Jin-Soo Kim
(*jinsoo.kim@snu.ac.kr*)

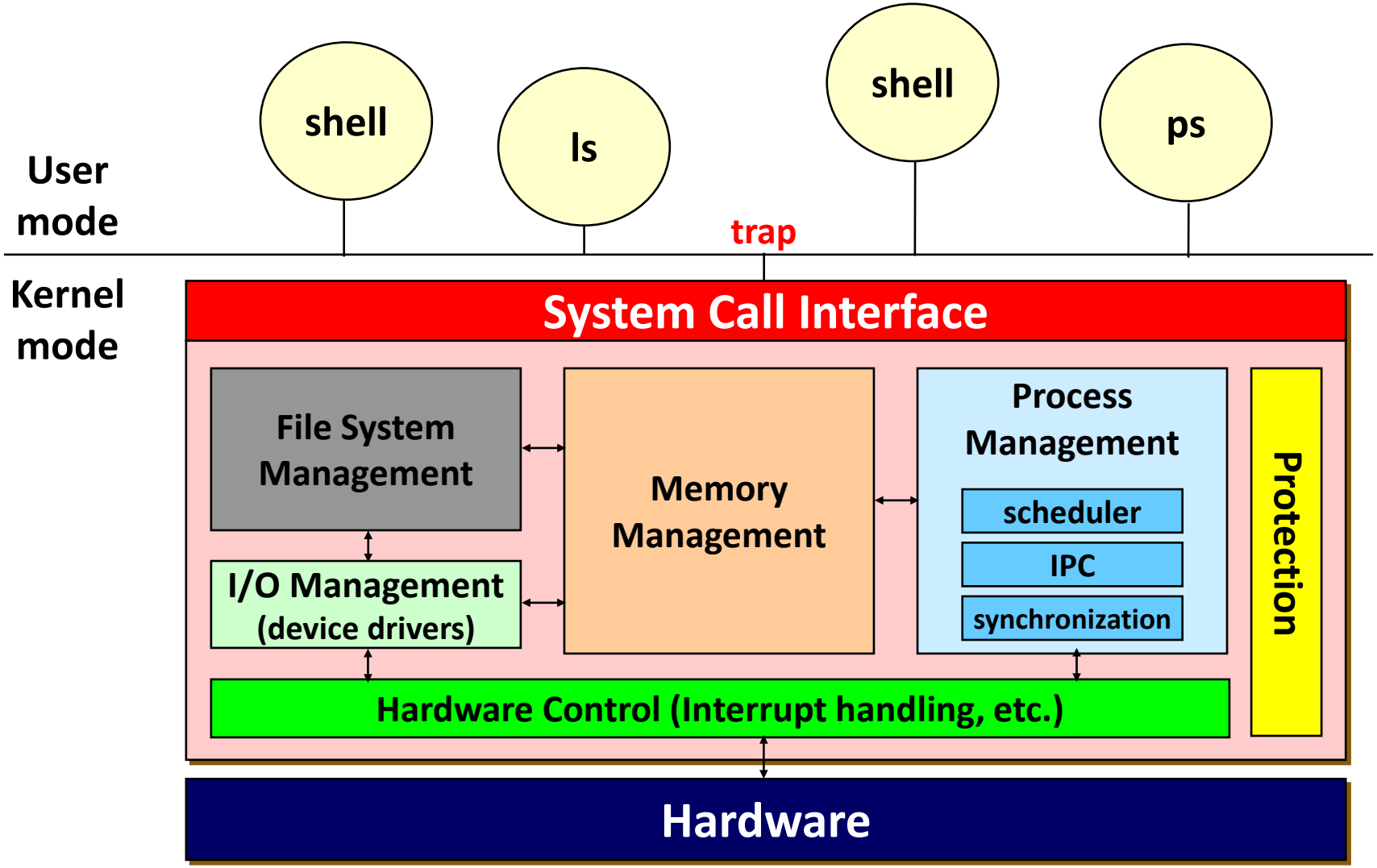
Systems Software &
Architecture Lab.

Seoul National University

Fall 2020

Introduction to Operating Systems

Operating System Internals



OS: Application View

- OS provides an execution environment for running programs
- OS provides a(an) _____ view of the underlying computer system
  - What are the correct abstractions?
  - How much of hardware should be exposed?
- Typical OS abstractions
  - Processors → Processes, Threads
  - Memory → Address space (virtual memory)
  - Storage → Volumes, Directories, Files
  - I/O Devices → Files (+ ioctls)
  - Networks → Files (sockets, pipes, …)

OS: System View

- OS manages various resources of a computer system

- Sharing
- _____
- Fairness
- Efficiency
- …

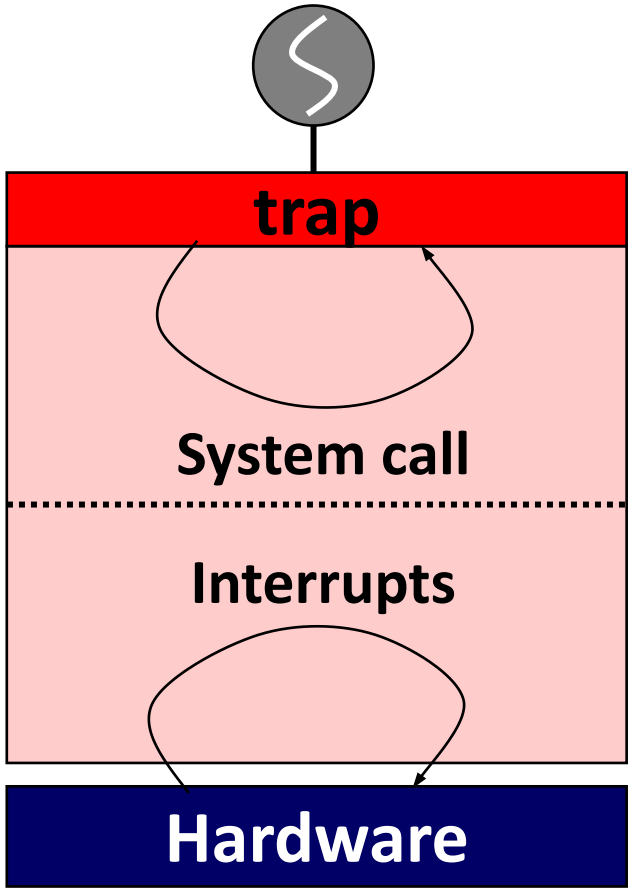
Resources

- **CPU**
- **Memory**
- **I/O devices**
- **Queues**
- **Energy**
- **…**

OS: Implementation View

- OS is highly-concurrent, _____ software

- Two kinds of events
  - System calls
  - Interrupts



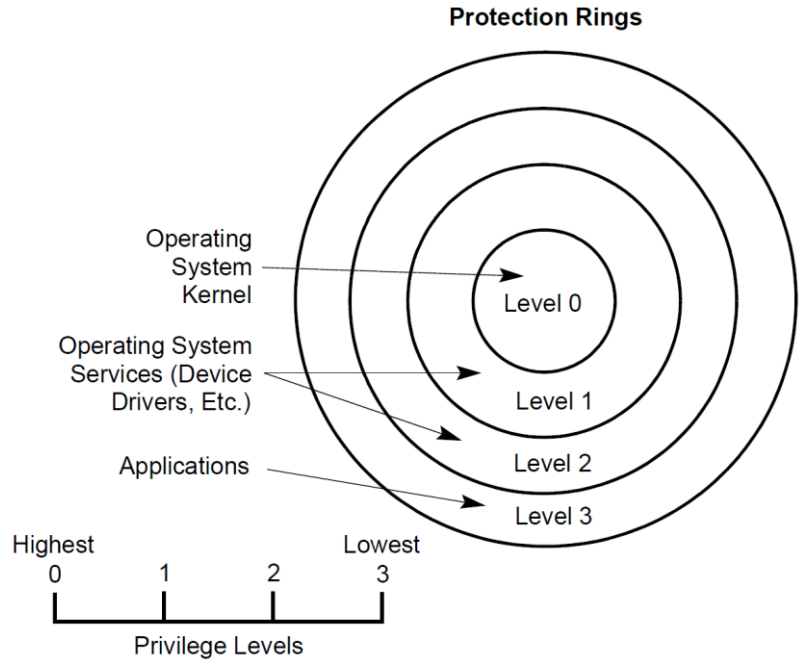
Unix Features

- Process control
  - `fork()`, `exec()`, `wait()`, `exit()`
  - Pipes for inter-process communication (IPC)
- Hierarchical file systems
  - Special files: uniform I/O, naming, and protection
  - Removable file systems via mount/umount
  - i-node
- Signals
- Shells
  - Standard I/O and I/O redirection, filters
  - Shell scripts

Architectural Support for OS (1)

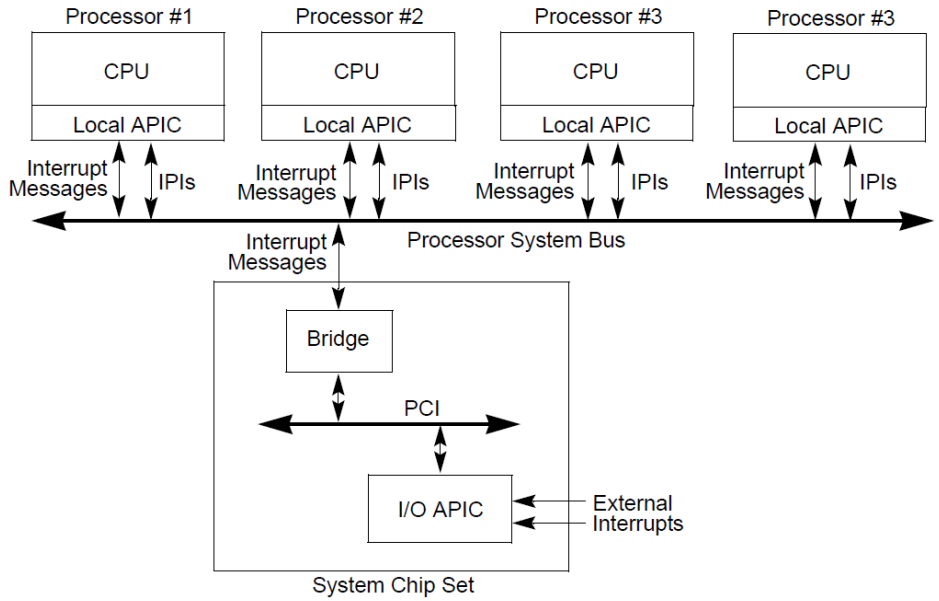
- CPU modes of operation: kernel vs. user
  - 4 levels in x86: Ring 0 > 1 > 2 > 3
  - 3 levels in RISC-V: Machine > Supervisor > User

- Protected or _____ instructions
  - Direct I/O access (e.g., `in`/`out` instructions in x86)
  - Accessing system registers
  - Memory state management
  - …



Architectural Support for OS (2)

- Interrupts
  - Generated by hardware devices
  - External interrupts vs. IPIs
  - Asynchronous



- Exceptions
  - Generated by software executing instructions
    - Faults (unintentional, but possibly recoverable): page faults, protection faults, …
    - Traps (intentional): `syscall` instruction in x86_64 or `ecall` instruction in RISC-V
    - Aborts (unintentional and unrecoverable): parity error, machine error, …
  - Synchronous
  - Exception handling is logically same as interrupt handling

Architectural Support for OS (3)

- Memory protection
  - Segmentation
  - Paging
- Timer
- DMA (Direct Memory Access)
- Atomic instructions
  - Atomic inc/dec
  - Test-and-Set
  - Compare-and-Swap
  - LL (Load Locked) & SC (Store Conditional)
  - …

System Calls

System Calls

- OS defines a set of system calls
  - Programming interface to the services provided by OS
  - OS protects the system by rejecting illegal requests
  - OS may impose a quota on a certain resource
  - OS may consider fairness while sharing a resource

- A system call is a _____ procedure call
  - System call routines are in the OS code
  - Executed in the kernel mode
  - On entry, user mode → kernel mode switch
  - On exit, CPU mode is changed back to the user mode

System Calls Example

- POSIX vs. Win32

Category	POSIX	Win32	Description
Process Management	`fork`	`CreateProcess`	Create a new process
	`waitpid`	`WaitForSingleObject`	Wait for a process to exit
	`execve`	`(none)`	CreateProcess = fork + exec
	`exit`	`ExitProcess`	Terminate execution
	`kill`	`(none)`	Send a signal
File Management	`open`	`CreateFile`	Create a file or open an existing file
	`close`	`CloseHandle`	Close a file
	`read`	`ReadFile`	Read data from a file
	`write`	`WriteFile`	Write data to a file
	`lseek`	`SetFilePointer`	Move the file pointer
	`stat`	`GetFileAttibutesEx`	Get various file attributes
	`chmod`	`(none)`	Change the file access permission
File System Management	`mkdir`	`CreateDirectory`	Create a new directory
	`rmdir`	`RemoveDirectory`	Remove an empty directory
	`link`	`(none)`	Make a link to a file
	`unlink`	`DeleteFile`	Destroy an existing file
	`chdir`	`SetCurrentDirectory`	Change the current working directory
	`mount`	`(none)`	Mount a file system

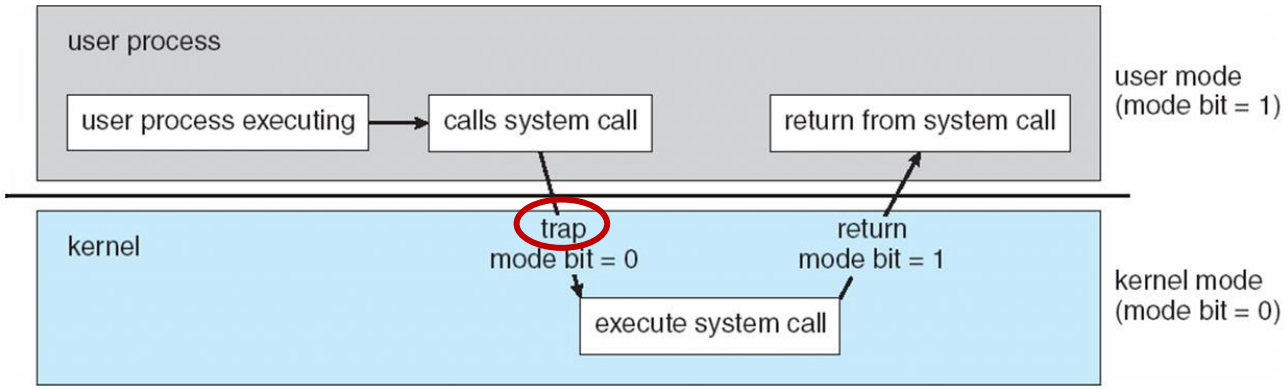
OS Trap

- There must be a special "trap" instruction that:
  - Causes an exception, which invokes a kernel handler
  - Passes a parameter indicating which system call to invoke
  - Saves caller's state (registers, mode bits)
  - Returns to user mode when done with restoring its state
  - OS must verify caller's parameters (e.g., pointers)

Examples:

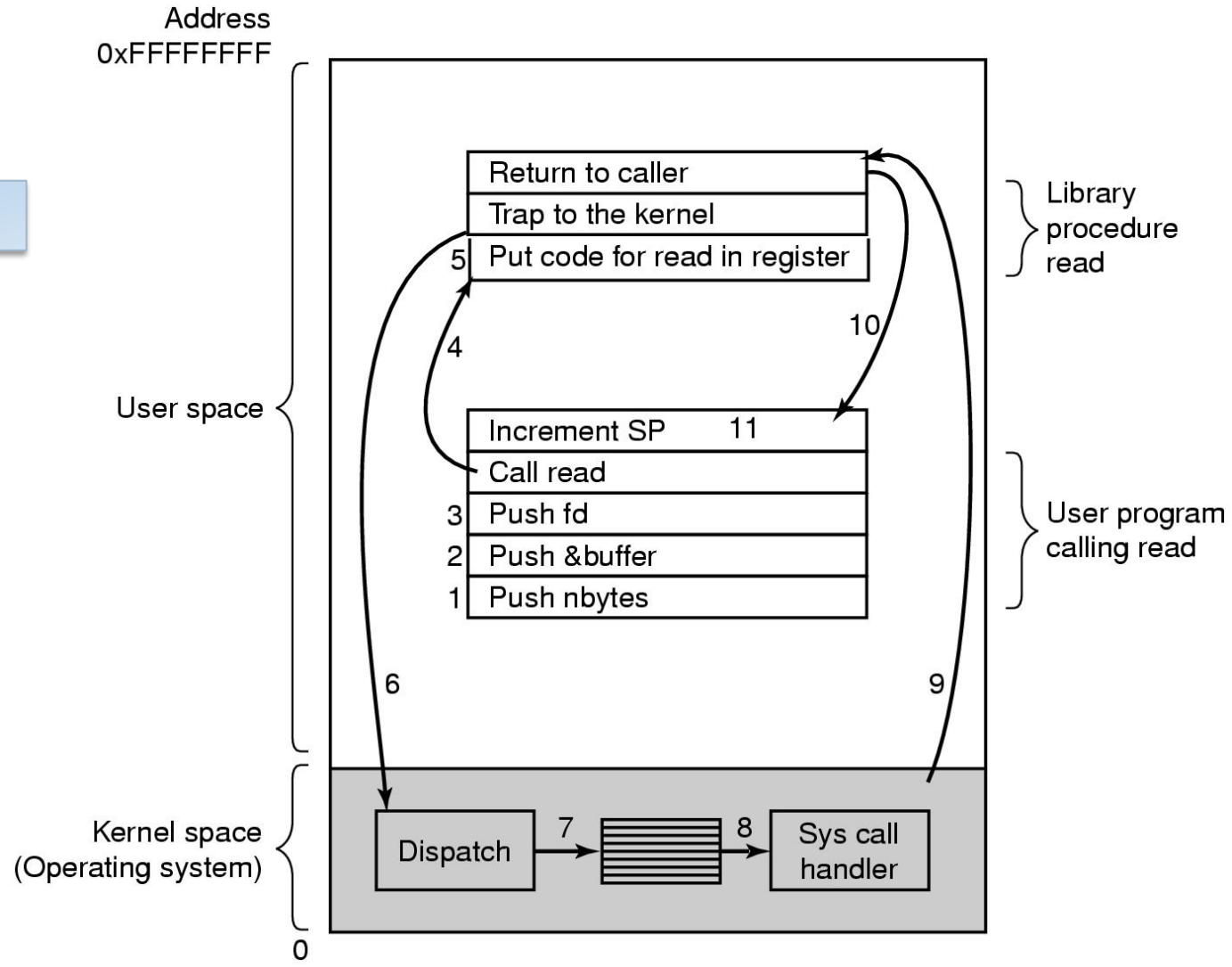
syscall instruction (x86_64)

ecall instruction (RISC-V)

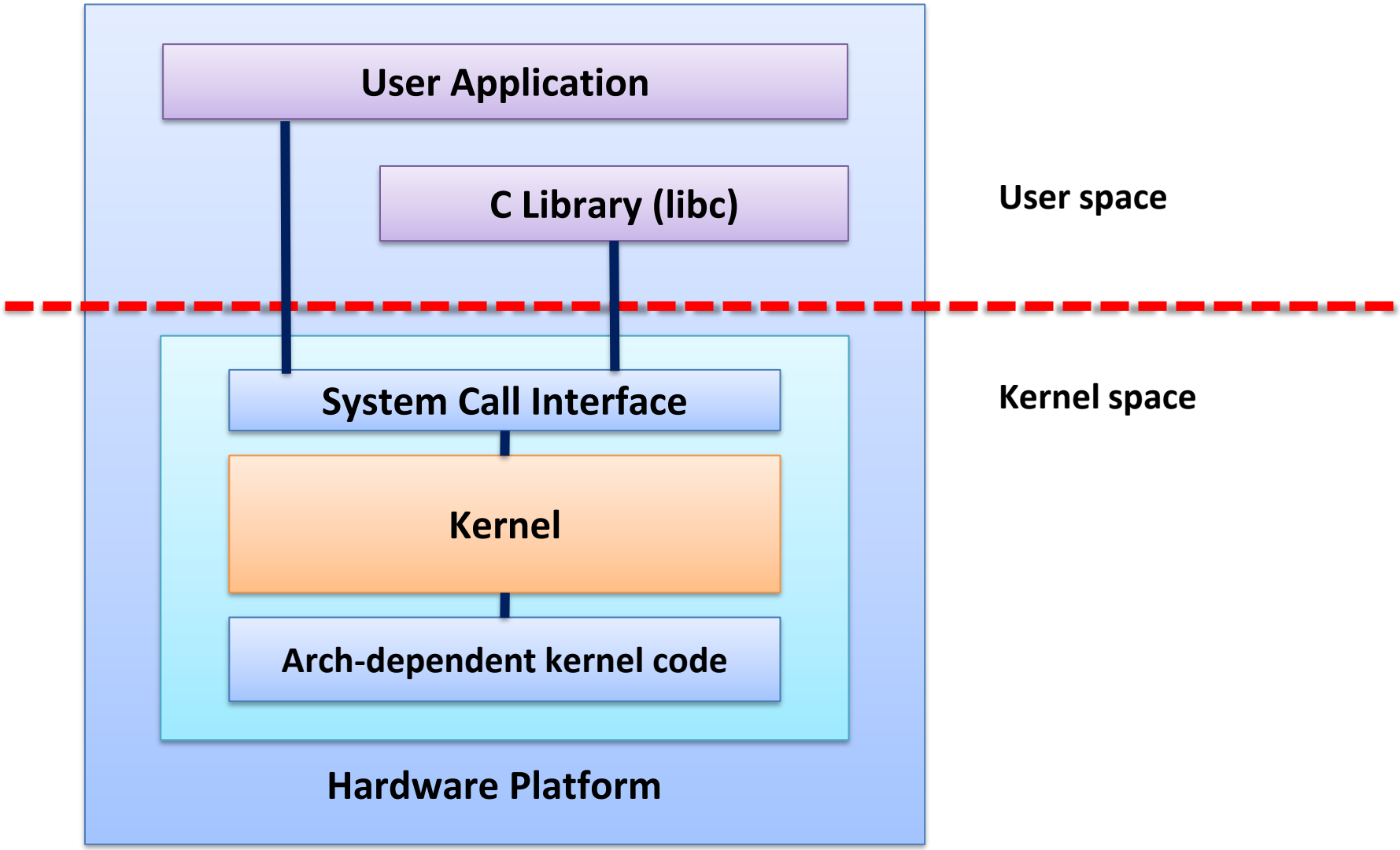


Implementing System Calls

```
count = read (fd, buffer, nbytes);
```



Typical OS Structure



Trap Instructions in x86

- `int 0x80` (+ `iret`)
  - "Software interrupt"
  - A legacy way to invoke a system call (used for 32-bit mode)
  - Slow: use the same mechanism as traps and interrupts
- `sysenter` (+ `sysexit`)
  - A new, fast instruction to invoke a system call in 32-bit mode
  - Introduced by Intel (not available in 64-bit mode on AMD CPUs)
- `syscall` (+ `sysret`)
  - Similar to **`sysenter`**, but used in 64-bit mode
  - Introduced by AMD (not available in 32-bit mode on Intel CPUs)

syscall

SYSCALL—Fast System Call

Opcode	Instruction	Op/ En	64-Bit Mode	Compat/ Leg Mode	Description
0F 05	SYSCALL	ZO	Valid	Invalid	Fast call to privilege level 0 system procedures.

- RCX ← RIP
- RIP ← MSR_LSTAR
- R11 ← RFLAGS
- …
- Initialize CS and SS from MSR_STAR
- Set CPL(Current Privilege Level) to 0

Using a System Call

- Example: `getpid()`

```c
#include <sys/types.h>
#include <unistd.h>

int main(void)
{
  return getpid();
}
```

Invoking a System Call

- System call number for `getpid()`: `0x27` (= 39)

```
00000000004005a0 <main>:
  4005a0: e9 fb 84 04 00        jmpq   448aa0 <__getpid>
  4005a5: 66 2e 0f 1f 84 00 00  nopw   %cs:0x0(%rax,%rax,1)
  4005ac: 00 00 00
  4005af: 90                    nop
```

```
0000000000448aa0 <__getpid>:
  448aa0: b8 27 00 00 00        mov    $0x27,%eax
  448aa5: 0f 05                 syscall
  448aa7: c3                    retq
  448aa8: 0f 1f 84 00 00 00 00  nopl   0x0(%rax,%rax,1)
  448aaf: 00
```

In C library

Numbering System Calls

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

```
#
# 64-bit system call numbers and entry vectors
#
# The format is:
# <number> <abi> <name> <entry point>
#
# The __x64_sys_*() stubs are created on-the-fly for sys_*() system calls
#
# The abi is "common", "64" or "x32" for this file.
#
0 common  read      __x64_sys_read
1 common  write     __x64_sys_write
2 common  open      __x64_sys_open
3 common  close     __x64_sys_close
4 common  stat      __x64_sys_newstat

...

37  common  alarm     __x64_sys_alarm
38  common  setitimer   __x64_sys_setitimer
39  common  getpid      __x64_sys_getpid
40  common  sendfile    __x64_sys_sendfile64
```

Setting up the System Call Entry

- @ `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);
```

Entering the Kernel

- @ 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

  /* 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 */
```

Jumping to the System Call Handler

- @ arch/x86/entry/common.c

```
__visible void do_syscall_64(unsigned long nr, struct pt_regs *regs)
{
  struct thread_info *ti;

  enter_from_user_mode();
  local_irq_enable();
  ti = current_thread_info();
  if (READ_ONCE(ti->flags) & _TIF_WORK_SYSCALL_ENTRY)
    nr = syscall_trace_enter(regs);

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

System Call Table

- @ arch/x86/entry/syscall_64.c

```
#define __SYSCALL_64(nr, sym) extern long __x64_##sym(const struct pt_regs *);
#include <asm/syscalls_64.h>
#undef __SYSCALL_64

#define __SYSCALL_64(nr, sym) [nr] = __x64_##sym,

asmlinkage const sys_call_ptr_t sys_call_table[__NR_syscall_max+1] = {
  /*
   * Smells like a compiler bug -- it doesn't work
   * when the & below is removed.
   */
  [0 ... __NR_syscall_max] = &__x64_sys_ni_syscall,
#include <asm/syscalls_64.h>
};
```

System Call Handlers

- @ arch/x86/include/generated/asm/syscalls_64.h

```
__SYSCALL_COMMON(0, sys_read)
__SYSCALL_COMMON(1, sys_write)
__SYSCALL_COMMON(2, sys_open)
__SYSCALL_COMMON(3, sys_close)
__SYSCALL_COMMON(4, sys_newstat)
__SYSCALL_COMMON(5, sys_newfstat)
__SYSCALL_COMMON(6, sys_newlstat)
__SYSCALL_COMMON(7, sys_poll)
__SYSCALL_COMMON(8, sys_lseek)
__SYSCALL_COMMON(9, sys_mmap)
__SYSCALL_COMMON(10, sys_mprotect)
__SYSCALL_COMMON(11, sys_munmap)
__SYSCALL_COMMON(12, sys_brk)
__SYSCALL_64(13, sys_rt_sigaction)
__SYSCALL_COMMON(14, sys_rt_sigprocmask)
__SYSCALL_64(15, sys_rt_sigreturn)
__SYSCALL_64(16, sys_ioctl)
```

vDSO

- Virtual Dynamic Shared Object (@ `arch/x86/entry/vdso/`)
  - A small shared library exported by the kernel that is mapped into the address space of all user-space applications
  - Mapped to a different location every time (for security)
  - Used to accelerate the execution of certain read-only system calls ("virtual system calls") without entering the kernel
    - `clock_gettime()`
    - `gettimeofday()`
    - `getcpu()`
    - `time()`
    - `clock_getres()`
  - @ `arch/x86/entry/vdso`
  - `$ man vdso`

vDSO Layout

```
$ cat /proc/self/maps
5611a0174000-5611a0176000 r--p 00000000 08:05 265118                     /usr/bin/cat
5611a0176000-5611a017b000 r-xp 00002000 08:05 265118                     /usr/bin/cat
5611a017b000-5611a017e000 r--p 00007000 08:05 265118                     /usr/bin/cat
5611a017e000-5611a017f000 r--p 00009000 08:05 265118                     /usr/bin/cat
5611a017f000-5611a0180000 rw-p 0000a000 08:05 265118                     /usr/bin/cat
5611a1ebb000-5611a1edc000 rw-p 00000000 00:00 0                          [heap]
7f9d19bdc000-7f9d19bfe000 rw-p 00000000 00:00 0
7f9d19bfe000-7f9d1ab21000 r--p 00000000 08:05 269248                     /usr/lib/locale/locale-archive
7f9d1ab21000-7f9d1ab46000 r--p 00000000 08:05 274111                     /usr/lib/x86_64-linux-gnu/libc-2.31.so
7f9d1ab46000-7f9d1acbe000 r-xp 00025000 08:05 274111                     /usr/lib/x86_64-linux-gnu/libc-2.31.so
7f9d1acbe000-7f9d1ad08000 r--p 0019d000 08:05 274111                     /usr/lib/x86_64-linux-gnu/libc-2.31.so
7f9d1ad08000-7f9d1ad09000 ---p 001e7000 08:05 274111                     /usr/lib/x86_64-linux-gnu/libc-2.31.so
7f9d1ad09000-7f9d1ad0c000 r--p 001e7000 08:05 274111                     /usr/lib/x86_64-linux-gnu/libc-2.31.so
7f9d1ad0c000-7f9d1ad0f000 rw-p 001ea000 08:05 274111                     /usr/lib/x86_64-linux-gnu/libc-2.31.so
7f9d1ad0f000-7f9d1ad15000 rw-p 00000000 00:00 0
7f9d1ad24000-7f9d1ad25000 r--p 00000000 08:05 273898                     /usr/lib/x86_64-linux-gnu/ld-2.31.so
7f9d1ad25000-7f9d1ad48000 r-xp 00001000 08:05 273898                     /usr/lib/x86_64-linux-gnu/ld-2.31.so
7f9d1ad48000-7f9d1ad50000 r--p 00024000 08:05 273898                     /usr/lib/x86_64-linux-gnu/ld-2.31.so
7f9d1ad51000-7f9d1ad52000 r--p 0002c000 08:05 273898                     /usr/lib/x86_64-linux-gnu/ld-2.31.so
7f9d1ad52000-7f9d1ad53000 rw-p 0002d000 08:05 273898                     /usr/lib/x86_64-linux-gnu/ld-2.31.so
7f9d1ad53000-7f9d1ad54000 rw-p 00000000 00:00 0
7ffe8b35b000-7ffe8b37c000 rw-p 00000000 00:00 0                          [stack]
7ffe8b3f3000-7ffe8b3f6000 r--p 00000000 00:00 0                          [vvar]
7ffe8b3f6000-7ffe8b3f7000 r-xp 00000000 00:00 0                          [vdso]
ffffffffff600000-ffffffffff601000 --xp 00000000 00:00 0                  [vsyscall]
```

vvar and vsyscall

- vvar
  - Mapped just before the vdso page
  - Contains data accessed by virtual system calls
  - Kernel periodically updates the values (if necessary)
  - User-space application can only read the values

- vsyscall
  - A legacy ABI for virtual system calls
  - Mapped to the fixed user-space address
  - Not recommended to use

syscall()

- A generic library function that performs the specified system call
  - Symbolic constants for system call numbers are specified in `<sys/syscall.h>`
  - Useful when you add a new system call that has no wrapper function in the C library

```c
#include <stdio.h>
#include <unistd.h>
#include <sys/syscall.h>

int main(void)
{
  printf("%ld\n", syscall(__NR_getpid));
  printf("%ld\n", syscall(SYS_getpid));
}
```

Reading Assignment #2

- Thomas E. Anderson, Brian N. Bershad, Edward D. Lazowska, and Henry M. Levy,
  "Scheduler Activations: Effective Kernel Support for the User-Level Management of Parallelism,"
  TOCS, 1992.

- Due: Before the class on Sep. 16

- There will be an online quiz for this paper during the class on Sep. 16