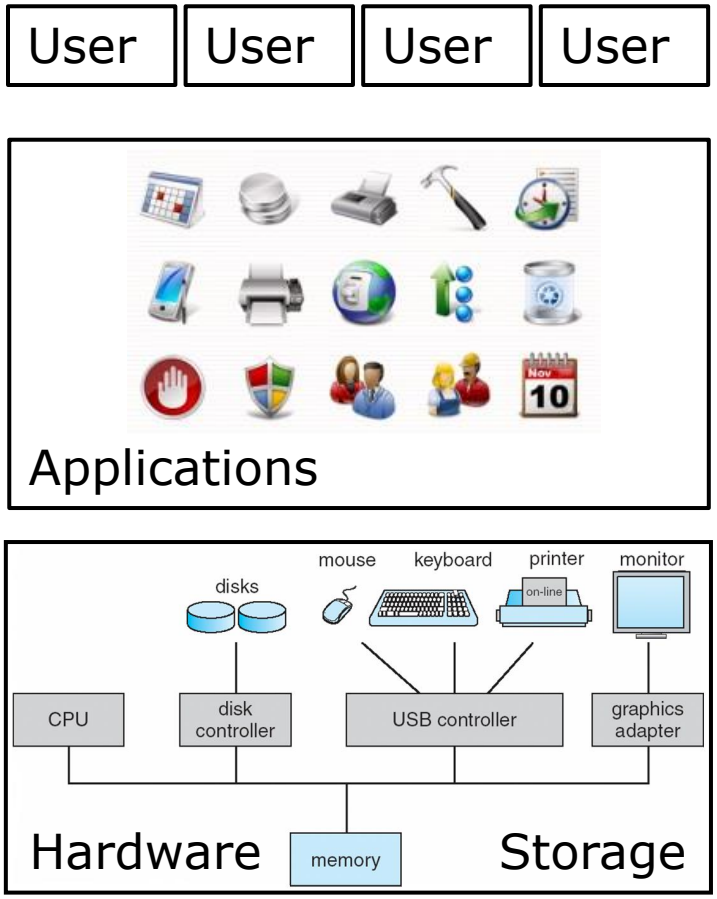
Operating Systems
kernel mode and interrupts

David Hay

Dror Feitelson

Simplified View of the OS



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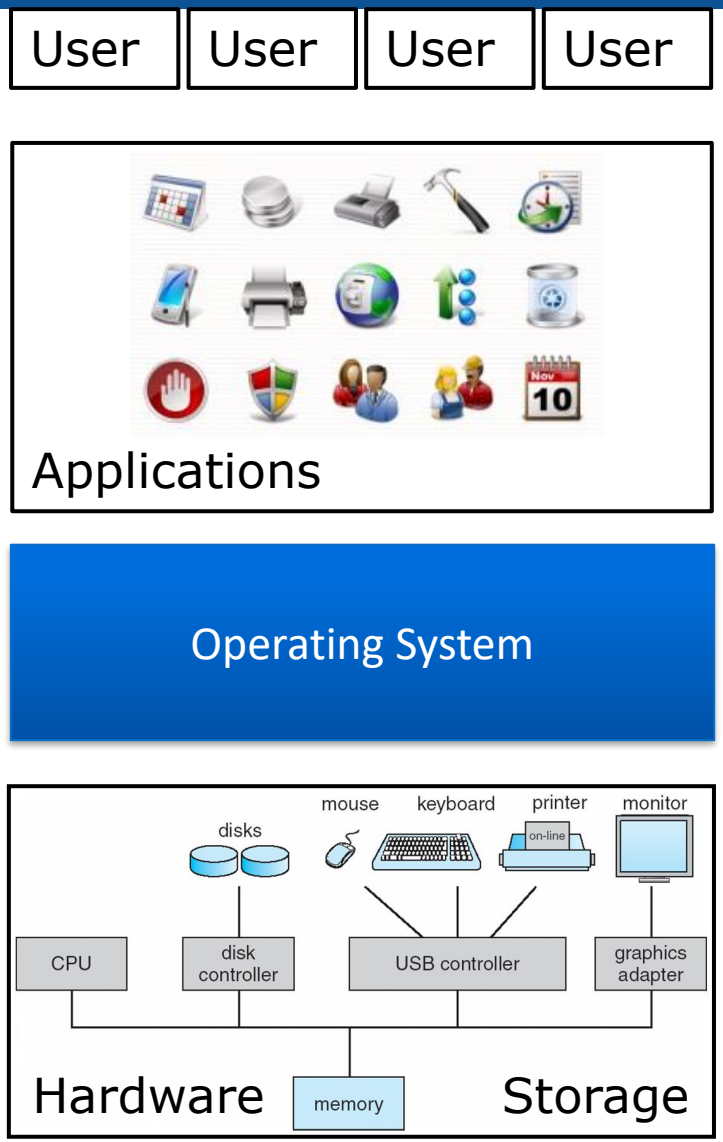

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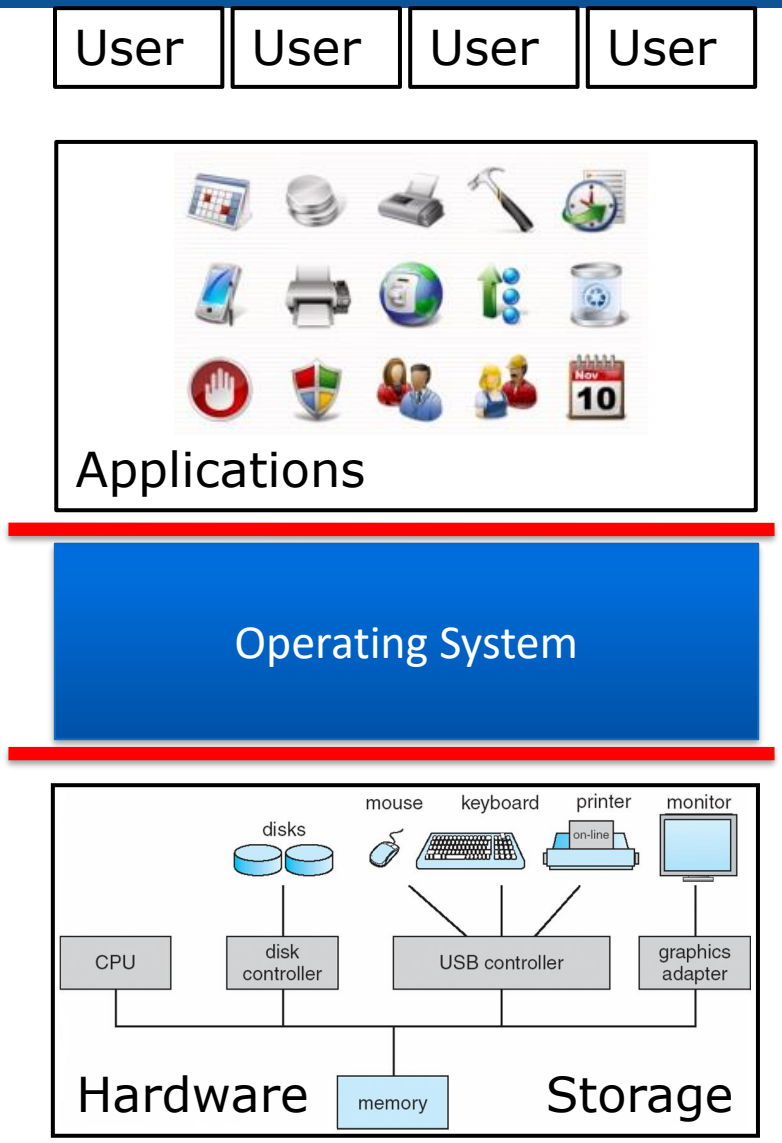

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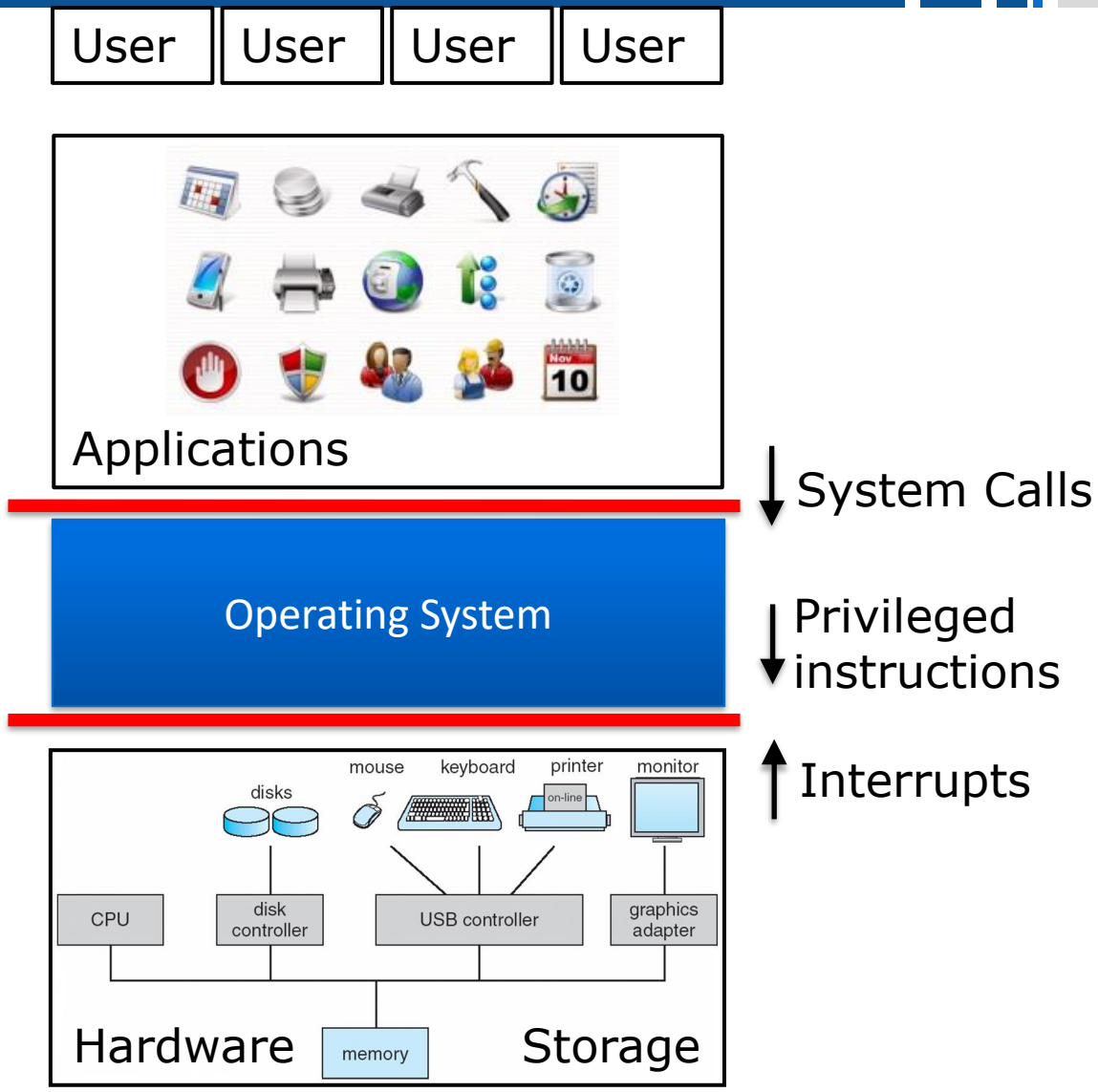

Two Classes of Instructions

- Non-Privileged Instructions
  - All the usual instructions you expect
  - Add, multiply, jump, …
- Privileged Instructions
  - Special instructions for the OS
  - We don't want user applications to use them
  - Example: activate the disk to get a block of data
    - OS uses this to support the abstraction of files
    - OS prevents access to other users' data (protection)

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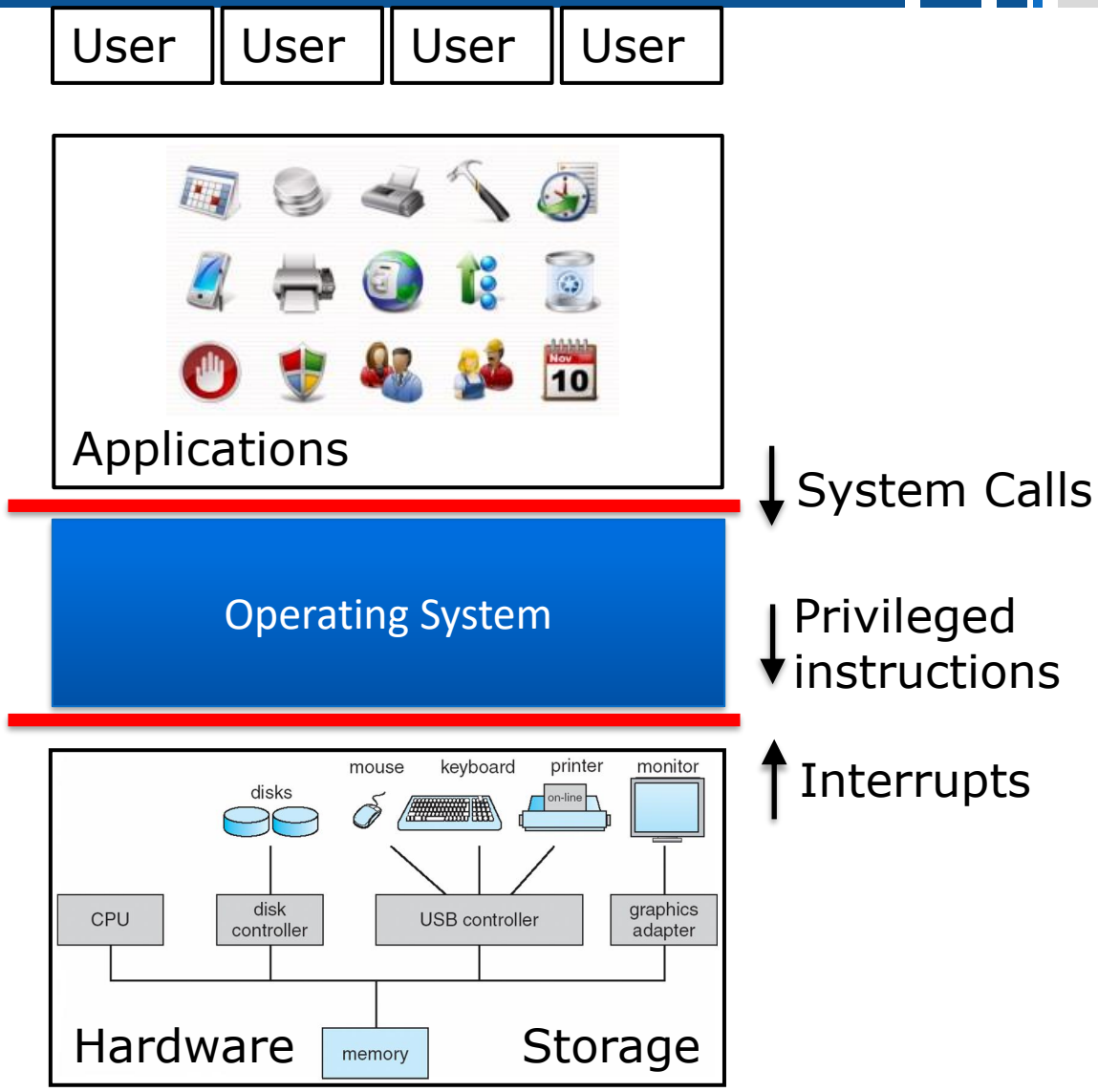


Simplified View of the OS

User Mode

Kernel Mode

User | User | User | User

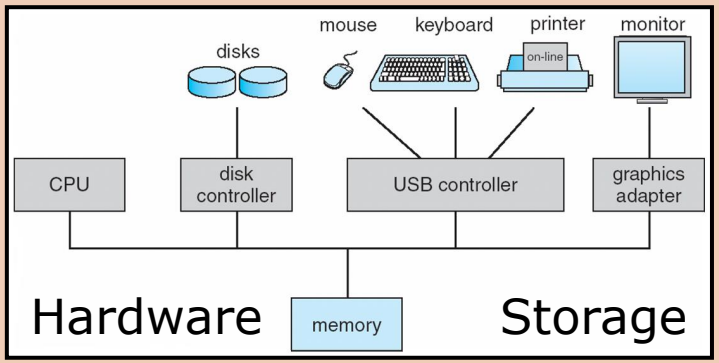
Applications

System Calls

Operating System

Privileged instructions

Interrupts



Two Modes of Operation

- Kernel mode (also called “privileged mode”)
  - The running mode of the OS
  - Can run hardware assembly commands
- User mode
  - Can not access hardware, etc.

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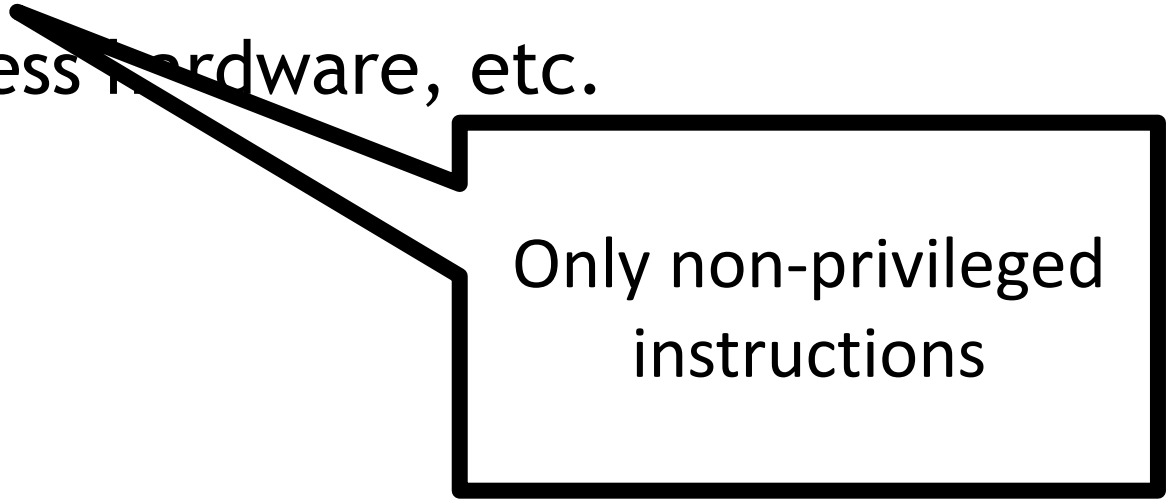

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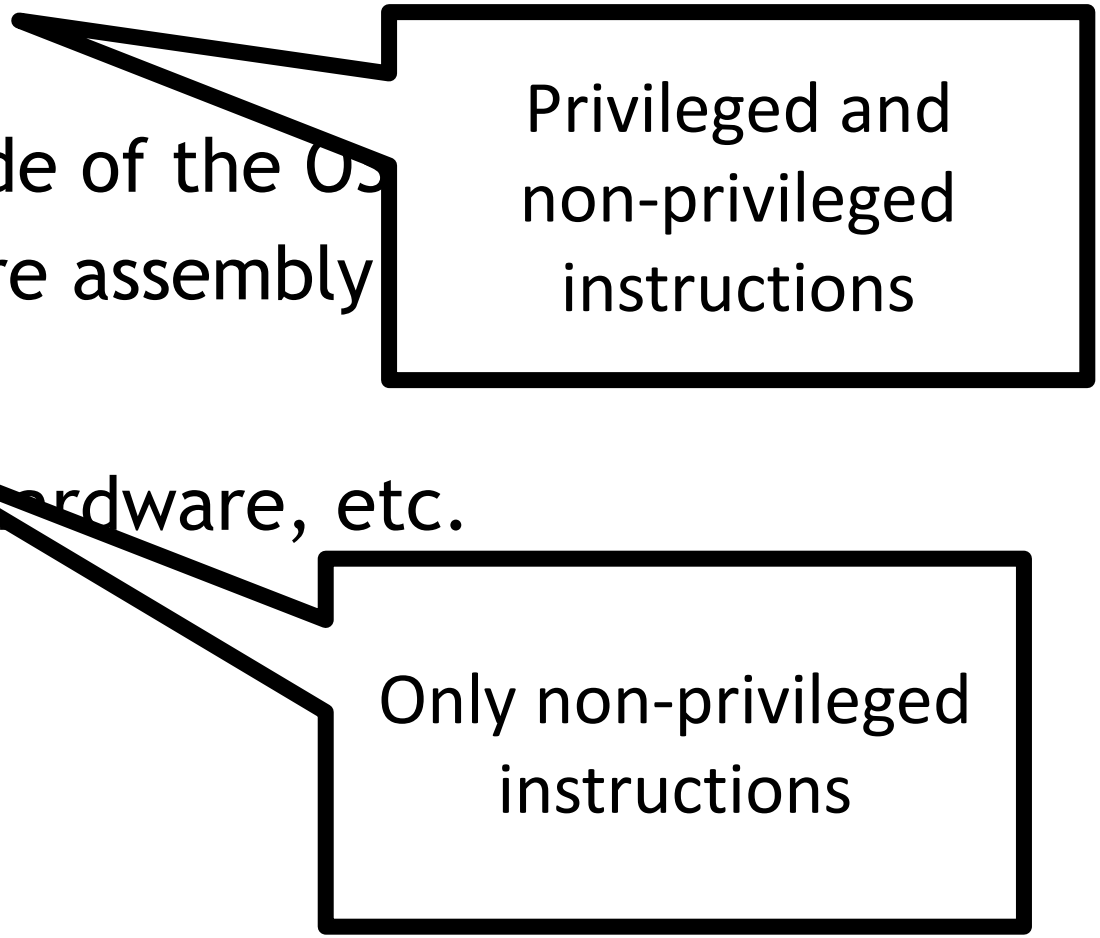
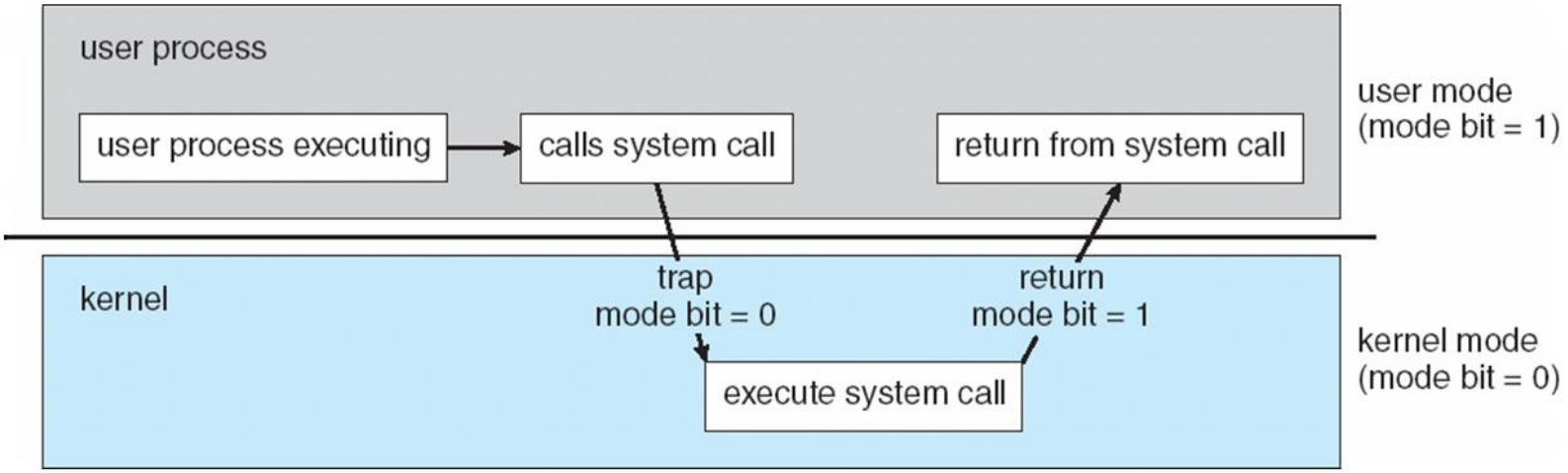


System Calls

- The user process gets the OS services thru system calls
- System calls are functions that can be called from the user programs
  - Not like a regular function calls!
- User programs cannot access/alter internal OS data structures, only thru system calls (protection!)
- System calls check the validity of the parameters (unlike other internal OS functions)
- System calls = portable interface and protection

Transition from User to Kernel Mode

- The process of switching between user and kernel mode is called a **trap**
- **Mode bit** provided and protected by hardware
  - Provides ability to distinguish when system is running user code or kernel code
  - Some instructions designated as **privileged**, only executable in kernel mode
  - System call changes mode to kernel, return from call resets it to user



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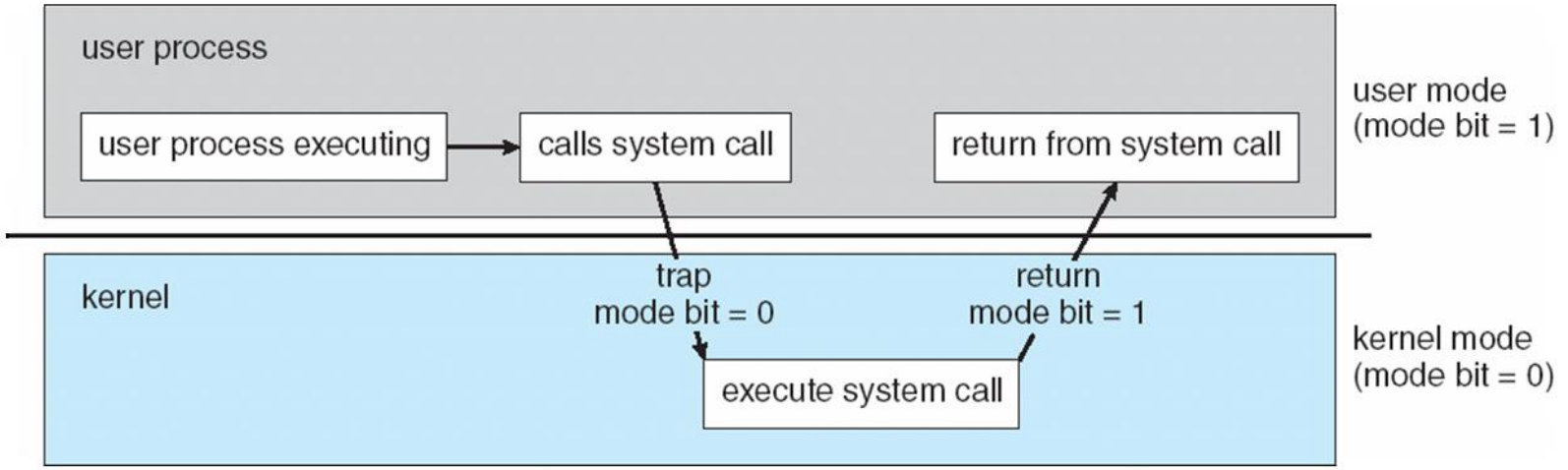

Transition from User to Kernel Mo

Modern OS has more than one bit, allowing more than 2 "modes" (a.k.a. rings)

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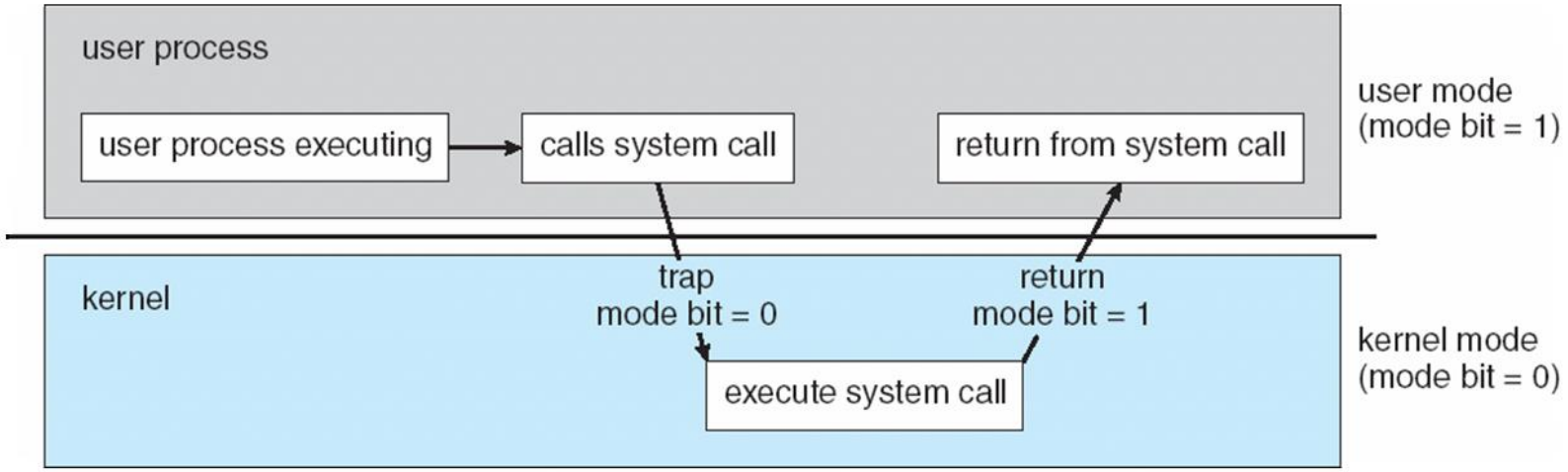
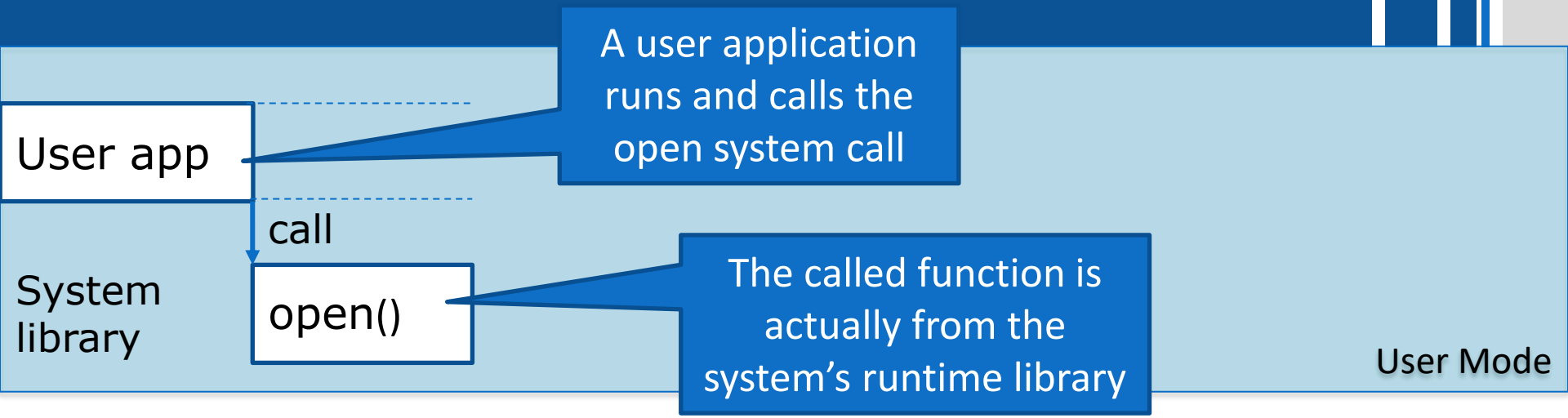


Trap in Detail



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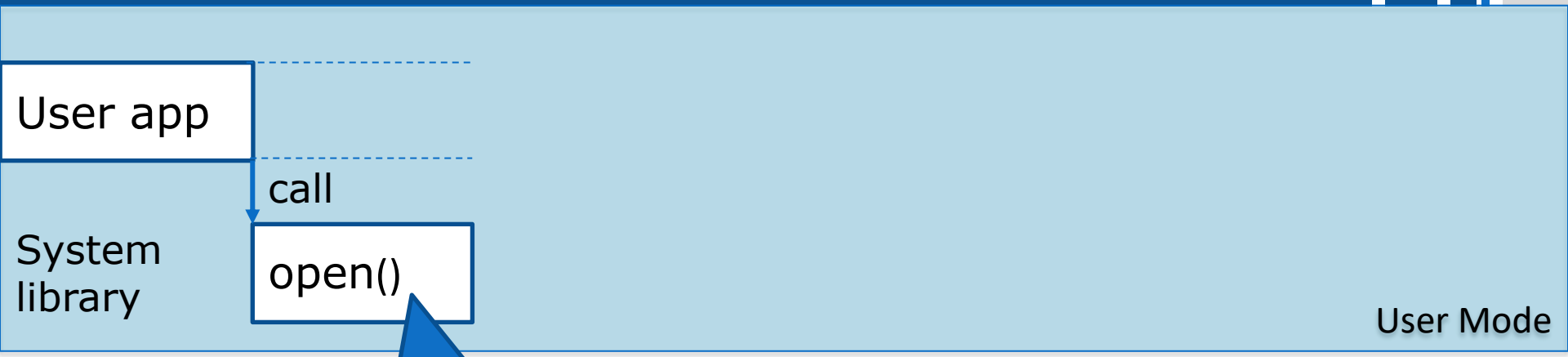

This function sets things up for entering the kernel.
Use registers to:

1. Store the parameters
2. Store the system call number for “open” (2)

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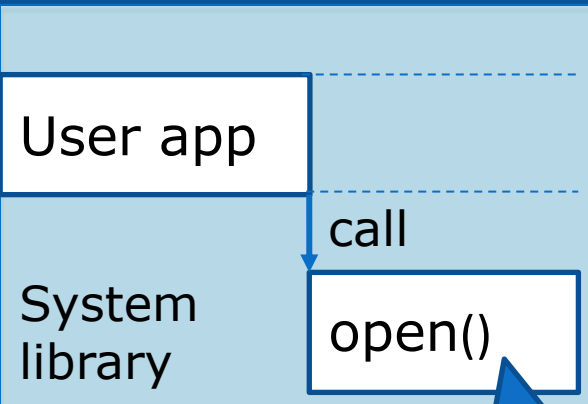

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0	read
1	write
2	open
3	close
4	stat
5	fstat
6	lstat
7	poll
8	lseek
9	mmap
10	mprotect
11	munmap
12	brk
13	rt_sigaction
14	rt_sigprocmask

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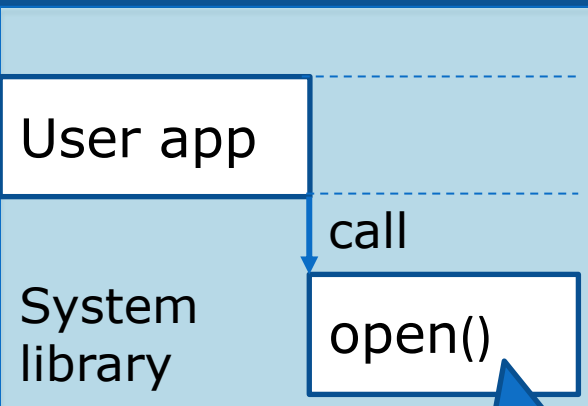

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Linux has 300-400 different system calls…

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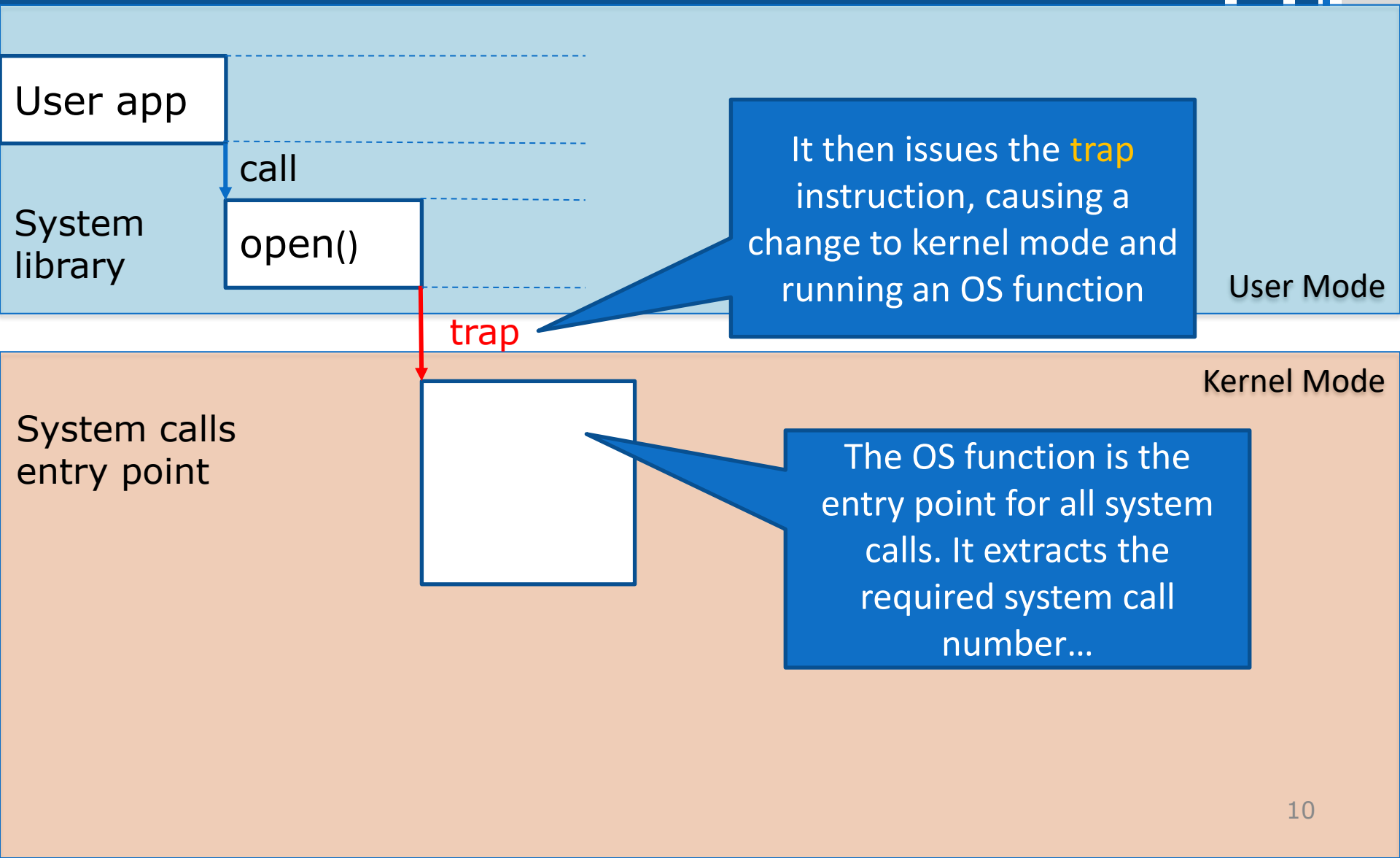

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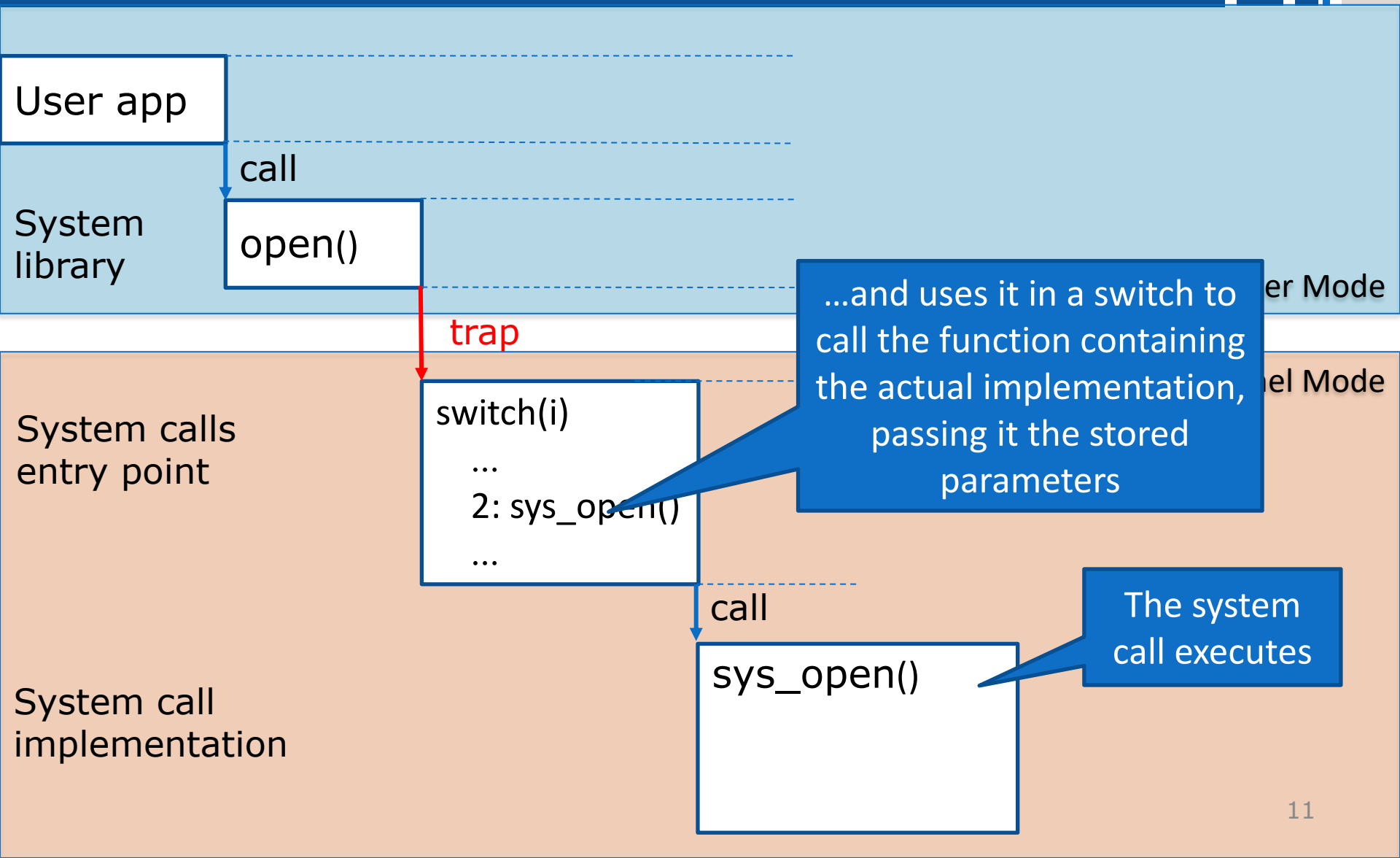

Trap in Detail

0	read	sys_read
1	write	sys_write
2	open	sys_open
3	close	sys_close
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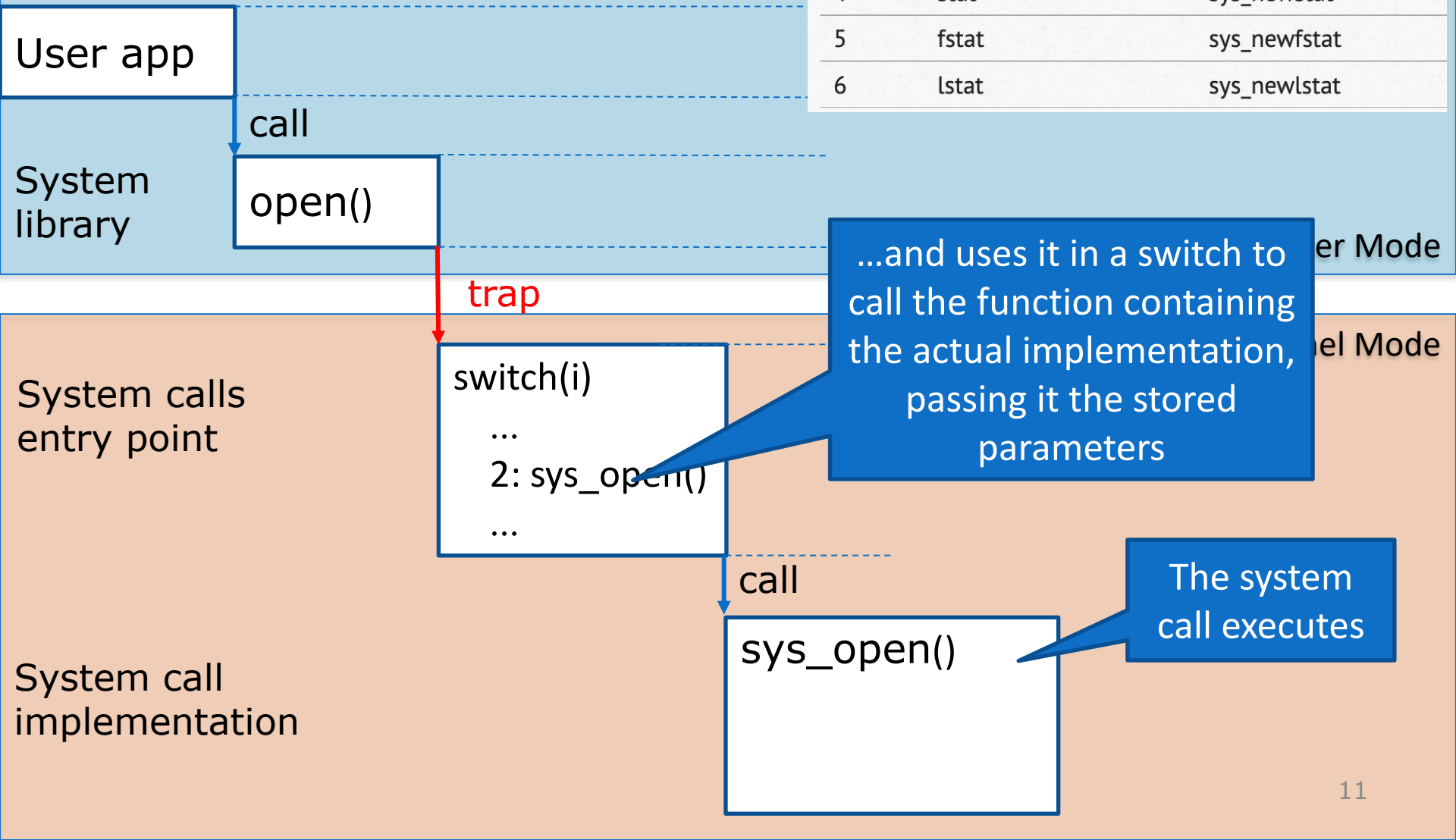
5	fstat	sys_newfstat
6	lstat	sys_newlstat



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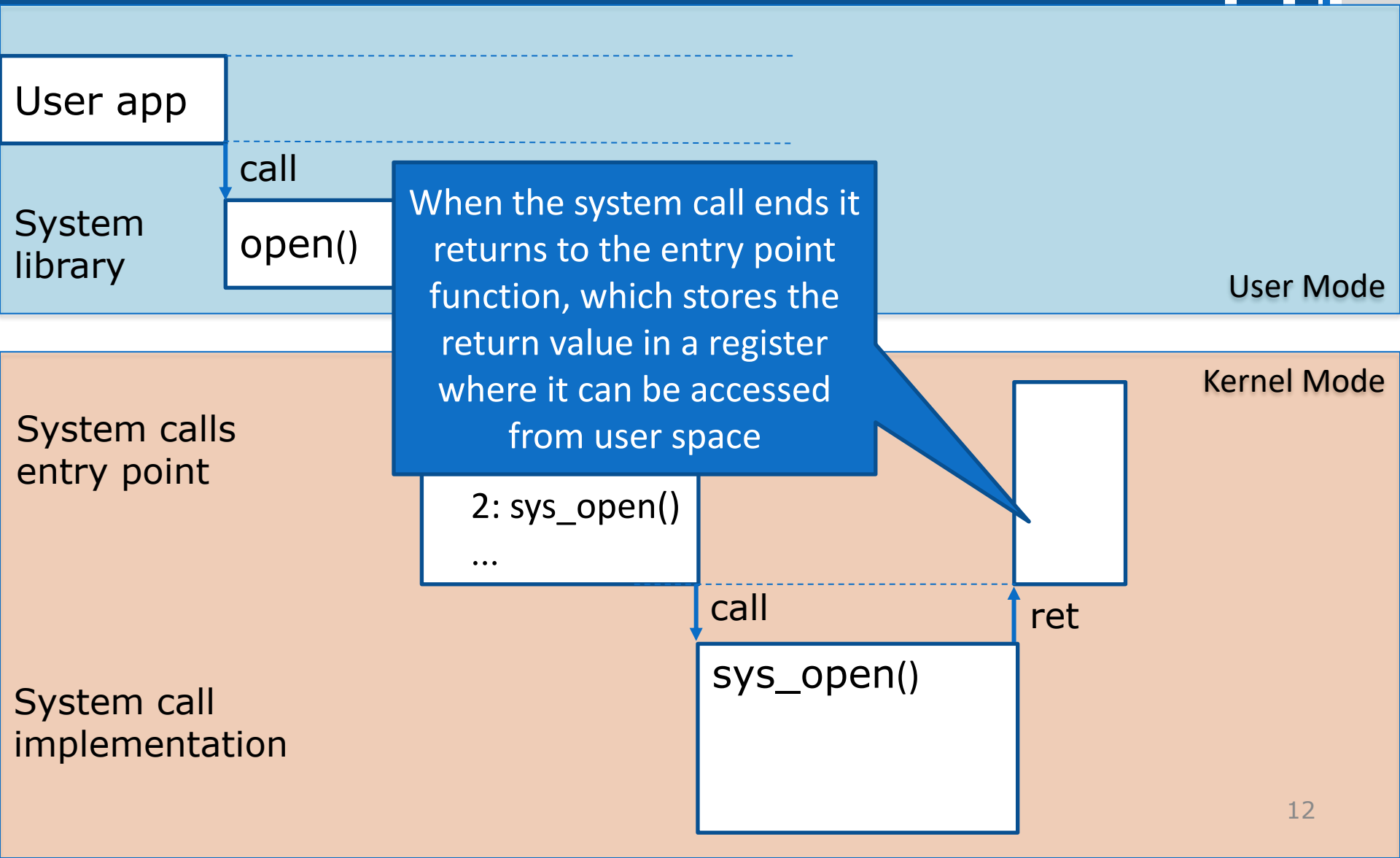

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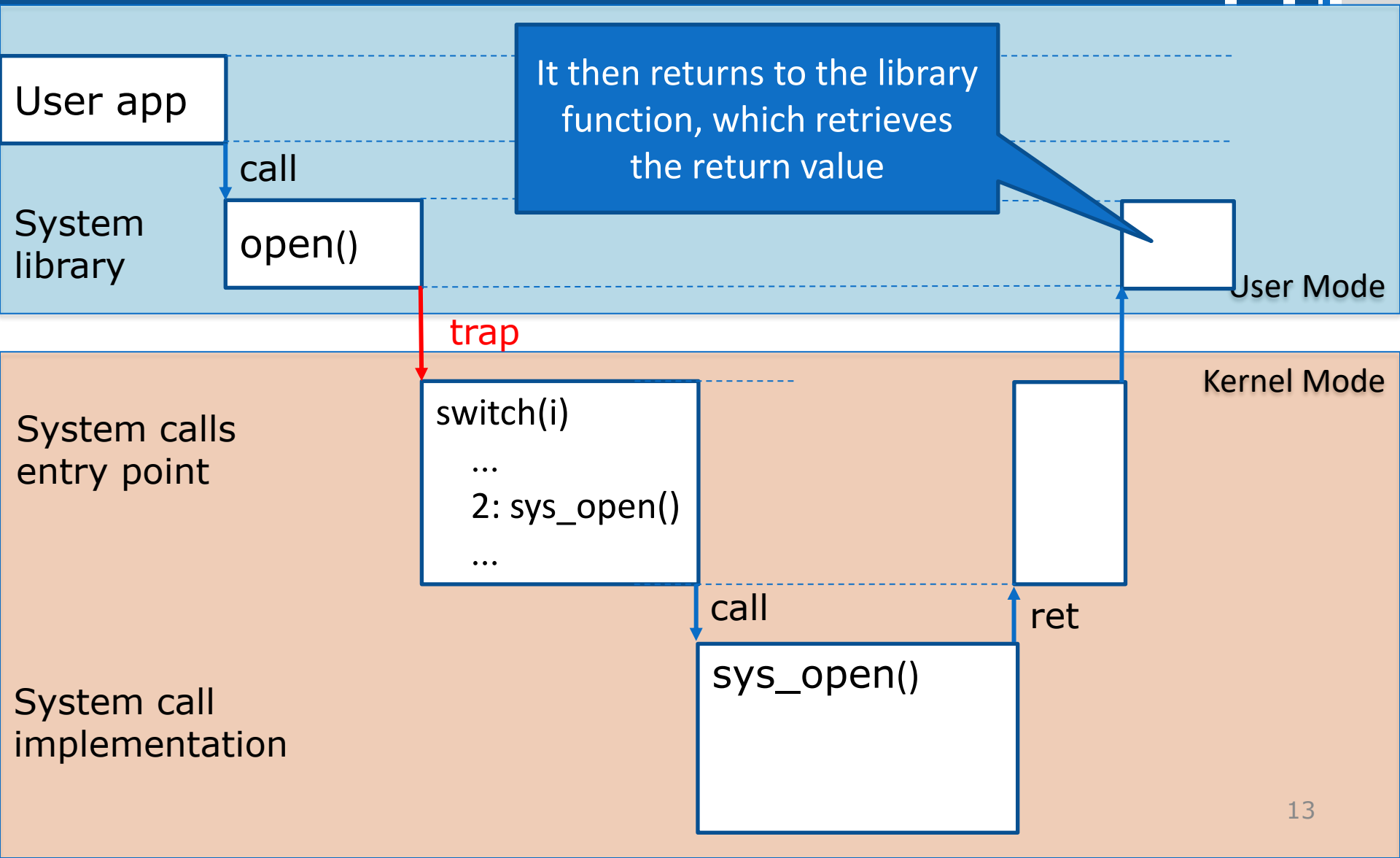

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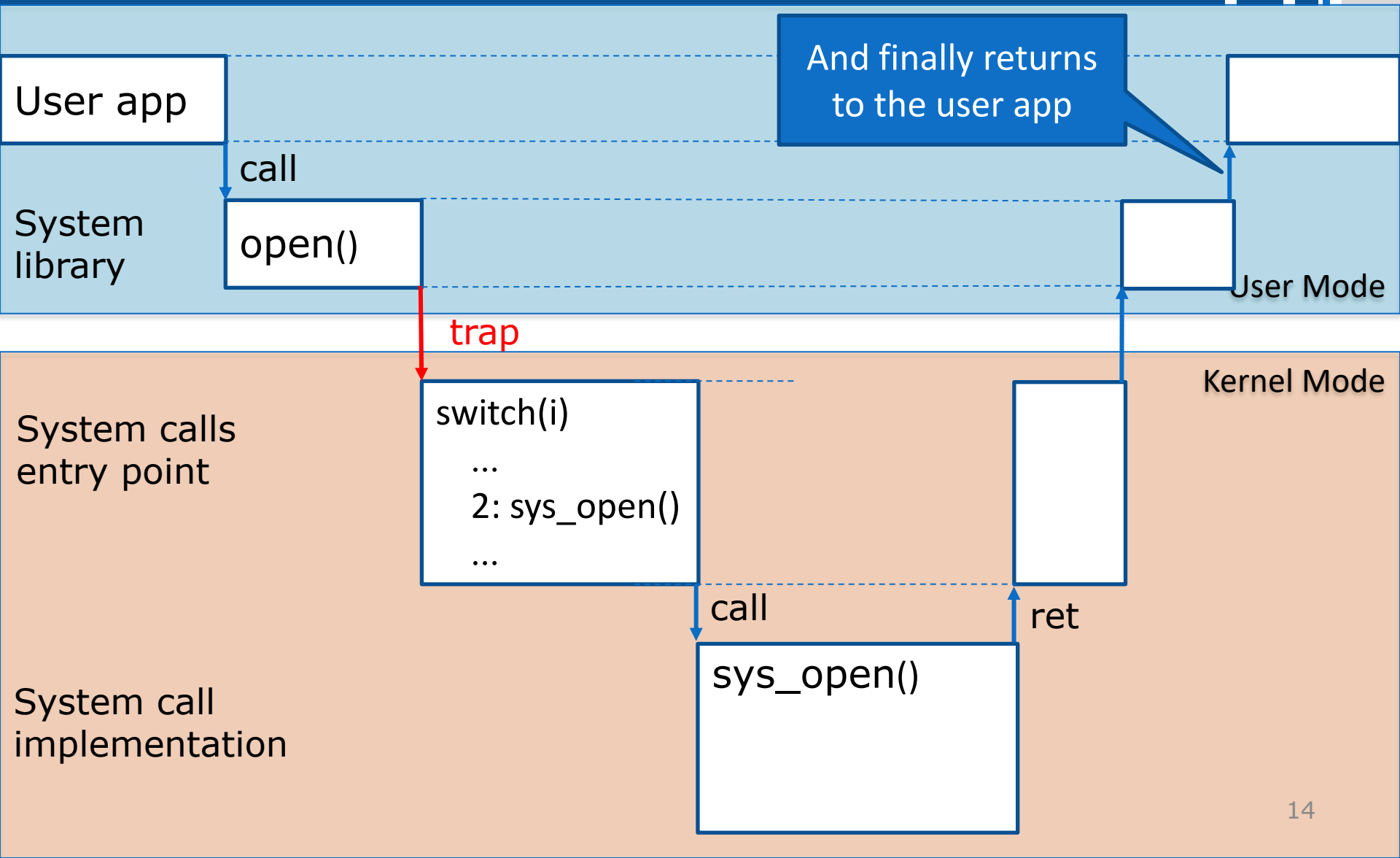

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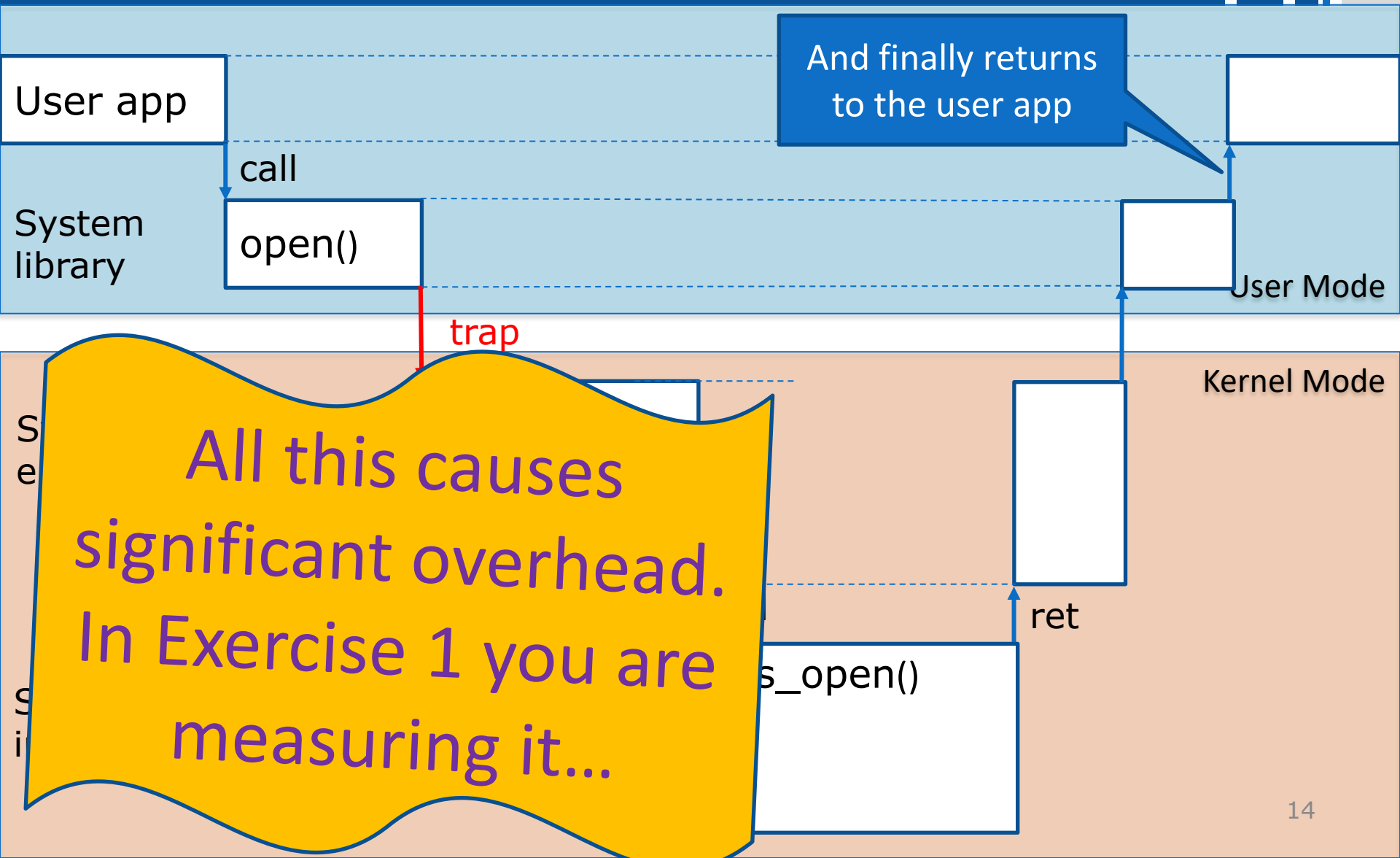

Types of System Calls

- Process Control
- File management
- Device management
- Information maintenance
- Communications
- Protection

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  - Bad memory address (segmentation violation)

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  - Runtime error (division by 0, …)
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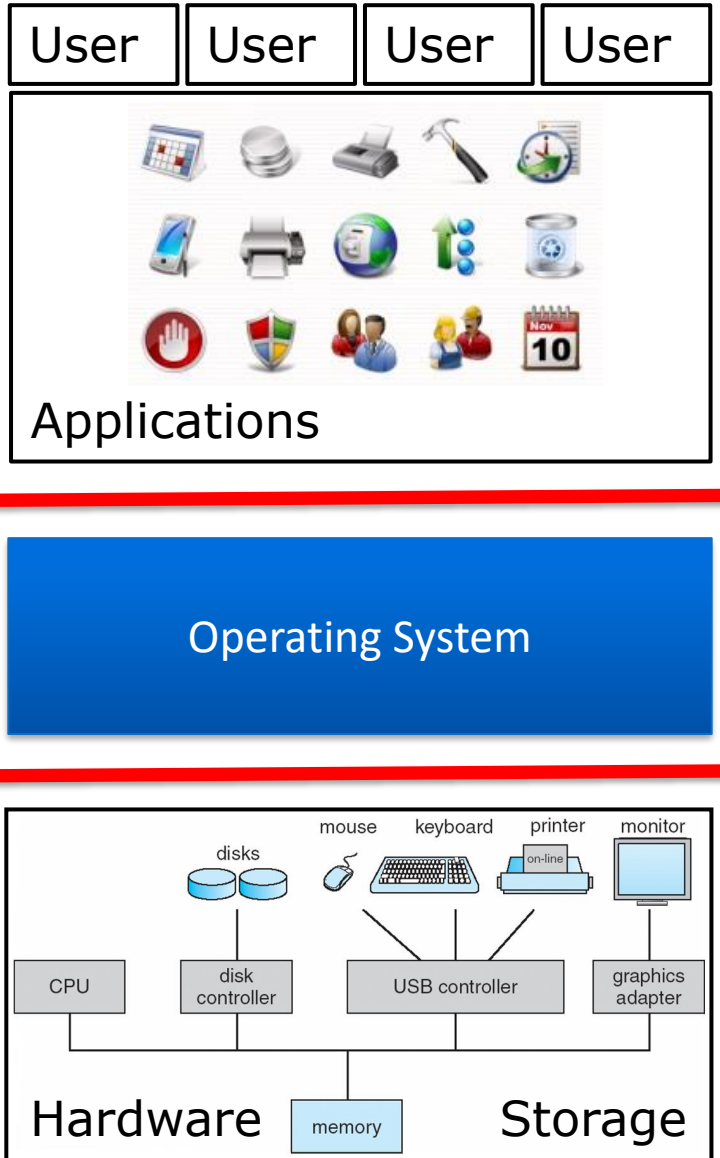
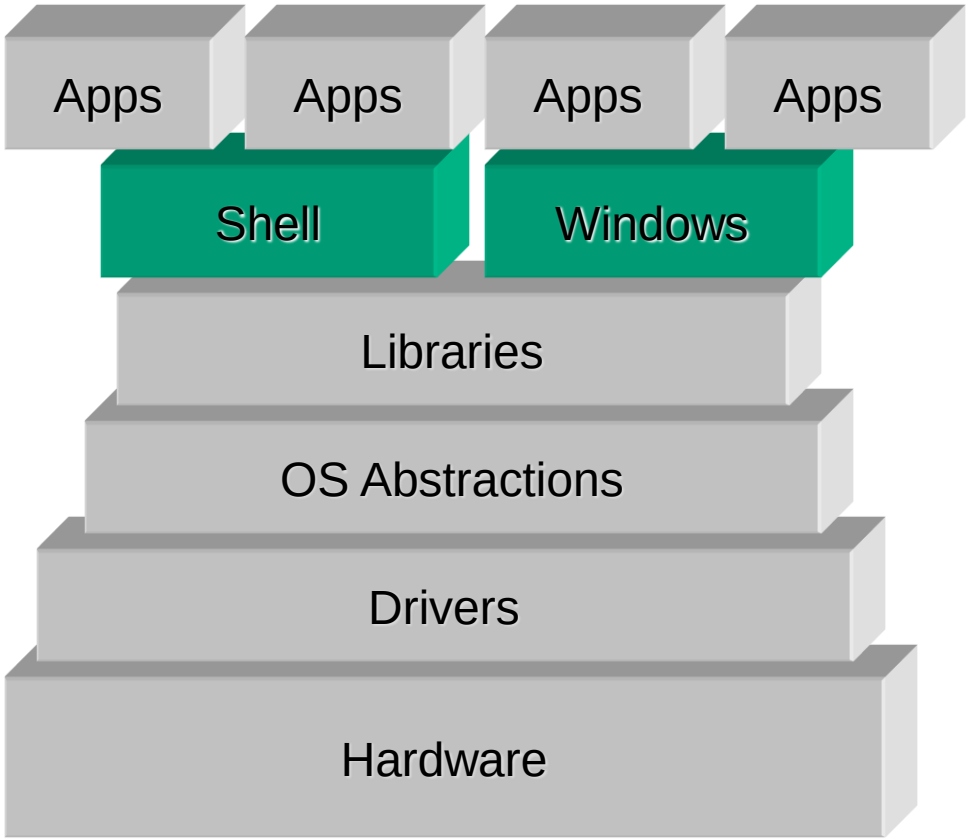
  - Bad memory address (segmentation violation)
- Exception handling is part of the CPU **architecture** (hardware)
  - Transfer the responsibility to the OS (and the user) to handle the exception condition → transition to kernel mode.

Simplified view of OS



Simplified view of OS

The reality is much more complicated…



User interface

- Make OS mechanisms available to user
- psychological issues are important

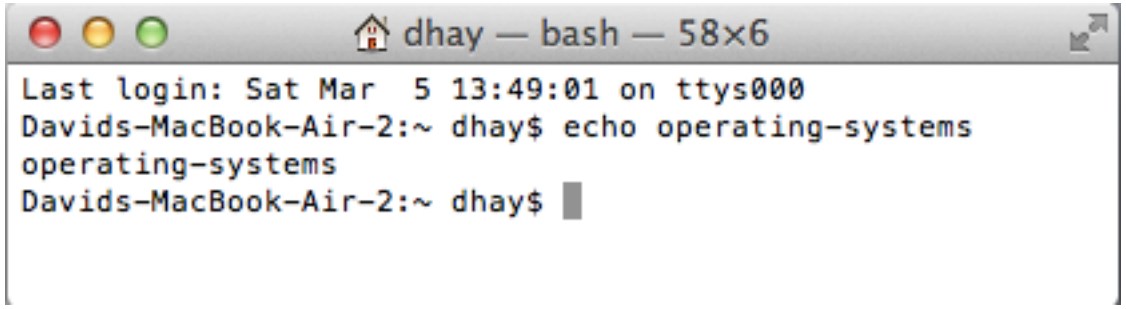
Is a web browser part of an Operating System ?

System Programs (or System Utilities)

- Modern OS comes along with system programs
  - Often an interface to a system call (run in user mode)
  - Sometimes more complex
  - Designed to provide service to other software
- Not to be confused with application programs
  - Sometimes also provided by the OS, but are not considered part of the OS
  - Run by users. Uses system programs to complete their operation
  - Example: Web browser

Example: echo system program

- echo: write argument to the standard output



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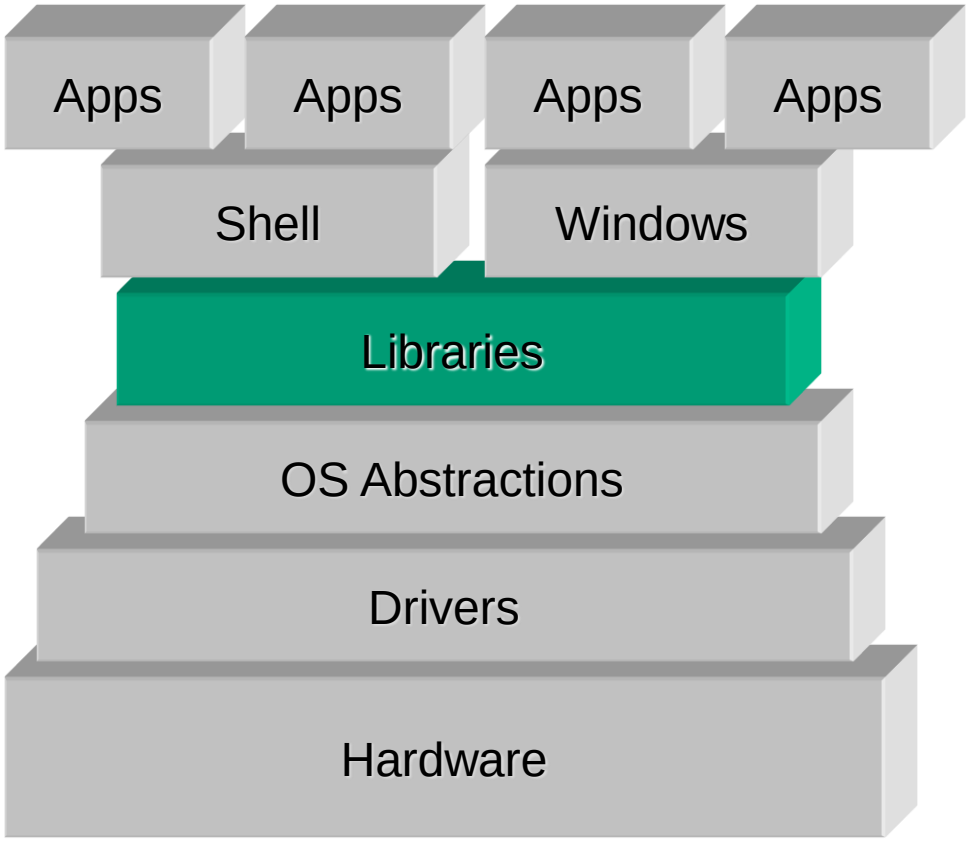
- Possibly several switches between the modes

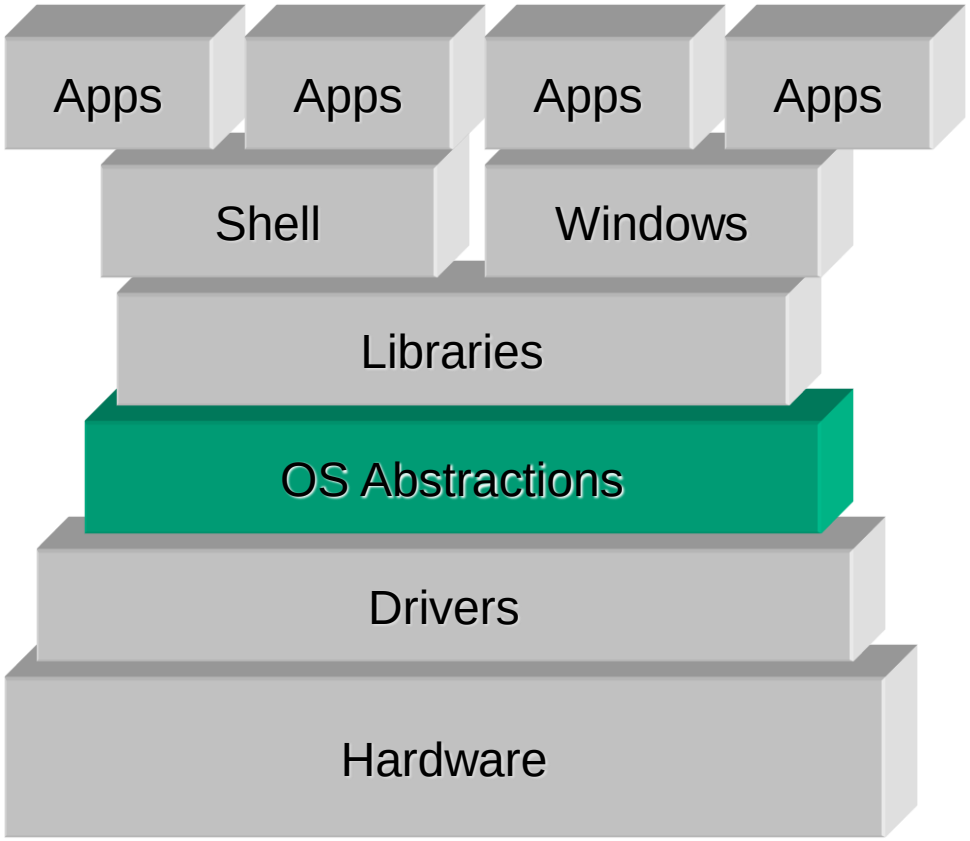
Layers of System



Libraries

- Usually language specific
  - java.io.*, java.net.*
  - stdio.h; stdlib.h
- Often higher level abstractions

Layers of System



OS Abstractions

- provide lower level abstractions and mechanisms
- Storage
  - File systems
- Computation
  - processes
- Communications
  - sockets

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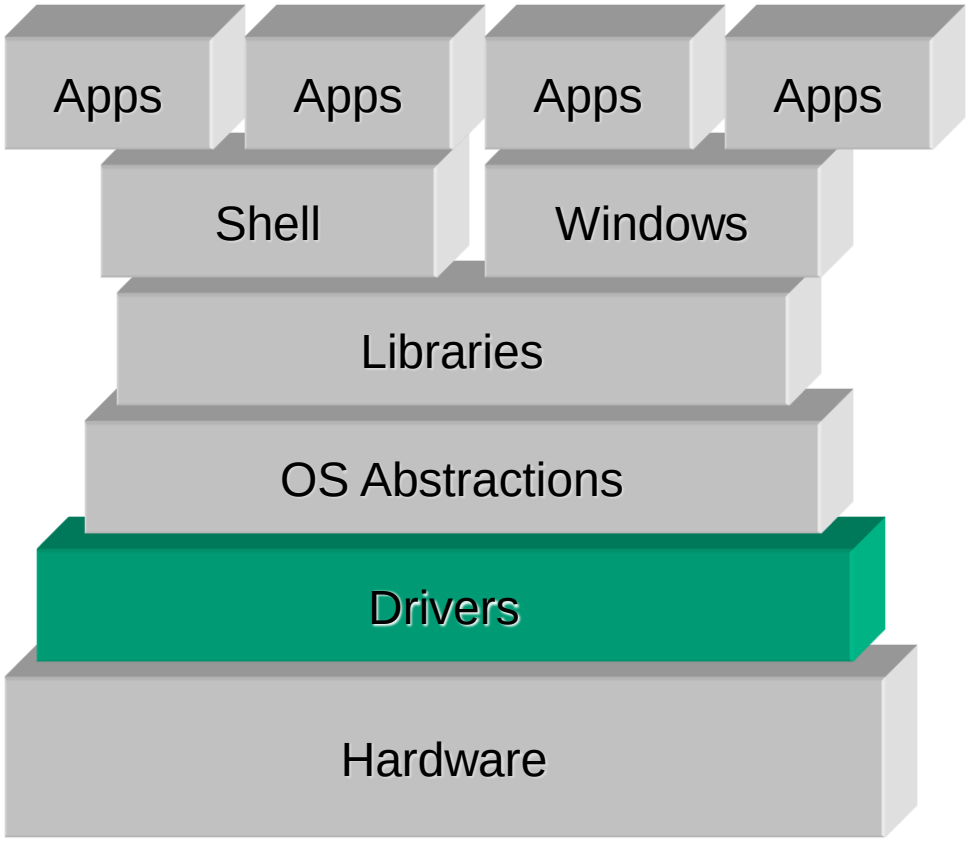
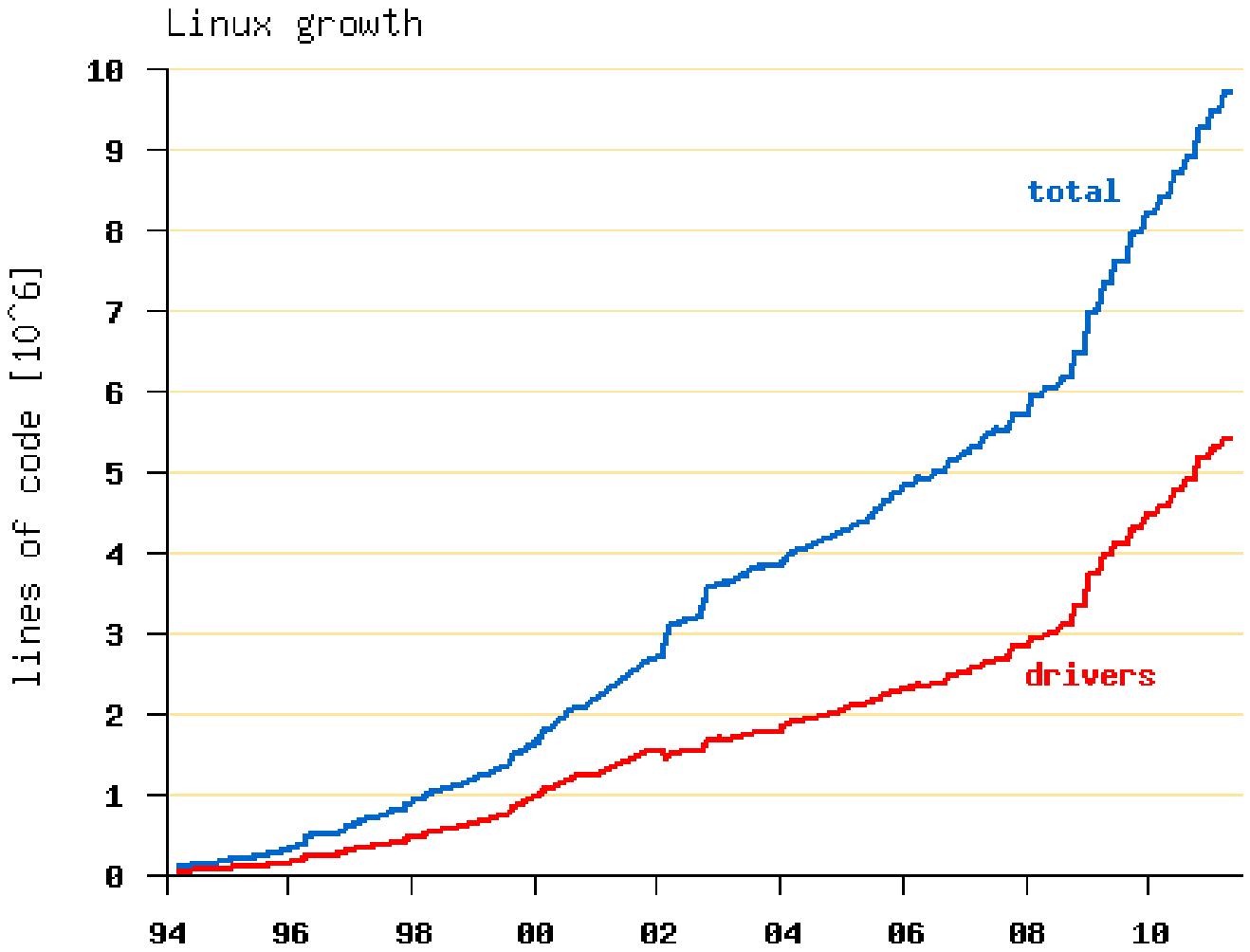


Hardware drivers

- provide usable interface to hardware
- A huge part of the system in terms of code volume
- Often written by device vendors

Drivers in Linux



Drivers and Protection

- Drivers are part of the OS
- So they execute in kernel mode
- And have access to all OS data structures
  - Example: driver can change process priority
- Is this a good idea?

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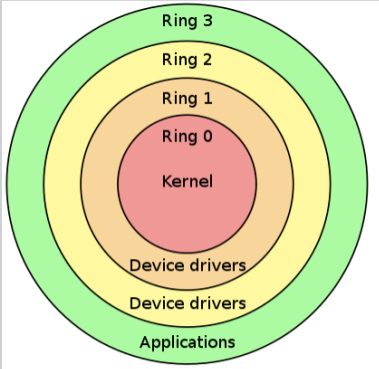
- So they execute in kernel mode
- And have access to all OS data structures
  - Example: driver can change process priority
- Solution: use lower privileges
  - A level (levels) between kernel mode and user mode
  - Exists in most processors
  - Not used by most OS



Privilege rings for the x86 available in protected mode

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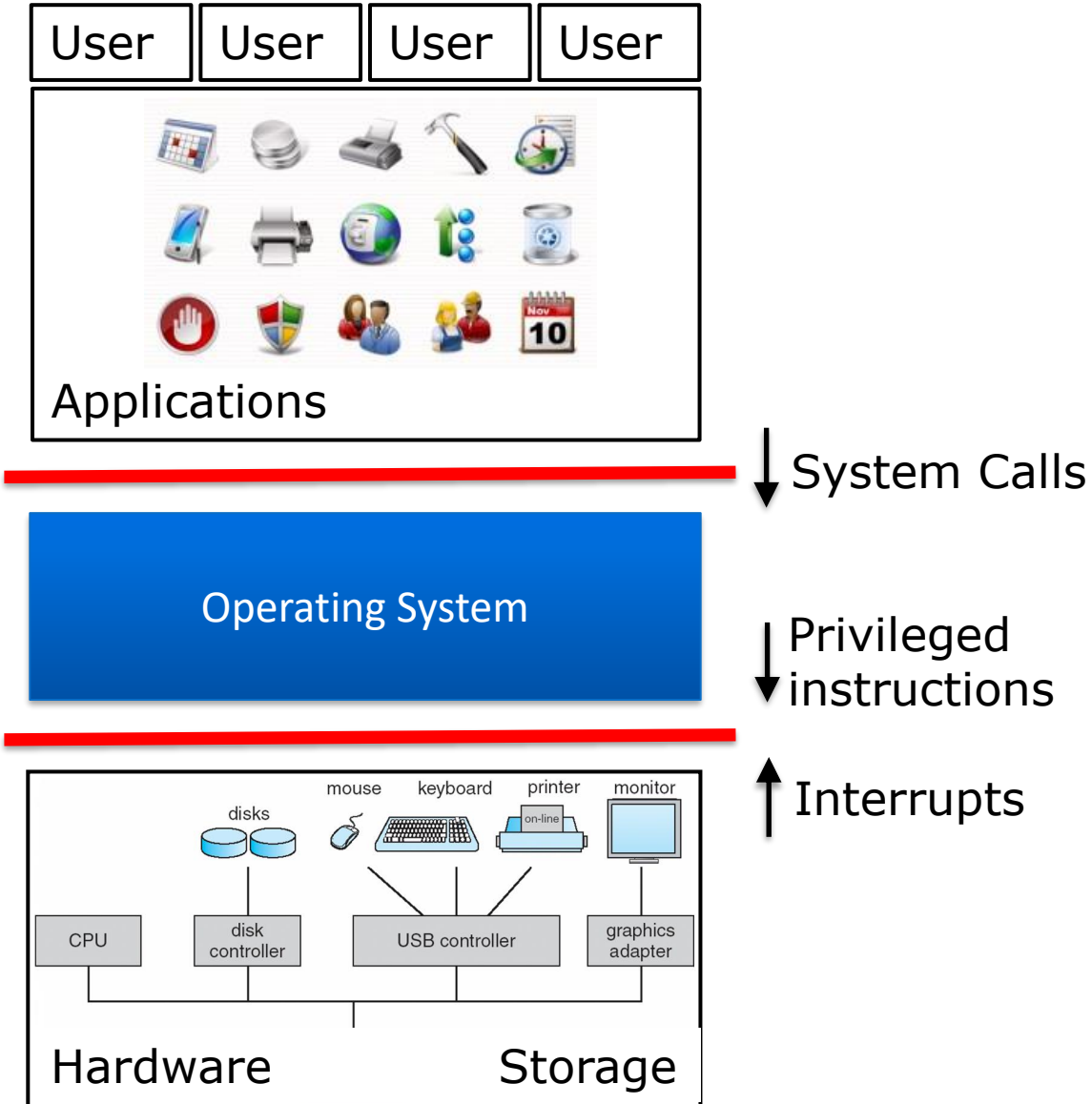

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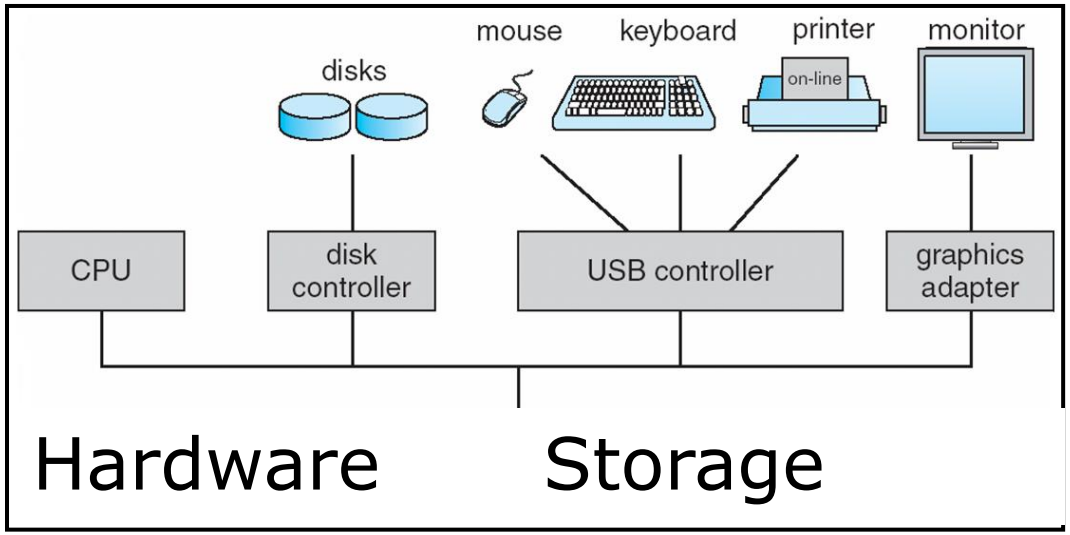
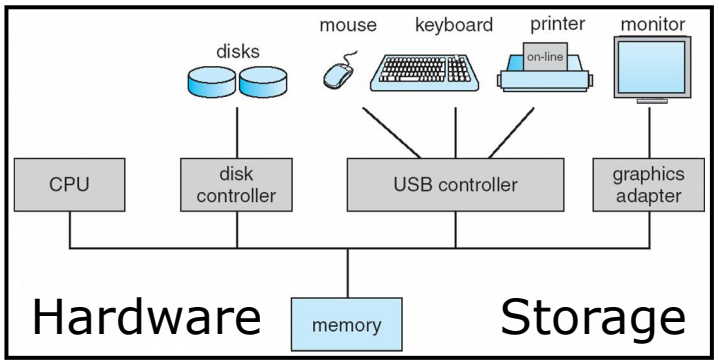


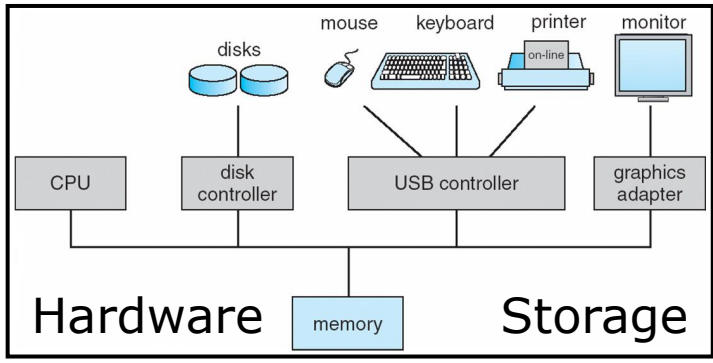
How to connect I/O devices? Bus

- Advantages:
  - Versatility:
    - New devices can be added easily
    - Peripherals can be moved between computer systems that use the same bus standard
  - Low Cost:
    - A single set of wires is shared in multiple ways

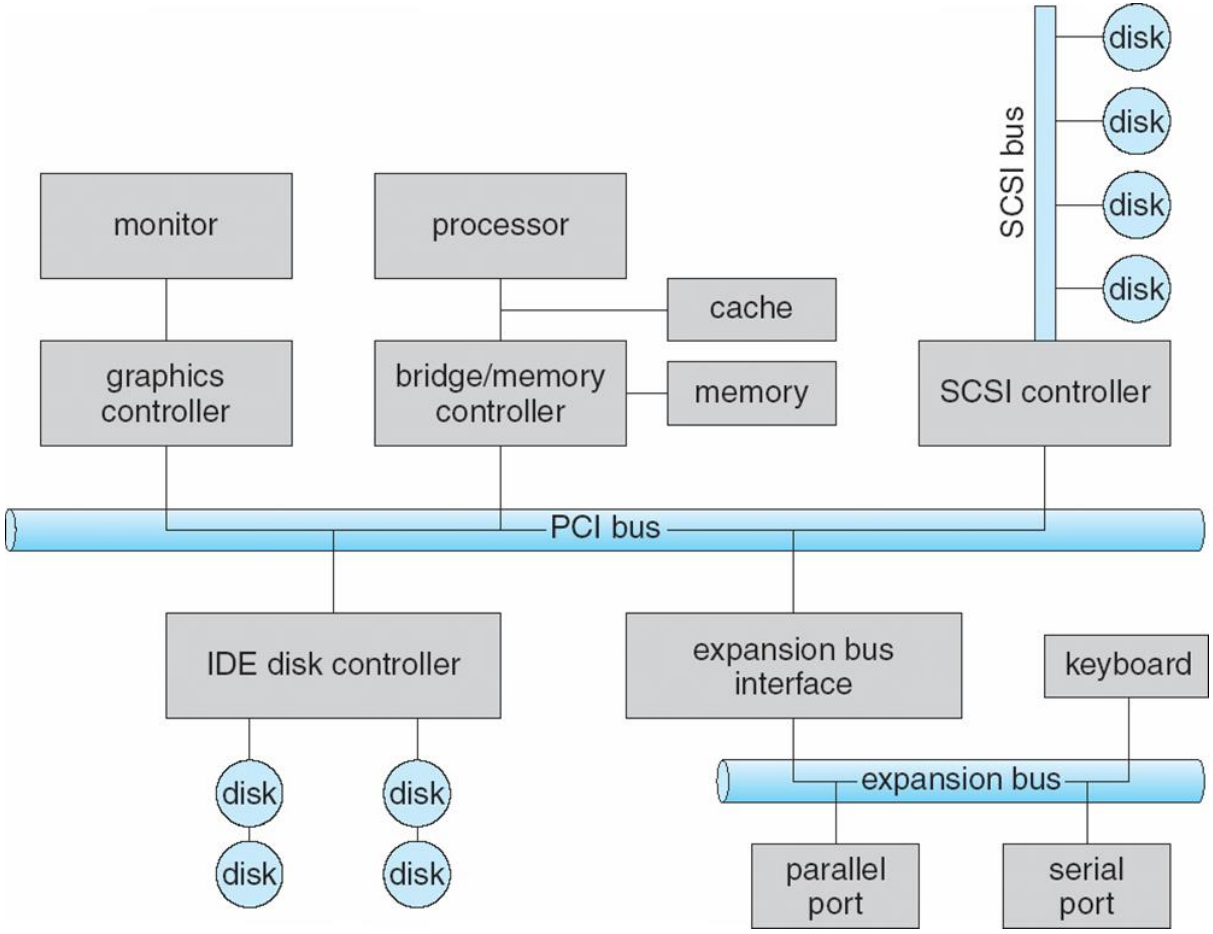


How to connect I/O devices? Bus

- Disadvantages:
  - It creates a communication **bottleneck**
    - The bandwidth of that bus can limit the maximum I/O throughput
  - The maximum bus speed is largely limited by:
    - The length of the bus
    - The number of devices on the bus
    - The need to support a range of devices with:
      - Widely varying latencies
      - Widely varying data transfer rates



Again, the reality is more complicated



How to communicate with I/O devices? Interrupts

- Devices have controllers with firmware
- Writing to certain bus addresses activates the controllers and transfers data to them
  - The driver for a device knows the specific details
- The controllers can then operate in the background (DMA)
- They then use interrupts to signal completion
- Also used by interactive devices
  - Every mouse click causes an interrupt
  - Every keystroke causes an interrupt

How to communicate with I/O devices? Interrupts

- Devices use interrupts to signal that they need service
  - Completion of an operation
  - Input from some external source (user, network)
- Cause the CPU to stop what it was doing
- And start running an OS function to handle the interrupt
- Just like exceptions and system calls

Interrupt Handling

- Upon an interrupt, the CPU needs to start running the correct interrupt handler
- This is part of the OS
- How does the hardware know where this OS function is located?
  - Hardware is hardwired – no flexibility
  - Maybe the OS was not even written when the CPU was manufactured!

The Interrupt Vector

- The solution: indirection via the interrupt vector
- The hardware defines an area in memory where it expects to find pointers to interrupt handlers
  - This is part of the architecture
  - Example: the first 1KB of memory (256 pointers)
- It is the responsibility of the OS to install pointers to the correct interrupt handlers in the cells of the interrupt vector
  - Happens during system boot and when new devices are installed
  - Defined as OS memory inaccessible to users

Interrupt Handling

- When an interrupt happens, the hardware will blindly load the address from the specified vector to the PC
- And atomically also set the mode bit to kernel mode
  - Identifying the device is part of the interrupt mechanism
  - Assigning IDs to devices is part of plug-and-play

Classifications of Interrupts

- Software vs. Hardware

  Software: causes by a software, this includes traps and exceptions.

  Hardware: caused by hardware, this includes interrupts from external devices.

- Internal vs. External

  Generally: Internal=Software, External=Hardware

- Synchronous vs. Asynchronous

  Synchronous: happens with the clock ticks (software, timer/clock interrupts).

- Maskable vs. Non-maskable

  Maskable: hardware interrupts that can be delayed if more important interrupts is currently handled.

- Periodic vs. Aperiodic

Examples of Interrupts

INT_NUM	Short Description PM [*clarification needed*]
0x00	Division by zero
0x01	Single-step interrupt (see trap flag)
0x02	NMI
0x03	Breakpoint (callable by the special 1-byte instruction 0xCC, used by debuggers)
0x04	Overflow
0x05	Bounds
0x06	Invalid Opcode
0x07	Coprocessor not available
0x08	Double fault
0x09	Coprocessor Segment Overrun *(386 or earlier only)*
0x0A	Invalid Task State Segment
0x0B	Segment not present
0x0C	Stack Fault
0x0D	General protection fault
0x0E	Page fault
0x0F	*reserved*
0x10	Math Fault
0x11	Alignment Check
0x12	Machine Check
0x13	SIMD Floating-Point Exception
0x14	Virtualization Exception
0x15	Control Protection Exception

x86 Architecture:

- there are 256 interrupt vectors
- First 32 are reserved

← Some examples

0x80 is used for system calls' traps

Disabling (Masking) Interrupts

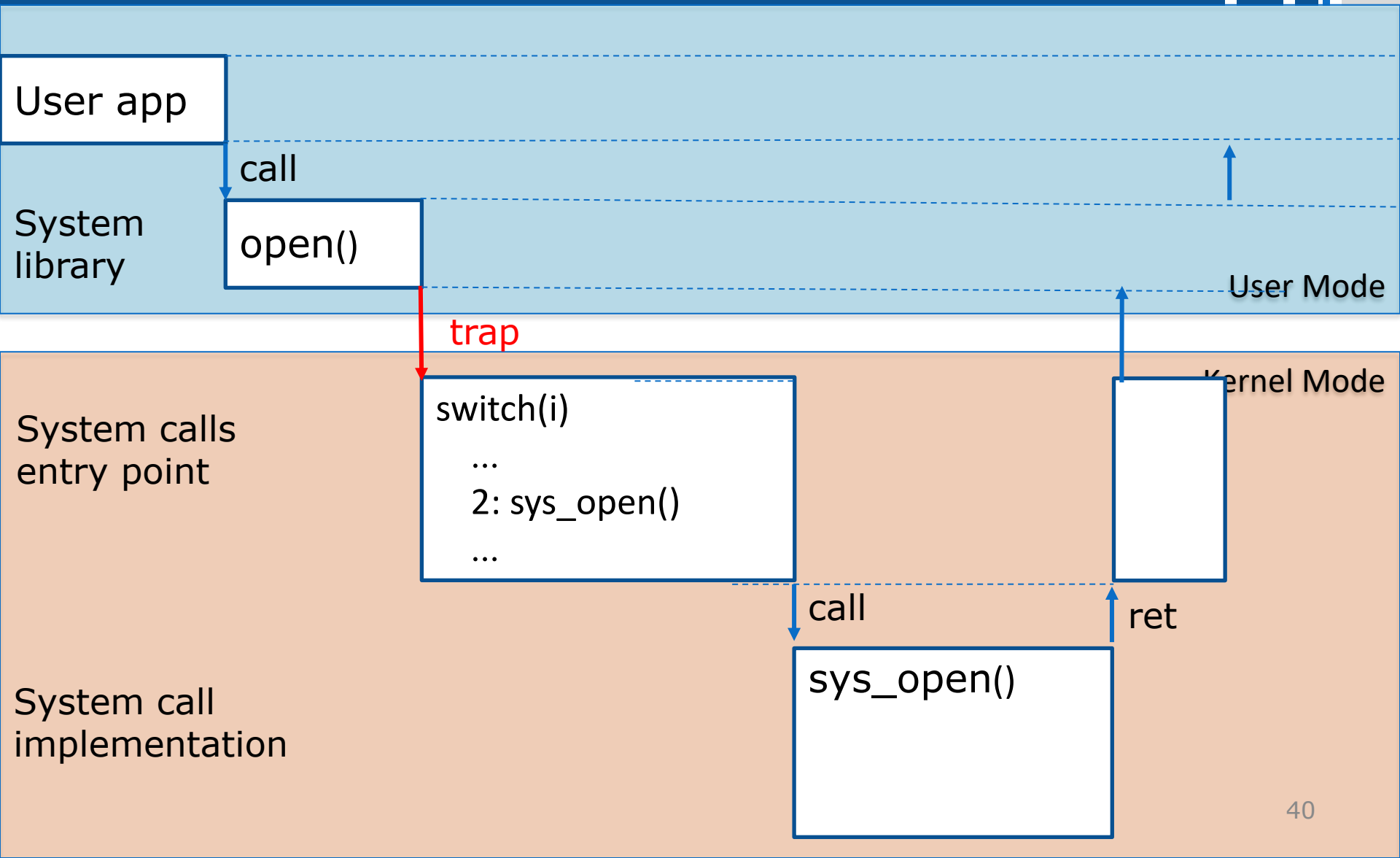
- An operating system is **interrupt driven**
  - Comes with being a reactive program
- Incoming interrupts are generally *disabled* while another interrupt is being processed to prevent a *lost interrupt*
  - But a few interrupts cannot be delayed…
- The OS can also disable interrupts so it won't be interrupted in the middle of critical work

Summary: Three ways to communicate with OS

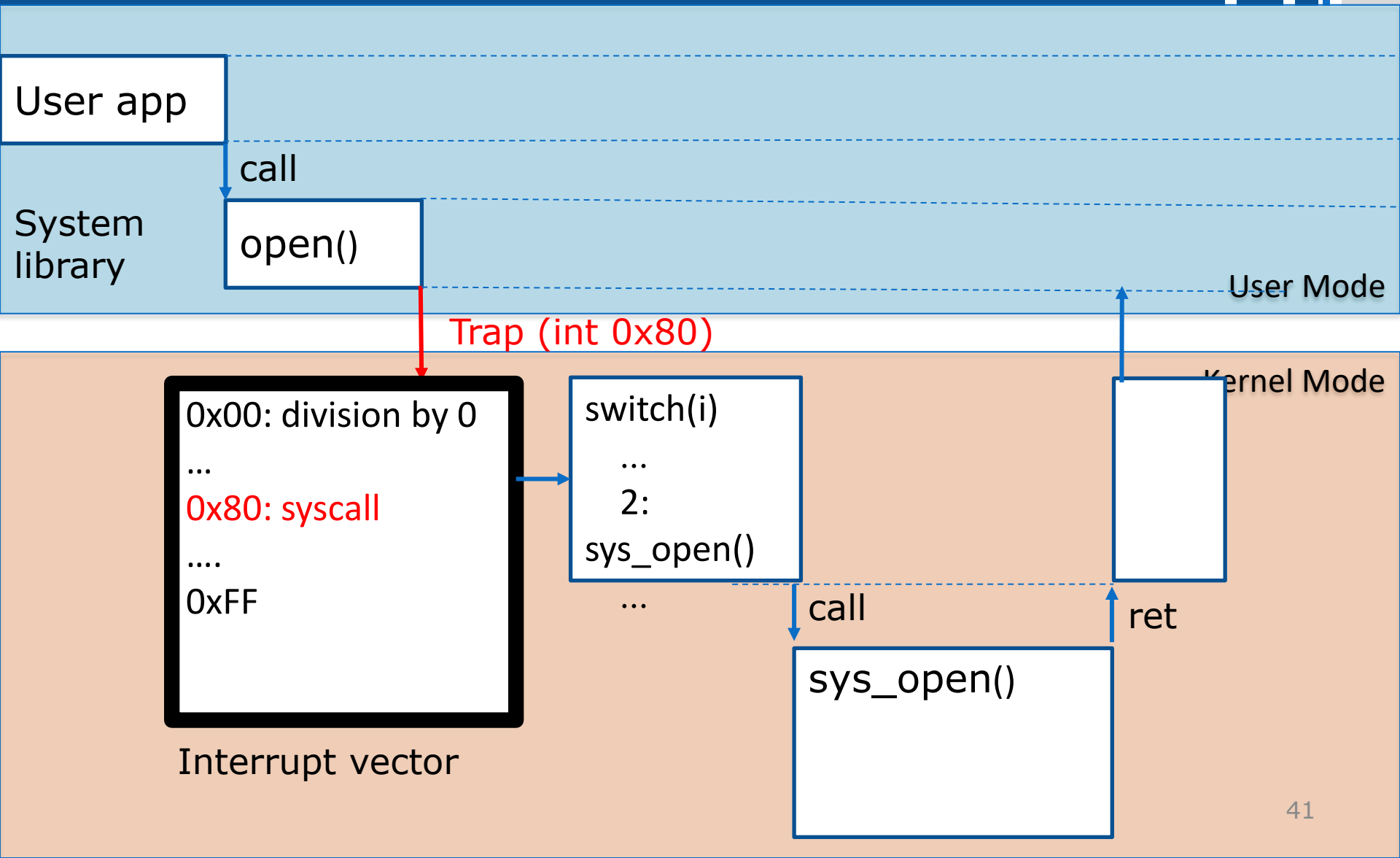
- **Interrupts** (a.k.a. hardware interrupts)
- **System calls**
  - that cause **traps** (a.k.a. software interrupts)
- **Exceptions** (when something wrong happens, also considered software interrupts)

Sometimes hardware interrupts, traps and exceptions are collectively called **interrupts**
Technically, the all use the same mechanism (the interrupt vector)

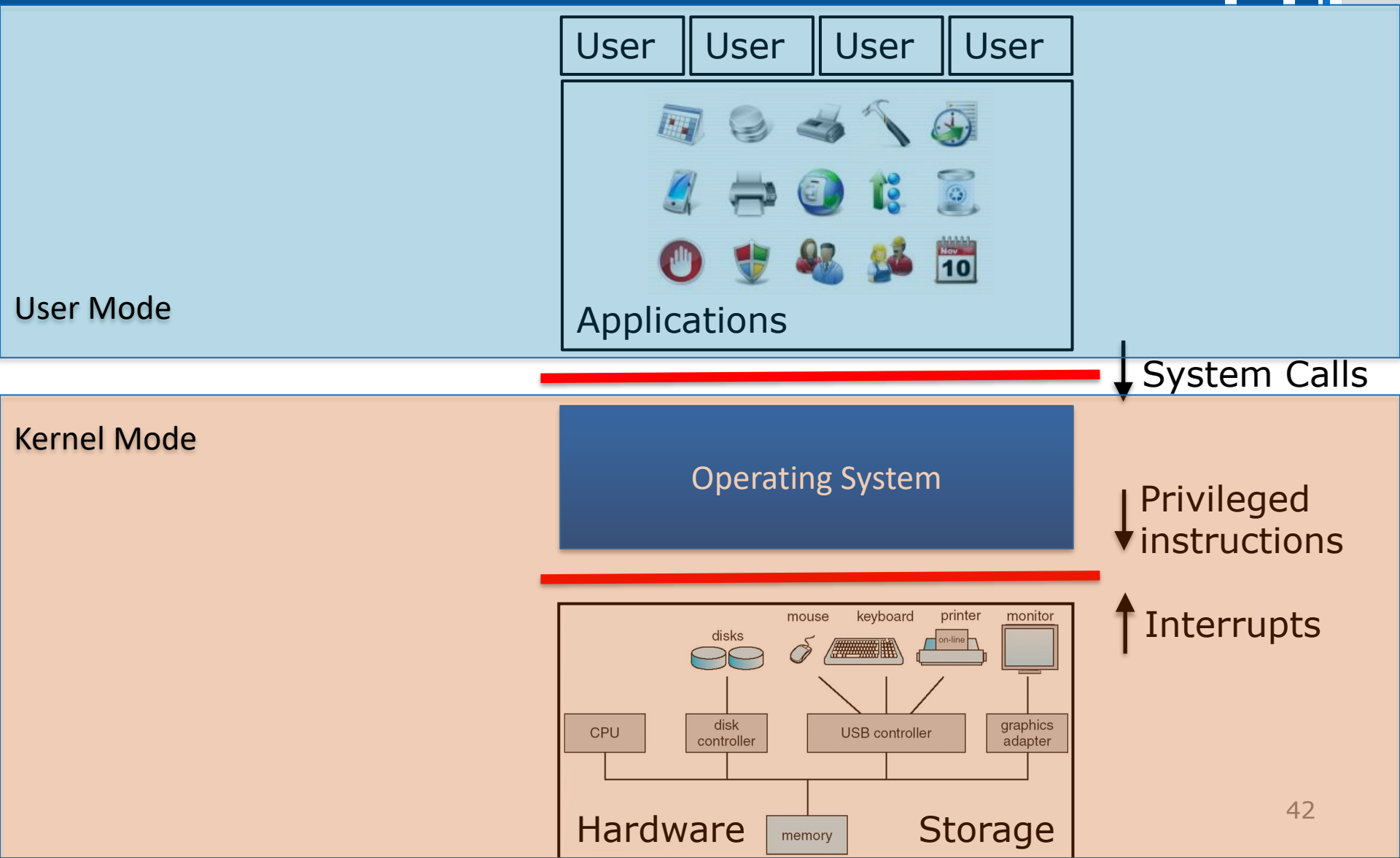
Trap in Detail



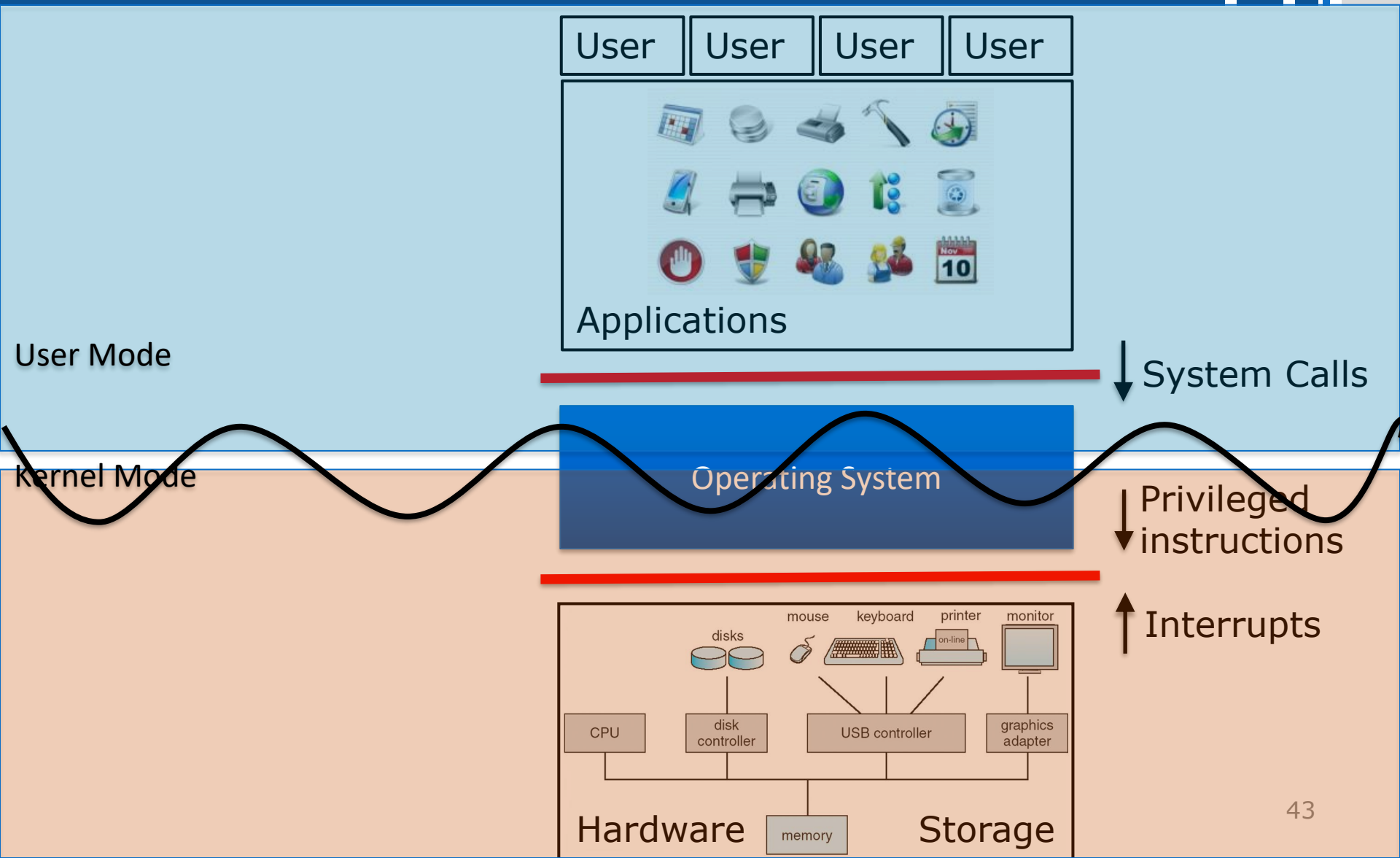
Trap in Detail



Kernel and User Modes revisited



Kernel and User Modes revisited



Trade-offs

- Smaller kernel:
  -  Less traps → less overhead → higher throughput
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- Smaller kernel → smaller memory footprint
- Smaller kernel → more functions outside kernel → if they change, no need to recompile the kernel

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dhay — bash — 171×50

```
Davids-MacBook-Air-2:~ dhay$ kextstat
Index Refs Address            Size       Wired      Name (Version) <Linked Against>
    1   70 0xffffff7f80757000 0x686c     0x686c     com.apple.kpi.bsd (12.6.0)
    2    6 0xffffff7f80742000 0x46c      0x46c      com.apple.kpi.dsep (12.6.0)
    3   94 0xffffff7f80761000 0x1b7ec    0x1b7ec    com.apple.kpi.iokit (12.6.0)
    4   98 0xffffff7f8074d000 0x99f8     0x99f8     com.apple.kpi.libkern (12.6.0)
    5   86 0xffffff7f80743000 0x88c      0x88c      com.apple.kpi.mach (12.6.0)
    6   38 0xffffff7f80744000 0x502c     0x502c     com.apple.kpi.private (12.6.0)
    7   57 0xffffff7f8074a000 0x23cc     0x23cc     com.apple.kpi.unsupported (12.6.0)
    8    0 0xffffff7f81806000 0x41000    0x41000    com.apple.kec.corecrypto (1.0) <7 6 5 4 3 1>
    9   22 0xffffff7f80d17000 0x9000     0x9000     com.apple.iokit.IOACPIFamily (1.4) <7 6 4 3>
   10   30 0xffffff7f80851000 0x29000    0x29000    com.apple.iokit.IOPCIFamily (2.8) <7 6 5 4 3>
   11    2 0xffffff7f825f6000 0x5a000    0x5a000    com.apple.driver.AppleACPIPlatform (1.8) <10 9 7 6 5 4 3 1>
   12    1 0xffffff7f80a72000 0xe000     0xe000     com.apple.driver.AppleKeyStore (28.21) <7 6 5 4 3 1>
   13    6 0xffffff7f8077d000 0x25000    0x25000    com.apple.iokit.IOStorageFamily (1.8) <7 6 5 4 3 1>
   14    0 0xffffff7f80dd8000 0x19000    0x19000    com.apple.driver.DiskImages (345) <13 7 6 5 4 3 1>
   15    0 0xffffff7f822dd000 0x2e000    0x2e000    com.apple.driver.AppleIntelCPUPowerManagement (214.0.0) <7 6 5 4 3 1>
   16    0 0xffffff7f8075e000 0x3000     0x3000     com.apple.security.TMSafetyNet (7) <7 6 5 4 2 1>
   17    2 0xffffff7f807f3000 0x4000     0x4000     com.apple.kext.AppleMatch (1.0.0d1) <4 1>
   18    1 0xffffff7f807f7000 0x11000    0x11000    com.apple.security.sandbox (220.4) <17 7 6 5 4 3 2 1>
   19    0 0xffffff7f80808000 0x6000     0x6000     com.apple.security.quarantine (2.1) <18 17 7 6 5 4 2 1>
```

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- Microkernels :
  - Mach

NEXT SUBJECT: PROCESS MANAGEMENT