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# x86/x64 ABIs

An overview of Application Binary Interfaces on x86

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`www.zenhack.it`

# Outline

## 1 Linux (Unix System V ABI)

- x86 ABI
  - Function calls
  - Stack layout
  - System calls
- x64 ABI

## 2 FreeBSD x86

## 3 Windows ABI

- x86 ABI
- x64 ABI
- WoW64

## 4 Bonus: Mixing 32 and 64 bit code (AKA *Heaven's Gate*)

# Data representation

Here:

- **word** → 32-bit object (which makes sense, OTOH it's confusing)
- a null pointer has the value zero

Type	C	sizeof	Alignment (bytes)	Intel386 Architecture
Integral	char	1	1	signed byte
	signed char	1	1	signed byte
	unsigned char	1	1	unsigned byte
	short	2	2	signed halfword
	signed short	2	2	signed halfword
	unsigned short	2	2	unsigned halfword
Integral	int	4	4	signed word
	signed int	4	4	signed word
	long	4	4	signed word
Integral	signed long	4	4	signed word
	enum	4	4	signed word
	unsigned int	4	4	unsigned word
Pointer	unsigned long	4	4	unsigned word
	<i>any-type</i> *	4	4	unsigned word
Floating-point	<i>any-type</i> (*) ()	4	4	unsigned word
	float	4	4	single-precision (IEEE)
	double	8	4	double-precision (IEEE)
Floating-point	long double	12	4	extended-precision (IEEE)

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# Function calling (32 bits)

ESP= stack pointer  
EIP=instruction pointer

- stack kept 16-byte aligned (32/64 in some special cases)
- argument words pushed in reverse order; i.e. C calling convention
  - argument size padded (if necessary) to keep word alignment
- EBP is the optional frame-pointer
- EBP, EBX, EDI, ESI, and ESP must be preserved for the caller
- integral/pointer return values are stored in EAX (if 64-bits, EDX too)
- EBX is the GOT base register (for PIC code only)
- flag *direction* of EFLAGS must be zero on entry and upon exit
- . . .

in caso di local variabile? le metto sotto alfa? cosa che funziona

alfa è l'indirizzo dell'EIP prima di chiamare f

f(1,2,3) ->  
push 3  
push 2  
push 1  
call f  
alfa: ADD ESP, 12  
stack:  
esp-> | 3 |  
| 1 |  
ESP -> | alfa |

## It's useful seeing how C gets compiled

Compiler explorer: <https://gcc.godbolt.org/>

Also (x64 only), "Just Enough Assembly for Compiler Explorer" by A. S. Knatten @ CppCon 2021: [https://youtu.be/\\_sSFtJwgVYQ](https://youtu.be/_sSFtJwgVYQ)

# Standard stack frame

dato che in una funzione possiamo creare variabili locali e chiamare altre funzione tutte cose che possono modificare lo stack (e di conseguenza ESP) per cui si inserisce un riferimento a dove sono i parametri EBP e nella casella di memoria in a cui punta EBP (subito dopo alfa) si inserisce il valore di EBP prima di cambiarlo che quindi sarà la funzione chamante

in ogni funzione:

Prologue: `PUSH EBP`  
`MOV EBP,ESP`  
`SUB ESP, 8`

epilogue: `MOV ESP,EBP`  
`POP EBP`  
`RET`

Position	Contents	Frame	
$4n+8$ (%ebp)	argument word $n$	Previous	<i>High addresses</i>
...	...		
8 (%ebp)	argument word 0		
4 (%ebp)	return address	Current	<i>Low addresses</i>
0 (%ebp)	previous %ebp (optional)		
-4 (%ebp)	unspecified		
...	...		
0 (%esp)	variable size		

Let's check `sum.c` (with/without frame-pointer)

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# Stack Layout (32 and 64 bits)

entry-point (indirectly) calls `main` passing: `argc`, `argv` ( $=\alpha$ ), `envp` ( $=\beta$ )

In the stack segment, from higher to lower addresses we have:

- NULL
- program name
- environment strings
- `argv` strings
- ELF Auxiliary Table
- NULL that ends `envp[]`
- environment pointers (at address  $\beta$ )
- NULL that ends `argv[]`
- `argv` pointers (at address  $\alpha$ )
- `argc`

# Stack layout (at the entry-point), an example

```
----- 0x7fff6c845000
0x7fff6c844ff8: 0x0000000000000000
      4fec: './stackdump\0'
env   /   4fe2: 'ENVVAR2=2\0'
      \   4fd8: 'ENVVAR1=1\0'
      /   4fd4: 'two\0'
args  |   4fd0: 'one\0'
      \   4fcb: 'zero\0'
      3020: random gap padded to 16B boundary
-----
      3019: 'x86_64\0'
auxv   3009: random data: ed99b6...2adcc7
data   3000: zero padding to align stack
. . . . .
      2ff0: AT_NULL(0)=0
      2fe0: AT_PLATFORM(15)=0x7fff6c843019
auxiliary 2fd0: AT_EXECFN(31)=0x7fff6c844fec
vector   2fc0: AT_RANDOM(25)=0x7fff6c843009
      2fb0: AT_SECURE(23)=0
      ...
. . . . .
      2ec8: environ[2]=(nil)
      2ec0: environ[1]=0x7fff6c844fe2
      2eb8: environ[0]=0x7fff6c844fd8
      2eb0: argv[3]=(nil)
      2ea8: argv[2]=0x7fff6c844fd4
      2ea0: argv[1]=0x7fff6c844fd0
      2e98: argv[0]=0x7fff6c844fcb
0x7fff6c842e90: argc=3
```

Source: <https://lwn.net/Articles/631631/>

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# System calls

Normal programs don't need to be concerned: they are just function calls to **wrapper functions** in C library

*... there are **functions in the GNU C Library** to do virtually everything that system calls do. These functions work by **making system calls** themselves.*

*For example, there is a system call that changes the permissions of a file, but you don't need to know about it because you can just use the GNU C Library's `chmod` function ...*

[https://www.gnu.org/software/libc/manual/html\\_node/System-Calls.html](https://www.gnu.org/software/libc/manual/html_node/System-Calls.html)

Indeed, you *cannot* invoke a system call in C (without asm)

# System call wrappers

- A wrapper function *w* leverages the “magic” of assembly code to
  - put the arguments into CPU registers
  - put the `syscall-#` into a register
  - “trap” into the kernel
- Kernel executes the syscall handler, that
  - checks the validity of `syscall-#` and arguments, then
  - calls the actual routine corresponding to that syscall
  - puts the result in a register
  - switches back to user-mode with a special instruction
- *w* checks the result
  - on error sets `errno` and returns an error code (typically: -1)
  - otherwise, return the result

So, syscalls are one/two orders of magnitude *slower* than a function call

# Syscall (32 bits)

Parameters are passed by setting:

- `EAX = syscall #`
  - syscall tables (x86 and x64 use different syscall-#):  
<https://syscalls.w3challs.com/>
- `EBX, ECX, EDX, ESI, EDI, EBP` = parameters 1 – 6

and issuing `INT 0x80`

On return,

- `EAX` contains the return value
- all other registers are preserved

# Syscall example (32 bit, AT&T syntax)

```
# taken from: https://en.wikibooks.org/wiki/X86\_Assembly/Interfacing\_with\_Linux
.data
msg: .ascii "Hello World\n"

.text
.global main

main:
    movl $4, %eax    # use the write syscall
    movl $1, %ebx    # write to stdout
    movl $msg, %ecx  # use string "Hello World"
    movl $12, %edx   # write 12 characters
    int $0x80        # make syscall

    movl $1, %eax    # use the exit syscall
    movl $0, %ebx    # status code 0
    int $0x80        # make syscall
```

To assemble and link:

```
as --32 -o hello32-att.o hello32-att.s
ld -m elf_i386 -e main ./hello32-att.o -o hello32-att
```

# Syscall example (32 bit, Intel syntax)


```
section .text
global _start

_start:
    mov eax, 4      ; use the write syscall
    mov ebx, 1      ; write to stdout
    mov ecx, msg    ; use string "Hello World"
    mov edx, msglen ; write 12 characters
    int 0x80        ; make syscall

    mov eax, 1      ; use the exit syscall
    mov ebx, 0      ; status code 0
    int 0x80        ; make syscall

section .data

msg:    db "Hello World", 10
msglen equ $-msg
```



To assemble and link:

```
nasm -f elf32 ./hello32-intel.asm
ld -m elf_i386 -o hello32-intel hello32-intel.o
```



# Faster syscalls

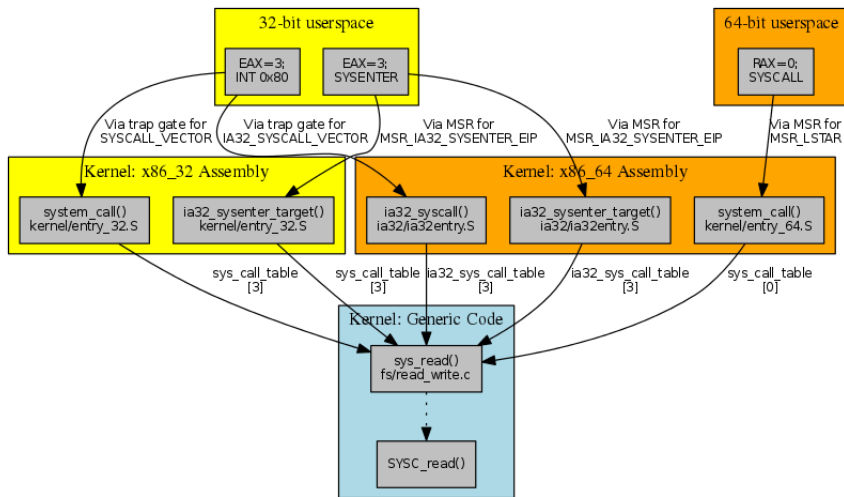
- modern CPUs allow **faster syscalls** via `sysenter` and `sysexit`
  - note: in 64 bit mode there are other instructions: `syscall` and `sysret`
- **making `sysenter` work properly is complicated**
  - the kernel takes care of it
  - the bookkeeping to executing a `sysenter` instruction can change over time (and it has changed)
  - (32 bit) user programs should use a **function called `__kernel_vsycall`**, which is implemented in the kernel, but mapped into each user process in vDSO
    - can be found via the ELF auxilliary vector
    - libc puts its value in `gs: [SYSINFO_OFFSET]`
  - **vDSO = virtual Dynamic Shared Object**, which allow programs to execute kernel code in userland

## The Definitive Guide to Linux System Calls

A well-written blog post with many details:

[https://blog.packagecloud.io/eng/2016/04/05/the-definitiv  
e-guide-to-linux-system-calls/](https://blog.packagecloud.io/eng/2016/04/05/the-definitiv-e-guide-to-linux-system-calls/)

# Syscalls



<https://lwn.net/Articles/604515/>

# Data representation (“word” is not used anymore!)

Type	C	sizeof	Alignment (bytes)	AMD64 Architecture
Integral	<code>_Bool</code> <sup>†</sup>	1	1	boolean
	<code>char</code>	1	1	signed byte
	<code>signed char</code>			
	<code>unsigned char</code>	1	1	unsigned byte
	<code>short</code>	2	2	signed twobyte
	<code>signed short</code>			
	<code>unsigned short</code>	2	2	unsigned twobyte
	<code>int</code>	4	4	signed fourbyte
	<code>signed int</code>			
	<code>enum</code>			
	<code>unsigned int</code>	4	4	unsigned fourbyte
	<code>long</code>	8	8	signed eightbyte
	<code>signed long</code>			
Pointer	<code>long long</code>			
	<code>signed long long</code>			
	<code>unsigned long</code>	8	8	unsigned eightbyte
	<code>unsigned long long</code>	8	8	unsigned eightbyte
	<code>__int128</code> <sup>††</sup>	16	16	signed sixteenbyte
	<code>signed __int128</code> <sup>††</sup>	16	16	signed sixteenbyte
	<code>unsigned __int128</code> <sup>††</sup>	16	16	unsigned sixteenbyte
	<code>any-type *</code>	8	8	unsigned eightbyte
	<code>any-type (*)()</code>			
Floating-point	<code>float</code>	4	4	single (IEEE)
	<code>double</code>	8	8	double (IEEE)
	<code>long double</code>	16	16	80-bit extended (IEEE)
	<code>__float128</code> <sup>††</sup>	16	16	128-bit extended (IEEE)
Packed	<code>__m64</code> <sup>††</sup>	8	8	MMX and 3DNow!
	<code>__m128</code> <sup>††</sup>	16	16	SSE and SSE-2

<sup>†</sup> This type is called `bool` in C++.

<sup>††</sup> These types are optional.

# Function calling (64 bits)

- arguments (of simple scalar types) are passed
  - first six: using registers: RDI, RSI, RDX, RCX, R8 and R9
  - the rest: using the stack
- return value: RAX (and, depending on type, RDX too)
- RBP, RBX, R12-R15 and RSP must be preserved for the caller
  - Note: in 32-bit also EDI and ESI must be preserved
- the end of argument area shall be aligned on a 16 byte boundary
- the *red-zone*, a 128-byte area beyond the location pointed to by RSP, is considered to be reserved and shall not be modified by signal or interrupt handlers
  - compilers can optimize leaf-function frames

Check `sum64` out

And add other four arguments to `sum`

# Syscall (64 bits)

Parameters are passed by setting:

- `RAX = syscall #`
  - syscall tables (x86 and x64 use *different* syscall-#):  
<https://syscalls.w3challs.com/>
- `RDI, RSI, RDX, R10, R8, R9 = parameters 1 – 6`

and issuing `syscall`

On return,

- `RAX` contains the return value
- all other registers, except `RCX` and `R11` are preserved
  - `RCX` and `R11` are implicitly used by the `syscall` instruction for saving `RIP` and `RFLAGS`

# Syscall example (64 bit, AT&T syntax)

```
# taken from https://en.wikibooks.org/wiki/X86_Assembly/Interfacing_with_Linux
.data
msg: .ascii "Hello World\n"

.text
.global main

main:
    movq $1, %rax    # use the write syscall
    movq $1, %rdi    # write to stdout
    movq $msg, %rsi  # use string "Hello World"
    movq $12, %rdx   # write 12 characters
    syscall          # make syscall

    movq $60, %rax   # use the exit syscall
    movq $0, %rdi    # error code 0
    syscall          # make syscall
```

To assemble and link:

```
as -o hello64-att.o hello64-att.s
ld -e main ./hello64-att.o -o hello64-att
```

# Syscall example (64 bit, Intel syntax)

```
    section .text
    global main

main:
    mov rax, 1      ; use the write syscall
    mov rdi, 1      ; write to stdout
    mov rsi, msg     ; use string "Hello World"
    mov rdx, msglen  ; write 12 characters
    syscall          ; make syscall

    mov rax, 60     ; use the exit syscall
    mov rdi, 0      ; error code 0
    syscall          ; make syscall

    section .data
msg:    db "Hello World", 10
msglen equ $-msg
```

To assemble and link:

```
nasm -f elf64 hello64-intel.asm
ld -e main -o hello64-intel hello64-intel.o
```

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By default, the FreeBSD kernel

- uses the **C calling convention** for arguments
- is accessed using **int 80h**
  - but, it is assumed the program will call a function that issues int 80h, rather than issuing int 80h directly
  - this allows programs written in any language to call the kernel

<https://docs.freebsd.org/en/books/developers-handbook/x86/>

<https://alfonsosiciliano.gitlab.io/posts/2021-01-02-freebsd-system-calls-table.html>

## Example: calling open

```
kernel:
    int     80h      ; Call kernel
    ret

open:
    push    dword mode
    push    dword flags
    push    dword path
    mov     eax, 5
    call    kernel
    add     esp, byte 12
    ret
```

that can be optimized to...

## Example: calling open (optimized)

open:

```
push    dword mode
push    dword flags
push    dword path
mov     eax, 5
push    eax      ; anything, really
int     80h      ; Call kernel
add     esp, byte 16
ret
```

# Function calls

There are several calling conventions, the most common are:

- `stdcall`, the “standard” calling convention, used by most Windows API
- `cdecl`, the C calling convention

As in Linux x86, both pass the arguments right to left on the stack, the difference lies in how the stack is cleaned up:

`stdcall` the callee is responsible to cleanup the stack

- less code (callers do not need to do anything), but fixed number of arguments

`cdecl` the caller is responsible

- the advantage is the fact that functions can handle a variable number of arguments

Registers EAX, ECX and EDX are caller-saved; (non-floating) return values are stored in EAX (and EDX, for 64-bit values)

# System calls

Wrappers functions are (almost) always used: too unreliable otherwise;  
e.g. `NtCreateFile` is

x86 0x163 on 8.0, 0x168 on 8.1, 0x016e on 10.1507, 0x170 on 10.1511, 0x172 on 10.1607, ...

x64 0x53 on 8.0, 0x54 on 8.1, 0x55 on 10.1507 to 10.20H2

However, see also:

- <https://github.com/jthuraisamy/SysWhispers2>
- <https://github.com/crummie5/FreshyCalls>
- <https://github.com/am0nsec/HellsGate>
- <https://www.mdsec.co.uk/2022/04/resolving-system-service-numbers-using-the-exception-directory/>

For more details, a nice video is *Intro to Syscalls for Windows Malware*:  
[https://www.youtube.com/watch?v=elA\\_eiqWefw](https://www.youtube.com/watch?v=elA_eiqWefw)

# Function calls

In x64 there is only one convention:

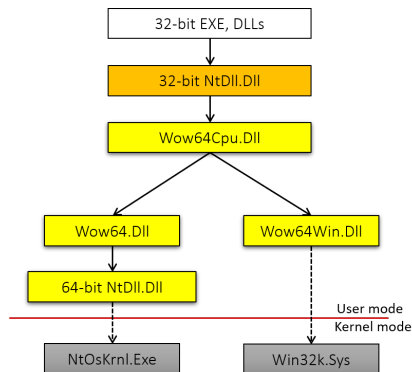
- (non-floating) arguments in the leftmost four positions are passed in left-to-right order in RCX, RDX, R8 and R9, respectively
- The fifth and higher arguments are passed on the stack

A scalar return value (that fits into 64 bits), is returned through RAX

RAX, RCX, RDX, R8, R9, R10, R11 are caller-saved

# WoW64 — DLLs

The 32-bit `ntdll.dll` does NOT invoke system calls but calls into the **translation layer** that leverages the **64-bit kernel**



From <https://leanpub.com/windows10systemprogramming/>

# WoW64 — Redirections

- A 32-bit process cannot load a 64-bit DLL and vice versa
  - In theory...however, see:  
<https://github.com/JustasMasiulis/wow64pp> and  
<https://github.com/rwfpl/rewolf-wow64ext>
- On x64, 64-bit files are confusingly stored in C:\Windows\System32, while 32-bit files are stored in C:\Windows\SysWow64 (in 32-bit processes, C:\SysNative gets you to real 64-bit PEs)
- File/registry accesses are automatically redirected; e.g. if a 32-bit process tries to open the former path, it is redirected to the latter

Original Path	Redirected Path for 32-bit x86 Processes
%windir%\System32	%windir%\SysWOW64
%windir%\lastgood\system32	%windir%\lastgood\SysWOW64
%windir%\regedit.exe	%windir%\SysWOW64\regedit.exe

<https://docs.microsoft.com/en-us/windows/win32/winprog64/file-system-redirector>



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# Mixing 32/64 bit code

- Each segment can be setup to run code in 32 or 64 bit mode
  - See, e.g., <https://www.malwaretech.com/2014/02/the-0x33-segment-selector-heavens-gate.html>
- Both Linux and Windows set up segment descriptors for
  - 32 bit code → 0x23
  - 64 bit code → 0x33
- Inside *any* process you can jump between 32 and 64 modes
- Technique used, for instance,
  - by malware; see, e.g., <https://www.malwaretech.com/2013/06/rise-of-dual-architecture-usermode.html>
  - as a way to escape (badly setup *seccomp*) sandboxes

→ `asm-examples/x86_64_polyglot`

- Linux system call list:  
<https://syscalls.w3challs.com/>
- Linux User/Kernel ABI: the realities of how C and C++ programs really talk to the OS  
by Greg Law @ ACCU 2018  
<https://www.youtube.com/watch?v=4CdmGxc5BpU>
- “The C++ ABI From the Ground Up”  
by Louis Dionne @ CppCon2019  
<https://youtu.be/DZ93lP1I7wU>