ROP is Still Dangerous: Breaking Modern Defenses

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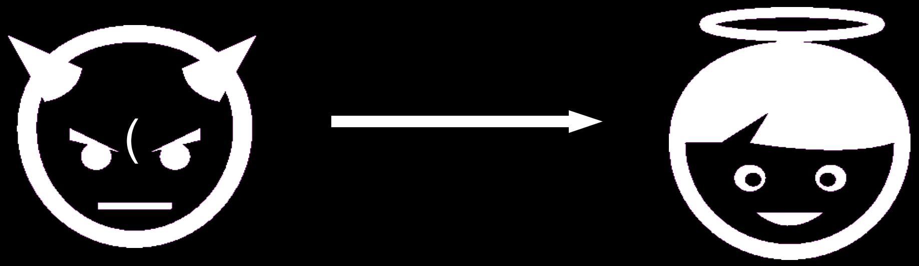
University of California, Berkeley

Background

Background

Code Injection

Background



Code Injection

Data Execution Prevention

Background

Code Injection

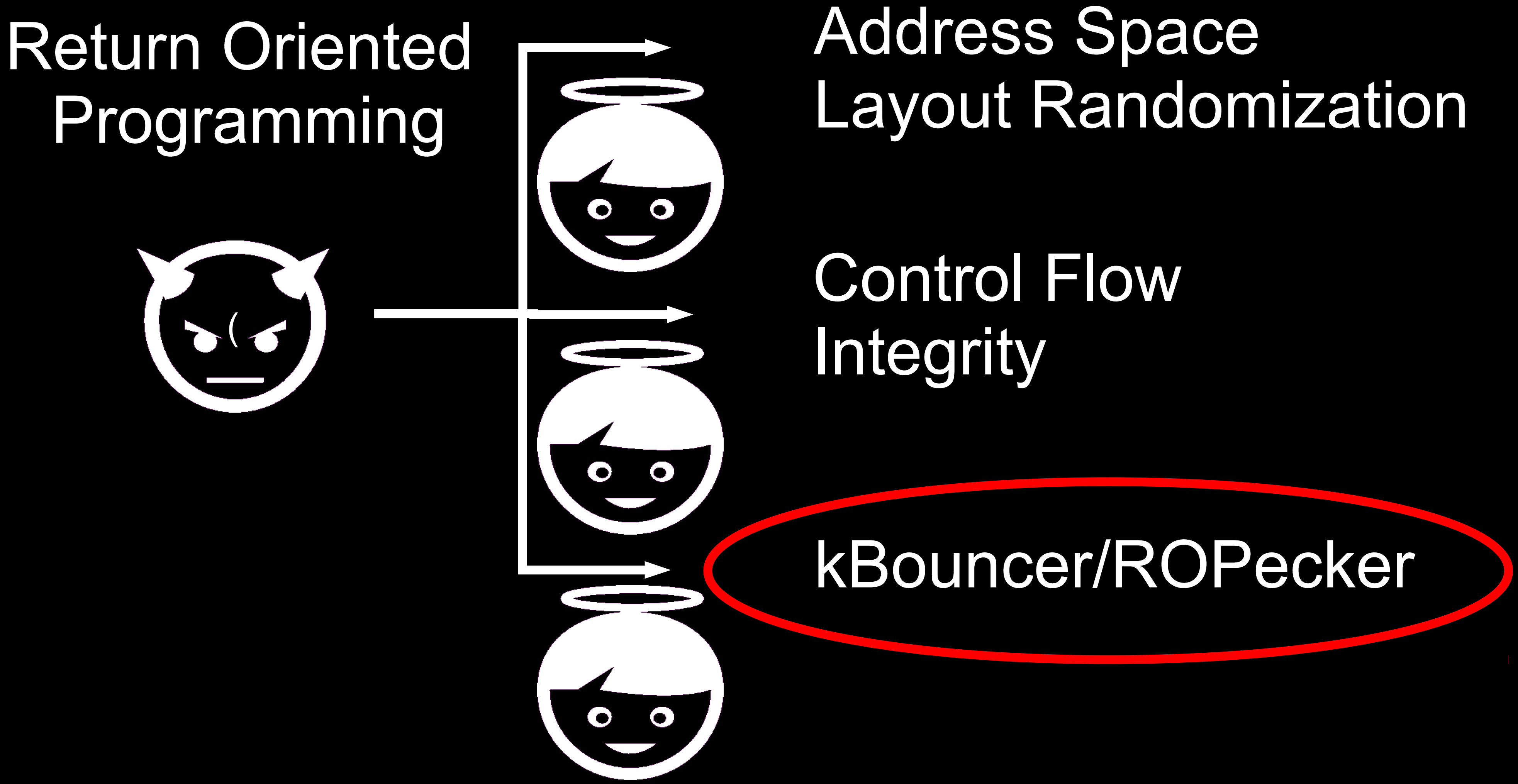
Data Execution Prevention

Return Oriented Programming

Background

Return Oriented Programming

Background



Return Oriented Programming

Address Space Layout Randomization

Control Flow Integrity

kBouncer/ROPecker

Return Oriented Programming

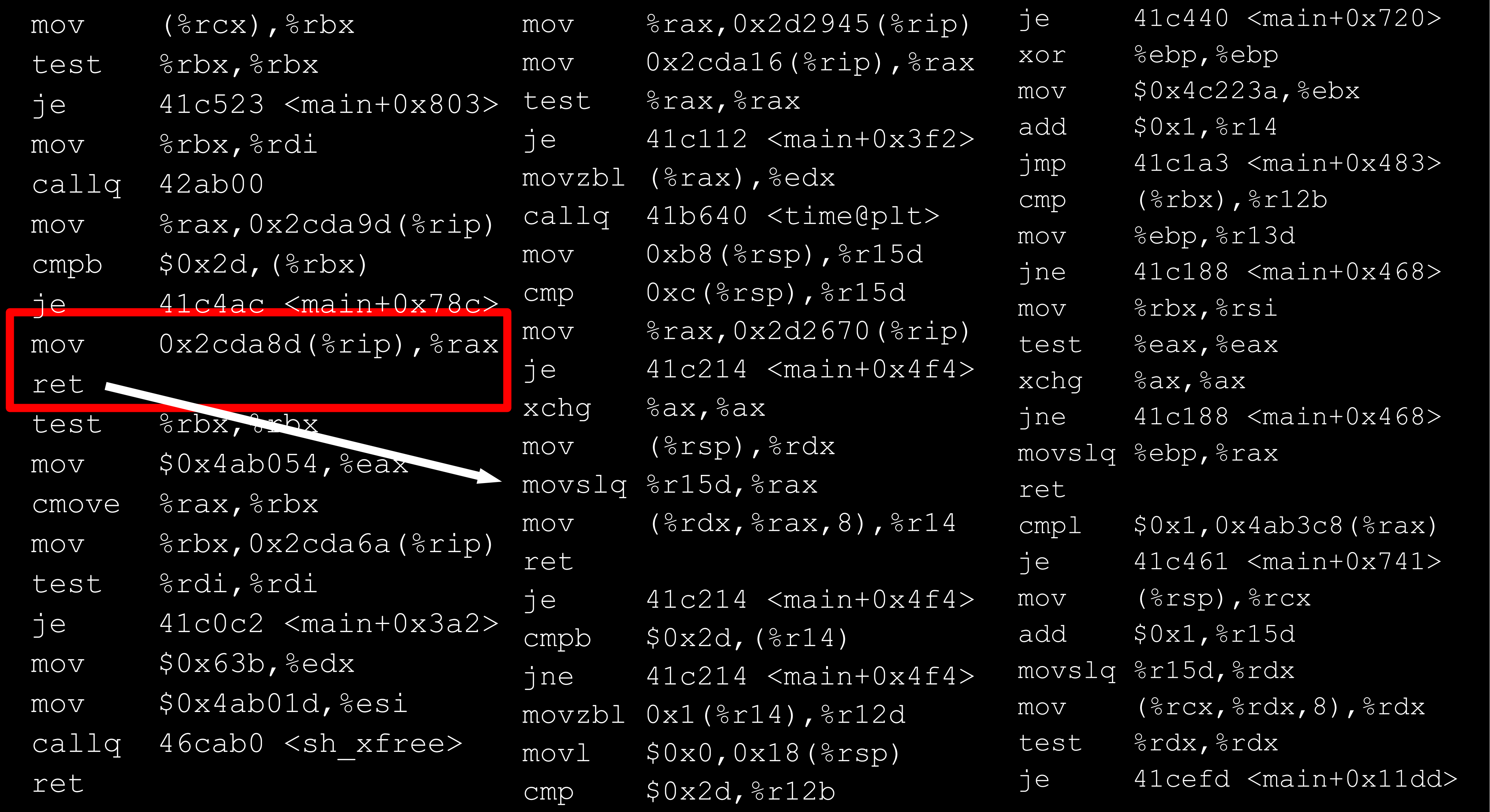
Return Oriented Programming

```
mov     (%rcx),%rbx
test    %rbx,%rbx
je      41c523 <main+0x803>
mov     %rbx,%rdi
callq   42ab00
mov     %rax,0x2cda9d(%rip)
cmpb    $0x2d,(%rbx)
je      41c4ac <main+0x78c>
mov     0x2cda8d(%rip),%rax
ret
test    %rbx,%rbx
mov     $0x4ab054,%eax
cmove   %rax,%rbx
mov     %rbx,0x2cda6a(%rip)
test    %rdi,%rdi
je      41c0c2 <main+0x3a2>
mov     $0x63b,%edx
mov     $0x4ab01d,%esi
callq   46cab0 <sh_xfree>
ret
```

```
mov     %rax,0x2d2945(%rip)
mov     0x2cda16(%rip),%rax
test    %rax,%rax
je      41c112 <main+0x3f2>
movzbl  (%rax),%edx
callq   41b640 <time@plt>
mov     0xb8(%rsp),%r15d
cmp     0xc(%rsp),%r15d
mov     %rax,0x2d2670(%rip)
je      41c214 <main+0x4f4>
xchg    %ax,%ax
mov     (%rsp),%rdx
movslq  %r15d,%rax
mov     (%rdx,%rax,8),%r14
ret
je      41c214 <main+0x4f4>
cmpb    $0x2d,(%r14)
jne     41c214 <main+0x4f4>
movzbl  0x1(%r14),%r12d
movl    $0x0,0x18(%rsp)
cmp     $0x2d,%r12b
```

```
je      41c440 <main+0x720>
xor     %ebp,%ebp
mov     $0x4c223a,%ebx
add     $0x1,%r14
jmp     41c1a3 <main+0x483>
cmp     (%rbx),%r12b
mov     %ebp,%r13d
jne     41c188 <main+0x468>
mov     %rbx,%rsi
test    %eax,%eax
xchg    %ax,%ax
jne     41c188 <main+0x468>
movslq  %ebp,%rax
ret
cmpl    $0x1,0x4ab3c8(%rax)
je      41c461 <main+0x741>
mov     (%rsp),%rcx
add     $0x1,%r15d
movslq  %r15d,%rdx
mov     (%rcx,%rdx,8),%rdx
test    %rdx,%rdx
je      41cefd <main+0x11dd>
```

Return Oriented Programming



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test    %rbx,%rbx
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cmove   %rax,%rbx
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mov     $0x63b,%edx
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test    %rax,%rax
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callq   41b640 <time@plt>
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test    %eax,%eax
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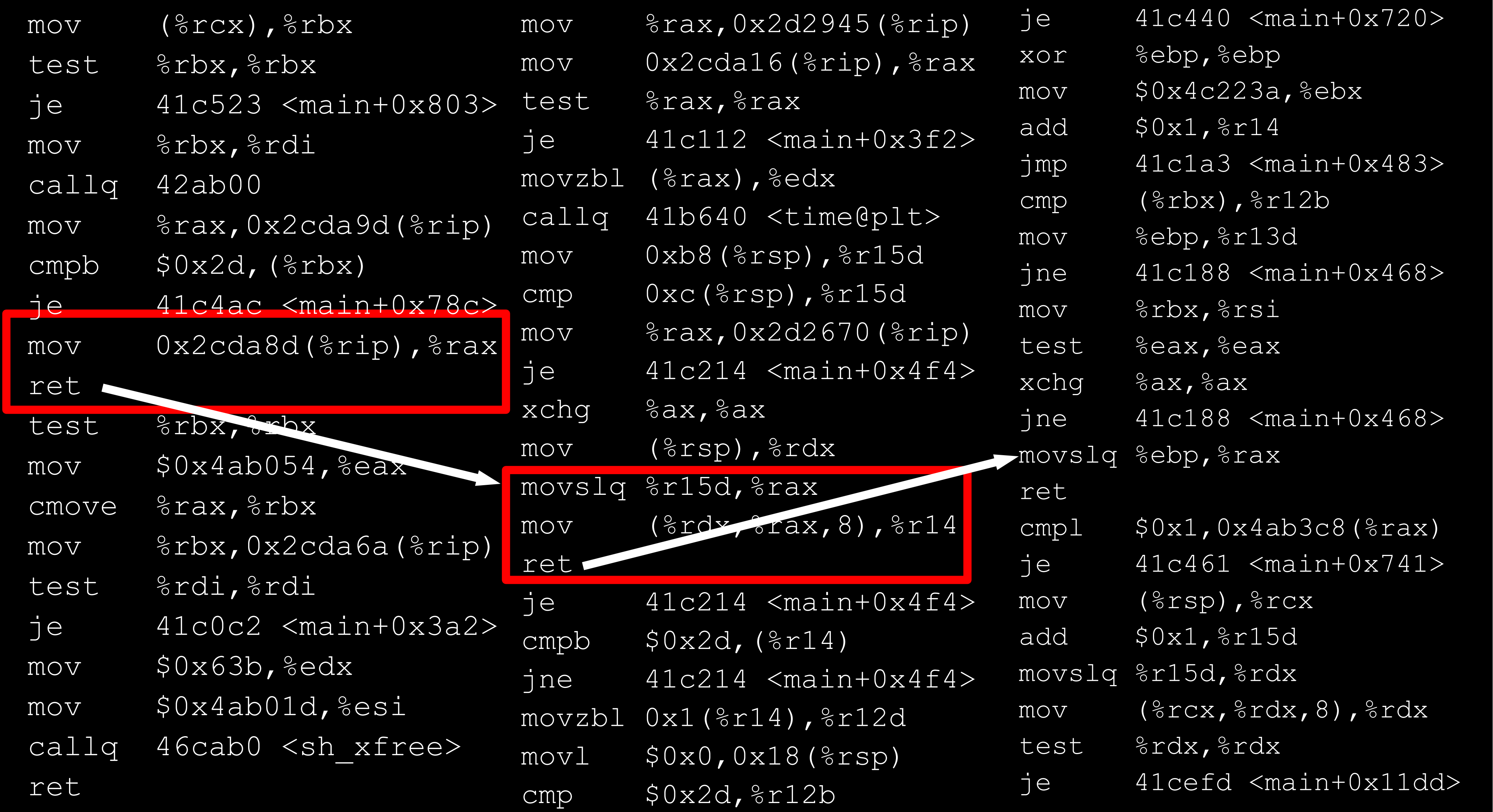
jne     41c188 <main+0x468>
movslq  %ebp,%rax
ret
cmpl    $0x1,0x4ab3c8(%rax)
je      41c461 <main+0x741>
mov     (%rsp),%rcx
add     $0x1,%r15d
movslq  %r15d,%rdx
mov     (%rcx,%rdx,8),%rdx
test    %rdx,%rdx
je      41cefd <main+0x11dd>
```

Return Oriented Programming



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movslq  %ebp,%rax
ret
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mov     (%rsp),%rcx
add     $0x1,%r15d
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test    %rdx,%rdx
je      41cefd <main+0x11dd>
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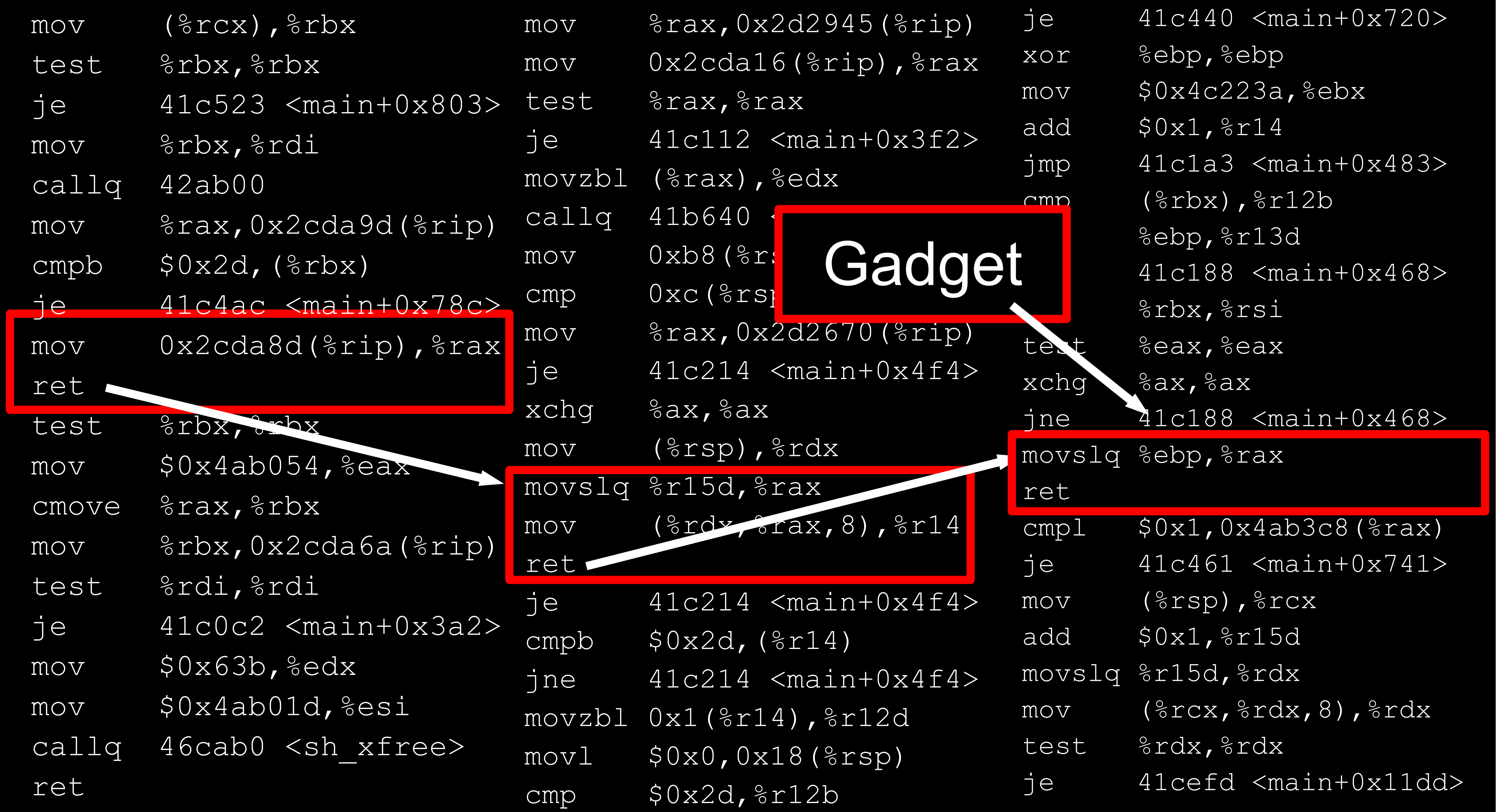
Return Oriented Programming



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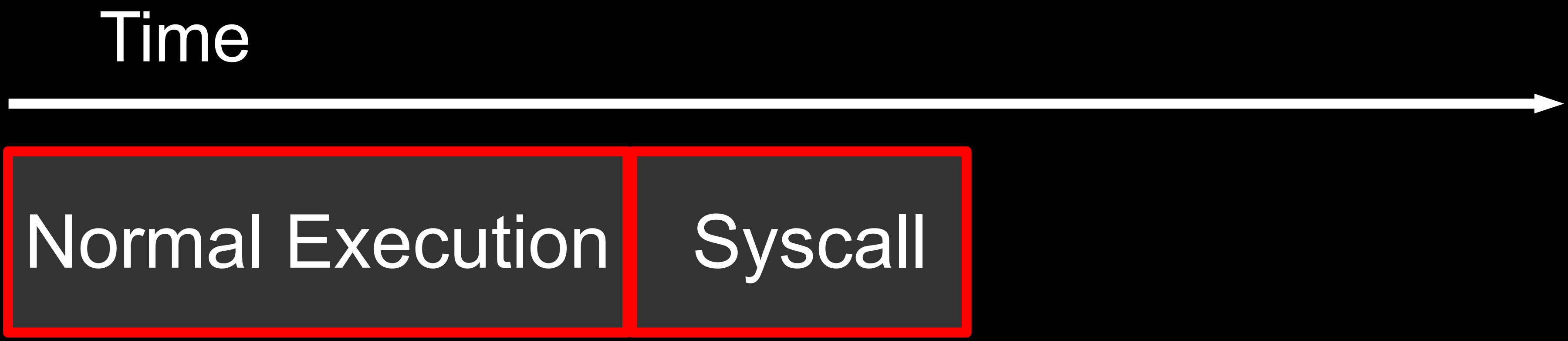
mov     (%rcx,%rdx,8),%rdx
test    %rdx,%rdx
je      41cefd <main+0x11dd>
```

kBouncer

If we could inspect the past execution …
… maybe we could detect ROP attacks

Transparent ROP exploit mitigation using indirect branch tracing.
Vasilis Pappas, Michalis Polychronakis, and Angelos D Keromytis.
USENIX Security, 2013.

kBouncer

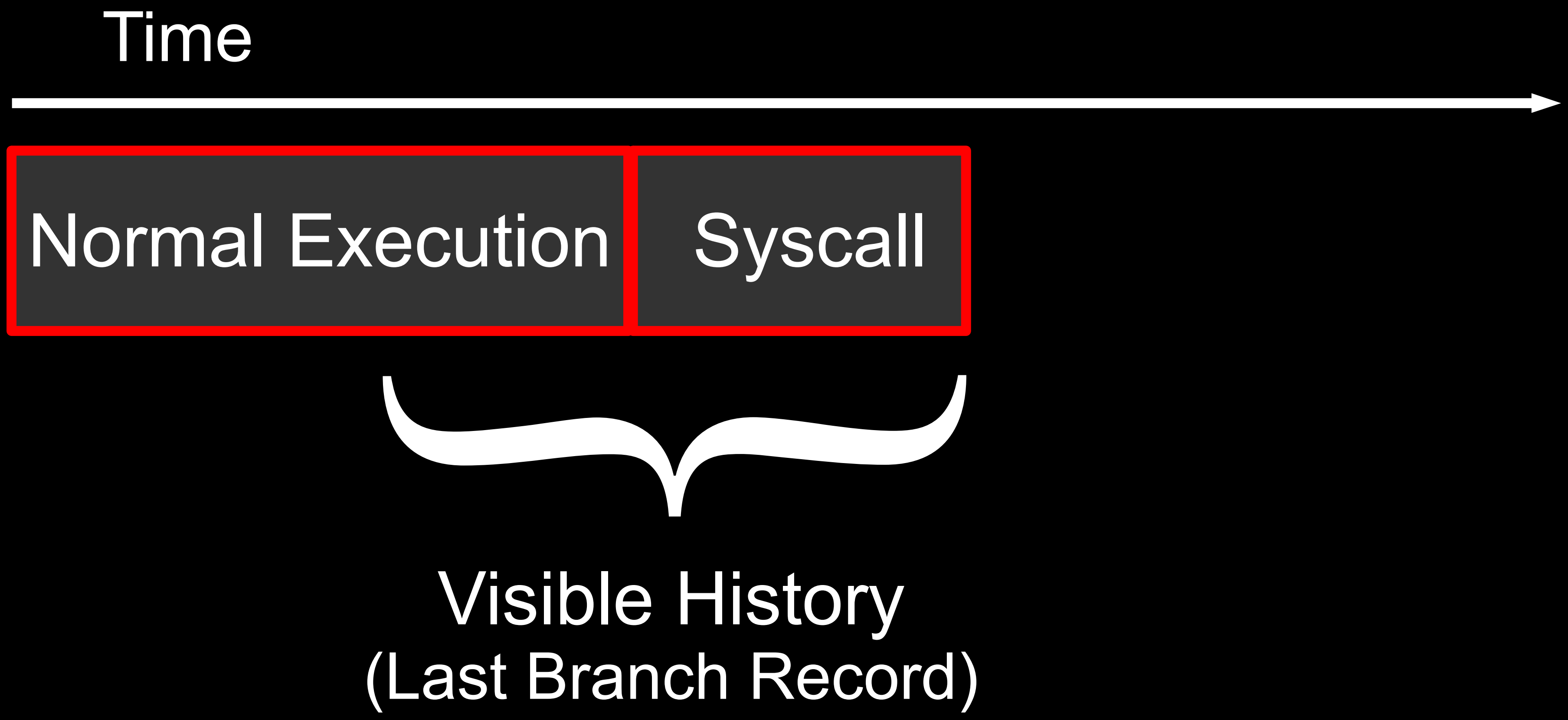


Time

Normal Execution

Syscall

kBouncer



Time

Normal Execution

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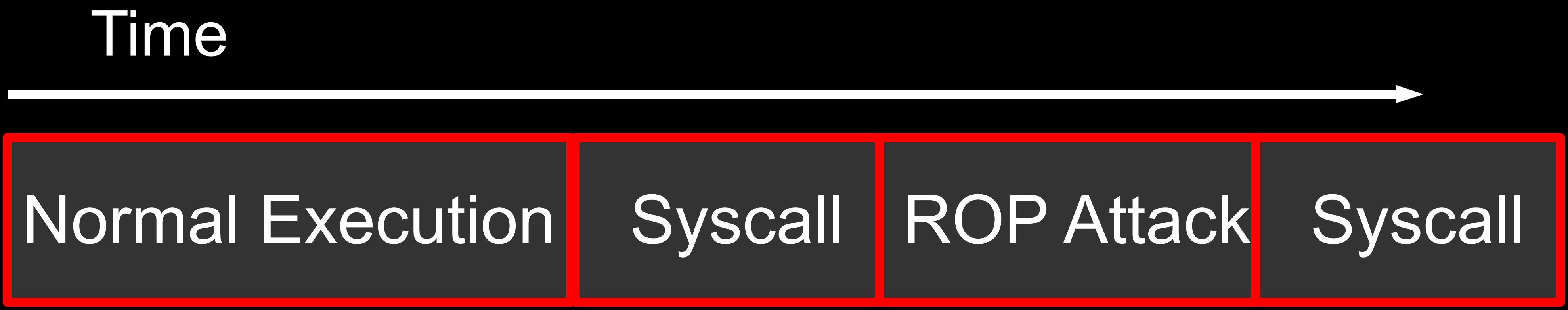
Visible History
(Last Branch Record)

kBouncer



Time

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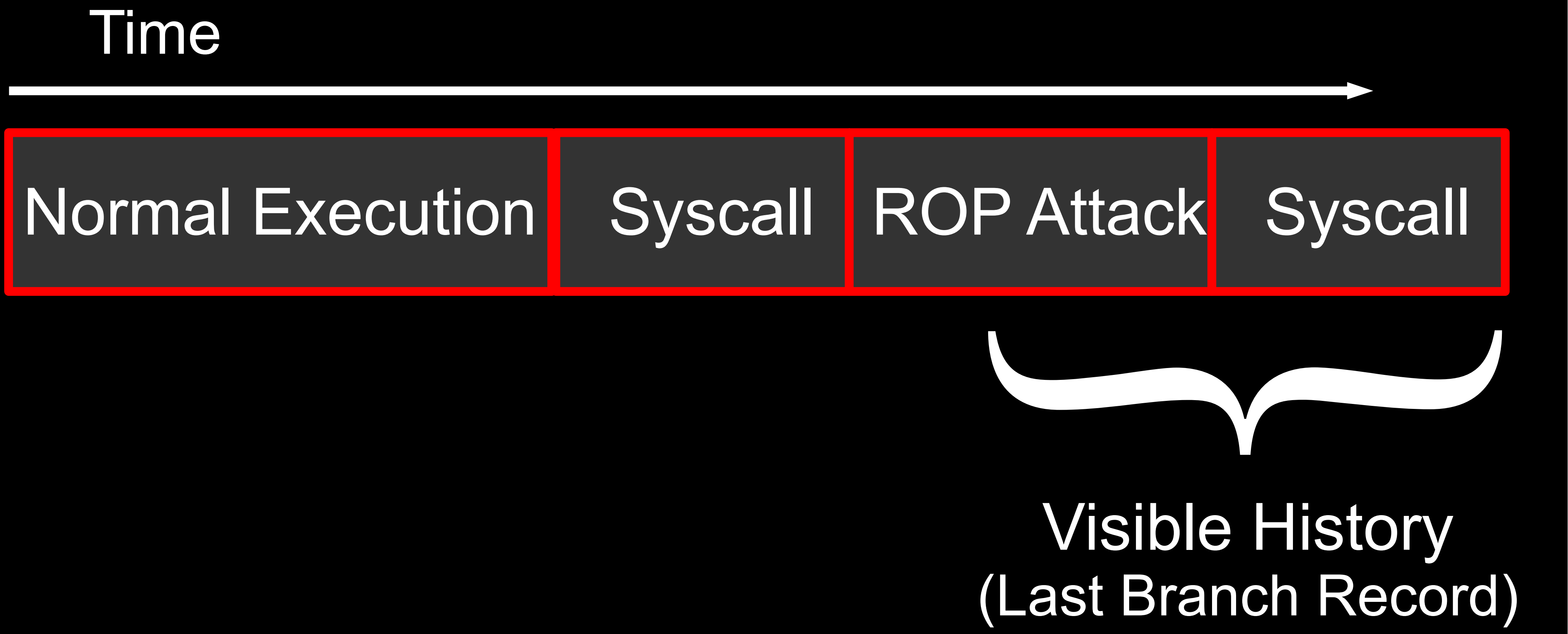
ROP Attack

Syscall

kBouncer



Time

Normal Execution

Syscall

ROP Attack

Syscall

Visible History
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kBouncer Observation (1):

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ROP attacks issue returns to non-*Call-Preceded* addresses.

Normal Execution

```
and     [rax],0xfd
mov     edx,0x768
mov     esi,0x4ab632
mov     rdi,rbx
call    0x2b2130
test    rbp,rbp
cmov    [rbp],0x0
add     rsp,0x8
pop     rbx
pop     rbp
ret
```

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```
0x2b2130:

  push rbx
  mov ebx, eax
  add ebx, ebx
  add ebx, eax
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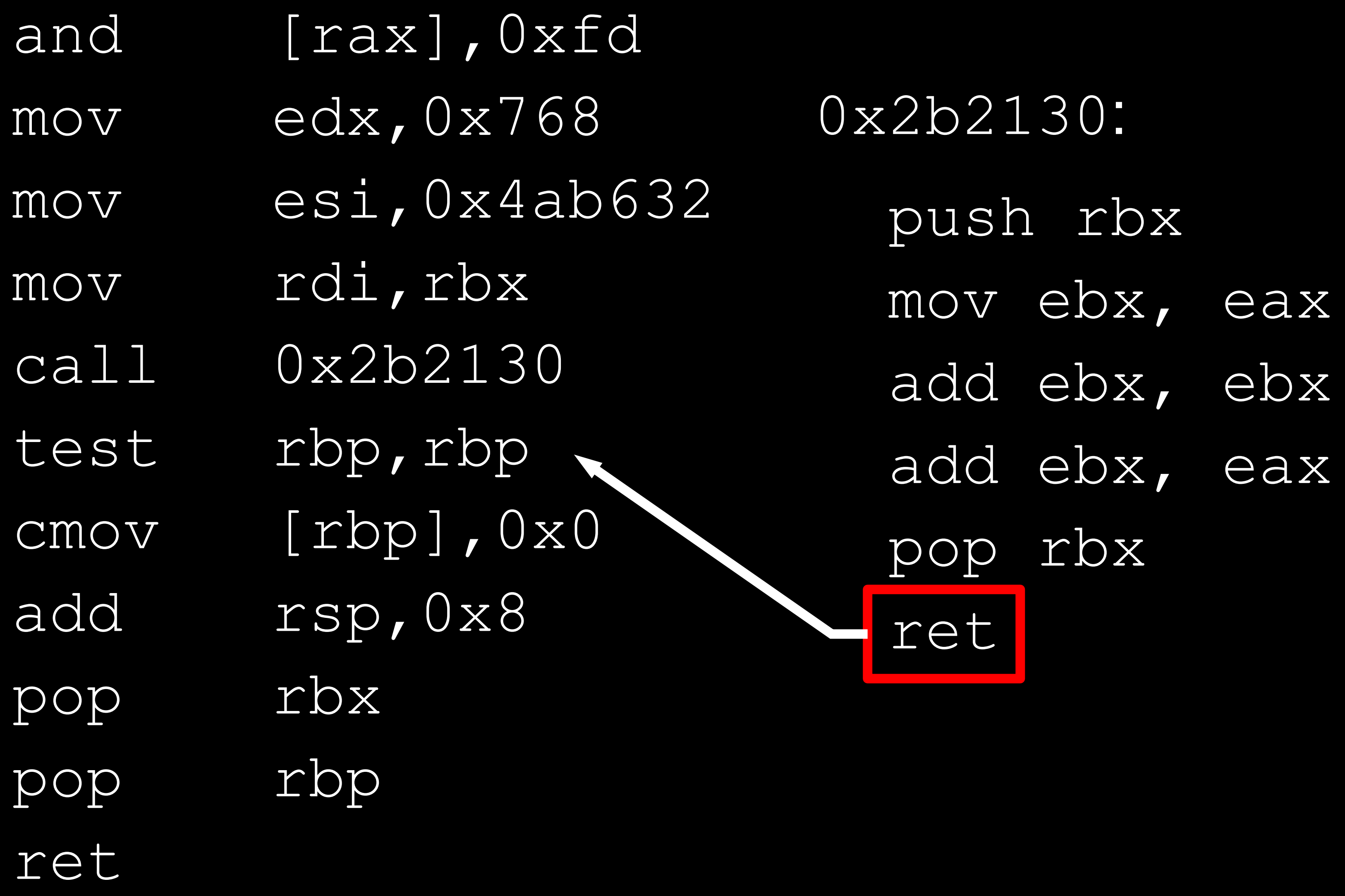

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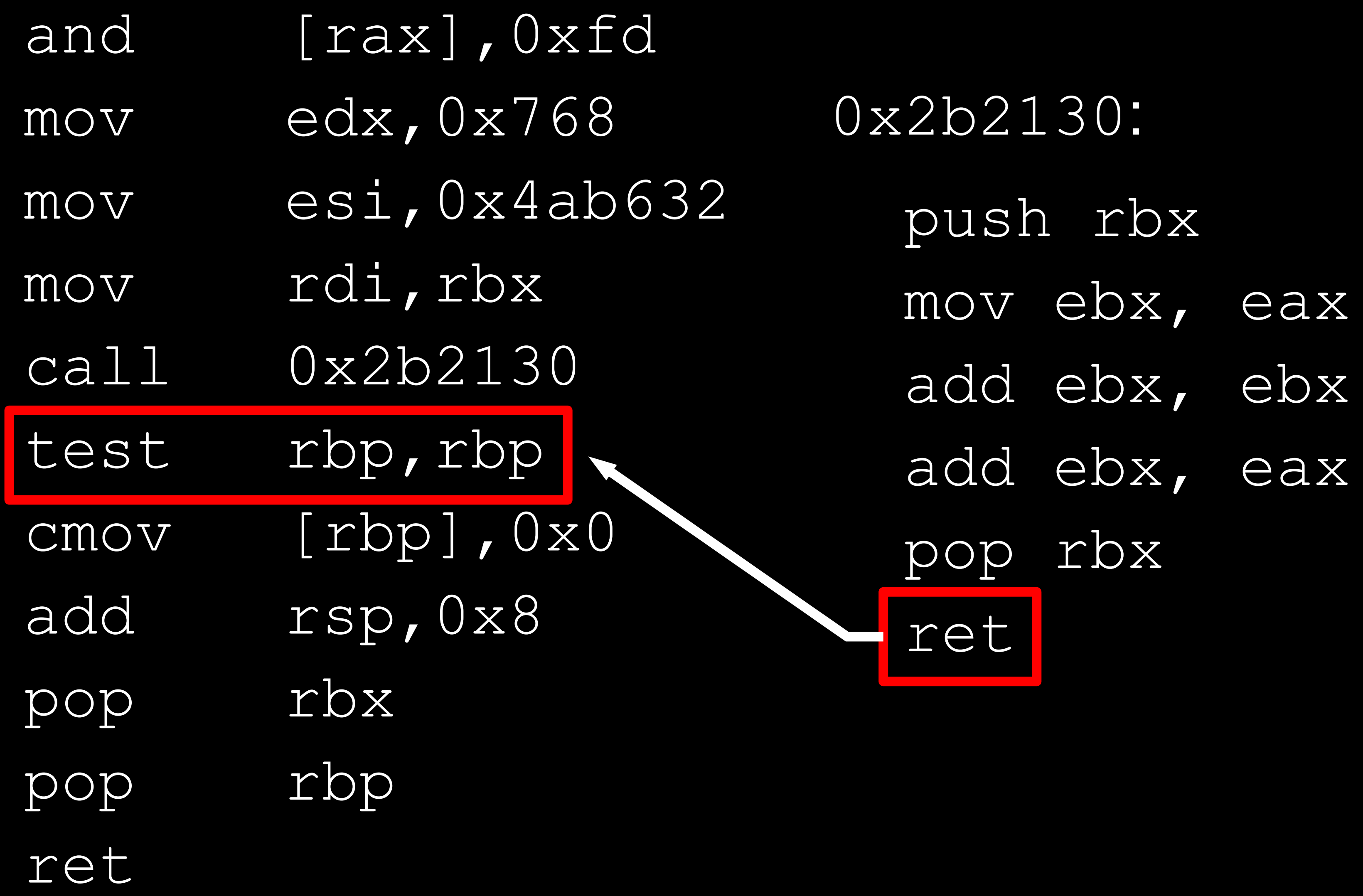
Call-Preceded Return



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```

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0x2b2130:
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Non-Call-Preceded Return

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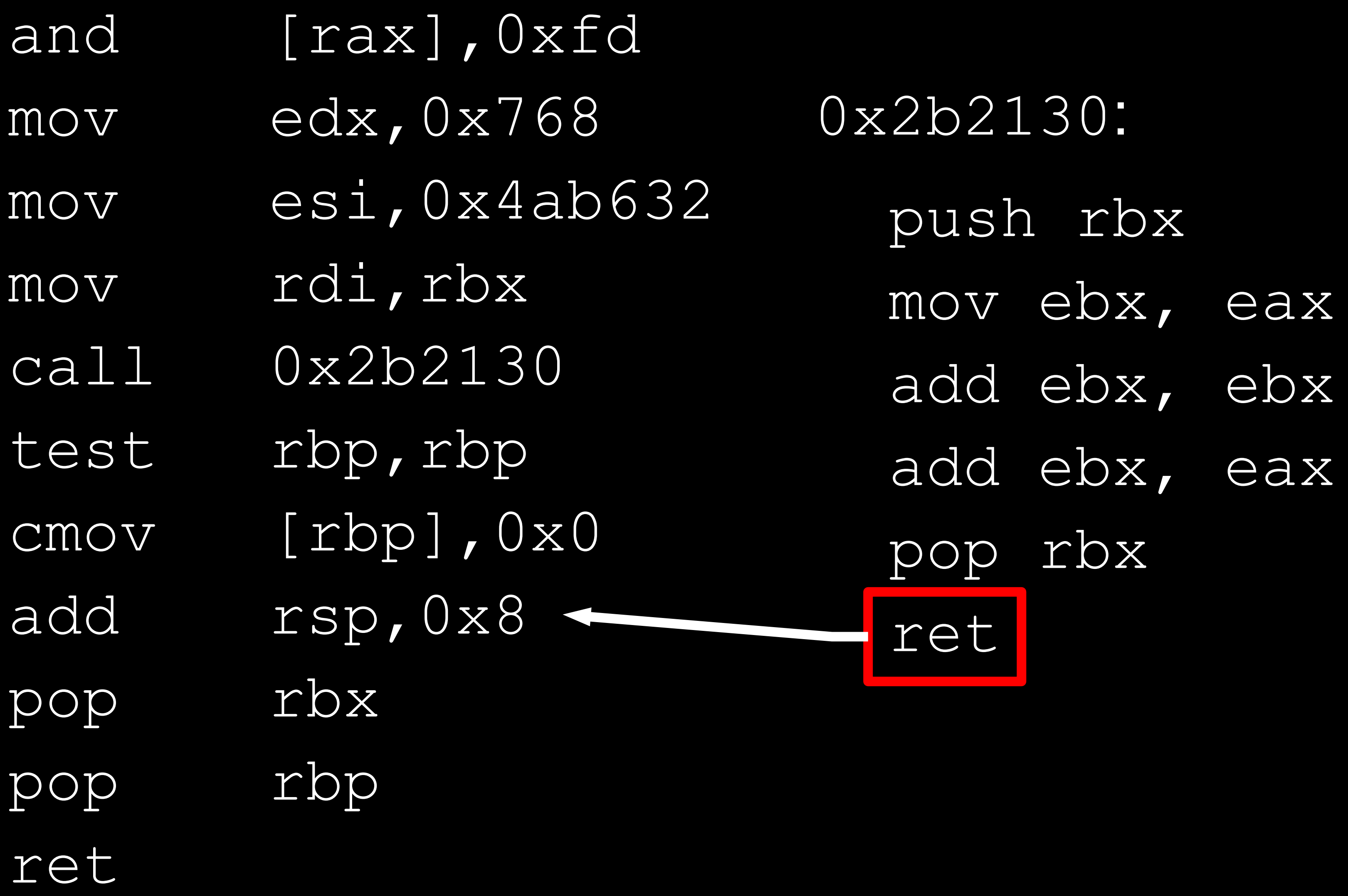
Non-Call-Preceded Return



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  pop rbx
  ret
```

Defense (1):

All return instructions target *Call-Preceded* addresses.

kBouncer Observation (2):

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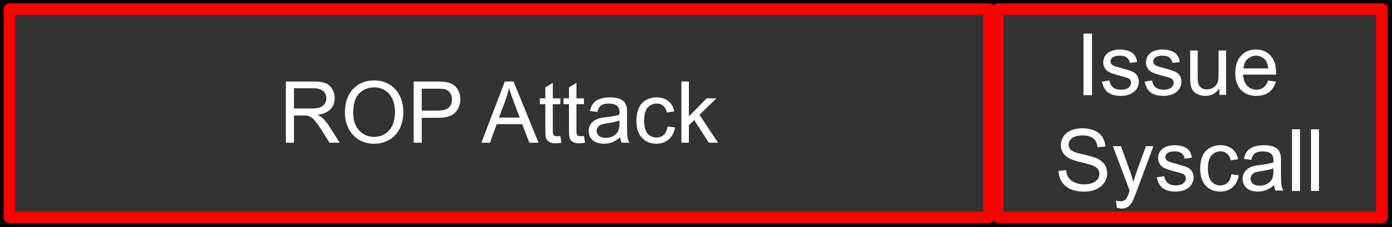
ROP attacks are built of long sequences of short gadgets.

“gadget”: sequence of <20 instructions, ending in `ret`

“long sequence”: 8 gadgets occurring sequentially

Defense (2):
Do not allow long sequences of short gadgets.

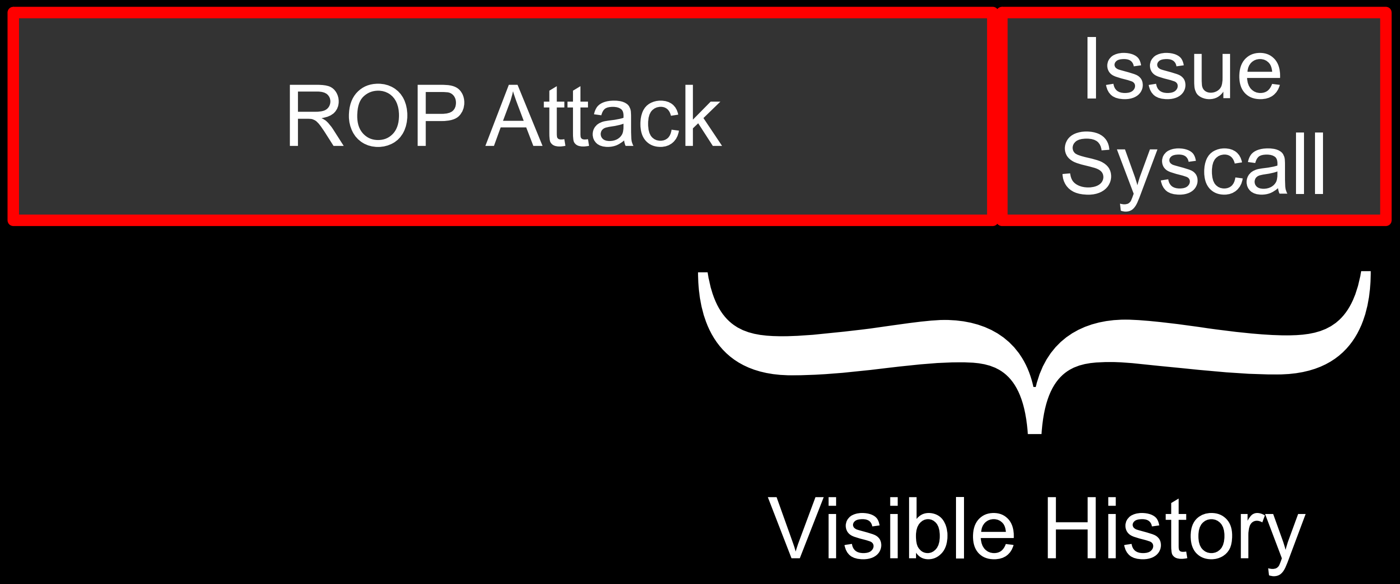
Detecting Attacks



ROP Attack

Issue Syscall

Detecting Attacks

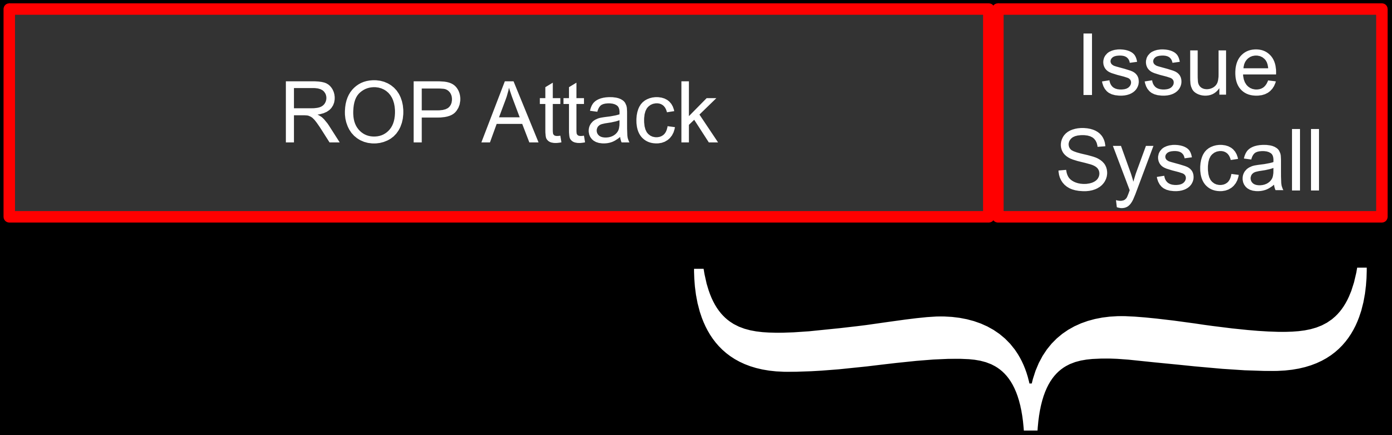


ROP Attack

Issue Syscall

Visible History

Detecting Attacks



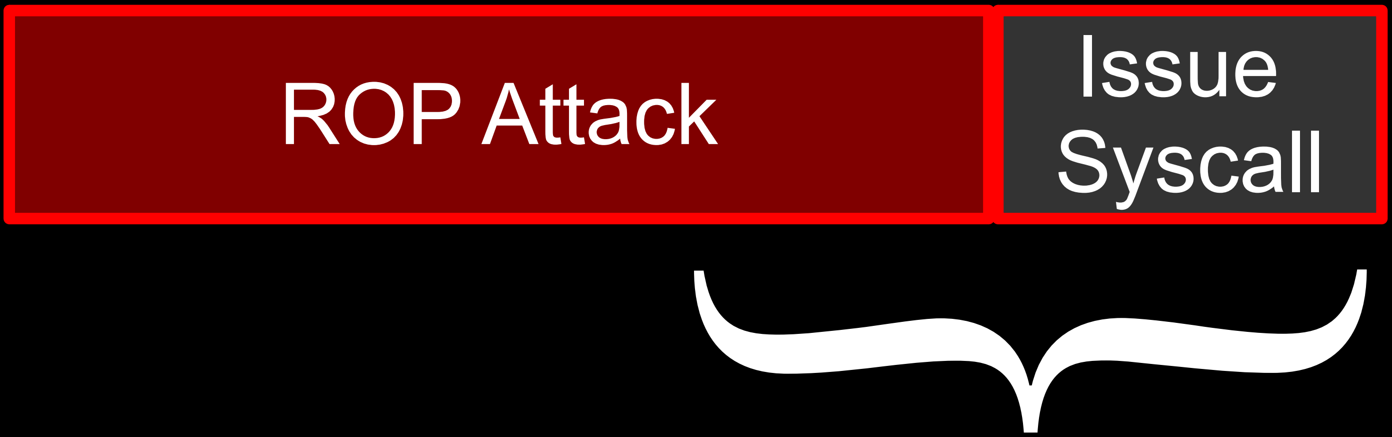
ROP Attack

Issue Syscall

Visible History

- Call-Preceded?
- No long chain?

Detecting Attacks



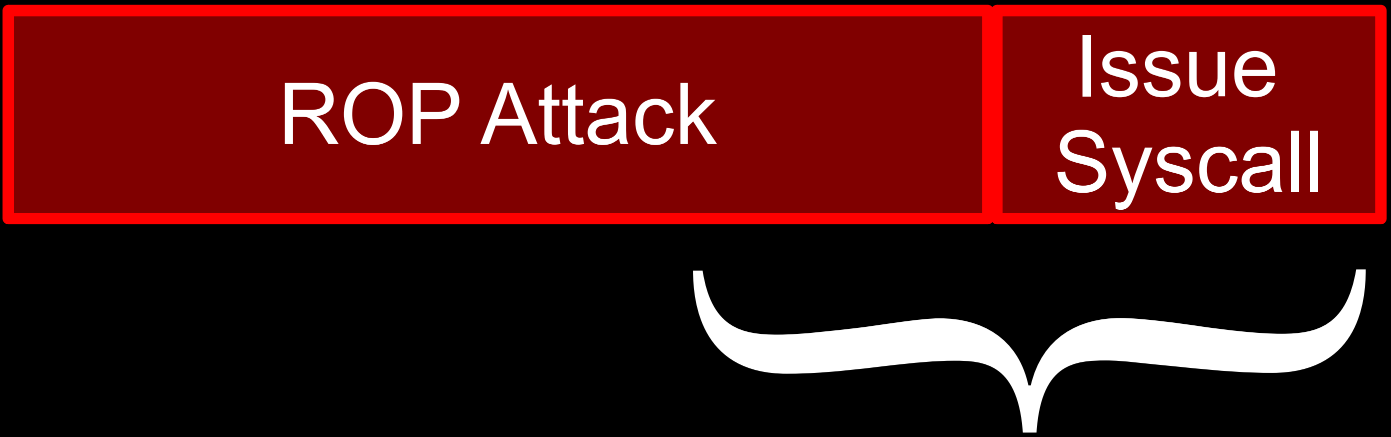
ROP Attack

Issue Syscall

Visible History

- Call-Preceded? X
- No long chain?

Detecting Attacks



ROP Attack

Issue Syscall

Visible History

- Call-Preceded? X
- No long chain? X

kBouncer is exciting

But does it work?

Breaking kBouncer with History Flushing

Breaking kBouncer with History Flushing

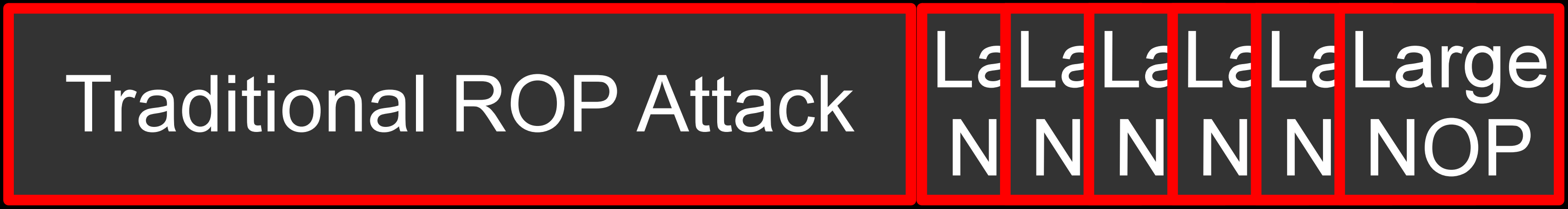
Goal: issue a single system call

Large NOP Gadget

- It must be Call-Preceded
- It must be long (>20 instructions)
- It must act as an effective no-op

```
   add  [esp+17Ch],ebx
   mov  ebx,[esp+17Ch]
   sub  ebx,ebp
   jmp  A
   ...
A: add  [esp+64h],ebx
   jmp B
   ...
B: mov  esi,[esp+1C0h]
   lea  eax,[esi*8-4]
   sub  eax,[esp+64]
   and  eax,7h
   mov  edi,[esp+64]
   lea  eax,[edi+eax+4]
   shr  eax,3
   cmp  eax,esi
   jbe  C
   ...
C: mov  eax,[esp+1C0h]
   add  esp,19Ch
   pop  ebx
   pop  esi
   pop  edi
   pop  ebp
   ret
```

History Flushing



Traditional ROP Attack

La N

La N

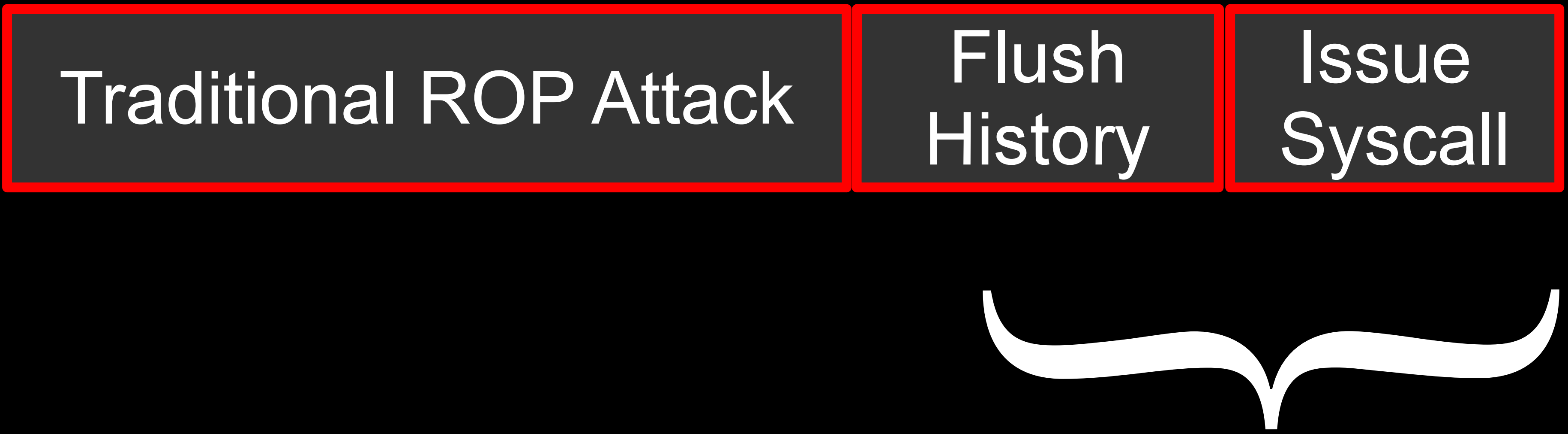
La N

La N

La N

Large NOP

History Flushing



Traditional ROP Attack

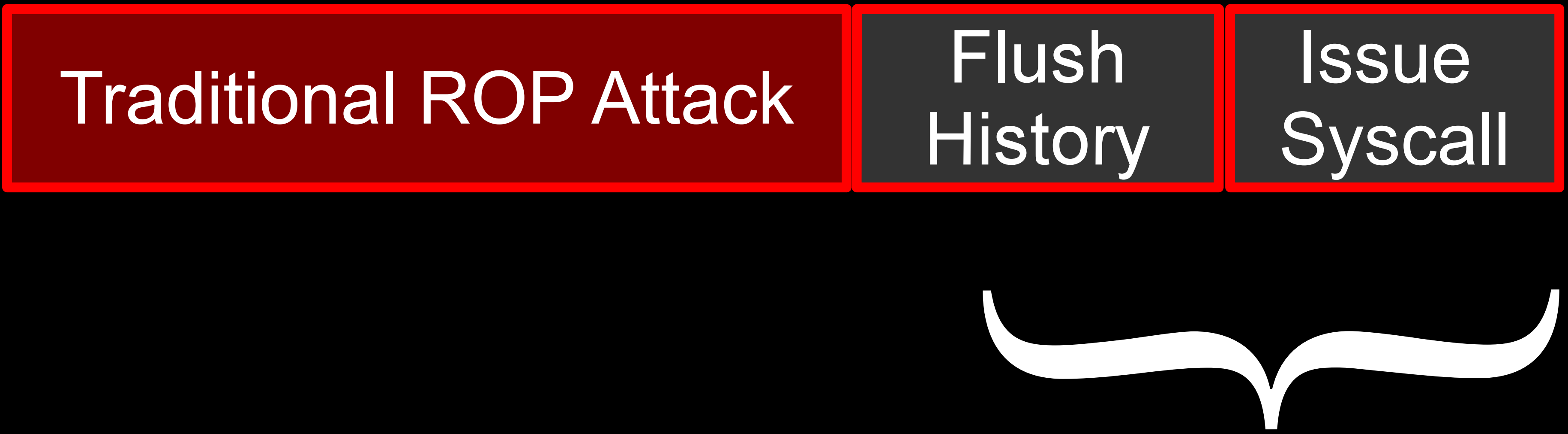
Flush History

Issue Syscall

Visible History

- Call-Preceded?
- No long chain?

History Flushing



Traditional ROP Attack

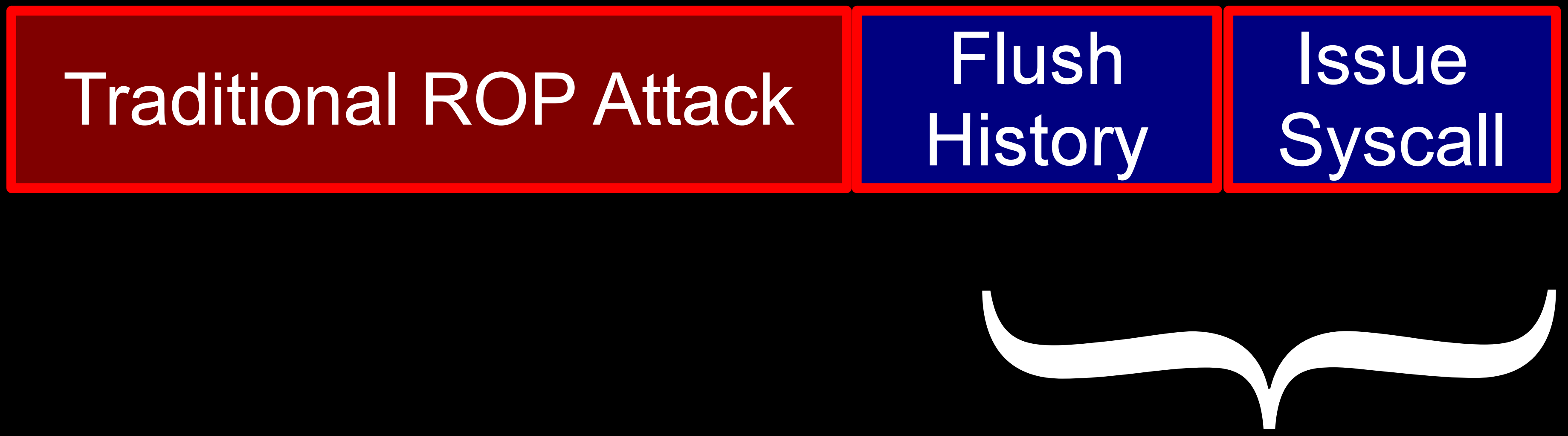
Flush History

Issue Syscall

Visible History

- Call-Preceded?
- No long chain?

History Flushing



Traditional ROP Attack

Flush History

Issue Syscall

Visible History

- Call-Preceded? ✔
- No long chain? ✔

So kBouncer is broken

any limited history defense

So ~~kBouncer~~ is broken

Can we fix it?

Introducing kBouncer++

LBR with infinite entries

Introducing kBouncer++

Defense runs continuously

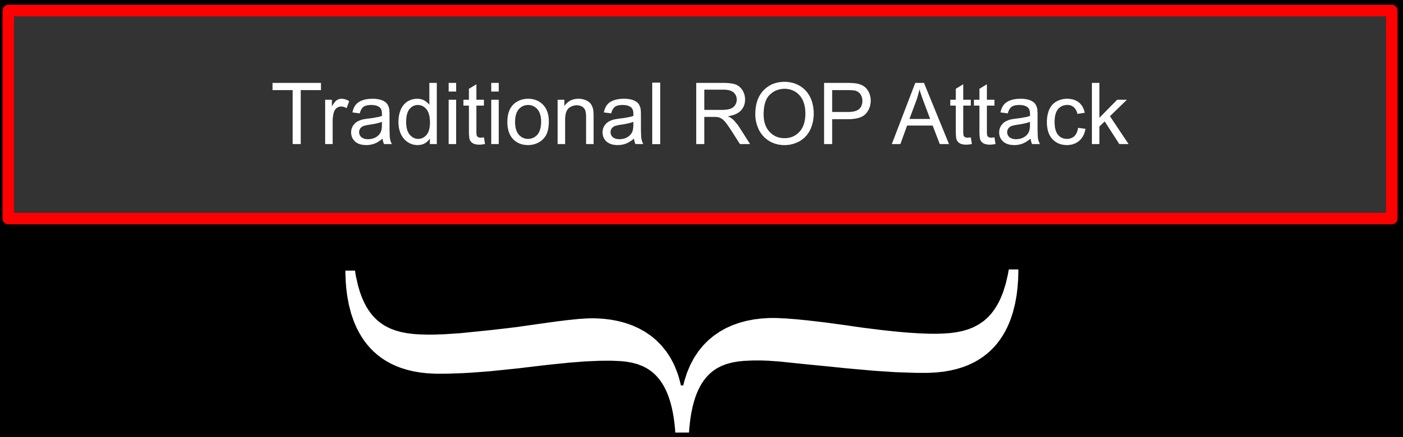
Introducing kBouncer++

Traditional ROP Attack

Visible History

- Call-Preceded?
- No long chain?

Introducing kBouncer++



Traditional ROP Attack

Visible History

- Call-Preceded?
- No long chain?

Introducing kBouncer++

Traditional ROP Attack

Visible History

- Call-Preceded?
- No long chain?

Does this work?

Breaking kBouncer++

Call-Preceded Detector Insufficient

- kBouncer: call-preceded ROP is *not* possible

- Our work: call-preceded ROP is possible

- 10 of 10 binaries of size 70k have sufficient text to mount a call-preceded ROP attack

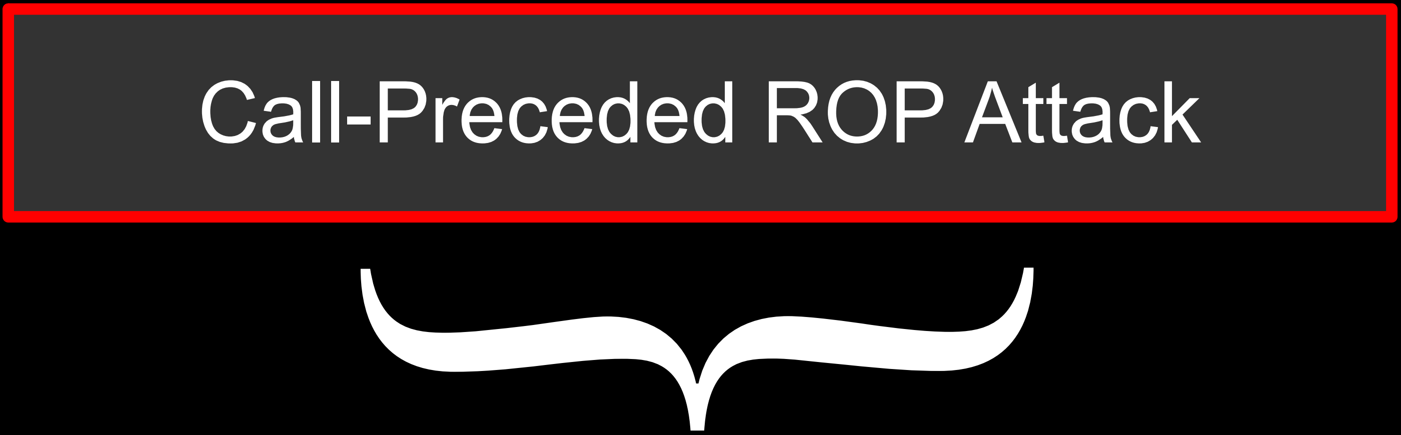
Defeating kBouncer++

Call-Preceded ROP Attack

Visible History

- Call-Preceded?
- No long chain?

Defeating kBouncer++

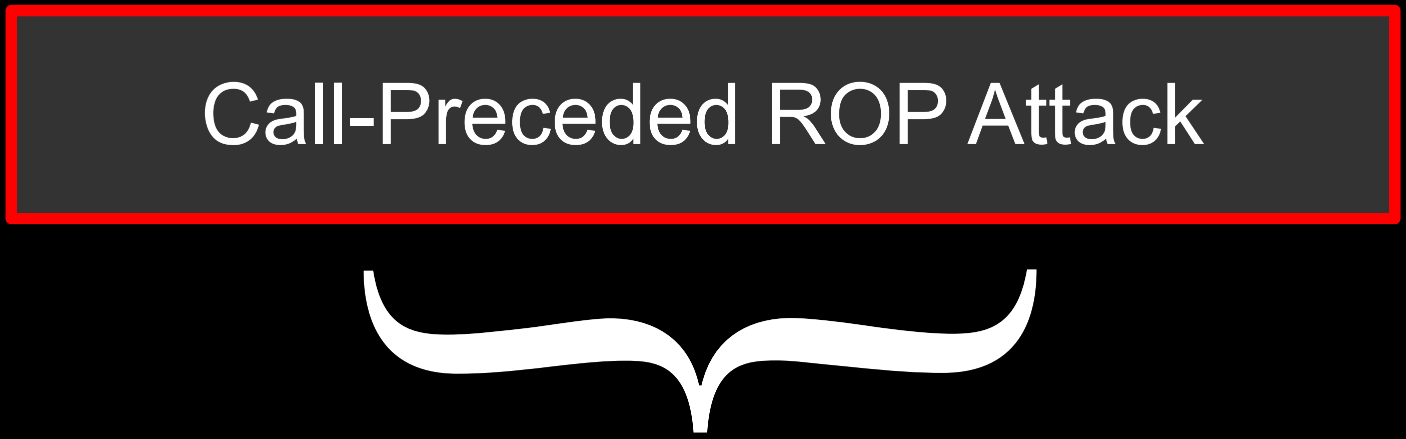


Call-Preceded ROP Attack

Visible History

- Call-Preceded? ✔
- No long chain?

Defeating kBouncer++



Call-Preceded ROP Attack

Visible History

- Call-Preceded? ✔
- No long chain? X

Large No-Op Gadgets

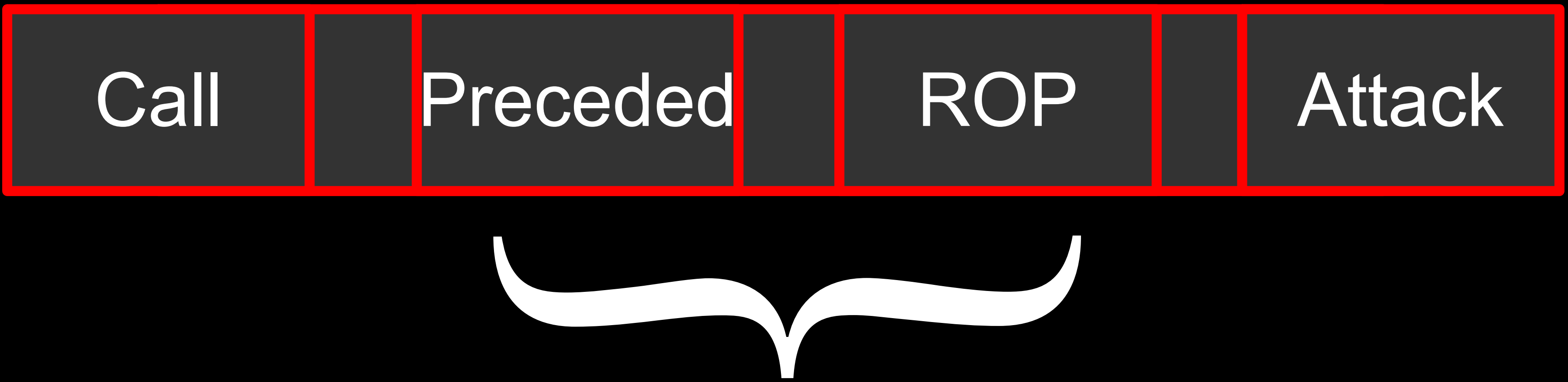
Defeating kBouncer++

Call-Preceded ROP Attack

Visible History

- Call-Preceded? ✓
- No long chain?

Defeating kBouncer++

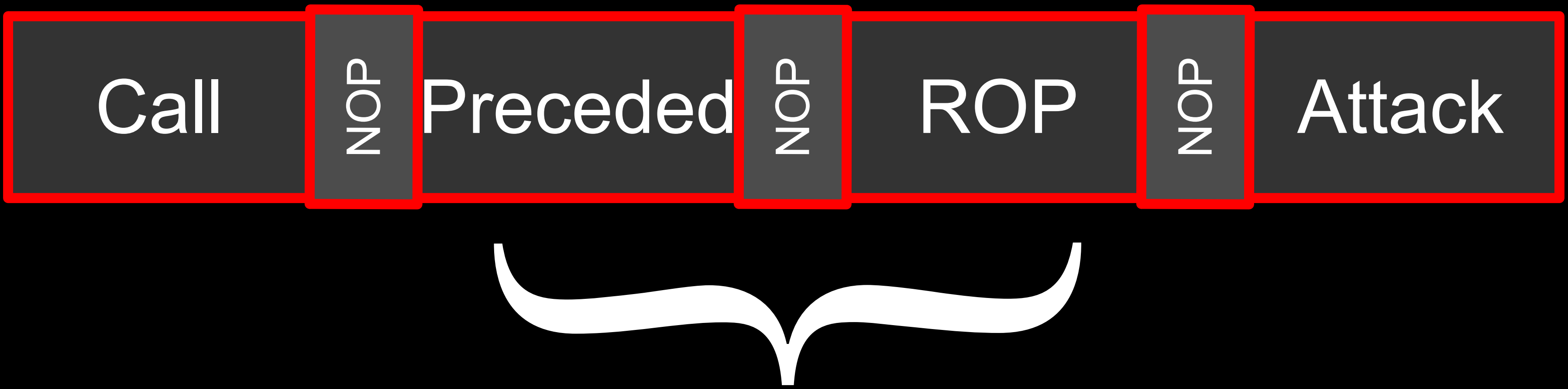


Call Preceded ROP Attack

Visible History

- Call-Preceded? ✔
- No long chain?

Defeating kBouncer++



Visible History

- Call-Preceded? ✓
- No long chain? ✓

Even with unlimited history, ROP attacks are possible

ROPecker is also broken

ROPecker: A generic and practical approach for defending against rop attacks.
Yueqiang Cheng, Zongwei Zhou, Miao Yu, Xuhua Ding, and Robert H Deng.
NDSS, 2014.

Results

Modified four real-world exploits so they won't be detected by kBouncer

Results

Modified four real-world exploits so they won't be detected by kBouncer

Adobe Reader 9
Adobe Flash 11
Mplayer Lite
Internet Explorer 8

Related Work

- [Goktas, S&P14] discussed the existence of call-preceded ROP and use it to break many existing CFI defenses

- [Davi, Usenix14] and [Goktas, Usenix14] both independently and concurrently discovered very similar attacks on kBouncer & ROPecker

Implication for Defenses

Implication for Defenses

Do not rely on limited history

Implication for Defenses

Call-Preceded ROP is possible

Implication for Defenses

CFI needs to return to its roots

Implication for Defenses

Classifying code as “gadget” vs. “non-gadget” is not easy

Defenses should focus on *fundamental* differences between normal execution and ROP attacks.