

CSCI 4907/6545 Software Security

Fall 2025

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Slides materials are partially credited to Gang Tan of PSU.

Outline of Today's Lecture

- Brief review of last lecture
- Return-oriented Programming (ROP)
- Integer overflows
- Heap overflows

Programming *Correctly* in C is (Extremely) Hard

Simple and primitive language features

- Basic data types (char, integer, boolean, etc.)
- struct
- **Pointers**
- Basic control flow (conditional branches, loops, etc.)

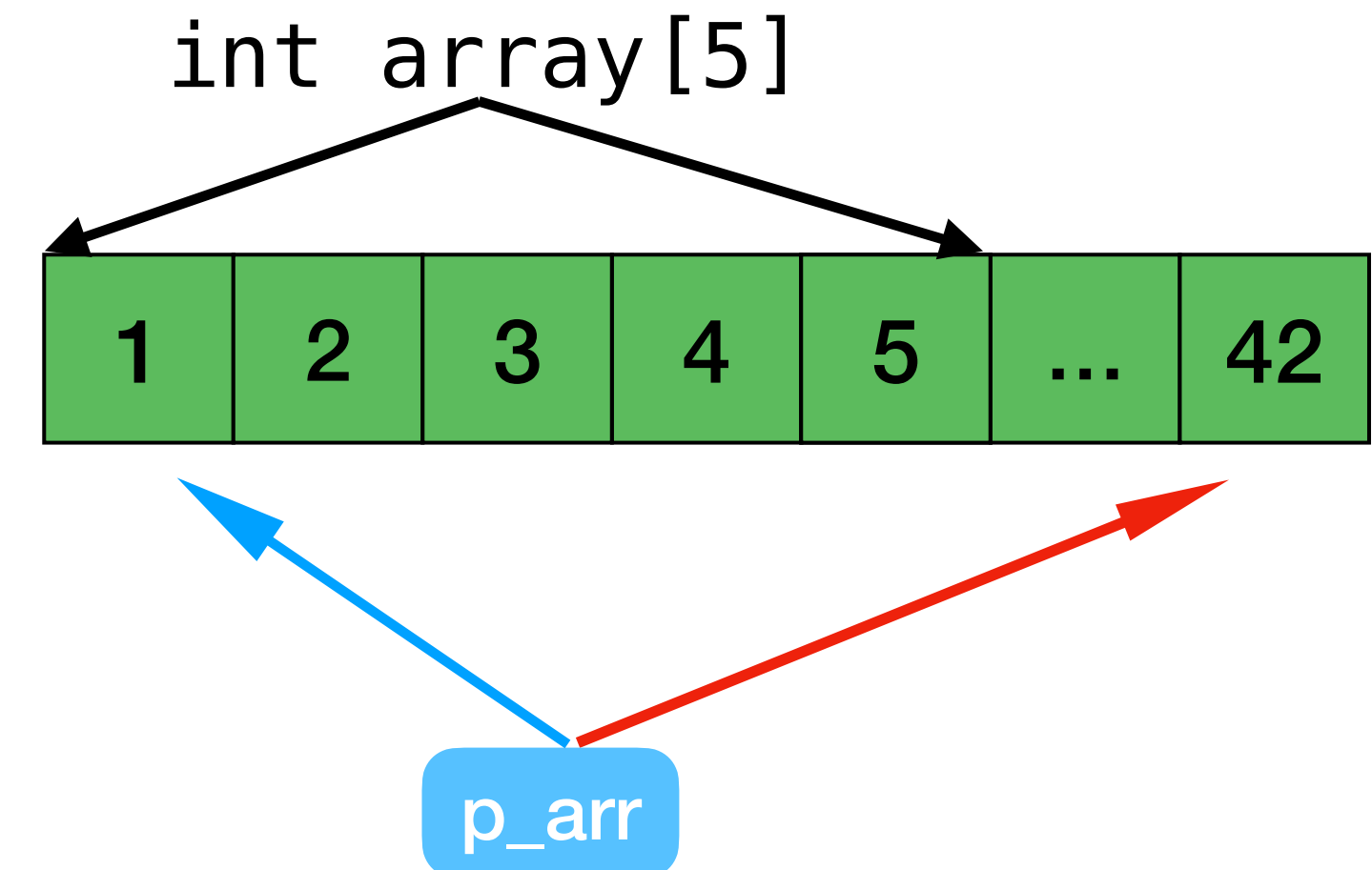
-  **Pointer:** Capability to manipulate memory.
- For C, pointer is usually implemented as a virtual address.
 - But this is not the only way to implement pointers.

-  **C pointers can do almost arbitrary memory manipulation!**
- The correctness is at the discretion of programmers.

Buffer Overflows



Reading/writing a buffer out of its bounds.



- It is C/C++ programmers' job to ensure such errors do not happen.
- In contrast, most modern languages (e.g., Java, Rust, ...) prevent buffer overflows by performing automatic bounds checking.
- The first Internet worm, Morris Worm, and many subsequent ones (CodeRed, Blaster, ...) exploited buffer overflows.
- Buffer overflows are still among the most commonly exploited vulnerabilities.

Better String Library Functions

- Instead of `strcpy()`, use `strncpy()`
- Instead of `strcat()`, use `strncat()`
- Instead of `sprintf()`, use `snprintf()`

Null-termination Errors

```
int main(int argc, char* argv[]) {  
    char a[16], b[16];  
    strncpy(a, "0123456789abcdef", sizeof(a));  
    printf("%s", a);  
    strcpy(b, a);  
}
```



What will be printed out?

- a [] not properly terminated.
 - Undefined behaviors, e.g., segmentation fault if printf is executed.

```
$ clang copy.c -o copy  
jie@gwsyssec: /tmp  
$ ./copy  
0123456789abcdef??  
??jie@gwsyssec: /tmp  
$ ./copy  
0123456789abcdef(??jie@gwsyssec: /tmp  
$ ./copy  
0123456789abcdef?86?jie@gwsyssec: /tmp
```

Example Illustrating Stack Buffer Overflows

```
void foo(int a, int b) {  
    char buffer[12];  
    gets(buffer);  
    return;  
}  
  
int main() {  
    int x;  
    x = 0;  
    foo(1,2);  
    x = 1;  
    printf("%d\n",x);  
    return 0;  
}
```

(gdb) disassemble main

Dump of assembler code for function main:

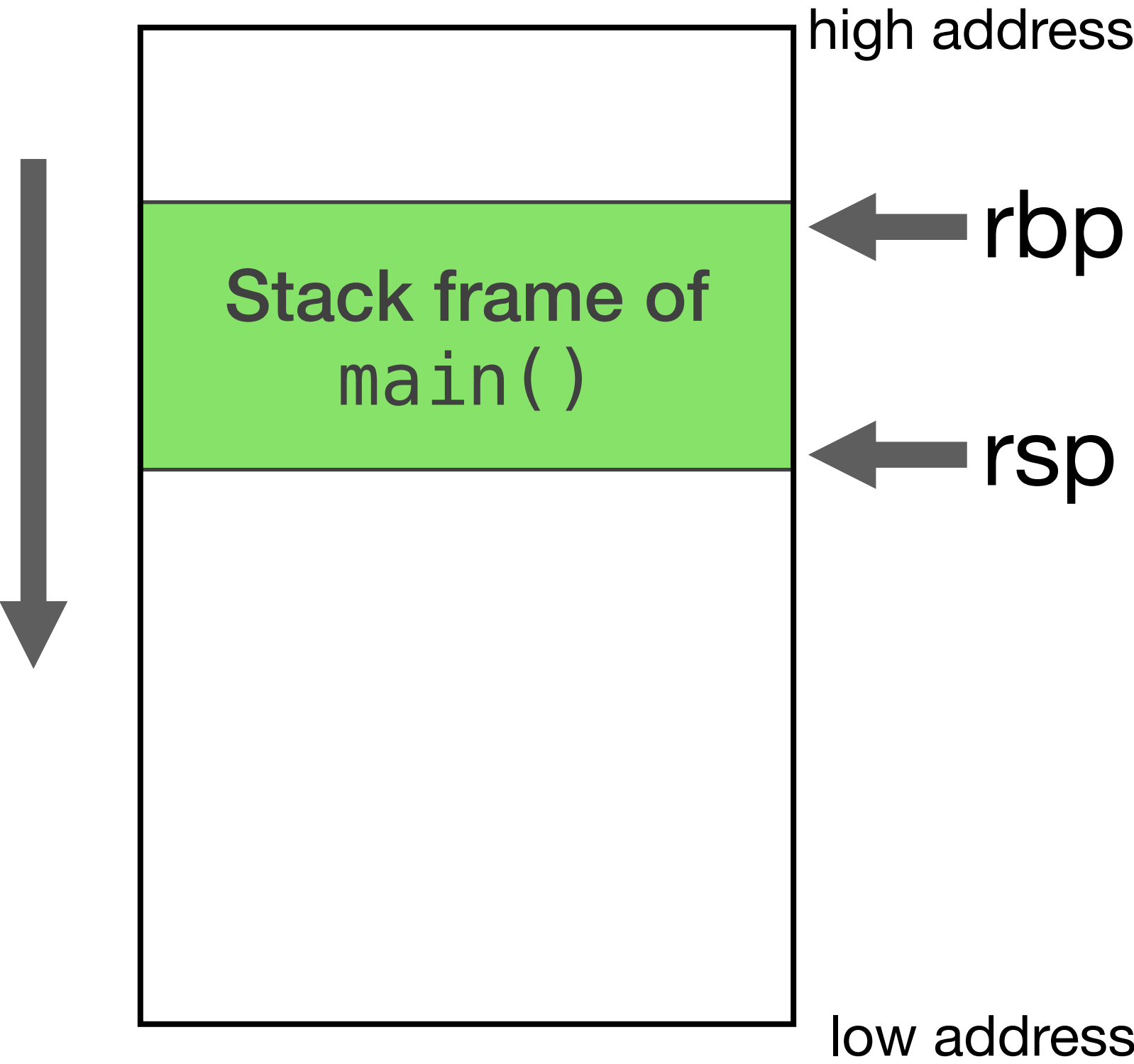
```
0x0000000000001170 <+0>:    push    %rbp  
0x0000000000001171 <+1>:    mov     %rsp,%rbp  
0x0000000000001174 <+4>:    sub     $0x10,%rsp  
0x0000000000001178 <+8>:    movl    $0x0,-0x4(%rbp)  
0x000000000000117f <+15>:   movl    $0x0,-0x8(%rbp)  
0x0000000000001186 <+22>:   mov     $0x1,%edi  
0x000000000000118b <+27>:   mov     $0x2,%esi  
0x0000000000001190 <+32>:   call    0x1150 <foo>  
0x0000000000001195 <+37>:   movl    $0x1,-0x8(%rbp)  
0x000000000000119c <+44>:   mov     -0x8(%rbp),%esi  
0x000000000000119f <+47>:   lea     0xe5e(%rip),%rdi  
0x00000000000011a6 <+54>:   mov     $0x0,%al  
0x00000000000011a8 <+56>:   call    0x1030 <printf@plt>  
0x00000000000011ad <+61>:   xor     %eax,%eax  
0x00000000000011af <+63>:   add     $0x10,%rsp  
0x00000000000011b3 <+67>:   pop     %rbp  
0x00000000000011b4 <+68>:   ret
```

Compiled by clang-14 on Linux/AMD64

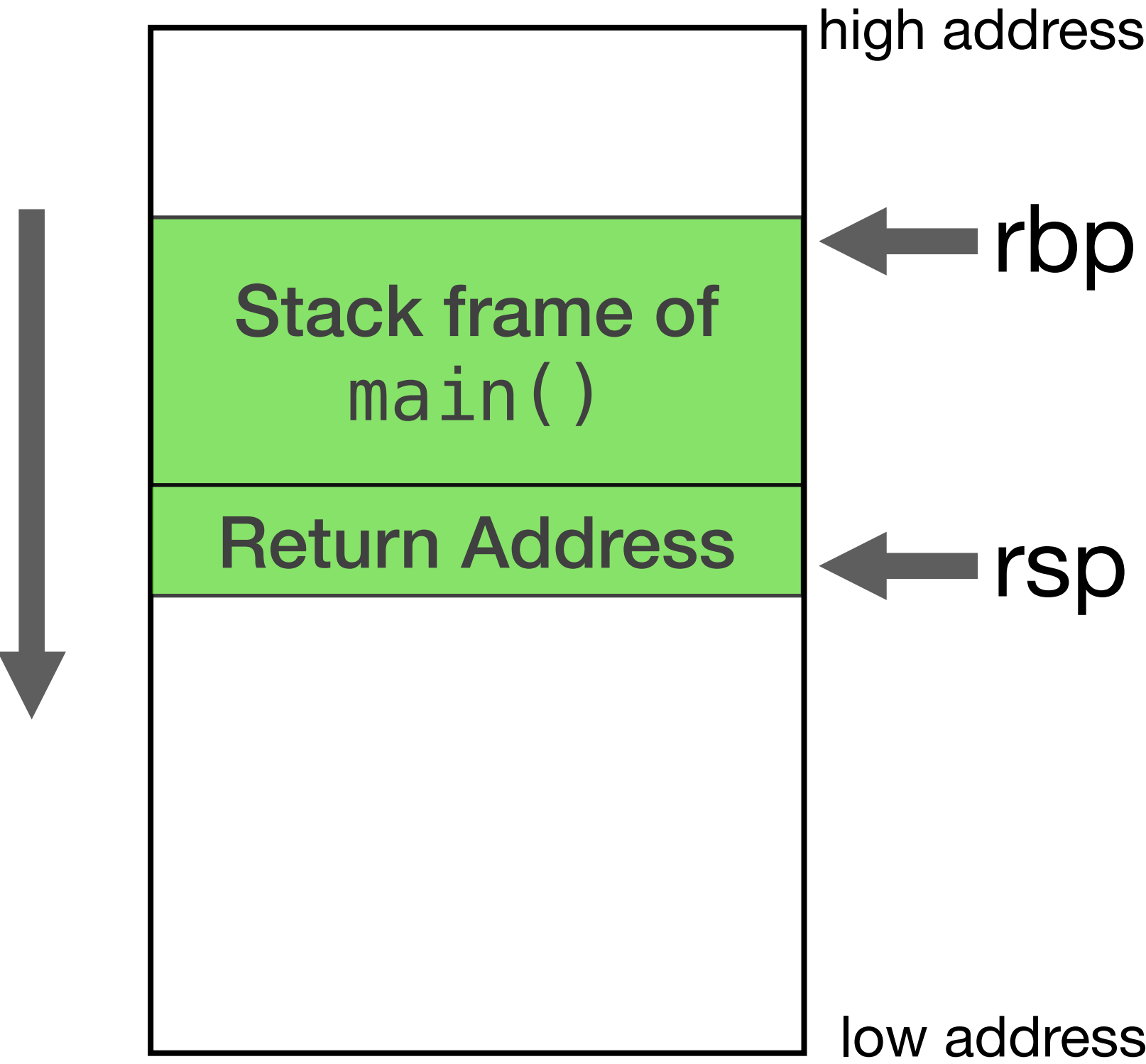
Function Calls: Stack

```
0x00000000000001186 <+22>:  mov    $0x1,%edi
0x0000000000000118b <+27>:  mov    $0x2,%esi
0x00000000000001190 <+32>:  call   0x1150 <foo>
```

Before the call



After the call

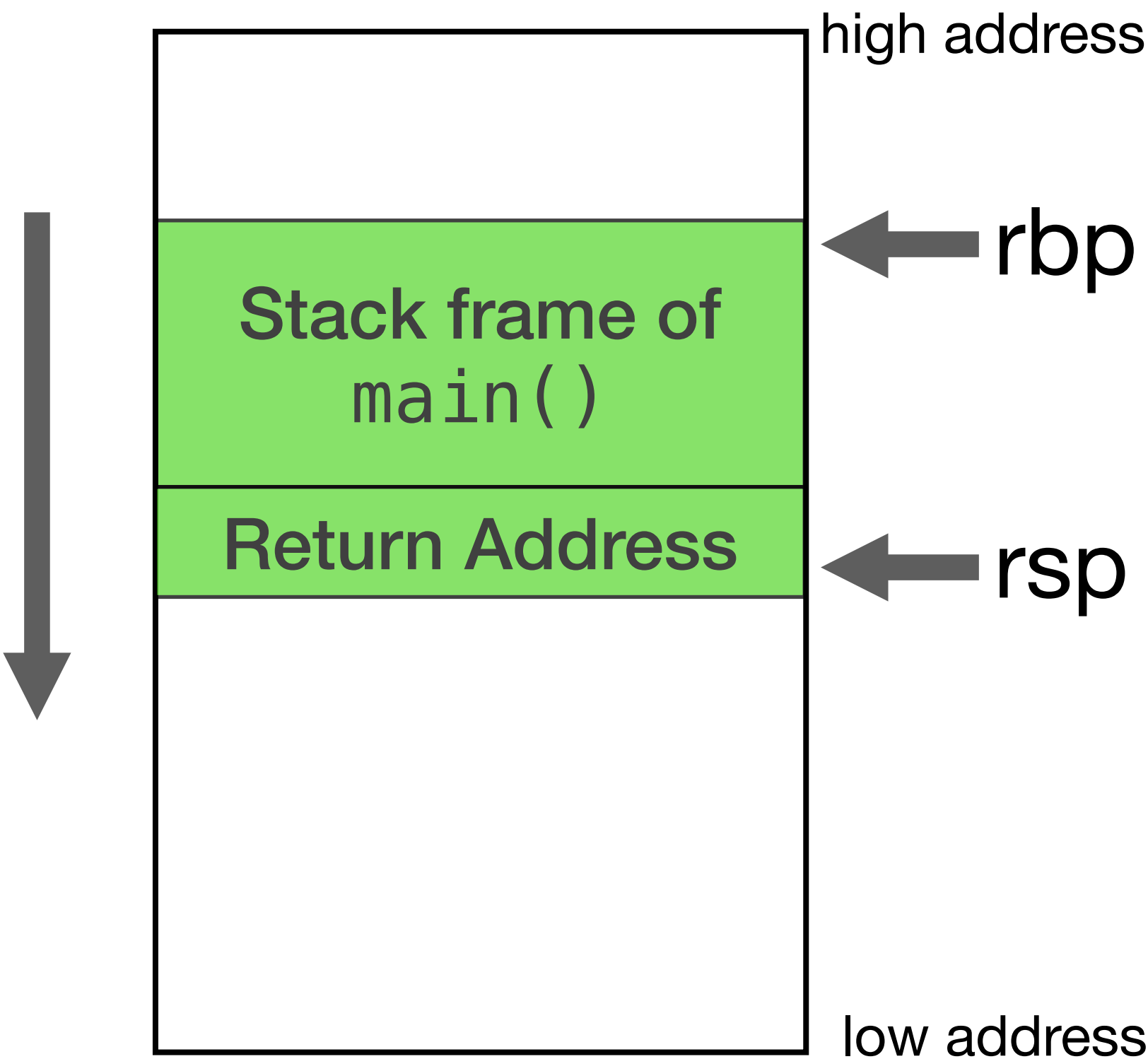


Function Initialization: Stack

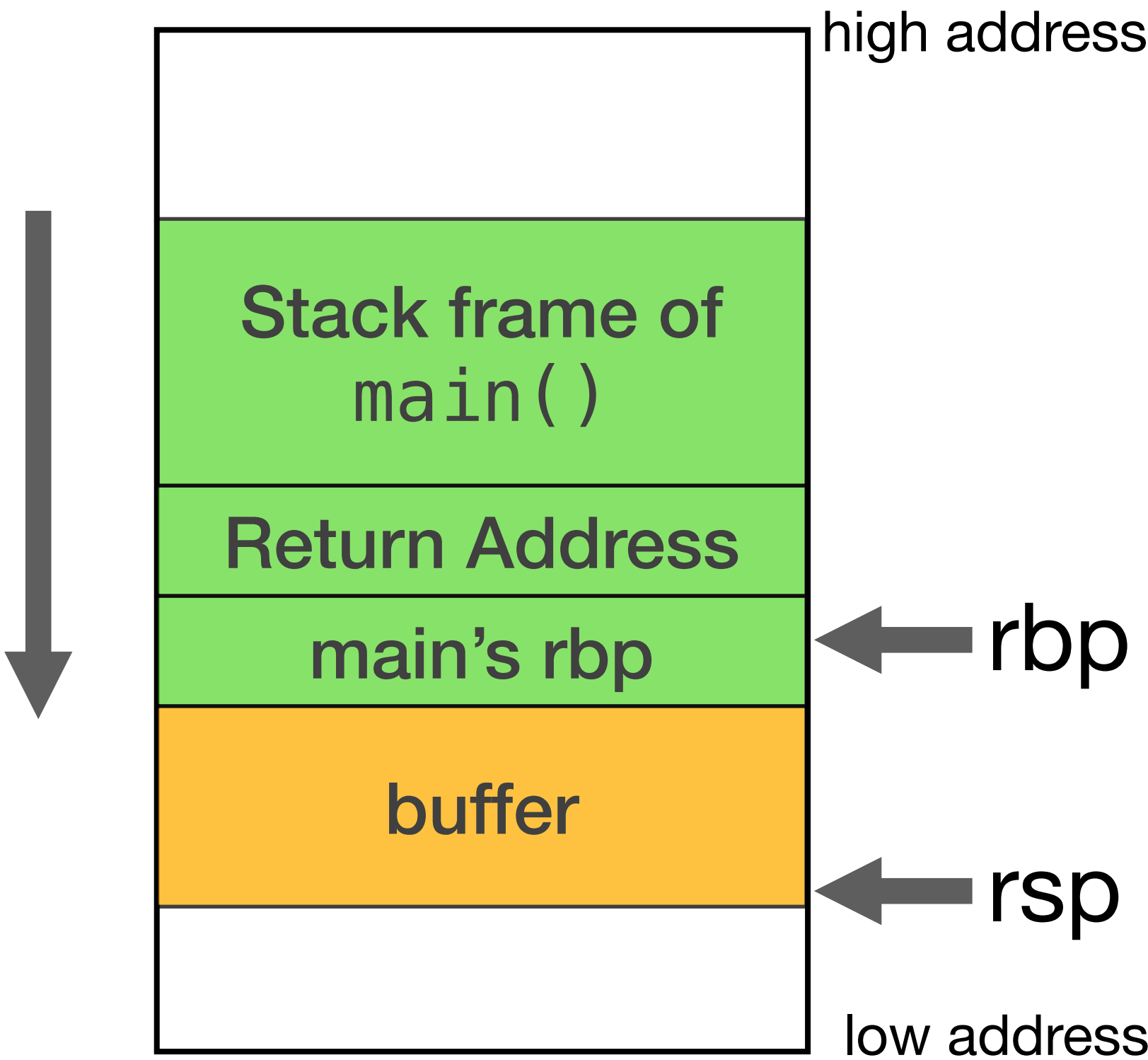
```
void foo(int a, int b) {  
    char buffer[12];  
    gets(buffer);  
    return;  
}
```

0x0000000000000150	<+0>:	push	%rbp
0x0000000000000151	<+1>:	mov	%rsp,%rbp
0x0000000000000154	<+4>:	sub	\$0x20,%rsp

Before the call



After the call

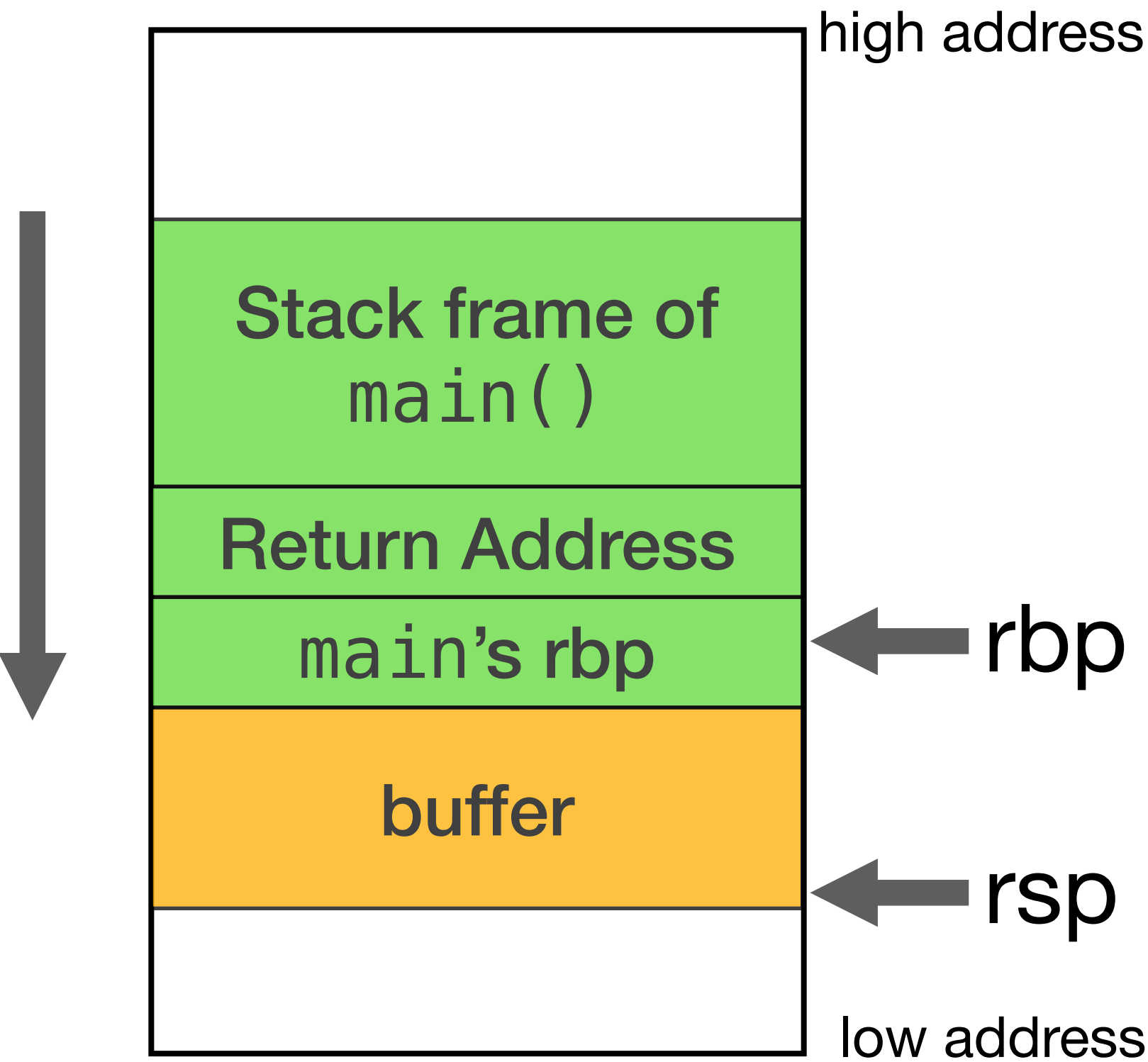


Function Return: Stack

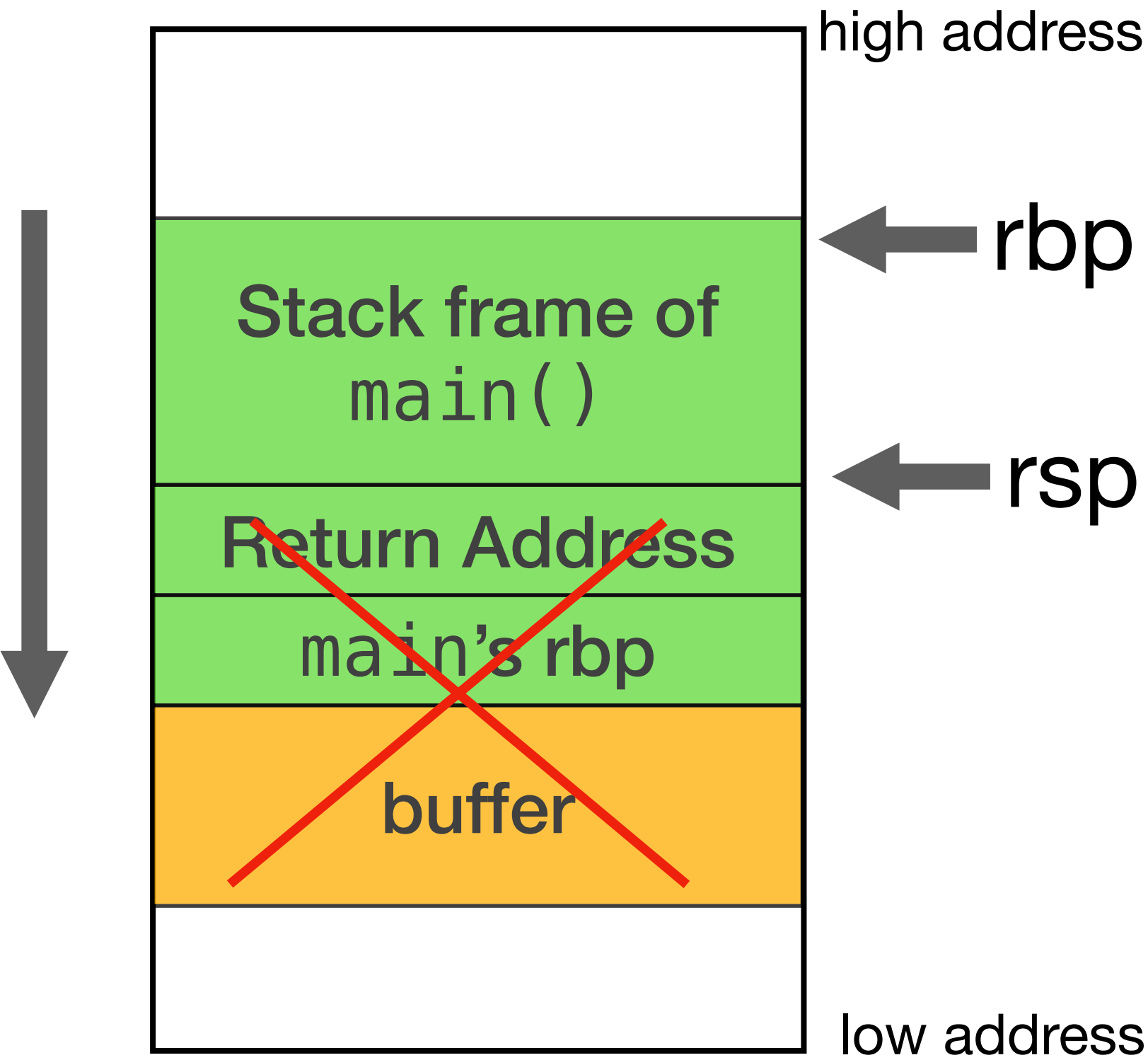
```
void foo(int a, int b) {  
    char buffer[12];  
    gets(buffer);  
    return;  
}
```

```
0x00000000000001169 <+25>:  add    $0x20,%rsp  
0x0000000000000116d <+29>:  pop     %rbp  
0x0000000000000116e <+30>:  ret
```

Before the call



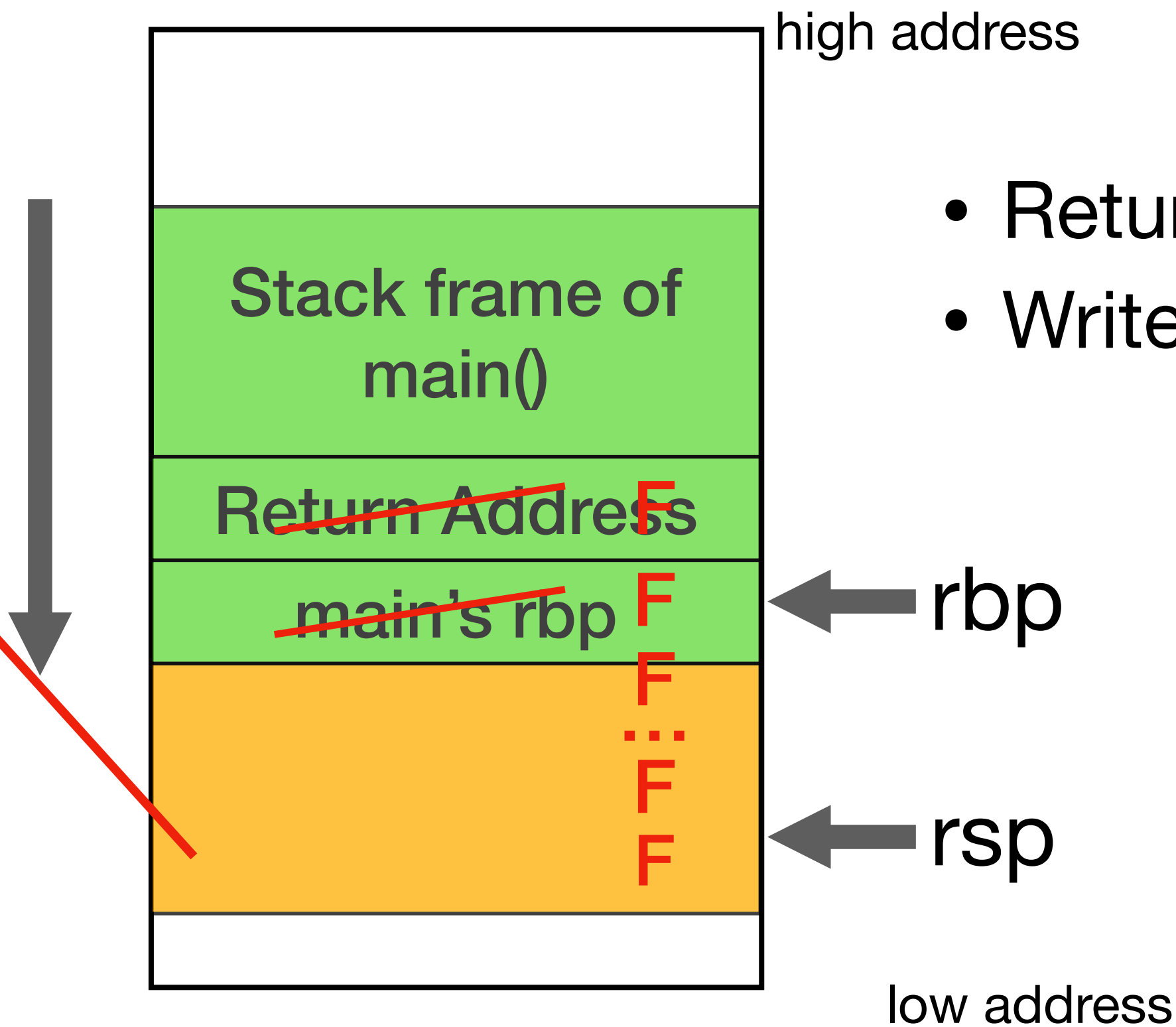
After the call



Smashing the Stack: What Happened?

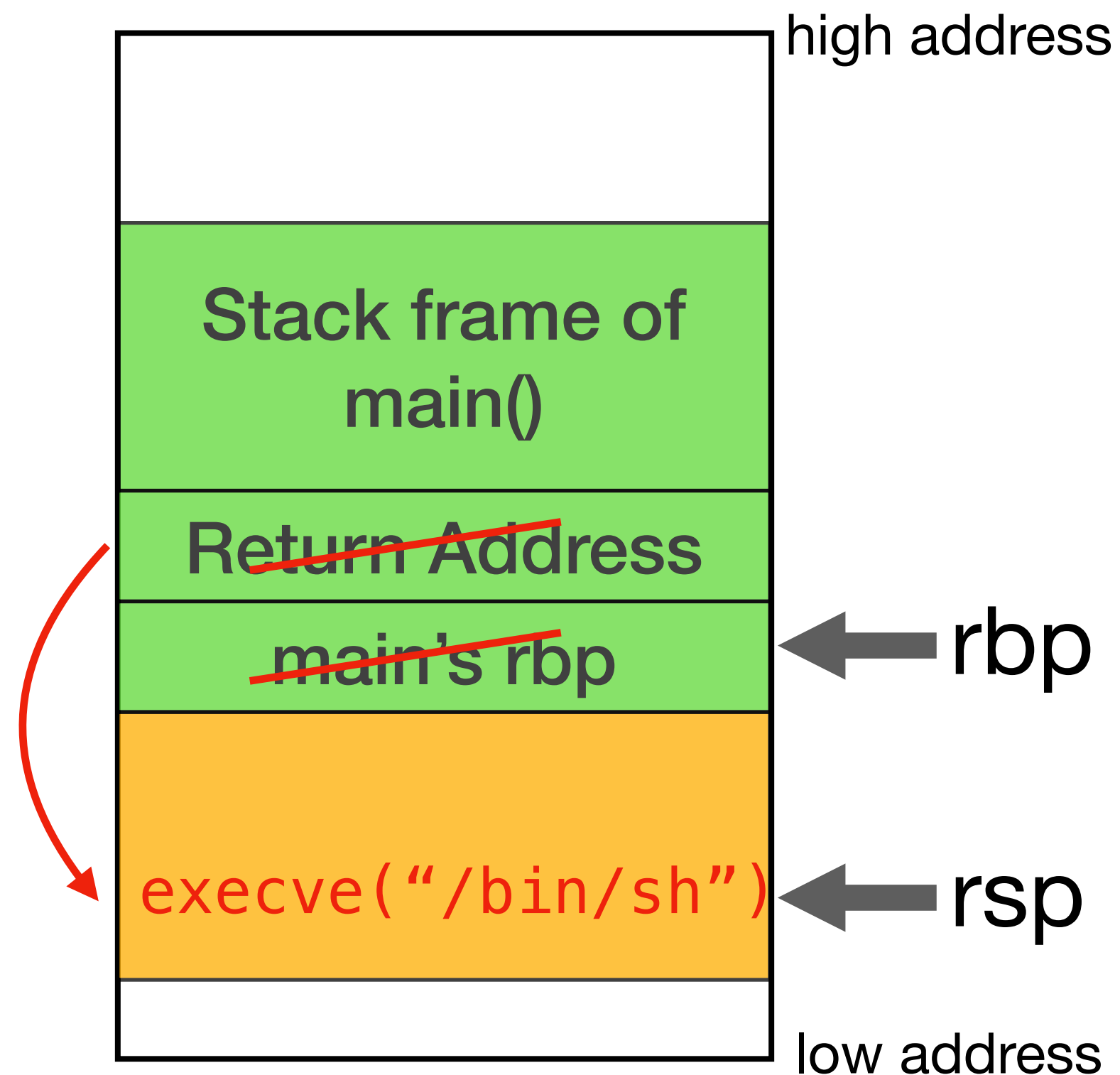
```
void foo(int a, int b) {  
    char buffer[12];  
    gets(buffer);  
    return;  
}
```

What happens if we input a large string?
./demo ffffffffffffffffffffffffffff...ffffff



- Return to an invalid address
- Write to an unwritable address

Smashing the Stack: Injecting Shell Code



- This brings up a shell.
- Attackers can execute *any* command in the shell.
- The shell has the same privilege as the process.

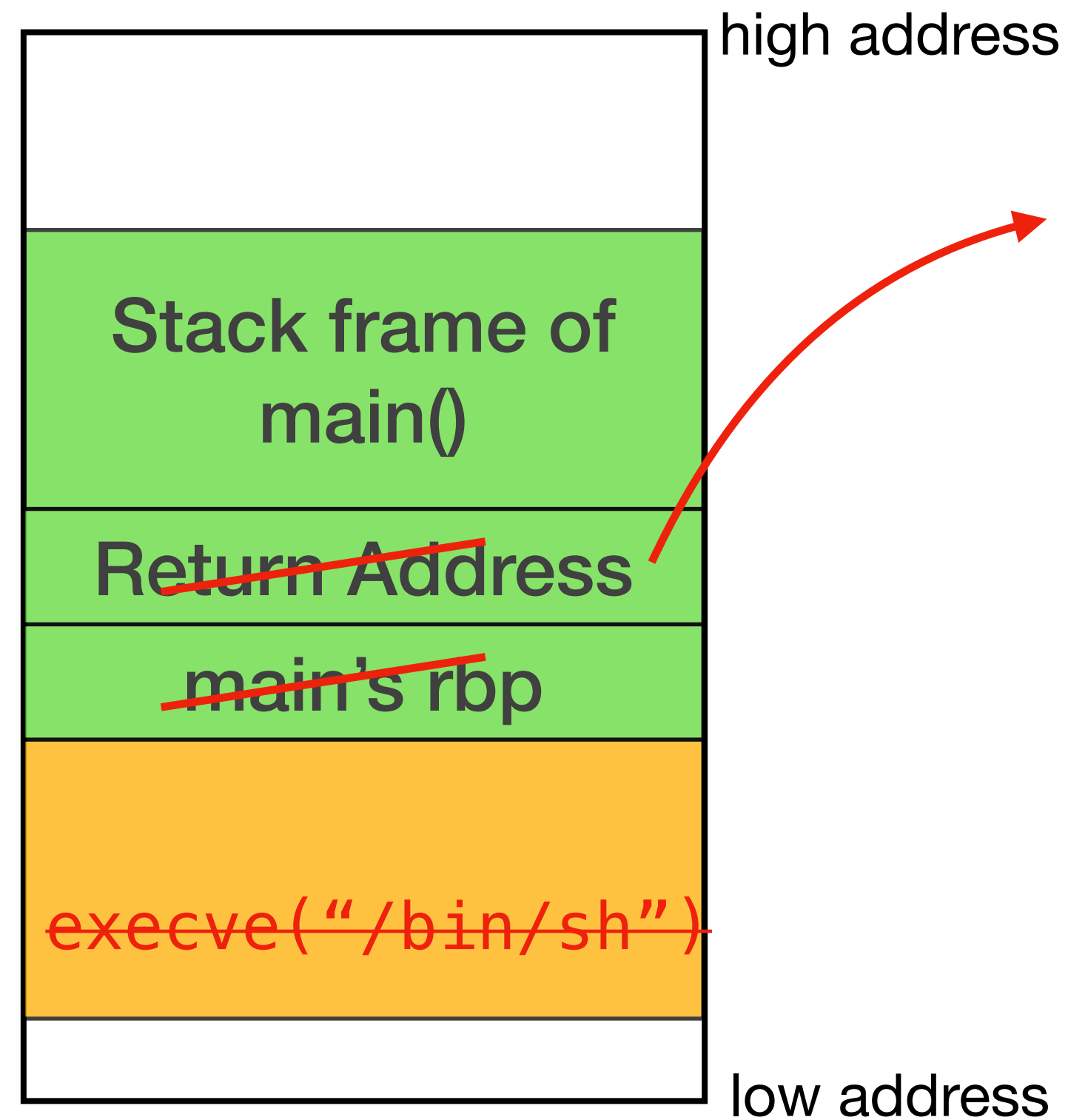


- Good news:
 - C/C++ stack is not executable by default.



- Bad news:
 - Code injection works in other cases, e.g. JIT.

Exploiting Existing and Executable Code



“return” to system()

(gdb) disassemble system

Dump of assembler code for function system:

```
0x00007ffff7c50d70 <+0>:    endbr64
0x00007ffff7c50d74 <+4>:    test    %rdi,%rdi
0x00007ffff7c50d77 <+7>:    je      0x7ffff7c50d80 <system+16>
0x00007ffff7c50d79 <+9>:    jmp     0x7ffff7c50900
0x00007ffff7c50d7e <+14>:   xchg    %ax,%ax
0x00007ffff7c50d80 <+16>:   sub     $0x8,%rsp
0x00007ffff7c50d84 <+20>:   lea     0x1878f5(%rip),%rdi
0x00007ffff7c50d8b <+27>:   call    0x7ffff7c50900
0x00007ffff7c50d90 <+32>:   test    %eax,%eax
0x00007ffff7c50d92 <+34>:   sete    %al
0x00007ffff7c50d95 <+37>:   add     $0x8,%rsp
0x00007ffff7c50d99 <+41>:   movzbl  %al,%eax
0x00007ffff7c50d9c <+44>:   ret
```

Return-to-libc(ret2libc) Attack: Exploiting system()

- system() libc function

NAME [top](#)

system – execute a shell command

LIBRARY [top](#)

Standard C library (*libc*, *-lc*)

SYNOPSIS [top](#)

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

```
int system(const char *command);
```

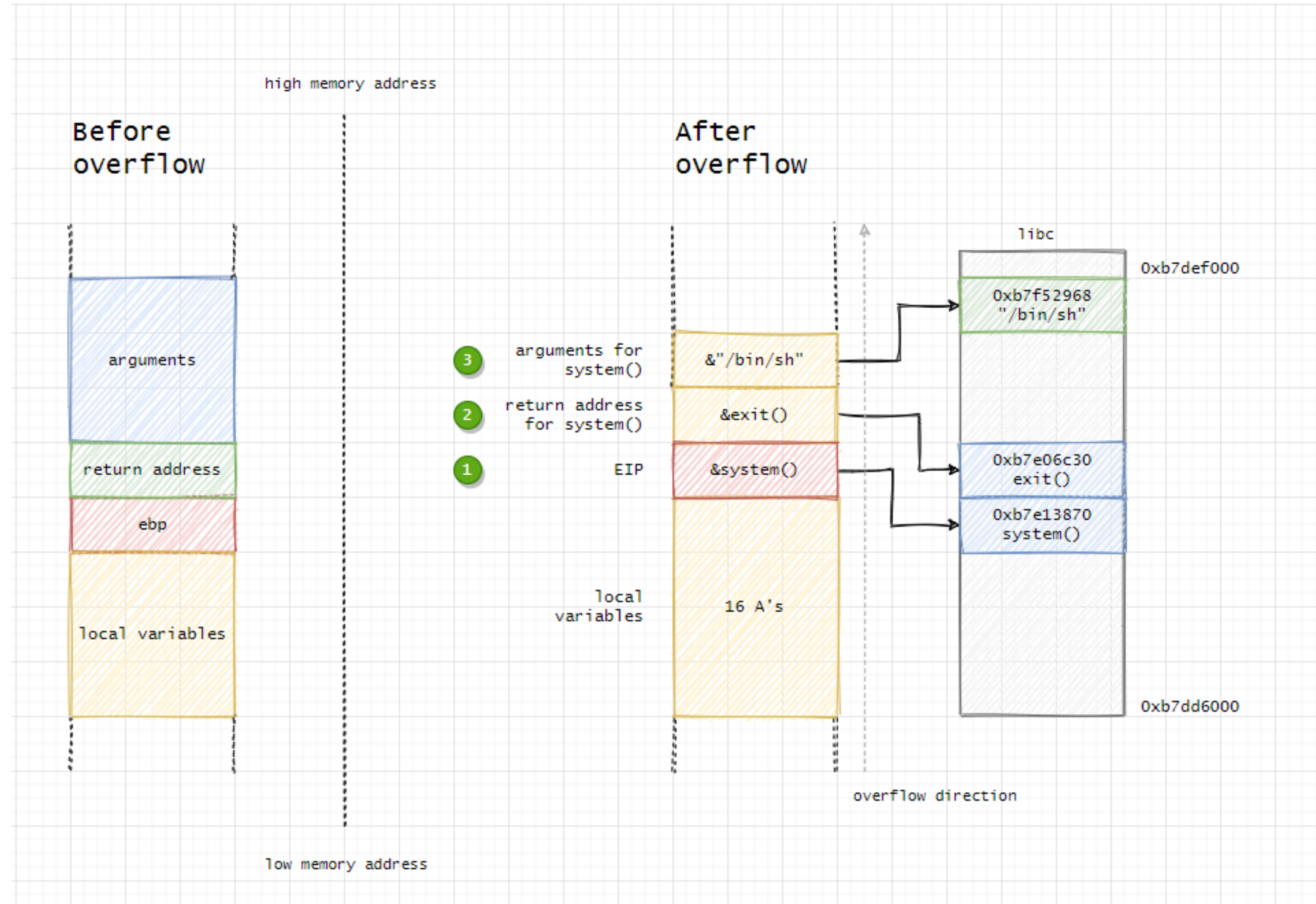
DESCRIPTION [top](#)

The **system()** library function behaves as if it used [fork\(2\)](#) to create a child process that executed the shell command specified in *command* using [execl\(3\)](#) as follows:

```
execl("/bin/sh", "sh", "-c", command, (char *) NULL);
```

system() returns after the command has been completed.

Exploiting ret2libc on x86-32



Stack memory layout of a 32-bit vulnerable program

System V AMD64 Calling Convention



How functions/subroutines pass arguments and return values at the macro-architecture level.

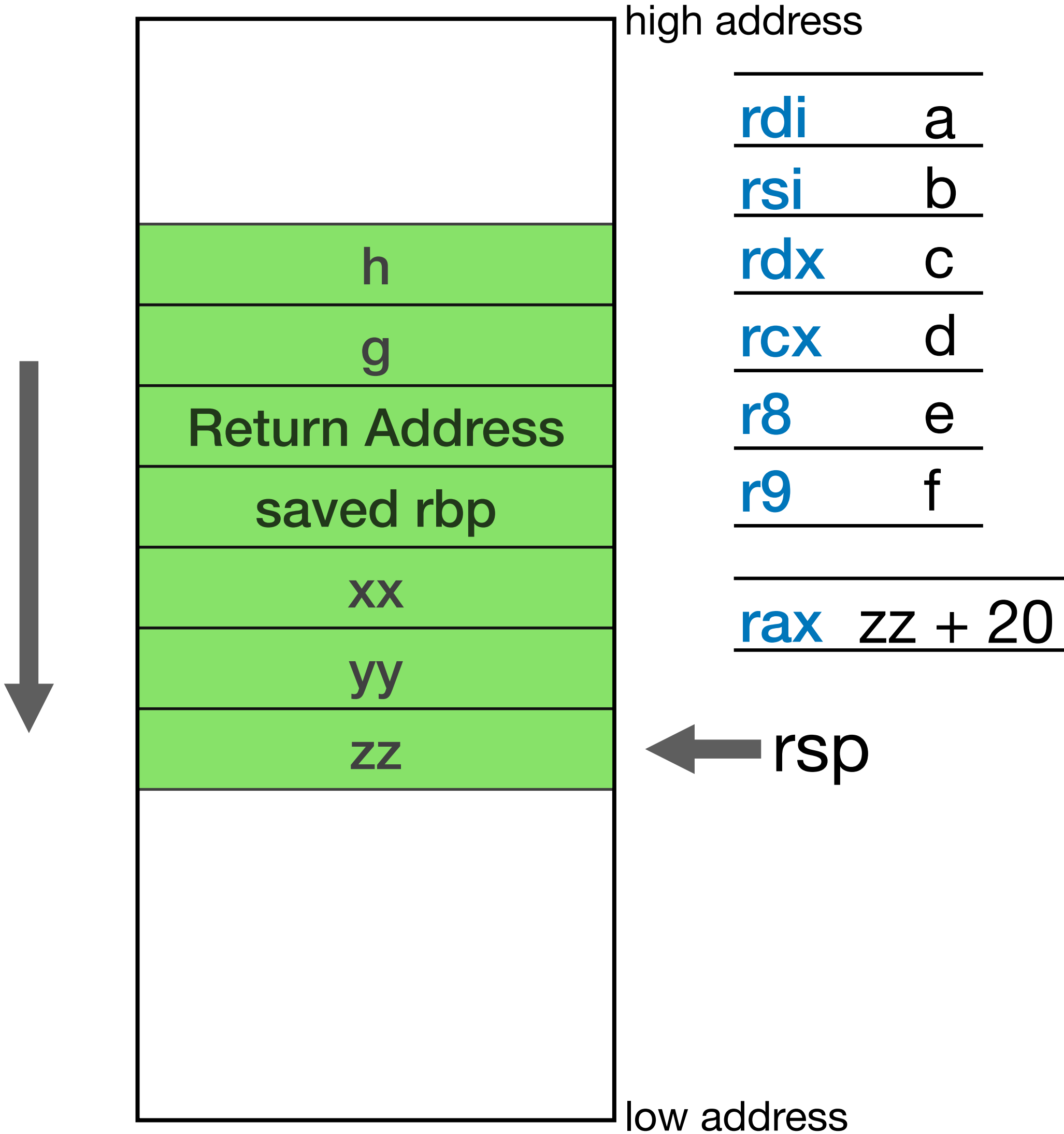
```
void foo() {  
    ...  
    bar(a, b, c, d, e, f, g, h);  
    ...  
}  
  
long bar(long a, long b, long c, long d,  
         long e, long f, long g, long h) {  
    long xx = a * b * c * d * e * f * g * h;  
    long yy = a + b + c + d + e + f + g + h;  
    long zz = utilfunc(xx, yy, xx % yy);  
    return zz + 20;  
}
```

- Where to put all the arguments?
- Where to put the return value?
- Arguments are passed
 - in registers: rdi, rsi, rdx, rcx, r8, r9
 - then via stack
- Return value is passed via
 - in registers: rax, rdx
 - then via stack

x86-64/AMD64 Calling Convention

```
void foo() {
    ...
    bar(a, b, c, d, e, f, g, h);
    ...
}

long bar(long a, long b, long c, long d,
        long e, long f, long g, long h) {
    long xx = a * b * c * d * e * f * g * h;
    long yy = a + b + c + d + e + f + g + h;
    long zz = utilfunc(xx, yy, xx % yy);
    return zz + 20;
}
```



**How to put malicious data
in target registers?**

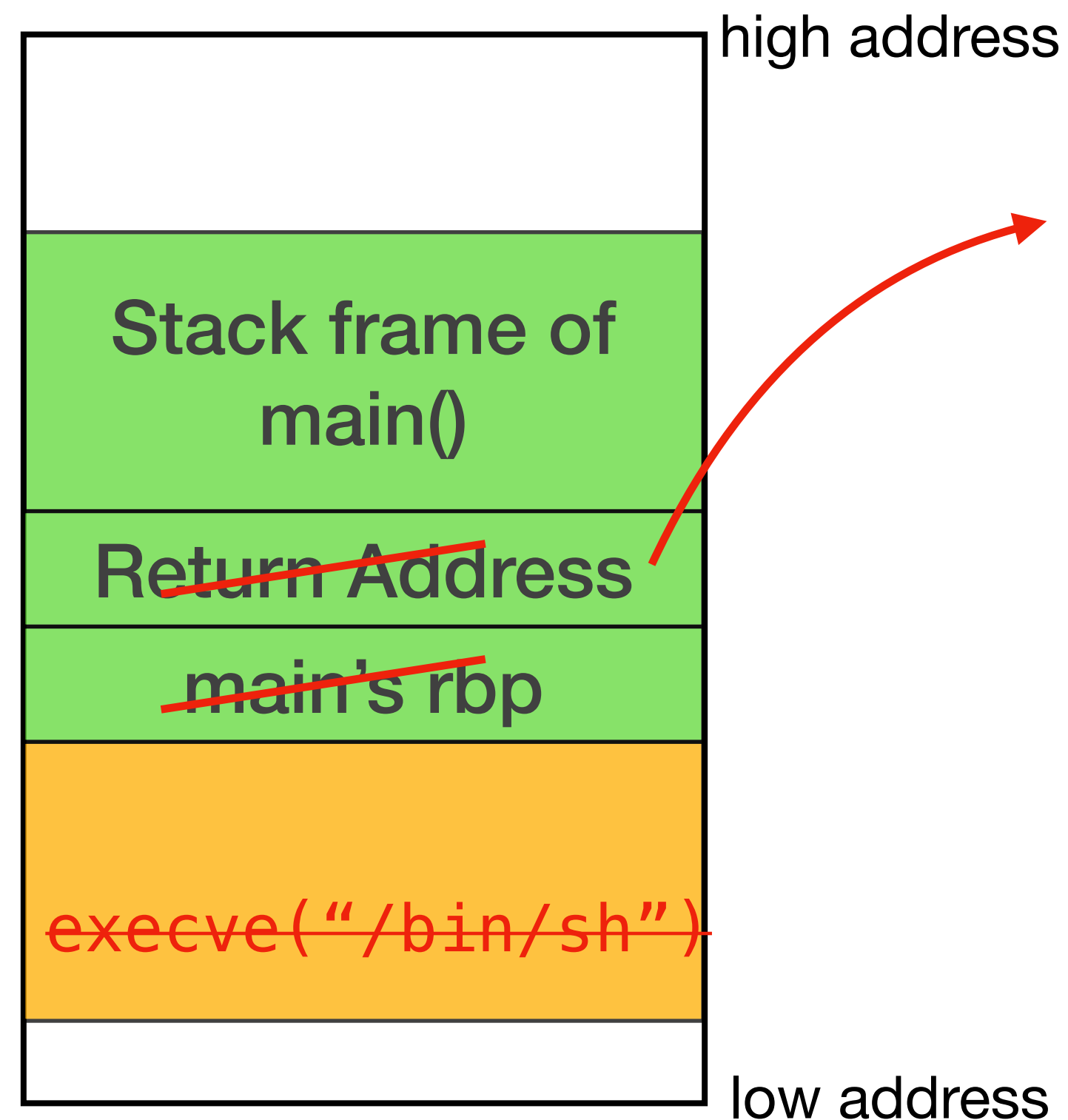
Limitations of ret2libc Attacks

- On AMD64 (and many other arch, e.g., AArch64), function arguments are first passed via registers instead of stack.
- Limited exploitable functions
 - `system()` and other “profitable” library functions could be removed.
- Can only execute straight-line code
 - Desired malicious computation may be invalidated by functions themselves.

Why do we need functions?

**Functions facilitate software development,
but are not necessary for computations.**

Exploiting Existing and Executable Code



“return” to system()

(gdb) disassemble system

Dump of assembler code for function system:

```
0x00007ffff7c50d70 <+0>:    endbr64
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0x00007ffff7c50d95 <+37>:   add     $0x8,%rsp
0x00007ffff7c50d99 <+41>:   movzbl  %al,%eax
0x00007ffff7c50d9c <+44>:   ret
```

How about setting the argument and executing the same instructions from other places?

Return-oriented Programming (ROP)

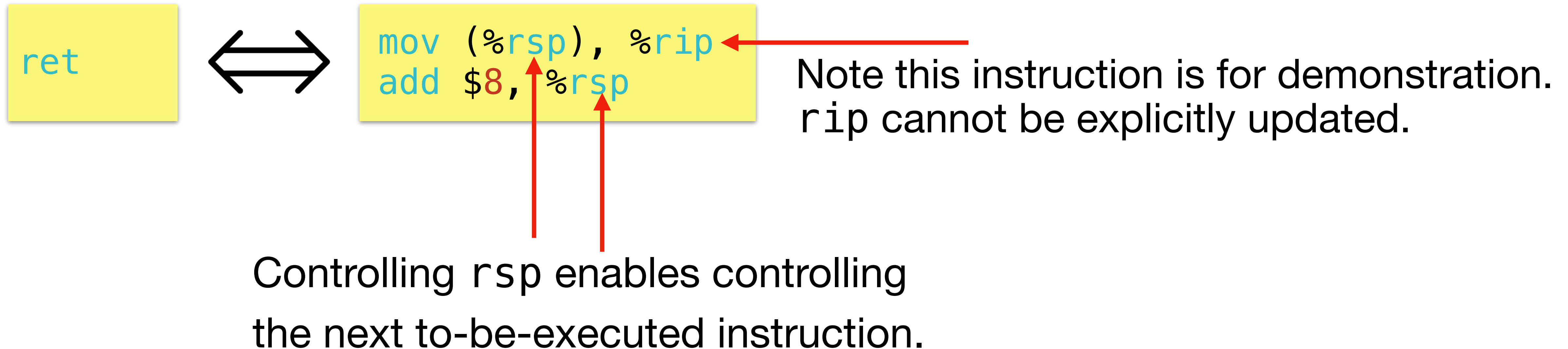


An exploit technique that allows arbitrary code execution without calling any functions.

- Exploiting memory corruption bugs
 - Often starting with a corrupted return address
- Chaining code sequences, called *gadgets*, that end with a `ret`
 - Generally, gadgets ending with control flow transfer instructions, e.g. `jmp`
- Turing-complete
 - Memory operations
 - Arithmetic and logic
 - Control flow

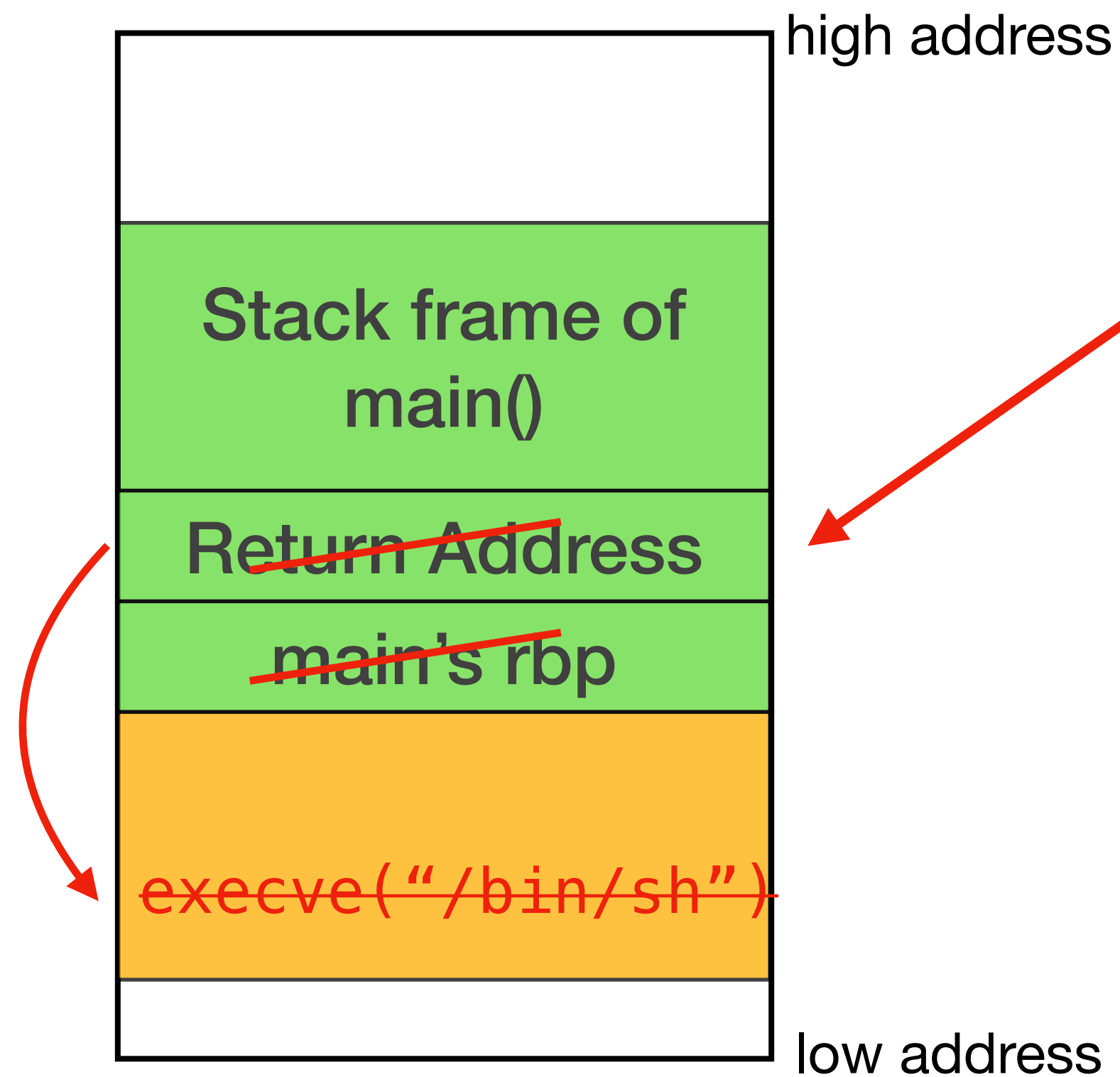
Return-oriented Programming (ROP)

- Use `ret` to jump to the “profitable” instructions to the attacker’s interest



- Use `rsp` as a confused deputy for `rip`
 - Attackers use `rsp` to control the flow of the victim program.

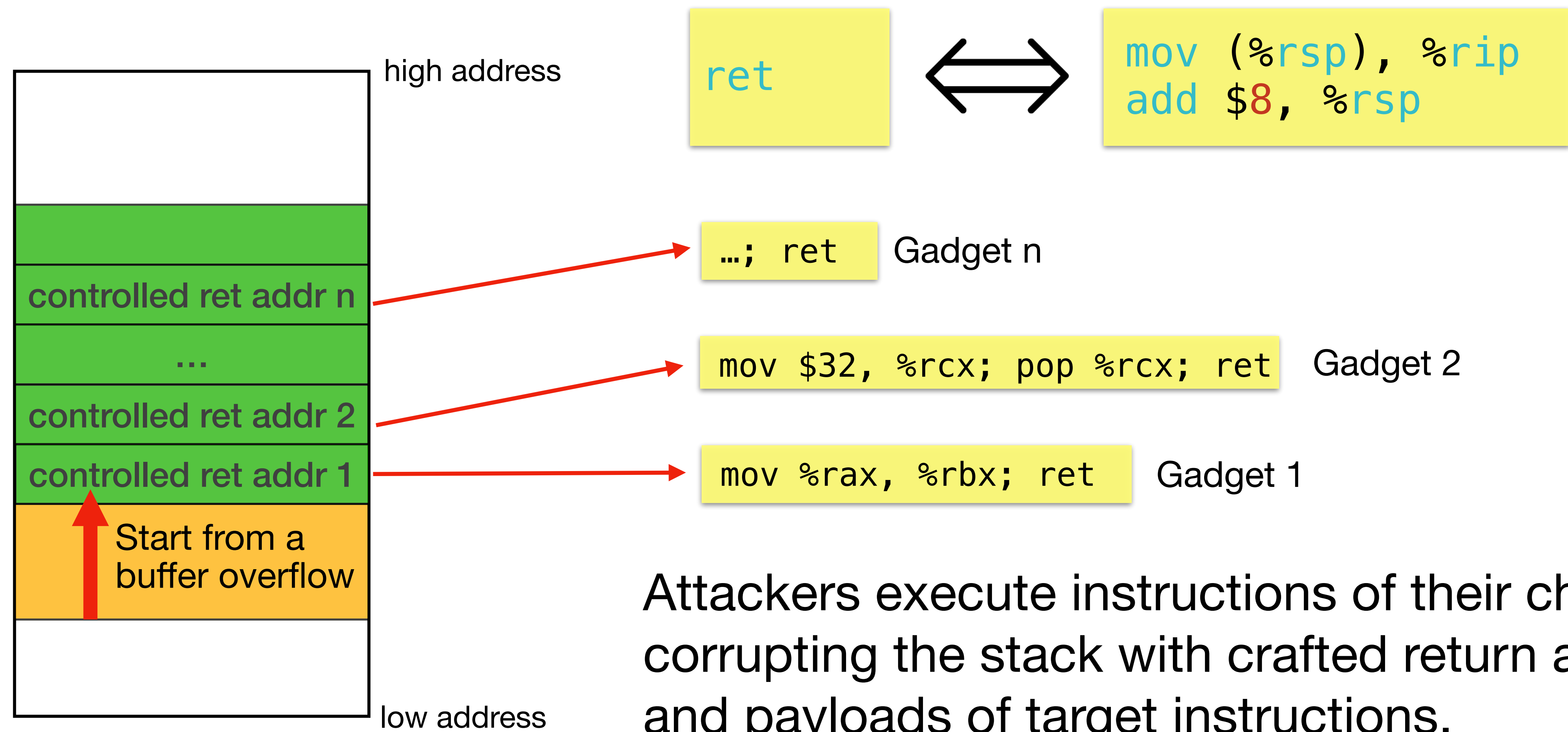
Exploiting Multiple ret



ret2libc exploits one ret instruction.

How about exploiting multiple ret?

Chaining Multiple ret

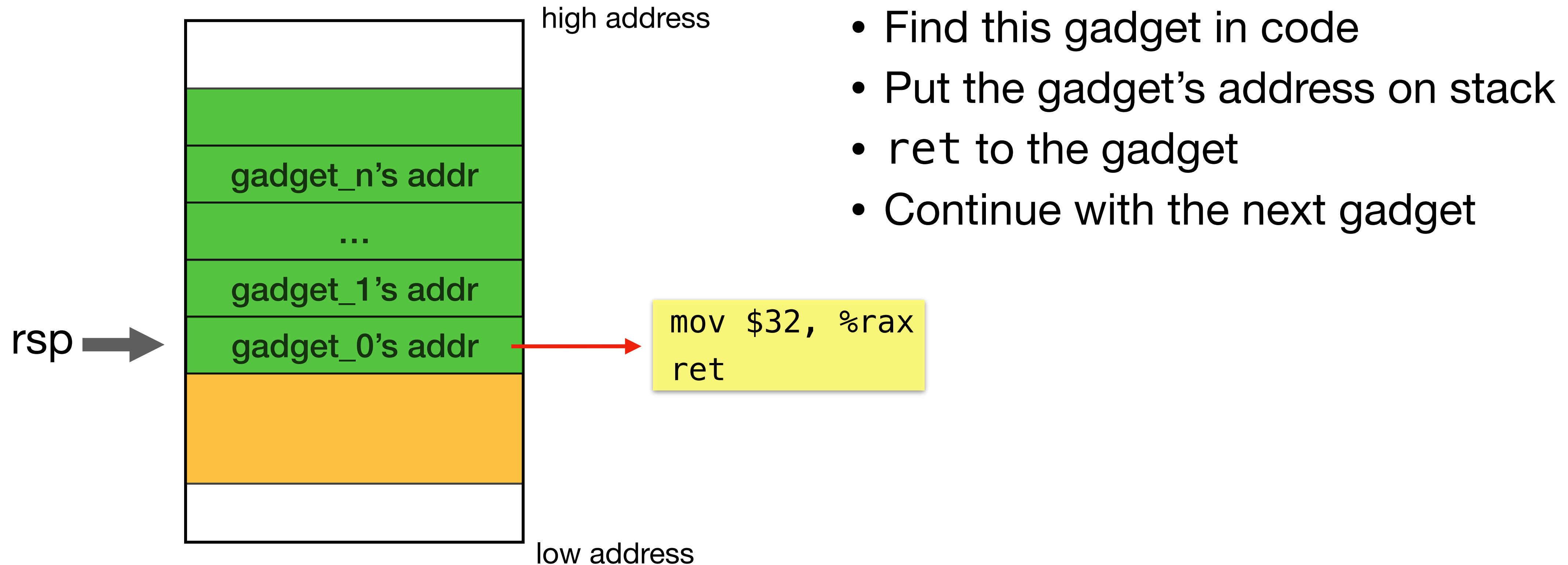


Attackers execute instructions of their choosing by corrupting the stack with crafted return addresses and payloads of target instructions.

Loading a Constant

💡 How to load a constant (e.g. 0x32) into a register?

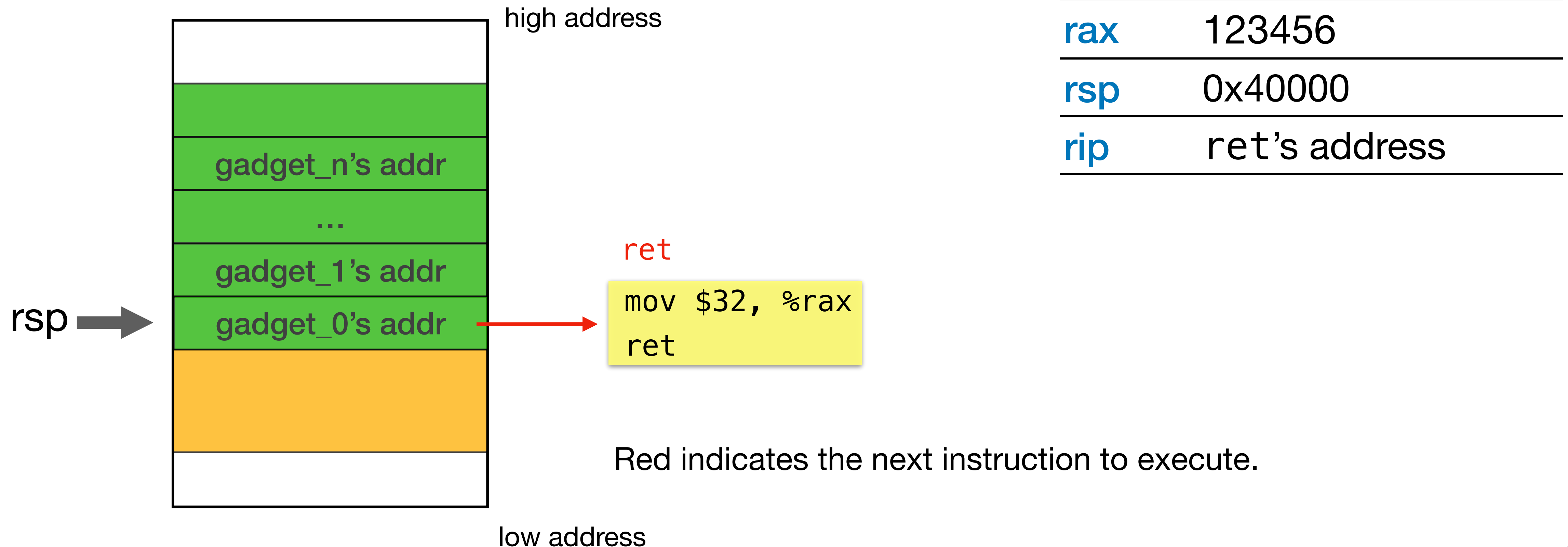
- Option 1: Find a gadget like `mov $32, %rax; ret`



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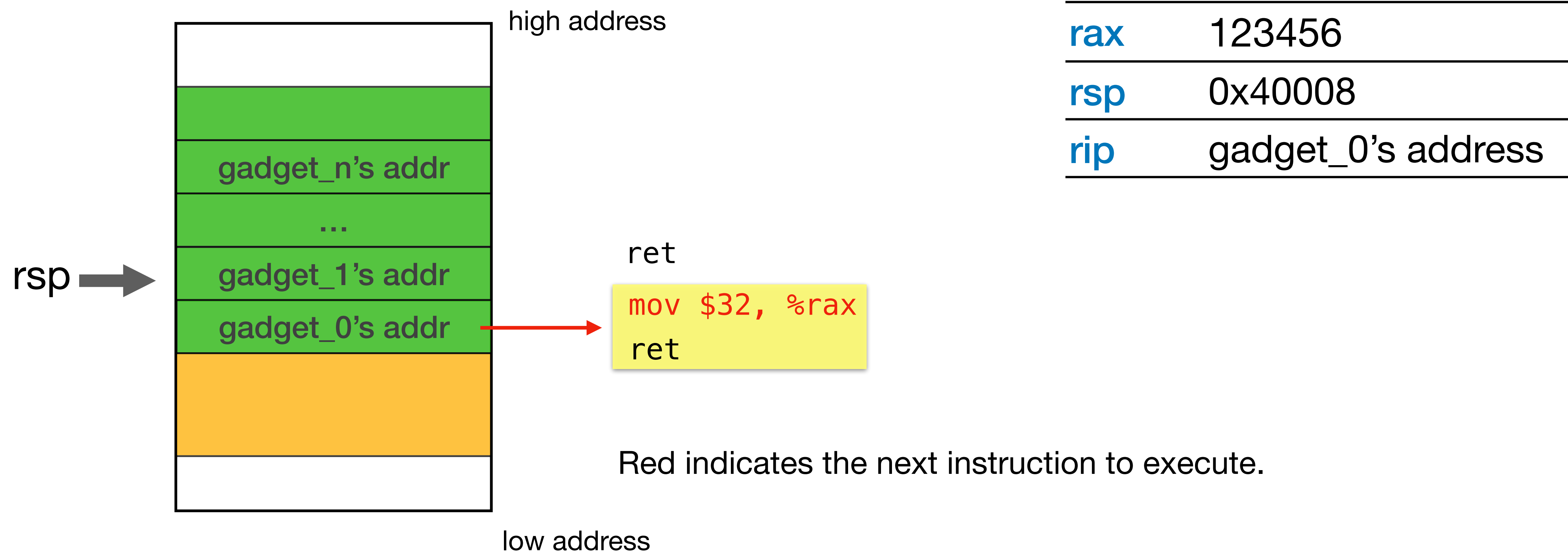
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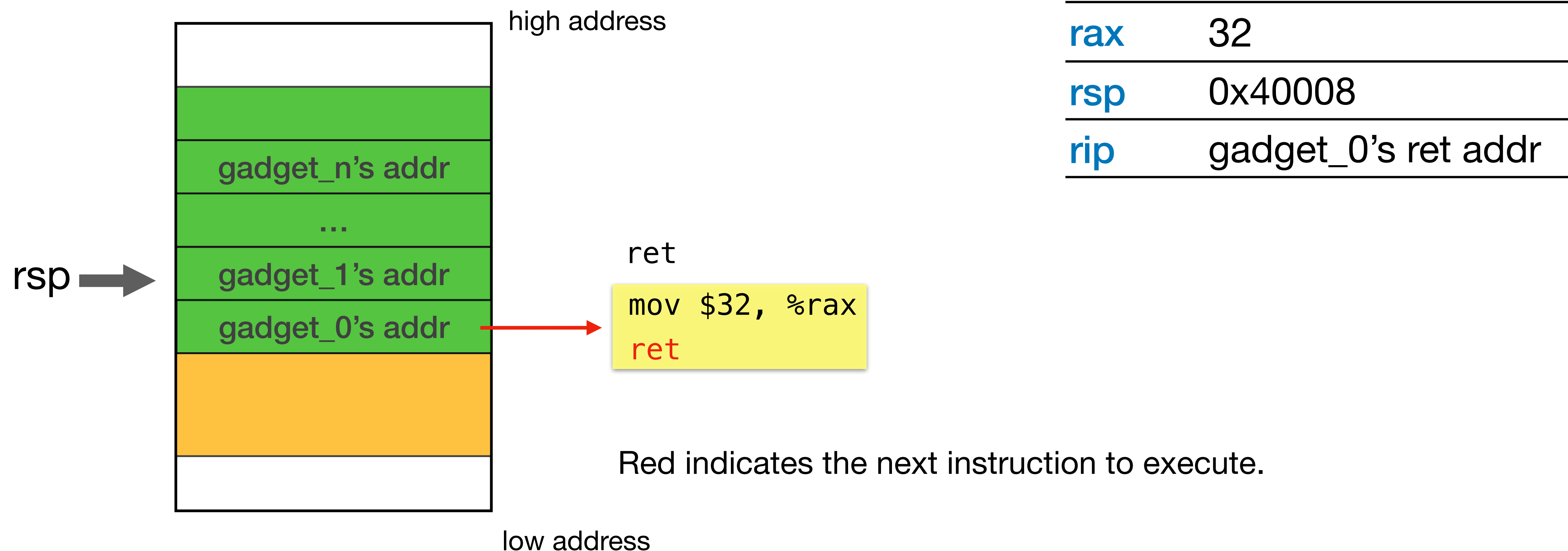
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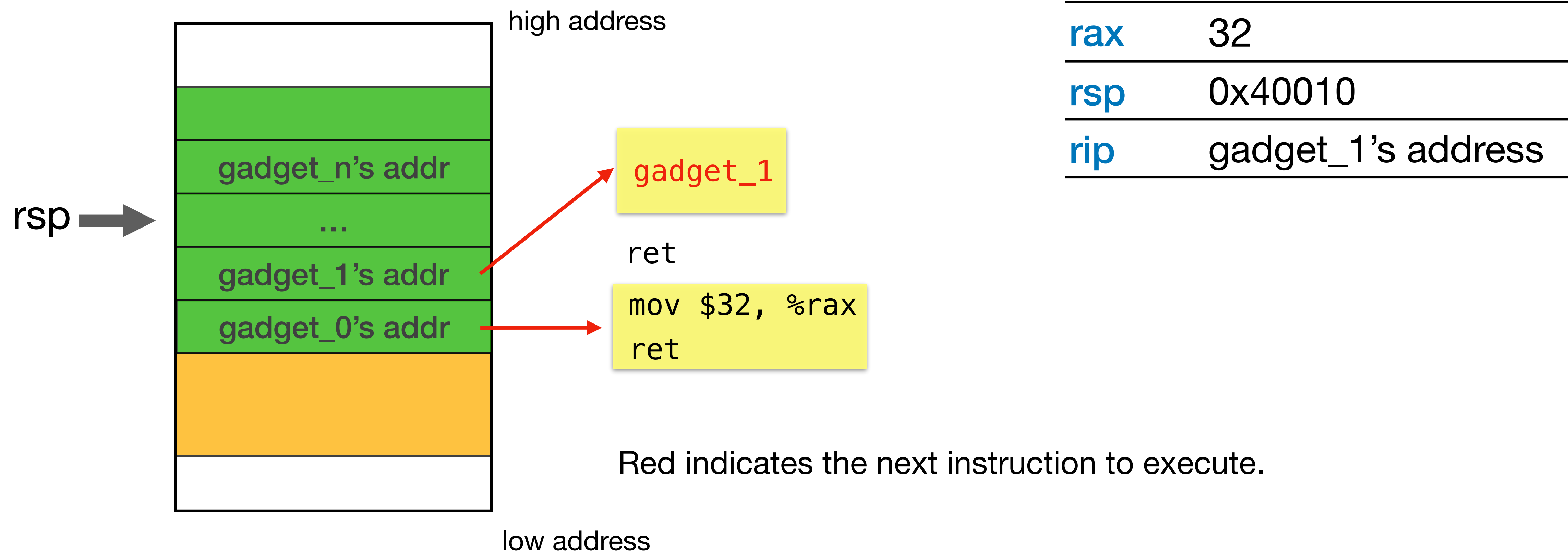
- Option 1: Find a gadget like `mov $32, %rax; ret`



Loading a Constant

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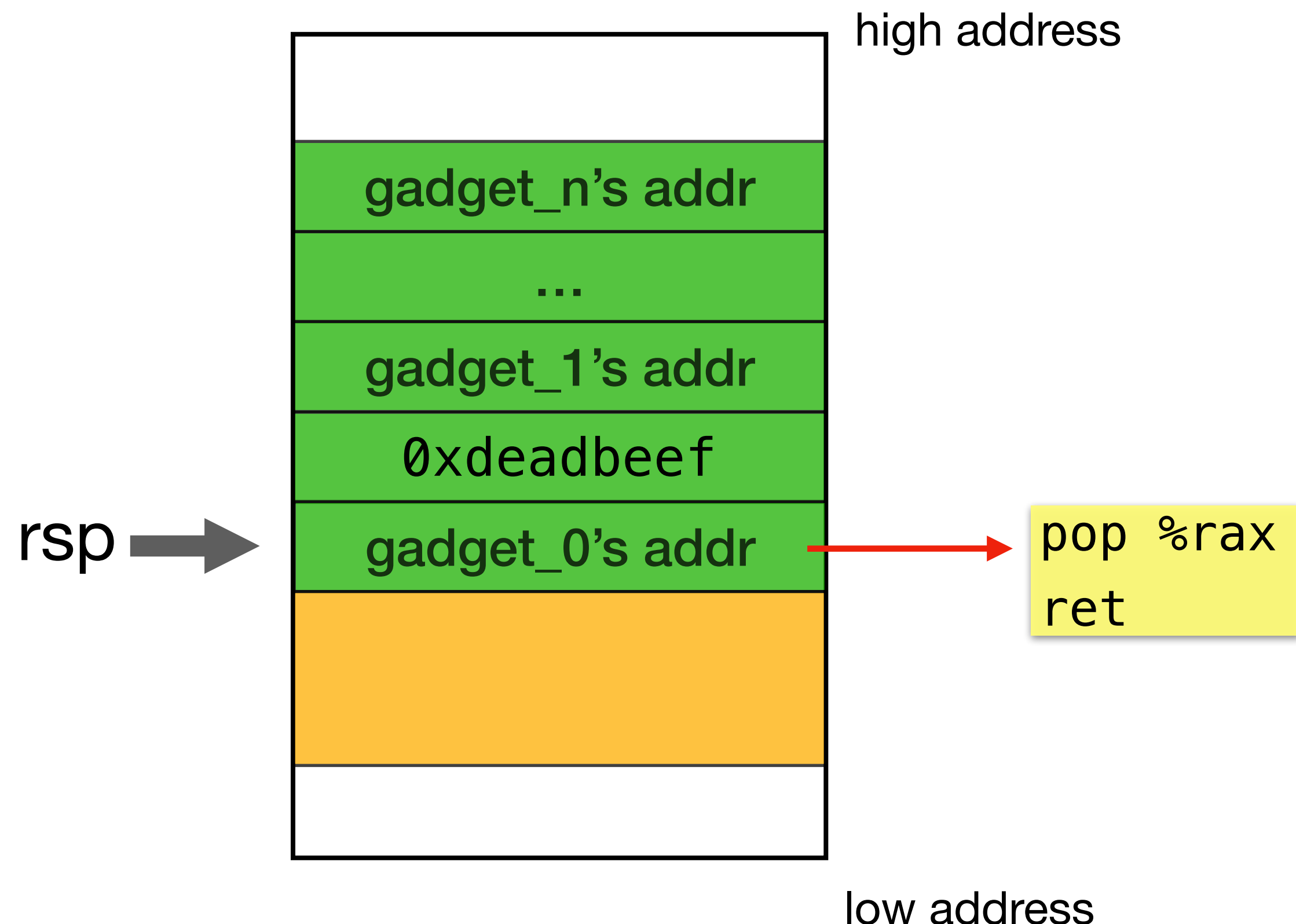
- Option 1: Find a gadget like `mov $32, %rax; ret`



Loading a Constant

💡 How to load an arbitrary constant (e.g. 0xdeadbeef) into a register?

- Option 1: Pop the constant to the target register

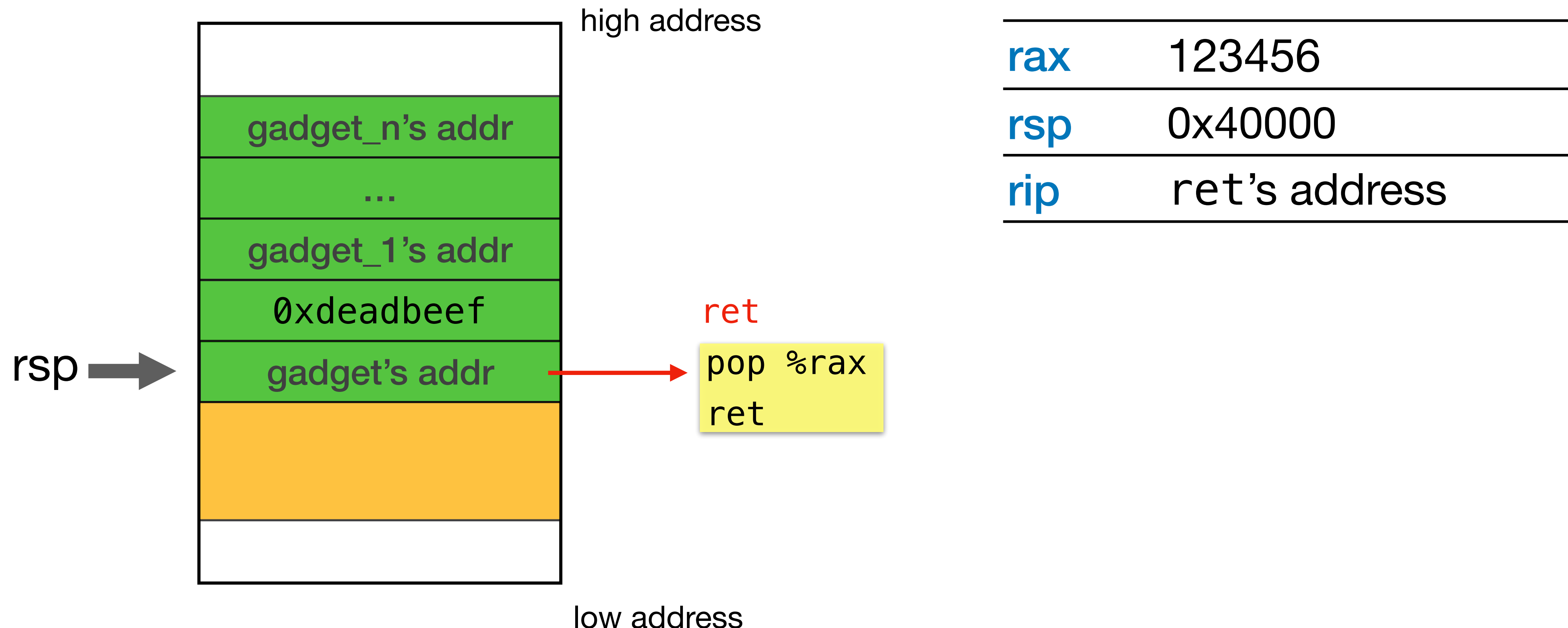


- Put gadget's address on stack
- Put target constant on stack (above rsp)
- ret makes rsp point to the constant
- pop loads the constant into the register

Loading a Constant

💡 How to load an arbitrary constant (e.g. 0xdeadbeef) into a register?

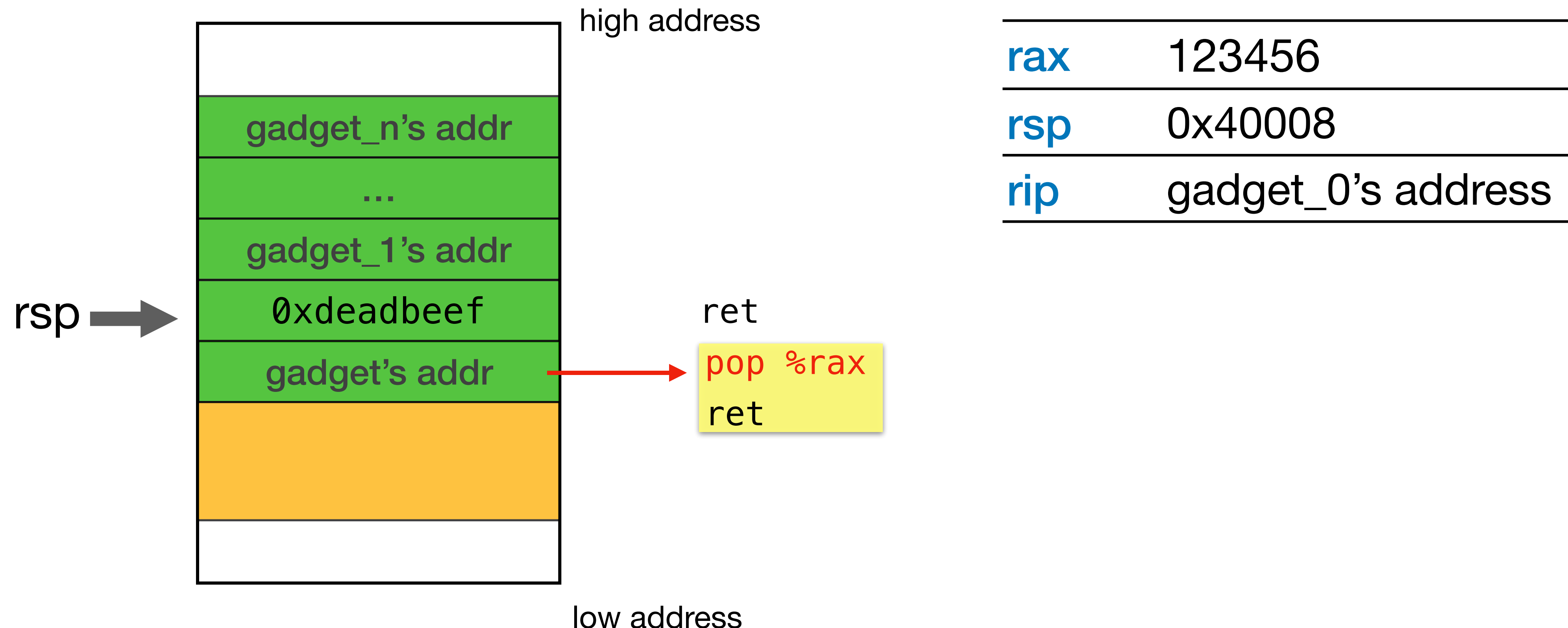
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Loading a Constant

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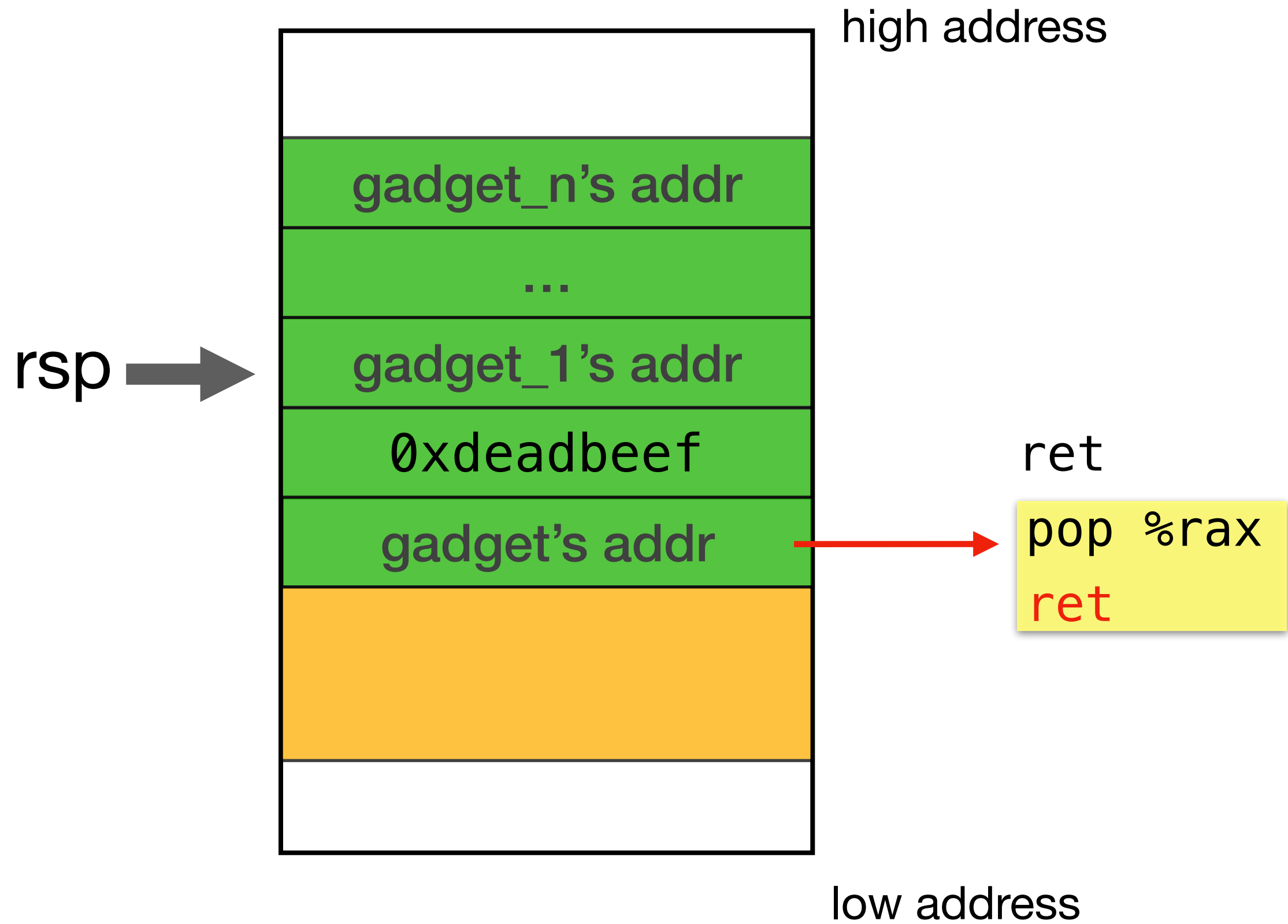
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Loading a Constant

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- Option 1: Pop the constant to the target register

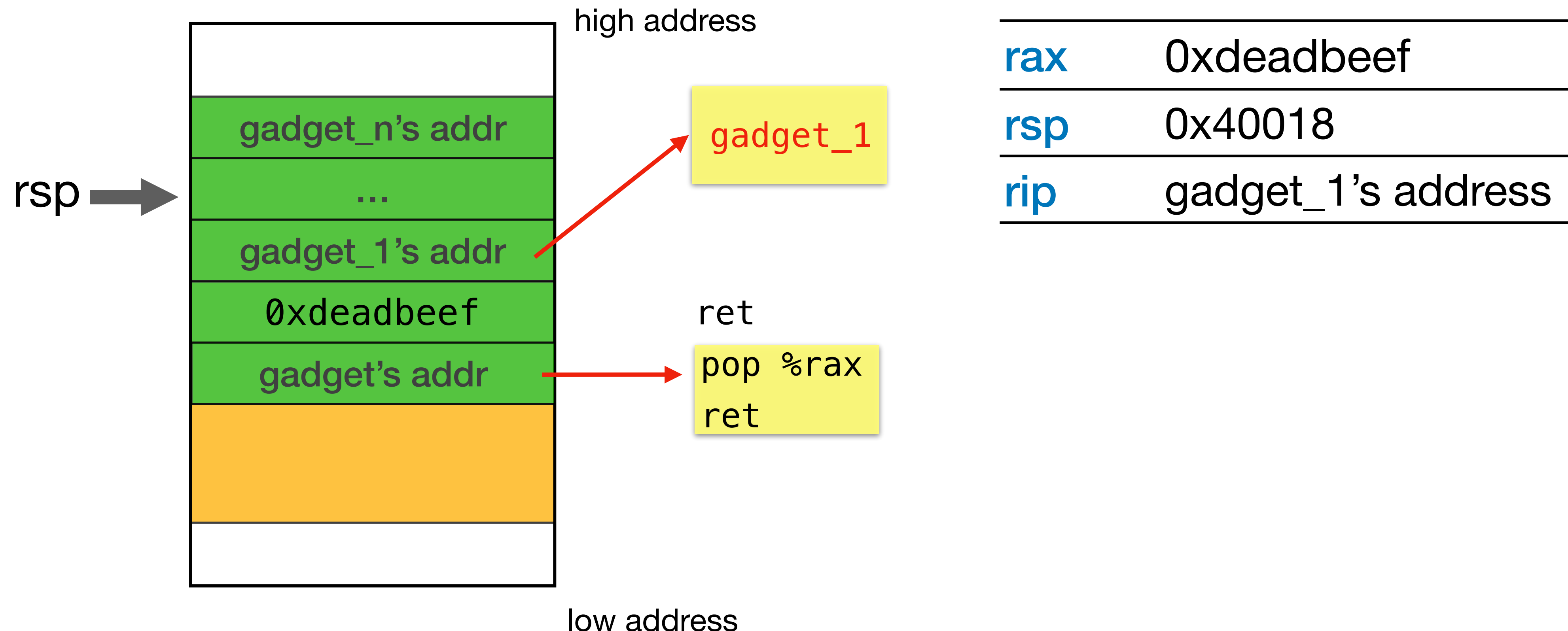


rax	0xdeadbeef
rsp	0x40010
rip	gadget_0's ret

Loading a Constant

💡 How to load an arbitrary constant (e.g. 0xdeadbeef) into a register?

- Option 1: Pop the constant to the target register



Loading From A Memory Address



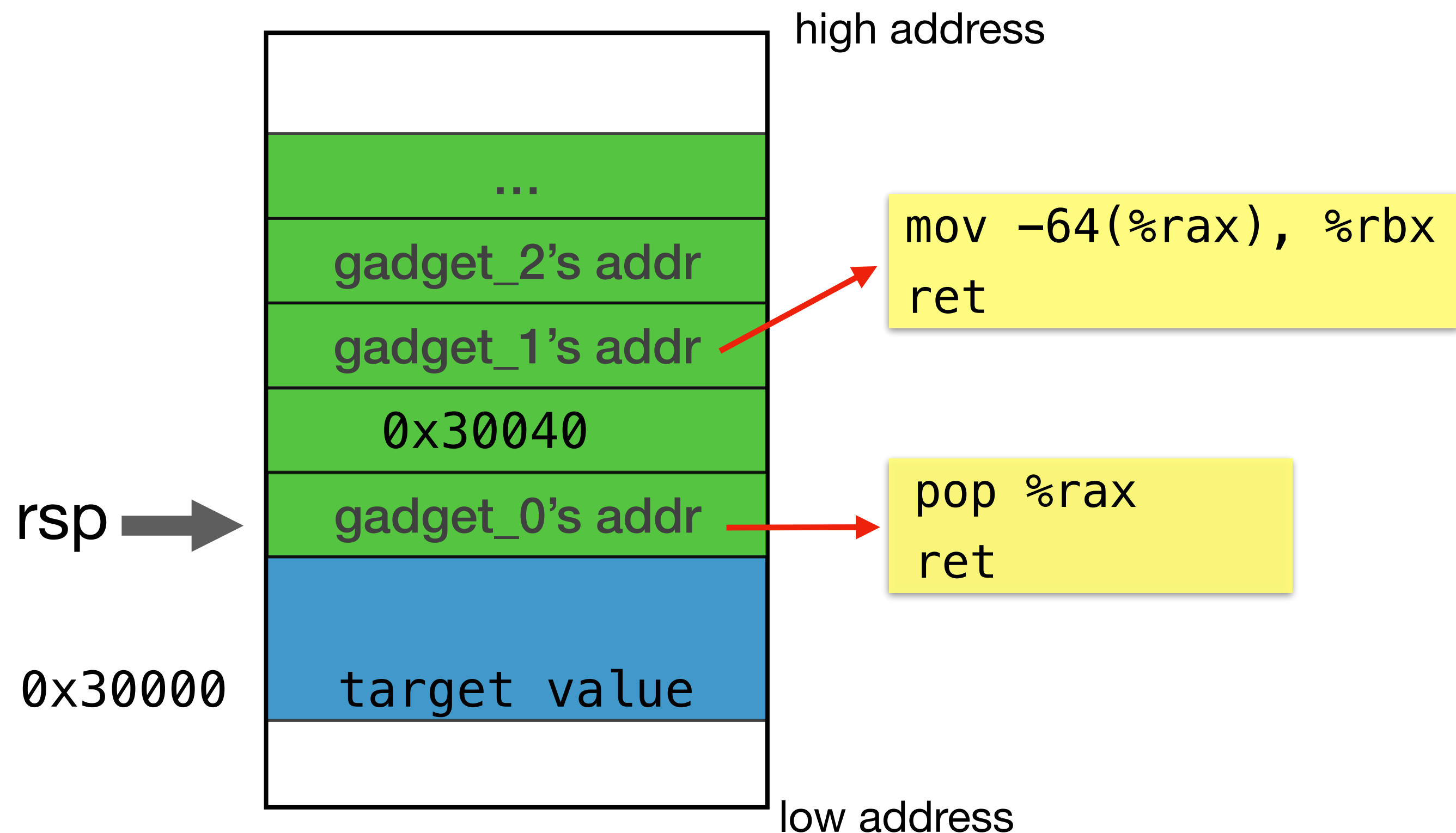
How to load a value in memory into a register?

- e.g., want to load the value in address `0x30000` into `rbx`.
- Common load: `mov offset(%rax), %rbx`
 1. Set up the target address to one register
 2. Load the value from the address into the target register
- We need two gadgets.

Loading From A Memory Address

💡 How to load a value in an arbitrary memory location into a register?

- e.g., want to load the value in address `0x30000` into `rbx`.

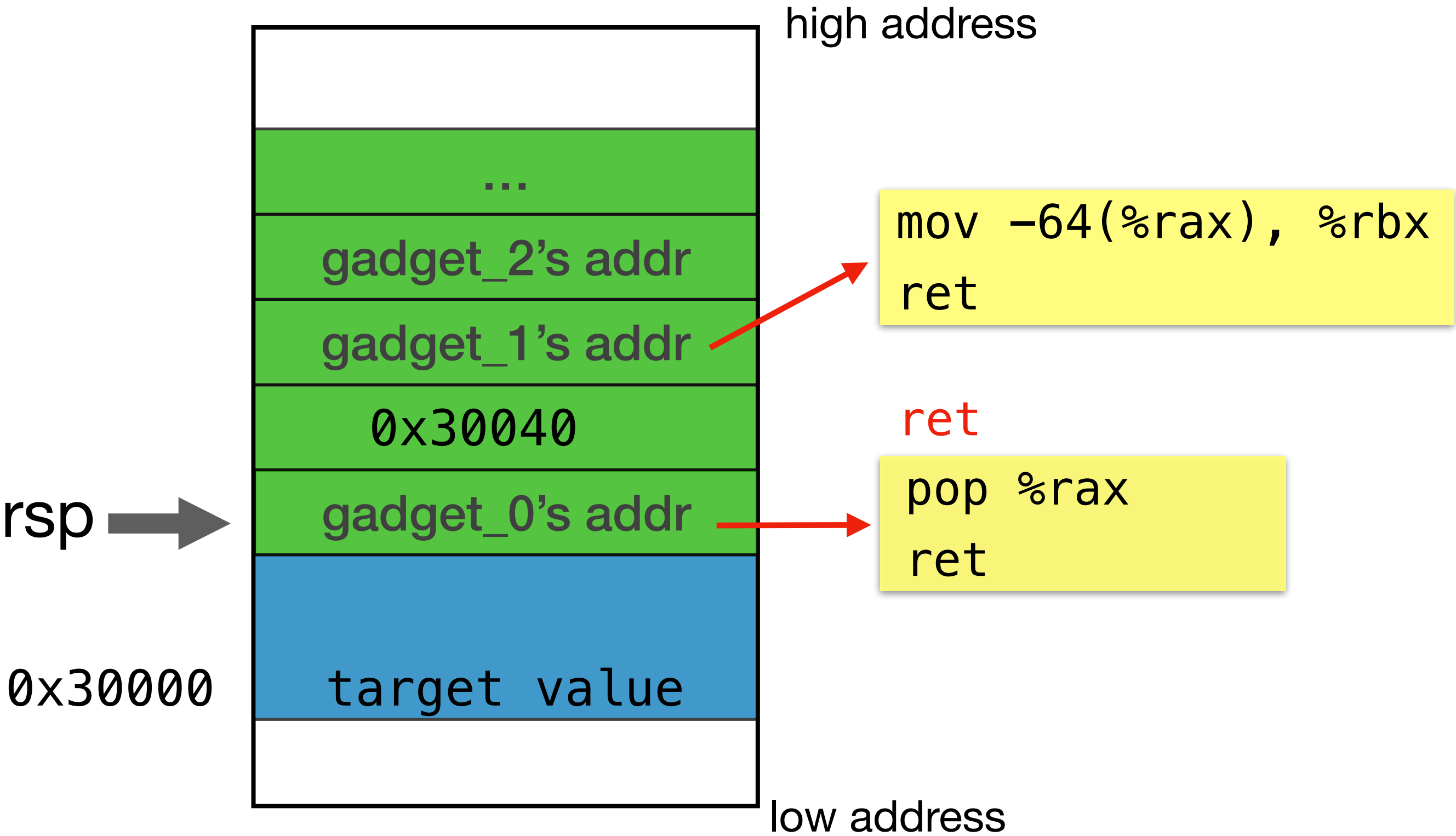


- Put gadgets' addresses on stack
- Put payload's addresses on stack
- gadget_0 prepares target address
- gadget_1 loads from adjusted address

Loading From A Memory Address

💡 How to load a value in an arbitrary memory location into a register?

- e.g., want to load the value in address 0x30000 into rbx.

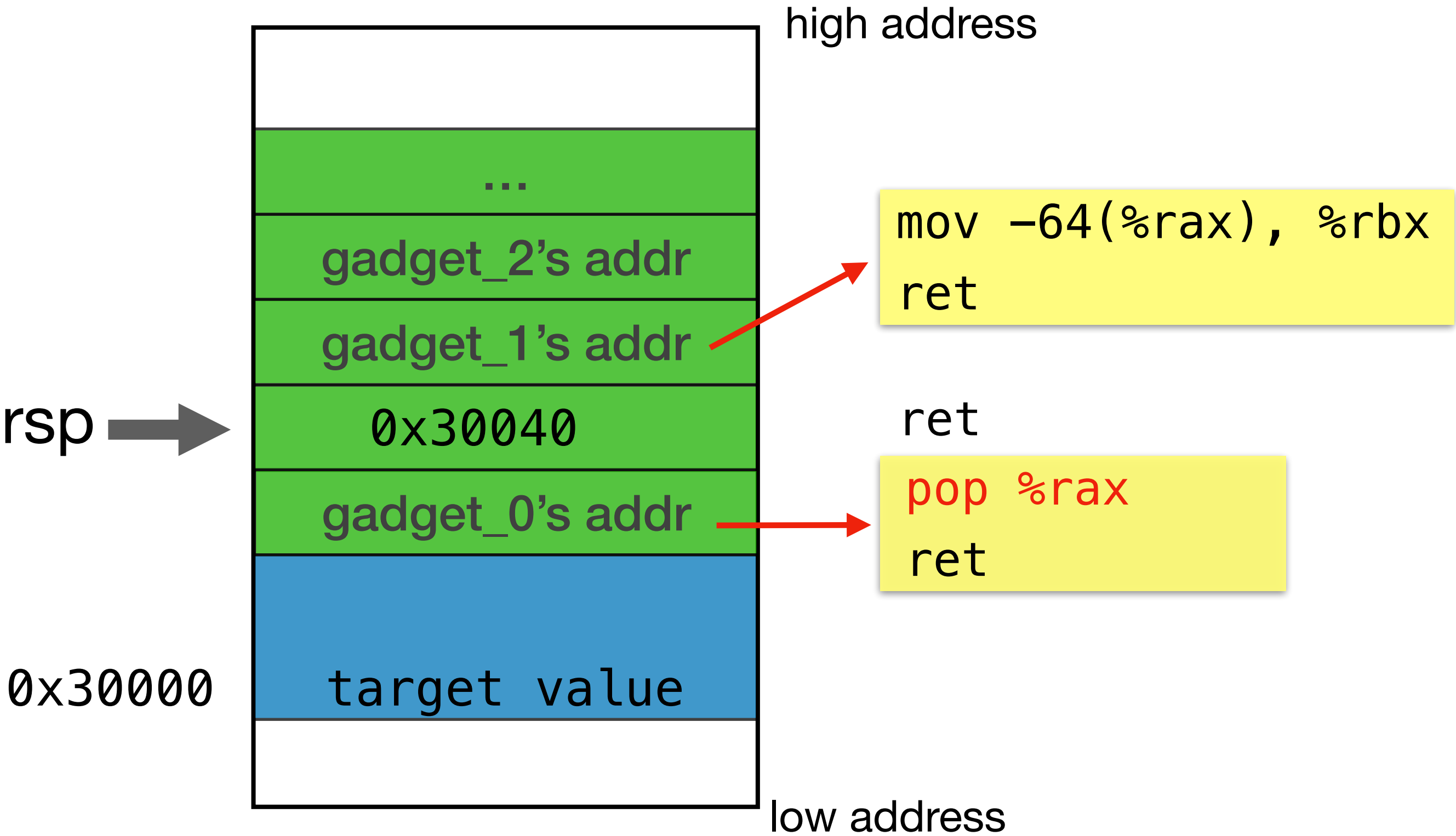


rax	0x123456
rbx	0x7890ab
rsp	0x40000
rip	ret's address

Loading From A Memory Address

💡 How to load a value in an arbitrary memory location into a register?

- e.g., want to load the value in address 0x30000 into rbx.

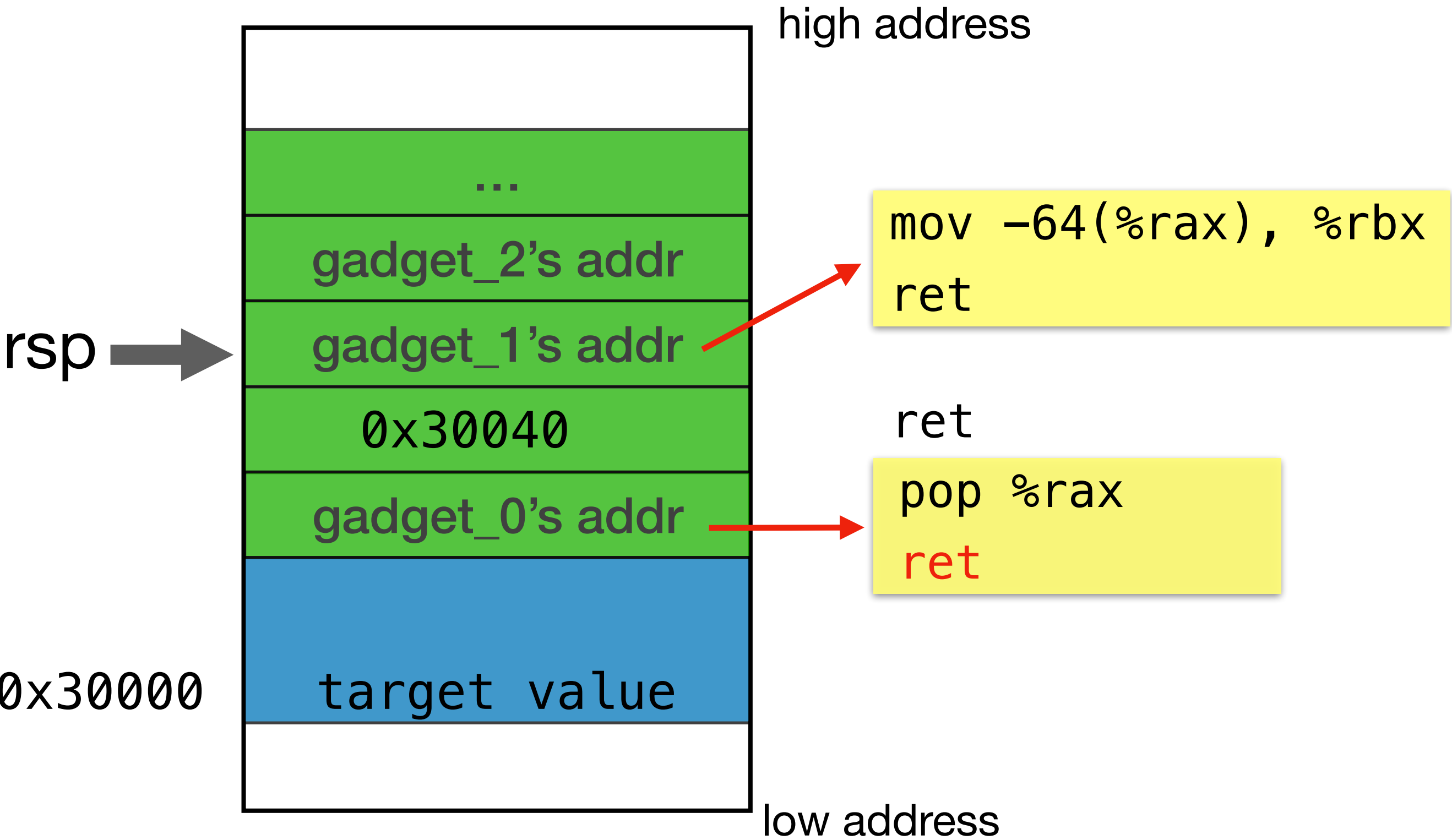


rax	0x123456
rbx	0x7890ab
rsp	0x40008
rip	gadget_0's address

Loading From A Memory Address

💡 How to load a value in an arbitrary memory location into a register?

- e.g., want to load the value in address 0x30000 into rbx.

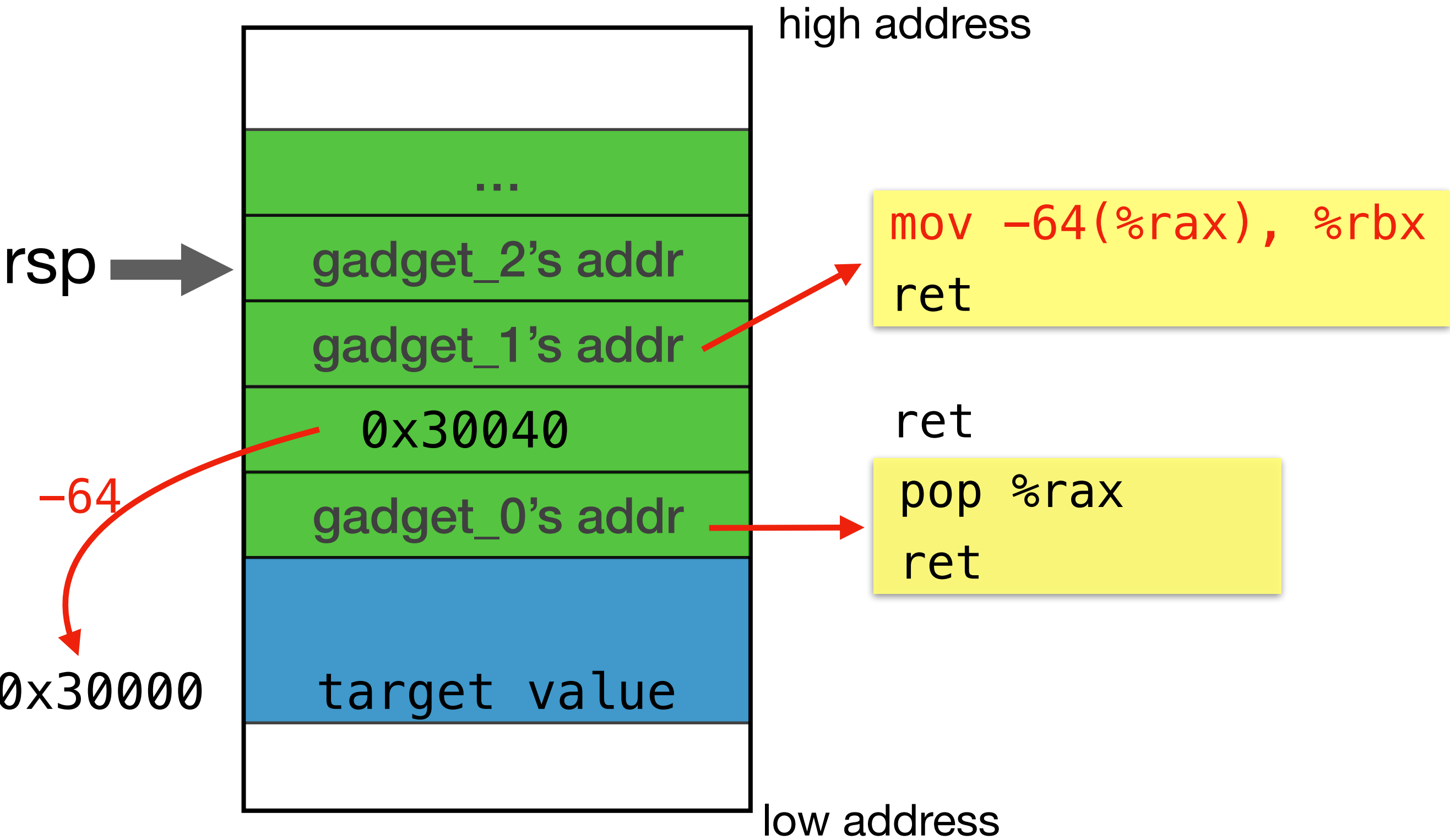


<code>rax</code>	0x30040
<code>rbx</code>	0x7890ab
<code>rsp</code>	0x40010
<code>rip</code>	gadget_0 ret's address

Loading From A Memory Address

💡 How to load a value in an arbitrary memory location into a register?

- e.g., want to load the value in address 0x30000 into rbx.

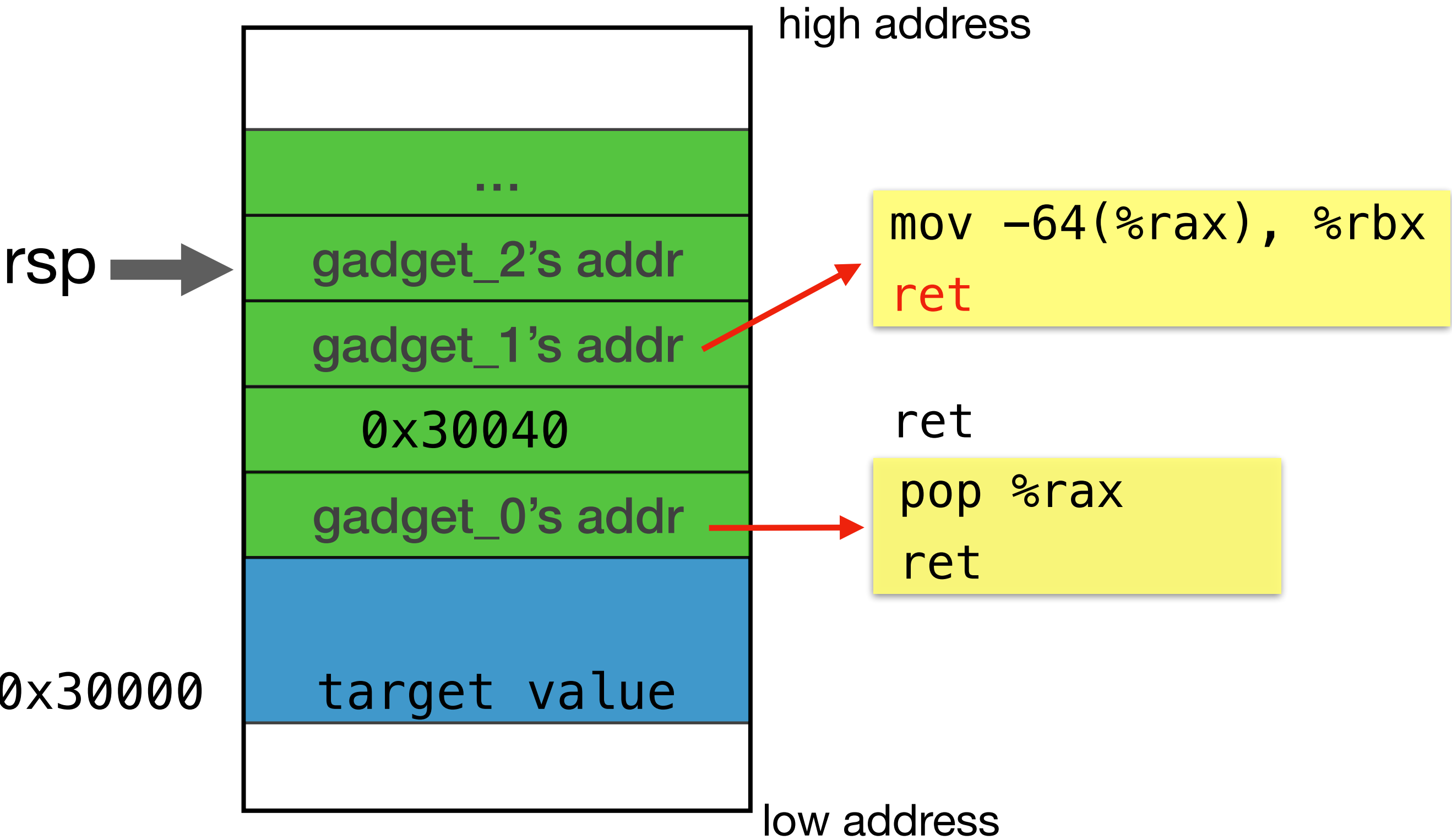


<code>rax</code>	<code>0x30040</code>
<code>rbx</code>	<code>0x7890ab</code>
<code>rsp</code>	<code>0x40018</code>
<code>rip</code>	<code>gadget_1's address</code>

Loading From A Memory Address

💡 How to load a value in an arbitrary memory location into a register?

- e.g., want to load the value in address 0x30000 into rbx.

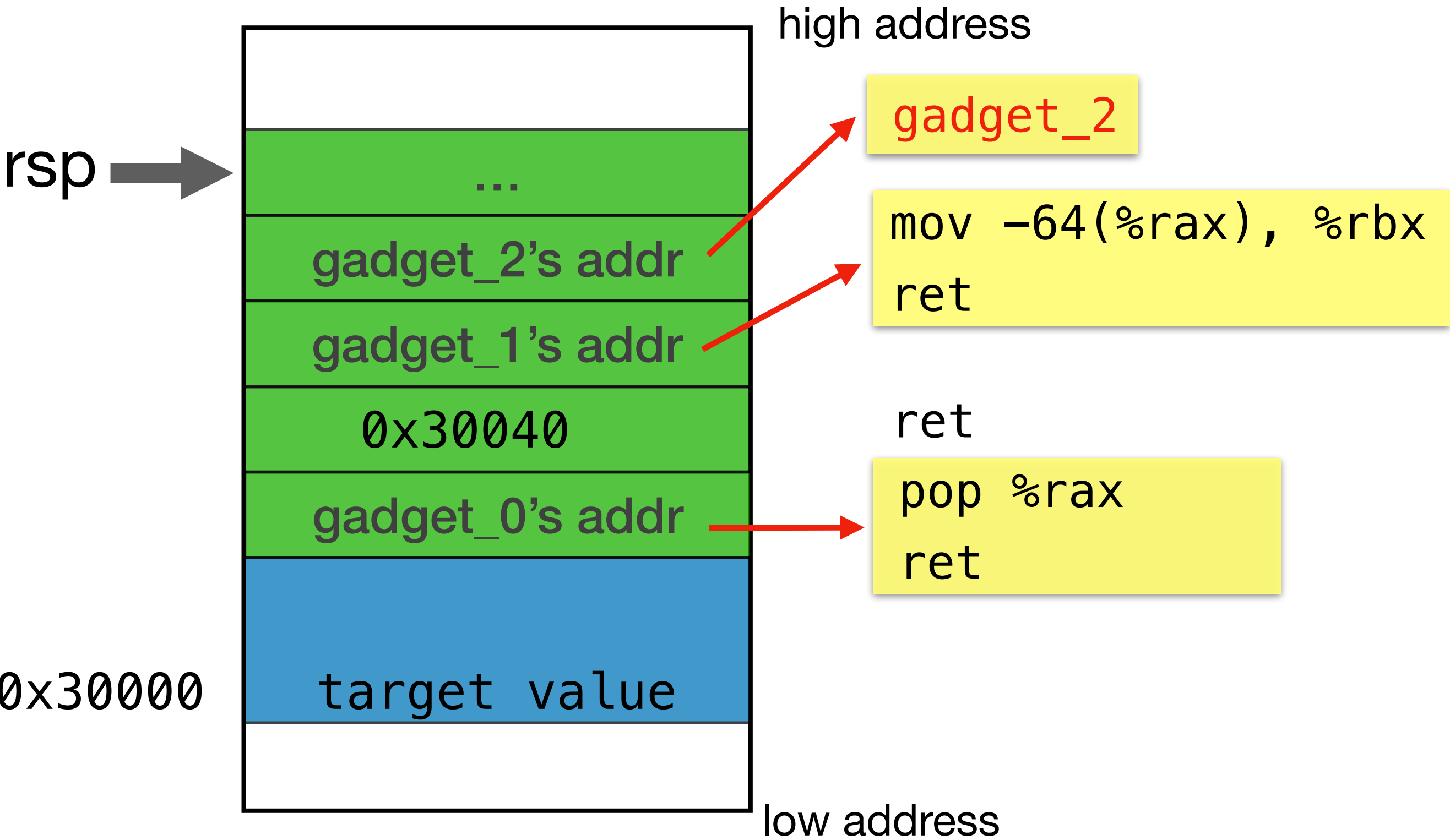


<code>rax</code>	0x30040
<code>rbx</code>	0x200000
<code>rsp</code>	0x40018
<code>rip</code>	gadget_1's ret address

Loading From A Memory Address

💡 How to load a value in an arbitrary memory location into a register?

- e.g., want to load the value in address 0x30000 into rbx.



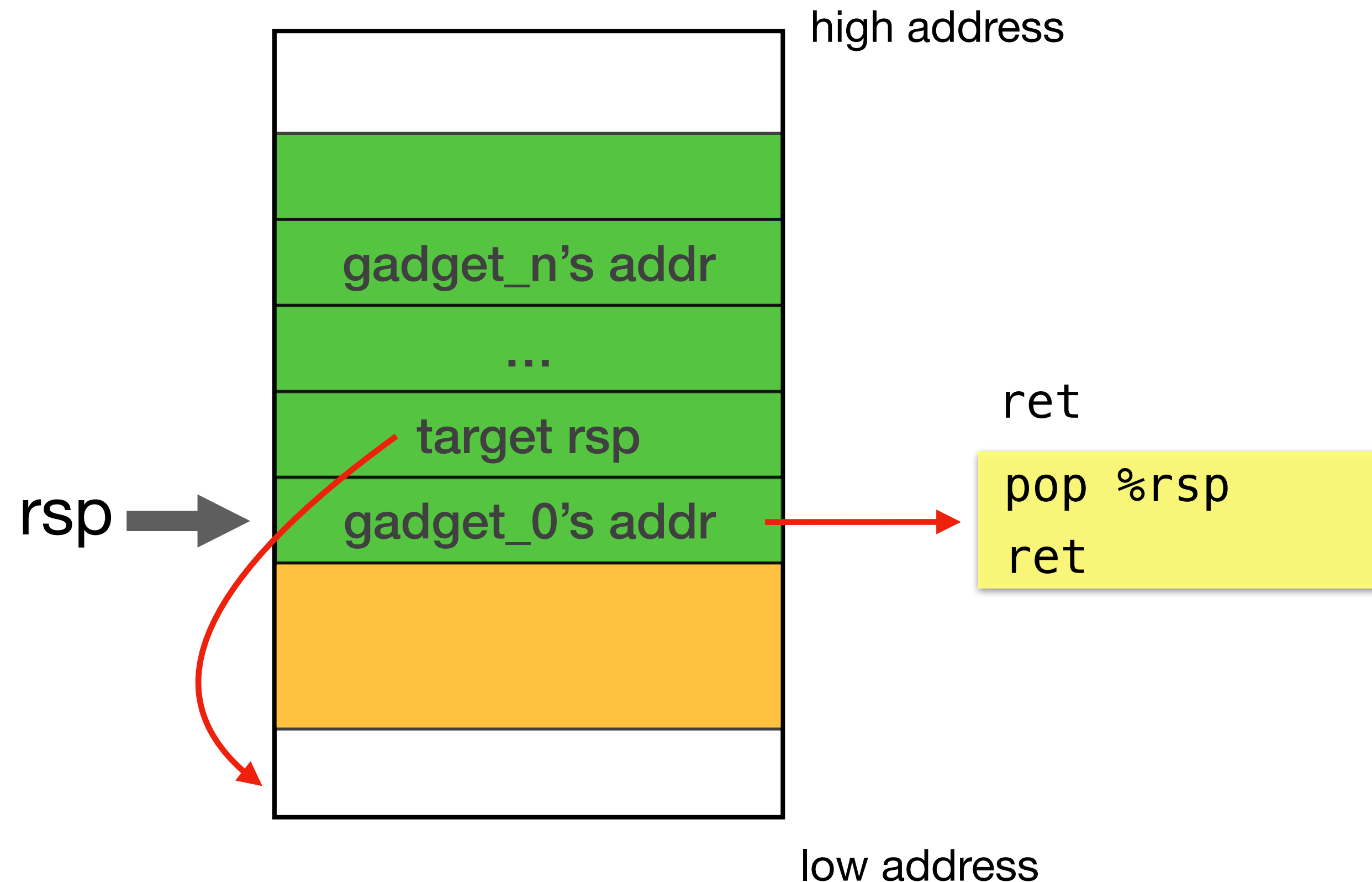
rax	0x30040
rbx	0x200000
rsp	0x40020
rip	gadget_2's address

What if the controllable stack space is insufficient for gadgets and their payloads?

Stack Pivoting

💡 How to enable a larger “stack”?

- Pop the target address to `rsp`, and `ret`.

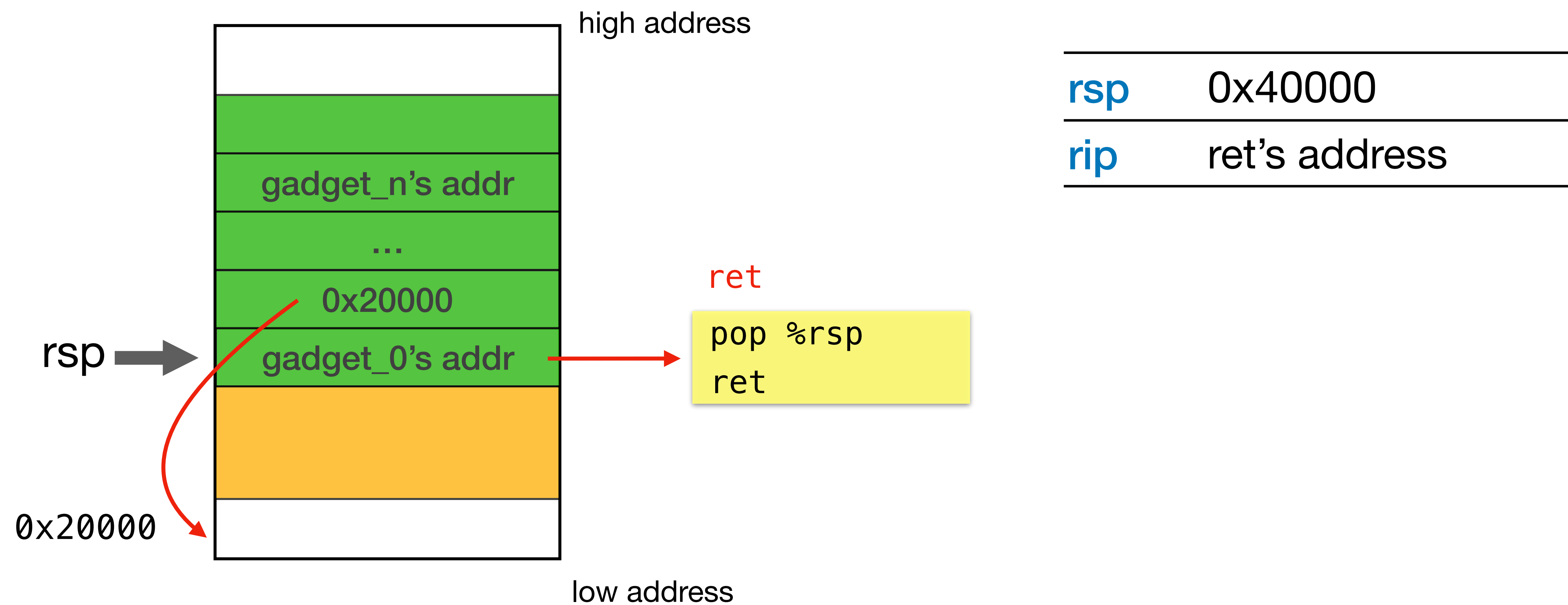


- Put gadget's address on stack
- Put target `rsp`'s address above
- Pop the target address to `rsp`

Stack Pivoting

💡 How to enable a larger “stack”?

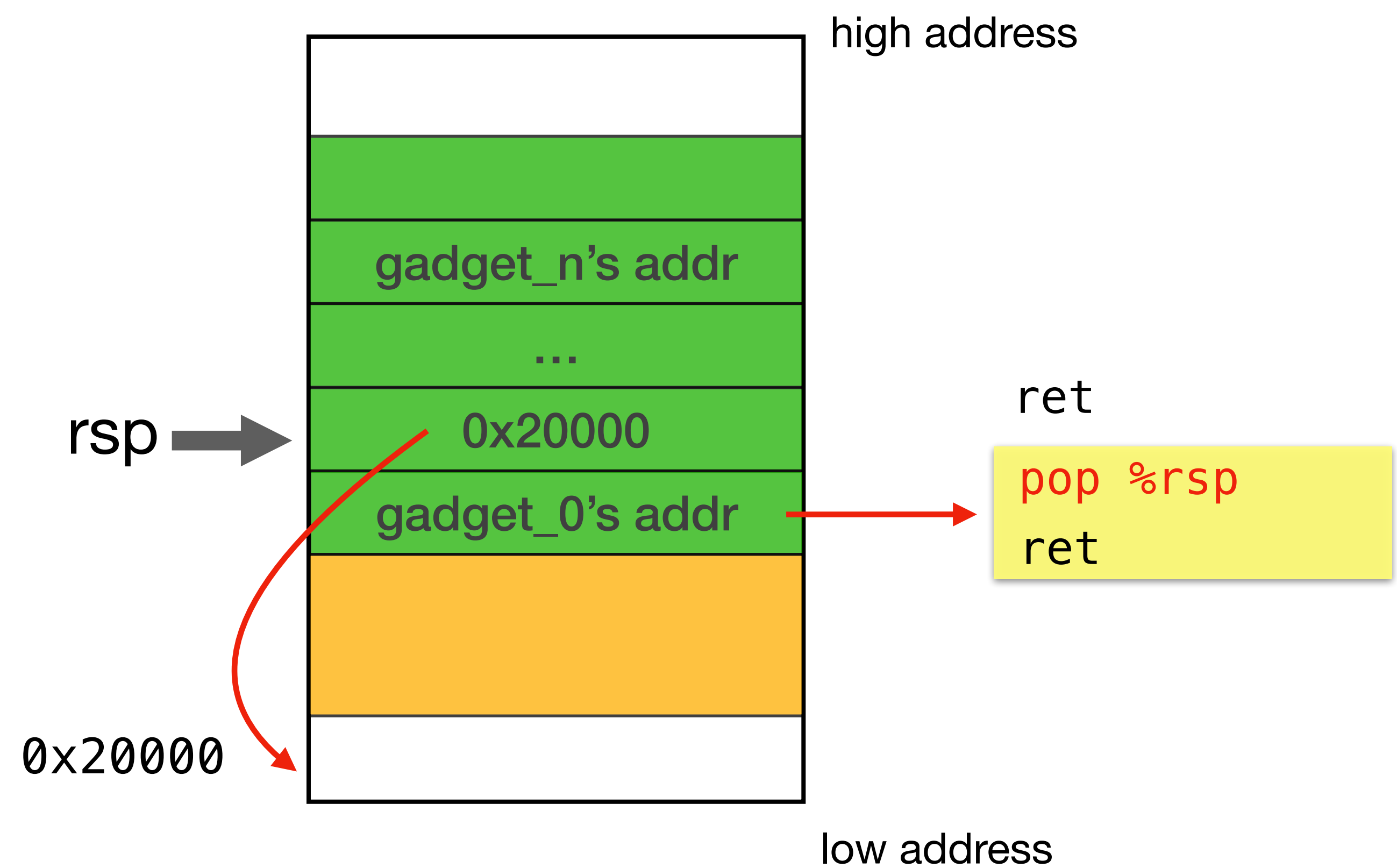
- Pop the target address (e.g. 0x20000) to `rsp`, and `ret`.



Stack Pivoting

💡 How to enable a larger “stack”?

- Pop the target address (e.g. 0x20000) to `rsp`, and `ret`.



<code>rsp</code>	0x40008
<code>rip</code>	gadget's address

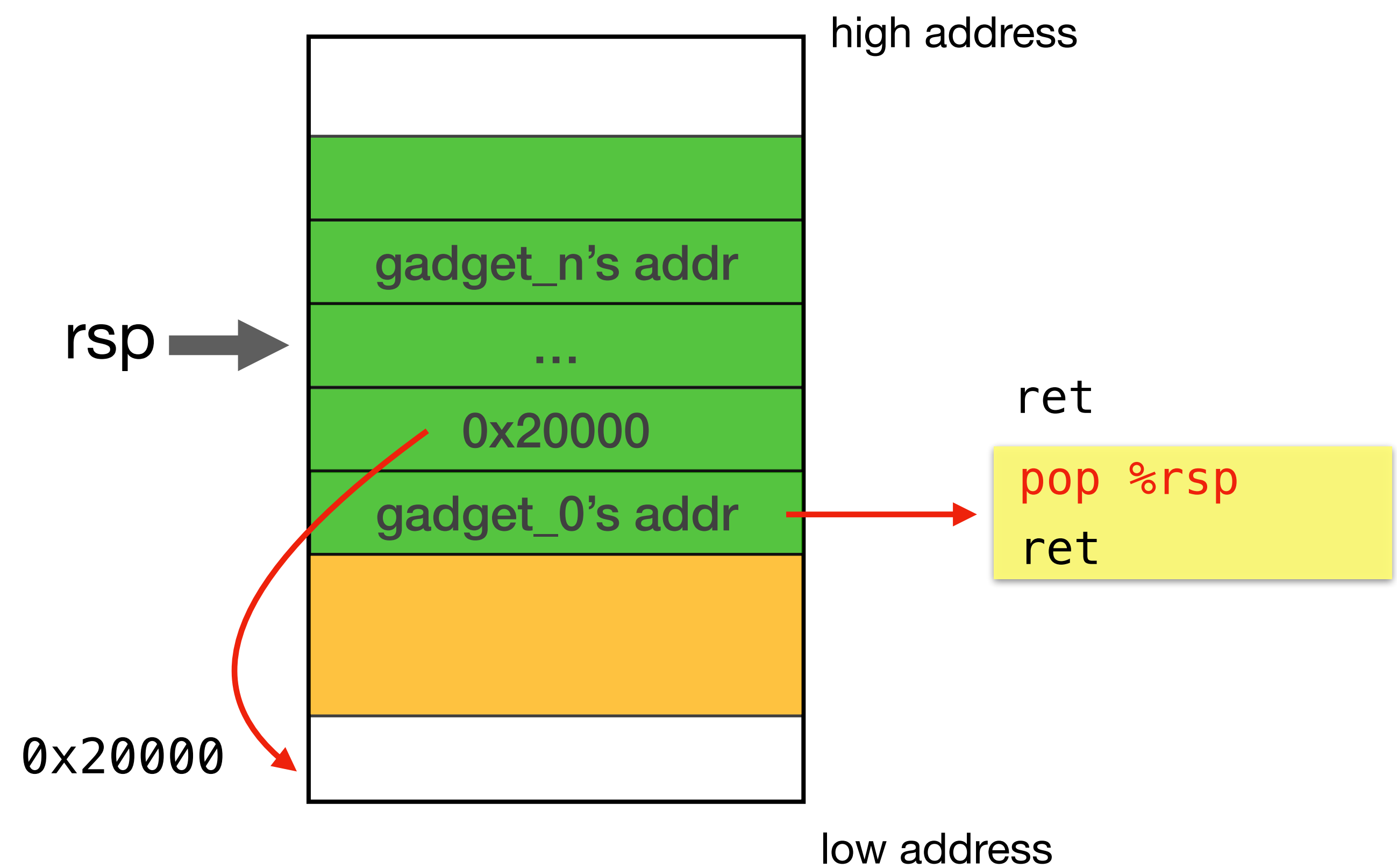
`pop %rsp` is special:

- `rsp` gets incremented by one word.
- Data pointed by old `rsp` is loaded to `rsp`.

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<code>rsp</code>	<code>0x40010</code>
<code>rip</code>	<code>gadget's address</code>

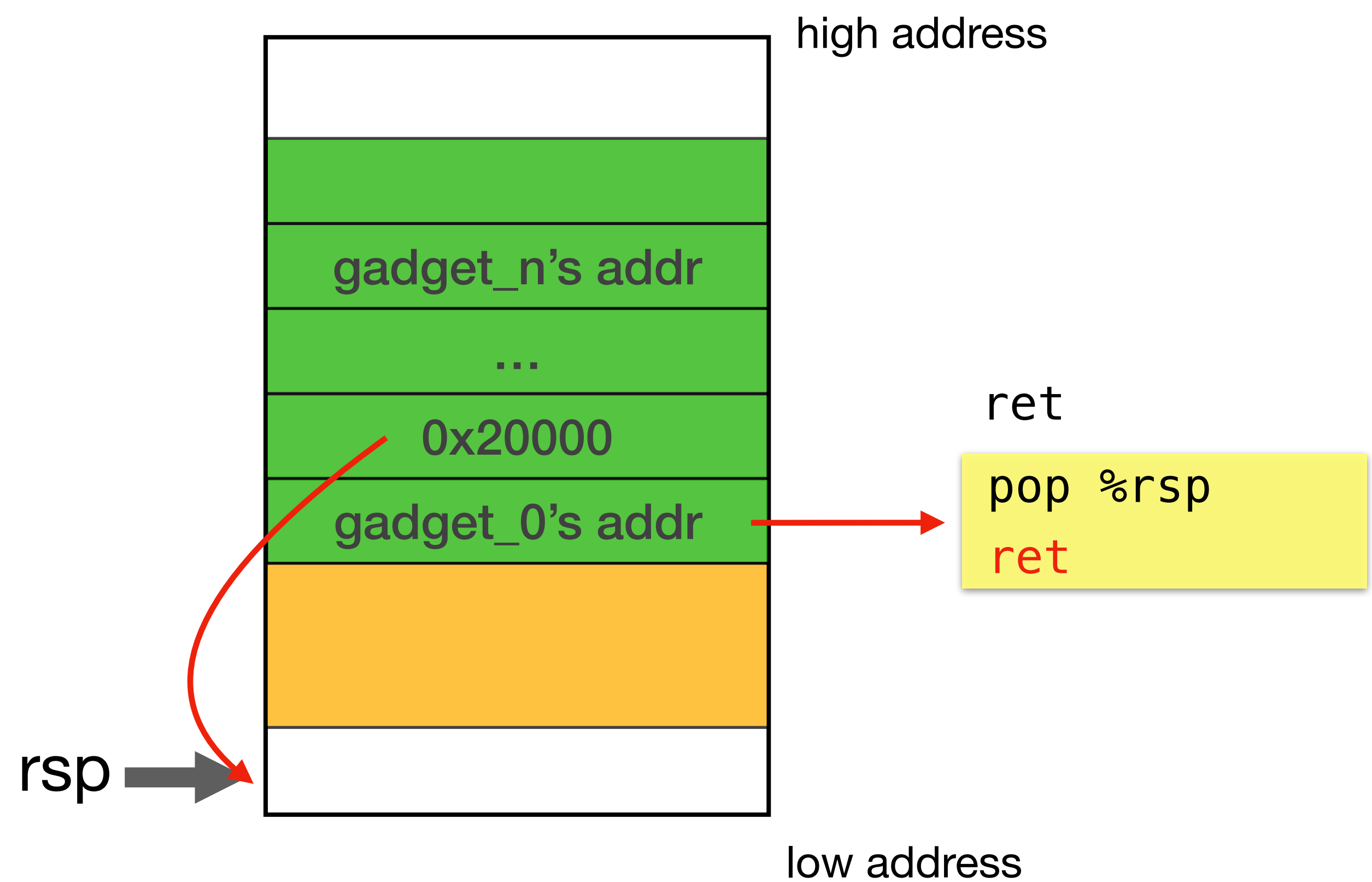
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<code>rip</code>	gadget's address

`pop %rsp` is special:

- `rsp` gets incremented by one word.
- Data pointed by old `rsp` is loaded to `rsp`.

Finding ROP Gadgets

ROP gadgets: Instructions sequences ending with a ret.

```
void foo(int a, int b) {  
    char buffer[12];  
    gets(buffer);  
    return;  
}  
  
int main() {  
    int x;  
    x = 0;  
    foo(1,2);  
    x = 1;  
    printf("%d\n",x);  
    return 0;  
}
```

(gdb) disassemble main

Dump of assembler code for function main:

```
0x0000000000001170 <+0>:    push    %rbp  
0x0000000000001171 <+1>:    mov     %rsp,%rbp  
0x0000000000001174 <+4>:    sub     $0x10,%rsp  
0x0000000000001178 <+8>:    movl    $0x0,-0x4(%rbp)  
0x000000000000117f <+15>:   movl    $0x0,-0x8(%rbp)  
0x0000000000001186 <+22>:   mov     $0x1,%edi  
0x000000000000118b <+27>:   mov     $0x2,%esi  
0x0000000000001190 <+32>:   call    0x1150 <foo>  
0x0000000000001195 <+37>:   movl    $0x1,-0x8(%rbp)  
0x000000000000119c <+44>:   mov     -0x8(%rbp),%esi  
0x000000000000119f <+47>:   lea     0xe5e(%rip),%rdi  
0x00000000000011a6 <+54>:   mov     $0x0,%al  
0x00000000000011a8 <+56>:   call    0x1030 <printf@plt>  
0x00000000000011ad <+61>:   xor     %eax,%eax  
0x00000000000011af <+63>:   add     $0x10,%rsp  
0x00000000000011b3 <+67>:   pop     %rbp  
0x00000000000011b4 <+68>:   ret
```

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(gdb) disassemble main

Dump of assembler code for function **main**:

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0x00000000000011af <+63>:   add     $0x10,%rsp
0x00000000000011b3 <+67>:   pop     %rbp
0x00000000000011b4 <+68>:   ret
```

Dump of assembler code for function **foo**:

```
0x0000000000001150 <+0>:    push    %rbp
0x0000000000001151 <+1>:    mov     %rsp,%rbp
0x0000000000001154 <+4>:    sub     $0x20,%rsp
0x0000000000001158 <+8>:    mov     %edi,-0x4(%rbp)
0x000000000000115b <+11>:   mov     %esi,-0x8(%rbp)
0x000000000000115e <+14>:   lea     -0x14(%rbp),%rdi
0x0000000000001162 <+18>:   mov     $0x0,%al
0x0000000000001164 <+20>:   call    0x1040 <gets@plt>
0x0000000000001169 <+25>:   add     $0x20,%rsp
0x000000000000116d <+29>:   pop     %rbp
0x000000000000116e <+30>:   ret
```



How many gadgets can you find in these two functions?

ROP Gadgets Are Abundant

ROP gadgets: Instructions sequences ending with a ret.

- Linked libraries provide a plethora of instructions.
- x86 ISA uses variable-length instructions.
 - Allows *unintended* instruction sequences

ROP Gadgets Are Abundant

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- **Linked libraries provide a plethora of instructions.**

7 English words

Linkedlibrariesprovideaplethoraofinstructions. *How many words can you find?*

linked

vid

let

fin

ion

any

scan

link

ink

Unintended words become available.

ROP Gadgets Are Abundant

ROP gadgets: Instructions sequences ending with a `ret`.

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`ret` is encoded as `0xc3` in hexadecimal format.

Dump of assembler code for function `foo`:

```
0x00000000000001150 <+0>:    push    %rbp
0x00000000000001151 <+1>:    mov     %rsp,%rbp
0x00000000000001154 <+4>:    sub     $0x20,%rsp
0x00000000000001158 <+8>:    mov     %edi,-0x4(%rbp)
0x0000000000000115b <+11>:   mov     %esi,-0x8(%rbp)
0x0000000000000115e <+14>:   lea     -0x14(%rbp),%rdi
0x00000000000001162 <+18>:   mov     $0x0,%al
0x00000000000001164 <+20>:   call    0x1040 <gets@plt>
0x00000000000001169 <+25>:   add     $0x20,%rsp
0x0000000000000116d <+29>:   pop     %rbp
0x0000000000000116e <+30>:   ret
```

[(gdb) x/4xb 0x0000000000000116e

```
0x116e <foo+30>:    0xc3    0x90    0x55    0x48
```

ROP Gadgets Are Abundant

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`ret` is encoded as `0xc3` in hexadecimal format.

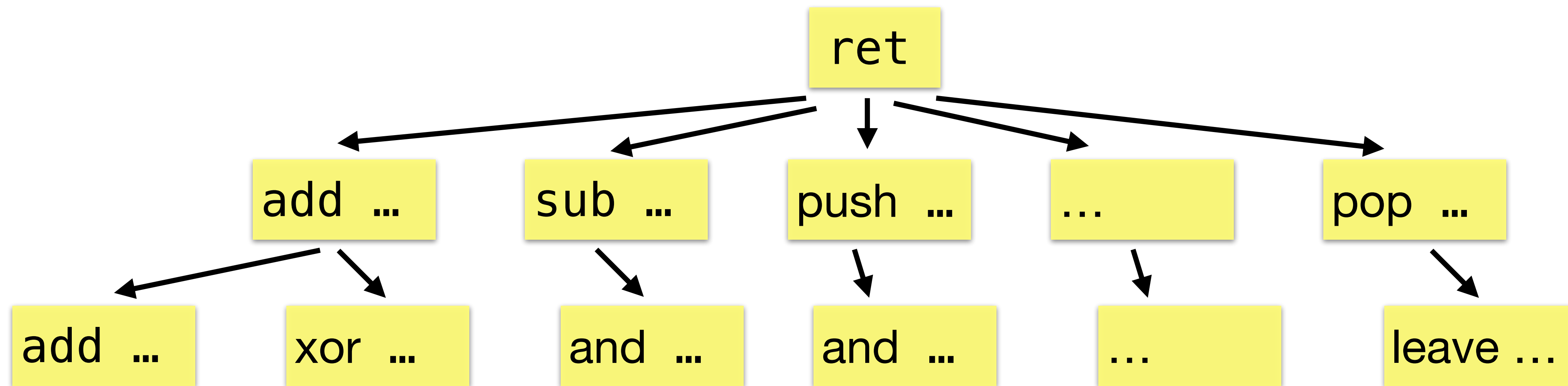
Starting one byte later, the attacker instead obtains

f7 c7 07 00 00 00	test \$0x00000007, %edi
0f 95 45 c3	setnzb -61(%ebp)

c7 07 00 00 00 0f	movl \$0x0f000000, (%edi)
95	xchg %ebp, %eax
45	inc %ebp
c3	ret

How to Find ROP Gadgets

- Start from a ret (0xc3) and backtrack to find gadgets.
 - Check whether the previous n bytes ($n \leq 15$ for AMD64) form an instruction
 - Recurse from the previously found instruction



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0f 95 45 c3	setnzb -61(%ebp)	95	xchg %ebp, %eax
		45	inc %ebp
		c3	ret

ROP Thesis

The Geometry of Innocent Flesh on the Bone: Return-into-libc without Function Calls (on the x86),
by Hovav Shacham.

“In any sufficiently large body of x86 executable code there will exist sufficiently many useful code sequences that an attacker who controls the stack will be able, by means of the return-into-libc techniques we introduce, to cause the exploited program to undertake arbitrary computation.”



Also true in all other major architectures.

Find ROP Gadgets

ROPGadget: A tool that examines binaries to find code-reuse gadgets.

```
void foo(int a, int b) {  
    char buffer[12];  
    gets(buffer);  
    return;  
}  
  
int main() {  
    int x;  
    x = 0;  
    foo(1,2);  
    x = 1;  
    printf("%d\n",x);  
    return 0;  
}
```

How many ret gadgets in this program?

```
$ ROPgadget --binary demo | grep ret  
4:0x000000000000010b3 : add byte ptr [rax], 0 ; add byte ptr [rax], al ; ret  
7:0x000000000000010b4 : add byte ptr [rax], al ; add byte ptr [rax], al ; ret  
8:0x00000000000001130 : add byte ptr [rax], al ; add dword ptr [rbp - 0x3d], ebx ; nop dword ptr [rax] ; ret  
13:0x000000000000010b6 : add byte ptr [rax], al ; ret  
17:0x000000000000010f5 : add byte ptr [rax], r8b ; ret  
18:0x00000000000001131 : add byte ptr [rcx], al ; pop rbp ; ret  
20:0x00000000000001132 : add dword ptr [rbp - 0x3d], ebx ; nop dword ptr [rax] ; ret  
21:0x0000000000000112e : add eax, 0x100002f ; pop rbp ; ret  
23:0x000000000000011b0 : add esp, 0x10 ; pop rbp ; ret  
24:0x0000000000000116a : add esp, 0x20 ; pop rbp ; ret  
25:0x00000000000001017 : add esp, 8 ; ret  
26:0x000000000000011af : add rsp, 0x10 ; pop rbp ; ret  
27:0x00000000000001169 : add rsp, 0x20 ; pop rbp ; ret  
28:0x00000000000001016 : add rsp, 8 ; ret  
31:0x000000000000011bb : cli ; sub rsp, 8 ; add rsp, 8 ; ret  
42:0x000000000000010f1 : loopne 0x1159 ; nop dword ptr [rax + rax] ; ret  
43:0x0000000000000112c : mov byte ptr [rip + 0x2f05], 1 ; pop rbp ; ret  
44:0x000000000000010f3 : nop dword ptr [rax + rax] ; ret  
45:0x000000000000010b1 : nop dword ptr [rax] ; ret  
46:0x000000000000010f2 : nop word ptr [rax + rax] ; ret  
47:0x000000000000010ef : or bh, bh ; loopne 0x1159 ; nop dword ptr [rax + rax] ; ret  
48:0x00000000000001133 : pop rbp ; ret  
51:0x0000000000000101a : ret  
52:0x00000000000001011 : sal byte ptr [rdx + rax - 1], 0xd0 ; add rsp, 8 ; ret  
53:0x000000000000011bd : sub esp, 8 ; add rsp, 8 ; ret  
54:0x000000000000011bc : sub rsp, 8 ; add rsp, 8 ; ret  
61:0x000000000000011ad : xor eax, eax ; add rsp, 0x10 ; pop rbp ; ret
```

Find ROP Gadgets

ROPgadget: A tool that examines binaries to find code-reuse gadgets.

```
void foo(int a, int b) {  
    char buffer[12];  
    gets(buffer);  
    return;  
}  
  
int main() {  
    int x;  
    x = 0;  
    foo(1,2);  
    x = 1;  
    printf("%d\n",x);  
    return 0;  
}
```

How many ret gadgets in this program with statically-linked libraries?

```
[$ ROPgadget --binary demo.static | grep ret | wc -l  
8375
```

Find ROP Gadgets

ROPgadget: A tool that examines binaries to find code-reuse gadgets.

How many ret gadgets are in libc?

```
[$ ROPgadget --binary /lib/x86_64-linux-gnu/libc.so.6 | grep ret | wc -l  
19219
```

Return-oriented Programming (ROP)



An exploit technique that allows arbitrary code execution without calling any functions.

- Exploiting memory corruption bugs
 - Often starting with a corrupted return address
- Chaining code sequences, called *gadgets*, that end with a `ret`
 - Generally, gadgets ending with control flow transfer instructions, e.g. `jmp`
- Turing-complete
 - Memory operations
 - Arithmetic and logic
 - Control flow

What are the lessons we can learn from ROP?







***“A single flower contains a whole world;
a single leaf embodies enlightenment.”***

—Buddhāvataṃsaka Sūtra

“一花一世界，一叶一菩提。” — 《华严经》

Integer Overflows

Signed vs. Unsigned Numbers

```
char buf[N];  
int len;  
...  
if (len > N) {  
    error("Invalid length");  
    return;  
}  
read(fd, buf, len);
```

What if *len* is negative?

```
ssize_t read(int fd, void *buf, size_t count);
```

len will be cast to unsigned and negative length overflows,
e.g., $-1 \rightarrow 2^{32} - 1 = 4294967295$

Integer Overflows



An integer overflow occurs when an integer is increased beyond its maximum value or decreased beyond its minimum value.

- Standard integer types (signed)
 - signed char, short int, int, long int, long long int
- Signed overflow vs unsigned overflow
 - A signed overflow occurs when a value is carried over to the sign bit.
 - An unsigned overflow occurs when the underlying representation can no longer represent an integer value.

Integer Overflow Examples

```
unsigned int ui;  
signed int si;  
ui = UINT_MAX; //  $2^{32} - 1 = 4,294,967,295$   
ui++;  
printf("ui = %u\n", ui);
```

What does it print?

0

```
si = INT_MAX; //  $2^{31} - 1 = 2,147,483,647$   
si++;  
printf("si = %d\n", si);
```

What does it print?

$-2^{31} = -2,147,483,648$

Integer Overflow Examples

```
unsigned int ui;  
signed int si;  
ui = 0;  
ui--;  
printf("ui = %u\n", ui);  
  
si = INT_MIN; // -2^31 = -2,147,483,648  
si--;  
printf("si = %d\n", si);
```

What does it print?

$2^{32} - 1 = 4,294,967,295$

What does it print?

$2^{31} - 1 = 2,147,483,647$

Security Threats of Integer Overflows

Take two strings from user input, and concatenate them on heap.

```
int main(int argc, char *const *argv) {  
    unsigned short int total;  
    total = strlen(argv[1]) + strlen(argv[2]) + 1;  
    char *buff = (char *) malloc(total);  
    strcpy(buff, argv[1]);  
    strcat(buff, argv[2]);  
}
```

What if the `total` variable overflows because of the addition operation?

Vulnerability: JPEG Example

Based on a real-world vulnerability in the handling of the comment field in JPEG files

```
void getComment(unsigned int len, char *src) {  
    unsigned int size;  
    size = len;  
    char *comment = (char *)malloc(size + 1);  
    memcpy(comment, src, size);  
    return;  
}
```

Will overflow to 0 if size is INT_MAX

How to fix it?

Vulnerability: JPEG Example

Based on a real-world vulnerability in the handling of the comment field in JPEG files

```
void getComment(unsigned int len, char *src) {  
    unsigned int size;  
    size = len - 2;  
    char *comment = (char *)malloc(size + 1);  
    memcpy(comment, src, size);  
    return;  
}
```

Any problem?

What if we do “getComment(1, “My Comment”);”?

- Overflow to cause malloc to allocate zero bytes.

Vulnerability: Truncation Errors

```
int func(char *name, unsigned int cbBuf) {  
    unsigned short bufSize = cbBuf;  
    char *buf = (char *)malloc(bufSize);  
    if (buf) {  
        memcpy(buf, name, cbBuf);  
        ...  
        free(buf);  
        return 0;  
    }  
    return 1;  
}
```

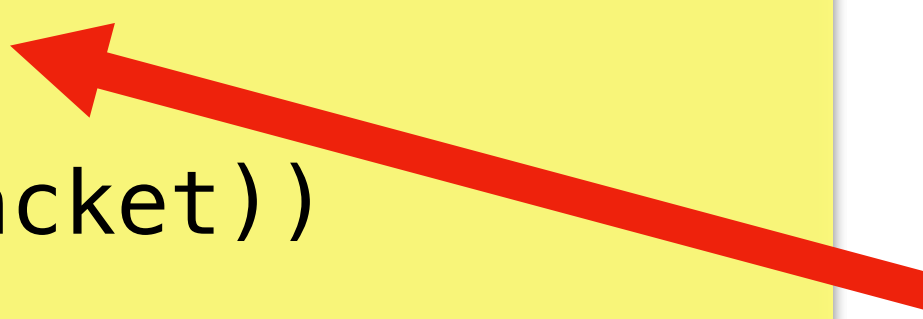
What if we call the function with cbBuf greater than USHRT_MAX?

Heap Overflows

Buffer Overflows

- Stack overflow: overflowing a memory region on the stack (e.g., overwriting a return address)
- Heap overflow: overflowing a memory region dynamically allocated on the heap

```
char *packet = (char *)malloc(1000);
while (!authenticated) {
    PacketRead(packet);
    if (Authenticate(packet))
        authenticated = 1;
}
if (authenticated)
    ProcessPacket(packet);
```



What happens if PacketRead overflows the packet buffer and overwrite important data in memory?

- e.g., authenticated is on the heap and corrupted

Overflowing Heap Critical User Data

```
typedef struct chunk {
    char inp[64]; /* vulnerable input buffer */
    void (*process)(char *); /* pointer to function */
} chunk_t;

void showlen(char *buf) {
    int len = strlen(buf);
    printf("buffer5 read %d chars\n", len);
}

int main(int argc, char *argv[]) {
    chunk_t *next = malloc(sizeof(chunk_t));
    next->process = showlen;
    printf("Enter value: ");
    gets(next->inp);
    next->process(next->inp);
    printf("buffer5 done\n");
}
```

Overflow the buffer on the heap to set the function pointer to an arbitrary address.

Overflow Heap Metadata

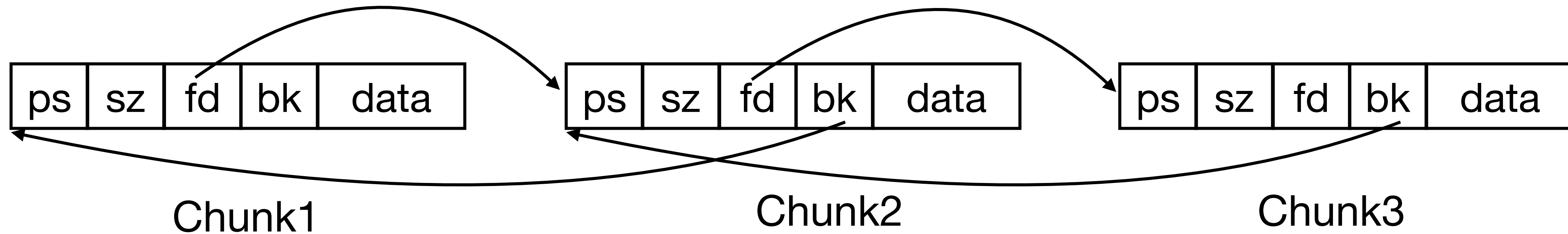
- Heap allocators (i.e., heap memory managers)
 - What regions have been allocated and their sizes
 - What regions are available for allocation
- Heap allocators maintain metadata such as chunk size, previous, and next pointers to other chunks.
 - Metadata are adjusted during heap-management functions.
 - `malloc()`, `calloc()`, `realloc()`, etc. and `free()`
 - Heap metadata are often adjacent to heap user data.

Example Heap Allocator

- Maintain a doubly-linked list of allocated and free chunks
- `malloc()` and `free()` modify this list

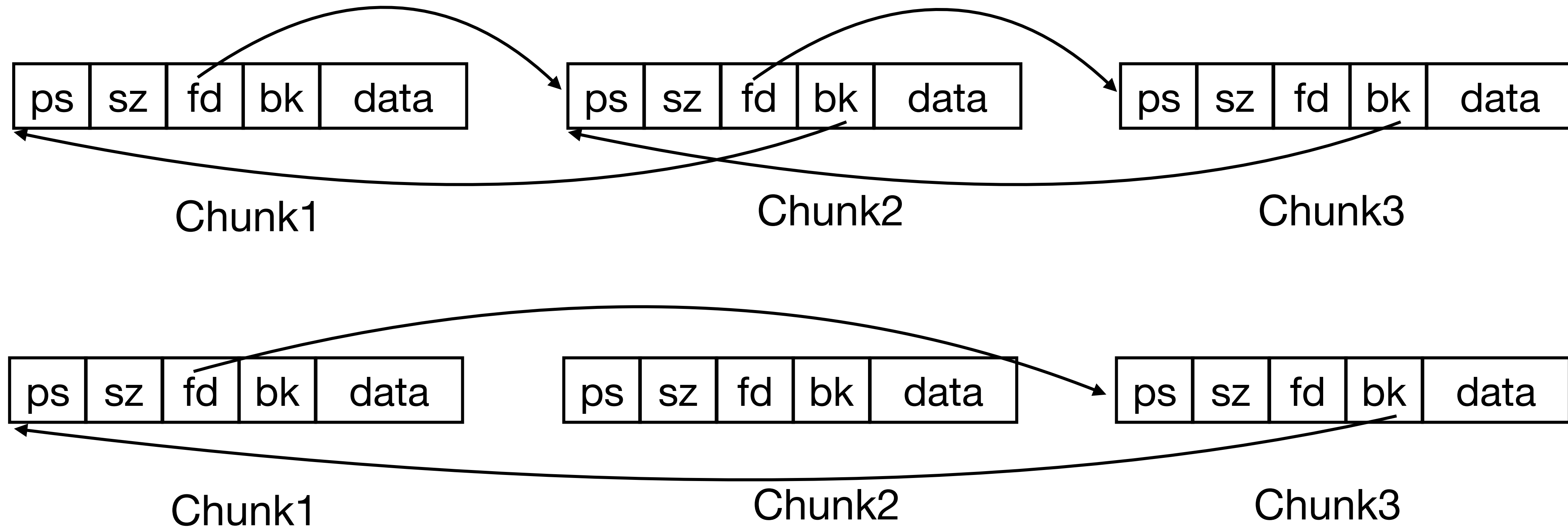
```
struct chunk {  
    size_t    ps;        // prev_size  
    size_t    sz;        // size  
    chunk_t *fd;         // forward pointer  
    chunk_t *bk;         // backward pointer  
    unsigned char data[]; // allocated space for user data  
};
```

Example Heap Allocator



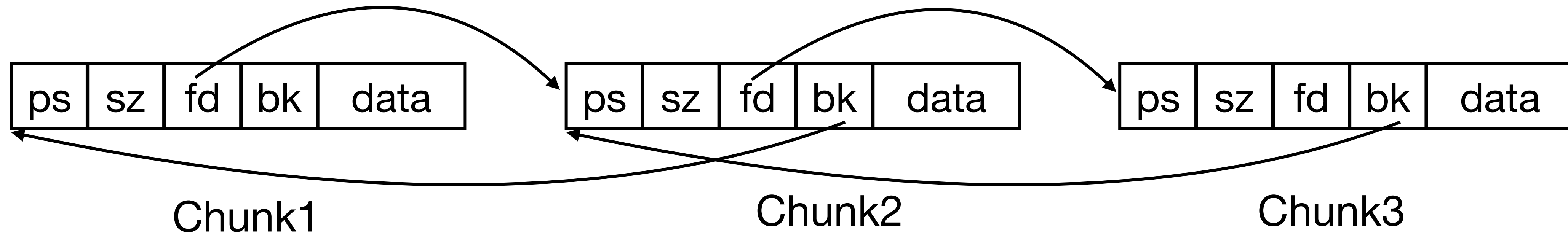
- ps: prev_size
- sz: size
- fd: forward pointer
- bk: backward pointer
- data: allocated space for user data

Example Heap Allocator



- `malloc()` removes a chunk from free list
 - `chunk2->bk->fd = chunk2->fd`
 - `chunk2->fd->bk = chunk2->bk`

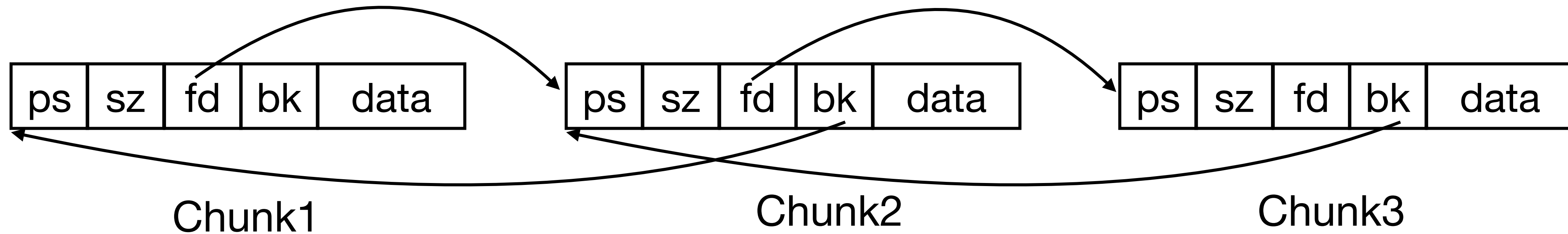
Attacking the Example Heap Allocator



- `malloc()` removes a chunk from allocated list
 - ▶ `chunk2->bk->fd = chunk2->fd`
 - ▶ `chunk2->fd->bk = chunk2->bk`
- By overflowing chunk2, attacker controls bk and fd of chunk2

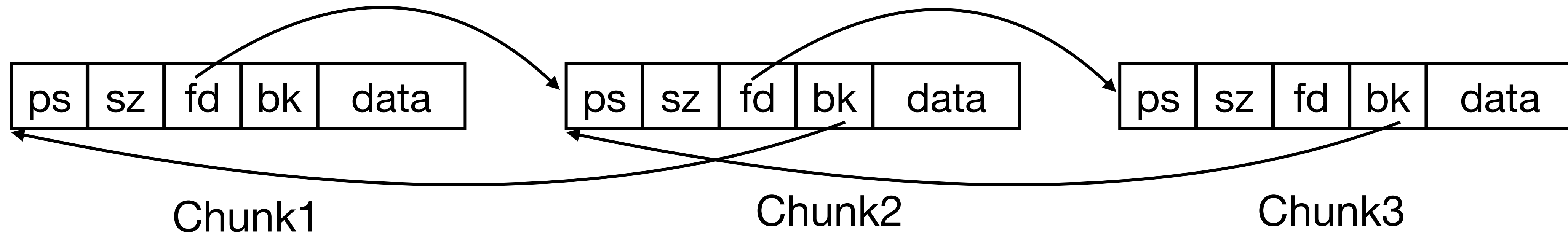
How to exploit this vulnerability for arbitrary writes (write-where-what vul.)?

Attacking the Example Heap Allocator



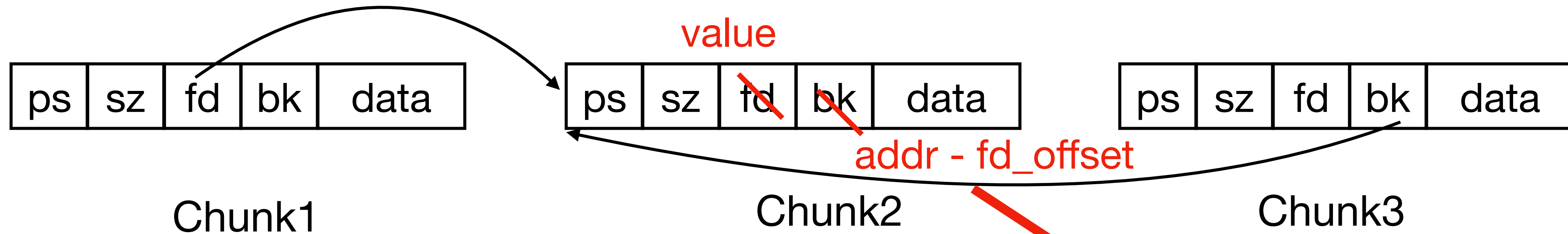
- `malloc()` removes a chunk from allocated list
 - `chunk2->bk->fd = chunk2->fd`
 - `chunk2->fd->bk = chunk2->bk`
- By overflowing `chunk2`, attacker controls `bk` and `fd` of `chunk2`
- Suppose the attacker wants to write **value** to memory address **addr**
 - Set `chunk2->fd` to be **value**
 - Set `chunk2->bk` to be `addr - fd_offset`, where `fd_offset` is the offset of the `fd` field in the chunk structure.

Attacking the Example Heap Allocator



- `malloc()` removes a chunk from allocated list
 - `chunk2->bk->fd = chunk2->fd`
 - `chunk2->fd->bk = chunk2->bk`
- By overflowing `chunk2`, attacker controls `bk` and `fd` of `chunk2`
- `malloc()` changes the program as follows:
 - `(addr - fd_offset)->fd = value`, the same as `(*addr) = value`
 - `value->bk = addr - offset`

Attacking the Example Heap Allocator



- `malloc()` removes a chunk from allocated list
 - `chunk2->bk->fd = chunk2->fd`
 - `chunk2->fd->bk = chunk2->bk`
 - By overflowing chunk2, attacker controls bk and fd of chunk2
 - `malloc()` changes the program as follows:
 - `(addr - fd_offset)->fd = value`, the same as `(*addr) = value`
 - `value->bk = addr - fd_offset`
- Enables arbitrary memory write!