Lecture 5

System Calls

Obtaining System Services

- Any application requiring a resource under OS care must request for it using the proper API

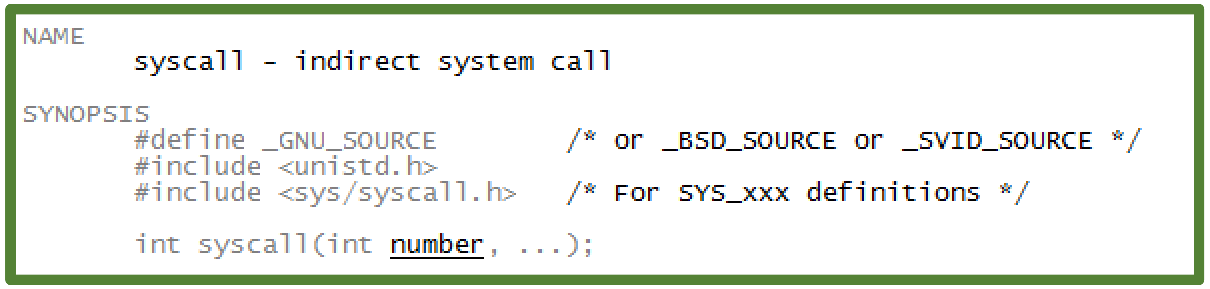
- Security an issue: how to ensure the OS boundary is crossed safely?

Typical OS services

- File services: create, open, read, write, close
- Terminal I/O
- Network processing
- Memory allocation, protection etc.

`syscall()`

- Typically, system calls wrapped in library API (such as file I/O)
- To call directly, need to use `syscall()` library function

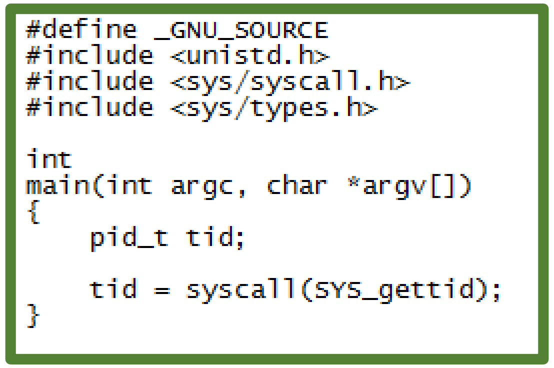


```
NAME
       syscall - indirect system call

SYNOPSIS
       #define _GNU_SOURCE         /* or _BSD_SOURCE or _SVID_SOURCE */
       #include <unistd.h>
       #include <sys/syscall.h>   /* For SYS_xxx definitions */

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

syscall() example



```
#define _GNU_SOURCE
#include <unistd.h>
#include <sys/syscall.h>
#include <sys/types.h>

int
main(int argc, char *argv[])
{
    pid_t tid;

    tid = syscall(SYS_gettid);
}
```

System calls in Linux

- System calls in Linux is identified by its number

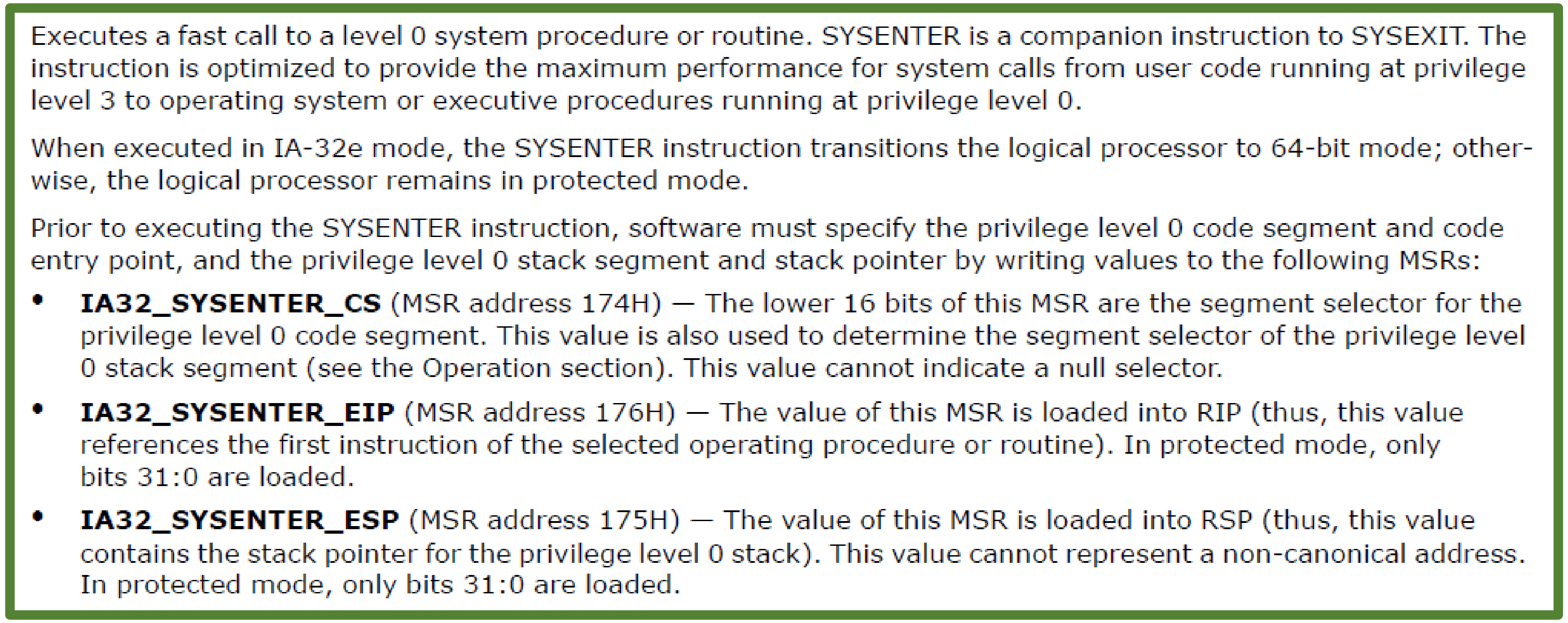
- Example: To read from an opened file requires the read system call. It is `__NR_read`
  - 3 in `/usr/include/asm/unistd_32.h` (32 bit systems)
  - 0 in `/usr/include/asm/unistd_64.h` (64 bit systems)

x86 system calls – the old way

- Uses a software interrupt
    - `int 0x80`
- Uses the interrupt servicing mechanism to elevate privileges to Ring 0
- But found to be slow
    - There are more things that need to be done to service interrupts in general

The new x86 way

- Uses the **`SYSENTER`**/**`SYSEXIT`** instructions



Executes a fast call to a level 0 system procedure or routine. SYSENTER is a companion instruction to SYSEXIT. The instruction is optimized to provide the maximum performance for system calls from user code running at privilege level 3 to operating system or executive procedures running at privilege level 0.

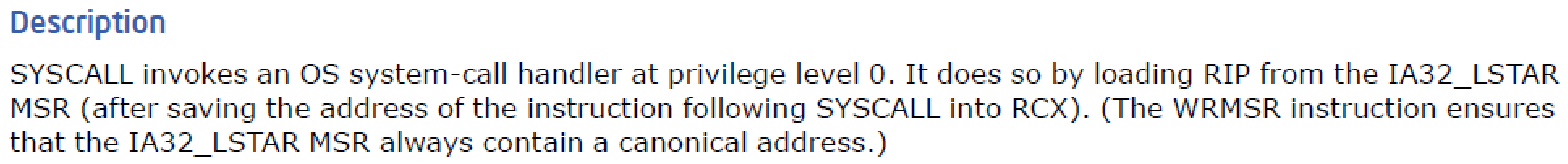
When executed in IA-32e mode, the SYSENTER instruction transitions the logical processor to 64-bit mode; otherwise, the logical processor remains in protected mode.

Prior to executing the SYSENTER instruction, software must specify the privilege level 0 code segment and code entry point, and the privilege level 0 stack segment and stack pointer by writing values to the following MSRs:

- **IA32_SYSENTER_CS** (MSR address 174H) — The lower 16 bits of this MSR are the segment selector for the privilege level 0 code segment. This value is also used to determine the segment selector of the privilege level 0 stack segment (see the Operation section). This value cannot indicate a null selector.
- **IA32_SYSENTER_EIP** (MSR address 176H) — The value of this MSR is loaded into RIP (thus, this value references the first instruction of the selected operating procedure or routine). In protected mode, only bits 31:0 are loaded.
- **IA32_SYSENTER_ESP** (MSR address 175H) — The value of this MSR is loaded into RSP (thus, this value contains the stack pointer for the privilege level 0 stack). This value cannot represent a non-canonical address. In protected mode, only bits 31:0 are loaded.

In 64 bits: SYSCALL/SYSRET

- Introduced by AMD but now also supported in Intel64



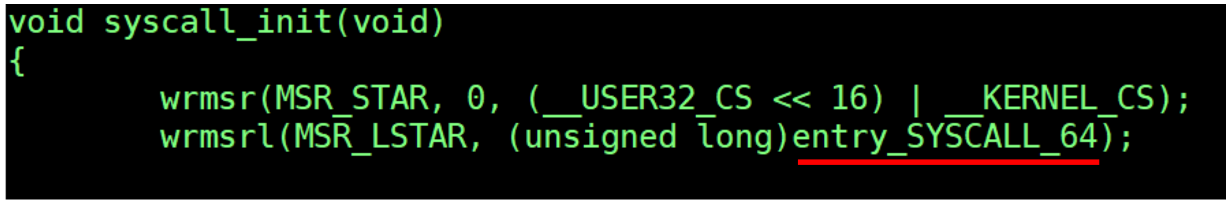
Description

SYSCALL invokes an OS system-call handler at privilege level 0. It does so by loading RIP from the IA32_LSTAR MSR (after saving the address of the instruction following SYSCALL into RCX). (The WRMSR instruction ensures that the IA32_LSTAR MSR always contain a canonical address.)

- Both **`SYSENTER`** and **`SYSCALL`** allows for a disciplined transition from Ring 3 to Ring 0
  - Just how to set up the context is done differently

In Linux

- In **`arch/x86/kernel/cpu/common.c`**



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

A small digression: x86 Model Specific Registers

- Special control “registers” in the x86 instruction set used for debugging, execution tracing, computer performance monitoring, and operating certain CPU features

- They may or may not be implemented in the processor you have at hand
  - Need to check the model

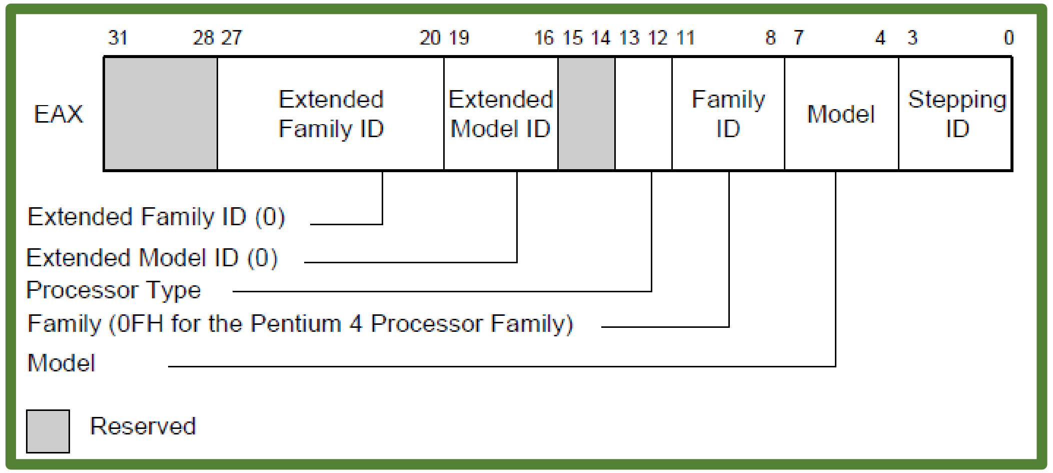
Using the MSR

- Use **`rdmsr`** to read a MSR
  - EDX:EAX = MSR[ECX]
- Use **`wrmsr`** to write a MSR
  - MSR[ECX] = EDX:EAX
- Must first confirm a particular MSR’s existence using the (complicated) **`cpuid`** instruction

Digression of a digression: CPUID

- Bit 21 (ID bit) of EFLAGS must be 1 to indicate support for CPUID
- Put a value in EAX for a query code
- Values returned in various registers (read the manual)

Input EAX = 1



Linux system calls

- A table of system call service routines is maintained by the kernel
    - `sys_call_table[]` in arch/x86/entry
        - Note: it is autogenerated at kernel build time from `arch/x86/entry/syscalls/syscall_{32|64}.tbl`
- The index to the table is the assigned system call number
- `arch/x86/entry/common.c` contains the dispatch code – after SYSENTER/SYSCALL
    - Wrapped in a bit of assembly code in `entry_{32|64}.S`

Summary

- There are only two ways to enter the kernel
    - Via interrupt
    - Using SYSCALL/SYSENTER
    - Important difference: a system call always transits from user to kernel mode, while an interrupt/exception/trap can happen even inside Ring 0

- In 64-bit, Linux expects user to enter the kernel only by the use SYSCALL/SYSENTER instructions

Important digressions

Stacks everywhere

- The modern Linux kernel is multithreaded
  - Need stacks to operate
  - No stack, no procedure call
  - If use user stack, security risk

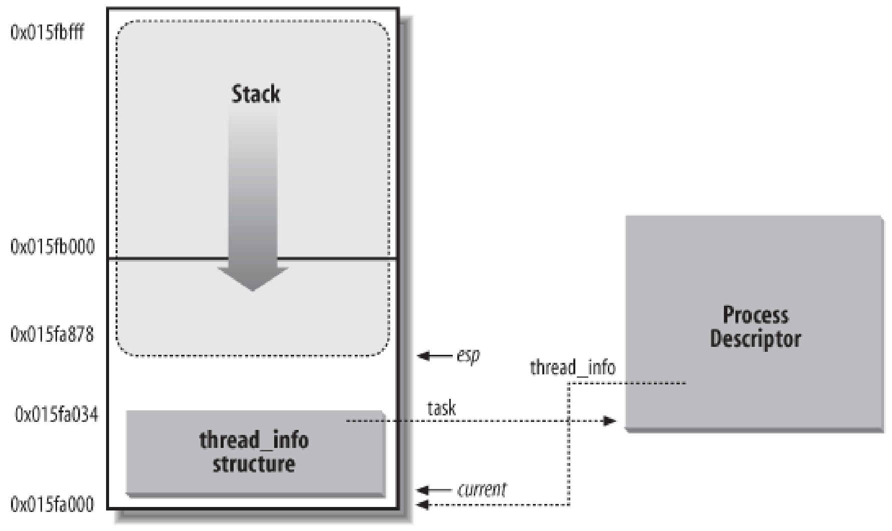
- Interrupts and stacks can happen any time

The stacks used by the kernel

- Per thread kernel stack
- Entry trampoline stack
- Interrupt Stack
- Hard IRQ Stack
- Soft IRQ Stack

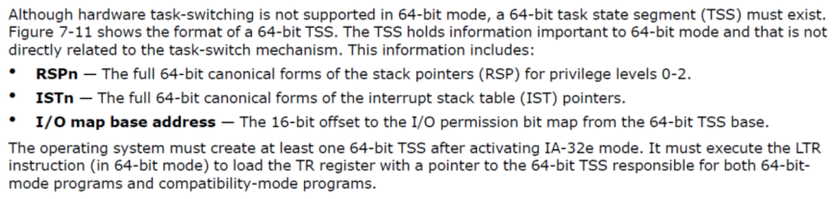
Per thread kernel stack

- 16KB
- It is in the **`task_struct`** of each process
- Grows towards the **`thread_info`** structure



Task State Segment

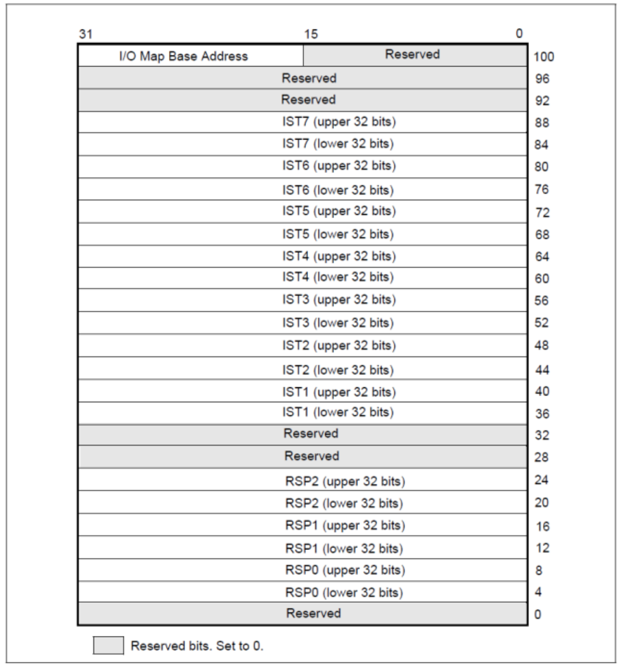
- Intel architecture provisions for OS tasks
  - Hardware task switching not supported in 64 bit mode
- Consists of pointers to stacks
  - 7 IST stacks for interrupt service routine usage
  - One for each protection ring
    - RSP0 – start of kernel stack. Use for quick access to thread_info
    - RSP1 – current top of kernel stack
    - RSP2 – scratch to contain user stack pointer on SYSCALL



Although hardware task-switching is not supported in 64-bit mode, a 64-bit task state segment (TSS) must exist. Figure 7-11 shows the format of a 64-bit TSS. The TSS holds information important to 64-bit mode and that is not directly related to the task-switch mechanism. This information includes:

- **RSPn** — The full 64-bit canonical forms of the stack pointers (RSP) for privilege levels 0-2.
- **ISTn** — The full 64-bit canonical forms of the interrupt stack table (IST) pointers.
- **I/O map base address** — The 16-bit offset to the I/O permission bit map from the 64-bit TSS base.

The operating system must create at least one 64-bit TSS after activating IA-32e mode. It must execute the LTR instruction (in 64-bit mode) to load the TR register with a pointer to the 64-bit TSS responsible for both 64-bit-mode programs and compatibility-mode programs.



31	15 0	
I/O Map Base Address	Reserved	100
Reserved		96
Reserved		92
IST7 (upper 32 bits)		88
IST7 (lower 32 bits)		84
IST6 (upper 32 bits)		80
IST6 (lower 32 bits)		76
IST5 (upper 32 bits)		72
IST5 (lower 32 bits)		68
IST4 (upper 32 bits)		64
IST4 (lower 32 bits)		60
IST3 (upper 32 bits)		56
IST3 (lower 32 bits)		52
IST2 (upper 32 bits)		48
IST2 (lower 32 bits)		44
IST1 (upper 32 bits)		40
IST1 (lower 32 bits)		36
Reserved		32
Reserved		28
RSP2 (upper 32 bits)		24
RSP2 (lower 32 bits)		20
RSP1 (upper 32 bits)		16
RSP1 (lower 32 bits)		12
RSP0 (upper 32 bits)		8
RSP0 (lower 32 bits)		4
Reserved		0

▨ Reserved bits. Set to 0.

Figure 7-11. 64-Bit TSS Format

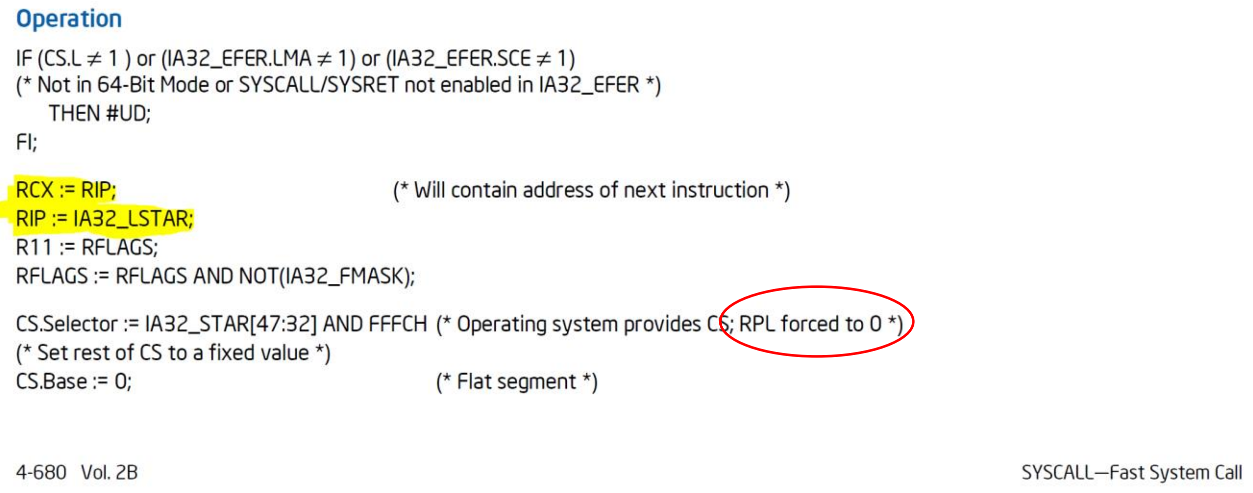
Page Table Isolation

- Full set of kernel page tables use to coexist with user page tables
- Potential security loophole!
- Two separate sets (duplicates) of kernel page tables
  - The full one
  - A minimal one in the user space just sufficient to transit to the kernel
- Implemented on Linux 4.15 onwards

Details of SYSCALL

Hardware execution

What the Intel manual says:



Operation

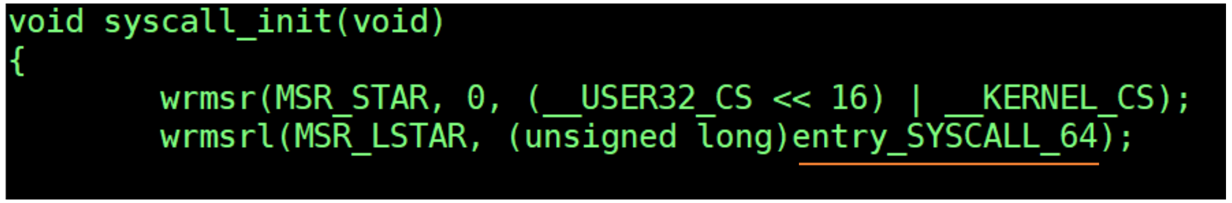
```
IF (CS.L ≠ 1 ) or (IA32_EFER.LMA ≠ 1) or (IA32_EFER.SCE ≠ 1)
(* Not in 64-Bit Mode or SYSCALL/SYSRET not enabled in IA32_EFER *)
    THEN #UD;
FI;

RCX := RIP;                              (* Will contain address of next instruction *)
RIP := IA32_LSTAR;
R11 := RFLAGS;
RFLAGS := RFLAGS AND NOT(IA32_FMASK);

CS.Selector := IA32_STAR[47:32] AND FFFCH  (* Operating system provides CS; RPL forced to 0 *)
(* Set rest of CS to a fixed value *)
CS.Base := 0;                              (* Flat segment *)
```

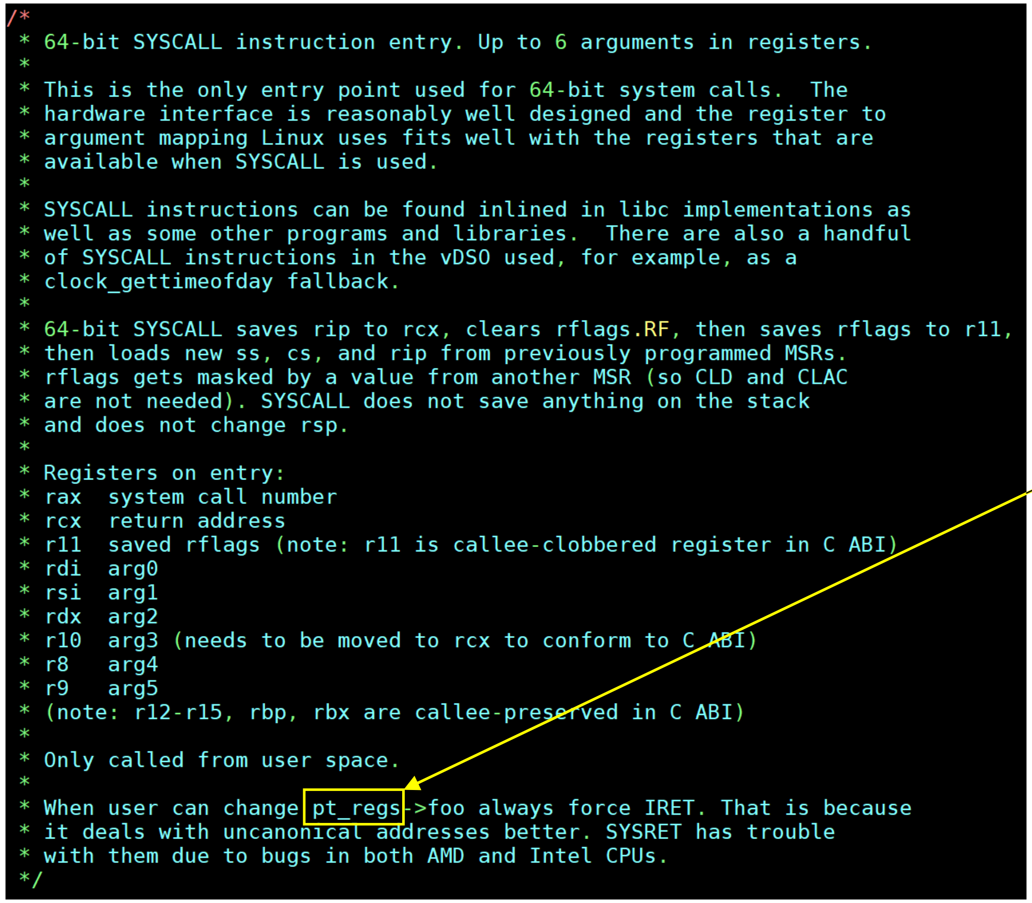
4-680 Vol. 2B SYSCALL—Fast System Call

arch/x86/kernel/cpu/common.c:1752



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

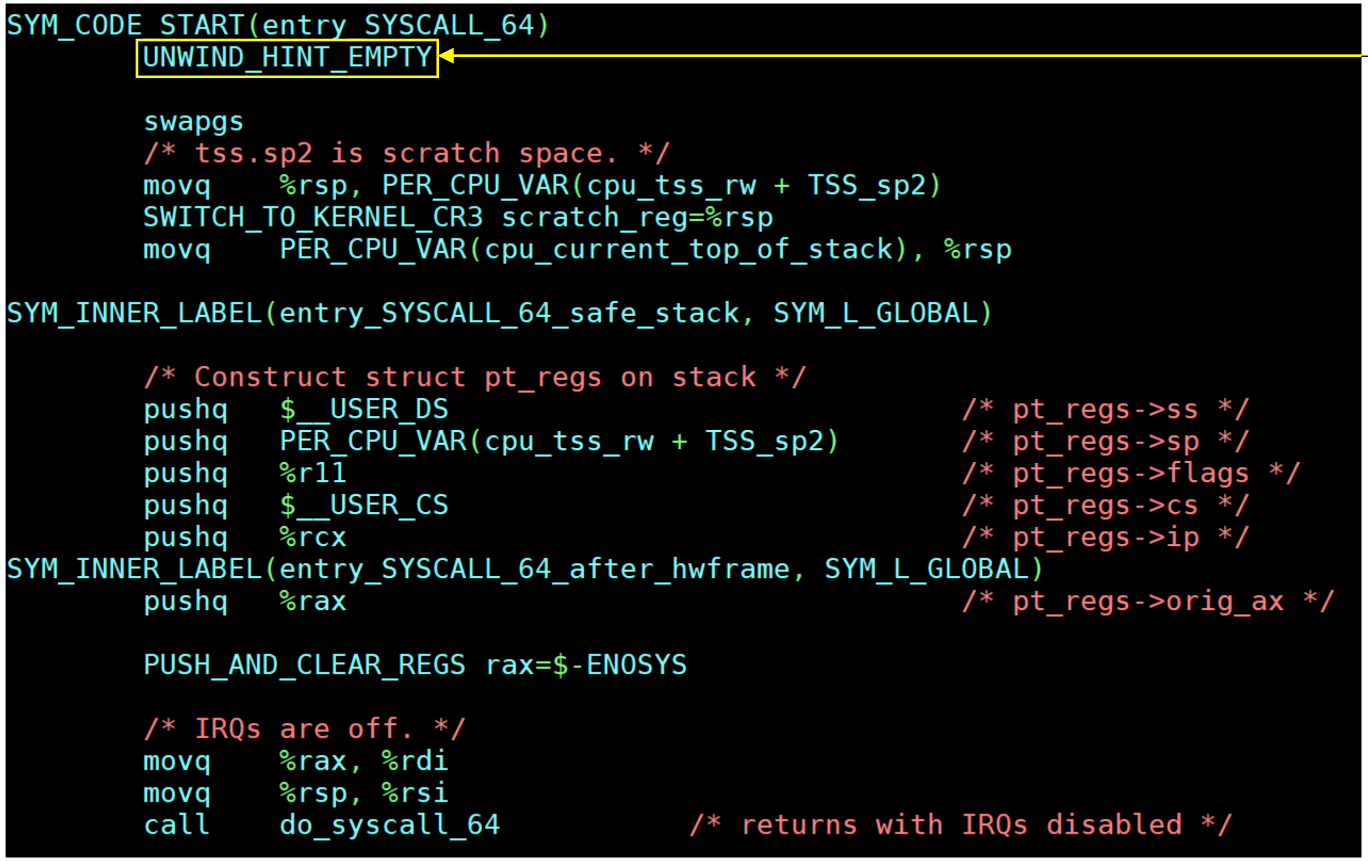
arch/x86/entry/entry_64.S



```
/*
 * 64-bit SYSCALL instruction entry. Up to 6 arguments in registers.
 *
 * This is the only entry point used for 64-bit system calls.  The
 * hardware interface is reasonably well designed and the register to
 * argument mapping Linux uses fits well with the registers that are
 * available when SYSCALL is used.
 *
 * SYSCALL instructions can be found inlined in libc implementations as
 * well as some other programs and libraries.  There are also a handful
 * of SYSCALL instructions in the vDSO used, for example, as a
 * clock_gettimeofday fallback.
 *
 * 64-bit SYSCALL saves rip to rcx, clears rflags.RF, then saves rflags to r11,
 * then loads new ss, cs, and rip from previously programmed MSRs.
 * rflags gets masked by a value from another MSR (so CLD and CLAC
 * are not needed). SYSCALL does not save anything on the stack
 * and does not change rsp.
 *
 * Registers on entry:
 * rax  system call number
 * rcx  return address
 * r11  saved rflags (note: r11 is callee-clobbered register in C ABI)
 * rdi  arg0
 * rsi  arg1
 * rdx  arg2
 * r10  arg3 (needs to be moved to rcx to conform to C ABI)
 * r8   arg4
 * r9   arg5
 * (note: r12-r15, rbp, rbx are callee-preserved in C ABI)
 *
 * Only called from user space.
 *
 * When user can change pt_regs->foo always force IRET. That is because
 * it deals with uncanonical addresses better. SYSRET has trouble
 * with them due to bugs in both AMD and Intel CPUs.
 */
```

Pt_regs is the structure for saving all registers.
Defined in **`arch/x86/include/uapi/asm/ptrace.h`**

arch/x86/entry/entry_64.S



```
SYM_CODE_START(entry_SYSCALL_64)
        UNWIND_HINT_EMPTY

        swapgs
        /* tss.sp2 is scratch space. */
        movq    %rsp, PER_CPU_VAR(cpu_tss_rw + TSS_sp2)
        SWITCH_TO_KERNEL_CR3 scratch_reg=%rsp
        movq    PER_CPU_VAR(cpu_current_top_of_stack), %rsp

SYM_INNER_LABEL(entry_SYSCALL_64_safe_stack, SYM_L_GLOBAL)

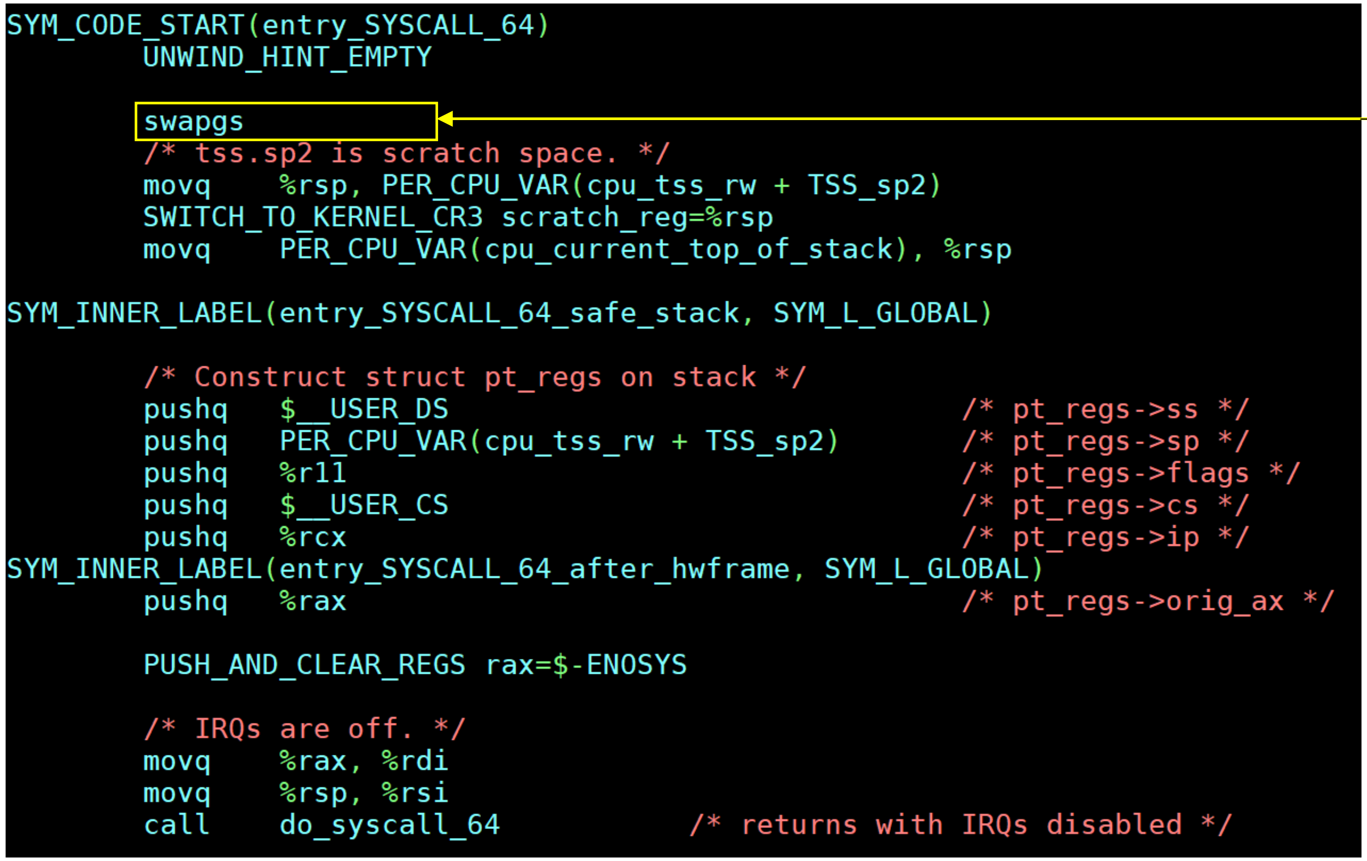
        /* Construct struct pt_regs on stack */
        pushq   $__USER_DS                              /* pt_regs->ss */
        pushq   PER_CPU_VAR(cpu_tss_rw + TSS_sp2)       /* pt_regs->sp */
        pushq   %r11                                    /* pt_regs->flags */
        pushq   $__USER_CS                              /* pt_regs->cs */
        pushq   %rcx                                    /* pt_regs->ip */
SYM_INNER_LABEL(entry_SYSCALL_64_after_hwframe, SYM_L_GLOBAL)
        pushq   %rax                                    /* pt_regs->orig_ax */

        PUSH_AND_CLEAR_REGS rax=$-ENOSYS

        /* IRQs are off. */
        movq    %rax, %rdi
        movq    %rsp, %rsi
        call    do_syscall_64           /* returns with IRQs disabled */
```

Code written in asembly can do funky things to the stack. This makes it hard for debugging tools to follow the stack frame properly as they don’t follow the proper calling convention. This is a macro that gives “hints” to such debuggers.

arch/x86/entry/entry_64.S



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SYM_INNER_LABEL(entry_SYSCALL_64_safe_stack, SYM_L_GLOBAL)

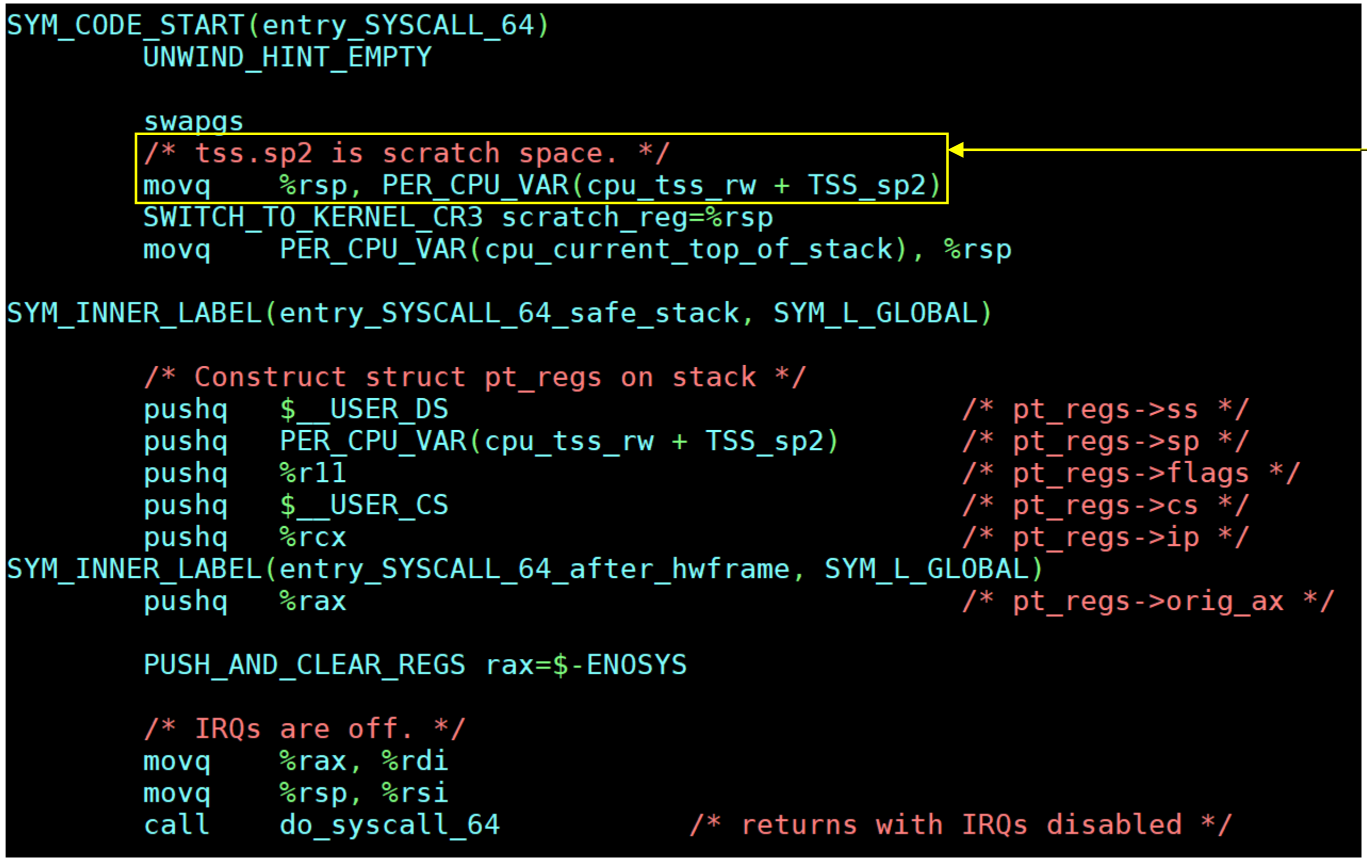
        /* Construct struct pt_regs on stack */
        pushq   $__USER_DS                              /* pt_regs->ss */
        pushq   PER_CPU_VAR(cpu_tss_rw + TSS_sp2)       /* pt_regs->sp */
        pushq   %r11                                    /* pt_regs->flags */
        pushq   $__USER_CS                              /* pt_regs->cs */
        pushq   %rcx                                    /* pt_regs->ip */
SYM_INNER_LABEL(entry_SYSCALL_64_after_hwframe, SYM_L_GLOBAL)
        pushq   %rax                                    /* pt_regs->orig_ax */

        PUSH_AND_CLEAR_REGS rax=$-ENOSYS

        /* IRQs are off. */
        movq    %rax, %rdi
        movq    %rsp, %rsi
        call    do_syscall_64           /* returns with IRQs disabled */
```

GS segment register is used for quick access to the per CPU region so as to get the per-CPU variables quickly .

arch/x86/entry/entry_64.S



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        SWITCH_TO_KERNEL_CR3 scratch_reg=%rsp
        movq    PER_CPU_VAR(cpu_current_top_of_stack), %rsp

SYM_INNER_LABEL(entry_SYSCALL_64_safe_stack, SYM_L_GLOBAL)

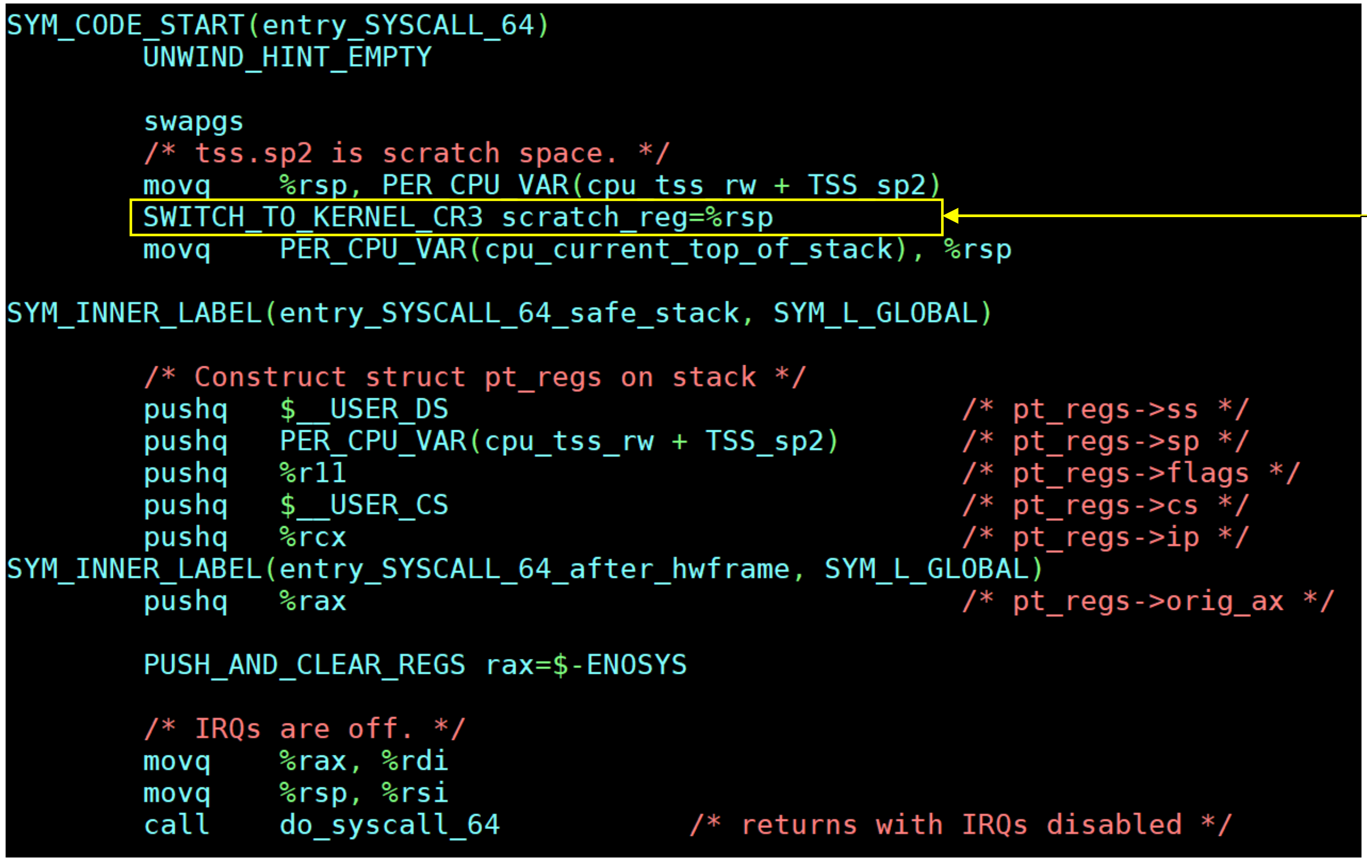
        /* Construct struct pt_regs on stack */
        pushq   $__USER_DS                              /* pt_regs->ss */
        pushq   PER_CPU_VAR(cpu_tss_rw + TSS_sp2)       /* pt_regs->sp */
        pushq   %r11                                    /* pt_regs->flags */
        pushq   $__USER_CS                              /* pt_regs->cs */
        pushq   %rcx                                    /* pt_regs->ip */
SYM_INNER_LABEL(entry_SYSCALL_64_after_hwframe, SYM_L_GLOBAL)
        pushq   %rax                                    /* pt_regs->orig_ax */

        PUSH_AND_CLEAR_REGS rax=$-ENOSYS

        /* IRQs are off. */
        movq    %rax, %rdi
        movq    %rsp, %rsi
        call    do_syscall_64           /* returns with IRQs disabled */
```

saves the user mode stack pointer into a scratch location, namely the **`sp2`** of the TSS which is also not used since Ring 2 is not used.

arch/x86/entry/entry_64.S



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        SWITCH_TO_KERNEL_CR3 scratch_reg=%rsp
        movq    PER_CPU_VAR(cpu_current_top_of_stack), %rsp

SYM_INNER_LABEL(entry_SYSCALL_64_safe_stack, SYM_L_GLOBAL)

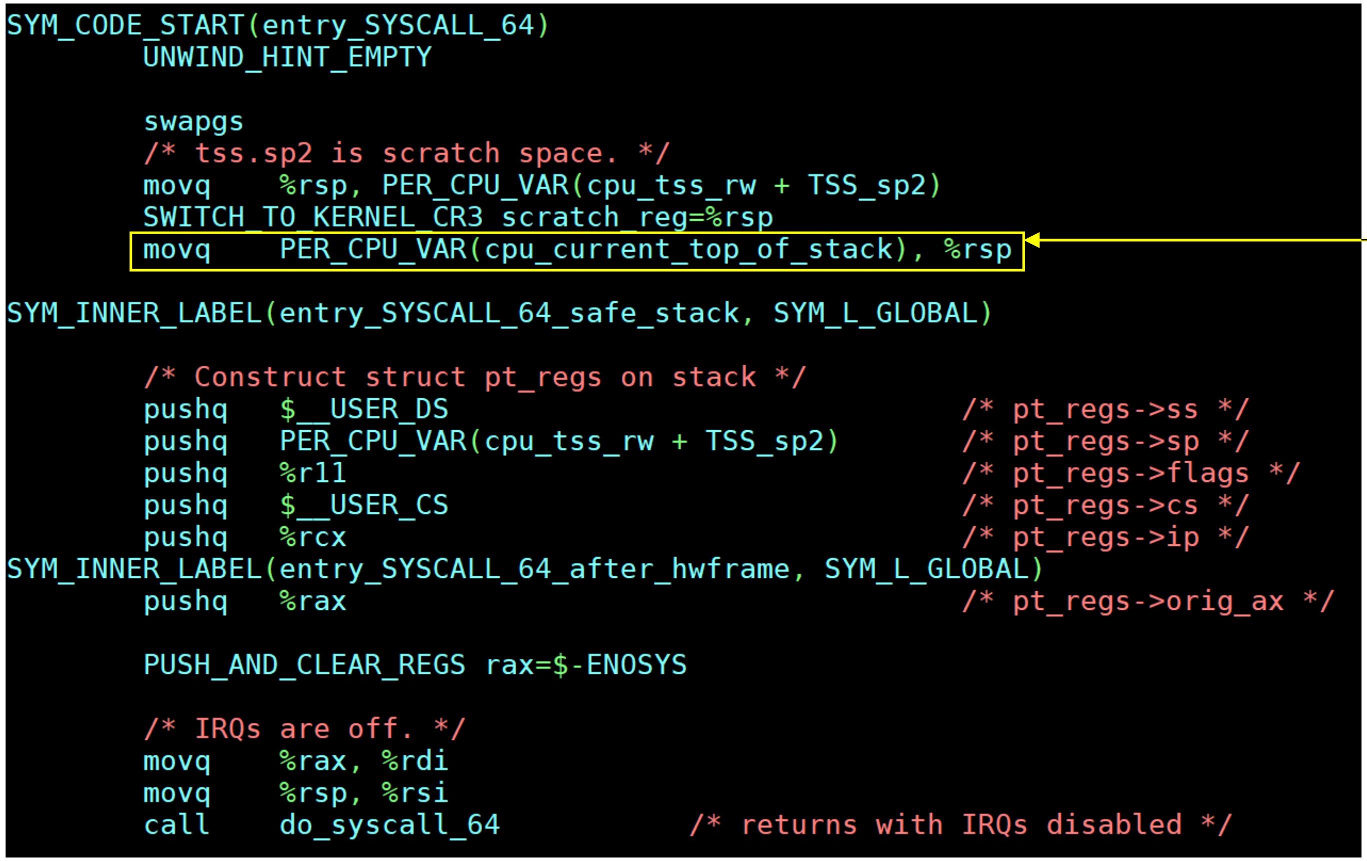
        /* Construct struct pt_regs on stack */
        pushq   $__USER_DS                      /* pt_regs->ss */
        pushq   PER_CPU_VAR(cpu_tss_rw + TSS_sp2)       /* pt_regs->sp */
        pushq   %r11                            /* pt_regs->flags */
        pushq   $__USER_CS                      /* pt_regs->cs */
        pushq   %rcx                            /* pt_regs->ip */
SYM_INNER_LABEL(entry_SYSCALL_64_after_hwframe, SYM_L_GLOBAL)
        pushq   %rax                            /* pt_regs->orig_ax */

        PUSH_AND_CLEAR_REGS rax=$-ENOSYS

        /* IRQs are off. */
        movq    %rax, %rdi
        movq    %rsp, %rsi
        call    do_syscall_64           /* returns with IRQs disabled */
```

Restore the full kernel page table. Use `%rsp` as a scratch since it was already saved up.

arch/x86/entry/entry_64.S



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        swapgs
        /* tss.sp2 is scratch space. */
        movq    %rsp, PER_CPU_VAR(cpu_tss_rw + TSS_sp2)
        SWITCH_TO_KERNEL_CR3 scratch_reg=%rsp
        movq    PER_CPU_VAR(cpu_current_top_of_stack), %rsp

SYM_INNER_LABEL(entry_SYSCALL_64_safe_stack, SYM_L_GLOBAL)

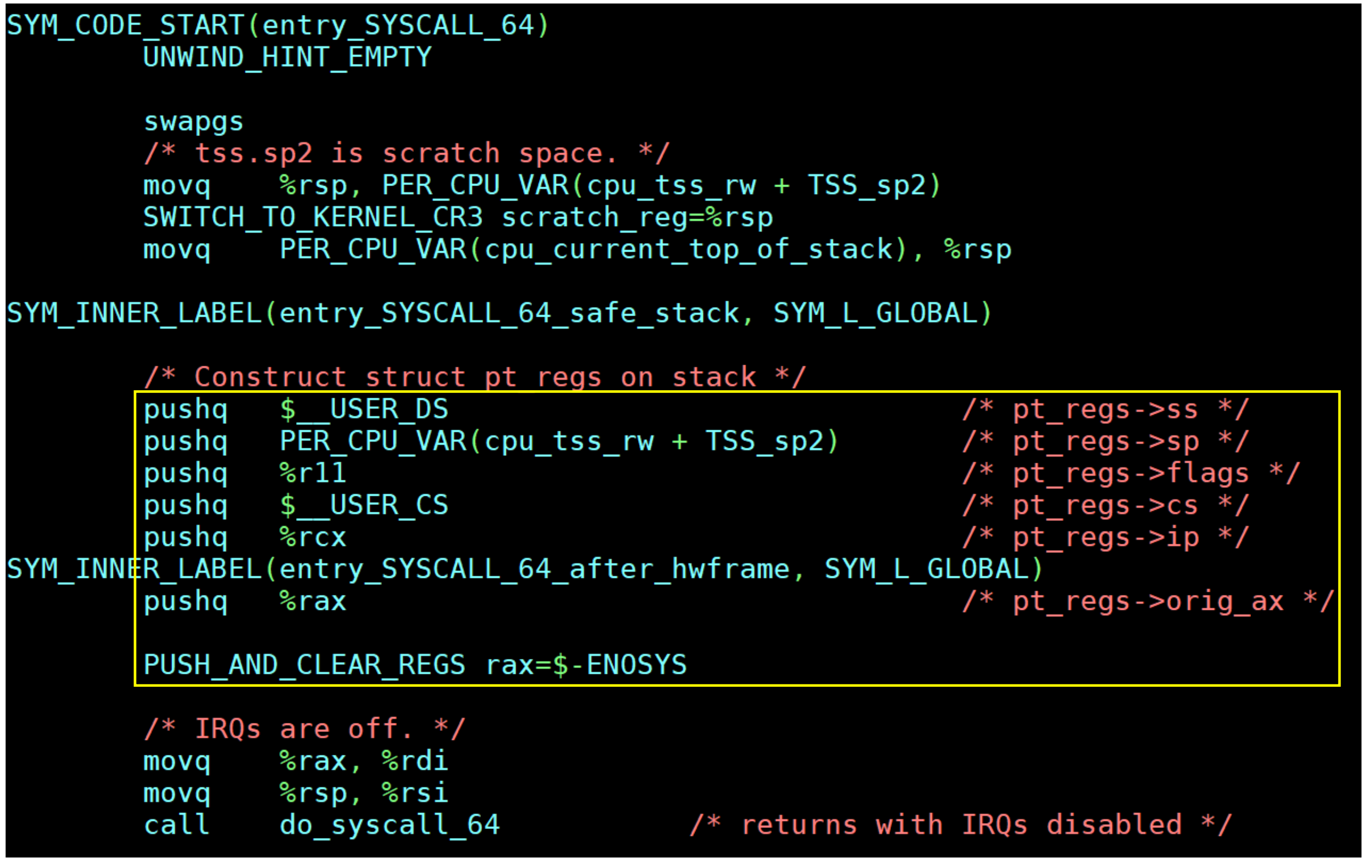
        /* Construct struct pt_regs on stack */
        pushq   $__USER_DS                              /* pt_regs->ss */
        pushq   PER_CPU_VAR(cpu_tss_rw + TSS_sp2)       /* pt_regs->sp */
        pushq   %r11                                    /* pt_regs->flags */
        pushq   $__USER_CS                              /* pt_regs->cs */
        pushq   %rcx                                    /* pt_regs->ip */
SYM_INNER_LABEL(entry_SYSCALL_64_after_hwframe, SYM_L_GLOBAL)
        pushq   %rax                                    /* pt_regs->orig_ax */

        PUSH_AND_CLEAR_REGS rax=$-ENOSYS

        /* IRQs are off. */
        movq    %rax, %rdi
        movq    %rsp, %rsi
        call    do_syscall_64           /* returns with IRQs disabled */
```

Switch to true kernel stack.

arch/x86/entry/entry_64.S



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        UNWIND_HINT_EMPTY

        swapgs
        /* tss.sp2 is scratch space. */
        movq    %rsp, PER_CPU_VAR(cpu_tss_rw + TSS_sp2)
        SWITCH_TO_KERNEL_CR3 scratch_reg=%rsp
        movq    PER_CPU_VAR(cpu_current_top_of_stack), %rsp

SYM_INNER_LABEL(entry_SYSCALL_64_safe_stack, SYM_L_GLOBAL)

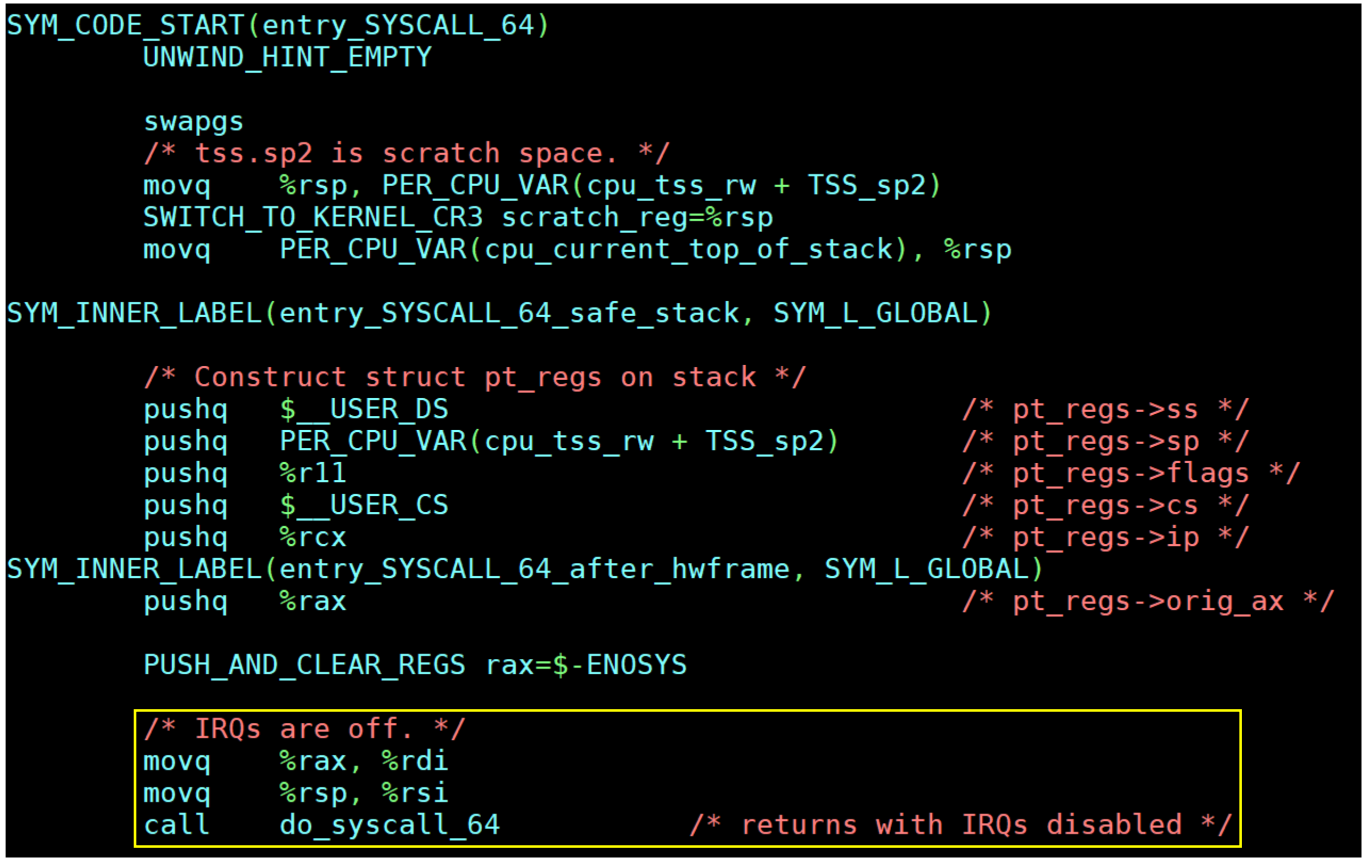
        /* Construct struct pt_regs on stack */
        pushq   $__USER_DS                              /* pt_regs->ss */
        pushq   PER_CPU_VAR(cpu_tss_rw + TSS_sp2)       /* pt_regs->sp */
        pushq   %r11                                    /* pt_regs->flags */
        pushq   $__USER_CS                              /* pt_regs->cs */
        pushq   %rcx                                    /* pt_regs->ip */
SYM_INNER_LABEL(entry_SYSCALL_64_after_hwframe, SYM_L_GLOBAL)
        pushq   %rax                                    /* pt_regs->orig_ax */

        PUSH_AND_CLEAR_REGS rax=$-ENOSYS

        /* IRQs are off. */
        movq    %rax, %rdi
        movq    %rsp, %rsi
        call    do_syscall_64           /* returns with IRQs disabled */
```

Saves (some) registers to pt_regs.

arch/x86/entry/entry_64.S



```
SYM_CODE_START(entry_SYSCALL_64)
        UNWIND_HINT_EMPTY

        swapgs
        /* tss.sp2 is scratch space. */
        movq    %rsp, PER_CPU_VAR(cpu_tss_rw + TSS_sp2)
        SWITCH_TO_KERNEL_CR3 scratch_reg=%rsp
        movq    PER_CPU_VAR(cpu_current_top_of_stack), %rsp

SYM_INNER_LABEL(entry_SYSCALL_64_safe_stack, SYM_L_GLOBAL)

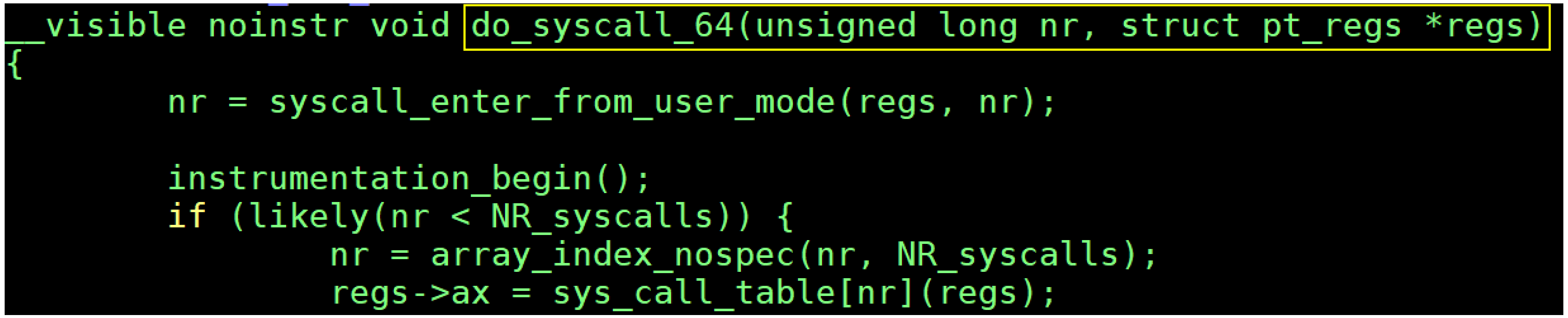
        /* Construct struct pt_regs on stack */
        pushq   $__USER_DS                              /* pt_regs->ss */
        pushq   PER_CPU_VAR(cpu_tss_rw + TSS_sp2)       /* pt_regs->sp */
        pushq   %r11                                    /* pt_regs->flags */
        pushq   $__USER_CS                              /* pt_regs->cs */
        pushq   %rcx                                    /* pt_regs->ip */
SYM_INNER_LABEL(entry_SYSCALL_64_after_hwframe, SYM_L_GLOBAL)
        pushq   %rax                                    /* pt_regs->orig_ax */

        PUSH_AND_CLEAR_REGS rax=$-ENOSYS

        /* IRQs are off. */
        movq    %rax, %rdi
        movq    %rsp, %rsi
        call    do_syscall_64           /* returns with IRQs disabled */
```

Call the service dispatcher.

arch/x86/entry/common.c



```
__visible noinstr void do_syscall_64(unsigned long nr, struct pt_regs *regs)
{
        nr = syscall_enter_from_user_mode(regs, nr);

        instrumentation_begin();
        if (likely(nr < NR_syscalls)) {
                nr = array_index_nospec(nr, NR_syscalls);
                regs->ax = sys_call_table[nr](regs);
```

Speeding up system calls (1)

vsyscall

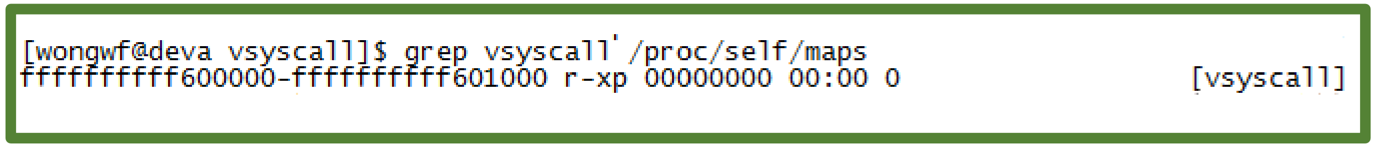
vsyscall

- Certain system calls can get called very often

- How to speed it up even faster?
  - Key: do not actually enter the kernel

Executing system call in userspace

- Linux kernel maps a page containing some kernel variables and implementation of some system calls into the user space
  - Key: read only!



```
[wongwf@deva vsyscall]$ grep vsyscall /proc/self/maps
ffffffffff600000-ffffffffff601000 r-xp 00000000 00:00 0                  [vsyscall]
```

Nuts and bolts

- Mapping of the **`vsyscall`** page occurs in the **`map_vsyscall`** function that is defined in the **`arch/x86/entry/vsyscall/vsyscall_64.c`**
- This is called during kernel initialization

Read only

- Used to be done for `gettimeofday()`, `time()` and `getcpu()`
  - All read only functions

- The vsyscall page contains the variables involved and the small amount of (kernel) code to read them
  - Page is readable, executable but not writable

Deprecated!

- Now deemed too dangerous!
  - Exposing a kernel physical page to the all user processes at a fixed known address

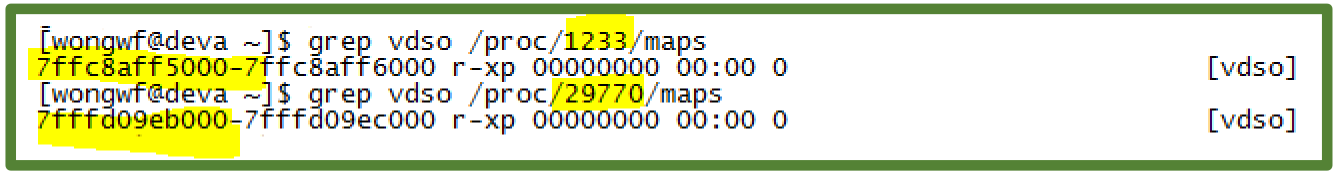
Speeding up system calls (2)

Virtual Dynamic Shared Object

vDSO

- Also same idea as vsyscall but allow linker to do address space randomization (ASR) and place the page anywhere in the virtual space

- Example from two different processes:



```
[wongwf@deva ~]$ grep vdso /proc/1233/maps
7ffc8aff5000-7ffc8aff6000 r-xp 00000000 00:00 0                          [vdso]
[wongwf@deva ~]$ grep vdso /proc/29770/maps
7fffd09eb000-7fffd09ec000 r-xp 00000000 00:00 0                          [vdso]
```

Kernel-GLIBC

- Kernel provide the dynamic shared object to the loader
  - **`vdso{32|64}.so`** in **`arch/x86/entry/vdso`**

- Kernel detects loading of shared executable, will then provide the shared object in the process image

- Final setup done by glibc ELF startup code

END