System Calls Management

Advanced Operating Systems and Virtualization

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Userspace Kernel API: System Calls

- For Linux (same for Windows), the gate for on-demand access (via software traps) to the kernel is only one
- For i386 machines the corresponding software traps are:
  - 0x80 for LINUX
  - 0x2E for Windows
- The software module associated with the on-demand access GATE implements a *dispatcher* that is able to trigger the activation of the specific system call targeted by the application

trap_init()

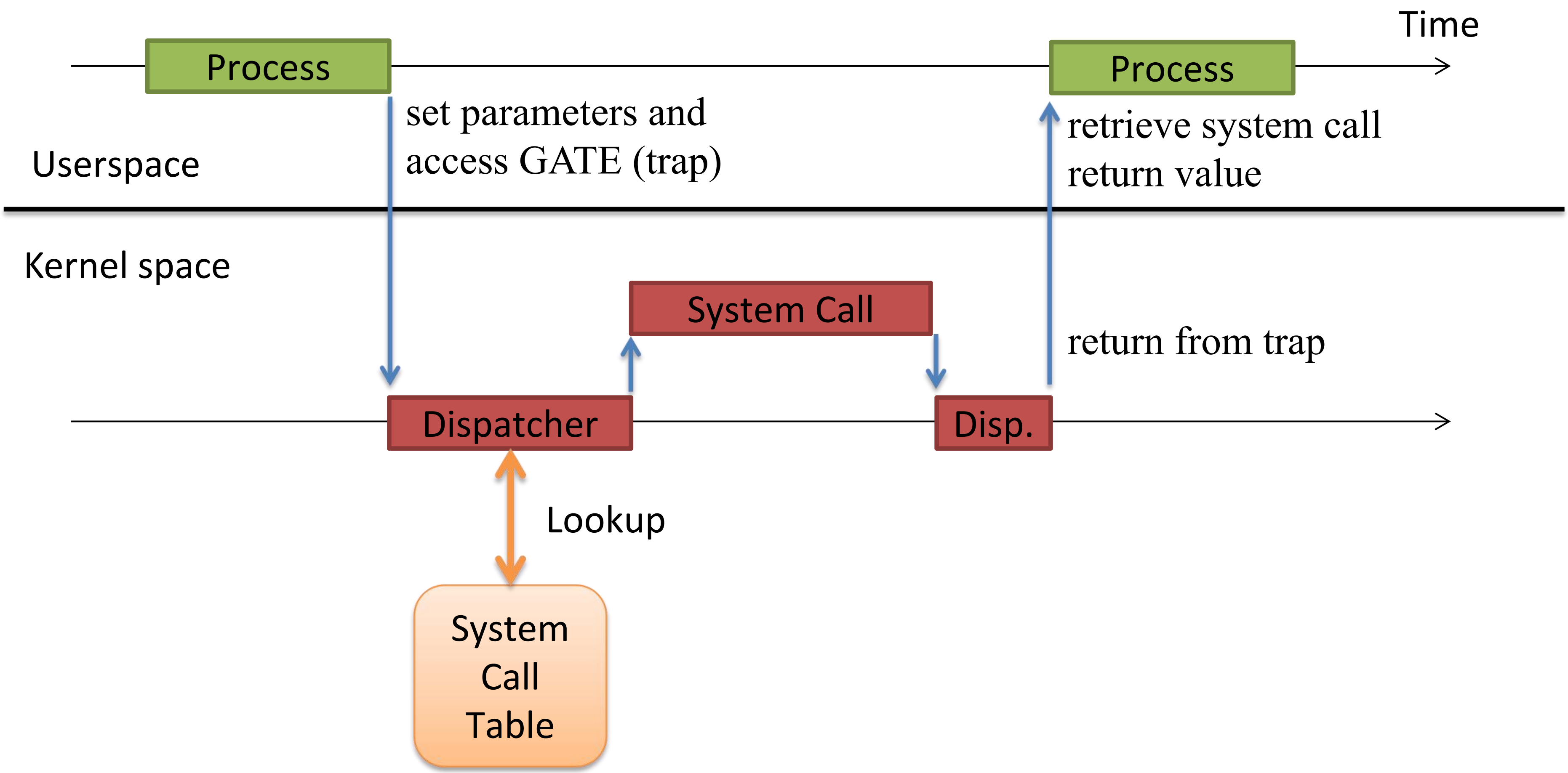
```
gate_desc idt_table[NR_VECTORS] __page_aligned_bss;

void __init trap_init(void) {
        set_intr_gate(X86_TRAP_DE, divide_error);
        set_intr_gate_ist(X86_TRAP_NMI, &nmi, NMI_STACK);
        set_system_intr_gate(X86_TRAP_OF, &overflow);
        set_intr_gate(X86_TRAP_BR, bounds);
        set_intr_gate(X86_TRAP_UD, invalid_op);
        set_intr_gate(X86_TRAP_NM, device_not_available);
        set_task_gate(X86_TRAP_DF, GDT_ENTRY_DOUBLEFAULT_TSS);
        set_intr_gate_ist(X86_TRAP_DF, &double_fault,
                          DOUBLEFAULT_STACK);
        set_intr_gate(X86_TRAP_OLD_MF,
                      coprocessor_segment_overrun);
        set_intr_gate(X86_TRAP_TS, invalid_TSS);
        ...
        set_system_trap_gate(SYSCALL_VECTOR, &system_call);
        ...
}
```

0x80

System Call Dispatching

- The main data structure is the *system call* table
- Each entry of the table points to a kernel-level function, activated by the dispatcher
- To access the correct entry, the dispatcher needs as input the system call number (provided in a CPU register)
- The code is used to identify the target entry within the system call table
- The system call is activated via an indirect call
- The return value is returned in a register

Dispatcher Mechanism



Compile-Time Syscall Interface (2.4)

- This is all based on macros
  - Macros for standard formats are in `include/asm-xx/unistd.h` (or `asm/unistd.h`)
- There we find:
  - System call numerical codes
    - They are numbers used to invoke a syscall for userspace
    - They are a displacement in the syscall table for kernel space
  - Standard macros to let userspace access the gate to the Kernel
    - There is a macro for each range of parameters, from 0 to 6

Syscall codes (2.4.20)

```
/*
 * 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_fallocate             324
```

Macro for a 0-Parameters Syscall

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

Example syscall: `fork()`

Return from a syscall

```
/* 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)
```

Only if `res` in [–1, -124]

What's that?!

Macro for a 1-Parameter Syscall

```
#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); \
}
```

Example syscall: `close()`

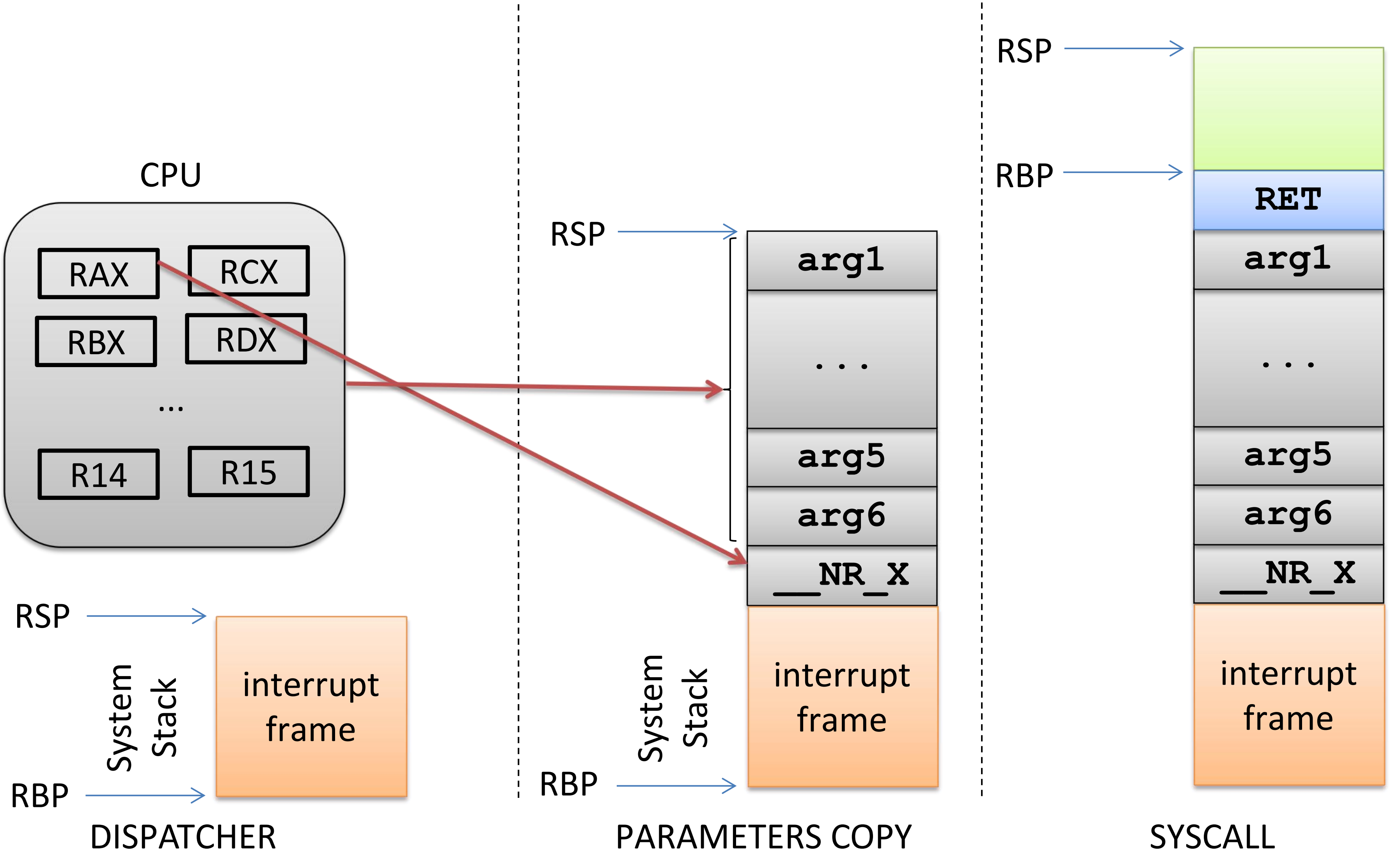
Macro for a 6-Parameters Syscall

```
#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); \
}
```

Dispatcher Activities

- Once gained control, the dispatcher takes a complete snapshot of CPU registers
- The snapshot is taken within the system-level stack
- Then the system call is invoked as a subroutine call (via a `call`)
- The system call retrieves the parameters from stack via the base pointer (remember `asmlinkage`?)

Dispatcher Activities



CPU Stack (i386)

pt_regs

```
/*
 *      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
 */
```

arguments

Syscall number

Interrupt frame

Syscall Dispatcher (i386)

```
ENTRY(system_call)
	pushl %eax  # syscall no.
	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
```

`syscall()`

- This is a construct introduced in Kernel 2.6 for the Pentium 3 chip
- Implemented through glibc (stdlib.h)
- It triggers a trap to execute a generic system call
- The first argument is the system call number
- The other parameters are the input for the system call code
- Based on new x86 instructions: `sysenter`/`sysexit` or `syscall`/`sysret` (initially for AMD chips)

i386 Fast syscall Path

SYSENTER

based on model-specific registers

CS register set to the value of (SYSENTER_CS_MSR)

EIP register set to the value of (SYSENTER_EIP_MSR)

SS register set to the sum of (8 plus the value in SYSENTER_CS_MSR)

ESP register set to the value of (SYSENTER_ESP_MSR)

SYSEXIT

based on model-specific registers

CS register set to the sum of (16 plus the value in SYSENTER_CS_MSR)

EIP register set to the value contained in the EDX register

SS register set to the sum of (24 plus the value in SYSENTER_CS_MSR)

ESP register set to the value contained in the ECX register

Model-Specific Registers for Syscalls

/include/asm/msr.h:

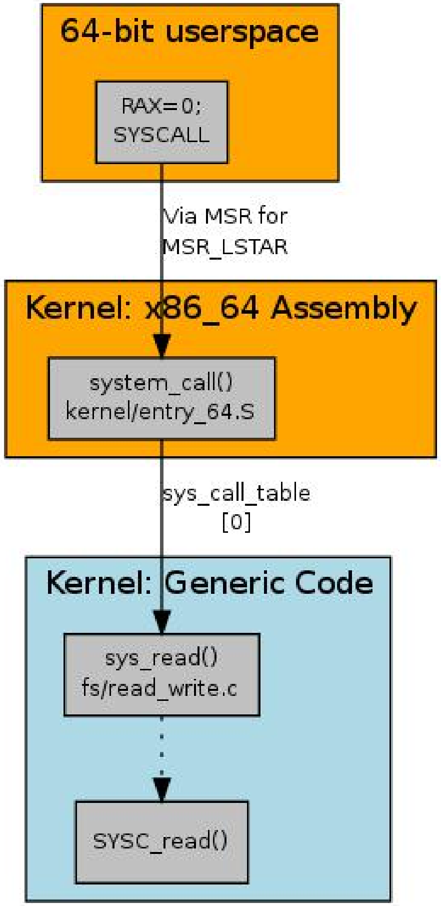
```
#define MSR_IA32_SYSENTER_CS   0x174
#define MSR_IA32_SYSENTER_ESP 0x175
#define MSR_IA32_SYSENTER_EIP  0x176
```

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

```
wrmsr(MSR_IA32_SYSENTER_CS, __KERNEL_CS, 0);
wrmsr(MSR_IA32_SYSENTER_ESP, tss->esp0, 0);
wrmsr(MSR_IA32_SYSENTER_EIP, (unsigned long)
     sysenter_entry, 0);
```

Again based on `rdmsr` and `wrmsr`

x64 syscall invocation



- SYSCALL/SYSRET
  - Again, based on MSRs

```
void syscall_init(void)
{
/*
 * LSTAR and STAR live in a bit strange symbiosis.
 * They both write to the same internal register.
 * STAR allows to set CS/DS but only a 32bit target.
 * LSTAR sets the 64bit rip.
 */
  wrmsrl(MSR_STAR,  ((u64)__USER32_CS)<<48  |
                    ((u64)__KERNEL_CS)<<32);
  wrmsrl(MSR_LSTAR, system_call);
  /* ... */
}
```

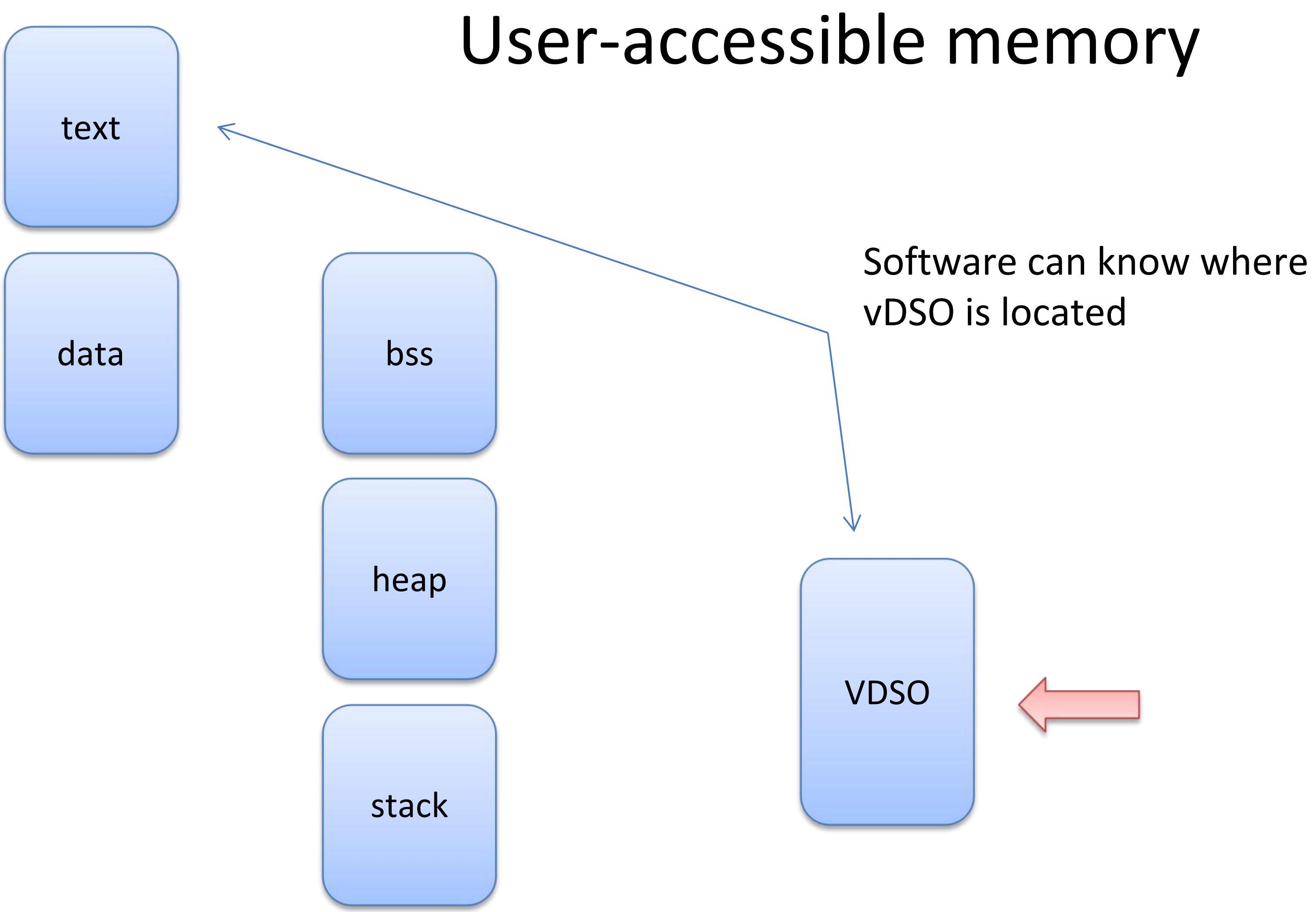
x64 Calling Conventions (syscalls)

```
/*
 * 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.
 */
```

Virtual Dynamic Shared Object (vDSO)

- Syscall entry/exit points are set by the Kernel
- Few memory pages are created and made visible to all processes' addres spaces when they are initialized
- There processes find the actual code for the syscall entry/exit mechanism
- For i386 the definition is (up to Kernel 2.6.23) in `arch/i386/kernel/vsyscall-sysenter.S`
- In later versions, it's become an actual shared library. The source tree is at `/source/arch/x86/vdso` and the entry point is thus moved to `/arch/x86/vdso/vdso32/sysenter.S`

Mapping vDSO



Exposing vDSO

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

The "vDSO" (virtual dynamic shared object) 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.

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
```

Considerations on the vDSO

- 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%
- It allows randomization: security is enhanced

The syscall Table

- 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`
- Entries keep a reference to the kernel-level system call implementation
- Typically, the kernel-level name resembles the one used at application level (traditionally `sys_`...)

C Syscall Entry Points (4.20)

- /arch/x86/entry/syscalls/syscall_64.tbl:

```
0 common read __x64_sys_read
```

- /include/linux/syscalls.h:

```
asmlinkage long sys_read(unsigned int fd, char __user
*buf, size_t count);
```

- /fs/read_write.c:

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

C Syscall Entry Points (4.20)

- `include/linux/syscalls.h`:

```
#define SYSCALL_DEFINE3(name, ...) \
SYSCALL_DEFINEx(3, _##name, __VA_ARGS__)

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

- The final macro `__SYSCALL_DEFINEx()` will generate the actual entry point of the system call, with additional protection mechanisms

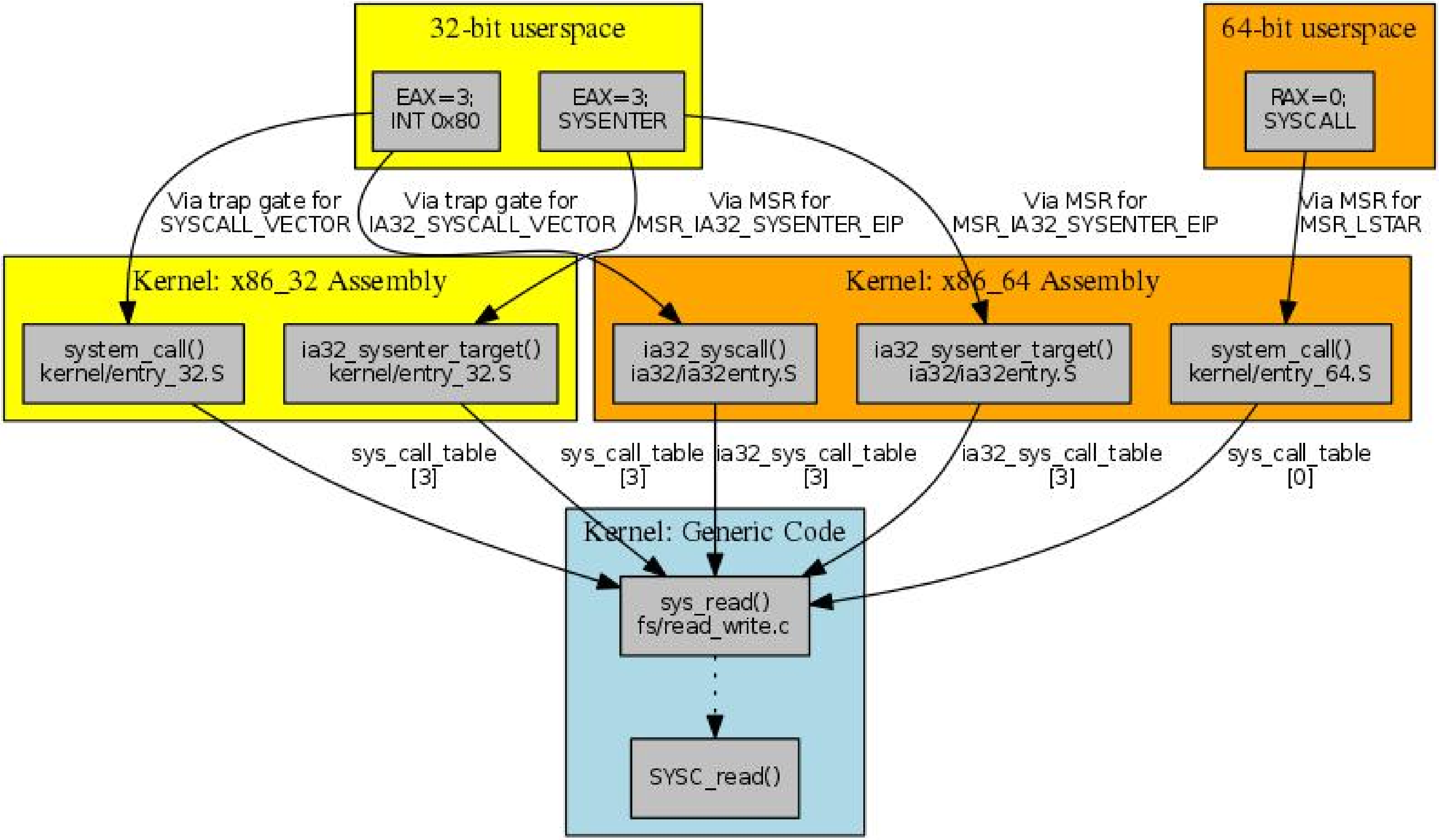
C Syscall Entry Points (4.20)

```
asmlinkage long sys_read(unsigned int fd, char __user * buf, size_t count)
__attribute__((alias(__stringify(SyS_read))));
```

for security reasons (sign extension)

```
asmlinkage long SyS_read(long int fd, long int buf, long int count)
{
    long ret = SYSC_read((unsigned int) fd, (char __user *) buf, (size_t) count);
    asmlinkage_protect(3, ret, fd, buf, count);
    return ret;
}

static inline long SYSC_read(unsigned int fd, char __user * buf, size_t count)
{
    return ksys_read(fd, buf, count);
}
```

The Final Picture



Security of SYSRET

- Before executing a sysret, the kernel must switch back to userspace stack
- This opens a race condition with NMI handlers
- This is the reason why the TSS has been modified
  - The Interrupt Stack Table allows to move NMIs off the main stacks