

Assembly x86-64

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Università Ca' Foscari Venezia

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Why Assembly??

Program exploitation: making a program do something **unexpected** and not planned

The *right bugs* can be used to **subvert** code execution

⇒ It is essential to understand how programs are **compiled** and **executed**

Executables are written in **machine code**

⇒ depends on computer architecture

Assembly language makes machine code more readable

⇒ depends on computer architecture

We focus on **x86-64** assembly (also known as **x64**, **AMD64** and **Intel 64**)

⇒ one of the most popular

Registers

General purpose: **rax**, **rbx**, **rcx**, **rdx**, **r8**, ..., **r15** : used to temporarily store values and addresses used in the computation

Stack: **rsp**, **rbp**, corresponding to **stack pointer** and **base pointer**, i.e., the two addresses delimiting the current stack

Instruction pointer: **rip**; points to the instruction to be executed

Indexes: **rsi**, **rdi**, source index and destination index: used for array, string copy and parameters

Single Instruction Multiple Data (SIMD): **xmm0**, ..., **xmm15**, 128 bits (up to 512 in AVX-512, **zmm0-zmm31**)

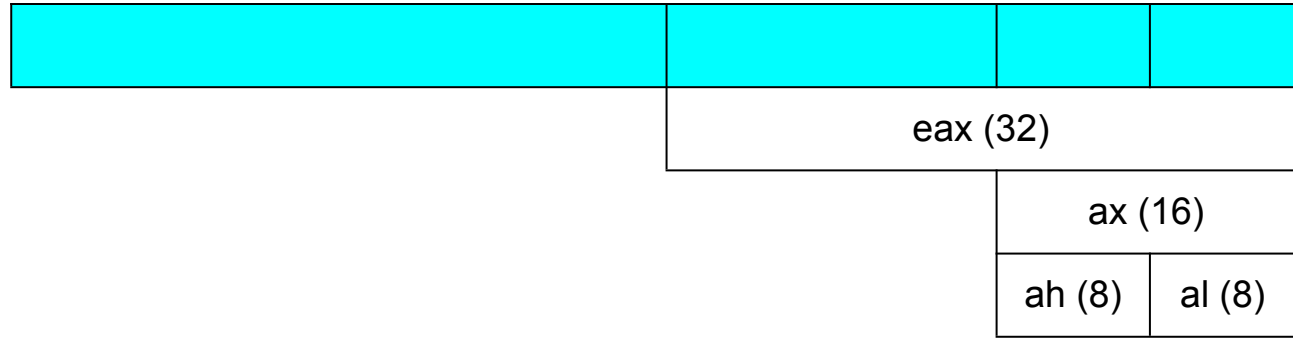
Flag register: **rFlag**, for status, es:
ZF - zero flag, when result is zero
CF - carry flag, result too large/small
SF - *sign* flag, when result is negative

Portions of registers

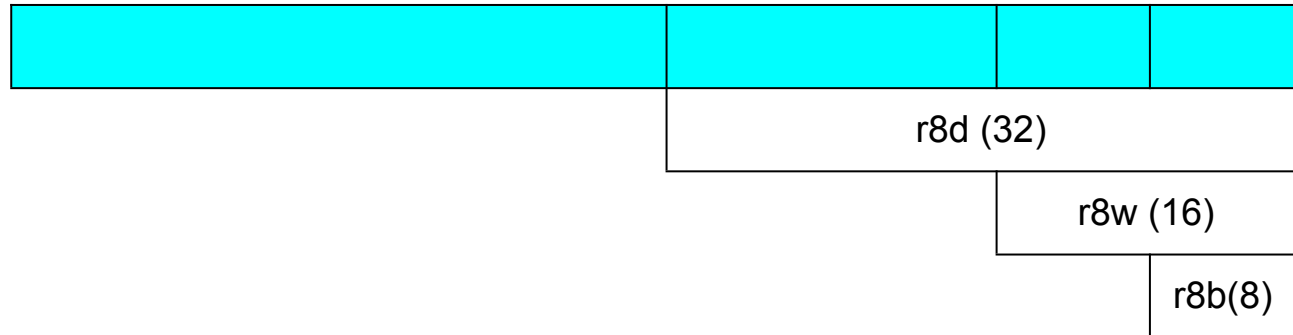
64 bits	lowest 32 bits	lowest 16 bits	lowest 8 bits	2nd lowest 8 bits
rax	eax	ax	al	ah
rbx	ebx	bx	bl	bh
...	...	...	...	
r8	r8d	r8w	r8b	-
r9	r9d	r9w	r9b	-
...	...	...	...	...

Registers portions

rax (64) =



r8 (64) =



Assembly syntax

AT&T Syntax:

command <source>, <destination>

Example:

```
mov $5, rax
```

Intel Syntax:

command <destination>, <source>

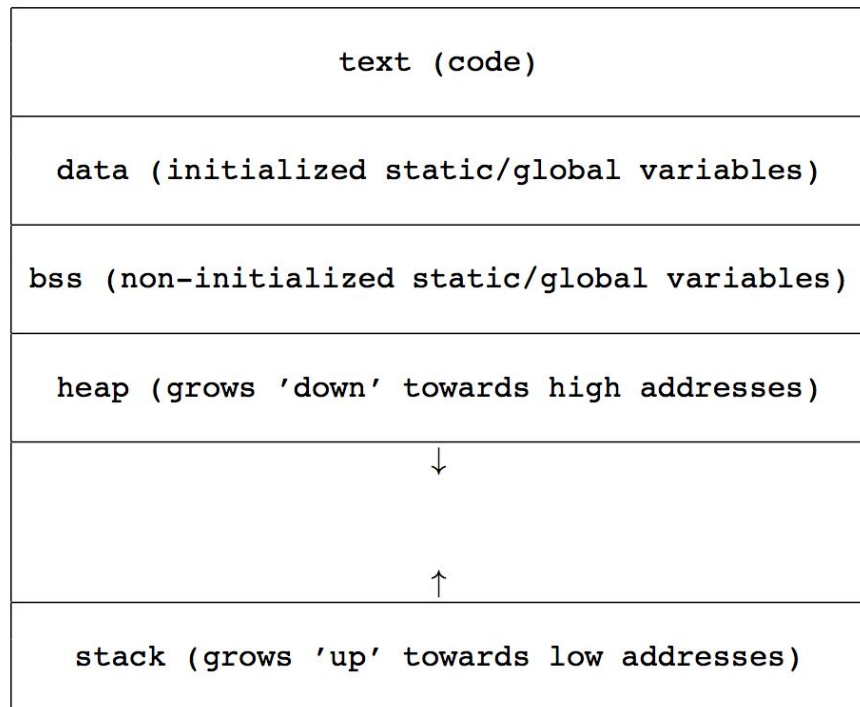
Example:

```
mov rax, 5
```

- ⇒ We will use the Intel syntax
- More documented
 - More explicit (e.g. size)

Memory layout

Low addresses



High addresses

Stack and calling convention

Region of memory where **local variables** are stored

Supports **push** and **pop** operations

Grows towards **lower** memory addresses

⇒ pushed values have lower address

When a function is called a **stack frame** is set up

rbp contains the address of the base of the current stack frame

rsp contains the address of the top element of the current stack frame

System V AMD64 ABI: Every function call stores first 6 arguments in **rdi**, **rsi**, **rdx**, **rcx**, **r8**, **r9**, pushes extra arguments on the stack, return value up to 128 bits in **rax** and **rdx**

Main commands

Commands

mov <dst>, <src>: **moves** the
<src> value to <dst>

add <dst>, <src>: **adds** the value
in <src> to <dst>

sub <dst>, <src>: **subtracts** the
value in <src> from <dst>

and <dst>, <src>: performs a
logical and between <src> and
<dst>, placing the result in <dst>

push <target>: **pushes** the value
in <target> to the stack

pop <target>: **pops** a value from
the stack into <target>

cmp <dst>, <src>: **compares**
<src> with <dst>. This is done by
subtracting <src> from <dst> and
updating **flags** that can be checked
by subsequent conditional operations

Commands (2) - control flow

call <address>: **calls** the function at <address>. Before jumping to the function, the address of the next instruction is **pushed** to the stack in order to be able to return

ret: pops the return address and **returns** control to it

leave: **restores** the stack frame (rsp←rbp and old rbp is popped)

jle <target>: **jumps** to the address in <target> if the previously compared <src> was **less than or equal** to <dst>. The test is done on the flags set by cmp

jge <target>: **jumps** to the address in <target> if the previously compared <src> was **greater than or equal** to <dst>. The test is done on the flags set by cmp

Commands (3)

jmp <target>: jumps to the address in <target>. Copies target address into the **rip** register

lea <dst>, <src> stands for “load effective address”: **loads the address** of <src> into <dst>;

int <value>: generates software **interrupt** <value>. This is commonly used to invoke system calls

nop: no-operation, does **nothing**

NOTE: There are various *addressing modes*. For example:

Register indirect:

mov DWORD PTR [rbp - 4], eax

Immediate: **mov** eax, 3

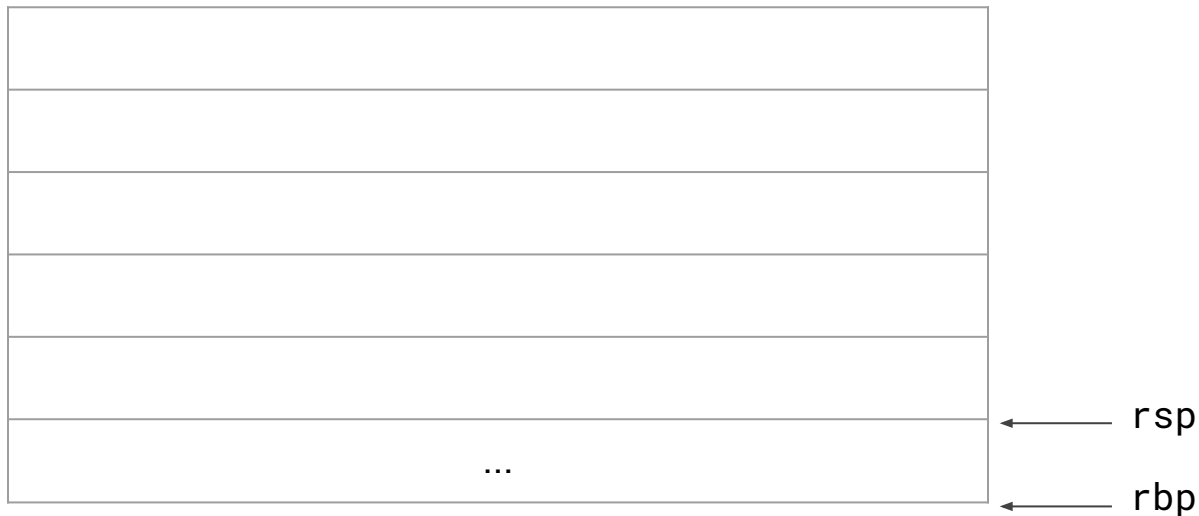
Note: DWORD is like a type: indicates a 32-bit “double word” value

Function calls

Example: function call

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

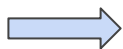
```
mov    edi,0xa # moves 10 to rdi  
call   <func>  # calls func  
...
```



Example: function call

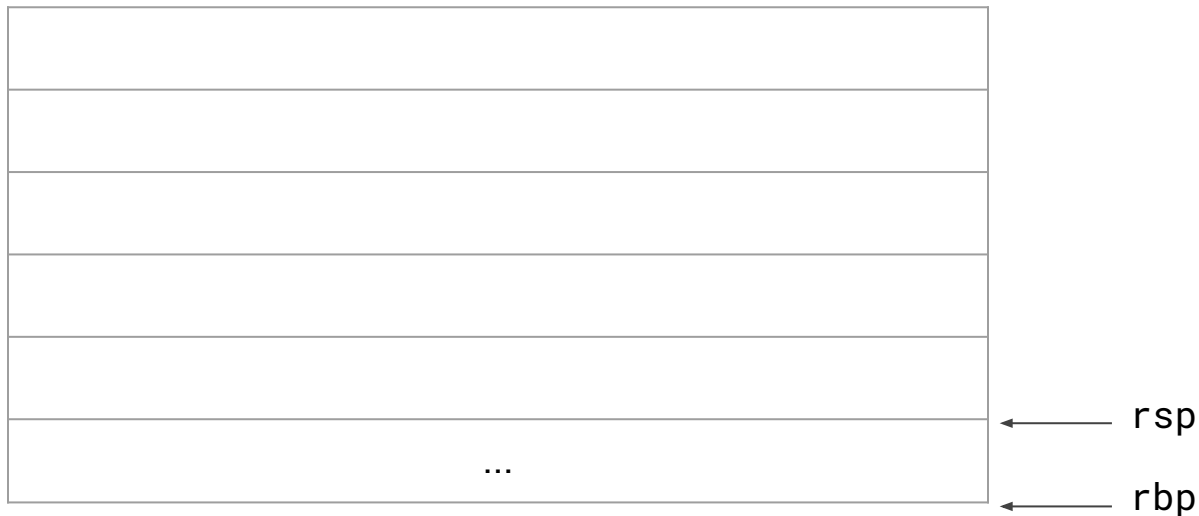
```
int main() {  
    func(10);  
    ...  
}
```

param. in rdi
(32 bits zeroed)



```
mov  
call  
...
```

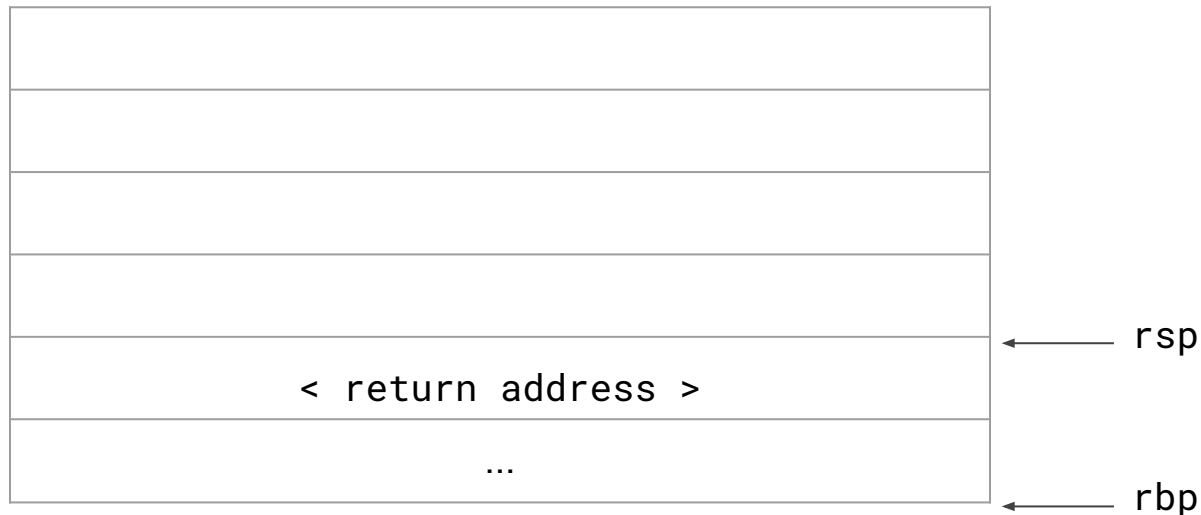
```
edi,0xa # moves 10 to rdi  
<func> # calls func
```



Example: function call

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

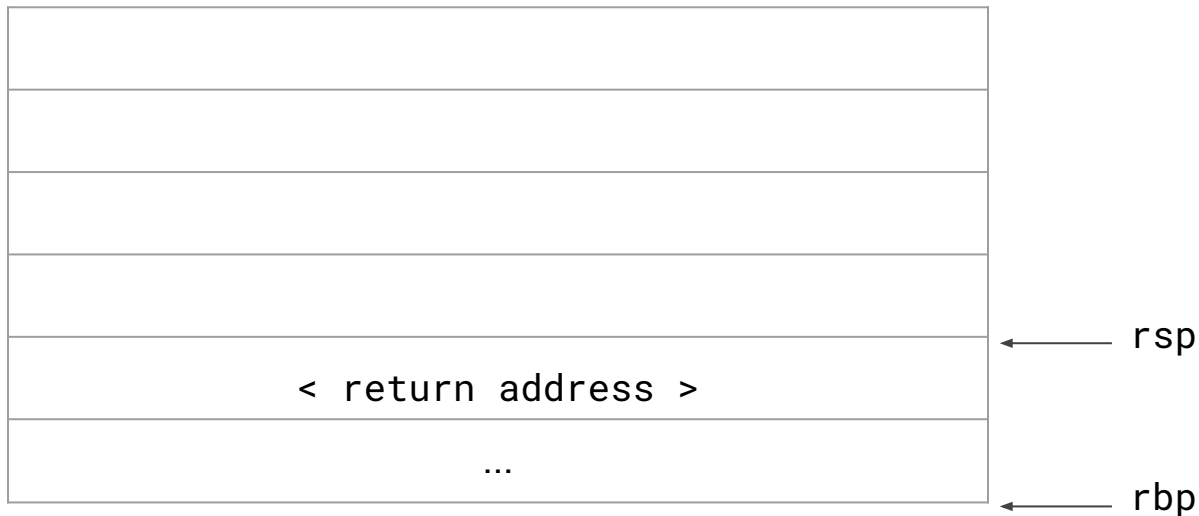
→ **mov** edi,0xa # moves 10 to rdi
call <func> # calls func
...



Example: function call

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

```
push    rbp  
mov     rbp, rsp  
sub     rsp, 0x18
```

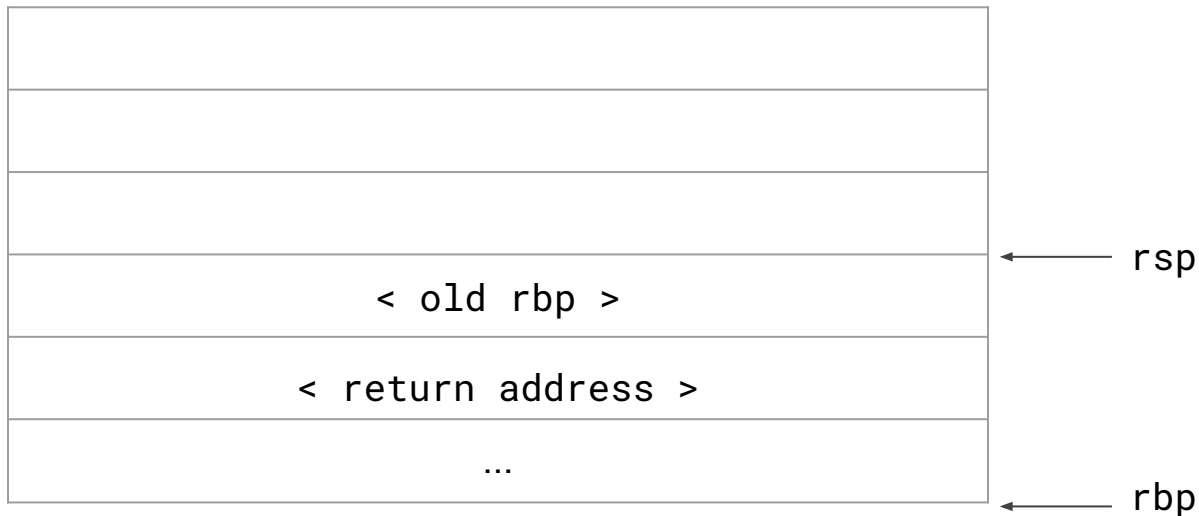


Example: function call

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



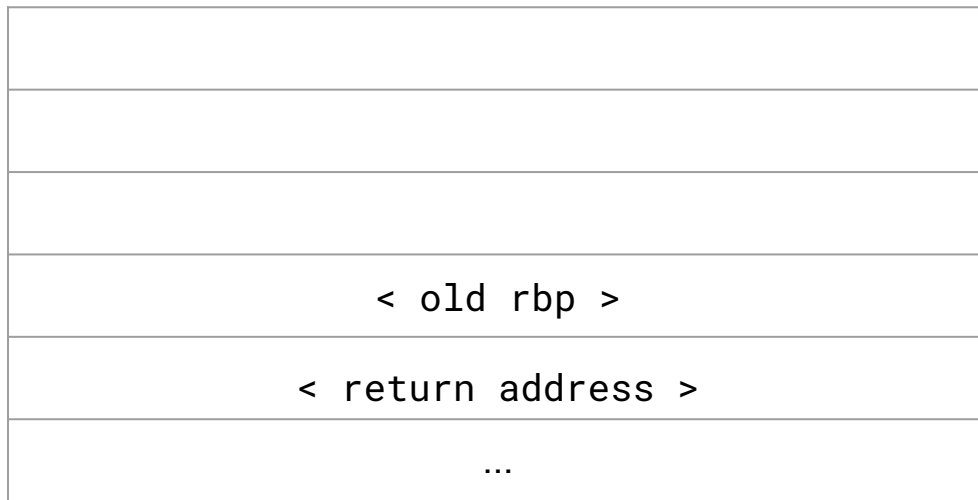
```
push    rbp  
mov     rbp, rsp  
sub     rsp, 0x18
```



Example: function call

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

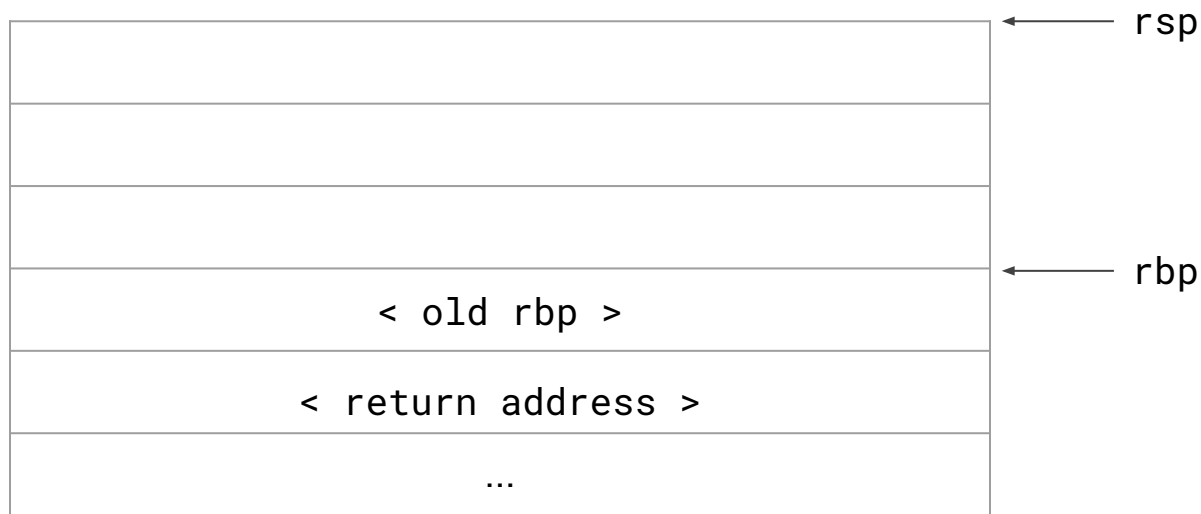
→ **push** rbp
mov rbp, rsp
sub rsp, 0x18



Example: function call

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

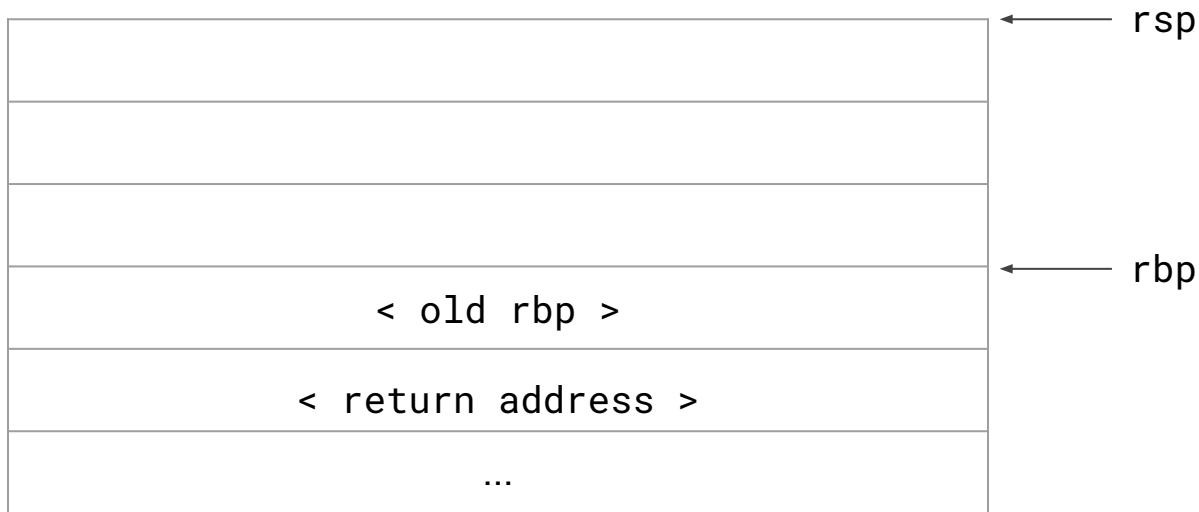
 **push** rbp
mov rbp, rsp
sub rsp, 0x18



Example: function call

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

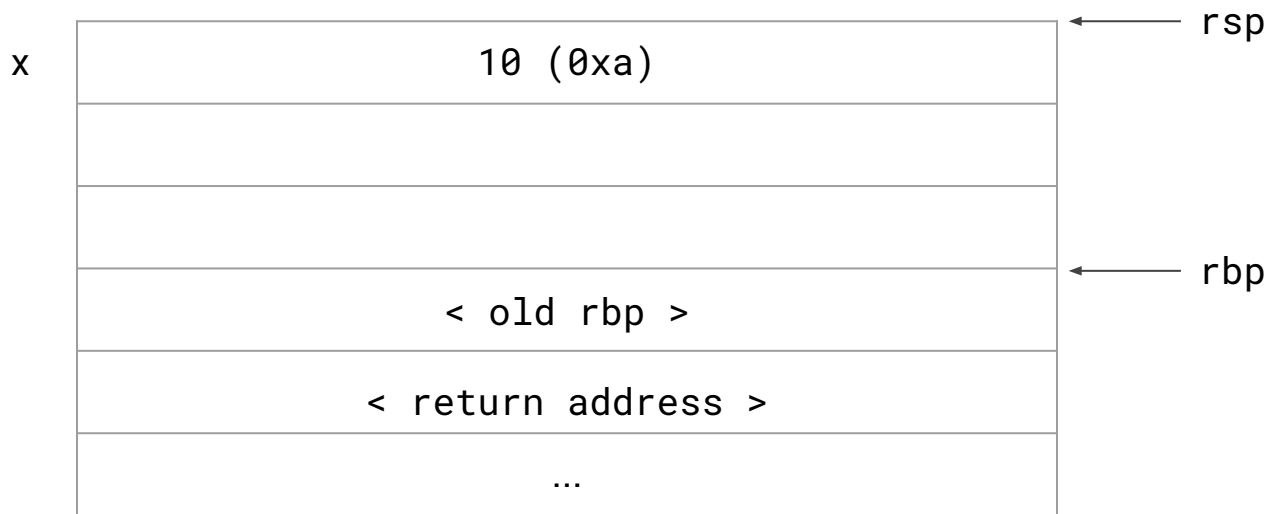
```
mov    QWORD PTR [rbp-0x18], rdi  
mov    QWORD PTR [rbp-0x10], 0x0  
mov    rax, QWORD PTR [rbp-0x18]  
mov    QWORD PTR [rbp-0x8], rax
```



Example: function call

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

→ `mov QWORD PTR [rbp-0x18], rdi`
`mov QWORD PTR [rbp-0x10], 0x0`
`mov rax, QWORD PTR [rbp-0x18]`
`mov QWORD PTR [rbp-0x8], rax`

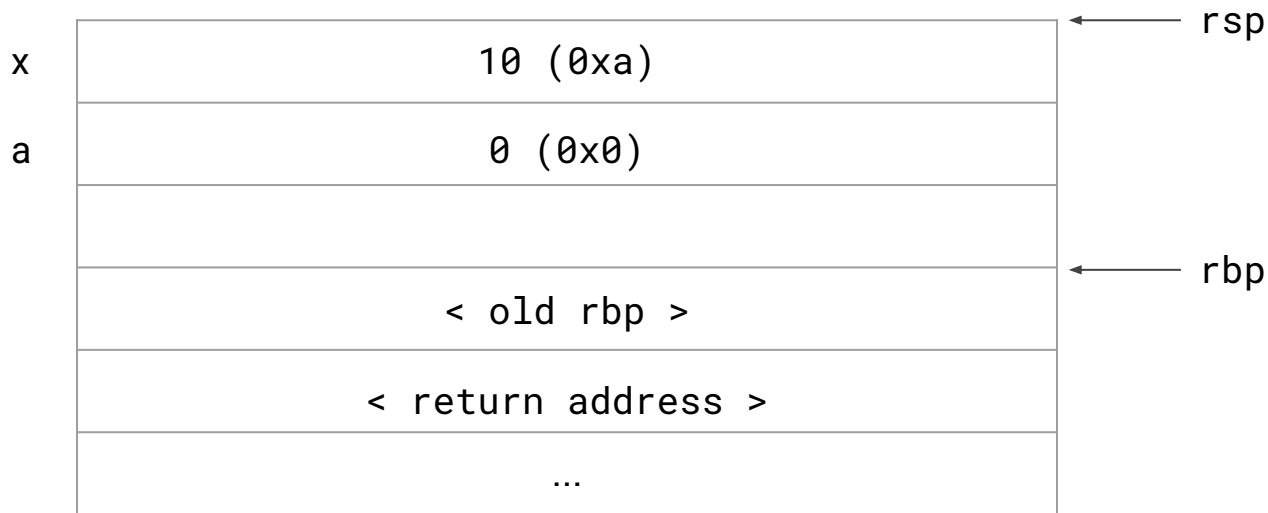


Example: function call

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

→

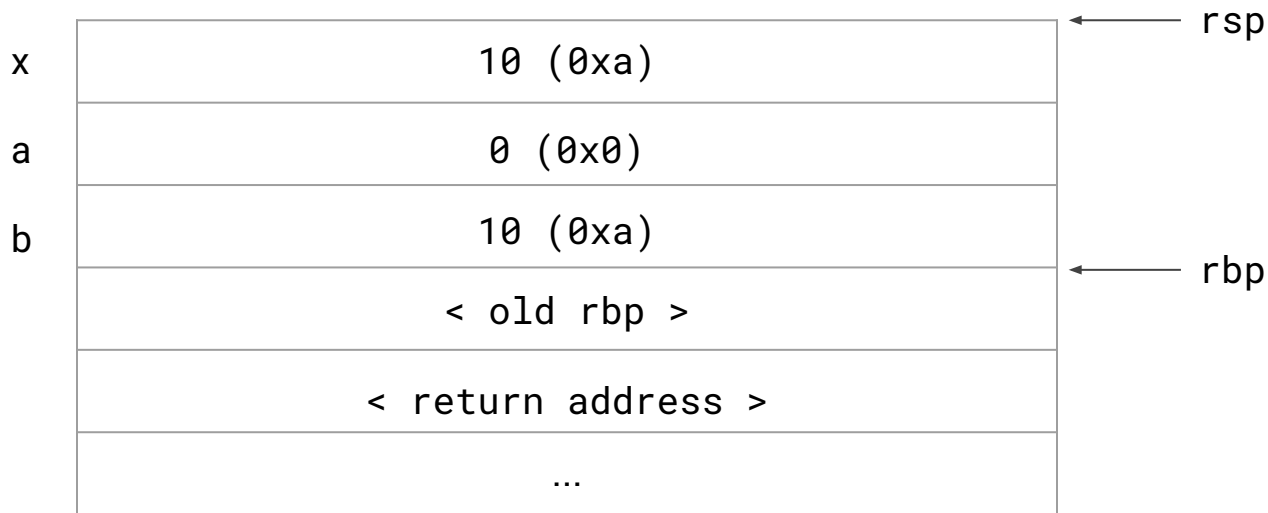
```
mov    QWORD PTR [rbp-0x18], rdi  
mov    QWORD PTR [rbp-0x10], 0x0  
mov    rax, QWORD PTR [rbp-0x18]  
mov    QWORD PTR [rbp-0x8], rax
```



Example: function call

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

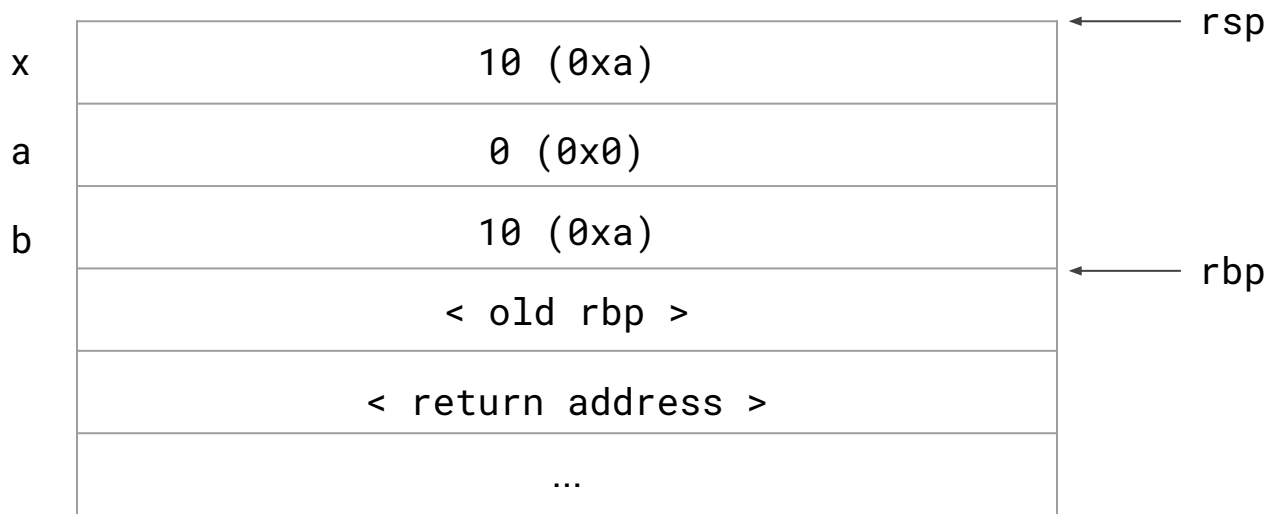
```
mov    QWORD PTR [rbp-0x18], rdi  
mov    QWORD PTR [rbp-0x10], 0x0  
mov    rax, QWORD PTR [rbp-0x18]  
→ mov  QWORD PTR [rbp-0x8], rax
```



Example: function return

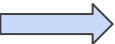
```
long func(long x) {  
    long a = 0;  
    long b = x;  
    ...  
    return b;  
}
```

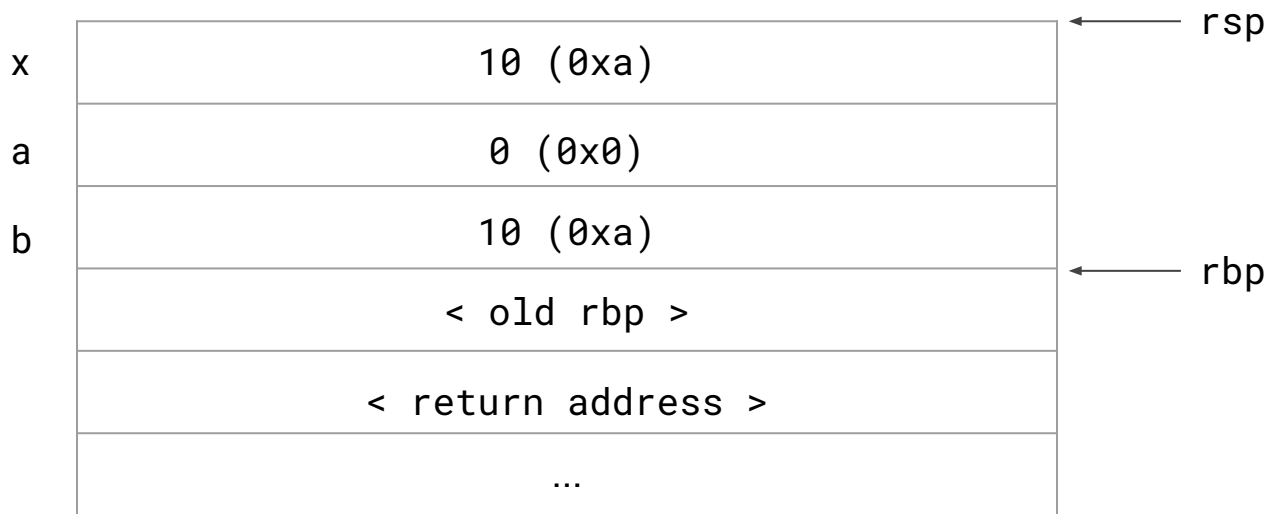
```
mov    rax, DWORD PTR [rbp-0x8]  
leave  
ret
```



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`



Example: function return

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

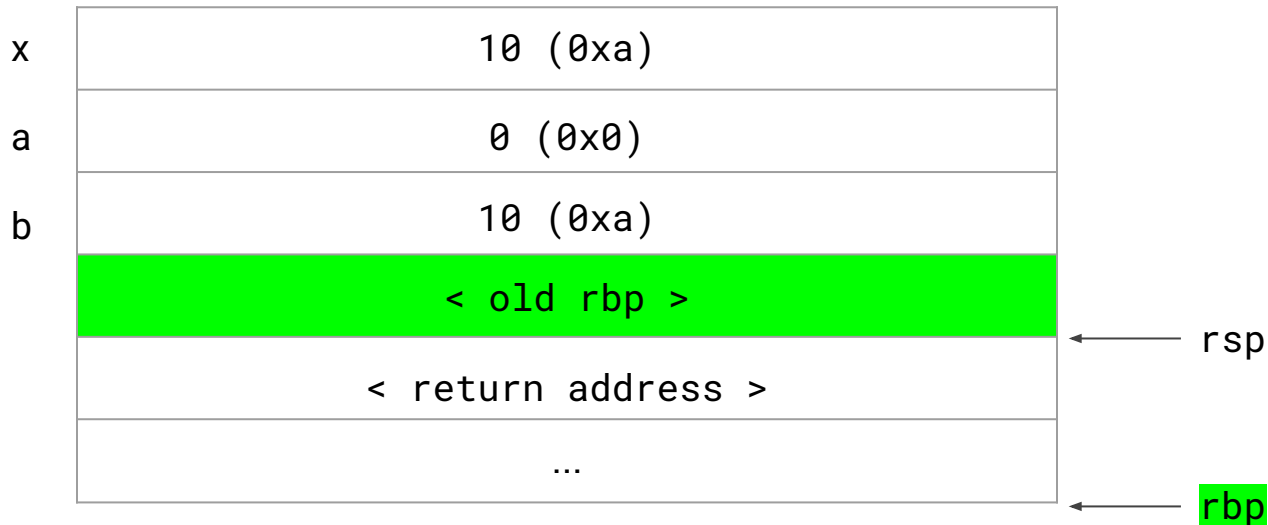
mov rax, DWORD PTR [rbp-0x8]
→ leave
ret

x	10 (0xa)	
a	0 (0x0)	
b	10 (0xa)	
	< old rbp >	← rbp, rsp
	< return address >	
	...	

Example: function return

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

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

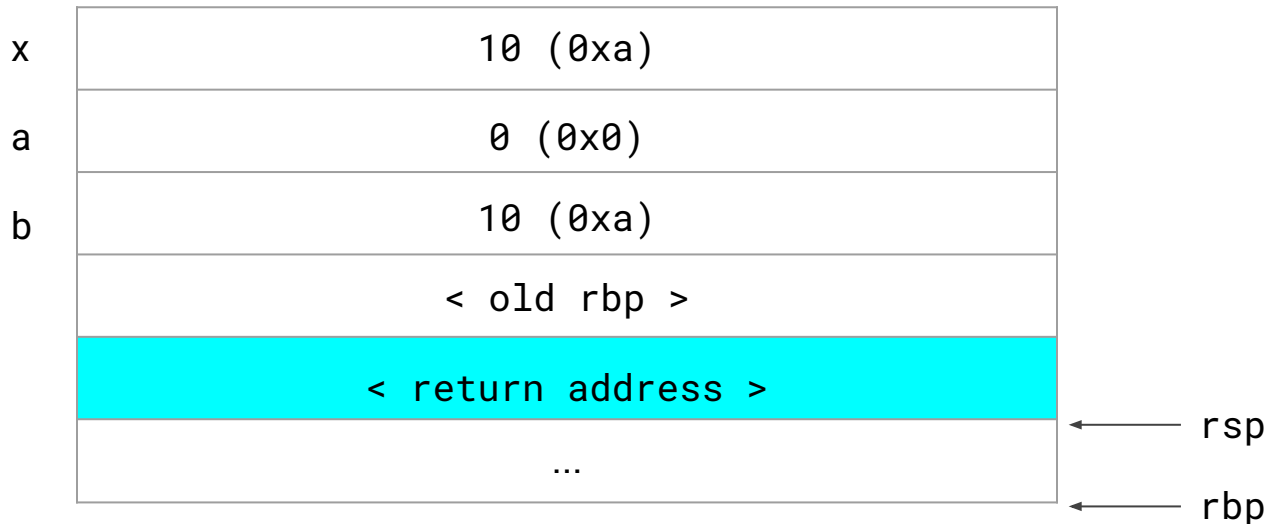


Example: function return

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

rip is set
to ret.
address

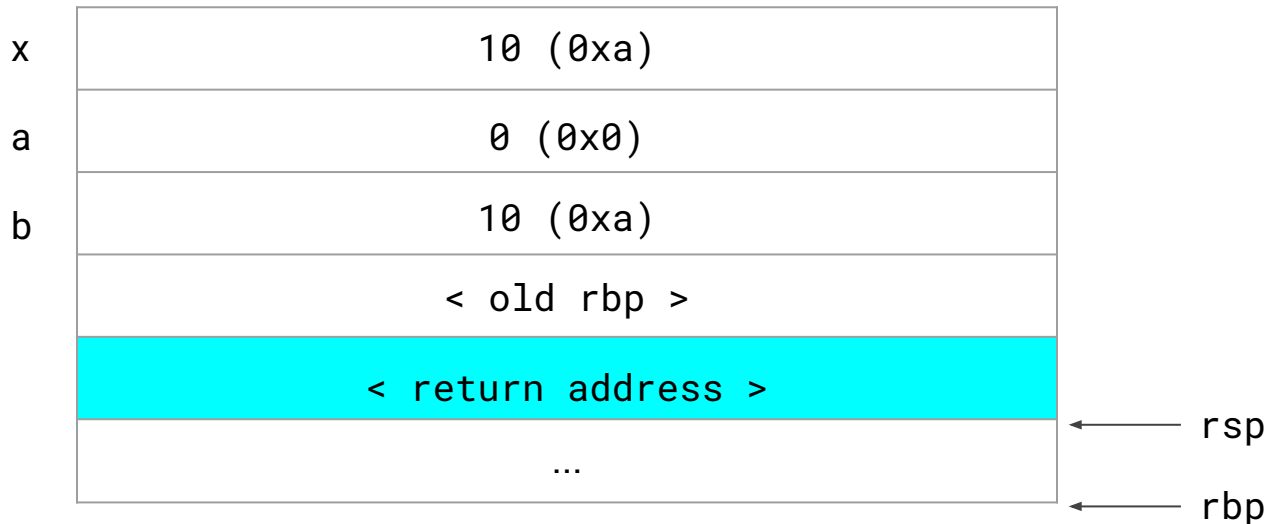
```
mov     rax, DWORD PTR [rbp-0x8]  
leave  
ret
```



Example: function return

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

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



Reading machine code

Disassembling with objdump

Simple example program count.c:

```
#include <stdio.h>
```

```
int main()
{
    int i;
    for (i=0; i<10; i++)
        printf("%d ",i);
    printf("\n");
}
```

```
$ gcc count.c -o count
```

```
$ ./count
```

```
0 1 2 3 4 5 6 7 8 9
```

With objdump we can produce the assembly code (-d) and display sections (-s) in Intel syntax (-M intel)

```
$ objdump -M intel -ds count > count.s
```

Assembly of count.c

0000000000000068a <main>:

68a:
68b:
68e:
692:
699:
...

55
48 89 e5
48 83 ec 10
c7 45 fc 00 00 00 00
eb 1a
...

push rbp
mov rbp, rsp
sub rsp, 0x10
mov **DWORD PTR** [rbp-0x4], 0x0
jmp 6b5 <main+0x2b>
...

Addresses
(can be
relocated)

The actual **machine code**
(as bytes). Commands
have **different lengths!**

Assembly x86-64
Intel syntax

Assembly of count.c

000000000000068a <main>:

68a: 55	push	rbp
68b: 48 89 e5	mov	rbp, rsp
68e: 48 83 ec 10	sub	rsp, 0x10
692: c7 45 fc 00 00 00 00	mov	DWORD PTR [rbp-0x4], 0x0
699: eb 1a	jmp	6b5 <main+0x2b>
69b: 8b 45 fc	mov	eax, DWORD PTR [rbp-0x4]
69e: 89 c6	mov	esi, eax
6a0: 48 8d 3d ad 00 00 00	lea	rdi, [rip+0xad] # 754 ...
6a7: b8 00 00 00 00	mov	eax, 0x0
6ac: e8 af fe ff ff	call	560 <printf@plt>
6b1: 83 45 fc 01	add	DWORD PTR [rbp-0x4], 0x1
6b5: 83 7d fc 09	cmp	DWORD PTR [rbp-0x4], 0x9
6b9: 7e e0	jle	69b <main+0x11>
6bb: bf 0a 00 00 00	mov	edi, 0xa
6c0: e8 8b fe ff ff	call	550 <putchar@plt>
6c5: b8 00 00 00 00	mov	eax, 0x0
6ca: c9	leave	
6cb: c3	ret	

```
#include <stdio.h>
```

```
int main()
{
    int i;
    for (i=0; i<10; i++)
        printf("%d ", i);
    printf("\n");
}
```

Assembly of count.c

0000000000000068a <main>:

68a: 55	push	rbp
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#include <stdio.h>
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int main()
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```

Assembly of count.c

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0000000000000068a <main>:
68a: 55                push    rbp
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69b: 8b 45 fc          mov     eax, DWORD PTR [rbp-0x4]
69e: 89 c6            mov     esi, eax
6a0: 48 8d 3d ad 00 00 00 lea     rdi, [rip+0xad]    # 754 ...
6a7: b8 00 00 00 00    mov     eax, 0x0
6ac: e8 af fe ff ff    call    560 <printf@plt>
6b1: 83 45 fc 01       add     DWORD PTR [rbp-0x4], 0x1
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6b9: 7e e0            jle     69b <main+0x11>
6bb: bf 0a 00 00 00    mov     edi, 0xa
6c0: e8 8b fe ff ff    call    550 <putchar@plt>
6c5: b8 00 00 00 00    mov     eax, 0x0
6ca: c9              leave   eax
6cb: c3              ret
```

```
#include <stdio.h>

int main()
{
    int i;
    for (i=0; i<10; i++)
        printf("%d ", i);
    printf("\n");
}
```

NOTE: we replace **DWORD PTR [rbp-0x4]** with **i** to improve readability

Assembly of count.c

000000000000068a <main>:

```
68a: 55                push    rbp
68b: 48 89 e5          mov     rbp, rsp
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69e: 89 c6            mov     esi, eax
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6b9: 7e e0            jle     69b <main+0x11>
6bb: bf 0a 00 00 00    mov     edi, 0xa
6c0: e8 8b fe ff ff    call    550 <putchar@plt>
6c5: b8 00 00 00 00    mov     eax, 0x0
6ca: c9              leave   rbp
6cb: c3              ret
```

```
#include <stdio.h>
```

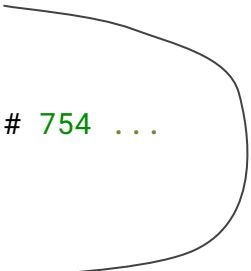
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int main()
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NOTE: we replace **DWORD PTR** [rbp-0x4] with **i** to improve readability

Assembly of count.c

000000000000068a <main>:

68a: 55	push	rbp
68b: 48 89 e5	mov	rbp, rsp
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6b5: 83 7d fc 09	cmp	i, 0x9
6b9: 7e e0	jle	69b <main+0x11>
6bb: bf 0a 00 00 00	mov	edi, 0xa
6c0: e8 8b fe ff ff	call	550 <putchar@plt>
6c5: b8 00 00 00 00	mov	eax, 0x0
6ca: c9	leave	
6cb: c3	ret	



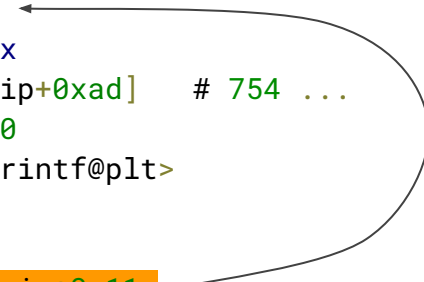
```
#include <stdio.h>
```

```
int main()
{
    int i;
    for (i=0; i<10; i++)
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    printf("\n");
}
```

Assembly of count.c

000000000000068a <main>:

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68e: 48 83 ec 10	sub	rsp, 0x10
692: c7 45 fc 00 00 00 00	mov	i, 0x0
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69b: 8b 45 fc	mov	eax, i
69e: 89 c6	mov	esi, eax
6a0: 48 8d 3d ad 00 00 00	lea	rdi, [rip+0xad] # 754 ...
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6ac: e8 af fe ff ff	call	560 <printf@plt>
6b1: 83 45 fc 01	add	i, 0x1
6b5: 83 7d fc 09	cmp	i, 0x9
6b9: 7e e0	jle	69b <main+0x11>
6bb: bf 0a 00 00 00	mov	edi, 0xa
6c0: e8 8b fe ff ff	call	550 <putchar@plt>
6c5: b8 00 00 00 00	mov	eax, 0x0
6ca: c9	leave	
6cb: c3	ret	



```
#include <stdio.h>
```

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{
    int i;
    for (i=0; i<10; i++)
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Assembly of count.c

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68a: 55                push    rbp
68b: 48 89 e5          mov     rbp, rsp
68e: 48 83 ec 10       sub     rsp, 0x10
692: c7 45 fc 00 00 00 00 mov     i, 0x0
699: eb 1a            jmp     6b5 <main+0x2b>
69b: 8b 45 fc          mov     eax, i
69e: 89 c6            mov     esi, eax          # 2nd param ← i
6a0: 48 8d 3d ad 00 00 00 lea     rdi, [rip+0xad]    # 1st param addr.
6a7: b8 00 00 00 00    mov     eax, 0x0
6ac: e8 af fe ff ff    call    560 <printf@plt>
6b1: 83 45 fc 01       add     i, 0x1
6b5: 83 7d fc 09       cmp     i, 0x9
6b9: 7e e0            jle     69b <main+0x11>
6bb: bf 0a 00 00 00    mov     edi, 0xa
6c0: e8 8b fe ff ff    call    550 <putchar@plt>
6c5: b8 00 00 00 00    mov     eax, 0x0
6ca: c9              leave
6cb: c3              ret
```

```
#include <stdio.h>
```

```
int main()
{
    int i;
    for (i=0; i<10; i++)
        printf("%d ", i);
    printf("\n");
}
```

Search in the data section

```
6a0: 48 8d 3d ad 00 00 00 lea    rdi,[rip+0xad]    # 1st param addr.  
6a7: b8 00 00 00 00      mov    eax,0x0
```

```
>>> hex(0x6a7 + 0xad)      ← in python  
'0x754'
```

We search in the assembly file an address close to 0x754:

contents of section .rodata:

```
0750 01000200 25642000          ....%d .
```

address 0x754 contains bytes 0x25 0x64 0x20 0x00 ⇒ the string "%d "

```
>>> b'\x25\x64\x20'      ← in python  
b'%d '
```

Assembly of count.c

000000000000068a <main>:

```
68a: 55                push    rbp
68b: 48 89 e5          mov     rbp, rsp
68e: 48 83 ec 10       sub     rsp, 0x10
692: c7 45 fc 00 00 00 00 mov     i, 0x0
699: eb 1a            jmp     6b5 <main+0x2b>
69b: 8b 45 fc          mov     eax, i
69e: 89 c6            mov     esi, eax          # 2nd param ← i
6a0: 48 8d 3d ad 00 00 00 lea     rdi, [rip+0xad]    # 1st param ← "%d "
6a7: b8 00 00 00 00    mov     eax, 0x0
6ac: e8 af fe ff ff    call    560 <printf@plt>
6b1: 83 45 fc 01       add     i, 0x1
6b5: 83 7d fc 09       cmp     i, 0x9
6b9: 7e e0            jle     69b <main+0x11>
6bb: bf 0a 00 00 00    mov     edi, 0xa
6c0: e8 8b fe ff ff    call    550 <putchar@plt>
6c5: b8 00 00 00 00    mov     eax, 0x0
6ca: c9              leave
6cb: cb              ret
```

```
#include <stdio.h>
```

```
int main()
{
    int i;
    for (i=0; i<10; i++)
        printf("%d ", i);
    printf("\n");
}
```

Assembly of count.c

000000000000068a <main>:

```
68a: 55                push    rbp
68b: 48 89 e5          mov     rbp, rsp
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692: c7 45 fc 00 00 00 00 mov     i, 0x0
699: eb 1a            jmp     6b5 <main+0x2b>
69b: 8b 45 fc          mov     eax, i
69e: 89 c6            mov     esi, eax           # 2nd param ← i
6a0: 48 8d 3d ad 00 00 00 lea     rdi, [rip+0xad]    # 1st param ← "%d "
6a7: b8 00 00 00 00    mov     eax, 0x0
6ac: e8 af fe ff ff    call    560 <printf@plt>
6b1: 83 45 fc 01       add     i, 0x1
6b5: 83 7d fc 09       cmp     i, 0x9
6b9: 7e e0            jle     69b <main+0x11>
6bb: bf 0a 00 00 00    mov     edi, 0xa
6c0: e8 8b fe ff ff    call    550 <putchar@plt>
6c5: b8 00 00 00 00    mov     eax, 0x0
6ca: c9              leave
6cb: cb              ret
```

```
#include <stdio.h>
```

```
int main()
{
    int i;
    for (i=0; i<10; i++)
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Assembly of count.c

000000000000068a <main>:

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68a: 55                push    rbp
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6bb: bf 0a 00 00 00    mov     edi, 0xa
6c0: e8 8b fe ff ff    call    550 <putchar@plt>
6c5: b8 00 00 00 00    mov     eax, 0x0
6ca: c9              leave
6cb: cb              ret
```

```
#include <stdio.h>
```

```
int main()
{
    int i;
    for (i=0; i<10; i++)
        printf("%d ", i);
    printf("\n");
}
```

Assembly of count.c

000000000000068a <main>:

```
68a: 55                push    rbp
68b: 48 89 e5          mov     rbp, rsp
68e: 48 83 ec 10       sub     rsp, 0x10
692: c7 45 fc 00 00 00 mov     i, 0x0
699: eb 1a            jmp     6b5 <main+0x2b>
69b: 8b 45 fc          mov     eax, i
69e: 89 c6            mov     esi, eax           # 2nd param ← i
6a0: 48 8d 3d ad 00 00 lea     rdi, [rip+0xad]    # 1st param ← "%d "
6a7: b8 00 00 00 00   mov     eax, 0x0
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6b1: 83 45 fc 01       add     i, 0x1
6b5: 83 7d fc 09       cmp     i, 0x9
6b9: 7e e0            jle     69b <main+0x11>
6bb: bf 0a 00 00 00   mov     edi, 0xa
6c0: e8 8b fe ff ff   call    550 <putchar@plt>
6c5: b8 00 00 00 00   mov     eax, 0x0
6ca: c9              leave
6cb: cb              ret
```

```
#include <stdio.h>
```

```
int main()
{
    int i;
    for (i=0; i<10; i++)
        printf("%d ", i);
    printf("\n");
}
```

NOTE: `printf` is implemented with `putchar`, `0xa` is `\n`

Assembly of count.c

000000000000068a <main>:

```
68a: 55                push    rbp
68b: 48 89 e5          mov     rbp, rsp
68e: 48 83 ec 10       sub     rsp, 0x10
692: c7 45 fc 00 00 00 00 mov     i, 0x0
699: eb 1a            jmp     6b5 <main+0x2b>
69b: 8b 45 fc          mov     eax, i
69e: 89 c6            mov     esi, eax           # 2nd param ← i
6a0: 48 8d 3d ad 00 00 00 lea     rdi, [rip+0xad]    # 1st param ← "%d "
6a7: b8 00 00 00 00    mov     eax, 0x0
6ac: e8 af fe ff ff    call    560 <printf@plt>
6b1: 83 45 fc 01       add     i, 0x1
6b5: 83 7d fc 09       cmp     i, 0x9
6b9: 7e e0            jle     69b <main+0x11>
6bb: bf 0a 00 00 00    mov     edi, 0xa
6c0: e8 8b fe ff ff    call    550 <putchar@plt>
6c5: b8 00 00 00 00    mov     eax, 0x0           # returns 0
6ca: c9              leave
6cb: cb              ret
```

#include <stdio.h>

```
int main()
{
    int i;
    for (i=0; i<10; i++)
        printf("%d ", i);
    printf("\n");
}
```

Patching executables

hexdump and back: xxd

Executables are binary files and can be edited using **specific editors** (es. `hexedit`) or standard editors that also support binary files (es. `sublime`)

xxd allows for producing a **text file** with hex code of bytes, so that they can be edited with any editor

xxd is able to **regenerate the binary** file from the modified hexdump

Example:

```
$ xxd -g 1 count > count.txt
```

Option `-g 1` writes distinct bytes

We edit and modify `count.txt` and we generate a new binary `count2` with option `-r`

```
$ xxd -r count.txt > count2
$ chmod +x count2 # executable
$ ./count2
```

Exercises

Exercise 1: change the branch. Modify the /home/rookie/Assembly/count executable file so that the loop ends at 8 instead of 9

Hint: try to change `jle` into `j1`, this [summary of x86 opcodes](#) will help you!

Exercise 2: change the value. Modify the /home/rookie/Assembly/count executable file so that it steps of 2 instead of 1 (only prints even values)

Hint: In this case you need to change data

Exercise 3: skip a branch. Modify the /home/rookie/Assembly/checkPassword so that it skips the password check

Hint: nop is your friend! (opcode 0x90)