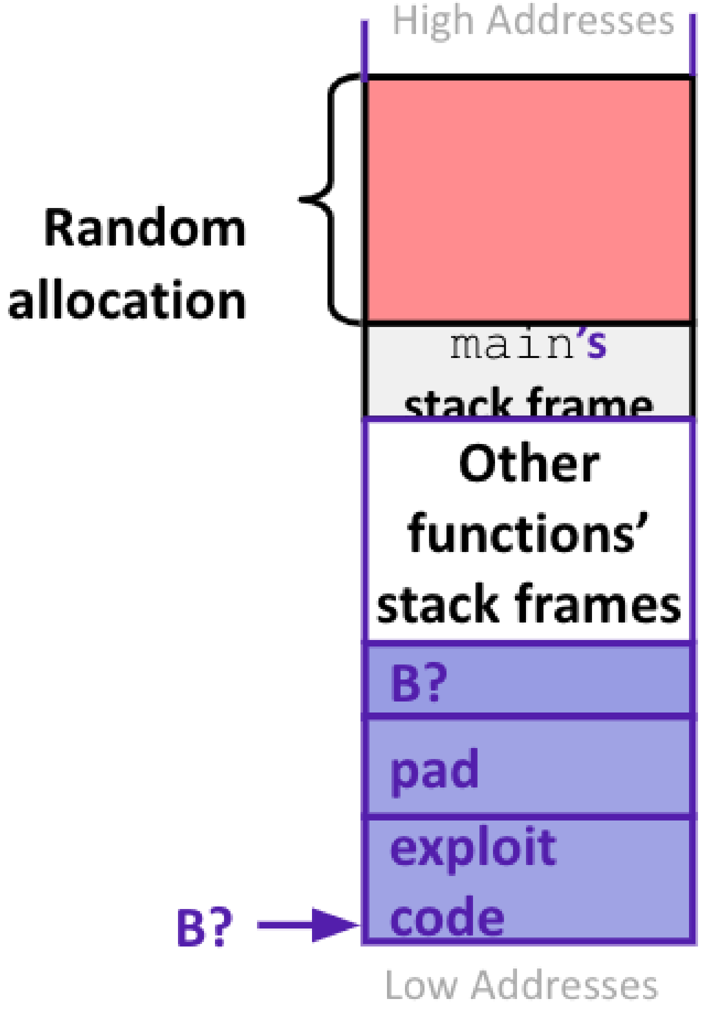
System Level Protections

- 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



System Level Protections

- Many embedded devices *do not* have feature to mark code as "non-executable"
  - Cars
  - Smart homes
  - Pacemakers
- 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);
}
```

- Or… 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 ***
```

What is Concurrency?

- Running multiple processes simultaneously
  - running separate programs simultaneously
  - running two different 'threads' in on program
- Each 'process' is one 'thread'
- parallelism refers to running things simultaneously on **separate** resources (ex. Separate CPUs)
- concurrency refers to running multiple threads on a **shared** resources
- sequential programming demands finishing one sequence before starting the next one
- previously, performance improvements could only be made by improving hardware
  - Moore's Law
- Allows processes to run 'in the background'
  - Responsiveness – allow GUI to respond while computation happens
  - CPU utilization – allow CPU to compute while waiting (waiting for data, for input)
  - isolation – keep threads separate so errors in one don't affect the others

Concurrency

- C and Java support parallelism similarly
  - one pile of code, globals, heap
  - multiple ”stack + program counter’s” – called threads
  - threads are run or pre-empted by a scheduler
  - threads all share the same memory
  - Various synchronization mechanisms control when threads run
    - don’t run until I’m done with this
- C: the POSIX Threads (pthreads) library)
  - #include <pthread.h>
  - pass –lpthread to gcc (when linking)
  - pthread_create takes a function pointer and arguments, run as a separate thread
- Java: built into the language
  - subclass java.lang.Thread, and override the run method
  - create a Thread object and call its start method
  - any object can ”be synchronized on” (later today)

Pthread functions

- `pthread_t thread ID;`
  - the threadID keeps trak of to which thread we are referring

- `int pthread_create(pthread_t *thread, const pthread_attr_t *attr, void *(*start routing) (void*), void *arg);`
  - note – pthread_create takes two generic (untyped) pointers
  - interprets the first as a function pointer and the second as an argument pointer

- `int pthread_join(pthread_t thread, void **value_ptr);`
  - puts calling thread 'on hold' until 'thread' completes – useful for waiting to thread to exit

https://pubs.opengroup.org/onlinepubs/7908799/xsh/pthread.h.html

Memory Consideration

- if one thread did nothing of interest to any other thread, why bother running?
- threads must communicate and coordinate
  - use results from other threads, and coordinate access to shared resources
- simplest ways to not mess each other up:
  - don't access same memory (complete isolation)
  - don't write to shared memory (write isolation)
- next simplest
  - one thread doesn't run until/unless another is done

Parallel Processing

- common pattern for expensive computations (such as data processing)

1. split up the work, give each piece to a thread (fork)
2. wait until all are done, then combine answers (join)

- to avoid bottlenecks, each thread should have about the same about of work

- performance will always be less than perfect speedup

- what about when all threads need access to the same mutable memory?

multiple threads with one memory

- often you have a bunch of threads running at once and they might need rthe same mutable (writable) memory at the same time but probably not
  - want to be correct, but not sacrifice parallelism

- example: bunch of threads processing bank transactions

data races

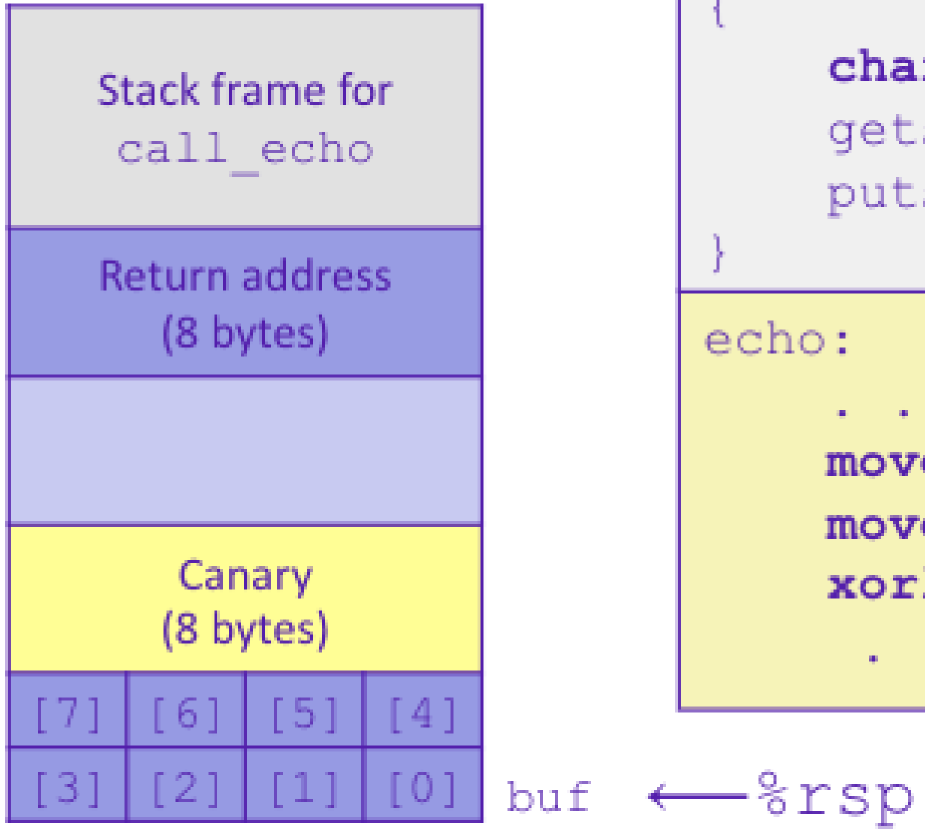
Questions

Protected Buffer Disassembly (buf)

```
400607:  sub    $0x18,%rsp
40060b:  mov    %fs:0x28,%rax
400614:  mov    %rax,0x8(%rsp)
400619:  xor    %eax,%eax
 ...     ... call printf ...
400625:  mov    %rsp,%rdi
400628:  callq  400510 <gets@plt>
40062d:  mov    %rsp,%rdi
400630:  callq  4004d0 <puts@plt>
400635:  mov    0x8(%rsp),%rax
40063a:  xor    %fs:0x28,%rax
400643:  jne    40064a <echo+0x43>
400645:  add    $0x18,%rsp
400649:  retq
40064a:  callq  4004f0
<__stack_chk_fail@plt>
```

Setting up Canary

Before call to gets

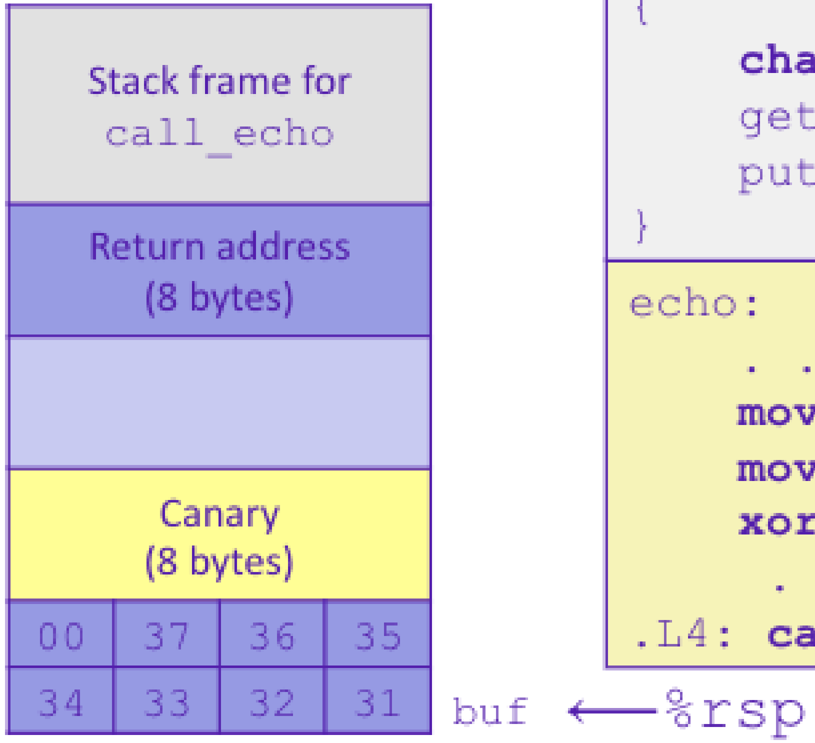



```
/* Echo Line */
void echo()
{
    char buf[8];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
echo:
    . . .
    movq    %fs:40, %rax     # Get canary
    movq    %rax, 8(%rsp)    # Place on stack
    xorl    %eax, %eax       # Erase canary
     . . .
```

Checking Canary

After call to gets




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

```
echo:
    . . .
    movq    %fs:40, %rax      # Get canary
    movq    %rax, 8(%rsp)     # Place on stack
    xorl    %eax, %eax        # Erase canary
     . . .
.L4: call   __stack_chk_fail
```

Input: *1234567*