x86 Crash Course

With a focus on Linux and a glance to x86_64

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Based on material from Mario Polino, Armando Bellante and Lorenzo Binosi

The x86 Architecture

Instruction Set Architecture (ISA)

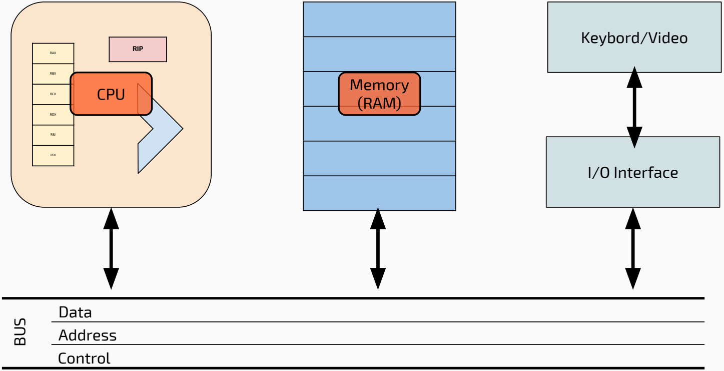
- “Logical” specification of a computer architecture
- Concerned with programming concepts
  - instructions, registers, interrupts, memory architecture, . . .
- May differ (widely) from the actual microarchitecture
- Examples:
  - x86 (IA-32 and x86_64)
  - ARM (mobile devices)
  - MIPS (embedded devices, e.g., consumer routers)
  - AVR, SPARC, Power, RISC V, . . .

The x86 ISA

- Born in 1978, 16-bit ISA (Intel 8086)
- Evolved to a 32-bit ISA (1985, Intel 80386)
- Evolved to a 64-bit ISA (2003, AMD Opteron)
- CISC design (e.g., string operations)
- Many legacy features (e.g, segmentation)
- We'll see the basics of the "core" ISA
    - There is also the floating point unit, processor-specific features, and extensions such as SIMD (MMX, SSE, SSE2) with their own instructions and registers[1]

[1] Complete reference: Intel Software Developer's Manual, about 5,000 pages (`https://software.intel.com/en-us/articles/intel-sdm`)

Von Neumann Architecture

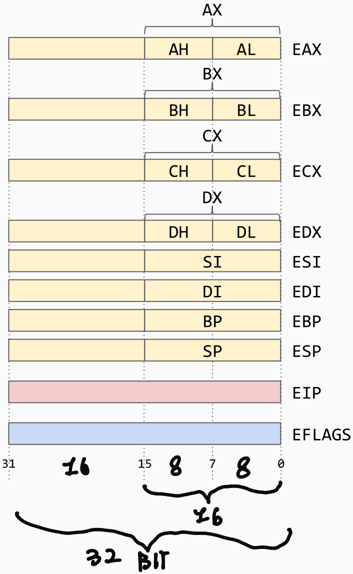


Memory

EACH CELL HAS A UNIQUE ADDRESS
IDENTIFIED AS AN EXADECIMAL NUMBER

	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
0x8040204...	00	01	02	03	04	05	06	07	08	09	0A	0B	0C	0D	0E	0F
0x8040203...	E8	FF	FF	FF	E0	FF	FF	FF	D8	FF	FF	FF	D0	FF	FF	FF
0x8040202...	50	20	40	80	60	20	40	80	70	20	40	80	80	20	40	80
0x8040201...	48	65	6C	6C	6F	20	77	6F	72	6C	64	00	00	00	00	00
0x8040200...	’H’	’e’	’l’	’l’	’o’	’ ’	’w’	’o’	’r’	’l’	’d’	00	00	00	00	00

IA-32: Registers



HYPOTETICALLY USED FOR ANY OPERATION

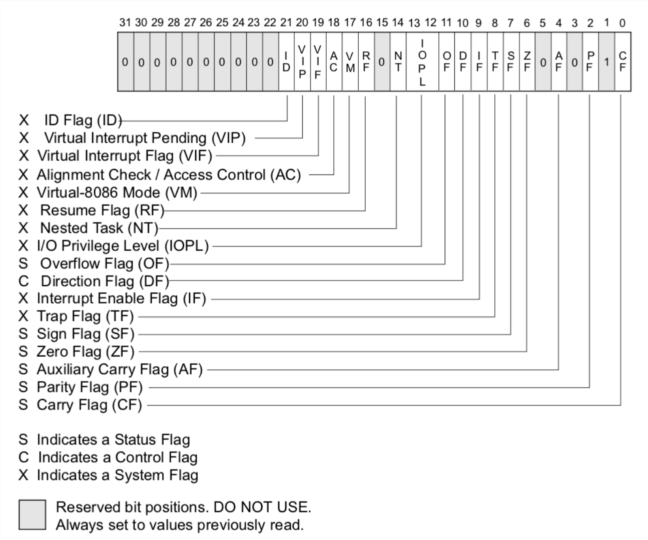
- General-purpose registers
  - EAX, EBX, ECX, EDX
  - ESI, EDI (source and destination index for string operations)
  - EBP (base pointer)
  - ESP (stack pointer)
- Instruction pointer: EIP
  - No explicit access
  - Modified by jmp, call, ret
  - Read through the stack (saved IP)
- Program status and control: EFLAGS
- (segment registers)

"SPECIAL PURPOSE"

IA-32: `EFLAGS` register

- 32-bits register, boolean flags
- **Program status**: overflow, sign, zero, auxiliary carry (BCD), parity, carry
  - Indicate the result of arithmetic instructions
  - Extremely important for control flow
- **Program control**: direction flag
  - controls string instructions (auto-increment or auto-decrement)
- **System**: control operating-system operations

IA-32: EFLAGS register



31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	0	0	0	0	0	0	0	ID	VIP	VIF	AC	VM	RF	0	NT	IOPL		OF	DF	IF	TF	SF	ZF	0	AF	0	PF	1	CF

X ID Flag (ID)
X Virtual Interrupt Pending (VIP)
X Virtual Interrupt Flag (VIF)
X Alignment Check / Access Control (AC)
X Virtual-8086 Mode (VM)
X Resume Flag (RF)
X Nested Task (NT)
X I/O Privilege Level (IOPL)
S Overflow Flag (OF)
C Direction Flag (DF)
X Interrupt Enable Flag (IF)
X Trap Flag (TF)
S Sign Flag (SF)
S Zero Flag (ZF)
S Auxiliary Carry Flag (AF)
S Parity Flag (PF)
S Carry Flag (CF)

S Indicates a Status Flag
C Indicates a Control Flag
X Indicates a System Flag

▨ Reserved bit positions. DO NOT USE.
Always set to values previously read.

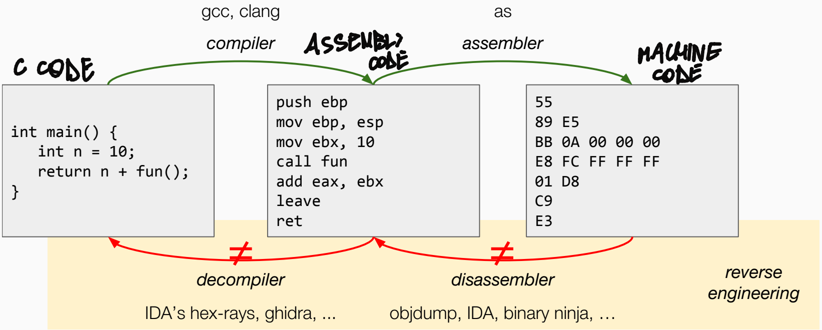
Fundamental data types

4 MAIN DIMENSIONS USED
TO ADDRESS MEMORY

byte	8 bits
word	2 bytes
dword	Doubleword, 4 bytes (32 bits)
qword	Quadword, 8 bytes (64 bits)

Assembly and Machine Code

Assembly language: specific to each ISA, mapped to binary code



gcc, clang

compiler

as

assembler

C CODE

```
int main() {
   int n = 10;
   return n + fun();
}
```

ASSEMBLY CODE

```
push ebp
mov ebp, esp
mov ebx, 10
call fun
add eax, ebx
leave
ret
```

MACHINE CODE

```
55
89 E5
BB 0A 00 00 00
E8 FC FF FF FF
01 D8
C9
E3
```

≠ *decompiler*

IDA's hex-rays, ghidra, ...

≠ *disassembler*

objdump, IDA, binary ninja, ...

reverse engineering

For simplicity, we don't deal with the *linking* process.

Assembly: Syntax

Two main syntaxes:

- **Intel**: default in most Windows programs (e.g., IDA)
- **AT&T**: default in most UNIX tools (e.g., `gdb`, `objdump`)

Beware: The order of the operands is **different**

We will use the Intel syntax

Assembly: Syntax

move the value 0 to EAX

Intel	AT&T
`mov eax, 0h`	`movl $0x0,%eax`

"0 AS HEXADECIMAL"

move the value 0 to the address contained in EBX+4

Intel	AT&T
`mov [ebx+4h],0h`	`movl $0x0,0x4(%ebx)`

x86: data movement

Examples

Immediate to register:

`mov eax, 4h`	EAX = 4

Register to register:

`mov eax, ebx`	EAX = EBX

Memory to register (and register to memory):

`mov eax, [ebx]`	EAX = *EBX
`mov eax, [ebx + 4h]`	EAX = *(EBC + 4)
`mov eax, [edx + ebx*4 + 8]`	EAX = *(EDX + EBX * 4 + 8)

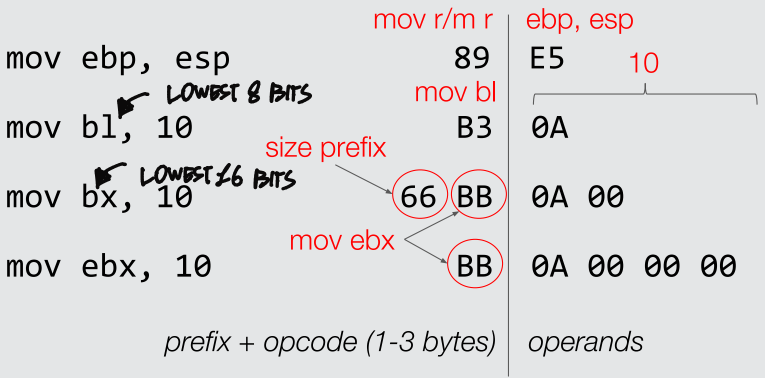
Note: memory to memory is an **invalid** combination[2]

[2] Except in some instructions, such as `movs` (move from string to string).

x86 Assembly and Machine Code

Instruction = opcode + operand

Example



```
mov ebp, esp      89      E5
mov bl, 10        B3      0A
mov bx, 10     66 BB      0A 00
mov ebx, 10       BB      0A 00 00 00
```

prefix + opcode (1-3 bytes) | *operands*

Beware: in x86, instructions have **variable length**.

Basic instructions

- **Data Transfer**: `mov`, `push`, `pop`, `xchg`, `lea`
- **Integer Arithmetic**: `add`, `sub`, `mul`, `imul`, `div`, `idiv`, `inc`, `dec`
- **Logical**: `and`, `or`, `not`, `xor`
- **Control Transfer**: `jmp`, `jne`, `call`, `ret`
- and lots more. . .

Data Transfer: `mov`

- `mov` **destination**, **source**

  source: immediate, register, memory location

  destination: register or memory location
- Basic load/store operations
  - Register to register, register to memory, immediate to register, immediate to memory
  - Memory to memory is INVALID (in every instruction)

Examples

`MOV eax, ebx`	`MOV eax, FFFFFFFFh`	`MOV ax, bx`
`MOV [eax],ecx`	`MOV [eax],[ecx]` NO!!!	`MOV al, FFh`

Integer Arithmetics: `add` and `sub`

`add` **destination**, **source**	`sub` **destination**, **source**
dest ← dest + source	dest ← dest − source

- Addressing:

  source: immediate, register, memory location

  destination: register or memory location

  (the destination has to be at least as large as the source)
- Negate a value: `neg` [op]
- Bitwise operations: `and`, `or`, `xor`, `not` work similarly

Examples

`add esp, 44h`	`add edx, cx`	`add al, dh`
`sub esp, 33h`	`sub eax, ebx`	`sub [eax], 1h`

Integer Arithmetics: unsigned multiply (`mul`)

- `mul` **source** SINGLE OPERAND

  source: register or memory location
- dest ← implied_op × source
- **Implied operands** according to the size of **source**
  - First operand: `AL`, `AX`, or `EAX`
  - Destination: `AX`, `DX:AX`, `EDX:EAX` (double the size of **source**)
- Signed multiply: `imul`

EXAMPLE: 8 bit · 8 bit
→ 16 bits
⇓
WE USE 2
DIFFERENT
REGISTERS TO
STORE THE RESULT

Example

- `mul ebx`: `EDX:EAX ← EAX * EBX`
  - most significant bits of the result in `EDX`
  - least significant bits of the result in `EAX`
- `mul cx`: `DX:AX ← AX * CX`
- `mul cl`: `AX ← AL * CL`

Integer Arithmetics: unsigned divide (`div`)

- `div` **source**

  source: register or a memory location
- Computes quotient and remainder
- Implied operand: `EDX:EAX` (according to the size of **source**)
- Signed divide: `idiv`

LOWEST HIGHEST

32 bits

Examples

- `div ebx` (4 bytes)
  - `EAX ← EDX:EAX / EBX`
  - `EDX ← EDX:EAX % EBX`
- `div bx` (2 bytes)
  - `AX ← DX:AX / BX     DX = DX:AX % BX`
- `div bl` (1 byte)
  - `AL ← AX / BX     AH = AX % BX`

Integer Arithmetics: `cmp` and `test`

`cmp` **op1**, **op2**	`test` **op1**, **op2**
Computes op1 − op2	Computes op1 & op2

RESULT: WHICH ONE IS HIGHER (OR =)

- Sets the flags (`ZF`,`CF`, `OF`, . . .)
- Discards the result

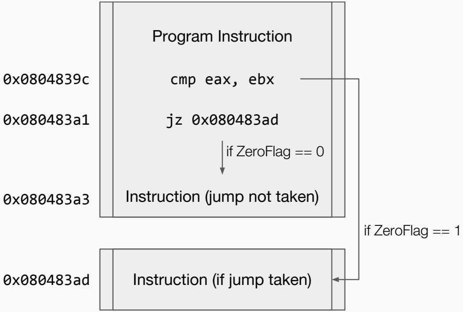
Examples

`cmp eax, ebx`	`cmp eax, 44BBCCDDh`	`cmp al, dh`
`cmp al, 44h`	`cmp ax,FFFFh`	`cmp [eax],4h`

Control-Flow Instructions: conditional jumps

`j<cc>` **address** or **offset**

Jump to **address** if and only if a certain condition is verified



`<cc>`: condition

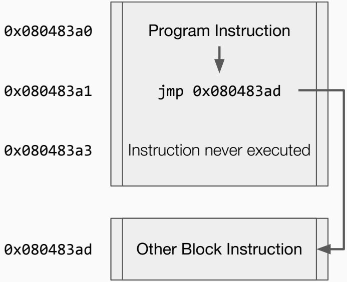
- O,NO,S,NS,E,Z,NE, . . .
- based on one or more status flags of `EFLAGS`

Examples:

- `jz` = jump if zero
- `jg` = jump if greater than
- `jlt` = jump if less than

Reference: `http://www.unixwiz.net/techtips/x86-jumps.html`

Control-Flow Instructions: unconditional jump `jmp`



- `jmp` **address** or **offset**
- Unconditional jump: just set the `EIP` to **address**
- Can be also *relative*: increment or decrement `EIP` by an offset

Exercise 1

Translate the following C code in assembly x86. Assume EBX ← b, ECX ← c. Finally, a goes in EAX.

```c
if (c == 0)
    a = b;
else
    a = -b;
```

Solution

```
    mov edx, 0
    cmp ecx, edx
    jne ELSE
    mov eax, ebx
    jmp ENDIF
ELSE:
    mov eax, 0
    sub eax, ebx
ENDIF:
    nop
    ...
```

Exercise 2

Translate the following C code in assembly x86. The variable a goes in EAX.

```c
a = 0;
for(i = 0; i < 10; i++)
    a += i;
```

Solution

```
    mov eax, 0
    mov ebx, 0
    mov ecx, 10
LOOP:
    cmp ebx, ecx
    jge END
    add eax, ebx
    inc ebx
    jmp LOOP
END:
    nop
    ...
```

A very simple example (what does it do?)

Assume that the input is in registers: ECX and EDX; output: EAX

```
    mov eax, ecx
    mov ebx, edx
    cmp ebx, 0
    jz LABEL
LOOP:
    cmp ebx, 1
    jle RET
    mul ecx
    sub ebx, 1
    jmp LOOP
LABEL:
    mov eax, 1
RET:
    ...
```

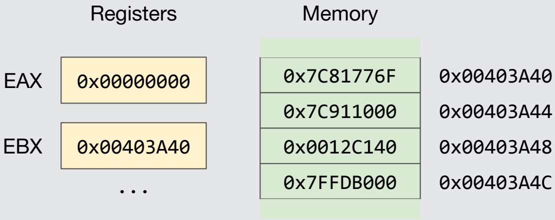
Load effective address (`lea`)

- `lea` **destination**, **source**

  source: memory location

  destination: register
- Like a `mov`, but it is storing the pointer, not the value
- It does NOT access memory

Example



Registers

EAX	0x00000000
EBX	0x00403A40
	...

Memory

0x7C81776F	0x00403A40
0x7C911000	0x00403A44
0x0012C140	0x00403A48
0x7FFDB000	0x00403A4C

`lea eax, [ebx + 8]` → `EAX = 0x00403A48`

N.B.: with `mov eax, [ebx+8]` → `EAX = 0x0012C140`

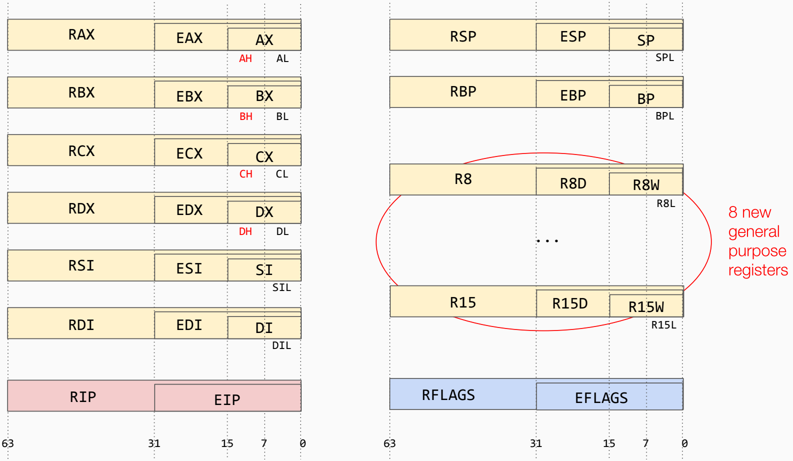
Basic Instructions: `nop`

- `nop` = **No Operation**. Just move to next instruction.
- The opcode is pretty famous and is `0x90`
- Really useful in exploitation (we will see!)

Interrupts and Syscalls

- `int` **value**
  - **value**: software interrupt number to generate (0-255)
  - Every OS has its set of interrupt numbers (e.g., `80h` for Linux system calls)
- `syscall` used for Linux 64-bit
- `sysenter` used by Microsoft Windows

The x86_64 ISA

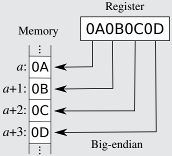


Endianness

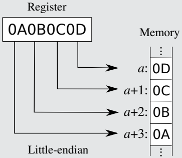
Endianness: convention that specifies in which order the bytes of a data word are lined up sequentially in memory.

Big-endian (left)

Systems in which the *most significant byte* of the word is stored in the *smallest address* given.



Little-endian



Systems in which the *least significant* byte is stored in the *smallest address*.
IA-32 is “little endian”.

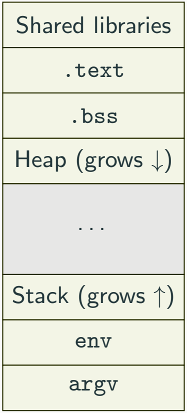
Program Layout and Functions

How an executable is mapped to memory in Linux (ELF)

Executable	Description
.plt	This section holds stubs which are responsible of external functions linking.
.text	This section holds the "text," or executable instructions, of a program.
.rodata	This section holds read-only data that contribute to the program's memory image
.data	This section holds initialized data that contribute to the program's memory image
.bss	This section holds uninitialized data that contributes to the program's memory image. By definition, the system initializes the data with zeros when the program begins to run.
.debug	This section holds information symbolic debugging.
.init	This section holds executable instructions that contribute to the process initialization code. That is, when a program starts to run, the system arranges to execute the code in this section before calling the main program entry point (called main for C programs).
.got	This section holds the global offset table.

Simplified program memory layout

Low addresses (`0x80000000`)



Shared libraries

`.text`

`.bss`

Heap (grows ↓)

. . .

Stack (grows ↑)

`env`

`argv`

High addresses (`0xbfffffff`)

The Stack

- LIFO (last in first out) data structure
- Used to manage functions
  - local variables
  - return addresses
  - ...
- Handled through the register ESP (stack pointer) IT ALWAYS POINTS AT THE TOP OF THE STACK
- Remember: the stack grows **toward lower addresses** (downward the address space)

Stack Management Instructions: `push`

PUSH: ADD VALUE ON THE TOP OF THE STACK

push **immediate** or **register**

Stores the immediate or register value at the top of the stack and decrements the ESP of the operand size

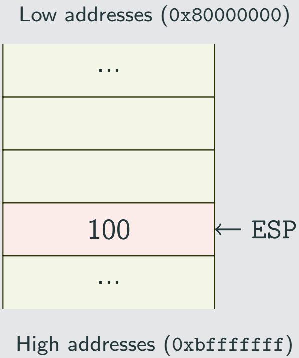
Example

Initial condition: EAX = 30

```
push eax
```

is equivalent to:

```
sub esp, 4
mov DWORD PTR [esp], eax
```



Low addresses (0x80000000)

...
100 ← ESP
...

High addresses (0xbfffffff)

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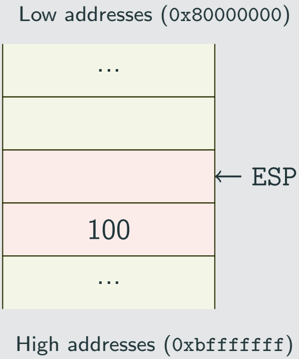


Stack Management Instructions: `push`

`push` **immediate** or **register**

Stores the immediate or register value at the top of the stack and decrements the `ESP` of the operand size

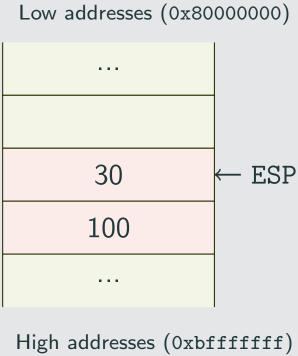
Example

Final condition: `EAX` = 30

```
push eax
```

is equivalent to:

```
sub esp, 4
mov DWORD PTR [esp], eax
```



Low addresses (`0x80000000`)

...

30 ← `ESP`

100

...

High addresses (`0xbfffffff`)

Stack Management Instructions: `pop`

POP: TAKE A VALUE FROM THE STACK AND INCREASE THE STACK POINTER VALUE MOVING IT DOWN AND "DISCARDING THE VALUE"

pop **destination**

Loads to the destination a word off the top of the stack, then it increases ESP of the operand's size.

Example

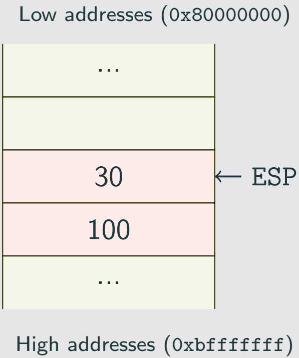
Initial condition: EAX = ???

```
pop eax
```

is equivalent to:

```
mov eax, DWORD PTR [esp]
add esp, 4
```

EVERYTHING ABOVE IS IGNORED



Low addresses (0x80000000)

...

30 ← ESP

100

...

High addresses (0xbfffffff)

Stack Management Instructions: `pop`

`pop` **destination**

Loads to the destination a word off the top of the stack, then it increases `ESP` of the operand's size.

Example

Initial condition: `EAX` = 30

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pop eax
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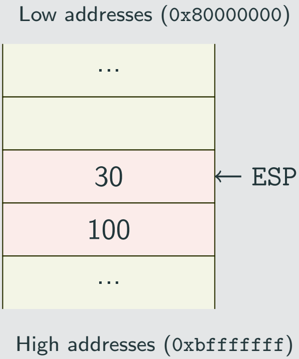

Low addresses (`0x80000000`)

...
30 ← ESP
100
...

High addresses (`0xbfffffff`)

Stack Management Instructions: pop

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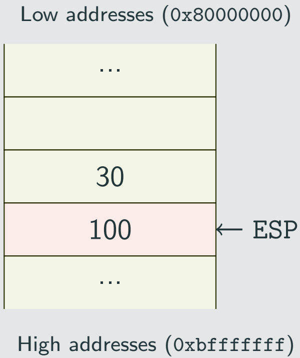


Low addresses (0x80000000)

...

30

100 ← ESP

...

High addresses (0xbfffffff)

Calling a function

Instruction `call`:

- Push to the stack the address of the next instruction
- Move the address of the first instruction of the callee into EIP

"SAFE-TO-TURN" ADDRESS

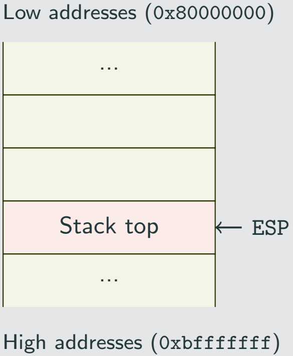
USEFUL FOR KNOWING WHERE TO RESUME AFTER THE FUNCTION'S EXECUTION

Example: Let's call `func`, located at 0x800bff00

Equivalent to:

- `push address(of the instruction after the call!)`
- `jmp func`

(reminder: we can't read or set EIP directly!)



EIP = 0x8001020

Calling a function

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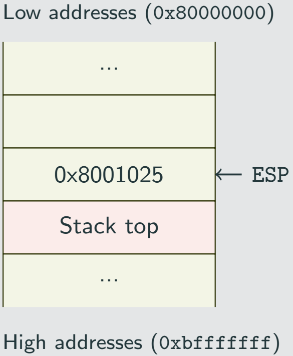

EIP = 0x8001020

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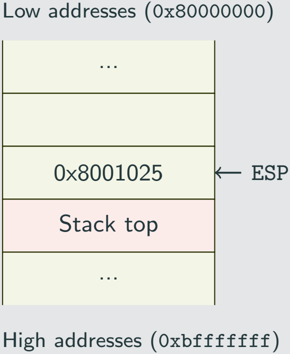


Low addresses (`0x80000000`)

…
0x8001025 ← `ESP`
Stack top
…

High addresses (`0xbfffffff`)

EIP = 0x800bff00

Returning from a function

Instruction `ret`:

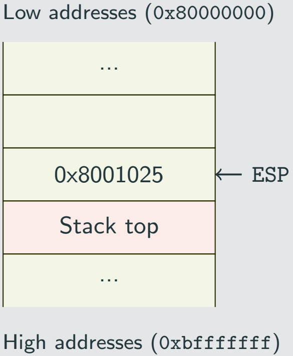
- Restores the return address saved by `call` from the top of the stack

Example: let's return from `func`

Equivalent to:

- `pop eip`

(reminde: we can't read or set `EIP` directly!)



Low addresses (`0x80000000`)

...

0x8001025 ← `ESP`

Stack top

...

High addresses (`0xbfffffff`)

EIP = 0x800bff00

Returning from a function

Instruction `ret`:

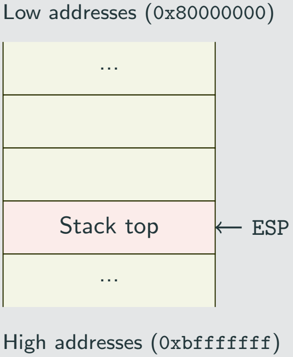
- Restores the return address saved by `call` from the top of the stack

Example: let's return from `func`

Equivalent to:

- `pop eip`

(reminde: we can't read or set `EIP` directly!)



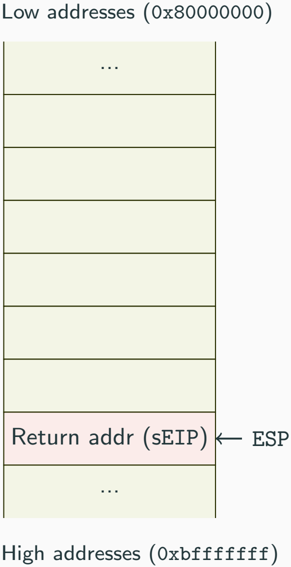
EIP = 0x8001025

Functions and Stack Frames

At the beginning of a function, the function itself must reserve space for its local variables.

```
void foo() {
  int a;
  int b;
  int c;

  b = 0;
}
```

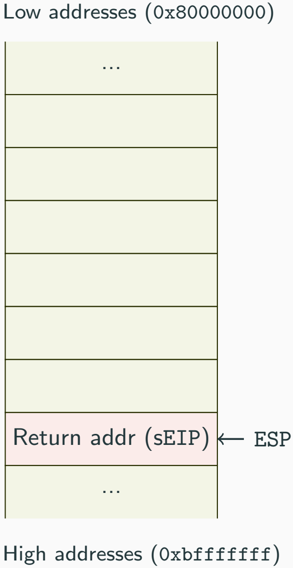
USED TO MAKE SPACE FOR ALL THE LOCAL VARIABLES



Functions and Stack Frames

At the beginning of a function, the function itself must reserve space for its local variables.

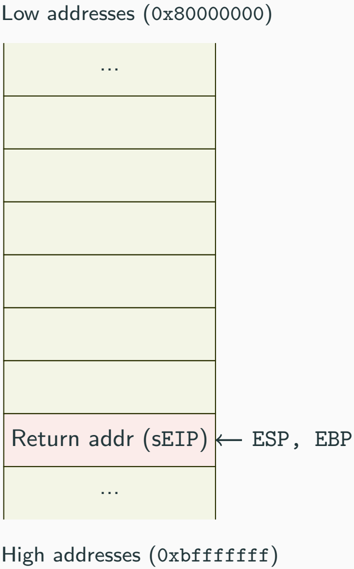
```
FOO:
    mov ebp, esp
    sub esp, 0xc
    mov [ebp - 0x8], 0x0
    add esp, 0xc
    ret
```



Functions and Stack Frames

At the beginning of a function, the function itself must reserve space for its local variables.

```
FOO:
    mov ebp, esp ←
    sub esp, 0xc
    mov [ebp - 0x8], 0x0
    add esp, 0xc
    ret
```



Low addresses (0x80000000)

...

Return addr (sEIP) ⟵ ESP, EBP

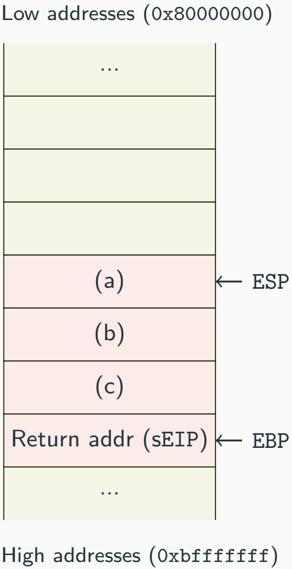
...

High addresses (0xbfffffff)

Functions and Stack Frames

At the beginning of a function, the function itself must reserve space for its local variables.

```
FOO:
    mov ebp, esp
    sub esp, 0xc ←
    mov [ebp - 0x8], 0x0
    add esp, 0xc
    ret
```



Low addresses (0x80000000)

...

(a) ← ESP

(b)

(c)

Return addr (sEIP) ← EBP

...

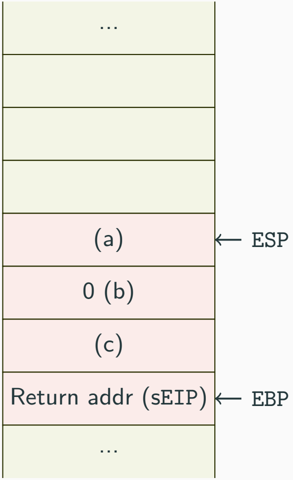
High addresses (0xbfffffff)

Functions and Stack Frames

At the beginning of a function, the function itself must reserve space for its local variables.

```
FOO:
    mov ebp, esp
    sub esp, 0xc
    mov [ebp - 0x8], 0x0 ←
    add esp, 0xc
    ret
```

Low addresses (0x80000000)



...

(a) ← ESP

0 (b)

(c)

Return addr (sEIP) ← EBP

...

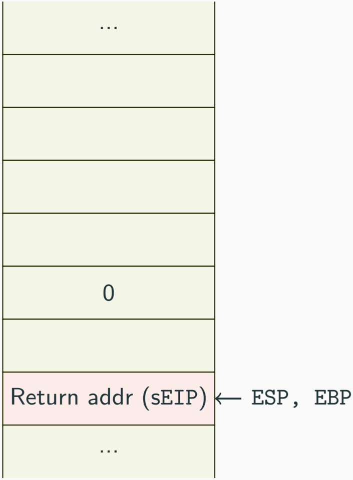
High addresses (0xbfffffff)

Functions and Stack Frames

At the beginning of a function, the function itself must reserve space for its local variables.

```
FOO:
   mov ebp, esp
   sub esp, 0xc
   mov [ebp - 0x8], 0x0
   add esp, 0xc ←
   ret
```

Low addresses (0x80000000)



...

0

Return addr (sEIP) ⟵ ESP, EBP

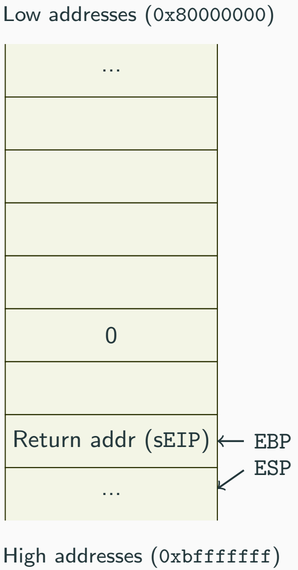
...

High addresses (0xbfffffff)

Functions and Stack Frames

At the beginning of a function, the function itself must reserve space for its local variables.

```
FOO:
    mov ebp, esp
    sub esp, 0xc
    mov [ebp - 0x8], 0x0
    add esp, 0xc
    ret ←
```



Low addresses (0x80000000)

...

0

Return addr (sEIP) ← EBP

ESP

...

High addresses (0xbfffffff)

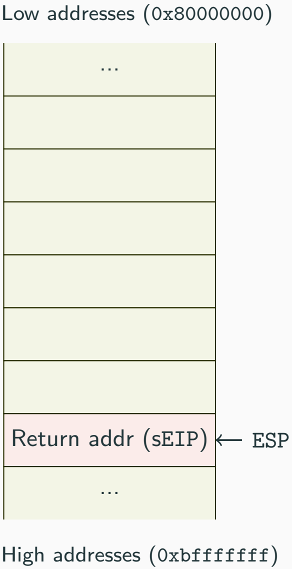
Functions and Stack Frames

That works!!! But what if `foo` calls `bar`.

```c
void foo() {
  int a;
  int b;
  int c;

  bar();
  b = 0;
}

void bar() {
  int d;

  d = 1;
}
```

Functions and Stack Frames

```
FOO:
    mov ebp, esp
    sub esp, 0xc
    call BAR
    mov [ebp - 0x8], 0x0
    add esp, 0xc
    ret

BAR:
    mov ebp, esp
    sub esp, 0x4
    mov [ebp - 0x4], 0x1
    add esp, 0x4
    ret
```



Low addresses (0x80000000)

...

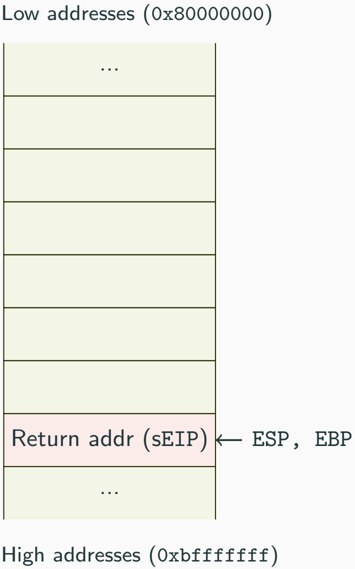
Return addr (sEIP) ⟵ ESP

...

High addresses (0xbfffffff)

Functions and Stack Frames

```
FOO:
    mov ebp, esp ←
    sub esp, 0xc
    call BAR
    mov [ebp - 0x8], 0x0
    add esp, 0xc
    ret

BAR:
    mov ebp, esp
    sub esp, 0x4
    mov [ebp - 0x4], 0x1
    add esp, 0x4
    ret
```



Low addresses (0x80000000)

...

Return addr (sEIP) ← ESP, EBP

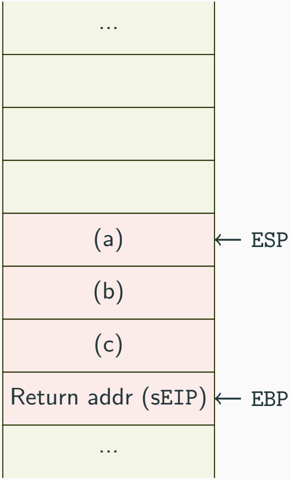
...

High addresses (0xbfffffff)

Functions and Stack Frames

```
FOO:
    mov ebp, esp
    sub esp, 0xc ←
    call BAR
    mov [ebp - 0x8], 0x0
    add esp, 0xc
    ret

BAR:
    mov ebp, esp
    sub esp, 0x4
    mov [ebp - 0x4], 0x1
    add esp, 0x4
    ret
```

Low addresses (0x80000000)

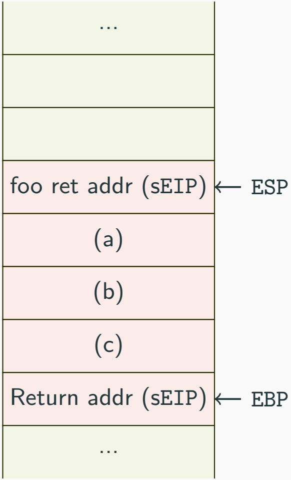


High addresses (0xbfffffff)

Functions and Stack Frames

```
FOO:
    mov ebp, esp
    sub esp, 0xc
    call BAR ←
    mov [ebp - 0x8], 0x0
    add esp, 0xc
    ret

BAR:
    mov ebp, esp
    sub esp, 0x4
    mov [ebp - 0x4], 0x1
    add esp, 0x4
    ret
```

Low addresses (0x80000000)



...

foo ret addr (sEIP) ← ESP

(a)

(b)

(c)

Return addr (sEIP) ← EBP

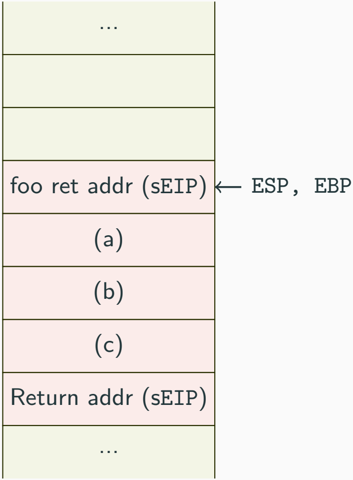
...

High addresses (0xbfffffff)

Functions and Stack Frames

```
FOO:
    mov ebp, esp
    sub esp, 0xc
    call BAR
    mov [ebp - 0x8], 0x0
    add esp, 0xc
    ret

BAR:
    mov ebp, esp ←
    sub esp, 0x4
    mov [ebp - 0x4], 0x1
    add esp, 0x4
    ret
```

Low addresses (0x80000000)



...

foo ret addr (sEIP) ← ESP, EBP

(a)

(b)

(c)

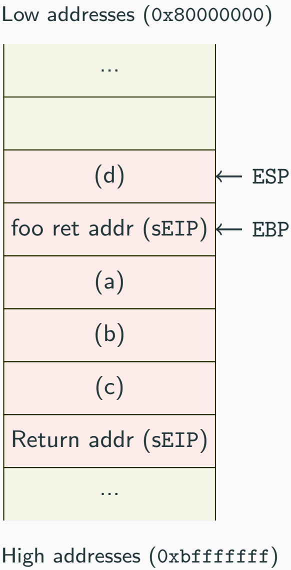
Return addr (sEIP)

...

High addresses (0xbfffffff)

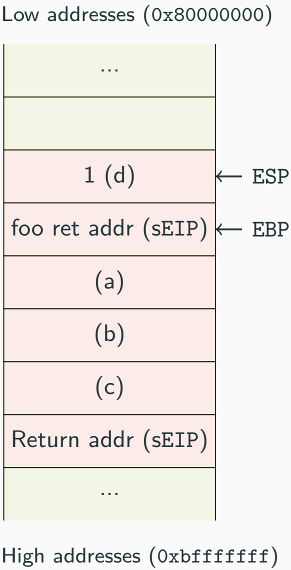
Functions and Stack Frames

```
FOO:
    mov ebp, esp
    sub esp, 0xc
    call BAR
    mov [ebp - 0x8], 0x0
    add esp, 0xc
    ret

BAR:
    mov ebp, esp
    sub esp, 0x4 ←
    mov [ebp - 0x4], 0x1
    add esp, 0x4
    ret
```



Functions and Stack Frames

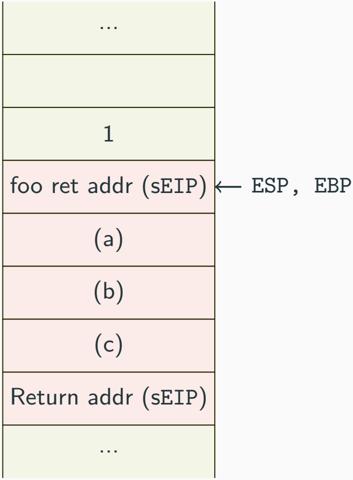
```
FOO:
    mov ebp, esp
    sub esp, 0xc
    call BAR
    mov [ebp - 0x8], 0x0
    add esp, 0xc
    ret

BAR:
    mov ebp, esp
    sub esp, 0x4
    mov [ebp - 0x4], 0x1 ←
    add esp, 0x4
    ret
```



Functions and Stack Frames

```
FOO:
    mov ebp, esp
    sub esp, 0xc
    call BAR
    mov [ebp - 0x8], 0x0
    add esp, 0xc
    ret

BAR:
    mov ebp, esp
    sub esp, 0x4
    mov [ebp - 0x4], 0x1
    add esp, 0x4 ←
    ret
```

Low addresses (0x80000000)



...

1

foo ret addr (sEIP) ← ESP, EBP

(a)

(b)

(c)

Return addr (sEIP)

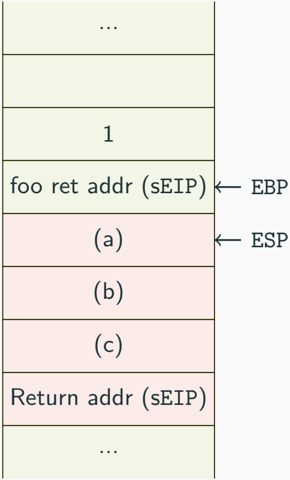
...

High addresses (0xbfffffff)

Functions and Stack Frames

```
FOO:
    mov ebp, esp
    sub esp, 0xc
    call BAR
    mov [ebp - 0x8], 0x0
    add esp, 0xc
    ret

BAR:
    mov ebp, esp
    sub esp, 0x4
    mov [ebp - 0x4], 0x1
    add esp, 0x4
    ret ←
```

Low addresses (0x80000000)



...

1

foo ret addr (sEIP) ← EBP

(a) ← ESP

(b)

(c)

Return addr (sEIP)

...

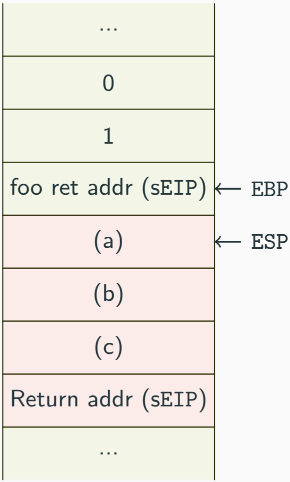
High addresses (0xbfffffff)

Functions and Stack Frames

Wrong memory access!!! EBP changed and we lost the old value!

```
FOO:
    mov ebp, esp
    sub esp, 0xc
    call BAR
    mov [ebp - 0x8], 0x0 ←
    add esp, 0xc
    ret

BAR:
    mov ebp, esp
    sub esp, 0x4
    mov [ebp - 0x4], 0x1
    add esp, 0x4
    ret
```

Low addresses (0x80000000)



...

0

1

foo ret addr (sEIP) ⟵ EBP

(a) ⟵ ESP

(b)

(c)

Return addr (sEIP)

...

High addresses (0xbfffffff)

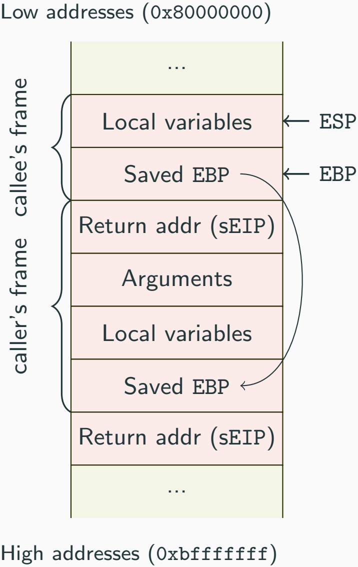
Functions and Stack Frames

Redacted!

```
FOO:
    push ebp
    mov ebp, esp
    sub esp, 0xc
    call BAR
    mov [ebp - 0x8], 0x0
    leave → USED TO STORE THE OLD VALUE OF EBP
    ret

BAR:
    push ebp
    mov ebp, esp
    sub esp, 0x4
    mov [ebp - 0x4], 0x1
    leave
    ret
```

Functions and Stack Frames

- Stack frame = stack area allocated to a function
- EBP register: pointer to the beginning (base) of a function's frame
- At the beginning of a function:
    - Save EBP to stack
    - Set EBP to the address of the function's frame

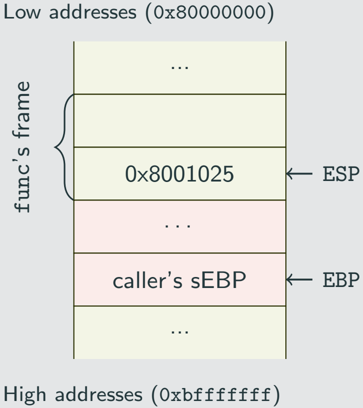


Entering a function

Example: We've just called `func`, located at 0x800bff00

Setup the stack frame

- `push ebp`
- `mov ebp, esp`



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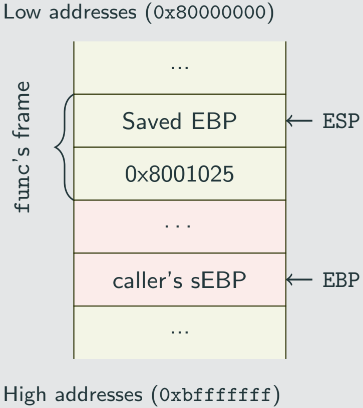
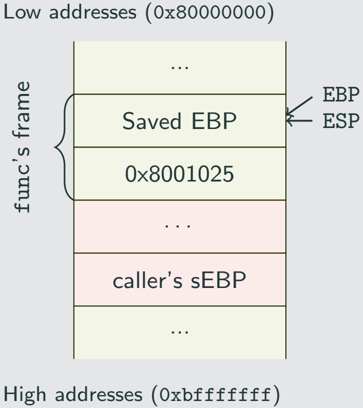


Entering a function

Example: We've just called `func`, located at 0x800bff00

Setup the stack frame

- `push ebp`
- `mov ebp, esp`



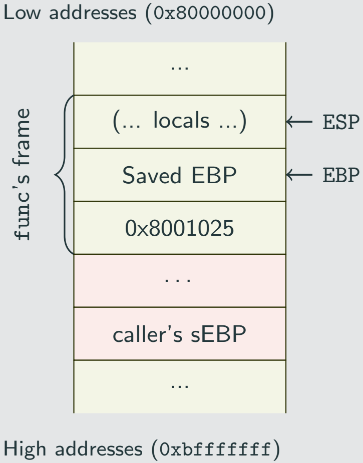
Leaving a function

Instruction `leave`: restores the caller's base pointer

Example: We're about to return from `func`

Equivalent to:

- `mov esp, ebp`
- `pop ebp`



Leaving a function

Instruction `leave`: restores the caller's base pointer

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Equivalent to:

- `mov esp, ebp`
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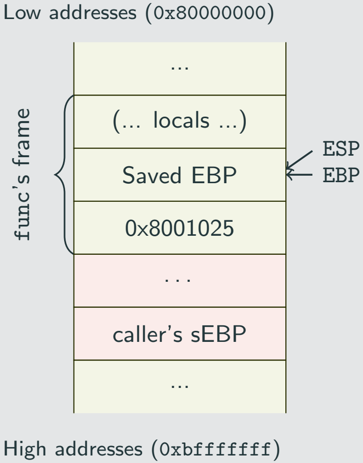


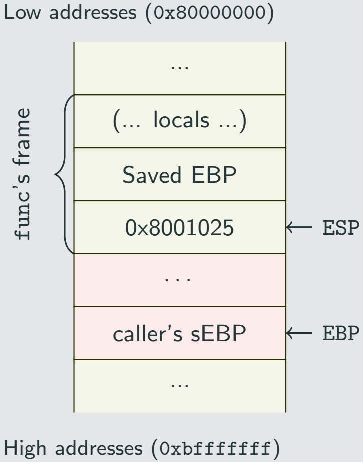
Leaving a function

Instruction `leave`: restores the caller's base pointer

Example: We're about to return from `func`

Equivalent to:

- `mov esp, ebp`
- `pop ebp`



Calling Conventions

DIFFERENT CONVENTIONS BASED
ON SPECIFIC NEEDS

- Defines
  - how to pass parameters (stack, registers or both, and who is responsible to clean them up)
  - how to return values
  - caller-saved or callee-saved registers
- The high-level language, the compiler, the OS, and the target architecture all together "implement" and "agree upon" a certain calling convention
  - it's part of the ABI, the Application Binary Interface

Calling Conventions: `cdecl` (C declaration)

- Default calling convention used by most x86 C compilers
    - Can be forced with the modifier `_cdecl`
- Arguments: passed **through the stack**, right to left order
- Cleanup: the **caller removes** the parameters from the stack *after* the called function completes
- Return: register `EAX`
- Caller-saved registers: `EAX`, `ECX`, `EDX` (other are callee-saved)

cdecl: Example

```c
void demo_cdecl(int a, int b, int c, int z);

//...

demo_cdecl(1, 2, 3, 4); //calling
```

```asm
; ...
push 4 ; push last parameter value
push 3 ; push third parameter value
push 2 ; ...
push 1
call demo_cdecl ; call the subroutine
add esp, 16 ; clean up the stack
```

Calling Conventions: `fastcall` (C declaration)

- Default calling convention used by most x86_64 C compilers
    - Can be forced with the modifier `_fastcall`
- Parameters passed **in registers**: `rdi`, `rsi`, `rdx`, `rcx`, `r8`, `r9`, subsequent ones on the stack (reverse order, caller cleanup)
- Callee-saved registers: `rbx`, `rsp`, `rbp`, `r12`, `r13`, `r14`, and `r15`
- Caller-saved registers (scratch): `rax`, `rdi`, `rsi`, `rdx`, `rcx`, `r8`, `r9`, `r10`, `r11`
- Return value: `rax` (if 128-bit: `rax` and `rdx`)

Linux x86-64 calling convention: Example

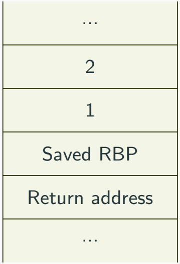
```
main:
  push rbp
  mov rbp, rsp
  sub rsp, 16
  mov DWORD PTR [rbp-4], edi
  mov QWORD PTR [rbp-16], rsi
  mov esi, 2 ; Second parameter
  mov edi, 1 ; First parameter
  call function
  mov esi, eax ; Return value -> first param
  mov edi, OFFSET FLAT:.LC0 ; "The return ...
  mov eax, 0
  call printf
  leave
  ret

function:
  push rbp
  mov rbp, rsp
  mov DWORD PTR [rbp-4], edi
  mov DWORD PTR [rbp-8], esi
  mov edx, DWORD PTR [rbp-4]
  mov eax, DWORD PTR [rbp-8]
  add eax, edx
  pop rbp
  ret
```

```c
int function (int a, int b) {
    return a + b;
}

int main (int argc, char** argv) {
    return printf("The return value is %d\n",
           function(1,2));
}
```

Low addresses


...

2

1

Saved RBP

Return address

...

High addresses

Tooling

Shell for Dummies [3]

important paths	/	#root (first) directory
	~/	#your home directory
	.	#current directory
	..	#parent directory
filesystem utils	pwd	#show current directory
	cd *path*	#change directory to *path*
	ls *path*	#list files in the directory at *path*
	cp *path_src path_dst*	#copy *path_src* to *path_dst, -r if copying directories*
	mv *path_src path_dst*	*#move path_src* to *path_dst*
basic text editor	nano *path/file*	#opens/create *file* in *path* (ctrl+x to exit)
	vim *path/file*	#opens/create *file* in *path* (i to edit; esc, :wq to save and quit)
remote actions	ssh *user@server_addr*	#ssh to *server_addr* as *user*
	scp [*u@s:*]*p_src* [*u@s:*]*p_dst*	#cp to/from remote server

[3] `cmd --help` or `cmd -h` to get the aviable options

Shell for Dummies [4]

file visualization	cat *file*	#print *file* to stdout
	less *file*	#visualize *file* better, q to quit
	hexdump -Cv *file*	#visualize raw bytes
redirections	command > file	#write stdout of command to *file*
	command >> file	#append stdout of command to *file*
	command < file	#use *file* as stdin of command
	cmd1 | cmd2	#stdout of cmd1 as stdin cmd2
argv from command	cmd `cmd2`	#executes cmd2 first and uses the output to eval the next command
	cmd $(cmd2)	
other useful commands	chmod +x *file*	#give exec permission to *file*
	grep *expression*	#search for *expr* in stdin
	python -c 'cmd1;cmd2;...'	#executes python commands

[4] `cmd --help` or `cmd -h` to get the aviable options

objdump

- `man objdump`

  objdump **displays information** about one or more **object files**.
- `-x` all-headers
- `-d` disassemble
- `-M intel` intel syntax (default is AT&T)

Debugging: GDB

- **What is GDB?**
  GDB is GNU Project's Debugger: allows to follow, step by step, at assembler-level granularity, a running program, or what a program was doing right before it crashed.[5]

[5] http://www.gnu.org/software/gdb/

Start, break and navigate the execution with gdb

- Suppose you have an executable binary and want run it
  - **gdb /path/to/executable** loads the binary in gdb
- Now you decide to start the program with two parameters
  - **run 1 ”abc”** passes 1 via `argv[1]` and `"abc"` as `argv[2]`
  - **run ‘printf ”AAAAAAAAAAAA”‘** (with the back ticks) we’re passing the output of the print (very useful when you need to pass non printable characters such as raw bytes)
- Suppose you want to stop the execution at the address of a certain instruction
  - **break *0xDEADBEAF** places a break point at that address
  - **break *main+1** with debugging symbols this can be less painful
  - **catch syscall** block the execution when a syscall happens

Start, break and navigate the execution with gdb

- Now the execution stops at our break point. Here we can do several things
- Examples:
  - **ni** allows to procede instruction per instruction
  - **next 4** moves 4 lines ahead (if you have the line-numbers information in the binary)
  - **si** step into function
  - **finish** run until the end of current function
  - **continue** runs until the next break point (if any)
- To see info about the execution state:
  - **info registers** to inspect the content of the registers
  - **info frame** to see the values of the stack frame related to the function where we are in
  - **info file** print the information about the sections of the binary

Navigate the stack

- Suppose we're stopped somewhere in the code and want to inspect the stack
- Some useful view of the stack is achievable with:
  - **x/100wx $esp** prints 100 words of memory from the address found in the ESP to ESP+100 (x = hexadecimal formatting)
  - **x/10wo $ebp-100** prints 10 words of memory from EBP-100 to EBP-100+10 (o = octal formatting)
  - **x/s $eax** prints the elements pointed by EAX (s = string formatting)
- Do you have debug symbols? (i.e., `gcc -ggdb`)
  - **print args** prints info about the main parameters
  - **print a** prints the content of variable 'a'
  - **print *b** prints the value pointed by 'b'

Our friend gdb

- **The '∼/.gdbinit' file**

  Gdb is a command line tool and it supports the configuration script as almost all the *nix software.

  Some options that you may want to tune are:

  - **set history save on**

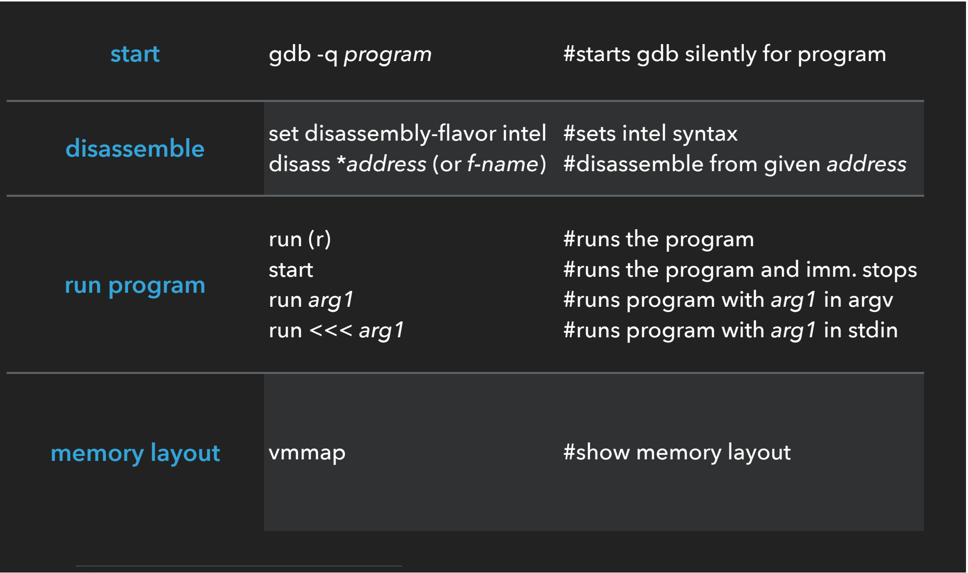
    To have the lastest commands always available also when we re-open gdb
  - **set follow-fork-mode child**

    Allows you, if the process spawns children, to follow them and not only wait their end.
  - **set disassembly-flavor [intel | att]**

    This option sets in which predefined syntax your disassembled will be showed up. The default one is at&t
- Highly recommended to install pwndbg

  `https://github.com/pwndbg/pwndbg`

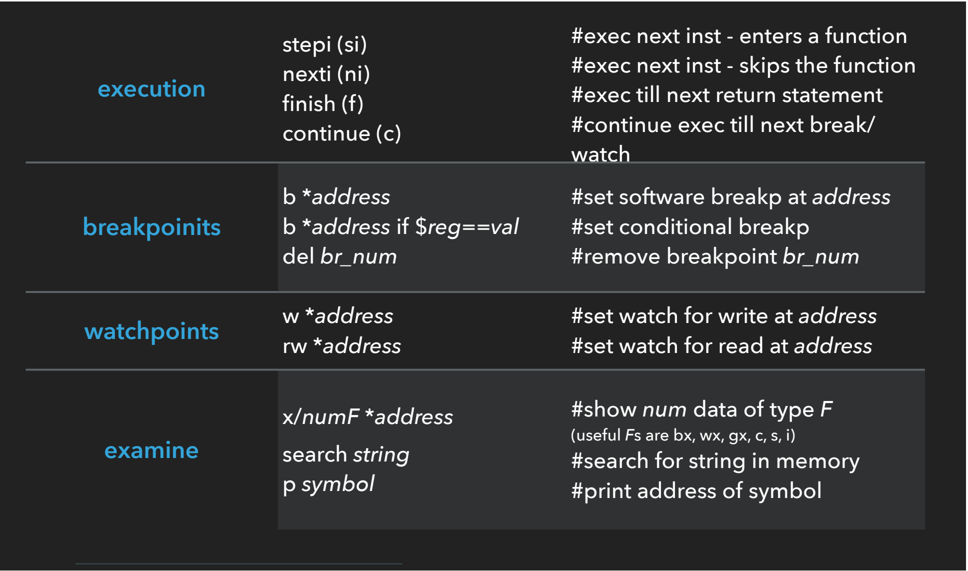
GDB - How to Survive [6]



start	gdb -q *program*	#starts gdb silently for program
disassemble	set disassembly-flavor intel disass **address* (or *f-name*)	#sets intel syntax #disassemble from given *address*
run program	run (r) start run *arg1* run <<< *arg1*	#runs the program #runs the program and imm. stops #runs program with *arg1* in argv #runs program with *arg1* in stdin
memory layout	vmmap	#show memory layout

[6] CTRL + C to Break and Debug

GDB - How to Survive [7]



execution	stepi (si) nexti (ni) finish (f) continue (c)	#exec next inst - enters a function #exec next inst - skips the function #exec till next return statement #continue exec till next break/ watch
breakpoinits	b **address* b **address* if *$reg==val* del *br_num*	#set software breakp at *address* #set conditional breakp #remove breakpoint *br_num*
watchpoints	w **address* rw **address*	#set watch for write at *address* #set watch for read at *address*
examine	x/*numF *address* search *string* p *symbol*	#show *num* data of type *F* (useful *F*s are bx, wx, gx, c, s, i) #search for string in memory #print address of symbol

[7] CTRL + D to Exit

strace

- Intercepts and records system calls and signals
- Dumps to standard error name, argument and return value of each system call

Useful options

- `-p <pid>` attach to existing process
- `-f` trace child process
- `-o <filename>` output to file
- `-e <expr>` modifies which events to trace (see manpage)

ltrace

- Intercepts and records dynamic library calls
- Similar to strace, but at a different layer

Questions?