

x86 Crash Course

With a focus on Linux and a glance to x86_64

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Credits — contributors as of March 22, 2019

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Instruction Set Architecture (ISA)

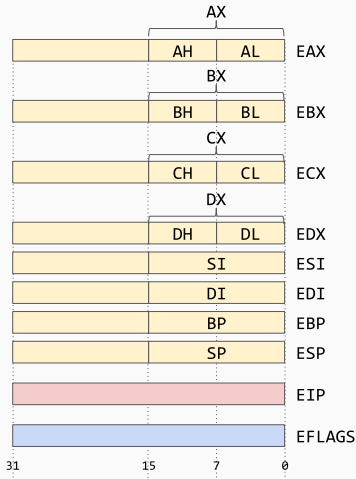
- “Logical” specification of a computer architecture
- Concerned with programming concepts
 - instructions, registers, interrupts, memory architecture, ...
- May differ (widely) from the actual microarchitecture
- Examples:
 - x86 (IA-32 and x86_64)
 - ARM (mobile devices)
 - MIPS (embedded devices, 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 registers¹

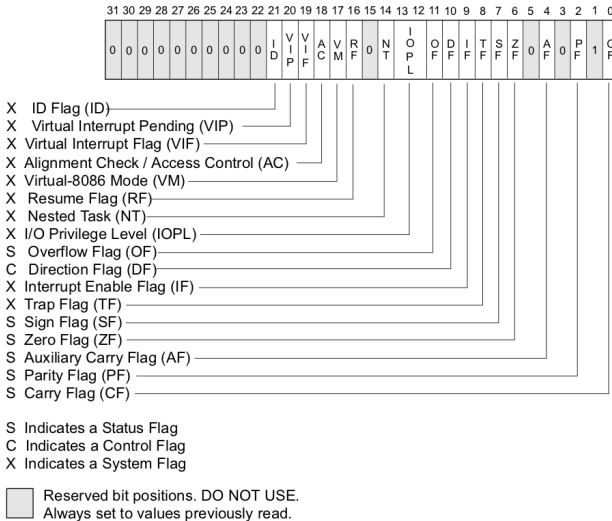
¹Complete reference: Intel Software Developer's Manual, about 5,000 pages (<https://software.intel.com/en-us/articles/intel-sdm>)

IA-32: Registers



- 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)

IA-32: EFLAGS register



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

Fundamental data types

byte 8 bits

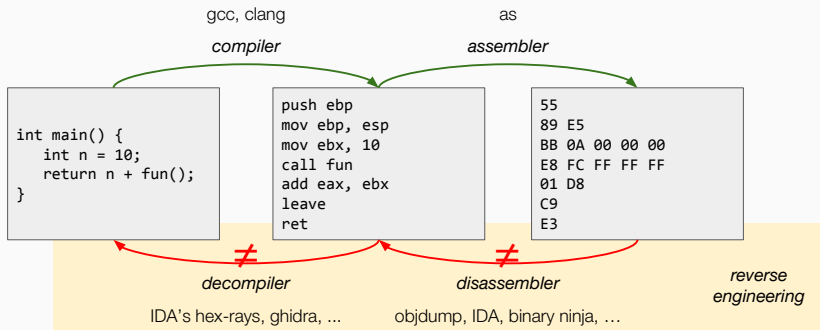
word 2 bytes

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



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

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

move the value 0 to EAX

Intel

`mov eax, 0h`

AT&T

`movl $0x0,%eax`

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

Intel

`mov [ebx+4h],0h`

AT&T

`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]` $EAX = *(EBX + 4)$

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

Note: memory to memory is an **invalid** combination²

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

x86 Assembly and Machine Code

Instruction = opcode + operand

Example

	mov r/m r	ebp, esp
mov ebp, esp	89	E5 10
	mov bl	
mov bl, 10	B3	0A
	size prefix	
mov bx, 10	66 BB	0A 00
	mov ebx	
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

<code>MOV eax, ebx</code>	<code>MOV eax, FFFFFFFFh</code>	<code>MOV ax, bx</code>
<code>MOV [eax],ecx</code>	<code>MOV [eax],[ecx] NO!!!</code>	<code>MOV al, FFh</code>

Integer Arithmetics: add and sub

add <u>destination</u> , <u>source</u>	sub <u>destination</u> , <u>source</u>
$\text{dest} \leftarrow \text{dest} + \text{source}$	$\text{dest} \leftarrow \text{dest} - \text{source}$

- 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
source: register or memory location
- $\text{dest} \leftarrow \text{implied_op} \times \text{source}$
- **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

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

Examples

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

Integer Arithmetics: `cmp` and `test`

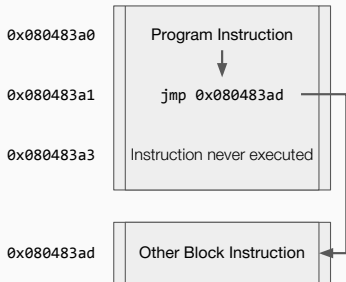
<code>cmp <u>op1</u>, <u>op2</u></code>	<code>test <u>op1</u>, <u>op2</u></code>
Computes $op1 - op2$	Computes $op1 \& op2$

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

Examples

<code>cmp eax, ebx</code>	<code>cmp eax, 44BBCCDDh</code>	<code>cmp al, dh</code>
<code>cmp al, 44h</code>	<code>cmp ax,FFFFh</code>	<code>cmp [eax],4h</code>

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

Control-Flow Instructions: conditional jumps

j<cc> address or offset

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

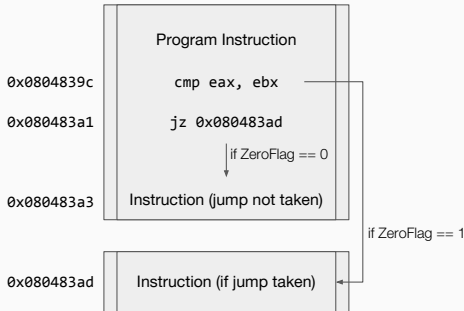
<cc>: condition

- 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>



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	Memory	
EAX	0x00000000	0x7C81776F	0x00403A40
		0x7C911000	0x00403A44
EBX	0x00403A40	0x0012C140	0x00403A48
	...	0x7FFDB000	0x00403A4C

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

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

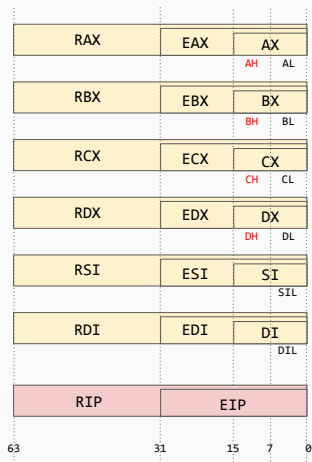
Basic Instructions: `nop`

- `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

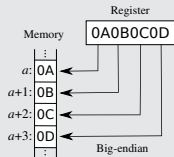


Endianness

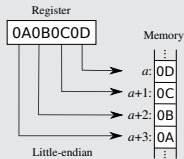
Endianness: convention that specifies in which order the bytes of a data word are lined up sequentially in memory.

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

- **PE (Portable Executable):** used by Microsoft binary executables
- **ELF:** common binary format for Unix, Linux, FreeBSD and others
- In both cases, we are interested in how each executable is mapped into memory, rather than how it is organized on disk.

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

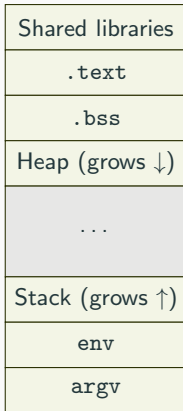
Executable	Description
.bss	This section holds uninitialized data that contributes to the program's memory image. By definition, the system initializes the data with zeros when the program begins to run.
.comment	This section holds version control information.
.data/.data1	These sections hold initialized data that contribute to the program's memory image
.debug	This section holds information symbolic debugging.
.text	This section holds the "text," or executable instructions, of a program.
.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.

How an executable is mapped to memory in Windows (PE)

Executable	Description
.text	Contains the executable code
.rdata	Holds read-only data that is globally accessible within the program
.data	Stores global data accessed throughout the program
.idata	stores the import function information;
.edata	stores the export function information;
.pdata	Present only in 64-bit executables and stores exception-handling information
.rsrc	Stores resources needed by the executable
.reloc	Contains information for relocation of library files

Simplified program memory layout

Low addresses (0x80000000)



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)
- Remember: the stack grows **toward lower addresses** (downward the address space)

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

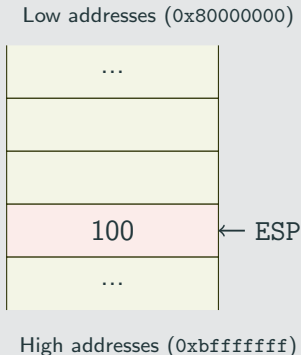
Initial condition: `EAX = 30`

`push eax`

is equivalent to:

`sub esp, 4`

`mov DWORD PTR [esp], eax`



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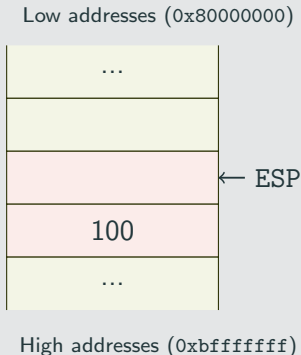
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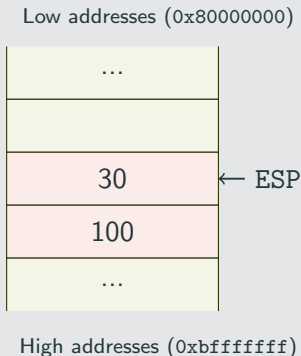
Final condition: `EAX = 30`

`push eax`

is equivalent to:

`sub esp, 4`

`mov DWORD PTR [esp], eax`



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 = ???

```
pop eax
```

is equivalent to:

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

```
add esp, 4
```



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

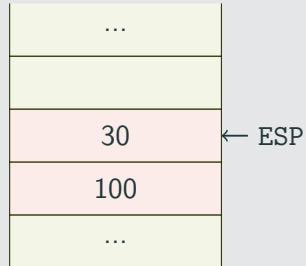
pop eax

is equivalent to:

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add esp, 4
```

Low addresses (0x80000000)



High addresses (0xbfffffff)

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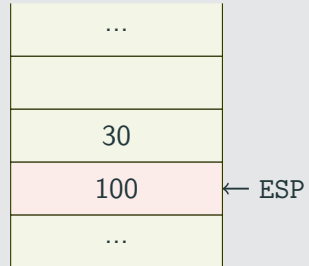
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High addresses (0xbfffffff)

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

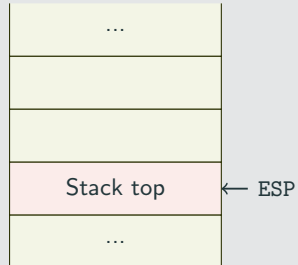
Example: Let's call `func`, located at `0x800bff00`

Equivalent to:

- `push eip`
- `jmp func`

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

Low addresses (0x80000000)



High addresses (0xbfffffff)

EIP = 0x8001020

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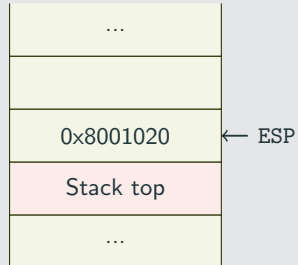
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High addresses (`0xbfffffff`)

`EIP = 0x8001020`

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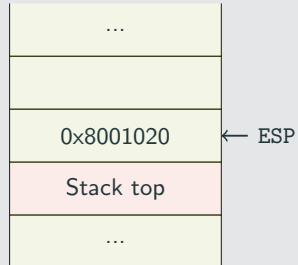
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Low addresses (0x80000000)



High addresses (0xbfffffff)

EIP = 0x800bff00

Returning from a function

Instruction `ret`:

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

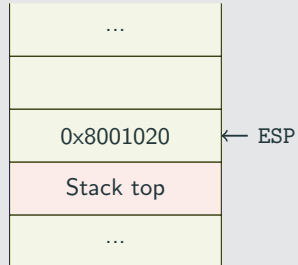
Example: let's return from `func`

Equivalent to:

- `pop eip`

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Low addresses (0x80000000)



High addresses (0xbfffffff)

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Returning from a function

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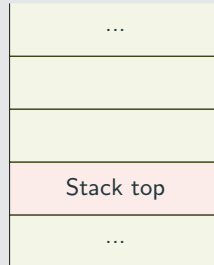
Example: let's return from `func`

Equivalent to:

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Low addresses (0x80000000)



← ESP

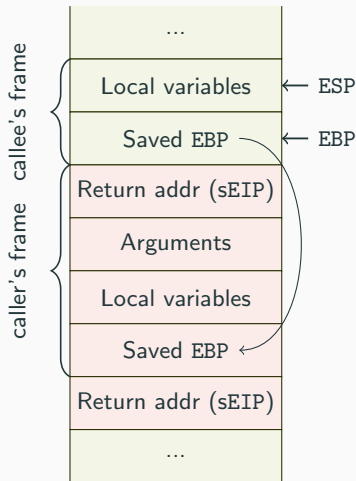
High addresses (0xbfffffff)

EIP = 0x8001020

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

Low addresses (0x80000000)



High addresses (0xbfffffff)

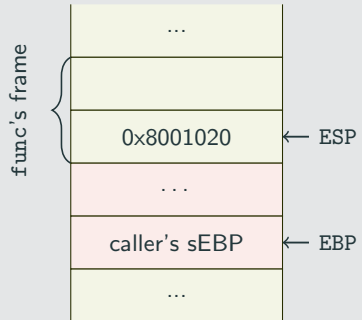
Entering a function

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

Setup the stack frame

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

Low addresses (`0x80000000`)



High addresses (`0xbfffffff`)

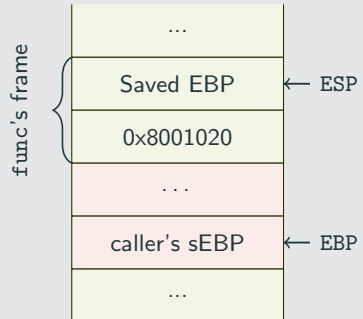
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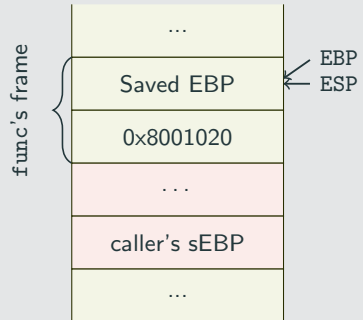
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Leaving a function

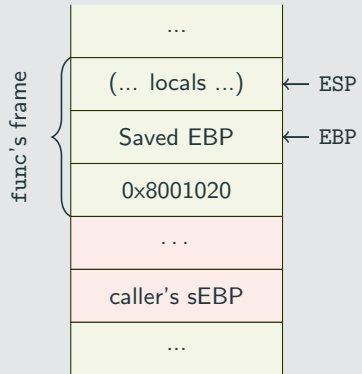
Instruction `leave`: restores the caller's base pointer

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

Equivalent to:

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

Low addresses (0x80000000)



High addresses (0xbfffffff)

Leaving a function

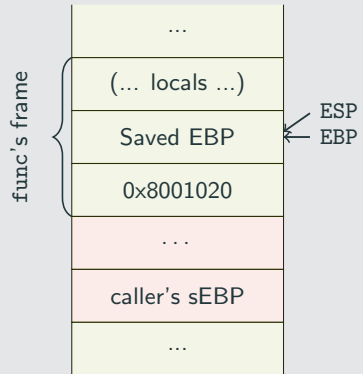
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High addresses (0xbfffffff)

Leaving a function

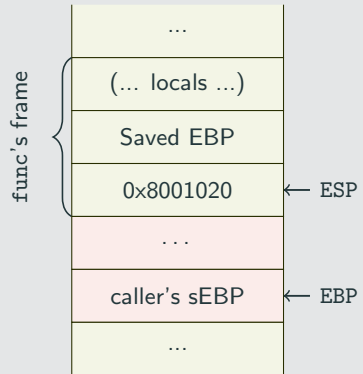
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Example: We're about to return from `func`

Equivalent to:

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

Low addresses (0x80000000)



High addresses (0xbfffffff)

Calling Conventions

- 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 RAX
- Caller-saved registers: EAX, ECX, EDX (other are callee-saved)

cdecl: Example

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

```
//...
```

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

```
; ...
```

```
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: stdcall

- Microsoft's Win32 API standard calling convention (modifier: `_stdcall`)
- Parameters: passed using the stack (as in `_cdecl`)
- Main difference: the callee is responsible for clearing the function parameters from the stack before returning
 - To do this, the function needs to know the right number of parameter passed → can be used only with functions having a fixed number of parameters (e.g., no `printf`).

```
void _stdcall demo_stdcall(int a, int b, int c);  
demo_stdcall(1, 2, 3);
```

```
ret 12 ; return and clear 12 bytes from the stack
```

stdcall: Example

```
void function (int a, int b) {  
    int array [5];  
}  
  
int main (int argc, char** argv) {  
    function(1, 2);  
    printf("This is where the ret  
        address points");  
}
```

Low addresses (0x80000000)

...
array[0]
...
array[4]
Saved EBP
Return address
1
2
...

High addresses (0xbfffffff)

Assembler-level View of the Same Example

```
public main
main proc near
push ebp
mov ebp, esp ; create stack
and esp, 0FFFFFFF0h
sub esp, 10h ; make room for vars
mov dword ptr [esp+4], 2 ; push 2
mov dword ptr [esp], 1 ; push 1
call function
mov dword ptr [esp], offset format; "This is..."
call _printf
leave
ret
main endp

public function
function proc near
push ebp
mov ebp, esp ; create stack
sub esp, 20h ; make room for array
leave
retn 8 ; remove 2 dwords
function endp
```

Low addresses (0x80000000)

...
array[0]
...
array[4]
Saved EBP
Return address
1
2
...

High addresses (0xbfffffff)

Calling Conventions: `fastcall`

- Modifier: `_fastcall`
- Up to 2 parameters passed via registers: ECX and EDX
- Other parameters pushed to the stack (right to left order, stack cleanup by callee as in `stdcall`)

```
; demo_fastcall(1, 2, 3, 4);  
push 4 ; push 4th parameter  
push 3 ; push 3rd parameter  
mov edx, 2 ; move 2nd parameter in EDX  
mov ecx, 1 ; move 1st parameter in ECX  
call demo_fastcall  
add esp, 8 ; clean up the stack
```

Calling Conventions: Linux x86-64 (System V ABI)

- 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:.LCO ; "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
```

```
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

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

- **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.³

³<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 "AAAAAAAAAAAAAA"'`** (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 proceed 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 to 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 to 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 latest 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 att

- Highly recommended to install pwndbg

<https://github.com/pwndbg/pwndbg>

- Text-based interface for GDB
 - **layout asm** turn the interface to the assembly view always visible during debugging
 - **layout src** if your binary has the debugging symbols you will have your c source view visible
 - **layout reg** add to the interface the register status view. It could be used in combination with one of the view described above
 - **gdb -tui ./mybin** runs gdb directly in this Text User Interface
- Use **CTRL+X A** to go back to standard interface.

- 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)

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

Thank you!
(time for more questions)