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Advanced Operating Systems and Virtualization

[4] System Calls

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Outline

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4.1

4. System Calls

Introduction

System Calls

Operating Systems offer processes running in User Mode a set of interfaces to interact with hardware devices. This extra layer between applications and hardware has several advantages:

1. making programming easier by freeing programmers to study low-level programming for hardware devices
2. increasing system security because the kernel can check the accuracy of the request at the interface level before attempting to satisfy it
3. increasing the programs portability because they can be compiled and executed correctly on every kernel that offers the same set of interfaces

Linux implements most interfaces between User Mode and Kernel mode by means of system calls.

POSIX APIs

There is a difference between an API and a system call. Since the former is and function definition and the latter is an explicit request to the kernel made via a software interrupt.

Most of the the system calls API that are provided to programmers are given by the libc and they refer to **wrapper routines** whose purpose is the one of invoking a system call. Usually, each system call has a corresponding wrapper routine but the converse is not true:

- the API could offer services directly in User Mode
- a single API function could make several system calls
- some API could wrap extra functions, for instance `malloc()`, `calloc()` and `free()` all use the `brk()` system call to enlarge or reduce the process heap and they keep track of the allocations

The POSIX standard only refers to API and not to system calls, a system that is POSIX compliant offers the set of POSIX APIs.

4.2

4. System Calls

Handler / Dispatcher

System Calls Handler

When a User Mode process invokes a system call the CPU switches to Kernel Mode and starts the execution of a kernel function. In the 8086 system calls can be invoked in two ways but both end with a jump to an assembly language function that is called the **system call handler**.

Each system call is identified by a **system call number** which must be expressed by the user mode process before starting the invoking process. This must usually be passed in the EAX register. All the system calls return an integer value, in general a positive or 0 indicates success, while negative values indicate error, in particular the negation of the error code -- the kernel does not set **`errno`**, that is set by wrapper routines.

The system call handler is very similar to other exception handlers (that we will see later in the course).

System Call Handler

V2.4

The system call handler, when invoked:

1. saves the content of most registers in the Kernel Mode stack
2. handles the system call by invoking a corresponding C function called **system call service routine** (via a `call`)
3. after completing the execution of the system call the registers are loaded with the values saved in the Kernel Mode stack and the CPU is switched back to User Mode

System Call **Invoking** placeholder

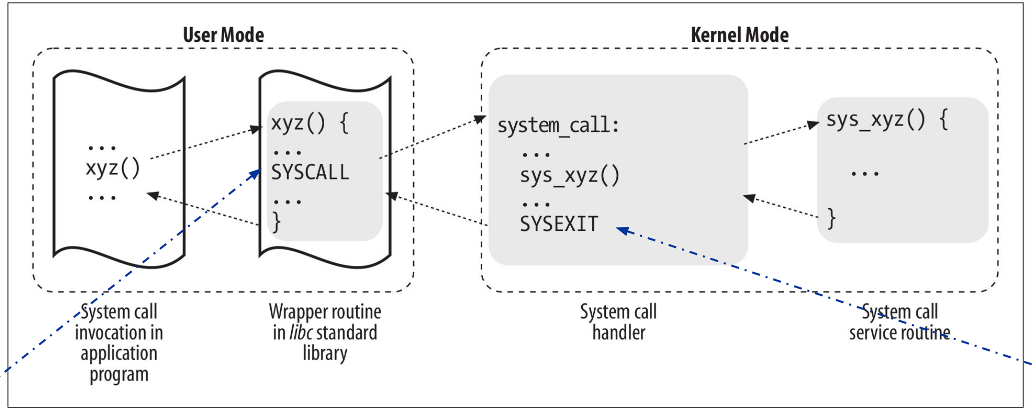
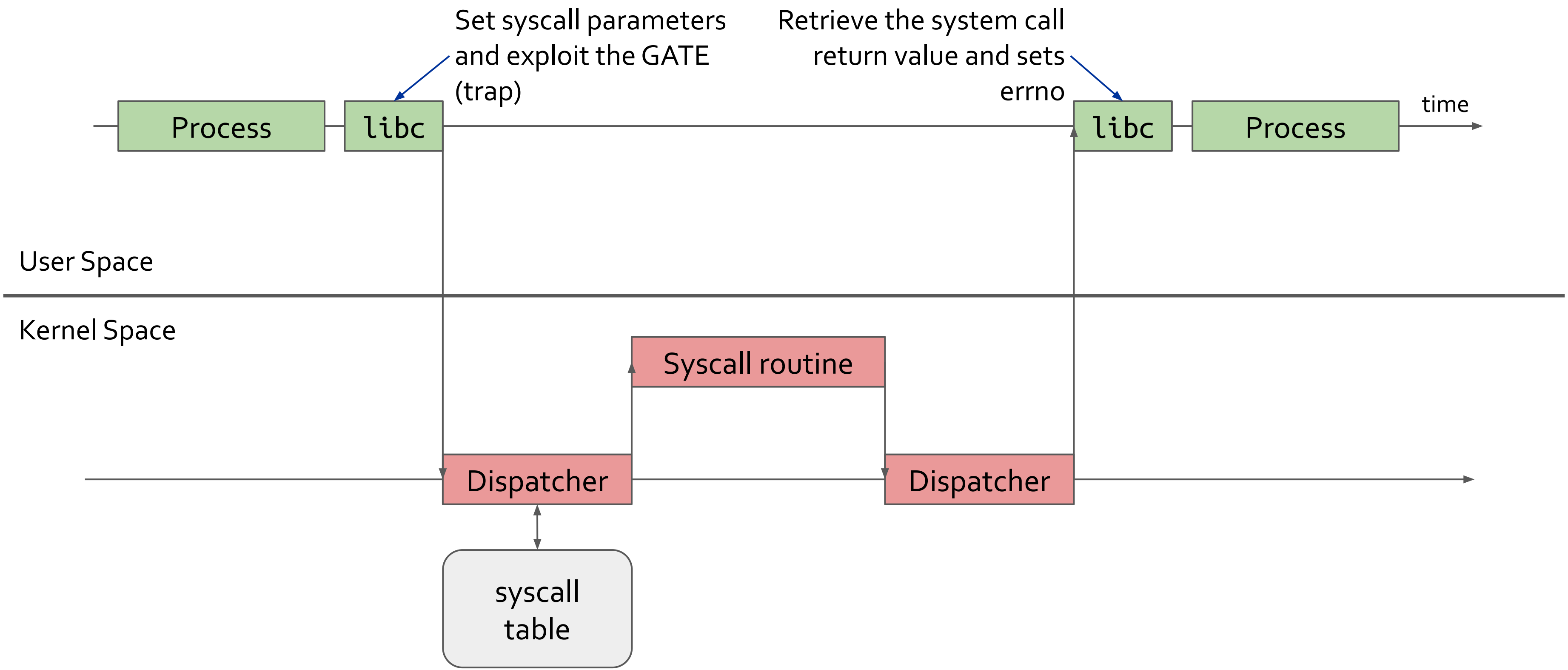


Figure 10-1. Invoking a system call

System Call **Exiting** placeholder

Bovet, Daniel P., and Marco Cesati. *Understanding the Linux Kernel: from I/O ports to process management*. " O'Reilly Media, Inc.", 2005.

System Call Flow



System Call Dispatch Table

V2.4

To associate each system call number with its corresponding to the corresponding service routine the kernel uses a **system call dispatch table**, which is stored in a fixed size array called `sys_call_table` array and has `NR_syscall` entries (289 in v2.6), the n^{th} entry of the array contains the address to the service routine for the syscall n.

Remind that NR_syscall is not the actual number of implemented system calls, is only the size of the possible maximum number of system calls, therefore there are free slots. In general the not-used entries points to sys_ni_syscall() which is the service routine for the "Non-implemented" system calls that always returns `-ENOSYS`.

kernel/timer.c

```
asmlinkage long sys_getuid(void)
{
        /* Only we change this so SMP safe */
        return current->uid;
}
```

Example of simple syscall service routine

System Call Dispatcher

V2.4

aka system_call()

```
 * Return to user mode is not as complex as all this looks,
 * but we want the default path for a system call return to
 * go as quickly as possible which is why some of this is
 * less clear than it otherwise should be.
 */

ENTRY(system_call)
        pushl %eax                      # save orig_eax
        SAVE_ALL
        GET_CURRENT(%ebx)
        testb $0x02,tsk_ptrace(%ebx)    # PT_TRACESYS
        jne tracesys
        cmpl $(NR_syscalls),%eax
        jae badsys
        call *SYMBOL_NAME(sys_call_table)(,%eax,4)
        movl %eax,EAX(%esp)             # save the return value
ENTRY(ret_from_sys_call)
        cli                             # need_resched and signals atomic test
        cmpl $0,need_resched(%ebx)
        jne reschedule
        cmpl $0,sigpending(%ebx)
        jne signal_return
restore_all:
        RESTORE_ALL
```

https://elixir.bootlin.com/linux/2.4.31/source/arch/i386/kernel/entry.S#L202

4.3

4. System Calls

Invoking Process

Entering and Exiting a System Call

Native applications can invoke a system call in two different ways:

1. by executing the **`int $0x80`** assembly instruction, this was the only way in older versions of the kernel
2. by executing the **`sysenter`** assembly instruction, introduced from Pentium II and <u>supported from kernel 2.6</u>

Similarly, the kernel can exit from a system call in two ways:

1. by executing **`iret`** assembly instruction
2. by executing the **`sysexit`** assembly instruction

The handlers for the two methods are:

1. `system_call()`
2. `sysenter_entry()`

However maintaining the compatibility of both strategies `int/iret` and `sysenter/sysexit` is not easy as it might look for different reasons, for example the kernel should allow to execute the system call even if the sysenter instruction is not supported.

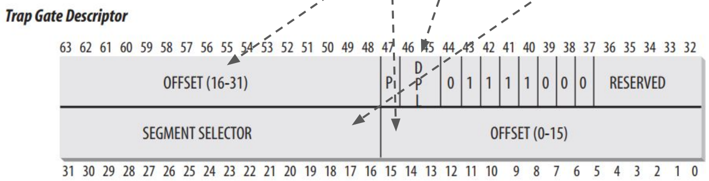
int $0x80

V2.4

```
#define IA32_SYSCALL_VECTOR         0x80
#ifdef CONFIG_X86_32
# define SYSCALL_VECTOR             0x80
#endif
```

The ox8o is registered during the trap_init() function as a trap gate.

```
static inline void set_system_trap_gate(unsigned int n, void *addr)
{
        BUG_ON((unsigned)n > 0xFF);
        _set_gate(n, GATE_TRAP, addr, 0x3, 0, __KERNEL_CS);
}
```




```
void __init trap_init(void)
{
        set_intr_gate(0, &divide_error);
        set_intr_gate_ist(2, &nmi, NMI_STACK);
        /* int4 can be called from all */
        set_system_intr_gate(4, &overflow);
        set_intr_gate(5, &bounds);
        set_intr_gate(6, &invalid_op);
        set_intr_gate(7, &device_not_available);
#ifdef CONFIG_X86_32
        set_task_gate(8, GDT_ENTRY_DOUBLEFAULT_TSS);
#else
        set_intr_gate_ist(8, &double_fault, DOUBLEFAULT_STACK);
#endif
        set_intr_gate(9, &coprocessor_segment_overrun);
        set_intr_gate(10, &invalid_TSS);

#ifdef CONFIG_X86_32
        set_system_trap_gate(SYSCALL_VECTOR, &system_call);
        set_bit(SYSCALL_VECTOR, used_vectors);
#endif
}
```

System call handler

https://elixir.bootlin.com/linux/v2.6.39.4/source/arch/x86/kernel/traps.c#L824

sysenter/sysexit

aka **Fast System Call**

The int assembly instruction is inherently slow, because it performs several consistency and security checks. The sysenter instruction is called Fast System Call by Intel, since it provides a faster way to switch from User to Kernel Mode, the instruction make use of **three MSR registers** (remember they are loaded with `wrmsr` and read with `rdmsr` - see Lab#3):

`SYSENTER_CS_MSR`
The Segment Selector of the kernel code segment

`SYSENTER_EIP_MSR`
The linear address of the kernel entry point

`SYSENTER_ESP_MSR`
The kernel stack pointer

Bovet, Daniel P., and Marco Cesati. Understanding the Linux Kernel: from I/O ports to process management. " O'Reilly Media, Inc.", 2005.

https://wiki.osdev.org/SYSENTER

The vsyscall page

v2.6

Obviously a libc wrapper can use the systenter instruction only if both the CPU and the Linux kernel supports it. This compatibility problem has a non-trivial solution.

During the kernel initialization phase the function `sysenter_setup()` builds a page frame called vsyscall page, containing a tiny ELF dynamic library. When a process issues an execve() system call to start executing an ELF program, the code in the vsyscall page is dynamically linked to the process address space. The code in that page uses the best available instruction to issue a system call, int $0x80 or sysenter.

Whenever a wrapper routine in the libc must invoke a system call it calls the function `__kernel_vsyscall()`, in the vsyscall page.

The vsyscall page has been replaced with the vDSO (see end of this pack of slides).

`sysenter/sysexit`

Procedure

`sysenter`

1. CS register set to the value of (`SYSENTER_CS_MSR`) (points to `__KERNEL_CS`)
2. EIP register set to the value of (`SYSENTER_EIP_MSR`) (points to `sysenter_entry()`)
3. SS register set to the sum of (8 plus the value in `SYSENTER_CS_MSR`)
4. ESP register set to the value of (`SYSENTER_ESP_MSR`)

`sysexit`

1. CS register set to the sum of (16 + `SYSENTER_CS_MSR`)
2. EIP register set to the value contained in the EDX register
3. SS register set to the sum of (24 + `SYSENTER_CS_MSR`)
4. ESP register set to the value contained in the ECX register

https://wiki.osdev.org/SYSENTER

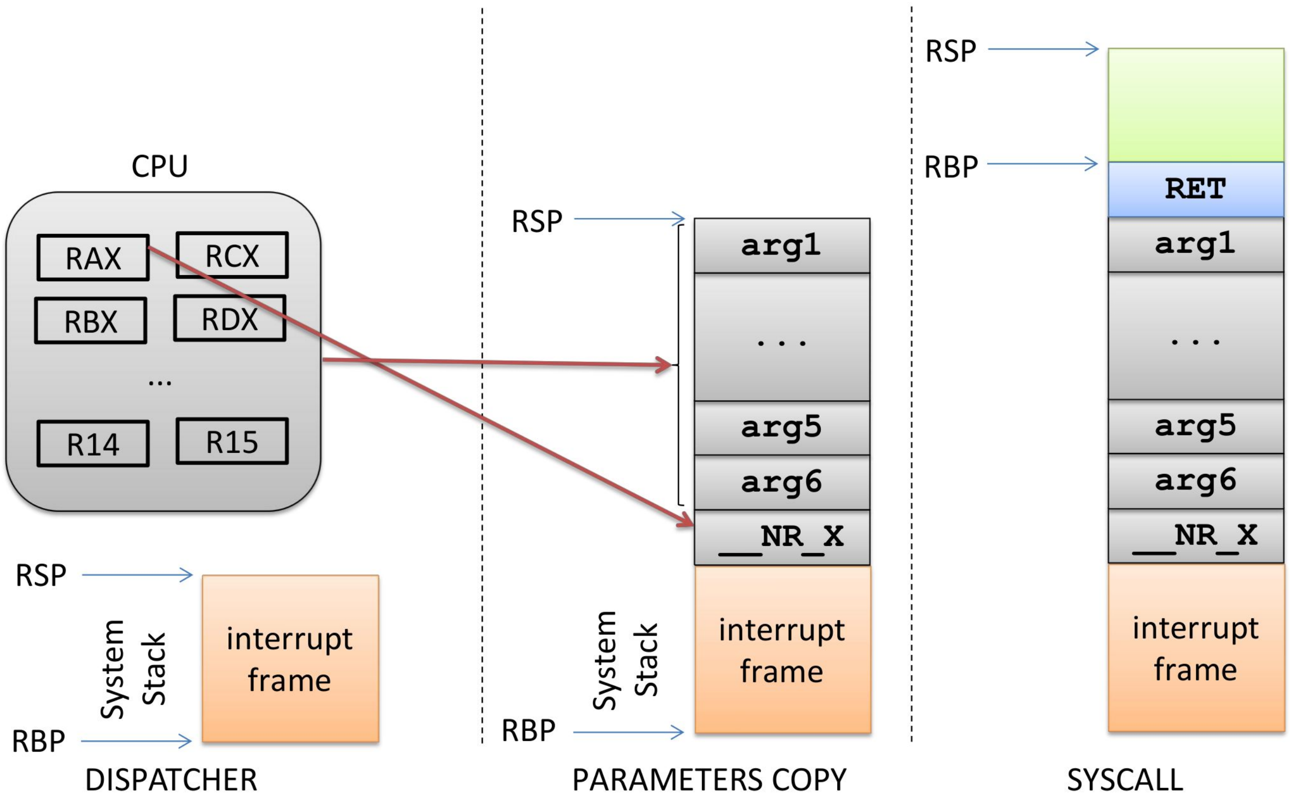
Parameter Passing

Independently by int/ret or sysenter/sysexit the system call handler has always at least one parameter: the system call number, always passed in the eax register.

The parameters of ordinary C functions are usually passed in the stack (CDECL standard) but since system calls are special functions that cross user and kernel lands, **neither** the user mode **nor** the kernel mode stacks **can be used**. For this reason the parameters are written in CPU registers before issuing the system call. The syscall dispatcher then copies the parameters stored in the CPU registers onto the Kernel Mode stack before invoking the system call service routine because the latter is a standard C function.

Why the kernel does not copy the parameters from the User Mode stack directly into the Kernel Mode one?

Parameter Passing



Parameter Passing

However, passing parameters in registers requires two conditions:

- the length is maximum the length of a register (32bit)
- the number of parameters cannot exceed six

In any case we can use pointers to memory areas. The registers used are in order eax, ebx, ecx, edx, esi, edi and ebp. The register copy in the stack is done by the `SAVE_ALL` macro and the return code of the syscall is always put in eax.

In some cases, even if the system call does not use parameters, we need to know the content of CPU registers (e.g. `do_fork()`), in these cases a single parameter of type `pt_regs` allows the service routine to access the values saved in the kernel mode stack by `SAVE_ALL`.

pt_regs

V2.4

```
/*
 *      0(%esp) - %ebx
 *      4(%esp) - %ecx
 *      8(%esp) - %edx
 *      C(%esp) - %esi
 *     10(%esp) - %edi
 *     14(%esp) - %ebp
 *     18(%esp) - %eax
 *     1C(%esp) - %ds
 *     20(%esp) - %es
 *     24(%esp) - orig_eax
 *     28(%esp) - %eip
 *     2C(%esp) - %cs
 *     30(%esp) - %eflags
 *     34(%esp) - %oldesp
 *     38(%esp) - %oldss
 */
```

pt_regs

arguments

Syscall number

Interrupt frame

4. System Calls
3. Invoking Process

User Space Invoking process

Compile Time Syscall interface

V2.4

The mapping to system call numbers for using in a user space program are defined in the header `include/asm-xxx/unistd.h`.

In that header we will find:

- **system call numerical codes**, that are numbers used to invoke a syscall for userspace and also a displacement in the syscall table for kernel space
- the **Kernel Wrapper Routines**, namely standard **macros** to let userspace access the **gate** to the Kernel, there is a macro for each range of parameters, from 0 to 6

System Call Codes

V2.4

```c
/*
 * This file contains the system call numbers.
 */

#define __NR_exit                1
#define __NR_fork                2
#define __NR_read                3
#define __NR_write               4
#define __NR_open                5
#define __NR_close               6
#define __NR_waitpid             7
#define __NR_creat               8
#define __NR_link                9
#define __NR_unlink             10
#define __NR_execve             11
#define __NR_chdir              12
#define __NR_time               13

#define __NR_io_submit         248
#define __NR_io_cancel         249
#define __NR_alloc_hugepages   250
#define __NR_free_hugepages    251
#define __NR_exit_group        252
```

https://elixir.bootlin.com/linux/2.4.31/source/include/asm-i386/unistd.h#L8

syscall()

syscall() is a construct that has been added in kernel 2.6 for the Pentium 3 chip, it is implemented through glibc (stdlib.h) and its role is to trigger a trap to execute a generic system call.

```
SYSCALL(2)                Linux Programmer's Manual               SYSCALL(2)

NAME
       syscall - indirect system call

SYNOPSIS
       #include <unistd.h>
       #include <sys/syscall.h>   /* For SYS_xxx definitions */

       long syscall(long number, ...);
```

The first argument is the system call number, the other parameters are the input for the system call code. The function is based on new x86 instructions: sysenter / sysexit or syscall/sysret (initially for AMD chips). See `man syscall` ([L](L)).

Complete path

If the kernel supports the vsyscall this is the complete path for calling a system call, suppose that you called syscall() from User Space, the function calls __kernel_vsyscall(), then

1. If the CPU **does not** support sysenter the function is

```
__kernel_vsyscall:
  int $0x80
  ret
```

2. If the CPU **supports** sysenter the function is:

```
__kernel_vsyscall:
  pushl %ecx
  pushl %edx
  pushl %ebp
  movl %esp, %ebp
  sysenter
```

These registers are going to be used by the system call handler so they are saved

Complete path

(1) int $0x80

1. `int` raises the interrupt at `0x80` index, that is a Trap Gate associated to the handler `system_call()` routine, namely the System Call Dispatcher
2. The dispatcher saves the CPU registers in the stack with SAVE_ALL macro
3. The validity of the system call number is checked against the NR_syscalls number
   a. If not valid the function stores -ENOSYS in the eax position in the stack and then jumps to `resume_userspace()`
   b. Otherwise the the system call service routine is called with the number passed in eax
4. When the system call service routines terminates system_calls gets its return code from eax and stores it the eax position in the stack
5. The kernel checks if there is some other work to do before returning in user mode (e.g. other interrupts, this will be clearer in next lectures)
6. RESTORE_ALL restores the contents of registers

Complete path

(2) `sysenter`

1. ebp, edx and ecx content are saved in the stack and esp is copied in ebp
2. the `sysenter` assembly instruction switches the CPU in kernel mode directly at the function `sysenter_entry()`, the System Call Handler
3. Sets up the kernel stack pointer
4. Enable local interrupts with sti command
5. Performs some operations that emulates the `int` assembly instruction
6. Invokes the System Call Service Routine is invoked exactly like `int $0x80` at the start of `system_call()`
7. The sysexit assembly instruction is used for returning in User Mode

4.3.2

4. System Calls

3. Invoking Process

Kernel Wrapper Routines

Kernel Wrapper Routines

V2.4

Although system calls are used mainly by User Mode processes, they can also be invoked by kernel threads, which cannot use library functions. To simplify the declarations of the corresponding wrapper routines, Linux defines a set of **seven** macros called `_syscall0` through `_syscall6`, where the number in the name is the number of the pass-able parameters (excluding the system call number).

```
_syscallX(type, name, type1, arg1, ....)
```

Examples

The wrapper routine to the `fork()` system call could be

```
_syscall0(int, fork)
```

The wrapper routine to `write()` could be:

```
_syscall3(int, write, int, fd, const char*, buf, unsigned int, count)
```

0-parameters call

V2.4

```c
#define _syscall0(type,name) \
type name(void) \
{ \
long __res; \
__asm__ volatile ("int $0x80" \
        : "=a" (__res) \
        : "0" (__NR_##name)); \
__syscall_return(type,__res); \
}
```

https://elixir.bootlin.com/linux/2.4.31/source/include/asm-i386/unistd.h#L8

__syscall_return

V2.4

```
/* user-visible error numbers are in the range -1 - -124: see <asm-i386/errno.h> */

#define __syscall_return(type, res) \
do { \
        if ((unsigned long)(res) >= (unsigned long)(-125)) { \
                errno = -(res); \
                res = -1; \
        } \
        return (type) (res); \
} while (0)
```

https://elixir.bootlin.com/linux/2.4.31/source/include/asm-i386/unistd.h#L263

?

1-parameter call

V2.4

```
#define _syscall1(type,name,type1,arg1) \
type name(type1 arg1) \
{ \
long __res; \
__asm__ volatile ("int $0x80" \
        : "=a" (__res) \
        : "0" (__NR_##name),"b" ((long)(arg1))); \
__syscall_return(type,__res); \
}
```

https://elixir.bootlin.com/linux/2.4.31/source/include/asm-i386/unistd.h#L283

6-parameters call

V2.4

```
#define _syscall6(type,name,type1,arg1,type2,arg2,type3,arg3,type4,arg4, \
          type5,arg5,type6,arg6) \
type name (type1 arg1,type2 arg2,type3 arg3,type4 arg4,type5 arg5,type6 arg6) \
{ \
long __res; \
__asm__ volatile ("push %%ebp ; movl %%eax,%%ebp ; movl %1,%%eax ; int $0x80 ; pop %%ebp" \
        : "=a" (__res) \
        : "i" (__NR_##name),"b" ((long)(arg1)),"c" ((long)(arg2)), \
          "d" ((long)(arg3)),"S" ((long)(arg4)),"D" ((long)(arg5)), \
          "0" ((long)(arg6))); \
__syscall_return(type,__res); \
}
```

https://elixir.bootlin.com/linux/2.4.31/source/include/asm-i386/unistd.h#L337

Newer kernel versions

V5.11

On latest version of the kernel, the Kernel Wrapper Routines are defined in `tools/include/nolibc/nolibc.h`, again they are specifically available for minimal programs which does not use the libc wrappers. They consists of three levels:

1. the macro assembly routines from `my_syscall0` to `my_syscall6`, architecture dependent (as the previous ones)
2. functions called `sys_<name_of_the_syscall>` which maps to the macros of the first level
3. call definition as libc does, also sets the errno

Further information are in the file [`include/nolibc/nolibc.h`]()

Do not call system calls from kernel.

V5.11

*System calls are, as stated above, interaction points between userspace and the kernel. Therefore, **system call functions such as sys_xyzzy() or compat_sys_xyzzy() should only be called from userspace via the syscall table,** but not from elsewhere in the kernel. If the syscall functionality is useful to be used within the kernel, needs to be shared between an old and a new syscall, or needs to be shared between a syscall and its compatibility variant, it should be implemented by means of a **"helper" function (such as ksys_xyzzy())**. This kernel function may then be called within the syscall stub (sys_xyzzy()), the compatibility syscall stub (compat_sys_xyzzy()), and/or other kernel code.*

-- https://www.kernel.org/doc/html/latest/process/adding-syscalls.html

Syscall Table

V5.11

The kernel level system call table is defined in specific files:

- for Kernel 2.4.20 on i386 it is defined in `arch/i386/kernel/entry.S`
- for Kernel 2.6 is in `arch/x86/kernel/syscall_table32.S`
- more recent versions: `arch/x86/entry/syscalls/syscall_32.tbl`

The entries in the table keep a reference to the kernel-level system call implementation and typically, the kernel-level name of the system call service routine resembles the one used at application level but starts with the "`sys_`" prefix.

Syscall Table

V5.11

For x86 architecture

```
#
# 32-bit system call numbers and entry vectors
#
# The format is:
# <number> <abi> <name> <entry point> <compat entry point>
#
# The __ia32_sys and __ia32_compat_sys stubs are created on-the-fly for
# sys_*() system calls and compat_sys_*() compat system calls if
# IA32_EMULATION is defined, and expect struct pt_regs *regs as their only
# parameter.
#
# The abi is always "i386" for this file.
#
0       i386    restart_syscall         sys_restart_syscall
1       i386    exit                    sys_exit
2       i386    fork                    sys_fork
3       i386    read                    sys_read
4       i386    write                   sys_write
5       i386    open                    sys_open                        compat_sys_op
6       i386    close                   sys_close
7       i386    waitpid                 sys_waitpid
```

```
436     i386    close_range             sys_close_range
437     i386    openat2                 sys_openat2
438     i386    pidfd_getfd             sys_pidfd_getfd
439     i386    faccessat2              sys_faccessat2
440     i386    process_madvise         sys_process_madvise
441     i386    epoll_pwait2            sys_epoll_pwait2                compat_sys_
```

https://elixir.bootlin.com/linux/v5.11/source/arch/x86/entry/syscalls/syscall_32.tbl

Defining a syscall service routine

V5.11

```c
SYSCALL_DEFINE3(read, unsigned int, fd, char __user *, buf, size_t, count)
{
        return ksys_read(fd, buf, count);
}
```

System call actual implementation

https://elixir.bootlin.com/linux/v5.11/source/fs/read_write.c#L642

```c
#define SYSCALL_DEFINE1(name, ...) SYSCALL_DEFINEx(1, _##name, __VA_ARGS__)
#define SYSCALL_DEFINE2(name, ...) SYSCALL_DEFINEx(2, _##name, __VA_ARGS__)
#define SYSCALL_DEFINE3(name, ...) SYSCALL_DEFINEx(3, _##name, __VA_ARGS__)
#define SYSCALL_DEFINE4(name, ...) SYSCALL_DEFINEx(4, _##name, __VA_ARGS__)
#define SYSCALL_DEFINE5(name, ...) SYSCALL_DEFINEx(5, _##name, __VA
#define SYSCALL_DEFINE6(name, ...) SYSCALL_DEFINEx(6, _##name, __VA

#define SYSCALL_DEFINE_MAXARGS  6

#define SYSCALL_DEFINEx(x, sname, ...)                          \
        SYSCALL_METADATA(sname, x, __VA_ARGS__)                 \
        __SYSCALL_DEFINEx(x, sname, __VA_ARGS__)
```

https://elixir.bootlin.com/linux/v5.11/source/include/linux/syscalls.h#L215

```c
/*
 * The asmlinkage stub is aliased to a function named __se_sys_*() which
 * sign-extends 32-bit ints to longs whenever needed. The actual work is
 * done within __do_sys_*().
 */
#ifndef __SYSCALL_DEFINEx
#define __SYSCALL_DEFINEx(x, name, ...)                                 \
        __diag_push();                                                  \
        __diag_ignore(GCC, 8, "-Wattribute-alias",                      \
                      "Type aliasing is used to sanitize syscall arguments");\
        asmlinkage long sys##name(__MAP(x,__SC_DECL,__VA_ARGS__))       \
                __attribute__((alias(__stringify(__se_sys##name))));    \
        ALLOW_ERROR_INJECTION(sys##name, ERRNO);                        \
        static inline long __do_sys##name(__MAP(x,__SC_DECL,__VA_ARGS__));\
        asmlinkage long __se_sys##name(__MAP(x,__SC_LONG,__VA_ARGS__)); \
        asmlinkage long __se_sys##name(__MAP(x,__SC_LONG,__VA_ARGS__))  \
        {                                                               \
                long ret = __do_sys##name(__MAP(x,__SC_CAST,__VA_ARGS__));\
                __MAP(x,__SC_TEST,__VA_ARGS__);                         \
                __PROTECT(x, ret,__MAP(x,__SC_ARGS,__VA_ARGS__));       \
                return ret;                                             \
        }                                                               \
        __diag_pop();                                                   \
        static inline long __do_sys##name(__MAP(x,__SC_DECL,__VA_ARGS__))
#endif /* __SYSCALL_DEFINEx */
```

The __se_sys_* stub is created for further protection and in the end calls __do_sys_* which calls the original ksys_read

4.3.3

4. System Calls

3. Invoking Process

x86_64 Invoking process

syscall/sysret

On x86_64 by AMD, there is a similar Fast System Call strategy that is based on the syscall and sysret assembly instructions. Again:

- it is based on MSR registers
- it is involved in the vsyscall page, now improved and called vDSO

During the initialization phase of the kernel the function `syscall_init()` initializes the registers

```
void syscall_init(void)
{
        wrmsr(MSR_STAR, 0, (__USER32_CS << 16) | __KERNEL_CS);
        wrmsrl(MSR_LSTAR, (unsigned long)entry_SYSCALL_64);

        wrmsrl(MSR_CSTAR, (unsigned long)ignore_sysret);
        wrmsrl_safe(MSR_IA32_SYSENTER_CS, (u64)GDT_ENTRY_INVALID_SEG);
        wrmsrl_safe(MSR_IA32_SYSENTER_ESP, 0ULL);
        wrmsrl_safe(MSR_IA32_SYSENTER_EIP, 0ULL);
```

https://elixir.bootlin.com/linux/v2.6.39.4/source/arch/x86/vdso/vdso32-setup.c#L283

https://wiki.osdev.org/SYSENTER

Syscall Calling Conventions

```
/*
* Register setup:
* rax system call number
* rdi arg0
* rcx ret.address for syscall/sysret, userspace arg3
* rsi arg1
* rdx arg2
* r10 arg3 (--> to rcx for userspace)
* r8 arg4
* r9 arg5
* r11 eflags for syscall/sysret, temporary for C
* r12-r15,rbp,rbx saved by C code, not touched.
*
* Interrupts are off on entry.
* Only called from user space.
*/
```

https://elixir.bootlin.com/linux/v5.11/source/arch/x86/entry/entry_64.S

Compatibility

Intel x86_64 ISA and AMD are similar but they are not the same. In particular

- *In 64-bit Long Mode - only SYSCALL works on both ISAs. (SYSENTER doesn't work on AMD.)*
- *In Legacy Mode - only SYSENTER works on both ISAs. (SYSCALL doesn't work on Intel.)*
- *There's no single instruction that works on both Intel and AMD in Compatibility Mode (SYSENTER doesn't work on AMD and SYSCALL doesn't work on Intel), but there's no need for one. A 32-bit kernel will stay in Legacy Mode after boot.*

https://reverseengineering.stackexchange.com/questions/16454/struggling-between-syscall-or-sysenter-windows

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4. System Calls

vDSO

From vsyscall to vDSO

The vsyscall page had several limitations:

- it was fixed in size
- it was allocated always at the **same address** in processes

The vDSO that stands for Virtual Dynamic Shared Object has been introduced for solving the security issues of the vsyscall architecture. *The vDSO is dynamically allocated which solves security concerns. The vDSO links are provided via the glibc library. The linker will link in the glibc vDSO functionality, provided that such a routine has an accompanying vDSO version, such as gettimeofday system call. When your program executes, if your kernel does not have vDSO support, a traditional syscall will be made.*

https://lwn.net/Articles/446528/

Exposing vDSO

```c
#include <sys/auxv.h>
void *vdso = (uintptr_t) getauxval(AT_SYSINFO_EHDR);
```

The vDSO is a small shared library that the kernel automatically maps into the address space of all user-space applications. Applications usually do not need to concern themselves with these details as the vDSO is most commonly called by the C library. This way you can code in the normal way using standard functions and the C library will take care of using any functionality that is available via the vDSO.

https://linux.die.net/man/3/getauxval

vDSO Entry Point

```
__kernel_vsyscall:
    push %ecx
    push %edx
    push %ebp
    movl %esp,%ebp
    sysenter
    nop
    /* 14: System call restart point is here! */
    int $0x80
    /* 16: System call normal return point is here! */
    pop %ebp
    pop %edx
    pop %ecx
    ret
```

vDSO Content

```
/* The ELF entry point can be used to set the AT_SYSINFO value.  */
ENTRY(__kernel_vsyscall);

/*
 * This controls what userland symbols we export from the vDSO.
 */
VERSION
{
	LINUX_2.6 {
	global:
		__vdso_clock_gettime;
		__vdso_gettimeofday;
		__vdso_time;
		__vdso_clock_getres;
		__vdso_clock_gettime64;
	};

	LINUX_2.5 {
	global:
		__kernel_vsyscall;
		__kernel_sigreturn;
		__kernel_rt_sigreturn;
	local: *;
	};
}
```

https://elixir.bootlin.com/linux/v5.11/source/arch/x86/entry/vdso/vdso32/vdso32.lds.S#L17

Remarks

The vDSO Kernel entry point exploits flat addressing to bypass segmentation and the related operations, it therefore reduces the number of accesses to memory in order to support the change to kernel mode.

Studies show that the reduction of clock cycles for system calls can be in the order of 75%

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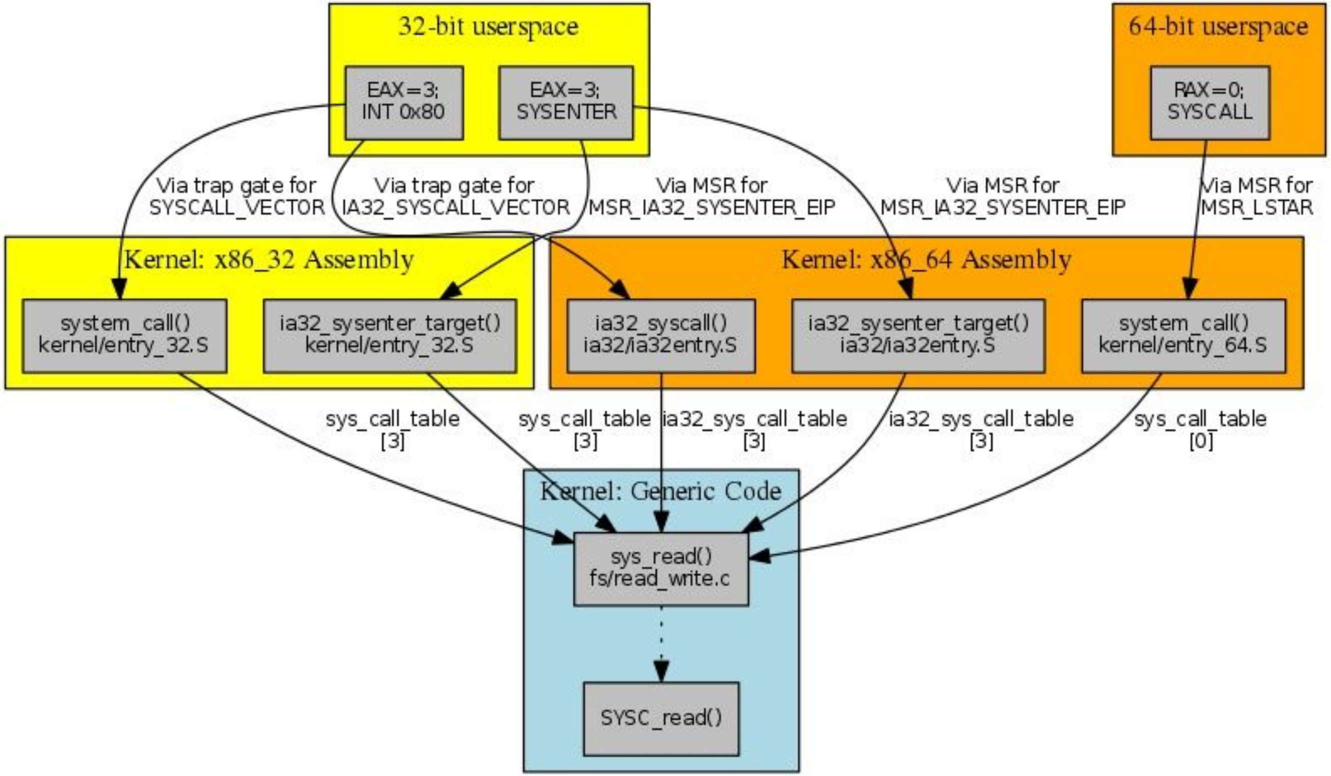
4. System Calls

Conclusions

Epilogue



32-bit userspace
EAX=3; INT 0x80
EAX=3; SYSENTER
64-bit userspace
RAX=0; SYSCALL
Via trap gate for SYSCALL_VECTOR
Via trap gate for IA32_SYSCALL_VECTOR
Via MSR for MSR_IA32_SYSENTER_EIP
Via MSR for MSR_IA32_SYSENTER_EIP
Via MSR for MSR_LSTAR
Kernel: x86_32 Assembly
system_call() kernel/entry_32.S
ia32_sysenter_target() kernel/entry_32.S
Kernel: x86_64 Assembly
ia32_syscall() ia32/ia32entry.S
ia32_sysenter_target() ia32/ia32entry.S
system_call() kernel/entry_64.S
sys_call_table [3]
sys_call_table [3]
ia32_sys_call_table [3]
ia32_sys_call_table [3]
sys_call_table [0]
Kernel: Generic Code
sys_read() fs/read_write.c
SYSC_read()

Advanced Operating Systems and Virtualization

[4] System Calls

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