ROP-ing Your Way on Aarch64

Introduction

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Who Am I

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- Security Consultant @ Recurity Labs
  - Reverse engineering
  - Exploit development
  - Mobile application security
  - Embedded systems
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What You Will See

- Aarch64 fundamentals
- Return Oriented Programming (ROP) Introduction
- Jump Oriented Programming (JOP) Introduction
- Demo Exploit

Why ARM?

Why ARM?

- Smartphones and Tablets
- Some Computers
- IoT devices
- AWS EC2 Instances

ARM Basics

ARM Introduction

- Reduced Instruction Set Computing
  - Small instruction set
  - Large uniform register file
  - Load / store architecture
  - Simple addressing modes
  - Fixed instruction size
- Conditional instructions (only Aarch32)

ARMv7 - Basics

- 32bit Architecture (Aarch32)
- Different states
  - ARM
  - Thumb
  - and more
- 16 registers
  - `r0-r12` (general purpose)
  - `r13` or `sp`
  - `r14` or `lr`
  - `r15` or `pc`

Privilege Levels

ARM	x86
User(USR)	RING 3
Fast Interrupt Request (FIQ)	
Interrupt Request (IRQ)	
Supervisor (SVC)	RING 0
Monitor (MON)	
Abort (ABT)	
Undefined (UND)	
System (SYS)	

ARMv7 - ARM State

- Default state
- `r0-r12`, `sp`, `lr`, `pc` are accessible

Instruction size	32 bit
Alignment	32 bit

ARMv7 - Thumb State

- Introduced wiht ARMv4T
- Smaller instruction size (16 bit) but less instructions
  - `pc` can only be modified by specific instructions
- better code density - less performance
- Only `r0-r7`, `sp`, `lr`, `pc` are accessible by most instructions
- Thumb-2 state introduced in 2003 with ARMv6T2
  - Extends Thumb state with 32 bit instructions
  - Those instructions can access all registers

Instruction size	16 / 32 bit
Alignment	16 bit

ARMv8 - Basics

- 64bit Architecture (Aarch64)
- Aarch32 state for compatibility reasons
  - A32 and T32
- Exception Levels

ARMv8 - Registers

- `x0-x29` (general purpose)
- `x30` or `lr`
- `sp`
- `pc`
- `xzr`
- `w0-w29` (lower 32bit part)

Exception Levels

Level	Description
EL0	Applications
EL1	OS kernels and associated functions
EL2	Hypervisor
EL3	RING Secure monitor

Function Prologue

ARMv7

```
    push    {fp, lr}
    add     fp, sp, #4
    sub     sp, sp, #136
```

ARMv8

```
    stp x29, x30, [sp, -0xa0]!
    mov x29, sp
```

Function Epilogue

ARMv7

```
    sub sp, fp, #4
    pop {fp, pc}
```

```
    sub sp, fp, #4
    pop {fp, lr}
    bx  lr
```

ARMv8

```
    ldp x29, x30, [sp], 0xa0
    ret
```

Old Way

What is Shellcode?

Shellcode is a sequence of bytes that can be interpreted and executed by the CPU. Historically it is called shellcode, because the first versions spawned a shell.

Mostly, shellcode consists of position indepedent code.

Shellcode must be free of so-called bad bytes. Bad bytes are bytes that interfere with the placement of the shellcode (e.g. a null byte if string operations like `strcpy` are used).

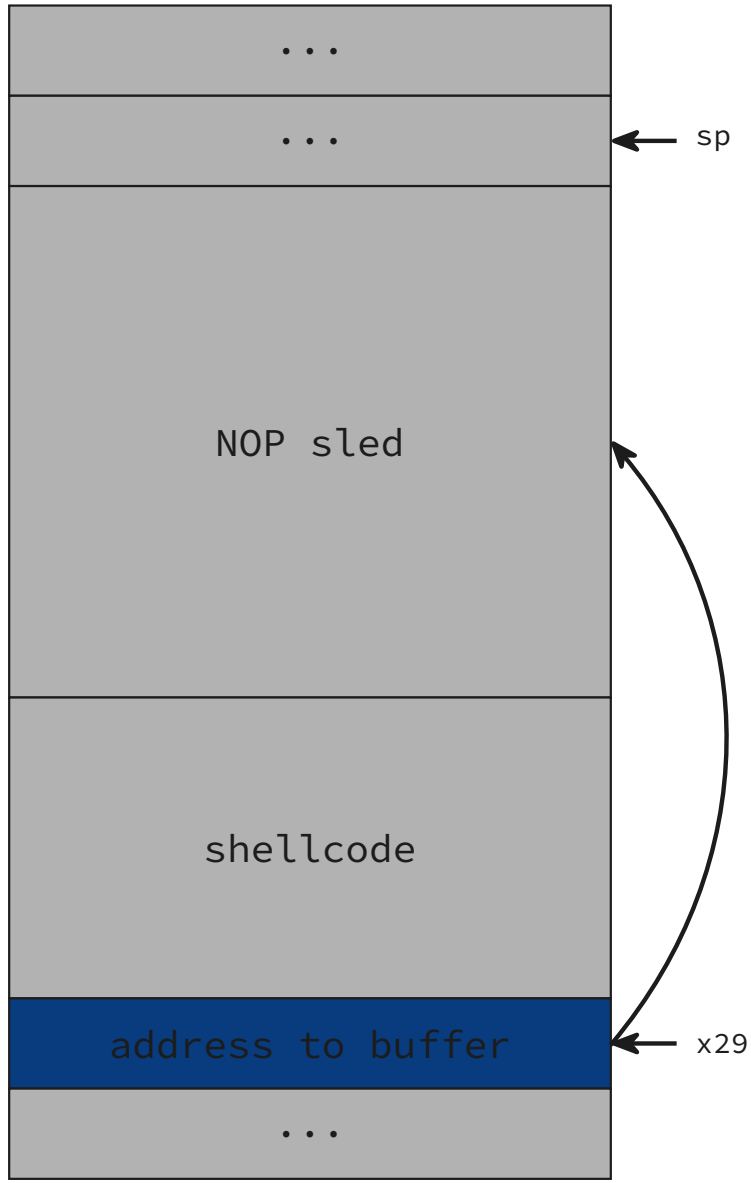
A vulnerability is used to jump to that shellcode

Example - Buffer Overflow

```
void dosomething(char *msg){
    char buf[128];
    strcpy(buf, msg);
    puts(buf);
}

void main(int argc, char *argv[]){
    dosomething(argv[1]);
}
```

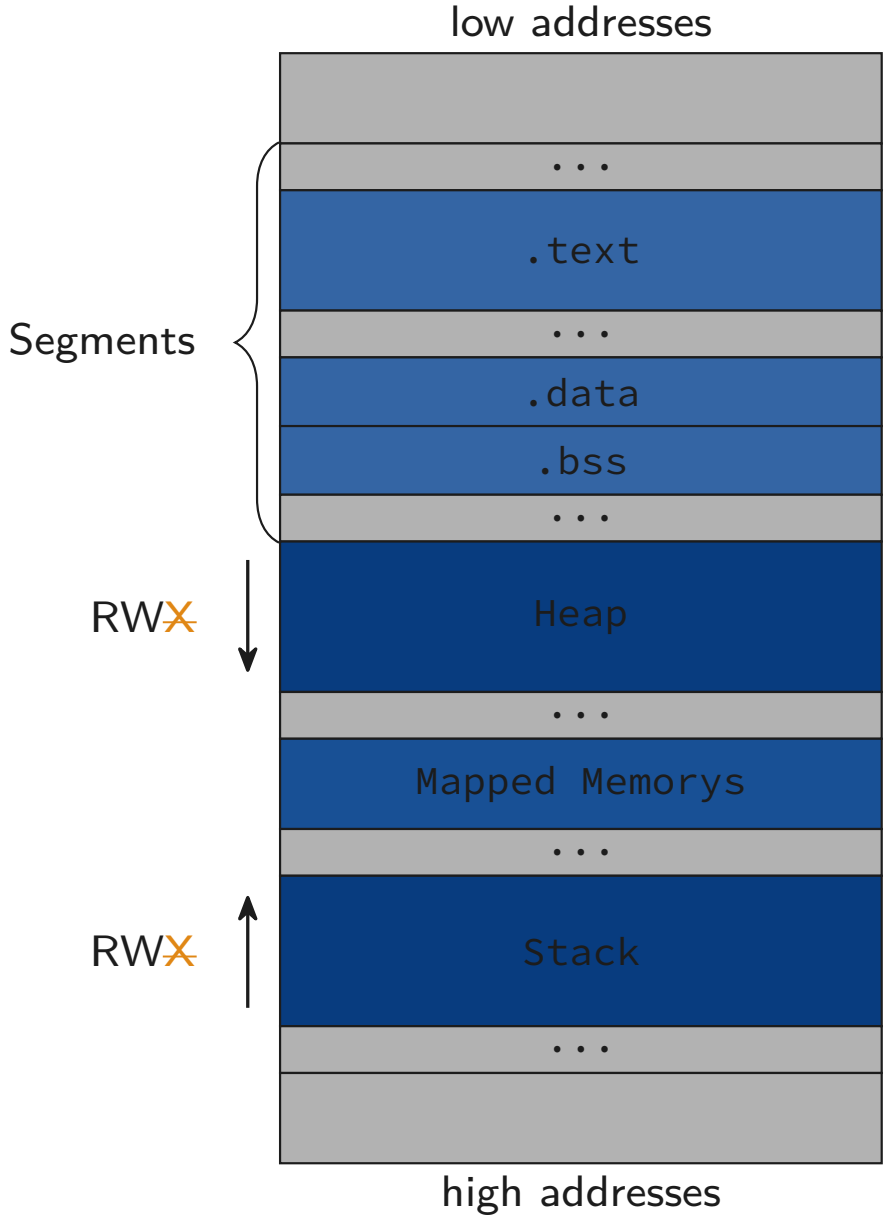
Example - Buffer Overflow



Return Oriented Programming

XN - Introduction

- Introduced by AMD
  - NX - No eXecute
- ARM introduced XN with ARMv6
  - XN - eXecute Never
- Additional bit in page table entry
- Known as
  - DEP
  - XN/NX/XD
  - W xor X



Return Oriented Programming

- Code reuse approach
- Use of small pieces of code called gadgets
- On ARMv7, gadgets end with a branch or pop instruction
  - `bx lr`
  - `pop {reg1, reg2, ..., regN, pc}`
- On ARMv8, gadgets can only end with `ret`
- It is important that `pc` is restored/loaded at the end of a gadget
- ROP chain consists of addresses to gadgets, chain of gadgets
- Each gadget is called by `ret` of the previously gadget

```
ldp x29, x30, [sp], #0x20;
ret
```

```
subs x0, x10, x9;
ret
```

Return Oriented Programming

Where to find gadgets?

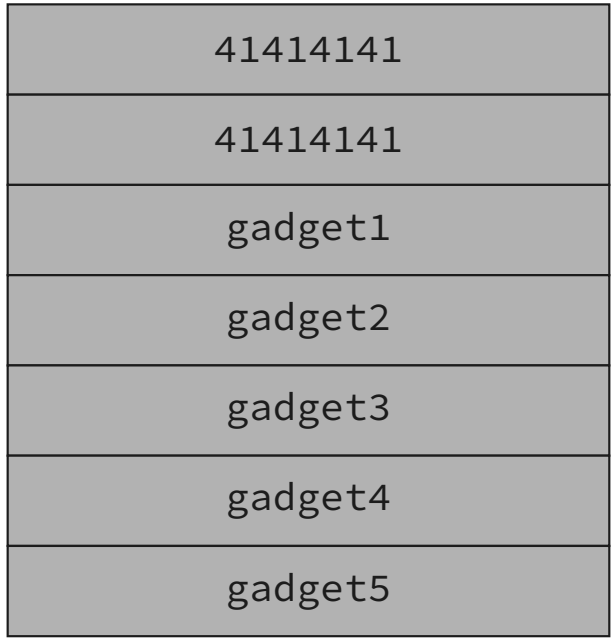
At least at the end of each function.

Different to ARMv7 and x86, gadgets can only be found there.

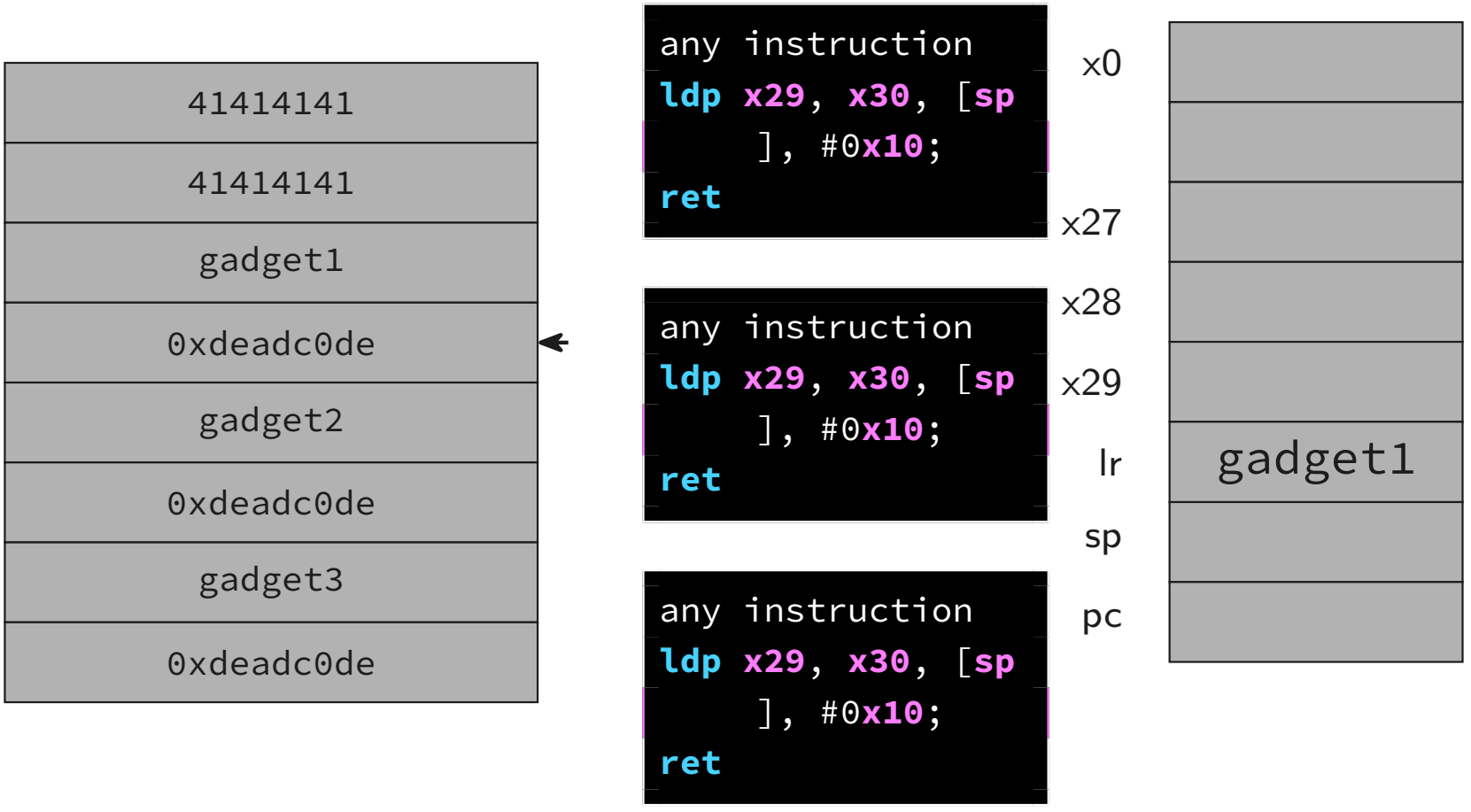
Return Oriented Programming

```
adds x3, x3, #1
ldp x29, x30, [sp], #0x10;
ret
```

ROP Chain Example



ROP Chain Example



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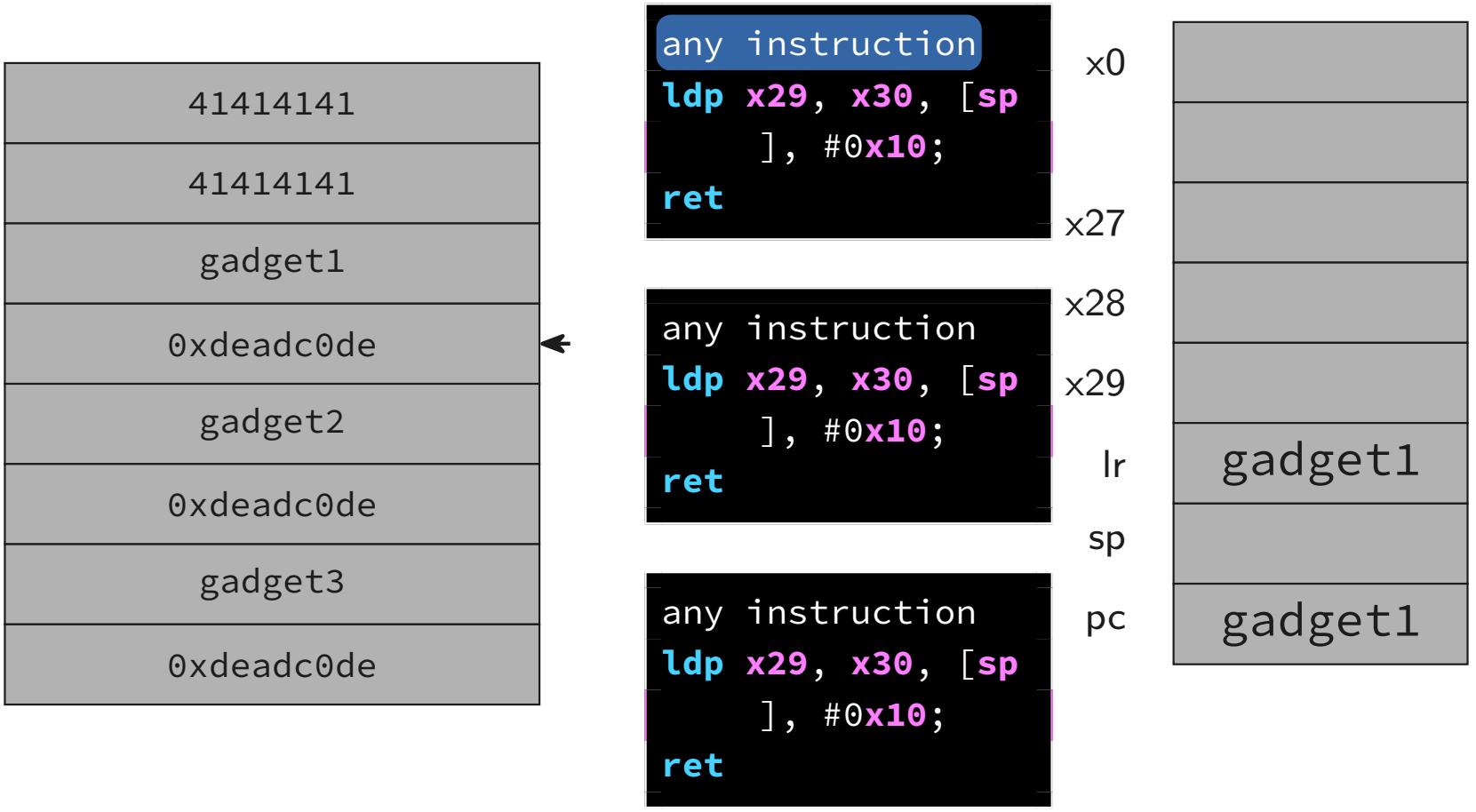
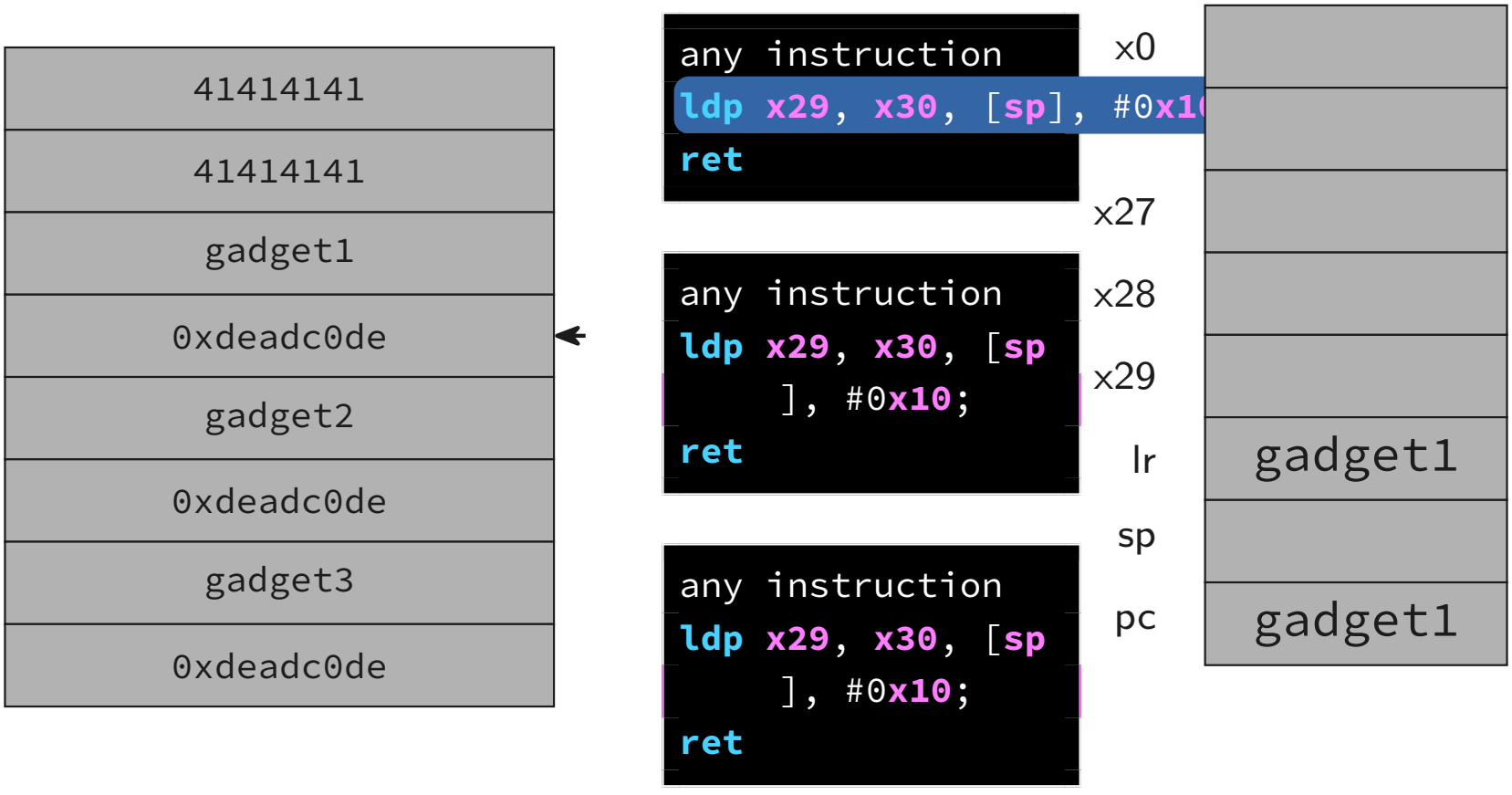
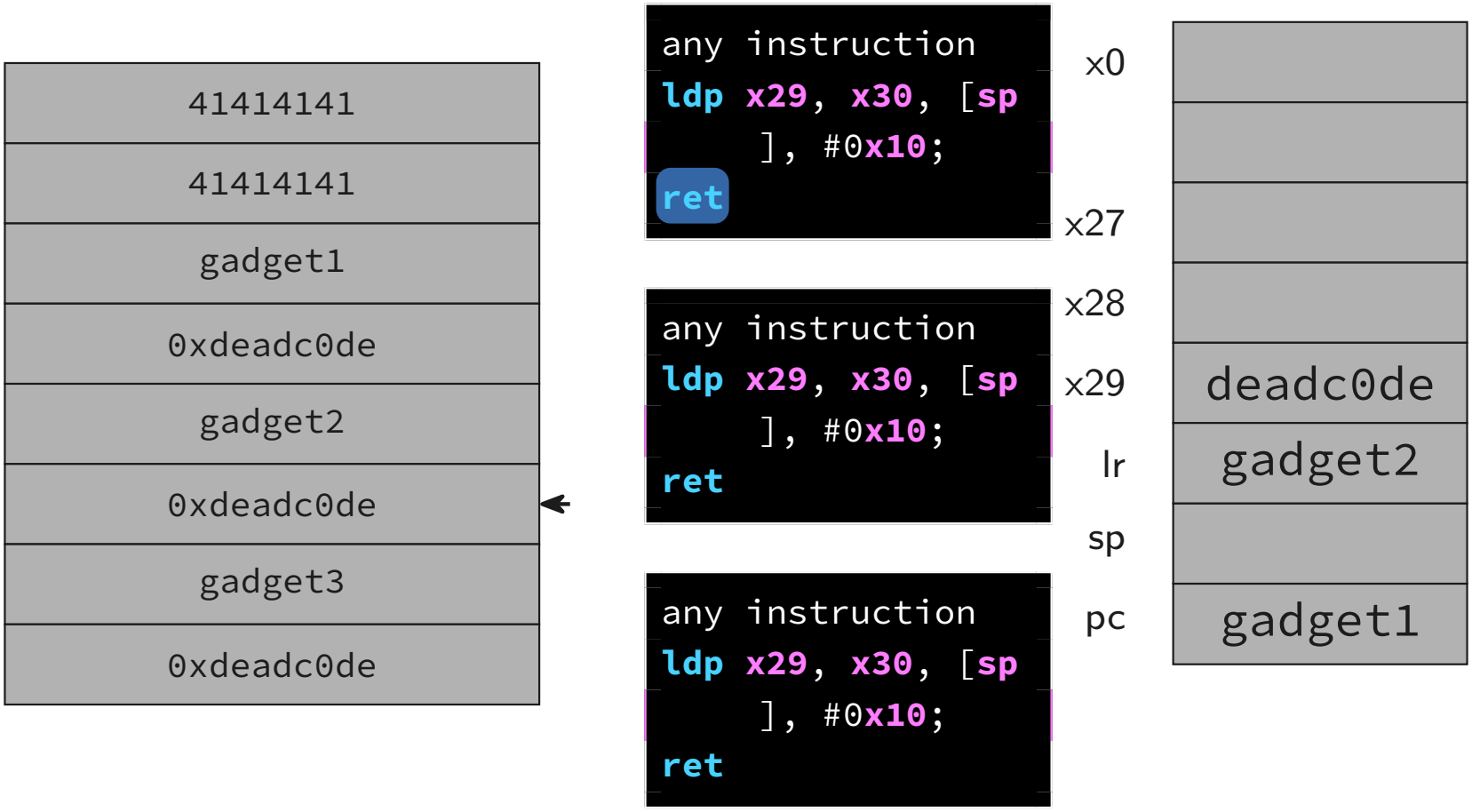


ROP Chain Example



ROP Chain Example



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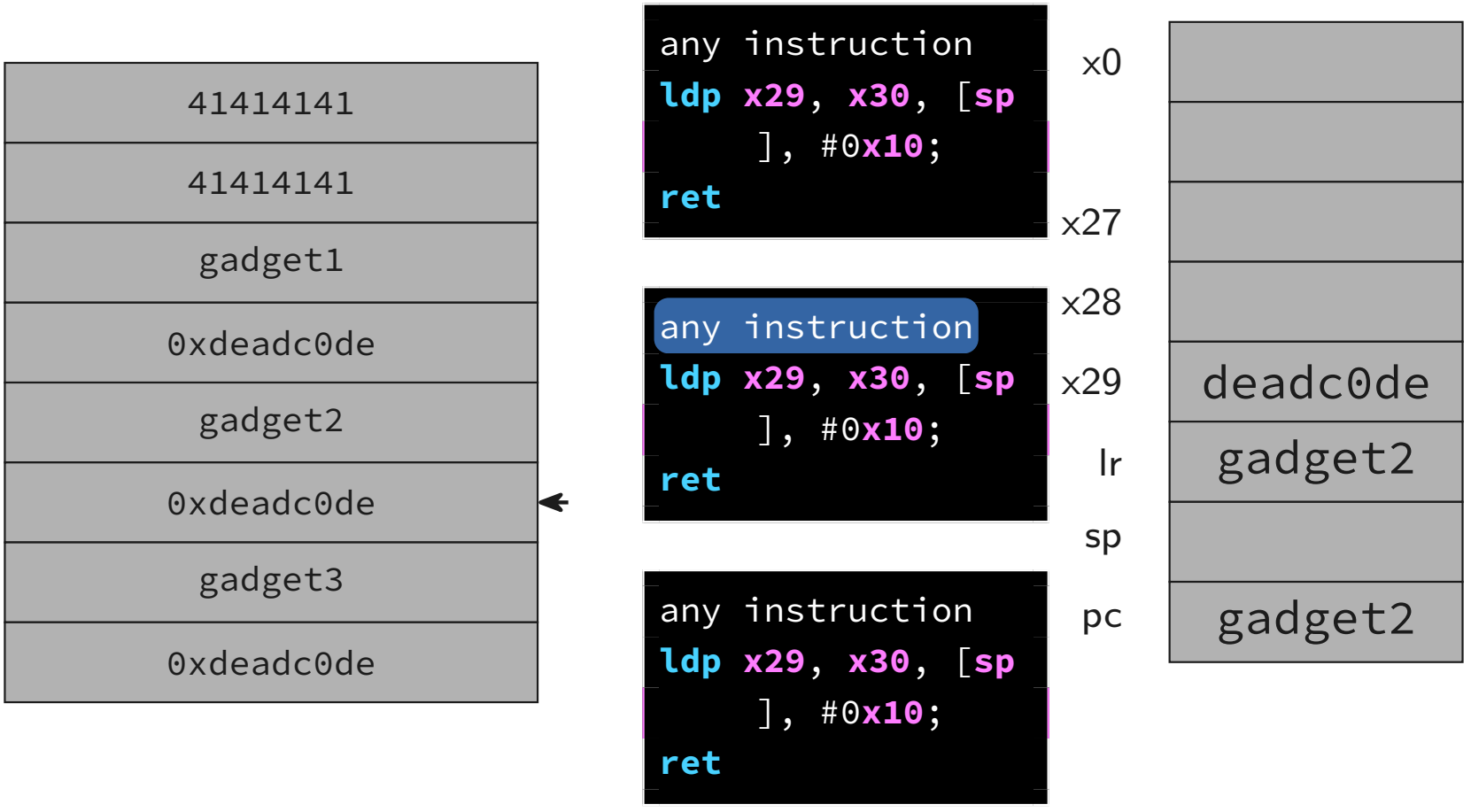
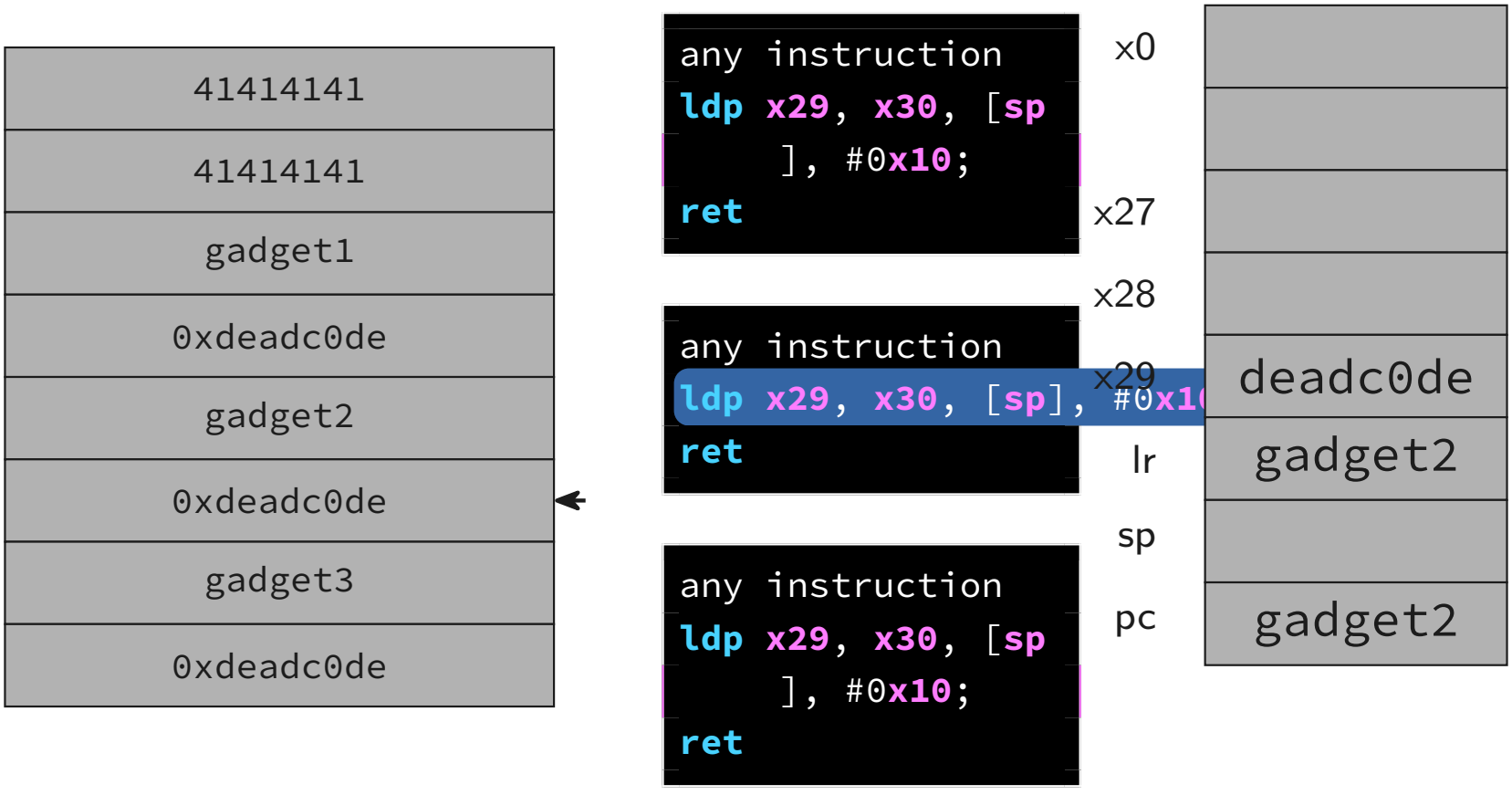


ROP Chain Example



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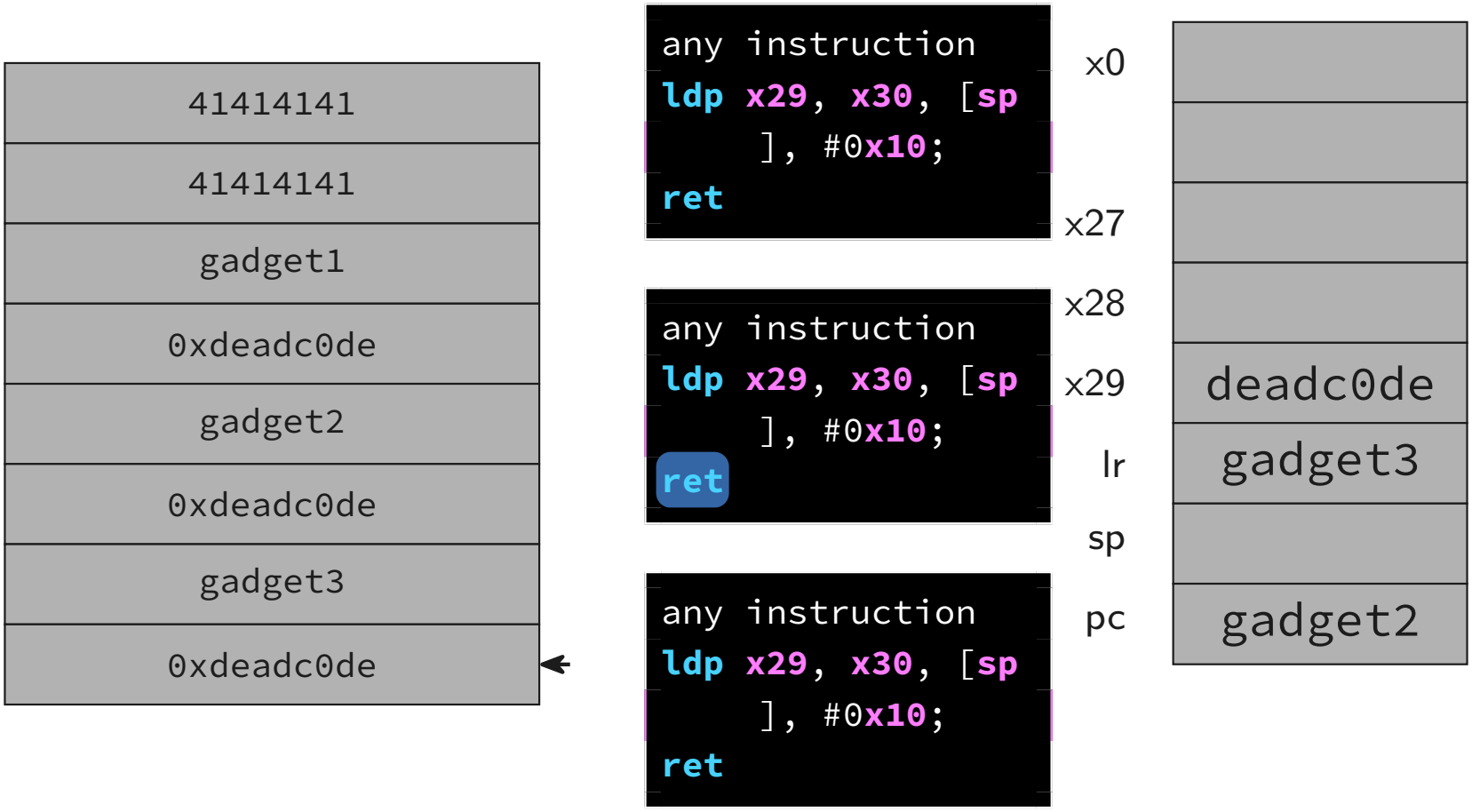
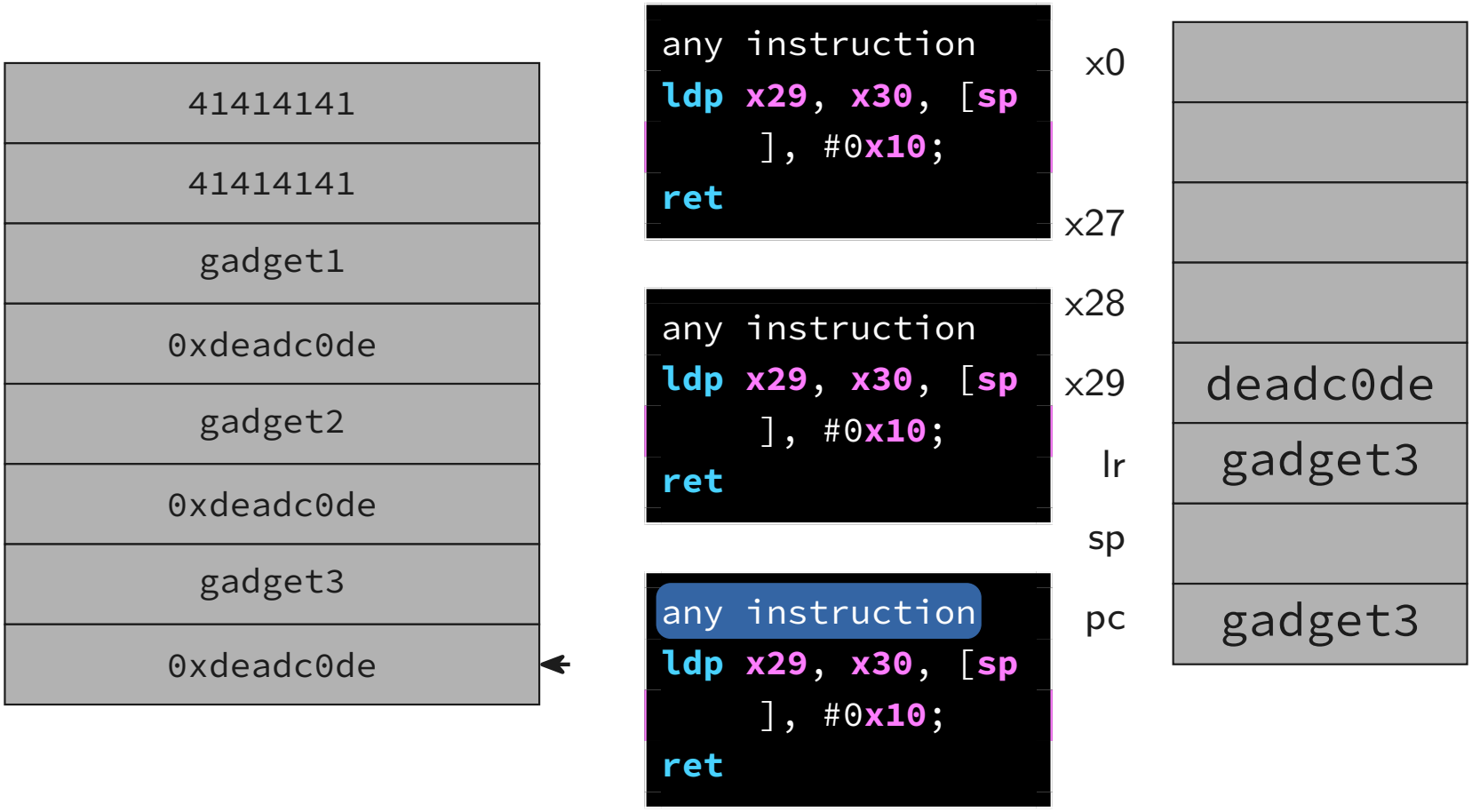
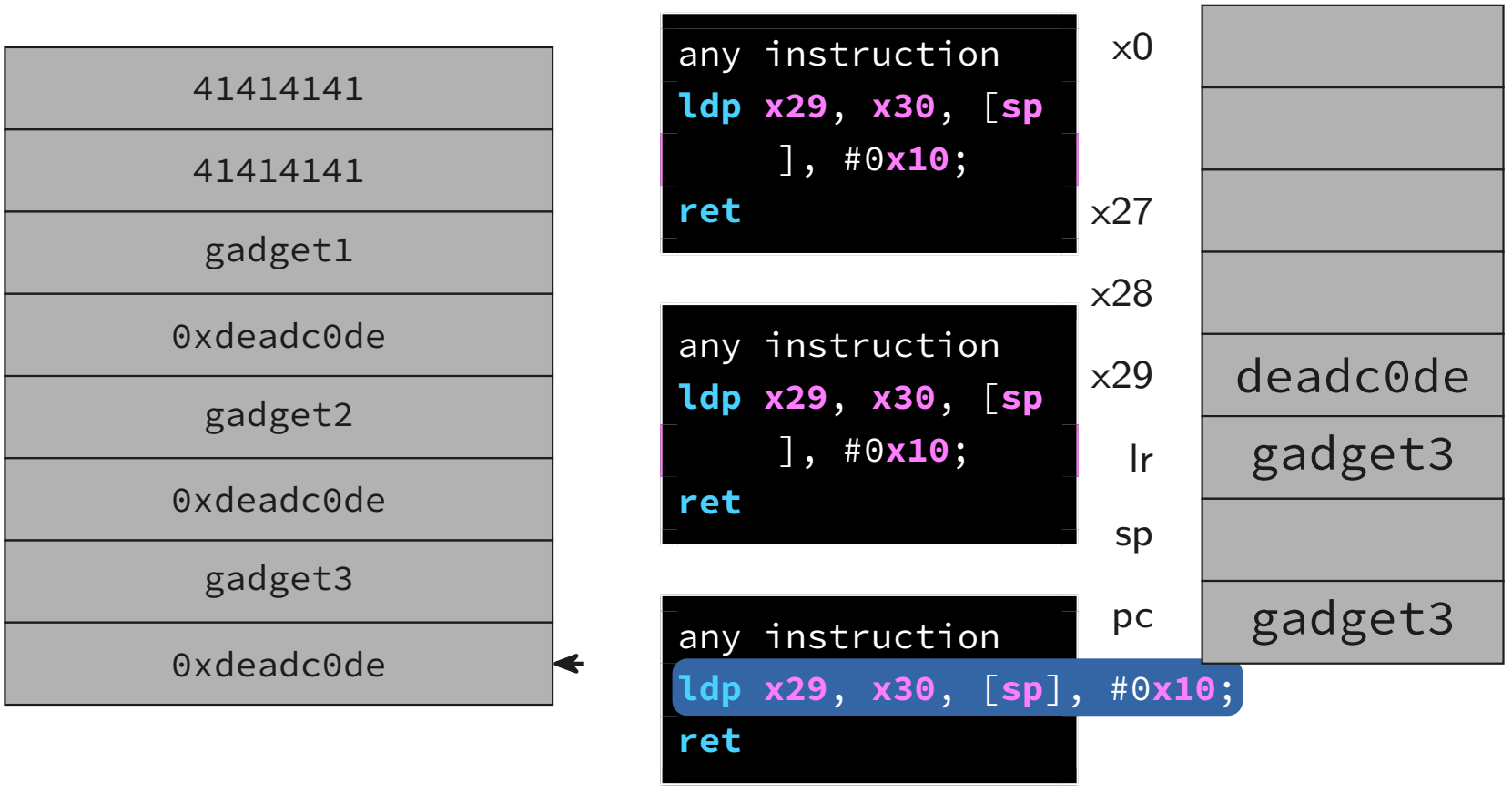


ROP Chain Example



ROP Chain Example



Jump Oriented Programming

Jump Oriented Programming

- Similar to ROP
- Gadgets ends with `br <reg>` or `blr <reg>`
- `<reg>` has to prepared with a gadget before

```
mov x0, x26
blr x3
```

```
add x2, x2, x3
blr x5
```

How to find Gadgets

Several tools available:

- ropper
  - https://github.com/sashs/ropper
- ropgadget
  - https://github.com/JonathanSalwan/ROPgadget # ROP on Aarch64

ROP on Aarch64

`x0`, `x1`, `x3`, ... need to be prepared for function calls or callinc syscalls

Values mostly need to be read from the stack.

Mostly no gadgets that set those registers with values from stack:

```
ldp x0, x1, [sp, #0x10]
ldp x29, x30, [sp], #0x20
ret
```

ROP on Aarch64

`x0`, `x1`, `x3`, ... need to be prepared for function calls or callinc syscalls

Values mostly need to be read from the stack.

It is possible to find that kind of gadgets

```
ldp x20, x21, [sp, #0x10]
ldp x29, x30, [sp], #0x20
ret
```

ROP on Aarch64

`x0`, `x1`, `x3`, ... need to be prepared for function calls or callinc syscalls

Values mostly need to be read from the stack.

It is possible to find that kind of gadgets

```
ldp x20, x21, [sp, #0x10]
ldp x29, x30, [sp], #0x20
ret
```

```
mov x0, x20
blr x3
```

ROP on Aarch64

- ROP and JOP is necessary
- Prepare higher registers
- Move values to lower registers
- Register of `br` or `blr` instruction has to prepared as well

```
ldp x20, x21, [sp, #0x10]
ldp x29, x30, [sp], #0x20
ret
```

```
mov x0, x20
blr x3
```

Vulnerabilities

- ASLR, StackCanaries, CFI and other mitigations
  - Requires another vulnerability
- Mostly in the heap
  - Double Free
  - Use After Free
  - Buffer Overflows
- ROP relies on the sp
- Only one gadget can be executed

Stack Pivot

- Necessary to move sp to the memory region which can be controlled
  - mostly heap
- Stack pivot is necessary
- Gadget that moves sp to that memory region

```
mov sp, x20
ldp x29, x30, [sp], #0x10
ret
```

Example

Example

- Android app
  - Using JNI (native code)
- Connects to REST service
- Get JSON data
- Parse JSON data and call native function

Example

```
{
    length: 123
    message: <base64 encoded>
}
```

Example

```
JNIEXPORT jstring JNICALL
Java_de_scoding_ropyourway_MainActivity_parseMessage(
        JNIEnv* env,
        jobject /* this */,
        jbyteArray message, jint length){

    jboolean isCopy;
    char buffer[32];
    jstring string = env->NewString(reinterpret_cast<const jchar *>("")
         , 5);

    char * nativeString = (char*)env->GetByteArrayElements( message, &
         isCopy);
    memcpy(buffer, nativeString, length);
return string;
}
```

Example

- Classic buffer overflow on the stack
- Return address will be overwritten

Example - Exploit

- Call `system` with a ROP chain to execute a command
- `x0` has to be prepared with the argument
  - Address to the command
  - Gadget that moves `sp` to `x0`
- Place the command on the stack

```
mov x0, sp
blr x??
```

Example - Exploit