SFU SIMON FRASER UNIVERSITY
ENGAGING THE WORLD

Shellcode Development

What is a program?

A program is just a set of instructions (assembly) with variables

- Where are the instructions stored?
- What if those instructions could be overwritten?
- What if the *pointer* to those instructions could be redirected?

Attacker Goal

To execute arbitrary code from a victim program

1. Open a new shell from a running program
   - Or a Root shell if the victim program is setuid root
   - The instructions to open a new shell is “shellcode”
2. Once you have a shell, you can execute arbitrary code
   - Add a new user with administrative privileges
   - Point “google.com” to an attacker server
   - …

Attacker Steps

1. Target a vulnerable program
2. Construct shellcode to attack the victim program
3. Inject this code in the normal flow of the program
    - To do this, an attacker needs to find a vulnerable function
    - Details next week!

This week's goal

1. Assembly revision

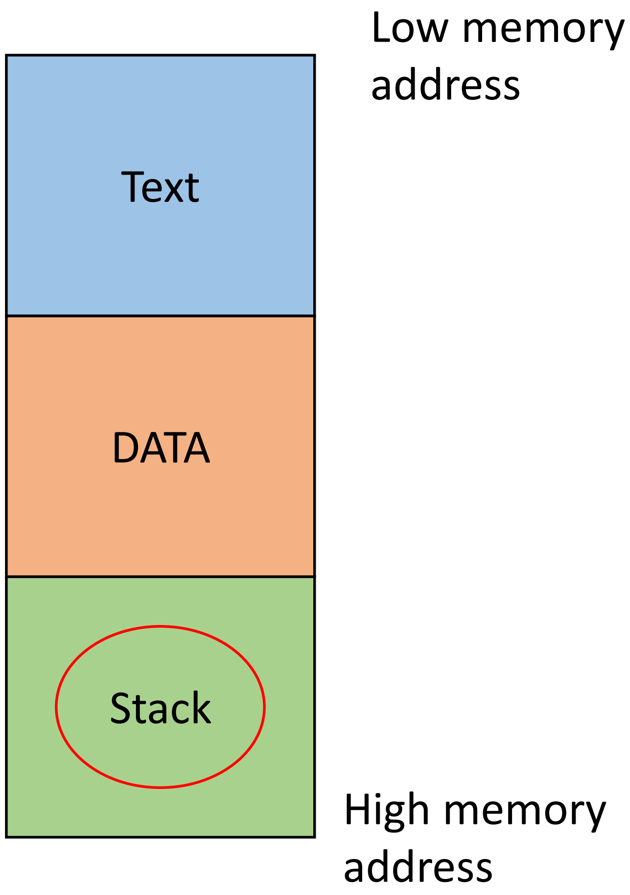
2. Understanding program flow and memory stack

3. Constructing shellcode

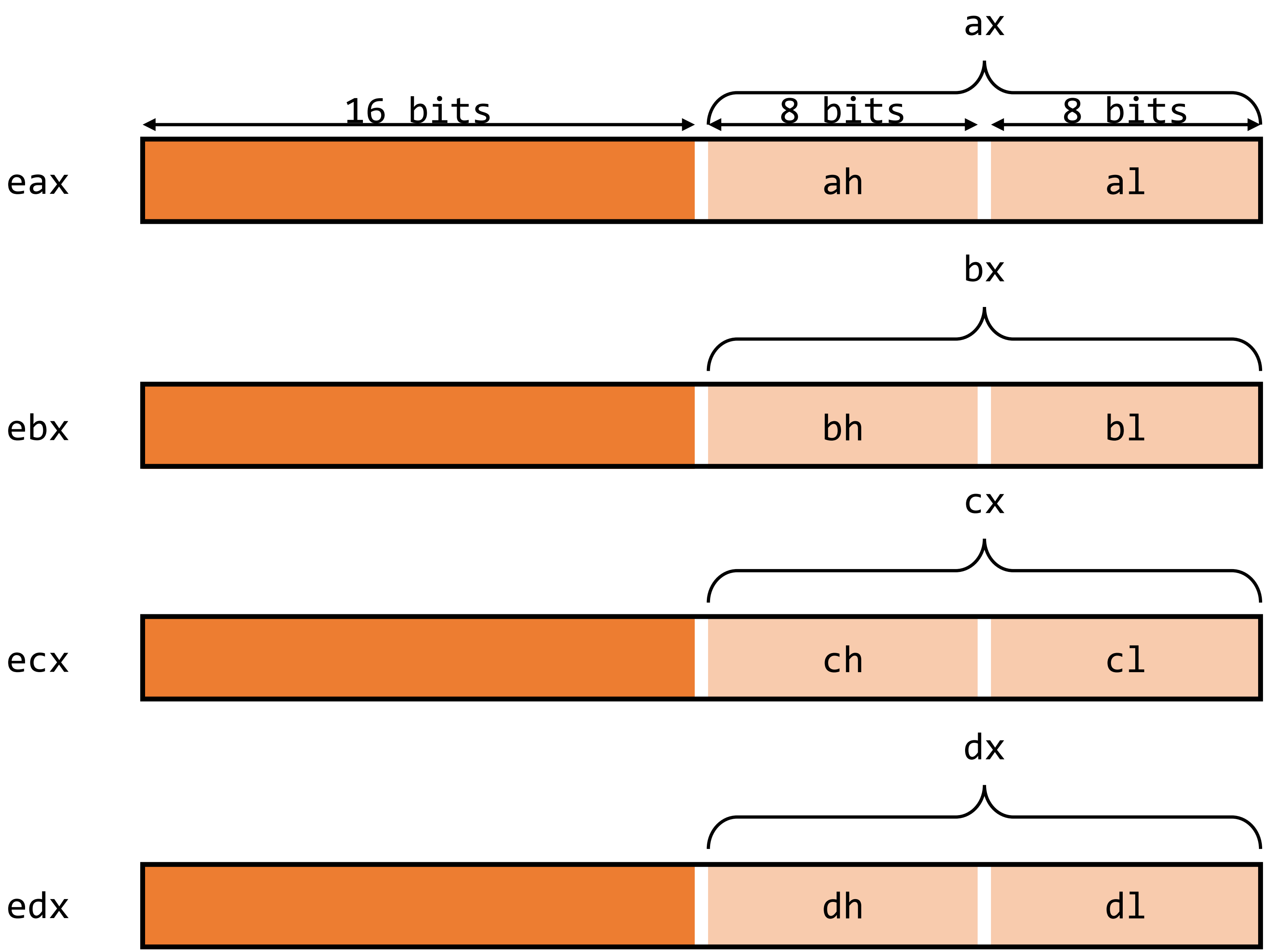
    - No injection yet – we will just call it directly

Process Memory Organization

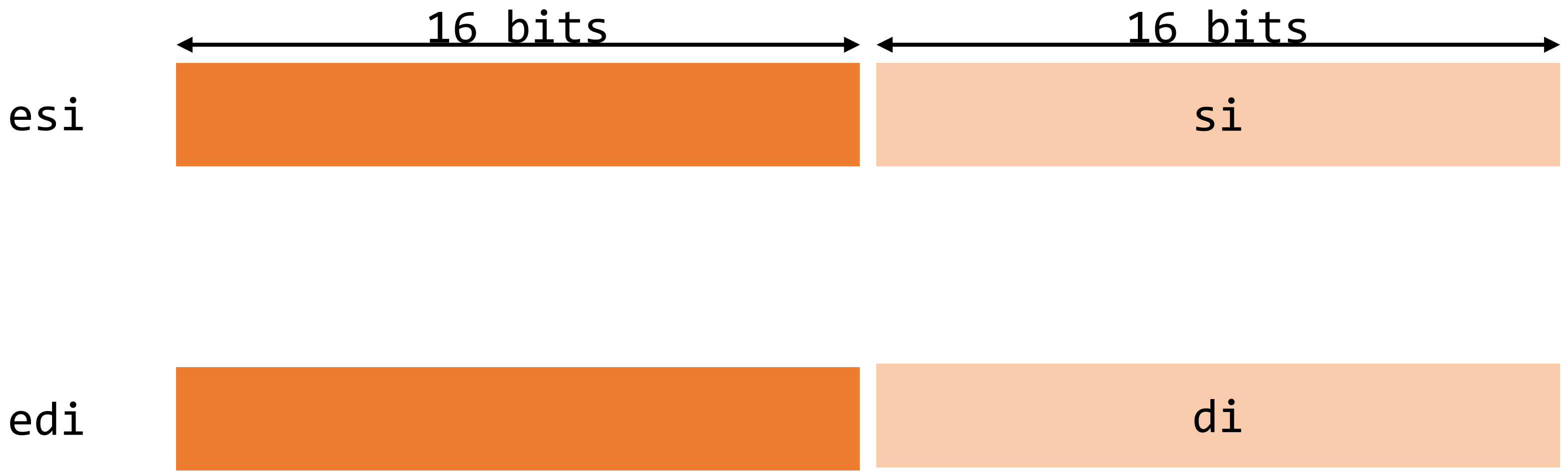
- A process is divided into three regions.
- Text
  - Fixed region
  - Includes instructions and Read-only data
- Data
  - Initialized and uninitialized data
  - Dynamic vars (heap)
- Stack (LIFO abstraction)
  - Maintains state of caller/callee of functions
  - Used for storing:
    - Local variables
    - Parameters
    - Return value



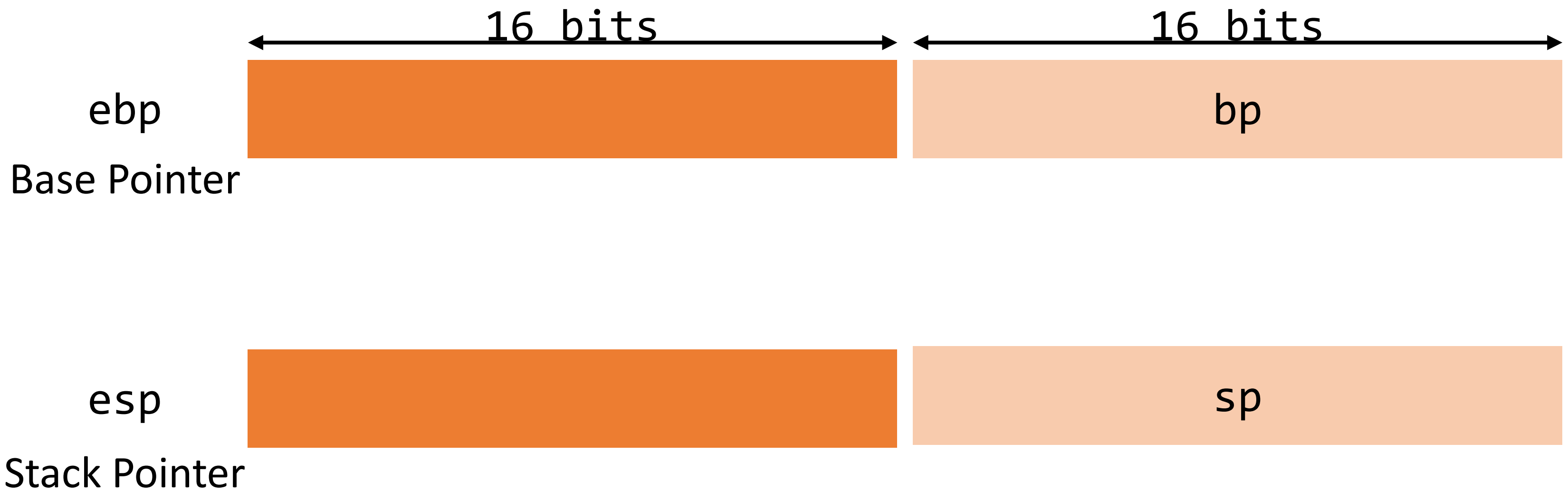
x86 Registers – General-purpose

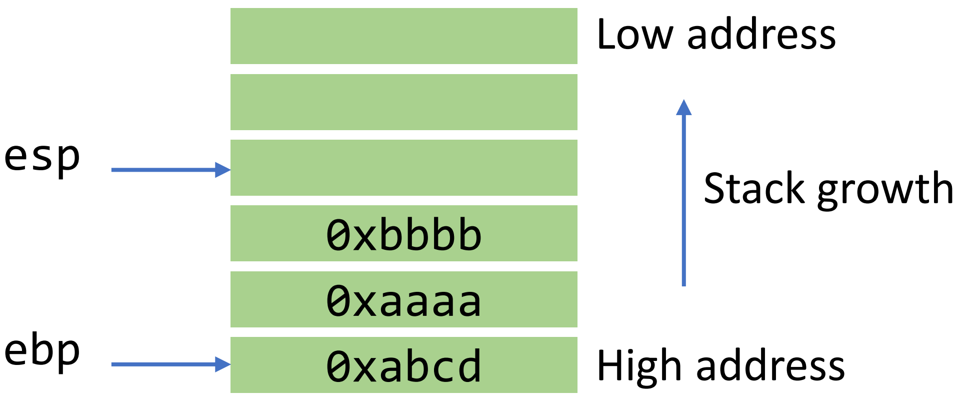


x86 Registers – General-purpose



x86 Registers – Special-purpose





Sample x86 Instructions – Arithmetic/Logic

```
add dst, src

inc dst

xor dst, src
```

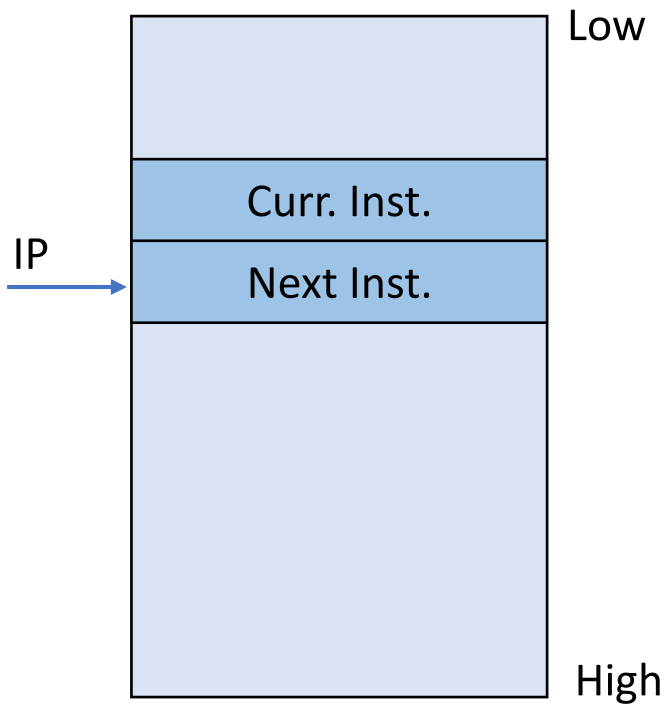
Sample x86 Instructions – Data Movement

```
mov dst, src

push src

pop dst
```

Control Flow

- A special register called IP:
  - Points to the next instruction to be executed
  - Cannot be **directly** altered
- CPU increments IP unless it executes an inst. that changes the flow of control, e.g.,:
  - `jmp, jne, jeq, …`
  - `call`
  - `ret`
  - …

(More on call and ret later)

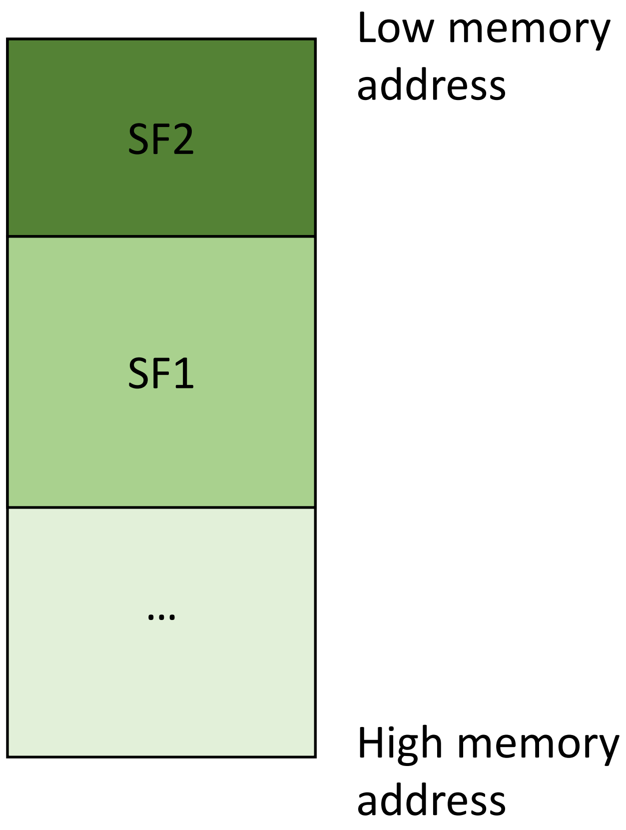


Stack Region

- Contiguous block of memory containing data
- Logically divided into Stack Frames

- Every Stack Frame is:
  - Pushed when calling a function
  - Popped when returning

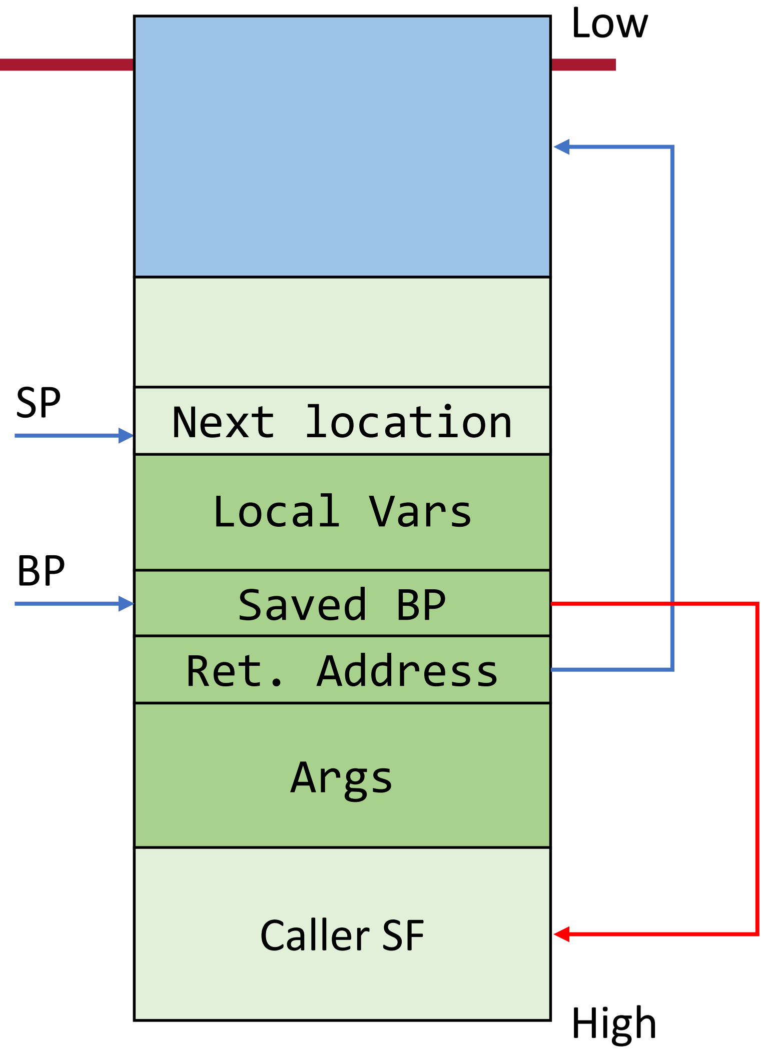
- Stack Frame (activation record) contains:
  - the parameters to a function,
  - its local variables, and
  - the data necessary to recover the previous stack frame



Stack Region

- Two pointers:
  - BP: points to a fixed location of a stack frame
  - SP: points to the top of the stack

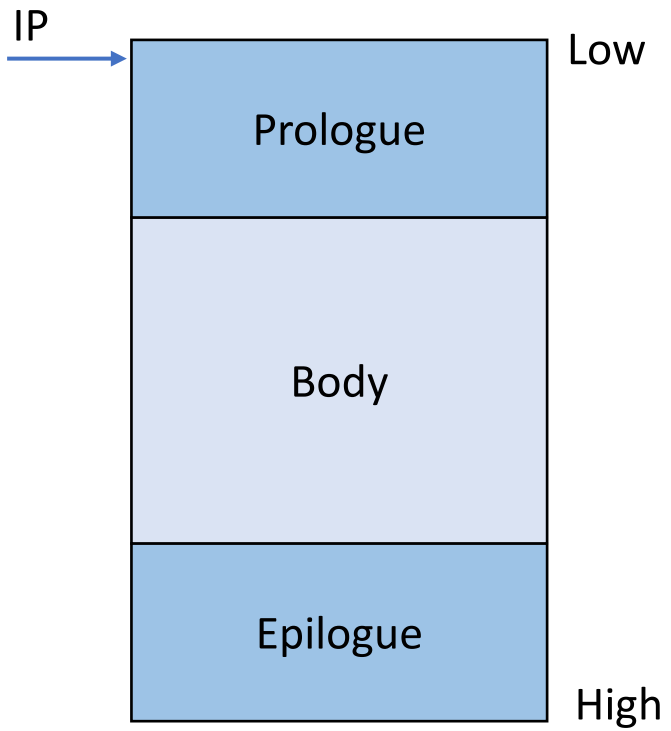
- On Intel CPU → ebp and esp



Functions: Calling Conventions

- A function prologue:
  - maintains a snapshot of ebp
    - push ebp to the stack
    - copy esp to ebp
  - allocates local variables by decrementing esp
  - saves register values on the stack

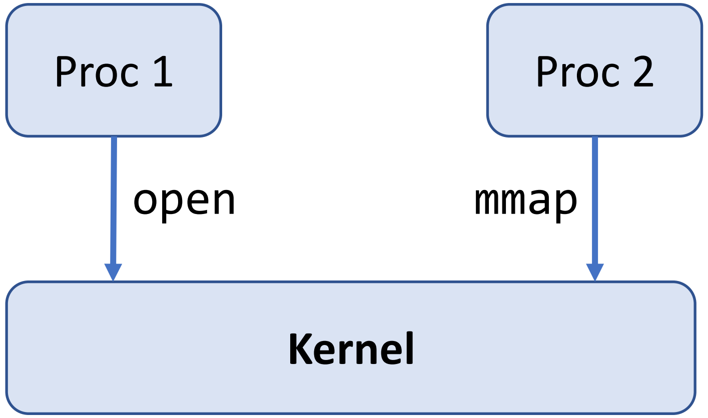
- A function epilogue:
  - recovers register values from the stack
  - deallocates the local variables by resetting esp
  - recovers the caller's ebp
  - calls ret



System Calls

- User-space programs often need services from the kernel:
  - IO (`open, read, write, …`)
  - Modify address space (`mmap, sbrk, …`)

- These programs trigger the kernel to perform these operations by using System Calls.
  - "Software Interrupts"



System Calls

- Move arguments to `ebx, ecx, edx, esi, edi`
- Move syscall number to `eax`
- `int 0x80`

- We need two pieces of info.
  - System call number
  - System call interfaces

Linux System Call Table

- System call numbers: [https://github.com/torvalds/linux/blob/master/**arch**/**x86**/entry/syscalls/syscall_**32**.tbl](https://github.com/torvalds/linux/blob/master/arch/x86/entry/syscalls/syscall_32.tbl)

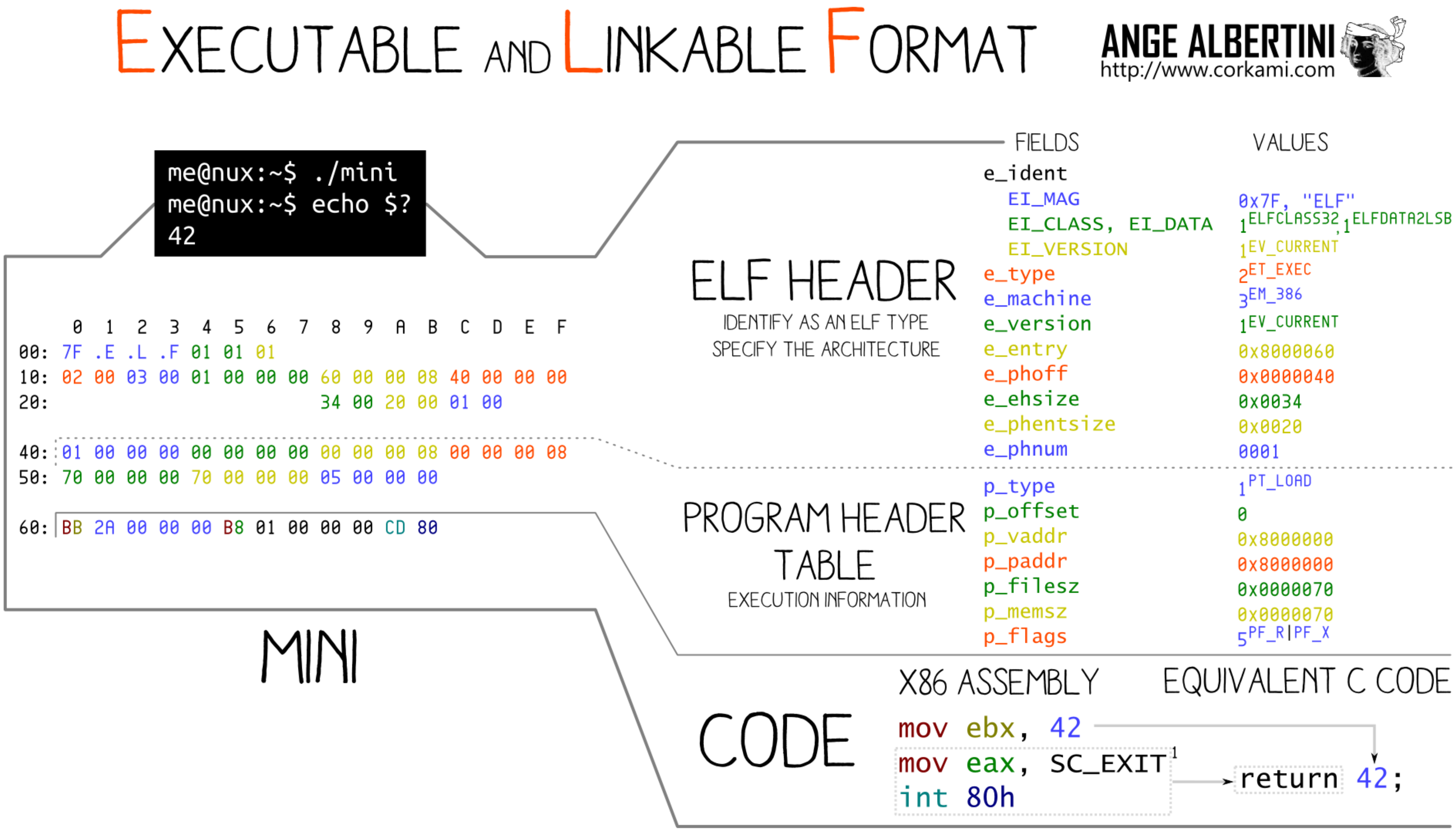
0	i386	restart_syscall	sys_restart_syscall
1	i386	exit	sys_exit
2	i386	fork	sys_fork
3	i386	read	sys_read
4	i386	write	sys_write
5	i386	open	sys_open
6	i386	close	sys_close
7	i386	waitpid	sys_waitpid
8	i386	creat	sys_creat
9	i386	link	sys_link
10	i386	unlink	sys_unlink
11	i386	execve	sys_execve
12	i386	chdir	sys_chdir
13	i386	time	sys_time32
14	i386	mknod	sys_mknod
15	i386	chmod	sys_chmod
16	i386	lchown	sys_lchown16

Linux System Call Table

- System call interfaces: https://github.com/torvalds/linux/blob/master/include/linux/syscalls.h

```
asmlinkage long sys_exit(int error_code);
asmlinkage long sys_read(unsigned int fd, char __user *buf, size_t count);
asmlinkage long sys_write(unsigned int fd, const char __user *buf,
                          size_t count);
```

ELF



EXECUTABLE AND LINKABLE FORMAT
ANGE ALBERTINI
http://www.corkami.com
me@nux:~$ ./mini
me@nux:~$ echo $?
42
0 1 2 3 4 5 6 7 8 9 A B C D E F
00: 7F .E .L .F 01 01 01
10: 02 00 03 00 01 00 00 00 60 00 00 08 40 00 00 00
20: 34 00 20 00 01 00
40: 01 00 00 00 00 00 00 00 00 00 00 08 00 00 00 08
50: 70 00 00 00 70 00 00 00 05 00 00 00
60: BB 2A 00 00 00 B8 01 00 00 00 CD 80
MINI
ELF HEADER
IDENTIFY AS AN ELF TYPE
SPECIFY THE ARCHITECTURE
FIELDS
VALUES
e_ident
EI_MAG
0x7F, "ELF"
EI_CLASS, EI_DATA
1 ELFCLASS32, 1 ELFDATA2LSB
EI_VERSION
1 EV_CURRENT
e_type
2 ET_EXEC
e_machine
3 EM_386
e_version
1 EV_CURRENT
e_entry
0x8000060
e_phoff
0x0000040
e_ehsize
0x0034
e_phentsize
0x0020
e_phnum
0001
PROGRAM HEADER TABLE
EXECUTION INFORMATION
p_type
1 PT_LOAD
p_offset
0
p_vaddr
0x8000000
p_paddr
0x8000000
p_filesz
0x0000070
p_memsz
0x0000070
p_flags
5 PF_R|PF_X
CODE
X86 ASSEMBLY
EQUIVALENT C CODE
mov ebx, 42
mov eax, SC_EXIT 1
int 80h
return 42;

Syntax

- AT&T syntax

```
mov $42, %ebx
mnemonic source, destination
```

- Intel syntax

```
mov ebx, 42
mnemonic destination, source
```

We will use the Intel syntax

Required tools

- `gcc`
- `gdb`
- `ld`
- `nasm` (https://www.nasm.us/)
- `objdump`

- `nasm` *and* `objdump` *can understand AT&T and Intel syntax*

Three Examples

- `mini`
- `HelloWorld`
- `Spawn a Shell`

- We will:
  - write the assembly code, get its machine code, and call it from a C program

Techniques

- Relative Addressing (or using code segment)
- Pushing data to stack
- Enable Privileges
- Shellcode Copying
- Reducing shellcode size (why?)

mini

- exit(42)

mini

```
[SECTION .text]
global _start
_start:
     mov ebx, 42
     mov eax, 0x1
     int 0x80
```

```
$ nasm -f elf mini.s  # creates an object file
$ ld –o mini mini.o   # runs the linker
$ ./mini              # executes the program
$ echo $?             # print status of mini
$ 42                  # output
```

Disassemble **mini**

```
$ objdump -Mintel --disassemble mini


mini:     file format elf32-i386

Disassembly of section .text:

08048060 <_start>:
 8048060:  bb 2a 00 00 00          mov    $0x2a,%ebx
 8048065:  b8 01 00 00 00          mov    $0x1,%eax
 804806a:  cd 80                   int    $0x80
```

`mini` executable bytes are: **`bb 2a 00 00 00 b8 01 00 00 00 cd 80`**

helloworld

- How many syscalls?

helloworld

- Two syscalls: `write` and `exit`

```
[SECTION .data]
      msg db "Hello, world!", 0xA, 0xD
[SECTION .text]
global _start
_start:
      mov eax, 4    ; opcode for write system call
      mov ebx, 1    ; 1st arg, fd = 1
      mov ecx, msg  ; 2nd arg, msg
      mov edx, 15   ; 3rd arg, len
      int 0x80      ; system call interrupt

      mov eax, 1    ; opcode for exit system call
      mov ebx, 0    ; 1st arg, exit(0)
      int 0x80      ; system call interrupt
```

Shellcode

- The set of instructions injected and then executed by an exploited program
  - usually, a shell is started
  - for remote exploits - input/output redirection via socket – use system call (execve) to spawn shell

- Shellcode can do practically anything:
  - create a new user
  - change a user password
  - modify the .rhost file
  - bind a shell to a port (remote shell)
  - open a connection to the attacker machine

Testing shellcode

```
#include <stdio.h>
#include <string.h>

char code[] = "bytecode will go here!";
int main(int argc, char **argv)
{
  int (*func)();
  func = (int (*)()) code;
  (int)(*func)();
}
```

```
$ gcc code.c -o output -fno-stack-protector -z execstack -no-pie -m32
```

Shellocode: **mini**

```
char code[] =
“\xbb\x2a\x00\x00\x00\xb8\x01\x00\x00\x00\xcd\x80”;
```

```
$ ./mini_shelltest
$ echo $?
$ 42
```

Shellocode: **`helloworld`**

```
char code[] = “\xb8\x04\x00\x00\x00\xbb\x01\x00\x00
               \x00\xb9\xa4\x90\x04\x08\xba\x0f\x00
               \x00\x00\xcd\x80\xb8\x01\x00\x00\x00
               \xbb\x00\x00\x00\x00\xcd\x80”
```

```
$ gcc helloworld.c -o shelltest -fno-stack-protector -z execstack -no-pie -m32
$ ./shelltest
```

[\

This isn’t “Hello, world!\n”, what happened?!

A bug!

Let’s disassemble **helloworld**

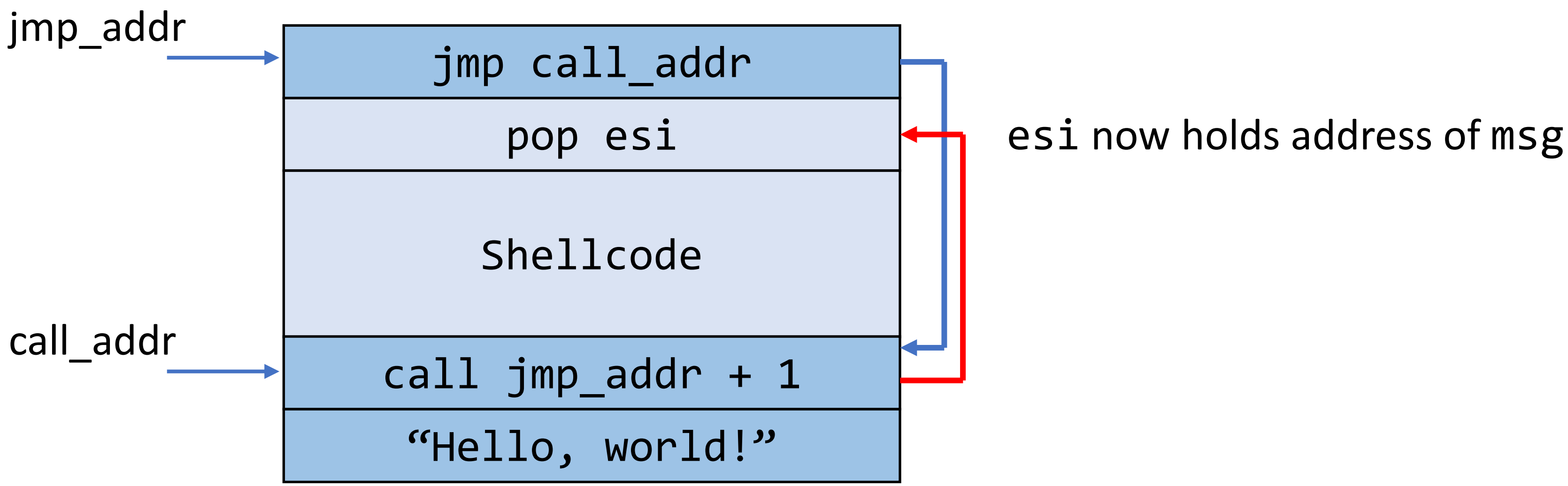
```
$ objdump -d helloworld

08048080 <_start>:
 8048080:   b8 04 00 00 00          mov    eax, 4
 8048085:   bb 01 00 00 00          mov    ebx, 1
 804808a:   b9 a4 90 04 08          mov    ecx, 0x080490a4
 804808f:   ba 0f 00 00 00          mov    edx, 15
 8048094:   cd 80                   int    0x80
 8048096:   b8 01 00 00 00          mov    eax, 1
 804809b:   bb 00 00 00 00          mov    ebx, 0
 80480a0:   cd 80                   int    0x80
```

Relative addressing (or Using Code Segment)

- Problem - position of code in memory is unknown
  - We cannot know the address of `msg`
- We can leverage instructions that modified the control flow
- `call` instruction saves IP on the stack and jumps

- Idea
  - `jmp` instruction at beginning of shellcode to `call` instruction
  - `call` instruction right before the string
  - `call` jumps back to first instruction after `jmp`
  - now address of "Hello, world!" is on the stack

Relative addressing (or Using Code Segment)



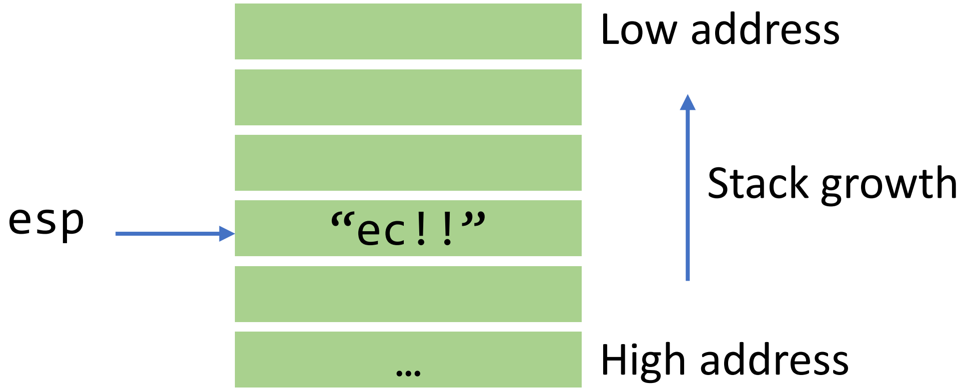
Shellocode: **helloworld_v2**

```
char code[] = "…"
```

```
$ gcc helloworld_v2.c -o shelltest_v2 -fno-stack-protector -z execstack -no-pie -m32
$ ./shelltest_v2
$ Hello, world!
```

Pushing Bytes to the Stack

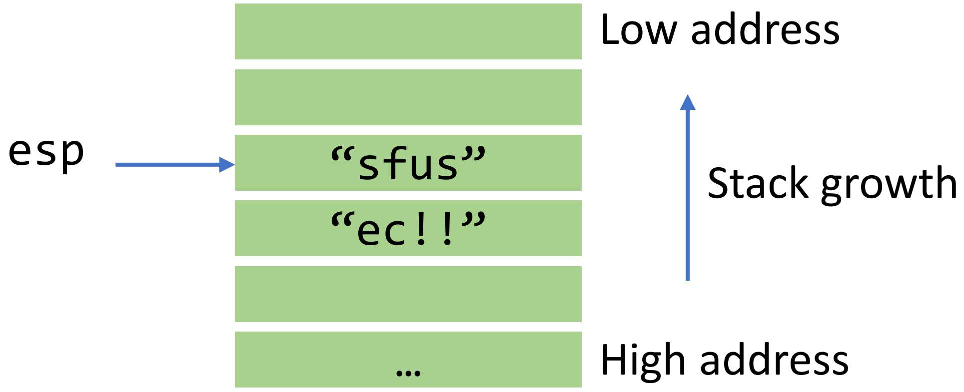
To print “sfusec!!”




```
push “ec!!”
```

Pushing Bytes to the Stack

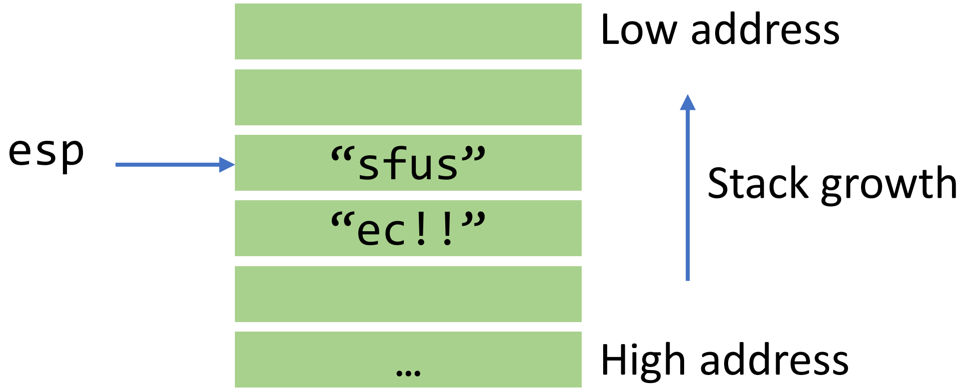
To print “sfusec!!”




```
push “ec!!”
push “sfus”
```

Pushing Bytes to the Stack

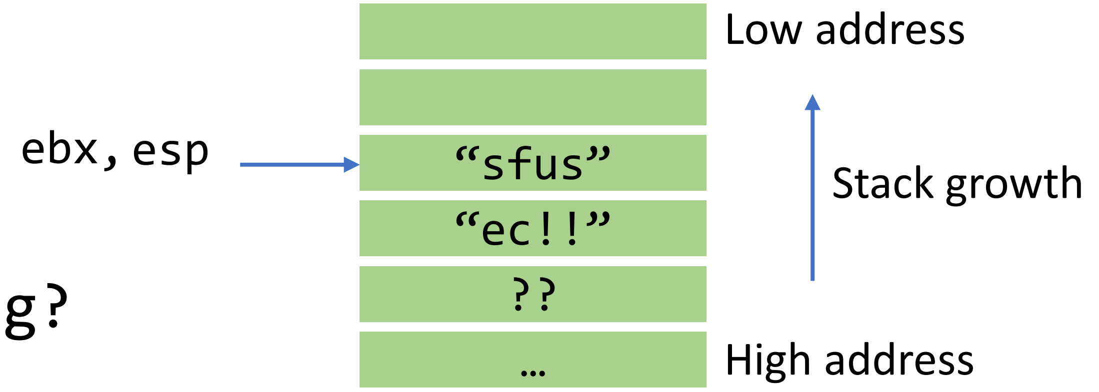
To print “sfusec!!”




```
push “ec!!”
push “sfus”
??              ; how to get string address?
```

Pushing Bytes to the Stack

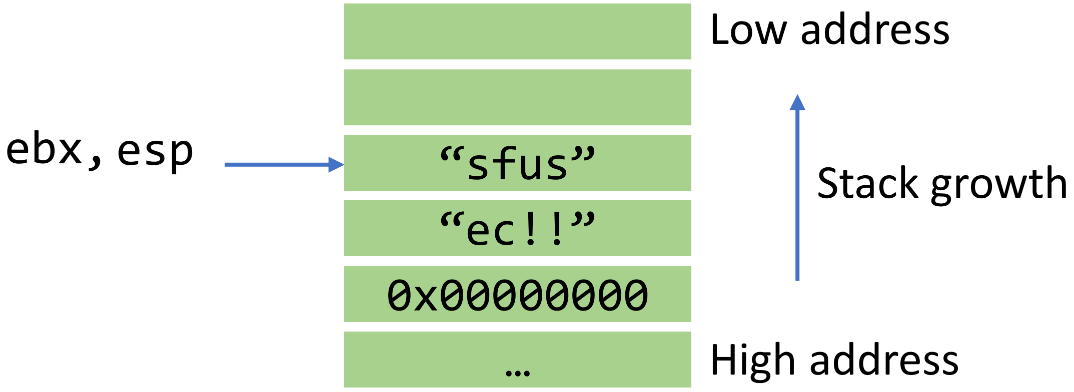
To print “sfusec!!”




```
??               ; what’s missing?
push “ec!!”
push “sfus”
mov ebx, esp   ; how to get string address?
```

Pushing Bytes to the Stack

To print "sfusec!!"




```
push 0x00      ; NULL
push "ec!!"
push "sfus"
mov ebx, esp   ; how to get string address?
```

Spawn a Shell

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

1. file: name of program to be executed
2. argv: address of null-terminated argument array
3. env: address of null-terminated environment array

Spawn a Shell

```
#include <stdlib.h>
#include <unistd.h>
void main(int argc, char **argv) {
        char *shell[2];
        shell[0] = "/bin/sh";
        shell[1] = 0;
        execve(shell[0], &shell[0], 0);
        exit(0);
 }
```

Spawn a Shell in Assembly

1. Check system call interface:

```
asmlinkage long sys_execve(const char __user *filename,
                           const char __user *const __user *argv,
                           const char __user *const __user *envp);
```

ebx

ecx

edx

- move address of string "/bin/sh0" into ebx
- move address of the address of "/bin/sh0" into ecx (how?)
- move address of null word into edx

2. Check system call number:

- move system call number (11) into eax

3. Execute the interrupt 0x80 instruction

Spawn a Shell in Assembly

- file parameter (ebx)
  - we need the null terminated string /bin/sh somewhere in memory
- argv parameter (ecx)
  - we need the address of the string /bin/sh somewhere in memory
  - followed by a NULL word
- env parameter (edx)
  - we need a NULL word somewhere in memory

Enable Privileges

- Concept of user identifiers (uids)
  - real user id: ID of process owner
  - effective user id: ID used for permission checks
  - saved user id: used to temporarily drop and restore privileges

- Problem:
  - exploited program could have temporarily dropped privileges
- Technique:
  - Shellcode has to enable privileges again (using setuid)
  - How?

Further Reading

- Hacking: The Art of Exploitation, 2nd Edition
  - Chapter 5
  - Available online at SFU library (using your SFU email)

Todo list

- Project ideas