Method for Analysis of Code-reuse Attacks

Reverse Engineering of ROP Exploits

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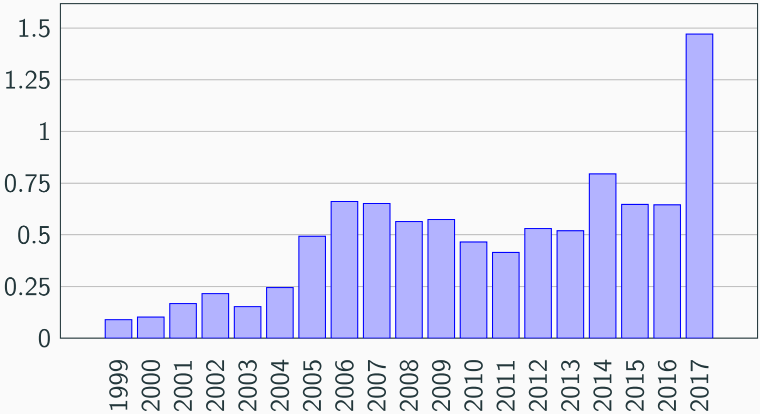
Vulnerabilities by Year

Number (tens of thousands) of new vulnerabilities (CVE) by year



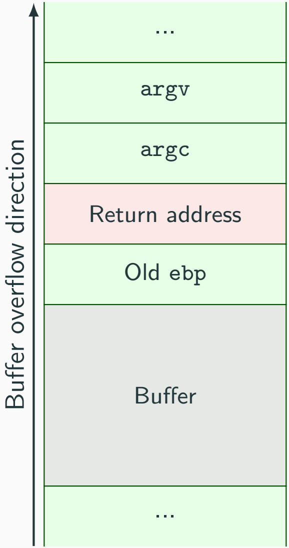
Source: cvedetails.com/browse-by-date.php

Motivation

- Deliberate exploitation of vulnerabilities can lead to information disclosure, financial losses, or even greater damage
- Big companies perform computer security incidents analysis
- Return-oriented programming (ROP) is an exploitation technique that can be used in presence of modern operating systems protections
- The main contribution of our work is to simplify ROP exploits reverse engineering

Stack Buffer Overflow

- **Buffer Overflow Vulnerability** exists when a program attempts to put more data in a buffer than it can hold
- Buffer overflow causes a return address overwrite



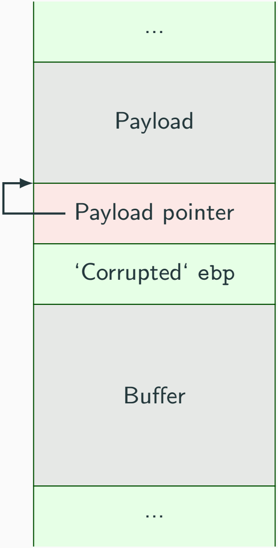
Stack Smashing and Executable Space Protection

Stack Smashing:

- Place payload on the stack
- Overwrite return address with a pointer to the payload
- Execute arbitrary code

Executable Space Protection:

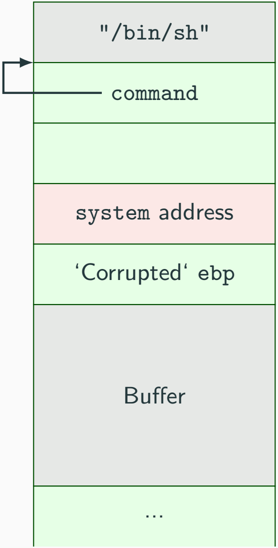
- **Executable space protection (DEP)** marks memory regions as non-executable
- In particular, the execution of malicious code placed on the stack is forbidden



Return-to-libc Attack

Return-to-libc attack bypasses DEP:

- Overwrite return address with a library function address, for instance, `system`
- Prepare function arguments on the stack



Address Space Layout Randomization

- **Address space layout randomization (ASLR)** is an operating system protection that randomly arranges the address space positions of key data areas of a process (base of the executable, stack, heap, dynamic libraries)
- Library function address is unknown before the program load
- Modern ASLR implementations leave some program address space areas non-randomized:
  - In Linux the base of the executable is often left constant
  - Some Windows dynamic libraries are loaded at constant offsets

Return-oriented Programming

- **Return-oriented Programming (ROP)** is a code-reuse attack that allows an attacker to bypass DEP in presence of non-randomized memory areas
- Attacker uses gadgets – code blocks from non-randomized memory address space
- Each gadget performs some computation (for instance, adds two registers) and transfers control to the next gadget
- Gadgets are chained together and executed consequently
- Thus, a gadget chain executes a malicious payload

ROP gadgets

- **Gadget** is an instruction sequence – in non-randomized executable memory area – that ends with a control transfer instruction (usually with `ret`)
- Because x86 architecture doesn't require instruction aligning, an instruction sequence can contain a gadget that is not present in original program code*

```
f7c7070000000f9545c3 → test edi, 0x7 ;
                       setnz BYTE PTR [ebp-0x3d]
  c7070000000f9545c3 → mov DWORD PTR [edi], 0xf000000 ;
                       xchg ebp, eax ; inc ebp ; ret
```

- Gadget addresses are placed on the stack starting from the return address so that the first gadget transfers control to the second one, the second one – to the third one, and so on

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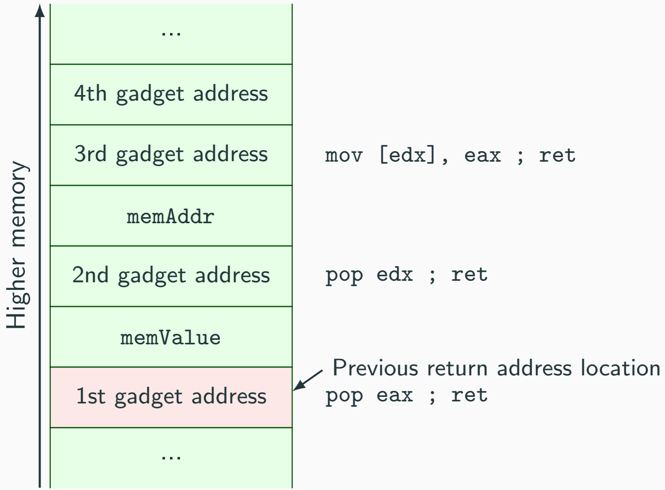
* Jonathan Salwan. An introduction to the Return Oriented Programming and ROP chain generation

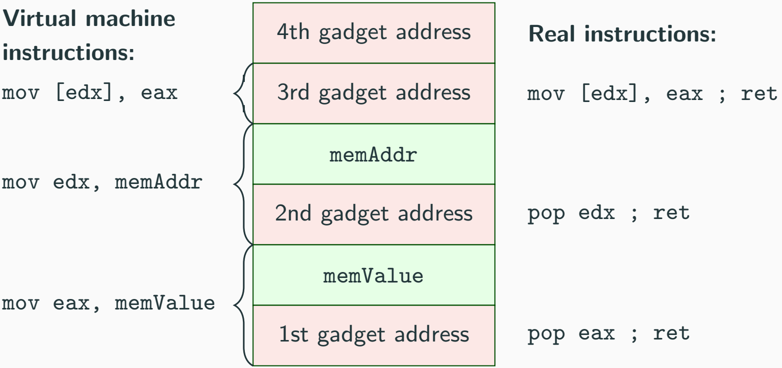
ROP Chain Example

Write `memValue` to `memAddr`



ROP Chain is a Program

- ROP chain is a program for a virtual machine defined by an executable
- Stack pointer acts as a program counter
- Instruction opcodes (gadget addresses) and operands are placed on the stack



Virtual machine instructions:		**Real instructions:**
	4th gadget address	
`mov [edx], eax`	3rd gadget address	`mov [edx], eax ; ret`
`mov edx, memAddr`	`memAddr`	
	2nd gadget address	`pop edx ; ret`
`mov eax, memValue`	`memValue`	
	1st gadget address	`pop eax ; ret`

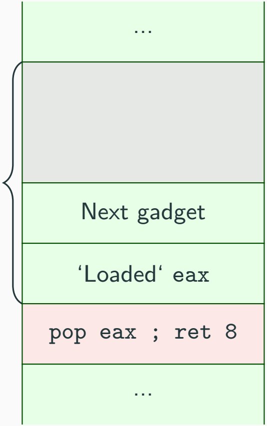
Problem Definition

Given a binary ROP chain, we should:

- Restore a gadget chain
- Determine semantics of each gadget
- Restore function calls with arguments
- Detect system calls

Gadget Frame

- In order to split ROP chain into gadgets, we define a *gadget frame* similar to x86 stack frame
- Frame size
  `FrameSize = 16`
- Next gadget address
  `NextAddr = [ESP + 4]`



Gadget Semantic Definition

- *Gadget type* is defined semantically by a postcondition – a boolean predicate that must always be true after executing the gadget[*]
  - `MoveRegG: OutReg ← InReg`
  - `LoadConstG: OutReg ← [SP + Offset]`
- Set of gadget types is an instruction set architecture (ISA)
- Gadget function is described with a set of parameterized types that satisfy the gadget
- Gadget classification determines a set of possible types and parameters

```
PUSH EAX
POP  EBX                   MoveRegG: EBX ← EAX
POP  ECX                   LoadConstG: ECX ← [ESP + 0]
RET
```

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[*] Schwartz, Edward J., Thanassis Avgerinos, and David Brumley. "Q: Exploit Hardening Made Easy." USENIX Security Symposium. 2011.

Gadget Classification

- We perform classification after analysing effects of gadget execution on different inputs
- Gadget instructions are translated into the intermediate representation*
- Then the interpretation of intermediate representation starts
  - All memory and register accesses are tracked
  - Initial values of registers and memory areas are generated randomly
  - As a result of interpretation, the initial and final values of registers and memory will be obtained
- We perform several more interpretations with different inputs and gather a list of types and parameters with true postconditions for all executions

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*Padaryan V.A., Soloviev M.A., Kononov A.I. "Modeling operational semantics of machine instructions (in Russian)." Trudy ISP RAN/Proc. ISP RAS. Vol. 19. 165-186. 2011.

ROP Chain Semantics Analysis

- Binary ROP chain is loaded onto the shadow stack
- Gadgets are classified one by one according to frame info
- Shadow memory is used to restore values of registers and memory before functions and system calls
    - Initially, a shadow memory is empty
    - We perform several interpretations of gadget with a shadow memory as an initial state
    - Final values of registers and memory – unchanged from execution to execution – are added to shadow memory

Restoring Functions and System Calls

- Names of indirect function calls are gathered from import tables
  `JMP [EAX]`
- Linux system calls and functions prototypes can be found in man-pages
- System call number and arguments are gathered from the shadow memory

Example: MongoDB Linux x86 (CVE-2013-1892)

Binary representation of the ROP chain:

```
00000000  68 f7 16 08 07 6d 66 08  00 70 33 31 00 20 00 00  |h....mf..p31. ..|
00000010  07 00 00 00 31 00 00 00  ff ff ff ff 00 00 00 00  |....1...........|
00000020  00 00 00 00 c8 e4 16 08  00 70 33 31 00 70 33 31  |.........p31.p31|
00000030  00 00 0b 0c 00 20 00 00                           |..... ..|
00000038
```

Example: MongoDB Linux x86 (CVE-2013-1892)

```
0x0816f768 : Asm : JMP DWORD PTR [08A1AF84h]
0x0816f768 : Call [0x8a1af84]
0x0816f768 : mmap(0x31337000, 0x2000, 0x7, 0x31, 0xffffffff, 0x0)
             from libc.so.6
0x08666d07 : Asm : ADD ESP, 00000014h ; POP EBX ; POP EBP ; RET
0x08666d07 : LoadConstG : EBX <- [ESP+20], EBP <- [ESP+24] :
             NextAddr=[ESP+28], FrameSize=32
0x08666d07 : ShiftStackG : ESP +<- 28
0x08666d07 : Values : EBX <- 0x0 ("\x00\x00\x00\x00"),
             EBP <- 0x0 ("\x00\x00\x00\x00")
0x0816e4c8 : Asm : JMP DWORD PTR [08A1AADCh]
0x0816e4c8 : Call [0x8a1aadc]
0x0816e4c8 : memcpy(0x31337000, 0xc0b0000, 0x2000) from libc.so.6
0x31337000 : Call 0x31337000
0x31337000 : Values : [ESP+4] <- 0xc0b0000, [ESP+8] <- 0x2000
```

Results

Application	CVE Number	Platform	Gadgets from
MongoDB	CVE-2013-1892	Linux x86	mongod
Nagios3	CVE-2012-6096	Linux x86	history.cgi
ProFTPd	CVE-2010-4221	Linux x86	proftpd
Nginx	CVE-2013-2028	Linux x64	nginx
AbsoluteFTP	CVE-2011-5164	Windows x86	MFC42.dll
ComSndFTP	N/A 2012-06-08	Windows x86	msvcrt.dll

Extra

Gadget Verification

- Gadget classification provides a set of postconditions describing possible gadget semantics
- Gadget verification formally proves these postconditions for each input
- Gadget verification implementation is based on Triton dynamic symbolic execution engine
  - Initially, all registers are assigned to free symbolic variables
  - Symbolic memory is implemented via select and store operations over SMT array
  - Symbolic execution of gadget instructions generates SMT formulas over constants and variables, it also updates the symbolic state of registers and memory
  - Postcondition validity is checked via unsatisfiability of its negation

Triton: github.com/JonathanSalwan/Triton

Gadget Verification Example

$ArithmeticLoadG : rbx \leftarrow rbx + [rax]$

Step	**Symbolic state**	**Instruction**	**Set of symbolic expressions**
initial	$M,\ rax = \phi_1,\ rbx = \phi_2,$ $rcx = \phi_3,\ rsp = \phi_4,$ $rip = \phi_5$	—	$S_0 = \emptyset$
1	$rcx = \phi_6$	`mov rcx, [rax]`	$S_1 = S_0 \cup \{\phi_6 = M[\phi_1]\}$
2	$rbx = \phi_7$	`add rbx, rcx`	$S_2 = S_1 \cup \{\phi_7 = \phi_2 + \phi_6\}$
final	$rip = \phi_8,\ rsp = \phi_9$	`ret`	$S_3 = S_2 \cup \{\phi_8 = M[\phi_4],$ $\phi_9 = \phi_4 + 8\}$
	Semantic definition		**Semantic verification**
verify	$(final(rbx) = initial(rbx) + initial(M[rax])) \wedge$ $(final(rip) = initial(M[rsp])) \wedge$ $(final(rsp) = initial(rsp) + 8)$		$\neg((\phi_7 = \phi_2 + M[\phi_1]) \wedge$ $(\phi_8 = M[\phi_4]) \wedge$ $(\phi_9 = \phi_4 + 8))$ is **UNSAT**