Systems and Networking I

Applied Computer Science and Artificial Intelligence

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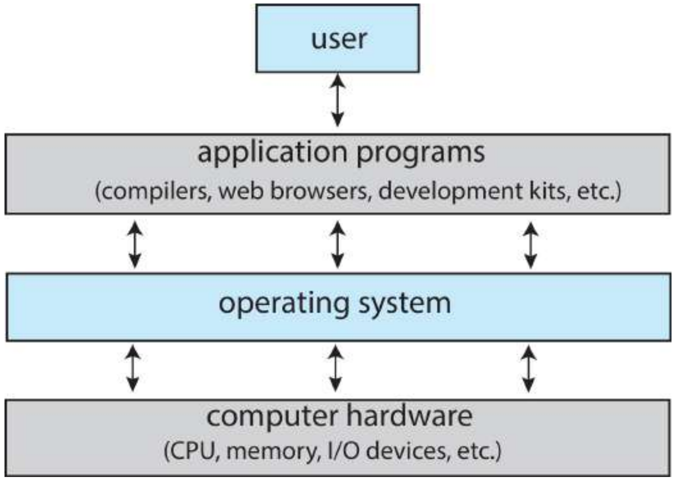
Recap from Last Lecture

- Operating System is a complex system which plays several roles:
  - resource manager
  - virtual machine
  - HW/SW interface



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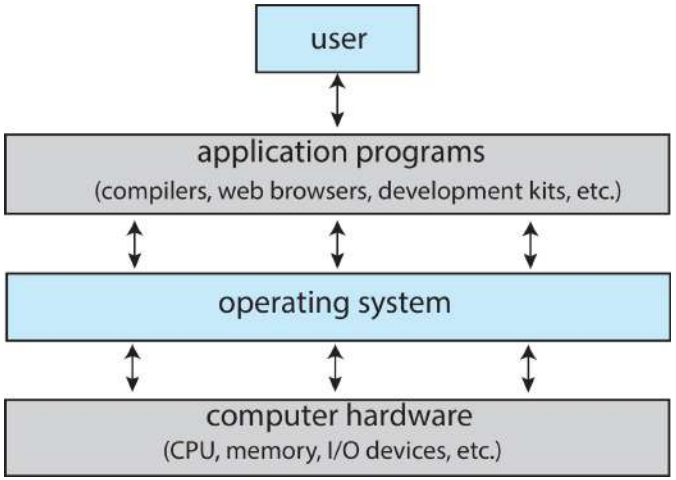

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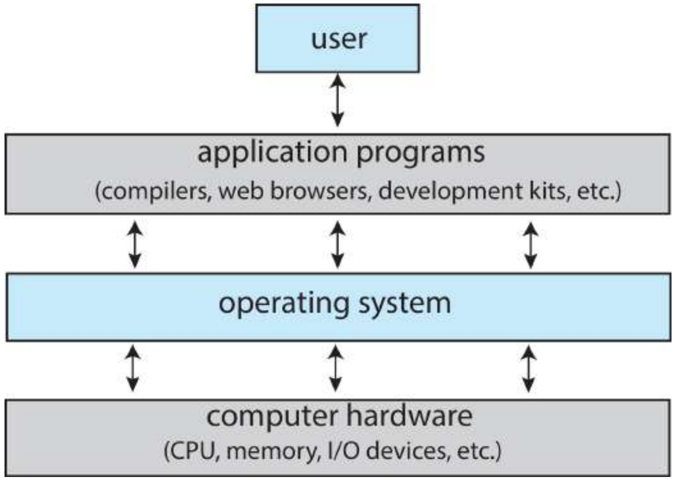
- Changes in HW may affect OS design



Outline of this Lecture

1. HW support for OS functionalities and services
2. OS design and implementation

HW Support for OS

OS and Computer Architecture

- Basic OS functionalities (enabled by architectural features)

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- What the OS can do is partially dictated by the underlying architecture
- Architectural support may significantly simplify or complicate the OS design

Architectural Features Enabling OS Services

OS Service	HW Support
Protection and Security	Kernel/user mode, protected instructions, base/limit registers
System calls	Trap instructions and interrupt vectors
Exception handling	Trap instructions and interrupt vectors
I/O operations	Trap instructions, interrupt vectors, and memory mapping
Scheduling	Timer
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Privileged Instructions

- Some CPU instructions are more sensitive than others
  - `MOV %eax, %ebx` → move the content of the register `ebx` into `eax`
  - `MOV %eax, [%ebx]` → move the content of memory indexed by register `ebx` to `eax`
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Idea:
privileged instructions can be executed **only** by the OS

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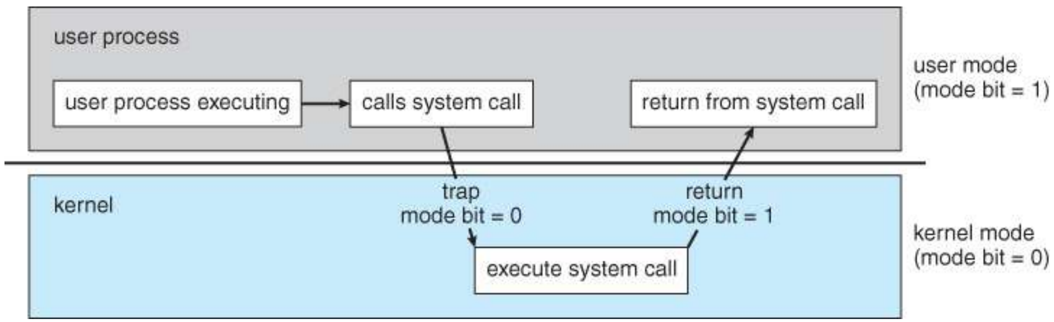
Implemented in HW!
A status bit stored in a protected CPU register (`0`=kernel, `1`=user)

Kernel vs. User Mode



System calls are just **one** way to "trap into" kernel mode

We'll soon talk about system calls

The idea is the same!
The control is transferred from the user to the system

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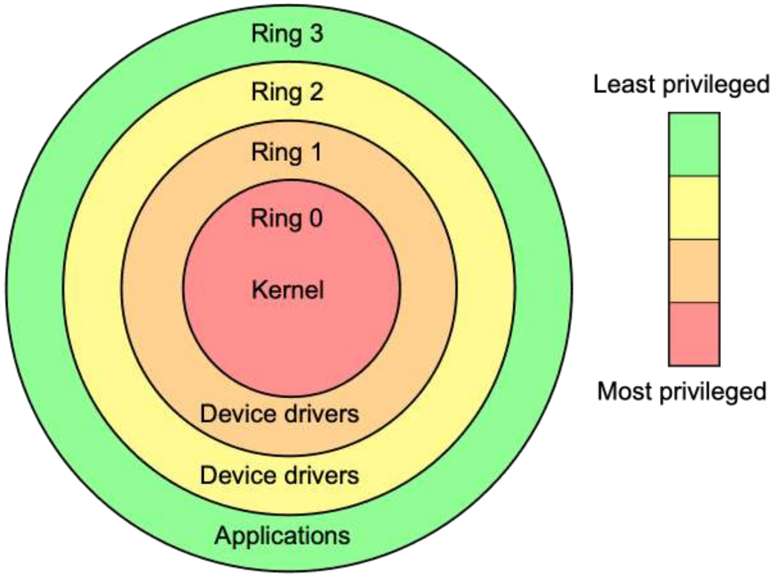
- **Protection Rings**
  - 4 different privilege levels {0, ..., 3}
  - Still implementable in HW (2 bits)



Memory Protection

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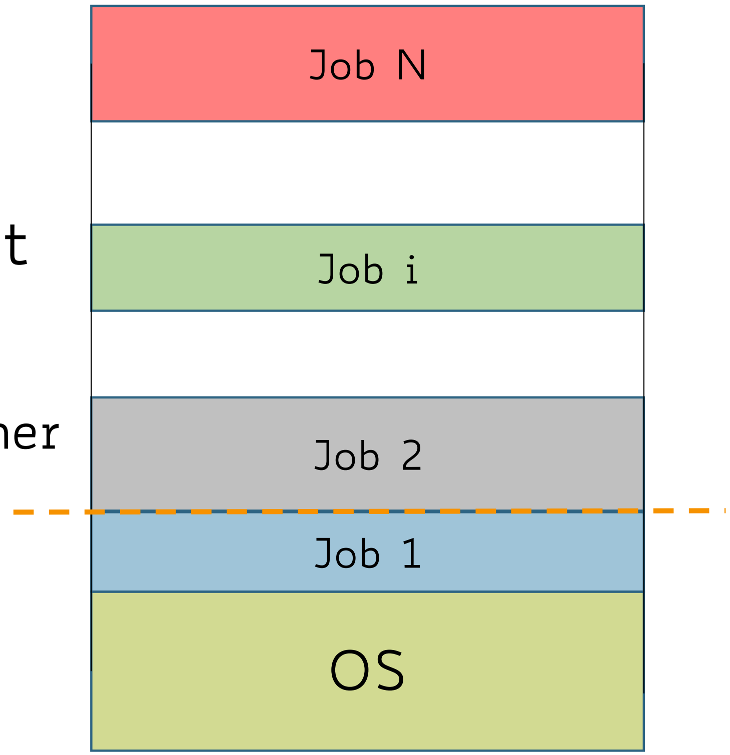
  - Protect user programs from each other



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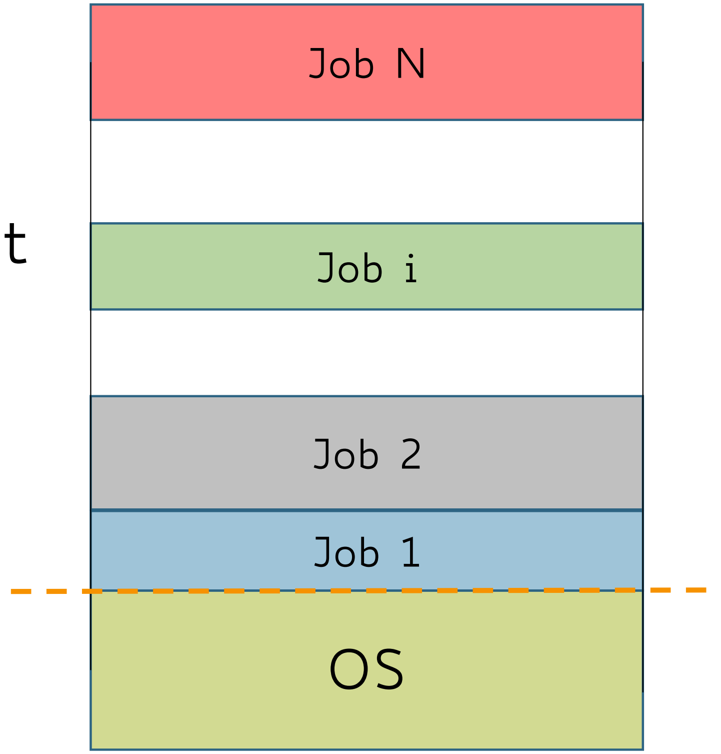

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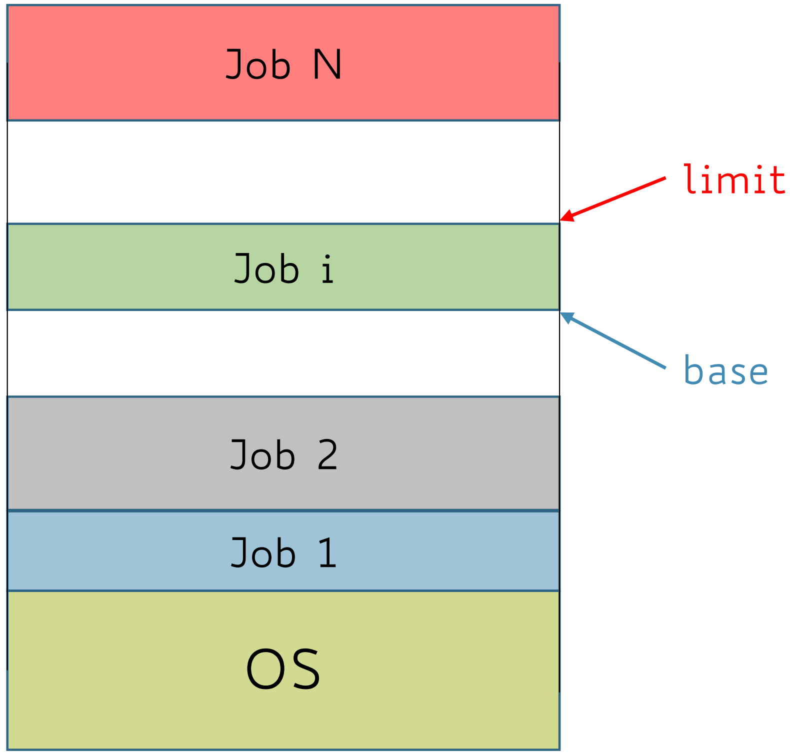
  - base → contains the starting valid memory address
  - limit → contains the last valid memory address



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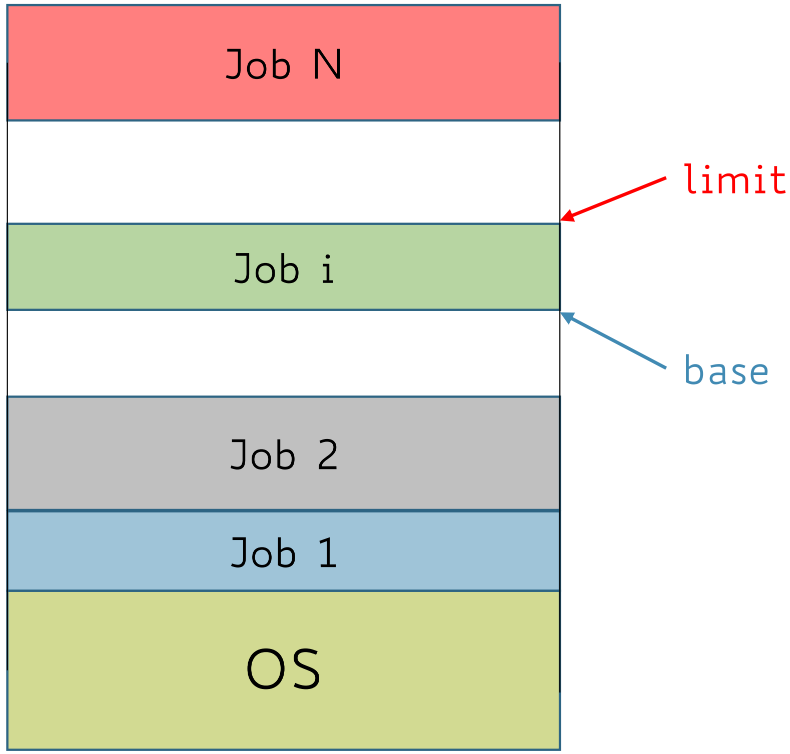

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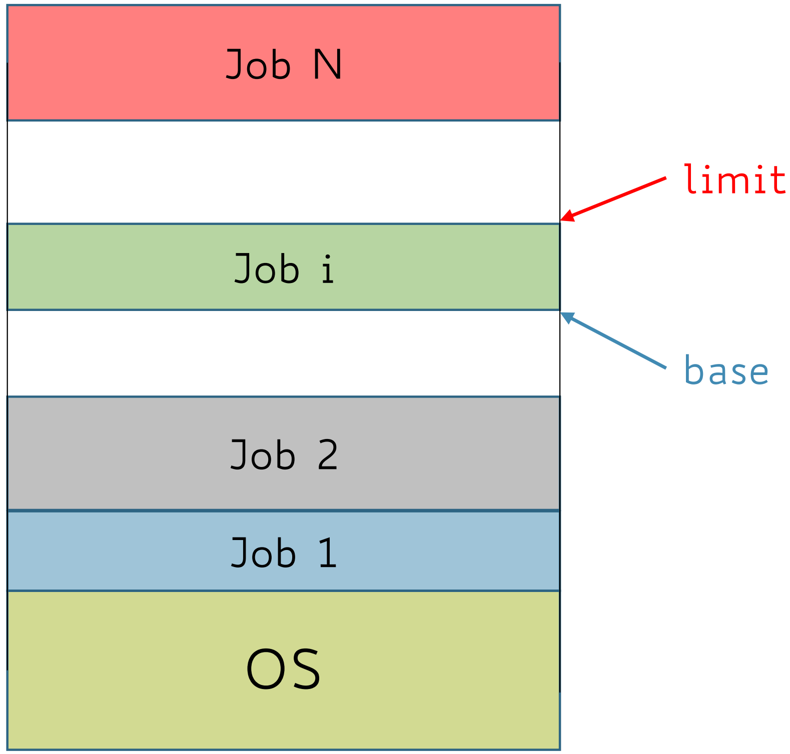
- The CPU checks every memory address referenced by user program falls between base and limit values



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Crossing protection boundaries using **system calls**

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- **Exceptions**
  - software-generated
  - e.g., program error like division by 0
- **Interrupts**
  - hardware-generated (by external devices)
  - e.g., I/O completion or timer interrupt on a multi-tasking system

A Quick Note on Terminology

TRAP

We will refer to **trap** as any event that causes switch to OS kernel mode

A Quick Note on Terminology

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SYSTEM CALL
(software trap)

synchronous
SW-initiated
request an OS
service
e.g., `SYSCALL`, `INT`
on the x86

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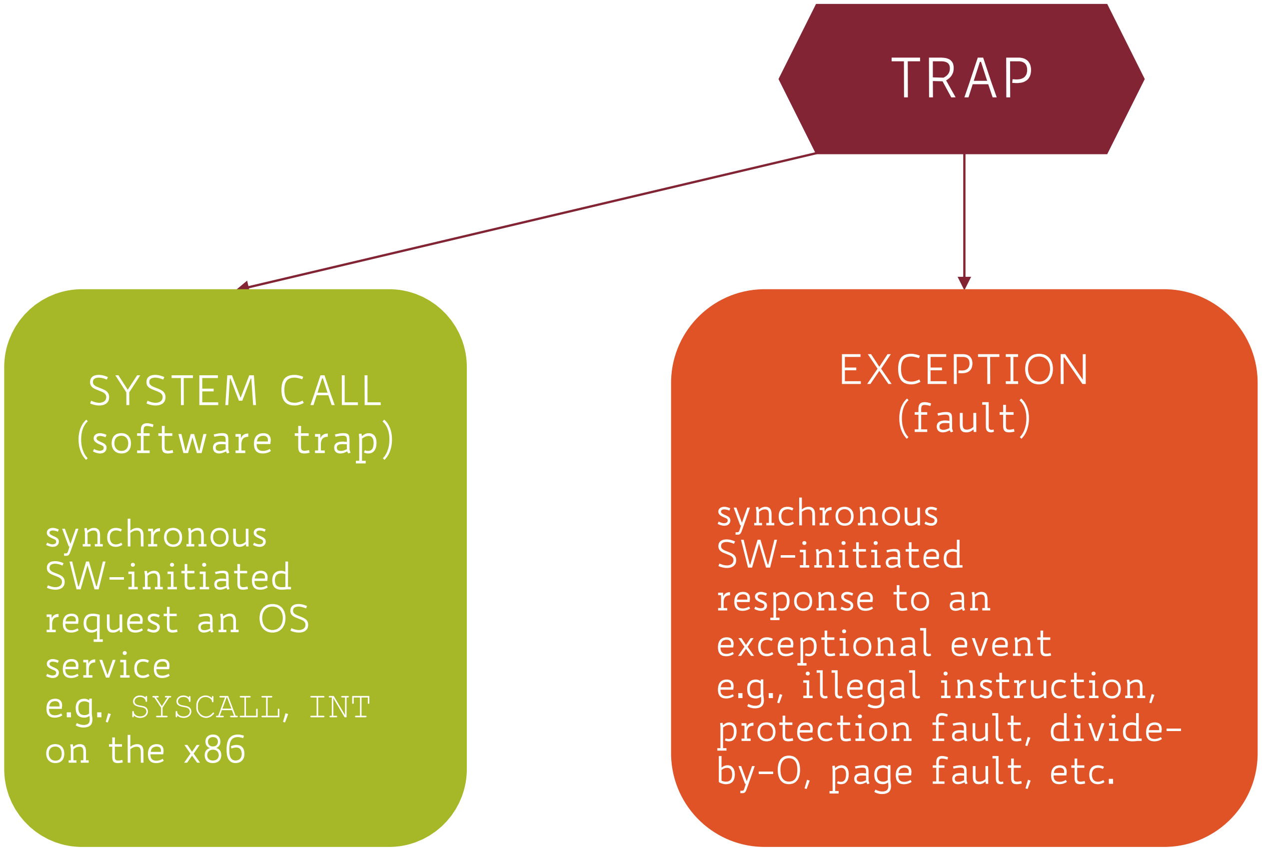

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EXCEPTION (fault)

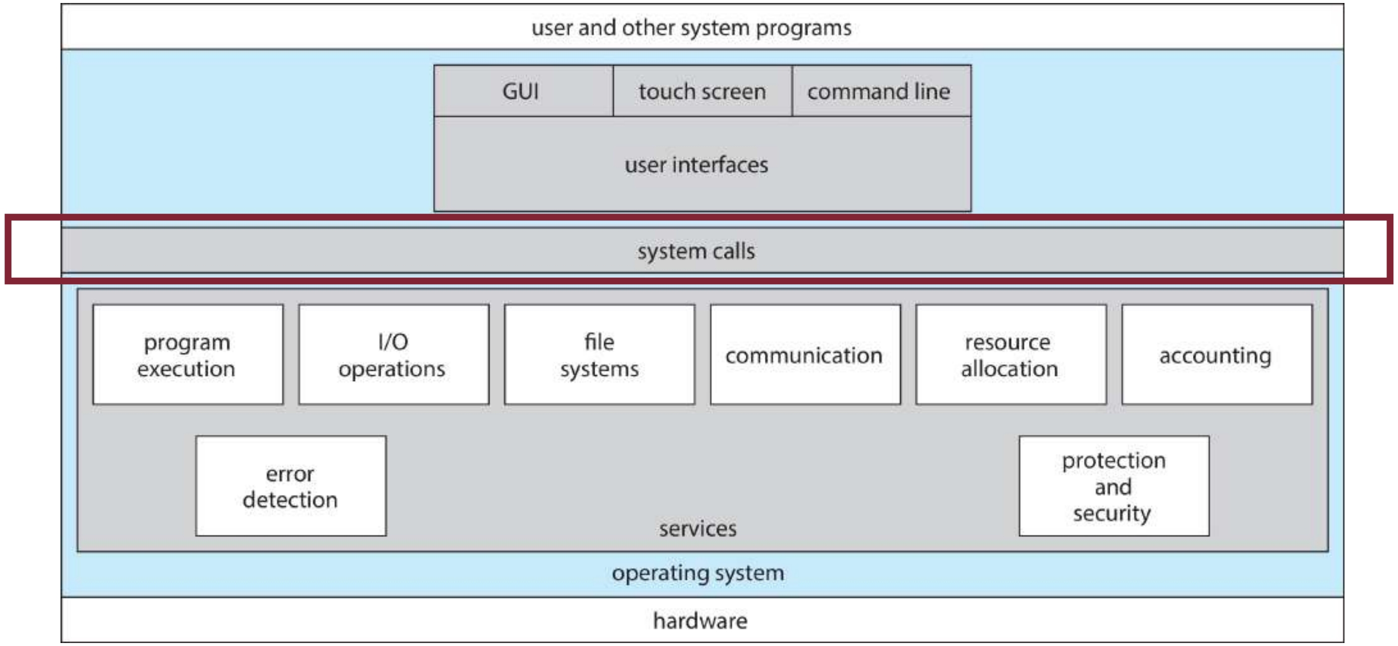
synchronous
SW-initiated
response to an exceptional event
e.g., illegal instruction, protection fault, divide-by-0, page fault, etc.

INTERRUPT

asynchronous
HW-initiated

e.g., network packet arrived, I/O completion, timer

User Programs-OS Interface



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- Programming interface to the services provided by the OS
- Typically written in a high-level language (C or C++)
- Mostly accessed by programs via a high-level Application Programming Interface (API) rather than direct system call
  - GNU C Library (POSIX-based systems like UNIX, Linux, macOS)
  - Win32 API (Windows systems)
  - Java API (JVM)

System Calls: Categories

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  - File management
  - Device management
  - Information maintenance
  - Communications

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- When processes stop abnormally it may be necessary to provide core dumps and/or other diagnostic or recovery tools

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- The actual directory structure may be implemented using ordinary files on the file system, or through other means (more on this later)

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- Devices may be physical (e.g., disk drives), or virtual/abstract (e.g., files, partitions, and RAM disks)
- Some systems represent devices as special files in the file system, so that accessing the "file" calls upon the appropriate OS device driver
  - e.g., the `/dev` directory on any UNIX system

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- Systems may also provide the ability to dump memory at any time
- Single step programs pausing execution after each instruction, and tracing the operation of programs (debugging)

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System Calls: Communication

- create/delete communication connection, send/receive messages, transfer status information, and attach/detach remote devices

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- 2 models of communication:
  - message passing
  - shared memory

Communication: Message Passing

- The **message passing** model must support calls to:
  - Identify a remote process and/or host with which communicate to
  - Establish a connection between the two processes
  - Open and close the connection as needed
  - Transmit messages along the connection
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Easier (particularly for inter-computer communications) and appropriate for small amounts of data

Communication: Shared Memory

- The **shared memory** model must support calls to:
  - Create and access memory that is shared amongst processes (and threads)
  - Provide locking mechanisms restricting simultaneous access
  - Free up shared memory and/or dynamically allocate it as needed

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Faster and generally the better approach
where large amounts of data are to be shared

Ideal when most processes need to read data rather than write

System Calls: Protection

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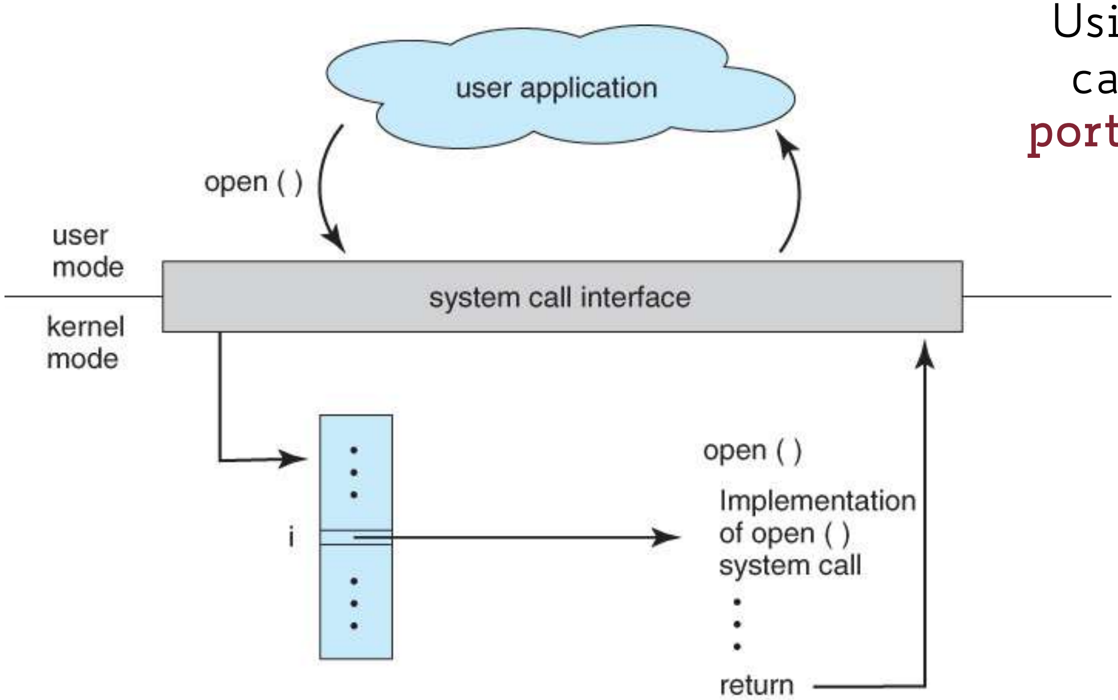
- Provides mechanisms for controlling which users/processes have access to which system resources
- System calls allow the access mechanisms to be adjusted as needed
- Non-priveleged users may temporarily be granted elevated access permissions under specific circumstances
- Crucial in the age of ubiquitous network connectivity

The Anatomy of a System Call



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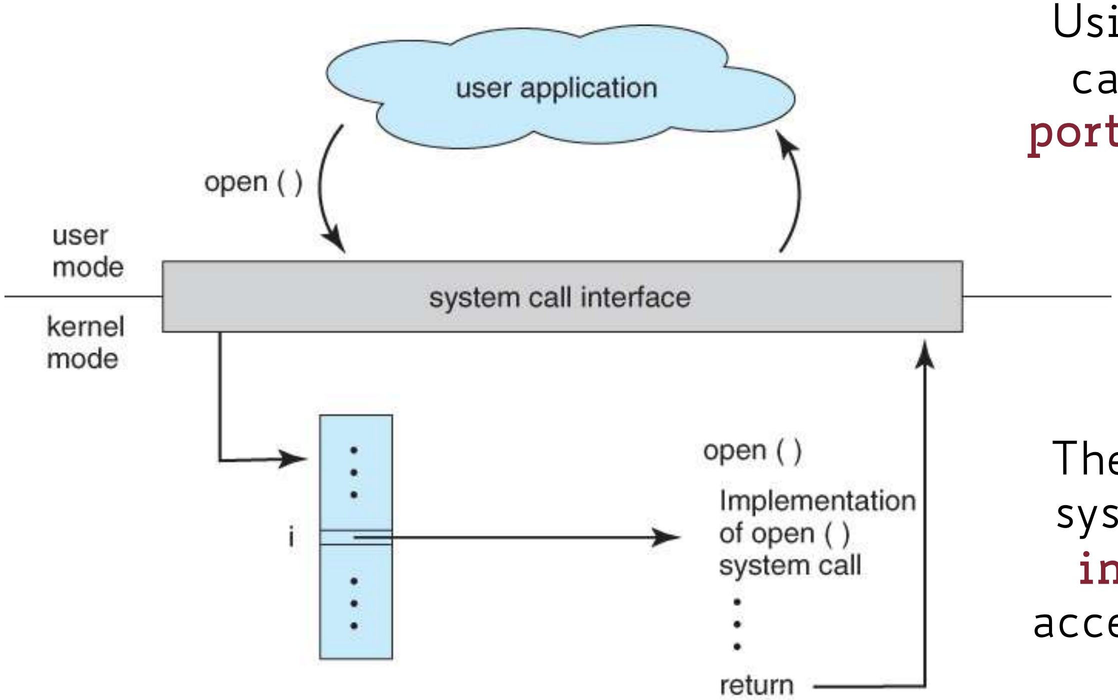

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The API then makes the appropriate system calls through the **system call interface**, using a table lookup to access specific numbered system calls

System Call: **read** (C API Library)

EXAMPLE OF STANDARD API

As an example of a standard API, consider the `read()` function that is available in UNIX and Linux systems. The API for this function is obtained from the `man` page by invoking the command

```
man read
```

on the command line. A description of this API appears below:

```
#include <unistd.h>

ssize_t     read(int fd, void *buf, size_t count)
```

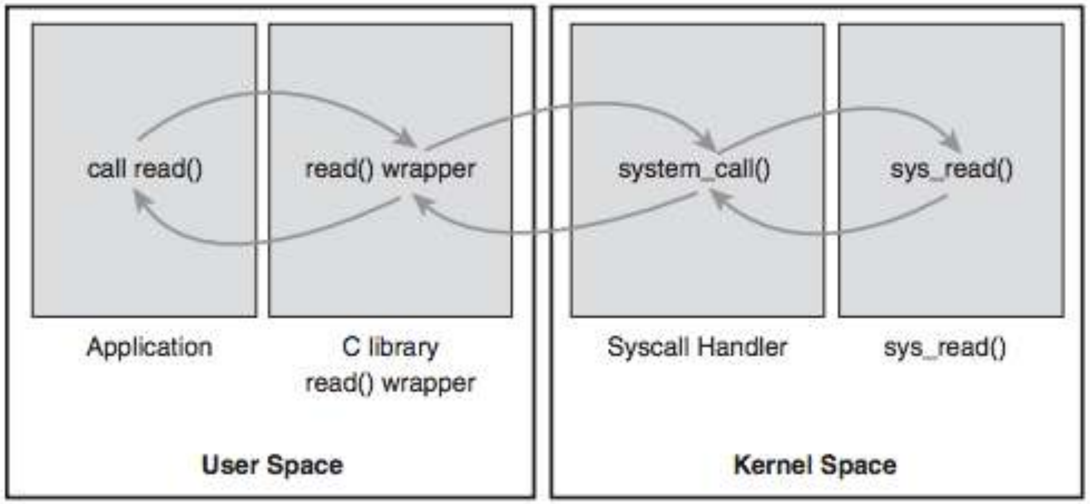
return value	function name	parameters

A program that uses the `read()` function must include the `unistd.h` header file, as this file defines the `ssize_t` and `size_t` data types (among other things). The parameters passed to `read()` are as follows:

- `int fd`—the file descriptor to be read
- `void *buf`—a buffer into which the data will be read
- `size_t count`—the maximum number of bytes to be read into the buffer

On a successful read, the number of bytes read is returned. A return value of 0 indicates end of file. If an error occurs, `read()` returns −1.

System Call: Flow



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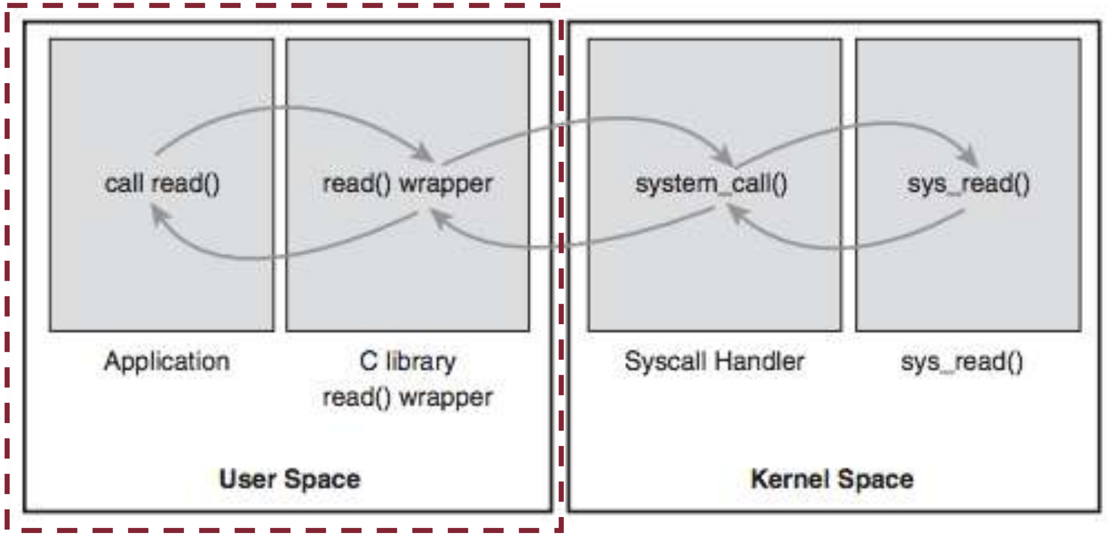

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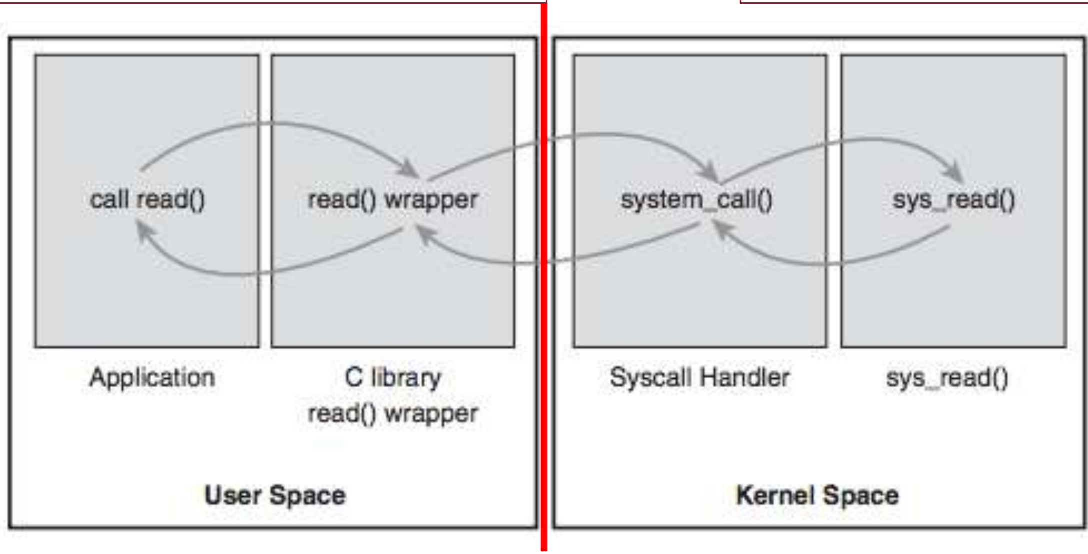

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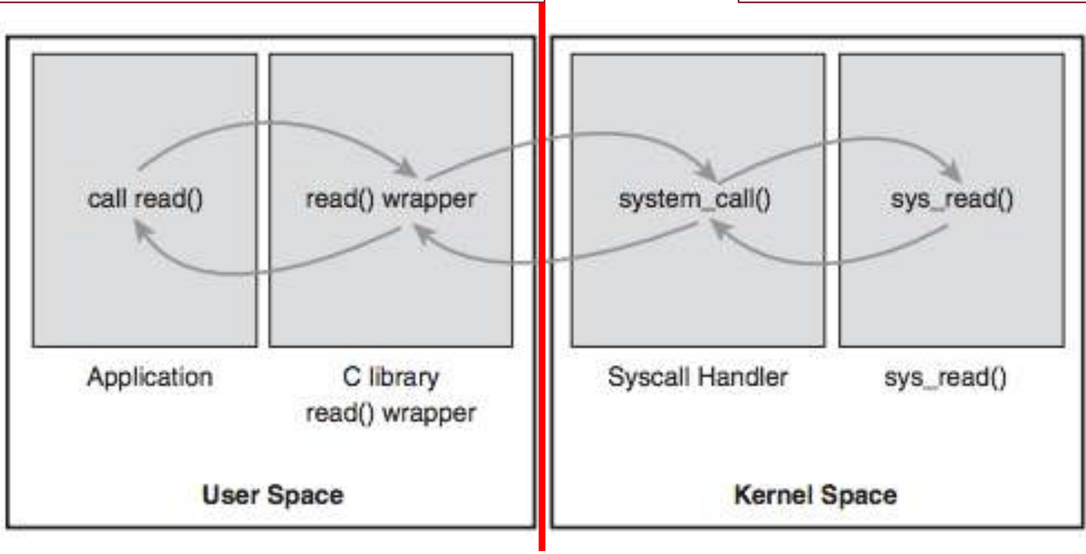

The caller must only obey to the API
(know the input arguments and the expected output from the OS)

System Call Example: Reading from File

```
int main() {
    …
    int nRead = read(fd, buf, count);
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MOV %eax, $sys_read
INT $0x80
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```

store the number which uniquely identifies the system call requested

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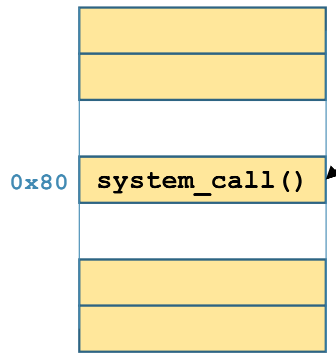
A trap jumps to the interrupt vector table (IVT) in the OS kernel



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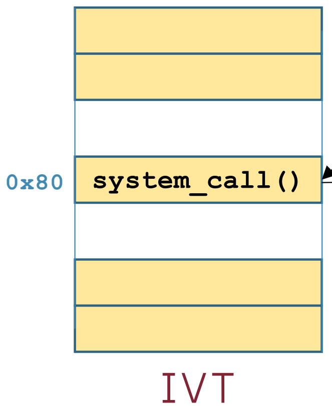
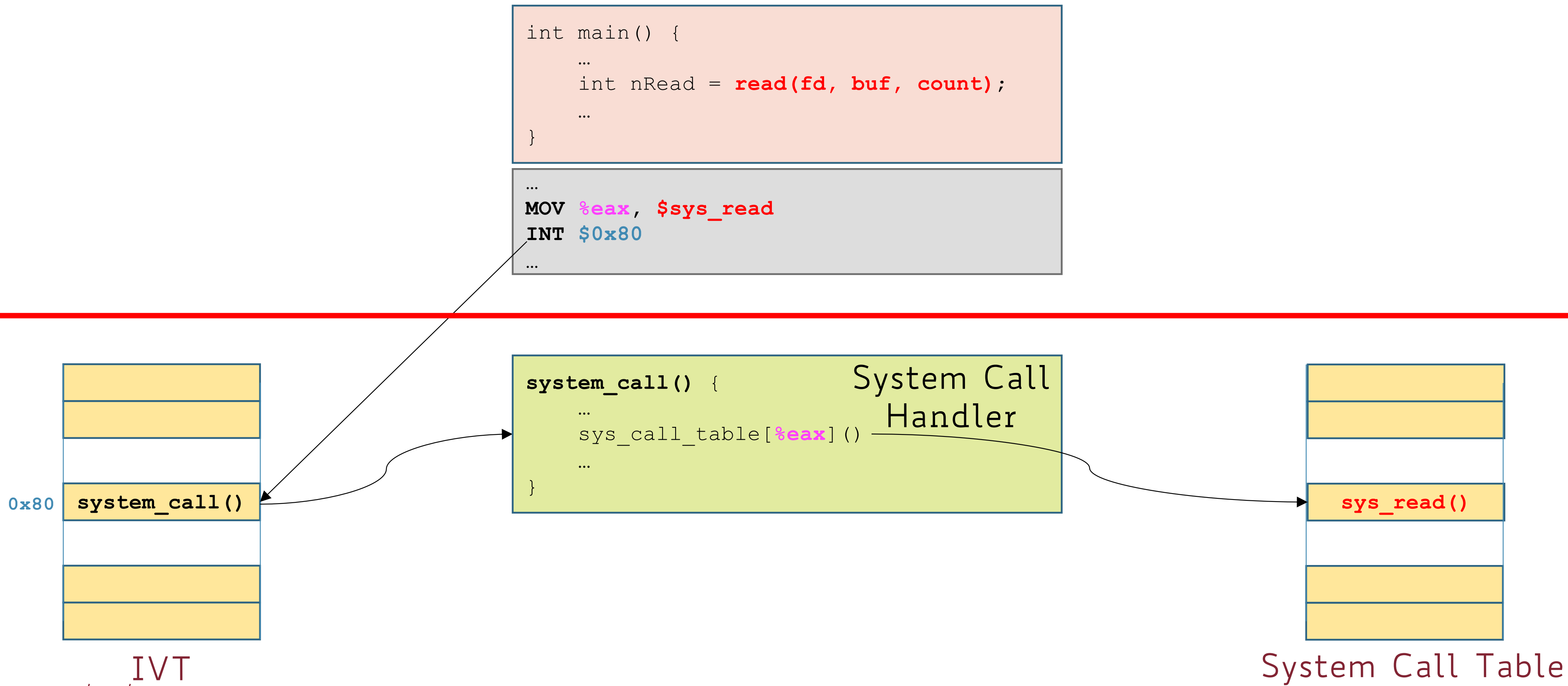



```
system_call() {
    …
    sys_call_table[%eax]()
    …
}
```

System Call Handler

System Call Example: Reading from File



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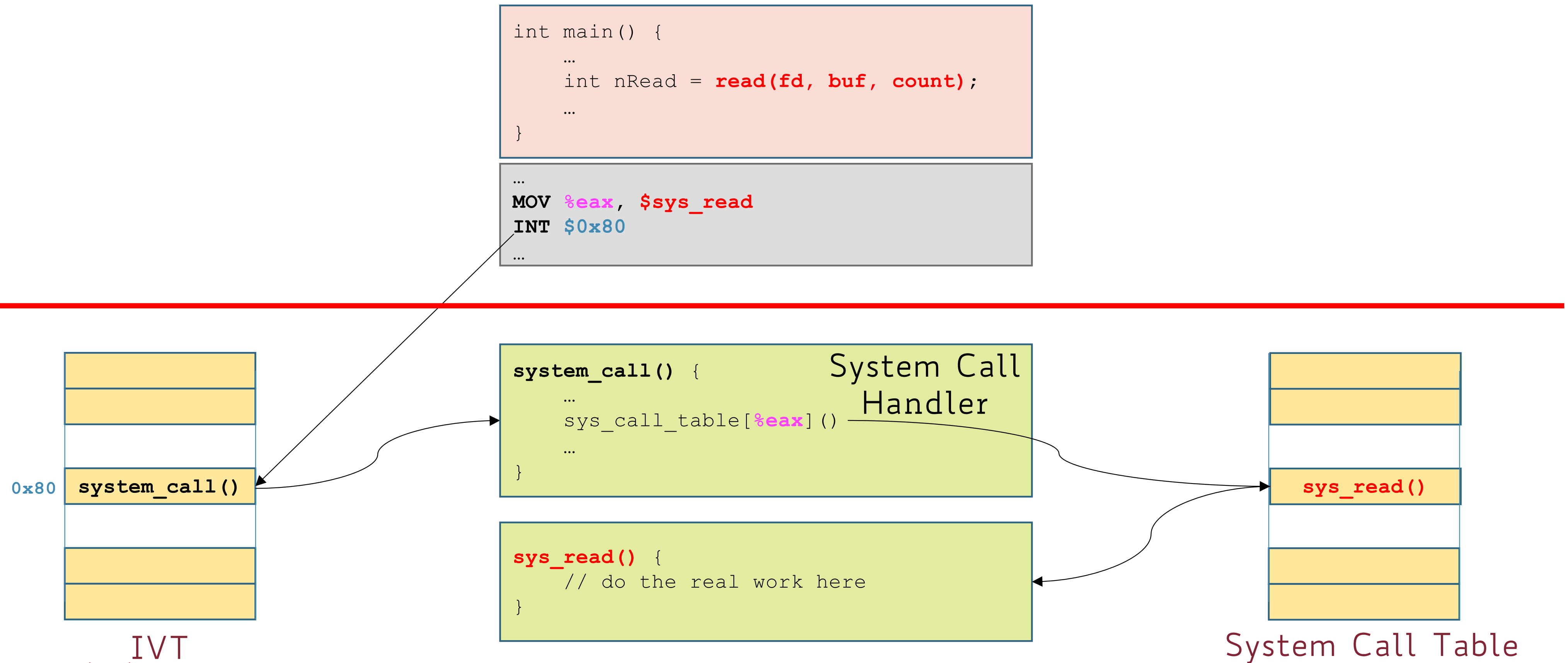

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- The **system call handler** is responsible for:
  - saving the status of user-mode computation on dedicated registers
  - finding and jumping to the correct routine for that trap (e.g., **`sys_read()`**)
  - restoring user-mode program's state upon the service routine is done (e.g., **`IRET`** privileged instruction)

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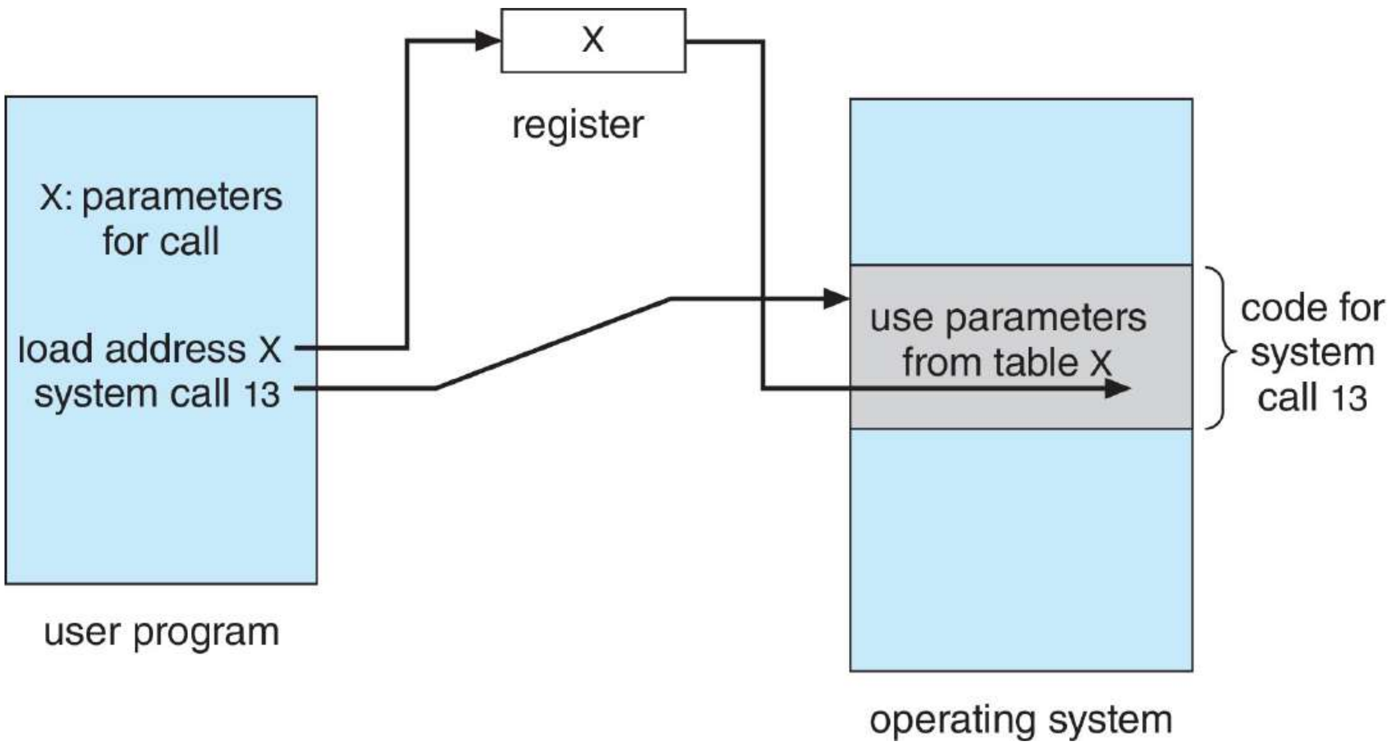
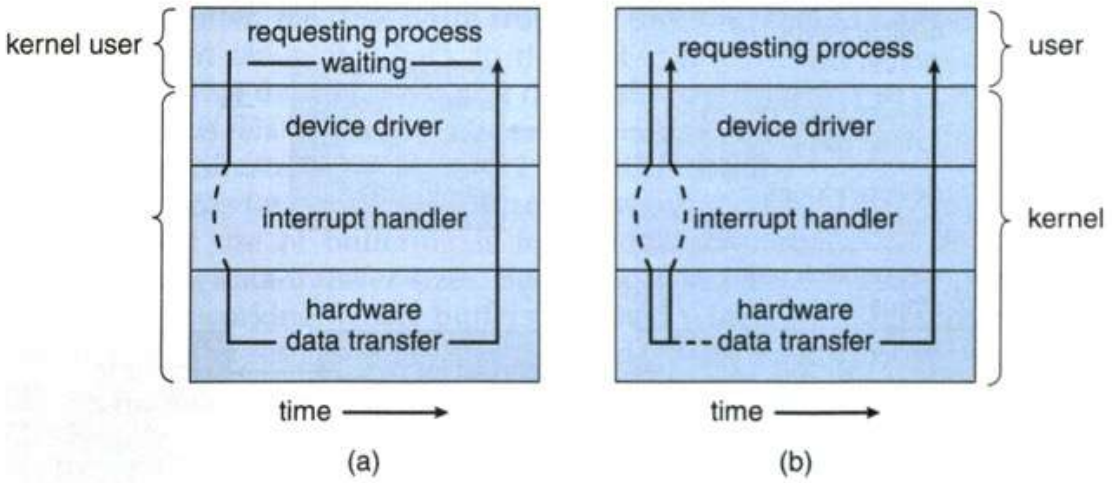
Block and stack methods do not limit the number or length of parameters being passed

Parameter Passing via Table



Blocking vs. Non-Blocking I/O

synchronous asynchronous



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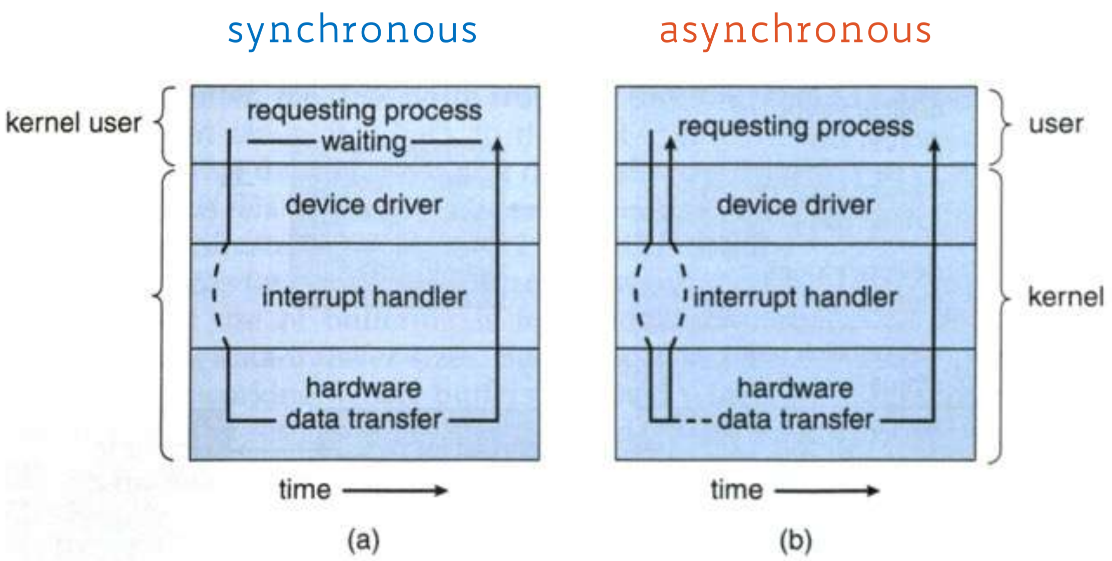

NOTE

In a multi-programming and multi-tasking system, blocking I/O will not leave the CPU idle until I/O task is completed!
In fact, the CPU will schedule another (ready) process to take over

System Calls: Windows vs. UNIX APIs

EXAMPLES OF WINDOWS AND UNIX SYSTEM CALLS

The following illustrates various equivalent system calls for Windows and UNIX operating systems.

	Windows	Unix

Process control	`CreateProcess()`
	`ExitProcess()`
	`WaitForSingleObject()`
		`fork()`
		`exit()`
		`wait()`

File management	`CreateFile()`
	`ReadFile()`
	`WriteFile()`
	`CloseHandle()`
		`open()`
		`read()`
		`write()`
		`close()`

Device management	`SetConsoleMode()`
	`ReadConsole()`
	`WriteConsole()`
		`ioctl()`
		`read()`
		`write()`

Information maintenance	`GetCurrentProcessID()`
	`SetTimer()`
	`Sleep()`
		`getpid()`
		`alarm()`
		`sleep()`

Communications	`CreatePipe()`
	`CreateFileMapping()`
	`MapViewOfFile()`
		`pipe()`
		`shm_open()`
		`mmap()`

Protection	`SetFileSecurity()`
	`InitlializeSecurityDescriptor()`
	`SetSecurityDescriptorGroup()`
		`chmod()`
		`umask()`
		`chown()`

Architectural Features Enabling OS Services

OS Service	HW Support
Protection and Security	Kernel/user mode, protected instructions, base/limit registers
System calls	Trap instructions and interrupt vectors
Exception handling	Trap instructions and interrupt vectors
I/O operations	Trap instructions, interrupt vectors, and memory mapping
Scheduling	Timer
Synchronization	Atomic instructions
Virtual memory	Translation Look-aside Buffer (TLB)

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- The timer generates an interrupt every, say, 100 microseconds
- At each timer interrupt, the CPU scheduler takes over and decides which process to execute next

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- OS must be able to synchronize the activities of cooperating, concurrent processes
- Hardware must ensure that short sequences of instructions (e.g., read-modify-write) are executed **atomically** by either:
  - Disabling interrupts before the sequence and re-enable them afterwards

  or
  - Special instructions that are natively executed atomically

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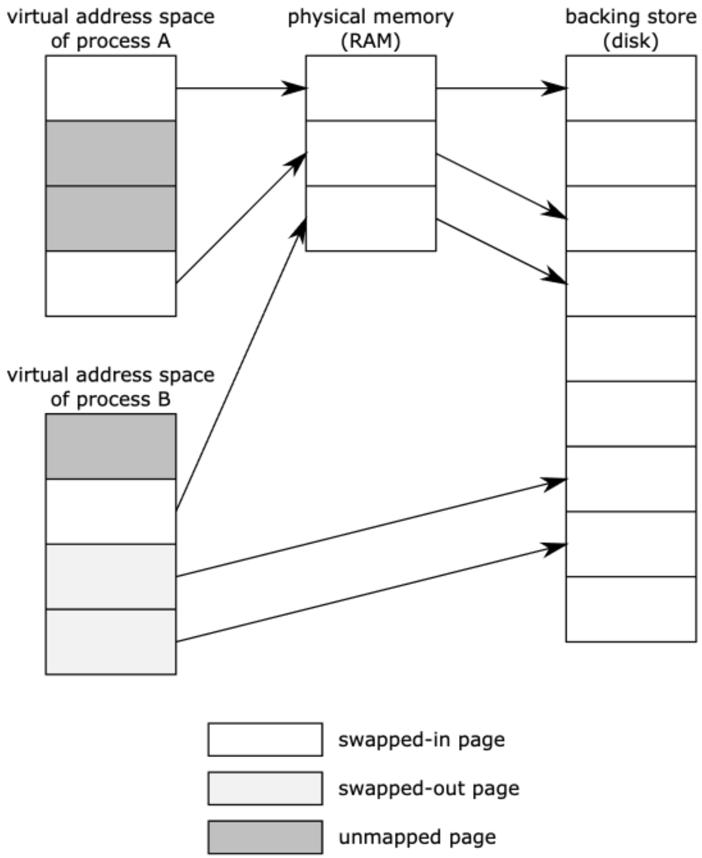
- It allows to run programs without them being entirely loaded in main memory
  - They are entirely loaded in virtual memory, though!
- Implemented both in HW (MMU) and SW (OS)
  - MMU is responsible for translating virtual addresses into physical ones
  - OS is responsible for managing virtual address spaces

Virtual vs. Physical Address Space

- On a 64 bit system the CPU is able to address 2^{64} bytes = 16 exbibytes (EiB)
- Virtual address space ranges from 0 to $2^{64} - 1$
- This is about a billion times more than main memory capacity currently available!
- Virtual address space is typically divided into contiguous blocks of the same size (e.g., 4 KiB), called **pages**
- Pages that are not loaded in main memory are stored on disk

Virtual vs. Physical Address Space



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- The OS must be aware of which pages are loaded in main memory and which ones are on disk

OS Design and Implementation

Design Goals

- The internal structure of different OSs can vary widely

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- **User** vs. **System** goals
  - easy to use vs. easy to design/implement
- It is crucial to separate policies from mechanisms
  - **policy** → *what* is to be done
  - **mechanism** → *how* to do it

Policy vs. Mechanism

- Decoupling policy logic from the underlying mechanism is a general design principle, as it improves system's:
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- Policy changes can be easily adjusted without re-writing (entirely) the code

OS Implementation

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- Early OSs developed in assembly language,
  - PRO → direct control over the HW (high efficiency)
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- Today, a mixture of languages:
  - Lowest levels in assembly
  - Main body in C
  - Systems programs in C, C++, scripting languages like PERL, Python, etc.

OS Structure

- OS should be partitioned into separate subsystems, each with carefully defined tasks, inputs, outputs, and performance characteristics

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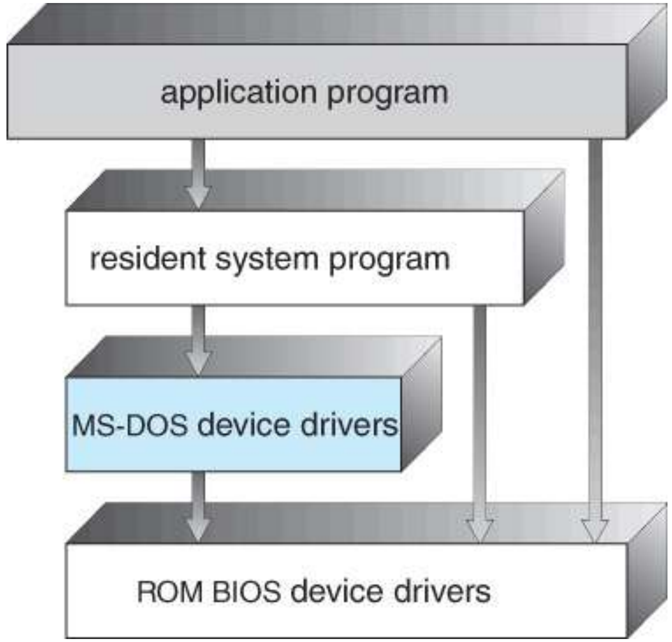
- Various ways to structure an operating system:
  - Simple → MS-DOS
  - Complex → UNIX
  - Layered → MULTICS
  - Microkernel → Mach

MS-DOS Structure: Simple Structure

No modular subsystems at all!

No separation between user and kernel mode



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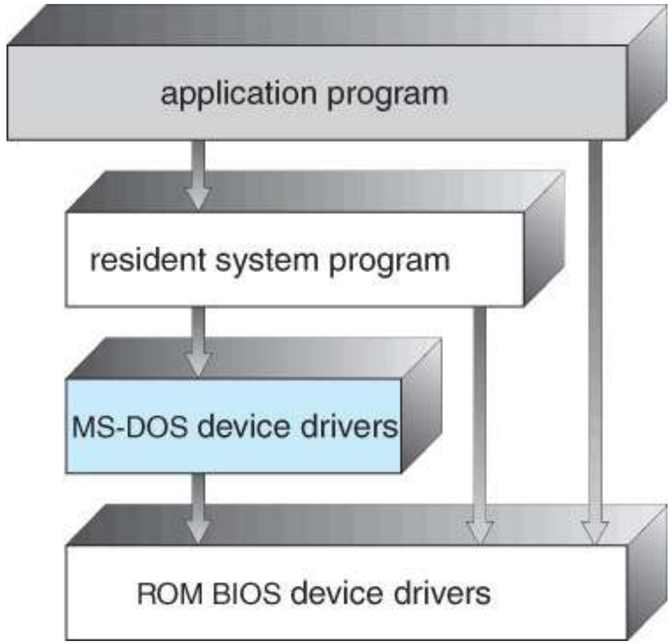
NOTE

user vs. kernel mode was not supported by the 8088 chip set anyway, so that really wasn't an option back then



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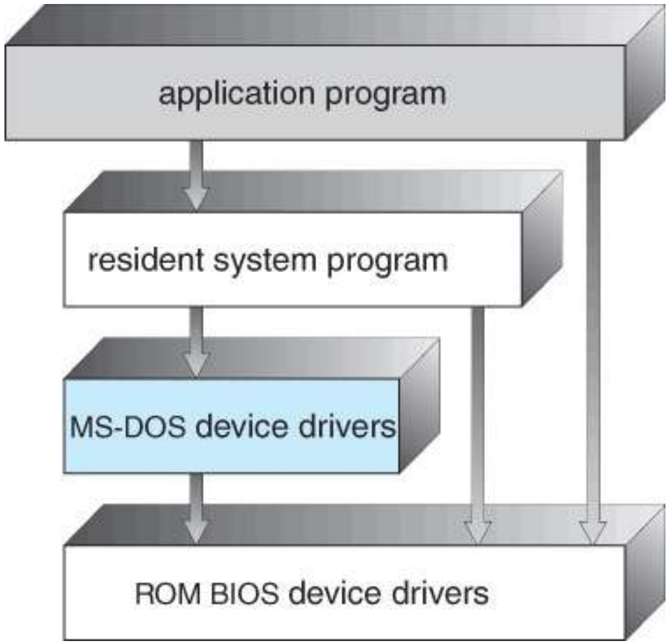
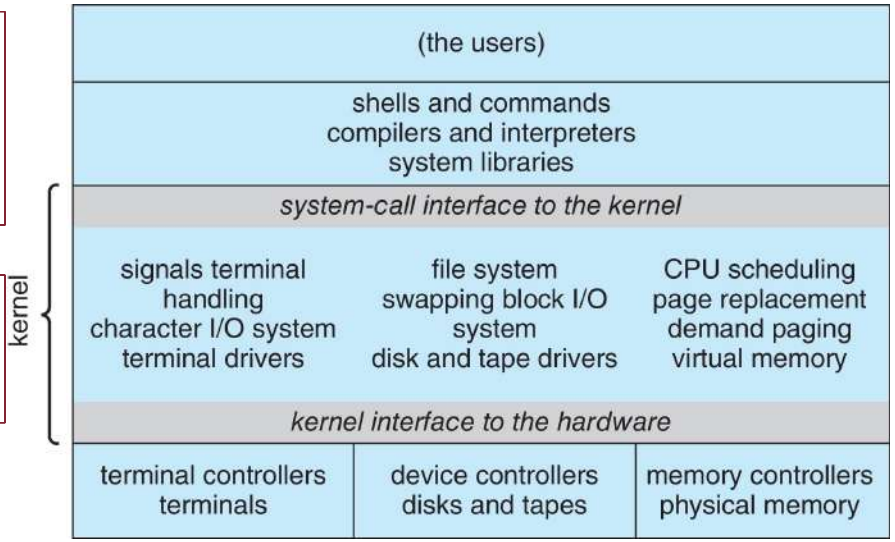
CONs: rigidity, security



UNIX Structure: Traditional Monolithic Kernel

Essentially, one huge piece of software with all services living in the same address space as one big process

Most of modern OSs are variant of this traditional monolithic structure



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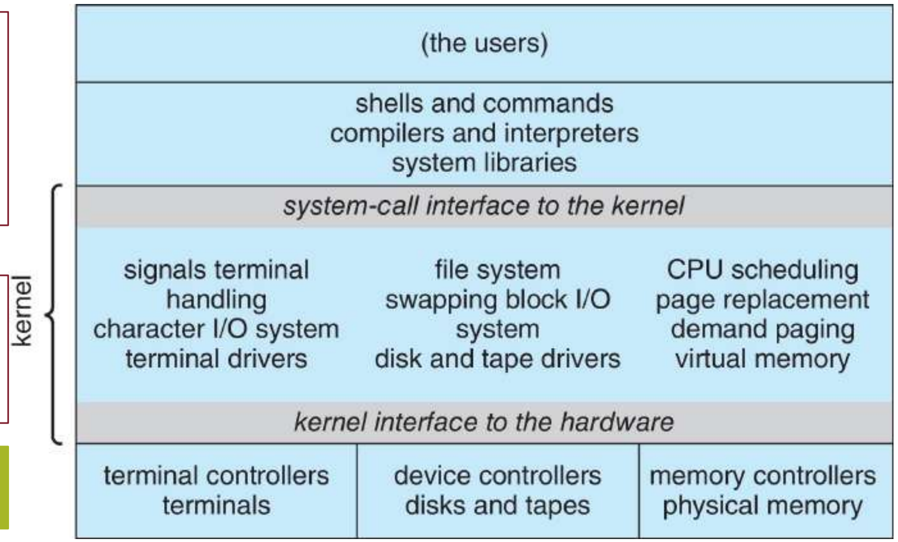
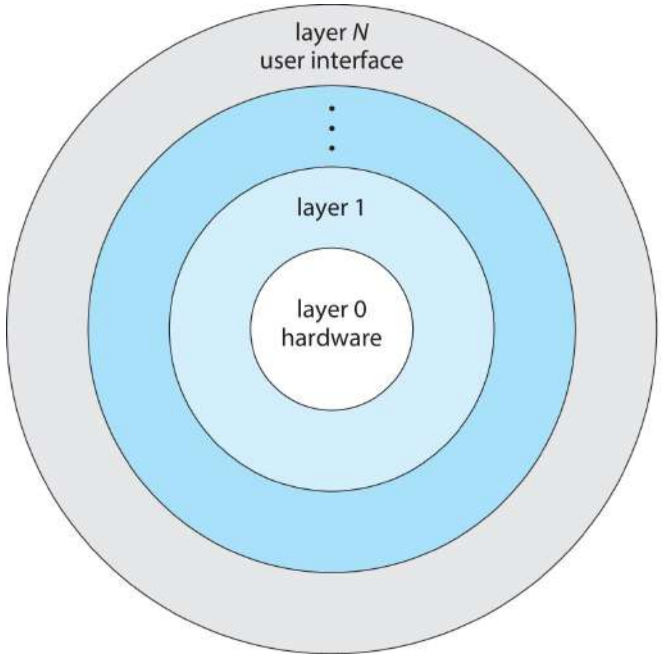


Layered Structure

The OS is divided into N layers
(HW = layer 0)

Each layer L uses the functionalities implemented by the layer L-1 to expose new functionalities to layer L+1



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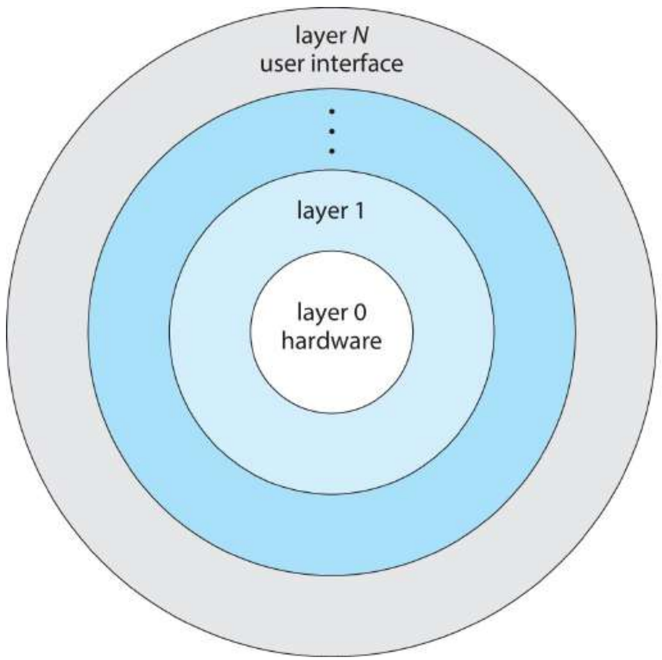
PROs: modularity, portability, easy to debug

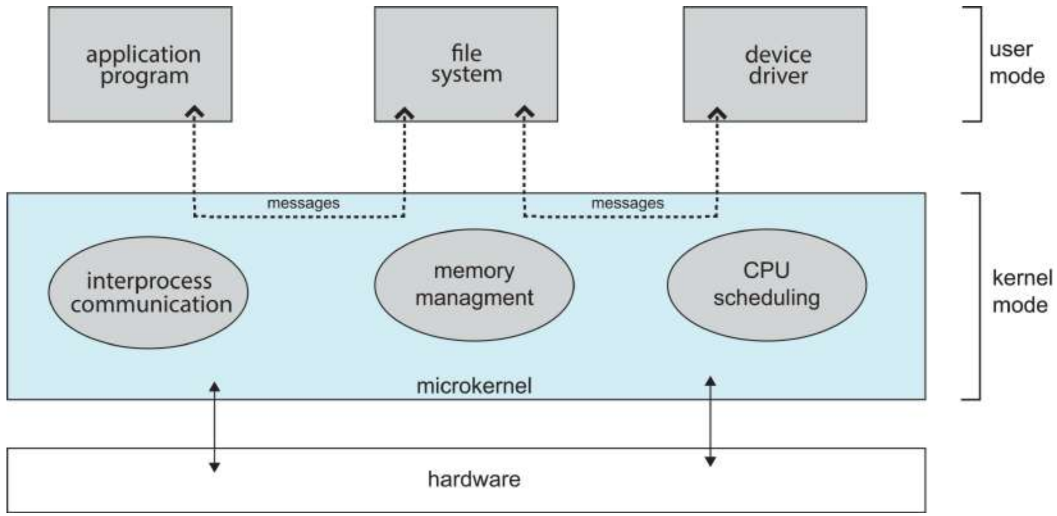
CONs: communication overhead, extra copy



Microkernel Structure

The opposite approach of monolithic

The kernel just contains very basic functionalities, everything else which is still logically part of the OS runs in user mode



Microkernel Structure

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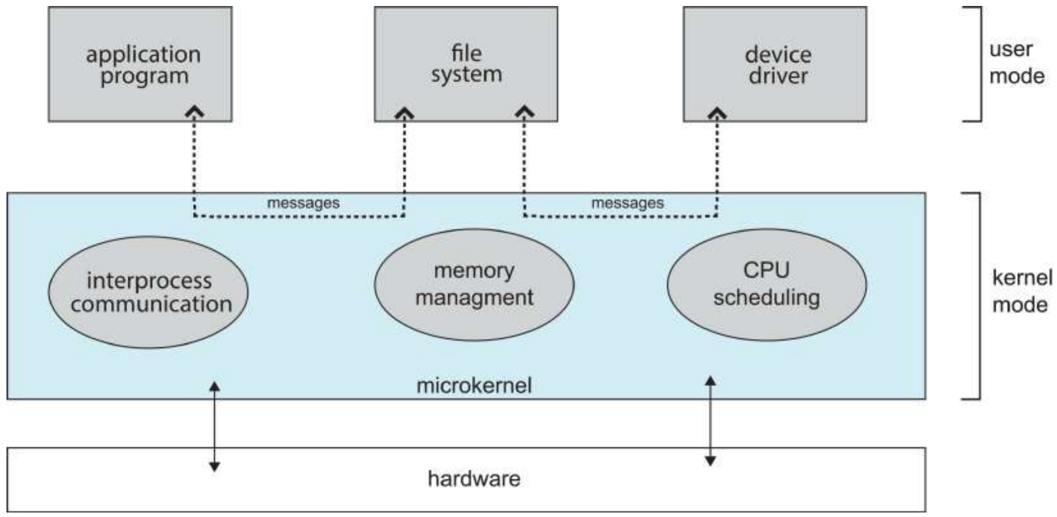
PROs: security, reliability, extendibility

CONs: efficiency (message passing)



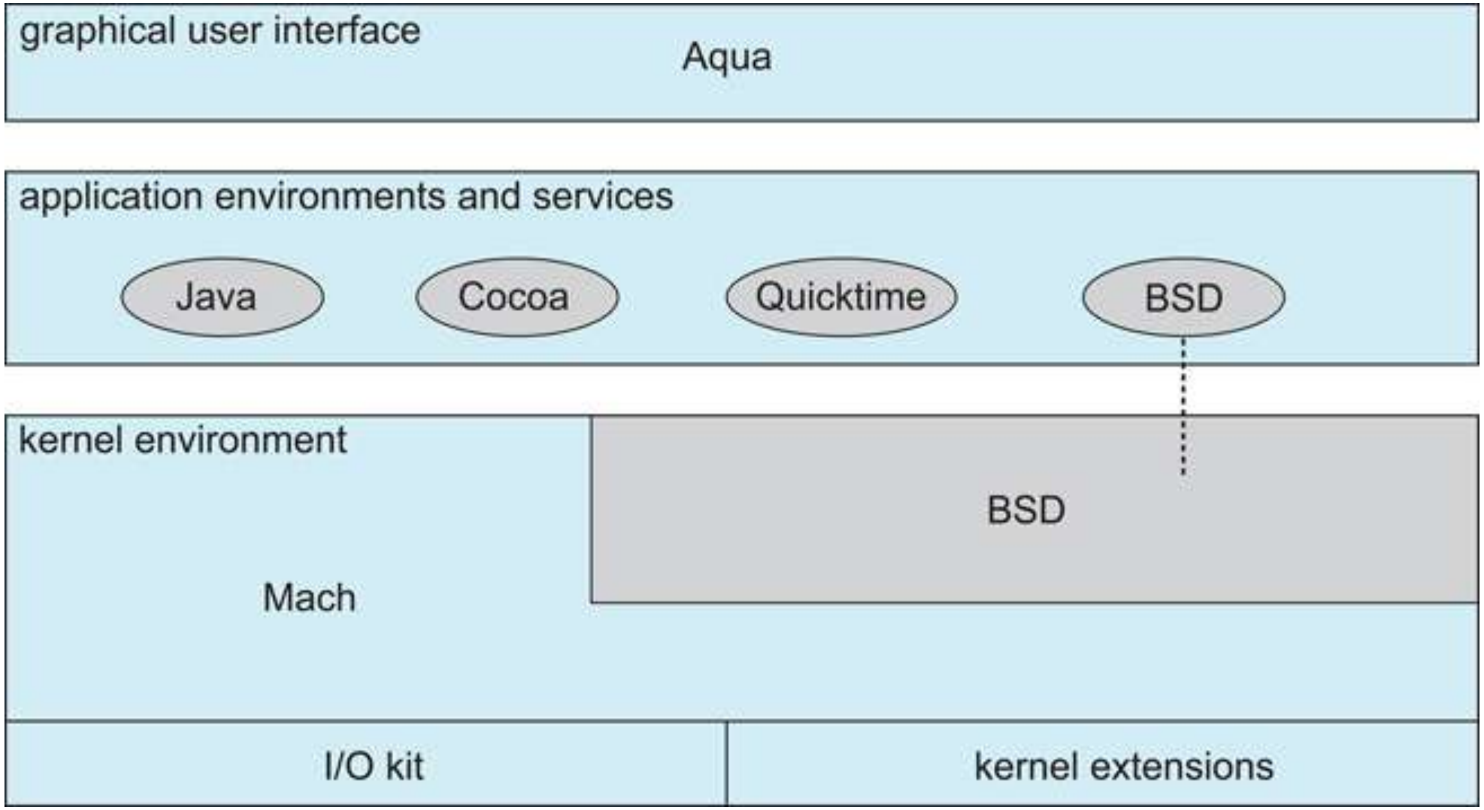
Loadable Kernel Modules (LKMs)

- Many modern OSs use loadable kernel modules (LKMs)
  - Uses object-oriented approach
  - Each core component is separate
  - Each talks to the others over known interfaces
  - Each is loadable as needed within the kernel (i.e., in kernel space)
- Similar to layered structure but more flexible

Monolithic vs. Microkernel: Hybrid

- Try to get the best out of both approaches
  - combining multiple approaches to address performance, security, usability needs
- Linux and Solaris: monolithic + LKMs (i.e., modular monolithic)
- Windows NT: mostly monolithic + microkernel for different subsystems
- Apple Mac OS X: monolithic (BSD UNIX) + microkernel (Mach) + LKMs

Hybrid OS: MacOS X



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- Architecture support is key to OS design
- Most of the services provided by the OS to the applications rely on specific HW features
- The OS is tightly coupled to the HW of the host machine
- Several approaches to OS design and implementation
- **Advice:** Keep your Computer Architecture book at hand!